Carbon Nanotubes and Graphene for Electronics Applications 2010-2020

Technologies, Players & Opportunities

Cathleen Thiele and Raghu Das
IDTechEx
www.IDTechEx.com

IDTechEx Ltd
Downing Park
Swaffham Bulbeck
Cambridge, CB25 0NW
United Kingdom

IDTechEx, Inc.
222 Third Street
Suite 0222
Cambridge MA 02142
United States

IDTechEx (Germany)
Weststraße 49
D - 09112 Chemnitz
Deutschland (Germany)

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Raghu Das, CEO
+ 44 1223 813703
r.das@idtechex.com

Dr Peter Harrop, Chairman
+ 44 1256 862163
p.harrop@idtechex.com

Glyn Holland, Senior Editor
+ 44 1223 813703
g.holland@idtechex.com

The publisher

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the authors

Cathleen Thiele MA graduated from Chemnitz University of Technology with a degree in Print and Media Technology and German Linguistics & Literature. For her final thesis for M.A. degree she worked on printed speakers. During her studies she worked at the Institute of Print and Media Technology processing research topics of printed electronics. She is now a consultant at IDTechEx. c.thiele@idtechex.com

Raghu Das MA (Cantab) is CEO of IDTechEx, the $5 million profitable analyst, consulting and event company. He has lectured on RFID, smart packaging and printed/organic electronics at over 250 events and conferences around the world and is author of several IDTechEx publications. r.das@idtechex.com.

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Executive Summary and Conclusions

Carbon nanotubes and graphene exhibit extraordinary electrical properties for organic materials, and have a huge potential in electrical and electronic applications such as sensors, microelectronic and semi-conductor devices, field emission displays (FEDs), nanoelectrodes and energy conversion devices (e.g., fuel cells and batteries). This report focuses on the latest progress of applying these materials to electronics applications, covering activities of major developers, target markets, what is still needed and market potential.

Carbon nanotubes are rod-like structures of carbon atoms. The strength and properties arise from the unique "rod" shapes. Indeed, applications cited include wires made of carbon nanotubes that are much stronger than steel for a given diameter such that they can even be used to pin satellites to the earth and act as a "lift" to move cargo into space. For the purpose of this report, carbon nanotubes are exciting to many because they enable transparent, flexible and stretchable circuits that are high performance and can even be printed, leading to low cost and large area device manufacture.

There are two types of carbon nanotubes – multi wall versions or single wall versions. It is the latter that are relevant to most electronics, offering metal-like conductivity from an organic material. This is because single wall versions allow for more predictable and controllable performance results compared to versions with many multiple walls rolled in on themselves. However, these are more expensive to make currently with the challenges being chemical complexity, reproducibility and purity.

Key applications are transistors and conductors

Depending on their chemical structure carbon nanotubes (CNTs) can be used as an alternative to organic semiconductors as well as conductors, but the cost is currently the greatest restraint. However, that has the ability to rapidly fall as applications grow and processing improves. Interest is high as CNTs have demonstrated to have carrier mobilities which are magnitudes higher than silicon, meaning that fast switching transistors can be fabricated. CNT will be able to provide high performing devices which can ultimately be made in low cost manufacturing processes over large areas. This is in contrast to polymer organic materials that many companies are developing for transistors, where the mobility is currently very low, severely restricting possible uses.

While the fabrication of CNT transistors is still in early research phases, they are starting to be used for their conductivity properties, in addition to the fact that they can be transparent, flexible and even stretchable. In particular, they are being applied as conductive layers for the rapidly growing touch screen market. They are also likely to become a viable replacement for Indium Tin Oxide (ITO) transparent conductors, which are expensive due to the rare Indium being used and have very limited flexing capability – such as easily cracking under 2% strain.

Opportunities for Carbon Nanotube material supply

A number of companies are already selling CNTs with metallic and semiconducting properties grown by several techniques in an commercial scale but mostly as raw material and in limited quantities. However, the selective and uniform production of CNTs with specific diameter, length and electrical properties is yet to be achieved in commercial scale. A significant limitation for the use of CNTs in electronic applications is the coexistence of semiconducting and metallic CNTs after synthesis in the same batch. Several separation methods have been discovered over the last few years – mostly complex, time-consuming and expensive. The need for purification due to occurring significant impurities adds to this.

In order to get a printable dispersion from raw CNT powder the carbon nanotubes need to be functionalized by physically or chemically attaching certain molecules, or functional groups, to their smooth sidewalls. After this the tubes are dissolvable or dispersible in most organic or inorganic solvents.

Opportunities for Carbon Nanotube device manufacture

There are still some hurdles to overcome when using printing for the fabrication of thin carbon nanotube films. There is relatively poor quality of the nanotube starting material, which mostly shows a low crystallinity, low purity and high bundling. Subsequently, purifying the raw material without significantly degrading the quality is difficult. Furthermore there is also the issue to achieve good dispersions in solution and to remove the deployed surfactants from the deposited films.

Given these issues and additional steps needed after the manufacture of the raw material, the final CNT films are still costly to produce and have high sheet resistance for a given transparency. However approximately 90% of the costs for product films are due to post processing, which does not include the CNT material cost. Given the amount of work on the topic, we expect this to improve dramatically over the next two years.

Market Opportunity and roadmap for Carbon Nanotubes and Graphene

Graphene and MWCNTs are already in fairly high production – tens of tonnes per year. Estimates of the amount of MWCNTs produced in 2008 are about 100 tons in total from companies such as

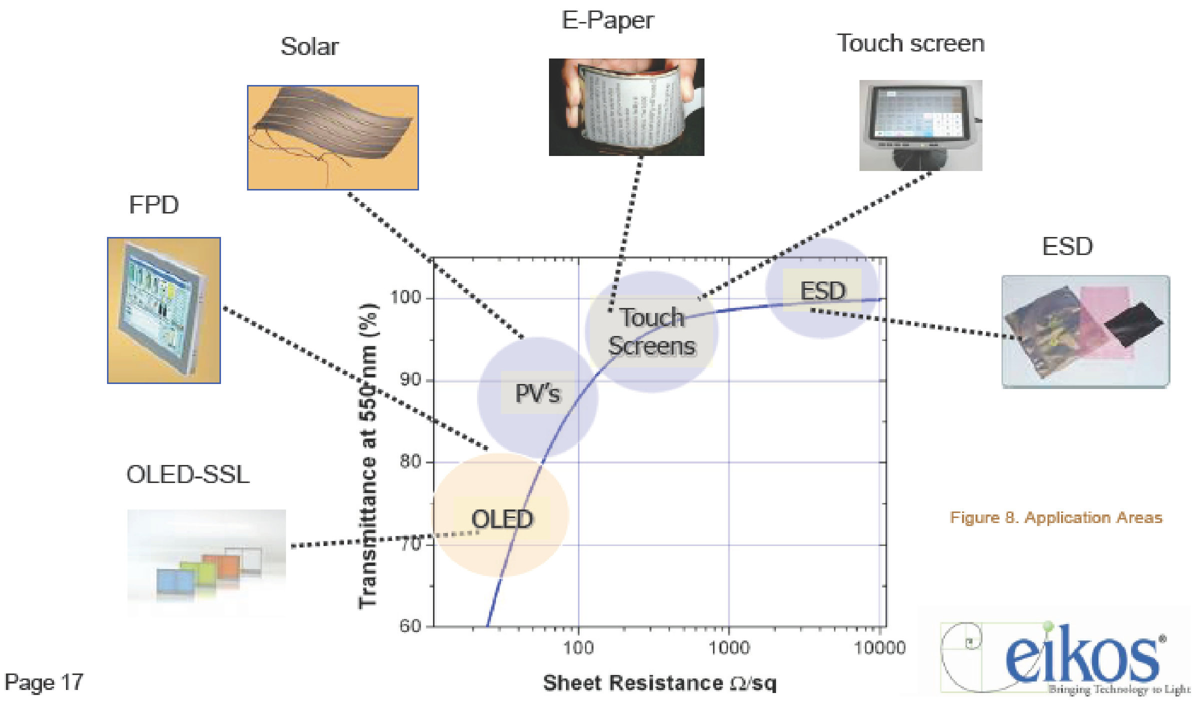
Bayer and Showa Denko. In 2009 the amount delivered could double. However, most of these uses are for non electronic/electrical products, or simple applications such as electromagnetic shielding.

The commercialization of SWCNTs, relevant to all the electronics described in this report, is still in its infancy. Of note, Eikos, Uniydym and Canatu are trying to scale up manufacturing, but we doubt that the others, such as NEC and Bayer, are not moving towards this goal either. The challenge, described in greater detail in this report, are mainly producing a high yield of SWCNT with a small variation in size in a cost effective, scalable manner. This is the bigger issue rather than processing the materials to make devices, which is nevertheless not insignificant. While there is capacity in place this year to make tens of tons of SWCNTs, these have a wide range of purity, but for some applications have now reached a tipping point.

Conductive films will come first

In electronics, other than electromagnetic shielding, one of the first applications for CNTs will be transparent conductors. Here, applications are for displays, replacing ITO, touch screens, photovoltaics and display bus bars, connecting TFTs to the front plane, such as OLEDs. The following figure shows different applications and their requirements in terms of sheet resistance and optical wavelength transmittance.

Figure 1 Targeted applications for carbon nanotubes by Eikos



Source Eikos

Canatu, a supplier of such films, told IDTechEx, "We will be selling homogeneous and prepatterned films in various conductivities, transparencies, patterning and fractional coverage. We will begin by supplying selected strategic partners with specialty films made to their specifications. In so called "equivalent square meters" (equivalent to 80% transparency, homogeneous film), we plan to be selling approximately 1,000 m^2 in 2010, 15,000 m^2 in 2011, 40,000 m^2 in 2012, 100,000 m^2 in 2013, and 300,000 m^2 in 2014." This is a strong growth – 300% over five years.

Transistors

Possibly the most exciting prospect is for CNTs or graphene to be used to printed transistors that work at 50 GHz or more, outperforming the tradition silicon chip at much lower cost. The state of play is summarised below.

Supercapacitors

Supercapacitors (ultracapacitors) are bridging the gap between batteries and capacitors, as shown below.

Table 1 Supercapacitors

TFT Type and typical mobility	Strength	Limitations	Improvements needed
Organic (OTFT) Up to 4cm^2/Vs but typically less than 1 cm^2/Vs for stable devices LOWEST MOBILITY OF FREQUENCY	Low process temperature Printable CMOS possible though n type is difficult Flexible Low cost in volume	Low mobility (improving) Low K dielectrics unless Inorganic Temperature rang Threshold voltage uniformity High voltage 10-100v	Breakthrough materials Self-assembled ordering Manufacturability
a-Si 1 cm^2/Vs	Process maturity and simplicity Cost Flexible versions available	Unacceptable threshold voltage shift for current driven OLEDs High temperature substrate Limited driver circuitry Integration Lifetime Not route to printing and low cost	Greater threshold voltage stability High mobility (nanocrystalline)
ZnO Family 10 cm^2/Vs for printed versions, 50 cm^2/Vs + for non printed	Moderate to good mobility Low process temperature CMOS possible but p type difficult Thermal stability Printable Transparent Potentially low cost	Relatively immature Exotic gate dielectric materials Stability unproven High process temperature but precursors are expect to permit low temperature	Demonstrated manufacturability Gate dielectrics Demonstrated stability CMOS capability
Silicon nanoparticle ink Over 400 cm^2/Vs demonstrated, typically 250 cm^2/Vs for printed versions	High mobility Printable Low cost CMOS	High temperature substrate required Difficulty in making ink – agglomeration	Low temperature sintering desirable for cheapest substrates
Poly crystalline-Si ~1500 cm^2/Vs	High mobility capability for integrated electronics Mature infrastructure CMOS	Intra-substrate process uniformity High temperature substrate Scalability and capital cost Not printable	Uniformity: tool / process Imaging optics and laser Cost Fragility
Carbon Nanotube (CNT) or graphene 100,000cm^2/Vs demonstrated for non printed, ~2000 cm^2/Vs for printed versions with the ability to go higher HIGHEST MOBILITY OF FREQUENCY	Highest known mobility/ frequency Transparent Flexible Printable Potential to be low cost CMOS	Material purity, cost High yield manufacturing Processes Consistency of performance Poor on-off ratios Little understood	Low cost high quality materials Breakthrough in processing Volume production Better theory leading to better on-off ratios

Source IDTechEx

Graphene, carbon nanotubes and certain conductive polymers, or carbon aerogels, may become practical for supercapacitors, products that are already in use today in a wide range of applications, from wireless sensors to portable consumer electronic devices. See the IDTechEx report "Batteries, Supercapacitors, Alternative Storage for Portable Devices".

Transistors, etc to follow

While several organizations have demonstrated CNTs for transistors, as covered in this report, but it will take time before these are and other CNT or graphene based electronic components commercialized. Conservatively, IDTechEx anticipate this may be available in volume from 2015 onwards or more optimistically it could be 2 years earlier. Challenges are cost, but also material purity, device fabrication, and the need for other device materials such as suitable dielectrics. However, the opportunity is large, given the high performance, flexibility, transparency and printability.

99 Organizations profiled

This report profiles 99 global organizations involved in the topic. The following table is a summary of the activities of these organizations. While manufacturers in North America seem to focus more on SWCNTs; Asia and Europe, with Japan on top, are leading the production of MWCNTs with Showa Denko, Mitsui and Hodogaya Chemical being the largest companies.

Table 2 Activities of 99 Organizations

Organizations	Supplier of MWCNT	Supplier of SWCNT	Graphene Supplier	CNT / Graphene ink or suitable printing machines	Conductors & films	Transistors	Photovoltaic	Super Capacitors / Batteries	Loud-speakers	Memory	Threads/ Textiles	Sensors
Aneeve Nanotechnologies LLC, USA	X	X	X	X	X							X
Angstron Materials LLC., USA			X									
Apex Nanomaterials, USA		X										
Applied Nanotech, USA						X						
Arry International Group, Hong Kong	X	X										
BASF, Germany			X									
Bayer MaterialScience, Germany	X											
Brewer Science, USA	X	X		X		X				X		
Canatu Ltd., Finland					X							
Carben Semicon Ltd, Russia			X									

Organizations	Supplier of MWCNT	Supplier of SWCNT	Graphene Supplier	CNT / Graphene ink or suitable printing machines	Conductors & films	Transistors	Photovoltaic	Super Capacitors / Batteries	Loud-speakers	Memory	Threads/ Textiles	Sensors
Carbon Solutions, Inc., USA		X										
CarboLex, Inc., USA		X										
Cap-XX Australia								X				
Case Western Reserve University, USA												
Catalyx Nanotech Inc., USA			X									
CheapTubes, USA	X	X										
Chengdu Organic Chemicals Co. Ltd. (Timesnano), China	X	X										
CNano Technology Ltd., USA	X											
Cornell University, USA				X								
CSIRO, Australia											X	
Dainippon Screen Mfg. Co., Ltd., Japan						X						
DuPont, USA				X								
Eikos, USA					X							
Frontier Carbon Corporation (FCC), Japan	X	X						X				
Fujitsu Laboratories, Japan						X						
Future Carbon GmbH, Germany	X			X								
Georgia Tech Research Institute (GTRI), USA					X	X	X					
Graphene Energy Inc., USA								X				
Graphene Industries Ltd., UK			X									
HeJi, Inc., China	X	X										
Helix Material Solutions Inc., USA	X	X										

Organizations	Supplier of MWCNT	Supplier of SWCNT	Graphene Supplier	CNT / Graphene ink or suitable printing machines	Conductors & films	Transistors	Photovoltaic	Super Capacitors / Batteries	Loud-speakers	Memory	Threads/ Textiles	Sensors
Hodogaya Chemical Co., Ltd., Japan	X											
Honda Research Institute USA Inc., USA												
Honjo Chemical Corporation, Japan	X	X										
HRL Laboratories, USA						X						
Hyperion Catalysis International, Inc	X											
IBM, USA						X						
ILJIN Nanotech Co. Ltd., Korea	X	X			X							
Intelligent Materials PVT. Ltd. (Nanoshel), India	X	X										
Massachusetts Institute of Technology (MIT), USA						X						
Max Planck Institute for Solid State Research, Germany								X				
MER Corporation, USA	X	X										
Mitsui Co., Ltd, Japan	X											
Mknano, Canada	X	X										
Nano-C, USA	X	X					X					
NanoCarbLab (NCL), Russia		X										
Nano Carbon Technologies Co., Ltd. (NCT), Japan	X											
Nanocomb Technologies, Inc. (NCTI), USA					X						X	
Nanocs, USA	X	X										
Nanocyl s.a., Belgium	X	X										
NanoIntegris, USA	X	X										
NanoLab, Inc., USA	X	X		X								

Organizations	Supplier of MWCNT	Supplier of SWCNT	Graphene Supplier	CNT / Graphene ink or suitable printing machines	Conductors & films	Transistors	Photovoltaic	Super Capacitors / Batteries	Loud-speakers	Memory	Threads/ Textiles	Sensors
NanoMas Technologies, USA	X	X										
Nano-Proprietary, Inc., USA			X									
Nanoshel, Korea	X	X										
Nanostructured & Amorphous Materials, Inc., USA	X	X										
Nanothinx S.A. , Greece	X	X										
Nantero, USA				X						X		
National Institute of Advanced Industrial Science and Technology (AIST), Japan					X	X		X				
NEC Corporation, Japan						X						
New Jersey Institute of Technology (NJIT), USA							X					
Noritake Co., Japan						X						
Northeastern University, Boston, USA												
Optomec, USA				X		X						
Pennsilvania State University, USA						X						
PETEC (Printable Electronics Technology Centre), UK						X	X					
Rice University, USA				X	X						X	
Rutgers University, USA			X		X							
Samsung Electronics, Korea					X					X		
SES Research, USA	X	X										
Shenzhen Nanotechnologies Co. Ltd. (NTP)	X	X										

Organizations	Supplier of MWCNT	Supplier of SWCNT	Graphene Supplier	CNT / Graphene ink or suitable printing machines	Conductors & films	Transistors	Photovoltaic	Super Capacitors / Batteries	Loud-speakers	Memory	Threads/ Textiles	Sensors
Showa Denko Carbon, Inc., Japan	X											
ST Microelectronics, Switzerland						X						
SouthWest NanoTechnologies (SWeNT), USA		X		X	X			X				
Sungkyunkwan University Advanced Institute of Nano Technology (SAINT), Korea			X		X							
Sun Nanotech Co, Ltd., China	X											
Surrey NanoSystems, UK	X	X										
Thomas Swan & Co. Ltd., UK	X	X										
Toray Industries, Japan	X	X										
Tsinghua University, China	X								X			
Unidym, Inc., USA					X	X						
University of California Los Angeles (UCLA), USA					X		X	X				
University of Cincinnati (UC), USA											X	
University of Michigan, USA											X	X
University of Oklahoma, USA		X										
University of Pittsburgh, USA												X
University of Southern California (USC), USA					X	X		X				
University of Stanford, USA						X		X			X	
University of Stuttgart, Germany					X	X						
University of Surrey, UK					X							
University of Texas at Austin, USA								X				

Organizations	Supplier of MWCNT	Supplier of SWCNT	Graphene Supplier	CNT / Graphene ink or suitable printing machines	Conductors & films	Transistors	Photovoltaic	Super Capacitors / Batteries	Loud-speakers	Memory	Threads/ Textiles	Sensors
University of Tokyo, Japan				X	X							
University of Wisconsin-Madison, USA							X					
Vorbeck Materials Corp, USA				X								
Wisepower Co., Ltd., Korea								X				
XG Sciences, USA			X									
Xintek Nanotechnology Innovations, USA	X	X			X							
Y-Carbon, USA	X											
Zoz GmbH, Germany												
Zyvex, Inc., USA			X									

Source IDTechEx

1. Introduction

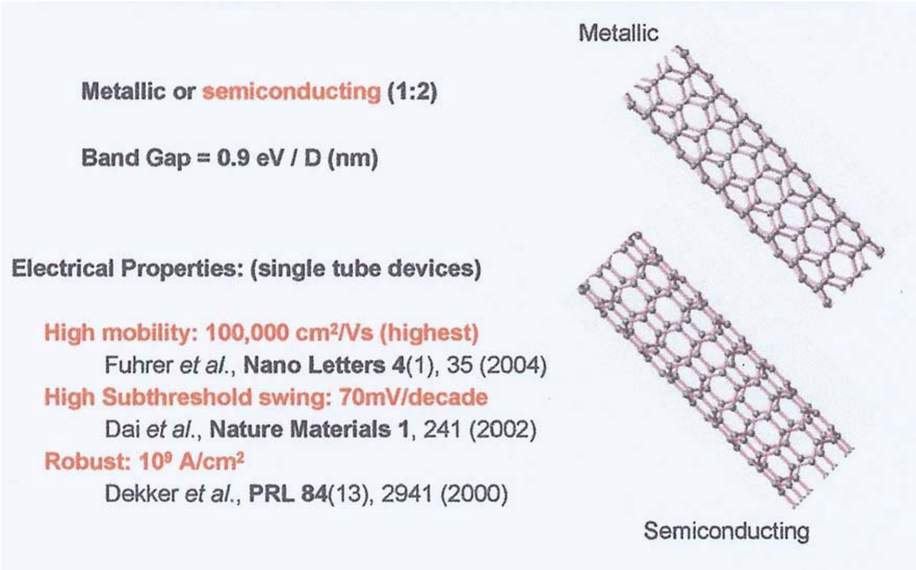
First discovered by Sumio Iijima from NEC in 1991/92, and now a global focus of research and development, carbon nanotubes (CNT) are nanoscale materials that are highly attractive for electronic devices, energy storage devices, sensors and actuators.

1.1. What are Carbon Nanotubes

Due to extraordinary mechanical, thermal and electrical properties and small size carbon nanotubes (also known as "bucky tubes") have a huge potential in conventional and high technology electronic applications, such as sensors, microelectronic and other semi-conductor devices, field emission displays (FEDs), nanoelectrodes and energy conversion devices (e.g., fuel cells and batteries). Depending on the chemical structure they can act as metallic conductor or semiconductor, similar to silicon, appearing in the same group in the periodic table.

CNTs consist either of only one graphene layer (single-walled carbon nanotubes, SWCNTs) or multiple ones (multi-walled carbon nanotubes, MWCNTs) rolled in on themselves forming a tube shape. They can range from less than a micrometer to several millimetres in length but are usually only a few nanometres wide, which is only a ten-thousandth the diameter of a human hair. The hollow, cylindrical tubes are composed entirely of carbon, like the members of the fullerene family; graphenes are planar sheets and the famous "buckyballs" are spherical fullerenes of 60 carbon atoms.

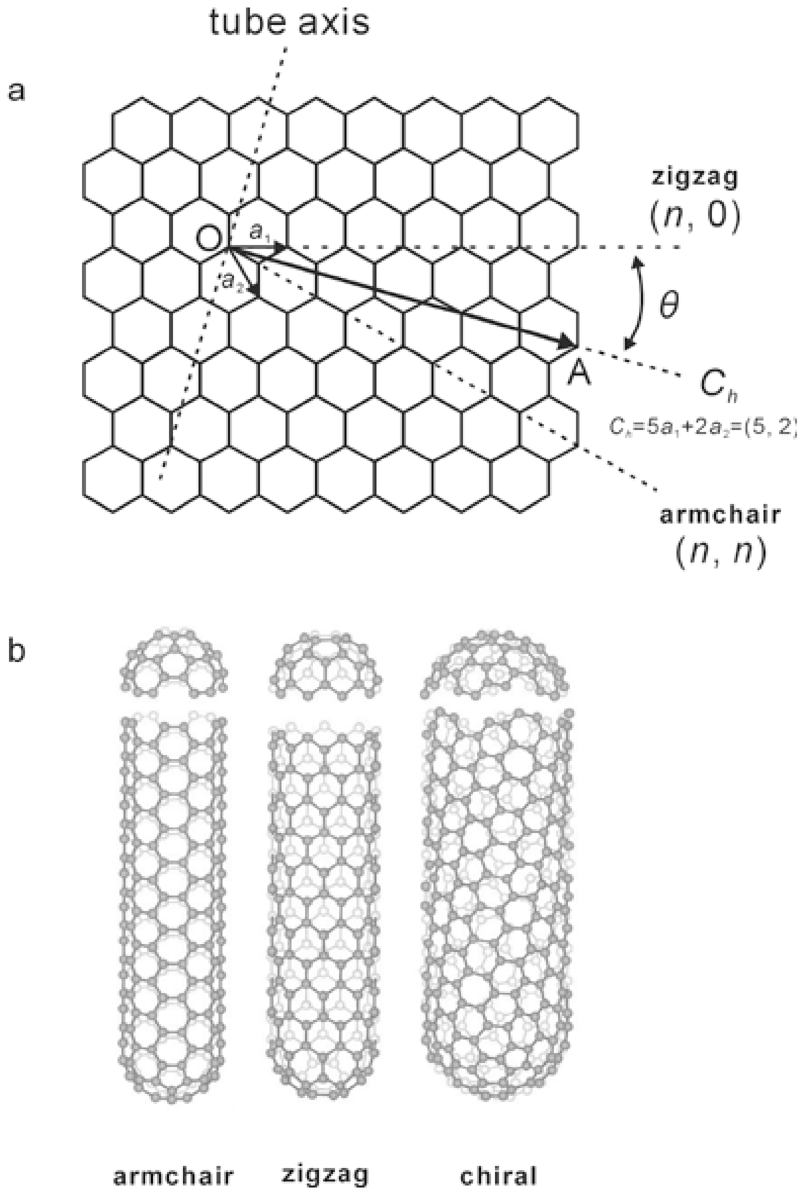
Fig. 1.1 **Structure of single-walled carbon nanotubes**



Source University of Illinois

The properties of CNTs, especially the electrical properties, are strongly dependent on the structure and the way the tubes are "wrapped up". This is represented by what is called the chiral vector, which is a pair of indices (n, m) standing for the number of unit vectors along two directions in the crystal lattice of graphene. The formation m=0 is called "zigzag" and n=m is called "armchair". All other formations are referred to as "chiral".

Fig. 1.2 **The chiral vector is represented by a pair of indices (n, m). T denotes the tube axis, and a1 and a2 are the unit vectors of graphene in real space**



Source http://fgmdb.kakuda.jaxa.jp/SSPSHTML/e-001st1.html

1.1.2. History of CNTs

In 1985 a group of scientists – Kroto, Heath, O'Brien, Curl and Smalley – discovered a new class of materials called fullerene. The most popular one is the C60 molecule.

In 1991 trying to improve the fullerene synthesis Sumio Iijima at NEC discovered MWCNTs for the first time in the soot of arc discharge. Two years later they were able to create SWCNTs and found different methods to produce them using transition-metal catalysts. Since the 1990s carbon nanotubes have been widely analysed for the use in applications.

1.2. What is graphene?

Graphene is being studied worldwide for electronics, displays, solar cells, sensors, and hydrogen storage.

Graphene has a two-dimensional structure that looks like chicken wire and can be thought of as unrolled CNTs - it consists of a single planar layer of carbon atoms arranged in a honeycomb lattice. Graphene forms the basic structural element of some carbon allotropes including graphite and carbon nanotubes. The surface area can be theoretically as high as around 2,600 m^2/g, but currently it reaches only 1,700 m^2/g in practice. Being 200 times stronger than steel, graphene is the strongest known material.

Graphene is an ideal candidate for many high-speed computing applications in the multibillion-dollar semiconductor device industry. Researchers found an electron moved at 1/300th the speed of light through graphene - potentially enabling terahertz computing, at processor speeds 100 to 1,000 times faster than silicon they claim.

"Graphene has extraordinary electron-transport properties; its monolayer thickness yields exquisite sensitivity to changes in environment, and its mechanical and thermal properties equal or exceed those of the best conventional materials," said Michael Spencer, professor of electrical and computer engineering at Cornell. He also adds: "The superior properties of graphene and graphene-related materials present an extraordinary opportunity for enabling new classes of electronic, optoelectronic and electromechanical devices and sensors."

Nevertheless, one crucial issue remained – getting it to perform as a true semiconductor. The material lacks the ability to act as a switch. The University of Illinois found a way to overcome this problem by cutting nanoribbons in a special way so that they could be turned on and off.

1.2.1. Manufacturing graphene

In 2004 physicists at the University of Manchester in England found a simple way to produce graphene. With a method known as mechanical exfoliation they peeled off layers from three-dimensional graphite using a piece of Scotch tape. Still, it is very difficult to create large batches of graphene. The Scotch tape method might be the simplest one, but it produces imperfect flakes that are useless for many practical applications.

Another approach is growing graphene on silicon-carbide crystals, which was pioneered by researchers at Georgia Tech. This produces a purer form of graphene but scaling is an issue – this is not applicable for the production of commercial quantities.

Single layers of graphene oxides are solution processable and already commercially available in large quantities. With single layer graphene oxides thin films with a thickness of 0.7 to 1.2 nm can be achieved.

A faster and cheaper way to produce graphene was presented in September 2009 by a research team led by Professor Yoo Ji-beom of Sungkyunkwan University's School of Advanced Materials Science and Engineering. The researchers worked in collaboration with the Samsung Advanced Institute of Technology and Russian scientists.

The team treated graphite with heat and a solution containing fluorine to produce expanded graphite - graphite with widened gap between the layers - which can then be placed in water-based solutions or organic solvents to produce graphene.

Another potential graphene material for printed electronics consists of nano-scale graphene-platelets (NGPs). However, processing in a solution is still a problem for many types of NGPs. Usually they are provided as oxides or other form of graphene.

NGPs are multilayered structures with 8 to 12 layers of Graphene and a typical thickness of 5 to 10 nm. NGPs are predicted to have a range of unusual physical, chemical, and mechanical properties. The NGPs can exhibit attractive properties like carbon nanotubes (CNTs) and carbon nano-fibers (CNFs).

1.3. Properties for electronic and electrical applications

Looking closer, the huge potential of carbon nanotubes for electronic application derives in particular from their excellent mechanical strength, exceptionally high elastic properties, large elastic strain, low density, high thermal conductivity, and relative chemical inertness, not just superlative electrical properties.

The unique strength of CNTs arises from the chemical bonding of the carbon atoms similar to graphite. Between the individual carbon atoms covalent sp^2 bonds are formed, which results in extraordinary resilience and stiffness in terms of tensile strength and elastic modulus. In particular, single-walled carbon nanotubes are characterized by an outstanding electrical conductivity that MWCNTs cannot rival. Challenges arise in chemical complexity, reproducibility and purity regarding conductivity state, to name only some.

With a specific strength of up to 48,000 $kN \cdot m \cdot kg^{-1}$ carbon nanotubes are the stiffest material known. In comparison, high-carbon steel has a specific strength of only 154 $kN \cdot m \cdot kg^{-1}$. In addition to that, carbon has a relatively low density for a solid of 1.3-1.4 $g \cdot cm^{-3}$.

Depending on the chemical structure carbon nanotubes could be an alternative to organic semiconductors as well as conductors, but the cost is currently a great restraint. The electrical conductivity along the tube axis is a function of the chirality, i.e. the degree of twist as well as diameter.

Dr. Yaniv, CEO of Applied Nanotech Inc. told IDTechEx, "Chirality relates to the skew of the rolled-up graphitic sheet of carbon atoms. This determines the semiconducting energy band gap affecting the mobility and threshold voltage." Thus having CNTs with all the same chirality allows a smaller variation in the mobility and threshold voltage.

In particular, the symmetry affects the electrical properties of a nanotube. The helicity of the graphene sheet determines the conductive state. It shows metallic properties when the relation of the unit vectors is "n = m". With a relation "n – m is a multiple of 3" it shows the best semiconducting properties and has a very small band gap. In all other cases the nanotube is only a moderate semiconductor. In theory, metallic nanotubes (n=m) can carry an electrical current density of 4×10^9 A/cm^2.

The tensile strength of CNTs is 60GPa and Young's modulus is over 1TPa, which makes them as stiff as diamond. Typically they have an electrically conductivity of 10^{-6} Ohm/m and a thermal conductivity of 1750 to 5800 W/mK. Due to their covalent chemical bonds they do not undergo electromigration or atomic diffusion, which has a positive effect on the current density being as high 4×10^9 A/cm^2 – 1,000 times greater than copper.

More important for the use in printed electronics are single-walled carbon nanotubes, because it is easier to control the shape and resulting properties of only one hallow tube than of multiple ones rolled in on themselves as it is the case for MWCNTs. SWCNTs can have a diameter varying from 0.4 to 3 nm, are relatively stiff and outstandingly strong. This results in a high Young's modulus and high tensile strength. SWCNTs tend to agglomerate and form bundles of several tens of nanotubes.

1.4. Manufacture of CNTs

Quite a few companies are already selling CNTs with metallic and semiconducting properties grown by several techniques in a commercial scale but mostly as raw material and in limited quantities. We cover the leading organizations involved throughout the value chain in this report – 77 in total. While manufacturers in North America seem to focus more on SWCNTs; Asia and Europe, with Japan on top, are leading the production of MWCNTs with Showa Denko, Mitsui and Hodogaya Chemical being the largest companies.

However, the selective and uniform large-scale production of CNTs with specific diameter, length and electrical properties is yet to be achieved. The coexistence of semiconducting and metallic CNTs after synthesis and the difficulty in separating them have been significant limitations for the use of carbon nanotubes in electronic applications. Lacking a method that reliably fabricates CNTs with the same structure and chirality, several separation methods have been discovered over the last years – mostly complex, time-consuming and expensive.

For all manufacturing processes a hot transition metal based on nanoparticles is needed as a catalyst. Placed in contact with a carbon source in form of a gas, the latter one deposits carbon atoms that grow on the catalyst surface. The characteristics of the resulting CNTs, i.e. structure (single-walled or multi-walled), diameter and others, strongly depend on the diameter of the catalyst.

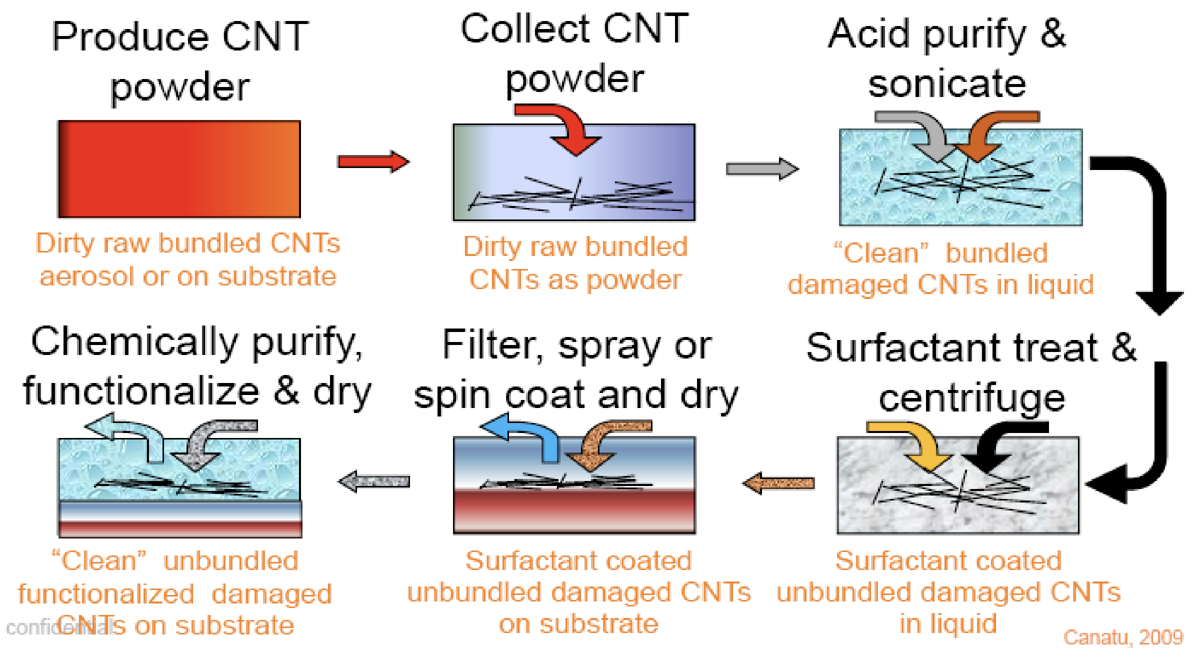
The original synthesis method from 1991 was Arc Discharge, which was later followed by several other processes. Today, the main ones are Arc Discharge, Laser Ablation and Chemical Vapor Deposition (CVD). The last one is mainly used to produce multi-walled carbon nanotubes (MWCNTs). Synthesis processes allow the production of large quantities of CNTs but most of them need to take place in vacuums or with process gases. Recent advances, e.g. in catalysis and continuous growth processes, make carbon nanotubes more commercially viable.

The synthetic techniques known for SWCNTs mostly generate significant quantities of impurities including amorphous carbon, residual metal catalyst and graphitic nanoparticles. There are currently three basic methods for separation, namely gas-phase, liquid-phase, and intercalation methods. However, purification procedures increase the production costs and by that limit the use in commercial applications.

A great challenge remains the dispersion of CNTs. The two main procedures used are probe style and bath style ultrasonic systems. However, to make nanotubes more easily dispersible in most solvents, a functionalization step is needed. That means it is necessary to physically or chemically attach certain molecules, or functional groups, to their smooth sidewalls. To fabricate thin films of nanotubes using dispersions several methods such as filtration, spraying, self-assembly, and spin coating as well as printing methods of nanotube 'ink' have been developed. Dispersions are already available from a few companies, namely Hyperion, Zyvex, Vorbeck Materials and others.

Single-walled CNTs are much more difficult to manufacture and analogous much more expensive. Currently, the capacity for MWCNT production exceeds that of SWCNTs and production costs need to go further down in order to achieve a large-scale market in the near future.

Fig. 1.3 **Traditional CNT film processes are complex**



Source Canatu

1.4.2. Arc Method

The discovery of the CNTs with arc discharge was more or less an accident. Sumio Iijima from NEC found multi-walled carbon nanotubes in the residue of an electrical arc discharge. Carbon nanotubes are self-assembling from the carbon vapor that is caused by an arc discharge between two carbon electrodes. Sometimes a catalyst is used. The yield of this method, which is around 30%, highly depends on the uniformity of the plasma arc and the temperature. Still, it is the most widely used method for the synthesis of both single-walled and multi-walled carbon nanotubes. However, it produces high impurities and requires further purification to separate the resulting complex mixture of components.

1.4.3. Laser Ablation Method

The laser ablation method was first developed in 1996 by Dr. Richard Smalley and co-workers at Rice University, USA. The procedure needs to take place in a high-temperature chamber containing inert gas. A pulsed laser vaporizing a graphite board with a following cooling of the vapor causes the carbon nanotubes to develop on the chamber surface. Using composite of graphite and metal catalyst particles, mainly single-walled carbon nanotubes can be produced at a yield of around 70% purity. The diameter of the SWCNTs can be determined by the reaction temperature. This process is more expensive than either Arc Discharge or CVD.

However, it has been unclear how to scale up production. Additionally, laser ablation leads to the growth of highly tangled CNTs - issues that are not easy to deal with when it comes to fabrication of nanotube-device architectures for applications.

1.4.4. Chemical Vapor Deposition (CVD)

Chemical Vapor Deposition is a very common method for the commercial production of CNTs, because of the large amounts that can be formed. A substrate containing catalytic metal particles (nickel, cobalt, iron, or a combination) on the surface is heated to approximately 700°C inside a vacuum chamber, in which two types of gas are poured. The carbon-containing one passing over the metal particles causes the metal to separate and form carbon nanotubes. The size of those can be controlled by the size of the metal particles.

Carbon nanotubes can also grown directly on a substrate using a CVD process where the catalyst is first deposited on the substrate. Fujitsu is a leading manufacturer of CNTs grown directly on the substrate.

1.5. Printing Carbon Nanotubes

In order to get a printable dispersion from raw CNT powder produced with the mentioned processes above, the carbon nanotubes need to be functionalized by physically or chemically attaching certain molecules, or functional groups, to their smooth sidewalls. After this the tubes are dissolvable or dispersible in most organic or inorganic solvents.

Traditional printing methods are already used by Eikos and Unidym, to name a few. Nevertheless, using these traditional methods for the fabrication of thin carbon nanotube films there are still some hurdles to overcome. At the beginning there is the relatively poor quality of the nanotube starting material, which mostly shows a low crystallinity, low purity and high bundling. Subsequently, purifying the raw material without significantly degrading the quality is difficult. Furthermore it is still an issue to achieve good dispersions in solution and to remove the deployed surfactants from the deposited films.

Given these issues and additional steps needed after the manufacture of the raw material, the final CNT films are still costly to produce and have high sheet resistance for a given transparency. However approximately 90% of the costs for product films are due to post processing, which does not include the CNT material cost. Significant further improvements on this side are expected in the next few years as an increasing number of companies and research institutes tackle the problem.

1.6. Latest progress with printing carbon nanotubes

Over the last few years, the fabrication of printable CNT-based dispersions, their printability with common printing methods and their use in different applications were studied in several projects. Here we cover the latest work.

In late 2007 the Nano-Mechanical Systems Research Center, Korea Institute of Machinery and Materials presented a SWCNT ink for inkjet printing on glass and polymer substrates. The advantage of the ink is that only one fabrication step (fabrication of conductive film and patterning in one step) is needed to create patterned thin films of CNTs, which is extremely time and material saving.

In summer 2008 Professor Takao Someya, electrical-engineering professor at the University of Tokyo, and his colleagues presented their recent development: a process for making long carbon nanotubes on an industrial scale and dispersing via high-definition screen-printing.

In a first step the carbon nanotubes are combined with an ionic liquid, that contains charged molecules, and a liquid polymer. The resulting nanotube rubber-like paste passes through a high-pressure jet, which is needed to spread the tubes in the material and make them thinner without shortening. Professor Takao Someya says: "The longer and finer bundles of nanotubes can form well-developed conducting networks in rubbers, thus significantly improved conductivity and stretchability". The process also increases the viscosity of the rubber material and thereby allows direct deposition by high-definition screen-printing.

1.6.1. Application of printed carbon nanotubes to flexible displays

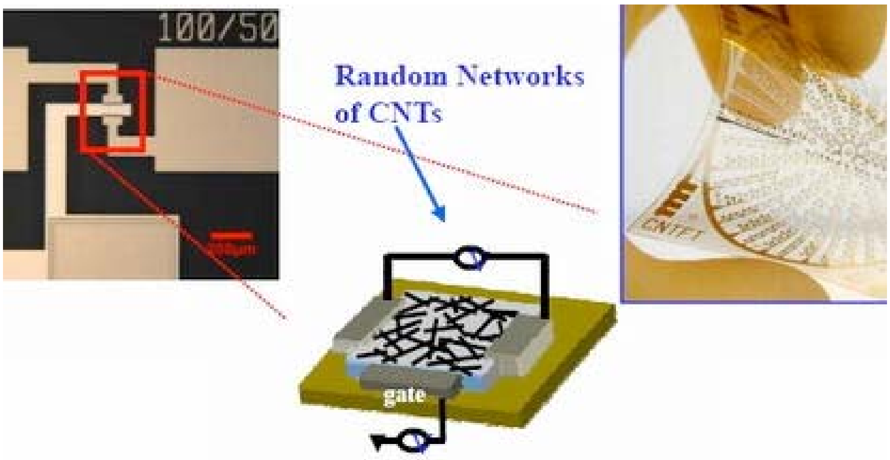
CNTs are flexible, highly conductive and transparent, making them of particular interest for display applications. In early 2009, after further investigations, the University of Tokyo presented Organic Light Emitting Diodes (OLEDs) incorporating their CNT conductor. The CNT conductor was used for the wire grid connecting the Organic Thin Film Transistors (OTFTs) and the OLEDs of the flexible display. They were screen printed 100-micrometer-wide lines. In the first project step the flexible conductive material was used to connect organic transistors in a stretchable electronic circuit. It was then used to connect organic light-emitting diodes (OLEDs) with the organic transistors addressing each OLED pixel. With improved conductivity and stretchability it is now possible to fold the display in half or even crumple it up without damage, and to stretch it up to 50 percent of the original shape.

The chair of Display Technology at the University of Stuttgart, and Nano-Proprietary, Inc.'s subsidiary Applied Nanotech, Inc. (ANI) announced in June 2008 their significant advancement in the application of carbon nanotubes for the flexible electronics industry. The team had obtained improved yield from TFTs made by employing a proprietary printing method, which avoids expensive photolithography. Furthermore, high mobility (100 cm^2/Vs) and high on/off ratio (10^5) was achieved, which is far better than printed TFTs using organic semiconductors (with mobilities typically of 1 cm^2/Vs or less).

Such a high mobility means that these TFTs can be made small enough to avoid obscuring too much light, and therefore do not need to be transparent or hidden on the other side of substrates or display layers. The on/off ratio compares with a value of <10 for previous attempts at the University of Maryland in 2005, in which printing of CNTs also was used. No details were given of the precise yield, pending more data, or the particular printing method used, but ANI said ink-jet and microcontact printing methods may work.

In collaboration the University Stuttgart, Germany, developed high performance carbon nanotube thin film transistors (TFTs) suitable for use in the flexible electronics industry. These devices are at the core of displays, electronic circuits, sensors, memory chips, and other applications that are transitioning from rigid substrates, such as silicon and glass, to flexible substrates. At the Society for Information Display (SID) International Symposium, the chair of Display Technology of the University of Stuttgart presented the world's first full colour active matrix LCD where ITO as transparent conductive film (TCF) was completely replaced by CNT networks. The display has a qVGA resolution (320xRGBx240) at 4" diagonal. The CNT networks are deposited by spray coating from suspension, which replaces a costly vacuum process. This demonstrates for the first time the applicability of CNTs as a transparent conductive film in a state-of-the-art amorphous silicon active matrix process. It also gives a great perspective for future flexible displays, since CNT networks are much more reliable in flexible applications than the amorphous ITO. The complete display, including AM-backplane, colour filters, and a dedicated addressing system was developed designed and fabricated at the University of Stuttgart.

Fig. 1.4 **CNT networks for flexible displays**



Source University of Stuttgart

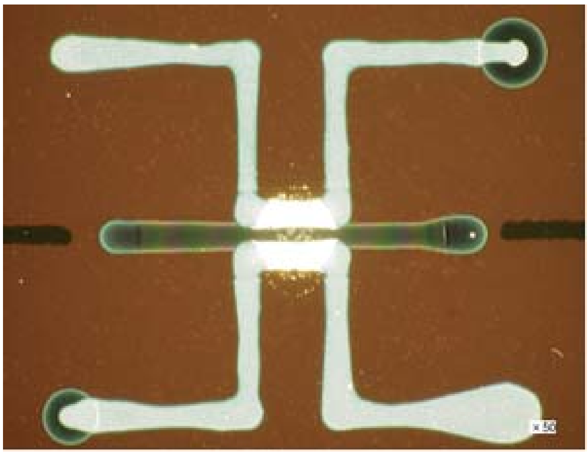
The main hurdle for CNT based displays over the last years has been the lack of a big enough supply of semiconducting carbon nanotubes. Now that simple and cheap purifying methods come up, it will only be a matter of time before products leave the labs and reach the market.

1.6.2. Application of printed carbon nanotubes to transistors

In February 2009 NEC Corporation, Japan, announced the successful realization of a CNT transistor on plastic film that is completely printed incorporating an advanced low-temperature printing process. All components of the CNT transistor – electrodes, insulator and CNT channels – are printed on a plastic substrate, which could be used due to production temperatures below 200°C. All materials used were optimized in order to keep interference between the layers low and to maintain printing conditions. The developed transistors demonstrate p-type conduction and an on/off ratio of 1,000. This is insufficient for managing grey levels in an active matrix display but adequate for general electronics.

The group was able to overcome several issues of an all-printed approach. For the various stacked layers, the required equal ink coverage throughout layers and robustness between layers to prevent current leakage could be realized. Inks were chosen that fit the low thermal tolerance, dispersions requirements and low temperature volatility.

Fig. 1.5 **CNT Transistors through Specialized Printing Processes from NEC Corporation**



Source NEC Corporation

1.6.3. Application of printed carbon nanotubes to energy storage devices - supercapacitors

Another group is working on using printable CNTs in energy storage devices. George Grüner, professor of physics at the University of California Los Angeles (UCLA), USA, and Yi Cui, assistant professor of materials science and engineering at Stanford University, USA, together led the research for new extremely cheap printable supercapacitors that incorporates carbon nanotubes.

The gel electrolyte of the high-performance energy-storage device is sandwiched between two CNT electrodes. These were fabricated by spraying water-soluble CNTs onto a plastic substrate. This production step could also be done with existing inkjet printing technologies. After the evaporation of the contained water the result is a 0.6 micron thick randomly entangled CNT layer.

The supercapacitor device stores energy at the surface of the carbon nanotubes when a voltage is applied to the sandwiched electrolyte gel.

A recent discovery of UC San Diego engineers could improve the charging capacity of CNT based supercapacitors. The team around Prabhakar Bandaru, a professor in the UCSD Department of Mechanical and Aerospace Engineering found that artificially introduced defects in nanotubes can aid the development of supercapacitors. These defects create additional charge sites enhancing the stored charge.

The researchers think that the energy density and power density obtained through their work could be practically higher than existing capacitor configurations, which suffer from problems associated with poor reliability, cost, and poor electrical characteristics.

2. CNT/Graphene Transistor

2.1. Comparison to other semiconductors

MWCNTs exhibit relatively low conductivity and low bandwidth in ohmic characteristics compared with SWCNTs. Therefore the focus is more on single-walled carbon nanotubes than on multi-walled ones. For SWCNT "ropes" a sheet resistivity of the order of 10^{-4} ohm-cm at 27°C can be shown. But the costs for high-purity SWCNTs as powder or ink are currently a great restraint. A significant limitation for the use of CNTs in electronic applications is the coexistence of semiconducting and metallic CNTs after synthesis due to variations in the chiral vector. Several separation methods have been discovered over the last years – mostly complex, time-consuming and expensive. The need for purification due to occurring significant impurities adds to this.

Many organisations are investigating carbon nanotubes CNTs as semiconductors in thin film transistors though this is long term work rendered even more long term by those hoping to print them. IBM, Intel, Nantero, DuPont and Carbon Nanotechnologies are researching in this area, with the latter holding key technology patents. Single walled carbon nanotubes are the main interest because they do not scatter the charge carriers. This lets them support current densities three times that of copper. The electrons are one hundred times as mobile as ones in bulk silicon. We note that, as yet, CNTs are only made by tedious processes, such as Laser Ablation or Chemical Vapor Deposition. Purification is a problem, though Northwestern University, the US National Institute of Standards, the National Renewable Energy Laboratory and DuPont have some answers for small quantities. Indeed, Dr Phaedon Avouris, leader of IBM's nanoscale science and technology group says, "There is currently no reliable way to mass produce a single type of CNT, a major problem for the development of nanotube electronics."

IBM claims to have a physical and a chemical way of preventing ambipolar CNT structures like this from having unacceptably high leakage current. However, another problem is the one now encountered with silicon chips where the dimensions are well below the wavelengths of the light used for photolithographic patterning. Despite all this, IBM has made logic gates and ring oscillators. There is a prospect of CNTs costing $12/g but the price is currently around $700/g. The whole world has only produced a few hundred kilograms of this material so far. All this compares to the situation with other semiconductors as follows:

Table 2.1 **Comparison of the main options for semiconductors**

TFT Type and typical mobility	Strength	Limitations	Improvements needed
Organic (OTFT) Up to 4cm^2/Vs but typically less than 1 cm^2/Vs for stable devices LOWEST MOBILITY OF FREQUENCY	Low process temperature Printable CMOS possible though n type is difficult Flexible Low cost in volume	Low mobility (improving) Low K dielectrics unless Inorganic Temperature rang Threshold voltage uniformity High voltage 10-100v	Breakthrough materials Self-assembled ordering Manufacturability
a-Si 1 cm^2/Vs	Process maturity and simplicity Cost Flexible versions available	Unacceptable threshold voltage shift for current driven OLEDs High temperature substrate Limited driver circuitry Integration Lifetime Not route to printing and low cost	Greater threshold voltage stability High mobility (nanocrystalline)
ZnO Family 10 cm^2/Vs for printed versions, 50 cm^2/Vs + for non printed	Moderate to good mobility Low process temperature CMOS possible but p type difficult Thermal stability Printable Transparent Potentially low cost	Relatively immature Exotic gate dielectric materials Stability unproven High process temperature but precursors are expect to permit low temperature	Demonstrated manufacturability Gate dielectrics Demonstrated stability CMOS capability
Silicon nanoparticle ink Over 400 cm^2/Vs demonstrated, typically 250 cm^2/Vs for printed versions	High mobility Printable Low cost CMOS	High temperature substrate required Difficulty in making ink – agglomeration	Low temperature sintering desirable for cheapest substrates
Poly crystalline-Si ~1500 cm^2/Vs	High mobility capability for integrated electronics Mature infrastructure CMOS	Intra-substrate process uniformity High temperature substrate Scalability and capital cost Not printable	Uniformity: tool / process Imaging optics and laser Cost Fragility
Carbon Nanotube (CNT) or graphene 100,000cm^2/Vs demonstrated for non printed, ~2000 cm^2/Vs for printed versions with the ability to go higher HIGHEST MOBILITY OF FREQUENCY	Highest known mobility/ frequency Transparent Flexible Printable Potential to be low cost CMOS	Material purity, cost High yield manufacturing Processes Consistency of performance Poor on-off ratios Little understood	Low cost high quality materials Breakthrough in processing Volume production Better theory leading to better on-off ratios

Source IDTechEx

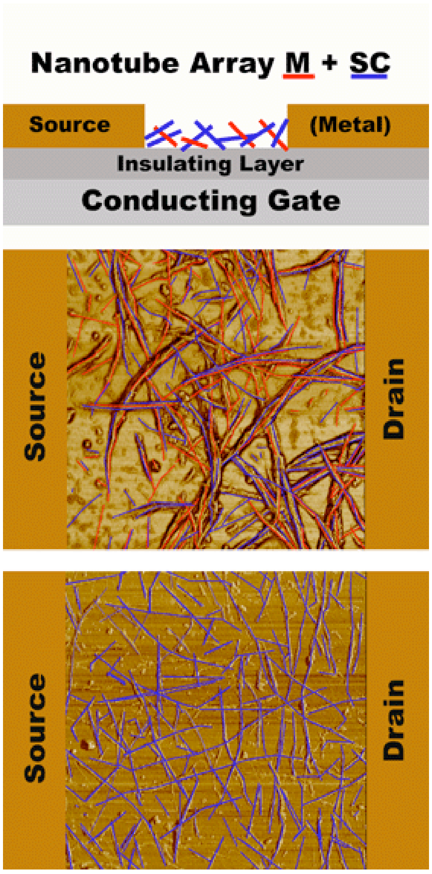
However, Nano ePrint has demonstrated a GaAs single layer transistor that performs at terahertz frequencies. It has a poor on-off ratio of 1000 but the company believes it can fix this.

2.2. Latest progress with CNT/Graphene Transistors

2.2.1. Separating metallic and semiconductor carbon nanotubes

Scientists at DuPont, USA, in collaboration with Cornell University, USA, developed a simple chemical process to convert mixtures of metallic and semiconducting carbon nanotubes into solely semiconducting carbon nanotubes. Dr. Graciela Blanchet, research fellow at DuPont pointed out: "A significant limitation in electronic application of carbon nanotubes has been the difficulty in separating metallic from semiconducting carbon nanotubes," Graciela said. In 2003, DuPont scientists already published a method to separate carbon nanotubes using DNA. DuPont has continued to investigate these materials. The current development proves to be a very promising approach to developing large quantities of CNT-based semiconductors and their applications.

