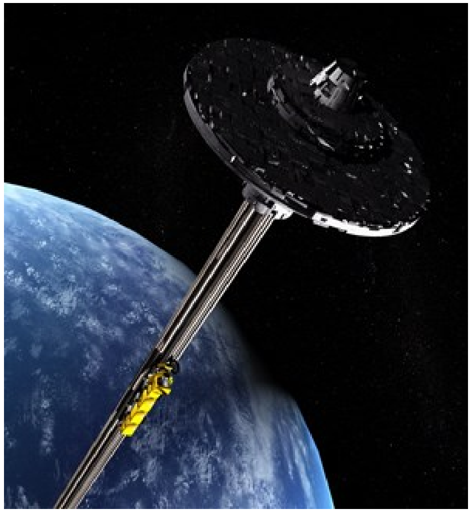
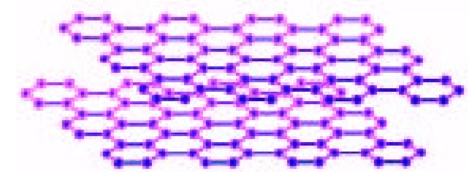


http://www.cosmosmagazine.com/node/2435

Carbon Nanotubes

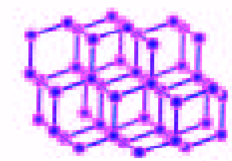
http://onorbit.com/node/825

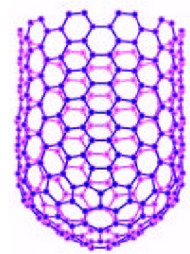
Why do Carbon Nanotubes form?

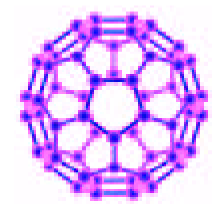

graphite

Carbon → Graphite (Ambient conditions)
sp^2 hybridization: planar

Carbon → Diamond (High temperature and pressure)
sp^3 hybridization: cubic


diamond


(10, 10) nanotube


C_{60} fullerene

Carbon → Nanotube/Fullerene (certain growth conditions)
sp^2 + sp^3 character: cylindrical

Finite size of graphene layer has dangling bonds. These dangling bonds correspond to high energy states.

Nanotube formation → Eliminates dangling bonds + Increases Strain Energy → Total Energy decreases

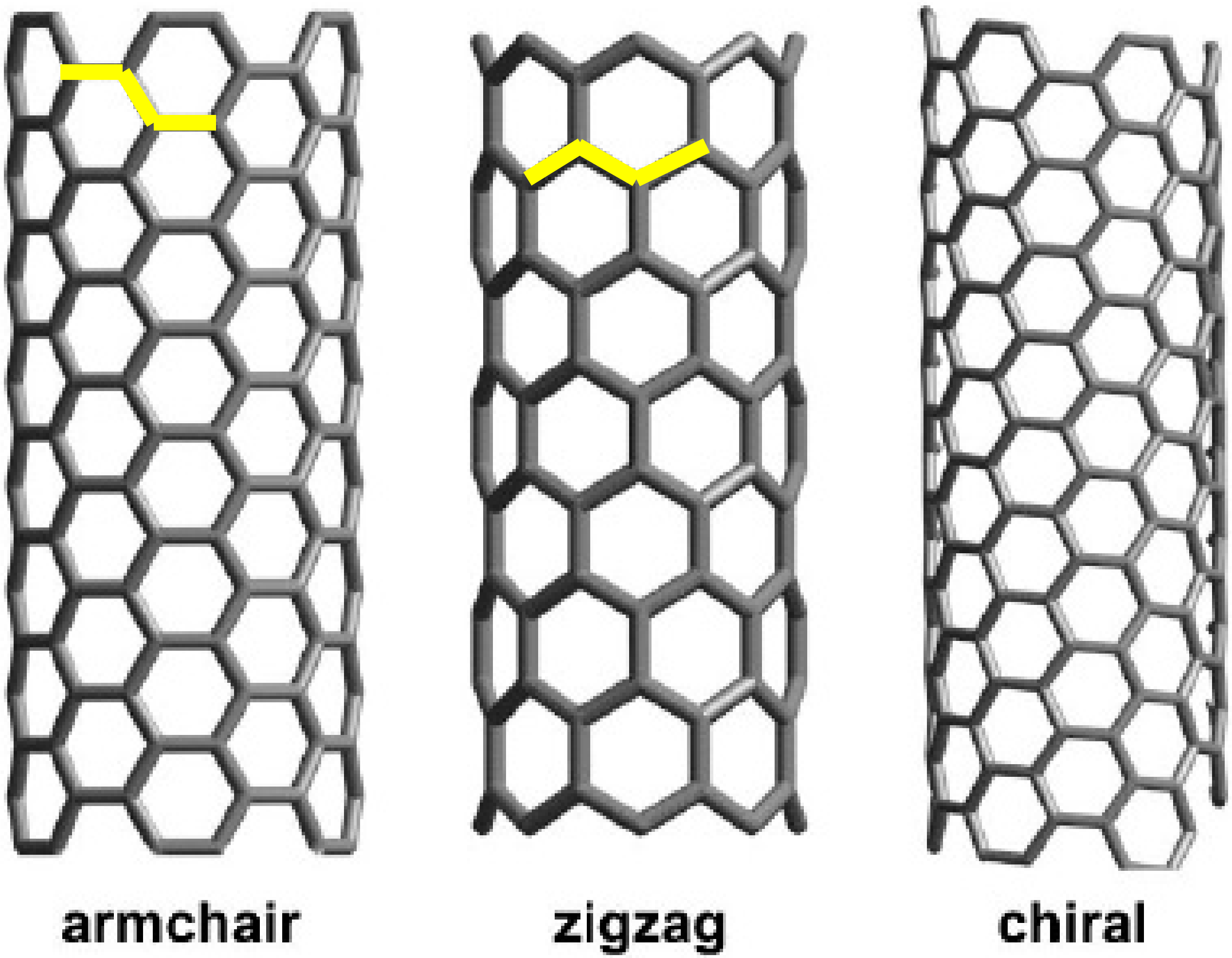
CNT types

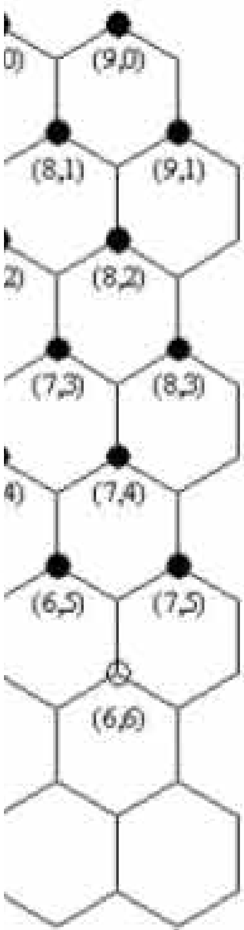
Based on symmetry

(n,m)

n= colu
m= row

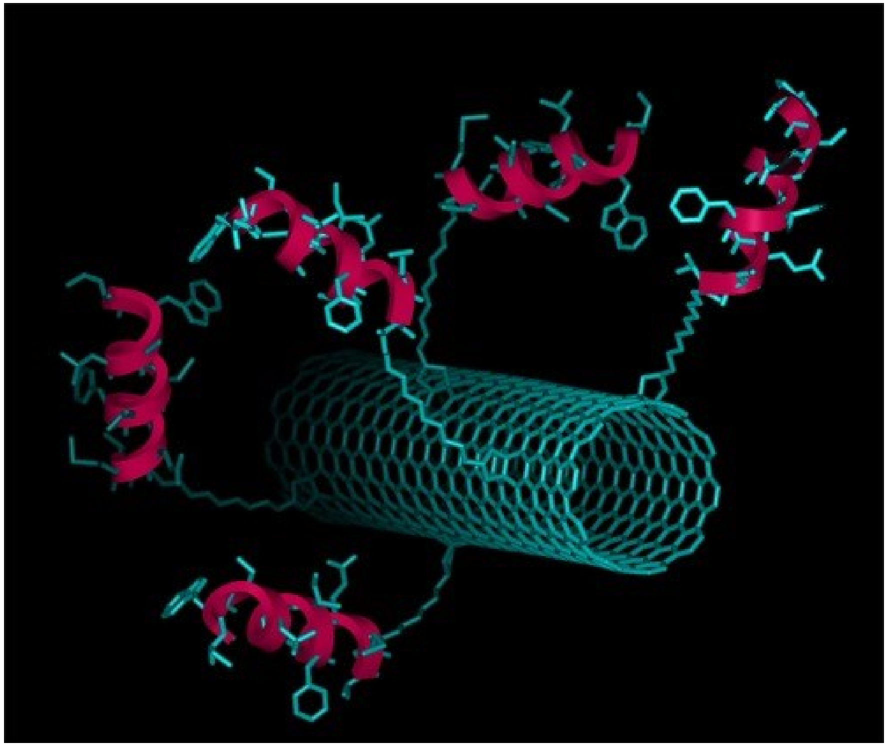
If:
n=m →
n≠m →
(n,0) →





Why Should We Care?