Fig. 2.1 **Atomic Force Microscope image of carbon nanotubes before and after processing.**

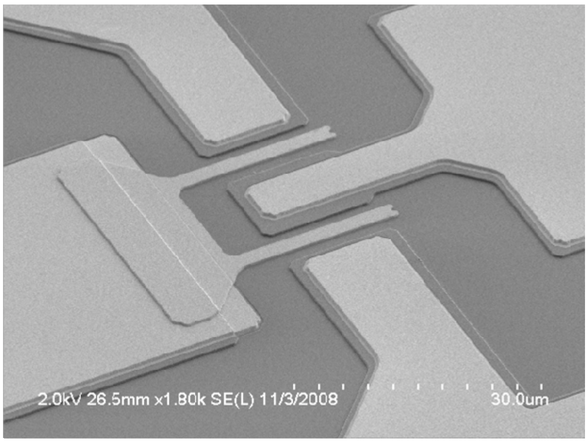


2.2.2. Graphene field effect transistors

HRL, USA

At the end of 2008, HRL Laboratories developed the world's first Graphene radio frequency (RF) field effect transistor (FET) under the DARPA's CERA Program (Carbon Electronics for RF Applications) under the management of the Space and Naval Warfare Systems Center (SPAWAR) and it is pictured below. Carbon-based radio-frequency (RF) integrated circuits can be used for ultra-high-speed, ultra-low-power applications. In the next step of the project they intend to fabricate FETs on 100-mm wafers and scale up the process to 200-mm wafers to create a demonstration prototype of the new generation of carbon-based RF integrated circuits.

Fig. 2.2 **Carbon nanotube Field Effect transistors**

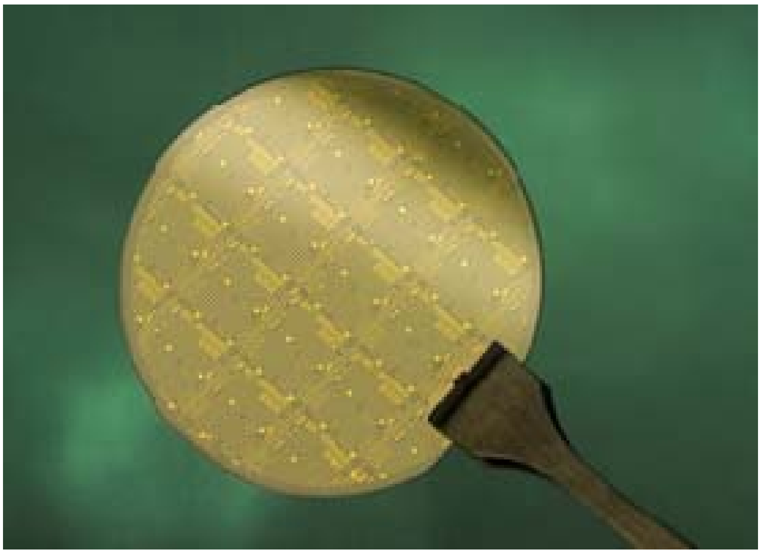


Source HRL

The FETs are made from epitaxially grown graphene materials with state-of-the-art, on-state current of 1180 μA/μm at a drain bias of 1 V. The transistor's RF performance showed an extrinsic current gain cut-off frequency of 4 GHz with 2 μm gate length. A record maximum oscillation frequency (fmax) of 14 GHz is achieved at Vds = 5 V. The RF speed performance is expected to be improved as the graphene FETs are scaled to below 100 nm gate length with reduced parasitic capacitance and resistance.

After further optimization of the material and device processing they presented in May 2009 epitaxial graphene FETs on a two-inch wafer scale. Dr. Jeong-Sun Moon, HRL Senior Scientist and CERA Program Manager commented: "Using a single layer of epitaxially grown graphene, these transistors demonstrate simultaneous world-record performance in key device parameters for the first time. They have world-record field effect mobility of ~6000 cm^2/Vs, which is six to eight times higher than current state-of-the-art silicon n-MOSFETs (metal-oxide semiconductor field effect transistors)." Goal for the ongoing project is the achievement of >10,000 cm^2/Vs hall mobility.

Fig. 2.3 **Epitaxial graphene FETs on a two-inch wafer scale**



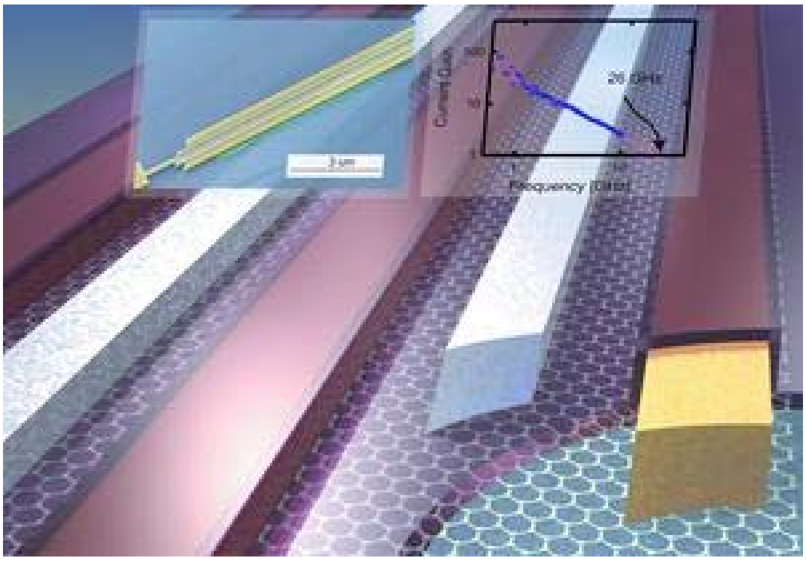
Source HRL Laboratories

IBM, USA

IBM developed the first thin-film transistor incorporating carbon nanotubes in 1998. At the end of 2008 IBM Scientists from the company's T. J. Waston Research Center demonstrated the operation of a graphene field-effect transistor at GHz frequencies. With a top gate design and a gate length of 150 nm the device achieved a cut-off frequency of 26 GHz, which is the highest frequency reported so far using this novel non-silicon electronic material. The used graphene material has the big advantage that it achieves very high electron speed with which electrons propagate in it, that is essential for high-speed, high-performance transistors.

Another fundamental finding was the scaling behaviour, i.e. the size dependence of the performance of the graphene transistors. The team found that the operational frequency increases with smaller device dimensions. They also found that the performance of the graphene transistor could be enhanced by improving the gate dielectric materials. In the next phase, the IBM researchers plan to pursue RF circuits based on these high-performance transistors.

Fig. 2.4 **Graphene field effect transistor from IBM**

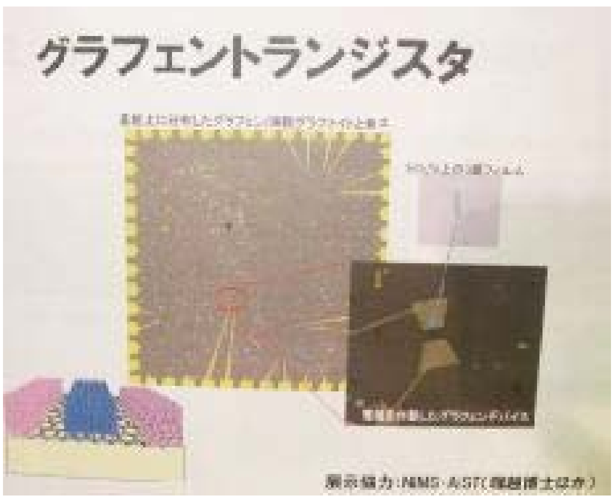


Source IBM

Fujitsu, Japan

In early 2009, Fujitsu, Japan, in collaboration with the Advanced Institute of Science and Technology (AIST) at Kyushu University, Japan, presented a CNT transistor (not printed). The transistor with a carbon-based material as channel has a gate width of 50nm, and an on/off ratio of 4. Fujitsu claimed it achieved this work with Kyushu University, by growing the CNTs on a specific crystal plane of sapphire. The CNT strands are grown to a length of about 100 microns. Fujitsu reports, "If the miniaturization of semiconductor devices continues to progress, uniform wiring cannot be formed appropriately by using copper. We are promoting the research on the expectation that the CNT wiring can be a substitute for copper wiring." Graphene has also been used.

Fig. 2.5 **An enlarged photo of a several-millimeter square chip with graphene transistors. The graphene transistors can be seen in the enlarged photo of the tips of the two electrodes**



Source Fujitsu

Fig. 2.6 **An LSI mounted on a flexible substrate by using CNT bumps**

Source Fujitsu

Optomec and the University of Massachusetts, USA

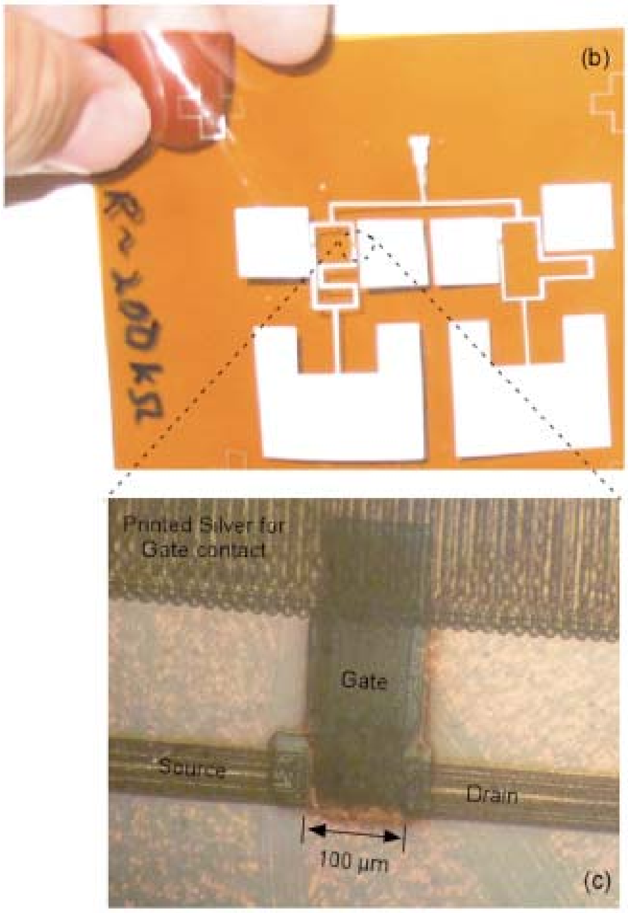
Optomec, USA, developed a proprietary Aerosol Jet system to fully print CNT-based TFTs with operating frequencies over 5GHz on polyimide substrate. Already showing on-off ratios of over 100, the CNTs offer high potential as an active carrier transport material. The CNT-based TFTs were fabricated in collaboration with the University of Massachusetts and Brewer Science, Inc. All four layers of the TFTs were fully printed including materials with a wide spectrum of viscosities, making it an ideal solution for this type of multi-layer device. With the Aerosol Jet, systems have achieved sub-micron layer thicknesses, and less than 10 micron features sizes and 5 micron registrations.

Aerosol Jet systems use a patented process that first aerosolizes conductive and nonconductive inks or pastes and then forms an aerodynamically focused droplet stream of the material. This direct write capability eliminates the need for screens or stencils required by traditional contact deposition processes while also enabling much finer feature sizes than possible with ink jet printing technology. Dr. Mike Renn states that "One of the unique benefits of the Aerosol Jet technology is that it is capable of printing TFT devices with high drain current, high on-off ratio, and low operation voltage. Additionally, Aerosol Jet systems have achieved sub-micron layer thicknesses, and less than 10 micron features sizes and 5 micron registrations."

L-NESS Politecnico di Milano, Italy

After several reported operations of single-transistors, L-NESS Politecnico di Milano presented an integrated complementary graphene inverter in April 2009. The complementary logic inverter consists of two graphene transistors (one p- and one n-type) integrated on a flake of monolayer graphene. The Graphene was isolated from a sheet of carbon using mechanical exfoliation and patterned on silicon substrate. The device exhibits clear voltage inversion, though remaining issues are power consumption and the inability for direct cascading at this time.

Fig. 2.7 **Printed CNT-TFT on a DuPont® Kapton® FPC polyimide film: (a) schematic structure cross-section view, [(b) and (c)] picture of the CNT-TFT, (b) circuit, and (c) optical microphotography of the CNT-TFT (top view). The CNT-TFT is in a top-gated configuration. The channel width and length are 200 and 100 μm, respectively.**



Source L-NESS Politecnico di Milano

2.3. Challenges

Further improvements in preparing purer CNTs have enabled monolayer CNTs for semiconducting channels of TFTs. This avoids the vast variations in mobility and threshold voltages. Although there is a huge amount of research in progress that started years ago, there is still a gap between the demonstrations in laboratory state and their translation into commercial products manufactured in high volumes preferably with cheap printing technologies.

One basic issue of incorporating carbon nanotube materials into electronic applications as the semiconductor, is the high production cost for semiconducting, high-purity nanotube materials as powder or even as printable ink. The need for separation of multi-walled and single-walled CNTs after synthesis as well as the need for purification are still complex and cost-intensive.

The all-printed approach from NEC Corporation demonstrates quite nicely the still remaining issues for carbon nanotubes incorporated in printed electronics, although a low-temperature fabrication process (›200°C) was used.

Other hurdles to overcome are the need for equal ink coverage throughout the various stacked layers of components that are deposited as well as robustness between layers to prevent leaking. Additionally, the CNT inks for the channels need to be stable dispersions and have to have low temperature volatility.

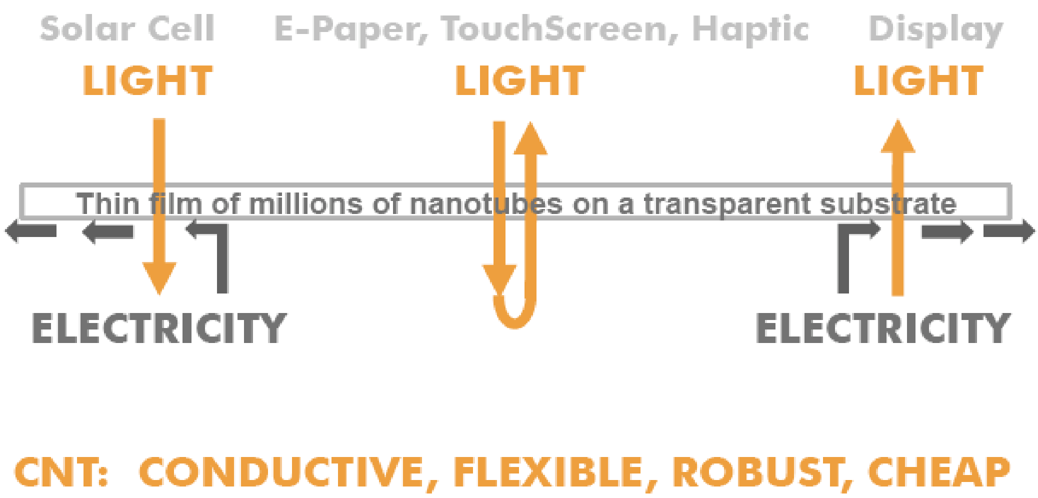
3. Carbon Nanotubes as conductors

With the right chiral vector (n=m) carbon nanotubes exhibit metallic properties. In theory, metallic nanotubes (n=m) can carry an electrical current density of 4×109 A/cm2. The promises of nanotube conductors are low cost, high performance, long life/durability, simple patterning, environmental friendliness, flexibility and transparency. Some of these benefits will allow CNTs to replace existing conductors but it will also enable new applications.

Fabricated as transparent conductive films, conductive carbon nanotubes can potentially be used as a highly conductive, transparent and cost efficient alternative to ITO (Indium tin oxide) for the use in flexible displays, for instance. Indium is an increasingly rare and therefore expensive material, and the oxide is not very flexible. Armin Reller, a materials chemist at the University of Augsburg in Germany, and his colleagues are among the few groups who have been investigating the problem. He estimates that we have, at best, ten years before we run out of indium, meaning it becomes too expensive. In January 2003 the metal sold for around $60 per kilogram but by August 2006 price had topped $1000 per kilo. The recession then provided a breathing space. Others argue that increased demand will lead to better extraction methods.

In its 26 May 2007 edition, the British journal New Scientist presented disturbing calculations of when many materials used in printed electronics will effectively run out. Given the widespread use of gallium and indium in electrical and non-electrical products already, the New Scientist is particularly concerned about adding massive demand for these materials in printed and laminar photovoltaics, notably InGaAs and copper indium gallium diselenide CIGS, where IDTechEx tracks over ten organisations planning major production soon in Japan, Europe and the USA. The New Scientist declares, "Take the metal gallium, which along with indium is used to make indium gallium arsenide. This is the semiconducting material at the heart of a new generation of solar cells that promise to be up to twice as efficient as conventional designs. Reserves of both metals are disputed, but in a recent report Rene Kleijn, a chemist at Leiden University in the Netherlands, concludes that current reserves 'would not allow a substantial contribution of these cells' to the future supply of solar electricity. He estimates gallium and indium will probably contribute to less than one per cent of all future solar cells – a limitation imposed purely by lack of raw material." However, InGaZnO is getting a lot of attention as a transistor. Semiconductor and there are many other new uses of indium and gallium. CNTs may offer a viable and even improved replacement for indium and gallium in many applications, including ITO.

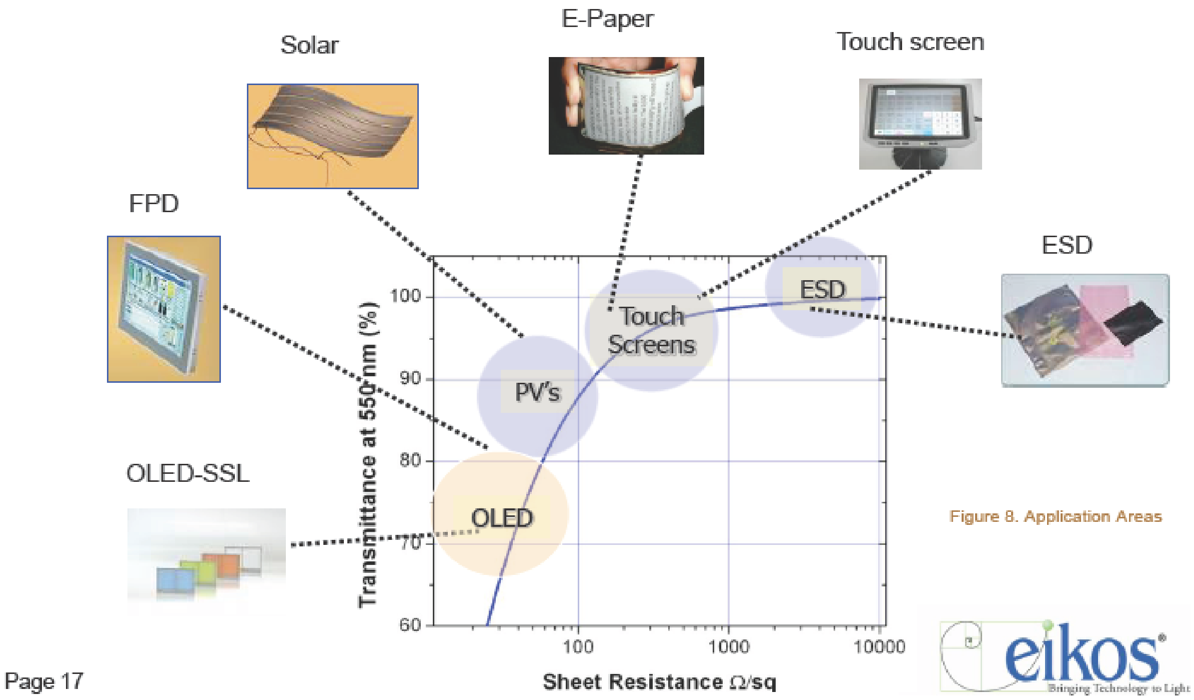
Fig. 3.1 **Potential applications are flexible solar cells, displays and touch screens.**



Source Canatu

The following figure shows different applications and their requirements in terms of sheet resistance and optical wavelength transmittance.

Fig. 3.2 **Targeted applications for carbon nanotubes by Eikos**



Source Eikos

3.2. Comparison to other conductors

In the conductive state, the electrical current density can be more than 1,000 times greater than in metals like silver, at least in theory, and the conductivity exceeds those of conducting polymers. In practice, the reactivity of carbon nanotubes highly depends on several parameters, like structure, size distribution, agglomeration state, purity and others more.

SWCNTs exhibit electric properties that are not shared by the multi-walled ones. Due to their excellent electrical conductivity they can ultimately be used as transparent conductive films that can meet requirements such as high conductivity and transparency as well as cost efficiency. Therefore they show huge potential to replace ITO for example in flexible displays.

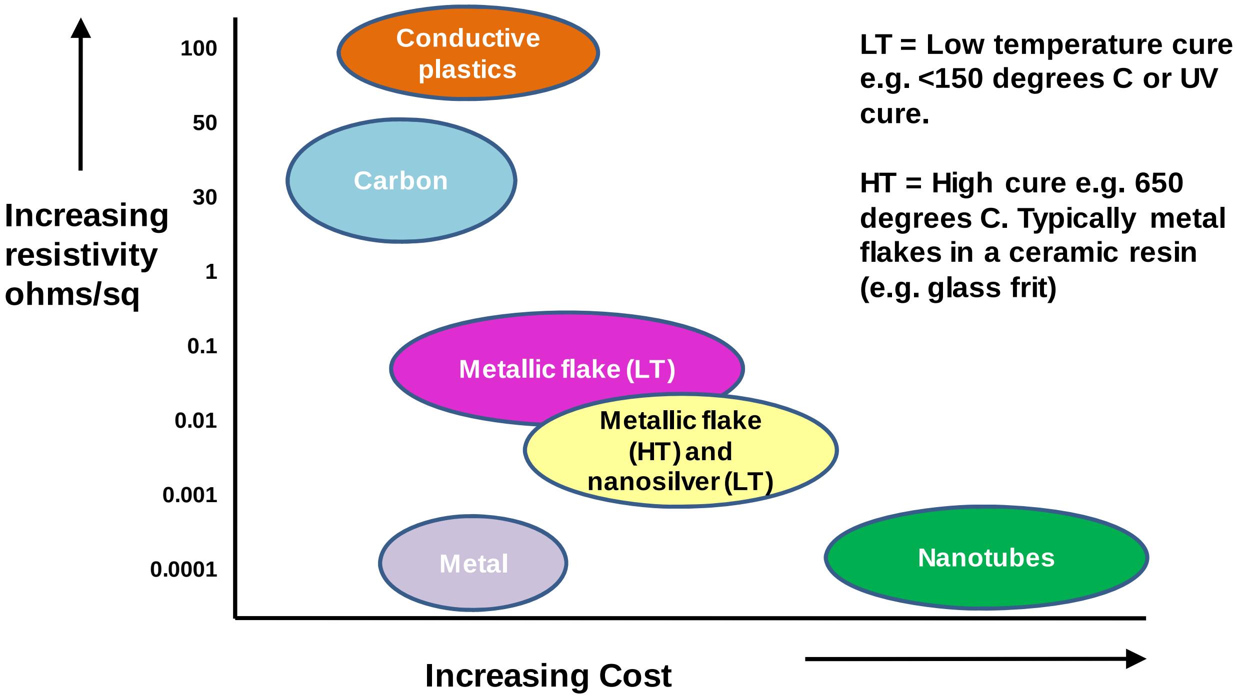
Table 3.2 **Typical Sheet Resistivity figures for conductors**

Material	Sheet resistivity
Printed silver ink	15 milliohm per square/mil
Copper etch	10^{-3} Ω·cm
SWCNT	10^{-4} Ω·cm
Graphene sheets	10^{-6} Ω·cm

Source IDTechEx

A simple comparison is shown in the following chart. Nanosilver and (not shown) fully dissolved silver inks lead to layers with similar performance.

Fig. 3.3 **Conductance in ohms per square for the different printable conductive materials, at typical thicknesses used, compared with bulk metal**



Source IDTechEx

3.3. Conductor deposition technologies and main applications

Conventional etching remains the most popular process of forming conductive tracks. However, this will increasingly be replaced by the printing of electronic circuits and metal plating technologies where printing can be higher speed, cheaper, and offer new benefits such as faster turn around times and the ability to make every circuit different.

Of the printing processes employed to print electronics, flat screen printing is the most popular technology today and it is used for touch pad circuits, laminar batteries, car windscreen heaters, plasma display ribs and diabetes diagnostic labels, for example. Screen printing has generally been sufficient for such applications where high conductivity has been required (i.e. thick layers), volumes are relatively low and set up cost is low.

Several companies use a hybrid print/metal plate method as an alternative high speed printed electronic process. A "seed" ink can be printed to pattern the area where the conductor should be. A metal plating process is then used to deposit the metal (e.g. copper) on the pattern.

Conductors are used for interconnects between electronic and electrical components such as displays, thin film transistor circuits, batteries etc. This requires highly conductive traces for best performance and the materials used to make the components are usually not good enough. The main applications of conductive inks today and some future uses, with examples of suppliers, are given in the table below.

Table 3.3 **Main applications of conductive inks and some major suppliers today**

Application	Strongly desired ink properties	Typical ink type	Examples of suppliers of inks and licensors of ink recipes
RFID smart labels and smart cards antenna	Low cost High conductance Short dry/cure time and temp	Silver ink, some use carbon based ink as seed layer for metal plating	Acheson, ASK, Sun Chemical, Dow Corning, Parelec, DuPont, InkTec
Display or touch screens	Transparency High conductance	Carbon nanotube as an alternative to Indium Tin Oxide (ITO) film.	Eikos, InkTec
Membrane switches and keyboards	Ease of manufacture on flexible substrates Reliability	Silver ink, carbon ink	Acheson, Sun Chemical, Dow Corning, Poly-Flex, InkTec
Smart blister packs and tamper evidence packs	Ease of manufacture on paper Cost	Carbon or low silver	Information Mediary, The Compliers Group
Vehicle dashboard displays	Ease of manufacture on flexible substrates Reliability	Silver thick film	The Dow Chemical Company, DuPont, Ferro, Heraeus and others
Electrostatic Discharge, EMI, RFI shielding	Cost Ease of manufacture	Carbon, silver, polymer, nanoparticles	Spraylat, Eikos
Hybrid Integrated Circuits, interconnections and electronic Circuits (e.g. resistors)	Reliability High conductance Ease of manufacture on flexible substrates	Silver, carbon, nanoparticles	Dow Chemical, DuPont, InkTec, Novacentrix, Sun Chemical, DuPont

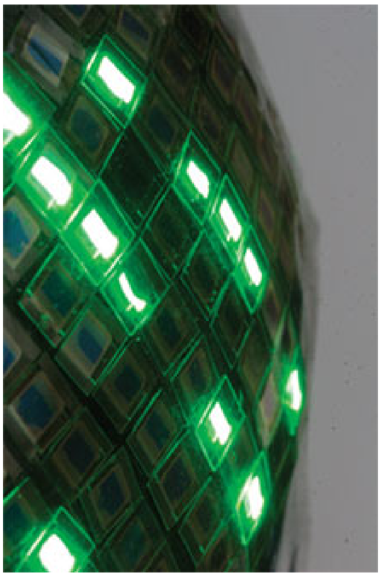
Source IDTechEx

3.4. Latest progress with Carbon Nanotube conductors

Few studies are presented on incorporating CNTs as conductor in electronic applications. So far the achievements found in research labs do not meet the requirements for an ITO replacement in commercial scale.

In May 2009 the possibility of cheap stretchable displays with an elastic CNT-based conductor was presented by the University of Tokyo, Japan. With the advantage of being printable, this brings us closer to cheap, flexible displays.

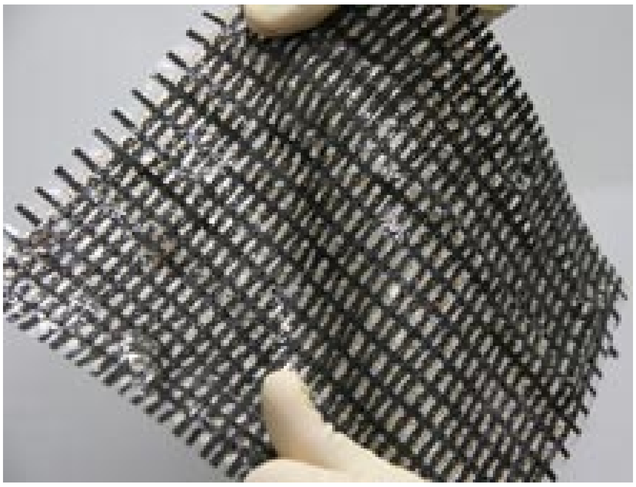
Fig. 3.4 **New printable elastic conductors made of carbon nanotubes are used to connect OLEDs in a stretchable display that can be spread over a curved surface**



Source Takao Someya, the University of Tokyo

The flexible CNT-based conductor is now used to connect organic light-emitting diodes (OLEDs) with the organic transistors addressing each OLED pixel. With improved conductivity and stretchability it is now possible to fold the display in half or even crumple it up without damage, and to stretch it up to 50 percent of the original shape. Such durability means that this can also be applied in many other applications such as flexible actuators, sensing "skin" etc.

Fig. 3.5 **Stretchable mesh of transistors connected by elastic conductors**



Source University of Tokyo.

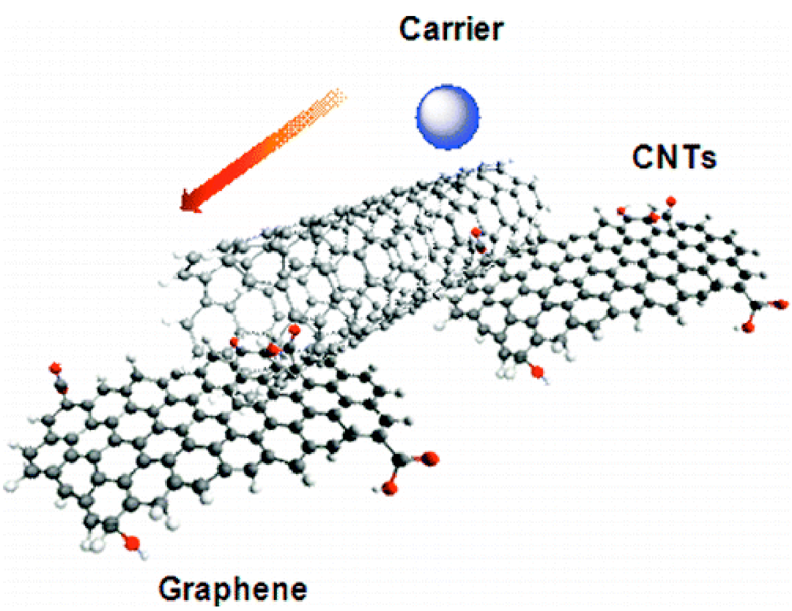
Prof. Takao Someya, electrical-engineering professor at the University of Tokyo, and his colleagues also developed a process for making long carbon nanotubes on an industrial scale. In a first step the carbon nanotubes are combined with an ionic liquid, that contains charged molecules, and a liquid polymer. The resulting nanotube-rubber like paste then has to pass a high-pressure jet, which is needed to spread the tubes in the rubber material and make them thinner without shortening.

According to Someya Dai Nippon Printing is interested in commercializing this invention. With further improvements especially regarding the width of the printed lines and resolution, a commercial product should be possible in five years.

At the same time Researchers at UCLA, USA, developed a new method for producing transparent conductors. The hybrid graphene-carbon nanotube material (G-CNT) shows great potential to be a high-performance alternative to ITO e.g. in flexible solar cells. Yang Yang, a professor of materials science and engineering at UCLA Henry Samueli School of Engineering and Applied Sciences, and Richard Kaner, a UCLA professor of chemistry and biochemistry, developed a new single-step to fabricate G-CNTs in an easy, inexpensive and scalable method. By placing graphite oxide and CNTs in a hydrazine solution a hybrid layer containing both materials can be produced. This method does not require the use of surfactants.

In comparison to ITO, G-CNTs retain efficiency when flexed and are compatibly with plastics, which makes it suitable for flexible solar cells and other flexible consumer electronics. A proof-of-concept polymer solar cell with power conversion efficiency of 0.85% was demonstrated.

Fig. 3.6 **Hybrid graphene-carbon nanotube G-CNT conductors**



Source UCLA

3.5. Challenges

The challenges of using CNT materials as conductors are quite similar to those for using them as semiconductors. The biggest restraint are the costs for suitable high-purity CNT materials, especially when it comes to printed electronics and the need for printable dispersions. This is due to complex, time-consuming and cost-intensive purification methods and funtionalization. Further improvement is needed for the production of consistent stable printable formulations that are attractive for electronic applications not only on the cost side but also in terms of performance.

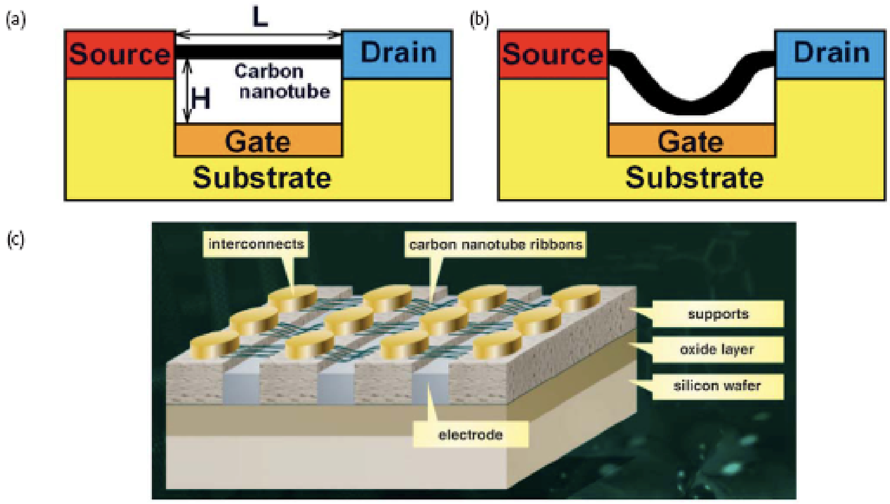
For the more proof-of-concept devices, such as the organic photovoltaic cell from UCLA, further investigate is needed into the actual performance and durability in working devices.

4. Other applications of CNTs

4.1. NRAM data storage device

In June 2008 the University of Nottingham, UK, in collaboration with Nantero Inc., USA, presented a carbon-nanotube-based electromechanical data storage device. The high-density nanotube-based non-volatile random access memory (NRAM) device was fabricated incorporating suspended, single or multiwalled CNTs. A bundle of these was suspended across a gap and connected to the two source and drain electrodes, as shown in the figure below. By applying a voltage the nanotubes is forced to flex and to come into van der Waals contact with the gate. This switches the device into the state '1'. This bent position is maintained until an applied pull-out voltage forces the nanotube to stretch back in the '0' state.

Fig. 4.1 **A three-terminal memory cell based on suspended carbon nanotubes: (a) nonconducting state '0', (b) conducting state '1', and (c) Nantero's NRAM™.**



Source Nantero, Inc.

4.2. Organic photovoltaic devices and hybrid organic-inorganic photovoltaics

In July 2007 researchers at New Jersey Institute of Technology (NJIT), USA, developed an inexpensive solar cell that can be painted or printed on flexible plastic sheets. The solar cell uses a carbon nanotube electrical wire. Dr Somenath Mitra, professor and acting chair of NJIT's Department of Chemistry and Environmental Sciences, and his colleagues combined the carbon nanotubes with carbon Buckyballs to form tadpole-like structures. When sunlight is present, it excites the polymer buckyballs into trapping electrons. The nanotubes, having a significantly better conductivity than copper, are able to make the electrons flow.

UCLA's work on hybrid graphene-carbon nanotube material, covered in section 3.3., has also been used in a proof-of-concept polymer solar cell with power conversion efficiency of 0.85%. The hybrid graphene-carbon nanotube material (G-CNT) shows great potential to be a high-performance alternative to ITO e.g. in flexible solar cells.

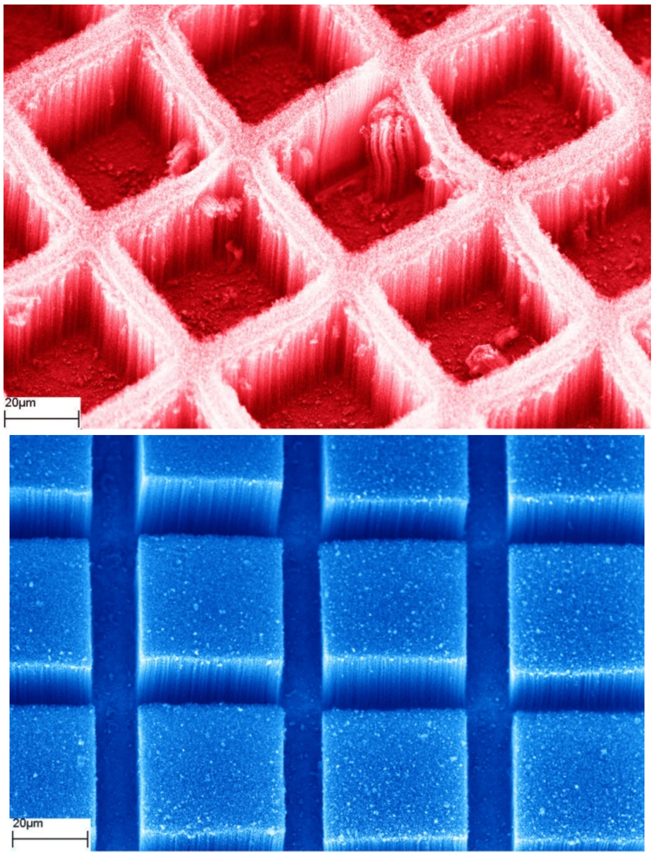
Hybrid organic-inorganic photovoltaics

The research and development organization Georgia Tech Research Institute (GTRI), USA, also presented its work on carbon nanotubes for more efficient solar cells. The GTRI photovoltaic cells trap light between their tower structures, which are about 100 microns tall, 40 microns by 40 microns square, 10 microns apart and built from arrays containing millions of vertically-aligned carbon nanotubes. Conventional flat solar cells reflect a significant portion of the light that strikes them, reducing the amount of energy they absorb. The carbon nanotube arrays serve both as support for the 3D arrays and as a conductor connecting the photovoltaic materials to the silicon wafer. The new cells remain efficient even when the sun is not directly overhead because the tower structures can trap and absorb light received from many different angles.

Fabrication of the cells begins with a silicon wafer, which can also serve as the solar cell's bottom junction. The researchers first coat the wafer with a thin layer of iron using a photolithography process that can create a wide variety of patterns. The patterned wafer is then placed into a furnace heated to 780 degrees Celsius. Hydrocarbon gases are then flowed into furnace, where the carbon and hydrogen separate. In a process known as CVD, the carbon grows arrays of MWCNTs atop the iron patterns.

Once the carbon nanotube towers have been grown, the researchers use a process known as molecular beam epitaxy to coat them with cadmium telluride (CdTe) and cadmium sulfide (CdS) which serve as the p-type and n-type photovoltaic layers. Atop that, a thin coating of indium tin oxide, a clear conducting material, is added to serve as the cell's top electrode. But there are still several hurdles to overcome before they can be commercially produced. Testing must verify their ability to survive launch and operation in space, for instance.

Fig. 4.2 **Georgia Tech Research Institute (GTRI) scientists have demonstrated an ability to precisely grow "towers" composed of carbon nanotubes atop silicon wafers. The work could be the basis for more efficient solar power for soldiers in the field.**



Source GTRI

Application to Infrared solar cells

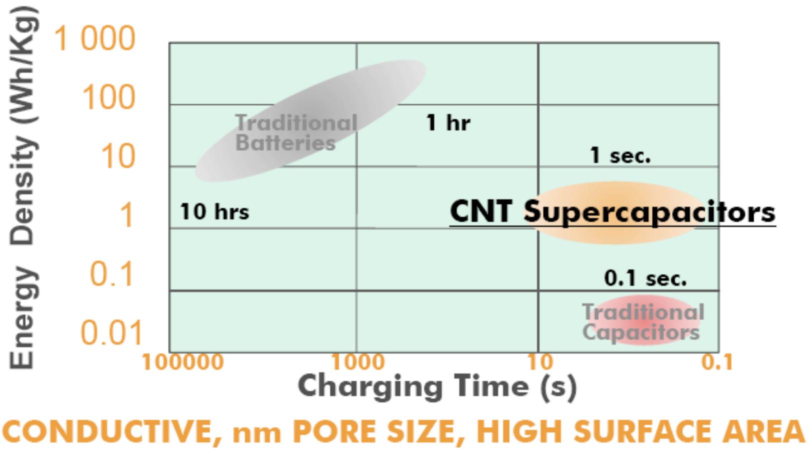
Physicists at the UCLA recently found that thin films of SWCNTs could also improve the efficiency of infrared solar cells due to their good infrared transmission. To form thin films Liangbing Hu, David Hecht, and George Grüner dispersed SWCNTs in water using a surfactant and sprayed them onto a heated substrate. The resulting SWCNT films have a sheet resistance value of 200 Ohm/sq and the average transmittance rate proved to be ›90% for wavelengths from 450nm to 20micron.

"One major application is the infrared solar cells, where transparent CNT films as well graphene films would allow the transmission of infrared energy to the active layer, which allows the fabrication of infrared solar cells," Hu said. The fabricated films could also be used for other applications like an infrared camera, which will be investigated soon by the researchers.

4.3. Supercapacitors and/or batteries

Apart from the good electrical conductivity, the extremely high surface area of CNTs make them a very good choice for electrodes in batteries and capacitors. CNTs have the highest reversible capacity of any carbon material, as shown in the following figure. Batteries have a high energy density but are slow to recharge, where as capacitors have the opposite problem. CNT based supercapacitors are being developed to bridge the gap. There are huge requirements for this in energy harvesting devices for small electronics, such as wireless sensors.

Fig. 4.3 **The carbon nanotube supercapacitor versus batteries and traditional capacitors**

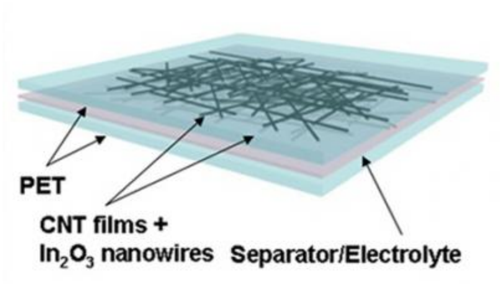


Source Canatu

University of Southern California, USA

In January 2009 researchers from the Viterbi School of Engineering at University of Southern California, USA, demonstrated a new flexible and transparent supercapacitor based on In2O3 nanowire/carbon nanotube heterogeneous films. The group headed by Chongwu Zhou, who holds the Jack Munushiun Early Career Chair at the USC Ming Hsieh Department of Electrical Engineering, used a metal oxide nanowire/CNT heterogeneous film to form the active layer and the current collecting electrodes of the energy storage device. A vacuum filtration method was used to fabricate the CNT films. With an energy density of 1.29 Wh/kg the device can store more energy than a conventional capacitor with usually only 0.1 Wh/kg.

Fig. 4.4 **Anatomy of a supercapacitor: two films combining Indium Oxide (In2O3) separated by a layer of Nafion film**



Source USC Viterbi School of Engineering, USA

Fig. 4.5 **Transparent film holds embedded nanotube/nanowire capacitor with high energy density and storage capacity**

Source USC Viterbi School of Engineering, USA

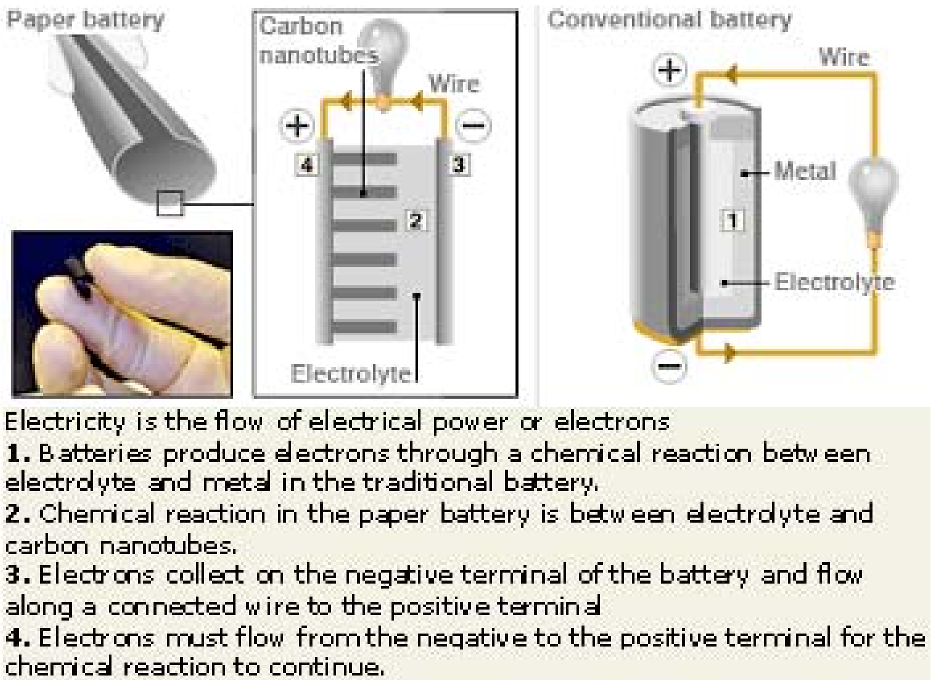
Rensselaer Polytechnic Institute, USA

A new energy storage device using carbon nanotubes was developed in August 2007 by researchers at Rensselaer Polytechnic Institute, USA. The nanoengineered battery is lightweight, ultra thin, completely flexible, and likely to meet the demands of the next generation of gadgets, implantable medical equipment, and transportation vehicles. More than 90 percent of the device is made up of cellulose. The paper is infused with aligned CNTs that act as electrodes and allow the storage devices to conduct electricity. The components are molecularly attached to each other: the carbon nanotube print is embedded in the paper, and the electrolyte is soaked into the paper.

The device, engineered to function as both a lithium-ion battery and a supercapacitor, can provide the long, steady power output comparable to a conventional battery, as well as a supercapacitor's quick burst of high energy. Additionally, it can function in temperatures up to 300 degrees Fahrenheit and down to 100 below zero. It is completely integrated and can be printed like paper.

The goal is to print the paper using a roll-to-roll system, but so far it is not developed in an inexpensively way attractive for mass production.

Fig. 4.6 **Battery from Rensselaer Polytechnic Institute, USA**



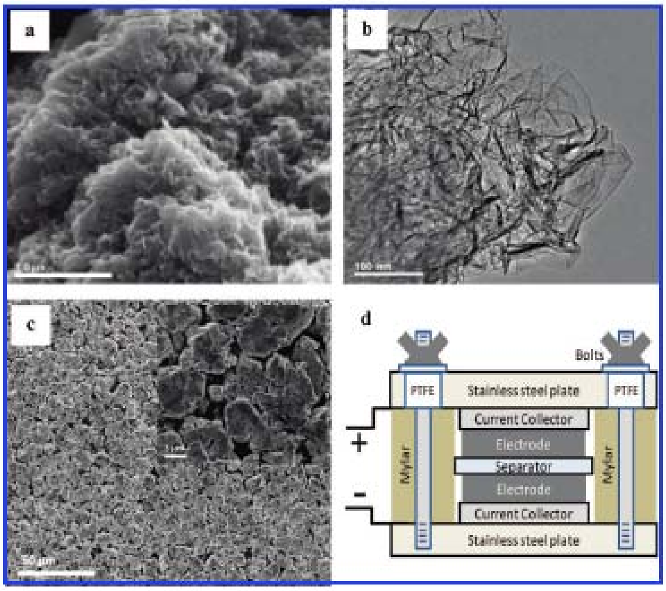
Source news.bbc.co.uk

University of Texas at Austin, USA

A graphene-based ultracapacitor was demonstrated in September 2008 by researchers at University of Texas at Austin, USA. The energy storage device is based on electrochemical double layer capacitance (EDLC) and is built using a CMG-based carbon electrode material and two porous carbon electrodes. The energy is stored inversely proportional to the thickness of the double layer.

The work was partially supported by a Korea Research Foundation Grant funded by the Korean Government (MOEHRD) and University of Texas at Austin and Texas Nanotechnology Research Superiority Initiative.

Fig. 4.7 **(a) SEM image of CMG particle surface, (b) TEM image showing individual graphene sheets extending from CMG particle surface, (c) low and high (inset) magnification SEM images of CMG particle electrode surface, and (d) schematic of test cell assembly.**



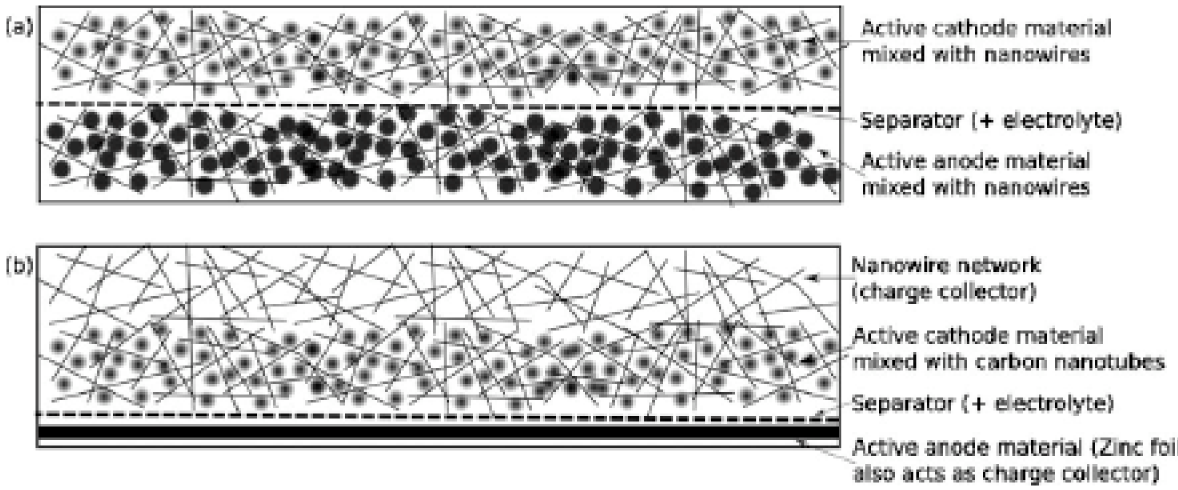
Source University of Texas at Austin, USA

UCLA, USA

In October 2007 researchers at UCLA developed a battery architecture that uses a CNT-based networks or a film of carbon nanotubes. The charge collector, typically made of metal sheets, meshes, or films, was replaced by these networks providing charge transport. Additionally, the plus cathode conductor, typically carbon black, was replaced by nanotubes providing conductance to the charge collector. The active CNT nanowire material can be applied by printing or roll-to-roll fabrication at room temperature.

The figure below shows the proposed battery design incorporating active electrode material and current collectors in one single layer, thus saving on overall mass, volume, and required manufacturing steps. _b_ Proof-of-concept device constructed with a single wall carbon nanotube film charge collector and active material MnO2-nanowire mixture.

Fig. 4.8 **Proposed battery design from UCLA**



Source UCLA

Stanford University, USA

George Grüner, professor of physics at the University of California Los Angeles (UCLA), and Yi Cui, assistant professor of materials science and engineering at Stanford, together led the research for a new extremely cheap printable supercapacitors that incorporates carbon nanotubes. The gel electrolyte of the high-performance energy-storage device is sandwiched between two CNT electrodes. These were fabricated by spraying water soluble CNTs onto a plastic substrate. This production step could also be done with existing inkjet printing technologies. After the evaporation of the contained water the result is an 0.6 micron thick randomly entangled CNT layer. The supercapacitor device stores energy at the surface of the carbon nanotubes when a voltage is applied to the sandwiched electrolyte gel.

4.4. CNTs for smart textiles

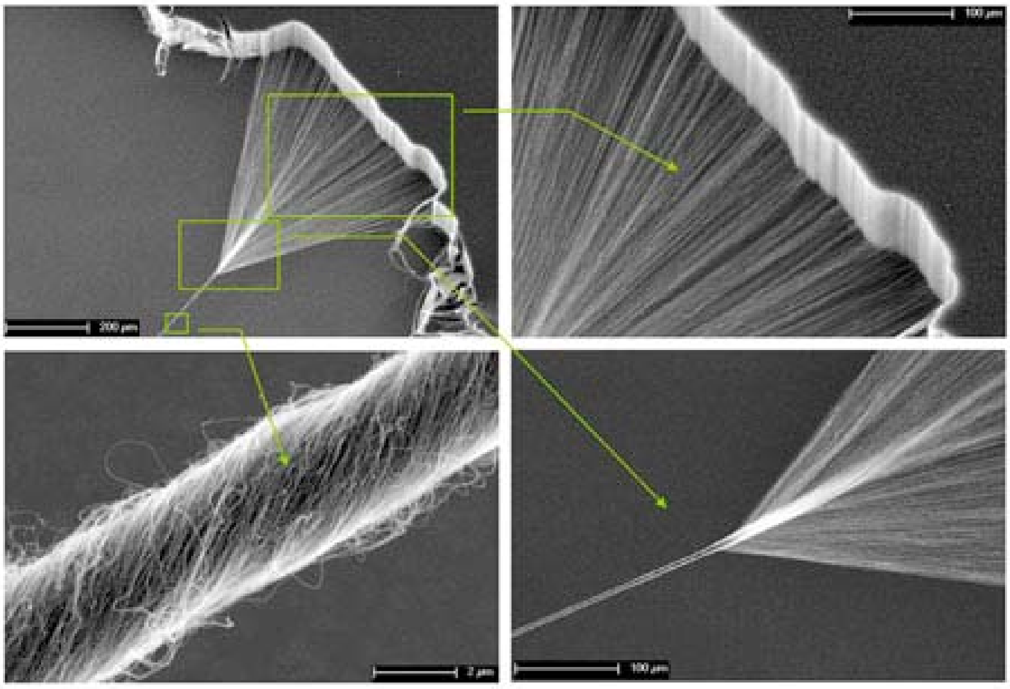
CSIRO, Australia

For smart textiles carbon nanotubes are attractive in form of spun fibres along with CNT composite fibers. The advantageous properties are their flexibility while being super-strong and electrical conductivity. Potential applications are for example body and vehicle armor, transmission line cables, woven fabrics and textiles, flexible photovoltaics and displays in fabric etc.

The Material Science & Engineering department at CSIRO, Australia, is focusing on carbon nanotubes, applying them to textiles and the industrialisation of these applications. For the production of yarns and sheets CSIRO has built special reactors and is using a spinning process. Together with the NanoTech Institute, University of Texas at Dallas, USA, CSIRO holds a provisional patent on the spinning process. The resulting yarns are strong, durable and flexible.

In addition the CNT-yarns, extruded fibers from CNT-blended polymers are studied regarding production process and properties.