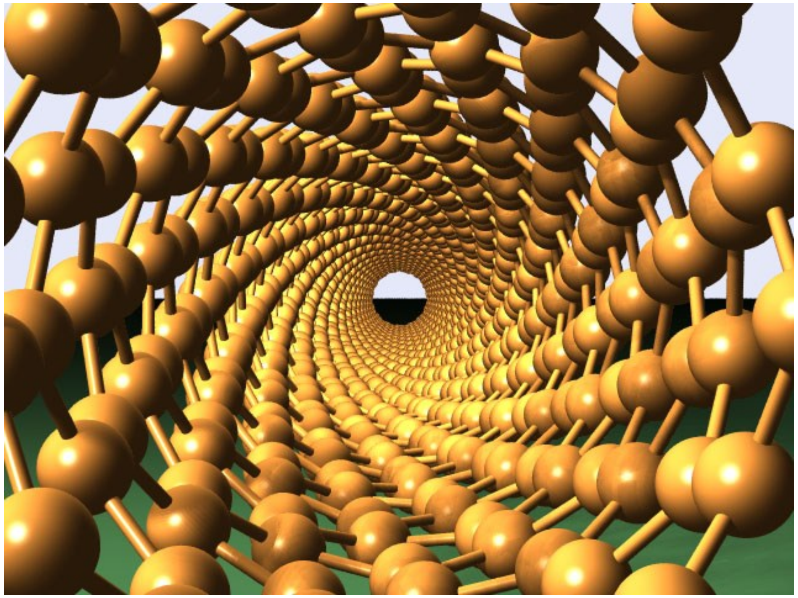
- Unique properties
- Material of the future
- Seemingly infinite applications
- Possible health issues



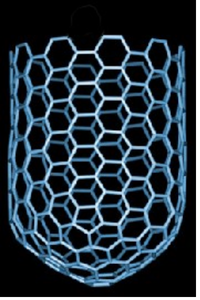
http://www-ibmc.u-strasbg.fr/ict/images/CNT_Peptide.jpg

Properties

- 132,000,000:1 Length-To-Diameter Ratio
- Diameter of 3 to 9 nm
- Lengths in the millimeter range
- Efficient electrical conductors
- Can act as both thermal conductors and thermal insulators



http://brent.kearneys.ca/wp-content/uploads/2006/05/carbon_nanotube.jpg



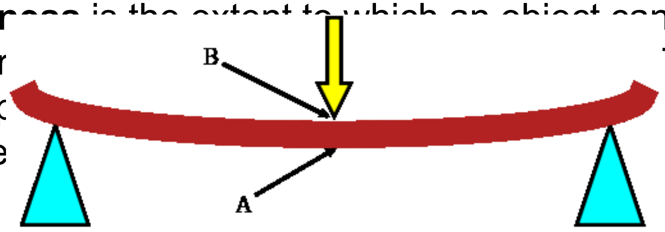
CNT Properties

Carbon nanotubes are the strongest ever known material.

- **Young Modulus (stiffness):**

Carbon nanotubes	1250 GPa
Carbon fibers	425 GPa (max.)
High strength steel	200 GPa

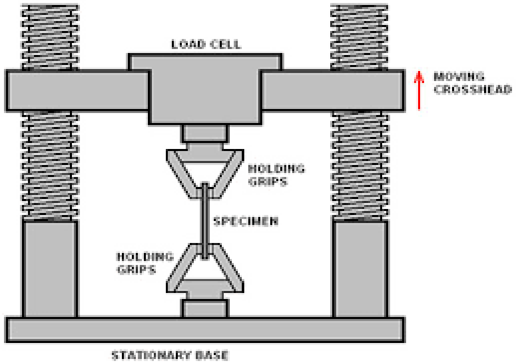
Stiffr n resists
defor The
comp ty: the
more



- **Tensile strength (breaking strength)**

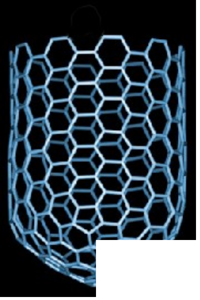
Carbon nanotubes	11- 63 GPa
Carbon fibers	3.5 - 6 GPa
High strength steel	~ 2 GPa

capaci ıstand loads
tendin



- **Density:**

Carbon nanotube (SW)	1.33 – 1.40 gram / cm^3
Aluminium	2.7 gram / cm^3



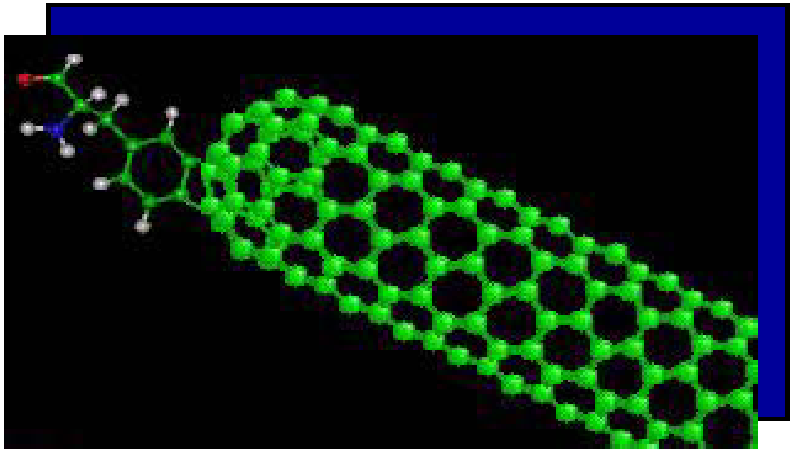
CNT Properties (cont.)

- Electrical conductivity six orders of magnitude higher than copper

- Can be metallic or semiconducting depending on chirality
    - ‘tunable’ bandgap
    - electronic properties can be tailored through application of external magnetic field, application of mechanical deformation…

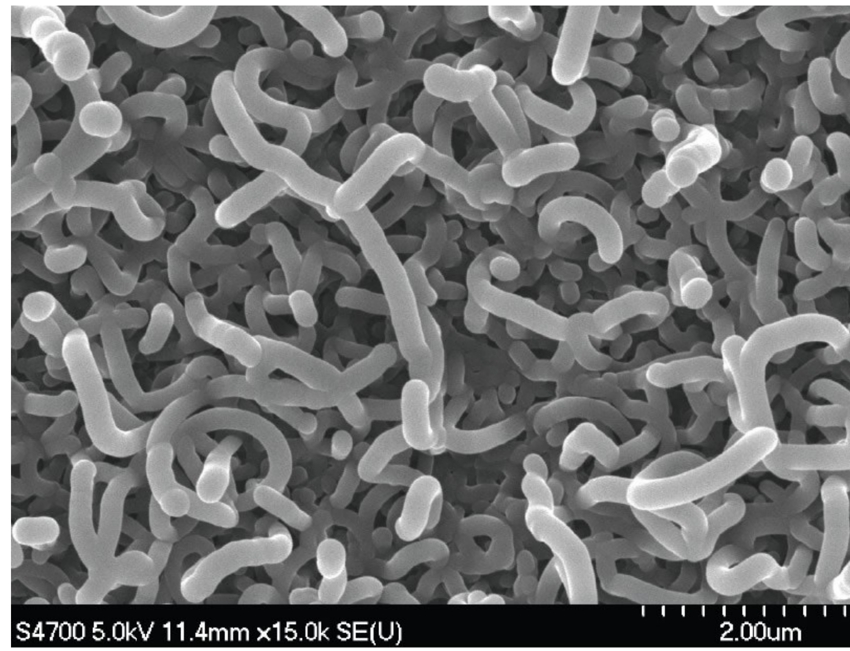
- Very high current carrying capacity

- Excellent field emitter; high aspect ratio and small tip radius of curvature are ideal for field emission



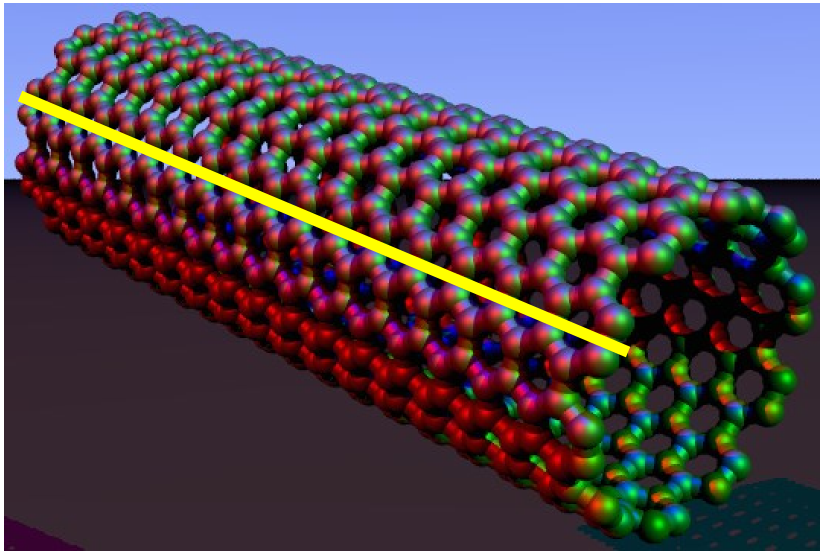
Toxicity

- Research is still in the early stages
- In rodents, carbon nanotubes have been found to cause several lung issues
- The needle-like shape of the fibers is similar to that of asbestos

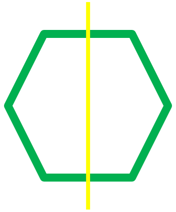


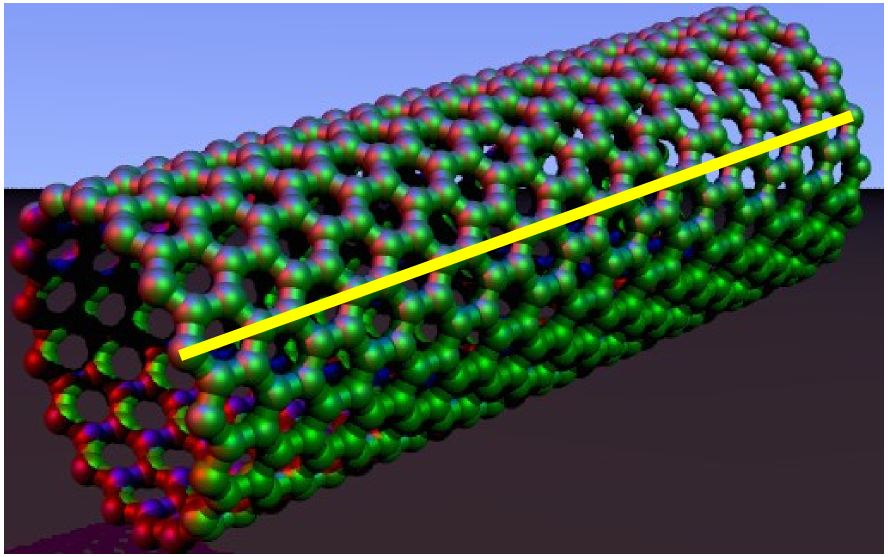
http://www.phy.mtu.edu/newsletter/research/FatNanotubes.jpg

Single-Wall Nanotube (SWNT)