Fig. 4.9 **Four scanning electron microscope images of the spinning of carbon nanotube fibres**

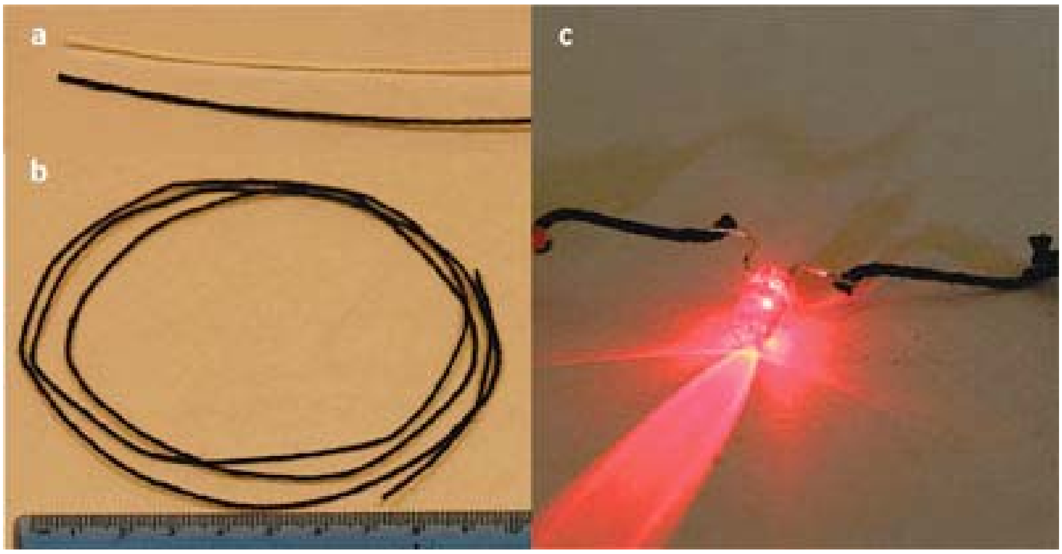


Source CSIRO, Australia

University of Michigan, USA and University of Wuxi, China

At the end of 2007, a conductive, carbon nanotube-modified cotton yarn was presented by researchers from the University of Michigan and from Prof. Chuanlai Xu's group at Jiangnan University in Wuxi, China. Together they had developed a simple low-cost method to coat regular cotton yarns with single-walled and multi-walled carbon nanotubes (CNT) and polyelectrolytes. The last ones were added to improve the stability of the coating. "The proof-of-principle CNT-cotton yarns that we fabricated showed high electrical conductivities as well as some functionality due to biological modification of internanotube tunnelling junctions" explains Kotov. He also pointed out that the invented process provides a fast, simple, robust, low-cost, and readily scalable process for making e-textiles.

Fig. 4.10 **Photographs of CNT-cotton yarn. (a) Comparison of the original and surface modified yarn. (b) 1 meter long piece as made. (c) Demonstration of LED emission with the current passing through the yarn.**



Source University of Michigan

4.5. Thin film loudspeakers

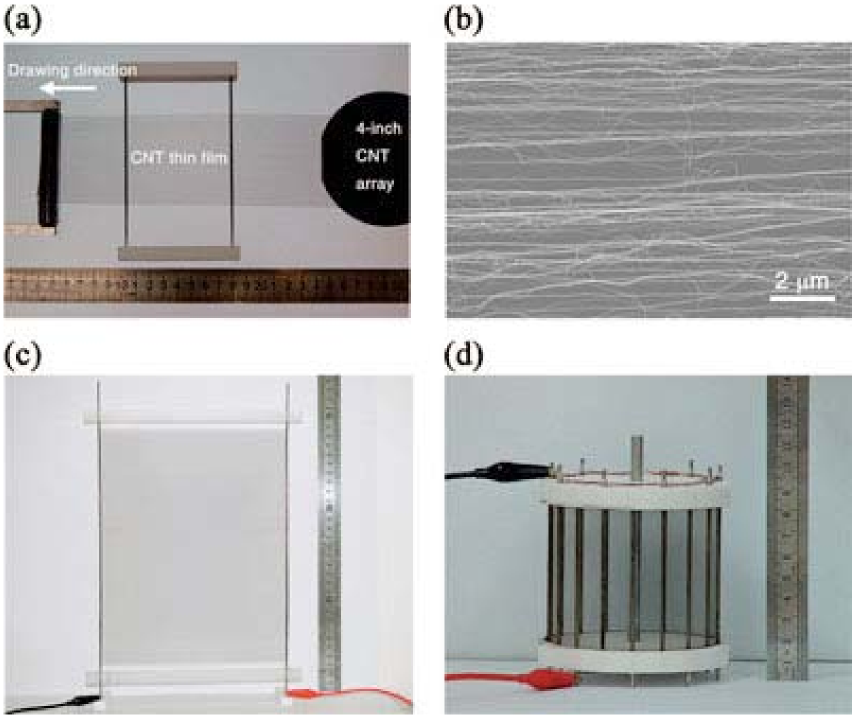
In September 2008 Tsinghua University, China, and Beijing Normal University, China, presented their collaborational work on flexible, stretchable, transparent thin film loudspeakers that incorporate CNT nano-ribbons. This device sounds roughly 260 times louder than that which can be produced from platinum foils. Applying an audio signal to the CNT thin film loudspeaker through a pair of electrodes causes the film's temperature to briefly spike and by that the directly surrounding air to oscillate, which produces sound waves.

Fig. 4.11 **The CNT thin film was put on a flag to make a flexible flag loudspeaker**

Source Tsinghua University, China, and Beijing Normal University, China

The figure below shows a carbon nanotube thin film loudspeaker. (a) The CNT thin film was pulled out from a super-aligned CNT array grown on a 4 inch silicon wafer and put on two electrodes of a frame to make a loudspeaker. (b) SEM image of the CNT thin film showing that the CNTs are aligned in the drawing direction. (c) A4 paper size CNT thin film loudspeaker. (d) The cylindrical cage shape CNT thin film loudspeaker can emit sounds to all directions, diameter 9 cm, height 8.5 cm.

Fig. 4.12 **Carbon nanotube thin film loudspeakers**



Source American Chemical Society

4.6. Sensors

4.6.1. Aneeve Nanotechnologies LLC

Aneeve's newest development is a CNT-based hormone sensor made by low-cost ink-jet printing and using technology from UCLA to increase hormonal detection sensitivity. Still early in research the sensor and transducer technology is designed to detect oestrogen and progesterone hormone levels in menopausal women but can also be used in other biomedical applications.

4.6.2. Michigan University, USA

Scientiest around Kotov developed a new biosensor, using a strip of paper infused with carbon nanotubes.

The sensor works by measuring the electrical conductivity of the nanotubes in the paper. Before the nanotubes are impregnated in the paper, they are mixed with antibodies for MC-LR. When the paper strips come in contact with water contaminated with MC-LR, those antibodies squeeze in between the nanotubes to bond with the MC-LR. This spreading apart of the nanotubes changes their electrical conductivity.

An external monitor measures the electrical conductivity. The whole device is about the size of a home pregnancy test with results appearing in fewer than 12 minutes. The process is 28 times faster than the complicated method most commonly used today to detect microcystin-LR.

The technology could also be adapted to detect a variety of harmful chemicals or toxins in water or food. To adapt the biosensor for other toxins scientists could simply replace the antibodies that bond to the toxin, Nicholas Kotov said, a professor in the departments of Chemical Engineering, Biomedical Engineering and Materials Science and Engineering who led the project.

4.6.3. University of Pittsburgh

A team led by chemistry professors Alexander Star and Stéphane Petoud developed a highly sensitive, fluorescent oxygen sensor that can detect minute amounts of Oxygen.

The oxygen sensor combines small-scale carbon nanotubes, with the reactivity of the europium compound coating. This produces a platform for low-cost, room-temperature detectors that are particularly sensitive to oxygen but less complicated than existing sensors. The new oxygen sensor would be small enough to incorporate into a portable or wearable device which would notify workers or rescuers any change in oxygen levels.

The ability to operate in a wide range of O2 concentrations, i.e. well below 1% to over 20%, will provide more opportunity for adoption of this technology.

5. Companies Profiles

5.1. Aneeve Nanotechnologies LLC, USA

Aneeve Nanotechnologies LLC
UCLA California Nanosystems Institute
570 Westwood Plaza, Suite 6532
Building 114, MC 722710
Los Angeles, CA 90095-7277

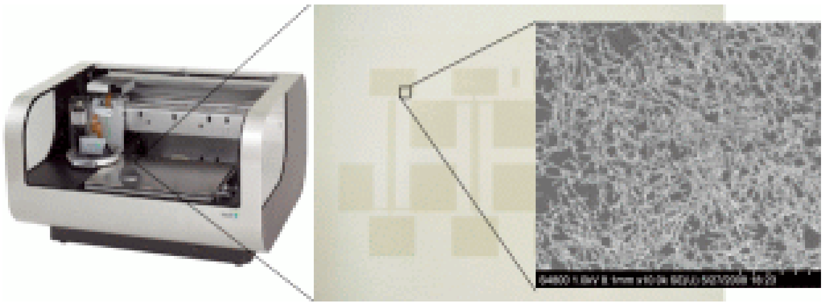
T: 1 310 874 3024
F: 1 310 825 8621
www.aneeve.com

Aneeve Nanotechnologies was founded in 2007 as a spin-off of University of California Los Angeles (UCLA). The company is a supplier of aligned CNTs and develops CNT applications. Currently located on-campus as part of the incubator initiative in conjunction with the California NanoSystems Institute (CNSI), the company's main target is to develop nanotechnology-based electronics for market sectors where cost and power consumption are key as it is for wireless and sensor applications.

Back in 2007 Aneeve provided CNTs on insulator materials and silicon to Northrup Grumman for high frequency, low noise and highly linear device applications.

Aneeve's newest development is a CNT-based hormon sensor made by low-cost ink-jet printing and using technology from UCLA to increase hormonal detection sensitivity. Still early in research the sensor and transducer technology is designed to detect oestrogen and progesterone hormon levels in menopausal women but can also be used in other biomedical applications.

Fig. 5.1 Hormone Sensing using CNT Printed Integrated Circuits



Source Aneeve Technologies, USA

"Aneeve's proof-of-concept work will be greatly aided by access to cutting-edge lab equipment and technical expertise at the incubator," University of Southern California professor Chongwu Zhou said. "This will propel the research and development efforts significantly and help Aneeve to get to market that much faster."

Aneeve is also working with Lockheed Martin, DARPA, Intel Stanford, USC and UCLA.

Aneeve is currently funded via the Defense Advanced Research Projects Agency (DARPA) with Small Business Innovation Research awards totalling more than $900,000.

5.2. Angstron Materials LLC., USA

1240 McCook Ave.
Dayton
OH 45404
937-331-9884
http://www.angstronmaterials.com

Angstron Materials is a manufacturer and provider of new nanoscale graphene platelets (NGPs), their composites and graphene nano-sheet as an alternative to CNTs. Their NGPs consist of one or more layers of a graphene plane, with a total thickness of 0.34 to 100 nm.

NGPs have striking properties outplaying CNTs, which are difficult to disperse in plastic, have purity issues and are cost-intensive. The intrinsic strength of NGPs is the highest existing as well as their thermal conductivity. They have exceptional in-plane electrical conductivity – up to ~ 20,000 S/cm and the electron mobility is 100 times faster than for silicon. NGPs can be modified to become semi-conducting or insulating when needed.

However, the material needs further improvement and practical electronic device applications are not envisioned to occur within the next 5 to 10 years. Potential applications are in aerospace, energy, defense, automotive and telecommunications.

Angstron Materials is a spin-off from Nanotek Instruments, Inc. with several US patents on this material, issued or pending. The company received research grants from the US Department of Energy (DOE) and National Science Foundation (NSF) Small Business Innovation Research (SBIR) Programs they have developed.

In December 2009 the company has been awarded an additional $1.494 million by the U.S. Commerce Department's National Institute of Standards and Technology (NIST). Angstron will use the money to develop mass-production methods for their functionalized NGPs through a scalable surface treatment procedure for graphene and graphene oxide platelets.

The company is also working on integrating the material in high-capacity lithium-ion batteries, high-capacity supercapacitors, solar cells and other energy storage and conversion products

5.3. Apex Nanomaterials, USA

7945 Silverton, Suite 1101
San Diego
CA, 92126
UNITED STATES
PH: 1 (877) 576 6038
E-Mail: sales@apexnanomaterials.com
www.apexnanomaterials.com/
Apex Nanomaterials is a manufacturer of SWCNTs at kg scale. The nanoscience and nanotechnology company was founded in San Diego in late 2003. They provide SWCNTs and their composites as a powder containing Arc, as-prepared or purified SWCNTs with a purity of 50 to 95%. Among the company's main competences are purification, processing and fictionalization.

5.4. Applied Nanotech, USA

3006 Longhorn Boulevard
Suite 107
Austin
Texas 78758-7631
United States
512-339-5020
www.appliednanotech.net

Applied Nanotech in collaboration with Chair of Display Technology, University Stuttgart, Germany, developed a proprietary printing-like method, which avoids expensive photolithography. With this they fabricated high performance SWCNT thin film transistors (TFTs) suitable for the use in the flexible electronics industry. They claim that inkjet, microcontact printing or a spaying technique are also possible. The SWCNT-based TFTs achieved results for mobility (100 cm^2/Vs) and on/off ratio (105) that outperform organic semiconductors.

ANI has its own methods, but also buys CNTs from other suppliers, and some of the latest separation methods are said to be more commercially viable and also allow selection of CNTs having the same "chirality."

At the Society for Information Display (SID) International Symposium in May 2008, the Chair of Display Technology of University of Stuttgart presented the world's first full color active matrix LCD where ITO as transparent conductive film (TCF) was completely replaced by random carbon nanotube (CNTs) networks. The display has a qVGA resolution (320xRGBx240) at 4" diagonal. The CNT networks are deposited by spray coating from suspension, which replaces a costly vacuum process. This demonstrates for the first time the applicability of CNTs as TCF in a state-of-the-art amorphous silicon active matrix process. It also gives a great perspective for future flexible displays, since CNT networks are much more reliable in flexible applications than the amorphous ITO. The complete display, including AM-backplane, color filters, and a dedicated addressing system was developed designed and fabricated at the University of Stuttgart.

5.5. Arry International Group, Hong Kong

Arry International Group Limited
Room 1401,Cambridge House 26-28,
Cameron Road, Tsimshatsui
Kowloon, Hong Kong
Telefon +852-3059 3048
Fax: +852-3059 3039
info@arry-nano.com
info@arry.eu
http://www.arry-nano.com

Arry International Group is a supplier of nano materials ranging from carbon nanotubes and nano elements to nano oxides. Using a scalable CVD method to produce high purity single-walled carbon nanotubes (SWNTs) they can make 2,000 grams of SWNTs with purity above 80% per day.

5.6. BASF, Germany

BASF Future Business GmbH
4. Gartenweg
Building Z 25
Ludwigshafen 67063
Germany
Telephone: +49 (0)621 60-0
Telefax: +49 (0) 621 60-42525
www.basf.com

BASF and Vorbeck Materials Corp. have established a joint research program to develop graphene-based formulations and composite materials. Together they are developing graphene dispersions for e.g. electrically conductive coatings and compounds especially for the electronics industry. Commercial applications are said to follow in the near future.

BASF is the world's leading chemical company. It has been developing printable and thin film transistor materials for some years and staff have lectured on ring oscillators and other devices that have been tested.

5.7. Bayer MaterialScience, Germany

Bayer MaterialScience AG
Communications, Geb. K12
Kaiser-Wilhelm-Allee
51368 Leverkusen
Deutschland
T: +49-(0)214 / 30-1
F: +49-(0)214 / 30-96 38810
http://www.bayermaterialscience.de

Bayer MaterialScience (BMS), part of the Bayer Group, is one of the world's leading producers of CNTs – sales of EUR 9.7 billion in 2008. The company focuses its activities on the automotive, construction, electrical and electronics, as well as the leisure and sports industry. In 30 production sites worldwide Bayer MaterialScience employs approximately 15,100 people (end of 2008).

BMS' printable conductive materials are mainly based on nanotechnology and include carbon nanotubes and nanosilver particles. With the inks and pastes thin conductive tracks can be created on flexible substrate. Potential applications of these are sensors, displays, RFID or photovoltaics.

In five production facilities on three continents Bayer MaterialScience is able to produce the proprietary high quality baytubes® (MWCNTs) at an industrial scale. The baytubes® were developed through a collaboration between Bayer Technology Services and Bayer MaterialScience.

Only recently Bayer MaterialScience (BMS), invested EUR 22 million into the newly opened pilot facility for the manufacture of CNTs at Chempark Leverkusen. With an annual production capacity of 200 metric tons it is the largest facility of its kind in the world. Since 2007 a pilot plant in Laufenburg in southern Germany is working with an annual capacity of 60 metric tons.

Leverkusen and the North Rine-Westphalia region have a leading role in the nanotechnology field worldwide. "We are expecting nanotechnology to create a total of 100,000 new jobs in the German industry in the medium term," said Dr. Joachim Wolff, member of the Bayer MaterialScience Executive segment.

Table 5.1 **Baytubes product specifications**

baytubes® C 150 HP

Product Specifications

Property	Value	Unit
C-Purity	> 99	%
Free amorphous carbon	Not detectable	%
Number of walls	3-15	-
Outer mean diameter	13-16	nm
Outer diameter distribution	5-20	nm
Inner mean diameter	4	nm
Inner diameter distribution	2-6	nm
Length	1 - >10	µm
Bulk density	140-230	kg/m^3

Source Bayer MaterialScience

The company is working with Zoz GmbH on the development of customized CNT-reinforced aluminum materials. Zoz GmbH, a German company headquartered in Wenden, is a global supplier of innovative systems and equipment, in particular for the manufacture of nanostructured materials.

5.8. Brewer Science, USA

Brewer Science
2401 Brewer Drive
Rolla, MO 65401
United States

T: 1 573 364 0300
www.brewerscience.com

Founded in 1981 and privately held, Brewer Science delivers innovative material, process and equipment solutions for lithography, advanced packaging, MEMS, nanotechnology, optoelectronics, and compound semiconductor applications. The core business is not based on carbon nanotubes.

Products include CENTRENE™ electronics-grade carbon nanotube solutions, ARC® antireflective coatings, Cee® processing equipment, ProTEK® temporary etch protective coatings, WaferBOND® temporary bonding materials, and OptiNDEX™ high-refractive index materials.

CENTRENE™ is a commercial available microelectronic-grade carbon nanotube coating. Brewer Science's refinement technology of the carbon nanotube material enables the removal of metallic and carbonaceous contaminants. However, they are working together closely with the raw material suppliers to get better nanotubes in the first place instead of having a complex and cost intensive refining process. The company's goal is to have the best scale vs. best price relation instead of having the purest and best solution.

Testing of the CNT solutions is done in-house as well as in collaboration with partners, customers and universities (PETEC, Optomec, University of Massachusetts, Nantero). The coating can be applied by spin, spray, micro-dispensing or ink-jet printing.

Brewer Science is selling CENTRENE™ to customers from research and industry, but the overall market is still considered to be a very small one. CNTs are only produced in the Missouri production facility with a production capacity of 70 to 100 liters per month at the moment, and with the capability to turn over into large scale production depending on the market change.

Stephen Turner, Product Manager of Carbon Nanotubes and Servises at Brewer Science, considers the CNT business to be in a "ramp up stage" at the moment with first commercial applications ready end of 2010. Nevertheless he predicts that it will take five years until they really appear in the market.

Brewer Science has had a focused business unit that encompasses research, development, and large-scale manufacturing of carbon nanotube based solutions since 2005. The company has 300 employees worldwide, approximately 10 working only in the CNT unit.

In addition to the electronics-grade material, development of other advanced materials include: highly conductive materials for large area substrate coverage, conductive materials for printed electronics, and semiconducting materials for thin-film transistors.

Fig. 5.2 **Fully printed CNT FET-based switch**

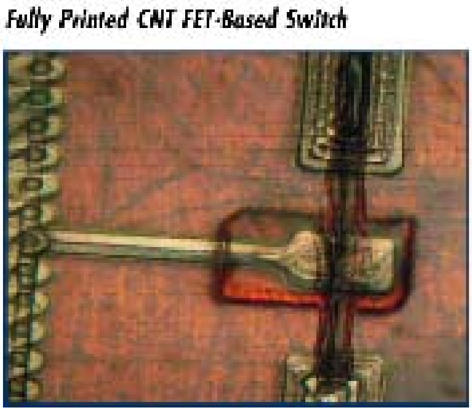
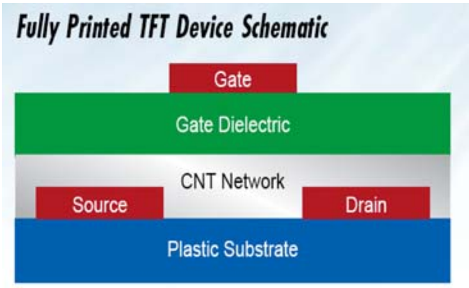


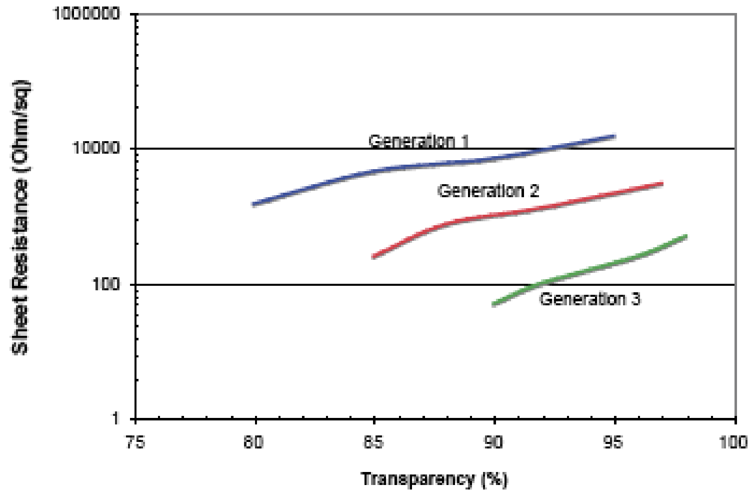
Fig. 5.3 **Fully printed TFT device schematic**



Recently, the semiconducting carbon nanotube materials have been used in a fully printed TFT that achieved operating frequencies over 5 Gigahertz (GHz).

	CNT FET	Organic FET
Electron Mobility (cm^2/Vs):	46,000	< 5
Hole Mobility (cm^2/Vs):	46,000	< 5
Operating Frequency:	> 5 GHz	
Thermal Conductivity:	Yes	No

Fig. 5.4 **Transparent conductive material roadmap: Gen 1 at the moment; Gen 2 is the goal for end of 2010, Gen 3 is the long term target**



	Brewer Science® CNT Materials	Alternative Technology 1	Alternative Technology 2	Alternative Technology 3
Transmission (%):	Up to 99	80-96	80-99	80-96
Sheet Resistance (Ohm/sq):	$10\text{-}10^6$	< 1000	$500\text{-}10^5$	< 1000
Color:	Neutral	Yellow Tint	Blue Tint	Varies
Printed Deposition:	Yes	No	Yes	Yes
Flexible Substrate Use:	Yes	Some	Yes	Yes
Environmental Stability:	Yes	Some	Some	Yes

At the end of 2009 Brewer Science Inc. and SouthWest NanoTechnologies, Inc. (SWeNT) announced that they have received a $6.5M award under the NIST's Technology Innovation Program (TIP).

The funding is in support of research and development programs that focus upon methodologies to attain the cost-effective production of high-purity, high-quality metallic and semiconducting carbon nanotube (CNT) inks. These advancements will enable production of a wide variety of high-performing electronic devices incorporating CNTs.

5.9. Canatu Ltd., Finland

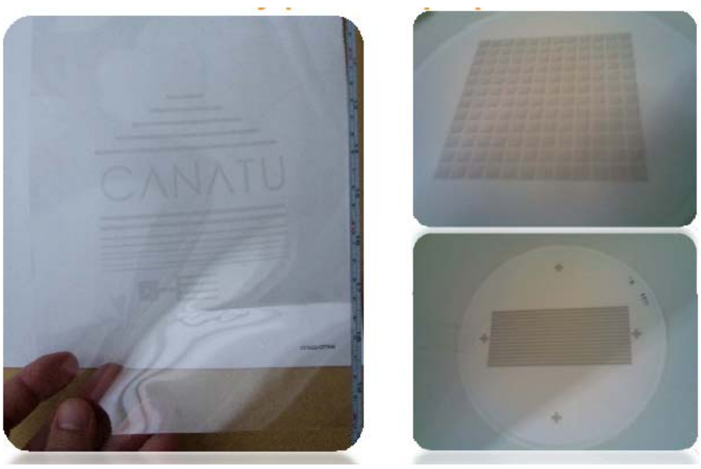
Tekniikantie 21
02150 Espoo
Finland
http://www.canatu.com

Founded in 2004, Canatu is a spin-off from the Helsinki University of Technology (TKK). Canatu Oy's produces films based on carbon nanotubes and their NanoBud™ nanomaterial. They have a laboratory scale production facility and are using a proprietary synthesis that allows direct deposition from an aerosol onto any substrate. With this patent pending Direct Dry Printing (DDP)-technology each synthesis step is independently controllable and leads to a highly homogeneous product.

Canatu is focusing on applications of conductive and semi-conductive thin films, which range from transparent electrodes in solar cells and displays, saturable absorbers in pulsed lasers to semiconducting films in field effects transistors. Their patterned transparent conductive films are suitable for replacing ITO in LCDs, OLED displays, thin film solar cells etc.

The current business is sampling films with a number of key customers. The company can provide ready-to-use transparent and conductive homogeneous and pre-patterned films produced to customer specifications. To date Canatu is not selling these films. First products are flexible, transparent, conducting CNT and NanoBud™ films on polymer substrates such as PET. Canatu is currently preparing to scale to large manufacturing volumes.

Fig. 5.5 **Directly produced prepatterned films**



Source Canatu

The focus will be on markets where high conductivity, transparency, stability and flexibility are required and where competing products like conducting polymers and ITO do not match the performance, customer specificity and costs of Canatu films. The production cost and performance are already competitive with existing and other emerging technologies and materials. In the long run when producing at high volumes Dr. David Brown expects to achieve clear cost and performance leadership in the target products.

The company is planning on selling homogeneous and pre-patterned films in various conductivities, transparencies, patterning and fractional coverage in the near future. They will begin by supplying selected strategic partners with specialty films made to their specifications. In "equivalent square meters" (equivalent to 80% transparency, homogeneous film), they plan to be selling approximately 1000 m2 in 2010, 15000 m2 in 2011, 40000 m2 in 2012, 100000 m2 in 2013, and 300000 m2 in 2014.

Due to own production of high quality, high purity material in the gas phase and direct deposition at room temperature with no need for intermediate, time consuming and costly wet processing steps, production costs are low at higher performance.

Canatu is working with companies on integrating their films into applications in the areas of e-readers, touch screens, thin film displays and solar cells. Additionally, the company is working closely with the Helsinki University of Technology.

Recently, the company was awarded with the Red Herring 100 Europe award. "Winning the prestigious Red Herring award is a great honor for the company and recognition for our success in making environmentally friendly and low cost organic electronics a reality", said Dr. David Brown, co-founder and CEO of Canatu.

5.10. Carben Semicon Ltd, Russia

Carben Semicon Limited
Miusskaya pl., 9, bldg. 5
125047, Moscow, Russia
Tel: +7 (495) 251-99-98
Fax: +7 (495) 251-99-65
http://www.carbensemicon.com

Carben Semicon is a start-up company that developed Ribtan® a graphene-based material that can be tuned and exploit insulating, semiconducting or metallic properties with a resistance ranging from 10^{14} to 10^{-4} Ohm/cm.

5.11. Carbon Solutions, Inc., USA

Carbon Solutions, Inc.
1200 Columbia Ave.
Riverside, CA 92507
(951) 682-5620
Fax: (951) 682-5627
E-mail: sales@carbonsolution.com
http://www.carbonsolution.com

Carbon Solutions is a provider of SWCNTs with different specifications; as prepared, purified with low or high functionality, organic-soluble, water-soluble or amid functionalized. In 2008 the company expended its manufacturing facility to be able to produce large scale. Chemical modification is used to carry out SWCNTs that achieve their full potential.

The company partners with other research institutes, namely DARPA (Defence Advanced Research Projects Agency), ONR (Office of Naval Research), NSF (National Science Foundation), the Air Force Office of Scientific Research, the US Department of Homeland Security, the University of Delaware and UCLA.

5.12. CarboLex, Inc., USA

460 Parkway
Broomall
PA 19008
U.S.A.
(859) 226-9210
http://carbolex.com

CarboLex was established in 1998 as a spin-off of the Advanced Science and Technology Commercialization Center at the University of Kentucky in Lexington. The company is a provider of SWCNTs. They use Arc method, which is processed in specifically designed chambers. The purity of their SWCNT is 50 to 70% for as-prepared and 70 to 90% for SE-grade. CarboLex' SWCNT production line has a capacity of approximately 100g/hour (>1kg/day).

5.13. Cap-XX Australia

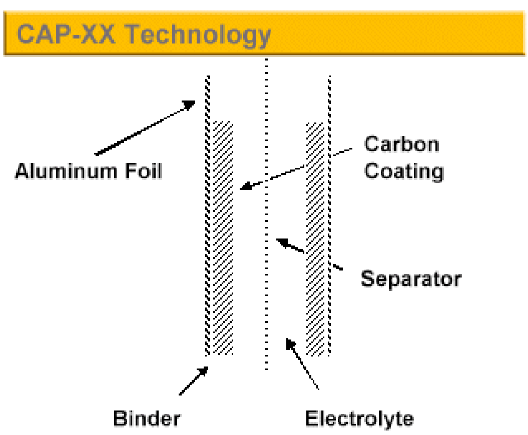
CAP-XX Ltd.
9/12 Mars Road
Lane Cove NSW 2066 Australia
Phone +61 2 9420 0690
Fax +61 2 9420 0673

CAP-XX develops high power, high energy supercapacitors in thin, flat, prismatic packages and focuses on solutions for portable and wireless applications.

They enable smaller, lighter, more functional and longer-running electronic products by providing peak power support to pulsed loads and short-term power support during interruptions to the primary source. In addition to providing pulse power, CAP-XX supercapacitors provide the following features and advantages:

- Extends battery run time by minimizing the voltage droop caused by a high-current load
- Provides the high-current pulses required by the load and smoothes the fluctuating power required from the low current source
- Minimizes electrical and acoustic noise generated by current pulses in ruggedized PDAs and other systems by smoothing the fluctuating power required from the battery
- Permits low-temperature operation in ruggedized PDA and LiTC applications and high temperature operation in PCMCIA and other modems
- Provides technical benefit in small volume/mass, particularly in compact flash and PCMCIA modems in which height and footprint are severely limited. Also enables thinner, smaller industrial design for PDAs, mobile phones, and other consumer applications
- Meets environmental standards for disposal and hazardous operation, which is essential for wireless modems, converged handhelds, the LiTC market, and DSCs

Fig. 5.6 **Cap-XX supercapacitor technology with carbon coating.**



Source Cap-XX

5.14. Case Western Reserve University, USA

Department of Chemical Engineering
10900 Euclid Ave.
Cleveland, Ohio 44106
T: 1 216 368 4182
www.case.edu/cse/eche

Case Western researchers mixed metals commonly used to grow nanotubes and found that the composition of the catalyst can control the chirality.

"We have established a link between the structure of a catalyst and the chirality of carbon nanotubes," Sankaran, an assistant professor of chemical engineering at the Case School of Engineering, said. "Change the catalyst structure by varying its composition, and you can begin to control the chirality of the nanotubes and their electrical and optical properties."

5.15. Catalyx Nanotech Inc. (CNI), USA

940-A E. Orangethorpe Ave
Anaheim, CA 92801
T: 1 714 449 9968
F: 1 714 870 1194
http://catalyxnano.com/

In July 2009 Catalyx announced, that it has signed an exclusive agreement with Strem Chemicals, Inc. to make their Stacked Graphene NanoFibres (SGNF) available for research and development purposes.

The company has a production capacity of 1.5 kg material per day, including Platelet Graphite NanoFibres, Graphite Nanochips and hexagonal Nanotubes.

Catalyx Nanotech Inc., a spin off from Catalyx Inc., was formed in 2007 as a manufacturer of nanomaterials. The company uses a patented cost-effective catalysis technology to produce their SGNFs from methane, which show exceptional performance in a wide variety of applications.

Stacked Graphene NanoFibres consist of a graphene sheet oriented perpendicular to the growth axis like a stack of cards, spaced 0.34nm apart with a width of 40-50nm and a length of 100-10,000nm. During the patented production process a carbon containing gas is decomposed in presence of metal catalyst particles.

"Our nanofibers could be used as a carbon-based catalyst support for fuel cells and other chemical processes, for the separation of volatile organic carbon pollutants from water and in supercapacitors and batteries" said Juzer Jangbarwala, Catalyx Nanotech Founder and Chairman. "We have also recently demonstrated the production of these nanofibers from renewable resources".

5.16. CheapTubes, USA

112 Mercury Drive,
Brattleboro, VT
05301 USA
Phone: 802.254.6969
Fax: 802.254.7070
http://www.cheaptubes.com

CheapTubes is a supplier of nanotechnology research and materials, namely single-walled and multi-walled carbon nanotubes as well as Fullerenes. The SWCNTs are fabricated using CCVD and acid purification. CheapTubes also sells OH- or COOH-functionalized CNTs for research and industry.

The company also provides Single Layer Graphene Oxide, which is suitable for a wide variety of applications including electronics and solar. The product is solution processable.

5.17. Chengdu Organic Chemicals Co. Ltd. (Timesnano), China

Chengdu Organic Chemicals Co. Ltd., Chinese Academy of Sciences
No.16, South section 2, the first Circle road, Chengdu, P.R.China
Tel: +86-28-85236765 85228839 85241016
Fax: +86-28-85215069 85223978
Mobile: +86-0-13880438669
Post code: 610041
E-Mail: carbon@cioc.ac.cn nano@cioc.ac.cn times@cioc.ac.cn
http://www.timesnano.com

The Chendu Organic Chemicals Co. Ltd. is a manufacturer of a series of CNTs since 1996 – single-walled, double-walled, multi-walled, functionalized and short multi-walled CNTs. The company developed a scalable CVD method and holds several patents about CNTs. Their SWCNTs have an average diameter of 1-2nm with a purity rate of >60% or >90%.

The company is being supported by the President Foundation of the Chinese Academy of Sciences, the Key Items of Knowledge Innovation Program of Chinese Academy of Sciences, the National High Technology Research and Development Program of China, the National Basic Research Program of China for carbon nanotubes synthesis and application research.

5.18. CNano Technology Ltd, USA

CNano Technology Ltd.
3333 Bowers Ave., Suite 130
Santa Clara, CA 95054
USA
T:1-408-826-0918
F: 1-408-899-5157
www.cnanotechnology.com

CNano, headquartered in Santa Clara, CA, was founded in 2007 with manufacturing located in China. CNano is a nano-material company that manufactures and develops carbon nanotubes for advanced energy, especially Li-ion battery, conductive plastic and structural applications.

In June 2009 the company announced that it has successfully scaled up its manufacturing technology to reach a production capacity of 500 tons per year for carbon nanotubes (MWCNTs). The proprietary manufacturing technology enables large scale production at a lower cost structure.

CNano platform production technology also facilitates the production of other types of carbon nanotubes. The Company plans to further leverage the 500 ton plant for additional products to be rolled out in the near future. CNano is working together with customers in several markets that include electronics, automotive and energy storage to integrate the CNTs into products.

"This manufacturing capability is an important milestone in the drive to meet current and future customer supply demands. The production line validates our technology at a much larger scale while providing a reliable large volume supply source for customers utilizing the unique properties of carbon nanotubes in their products," said Xindi Wu, President and CEO of CNano.It has received venture capital funding from CMEA Capital, Pangaea Ventures, and WI Harper.

5.19. Cornell University, USA

Cornell Laboratory for Organic Electronics
Department of Materials Science and Engineering
Cornell University
Ithaca, NY 14853-1501
United States
(607) 255-1956
http://www.cloe.cornell.edu/

Earlier in 2009, scientists at Cornell and DuPont invented a new and relatively simple process to separate metallic and semiconducting carbon nanotubes into a high-performance CNT 'ink' that solely contains semiconducting tubes. Funded by the U.S. Air Force, the development is a highly promising approach towards printed, thin and flexible electronics for TFTs and Photovoltaics.

Graciela B. Blanchet, a research fellow at DuPont, said: "Our work suggests that careful control of the chemical reaction enables the complete conversion of metallic tubes without the degradation of semiconducting tubes."

The McEuen Group, Laboratory of Atomic and Solid State Physics, is focusing on carbon nanotubes and single graphene sheets.

A Cornell team led by Michael Spencer, professor of electrical and computer engineering, gets a $1.5 million, five-year grant from the U.S. Department of Defense, Air Force Office of Scientific Research, to fabricate graphene in large sheets suitable for use in microchips. Goal of the project is to develop new growth and fabrication technologies for graphene and to enable novel device concept.

In September 2009 the McEuen Group presented a simple solar cell called photodiode that is based on an individual carbon nanotube and promises more efficient conversion of light into electricity.

A single CNT was wired between two electrical contacts and close to two electrical gates, one negatively and one positively charged. The developed conversion process multiplies the amount of electrical current that flows, meaning higher levels of photon energy have a multiplying effect on how much electrical current is produced.

This finding could prove important for next-generation high efficiency solar cells. Instead of loosing extra energy in the form of heat, as it is the case for today's solar cells, this single CNT photodiode may be nearly ideal, because electrons create more electrons using the spare energy from the light. Loss of energy to heat limits the efficiency of the best solar cells to about 33 percent.

The next step will be to develop methods for making large arrays of the CNT photodiodes to take advantage of the super efficiency.

The research was supported by Cornell's Center for Nanoscale Systems and the Cornell NanoScale Science and Technology Facility, both National Science Foundation facilities, as well as the Microelectronics Advanced Research Corporation Focused Research Center on Materials, Structures and Devices. Research collaborators also included Zhaohui Zhong, of the University of Michigan, and Ken Bosnick, of the National Institute for Nanotechnology at University of Alberta.

5.20. CSIRO, Australia

CSIRO Materials Science & Engineering, Geelong
Cnr Henry St and Colac Rd
Belmont, Geelong VIC 3216
Australia
Phone: +61 3 5246 4000
Fax: +61 3 5246 4057
http://csiro.au/org/CMSE.html

The Material Science & Engineering department at CSIRO is focusing on carbon nanotubes, applications of them in textiles and the industrialisation of these applications. For the production of yarns and sheets CSIRO has built special reactors and is using a spinning process. Together with the NanoTech Institute, University of Texas at Dallas, CSIRO holds a provisional patent on the spinning process. The resulting yarns are strong, durable and flexible.

In addition the CNT-yarns to that extruded fibers from CNT-blended polymers are studied regarding production process and properties.

5.21. Dainippon Screen Mfg. Co., Ltd., Japan

Tenjinkita-cho 1-1,
Teranouchi-agaru 4-chome,
Horikawa-dori,
Kamigyo-ku,
Kyoto 602-8585, JAPAN
Telephone +81 75 414 7111
www.screen.co.jp/index.html

Dainippon Screen Manufacturing Co., Ltd. (TSE: 7735) was established in 1943. The company's principal activity is the design, manufacture and distribution of desktop publishing (DTP), press equipment and systems for the graphic arts industry. The Company has developed a wide range of equipment used in semiconductor, liquid crystal display, hybrid substrate and printed circuit board manufacturing supplier of shadow masks and ultrafine metal meshes for use in colour television picture tubes and other electronic applications. Operations are carried out through the following divisions: electronic equipment and components accounted for 56% of fiscal 2000 revenues; graphic art equipment, 38%; office equipment and other, 6%.

Research in collaboration with Department of Chemical System Engineering, School of Engineering, The University of Tokyo, Tokyo, Japan

1-Second Implementation of CNT-Emitter Arrays on Glasses for BLUs

Abstract

We realized simple fabrication of carbon nanotube field emitters for backlight units. Carbon nanotubes were directly grown on cathode lines patterned on low-strain glasses by atmospheric pressure CVD with pulse electrical heating of cathodes for 1 second. Field emission current density was as high as 5.6 mA/cm2 at 3.3 V/!m.

1. Introduction

In recent years, environmentally friendly mercury-less backlight units (BLUs) for liquid crystal displays (LCDs) are extensively studied for the next generation following the cold cathode fluorescent lamp (CCFL) BLUs. Light-emitting diode(LED) BLUs are one of the candidates, however main drawbacks are their cost and color reproduction characteristics.

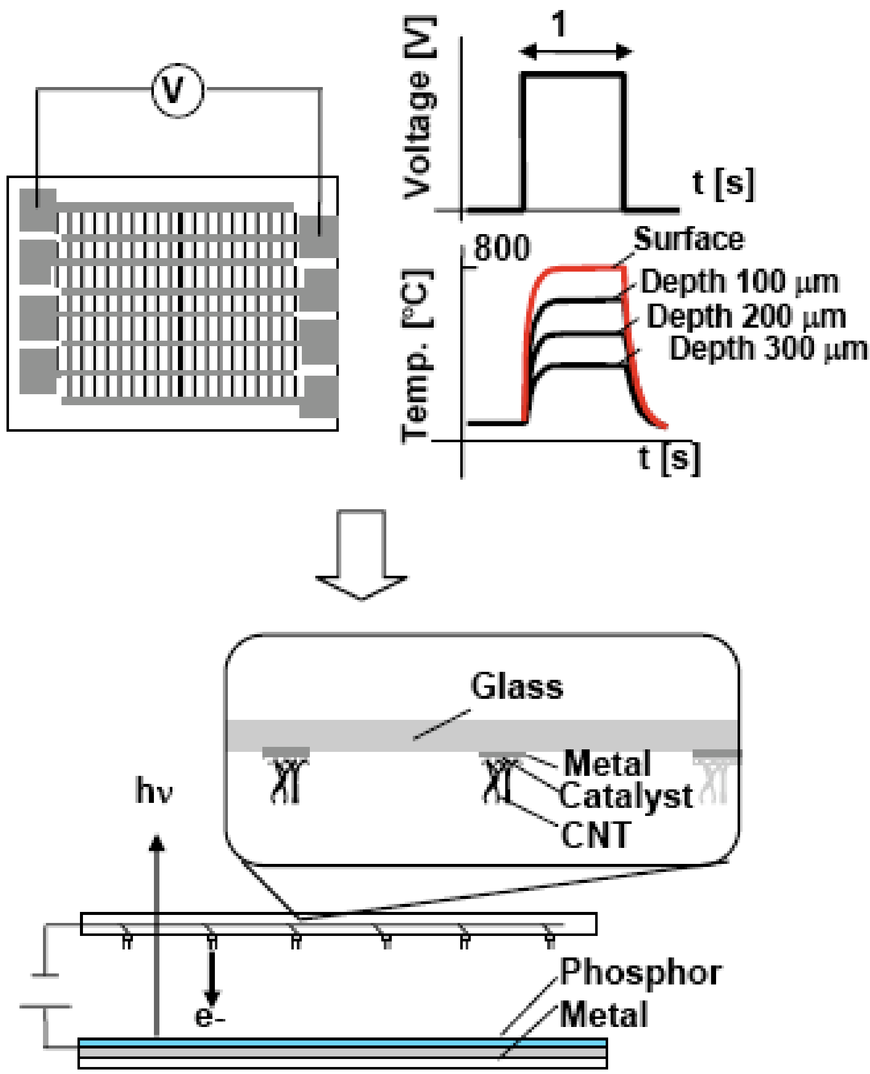
In this context, carbon nanotube field-emission (CNT-FE)BLUs have been reported [1-3]. Direct growth of CNTs by chemical vapor deposition (CVD) can hardly be applied to lows train glasses such as non-alkali glasses due to the growth temperature typically above the glass strain points. Screen printing of a CNT-paste is a simple and low-cost process to prepare CNT-emitters, however, practical emission uniformity may not be obtained due to a small number of effective emitters per array. In order to increase emission sites, one might have to apply raising processes such as adhesive taping, plasma treatment and laser irradiation [4,5].

We have developed a combinatorial catalyst preparation method on substrates and been studying the direct growth of CNTs [6,7]. CNT-emitters grown within 10-60 seconds showed various FE performance depending on the CNT morphologies[8,9]. Millimeter-growth of CNTs within several minutes is now possible [10], which means micrometer-long CNTs can be grown within even sub-seconds.

Here, we propose a simple and low-cost route to directly install a large number of CNT-emitters on micro-patterned cathodes by pulse-electrical heating of the cathodes. The layout of CNT-FEBLU in the present work is shown in fig 5.3.

CNT-emitters are prepared in 1 second by CVD using micropatterned cathodes as micro-heaters. Local and short time surface heating by an electrical pulse enabled the application of CVD to low-cost glasses as substrates. Luminescent light can be extracted from the backside of the cathode. We expect higher luminous efficiency for the preset device than conventional devices because of a high aperture rate of the cathodes and reflection from the metal anode.

Fig. 5.7 **Layout of CNT-FE BLU fabricated through pulse**



Source Dainippon Screen Mfg

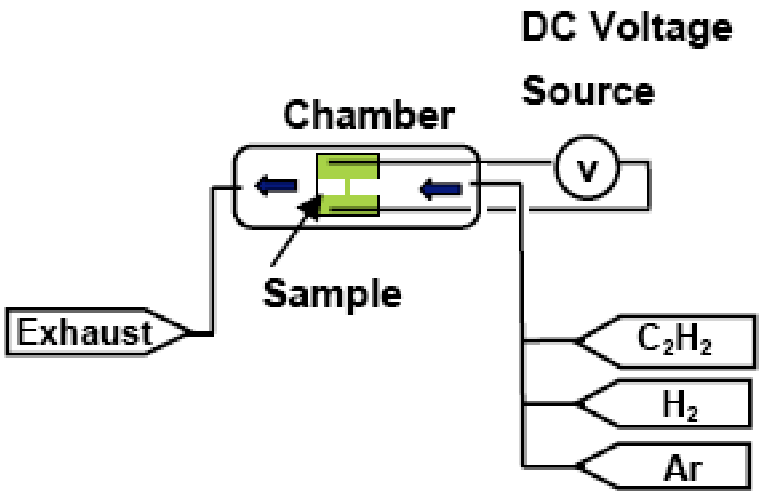
CVD

2. Experiments

Schematic illustration of experimental set up is shown in fig 5.4. Quartz (t=0.5mm), non-alkali (CORNING #1737,t=0.75mm), soda-lime (MATSUNAMI slide glass S1225,t=1.3mm) and PD200 (AGC, t=2.8mm) glasses were used as substrates. A Mo cathode on glass substrates was formed by a conventional RF magnetron sputtering. Line patterns were prepared through photolithography and conventional wet processes.

An Al2O3 catalyst supporting layer (20 nm) and aFe catalytic layer (ranging from 1 to 6 nm) were subsequently deposited.

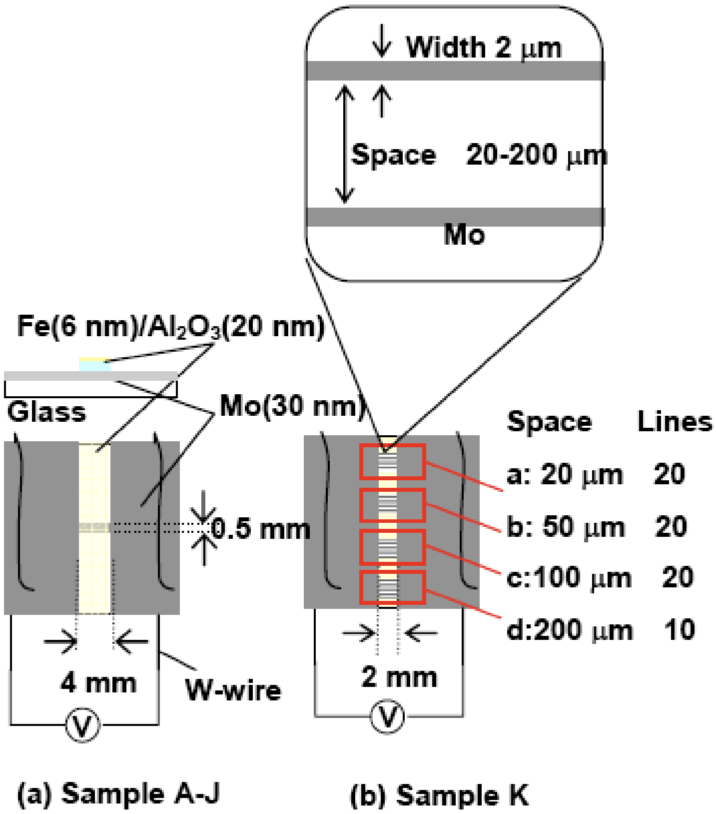
Fig. 5.8 **Schematic illustration of experimental setup**



Source Dainippon Screen Mfg

Illustrations of micro-patterned cathodes are shown in fig 5.5. A heating area in the first one is 500 !m in width $ 4 mm in length(Fig. 3a). The second one is designed for FE measurements. Molines had a length and a width of 2 mm and 2 !m, respectively, with 20-, 50-, and 100-!m-spacing (20 lines each) and 200-!mspacing(10 lines) (Fig. 3b).

Fig. 5.9 **Illustrations of micro-patterned cathodes**



Source Dainippon Screen Mfg

CNTs are selectively grown on micro-patterned cathodes by pulse-heating the cathodes under C2H2 (0.5kPa)/ H2 (27 kPa)/ Ar balance at atmospheric pressure. One shot pulse-voltage was applied to the cathodes by Keithley 2400 for 1 second. Dc voltages were adjusted between 80 and 210 V considering the resistivity of cathodes of different thicknesses.

CNTs and Mo micro-patterned cathodes are observed by a Hitachi S-4700 field emission scanning electron microscope(SEM).

A Mo anode layer is deposited on glass substrates. Phosphor layers were prepared by screen printing of ZnO: Zn powders (NICHIA Co.) dispersed in a cellulose vehicle (NISSHIN KASEI Co.) and subsequent binder burnout at 500 #C for 10 minutes. FE measurement was carried out at a pressure of 1.2$10-5 Pa and extracted current was measured by Keithley 2410 high-voltage digital multimeter. 150-!m-thick glass slides are used as spacers.

3. Results and discussion

Results of CNT-growth on several glasses are summarized in the table below. CNT growth was examined on 4 types of glass substrates used in this work. The initial power was adjusted to realize appropriate surface temperatures for each substrates with different thermal conductivities.

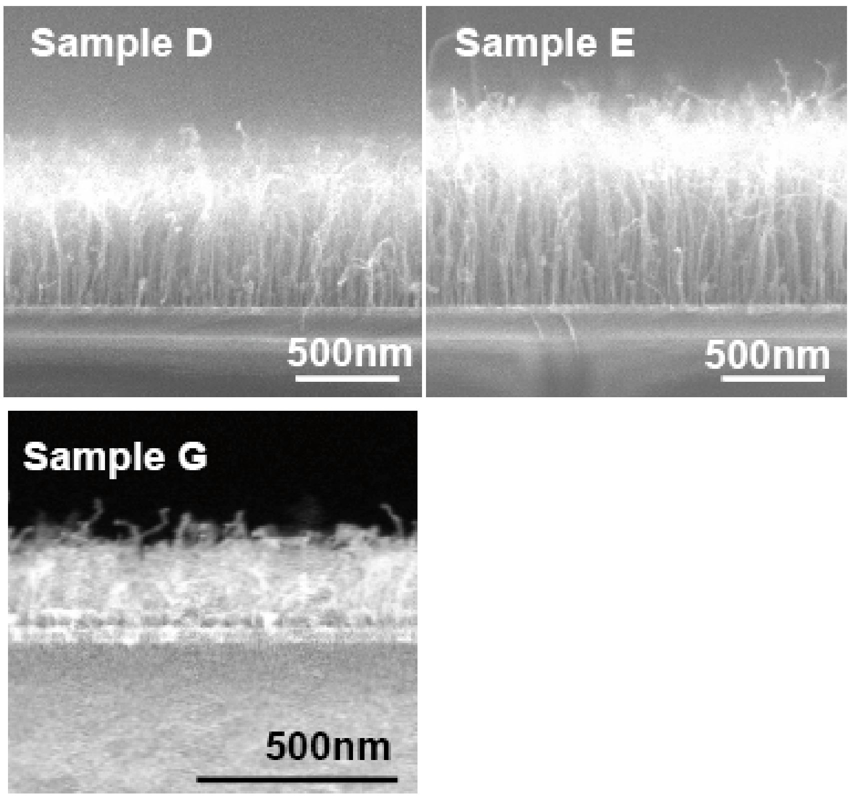
Table 5.2 **Results of pulse-heat CVD**

Sample	Glass	Power MW/m²	CNTs*	Damage
A	Quartz	8.0	○	—
B	Quartz	9.1	○	—
C	#1737	3.9	×	—
D	#1737	4.9	○	—
E	#1737	5.8	○	—
F	Soda-lime	2.4	×	—
G	Soda-lime	2.6	○	—
H	Soda-lime	3.0	○	Crack
I	PD200	4.0	○	—
J	PD200	4.5	○	Crack

* Open circles: growth, crosses: no growth

Source Dainippon Screen Mfg

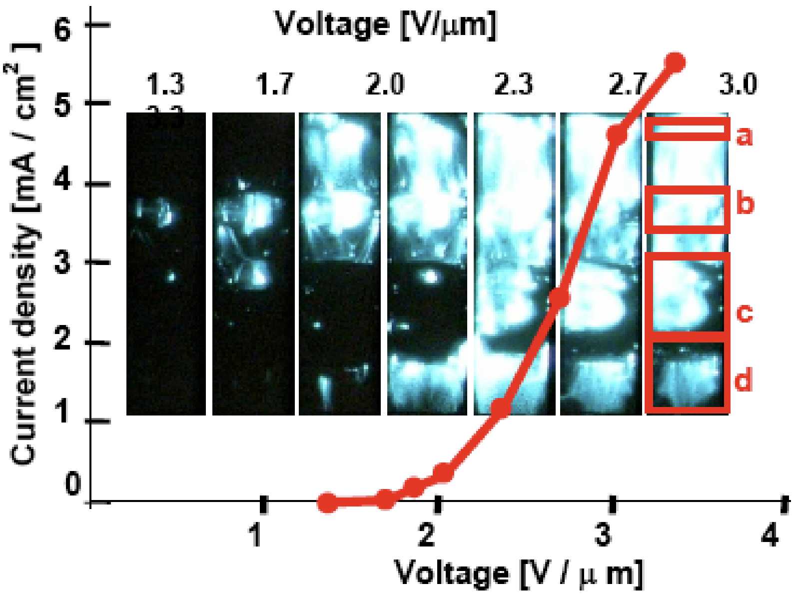
Fig. 5.10 **SEM images of CNTs on Samples C, D and E**



Source Dainippon Screen Mfg

The figure above shows SEM images of CNTs obtained for Samples E, D and G. Heights of vertically aligned CNTs ranged from 300 nm to 1 !m.

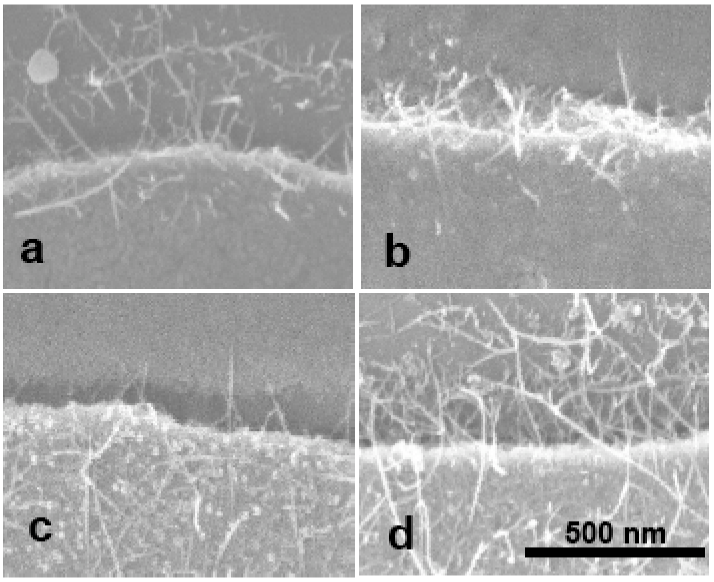
Fig. 5.11 **Field emission properties of CNT-emitters patterned on a glass substrate by pulse-heat CVD. Luminescence images from the backsides of the cathode at various applied voltages are indicated in inset.**



Source Dainippon Screen Mfg

The figure shows the FE characteristics obtained for a sample with CNT-emitters on Sample K. The maximum current density was 5.6 mA/cm2 at 3.3 V/!m.! The area with 50-!m-spacingemitted electrons at 1.3 V/!m.

Fig. 5.12 **SEM images of CNTs on the micro-patterned electrodes with interline spacing (a) 20, (b) 50, (c) 100 and (d)200 !m (top view).**



Source Dainippon Screen Mfg

SEM images of CNTs obtained for each area are shown in fig 5.8. For the 20- and 50-!m-spacing areas, CNTs grow only on edges of the micro patterned electrodes (Figs. 5.8a and 5.8b), which yielded strong luminescence (Fig. 5.7). For the 100- and 200-!mspacingareas, grass type CNTs existed on the micro-patterned cathodes, which yielded weaker luminescence (Fig. 5.7). Different line-spacing caused different cathode temperature, resulted in CNT emitters of different morphologies showing different FE performance.

In order to optimize pattering designs, which give preferable FE properties, combinatorial experiments for samples with a distribution of not only line width or spacing but also thickness of a catalyst layer are ongoing [9].

4. Conclusion

CNT-emitter arrays were installed on 1 second on micropatterned cathodes on low-strain glasses by pulse-heating CVD. The present process and line-patterned configuration can be expected as one of the candidates for CNT-FE BLU manufacturing.

5.22. DuPont, USA

4417 Lancaster Pike
Wilmington
Delaware 19880
United States
1-302-774-1000

DuPont is a science-based products and services company. Founded in 1802, DuPont puts science to work by creating sustainable solutions essential to a better, safer, healthier life for people everywhere.

Operating in more than 70 countries, DuPont offers a wide range of innovative products and services for markets including agriculture and food; building and construction; communications; and transportation.

Scientists at DuPont in collaboration with Cornell University developed a simple chemical process to convert mixtures of metallic and semiconducting carbon nanotubes into solely semiconducting carbon nanotubes. In 2003, DuPont scientists already published a method to separate carbon nanotubes using DNA. DuPont has continued to investigate these materials. The current development proves to be a very promising approach to developing large quantities of CNT-based semiconductors and their applications. Dr. Graciela Blanchet, research fellow at DuPont pointed out: "A significant limitation in electronic application of carbon nanotubes has been the difficulty in separating metallic from semiconducting carbon nanotubes," Graciela said.

The research was funded by a U.S. Air Force grant to Cornell University.

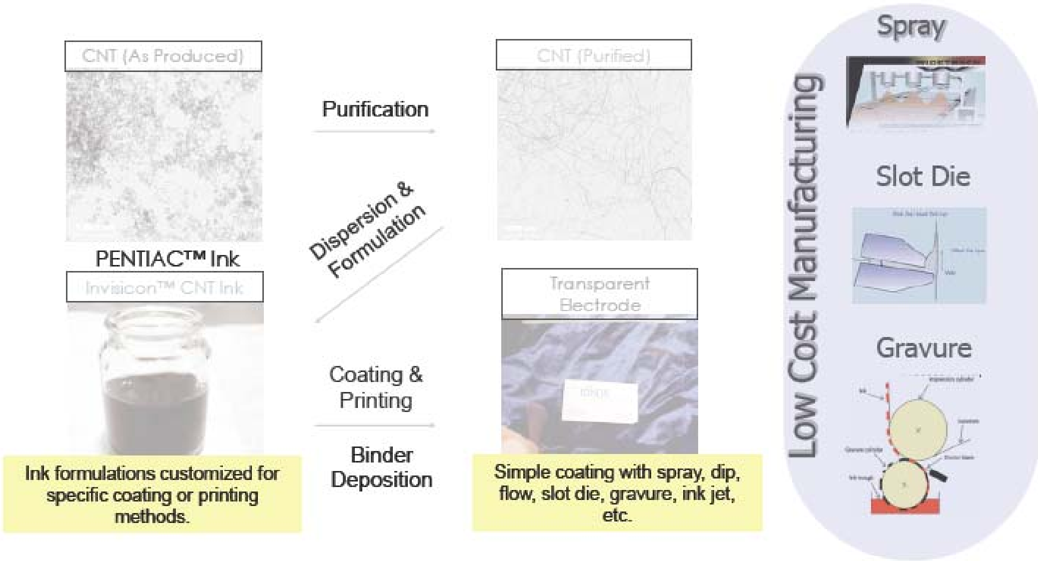
5.23. Eikos, USA

2 Master Drive
Franklin, MA 02038
United States
(508) 528-0300
www.eikos.com

Eikos is a materials science company founded in 1996 focusing on optoelectronics, printed electronics and currently working on building a CNT conductors business. Besides the area of Carbon Nanotube Coatings, the company also tries to incorporate CNT films in organic solar cells as transparent electrode, and the replacement of ITO in OLEDs, electro-chromic windows and other applications.

The company has a 14,000 sq ft production and research facility and plans the commercial production of touch screen sensors for 2009.

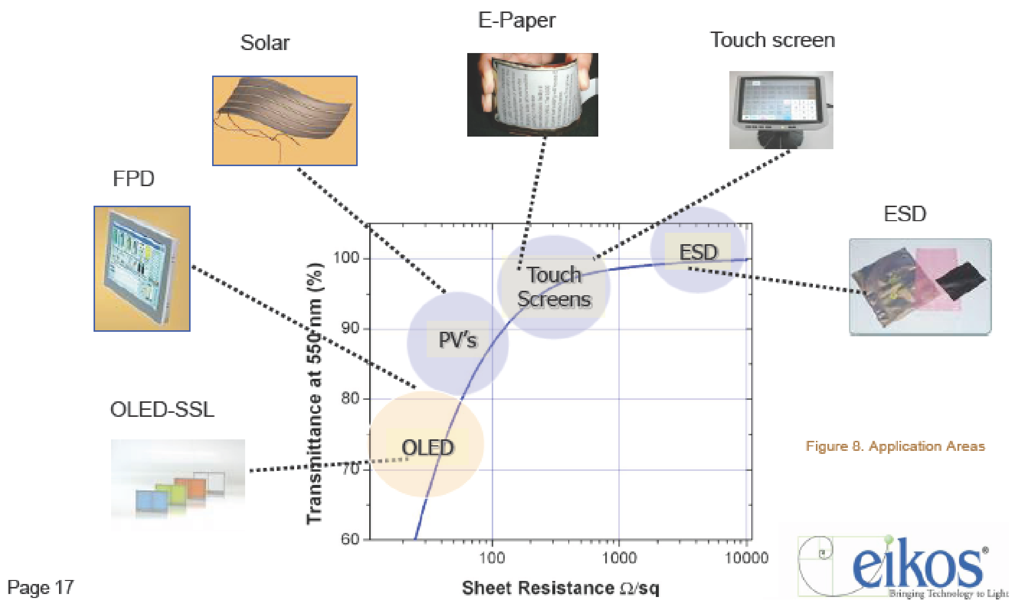
Fig. 5.13 **CNT Ink Production Process**



Source Eikos

PENTIAC (Printable Electronic Nanotube Inks and Concentrates) is platform technology with which the company plans to develop materials that fit the demands for displays, microelectronics, and solar. The inks will be available in different volume conductivities and can be used for simple coating processes like spray printing, inkjet or gravure. With a targeted volume conductivity ranging from >400S/cm to 20,000S/cm Eikos wants to develop materials that can replace the currently used carbon black, Pedot inks, ITO and silver inks.

Fig. 5.14 **Target application areas of Eikos**



Source Eikos

5.24. Frontier Carbon Corporation (FCC), Japan

1-1, Shiroishi, Kurosaki
Yahatanishi-ku
806-0004 Kitakyushu-shi
Japan
P +81 93 643 4400
F +81 93 643 4401
www.f-carbon.com

Frontier Carbon Corporation (FCC), headquartered in Tokyo Japan, is a joint venture between Mitsubishi Chemical Corporation, Mitsubishi Corporation, and Nanotech Partners. FCC is the first company in the world to mass produce fullerene at a commercial scale and has increased its fullerene production capacity to 40ton/yr in April 2003. It has refined a process to make fullerene - at a bulk level cheaper than previously possible.

FCC which was established in 2001, produces and sells Fullerenes and Fullerene related products as the industrial material supplier. FCC was realized the combustion production system for the large amount of Fullerene and completed the industrial production systems in 2003. Then FCC also developed a variety of technologies in many Fullerene applications as well as the Fullerene production.

The company is not only a material supplier of Fullerenes but also Fullerene related products, OPV acceptor materials in dry fabrication system (C60) and in wet fabrication system (PCBM and its family compounds).

FCC now sells fullerene at a price 1/10th of that of the existing market and has further plans to decrease its price. FCC has named its fullerene products to be 'nanom', an acronym of NAno + eNOrmous + Molecule and now exports 'nanom' products to North America, Europe, and Asia.

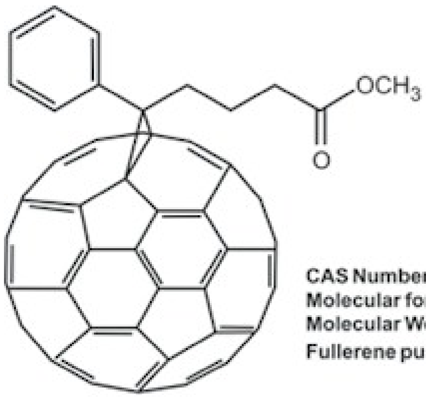
Dr Peter Harrop, Chairman of IDTechEx met Mineyuki Arikawa, President of Japanese start up Frontier Carbon Corporation in the opulent Institute of Directors, Pall Mall, London on the evening of Thursday 20.11.08. Mr Arikawa spoke at the recent IDTechEx conference Printed Electronics Asia in Tokyo and attracted much interest. He is now researching electronic opportunities for his fullerine (C60 etc buckyball carbon) in Europe, notably in organic photovoltaics OPV.

He is particularly interested in OPV acceptor materials where he says 75% of the research in Japan is on PCBM - the fullerene derivative 6,6-phenyl-C61-butyric acid methyl ester first synthesized by Fred Wudl in the University of California Santa Barbara (UCSB), which is very reproducible. However, 25% of the research in Japan on OPV acceptor materials now focuses on using pure fullerenes despite these being solid -not solvent based like PCBM.

He says pure fullerene acceptor layers can be better electrically and they can now be deposited in layers of high integrity. Indeed, he thinks 0.6 meter wide web production of fullerene acceptor layers for OPV is conceivable employing vapor deposition. Nowadays, Frontier Carbon employs "nearly 20 people" and expects profit in 2010. It sells fullerine and fullerine derivatives, such as those with extensive OH or O-CH3 links for everything from very expensive cosmetics (suppresses free radicals) to golf balls and $3000 tennis racquets which are stronger and lighter when carbon reinforced plastic or titanium metal have the fullerene added.

He also targets capacitors, fuel cell membranes, lithium batteries, organic field effect transistors FETs and industrial materials. In some applications a mixture of C60, C70 and other molecules is used and in others a specific molecule is synthesised and used.

Electron beam photoresist containing fullerine is more temperature tolerant in the manufacture of silicon integrated circuits, this leading to smaller feature sizes, he says.



CAS Number:	CAS 160848-22-6
Molecular formula:	C72H14O2
Molecular Weight:	910.9
Fullerene purity:	≥ 99.5% by HPLC with respect to fullerene content

Source Frontier Carbon Corporation

5.25. Fujitsu Laboratories, Japan

Fujitsu Ltd / Fujitsu Laboratories Ltd
Nanotechnology Research Center
5-5 Hikari-no-Oka
Yokosuka239-0847
Japan
P +81-46-250-8234
F +81-46-250-8844
http://jp.fujitsu.com/labs/en/
nanotech-RC@labs.fujitsu.com

Fujitsu has demonstrated a CNT transistor (not printed) with a gate width of 50nm, and an on/off ratio of 4. A carbon-based material was used as a channel. The biggest issue usually facing CNT transistors is how to control the orientations of the CNTs - they need to be aligned in one direction. Fujitsu claimed it achieved this work with Kyushu University, by growing the CNTs on a specific crystal plane of sapphire. The CNT strands are grown to a length of about 100microns.

Fujitsu reports, "If the miniaturization of semiconductor devices continues to progress, uniform wiring cannot be formed appropriately by using copper. We are promoting the research on the expectation that the CNT wiring can be a substitute for copper wiring."

Fujitsu is also working on carbon nanotube interconnect technology, flexible and thermal assembling technologies utilizing CNT bumps, and a synthesis technology of a self-organizing graphene/CNT composite. The compatibility with device applications is a main priority for all related developments at Fujitsu.

Graphene transistors also demonstrated

Fujitsu have also demonstrated a graphene transistor, where graphene is used as a channel layer. The transistor was made by Kazuhito Tsukakoshi, a researcher at Japan's National Institute of Advanced Industrial Science and Technology (AIST).

Graphene, in the form of a sheet, has a carrier mobility of 2,000cm2/Vs - similar to that of CNTs. Being in the form of a sheet, it can be easily laid out as the channel layer in transistor design compared to CNTs, where it is harder to control the orientation of CNTs and connect the electrodes.

Fujitsu revealed that the graphene transistor has an on/off ratio of 5-10. The company is now working on ribbon-like graphene sheets by reducing its width, in order to improve the on/off ratio.

Founded in 1968 as a wholly owned subsidiary of Fujitsu Limited, Fujitsu Laboratories Ltd. is one of the premier research centers in the world. With a global network of laboratories in Japan, China, the United States and Europe, the organization conducts a wide range of basic and applied research in the areas of Multimedia, Personal Systems, Networks, Peripherals, Advanced Materials and Electronic Devices.

Fujitsu is a leading manufacturer of CNTs grown directly on the substrate using a CVD process. In 2005 they presented the research on CNT-based heat sink technology for semiconducting chips. Additionally, Fujitsu is researching the patterned growth of carbon nanotubes for large-scale integration.

In November 2009 Fujitsu Laboratories announced that they have developed new technology for forming graphene transistors directly on the surface of large-scale insulating substrates at low temperatures while employing chemical-vapor deposition techniques which are in widespread use in semiconductor manufacturing.

Compared to the temperatures of 800-1000 degree C at which graphene is formed with conventional methods, Fujitsu has succeeded in significantly lowering the graphene fabrication-temperature to 650 degree C thus allowing for graphene transistors to be formed directly on a variety of insulator substrates, including substrates that are sensitive to the higher temperatures.

5.26. Future Carbon GmbH, Germany

Future Carbon GmbH
Gottlieb-Keim-Str. 60
D-95448 Bayreuth
Germany

T: 49 921 507388-0
F: 49 921 507388-99
www.future-carbon.de

Future Carbon is a developer and manufacturer of synthesized and refined carbon materials, like MWCNTs and nanofibres, in industrial quantities.

With the company's redispersible and non-dusty CNT granulates CarboGran own stable dispersions can be produced simply by mixing with solvents, like water, alcohol, ethylene glycol and others. Other products include the ready water based dispersion CarboDis.

Future Carbon GmbH is part of the Innovationsallianz Carbon Nanotubes (Inno.CNT).

5.27. Georgia Tech Research Institute (GTRI), USA

Electro-Optical Systems Laboratory
Georgia Tech Research Institute
925 Dalney St.
Atlanta, GA 30332-0810
eosl@gtri.gatech.edu
http://eosl.gtri.gatech.edu
Phone: 404-407-6100
Fax: 404-407-6131

The research and development organization Georgia Tech Research Institute (GTRI) presented its work on carbon nanotubes for more efficient solar cells. The GTRI photovoltaic cells trap light between their tower structures, which are about 100 microns tall, 40 microns by 40 microns square, 10 microns apart-and built from arrays containing millions of vertically-aligned carbon nanotubes. Conventional flat solar cells reflect a significant portion of the light that strikes them, reducing the amount of energy they absorb. The carbon nanotube arrays serve both, as support for the 3D arrays and as a conductor connecting the photovoltaic materials to the silicon wafer.

The research has been sponsored by the Air Force Office of Scientific Research, the Air Force Research Laboratory, NewCyte Inc., and Intellectual Property Partners, LLC. A global patent application has been filed for the technology.

As part of the research GTRI has also developed several purification methods for CNTs.

In June 2009 GTRI researchers presented results of an analysis of resistivity in graphene nanoribbon interconnects as narrow as 18 nanometers; graphene for on-chip interconnects between transistors could out-perform copper and improve silicon-based integrated circuit technology. Additionally, graphene offers higher electron mobility, better thermal conductivity, higher mechanical strength and reduced capacitance coupling between adjacent wires.

Raghunath Murali, a research engineer in Georgia Tech's Microelectronics Research Center, said: "As you make copper interconnects narrower and narrower, the resistivity increases as the true nanoscale properties of the material become apparent. Our experimental demonstration of graphene nanowire interconnects on the scale of 20 nanometers shows that their performance is comparable to even the most optimistic projections for copper interconnects at that scale. Under real-world conditions, our graphene interconnects probably already out-perform copper at this size scale."

The research was supported by the Interconnect Focus Center, one of the Semiconductor Research Corporation/DARPA Focus Centers, and the Nanoelectronics Research Initiative through the INDEX Center.

Early in 2010 researchers at GTRI found a simple one-step process to produce n-type and p-type doping of large-area graphene surfaces, that could also be used to increase the conductivity in graphene nanoribbons used for interconnects. The process is believed to be the first to provide both electron and hole doping from a single dopant material.

"This is an enabling step toward making possible complementary metal oxide graphene transistors," said Raghunath Murali, a senior research engineer in Georgia Tech's Nanotechnology Research Center.

In volume manufacturing, the used electron beam radiation would likely be replaced by a conventional lithography process, Murali said. Varying the reflectance or transmission of the mask set would control the amount of radiation reaching the spin-on-glass (SOG) material, and that would determine whether n-type or p-type areas are created.

"Making everything in a single step would avoid some of the expensive lithography steps," he said. "Gray-scale lithography would allow fine control of doping across the entire surface of the wafer."

The research was supported by the Semiconductor Research Corporation and the Defense Advanced Research Projects Agency (DARPA) through the Interconnect Focus Center.

5.28. Graphene Energy Inc., USA

Graphene Energy Inc.
7217 McNeil Dr, Suite 108
Austin, TX 78729
Phone: (512) 401-6666
Fax: (512) 600-1018
http://www.grapheneenergy.net

Graphene Energy Inc. develops a Ultracapacitors that incorporates Graphene as electrode material. The patent pending technology is a result of Ruoff research group at University of Texas at Austin.

Graphene Energy has shown storage abilities similar to those of ultracapacitors already on the market. The goal is to stack thin sheets of the material to increase the energy storage and possibly double the current capacity of ultracapacitors. If successful, it would allow fort he use of ultracapacitors in the solar energy industries where energy storage is a challenge when the sun isn't shining.

5.29. Graphene Industries Ltd., UK

Graphene Industries Limited
24 Ellerslie Court
Upper Park Road
Manchester
M14 5RH
United Kingdom
http://grapheneindustries.com

Graphene Industries Ltd. is a start-up company that manufactures and sells graphene flakes in research quantities. The samples have lateral dimensions of 100μm and are built on silicon substrates. The company is the first commercial supplier of graphene for micro- and nanoelectronic fabrication and research.

The company was found in 2007 as a spin-out from Manchester University and is built on the developments of Professor Andre Geim's research group.

5.30. HeJi, Inc., China

Room 304, The east one building,
Xicheng Road, Licheng Town, Zengcheng City
China
Postcode: 511300
Tel: 0086 139 2275 1668
Fax: 0086 755 82600686
http://www.nanotubeseu.com

HeJi Inc. supplies Nano powders in any quantities (grams or tons) mainly Carbon Nanotubes, Chiral Drugs and Pearlescent Pigment. Their manufacturing facilities have an output of 1.5kg SWNTs per day using a scalable CVD method.

5.31. Helix Material Solutions Inc., USA

819 West Arapaho Road, Suite 24B-187
Richardson TX, 75080
http://www.helixmaterial.com

Helix Material Solutions Inc. is a supplier of CNT materials (SWCNT, MWCNT). The company uses proprietary CVD and Arc processes to get nanotubes of controlled diameter and length.

5.32. Hodogaya Chemical Co., Ltd., Japan

2-4-1,Shiba koen, Minato-ku,
Tokyo 105-0011 Japan
TEL +81-3-6430-3600
FAX +81-3-6430-3620
http://www.hodogaya.co.jp/English2/web/

Hodogaya Chemical Co., Ltd. is one of the leading manufacturers of MWCNTs in Japan.

In April 2006 in a joint venture with Mitsui Co., Ltd., the company Nano Carbon Technologies Co., Ltd. (NCT) was established as a manufacturer of MWCNTs and MWCNTs containing composites.

5.33. Honda Research Institute USA Inc. (HRI-US), USA

Materials Science Division
1381 Kinnear Rd., Suite 116
Columbus, OH 43212
T: 1 614 340 6081
F: 1 614 340 6082
www.honda-ri.com/HRI_Us/

Honda Research Institute USA, Inc. (HRI-US) was founded in January 2003 along with HRI-EU (Europe) and HRI-JP (Japan). U.S. offices are located in California, Ohio and Massachusetts and include a computer science research division focused on human intelligence technologies and a materials science research division focused on functional nano-materials.

Honda has worked in the field of carbon nanotube synthesis for almost a decade.

Led by Avetik Harutyunyan scientists an the Materials Science Division developed a method to control the formation of carbon nanotubes during production. This means they were able to control if the produced CNTs are metallic or semiconducting.

"This is the first report that shows we can control fairly systematically whether carbon nanotubes achieve a metallic state. Further research is in progress with the ultimate goal to take complete control over grown nanotube configurations to support their real world application," Harutyunyan said. "We have a 91 percent success rate of producing metallic nanotubes."

"Our finding shows that the nanotube configuration which defines its conductivity depends not only on the size of the metal nanocatalyst used to nucleate the tube as was previously believed, but importantly also is based on its shape and crystallographic structure, and we learned to control it."

The research was done in collaboration with Purdue University and University of Louisville.

"This problem of how to control whether you have a metal or a semiconductor is the key stumbling block in making transistors out of carbon nanotubes," said Eric Stach, an associate professor of materials engineering at Purdue. "Solid-state electronics is built around the fact that you can control the semiconducting properties of silicon."

"Our results indicate that you might be able to control the size and shape of the catalyst sufficiently to control the structure and thus the conductivity of the nanotubes. It is the first demonstration of a deterministic relationship between the catalyst state and the resulting nanotube structure," Stach said.

The findings open new possibilities for miniaturization and energy efficiency, including much more powerful and compact computers, electrodes for supercapacitors, electrical cables, batteries, solar cells, fuel cells, artificial muscles, composite material for automobiles and planes, energy storage materials and electronics for hybrid vehicles.

5.34. Honjo Chemical Corporation, Japan

5-24 Miyahara 3-Chome Yodogawa-ku
Osaka 532-0003
JAPAN
http://www.honjo-chem.co.jp/e_index.html

Apart from several other fields the material supplier Honjo Chemical Corporation is doing research and development in the field of Fullerene and Carbon Nanotubes. These are for example tested as electrode material for the next generation flat display's panel.

In May 2000 in corporation with Mitsubishi Corp. Fullerene International Corp. (FIC) and MER Corp the first mass-production plant in Japan at Neyagawa Factory was built. Later in 2003 the Mitsubishi Corporation teamed up with Honjo Chemical to extend the temperature ranges at which fuel cells can operate. Fullerenes are added exchange membrane of fuel cells. The project profits from Honjo Chemical's fullerene to the modification system.

5.35. HRL Laboratories, USA

HRL Laboratories, LLC.
3011 Malibu Canyon Road,
Malibu, CA 90265-4797
Telephone: 310.317.5000
http://www.hrl.com

After further optimization of the earlier developed graphene FET material and device processing they presented in May this year epitaxial graphene FETs on a two-inch wafer scale. The initial milestone was reached in December by successfully integrating and demonstrating the world's first graphene FETs in the RF frequency range.

Dr. Jeong-Sun Moon, HRL Senior Scientist and CERA Program Manager commented: "Using a single layer of epitaxially grown graphene, these transistors demonstrate simultaneous world-record performance in key device parameters for the first time. They have world-record field effect mobility of ~6000 cm2/Vs, which is six to eight times higher than current state-of-the-art silicon n-MOSFETs (metal-oxide semiconductor field effect transistors)."

Goal for the ongoing project is the achievement of >10,000 cm2/Vs Hall mobility.

The project was sponsored by the Defense Advanced Research Projects Agency and under the management of the Space and Naval Warfare Systems Center.

HRL Laboratories, LLC, Malibu, California is a corporate research-and-development laboratory owned by The Boeing Company and General Motors specializing in research into sensors and materials, information and systems sciences, applied electromagnetics, and microelectronics. HRL provides custom research and development and performs additional R&D contract services for its LLC member companies, the U.S. government, and other commercial companies.

5.36. Hyperion Catalysis International, Inc.

Hyperion Catalysis International, Inc.
Headquarters & Main Sales Office
38 Smith Place
Cambridge, MA 02138, U.S.A.
phone: 1-617-354-9678
fax: 1-617-354-9691
email: info@hyperioncatalysis.com
http://www.fibrils.com

Hyperion Catalysis' core technology are FIBRIL™ nanotubes, which are conductive, vapor grown MWCNTs. These are supplied as master batches, that require subsequent letdown and compounding, or ready-to-mold compounds. Based on the pioneering work by Dr. Howard G. Tennent the company has been selling FIBRIL™ since 1983. The production capacity of Hyperion is around 50 tons/year MWCNT.

Hyperion has hundreds of issued and pending patents regarding production and applications of CNTs.

Hyperion Catalysis International, Inc. (Hyperion) has concluded a patent license agreement and a supply agreement with Showa Denko K.K. (SDK) of Japan.

5.37. IBM, USA

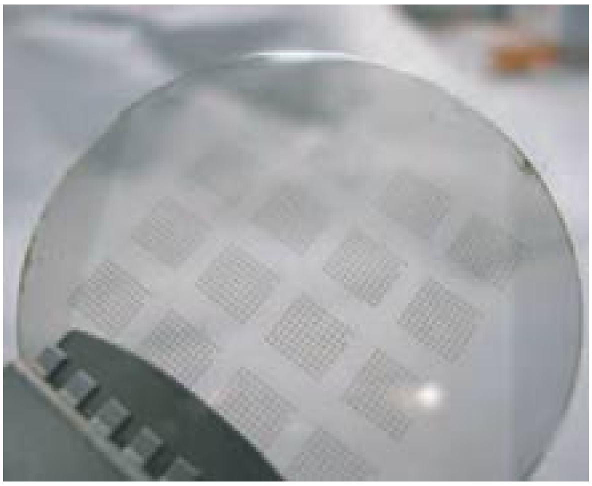
IBM T. J. Waston Research Center
1101 Kitchawan Road,
Route 134,
Yorktown Heights, N.Y. 10598
United States
(914) 945-3000
Fax: (1914) 945-2141
http://www.watson.ibm.com

In February 2010 IBM researchers announced the highest cut-off frequency so far for a graphene device of 100 billion cycles/second (100 GigaHertz).

The researchers reported that, "The frequency performance of the graphene device already exceeds the cut-off frequency of state-of-the-art silicon transistors of the same gate length (~ 40 GigaHertz). Similar performance was obtained from devices based on graphene obtained from natural graphite, proving that high performance can be obtained from graphene of different origins."

"Uniform and high-quality graphene wafers were synthesized by thermal decomposition of a silicon carbide (SiC) substrate. The graphene transistor itself utilized a metal top-gate architecture and a novel gate insulator stack involving a polymer and a high dielectric constant oxide. The gate length was modest, 240 nanometers, leaving plenty of space for further optimization of its performance by scaling down the gate length."

Fig. 5.15 **IBM has patterned graphene transistors with a metal top-gate architecture (top) fabricate on 2-inch wafers (bottom) created by the thermal decomposition of silicon carbide.**



The research was conducted under the Carbon Electronics for RF Applications (CERA) programme, which aims to develope next generation devices using graphene-based RF electronics that will lead to ultra-high-speed, ultra-low-noise, ultra-low power RF circuits.

At the end of 2008 researchers from the IBM T. J. Waston Research Center published the results of their study on Graphene FETs that were developed in an inter-disciplinary collaboration. Being a part of the Carbon Electronics for RF Applications (CERA) sponsored by DARPA this demonstrates an important milestone.

At a gate length of currently 150nm a cut-off frequency of 26GHz was demonstrated. Key for this result is the very high electron speed that can be achieved in Graphene. Also established for the first time was the scaling behaviour of such a Graphene FET, esp. the size dependence.

In the next round of the project they want to development a complex circuits based on these Graphene FETs.

Additionally, IBM is one of the companies working on coupling of CNT electronic devices to form logic gates or oscillators.

5.38. ILJIN Nanotech Co. Ltd., Korea

Room 502, Kayang Techno Town, 1487 Kayang 3 Dong, Kangseo Ku
Seoul
Korea 157-810
Telephone : 82-2-3665-7114
Fax : 82-2-3665-7986
http://www.iljinnanotech.co.kr/

ILJIN Nanotech Co. Ltd. is a start-up venture funded by the ILJIN Group. The company is working on bulk production of MWCNTs, provides carbon nanotube materials, i.e. single-walled and multi-walled CNTs, and is developing devices applying these materials. The company is researching growth and post-production processes as well as the usage of CNTs for the transparent electrode of FEDs (field emission displays). ILJIN Nanotech is holding several patents.

ILJIN is a leading provider of carbon nanotubes in the Korean area.

5.39. Intelligent Materials PVT. Ltd. (Nanoshel), India

INTELLIGENT MATERIALS PVT. LTD.
Plot No 211, Sector 12
Panchkula - 134112
Haryana
India
Telephone: +91 - 9779-880077, +91 - 9779-550077
Fax: +91 - 172 - 5064955
sales@nanoshel.com
http://www.nanoshel.com

Intelligent Materials PVT Ltd is a nanotechnology company specializing in research & development, production and distribution of industrial carbon nanotubes. The company provides of more than 50 types of nanotechnology products, with nanotubes, SWCNTs, MWCNTs, and nanoparticles being the main ones. They use an Arc Discharge Method (Arc) to produce high purity (90% to 97%) CNT powders.

5.40. Massachusetts Institute of Technology (MIT), USA

77 Massachusetts Avenue
Cambridge, MA 02139-4307
T: 1 617 253 1000
www.mit.edu

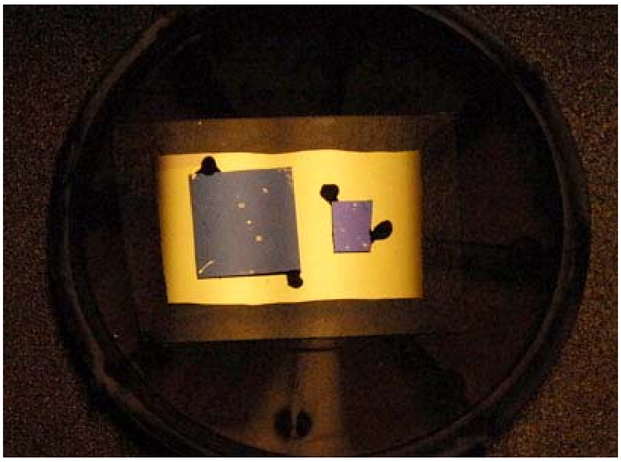
Researchers at MIT developed an experimental graphene chip known as a frequency multiplier. This device is capable of producing a multiple of the frequency incoming electrical signal. It could be shown that the MIT graphene chip doubles the frequency of an electromagnetic signal, but is still in a laboratory stage.

Tomás Palacios, assistant professor in MIT's Department of Electrical Engineering and Computer Science and a core member of the Microsystems Technology Laboratories, comments: "It's very difficult to generate high frequencies above 4 or 5 gigahertz". However, the new graphene technology could achieve 500 to 1,000 gigahertz in practical systems.

Jing Kong, EECS Assistant Professor, and co-workers of this project have been developing a method for growing entire wafers of graphene.

The project was partially funded by the MIT Institute for Soldier Nanotechnology and by the Interconnect Focus Center program.

Fig. 5.16 **The graphene microchip mostly based on relatively standard chip processing technology**



Source MIT

In August 2009 it was reported that MIT researchers have for the first time shown that carbon nanotubes can be grown without a metal catalyst. The team under Brian Wardle, professor of aeronautics and astronautics, used zirconium oxide instead and could even avoid the unwanted side effects that come with a metal catalyst based process. Additionally, the zirconia-grown nanotubes assemble directly on the surface instead of dissolving into the nanoparticle and precipitating out.

5.41. Max Planck Institute for Solid State Research, Germany

Max Planck Institute for Solid State Research
Heisenbergstraße 1
D-70569 Stuttgart
Germany
T: 49 711 6 89-0
F: 49 711 6 89-10 10
www.@fkf.mpg.de

Max Planck Society operates 80 research institutes all over Germany (and in some cases in other European countries), which usually bear the name "Max Planck Institute (MPI) of ...". Their task is basic research in the natural sciences as well as in the social sciences and humanities.

The Max Planck Society, an independent German non-profit research organization funded by the federal and state governments, has a world-leading reputation as a science & technology research organization. Work proceeds on carbon nanotubes, organic transistors and polymer sensors and many other topics.

The German Max Planck Institute for Solid State Research in Stuttgart is collaborating with the Beijing National Laboratory for Molecular Sciences in China on coated carbon nanotubes for high-capacity batteries.

Lithium-ion batteries are in great demand for applications from laptops to hybrid cars - but the list of requirements is long. They need to be lightweight, cheap and environmentally friendly, but also store enormous charge. Coating CNTs with a nanoporous layer of TiO2 results in a crystalline solid made up from 'coaxial cables' that are perfect for trapping lithium ions. When combined, the storage capacity of TiO2 is four times higher than usual and the nanotubes hold three times as many ions. Since the material is simple to produce and far cheaper than electrodes that are based on rare metals, the team is hoping that it can be more widely applied - perhaps for other energy storage devices such as supercapacitors.

5.42. MER Corporation, USA

Materials and Electrochemical Research
MER Corporation
7960 South Kolb Road
Tucson, Arizona 85706
T: (520) 574-1980
F: (520) 574-1983
www.mercorp.com
mercorp@mercorp.com

MER Corporation manufactures and sells advanced composites, coatings, fullerenes and nanotubes. MWCNTs and SWCNTs are produced by both Arc Discharge and catalytic CVD processes.

The company has a joint venture with Mitsubishi focussing on the development and production of fullerene and nanotube applications. In May 2000 in corporation with Mitsubishi Corp. Fullerene International Corp. (FIC) and Honjo Chemical Corporation the first mass-production plant in Japan at Neyagawa Factory was built.

5.43. Mitsui Co., Ltd, Japan

Mitsui & Co. Bldg. 2-1, Ohtemachi 1-chome,Chiyoda-ku, Tokyo 100-0004, Japan
TEL (81-3) 3285-1111
FAX (81-3) 3285-9819
http://www.mitsui.co.jp/en/

Mitsui Co., Ltd. is one of the leaders in production of MWCNTs in Japan.

In April 2006 in a joint venture with Hodogaya Chemical Co., Ltd., Nano Carbon Technologies Co., Ltd. (NCT) was established as a manufacturer of MWCNTs and MWCNTs containing composites.

5.44. Mknano, Canada

M.K. IMPEX CANADA
6382 Lisgar Drive
Mississauga, Ontario L5N 6X1
Canada
Ph: 416-509-4462
Fax: 905-824-1259
sales@mknano.com
info@mknano.com
http://www.mknano.com

Mknano is a division of M.K. Impex Canada that offers a large variety of nano products in various forms, in terms of carbon nanotubes these are mainly SWCNTs, DWCNTs, MWCNTs, aligned, tangled, dispersible, functionalized. The conducting and semiconducting materials can be provided in industrial grades. The company also offers special applications of CNTs.

5.45. Nano-C, USA

33 Southwest Park
Westwood, MA 02090
T: 781-407-9417
F: 781-407-9419
info@nano-c.com
http://www.nano-c.com

Nano-C is a developer and manufacturer of nanostructured carbon materials, esp. CNTs as powder with different specifications: 70% purity, pre-purified, or as produced with 25% purity, or purified with 97% purity.

Nano-C is a privately held company that was establishesd in 2001. The company's main target is to enable applications of their nanostructured carbon materials.

Earlier in 2009 it was announced that Unidym has entered an exclusive license agreement with Nano-C for patents covering fullerene derivatives. The license provides Nano-C exclusive rights to U.S.Patent No. 5,739,376 and foreign counterparts in the field of photovoltaics.

"The '376 patent family covers many of the fullerene derivatives used in OPV, including the widely used C60 and C70 PCBM compounds," stated Viktor Vejins, CEO of Nano-C. "We are delighted to add this patent to our growing IP portfolio, which further strengthens our position in fullerene manufacture, purification, separation and derivatization. As a fully integrated supplier, the exclusive rights obtained by Nano-C under this agreement will benefit our customers as they commercialize OPV-based devices."

5.46. NanoCarbLab (NCL), Russia

MedChemLabs Inc. (MCL) Division
1812 year street 7 apt. 6
121170 Moscow, Russia
tel: +7-095-7781037
http://www.nanocarblab.com

NanoCarbLab is the nanotechnology division of MedChemLabs Inc. (MCL) founded in 2001. They produce SWCNT using catalytic Arc method followed by purification, functionalization and/or shortening. The purity ranges from 40 to 90% for laboratory researches and for industrial applications. The preparation of solutions in different solvents is also possible.

5.47. Nano Carbon Technologies Co., Ltd. (NCT)

Nano Carbon Technologies Co., Ltd. (NCT)
66-2, Horikawa-Cho
Saiwai-Ku Kawasaki 212-8588
Japan
http://www.nanocarbontechnology.com/

Established in April 2006 as a joint venture between Hodogaya Chemical Co., Ltd., and Mitsui Co., Ltd., Nano Carbon Technologies Co., Ltd. (NCT) is a manufacturer of MWCNTs and post-process MWCNTs for applications like composites and battery additives. NCT uses a floating catalyst CVD pioneered by Prof. Morinubo Endo of Shinshu University. The company supplies high-purity grade MWCNTs (99.5 wt. % carbon), or MWCNTs containing composites. Additionally they developed a post-processing method to pre-treat CNTs for specific applications.

Currently, NCT has a production capacity is a few kilograms/hour and is planning to scale up to 100 tons per year.

5.48. Nanocomb Technologies, Inc. (NCTI), USA

162 Pembroke Road,
Concord, NH 03301
T: 1 603 442 8992
F: 1 603 513 7119
www.nanocomptech.com

Nanocomb Technologies, Inc. was established in 2004 as a spin-out of Synergy Innovations, Inc., a developer of energy saving performance materials and component products from carbon nanotubes (CNTs)

The company uses a patent-pending method for high-volume production of very long CNTs (approximately one millimeter in length), and then processing the nanotubes into contiguous macrostructures.

Nanocomb is producing long CNTs and also able to fabricate them into physically strong, lightweight and electro-thermally conductive yarns and sheets. The company has the production capability to deliver 4-foot by 8-foot CNT mats, the largest of their kind in the world. The company is currently the only U.S. commercial company to fabricate industrially relevant finished materials from carbon nanotubes.

5.49. Nanocs, USA

244 Fifth Avenue
#2949, New York
NY 10001
Tel: 917-400-4863
Fax: 917-591-2212
sales@nanocs.com
http://www.nanocs.com

Nanocs manufactures CNTs with proprietary CVD or Arc-discharge method to produce CNTs with controlled diameter, length as well as purity. They are also able to provide films made by appropriate coating method.

5.50. Nanocyl s.a., Belgium

Rue de l'Essor, 4
B-5060 Sambreville
BELGIUM
Tel: + 32 71 750 380
http://www.nanocyl.com

Nanocyl, a global manufacturer of specialty and industrial CNTs, uses a catalytic Carbon Vapor Deposition (CVD) method for CNT technologies. The company also offers support for integration of CNT in commercial applications.

The company's MWCNT product line NC 7000 is one of the highly electrically conductive CNT products currently available.

Monique Lempereur, global commercial executive director said: "South Korean customers know the value of integrating conductive carbon nanotubes into electronic applications. CNTs are cost-competitive, and can offer better overall performance compared to carbon black and carbon fibers."

Nanocyl will invest in additional capacities in 2010 to respond to the increasing demand for carbon nanotube technologies. The company is opening a subsidiary in Seoul to support growth and development of new applications in that area with local sales and customer service. Nanocyl is headquartered in Belgium, and has a division in the U.S. The Asia-Pacific market is covered through a network of partners in South Korea, Japan, India, Malaysia, Singapore, Taiwan and China.

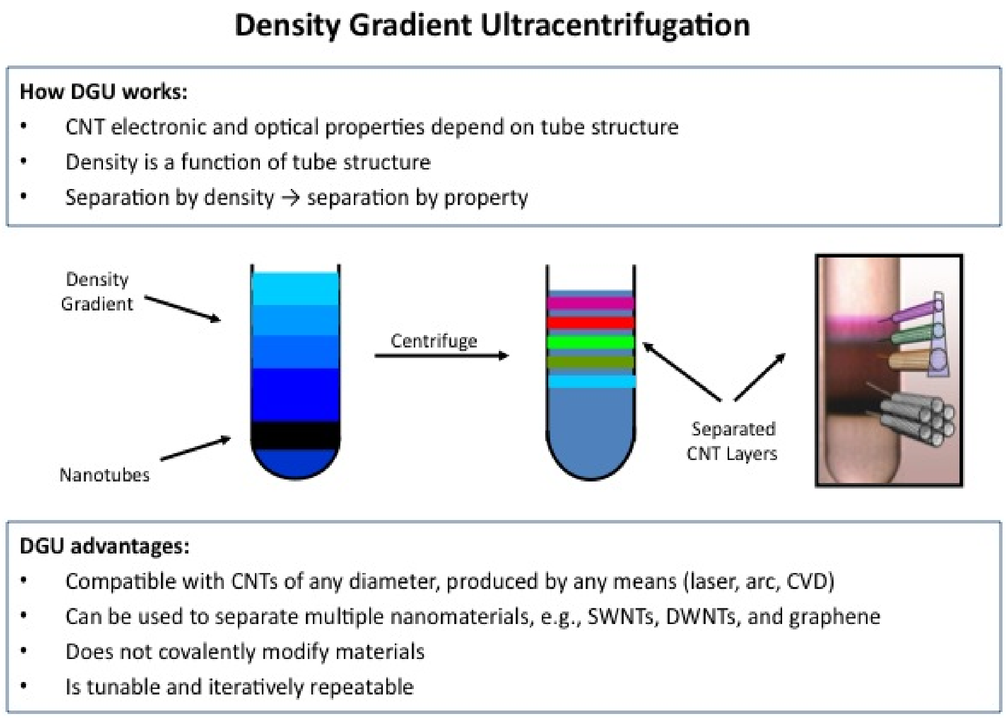
Nanocyl was established in 2002 as a spin-off from the Universities of Namur and Liège by Professor B. Nagy and Professor Pirard supported by private investors.

5.51. NanoIntegris, USA

NanoIntegris
8025 Lamon Avenue
Suite 43
Skokie, IL 60077
Tel: 847-581-1481
Fax: 847-556-6125
info@nanointegris.com
http://www.nanointegris.com

NanoIntegris was found in January 2007 as a spun out from Hersam Group at Northwestern University to commercialize their technology for separating CNTs.

Fig. 5.17 **Density gradient ultracentrifugation**



The company is now selling their carbon nanotube brands IsoNanotubes™ and PureTubes™. IsoNanotubes are available in metallic or semiconducting state as aqueous solution with purities ranging from 70 to 95%. PureTubes are SWNTs with a purity of up to 99% also delivered as aqueous solution.

NanoIntegris has several patents pending on materials, methods and applications.

5.52. NanoLab, Inc., USA

55 Chapel Street
Newton, MA 02458
Phone: 617-581-6747
http://www.nano-lab.com

Established in 2000 NanoLab Inc is manufacturer of carbon nanotubes as well as a developer of nanoscale devices. Main products are SWCNTs, Bucky Paper made from SWCNTs, NInk (CNT ink) and nanotube monolayers. The monolayers can be deposited on most surfaces using lithography for patterning.

5.53. NanoMas Technologies, USA

NanoMas Technologies, Inc.
Innovative Technologies Complex
101 Murray Hill Road, PO Box 6000
Binghamton, NY 13902-6000
Ph: 585-820-8971
Fax: 866-367-1128 (toll-free)
Email: admin@nanomastech.com
www.nanomastech.com
NanoMas Technologies was incorporated in January 2006. The three founders hold several patterns in this field. The company specializes in nanotechnology R&D and nanomaterials engineering and commercialization, especially mass production of carbon nanotubes and nanofibers. BASF is a recent investor in NanoMas.

5.54. Nano-Proprietary, Inc., USA

3006 Longhorn Blvd, Suite 107
Austin
Texas, 78758
UNITED STATES
T: 1 (512) 3395020
http://appliednanotech.net

Nano-Proprietary, Inc. is a holding company consisting of two wholly owned operating subsidiaries. Applied Nanotech, Inc. is a research and commercialization organization dedicated to developing applications for nanotechnology with an extremely strong position in the fields of electron emission applications from carbon film/nanotubes, sensors, functionalized nanomaterials, and nanoelectronics. Electronic Billboard Technology, Inc. (EBT) possesses technology related to electronic digitized sign technology. The Companies have over 250 patents or patents pending. Nano-Proprietary's business model is to license its technology to partners that will manufacture and distribute products using the technology.

5.55. Nanoshel, Korea

NANOSHEL - Japan, South Korea
Grace Technology
Young Kuk CHOI, CEO/Ph.D.
2-1-21, Simomaki, Kanmaki-cho,
Kitakaturagi-gun,
Nara-ken, 639-0205,
Japan
Tel: +81 (0)745-51-3770
Fax: +81 (0)745-51-3770
Mobile: +81 (0)80-3769-0506
E-mail : ykchoi@grace-technology.com

NANOSHEL-Iran
Fanavaran Araz Tajhiz Co.
Unit 5- No. 36- Sahhafzadeh Ave.
Ali Akbari St.- Motahhari st.
Tehran-1576944617
IRAN.1576944617
Tel : (+9821) 88515989-88755265
Tel/Fax : (+982) 88755265
E-mail : info@araztajhiz.com

Nanoshel is the worldwide distributor of Intelligent Materials PVT. Ltd.

5.56. Nanostructured & Amorphous Materials, Inc., USA

16840 Clay Road, Suite #113
Houston, TX 77084
USA
281-858-6571
http://www.nanoamor.com

Established in 2001 Nanostructured & Amorphous Materials is leading nanomaterials company, involved in manufacturing, research and development, processing and supplying nanostructured materials and their dispersions.

5.57. Nanothinx S.A. , Greece

Nanothinx S.A.
Stadiou Street, Platani
P.O. Box 1414
Rio Patras 26504
Greece
Tel: +30-2610-965208
email: info@nanothinx.com
http://www.nanothinx.com

Nanothinx is a spin-off company of the Institute of Chemical Engineering and High Temperature Chemical Processes (ICE-HT), which is one of the seven Institutes of the Foundation for Research and Technology Hellas (FORTH). The company focuses on development of methods for the large-scale, high-yield and low-cost production of SWCNTs and MWCNTs. Both can be provided in research quantities (grams) based on the CVD or catalytic CVD. Nanothinx also offers R&D services.

5.58. Nantero, USA

25-E Olympia Avenue
Woburn, Massachusetts 01801
United States
Phone: 781-932-5338
Fax: 781-932-5339
http://www.nantero.com

The nanotechnology company Nantero, Inc. developed a nanotube-based data storage device. In their high-density, non-volatile random access memory device (NRAM) individual SWCNTs are incorporated as molecular device elements, i.e. electromechanical nanoscale NRAM switches, and molecular wires for the read-write scheme. The company is confident, that the logic gates can be integrated with CMOS (complementary metal oxide semiconductor) technology.

Apart from the main focus, development of NRAM™ universal memory, the company is also working with licensees on other next-generation semiconductor devices incorporating carbon nanotubes technology, e.g. logic and sensors.

In collaboration with HP, Nantero is working with the HP Thermal Inkjet Pico-Fluidic System (TIPS) research and development tool. The company is exploring the use of inkjet printing for low cost memory applications based on its CNT technology.

In June 2008 Nantero announced collaboration with SVTC Technology to achieve commercialization of nanotube-based electronics. Nantero's proprietary "CMOS-friendly" CNT process will be installed at SVTC's two development fabs, in San Jose, Calif., and Austin, Texas.

Only two months later it was announced that Lockheed Martin has entered an exclusive license arrangement with Nantero for government applications. "Lockheed Martin is already a leader in the research, development and application of nanotechnology to future military and intelligence applications," said Joanne Maguire, Executive Vice President of Lockheed Martin's Space Systems Business Area.

5.59. National Institute of Advanced Industrial Science and Technology (AIST), Japan

AIST
Tsukuba Central 4
Tsukuba
Ibaraki
305-8562
Japan
T: 81-29-861-2500
www.aist.go.jp

The Nanotube Research Center and the Energy Technology Research Institute of AIST jointly pursued researches on the use of SWCNTs in capacitor electrodes including a research on a processing method for increasing the specific surface area.

AIST developed the Super Growth method, a synthesis method for SWCNTs, and an oriented high-purity SWCNT structure in which SWCNTs are vertically aligned. This structure is named "CNT Forest". The CNT Forest synthesized by the Super Growth method consists of SWCNTs (99.5%) and the SWCNTs are aligned in a single direction. The SWCNTs in CNT Forest have larger diameters and are of higher purity than other SWCNTs.

AIST has recently developed a technique for densifying this aligned structure and has been conducting research on utilizing this structure as electrode materials for capacitors.

Early in 2010 AIST reported the development of a fibrous material using SWCNTs with a surface area of 2240m2/g. The new material can be used for energy storage as electricity storage device including capacitors. Materials with large specific surface are also used for storage, purification and separation of substances.

The produced prototype capacitor using the fibrous material as electrodes was found to have a high energy density of 24.7Wh/kg and a high power density of 98.9kW/kg. These results show a better performance than that of conventional capacitors.

5.60. NEC Corporation, Japan

7-1 Shiba 5-chome
Minato-ku
Tokyo 108-8001
Japan
www.nec.co.jp

Japan's NEC Corporation says it has successfully fabricated CNT transistors using printing on plastic film. NEC says that CNT transistors can have better properties than silicon transistors of an equivalent size. The device uses zirconium oxide rather than silicon dioxide, which has a lower dielectric constant as the gate insulator, ensuring efficient charge injection into transistor channels and reducing direct-tunnelling leakage currents.

NEC reports the following features of its transistors:

- Each component of the CNT transistors, including electrodes, insulating layers, and CNT channels, are completely printed.
- The composition of materials, solvent concentration, and conditions for insulator ink and metal ink were each optimized in order to eliminate interference between stacked layers, and to maintain printing conditions.
- Low-temperature production (below 200°C) enabled the use of plastic substrates.
- The fabricated transistors demonstrate p-type conduction and an on/off ratio of 1,000.

NEC view CNTs as a key enabling technology platform for printed electronics, and intend to increase development on the topic.

The NEC Group focuses on two core areas of business – integrated IT / Network Solutions and Semiconductor Solutions. The IT/Network Solutions business provides solutions for the ubiquitous networking era, mainly to government agencies, communications service providers, and other private-sector enterprises. The Electron Devices business provides the semiconductors, liquid crystal displays, electronic components and other products that play a vital role in realizing higher performance devices mainly for manufacturers involved in digital home electronics and automobiles. This business' strengths lie in its ability to propose optimal solutions based on unique cutting-edge technologies that meet the requirements of our worldwide customers.

5.61. New Jersey Institute of Technology (NJIT), USA

Department of Chemistry and Environmental Science
New Jersey Institute of Technology
University Heights
Newark, New Jersey 07102-1982
T: 1 973-596-3595
F: 1 973-596-3586
www.njit.edu/

In July 2007 researchers at New Jersey Institute of Technology (NJIT), USA, developed an inexpensive solar cell that can be painted or printed on flexible plastic sheets. The solar cell uses a carbon nanotube electrical wire. Dr Somenath Mitra, professor and acting chair of NJIT's Department of Chemistry and Environmental Sciences, and his colleagues combined the carbon nanotubes with carbon Buckyballs to form tadpole-like structures. When sunlight is present, it excites the polymer buckyballs into trapping electrons. The nanotubes, having a significantly better conductivity than copper, are able to make the electrons flow.

5.62. Noritake Co., Japan

Noritake Co., Japan
3-1-36, Noritake-shinmachi,
Nishi-ku, Nagoya-shi,
Aichi 451-8501 Japan
Phone: +81-52-561-7111
http://www.noritake.co.jp/eng

The Noritake Group has established five different business fields with the application and development of a variety of ceramics manufacturing technologies: Industrial Products, which supports industries with grinding wheels and diamond tools, Tabletop, which offers tableware to create rich and luxurious dining, Electronics, providing vacuum fluorescent displays, Ceramics & Materials, which supplies ceramic raw materials to many kinds of manufacturers, and Environmental Engineering which develops and proposes manufacturing equipment and technologies.

Noritake Electronics: Leading the world in developing Vacuum Fluorescent Displays, our display devices are readily available in many different fields.

Distinguished Paper: Improvements of Color CNT-FED Character-Displays
Noritake Co. is doing research in collaboration with Fuji Electric Systems Co., Ltd. and Nagoya University, Japan.

Since the discovery CNTs were accepted as an emitter material because of their high-aspect ratio. But industrial-scale fabrication processes and imaging performance had not been reported on display applications of CNTs.

Since 1997, we have been developing the process technology to use CNTs as an electrode that can be applied to the industrial products. The experimental FEDs have been manufactured with the CNT emitters, and the CNT emitter showed an excellent field- emission property because of a high chemical stability and a high mechanical strength of the CNT emitter.