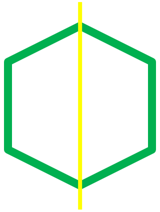


Armchair



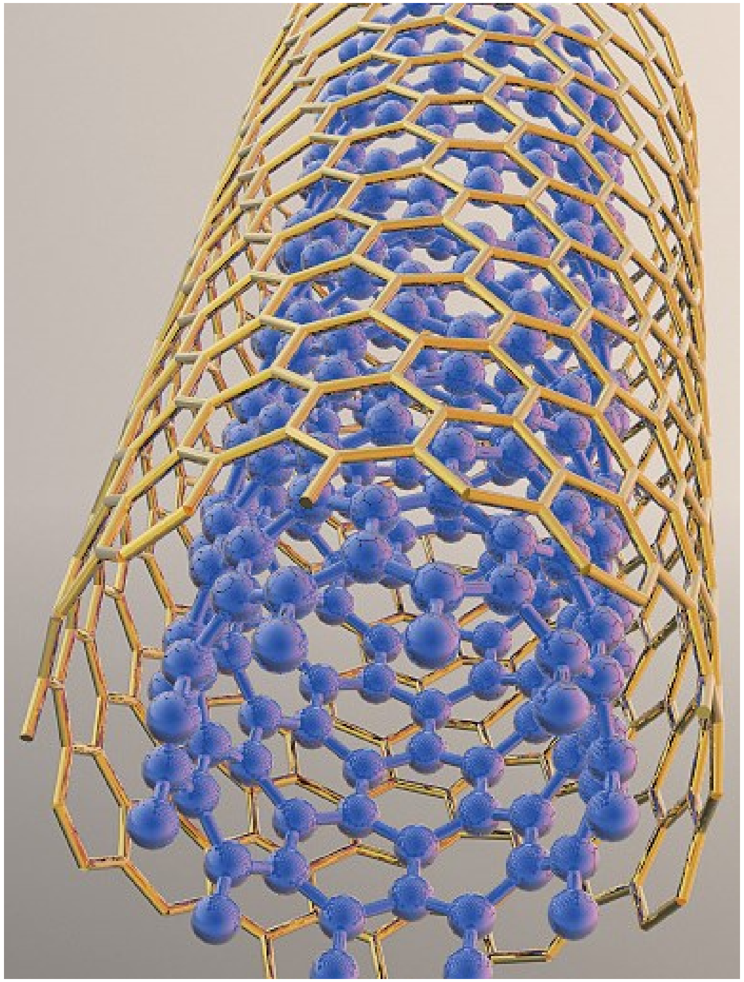


Zig-Zag



Multi-Walled Nanotubes (MWNT)

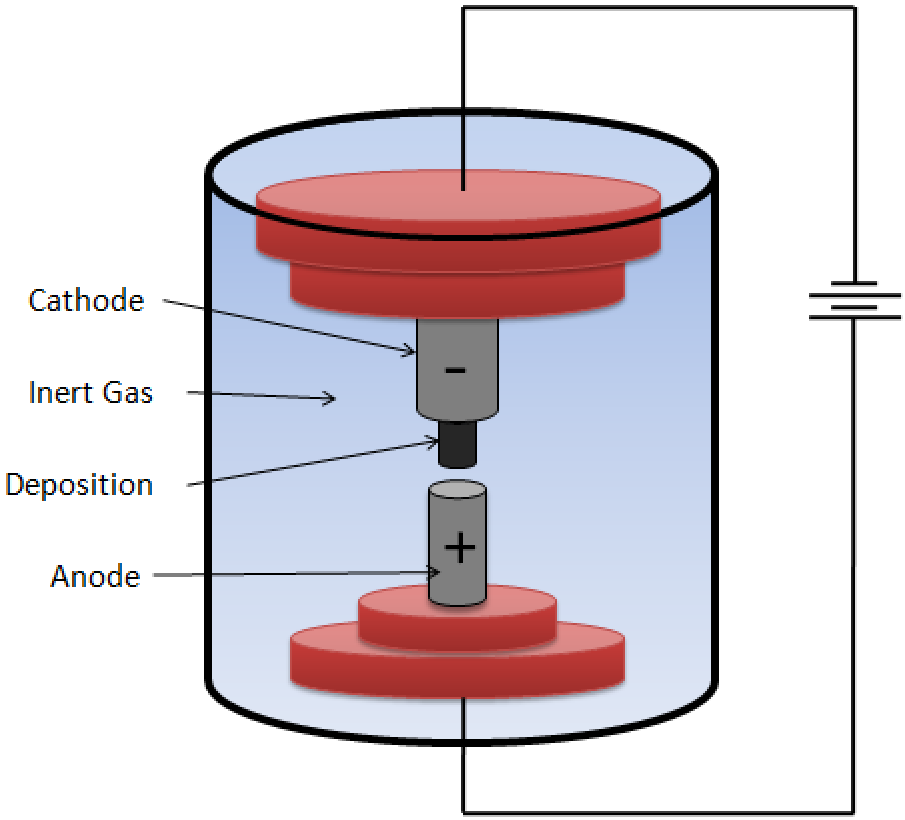
- Multiple rolled layers of graphene sheets
- More resistant to chemical changes than SWNTs



http://www.siemens.com/innovation/en/about_fande/corp_technology/partnerships_experts/uc_berkeley.htm

SYNTHESIS

I. Arc discharge method

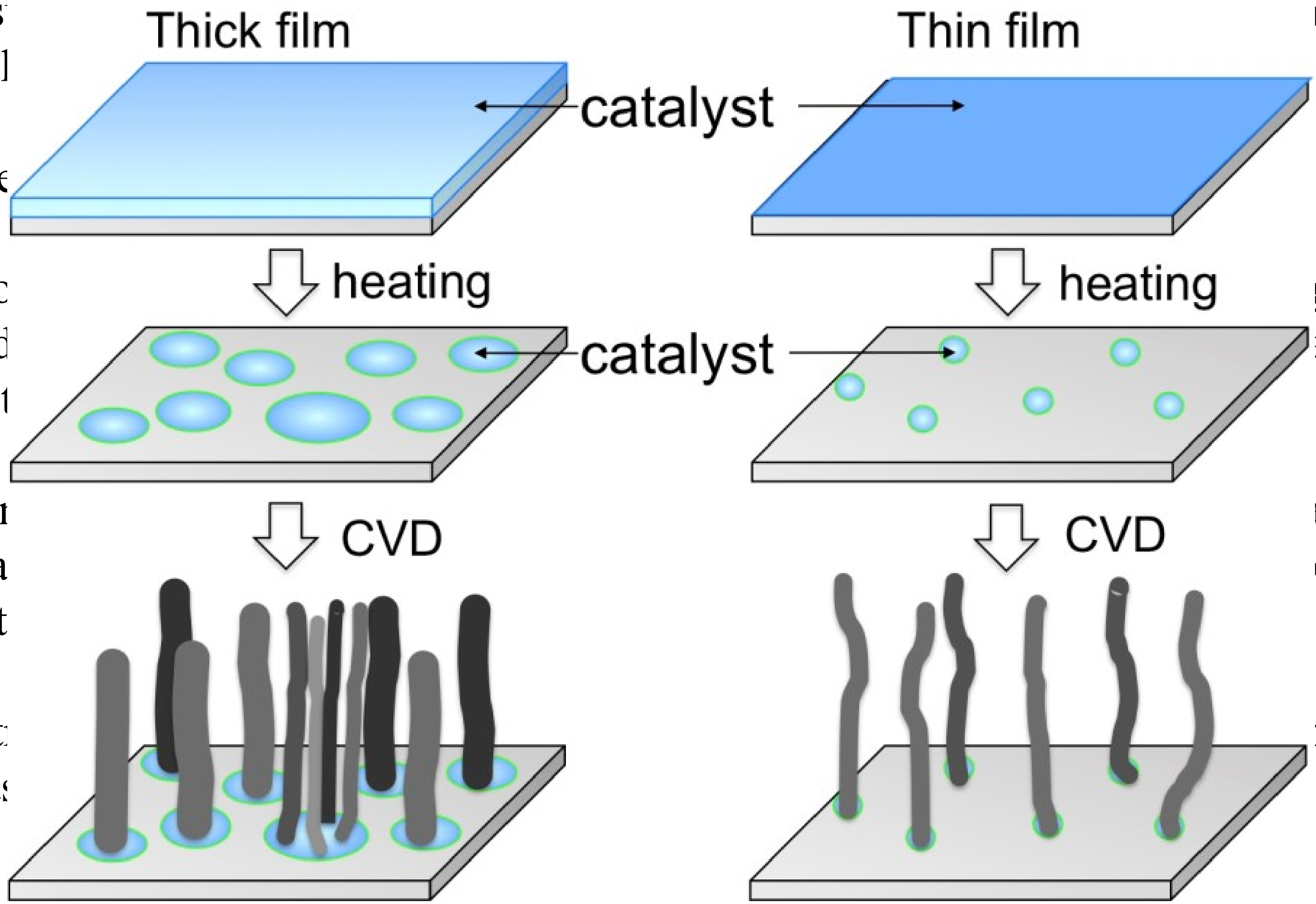


- The most c… CNTs.
- Carbon con… ecause of the high-discha…
- The yield f… produces both single- and … 50 micrometers with few st…
- Produces a … es further purification … e residual catalytic metals pres…

SYTHESIS

II. Chemical vapor deposition (CVD)

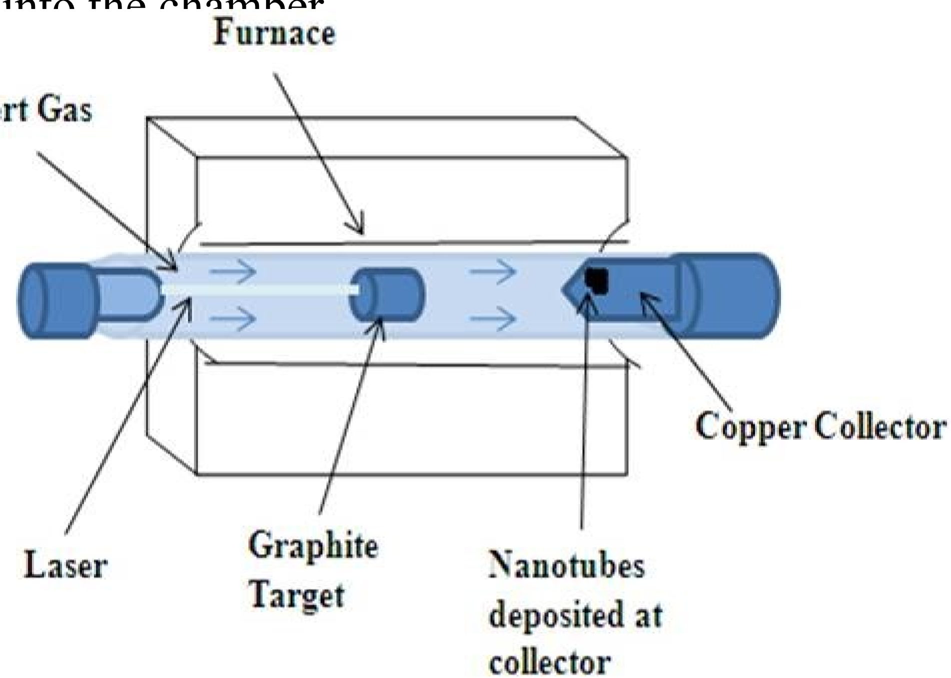
- A s … only
  nicl
- The
- twc … gen or
  hyd … anol or
  met
- Nar … s is broken
  apa … the edges
  of t
- Att … on with
  reas



SYNTHESIS

III. Laser ablation

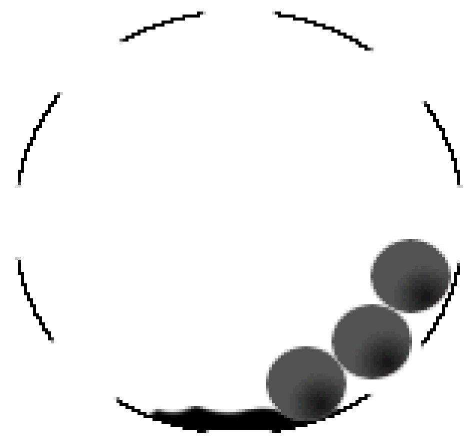
- A pulsed laser vaporizes a graphite target in a high-temperature reactor while an inert gas is bled into the chamber.