The greatest benefit of a display using CNT technology is high luminance performance with low power consumption. So, we intend to develop a CNT-FED for half-meter-sized character displays, which will be used for message displays with color. Such displays are usually constructed with light-emitting-diodes (LEDs). These devices have the characteristics of high luminance, but LEDs consume high current and high power. LEDs are used for large-sized multi-color character-displays. For medium-sized character displays, LEDs are difficult to manufacture in a half- meter sized package. Also, the power-consumption rates of CNT- FEDs are approximately 5–10 times less than that of an LED character-display.

Fig. 5.18 **Color pixel; 3mm, display area; 48mm x480mm**

Source Noritake Co

This feature will significantly contribute to energy conservation when applied to ubiquitous displays. In addition, the high- definition capability of a CNT display can provide good visibility when installed in outdoor locations, enabling public use. CNT-FEDs also have the potential for multi-functionality, which could be battery driven. The development and practical application of this new technology is highly expected to benefit an advanced information society.

2. Applications of CNT-FED
One of applications of CNT-FED character displays is message display in public space. In these days, liquid-crystal- displays(LCDs) are used for digital signage, but too many LCDs cancel the eye-catch effect. Moreover, electric-paper-displays(e- paper) will be used for such low-power detail information tool, also in this case the eye-catch effect will be limited. The 3mm- color-pixel-pitch

CNT-FED will be appropriate to get the eye- catch effect and one phrase message from railway or bus stations.(see Figure 5.12) In these cases, the CNT-FED message displays should be act as emergent displays even in power line downed condition of earthquake or fire. But the 3mm-pixel-pitch displays(Figure 5.12) is too large to install in vending machine, as shown in Figure 5.14. The 1.8mm-color-pixel-pitch CNT- FED(Figure 5.13) was developed to install even in such narrow space applications.

In Japan, vending machines were set up in anywhere, indoor and outdoor. As they could be connected by ubiquitous communication technology, the information board in vending machine is highly expected to display important message to evacuate from the disaster area under emergent condition. Usually at the emergency, the electric power should be downed to prevent the fire. So, the display should be battery-driven. Table 5.2 shows power consumption of CNT-FED compared with other-character- displays. The 1.8mm-pitch CNT-FED size was required to fit the vending machine, and the size could not be realized by LED.

Fig. 5.19 **Color pixel; 1.8mm, display area; 57.6mm x 460.8mm.**

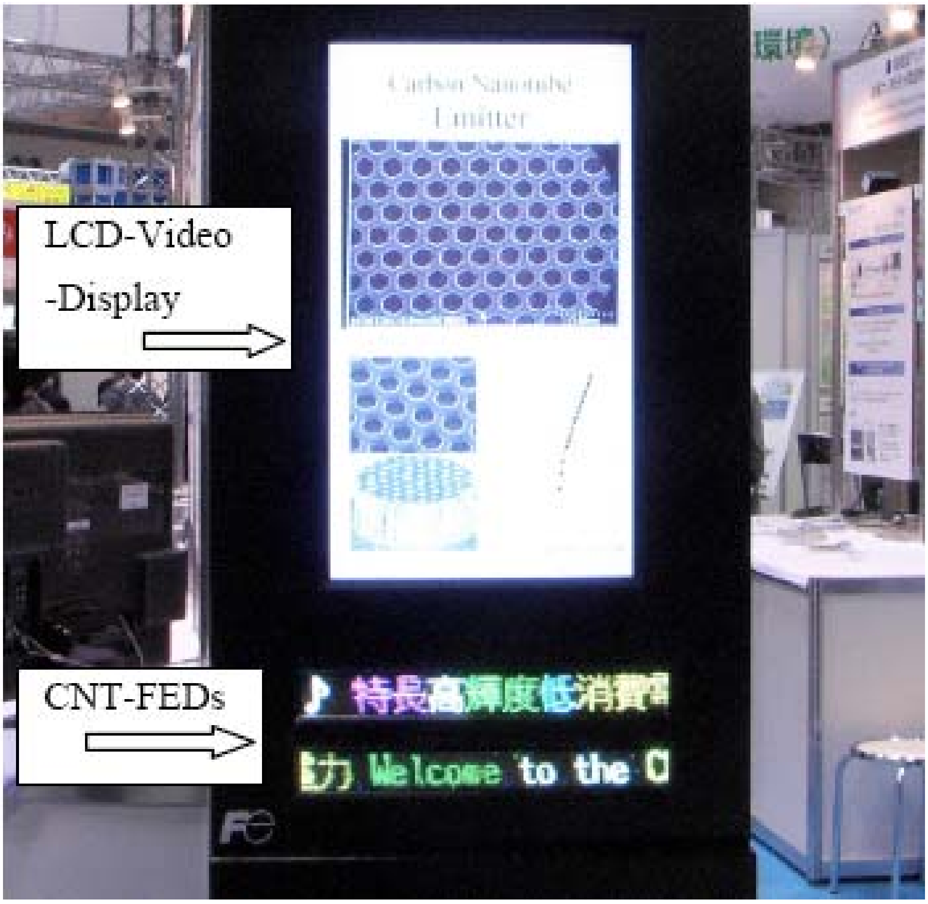
Source Noritake Co

Table 5.3 **Characteristics of the CNT-FED compared with LEDs**

Character display	CNT-FED	RGB-LED	RG-LED
Pixel-pitch	**1.8mm 3.0mm**	4.0mm 5.0mm	2.5mm 3.0mm
Multi color	○	⊗	▲
Luminance (cd/m²)	**ca.1,000**	ca.1,200 ca.1,500	ca.650 ca.900
Viewing angle (degree)	**170**	120	120
Power consumption per character (white)	**ca.0.3W ca.0.85W (ca.0.6W) (ca.2.0W)**	ca.6W ca.7W (ca.13W) (ca.15W)	ca.2.8W ca.7W (ca.6W) (ca.15W)
Operating temperature (°C)	-40 ~ +85	-20 ~ +60	-10 ~ +60
Weight per character (g)	**ca.35, ca.100**	ca.100	ca.100
Cost per character (%)	**18, 36**	100	36
Life time (hours)	**ca.50,000 (expected)**	50,000	50,000

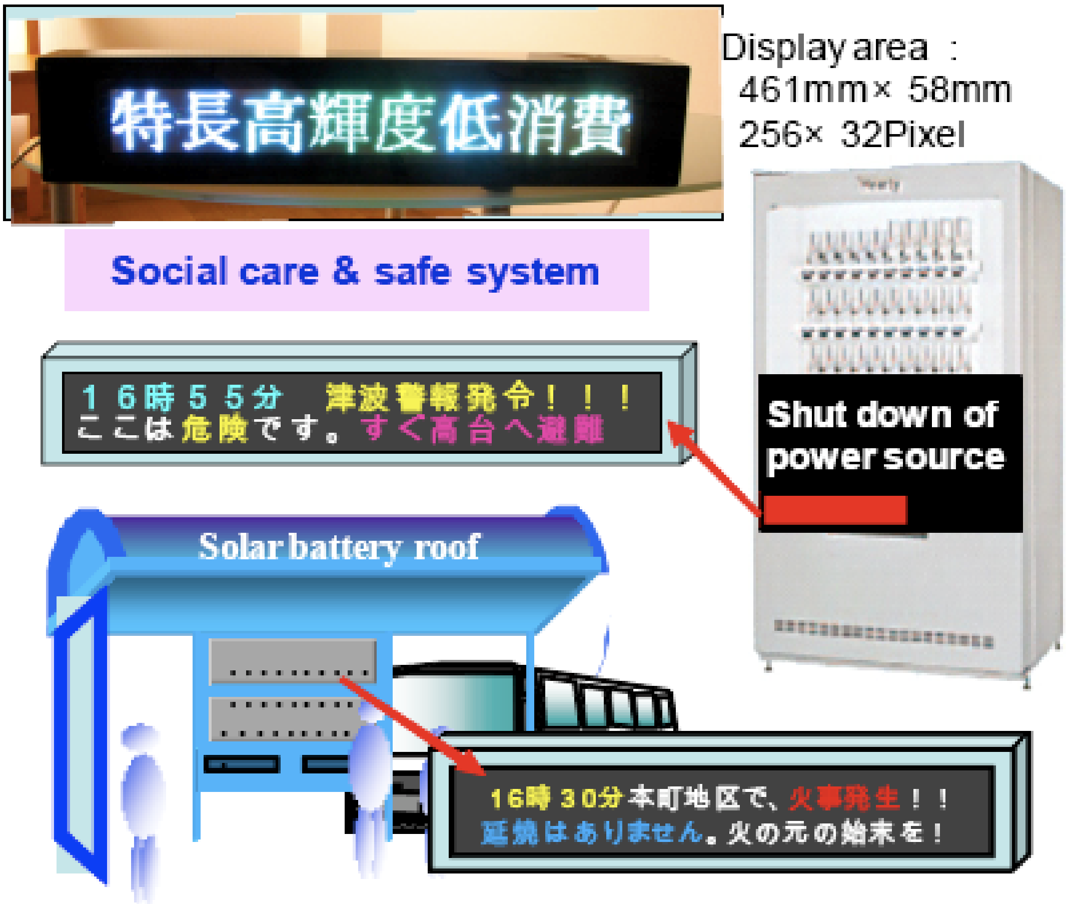
Source Noritake Co

Fig. 5.20 **A prototype display of digital signage.**



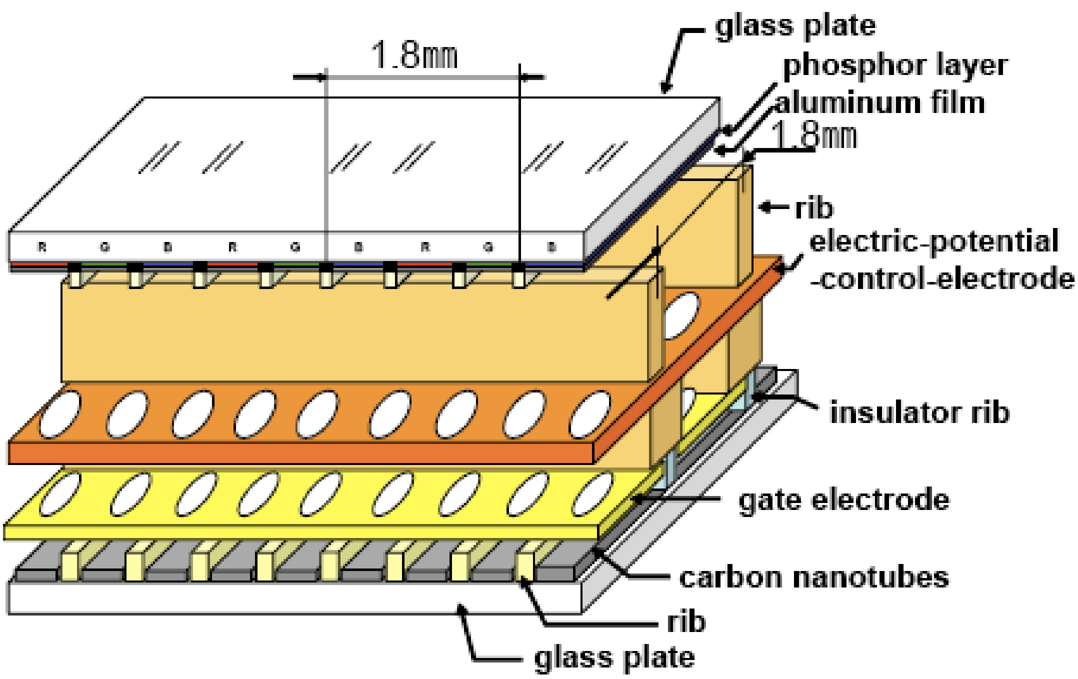
Source Noritake Co

Fig. 5.21 **Application images of public displays.**



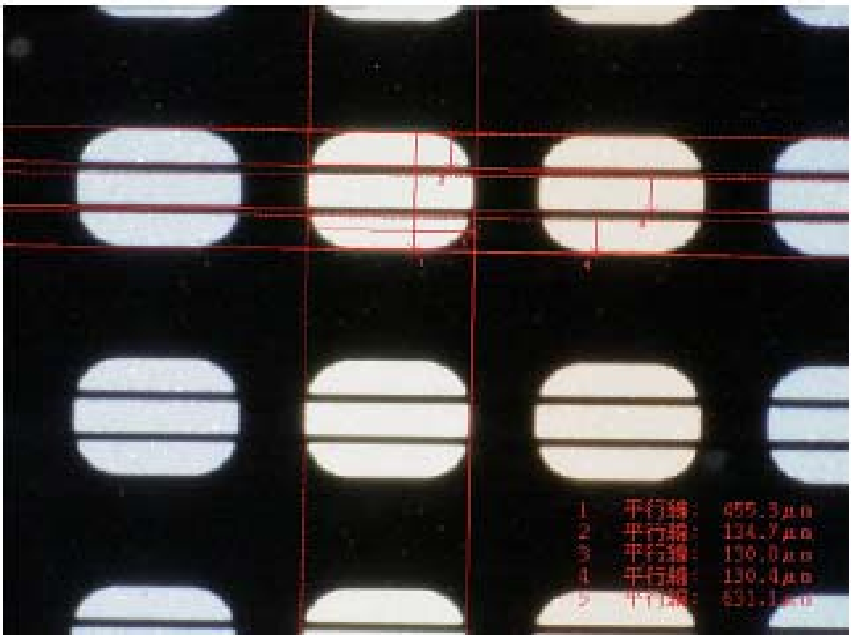
Source Noritake Co

Fig. 5.22 **Schematic structure of CNT-FED using line rib spacer.**



Source Noritake Co

Fig. 5.23 **Phosphor-dot pattern and conductive black-matrix pattern.**



Source Noritake Co

Fig. 5.24 **An application on the information desk. The color pixel pitch were 3mm(left) and 1.8mm (right).**

Source Noritake Co

Fig. 5.25 **A photograph of a displayed color character pattern in two lines. The color pixel pitch was 1.8mm.**

Source Noritake Co

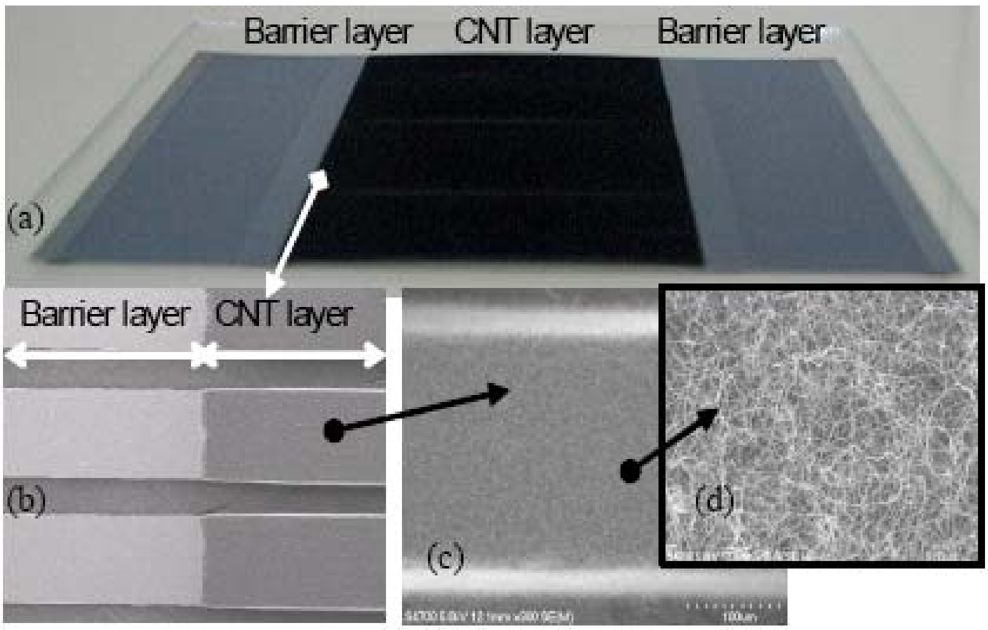
3. Design and Structure with High contrast

Phosphor substrate fig 5.16 shows the schematic structure of the CNT-FEDs. In order to realize high-luminance with long-life characteristics, a high anode voltage is required. We intended to increase the anode voltage up to ca.7kV, which required 2mm tall spacers to keep the distance between anode electrode and gate electrode. The structure was designed to apply the new low cost process technology. Anode electrode is operated at a high-positive potential. They are consisted of 160x3-lines and 256x3-lines of RGB (red, green, blue) P22-color-phosphor backed with thin aluminum film, respectively. The black-matrix layer was formed by spattering to thin film black layer on glass substrate, and it was patterned by photolithography. It improved the accuracy and conductivity of phosphor layer, as the result the contrast and legibility was improved. (fig 5.17)

The phosphor layer, 10-15!m in thickness, was formed by the screen-printing method. The 2mm tall ribs as spacers were formed on the metal sheet, which acts as the electric-potential-control-electrode. And also, insulating ribs were formed on the reverse side of the metal sheet for supporting metal gate electrodes. The rib-design was investigated to prevent the miss-addressing of electron-beam on the color-phosphor line. The anode substrate needed only very shallow ribs to touch the rib-top on gate-substrate-ribs. It takes very low-cost.

CNT-electrodes were formed by the direct growth of CNT on metal electrodes of 426-alloy (Fe -42wt%Ni -6wt%Cr) like a frame. The alloy has a special thermal property, i.e., its thermal expansion coefficient coincides with that of glass which is used as a material of vacuum vessels. Figure 5.20 shows a completed frame (a) and partial SEM images (b,c) of the CNT electrode. The lead wire pitch was 0.6mm, which was equal to phosphor-line pitch.

Fig. 5.26 **SEM images of CNT deposited metal electrode.(a) A photograph of the CNT deposited metal frame. (b) SEM image; boundary of barrier area. (c) SEM image; surface of the CNT layer. (d) SEM image; a surface morphology of CNT.**



Source Noritake Co

Fig. 5.27 **One of prototype displays on the vending machine. The display was under field-testing in out-door. The CNT-FED and display module were under testing continuously during ca.15months in Osaka-city up to date, and they were still continued.**

Source Noritake Co

4. Results

The improvements of CNT-FED color character displays opened the way to use the no power line applications in out-door use.

Reliability Test

1. The reliability test was applied to the display modules, test items were;1.vibration of 10-55-10Hz 2hours for XYZ-direction respectively, 2.temperature cycling of -40-+85degree C, 3.high temperature storage of +85degree C 90percentRH 1000hours, 4.low temperature storage of -40degreeC 1000hours, 5.high temperature operating of +85degreeC 85percentRH1000hours, 6.low temperature operating -40degreeC 1000hours, thermal shock of +85 to -40degreeC 100cycles.

The modules passed all above mentioned environmental examinations, usually such test-items were applied for automobile applications. Figure 10 shows one of field tests, the display was under field-testing in out-door. The CNT-FED and display module were under testing continuously during ca.15months in Osaka-city up to date, and they were still continued.

Driving under no power line

Figure 5.22 shows the photograph of the panel which was driven by solar cell and small battery (fig 5.22). In fig 5.22, solar cell and the charging controller, small battery and CNT-FED module were used.

Fig. 5.28 **A photograph of driving system. A solar cell and the charging controller, yellow small battery and CNT-FED module.**

Source Noritake Co

Fig. 5.29 **A photograph of a displayed color character which was driven by solar cell and small battery. The color pixel pitch was 1.8mm.**

Source Noritake Co

5. Conclusion

In this paper, we improved the characteristics of the CNT-FEDs, and we revealed the CNT-FED color character-displays were driven by solar cell and small battery. It will be the great feature to competitive other bright display devices such as LEDs. In this paper, we described the following developments.

1. Contrast: The contrast of phosphor screen was improved by thin film black layer.

2. Reliability: For applications in out-door, the reliability of CNT-FED character displays was improved and tested underspecified inspection for automobile.

3. Interface to battery: The characteristics of power source was improved to connect batteries, especially inrush current was diminished.

4. Solar cell charging: For applications at no power condition or energy conservation requirement, the solar cell charging was investigated by developing the battery charging controller.

One of applications of CNT-FED character displays is message display in the city at many dangerous spots. But many such dangerous spots are distributed in the countryside, some of such spots have no power line, and require timely caution message to people. Also, even in the down town, many public information systems are required energy conservation up to no power consumption from usual power line. So, the CNT-FED color character-displays driven by solar cell and small battery will be useful and effective to public information systems.

6. Acknowledgements
This work was supported by New Energy and Industrial Technology Development Organization (NEDO). We thank to Nanotechnology and Material Technology Department of NEDO.

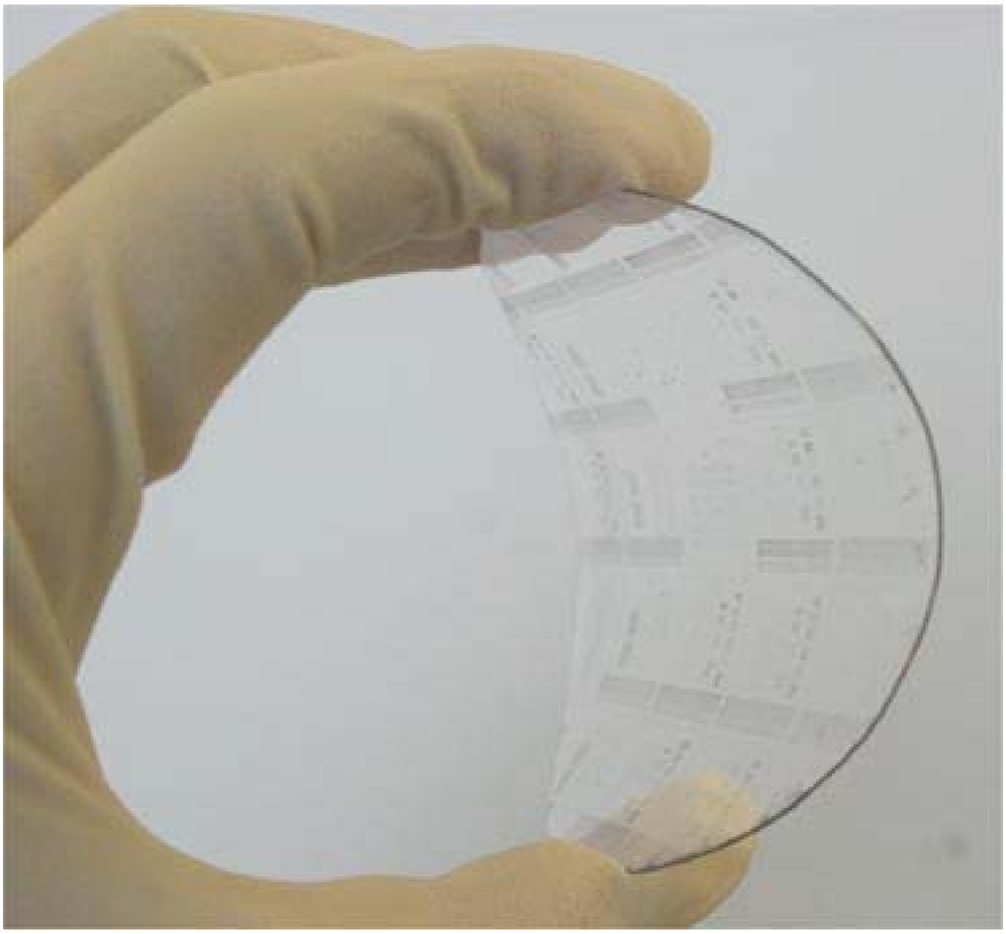
5.63. Northeastern University, Boston, USA

122 Saint Stephen St
Boston, MA 02115-4347, United States
+1 617-373-2340
www.northeastern.edu
Researchers at Northeastern University, Boston, US, recently demonstrated high-density single-walled carbon nanotube (SWCNT) networks in microscale structures on a wafer-level flexible substrate. The developed method using dip coating has huge potential in flexible electronics such as thin film transistors (TFTs), interconnects and various sorts of sensors.

The successful direct assembly of CNT structures with controllable dimensions using a dip coating process marks an enormous step towards the implementation of SWCNTs in microscale flexible electronics. To date, the complicated processing often including transfer printing represents a major technological barrier limiting the breakthrough of CNT electronics.

For practical applications in flexible and printed electronics an enhanced current drive is needed. As individual single-walled carbon nanotubes have only limited current-carrying capacity, a group, bundle or network of SWCNTs like the researchers at Northeastern University, Boston, used is required.

Fig. 5.30 **High density SWCNT structures on wafer-scale flexible substrate.**



Utilizing a dip coating process, the researchers fabricated high density and uniform micropatterns of SWCNT networks onto a flexible parylene-C polymer substrate.

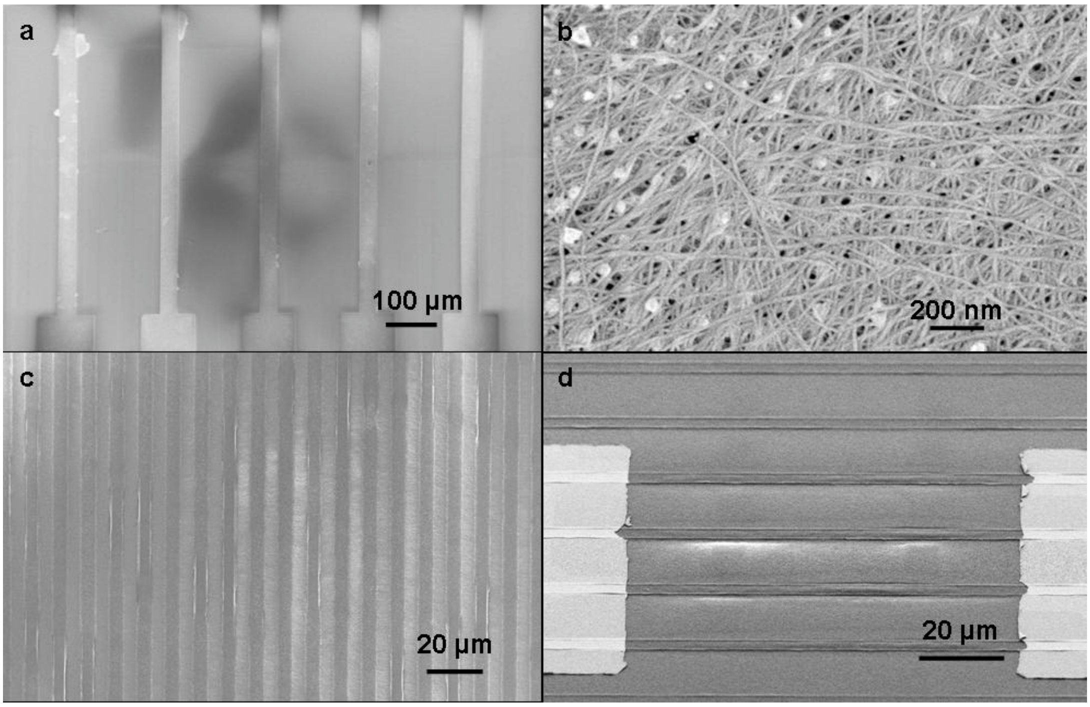
Parylene-C is lightweight and biocompatible, with high tensile strength (10.000 psi) and mechanical strength (Young's modulus of 400 kpsi). Due to its mechanical properties, parylene-C can be deposited at room temperature with very low thickness, i.e. down to 5 micron. Hydrophobic in nature, which cannot be easily changed using a chemical process, the low surface energy of the substrate makes a direct assembly difficult.

Employing a short O_2 plasma treatment the researchers were able to modify the surface properties from hydrophobic to hydrophilic, which makes it comparatively easy for the SWCNT solution to directly assemble on the substrate. Key advantage of the polymer material is that the altered properties maintain for several days, which allows for a rather extended processing time.

After depositing the polymer with a thickness of 10 micron onto silicon chips (15 mm x 15 mm) – as temporary carrier – and surface pre-treatment, micro-channels were created using a spun coated photoresist followed by an optical lithography process. Dip coated (KSV Intruments) into a SWCNT solution obtained from Nantero Inc. the fluidic assembly took place.

Due to the altered surface properties of the polymer, single-walled carbon nanotube networks selectively assembled onto the substrate. Afterwards, the photoresist was removed leaving only the SWCNT arrays. Finally, the parylene-C film was peeled off from the temporary silicon carrier.

Fig. 5.31 **SEM micrographs of assembled SWNT structures on a soft polymer surface. (a) Patterned SWNT arrays on parylene-C substrate; (b) high magnification view of a typical central area; (c) SWNT micro-arrays that are 4 μm wide with 5 μm spacing; (d) SEM image of an interconnect device viewed at an oblique angle.**



Using this new processing technique – a combination of optical photolithography and dip coating – carbon nanotube network arrays with controllable dimensions were fabricated; electrically continuous CNT network micro-arrays as small as 4 micron wide and up to 1500 micron long. Measured resistances of these test structures are significantly low (256 to 321 Ohm). Bending tests in both directions for up to 5 times have shown consistent results without deteriorating the structures, and a good stability of the assembled networks in microstructures.

Another true advantage is the eliminated need for any printing, transfer or chemical functionalization technique. This bottom-up chemical-free patterning technology is versatile and scalable with direct applications in flexible electronics.

The presented research provides a framework for making low-cost, high performance, disposable, and flexible functional devices and sensors based on carbon nanotubes highly suitable for large area applications.

The work was supported by the National Science Foundation Nanoscale Science and Engineering Center (NSEC) for High-rate Nanomanufacturing.

5.64. Optomec, USA

Optomec Advanced Applications Laboratory
1000 Westgate Dr.
Suite 123
Saint Paul, MN 55114
United States
1 651 641 2850
www.optomec.com

Optomec's Aerosol Jet system has been used to fully print CNT based Thin Film Transistors (TFT) with operating frequencies over 5 Gigahertz (GHz). The work was conducted in collaboration with the University of Massachusetts and Brewer Science, Inc.

Printing TFTs on flexible substrates at room temperature offers a cost-effective way to achieve mass production of large-area electronic circuits without using special lithography equipment. This is important for many emerging applications such as flexible displays, RFID tags, electronic paper, and smart skins. The Aerosol Jet deposition process was used to completely print all four layers of the Thin Film Transistor including materials with a wide spectrum of viscosities, making it an ideal solution for this type of multi-layer device.

A recently published paper states that *"Printed flexible electronics have been reported by using various organic semiconducting polymers. However, the carrier mobility of organic semiconducting polymers is still less than 1.5 cm2~V s, which limits the device operation speed to only a few kilohertz. Carbon nanotube (CNT), a material with exceptional aspect ratio and great mechanical flexibility, has shown great promises as an active carrier transport material in making high-speed flexible field-effect transistors (FETs). All the elements of the TFT are fabricated solely by using Aerosol Jet printing technology without involving any photolithography fabrication steps. An ultra-high operating frequency of over 5 GHz was demonstrated with an on-off ratio of over 100."*

Dr. Mike Renn, (a co-author of the paper) states that *"One of the unique benefits of the Aerosol Jet technology is that it is capable of printing TFT devices with high drain current, high on-off ratio, and low operation voltage. Additionally, Aerosol Jet systems have achieved sub-micron layer thicknesses, and less than 10 micron features sizes and 5 micron registrations."*

Optomec's Aerosol Jet systems are used in the development of next generation printable devices such as solar cells, fuel cells, embedded sensors, and more. Aerosol Jet systems use a patented process that first aerosolizes conductive and nonconductive inks or pastes and then forms an aerodynamically focused droplet stream of the material. This Direct Write capability eliminates the need for screens or stencils required by traditional contact deposition processes while also enabling much finer feature sizes than is possible with ink jet printing technology.

Optomec is the world-leading provider of additive manufacturing systems for high-performance applications in the Electronics, Photovoltaic, and Aerospace & Defense markets. Optomec's Aerosol Jet Deposition System (formerly known as M3D) is a breakthrough additive technology enabling finer feature sizes than traditional inkjet and screen printing processes. The Aerosol Jet system utilizes an innovative aerodynamic focusing technology that produces electronic and physical structures with feature sizes down to 10 microns. The Aerosol Jet system supports a wide variety of materials including nanoparticle inks and screen-printing pastes, conductive polymers, insulators, adhesives, and even biological matter that can be accurately deposited onto non-planar substrates. Aerosol Jet is a registered trademark of Optomec, Inc.

In June 2009 Optomec announced that the company's Aerosol Jet deposition system has been selected to be part of the PETEC (Printable Electronics Technology Centre) facility.

The Aerosol Jet system, which will be installed at PETEC's location in County Durham, UK, will be primarily used to prototype Organic Thin Film Transistors (OTFTs). The system will be located in a Class 100 clean-room that contains process equipment for 300mm panel fabrication on glass or flex. The system is one of the items of equipment purchased under the LACE project (Large Area Coating Equipment), and is partly financed by the European Union's ERDF Competitiveness Programme 2007-13.

The Aerosol Jet system is ideally suited to be part of the PETEC facility because the technology is able to print the fundamental building blocks for printed electronics. The technology is most suited to printing the challenging fine resolution features of the source and drain electrodes in TFTs, in addition to the active channel and other material layers in these electronic device structures.

These materials can be combined and layered to make more complex devices and circuits. The ability to print fine features (<10 microns) and work at room temperatures without vacuum processing means the process is an enabling technology for many emerging printed and large area applications.

Dave Ramahi, Optomec President/CEO states that: "PETEC is a state of the art facility that is breaking new ground in the development of printed thin film transistors. The Aerosol Jet system will help PETEC and their clients to take TFT printing to the next level."

In January 2010 Optomec announced that it has received a new contract from the Air Force Research Laboratory (AFRL) to deliver high throughput enhancements to its Aerosol Jet system. With this new contract the total amount of project funding is now more than $1.5 million.

Dave Ramahi said: "Optomec is proud to be working closely with the AFRL team, a recognized leader in the field of SOFC development. Their guidance has provided a critical understanding of the needs of this industry and we are confident that the high volume enhancements being developed under this contract will meet with strong demand from the fuel cell and other industries."

5.65. Pennsylvania State University, USA

Penn State
Electro-Optics Center (EOC)
222 Northpointe Blvd
Freeport, PA 16229

T: 1 724 295 7000
F: 1 724 295 7001
www.electro-optics.org/

Created in 1999 under a cooperative agreement with the Office of Naval Research (ONR) and managed by Penn State University, the Electro-Optics Center (EOC) promotes the development of electro-optic materials, components, and systems needed to advance the state-of-the-art in electro-optic science and technology for the defense forces.

In February 2010 researchers at the Electro-Optics Center (EOC) Material Division at Pennsylvania State University presented their breakthrough Graphene wafers. With reported 100mm they have the largest diameter that is commercially available for silicon carbide wafers. The wafers exceeded the previous demonstration of 50mm. Focussing on graphene materials the team's goal is to improve the transistor performance in various radio frequency (RF) applications.

According to EOC materials scientist Joshua Robinson, "Penn State is currently fabricating field effect transistors on the 100 mm graphene wafers and will begin transistor performance testing shortly."

With further research they hope to be able to improve the speed of electrons in graphene made from silicon carbide wafers to closer to the theoretical speed – approximately 100 times faster than silicon. "That will require improvements in the material quality," said Robinson, "but the technology is new and there is plenty of room for improvements in processing."

Additionally, the EOC researchers are developing the synthesis and device fabrication of graphene on silicon in order to achieve wafer diameters exceeding 200mm. This scale would be necessary for integrating graphene into the existing semiconductor industry.

The work is supported by the Naval Surface Warfare Center in Crane, Ind.

5.66. PETEC (Printable Electronics Technology Centre), UK

PETEC
CPI
Thomas Wright Way
NETPark, Sedgefield,
County Durham TS21 3FG
T: +44 (0) 1740 625700
F: +44 (0) 1740 625763
www.uk-petec.com

PETEC, a new business unit of CPI, is a UK national prototyping facility for the development and commercialisatization of printed electronics. It offers a unique blend of materials, process and people capabilities which de-risk and accelerate clients' development and commercialization of printed electronics' technologies.

PETEC's role is to drive product innovation through all the necessary stages of development, including concept, design, materials formulation, prototyping and fabrication. These functions are supported by a range of application development, testing, validation, process development and optimization services. Several European-based companies are already using the PETEC facilities to test and develop their new organic electronic prototypes.

Key areas of focus encompass OTFT, solid state OLED lighting and Organic Photovoltaics.

In June 2009 it was announced that Optomec's Aerosol Jet deposition system has been selected to be part of the PETEC facility.

The Aerosol Jet system, which will be installed at PETEC's location in County Durham, UK, will be primarily used to prototype Organic Thin Film Transistors (OTFTs). The system will be located in a Class 100 clean-room that contains process equipment for 300mm panel fabrication on glass or flex.

Dr. Simon Ogier, PETEC R&D manager states, *"We are eager to work with this new technology for depositing active layers of organic devices. It will allow us to learn much about the performance that can be achieved in high resolution printed devices"*. The system is one of the items of equipment purchased under the LACE project (Large Area Coating Equipment), and is partly financed by the European Union's ERDF Competitiveness Programme 2007-13.

PETEC's LACE project has secured a total of £2M ERDF investment through regional development agency One North East. The ERDF programme is bringing over £250m into the North East to support innovation, enterprise and business support across the region.

5.67. Rice University, USA

Robert Vajtai, Faculty Fellow
Rice University, Department of Mechanical Engineering and Materials Science
Mail: MS321, P.O. Box 1892, Houston, Texas 77251-1892
Visit: MEMS 218, 6100 Main Street, Houston, Texas 77005
Phone: 713-348-2344;
Fax: 713-348-5423
E-mail: Robert.Vajtai@rice.edu
www.mems.rice.edu

Within the laboratories of Rice University, as well as the facilities within the Smalley Institute for Nanoscale Science and Technology and the Carbon Nanotechnology Laboratory, the researchers have access to a wide variety of instrumentation for the synthesis and analysis of nanomaterials. Rice University also has active collaborations with several other institutions including the University of Texas Health Sciences Center in Houston and Galveston, MD Anderson, and several national and defense department laboratories.

In November 2009 Rice University scientists unveiled a method for the industrial-scale processing of pure carbon-nanotube fibers that could lead to revolutionary advances in materials science, power distribution and nanoelectronics. The result of a nine-year program, the method builds upon tried-and-true processes that chemical firms have used for decades to produce plastics.

The new process builds upon the 2003 Rice discovery of a way to dissolve large amounts of pure nanotubes in strong acidic solvents like sulfuric acid. The research team subsequently found that nanotubes in these solutions aligned themselves, like spaghetti in a package, to form liquid crystals that could be spun into monofilament fibers about the size of a human hair.

Following the 2003 breakthrough with acid solvents, the team methodically studied how nanotubes behaved in different types and concentrations of acids. By comparing and contrasting the behavior of nanotubes in acids with the literature on polymers and rodlike colloids, the team developed both the theoretical and practical tools that chemical firms will need to process nanotubes in bulk.

"One good thing about the process that we have right now is that if anybody could give us one gram of pure metallic nanotubes, we could give them one gram of fiber within a few days," Pasquali said.

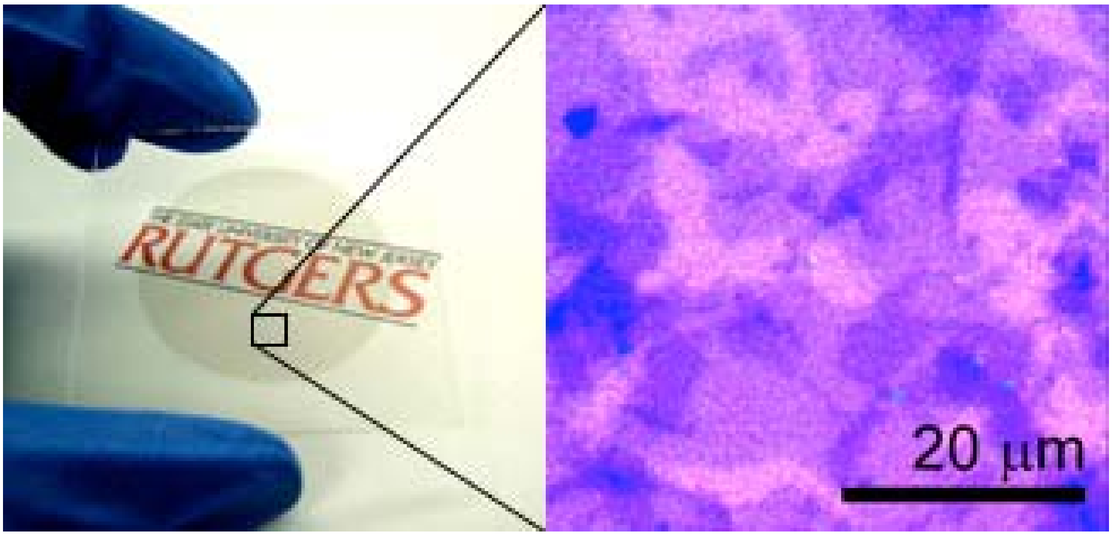
The report was co-authored by an 18-member team of scientists from Rice's Richard E. Smalley Institute for Nanoscale Science and Technology, the University of Pennsylvania and the Technion-Israel Institute of Technology.

The research was funded by the Office of Naval Research, the Air Force Office of Scientific Research, the Air Force Research Laboratory, the National Science Foundation, the USA-Israel Binational Science Foundation and the Welch Foundation.

5.68. Rutgers University, USA

Rutgers - The State University of New Jersey
Department of Materials Science and Engineering
607 Taylor Road, Piscataway, NJ 08854,USA
Ph: (732) 445-5619
Fax: (732) 445-3258
E-mail: manish1@rci.rutgers.edu
http://nanotubes.rutgers.edu

Fig. 5.32 **CNT films from Rutgers University**



Source Rutgers University, USA

Nanomaterials and Devices Group at Rutgers University developed a solution-processed graphene to fabricate large area ultra-thin films. These are potentially useful for macro-scale electronic devices such as photovoltaics, sensors, and thin film transistors. Their aim is to optimize the opto-electronic properties of solution-processed graphene and incorporate it into large area thin film electronics.

The researchers found a simple way to uniformly deposit between one and five layers of graphene from reduced GO in the form of thin films to create transistors and proof-of concept electrodes for organic photovoltaics.

One of the major challenges of this work is the complete removal of functional groups from the starting graphene oxide solution (which are initially required for processability) to fully recover the intrinsic properties of graphene.

5.69. Samsung Electronics, Korea

Samsung Electronics Co Ltd
Samsung Advanced Institute of Technology (SAIT)
San #14-1, Nongseo-dong, Giheung-gu
Yongin-si
Gyeonggi-do
446-712
Korea

In May 2009 Samsung Electronics demonstrated a 2.3 inch black and white active matrix EPD made with carbon nanotubes, but this is the first color large scale EPD e-paper device, in an A4 format claims Unidym's CEO and President Arthur Swift. The researchers showed that the CNT materials where able to demonstrate conductivity comparable to the incumbent ITO technology, uniformity over large areas in films, and compatibility with different display technologies and fabrication processes.

Samsung Electronics is also working with Advanced Institute of Technology (SAINT) on a nano data storage device. In March 2009 SAINT and Samsung Electronics presented a co-developed new method for fabricating graphene films at a large scale. "Samsung Electronics plans to extend the applications for graphene-related technology to other areas such as ultra-high-speed nano memories, transparent flexible displays and next-generation solar batteries, " said Hong, Prof at Advanced Institute of Nano Technology (SAINT) in Sungkyunkwan University.

Already a few years ago Samsung electronics started to invest in the development of large-area FEDs using a conductive CNT polymer paste on the back electrode. Bulk carbon nanotubes blended with a polymer are used to form the paste.

5.70. SES Research, USA

5999 West 34th
Suite 106
Houston
TX 77092
Tel. (713) 686-9662
http://sesres.com

SES research is a provider of purified CVD produced MWCNTs and SWCNTs in variable diameter and length with purities greater than 90%.

5.71. Shenzhen Nanotechnologies Co. Ltd. (NTP)

Hi tech park, Nanshan, Shenzhen China 518057
Service Hotline:
+86-755-88850689
Email: nanotubes@263.net
http://www.nanotubes.com.cn/

Shenzhen Nanotechnologies Co. Ltd. (NTP) is one of the major producers of bulk CNT material within China. The company's main focus is R&D regarding manufacture and applications of carbon nanotubes.

Since 2001, Shenzhen produces carbon nanotubes in large scale, i.e. MWCNTs with a purity higher 90% and SWCNTs with around 50% purity.

5.72. Showa Denko Carbon, Inc. (SDK), USA

Showa Denko Carbon, Inc.
478 Ridge Road
P.O. Box 2947201
Ridgeville, South Carolina 29472
800-525-7031
http://www.sdkc.com/

Showa Denko Carbon, Inc., one of the leaders in production of MWCNTs in Japan, is a part of the Showa Denko KK group. The company specialises in manufacture of synthetic graphite and large-diameter, ultra-high-power, graphite electrodes. Additionally, Showa Denko develops carbon nanofibers and nanotubes at a capacity of 100 tons per year – mainly for battery applications.

In the fully-integrated manufacturing plant MWCNTs with a diameter of ›100nm are grown using a vapor based process. Additionally they developed a post-processing method to pre-treat CNTs for specific applications.

In January this year Showa Denko announced the concluded patent license agreement and supply agreement with Hyperion Catalysis International, Inc. SDK will sell products based on Hyperion's FIBRIL™ CNTs combined with the own CNT product line.

5.73. ST Microelectronics, Switzerland

STMicroelectronics
39, Chemin du Champ des Filles
C. P. 21
CH 1228 Plan-Les-Ouates
GENEVA, Switzerland
Tel: +41 22 929 29 29
Fax: +41 22 929 29 00

ST Microelectronics has recently filed numerous patent applications for SST inventions, including carbon nanotubes for molecular and biomolecular memories, single-electron transistors based on functionalized metal nanoclusters, polymeric materials for fuel cell membranes, and DNA biosensors.

5.74. SouthWest NanoTechnologies (SWeNT), USA

SouthWest NanoTechnologies Inc.
2501 Technology Place
Norman, OK 73071-1102 U.S.A.
Telephone: (405) 217-8388
Fax: (405) 217-8389
E-mail: info@swentnano.com
Web: http://swentnano.com

The startup company South-West Nanotechnologies (SWeNT) was found 2001 and commercializes the CoMoCAT® CNT production process developed at the Carbon Nanotube Technology Center (CaNTeC) at University of Oklahoma. The company provides SWCNTs under the brand names SWeNT®CG and SWeNT® SG. The first ones are SWCNTs with high electrical conductivity, whereas the second ones are semiconducting. SWeNT is able to tailor the characteristics of SWCNTs such as diameter, length, chirality, purity, and surface chemistry.

Early in 2010 the company introduced CNT Inks based on V2VTM Ink Technology developed by alliance partner, Chasm Technologies, Inc. For the first time, carbon nanotubes can now be printed using commercial, high-volume printing methods and equipment, including flexographic, gravure and screen printing.

This breakthrough ink technology combined with SWeNT's unique ability to tailor the synthesis of CNT materials for applications (using its patented CoMoCAT® process) will enable customers to print large area, low-cost devices for a wide range of applications including energy-efficient lighting, affordable photovoltaics, improved energy storage and printed electronics.

When these inks are dried, all but the CNT itself vanishes, leaving behind no residual materials from dispersing aids or viscosity modifiers that can compromise printed CNT performance. According to Chasm Co-Founder, Bob Praino, "The combination of CNTs tailored for performance with our V2V™ ink vehicle tailored for the desired printing method is a very exciting innovation that makes it easier and less costly to incorporate CNTs into a number of printed electronics applications."

Additionally, with the new SWeNT® CG 200 the company offers a more conductive SWCNT for coatings in commercial quantities, which will most likely expand the range of application of CNTs

Dave Arthur, SWeNT's CEO said: "Lots of great work has been done on SWCNT-based conductive coatings in laboratories around the world, opening the doors for new solutions in a range of applications. However, most of this work has been done using SWCNT from non-scalable synthesis processes, and employing low-yield, expensive, secondary purification and separation methods, thereby making them impractical for commercial use"

Ricardo Prada Silvy, director of research and development at SWeNT, added: "By making adjustments to our catalyst systems and other process variables we are able to make a very pure, very consistent product, and to achieve our target of longer, larger diameter tubes.

In December 2009 it was announced that SWeNT together with Brewer Science Inc. has received a $6.5M award under NIST's Technology Innovation Program (TIP). The funding supports R&D of methodologies to attain the cost-effective production of high-purity, high-quality metallic and semiconducting carbon nanotube (CNT) inks.

The two companies will team up to develop superior CNTs and improved inks on a commercial scale. These new products will support a wide variety of applications including high-performance optical devices, photovoltaic cells, batteries, supercapacitors, lighting products, flexible electronic devices, and sensors.

Earlier in August 2009 SWeNT in partnership with Chasm Technologies, Inc. (Chasm), a consulting firm specializing in nanomaterials and thin film coating & patterning, established a CNT coatings application development center at Chasm's facility located in the Boston area.

The center provides a variety of thin film coating and patterning technologies, including rod coating, slot die coating, spray coating, ink jet printing, flexographic printing, screen printing and imprint lithography. Coating trials can be done at bench scale (sheets) or pilot scale (continuous lengths up to 12" wide), accommodating a wide range of substrates. Customized coating formulations can be prepared on-site. The center also includes a wide range of test equipment to characterize coated product structures.

"Many commercial opportunities for SWeNT® nanotubes were being held back because it was too difficult for our customers to integrate carbon nanotubes into industrial coating and printing processes," says Dave Arthur, SWeNT CEO and Chasm co-founder.

In July 2009 it was announced that SouthWestNanoTechnologies Inc. (SWeNT) will receive up to a $3 million equity infusion from the Insight Technology Capital Partners, LP, (Insight) a Growth Capital Fund based in Troy, Michigan.

SWeNT will use the proceeds from this equity investment from the Insight 2811 Technology Entrepreneur Fund managed by Insight to develop, manufacture and market new products as well as its current portfolio of carbon nanotube offerings.

SWeNT expanded production with a new manufacturing facility in Norman, Oklahoma late 2008, increasing its single-wall carbon nanotube production capability 100-fold at one-tenth the unit cost. Its scalable, low-cost CoMoCAT® process ensures consistent high quality and the flexibility to provide tailored products.

SWeNT also has an applications development center in the Route 128/Boston, Massachusetts area, where SWeNT can work with customers on integrating SWeNTnanotubes into their products.

In announcing their investment, Insight Principal Joe Nathan said, "We welcome the opportunity to support SWeNT's continued development as a world leader in carbon nanotechnology. Their leadership in product quality and performance, coupled with their proprietary scalable synthesis process, convinced us that SWeNT is the right vehicle for investment in this burgeoning area of materials technology."

"Insight is an ideal investment partner for SouthWestNanoTechnologies," explains Dave Arthur, CEO. "They bring extensive financial resources, broad industry knowledge and a successful track record of investing in advanced materials companies. We look forward to working together and benefitting from their advice, counsel and contacts."

5.75. Sungkyunkwan University Advanced Institute of Nano Technology (SAINT), Korea

Advanced Institute of Nano Technology
Sungkyunkwan University
300 Cheongcheon-dong
Japan-gu
Suwon
Gyeonggi-do
440-746
South Korea
T: 82-31-299-4112-5
F: 82-31-299-4119
E: saint@skku.edu
http://saint.skku.edu/e_saint2/index.htm

In March 2009 SAINT and Samsung Electronics presented a co-developed new method for fabricating graphene films at a large scale. Future applications for these could be stretchable, transparent electrodes for flexible displays, touch-screen sensors and transformable electronics.

The aim to find an alternative to ITO, which is currently used in flat panel displays, touch screens and solar batteries, but is fragile and therefore not matching the requirements for flexible displays.

Prof Byung Hee Hong at Advanced Institute of Nano Technology (SAINT) in Sungkyunkwan University, and Dr Jae-Young Choi at Samsung Advanced Institute of Technology (SAIT) in Samsung Electronics developed the graphene films using integrated wafer-scale graphene growth by chemical vapor deposition (CVD) onto a nickel-based substrate. The resulting single-layer films with dimensions of a few centimetres exhibit excellent electronic and mechanical properties matching those of the micro-scale graphene films are transparent and can be stretched without degradation.

5.76. Sun Nanotech Co, Ltd., China

Address: 339 East Beijing Road, Nanchang, Jiangxi 330029, P.R.China
Email: xiaoshuzeng@sunnano.com
www.sunnano.com
Phone: +86-791-6270959 8304572
fax: +86-791-6217509

Sun Nanotech Co., Ltd. is one of the major producers of bulk CNT material, i.e. MWCNTs, in China.

5.77. Surrey NanoSystems, UK

Unit 24 Euro Business Park
New Road
Newhaven BN9 0DQ
UK
Tel: +44 (0) 1273 515899
Fax: +44 (0) 1273 512311
http://www.surreynanosystems.com

Surrey NanoSystems uses CNT equipment and nanowire deposition systems for low temperature, as well as CVD and plasma-enhanced CVD for the growth on nanotubes, nanowires and else.

Surrey NanoSystems was established in 2006 as a spin-off from the University of Surrey's

Advanced Technology Institute (ATI), with the help of individuals having a successful background in the design of thin-film deposition systems. ATI had developed pioneering IP concerning the fabrication of CNTs at low temperature.

The used equipment NanoGrowth implements a unique process incorporating ATI's patented know-how, and several unique additional techniques, that deliver the conditions for the growth of precision CNTs at both the temperatures and densities needed for state-of-the-art CMOS ICs.

The initial focus has been the provision of equipment to developers researching and prototyping CNTs to advance the performance and integration density of semiconductors and electronic devices. Now it is optimizing the technology for mass-volume manufacturing environment, by scaling the hardware and refining and scaling the materials processing technology.

In August 2009 the company announced that it has secured second round funding of £2.5 million (~US$4.2m) from Octopus Ventures, IP Group, The University of Surrey and other investors.

The funding will be used to commercialize their low-temperature growth process for

CNTs, targeted for use as an interconnection technology in semiconductor devices. With this CNT structures can be grown at processing temperatures of 350°C and less. The company is planning to extend its engineering and development capabilities with a new technology laboratory, several brand-new systems of its own design, and more staff.

Carbon nanotubes (CNTs) can be structured to act as extremely efficient conductors, but their adoption as a replacement for copper has been hindered by the fact that conventionally-grown CNTs require temperatures of around 700 degrees C, too high for semiconductor processing.

Alongside its development work, Surrey NanoSystems is pursuing technology partnerships with both semiconductor manufacturers and volume cluster tool suppliers, to shorten the path to market for its technology.

5.78. Thomas Swan & Co. Ltd., UK

Consett
County Durham
UK
DH8 7ND
+44 (0) 1207 505131
http://www.thomas-swan.co.uk

Thomas Swan & Co. Ltd. was founded in 1926 and is one of UK's largest family-owned chemical manufacturing companies. Nowadays providing performance chemicals and custom manufacturing services, the business focus has significantly changed since the early days. In April 2004, Thomas Swan launched a carbon nanomaterials business, which provides purified SWCNTs and MWCNTs at commercial scale. SWCNTs are delivered as a dry powder, aqueous or alcohol wet cake.

The company has its own Chemical Vapor Deposition plant. The fully scalable production was developed in collaboration with the University of Cambridge. Elicarb® is the name of the trade mark, which aims for a wide variety of industrial and academic applications including advanced electronics, energy storage, fuel cells and supercapacitors.

5.79. Toray Industries, Japan

Nihonbashi Mitsui Tower, 1-1, Nihonbashi-Muromachi 2-chome, Chuo-ku, Tokyo 103-8666, Japan
Tel: +81-3-3245-5111
Fax: +81-3-3245-5555
http://www.toray.com/

Toray Industries is produces and sells mainly MWCNTs, but also SWCNTs and DWCNTs in bulk quantities. Intensely working on the development of double-walled CNTs (DWCNTs) and application development they found a low-cost method that is suitable for the production of DWCNTs and SWCNT with well-defined chirality.

5.80. Tsinghua University, China

Department of Chemical and Reaction Engineering
Professor Fei Wei's group
Dept. of Chemical Engineering, Tsinghua Univ.
Address: Dept. of Chemical Engineering, Tsinghua Univ., Beijing P.R.China, 100084
Telephone: +8610-62782243, Fax: +8610-62770304
E-mail：webmaster@mail.chemeng.tsinghua.edu.cn

The Department of Chemical Engineering at Tsinghua University under Professor Fei Wei is focusing on the development of continuous processing techniques and applications of CNTs. Doing so the university is one of the major producers of bulk CNT material within China, but mainly for research activities.

In September 2008 Tsinghua University, China, and Beijing Normal University, China, presented their collaborational work on flexible, stretchable, transparent thin film loudspeakers that incorporate CNT nano-ribbons.

5.81. Unidym, Inc., USA

Unidym, Inc.
1430 O'Brien Drive, Suite G
Menlo Park, CA 94025
Tel: (650) 462-1935
Fax: (650) 462-1939
info@unidym.com
www.unidym.com

Unidym Inc. is developing novel materials architectures that will enhance the areas of electronics, optoelectronics and photovoltaics. The technology is based on networks of nano-scale materials, such as CNTs, with advantages being high electrical conductivity, mechanical flexibility, transparency, and environmental resistance. Initially, Unidym provides conductive films based on its core technology that uses novel materials architecture coupled to simple room temperature fabrication processes. The architecture consists of a random network of CNTs that serves as an electrically conductive medium.

Intended to replace ITO as transparent electrode Unidym's first product can be used in flat-panel displays, laptops, mobile phones and touch screens, solar cells, and solid state lighting. The second product will be a CNT-based TFT. Unidym was founded to capitalize on recent breakthroughs in the area of new electronic materials and architectures by the research group of Dr. George Grüner, professor of Physics at UCLA.

Early in February 2010 the company announced that it has signed a definitive agreement to create a joint venture partnership with Wisepower, a publicly traded Korean company, to market and co-develop Unidym's proprietary film and electronic ink products into the Korean touch panel and display industries. The newly formed entity will be called Unidym Korea.

"South Korea is becoming an increasingly important geography for our target markets in touch panel, LCD and other display and solar markets. By creating Unidym Korea in partnership with Wisepower, we will have the local presence to support our efforts with major Korean display manufacturers and accelerate our business development activities with local partners," said Mark Tilley, CEO of Unidym.

Unidym will retain a significant ownership position in Unidym Korea in exchange for a license to the new company for certain intellectual property. Under the arrangement, Unidym has agreed to supply its CNT based transparent conductive film to Unidym Korea. Wisepower has agreed to contribute operating capital and provide local manufacturing, sales, and distribution expertise.

Earlier it was announced that Unidym has entered an exclusive license agreement with Nano-C for patents covering fullerene derivatives. The license provides Nano-C exclusive rights to U.S.Patent No. 5,739,376 and foreign counterparts in the field of photovoltaics.

"We chose to execute this license agreement because we believe Nano-C is the leader in fullerene technology and products for the emerging thin film solar industry," stated Mark Tilley, CEO of Unidym. "We are pleased to enable Nano-C to unleash the potential of modified fullerenes in thin film solar."

Unidym will also cooperate with Nano-C to supply a variety of patented derivatives to customers for uses beyond Photovoltaics.

Additionally, Unidym enters into a third year of joint development agreement with Samsung Electronics. The objective of the collaboration is the integration of CNT materials as the transparent conductive layer in display devices. In the past 12 months Samsung Electronics has used Unidym's film product to demonstrate the world's first 14.3-inch color electrophoretic display (EPD).

CNTs simplify the transparent conductor deposition process because they can be wet-processed utilizing printing techniques, or through roll-to-roll coating processes, in contrast to the current time-consuming vacuum sputtering deposition process required by indium tin oxide (ITO) and indium zinc oxide (IZO). Additionally, ITO and IZO are not very flexible and can show degradation in conductivity up to 100 per cent after only 100 bending cycles.

On April 23, 2007 the company announced that it has closed the merger with Carbon Nanotechnologies, Inc. ("CNI"). CNI, which will operate under the Unidym name, has the several CNT-related patents and is one of the largest manufacturers of CNTs in the world.

"In addition to integrating the operations of the two companies, our priority over the coming months will be developing strategic partnerships and the licensing program," said R. Bruce Stewart, Arrowhead's Chairman. "We expect the merger to stimulate increased interest in carbon nanotube technology."

October 2008 Samsung Electronics presented world's first carbon nanotube CNT-based color active matrix electrophoretic display (EPD) e-paper at the International Meeting on Information Display (iMiD) at KINTEX, Ilsan, Korea. The 14.3" e-paper display is the result of an ongoing joint development program with Unidym and incorporates a transparent CNT electrode.

"Our ongoing successful collaboration with Samsung Electronics has delivered yet another world's first achievement this year," said Arthur L. Swift, Unidym's president and CEO. "In May of this year Samsung demonstrated the world's first 2.3 inch black and white active matrix EPD made with carbon nanotubes, and now they have demonstrated the first color large scale EPD e-paper device, in an A4 format."

5.82. University of California Los Angeles (UCLA), USA

UCLA Department of Physics & Astronomy
G. Grüner Nano-Biophysics Group
405 Hilgard Avenue
Los Angeles
CA 90095
United States
(310) 794-6491
www.ucla.edu

George Gruner, professor of physics at the University of California, Los Angeles (UCLA), and Yi Cui, assistant professor of materials science and engineering at Stanford, together led the research for a new extremely cheap printable supercapacitors that incorporates carbon nanotubes.

In November 2009 they presented their printed supercapacitor, following earlier work in 2007 where Gruner produced printable batteries less than a millimetre thick by depositing a layer of nanotubes ink onto the surface. The layer acts as the charge collector, which removes current from the battery. A layer of nanotube ink is then mixed with manganese oxide powder and electrolytes, which carries charge within the cell, and is applied on top acting as the cathode. Finally, a piece of zinc foil is applied, which acts as the anode.

For the printed supercapacitor they used a spraying technique to apply a film of CNTs onto a plastic substrate. Two such films were then used as both the device's electrodes and charge collectors. Between the two films is placed a gel electrolyte made by mixing a water soluble synthetic polymer with phosphoric acid and water.

The printed supercapacitor has a power density of 70 kilowatts per kilogram to allow rapid charging and discharging but improvements in efficiency are still to be made and the team is working on increasing the power output. As both the printed supercapacitors and batteries can be made at room temperature it would be feasible for these to be mass produced according to Gruner.

CNSI at UCLA
UCLA
570 Westwood Plaza
Building 114
Mail Code: 722710
Los Angeles, CA 90095
cnsi411@cnsi.ucla.edu
Tel: (310)267-4838

Fax: (310)267-4918
http://www.cnsi.ucla.edu

Recently, a new method for producing a transparent conductor has been developed by Researchers NanoSystems Institute at UCLA. The hybrid graphene-carbon nanotube material (G-CNT) shows great potential to be a high-performance alternative to ITO e.g. in flexible solar cells.

Yang Yang, a professor of materials science and engineering at UCLA Henry Samueli School of Engineering and Applied Sciences, and Richard Kaner, a UCLA professor of chemistry and biochemistry, developed a new single-step to fabricate G-CNTs in an easy, inexpensive and scalable method. By placing graphite oxide and CNTs in a hydrazine solution a hybrid layer containing both materials can be produced. This method does not require the use of surfactants.

In comparison to ITO G-CNTs retain efficiency when flexed and are compatibly with plastics, which makes it perfectly suitable for flexible solar cells and other flexible consumer electronics.

The California NanoSystems Institute at UCLA (CNSI) is an integrated research center operating jointly at UCLA and UC Santa Barbara whose mission is to foster interdisciplinary collaborations for discoveries in nanosystems and nanotechnology; train the next generation of scientists, educators and technology leaders; and facilitate partnerships with industry, fuelling economic development and the social well-being of California, the United States and the world. The CNSI was established in 2000 with $100 million from the state of California and an additional $250 million in federal research grants and industry funding. At the institute, scientists in the areas of biology, chemistry, biochemistry, physics, mathematics, computational science and engineering are measuring, modifying and manipulating the building blocks of our world — atoms and molecules. These scientists benefit from an integrated laboratory culture enabling them to conduct dynamic research at the nanoscale, leading to significant breakthroughs in the areas of health, energy, the environment and information technology.

At Printed Electronics USA 2009 Prof. Yang Yang presented on the facile synthesis of a nano-composite comprised of chemically converted graphene (CCG) and carbon nanotubes (CNTs). The key feature of this solution-based approach is a counter-ion formation, which stabilizes both components in solution without the use of surfactants. Through both XPS and UV/Vis spectroscopy the researchers observed the preservation of bond integrity and assigned the enhanced electronic properties to π-π interactions. By carefully controlling the nano-scale morphology of such hybrid materials, they are able to deliver high electrical conductivities at low optical densities on rigid and flexible substrates, which are ideal for printed electronics. The conductivity and optical transmittance is comparable to that of indium tin-oxide on flexible substrates. Proof-of-principle was demonstrated in a polymer solar cell. Further material improvement was achieved by chemically doping the Graphene-CNT composites, suggesting that the electrical conductivity can be improved without sacrificing optical transparency.

5.83. University of Cincinnati (UC), USA

2600 Clifton Ave.
Cincinnati
Ohio 45221
Tel. 513-556-6000
http://www.uc.edu

The University of Cincinnati has long been known for its world-record-breaking carbon nanotubes. In March 2009 they discovered new uses by spinning carbon nanotubes (CNTs) into longer fibers with additional useful properties to transmit radio signals. Vesselin Shanov and Mark Schulz from the UC College of Engineering NanoWorld Lab used a 25-micron MWCNT thread and created a dipole antenna using double-sided transparent tape and silver paste, that could successfully be used to transmit radio signals. Additionally, they created a cell phone antenna, using CNT thread and tape.

Schulz explains that the carbon nanotube threads work well as an antenna because of something called the "skin effect": "The electrons transfer well because they want to go to the surface," he says. "Instead of traveling through a bulk mass, they are traveling across a skin." Earlier in 2007 engineering researchers at UC developed a new composite catalyst for the oriented growth of MWCNT arrays and demonstrated world leading long aligned ones.

5.84. University of Michigan, USA

University of Michigan
Ann Arbor, MI 48109
USA
T: 1 734-764-1817
www.umich.edu/

Late in 2008 scientists at the University of Michigan developed a smart fabric that could be used to power a light emitting diode (LED) by dipping cotton fibres into CNT containing water.

"Currently, smart textiles are made primarily of metallic or optical fibers. They're fragile. They're not comfortable. Metal fibers also corrode. There are problems with washing such electronic textiles. We have found a much simpler way - an elegant way - by combining two fibers, one natural and one created by nanotechnology," said Nicholas Kotov, a professor in the departments of Chemical Engineering, Materials Science and Engineering and Biomedical Engineering.

To make these "e-textiles," the researchers dipped 1.5-millimeter thick cotton yarn into a solution of carbon nanotubes in water and then into a solution of a special sticky polymer in ethanol. After being dipped just a few times into both solutions and dried, the yarn was able to conduct enough power from a battery to illuminate a light-emitting diode device.

In order to put this conductivity to use, the researchers added the antibody anti-albumin to the carbon nanotube solution. Anti-albumin reacts with albumin, a protein found in blood. When the researchers exposed their anti-albumin-infused smart yarn to albumin, they found that the conductivity significantly increased. Their new material is more sensitive and selective as well as more simple and durable than other electronic textiles, Kotov said.

"The concept of electrically sensitive clothing made of carbon-nanotube-coated cotton is flexible in implementations and can be adapted for a variety of health monitoring tasks as well as high performance garments," Kotov said.

This research was funded by the National Science Foundation, the Office of Naval Research, the Air Force Office of Scientific Research and the National Natural Science Foundation of China.

Early in 2010 it was reported that Scientists at Michigan University may soon be able to detect the toxin Microcystin-LR quickly and cheaply with the development of a new biosensor, using a strip of paper infused with carbon nanotubes.

Microcystin-LR is a chemical compound produced by cyanobacteria, or blue-green algae found in freshwater reservoirs in places like Northern Thailand, where a high proportion of the population consume untreated surface water. Even in small quantities, Microcystin is suspected of causing liver damage and possibly liver cancer.

The sensor works by measuring the electrical conductivity of the nanotubes in the paper. Before the nanotubes are impregnated in the paper, they are mixed with antibodies for MC-LR. When the paper strips come in contact with water contaminated with MC-LR, those antibodies squeeze in between the nanotubes to bond with the MC-LR. This spreading apart of the nanotubes changes their electrical conductivity.

An external monitor measures the electrical conductivity. The whole device is about the size of a home pregnancy test with results appearing in fewer than 12 minutes. The process is 28 times faster than the complicated method most commonly used today to detect microcystin-LR.

Water treatment plants even in developed countries like the US can't always remove MC-LR completely, nor can they test for it often enough. The biosensor Kotov and his colleagues developed provides a quick, cheap, portable and sensitive test that could allow water treatment plants and individuals to detect multiple toxins, verifying the safety of water on a more regular basis.

The technology could also be adapted to detect a variety of harmful chemicals or toxins in water or food. To adapt the biosensor for other toxins scientists could simply replace the antibodies that bond to the toxin, Nicholas Kotov said, a professor in the departments of Chemical Engineering, Biomedical Engineering and Materials Science and Engineering who led the project.

The research was in collaboration with the laboratory of Professor Chuanlai Xu at Wuxi University in China.

5.85. University of Oklahoma, USA

Carbon Nanotube Technology Center (CaNTeC)
Prof. Daniel E. Resasco
D. and H. Bourne Chair and George Lynn Cross Professor
School of Chemical, Biological and Materials Engineering
University of Oklahoma
100 East Boyd St, Norman, Oklahoma 73019
USA
++1 (405) 325-4370
resasco@ou.edu
http://www.ou.edu/engineering/nanotube/home.html

The Carbon Nanotube Technology Center (CaNTeC) at University of Oklahoma developed a proprietary catalyst method for the production of SWCNTs. The CaNTeC holds 6 key patents on the scalable production process CoMoCat®, with which high-quality SWCNTs with high selectivity and narrow distribution of tube diameters can be created. During this method a CO disproportionation (decomposition into C and carbon dioxide) at 700-950° in flow of pure CO at a total pressure that typically ranges from 1 to 10 atm leads to SWCNTs. This way nanotubes of controlled diameter and chirality can be produced.

Research objectives of the Center regarding carbon nanotubes are the optimization of synthesis, purification, and separation of SWNT, the development of smart SWNT films as well as novel SWNT-metal composites with improved mechanical, thermal, and electrical properties.

The Center is funded by DoE, OCAST (Oklahoma Center for the Advancement of Sci. and Tech.).

The startup company South-West Nanotechnologies (SWeNT) was recently found and uses the CoMoCAT® process with the goal to increase the availability of SWNT.

5.86. University of Pittsburgh, USA

University of Pittsburgh
Department of Chemistry
Chevron Science Center
219 Parkman Avenue
Pittsburgh, PA 15260
T: (412) 624-8200
F: (412) 624-8611
www.pitt.edu/

A team led by chemistry professors Alexander Star and Stéphane Petoud at University of Pittsburgh revealed the development of a highly sensitive, fluorescent oxygen sensor that can detect minute amounts of Oxygen.

The recently developed sensor that consists of carbon nanotubes coated with a luminescent compound incorporating europium, a reactive metal found in fluorescent bulbs, television/computer screens, and lasers, among other applications is able to gauge minute amounts of oxygen by measuring the intensity of its glow when exposed to ultraviolet light and the tubes' change in electrical conductance.

The oxygen sensor combines small-scale carbon nanotubes, with the reactivity of the europium compound coating. This produces a platform for low-cost, room-temperature detectors that are particularly sensitive to oxygen but less complicated than existing sensors.

The new oxygen sensor would be small enough to incorporate into a portable or wearable device which would notify workers or rescuers any change in oxygen levels.

Professor Alexander Star explained how this new technology improves upon the commercial sensors used today because it relies on the electrical conductance of carbon nanotubes (CNTs) decorated with a polymeric material to operate at room temperature without the need for complicated optical equipment. He said, "For example, after brief illumination with a UV light source, which can be quite compact and inexpensive (i.e. an LED), the electrical conductance of the CNT-based sensor devices changes in proportion to the concentration of O2 gas. An added benefit of this approach is that the luminescence of the polymeric material is also sensitive to O2, so one could design a measurement technique that simultaneously monitored the electrical and optical signal of the sensor - providing bimodality to the device and increasing the accuracy of the measurement."

The ability to operate in a wide range of O2 concentrations, i.e. well below 1% to over 20%, will provide more opportunity for adoption of this technology.

5.87. University of Southern California (USC), USA

Viterbi School of Engineering
Ming Hsieh Department of Electrical Engineering
University of Southern California
Ming Hsieh, EEB 100
Los Angeles, CA 90089-2560
USA
Tel:(213)740-4447
Fax:(213) 740-4449
eesystem@usc.edu
http://ee.usc.edu/

In January 2009 researchers from the Viterbi School of Engineering at University of Southern California presented a new flexible and transparent supercapacitor based on In2O3 nanowire/carbon nanotube heterogeneous films.

The group headed by Chongwu Zhou, who holds the Jack Munushiun Early Career Chair at the USC Ming Hsieh Department of Electrical Engineering, used a metal oxide nanowire/CNT heterogeneous film to form the active layer and the current collecting electrodes of the energy storage device. A vacuum filtration method was used to fabricate the CNT films.

Later in 2009 USC researchers demonstrated large functional arrays of CNT transistors using a solution-processing technique at room temperature. This is the first time solution-deposited, purified semiconducting CNTs have been successfully used for high-quality transistors.

During the production process a silicon wafer is put in a chemical bath and coated with a CNT attracting chemical. Immersed in a solution of semiconducting CNTs the result is a wafer coated with a carpet of nanotubes.

The researchers were able to control a simple organic LED display with their four-inch silicon wafer prototype. Significant about the results is that the arrays made from only 95% semiconducting CNTs that aren't aligned still have good enough performance for displays.

As a next step the researchers are planning to eliminate the rigid silicon and replace the stiff metal electrodes.

Earlier in 2008 the researchers not only created printed circuit lattices of CNT based transistors to the transparent plastic but also additionally connected them to commercial gallium nitride (GaN) light-emitting diodes, which change their luminosity by a factor of 1,000 as they are energized.

The thin transparent thin-film transistor technology developed employs CNTs as the active channels for the circuits, controlled by iridium-tin oxide electrodes which function as sources, gates and drains.

Chongwu Zhou of the School's Ming Hsieh Department of Electrical Engineering has been working on transparent electronics for the past three years and reported earlier on prototype devices in which transparent electronics were built on top of a flexible transparent base. He is the principal investigator for both pieces of these reported works.

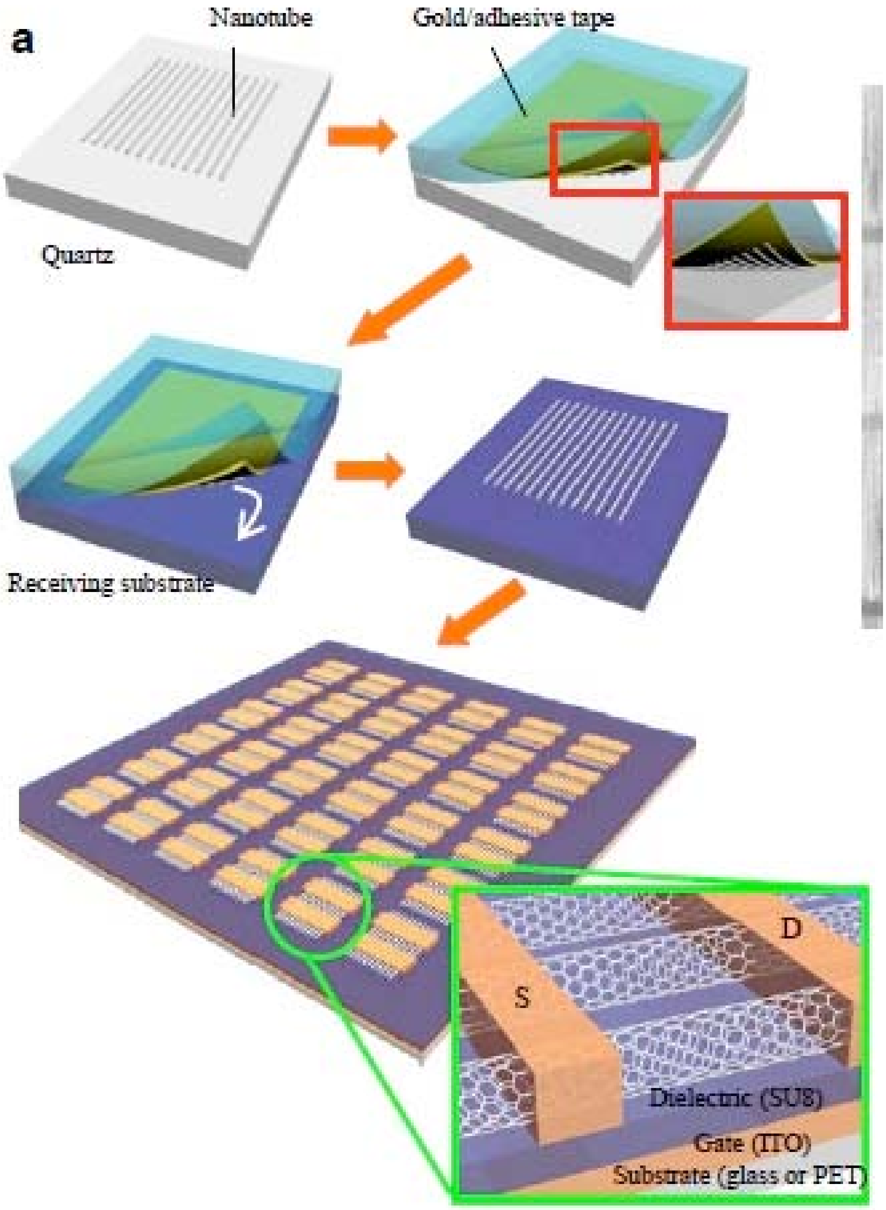
He explained: "Previously we used indium oxide nanowires as the active materials for transparent transistors. In the current paper, our innovation is to use massive aligned nanotubes, and we observed better performance (in terms of higher carrier mobility ~1,300 cm2V-1s-1) than before."

Earlier attempts at transparent devices used other semiconductor materials with disappointing electronic results, enabling one kind of transistor (n-type); but not p-types; both types are needed for most applications.

The critical improvement in performance, according to the research, came from the ability to produce extremely dense, highly patterned lattices of nanotubes, rather than random tangles and clumps of the material.

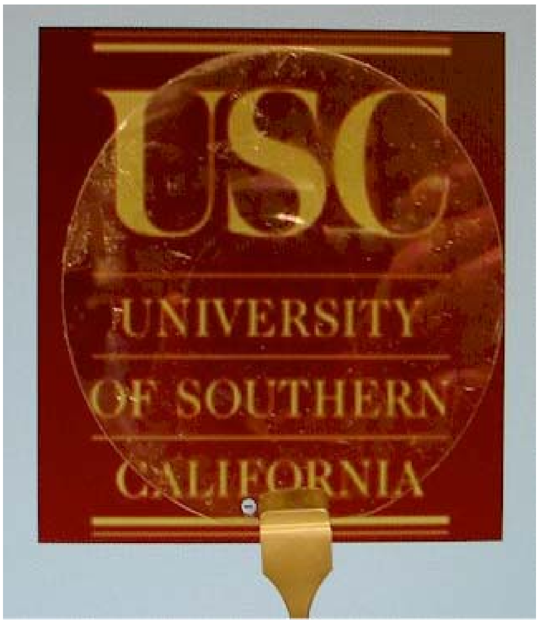
Zhou continued "The devices are made by first growing aligned nanotubes on quartz which are then transferred to transparent glass or polymer substrates with prepatterned gate electrodes, followed by patterning of transparent source and drain electrodes. This way all components of the transistors are transparent to visible light."

Fig. 5.33 **Fabrication steps, leading to regular arrays of single-wall nanotubes (bottom).**



These aligned nanotube transistors are easy to fabricate and integrate, as compared to individual nanotube devices. The transfer printing process allows the devices to be fabricated through low temperature processes, which is important for realizing transparent electronics on flexible substrates.

Fig. 5.34 **The colourless disk with a lattice of more than 20,000 nanotube transistors in front of the USC sign.**



Zhou believes that we may be 5 to 10 years away from mass production of transparent electronics. One barrier is the inertia of old existing technology.

5.88. University of Stanford, USA

Department of Materials Science and Engineering
Stanford University
McCullough Building, Room 343
476 Lomita Mall
Stanford, CA 94305
Phone: 650-723-4613
Fax: 650-725-4034
http://www.stanford.edu/group/cui_group/yicui.html

Yi Cui, assistant professor of materials science and engineering at Stanford, and George Grüner, professor of physics at the University of California Los Angeles (UCLA), together led the research for a new extremely cheap printable supercapacitors that incorporates carbon nanotubes.

The researchers are also studying the potential of CNT paper batteries for energy storage. Therefore they painted off-the-shelf copier paper with carbon nanotube ink and then dipped it in lithium-containing solutions and an electrolyte.

The CNT paper batteries are also capable of releasing the stored energy quickly.

Located between San Francisco and San Jose in the heart of Silicon Valley, Stanford University is recognized as one of the world's leading research and teaching institutions. One of the widely spread research areas at Stanford are CNT-based Macro and Nanoelectronics with projects on the fundamental understanding of molecule-CNT interaction, the development of metallic/semiconducting CNT separation techniques, the fabrication and optimization of large-area film transistors from purified CNTs as well as self-assembly and patterning of CNTs.

Early in 2010 it was reported that a research team at Stanford found that ordinary textiles could be transformed into batteries that hold up to three times more energy than a mobile phone battery. The team used a simple "dipping and drying" procedure, whereby a strip of fabric is coated with a into nanoparticle-infused ink and dehydrated in the oven.

Prof. Yi Cui's team had previously developed paper batteries and supercapacitors using a similar process, but the new energy textiles exhibited some clear advantages over their paper predecessors. With a reported energy density of 20 Watt-hours per kilogram, a piece of eTextile weighing 0.3 kilograms (about an ounce, the approximate weight of a T-shirt) could hold up to three times more energy than a cell phone battery.

"Wearable electronics represent a developing new class of materials... which allow for many applications and designs previously impossible with traditional electronics technologies," said the researchers at Stanford University who are developing the batteries and simple capacitors.

The procedure works for manufacturing batteries or supercapacitors, depending on the contents of the ink - oxide particles such as $LiCoO_2$ for batteries; conductive carbon molecules (single-walled carbon nanotubes, or SWNTs) for supercapacitors. Up to now, the team has only used black ink, but Yi Cui, assistant professor of materials science and engineering at Stanford, said it is possible to produce a range of colors by adding different dyes to the carbon nanotubes.

The lightweight, flexible and porous character of natural and synthetic fibers has proven to be an ideal platform for absorbing conductive ink particles, according to postdoctoral scholar Liangbing Hu, who led the energy textile research. That helps explain why treated textiles make such efficient energy storage devices, he said.

"The whole thing can be stretchable as well, and extend to more than twice its length," Hu explained. "You can wash it, put it in all kinds of solvents - it's very stable."

They have already received interest from some big-name brands in high performance sportswear and suggest that the military are looking at the possibility of integrating energy textiles into its battle array, a move that could considerably lighten a soldier's load.

Aside from enhanced energy storage capacity, eTextiles are remarkably durable and can withstand greater mechanical stress. Potential applications range from health monitoring to moving-display apparel.

5.89. University of Stuttgart, Germany

Chair of Display Technology
Allmandring 3b
70569 Stuttgart
Germany
Phone +49 (0)711 685 -66922
Fax +49 (0)711 685 -66924

At the Chair of Display Technology at University of Stuttgart a high performance carbon nanotube thin film transistors (TFTs) suitable for use in the flexible electronics industry was developed.

In related work on use of transparent CNTs as replacement for the usual thin-film transparent indium tin oxide (ITO) pixel electrodes, Prof. Dr. Ing Norbert Fruehauf at the University of Stuttgart presented a paper in May at SID '08 revealing a working demonstration of a 4-inch diagonal 320 x RGB x 240 a-Si TFT-LCD made in this way. Prepared entirely at the university's facilities, CNTs were deposited by a low-cost spray method. Sheet resistance for electrodes does not need to be so low, but high transmittance is more important. The researchers found purified CNTs prepared by the HiPCO process gave a transmittance up to about 94% for a sheet resistance of 2,000 to 3,000 Ohms/square. Using conventional a-Si TFTs with such electrodes resulted in an on/off ratio of 106 and mobility of 0.4 -0.6 cm2/Vs.

The Chair of Display Technology at University of Stuttgart, Germany is well known as one of the leading Research Laboratories in the field of application oriented technology development of all kinds of flat panel display devices. It maintains a clean room laboratory with a footprint of more than 480m² with cleanroom class 10-100 equipped with thin film technology for the development and fabrication of active matrix liquid crystal and OLED displays on up to 400mm x 400mm substrates. The laboratory has more than 17 years of experience in prototyping various kinds of flat panel display technologies including passive and active matrix LCDs and OLEDs on rigid and flexible substrates.

5.90. University of Surrey, UK

Advanced Technology Institute
University of Surrey
Guildford
Surrey
GU2 7XH
United Kingdom
+44 (0)1483 300800
www.ati.surrey.ac.uk

In early 2008 researchers at the Advanced Technology Institute of the University of Surrey, UK, in collaboration with researchers from China and the USA, have demonstrated a 100-fold increase in the light emission from a nylon polymer sample, by incorporating multi-walled carbon nanotubes (MWCNT). This increase in light-emission only occurred when they acid treated the MWCNT prior to inclusion in the polymer. This increase is due to a novel energy transfer mechanism, from the acid-damaged surface of the MWCNT to the emitting sites in the polymer. In addition to the enhanced light-emission, the study also demonstrates that the MWCNT produced an improvement in the stability of the polymer to light-induced degradation.

The lifetime of optoelectronic devices can be improved by incorporating carbon nanotubes in the polymer to form a composite. However, the presence of the CNTs reduces the emission from the composite, due to quenching of charge carriers at the nanotubes, which are generally metallic in nature for multi-walled CNT. This quenching reduces the emission efficiency of the devices.

The Advanced Technology Institute is an interdisciplinary research centre dedicated to advancing next-generation electronic and photonic device technologies. Research activity in the ATI spans the fields of: solid-state electronics advanced silicon-based devices microwave devices and circuits large area electronics, including solar cells and displays nanoelectronics, including carbon nanotubes optoelectronics and photonics compound semiconductor optoelectronic devices and materials silicon photonics ultrafast dynamics and spintronics optical sensors ion beam technology ultra-precise implantation materials modification ion beam analysis, including forensics bio-medical applications theoretical and computational modelling computational quantum electronics atomistic modelling collaborative research in biosensors, food science, etc.

Currently, the institute has collaborative projects with Universities of Cambridge and Sussex as part of the EPSRC funded Carbon Based Electronics Project as well as Trinity College Dublin and other overseas universities. Industrial partners who have supported our work in LAE have included Philips, British Aerospace, Matsushita, GPS and MultiArc.

5.91. University of Texas at Austin, USA

Nanoscience and Technology Lab
204. E Dean Keeton
The University of Texas at Austin
Mechanical Engineering Building 1.224A
Austin, TX 78712
http://bucky-central.me.utexas.edu/
r.ruoff@mail.utexas.edu

Last year the Ruoff Group at University of Texas at Austin under mechanical engineering professor Rod Ruoff has achieved a breakthrough in ultracapacitors by using graphene. Ruoff says, "Graphene's surface area of 2630 m2/gram means that a greater number of positive or negative ions in the electrolyte can form a layer on the graphene sheets resulting in exceptional levels of stored charge."

The built devices have shown storage abilities similar to those of ultracapacitors already on the market, and they believe graphene's ultra thin structure will allow for sheets of the material to be stacked to increase energy storage and possibly double the current capacity of ultracapacitors. This would allow ultracapacitors to expand into many other renewable and clean energy applications for both solar power and wind farms.

5.92. University of Tokyo, Japan

University of Tokyo
Department of Electrical Engineering
School of Engineering
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
Phone: +81-3-5841-6828
Fax: +81-3-5841-6828
http://www.ntech.t.u-tokyo.ac.jp

The Department of electrical Engineering at University of Tokyo is doing research on combining CNTs and a stretchy polymer to make a flexible conductive material. The researchers developed a process for making long CNTs on industrial scale.

After presenting an elastic conductor based on a mixture of carbon nanotubes and rubber they developed a stretchable display using this rubbery conductor with improved properties. Besides the facts that the material can be stretched to more than twice its original sizes, it can be printed. The researchers used a printing mask to deposit 100-micrometer wide lines, which were then used as wire grid to connect OTFTs and OLEDs.

The University of Tokyo has worked on organic transistors for many years, including the integration of sensors into printed transistors.

5.93. University of Wisconsin-Madison, USA

Materials Science and Engineering Department
University of Wisconsin-Madison
276 Materials Science and Engineering Building
1509 University Avenue
Madison, WI 53706-1595

T: 608/262-3732
F: 608/262-8353
www.engr.wisc.edu/mse

University of Wisconsin-Madison researchers are studying how to create inexpensive, efficient solar cells from carbon nanotubes. While many researchers are studying how to use nanotubes for mechanical and electronics applications, Materials Science and Engineering Assistant Professor Michael Arnold is one of the first to apply them to solar energy.

"We are developing new materials and methods to create scalable, inexpensive, stable and efficient photovoltaic solar cell technologies," Arnold says. "Semiconducting carbon nanotubes have remarkable electronic and optical properties that are ideally suited for photovoltaics, so they are an interesting starting point."

Carbon is a promising choice for solar cells because it is an abundant, inexpensive element, and carbon nanotubes have excellent electrical conductivity and strong optical absorptivity. Most current solar cells use silicon, which converts 10 to 30 percent of sunlight absorbed into electricity. This is a good rate, but silicon cells are expensive.

"The cost is upfront for silicon cells, and the cost per kilowatt-hour is five times more than you'd pay for coal over 20 years — that's not very motivating for people," says Arnold. With carbon nanotubes, he hopes to achieve efficiency comparable to silicon solar cells for less cost.

To create the new carbon nanotube solar cells, Arnold and his students grow nanotube structures and then separate the useful semiconducting nanotubes from undesirable metallic ones. They also separate the tubes according to diameter, which determines a particular nanotube's bandgap, or wavelength of light the tube can absorb. Certain bandgaps are more suitable than others for absorbing sunlight.

After sorting out the useful nanotubes, the team wraps them in a semiconducting polymer to make the tubes soluble. They turn the combined nanotubes and polymer into a solution, which can be sprayed in a thin film onto transparent indium-tin-oxide coated glass substrates. The researchers then deposit an electron-accepting semiconductor and a negative electrode on top of the nanotubes to complete the entire cell.

The research is funded by the National Science Foundation.

5.94. Vorbeck Materials Corp, USA

8306 Patuxent Range Road
Unit 112 ·
Jessup MD 20794
tel 301.497.9000
fax 301.362.4709
http://www.vorbeck.com

Vorbeck Materials supplying several types of Graphene ink enables the use of this extraordinary material for printed electronics. At Printed Electronics Europe 2009 Dr John S. Lettow, President, delivered a highly interesting talk about the several conductive Vor-Inks available in ton scale for inkjet, screen, gravure and spray printing. The eco-friendly formulations show repeatable quality, high conductivity, excellent flexibility and form robust films, that don't need to be sintered, on a wide range of substrates.

Performance: 1 Ω/sq resistivity @ 1 mil, ~ 300 S/cm @ 1-5 µm, abrasion resistance: 2-3H, rub resistance: 5-8% loss after 10 rubs, flex resistance: 13-15% loss after 100 flexes. These conductive materials can potentially be used for flexible backplanes for displays and photovoltaic's as well as for UHF, capacitive RFID, interconnects, antennae, and smart packaging.

Vorbeck Materials uses scalable process for manufacturing graphene in ton quantities. This core technology to make single-sheet graphene by chemical exfoliation was developed at Princeton University.

A pilot plant was commissioned in October 2007 with a 4-ton rated capacity of the proprietary Vor-x™ graphene material. The produced graphene powder is used to supply the application development efforts of the company's partners as well as the development of the own conductive Vor-ink™. Currently, the company is only selling samples (multiple kilograms) to evaluate the performance in printed electronics applications. However, a commercial phase of customers' applications is expected for end of the year. Correspondingly, Vorbeck is planning to scale up the production to ton scale in the next 3 to 7 years.

Vorbeck recently introduced its screen and gravure forms of Vor-ink. Customers are currently engaged in product trials with these to assess performance on their specific substrates to meet their specific application needs. As reaction to the recognized interest in inks for flexographic and inkjet printing, new materials are already under development. Moving closer to product trials with key customers, the availability of new inks for flexographic and inkjet printing is expected for end of 2009.

All conductive Vor-inks™ are sinter-free and aqueous or based on other organic, environmentally friendly solvents. Suitable curing temperatures are 80 to 120°C, which meets standard graphic ink curing conditions. The material is taking advantage of the high surface area of Vor-x™ graphene, which is around 1700sqm/g, the sheet-like structure and the inherent conductivity. Vor-ink™ films maintain rated resistivity in very thin coatings and after repeated, rigorous flexing.

The strengths of Vor-ink™ are conductivity, flexibility, and printability. Although, the material is not as conductive as commercial available silver-based inks, it is to a certain amount cheaper, which makes it highly lucrative where lower conductivities are needed.

Vorbeck uses own lab scale printing facilities to test its materials, but is also working with commercial printers. In several trials, for example with RFID partners, the properties are evaluated.

Vorbeck Materials Corp. is a global technology company established in 2006 in Jessup, Maryland USA to manufacture and develop applications using Vor-x™, Vorbeck's novel graphene material.

At the end of 2008 the company established a joint research program together with BASF to develop composites based on graphene. The target of the program are graphene dispersions for electrically conductive coatings with first products planned for 2009.

End of July 2009 Vorbeck Materials Corp. announced that it has secured $5.1 million in a Series 2 financing led by Stoneham Partners, a private investment firm, with contributions from the Maryland Department for Business and Economic Development and a syndicate of individual investors. The company will use the capital to expand development of its Vor-x™ graphene and Vor-ink™ conductive inks for printed electronics applications.

In association with the financing, Vorbeck has named two new members to its Board of Directors. Joining the existing board are the honorable Kristen L. Silverberg, former U.S. Ambassador to the European Union and former U.S. Assistant Secretary of State, and Dr. Robert G. Hirsch, former Global Managing Director for DuPont's Intellectual Assets Business and Corporate New Ventures and manager of five global businesses for DuPont.

Early in December 2009 Vorbeck announced the EPA approval to manufacture graphene as a conductive additive for inks. This makes Vor-ink™ is the first commercially available, EPA-approved graphene product in the U.S. market.

5.95. Wisepower Co., Ltd., Korea

Wisepower Co., Ldt.
5F, Ace Techno Tower 55-7
Munraedong 3-Ga Yeongdeungpo-Gu
Seoul, 150-992
South Korea

T: +82-31-4822060
F: +82-31-2919640
www.wisepower.co.kr/

Wisepower, a publicly traded Korean company, is a leading supplier of Li-polymer batteries for mobile appliances in Republic of Korea. Its customers include cellular phone manufacturers such as LG Electronics, Pantech, and KTFT. Wisepower has recently developed high quality LED packages and solid-state lighting. The company's products also include wireless charging system for electronic applications.

Early in February 2010 it was announced that Wisepower and Unidym signed a definitive agreement to create the joint venture Unidym Korea, to market and co-develop Unidym's proprietary film and electronic ink products into the Korean touch panel and display industries.

"We look forward to working with Unidym to expand this business in Korea. Furthermore, we intend to explore the possible applications of CNTs in the areas of LEDs and rechargeable batteries. This cooperation with Unidym will enable Wisepower to use new materials such as CNTs to enhance its rechargeable batteries and LED product position in the market," said Gi Ho Park, CEO of Wisepower.

On July 28, 2009, the Company completed the merger with CYLUX CO.,LTD. Through the merger, the Company is also engaged in light emitting diode (LED) business. The Company acquired a 85.00% stake in GrandTech Co., Ltd., a Korea-based manufacturer of light emitting diode (LED) lighting GaN substrates and semiconductor gas line facilities, on July 31, 2009. The Company completed the spin-off of its PDP power supply business, effective August 18, 2009.

5.96. XG Sciences, USA

XG Sciences, Inc.
5020 Northwind Drive
Suite 212
East Lansing, MI 48823
Phone: 517-203-1110
Fax: 517-203-4140
http://www.xgsciences.com

XG Sciences is using a proprietary process to manufacture their xGnP™ graphite nanoplatelets with a variable diameter of 5 to 25 micron and various surface treatments. Supplied as dry powder can be used for applications like batteries and fuel cells.

The used know-how was mainly comes from the Composite Materials and Structures Center in the Michigan State University College of Engineering (MSU), where many XG Science patents are licensed.

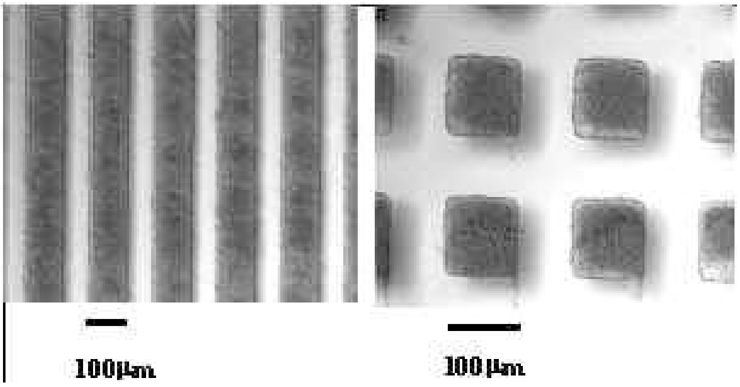
5.97. Xintek Nanotechnology Innovations, USA

7020 Kit Creek Road Suite 200
PO Box 13788
Research Triangle Park
NC 27709
Tel: 919-313-9638
Fax: 919-313-9639
http://www.xintek.com

Xintek Nanotechnology Innovations produces CNTs with a proprietary CVD process and develops and manufactures nanotechnology-enabled products including CNT-based field emission electron sources, field emission grade CNT materials, field emission x-ray sources and CNT AFM probes. The company has over 40 issued and pending U.S. patents obtained through licensing agreements with the University of North Carolina at Chapel Hill (UNC) and Duke University, as well as from in-house R&D. Xintek's high-quality CNTs can be produced with a purity of up to >90%.

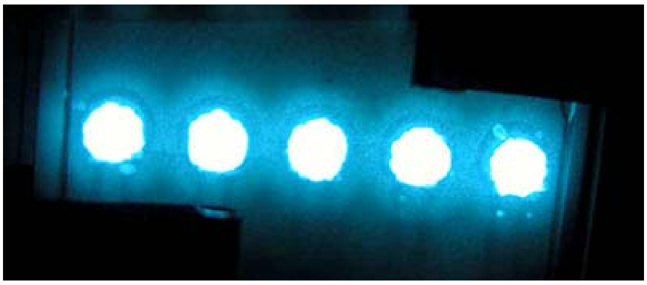
For fabricating patterned CNT films Xintek also developed a proprietary thin film deposition technologies, which offers several advantages ranging from room temperature deposition, rigid control over the film thickness (0.5um < d < 50 um) to excellent field emission properties of the deposited CNT films. Various substrates can be used including glass, silicon and metal substrates, and the pattern is variable with a thickness from sub-micron to 50 micron.

Fig. 5.35 **Optical microscope image of Xintek's CNT films**



Source Xintek

Fig. 5.36 **A field emission image of an array of CNT dots of 2mm in diameter (1.55V/µm)**



Source Xintek

5.98. Y-Carbon

900 First Ave
Building 4, Suite 242
King of Prussia, PA 19406
E-mail: info@Y-Carbon.us
Phone: 610 878 6226
http://www.y-carbon.us/

Y-Carbon is a nanotechnology start-up company based in King of Prussia, PA. As a spin off from the A.J. Drexel Nanotechnology Institute, Drexel University, Philadelphia, PA, Y-Carbon has obtained exclusive rights to intellectual property invented and patented by Prof. Gogotsi's team of Drexel University. Y-Carbon's core mission is to develop and promote an innovative method of making novel nanostructured carbon materials with precisely defined structure, porosity, and surface chemistry. The ability to tailor the properties of porous carbon material is unique to Y-Carbon technology and thus provides a quantum leap in performance in many applications such as supercapacitors, gas (hydrogen, methane and chlorine) storage, protein filtration, water purification, fuel cell catalysts, etc. These applications have enormous business opportunities in the fields of energy, water and medicine. Y-Carbon is a portfolio company of the Pennsylvania NanoMaterials Commercialization Center, Ben Franklin Technology Partners of SouthEastern Pennsylvania and The Nanotechnology Institute

5.99. Zoz GmbH, Germany

Zoz Group
Maltoz-Strasse
D-57482 Wenden-Huensborn
T: 49 2762 9756-0
F: 49 2762 9756-7
www.zoz.de

Zoz GmbH, headquartered in Wenden, Germany, is a global supplier of innovative systems and equipment, in particular for the manufacture of nanostructured materials. The company has extensive experience in areas such as the high-energy grinding and mechanical alloying of these materials.

Zoz GmbH is working with Bayer MaterialScience on the development of customized CNT-reinforced aluminium materials with a planned a production capacity of several hundred to thousand tons per year.

5.100. Zyvex, Inc., USA

Zyvex Instruments
1321 North Plano Road
Richardson, Texas 75081-2426
info@zyvex.com
214.566.5234
F: 972.235.7882
http://www.zyvex.com/

Zyvex Inc., a provider of nanotechnology solutions, is focusing on the development and implementation of CNT dispersions and needed technology. The company developed a functionalization method that improves the dispersion and adhesion qualities to solvents by bridging functional groups onto the carbon nanotubes.

6. Network Profiles

6.1. CONTACT

http://www.contactproject.eu

CONTACT, a new research and training project funded by the European Commission's "Marie Curie" programme, involves 10 partner organisations from 7 different countries. Coordinated by the German Fraunhofer ICT (Institute for Chemical Technology), the main objective is to carry out research and development on nanomaterials and processes, characterisation methods, simulation tools and of course the implementation of the materials in real world applications including rotor blades for wind power plants and energy storage materials for e-mobility applications.

The research aim of CONTACT is the tailored industrial supply-chain development of CNT-filled polymer composites with improved mechanical and electrical properties. This will involve the optimisation of CNT synthesis and dispersion, and the processing of CNT compounds, as well as the modelling and characterisation of CNT and CNT composites. The new technologies will be upscaled for applications in four industrial case studies: construction, wind blades, electrically conducting parts and electrodes for redox-flow batteries.

Contact partners:

- Fraunhofer Institute for Chemical Technology (ICT), Germany
- University of Oxford, UK
- Bayer Technology Services GmbH, Germany
- Polymaterials AG, Germany
  Acciona Infraestructuras S.A., Spain
- Amroy Europe OY, Finland
- Asociacion de Investigacion de Materiales Plasticos y Conexay – AIMPLAS, Spain
- I3N – Institute for Nanostructures, Nanomodelling and Nanofabrication, Portugal
- Research Institute for Technical Physics and Materials Science – MFA, Hungary
- Promolding BV, Netherlands

Associated partners:

- Tampere University of Technology, Finland
- Wilhelm Eisenhuth GmbH KG, Germany
- Eagle Wind Oy, Findland

6.2. Inno.CNT

www.cnt-initiative.de/en/

The Innovation Alliance Carbon Nanotubes (Inno.CNT) is a research alliance involving around 80 partners from science and industry. Inno.CNT is part of the German government's high-tech strategy and is supported by the German Federal Ministry for Education and Research under its "Materials Innovations for Industry and Society" program.

The initiative comprises 18 coordinated projects. Three of them are involved with crossover technologies and aim to develop solutions for the production, functionalization and dispersion of carbon nanotubes:

- CarboScale: Cost-effective production of various grades of CNTs on an industrial scale
- CarboFunk: Develop processes for functionalizing CNT surfaces
- CarboDis: Develop tailor-made dispersion technologies for thermosetting, thermoplastic and elastomeric systems

The projects in the field of energy & environment are concentrated on specific applications of energy conversion, energy storage and energy saving.

- CarboPower: Substitute classical conductive carbon black by CNTs as the electrically conductive material
- CarboInk: Develop innovative inks that can enhance the construction of solar cells
-
- Partners (all in Germany):
  altropol Kunststoff GmbH
- BAM Bundesanstalt für Materialforschung und -prüfung
- BASF SE
- Bayer MaterialScience AG
- Bayer Technology Services GmbH
- Bond-Laminates GmbH
- Büsing & Fasch GmbH & Co. KG
- BYK-Chemie GmbH
- Canyon Bicycles GmbH
- Clariant Masterbatches (Deutschland) GmbH
- Coperion GmbH

- Deutsches Institut für Kautschuktechnologie e. V.
- Deutsches Zentrum für Luft- und Raumfahrt e. V.
- Dyckerhoff AG
- EADS Astrium GmbH
- EADS Deutschland GmbH
- Ehrfeld Mikrotechnik BTS GmbH
- Evonik Degussa GmbH
- EVT Gesellschaft für Energieverfahrenstechnik mbH
- EXAKT Apparatebau GmbH & Co. KG
- Forschungszentrum Jülich GmbH
- Fr. Fassmer GmbH & Co. KG
- Fraunhofer-Institut für Chemische Technologie ICT
- Fraunhofer-Institut für Fertigungstechnik und Angewandte Materialforschung IFAM
- Fraunhofer-Institut für Werkstoff- und Strahltechnik IWS
- Fraunhofer-Center für Windenergie und Meerestechnik CWMT
- Fraunhofer-Pilotanlagenzentrum für Polymersynthese und -verarbeitung PAZ
- Freudenberg Forschungsdienste KG
- Friedrich-Alexander-Universität
- Erlangen-Nürnberg
- Future Carbon GmbH
- Gala Kunststoff- und Kautschukmaschinen GmbH
- Georg-Simon-Ohm Hochschule Nürnberg
- Gerodur MPM Kunststoffverarbeitung GmbH & Co KG
- GKSS – Forschungszentrum Geesthacht GmbH
- H.C. Starck GmbH
- Halberg Guss Management GmbH
- HPS GmbH
- Ingenieurbüro TARTLER GmbH
- Institut für Energie- und Umwelttechnik e. V.
- Institut für Verbundwerkstoffe GmbH
- INVENT GmbH
- Jackon GmbH
- Jacob Composite GmbH
- Kunststoff-Technik Scherer & Trier GmbH & Co KG
- Leibniz-Institut für Festkörper- und Werkstoffforschung Dresden e. V.
- Leibniz-Institut für Polymerforschung Dresden e. V.
- LiEtec Licht- & Energietechnik GmbH
- Max-Planck-Gesellschaft zur Förderung der Wissenschaften e. V.
- Mayr Faserverbundtechnik GmbH
- Nexans Deutschland Industries GmbH & Co. KG
- PEAK Werkstoff GmbH
- Putsch GmbH & Co. KG
- Q-Cells SE

- qtec
- Kunststofftechnik GmbH
- Rhein Chemie Rheinau GmbH
- Rheinisch-Westfälische Technische Hochschule Aachen
- RUCH NOVAPLAST GmbH + Co. KG
- Ruhr-Universität Bochum
- SAERTEX GmbH & Co. KG
- Schuberth Engineering AG
- SGL Carbon GmbH
- SGL TECHNOLOGIES GmbH
- Siemens AG
- Sto AG
- T. Michel Formenbau GmbH & Co. KG
- Technische Universität Chemnitz
- Technische Universität Clausthal
- Technische Universität Dresden
- Technische Universität Hamburg-Harburg
- Technische Universität Ilmenau
- Universität Duisburg-Essen
- Universität Siegen
- VARTA Microbattery GmbH
- Weidmüller Interface GmbH & Co KG
- xperion AEROSPACE GmbH
- xperion FS Composites GmbH & Co. KG
- Zentrum für BrennstoffzellenTechnik ZBT GmbH
- Zentrum für Sonnenenergie- und Wasserstoff-Forschung

6.3. National Technology Research Association (NTRA)

70 partners led by LG Electronics

7. Forecasts and Costs

7.1. Market Opportunity and roadmap for Carbon Nanotubes and Graphene

Graphene and MWCNTs are already in fairly high production – tens of tonnes per year. Estimates of the amount of MWCNTs produced in 2008 are about 100 tons in total from companies such as Bayer and Showa Denko. In 2009 the amount delivered could double. However, most of these uses are for non electronic/electrical products, or simple applications such as electromagnetic shielding.

The commercialization of SWCNTs, relevant to all the electronics described in this report, is still in its infancy. Of note, Eikos, Uniydym and Canatu are trying to scale up manufacturing, but we doubt that the others, such as NEC and Bayer, are not moving towards this goal either. The challenge, described in greater detail in this report, are mainly producing a high yield of SWCNT with a small variation in size in a cost effective, scalable manner. This is the bigger issue rather than processing the materials to make devices. While there is capacity in place this year to make tens of tons of SWCNTs, these have a wide range of purity, but for some applications have now reached a tipping point

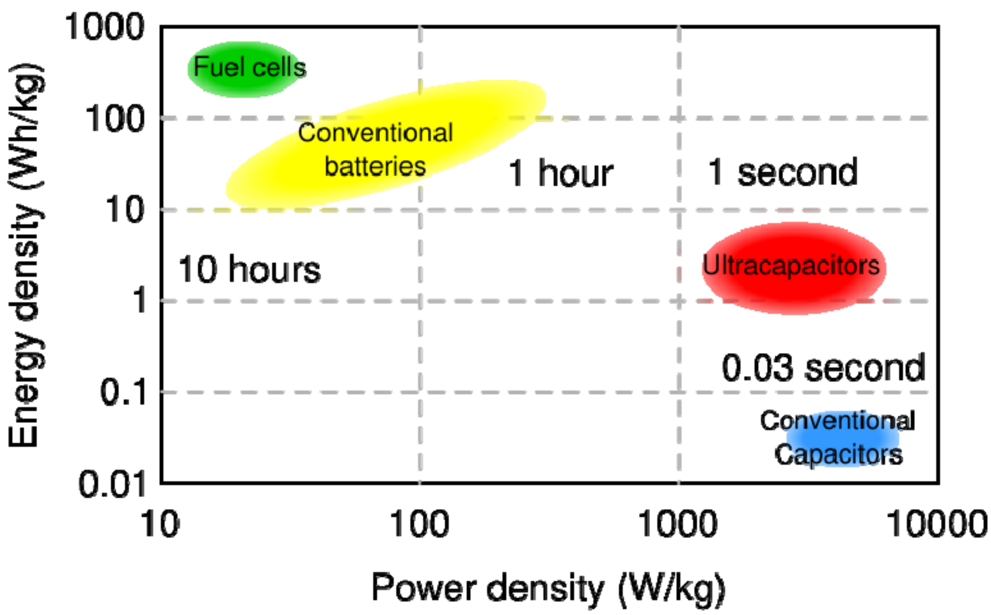
Conductive films will come first

In electronics, other than electromagnetic shielding, one of the first applications for CNTs will be transparent conductors. Here, applications are for displays, replacing ITO, touch screens, photovoltaics and display bus bars, connecting TFTs to the front plane, such as OLEDs. Canatu, a supplier of such films, told IDTechEx, "We will be selling homogeneous and prepatterned films in various conductivities, transparencies, patterning and fractional coverage. We will begin by supplying selected strategic partners with specialty films made to their specifications. In so called "equivalent square meters" (equivalent to 80% transparency, homogeneous film), we plan to be selling approximately 1000 m2 in 2010, 15000 m2 in 2011, 40000 m2 in 2012, 100000 m2 in 2013, and 300000 m2 in 2014." This is a strong growth – 300% over five years.