- Nanotubes de ... orized carbon condenses.
- A water-coole ... ne nanotubes.
- The laser abla ... rily single-walled carbon ... by the reaction temperature .
- However, it is ... al vapor deposition.

Ball Milling

- Powder graphite is placed in a stainless steel container
- Argon gas is used
- Process occurs at room temperature
- Powder is then annealed

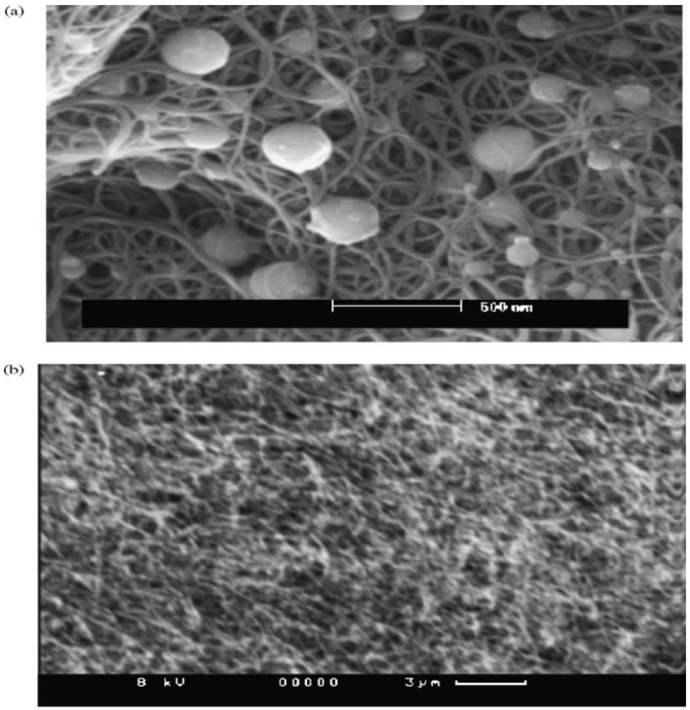


http://www.rsphysse.anu.edu.au/nanotube/

Electrical Application: FED

Field Emission Display (FED)

- Uses electron beam to produce color images (FED)
- Traditionally cathode ray tubes are used but recently more focus on using carbon nanotubes
- NASA is researching this technology to use in space exploration



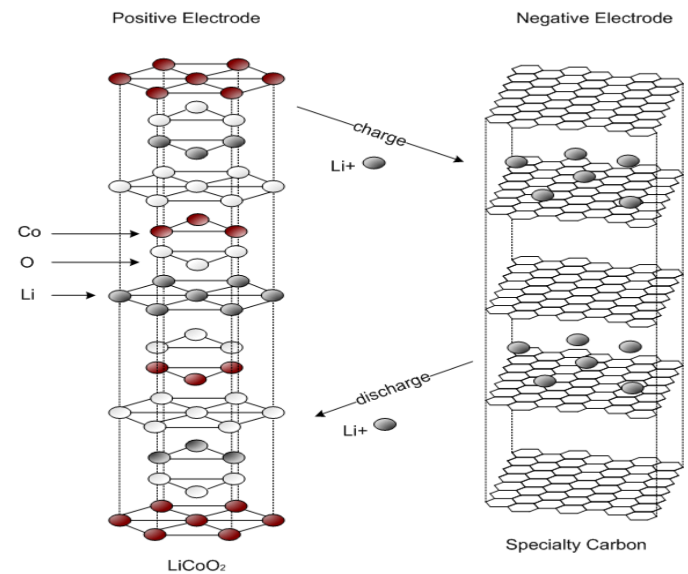
Energy Storage: Lithium batteries

- Nanotubes have the highest reversible capacity of any carbon material for use in Lithium ion batteries

- Nanotubes have intrinsic characteristics desired in material used as electrodes in batteries and capacitors

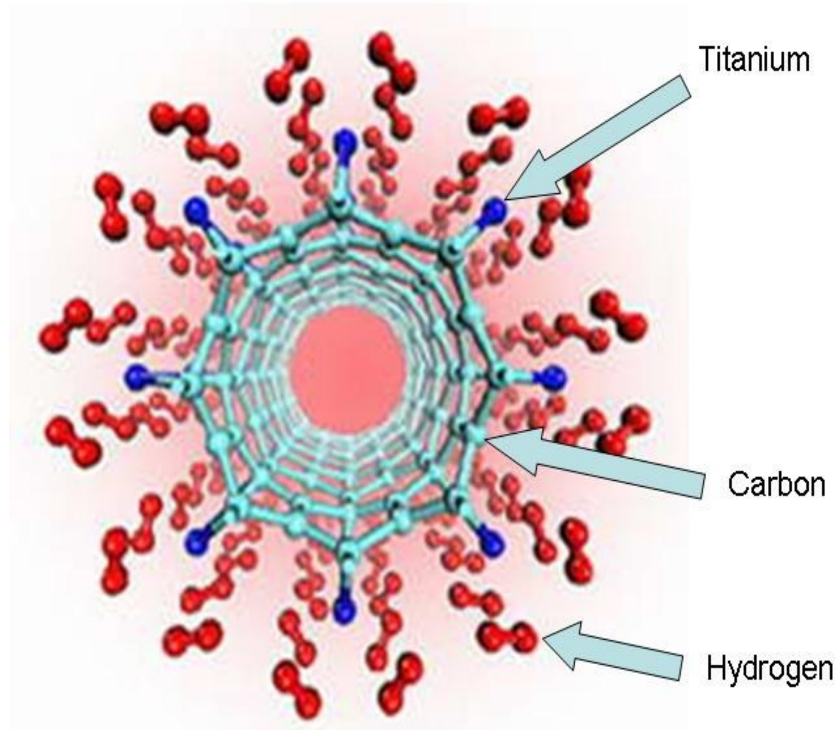
- Nanotubes are outstanding materials for super capacitor electrodes

- They also have a number of properties including high surface area and thermal conductivity that make them useful as electrode catalyst supports in Polymer Electrolyte Membrane (PEM) fuel cells



Energy storage: Hydrogen storage

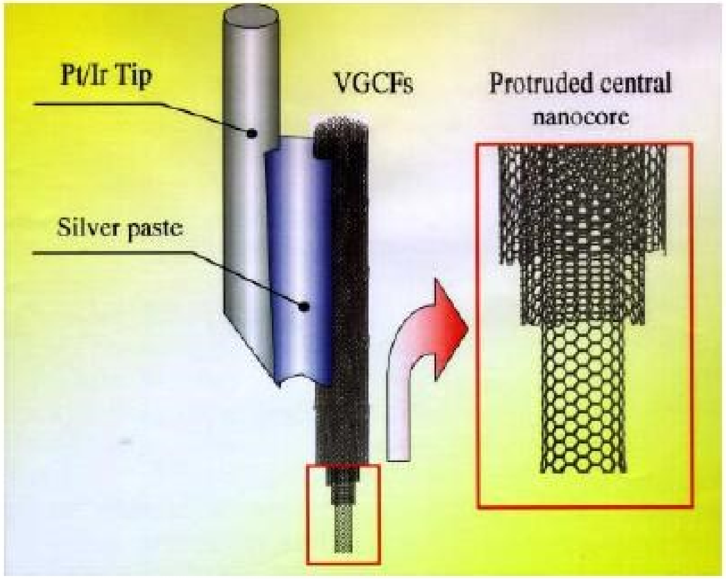
- Single-walled carbon Nanotubes can store hydrogen
- Nano tube technology will meet the challenge of storing hydrogen and releasing them adequately in hydrogen fuel car in future
- Physisorption and chemisorption are mechanisms used for hydrogen storage in carbon nanotubes

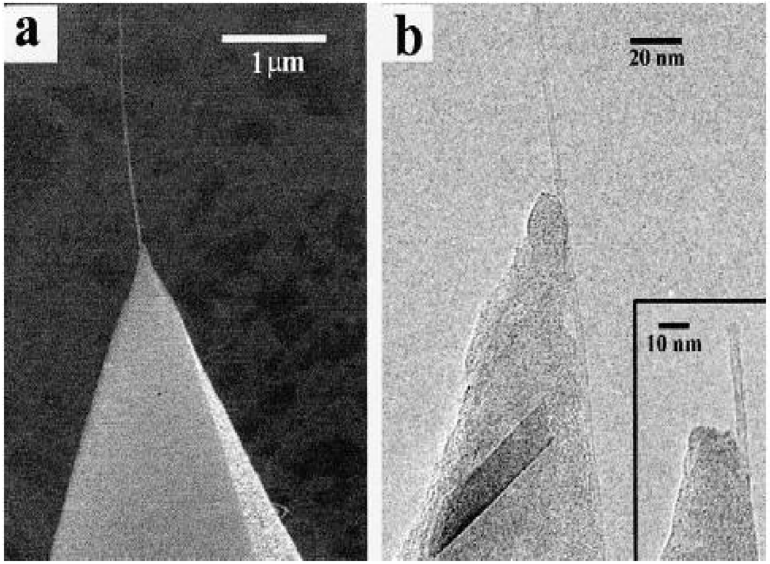


Biological applications: AFM tips

Carbon nanotubes as AFM probe tips:

1. Small diameter – maximum resolution

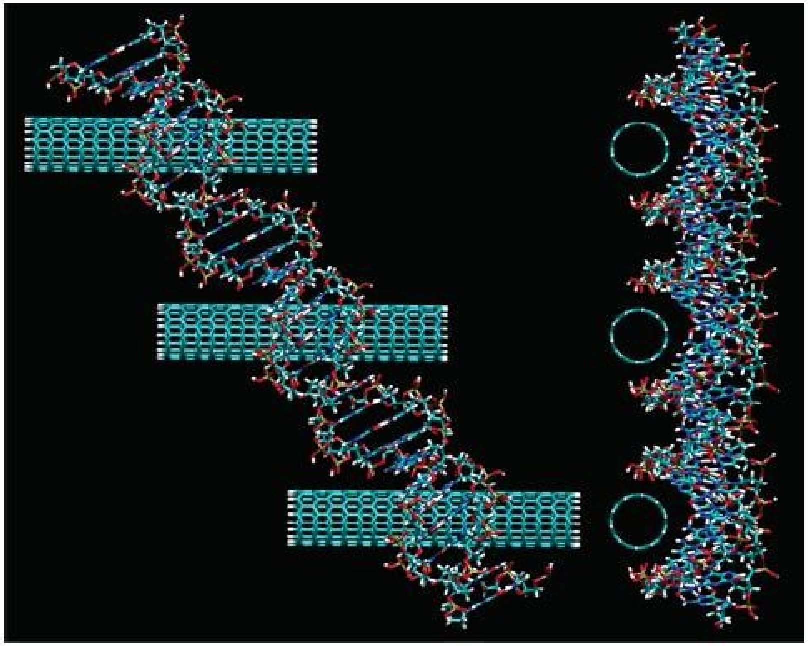




Resolution of ~ 12nm is achieved

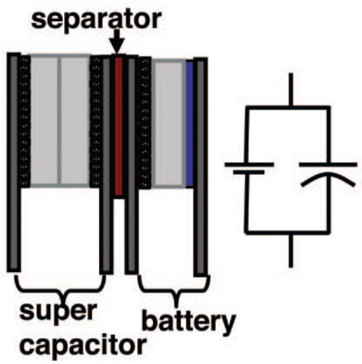
Biological applications: DNA sequencing

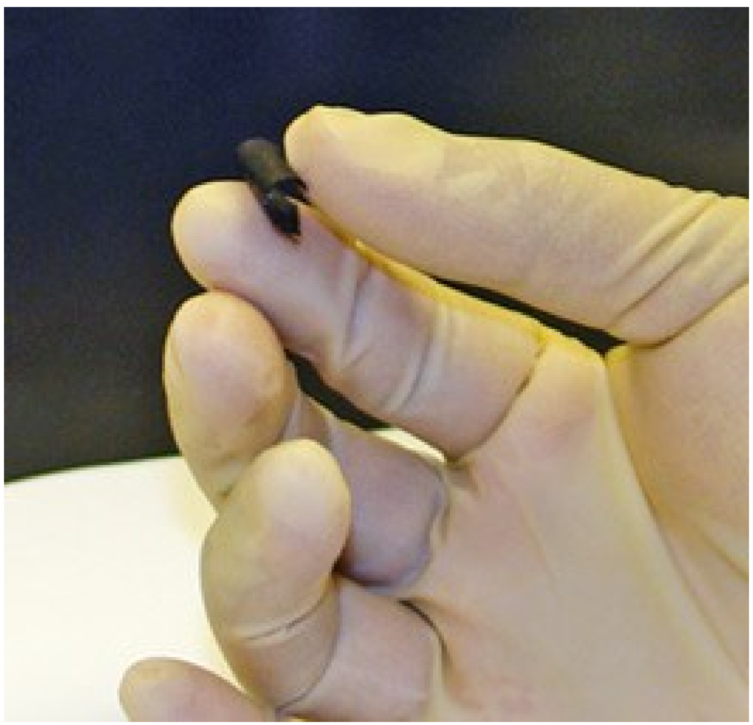
- Nanotubes fit into the grove of the DNA strand
- Apply voltage across CNT, different DNA base-pairs give rise to different current signals
- With multiple CNT, it is possible to do parallel fast DNA sequencing



Top view and side view of the assembled CNT-DNA system

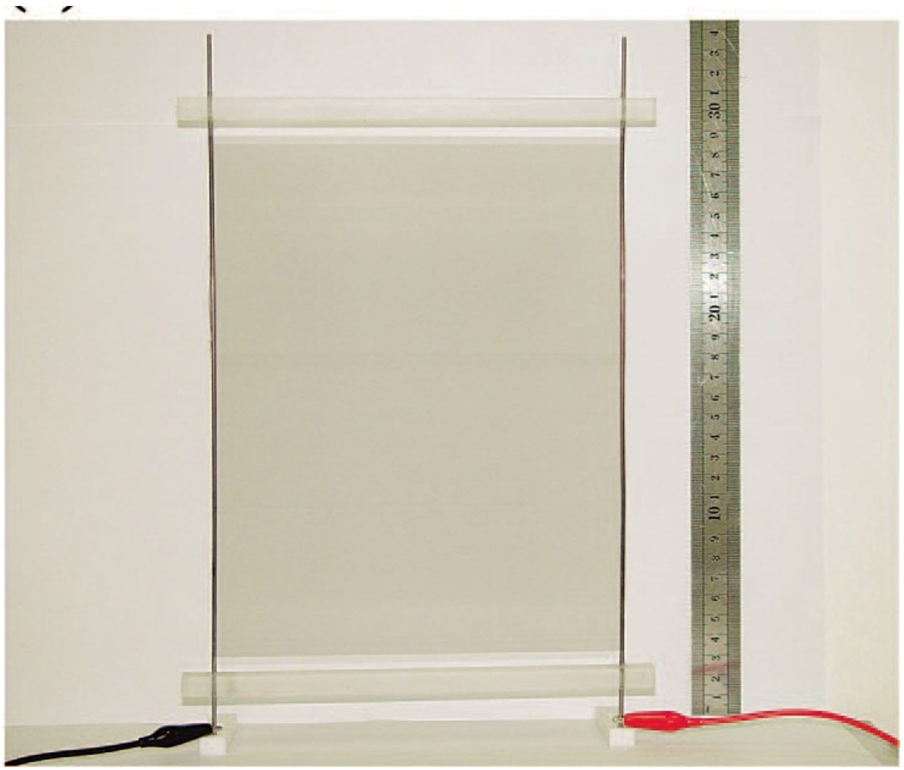
Paper battery





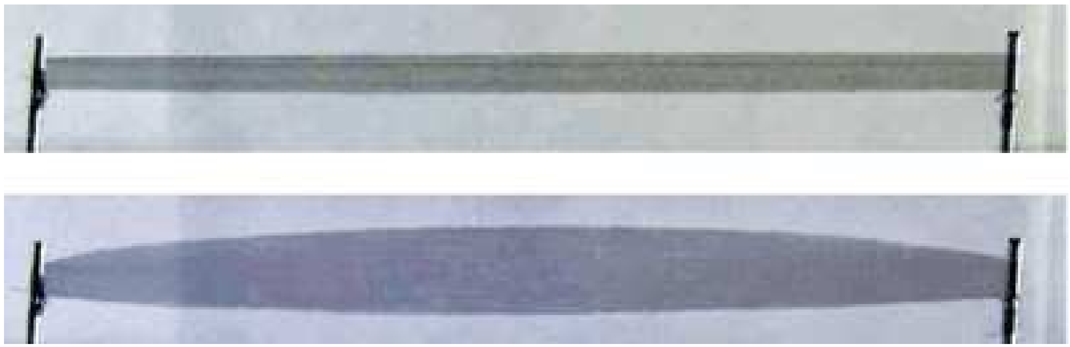
- Could easily be mistaken for a sheet of black paper
- Functions as both a lithium-ion battery and a supercapacitor
- Lightweight, thin, flexible
- Can function at a wide range of temperatures

Nanotube speakers



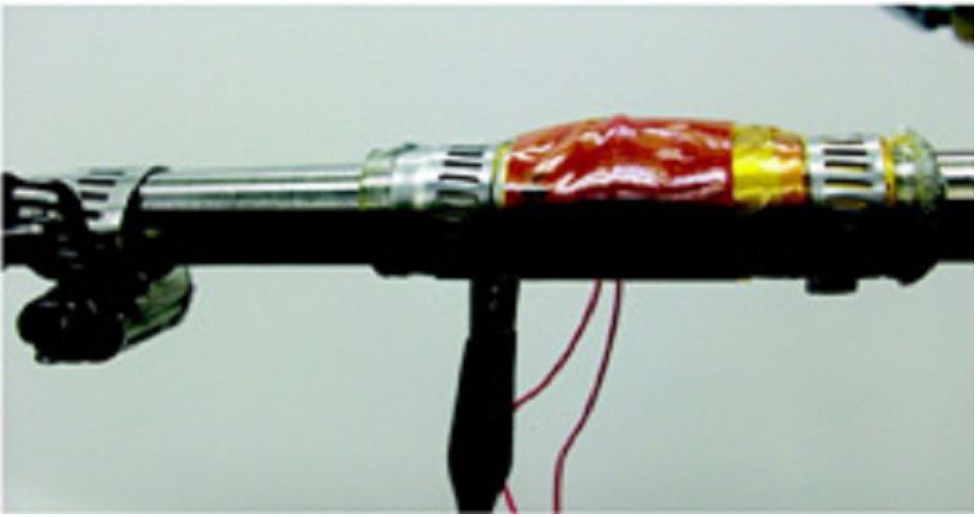
- Thin carbon nanotube films can act as speakers
- New generation of cheap, flat speakers
- Transparent, flexible, stretchable, and magnet free

Artificial muscles



- Aerogels made from carbon nanotubes (CNTs) can serve as electrically powered artificial muscles
- Sheet becomes 220% wider and thicker when voltage is applied
- Flexes about 3 orders of magnitude faster and generates more than 30 times the force than human muscles of the same size

Nanotube thermocell



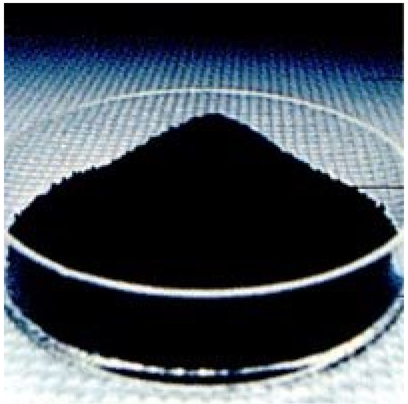
- uses multiwalled carbon nanotubes as electrodes
- 3 times efficient than conventional
- Converts waste heat from industrial plants, pipelines into electricity

SPECIFIC APPLICATION

SUPER STRONG BULLET PROOF JACKETS:-

- One of the main applications of carbon nanotubes is super strong bullet proof jackets.
- Bullet proof jackets are formed by the carbon nano fibers which are made up of millions of tiny carbon nano tubes is starting to reveal exciting properties.