Supercapacitors

Supercapacitors are bridging the gap between batteries and capacitors, as shown below.

Fig. 7.1 **Supercapacitors**



Graphene, carbon nanotubes and certain conductive polymers, or carbon aerogels, are practical for supercapacitors. These are already in use today in a wide range of applications, from wireless sensors to portable consumer electronic devices.

Transistors, loudspeakers to follow

While several organizations have demonstrated CNTs for transistors, as covered in this report, it will take time before these are commercialized. Conservatively, IDTechEx anticipate this may be available in volume from 2015 onwards or more optimistically it could be 2 years earlier. Challenges are material purity, device fabrication, and the need for other device materials such as suitable dielectrics. However, the opportunity is large, given the high performance, flexibility, transparency and printability.

The following table and figure show the total market size by component type for printed and potentially printed electronics from 2009 to 2029. There are applications for CNTs and graphene beyond this application area but this represents the biggest opportunity for the materials – i.e. flexible circuits.

CNTs and graphene are part of the ink values shown, and will make an increasing impact in logic, displays and photovoltaics. The market values shown are for the individual components only, such as the front plane of displays, discrete batteries etc. For some sectors, the market will be higher depending on the application. For example, Plastic Logic is intending to make complete e-book readers or e-book reader modules using an organic printed transistor drive circuit for an electrophoretic display. The figures shown attribute the cost of the transistor drive circuit to logic and the electrophoretic display module to the electrophoretic line. However, the end product will combine conventional electronics and electrics too and could be sold for a premium price, as the Apple iPod has been. As another example, our forecasts below include the cost of the OLED display module in a cellphone but not the entire cost of the cellphone which would distort the forecast. The World's largest maker of e-paper technology, E-ink, will have about $75 million revenue this year for their front plane material, which we give below, but the value of the products that use the technology is much higher – to date their displays have been used in over $1 billion worth of products.

While speculative, we give a forecast for 2029 to give an indication of the opportunity of these technologies. It will eventually be larger than the silicon semiconductor industry, which is not a surprise given that it is applicable to so many more things – from lighting to displays.

Table 7.1 **Market forecast by component type for 2010 to 2020 in US $ billions, for printed and potentially printed electronics including organic, inorganic and composites**

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Logic/memory	0.01	0.02	0.04	0.07	0.15	0.35	1	1.8	3	4	7
OLED display ~	0.8	0.9	1.1	1.5	2.2	4.2	6	7.8	9.1	11.4	17
OLED light *	0.01	0.03	0.08	0.16	0.28	0.41	0.67	0.91	1.4	1.8	2
Electrophoretic *	0.12	0.18	0.4	0.68	1	1.4	2	3	4	5	6
Electrochromic *	0.002	0.002	0.003	0.004	0.006	0.01	0.02	0.03	0.045	0.07	0.1
Electroluminescent *	0.09	0.11	0.16	0.22	0.24	0.26	0.3	0.35	0.4	0.4	0.4
Other display (electrowetting, thin film LED, Flexible LCD etc) *	0.015	0.02	0.06	0.08	0.12	0.2	0.35	0.5	0.6	0.8	1
Battery	0.015	0.015	0.02	0.03	0.05	0.08	0.13	0.17	0.34	0.56	0.7
Photovoltaics #	0.4	0.707	1.211	2.016	3.03	4.57	6.31	8.15	11.29	15.2	17
Sensors	0.12	0.15	0.2	0.25	0.35	0.5	0.9	1.1	1.3	1.5	1.6
Conductors (ink only) ^	0.4	0.42	0.48	0.65	0.9	1	1.2	1.4	1.6	2	2
Other	0.01	0.01	0.03	0.05	0.08	0.12	0.18	0.2	0.24	0.3	0.3
Total ($ billion)	1.99	2.56	3.78	5.71	8.41	13.10	19.06	25.41	33.32	43.03	55.10

^ Excludes ESD/RF shielding

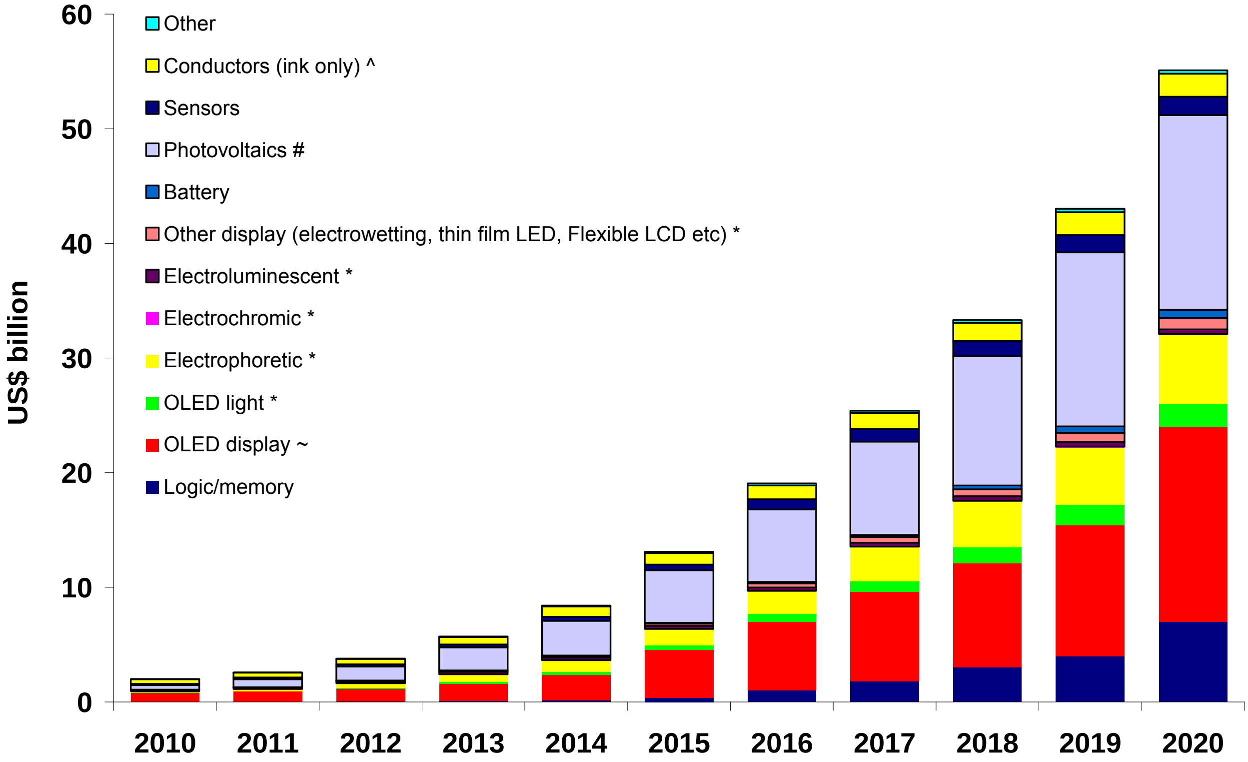
* Front plane only

~ OLED modules (includes Thin Film Transistor TFT drive circuit and OLED front plane)

Includes all thin film photovoltaics but excludes CdTe and conventional crystalline silicon types e.g. crystalline or amorphous silicon

Source IDTechEx

Fig. 7.2 **Market forecast by component type for 2010 to 2020 in US $ billions, for printed and potentially printed electronics including organic, inorganic and composites**



Source IDTechEx

7.2. Costs of SWCNTs

Being a relatively new technology, carbon nanotube are relatively expensive. Some of the purest forms of carbon nanotubes cost $500 per gram and some observers have likened the cost of nanotube production plants to that of silicon foundries. In mid 2009, prices of different SWCNTs from several different companies were obtained by IDTechEx.

These are shown below.

Table 7.2 **Costs of SWeNTs**

SWeNT	
Cost/Gram	Quantity
$500	1-99 grams
$200	100-999 grams
$50	kilogram and up

SWeNT¨ SG # ›90% of tubes are semiconducting	
Cost/Gram	Quantity
$500	1–99 grams
$400	100 grams and up

Table 7.3 **SES Research**

	(long) L-Purified Single Wall Nanotubes Outer dia.: ‹2nm, Length: 5-15µm Purity: ≥ ›90%CNT~ ›50% SWNT* Ash: ≤ 2% wt., Amorphous carbon: ‹5% wt.	
Catalog #	L-Purified Single-Wall Nanotube	Price ($U.S.)
900-1301-250MG	L-Purified SWNT, Length 5-15um, 250mg	$100.00
900-1301-1G	L-Purified SWNT, Length 5-15um, 1 gram	$230.00
900-1301-5G	L-Purified SWNT, Length 5-15um, 5 gram	$875.00

	(short) S-Purified Single Wall Nanotubes Outer dia.: ‹2nm, Length: 1-5µm, Purity: › ›90%CNT~ ›50% SWNT* Ash: ‹ 2% wt., Amorphous carbon: ‹5% wt.	
Catalog #	S-Purified Single-Wall Nanotube	Price ($U.S.)
900-1351-250MG	S-Purified SWNT, Length 1-5um, 250mg	$125.00
900-1351-1G	S-Purified SWNT, Length 1-5um, 1 gram	$250.00
900-1351-5G	S-Purified SWNT, Length 1-5um, 5 gram	$995.00

Source SES Research

Table 7.4 **Nanothinx S.A. (price per gram in Euros)**

Product Ref.	Product Type	Purity	1g ≤ Order ≤ 5g	5g ‹ Order ≤ 10g
NTX8	Raw SWNT	60-65%	55	50
NTX9	Purified SWNT	›85%	85	80
NTX10	NTX8 with COOH functional groups	60-65%	105	95
NTX11	NTX9 with COOH functional groups	›85%	125	110

Source Nanothinx

Table 7.5 **Nanocs**

Product	Quantity	USD
High purity SWNTs	<1 g	350.00/g
	1~5 g	250.00/g
SWNT-COOH	200 mg	200
SWNT-NH2	100 mg	180
SWNT-PEG	100 mg	200
SWNT-SH	100 mg	250
Free Standing SWNTs	5 (10 mm x 10 mm)	250

Table 7.6 **Arry International Group**

Prices	
SWCNTs (60%, 1-2nm)	49 Euro/1g, 219 Euro/5g, 389 Euro/10g, 799 Euro/25g
High purity SWNTs (90%, 1-2 nm)	99 Euro/1g, 419 Euro/5g, 699 Euro/10g, 1199 Euro/20g
Functionalized SWCNTs (-OH; -COOH)	199 Euro/1g, 899 Euro/5g, 1609 Euro/10g, 2899 Euro/20g

Source Arry International Group

Table 7.7 **Carbon Solutions**

PRODUCT	DESCRIPTION	CARBONACEOUS PURITY*	METAL CONTENT wt% from TGA in air	PRICE***	MINIMUM ORDER
AP-SWNT	As prepared	40-60%	30	$50/g	2 grams
P2-SWNT	Purified, low functionality	>90%	4-7	$400/g	0.5 grams
P3-SWNT	Purified, high functionality	>90%	5-8	$400/g	0.5 grams
P5-SWNT	Organic soluble (functionalized with ODA)	>80%** (60-70% SWNT loading)	2-4	$150/100mg	0.1 grams
P7-SWNT	Water soluble (functionalized with PEG)	>80%** (75-85% SWNT loading)	4-5	$150/100mg	0.1 grams
P8-SWNT	Water soluble (functionalized with PABS)	>80%** (30-45% SWNT loading)	2-3	$150/100mg	0.1 grams
P9-SWNT	Amide functionalized SWNTs	>80%**	5-8	$150/100mg	0.1 grams

* Determined according to the procedure described in NanoLett, 2003, 3, 309-314and NIST Recommended Practice Guide "Measurement Issues in Single Wall Carbon Nanotubes": http://www.nist.gov/public_affairs/practiceguides/NIST%20SP960-19.pdf

** Relative carbonaceous purity of the SWNT material used for the functionalizaion.

*** Prices subject to change without notice.

Source Carbon Solutions

Table 7.8 **Carbolex**

Quantity as-prepared SWCNTs	Price
More than 100 grams	$60/g
Less than 50 grams	$80/g
50-100 grams	$100/g

Source Carbolex

Table 7.9 **Cheaptubes**

Quantity – Single Layer Graphene Oxide	Prices
‹1 gram	$2,250 per 100 mgs
1-9 grams	$6,000 per gram
10-99 grams	$2,000 per gram
›100 grams	$500 per gram
›200 grams	$450 per gram
›500 grams	$400 per gram
›1000 grams	$350 per gram

Source Cheaptubes

Fig. 7.3 **Chengdu Organic Chemicals Co. Ltd. (Timesnano)**

SWNT 60+%				
Gram Item	‹50g	50g-500g	500g-5kg	5kg-50kg
SWCNT (IS) (1-2nm, ›60%)	$42/g	$35/g	$30/g	$25/g
SWCNT (ISH) (-OH, 1-2nm, ›60%)	$48/g	$42/g	$37/g	$32/g
SWCNT (ISC) (-COOH, 1-2nm, ›60%)	$48/g	$42/g	$37/g	$32/g
Short-SWCNT (SIS) (1-2nm, ›60%)	$55/g	$50/g	$42/g	$35/g
Short-SWCNT (SISH) (-OH, 1-2nm, ›60%)	$68/g	$60/g	$52/g	$46/g
Short-SWCNT (SISC) (-COOH, 1-2nm, ›60%)	$68/g	$60/g	$52/g	$46/g

SWNT 90+%				
Gram Item	‹50g	50g-500g	500g-5kg	5kg-50kg
SWCNT (S) (1-2nm, ›90%)	$65/g	$58/g	$52/g	$48/g
SWCNT (SH) (-OH, 1-2nm, ›90%)	$75/g	$70/g	$65/g	$58/g
SWCNT (SC) (-COOH, 1-2nm, ›90%)	$75/g	$70/g	$65/g	$58/g
Short-SWCNT (SS) (1-2nm, ›90%)	$95/g	$85/g	$75/g	$65/g
Short-SWCNT (SSH) (-OH, 1-2nm, ›90%)	$118/g	$106/g	$92/g	$82/g
Short-SWCNT (SSC) (-COOH, 1-2nm, ›90%)	$118/g	$106/g	$92/g	$82/g

Source Chengdu Organic Chemicals

Fig. 7.4 **HeJi Inc**

Single-wall nanotubes						
Items	Purity	Outside Diameter	5g	10g	25g	100g
S4401	60+%	1-2 nm	---	€250	€500	€1400
S4402	90+%	1-2 nm	€400	€600	€1200	€---

Short Single-wall nanotubes						
Items	Purity	Outside Diameter	5g	10g	25g	100g
SS01	60+%	1-2 nm	€500	€1000	€2000	€7000
SS02	90+%	1-2 nm	€700	€2000	€4000	€10000

Source HeJi Inc

Table 7.10 **Helix Material Solutions**

Package (gram)	SWNT	
	High Purity	Arc CNT
1	$210	$83
10	$1,600	$700
50	$6,850	$3,050
100	$12,400	$5,500
500	Call	Call
1,000	Call	Call

Source Helix Material Solutions

Table 7.11 **MER Corporation**

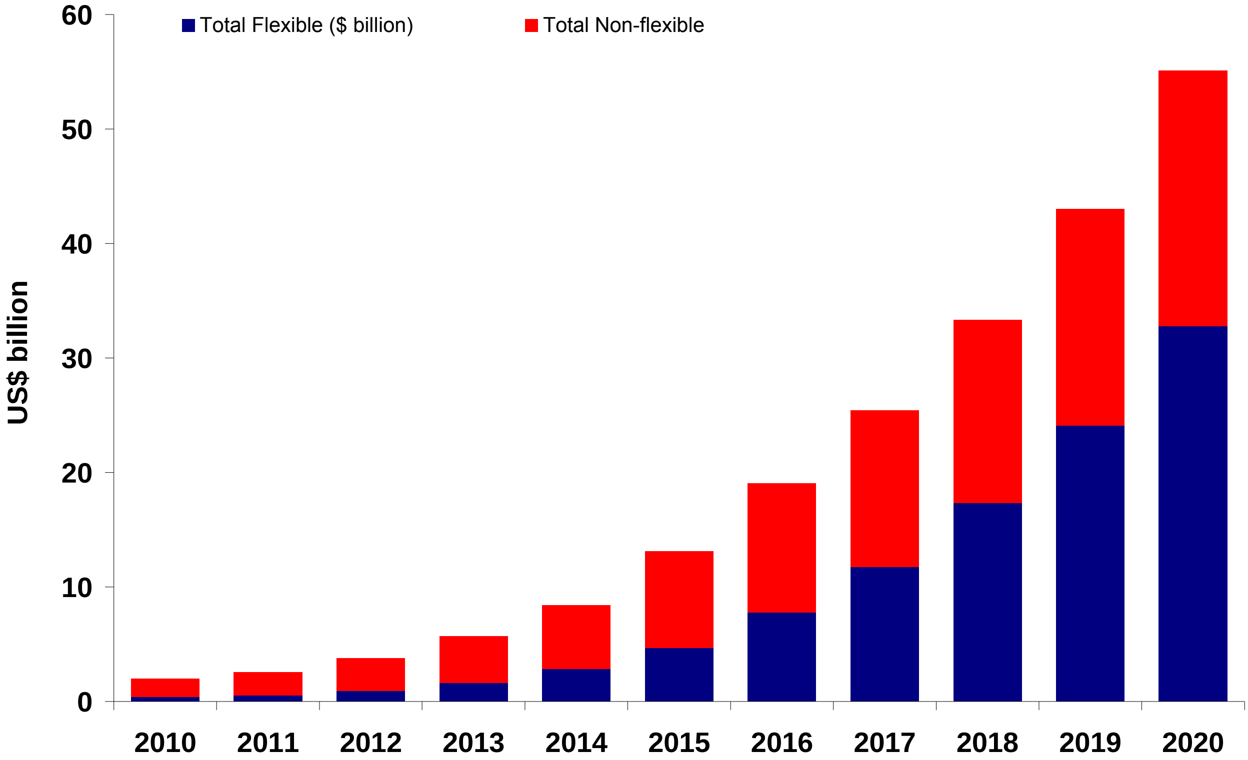
Prices PER GRAM	
1-10 g	US$ 60.00
11-50 g	US$ 50.00
51-100 g	US$ 40.00
over 100 g	US$ 35.00

Source MER Corp

7.3. New Focus for Printed Electronics – the importance of flexible electronics

In the last year, the burgeoning printed and thin film electronics industry has greatly enhanced its repertoire and changed its priorities, encompassing such things as rapid commercialization of disposable and invisible electronics. The percentage of printed and partly printed electronics that is flexible is rapidly increasing as shown below.

Fig. 7.5 **The percentage of printed and partly printed electronics that is flexible 2010-2020**



Source "Printed, Organic and Flexible Electronics Forecasts, Players, Opportunities 2009-2019" IDTechEx

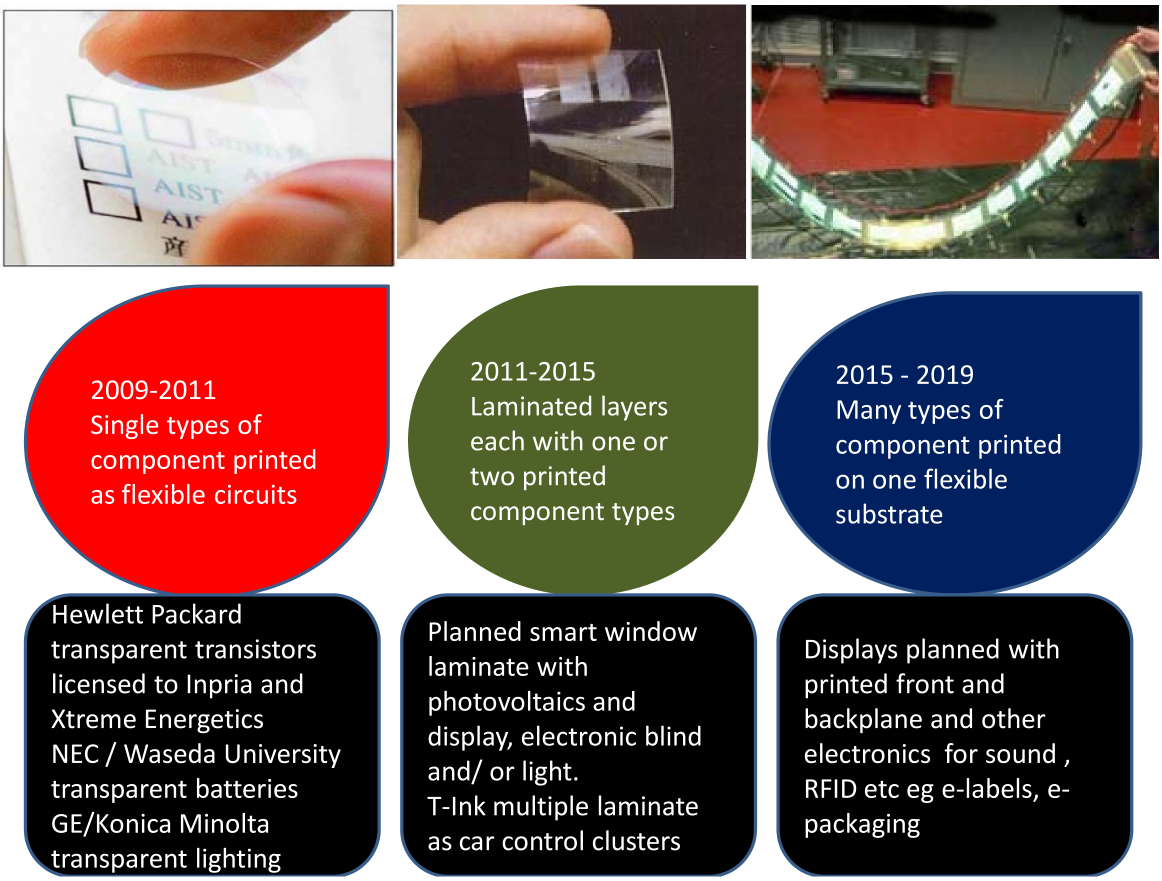
Much bigger toolkit

The toolkit of components that can be printed or at least partially printed is now expanding very rapidly. There is work on printed and thin film organic and inorganic piezoelectric and thermoelectric energy harvesters, inorganic photovoltaics, inorganic and composite fuel cell elements, thin film supercapacitors, supercabatteries , lasers, thermistors, new forms of resistor. Many more printed sensors of biological, physical and chemical processes are appearing. The list goes on and on and it is increasingly common to hear the statement "We shall be providing samples this year".

It is now clear that there will be rapid evolution of the physical structures that prove feasible over the next ten years. Today's practice of few types of component being printed on one flexible layer will be followed by the practice of laminating many such films each supporting a different component.

Finally, the far more demanding printing of many electrical and electronic components alongside and over each other on one flexible substrate will become possible. This is tricky because one ink can damage another and one annealing process can damage a pre-existing layer. However, success will mean radically new product concepts can become a reality at lowest cost, weight and size and with maximum flexibility and reliability by removing interconnects. To some extent that is like the silicon chip forty years ago but with many capabilities and price points that the silicon chip and conventional display technologies can never reach. Include fault tolerance and making every circuit different in that. The physical evolution is illustrated below.

Fig. 7.6 **Evolution of printed electronics structures**



Source IDTechEx with images from AIST, Waseda University and GE

7.4. Focus on invisible electronics

Transparent electronics is now very much a subject in its own right, and CNTs have a huge role to play in this. There is the imminent prospect of co-laminating transparent substrates supporting such things as flexible PVDF piezoelectrics for power and sensors, organic batteries and photovoltaics, zinc oxide/ hafnium oxide based transistor circuits, conductors, antennas, partly organic memory and OLED lighting on top of each other. This will even become affordable on disposable medical and consumer products. For example, a recent breakthrough was InkTec in Korea achieving very high yield when printing, reel to reel, the transparent mega memory of Thin Film Electronics in Sweden. This employs a ferroelectric organic layer and two conductive layers. Hewlett Packard continues to license its proven inkjetted transparent transistor technology. Indeed, there are two more phases of invisible electronics to come. Creative designers step forward please.

Phase two invisibility
Phase two will be printing many of these transparent components on top of each other in unusually reliable, contact-free, very thin and often very low cost constructions. We shall then have the electrics such as batteries, power conversion, energy harvesting and lighting integral with the necessary electronics as described above but all of it transparent.

Phase three invisibility
Phase three is further off but it is now attracting large investments. This other form of invisible electronics is even more dramatic in its potential impact. We refer to nanopatterning on dielectric film to create so-called metamaterials. These will lead to many previously impossible optronic and electronic components and cloaking – rendering objects invisible to light, infrared, microwaves... You choose.

7.5. Shakeout in organics

The Japanese and Koreans continue to invest nearly ten times their gross sales value in Organic Light Emitting Diode OLED displays. This will enable new versions to be made, notably for large flat panel e television, and improvements are now very frequent, with flexible TV versions also in prospect. One example of progress is Seiko Epson overcoming the unevenness of previous ink jet procedures but using its micro piezo ink jet machines in a new way. However, it is a battle for a very few massively funded companies defending their existing display and television businesses. Others are falling by the wayside. In addition, some companies developing organic transistors and other components and some developing organic materials have ceased activities or are for sale but new entrants have also appeared.

Shakeout in organic FETs
Following on from the shakeout in OLED developers, IDTechEx sees the same thing happening now in Organic FETs.

For example, ORFID, a developer of vertical geometry organic transistors, has now shut. Motorola has been trying to spin out its printed electronics activities – which are particularly focussed on organic transistor fabrication – but to our knowledge, have failed so far and we believe all work there has stopped. German based organic device printer PrintedSystems GmbH has also closed. IDTechEx is aware that the owner of another company focused on organic transistors is looking for a buyer.

Why?
Such a shakeout is common for most embryonic technologies that exhibit the potential to create massive markets but require significant work to get there. As with OLEDs, huge investment is needed to improve the performance and manufacture scaling of organic transistors to make them applicable to the highest volume markets.

Success is on the way, albeit delayed, with companies using organic transistors to drive e-paper displays. PolymerVision intend to launch product this year and Plastic Logic next year. For RFID, other than PolyIC, OrganicID and Sunchon University Korea, there are few who are seriously bringing organics to market here. If, as promised, Kovio really do supply RFID to the world's favourite RFID specification ISO14443 at much less than the price of the silicon chip version, it may be difficult to find a place in the market for much more primitive organic RFID. And Kovio is not alone.

While there is significant work and even industry collaboration to improve the mobilities of organics, we have seen increased interest in printable inorganic materials for transistors such as metal oxides and silicon based inks. However, trumping all of those in terms of mobility are relatively new forms of organic material - graphene and carbon nanotubes, which have shown mobilities exceeding that of crystalline silicon. As discussed in this report, CNTs can provide complete organic displays – high flexible, printed and event transparent.

7.6. Market pull

At last, there is much more market pull following the "answers looking for problems" of the engineering led early phase of this industry. Indeed, there has been far too much extrapolation planning by engineers wanting to make a slightly better TV, mobile phone or this and that, when the main opportunity is for creative design of completely new products. The new e-books are a splendid example with the Amazon Kindle selling 500,000 last year compared with 300,000 for the iconic i-Pod in its first year of trading. In the last twelve months, similar electrophoretic display technology has appeared in Esquire magazine, wristwatches, shelf edge displays, apparel pricing tags and a host of other applications or potential applications.

Center stage

Printed electronics is now center stage as an enabling technology to invigorate Consumer Packaged Goods CPG, publishing, paper products, healthcare products, electrical goods and so much more. It is very significant that many of the non-electronic companies in these sectors now have internal multi-disciplinary task teams scoping what they can do with the new printed electronics toolkit. Many are already doing trials to gain competitive advantage.

Appendix 1

Glossary

Appendix 1: Glossary

A

ADC	Automatic Data Capture
AIAG	Automotive Industry Action Group. Organisation that has created various numbering standards such as tire and identification standard (optical and RFID)
AIDC	Automatic Identification and Data Capture
AIM	Automatic Identification Equipment Manufacturers' Association
AIT	Automatic Identification Technology
ASIC	Application Specific Integrated Circuit
ASN	Advance Ship Notice (automotive)
AVI	Automatic Vehicle Identification – usually RFID
Acoustomagnetic EAS or RFID	Acoustomagnetic EAS and RFID systems, otherwise known as electroacoustic or, incorrectly, electromechanical, use a transmitter to create a surveillance area where tags and labels are detected. The transmitter sends a radio frequency signal at a frequency such as 58 KHz (thousands of cycles per second). The frequency is sent in pulses. The transmitted signal energizes a tag in the surveillance zone. When the transmitted signal pulse ceases, the tag responds, emitting a single frequency signal like a tuning fork. The tag signal is at about the same frequency as the transmitter signal. The active part of the tag actually vibrates. Its packaging must therefore leave it free to move. It cannot be curved around a surface. When the transmitter is off between pulses, the tag signal is detected by a receiver. A microcomputer analyses the tag signal detected by the receiver to verify that it is at the correct frequency and occurs in time synchronized to the transmitter, at the proper level, and the correct repetition rate. If the criteria are met, an alarm occurs, such as a bell or a signal to a pager on a security official plus zooming in of video cameras. Acoustomagnetic tags can be used on or in most forms of bulk packaging but not primary or paper packaging in the main because they are thick and will not operate if bent. However, the world leader in EAS, Sensormatic (now owned by Tyco) has standardised on them, making them something of a de facto standard in North America and quite popular elsewhere. Heavy, reusable versions are used on apparel for example.
Active tag	A tag, such as an RFID tag, with its own power source, usually a battery. Some have replaceable batteries and some, called unitised active tags, do not.
Addressability	The ability to address bits, fields, files or other portions of the data storage in a tag or other data store.
Aerobic microorganisms	Organisms depending on free oxygen or air.

Aldehyde	A colourless, mobile, and very volatile liquid obtained from alcohol by certain processes of oxidation. Low molecular weight aldehydes, e.g., formaldehyde and acetaldehyde, have sharp, unpleasant odours.
Algorithm	A step-by-step procedure for solving a problem; in encryption, the mathematical procedure used to create a cipher.
Alignment	In RFID it means the orientation of the tag to the interrogator.
Ambipolare	Conducting by both electrons and holes
Antenna	Conductive electronic components that radiate and or receive electromagnetic energy in the radio frequency spectrum or thereabouts. An aerial on an RFID tag or interrogator, for example..
ANSI	American National Standards Institution
ANSI X12	American National Standards Institute EDI Standard
Arc Discharge	Carbon nanotubes are self-assembling from the carbon vapor that is caused by an arc discharge between two carbon electrodes. Sometimes a catalyst is used. The yield of this method, which is around 30%, highly depends on the uniformity of the plasma arc and the temperature. Still, it is the most widely used method for the synthesis of both single-walled and multi-walled carbon nanotubes. However, it produces high impurities and requires further purification to separate the resulting complex mixture of components.
ASCII	American standard code for information interchange. ASCII is a seven bit code with an eighth bit used to describe the format for transmission and for storage.
Audit trail	A chronological record of computer activity automatically maintained to trace all use of the computer. For security it is preferable that the record be maintained by the operating system.
Authentication	The process of establishing the validity of a message or of verifying a user's authorisation for access to data.

B

B2B	Business to Business
B2C	Business to Consumer
B2D	Business to Distributor
B2E	Business to Employee
B2G	Business to Government
BAPT	Battery Assisted Passive Tag. US Military tag using battery to manage sensor data not increase range.
BI	Business Intelligence such as data mining
BPI	Business Process Improvement
BPM	Business Performance Management
BPO	Business Process Optimisation i.e. process engineering.
Barkhausen effect	An effect employed in one form of chipless RFID tags where an interrogatory electromagnetic field causes a pulsed response in appropriate non-homogeneous magnetically-active wire arrays.
Bi-directional	Capable of operating from two directions. E.g. an RFID tag that can be written to and read for opposite directions.
BID	Baggage Information Database (air industry)
Biometrics	Technologies which enable people to be identified by their individual physical or behavioural characteristics. These characteristics can be based on an individual's signature, fingerprint, hand geometry, retinal eye pattern, voice or keyboard rhythm.
Biomimetics	The scientific study of the structure and function of biological forms in Nature.

Bit	Bit is an abbreviation of binary digit, the fundamental building block of digital computer systems. A bit can either be a one or a zero. Several bits, usually in groups of 8, make up binary numbers, which may represent an alphanumerical character, a value, a program instruction or other information. The memory capacity of a smart card is usually quoted in bits.
Bluetooth™	A technology aim to create a common standard for simple yet secure and reliable communication solutions through wireless connections, enabling wireless networks (WLAN). It was primarily intended for communication between mobile telephones, personal computers, speakers and microphones. The standard was founded by Ericsson in 1994 but later joined by Nokia, IBM, Toshiba and Intel in 1998 to form the Bluetooth Special Interest Group, which campaigns for further Bluetooth adoption. Today, there are often Bluetooth features on cellphones but, as yet, they are little used. Bluetag of Denmark combine Bluetooth and RFID in pendants used for locating children in theme parks etc.
BSE	Bovine spongiform encephalopathy, a progressive neurological disorder of cattle that results from infection by an unconventional transmissible agent, commonly referred to by the media as mad cow disease.
Byte	A byte is a group of bits, usually eight. As memory capacities increase, the capacity of chip cards is often quoted in bytes rather than in bits as in the past.

C

CCTV	Closed Circuit Television – surveillance cameras
CD-ROM	Compact disc read-only memory
CEN	Comité Européen de Normalisation (standards body)
CENELEC	CEN standards body for electrical systems
CEO	Chief Executive Officer
CEPT	The European telecommunications and posts administration committee
CLO	Chief Logistics Officer
CMOS	Complementary metal oxide semiconductor : one of several chip fabrication technologies. Its advantages for chip cards, tickets and tags are that it has a low power consumption, operates faster and is resistant to electronic noise. CMOS can operate over a wide range of supply voltages. This technology is in widespread use and recent inventions mean that it is now possible with the new ultra low cost printed transistor circuits that employ soluble polymer semiconductors because these are no longer confined to p type transistors. This is particularly significant for smart packaging. However, CMOS circuits are susceptible to damage by static electricity so care is required when handling them.
CNT	Carbon nanotubes (CNT) are nanoscale materials that are highly attractive for electronic devices, energy storage devices, sensors and actuators. The attraction of CNTs comes from their small size as from their unique thermal and electrical properties. CNTs consist either of only one graphene layer (single-walled carbon nanotubes, SWCNTs) or multiple ones (multi-walled carbon nanotubes, MWCNTs) rolled in on themselves forming a tube shape. They can range from less than a micrometer to several millimetres in length but are usually only a few nanometres wide, which is only a ten-thousandth the diameter of a human hair. The hollow, cylindrical tubes are composed entirely of carbon.
COO	Chief Operating Officer
CPG	Consumer Packaged Goods
CVD	Chemical Vapor Deposition is a very common method for the commercial production of CNTs, because of the large amounts that can be formed. A substrate containing catalytic metal particles (nickel, cobalt, iron, or a combination) on the surface is heated to approximately 700°C inside a vacuum chamber, in which two types of gas are poured. The carbon-containing one passing over the metal particles causes the metal to separate and form carbon nanotubes. The size of those can be controlled by the size of the metal particles.

Capacitive coupling	Contactless signal transmission by electrostatic effect, i.e. the capacitance of the (small) gap. A minority of contactless chip cards and tags use this principle, notably Motorola BiStatix process licensed to DNP, Flint Ink, Power Paper, etc and Cypak technology used in patient compliance monitoring blister packs.
Capacity	The amount of data (bits or bytes) that can be programmed into a tag or smart package. This may represent bits available to the user or the total number of bits including those used by the manufacturer etc.
Capture field	Region of the interrogator field in which an RFID tag will operate.
Capture window	As above.
Cardinal Healthcare	One of the largest healthcare services companies in the USA. has its own RFID smart dispensing trolley for its hospitals.
Chip card	Cards with one or more microchips (integrated circuits) in them. See IC cards, memory cards, simple logic chip cards, smart cards and super-smart cards.
Chipless tag	A tag without a microchip (integrated circuit).
Chipless first generation	Chipless RFID tags are evolving in two stages. First has come those that are intended for closed, usually secure systems where non-conformance to standards is a positive advantage. The two big successes here have been Wiegand/Barkhausen electromagnetic wire arrays in HID contactless cards for secure access, where 80 million have been sold at about $2 each and acoustomagnetic foils forming ten cent labels in 25 million AstraZeneca Diprivan syringes for error prevention. By contrast, the largest supply of one type of chip-based RFID tag into a single application has been 30 million Innovision tags for Hasbro toys. Both of the chipless best-sellers store about 24 bits and can be interrogated at a few centimetres. The Diprivan application is error prevention by electronic handshake: the wrong drug or dose can not be dispensed. It completely eliminated such errors over the seven years it has been used and currently 4.5 million such labels are used yearly just on Diprivan.
Chipless second generation	The second stage of chipless RFID, which can lead to sales of billions to trillions yearly, is its use in open RFID systems i.e. where many service providers are involved with any one system. This stage has been delayed not by lack of suitable technology but by the fact that the chipless proponents involved were undercapitalised, let the standards be written around more expensive chip tags and were often poorly managed, chasing the wrong opportunities. The standards in question were the operational standards defining frequencies, signalling protocols etc. Chipless labels have no problem with the numbering conventions, though versions with more than 24 bits have tended to be unnecessarily stuck in the laboratory.
Chromogenic	Producing colour
Cipher	An encryption system that arbitrarily represents each character by one or more other characters.
Ciphertext	The encrypted, unintelligible text produced by a cipher.
Client	A computer connected to a network that requests services from another computer connected to the network.
Closed system	Physically Closed: A system in which relevant data regarding the object are stored in a common database, accessible via datalink by referencing the individual ID code. In traffic management, a parking or road transit control achieved by monitoring both entry and exit e.g. with RFID cards. Any transaction takes place on exit with charges based on time parked, distance travelled etc. Commercially Closed: A system, such as RFID, that is under the control of one owner or authority. In the plastic card arena, a closed system is sometimes referred to as one which involves only one card issuer and which does not need to interact with the cards of any other issuer. Closed systems may be for a single or multiple applications within those sites. They do not have a system operator that is independent of the service provider. See Open System and Open System Architecture.
Code	An encryption system whose components represent characters, words or sentences.
Computer network	A system of two or more computers connected by communications channels.
Conditional	A statement in a segment or message directory of a condition for the use of a segment, a data element, or a component data element.

Contacted chip card	A chip card which communicates and receives power via metal contacts located on its surface.
Contactless chip card	Card which does not need to make physical contact with the read-writer in order to work because it passes electrical or magnetic signals through the air. Some operate only a few millimetres away from the reader; others work at many metres. The remote linking is either by capacitative or inductive coupling. More expensive but more reliable and sometimes more tamper-proof than contacted cards. The remote link is by either capacitative or inductive coupling.
CRDA	Cooperative Research & Debt Agreements (US Military)
Cryptography	The enciphering and deciphering of messages using secret ciphers or codes.

D

Decryption	The process of converting encrypted data back into its original form so that it may be understood and/or processed.
Dedicated network	A communications facility established for a specific purpose. Each remote terminal on the network is assigned to a specific termination point.
DB	Database
DES	Data encryption standard is a private key encryption algorithm, where the same key is used for encryption and decryption. The key must be kept secret and distributed securely to maintain system security. DES has been adopted by the National Bureau of Standards and is used extensively in banking. Smart cards are available that can encrypt and decrypt DES messages internally.
DPM	Defects Per Million
Diagnostics	Diagnostics in the context of labelling and packaging is the use of devices that visually or electronically reveal a change of condition. Usually special inks or laminates are employed and conditions revealed can include: • Unacceptable levels of bacteria (e.g. meat storage) • Sterilisation process successful (e.g. medical disposables) • Time/temperature excursion (high temperature short time or somewhat raised temperature for a long time). This may show food is cooked or vaccines have been properly refrigerated • Time elapsed (e.g. hair dye) • Temperature (e.g. wine is cool) • Tilt • Shock • State of charge of a battery The various forms of diagnostics can be in real time or historical, depending on the design of the intelligent packaging notably the type of ink or laminate used. More expensive, more accurate alternatives are just becoming available that are electronic.
Digital	Pertaining to the representation, manipulation or transmission of information by discrete, or on-off, signals.
Digital paper	Thin flexible transparent film having tiny 'bichromal' plastic beads embedded in it that can be switched between contrasting colours such as black and white.
Domain name system	The Internet's domain name system (DNS) allows Internet routing computers to identify where the pages associated with a particular web site are stored. The DNS is used every time a web site is accessed.
Dumb	In the plastic card arena, this term is used to refer to any card, tag or token without any processing capability, i.e. it only stores information or units of value.
DUST	Dual Use Science and Technology (US Military) e.g. sterilisation by UHF etc rather than high heat

DWCNT	Double-walled carbon nanotubes (DWCNTs) are CNTs that consist of two graphene layer rolled in on themselves forming a tube shape

E

EAN	An association which manages a worldwide identification system and standards for communicating data for products, services, transport units, locations and assets. EAN develops and maintains international and multi-sectoral standards related to the identification system and its application in automatic data capture and electronic commerce technologies. The global objective is to provide a common language to be used in national and international trade. In 1974, manufacturers and distributors of 12 European countries formed a council to examine the possibility of developing a standard article numbering system for Europe, similar to the Universal Product Code (UPC) system already set in the USA by the Uniform Code Council (UCC). As a result a not for profit association called European Article Numbering Association (EAN) was created in 1997. The Head Office was established in Brussels, Belgium. The success of the EAN System led to the establishment of new Numbering Organisations in countries from all continents. EAN quickly acquired an International status and changed its name to EAN International. Today, more than 550,000 companies worldwide use the EAN system through an international network of numbering organisations represented in over 90 countries. In addition, UCC's membership reaches 220,000 companies in the USA and Canada. EAN International was originally involved with the numbering and bar coding of products in the retail industry. The success in this sector led to other industries adopting EAN standards to meet their item identification needs. Health care, packaging, transport, publishing, shoe, electronics, postal services, and defence, are examples of sectors adopting the EAN system. EAN now partners with UCC (EAN.UCC) and they are involved in the EPC and associated standards for The Internet of Things.
EAS	Electronic Article Surveillance e.g. anti theft radio tags.
ECP	Electronic Compliance Package
ECR	Efficient Consumer Response initiative.
EDI	Electronic Data Interchange: the electronic exchange between commercial entities (in some cases also public administrations), in a standard format, of data relating to a number of message categories, such as orders, invoices, customs documents, remittance advice and payments. EDI messages are sent through public data transmission networks or banking system channels. Any movement of funds initiated by EDI is reflected in payment instructions flowing through the banking system.
EEPROM	Electronically erasable programmable read-only memory: like EPROM memory, EEPROM memory retains its contents when no power is available and can be both read from and written to. Unlike EPROM, information stored in EEPROM memory may be rewritten as and when required. In chip card terms the memory cannot become full and the lifespan of the card is determined by other factors. It is also sometimes known as E2PROM or simply E2. Chip cards can have EPROM or EEPROM memory.
EID	Electronic Identification. Term used for RFID tagging of animals.
EID	Enterprise ID

EPC or ePC

Electronic Product Code. A numbering scheme that can provide unique identification for physical objects, assemblies and systems. Information is not stored directly within the code – rather, the code serves as a reference for networked (or Internet-based) information, in other words, the code is an 'address' – it tells the computer where it should go to find information on the Internet.
The EPC requires relatively few parameters to determine the design:

- Number of bits – i.e. How much information is needed to provide a unique identity in every single product manufactured, sold and consumed in the global supply chain?
- Bit partitions – i.e. What is the best way to organise – or break up – the numbers/figures so that we achieve as many unique combinations as possible, while also expediting Internet searches? Consider this an exercise in determining the best 'search hierarchy' – like a postal address – which goes from country to city, to zip code, to street, to house and individual.

As the detail or level of the hierarchy increase, the speed and accuracy of the search will likewise increase, but the possible combinations of unique numbers will decrease.

EPC and RFID

EPC (Electronic Product Code) is simply a number, typically from 64 to 256 bits long, that is being standardized so thousands of trillions of items in the world can be assigned a unique identification number, a unique EPC, which is the equivalent of an electronic barcode. This is vital so that everyone uses one type of system and not their own code – which would lead to great confusion because so many different people need to read the same tag. Closed systems – such as a library, use their own numbering system (i.e. not EPC) as books may only be read in that library and not all around the world. That is why we see many case studies of tags being used in small closed applications – they don't have to wait for standards, but tagging things on a large open infrastructure means there has to be just one way of identifying everything, in this case EPC. This requires standardization which in turn needs time for everyone to agree on the right way to structure the numbers – which was one purpose of the Auto-ID Center. Now this project is managed by the newly formed EPCglobal which will licence usage in a similar way to barcodes. The same organisations are involved with both – UCC and EAN. In the simplest terms, EPC is just a number.
RFID is the favoured medium used to transmit and read that number remotely, e.g. through packaging, or many tags at once for example. RFID systems don't have to use EPC, as in the library case and many others, but if they do the readers need to use the same type of database to determine what the EPC number is and which item it is connected to. This database is known as SAVANT.
Auto ID Center developed and researched the EPC and SAVANT and a few other software add-ons. It allowed all the sponsor members to agree on how the code should be structured. Companies joined the Center to have a say in how the items should be numbered. Now EPCglobal is standardizing it so people can use it like they do barcodes – companies pay UCC and EAN, the standardization organisations, to use a range of EPC numbers. The more EPC numbers you need (the more items you tag), the more you pay. The Auto-ID Center decided that RFID would be the medium to read EPC tags, but they did not determine the type of RFID system to be used – so people can use different frequencies, for example 13.56MHz and UHF, to read the same code. Therefore EPC and RFID are complementary, but EPC is not the only way to do things. For example, RFID is really big in transport for contactless smart cards, and these were standardized a long time ago and use a numbering system that is completely different to EPC.

EPROM	Electronically programmable read-only memory: data stored in EPROM memory is retained when there is no power supply. Data can be both read and written but new data cannot be partially written over existing data. Usually the only way to do this is to expose the memory to ultraviolet light, thus erasing the entire contents, and then add the new information to the blank area. In a chip card this means that, when an EPROM card's memory is full, it is no longer of practical use as, for example, a prepayment card.
EMID	Electromagnetic Identification. Term coined by chipless RFID company Flying Null in the UK to distinguish its electromagnetic product from conventional silicon chip RFID.
ESD	Electrostatic discharge (protection)
ETSI	The European Telecommunications Standards Institute. ETSI has been active in the smart card field, building European standards where there are gaps in the ISO standards. ETSI card standards work is based on ISO standards where published.
Electric field coupling	'Efield' data transfer typically UHF or higher frequency e.g. a dipole 'talking' to a dipole.
Electroactive polymers	Polymers that can change shape in response to electrical stimulation, of interest as artificial muscles and other smart devices.
Electrochromic material	A substance that changes colour or transparency when subjected to an electric current, as in the liquid crystal display of many calculators.
Electromagnetic coupling	'HField' use of a magnetic field as a means of transferring data or power. Usually a coil talking to a coil. Alternatively use of any electromagnetic transmission for data or power transfer.
Electromagnetic EAS and RFID	The electromagnetic EAS system creates a low frequency electromagnetic field between two pedestals at an exit or checkout aisle. The RFID equivalent returns a signal from a fixed or handheld interrogator. Frequencies between 70 Hz and 1 KHz are often used for electromagnetic EAS. The field is varied in strength and polarity, repeating a cycle from positive to negative and back to positive again. With each half cycle, the polarity of the magnetic field between the pedestals will change. Responding to the changing magnetic field created by the transmitter, the magnetic field of the tag material switches as the field strength varies past a particular point, positive or negative, during each half of the transmit cycle. This sharp change in the magnetic state of tag material generates a momentary signal that is rich in harmonics (multiples) of the fundamental frequency. Electronic signal processing techniques are used to verify that the harmonics are at the right frequencies and levels, and that they occur at the proper time in relation to the transmitter signal. If this is the case, an alarm is triggered. Electromagnetic EAS devices are the thinnest and fairly tolerant of bending and therefore the most suitable for thin packaging. However, they do not work with acoustomagnetic pedestals, the largest installed base and range is limited. They are the third most popular EAS technology and are losing market share. Electromagnetic EAS employs wire (e.g. ACS) or RF sputtered thin films of high permeability, low coercivity materials the same as that used for EAS (e.g. Flying Null). Flying Null uses the term Electromagnetic Identification EMID to distinguish it from mainstream RFID.
Electro-rheological materials	Materials that are fluids that solidify into a pasty consistency in the presence of an electric field (as molecules assemble in somewhat stiff chains along field lines), and then re-liquefy when that force is removed.
Electrostatic coupling	Inducing a voltage on a plate as a means of transferring data or power.
Encryption	Using ciphers to alter information before it is transmitted over a network. Encryption ensures, to the greatest extent possible, that messages cannot be read or altered during transmission.

Enzymatic hydrolysis	The use of an enzyme to convert starch into simple sugars; a stage in the production of ethanol
EPCglobal	The EPC standardization work is being conducted by EPCglobal, which is owned by UCC and EAN, responsible for standardizing barcodes. UCC and EAN were involved in the instigation of the Auto-ID Center, and the work completed by the Center is now being commercially standardized by them. EPCglobal will be funded by new sponsorship tiers, which will be necessary to be actively involved in the standardization process. EPCglobal will initially finance the Auto-ID Labs, but then they will seek their own sources of funding. Programmes within Auto-ID Labs will look into further application areas, as much of the work finally focused around the supply chain and retailing, but now application areas under consideration include pharmaceutical and baggage tagging. For more information, the EPCglobal website is www.epcglobalinc.org
Envision America	Envision make RFID tag systems that make pots of tablets talk to patients. Works with Zebra, a leading manufacturer of label printing machinery
Error rate	Number of errors per number of transactions.

F

FMCG	Fast Moving Consumer Goods
FPD	Flat Panel Display `
Factory programming	The programming of information into a tag as part of its manufacture. The result is a read only tag.
Field programming	Programming a tag after it has left manufacture e.g. by the user. This is usually done before the tag is attached to the object to be identified. Field programming permits data specific to the application to be recorded in the tag. Some tags are made so that part of the memory is dedicated in the factory and part in the field.
Field protection	The ability to limit the operations which can be performed on portions or fields of the data stored in the tag.
Flash memory	An advanced type of EEPROM memory: it is a high density, low power consumption, rewriteable non-volatile medium used in some modern chip cards and computers.
Flat panel antenna	Flat conductive sheet aerial on tag or interrogator, usually made of metal plate or foil.
Frequency	The number of times a signal executes a complete excursion through its maximum and minimum values (cycle) and returns to the same value.

G

GAV	(US Military) Global Asset Visibility
GB	Gigabyte. This is used to describe a memory size of 1,073,741,824 bytes. A byte is eight binary digits or 'bits'. 1 GB equals 1,024 megabytes (MB).
GCI	Global Commerce Initiative
G-CNT	The hybrid graphene-carbon nanotube material (G-CNT) shows great potential to be a high-performance alternative to ITO e.g. in flexible solar cells. In comparison to ITO, G-CNTs retain efficiency when flexed and are compatibly with plastics. Yang Yang, a professor of materials science and engineering at UCLA Henry Samueli School of Engineering and Applied Sciences, and Richard Kaner, a UCLA professor of chemistry and biochemistry, developed a single-step to fabricate G-CNTs in an easy, inexpensive and scalable method.
GHz	Gigahertz. The Hertz is the unit of frequency – it means cycles per second. 'Giba' in engineering means one thousand million – rather less than the 'giga' used to describe memory size in some computers! For the confused, the reason for the difference is that in computers binary codes are used to contact, or 'address' each stored byte of data. The number of different codes on 'addresses' that can be generated by binary numbers is calculated from two raised to the power of the number of bits in the code. So 2-bit code provides two to the power of two which equals four addresses and so on. The closest we can get to one thousand million is to use a 30-bit binary code which yields 1,073,741,824 – the 'giga' used to describe computer memory capacity.

GIS	Goods Information Server.
GPRS	General Packet Radio Service: a radio technology for GSM networks that adds packet-switching protocols, shorter set-up time for ISP connections, and offer the possibility to charge by amount of data sent rather than connect time. GPRS promises to support flexible data transmission rates typically up to 20 or 30 Kbps (with a theoretical maximum of 171.2 Kbps), as well as continuous connection to the network. A 2.5G enhancement to GSM, GPRS is the most significant step towards 3G, needing similar business model, and service and network architectures. GPRS started to appear in some networks during 2000. The European Commission ParcelCall project envisages using it in conjunction with RFID for parcel tracking.
GPS	Global Positioning System, by satellite. Sometimes used in conjunction with RFID.
Graphene	Graphene has a two-dimensional structure that looks like chicken wire and can be thought of as unrolled CNTs - it consists of a single planar layer of carbon atoms arranged in a honeycomb lattice. Graphene forms the basic structural element of some carbon allotropes including graphite and carbon nanotubes. The surface area can be theoretically as high as around 2,600 m2/g, but currently it reaches only 1,700 m2/g in practice. Being 200 times stronger than steel, graphene is the strongest known material.
GSM	Global system for mobile communications. The digital system for mobile phone communications. For computer communications, GSM offers a higher rate of data transfer (9,600bps) compared with analogue mobile phones (4,800bps). Portable PCs can connect to a mobile phone by using a PCMCIA communications card.
GTAG™	'Global Tag', a standards body that was run by UCC and EAN to develop standards for RFID smart labels and tags, for use in logistics. Now subsumed in other work. (ISO 18000)
GTS	Goods Tracing Server

H

H field	See Electromagnetic coupling

I

IC	Integrated circuit. Arrays of electronic components such as transistors, diodes and resistors made with their interconnects on or in a single piece of semiconducting material such as silicon. This can save cost, improve speed of working and improve reliability.
IC cards	Integrated circuit cards: the term favoured in Japan, Denmark and elsewhere to describe chip cards.
ID	Identification, for example the identification number in an RFID tag.
IEC	International Electrotechnical Commission
IP	Intellectual Property
ISO	International Standards Organisation. A United Nations agency which coordinates and publishes standards of product performance.
IT	Information Technology
IWG	Internet Working Group
ID filter	Software that compares a newly read ID with that in a database or set.
In use programming	New data or revisions to data being recorded e.g. on an RFID tag in use. Otherwise known as field programming.