Carbon black



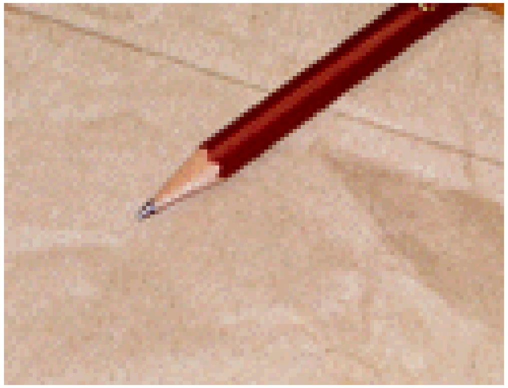
Large industry

- mill. tons each year

• Tires, black pigments, plastics, dry-cell batteries, UV-protection etc.

• Size: 10 – 400 nm

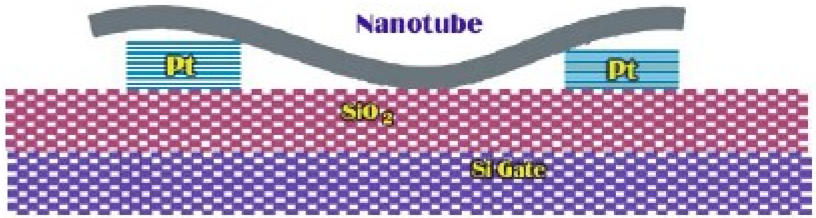
Writing



Carbon – graphite

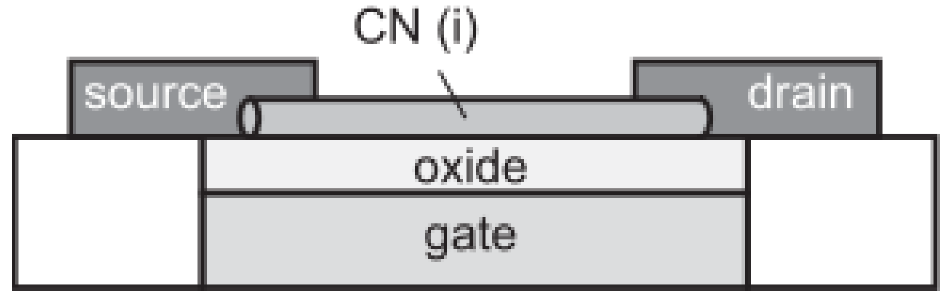
C_{60}: 1000x better resolution than ink (Xerox)

CNT: Implications for electronics



- Carrier transport is 1-D.
- All chemical bonds are satisfied $\Rightarrow$ CNT Electronics not bound to use SiO_2 as an insulator.
- High mechanical and thermal stability and resistance to electromigration $\Rightarrow$ Current densities upto 10^9 A/cm^2 can be sustained.
- Diameter controlled by chemistry, not fabrication.
- Both active devices and interconnects can be made from semiconducting and metallic nanotubes.

CNT: Implications for electronics



- Carrier transport is 1-D.
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- High mechanical and thermal stability and resistance to electromigration ⇒ Current densities upto 10^9 A/cm^2 can be sustained.
- Diameter controlled by chemistry, not fabrication.
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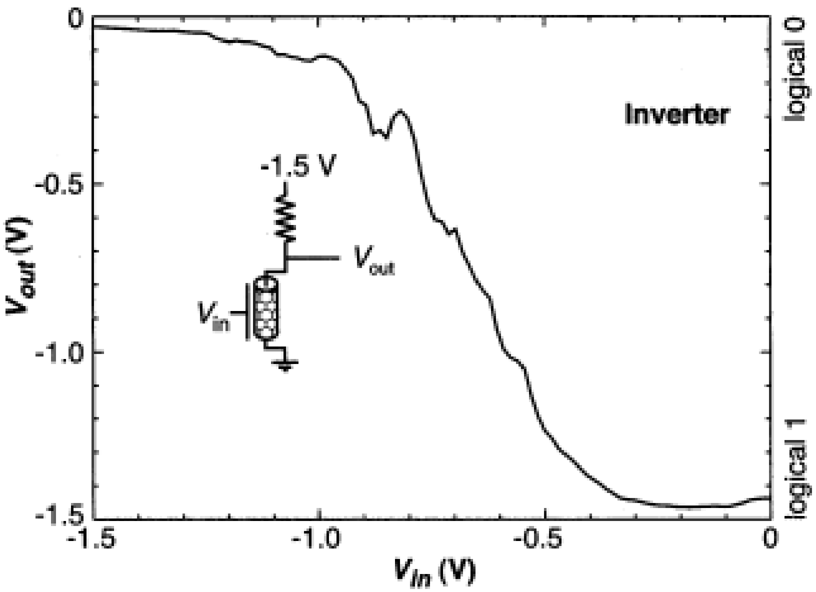
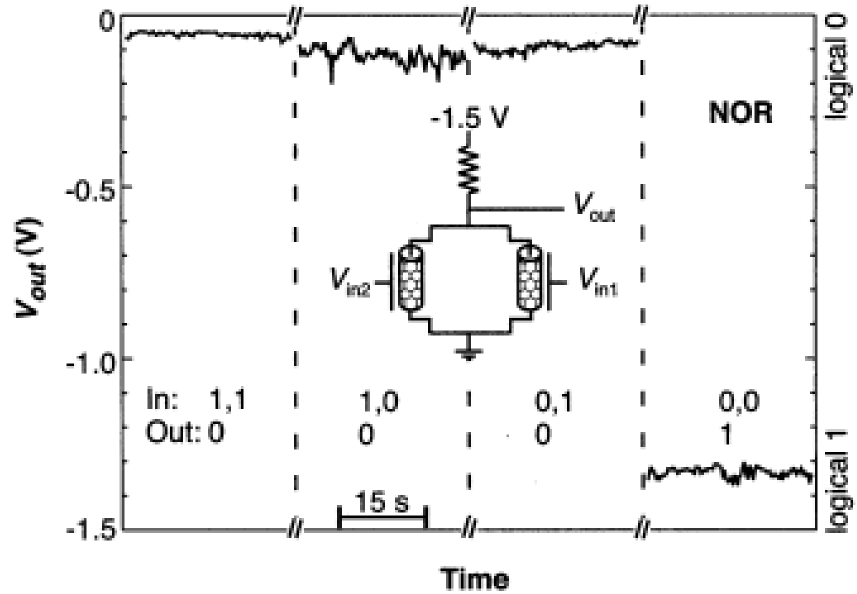
CNT circuits



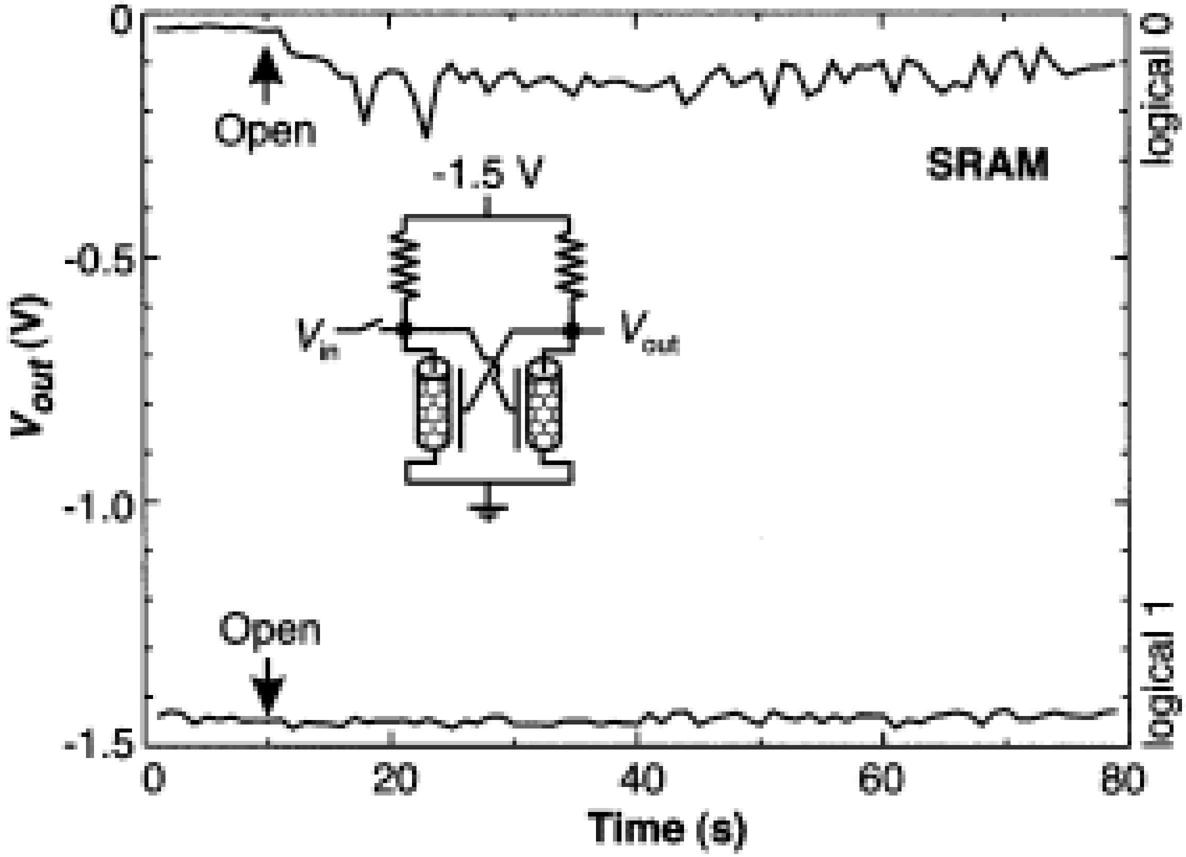


The input-output characteristics of an inverter stage realized by a CNTFET and an external resistor.

Two CNTFETs in parallel working on a common resistor. Input/output characteristics showing NOR Function

A. Bachtold, P. Hadley, T. Nakanishi and C. Dekker, Science 294, 1317 (2001)

Nanotubes for Memory Applications



A simple SRAM cell made by two cross-coupled CNTFETs with external resistors. Writing either 1 or 0 to the input and disconnecting the input shows that the output remains in the stored state

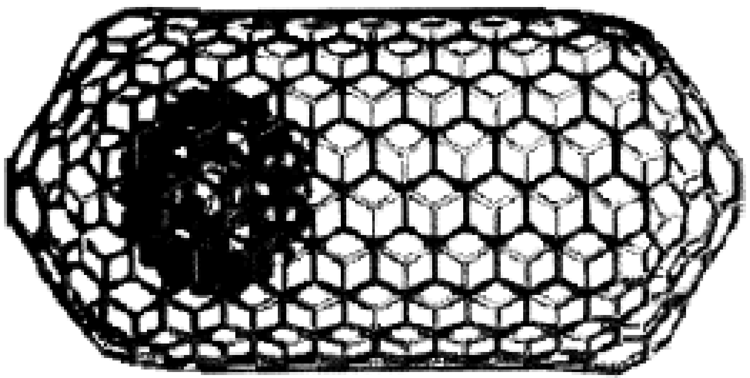
A. Bachtold, P. Hadley, T. Nakanishi and C. Dekker, Science 294, 1317 (2001)

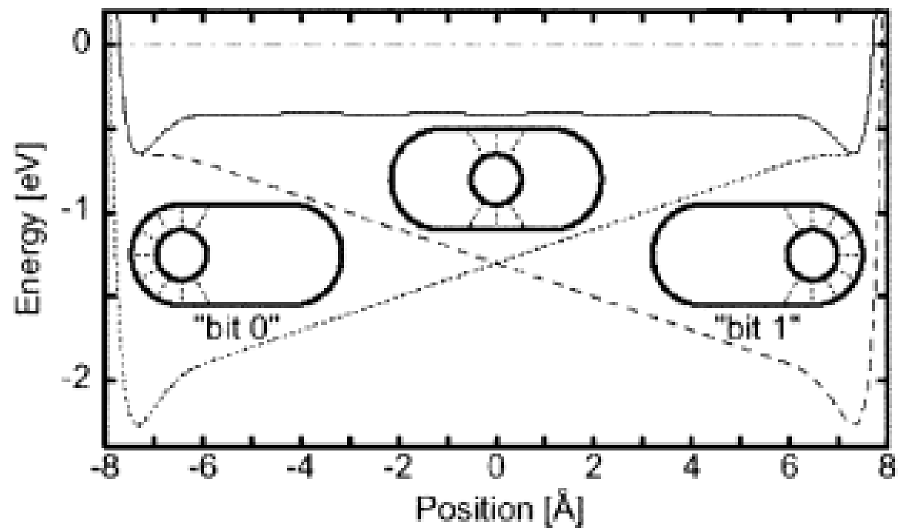
Nanotubes for Memory Applications

Crossbar arrangement of rows and columns of nanotubes separated by supporting blocks. Application of an appropriate voltage between the desired column and row bends the top tube into contact with the bottom nanotube. The resistance drop is used for bit storage. Van der Waals forces maintain the contact even if the voltage is removed (after [68]). Separation of the CNTs is achieved by application of a voltage pulse of equal polarity at the crossing point.

Th. Rueckes, K. Kim, E. Joselevich, G. Y. Tseng, C. Cheung and Ch. M. Lieber, Science 289, 94 (2000)

Nanotubes for Memory Applications

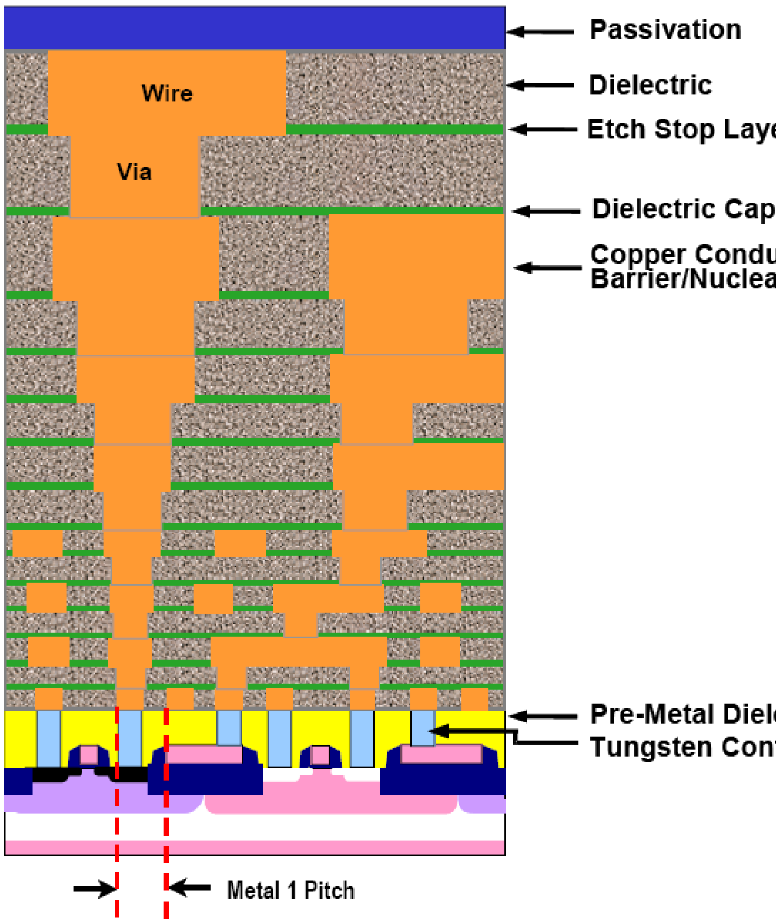




A bucky ball incorporated in a short closed carbon nanotube (right). The Van der Waals forces favor two stable positions at both ends of the tube (left) which can be exploited for bit storage.

Y. Kwon, D. Tomanek and S. Iijima, Phys. Rev. Lett. 82, 1470 (1999).

Overview of Interconnects



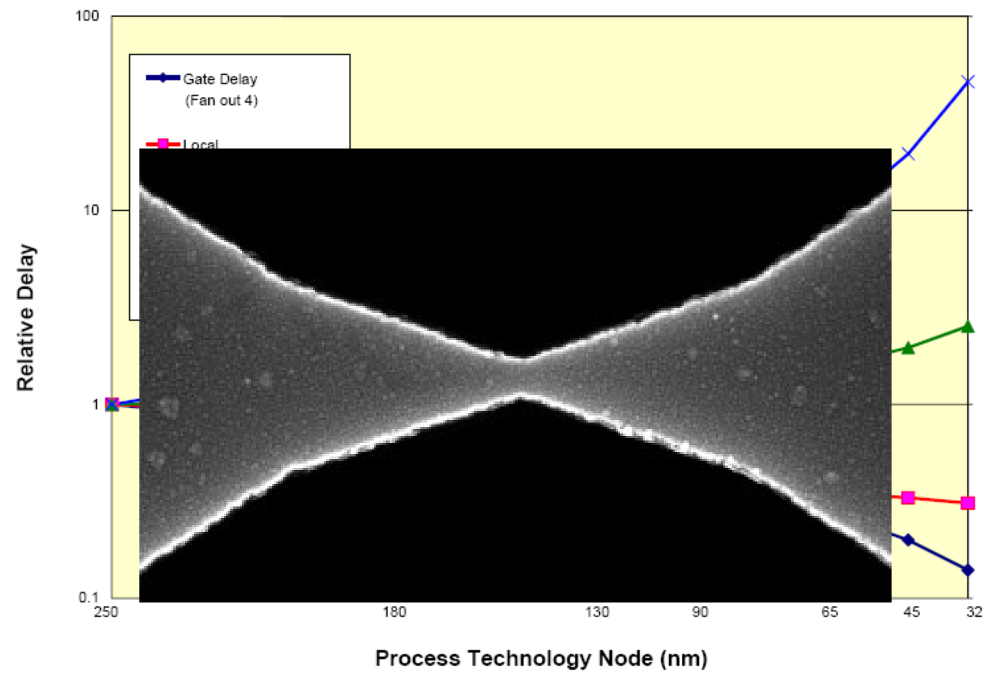


Figure 69 Delay for Metal 1 and Global Wiring versus Feature Size

- Increased resistance and decreased current carrying capability due to electromigration are two critical issues affecting the use of copper interconnects

Why Carbon Nanotube Interconnects?

Advantages	CNT	Cu
Mean free path (nm) @ room temp	>1000	40
Max current density (A/cm^2)	$>1x10^{10}$	$\sim 1x10^{6}$
Thermal conductivity (W/mK)	5800	385

Problems

1. High resistance ~6.45kΩ
2. Contact resistance~100Ω
   - Therefore, the NEED FOR CNT BUNDLE
3. Lack of control on chirality

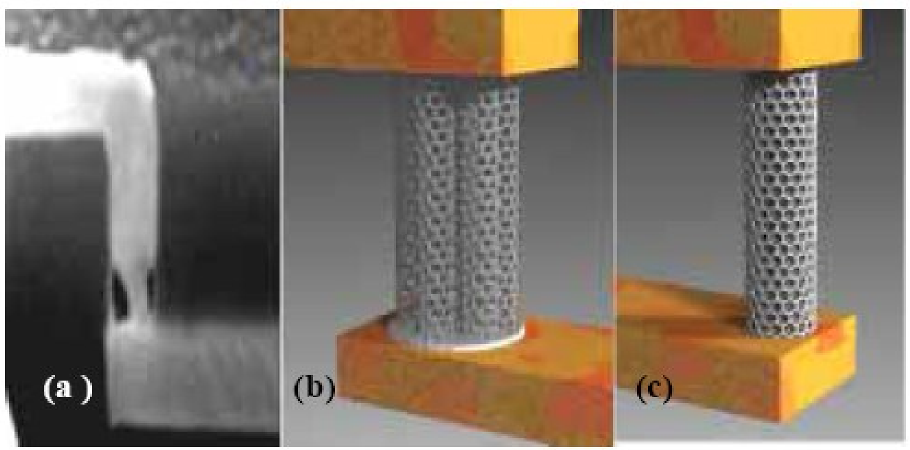
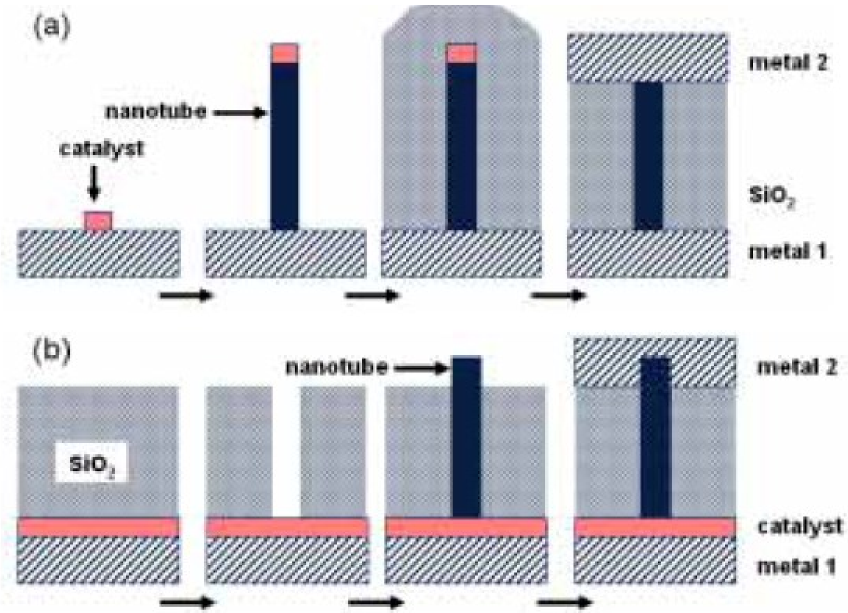