Inductive coupling This technique is used in many contactless cards in order to deliver power to the card and to allow it to communicate with the outside world. Same technique used to interrogate early types of in-car tag. A coil is embedded within the surface of the card or the road and a card is placed in or connected to the read-write unit. When the current is passed through one coil, say the read-write unit, magnetic field is created and, if the second coil, say in the contactless card, is bought close enough to it, this magnetic field leads to current being delivered to that coil as well. Once this occurs, the card has sufficient power to function and data can be exchanged between the card and the read-write unit.

Infineon Split off from Siemens several years ago, it is one of the world's largest chip manufacturers and the largest supplier of chips for smart cards. Researching oligomer TFTCs.

Information Mediary Small Canadian company making RFID/patient compliance blister packs and plastic bottles and RFID electronic time temperature labels.

Insult rate Percentage of rejections as false of what are actually valid inputs, e.g., in biometrics.

Intelligent packaging Intelligent packaging is a term that is not used as often as smart packaging. Sometimes it is used as synonymous and sometimes as a subset of smart packaging, usually limited to features that respond to circumstances. Sometimes people constrain their use of the term intelligent packaging to electronic features alone.

Intermodal containers Standard oblong freight containers the size of a truck that are used for road, rail and sea transport.

Internet of Things Term coined by MIT Auto ID Center for things 'talking' electronically to thing over the Internet. See EPC and EPCglobal.

Interrogator Electronic device that remotely interrogates the data on an RFID tag and may or may not be able to rewrite it, i.e. an interrogator may be a reader or a read-writer.

J

JTAV Joint total asset visibility. In April 1992, the US Military decided to pursue TAV with considerable investment. To date, about $600 million has been spent on the core aspects of this program. It had to involve all arms of the service so the term Joint Total Asset Visibility (JTAV) was coined. It is not confined to the modest level of RFID tagging but encompasses all existing data acquisition methods as updating proceeds. JTAV is the Defense Department's automated information capability for tracking equipment, personnel and supplies. It gives increasingly pervasive information on location, movement, status, identity of units, personnel, equipment and supplies. There is an overarching logistics strategy to support global end to end distribution and visibility capability, to coin the words of the US Military.

The Deputy Under Secretary of Defense for Logistics (DUSD(L)), as the Secretary of Defense's Principal Staff Assistant (PSA) for logistics, designated the Army as Executive Agent to lead the initiatives for further development and implementation of the JTAV program. In 1995, The Army Deputy Chief of Staff for Logistics (DCSLOG) established the JTAV Office to provide management of the effort. In 1998, the DUSD(L) reassigned the JTAV Program Executive Agency to the Defense Logistics Agency (DLA). The DUSD(L) chairs the JTAV Council which consists of the Joint Staff J-4, Joint Staff J-1, the Service Logistics Chiefs, Director Defense Logistics Agency (DLA), Director Defense Information Systems Agency (DISA) and Deputy Commander-in-Chief (DCINC) United States Transportation Command (USTRANSCOM).

The JTAV Office operates as a joint organization with guidance provided by the DUSD(L) to the Executive Agent. The JTAV Office is responsible to ensure a JTAV capability is provided throughout the DOD by ensuring JTAV functional requirements are satisfied by DOD-wide automated information systems. It focuses on providing asset visibility in-storage, in-process and in-transit to help optimise DOD's warfighting capability and the ability to conduct operations other than war. The JTAV Office also evaluates the design, development, integration, and implementation of logistics processes, technologies and systems to achieve these requirements. Using active

RFID tags (i.e. With battery for long range etc.), assets are now monitored in 40 countries at 400 nodes at seaports, airports, rail terminals and army bases.
The JTAV Office ongoing mission is to ensure that the required level of TAV capability is provided to the Combatant Commanders. This includes subordinate Joint Task Force (JTF) Commanders, the Services and DOD activities. The focus of the JTAV Office is on executing the JTAV Implementation Plan in support of this. The JTAV Office performs the central role as the functional integrator. It serves as the proponent for JTAV and will lead and manage the Joint TAV effort DOD-Wide.

JTAV database The Joint Total Asset Visibility program revolves around a centralized database that allows commanders to have total visibility over Army and DOD assets that are stored or in-transit in the supply pipeline. The visibility data is taken from several interrelated databases : Global Transportation Network (GTN), Logistics Information Processing System (LIPS), Inventory Control Points Automated Information Systems (JLOG), The Standard Army Retail Supply System (SARSS), The Standard Property Book System-Redesigned (SPBS-R), and the Defense Automatic Addressing System Center (DAASC). The GTN is a command and control system that aids the United States Transportation Command's (USTRANSCOM) visibility of material in transit. The LIPS is the central point for information on all ICP-managed assets. The JLOG helps commanders manage assets to improve utilization, to cross level and to redistribute parts. The SARSS provides retail level inventory updates to the Army Total Asset Visibility (ATAV) through DAASC. The ATAV major end item information is updated by SPBS-R through the Continuing Balance Asset System-Expanded (CBS-X). Most of these databases are at the wholesale level. However, SARSS is used by supply support activities at the Direct Support (DS) level and SPBS-R and TAV are used at the Property Book level.

K

Kb Kilobit. This is 210 (1024) bits—not simply 1000 bits as the term suggests. In computing, the term kilo suggests 210 rather than 103.

KB Kilobyte. This is 210 (1024) bytes.

Key A secret value used in encrypting algorithm known by one or both of the communicating parties; it is similar to a combination number for a vault. A symmetric key is used to control both the encryption and decryption processes. Public key encryption uses a pair of different values to control a related encryption and decryption process: the sender encrypts with the receiver's public key, and the receiver decrypts with his/her private key. A session key uses a unique key for a simple data exchange or set of data exchanges.

Key management The process by which keys are distributed to usage points while kept in a protected form by encryption.

Key-distribution centre A communications facility in a single-key encryption network that translates a session key encrypted by a message.

L

LAN Local Area Network.

LC Inductor with capacitor in parallel. The basis of Swept RF EAS tags.

LC Array Several LC elements constituting an RFID version of swept RF EAS.

LCD Liquid crystal display.

LED Light emitting diode.

Laminar electronics Thin flat electronic circuits, usually flexible.

Laser Ablation — The laser ablation method was first developed in 1996 by Dr. Richard Smalley and co-workers at Rice University, USA. The procedure needs to take place in a high-temperature chamber containing inert gas. A pulsed laser vaporizing a graphite board with a following cooling of the vapor causes the carbon nanotubes to develop on the chamber surface. Using composite of graphite and metal catalyst particles, mainly single-walled carbon nanotubes can be produced at a yield of around 70% purity. The diameter of the SWCNTs can be determined by the reaction temperature. This process is more expensive than either Arc Discharge or CVD.

Level — A means of indicating the hierarchical and processing order of segments and groups in a message.

M

MAP — Modified Atmosphere Packaging

MIV — Mobile Inventory Vehicle. A vehicle equipped with a system such as RFID for locating tagged vehicles, inventory etc for the purpose of inventory control.

MLS — Mobile Logistics Server.

ms — Millisecond. One thousandth of a second.

MWCNT — Multi-walled carbon nanotubes (MWCNTs) are CNTs that consist of multiple graphene layer rolled in on themselves forming a tube shape. MWCNTs cannot compete with the outstanding electrical conductivity of single-walled carbon nanotubes.

Magnetic stripe cards — Cards with a magnetisable material in or on them (as found on the world's most popular credit, debit and prepayment cards). ISO standard magnetic stripe cards have three tracks of data, the first being assigned to the airline industry – accepts alphanumeric entries, the second to financial transactions – numeric content only, and the third being a rewriteable track designed for off-line magnetic stripe based transactions; it is rewritten each time. Magnetic stripe cards carrying non-standard stripes and multiple stripes are also used in large numbers for access control and storing value. Magnetic stripes are also applied to cardboard tickets.

Magnetostriction — A change in dimensions of a ferromagnetic material that is subjected to a magnetic field.

Mandatory — A statement in a segment or message directory which specifies that a segment, a data element, a composite data element or a component data element must be used.

Memory card — A chip card without processor, i.e. not a true smart card. Also used for data storage devices of the type being standardised by the American PCMCIA and the Japanese JEIDA organisations. This second type of card was originally a memory-only storage device in the shape of a thick bank card, but has now evolved to include, for example, receiving faxes.

MEMS (electronic) — Micromachined Electromechanical Systems are microscopic machined devices moved by electricity and usually repeated in large numbers across a surface for some purpose

MEMS (medical) — Medication Event Monitoring System. A patient compliance monitoring system by Aardex Switzerland/ USA using clocks in vials. MEMS is a registered trademark.

Metabolite — A product of metabolism; a substance produced by metabolic action, as urea. The decomposition signatures of foodstuffs.

Metadata — Data about data, describing the structure and format of the data.

Microencapsulation — A process by which tiny parcels of a gas, liquid, or solid active ingredient are packaged within a second material for the purpose of shielding the active ingredient from the surrounding environment. These capsules, which range in size from one micron (one-thousandth of a millimetre) to seven millimetres, release their contents at a later time by means appropriate to the application.

Micromuscle AB — Swedish company developing polymer actuators for biomedical applications. They can be in the form of films.

Misread — The condition that exists when data presented by the interrogator is different from the data in the tag.

Modulation Ways of altering the carrier electromagnetic wave in order to transmit a signal efficiently. Examples are amplitude modulation AM (data contained in amplitude of carrier), phase modulation PM (data contained in changes of phase), frequency modulation FM (data contained in changes of frequency), Frequency shift keyed FSK (data contained in changes between two frequencies of carrier), pulse duration PDM (data contained in the duration of pulses), pulse position PPM (data contained in the position of the pulses relative to a reference point), continuous wave CW (data contained in a carrier which is switched on and off). In some cases, it is best to use a different modulation technique to and from a tag.

MRE US Military. Meals Ready to Eat (rudely called Meals Rejected by Everyone in the early days). Often employ 'active packaging'.

Multipacks Packs containing many, usually packaged, products. Usually a form of secondary packaging.

Multi-purpose card Cards that operate in more than one applicational mode such as credit, debit, prepay, secure access, ID. Particularly used where financial and non-financial functions are combined.

N

NGP Nano-scale graphene-platelets (NGPs) are multilayered structures with 8 to 12 layers of Graphene and a typical thickness of 5 to 10 nm. NGPs are predicted to have a range of unusual physical, chemical, and mechanical properties. The NGPs can exhibit attractive properties like carbon nanotubes (CNTs) and carbon nano-fibers (CNFs).

(n, m) The properties of carbon nanotubes, especially the electrical properties, are strongly dependent on the structure and the way the tubes are "wrapped up". This is represented by what is called the chiral vector, which is a pair of indices (n, m) standing for the number of unit vectors along two directions in the crystal lattice of graphene. The electrical conductivity along the tube axis is a function of the chirality, i.e. the degree of twist as well as diameter. Depending on the chemical structure carbon nanotubes could be an alternative to organic semiconductors as well as conductors. The formation m=0 is called "zigzag" and n=m is called "armchair". All other formations are referred to as "chiral".

O

OFET Organic Field Effect Transistor

OLED Organic Light Emitting Diode displays. A form of laminar electronics The diodes in these displays emit light when a voltage is applied to them, and can be selectively turned on or off to form images on the screen. The devices use organic not silicon semiconductor materials.

OLED SSL Solid State Lighting SSL refers to a type of lighting that utilizes light-emitting diodes LEDs, organic light-emitting diodes OLED, or polymer light-emitting diodes as sources of illumination rather than electrical filaments or gas. The term "solid state" refers to the fact that light in an LED is emitted from a solid object—a block of semiconductor—rather than from a vacuum or gas tube, as is the case in traditional incandescent light bulbs and fluorescent lamps. Unlike traditional lighting, SSL creates visible light with virtually no heat or parasitic energy dissipation and its solid-state nature provides for greater resistance to shock, vibration, and wear, thereby increasing its lifespan significantly.

OSI Open Standards Institute

ONS Object Naming Service, or ONS, tells computer systems where to locate information on the internet about any object that carries an EPC (electronic Product Code). ONS was developed at the Massachusetts Institute of Technology by Dr David Brock, Professor Sanjay Sarma and Joseph Foley. ONS is similar to – and (in part) based on – the Internet's existing DNS (Domain Name System), which allows Internet routing computers to identify where the pages associated with a particular Web site are stored. The DNS is used every time a web site is accessed. The ONS will be used every time information is needed about a physical object. It is likely that the ONS will be many times larger than today's DNS. Although conceptually simple, designing ONS was a challenge. The system must be capable of quickly locating data for every single one of the trillions of objects that could potentially carry an EPC code in the future. The ONS must serve as a lightning-fast post office that, on a daily basis, receives and delivers millions (if not billions) of letters.

Omnidirectional Ability of a tag to work in any direction.

Optical memory In the context of cards and tickets, this means a raster scanned optical memory stripe invented by Drexler Corporation and licensed to Canon and others, its own version being branded LaserCard. RFID cards for national ID in Italy and China have an optical memory stripe because it is not yet cost effective to have the one megabit or more of memory for biometrics etc on the chip.

Off-line A mode of operation that does not require a network and/or third party authentication.

On-line A mode of operation that does require a network and/or third party authentication.

Open system In computing, conforming to standards that facilitate different manufacturers' computers and allied equipment interconnecting widely. In transport, an open system can mean that not all entrances and exits have barriers. For example, for RFID i.e. contactless smart cards to be used it is usually necessary to install automatic barriers at all entrances and exits to stations or all entrances to buses.

Open system architecture In an open system, different hardware, application, operating systems and user interfaces can coexist and interact because each part meets the standard that governs communication and data exchange. EPC and barcoding systems are intended to be open so any service provider can use them. The Hitachi Mew Solutions numbering system for its RFID tags is intended to be closed for maximum security, any tranche of numbers that it issues being intended for one service provider.

Operating system A complex set of programmes that control, assist and supervise all other programmes run on a computer.

Organoleptic Relating to the senses (taste, colour, odour, feel).

P

PCM Phase Change Materials, are compounds which melt and solidify at certain temperatures and in doing so are capable of storing or releasing large amounts of energy. The temperature at which the transition from solid to liquid occurs is the melting point or phase change temperature.
In electronics, it means Pulse Code Modulation

PCMCIA Personal Computer Memory Card International Association. A committee which has produced the standard format for the credit card sized plug in memories, modems, sound cards and now RFID tag interrogators that are used with portable computers.

PDA Personal Digital Assistant

PEDs Printable Electronics and Displays

PIN Personal identity number given to and associated with a user and keyed in when gaining access to ATMs, etc.

PhRMA Pharmaceutical Research and Manufacturers of America

PMR Programmable Magnetic Resonance. An acoustomagnetic technique used for chipless RFID tags. Origin Scientific Generics UK.

Packaging Packaging is the covering of merchandise or assets for protective, promotional and other reasons.

Parity A bit that indicates whether the number of ones in a bit string is odd or even.

Passive tag	In electronics this means either unable to generate its own signal, therefore has no power supply (e.g. passive RFID tag) or an electronic component that cannot amplify signals and/or obeys Ohms Law (e.g. resistors or capacitors).
Pathogen	A disease-causing agent, such as viruses and bacteria.
Pentacene	Organic oligomer used as the semiconductor in thin film field effect transistors. Needs vacuum processes because it is insoluble but gives higher charge carrier mobility than the soluble organic semiconductors that can be printed. This means that the transistors can work at higher frequency and be used in more applications technically, though cost is a challenge.
Personal authentication	Techniques used to authenticate an individual (i.e., validate an individual's unique identity) by testing for knowledge of secret codes or unique physical traits.
Personal identification number (PIN)	A unique number used to identify a customer when using credit and debit cards in ATMs, etc. A PIN is normally four-to-six digits long and is to be kept secret by the user.
Photochromic	Changes colour with the intensity of incident light, for example, as found in sunglasses that darken in sunlight.
Photoinitiator	An agent that initiates, under the action of light, certain chemical transformations and is consumed.
Photonic crystal	A microstructured material is one that is structured on the scale of the optical wavelength. A diffraction grating is a simple example. If the structure is periodic – regularly repeating – then the material is called a 'photonic crystal'.
Photo-oxidation	The mechanism by which ultraviolet light reduces organic carbon to carbon dioxide. If halogenated organics are present, both CO_2 and mineral acids can be formed.
Piezoelectric	A material that generates an electric charge when mechanically deformed. Conversely, when an external electric field is applied to piezoelectric materials they mechanically deform.
Polyfluorenes	Used in thin film light emitting diodes and thin film solar cells as the active element.
Polythiophenes	Organic materials used to print field effect transistors and electrochemical electronic components.
Polyvinyl-enephenylene	Used in thin film light emitting diodes and thin film solar cells as the active element.
Power levels	In RFID, the levels of power radiated from an interrogator or tag, usually measured in volts/ metre.
Primary packaging	Packaging designed to come into direct contact with the contents. Primary packaging is an integral part of a product : the outer case of a battery, the packet of seeds or the whisky bottle are examples.
Probiotics	Live microorganisms which when consumed improve health and well-being by improving the properties of the resident microorganisms.
PML	Product Mark-up Language, or PML, is a standard language for describing physical objects in EPC systems. It is based on the extensible Mark-up Language (XML). Today, HTML (Hyper Text Mark-up Language) is the common language on which most websites are based, allowing individuals to surf the Internet from their desktops. Where HTML tells a computer how information should be displayed (e.g. what colour and size it should be) – XML goes a step further, telling the computer what kind of information it is viewing (e.g. an address or a telephone number). The PML will go even further, building in layers of increasingly specific data in order to describe physical objects, their configuration and state. In the end, PML: • should translate or contain static data such as dosage, shipping, expiration, advertising and recycling information • should provide instructions for machines that process or alter a product, such as: microwaves, laundry appliances, machine tools and industrial equipment

- may need to communicate dynamic data: information that changes as a product ages or as it is consumed, such as: volume, temperature, moisture and pressure
- may need to include software, or programs, which describe how an object behaves, for instance: a PML file may contain the program which describes how fast the tyres on your car will wear before they need to be replaced, or how fast an object may burn in case of a fire

Programmability In order to be the electronic identifiers of specific objects, RFID tags must have their identity or other data entered into them. This capability is called programmability.

Programmer Some RFID tags can have their contents changed by electronic equipment nearby or connected to them. This equipment is called a programmer.

Protocol A specified procedure or process used to achieve a specific and common result, such as a network communications message format.

Proximity sensor A sensor that detects if something of a defined type is nearby.

Public key system Cipher that employs a pair of mathematically related keys, one that is public knowledge within the computer network, the other known only to its owner. The sender uses the receiver's public key to encrypt data, which may be decrypted only with the related private key.

R

RFAIS Radio Frequency Automatic Identification Systems

RFID Radio frequency identification. Use of small devices that can be electronically identified (and sometimes their data changed) at a distance without line of sight. Although radio is typically defined as 300Hz to 300MHz, nowadays the term even encompasses tags interrogated at 100Hz and others at microwave frequencies (GHz).

RSA A public-key cipher for commercial data that is based on the products of prime numbers; the initials stand for Rivest, Shamir and Adleman, the system's designers. Regarded as more secure than DES, when properly employed.

Range The distance at which a successful read or write can be performed.

Read The decoding, extraction and presentation of data from formatting, control and error management bits sent from a tag.

Read-access User's authorisation to read information stored in a computer.

Read rate The maximum rate at which data can be read from a tag expressed in bits or bytes per second.

Readability The ability to extract data from a tag, often under less than optimal conditions.

Reader Device containing the digital electronics that extracts and separates information from the format definition and error management bits of RFID tags.

Read writer An RFID interrogator that can also write data remotely onto an RFID tag.

Remote A transfer mode that, among other things, allows payment transactions to be conducted over public networks between two or more parties that are physically separated.

Remote magnetics or RM Principle of chipless RFID and EAS smart labels that use magnetic properties of materials instead of electronic circuits in the tag.

Reprogrammable Ability to alter data on a tag while it is attached to the object it identifies. Usually this can be achieved remotely even if the tag is moving.

Retortable Capable of processing in a retort at temperatures above 100°C.

RTLS Real Time Location System. Superset of RFID.

S

SAVANT	RFID readers need to use the same type of database to determine what the EPC number is and which item it is connected to. This database is known as SAVANT. Auto ID Center developed and researched the EPC and SAVANT and other enabling software for the EPC system. It allowed all the sponsor members to agree on how the code should be structured.
SAW	Surface Acoustic Wave. In RFID, a phenomenon where radio waves captured by an antenna are converted by an interdigital transducer into acoustic waves passing across the surface of a piezoelectric material. These can then be reflected by deposited patterns, returning to the transducer at different times, representing bits of data and retransmitted. This form of SAW device is a read only RFID tag. It is chipless and has potential cost and performance advantages over chip RFID tags.
SVC	Stored Value Card, known as an electronic purse in Europe. A card that stores a notional value of money that is gradually spent down at each electronic transaction made using the card. A replacement for cash. Term usually therefore refers to a stored value card that can be used with more than one service provider.
SWCNT	Single-walled carbon nanotubes (SWCNTs) are CNTs that consist of only one graphene layer rolled in on themselves forming a tube shape. SWCNTs are characterized by an outstanding electrical conductivity that MWCNTs cannot compete with.
Scalping	Removal of desirable flavour components of a food or beverage in contact with plastic packaging materials.
Scanner	Part of an RFID interrogator, consisting of antenna, transmitter and receiver electronics. Addition of a microprocessor and additional digital electronics would usually make it an interrogator (reader or read-writer).
Secondary packaging	Packaging designed to contain one or more primary packages together with any protective materials where required.
Segment	A pre-defined and identified set of functionality related data elements values which are identified by their sequential positions within the set. A segment starts with a segment tag and ends with a segment terminator.
Segmental numbering schemes	Barcode numbering schemes are segmented for better accuracy and data handling. Schemes for large and ultra large numbers of RFID tags use segmented numbering, to some extent mimicking barcodes. For example a barcode numbering scheme may involve four tranches of numbers respectively representing manufacturer, type of product etc and the EPC RFID numbering system mimics this with a far larger choice of identities.
Sequential numbering systems	Sequential numbering systems simply allot numbers in sequence such as 1,2,3,4 ... They are usually used in closed systems. Contrary to popular understanding, the UCC EAN segmented numbering systems can be linked compatibly to segmental numbering systems.
SHOT	Serious Hazards of Transfusion (UK monitoring project)
Shrinkage	Theft by retail staff or customers and misplacement or damage to products before sale.
Simple logic chip cards	Unlike the simplest memory chip cards these are able to perform specific application functions beyond the simple decrementing of value or units and have their contents protected by a PIN. Unlike smart cards, they cannot process the information stored on them. Their operation is governed by hardwired logic. They are less expensive than full microprocessor-equipped cards but are not so flexible. They are used in some prepayment cards as a good compromise of cost and security.
Smart and Secure Tradelanes (SST)	Major RFID systems, modelled on the US JTAV military system, are now being installed in civilian logistics systems. The largest recent example, initiated in mid 2002, addresses sea containers in the context of the new terrorism. Over 17,000 sea containers, carrying more than 80 per cent of US imports, arrive daily at US seaports, often located near major cities and industrial centres. The initiative aims to enhance the safety, security and efficiency of cargo containers and their contents moving through the global supply chain into US ports. Driven and initially funded by industry, this initiative called 'Smart and Secure

	Tradelanes' (SST), is focused on container security and tracking and will be built on existing infrastructure and technologies that are both proven, available for immediate deployment, open and adaptable to enable integration of new 'best-of-breed' technologies as they emerge. The industry-driven SST initiative will demonstrate the principles of the US Customs Container Security Initiative (CSI), Customs-Trade Partners Against Terrorism (C-TPAT), and the US Department of Transportation's Transportation Security Agency's (TSA) maritime security initiative, such as Operation Safe Commerce. Implementation of SST began immediately and was operational by year-end. It involves automated information technology infrastructure linking ports such as Singapore, Rotterdam and Hong Kong with major US ports such as Seattle/Tacoma which is the first domestic port to rollout. As in the military, the system improves the tracking and security of shipments coming into the United States through electronic event-driven alerts, anti-tamper systems, virtual inspection and authenticated audit trails. The TAV network is built on existing US and international standards and on the Universal Data Appliance Protocol (UDAP), which allows open 'plug and play' integration of automatic data collection devices, such as RFID and GPS, along with sensors, scanning and biometric systems. Savi Technology report that, initially, the SST rapid deployment implementation calls for an integrated security and container security system to register individuals, authorize roles, and to capture tracking a security events throughout the supply chain. Working with shippers, carriers, service providers, foreign and US port terminal operators, containers will be tracked and automatically authenticated from the point of manufacturing, port of loading, transhipment port and to final discharge in the USA. SST, which will work in close coordination and consultation with government agencies, will develop and test potential auditable security standards for maintaining secure ports, shipping facilities and container tracking and security.
Smart cards	Chip cards which have an onboard CPU (central processing unit), which is able to perform functions on the data stored in it. Microprocessor cards. Some journalists and manufacturers have widened the term to include all chip cards.
Smart packaging	Smart packaging has no official definition but it is a commonly used term. It refers to relatively new packaging features that go beyond simple changes of shape or colour, alphanumerics, graphics, barcodes or better inactive protection. The heart of the subject is responsive features such as coverings that let certain gases out and other gases in or radio tags that return a signal when interrogated electronically. However, some would include modern forms of anticounterfeiting or antitamper feature in the definition.
Sol-gel	A versatile solution process for synthesising inorganic materials, involving the transition of a system from a liquid 'sol' (mostly colloidal) into a solid 'gel' phase.
START	Safer Transfusion with Advanced RFID Technology (US)
Subset	An extract of a message type for use within one industry or application. The subset usually indicates only those segments, elements and code values needed by the industry or application.
Super smart cards	Cards to ISO dimensions with their own keyboard, display and battery, can act as completely self-contained units without the need for a terminal. Their high level of complexity, however, makes them extremely expensive, they are not currently used in road pricing, or much else for that matter.
Superhydrophobic	Extreme water-repellence, where droplets of water on a slightly sloping superhydrophobic surface bead up and roll off without a trace. Contact angles are considerably greater than 140 degrees and in some instances may be as large as 170 degrees.
Susceptor	A metallic patch attached to microwaveable packages of food in which radiant energy produced in the patch by microwaves helps cook the food, often by browning its surface.
Swept RF EAS and RFID	Like the other two EAS technologies swept-RF also uses a transmitter to create a surveillance area where tags and labels are detected. However, the transmitter sends a signal that sweeps frequency, a typical range being from 7.4 to 8.8MHz. The transmitter signal energizes the swept-RF device which usually consists of a flat

circuit containing a capacitor and an inductor (a printed or wound coil) both of which store electrical energy. When connected together in a loop (i.e. in parallel), these components pass energy back and forth (resonate). The resonant frequency is chosen by matching the storage capacity of the coil and capacitor. The tag responds by emitting a signal that is detected by a receiver. Accordingly, sweeping frequency picks up each differently specified inductor – capacitor (LC) pair, one at a time.
In addition to the small tag signal, the receiver also responds to the much larger transmitter signal. By detecting a phase difference between these two signals, and certain other properties of the tag signal, the receiver recognises the presence of a tag and generates an alarm, without being confused by other electronic devices in the neighbourhood.
Swept RF EAS is supplied by Checkpoint, world number two in EAS and many other companies including Lintec and Miyake in Japan and Nedap in The Netherlands. Not all systems are compatible, Though the tag designs are very similar and there is common cause for an interoperable standard. This is of particular interest in Europe and Japan.
Swept-RF is the second most popular EAS technology being of reasonable range and cost, fairly tolerant of bending and of thickness that is intermediate between magnetoacoustic and electromagnetic tags. It is suitable for most packaging.
About five other companies make RFID i.e. multibit versions of Swept RF with modest commercial success.

Syntax rules Rules governing the structure of an interchange and its functional groups, messages, segments and data elements.

T

TAV Total asset visibility. The quest to know the position and status of items of interest at all times. Programs that largely achieve this – usually based on RFID with or without other inputs.
In the Gulf war, the US military had to open 25,000 containers just to find what was in them. The paper labels and manifests had been destroyed by sand and by handling. This was clearly a very serious and mission-critical failure of " asset visibility " and it is one of the things that has led the US military to become one of the most energetic pursuers of so called " Total Asset Visibility, TAV ", the dream being to know the location and status of everything in real time and at all times, right down to the cheapest, least-important consumable. There are obvious potential benefits. They include less danger, greater effectiveness, and lower costs. Less manpower is needed and tasks can be deskilled. However, in many situations TAV, or some progress towards it, can make new things possible. For example a rapid response force may be effective in some distant land when it was previously impossible to mount an operation in the necessary timescale.
Manufacturing industry, the medical services and many other organisations are keenly interested in TAV for reasons that include competitive advantage, service improvement, and the need to survive on slashed budgets. We shall see that many of these organisations need to develop the concept of the Internet of Things to achieve these objectives.

TCP/IP Transmission Control Protocol over Internet Protocol. An industry standard set of rules which allow different types of computer to communicate with each other over the internet.

TFE Thin Film Electronics, a subsidiary of Opticom ASA in Sweden which develops non-volatile thin film electronic polymer memories. One type is on microchips and the other is on low cost flexible polymer film.

TFTC Thin Film Transistor circuit such as an OFET

TTI Time Temperature Indicator. Device ,such as a smart label, that indicates if a product has exceeded a defined combination of time and temperature by changing colour or an electronic device that records the temperature as a function of time

Tag A unique identifier for a component. This usually consists of some electronics containing a unique digitally encoded number and a means whereby the number can be read remotely. Tags can be read only or read-write and some are 'killable' i.e. can be permanently disabled from a distance.

Tertiary packaging	Packaging designed to facilitate handling and transport of a number of sales units or grouped secondary packs in order to prevent physical handling and transport damage. Tertiary packaging usually encloses many secondary packages for transit, crates air ULDs and intermodal containers being examples.
Transdermal	Entering the bloodstream by absorption through the skin. See Iontophoresis
TREAD Act	US legislation requiring recording/reporting of identification codes of vehicle tires for safety i.e. to ensure that the right tire is on the right vehicle. Transportation Recall Enhancement Accountability and Document (US) Act. The tyre is linked to the Vehicle Identification Number (VIN). A recording requirement that has the effect of getting RFID into tyres. This is best achieved with RFID tags embedded in the tyres at manufacture e.g. 125.135Khz, 13.56Mhz or UHF

U

Ubiquitous ID Center	A standards group in Japan promoting an alternative to EPC. Apparently, the motivation includes what it perceives as US dominance of EPC and the restricted nature of the EPC concept. uID can even be used to 'tag' lines of software code, they say. uIC is backed by 170 companies, nearly all of them Japanese. The center expects to have compliant tags available for purchase in 2004.
UCC	Uniform Commercial Code. North American standards body for barcodes and other item identification. See EAN for partnership.
UIC	Ubiquitous Identification Code, eg with barcodes
UID	Unique ID
ULD	Unit Load Device (air conveyance)
UMTS	Universal Mobile Telecommunications System. UMTS is a future mobile communications system which, among other features, will offer direct connection between terminals and satellites. UMTS is one of the ITU's proposals for technologies for world standards for 3rd generation mobile communications (IMT-2000).

V

Vehicle Identification Number (VIN)	Legal requirement of vehicle identification in the USA.
vCJD	Variant Creutzfeldt-Jakob Disease, a rare brain disorder identified in humans, and strongly linked to BSE.
Viscoelastic	A material whose response to a deforming load combines both viscous and elastic qualities. The common name for such a material is 'plastic'.

W

Water activity	The ratio of the vapour pressure of water in a material to the vapour pressure of pure water at the same temperature.
WHO	World Health Organisation
Widget	A small device in a beer can which, when the can is opened, releases nitrogen gas into the beer, giving it a head.
WiFi	Popular name for the IEEE 802.11 family of wireless standards, embraced by the computer community to connect laptops wirelessly to broadband networks in airports, homes, coffee shops, bars and parks. It predates Bluetooth. WiFi has been installed in many laptops and handheld devices but it has yet to be widely used in mobile telephones, partly because it is more power hungry than Bluetooth. It is faster and gives devices longer range. The main frequency used is 2.45GHz. There is some interest in combining WiFi and RFID functionality for certain applications.
WiFi Alliance	A non profit international association that certifies products to ensure interoperability based on IEEE 802.11.
Write	The transfer of data to a tag and the tag's internal operation in storing the data. It may include reading the data in order to verify the operation.
Write rate	The rate at which the information is transferred to the tag, written into the tag's memory and verified as correct. It is measured as the average number of bits or bytes per second in which the complete transaction can be performed.

Z

Zeolite A class of hydrated aluminium silicates of calcium, sodium, or potassium used in ion exchange and as selective absorbents.

ZigBee Alliance A group of about 50 companies developing the IEEE 802.15.4 standard. This is for a relatively low speed, low power consumption wireless network technology. The Alliance targets devices that need long battery lives – months to years – such as remote controls and sensors. It is likely to complement Bluetooth rather than compete with it.

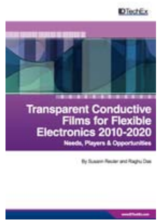
Appendix 2

IDTechEx Publications and Consultancy

Appendix 2: IDTechEx Publications and Consultancy

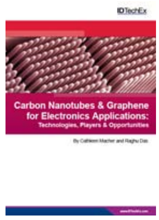
Printed Electronics Reports

Transparent Conductive Films for Flexible Electronics 2010-2020



This report focuses on the requirements and achievements to date on the topic of flexible transparent conductors, where high transparency and high conductivity are required. Worldwide research and design efforts are presented, both from research institutes and companies that are developing the necessary materials and processes. Several technical solutions available are compared, and forecasts are given for the next 10 years.

Carbon Nanotubes and Graphene for Electronics Applications: Technologies, Players & Opportunities



Carbon Nanotubes (CNTs) and graphene exhibit extraordinary electrical properties for organic materials, and have a huge potential in electrical and electronic applications such as sensors, semiconductor devices, displays, conductors and energy conversion devices (e.g., fuel cells, harvesters and batteries). This report brings all of this together, covering the latest work from 78 organizations around the World to details of the latest progress applying the technologies. Challenges and opportunities with material production and application are given.

E-Paper Displays: Markets, Forecasts, Technologies 2010-2020

A variety of e-paper display technologies have been developed which enable completely new products or the introduction of electronic functionality in products where it was previously unavailable. This new report from IDTechEx assesses the full range of non emissive, bistable display technologies, such as electrophoretic, electrochromic, electrowetting, cholesteric LCDs and others. A detailed appraisal of the markets are given with forecasts by application type to 2020.

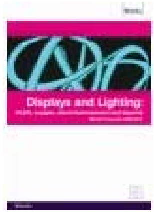
Brand Enhancement by Electronics in Packaging 2010-2020

The report reveals many ways in which brands can create a sharp increase in market share, customer satisfaction and profitability. For brand facing electronics companies that means a market of $7.7 billion by 2020, as analysed in the report. To gain very high volume, and therefore lowest costs, by selling across all industries, basic hardware platforms such as the very low cost talking label must be developed. These are discussed. There are 250 pages and a large number of original figures and tables - over 150.

Organic & Printed Electronics Forecasts, Players & Opportunities 2009-2029

This report brings you new, unique information researched globally by IDTechEx. 20 year forecasts are given for the full range of organic and printed inorganic electronics - including logic, displays, memory, power, electrostatic and RF shielding and sensors. We analyze the market in many different ways, with over 90 tables and figures. They include markets by geographical region, numbers of units and value. Realistic timescales and the emergence of new products are given, as are impediments and opportunities for the years to come.

Displays and Lighting: OLED, e-paper, electroluminescent and beyond

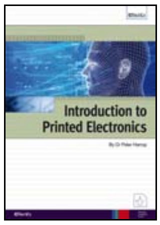


A revolution is in the making. Electronics will never be the same as new applications are spawned. Invisible, origami, edible electronics, low cost materials and manufacturing will lead to the use of electronics in spaces traditionally bare of their functionality. The research and growth of new technologies, along with new materials and processing methods, is resulting in the increasing penetration of innovative electronics and the emergence of new products in the competitive fields of displays and lighting. Eye-catching, animated billboards; large-area, thin, flexible displays with amazing colour contrasts; windows that are converted into surface lighting elements at night.

Inorganic and Composite Printed Electronics 2009-2019

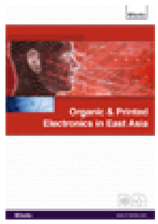
The future $300 billion market for printed electronics is emerging via thin film electronics. The contribution of organic materials to this is greatly publicised and it has attracted over one thousand participants already. However, the best devices being developed usually rely on inorganic or combined inorganic/organic technology that is little publicised. With over 115 tables and figures, it critically compares the options, the trends and the emerging applications and is the first in the world to comprehensively cover this exciting growth area. The emphasis is on technology basics, commercialisation and the key players.

Introduction to Printed Electronics



Your essential report on printed electronics markets, technologies and companies. Printed electronics is a term that encompasses thin film transistor circuits (TFTCs), displays, interconnects, power, sensors and even actuators. Thousands of companies have now entered this market. The printing companies today will be the new electronic giants tomorrow. This report is vital reading to understand the opportunity of the technology, players, needs and timelines, giving global coverage from the biggest printing companies in the Far East to paper and packaging companies in Scandinavia to applications of the technology in the Americas.

Organic and Printed Electronics in East Asia



This is major new 283 page report analysing activity in printed electronics in Asia, where much is happening but relatively little has been reported openly. It covers 196 organisations in Japan, China, Korea, Taiwan, India, Bangladesh, Thailand and Singapore with addresses and contact details, organisational structure, appropriate technology, device objectives, recent and planned announcements, and plans for commercialisation. Much of the information and analysis of trends in this essential reference book is not available elsewhere.

Organic and Printed Electronics in Europe

This is the world's first and only report analysing the subject in depth. It compares and analyses the activities of 267 organisations in 19 countries by technology and region. It gives full contact details of these companies and, where appropriate, examples of patenting performance, research programs and scientific papers presented in 2007 onwards.

Organic and Printed Electronics in North America

This is the world's first and only report analysing the subject in depth. It compares and analyses the activities of 208 organizations in North America by technology and region. It gives full contact details of these companies and, where appropriate, examples of patenting performance, research programs and scientific papers presented in 2007 onwards.

Printed and Thin Film Transistors and Memory 2009-2029

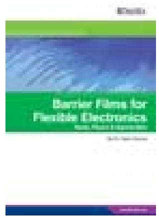
Printed electronics will be a $300 billion market within 20 years. The largest segment will be printed transistors and memory. They will drive lighting, displays, signage, electronic products, medical disposables, smart packaging, smart labels and much more besides. The chemical, plastics, printing, electronics and other industries are cooperating to make it happen. Already, over 100 organisations are developing printed transistors and memory, with first products being sold in 2007.

Printed Photovoltaics and Batteries: Technologies, Forecasts and Players

This comprehensive new report gives a thorough analysis of the subject by the well known consultant and academic Dr Bruce Kahn and Dr Harry Zervos with backing from the IDTechEx team of technical specialists. It covers the science and the manufacturing technology extremely thoroughly yet in an understandable form. 57 companies are profiled and forecasts are to 2018 are given, with projects for ten years after that to 2028.

Barrier Films for Flexible Electronics

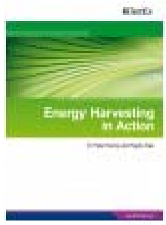
The biggest opportunity for OLED displays and organic photovoltaics is when these devices can be flexible, allowing them to be more robust, versatile and made in large areas compared to conventional displays and photovoltaics. However, many of the materials used in OLED displays and organic photovoltaics are sensitive to the environment, limiting their lifetime. These materials can be protected using substrates and barriers such as glass and metal, but this results in a rigid device and does not satisfy the applications demanding flexible devices. Plastic substrates and transparent flexible encapsulation barriers can be used, but these offer little protection to oxygen and water, resulting in the devices rapidly degrading.



Energy Harvesting and Energy Storage Reports

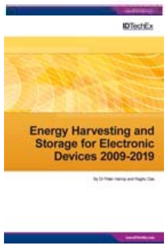
Energy Harvesting in Action

Energy harvesting is the use of ambient energy to provide electricity for small and or mobile equipment, whether electrical or electronic. It is concerned with providing relatively maintenance free, long life equipment, reducing the need for batteries. As is typical in relatively new technologies, there is much hype about energy harvesting and it is tough to find which countries, technologies and suppliers see success and why. This report answers those questions using hard facts.



Energy Harvesting and Storage for Electronic Devices 2009-2019

Energy harvesting is otherwise known as power harvesting or energy scavenging. It is the use of ambient energy to power small electronic or electrical devices. That means solar cells on satellites, heat powered sensors buried in engines, vibration harvesting for helicopter electronics and the wind-up radio or lantern. However, there are also several more esoteric options.



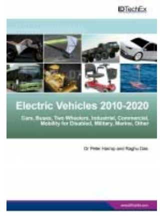
Batteries Supercapacitors

Batteries, Supercapacitors, Alternative Storage for Portable Devices 2009-2019

Energy storage for small devices, the subject of this report, forms by far the largest mobile energy storage market today, being much larger and faster growing than the market for heavy energy storage such as automotive and enjoying greater innovation for the future, including transparent and printed batteries. The report mainly concentrates on batteries and capacitors - including the rapid adoption of supercapacitors and hybrids of the two.

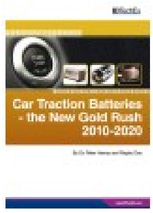
Electric Vehicles

Electric Vehicles 2010-2020



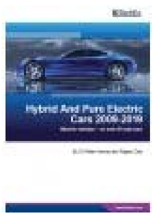
This report, brand new for 2010, is based on ten years of researching the subject, intensive desk research, visits and interviews. There are chapters on Heavy Industrial, Light Industrial and Commercial, Mobility for the Disabled, Two Wheelers, Golf Cars, Cars, Military, Marine and Other vehicles. That even extends to electric mobile robots, surveillance jellyfish and other Autonomous Underwater Vehicles AUVs, bats and electric aircraft. Detailed forecasts for these vehicle categories by numbers and value and the key components are provided for 2010-2020. The trends, technology and planned vehicles are clarified in 185 figures and 58 tables including the historical context. Winning and losing strategies are evaluated. Timelines are given of events to come.

Car Traction Batteries - the New Gold Rush 2010-2020



This report is intended for industrialists, investors, market researchers, legislators and others interested in the large new market now being created for batteries that propel hybrid and pure electric cars along the road. It will also inform those studying associated technology and industrial and government initiatives and legislation. The report is suitable for the non technical reader, with introductory appendices and glossary for those new to the subject. However, there are many comparison graphs, tables and sections concerning technical aspects, so those with appropriate technical training will find much to interest them as well.

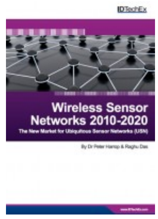
Hybrid And Pure Electric Cars 2009-2019



Electric vehicles just became exciting. For 111 years, electric cars that rely only on a battery - "pure EVs" - have had a range of only 30-50 miles and the humble golf car has been the only type selling in hundreds of thousands every year. However, huge changes have been announced in 2009. Electric vehicles will penetrate the market rapidly to constitute 35% of the cars made in 2025 - 25% hybrids, 10% pure EV. Any motor manufacturer without a compelling line up of electric vehicles is signing its death warrant.

RFID and Smart Label Reports

Wireless Sensor Networks 2010-2020

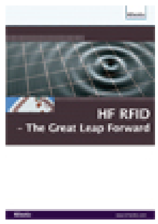


Wireless Sensor Networks WSN - self organising, self healing networks of small "nodes" - have huge potential across industrial, military and other many other sectors. While appreciable sales have now been established, major progress depends on standards and achieving twenty year life..

RFID Forecasts, Players and Opportunities 2009-2019

In 2009 the value of the entire RFID market will be $5.56 billion, up from $5.25 billion in 2008. This includes tags, readers and software/services for RFID cards, labels, fobs and all other form factors. By far the biggest segment of this is RFID cards, and $2.57 billion of the total $5.56 billion being spent on all other forms of RFID - from RFID labels to active tags..

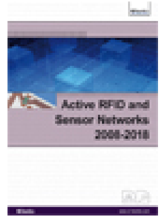
HF RFID – The Great Leap Forward



This unique 180 page report details the great leap forward in HF RFID technologies, with unprecedented advances hitting the market in the next two years and some earlier inventions entering the mainstream at the same time. It is an unbiased assessment, with the problems of all these approaches being assessed as well as the opportunities.

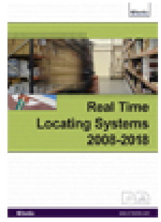
Active RFID and Sensor Networks

Active RFID is little reported but its use is growing rapidly. Already several applications have been above $100 million and there is more to come. Learn how to use it and how to sell it. Ten year forecasts from 2007 to 2017 show how Active RFID will develop in the years ahead



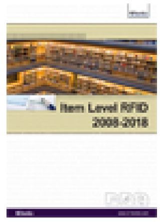
Real Time Locating Systems (RTLS)

This unique report covers the technology and market for what will be a multi-billion dollar market by 2013. It includes active RFID devices based on WiFi, etc, and over 60 case studies. There are also detailed forecasts.



Item Level RFID – Forecasts 2008-2018 and 100 Case Studies

Item level RFID will shortly be the largest and most prosperous sector, driven by anticounterfeiting, archiving, standing assets and supply chain efficiency of high priced products. This unique new two part report gives the full picture and ten year forecasts.

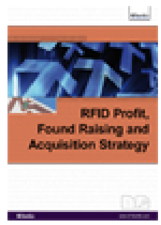


RFID Smart Cards, Tickets and Near Field Communication

This major new report, globally researched in 2006, compares and contrasts contactless smart cards and tickets with NFC and other methods of using the mobile phone to replace the card or ticket. It has over 110 figures and tables and three appendices of further information. It forecasts progress for the next ten years with contactless smart cards, tickets and RFID enabled phones, from technology to applications, numbers and values

RFID Profit, Fund Raising and Acquisition Strategy

There is a great need for profit optimization and careful product positioning and repositioning in the frenetic but unforgiving RFID market that is increasing ten times to become a $26 billion business in 2016. RFID is entering most sectors of corporate, public and private life so understanding how to create enduring profit from such a choice of designs and applications, software, hardware and services, calls for great care and modern management tools.



Printed and Chipless RFID Forecasts, Technologies & Players 2008-2018

This report analyzes the prospects of the end game of RFID - ultra low cost tags that do not include a silicon chip. We assess the technologies that are available and emerging, players, challenges, the opportunity and give ten year forecasts.

RFID in Australasia

Ten year forecasts of tag numbers, unit prices and value, plus systems projections are presented. The total market by country is given. There is a full analysis of how IDTechEx sees the number of tags sold increasing tenfold over the next ten years and the market rocketing to around US$632 million in 2017. This 185 page report has over 60 tables and figures and more than 50 case studies.

RFID in China

Researched over 12 months by IDTechEx analysts including Chinese native Ning Xiao, this report covers over 150 companies developing RFID in China, actual and potential sales, successes and impediments, standards, frequencies and case studies. Your complete guide to the RFID market in China.

Application Specific Reports

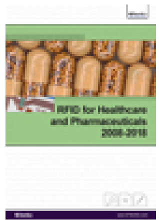
RFID for Animals, Food and Farming 2008-2018

This report concerns RFID in the food supply chain, from arable farming and livestock to presentation in the retail store. We even cover some benefits if the RFID tag stays on the food to the private home. Because the tagging of pets and use of RFID on animals and in conservation are closely allied topics, we cover these as well. Consumers also demand more information, as do the police and customs. This report analyses the use of RFID and allied technologies, with a profusion of case studies from across the world.

RFID in Airports and Airlines 2008-2018

RFID is an extremely powerful enabling technology in airports and aircraft, serving to improve security against criminal attack, safety against general hazards, efficiency, error prevention and data capture and to remove tedious tasks. It can even create new earning streams where it makes tolling feasible without causing congestion and where new airport "touch and go" cards offer new paid services without delays.

RFID in Healthcare and Pharmaceuticals 2008-2018



The RFID business is growing so fast that few applicational sectors can beat that scorching rate of growth. Healthcare is one of them thanks to the new tagging of drugs, real time location of staff and patients and other developments including automated error prevention. This unique report gives a full technical and market analysis illustrated by over 70 case studies. It is a vital resource for the healthcare profession and all who wish to support it.

RFID for Postal and Courier Services 2008-2018

Detailed ten year forecasts are given plus a full explanation of the technologies. In detail, there are 30 new case studies of RFID in action in the postal and courier service in North America, Europe, the Middle East and East Asia. The major breakthroughs that will provide future success are discussed. Postal services ignoring this accelerating change will become uncompetitive and suppliers missing out will regret it.

Apparel RFID 2008-2018

Apparel RFID is the first big retail RFID success. This report is unique in analysing the use of RFID in the apparel value chain from tagging cloth in manufacture to retail fashion and rented apparel. 138 users and suppliers are profiled. From Chile to Canada and Sweden to Taiwan, there is something to learn from all of them, not just from the unusually broad approach in Germany, Italy, China, Japan and the USA. This industry is on the move in a manner unmatched almost anywhere else in the RFID market.

IDTechEx Subscription Services

RFID Case Studies Knowledgebase – the largest in the world

Over 3,750 case studies, over 4,800 organisations, 109 countries and growing rapidly. The variety of case studies in this Knowledgebase is a salutary reminder that, although the supply chain is seen as ultimately the biggest application for RFID, the less hyped applications such as Libraries & Archiving, Passenger & Personal Transportation, and Healthcare, are moving ahead extremely rapidly. This is a searchable electronic database, with many links and slide presentations, by far the largest available.

Also available from IDTechEx

Consumer Smart Packaging
Electronic Smart Packaging
Smart Packaging
Food and Livestock Traceability
Food and Livestock Traceability Encyclopedia
RFID Food and Livestock Case Studies
Near Field UHF RFID vs HF for Item Level Tagging
Short Range Wireless
The Encyclopaedia of Printed Electronics
The IDTechEx RFID Encyclopedia
Thirty RFID Case Studies in Logistics
Thirty RFID Case Studies in Retail

Introduction to IDTechEx Consultancy

IDTechEx provides independent consulting, research and analysis services on printed/organic electronics, RFID, smart labels and smart packaging. We uniquely offer global insight into these topics and provide both technical and commercial advice from experienced industry experts. We help companies throughout the value chain from inventors and venture capitalists to value added suppliers, system integrators, major users and facilities managers.

Our services include:

- Evaluating and assessing the market potential and position of new products
- Market analysis by application type
- Technology forecasting and benchmarking
- Company benchmarking, profiling and SWOT analysis
- Needs by industry and new opportunities
- Company training and brainstorming masterclasses
- Business due diligence for acquisitions and investments
- Assistance with fundraising

Our technical graduates are particularly well informed about the technologies and appropriate enabling technologies and unusually rapid in response to customer's requirements and work hard to "see the future". IDTechEx sponsor relevant academic and not-for-profit organisations to support the industry and this also enables us to provide our clients with the latest knowledge which they may not have access to. For example, we are sponsors of EPCglobal, SAL-C (Smart Active Labels Consortium), Ubiquitous Computing (Japan) and active members of EuroTag. IDTechEx is also a member of AIM, IEE and the Institute of Packaging. This support does not, however, conflict with our strict independence.

Our publications, conferences and consultancy services are global in reach. Our staff includes native foreign speakers for example and we regularly visit companies and conferences across the whole world and our conferences are in the US, Europe, Middle East and Asia. We have provided consultancy services in Europe, the USA, Japan and Korea.

Our clients include:

- Hewlett-Packard, USA
- Schiphol International Airport (Amsterdam)
- Whirlpool Europe, Italy
- ADT Security Services, Inc. / Tyco Fire & Security
- Shell Limited
- Manchester Airport, UK
- PolyTechnos, Germany
- Plastic Logic, UK
- Guinness UDV, UK

- Cazenove Private Equity, UK
- Power Paper, Israel
- Magnadata, UK
- Amadeus Capital Partners, UK
- Rexam, USA Esprit, UK

Our confidential clients include:

- Several of the world's largest chemical companies, USA
- A global leader in EAS and smart labels, USA
- Three of the world's largest companies in packaging and printing, USA/Europe
- Several of the most famous Japanese electronics companies

IDTechEx Services

We have a high level of technical skill, with most staff being at degree standard, many PhDs, and several being globally acknowledged experts in their field. However, we do not design products or systems or sell them on your behalf. We assess them, conceive new product ideas, conduct market research, help with business plans, offer tutorials, help raise funding, find licensees for inventions, advise on sales strategy, investments, acquisitions, profit improvement and so on. We update our publications very frequently. For example, our web journal Smart Labels Analyst is monthly and, where our reports cover fast-moving topics, we update them every three months.

Recent work includes:

- Assessing and forecasting organic photovoltaics commercialisation for a major Japanese chemical company
- Assessing new printed conductor technologies for a major materials company
- Assisting in presentations and fundraising for an active RFID company
- Teach-ins and brainstorming of strategy at Amsterdam Schiphol Airport, Shell oil company, a major food manufacturer, clothing retailers and a microchip manufacturer
- Internal training courses in both RFID and smart packaging in the US and UK for a major packaging company
- Assessing optimal technologies and materials for ultra low-cost smart labels of various types and business plans for such products for various companies
- Assistance with strategy of a security printer
- Business due diligence of a planned acquisition for a US multinational and similar work for two venture capitalists planning certain investments.
- Recent work includes business due diligence for PolyTechnos of Munich, Germany for investment in Plastic Logic, UK.
- Evaluating and assessing the market potential and position of new products and technologies in development
- Helping startups in France, UK, USA, Sweden and New Zealand
- Strategic advice for a major Australian power company

Case Studies - Printed Electronics

Case Study 1:

A $40 billion company who was looking to participate in the printed electronics market and leverage their expertise as a global materials company. It needed to understand how it could get involved in this sector based on unmet needs, companies to potentially partner with or even acquire, and company progress, particularly in East Asia.

IDTechEx profiled over 150 companies around the world, in particular those in East Asia. Full patent searches, company SWOT reports and analysis was given. Recommendations of partners and unmet needs (i.e. opportunities for the client) were given.

The client invested in one of our recommended companies and grew effort on topic accordingly. The client later has attended IDTechEx events for ongoing market updates.

Case Study 2:

A $60 billion company sought impartial assessment of their technology and applications they could address over different time scales.

IDTechEx analyzed their technologies versus others in the industry to identify what still needed to be done. IDTechEx then looked at all the relevant applications, their technology needs and timelines, and recommended first products.

The client grew their R&D activities to focus on unmet needs we identified. The client gave IDTechEx a second follow on study and has attended many IDTechEx events and bought our research publications for ongoing updates.

Case Study 3:

A German Venture Capital wanted us to provide due diligence prior to their investment in a UK based plastic electronics startup.

IDTechEx provided due diligence on the company and their opportunities in light of the competitive landscape and applicational demands.

The VC company invested in the company on our recommendation. The target company has gone on to raise significant funds in later rounds and become a globally recognized leader in its field.