Fig. 2: (a) Conventional Cu-via with voids at the bottom. (b) Proposed replacement of the Cu-via by an array of CNTs. (c) Proposed replacement of the Cu-via by a single MWCNT.

Metallic Carbon Nanotubes are potentially viable for use as interconnects due to their large mean-free path (which leads to low resistance) and low electromigration (which increases current carrying capability)

Growth Strategies



(a) Bottom-up approach (b) Buried catalyst approach

Two major growth strategies

- Bottom-up, where CNTs are grown before ILD deposition
- Buried catalyst, where CNTs are grown after ILD deposition

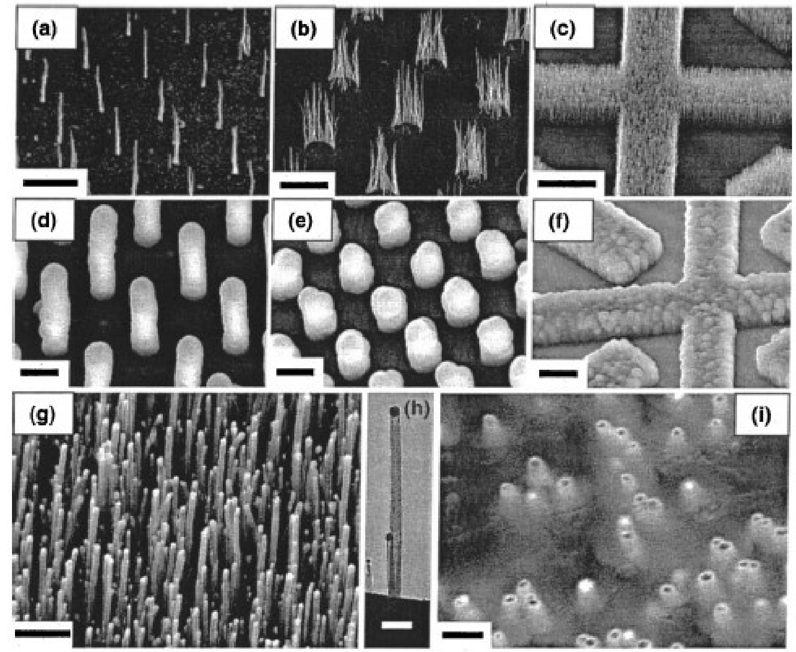


FIG. 2. SEM images of as-grown MWNTs on (a) 100 nm diam catalyst spots and (b) 2 μm diam catalyst spots, and (c) a catalyst film deposited at alignment markers over 10 μm in size; (d)–(f) images corresponding to those in (a)–(c), respectively, after being encapsulated with SiO_2; (g) high magnification SEM image of a MWNT array; (h) TEM image of a single

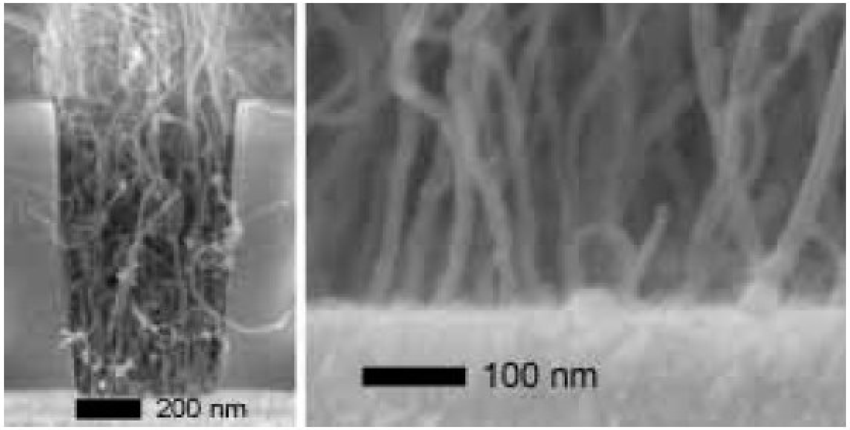


Fig. 7: Cross-section SEM images of vias with CVD-grown MWCNTs. The catalyst particles are based on Fe and the supporting metal layer is Ta.

Results

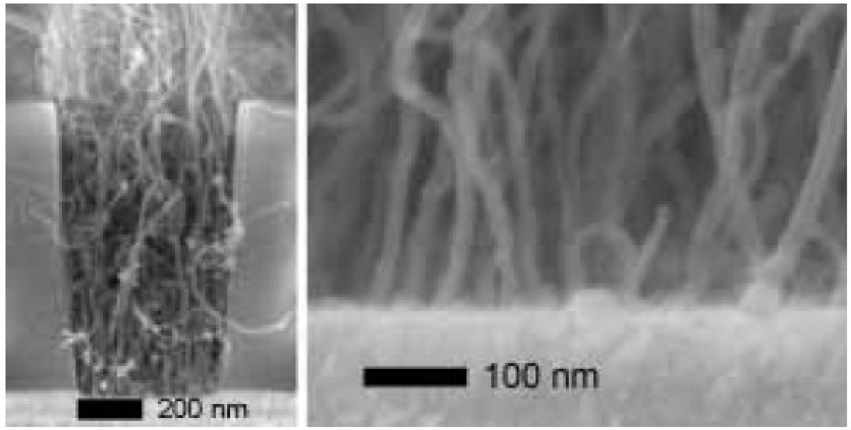


Fig. 7: Cross-section SEM images of vias with CVD-grown MWCNTs. The catalyst particles are based on Fe and the supporting metal layer is Ta.

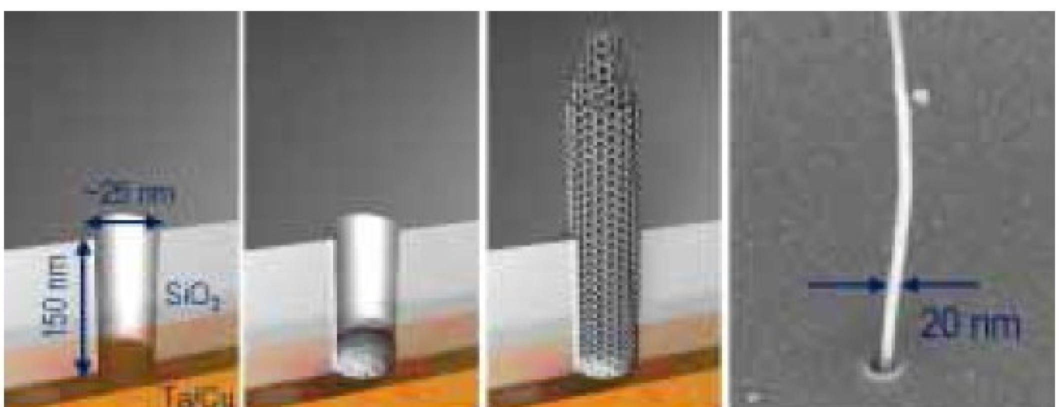


Fig. 8: Fabrication of end-of-the-roadmap sized MWCNT vias with ~20 nm in diameter and 150-200 nm in depth by e-beam lithography and dry-etching using hardmasks. A 20 nm diameter MWCNT is protruding from the via.

Issues

- Contact resistance eliminates any advantage seen versus “bulk” Cu interconnects
- To make a good low resistance contact, high annealing temperatures are required which exceed the thermal budget
- Variability of grown nanotubes continues to be an issue
- Large diameter nanotubes underperform Cu vias even under ideal conditions

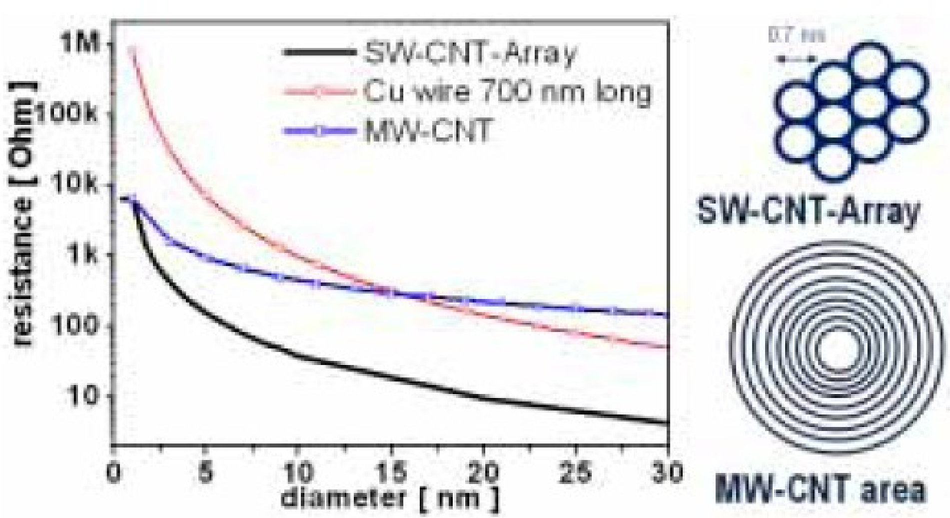
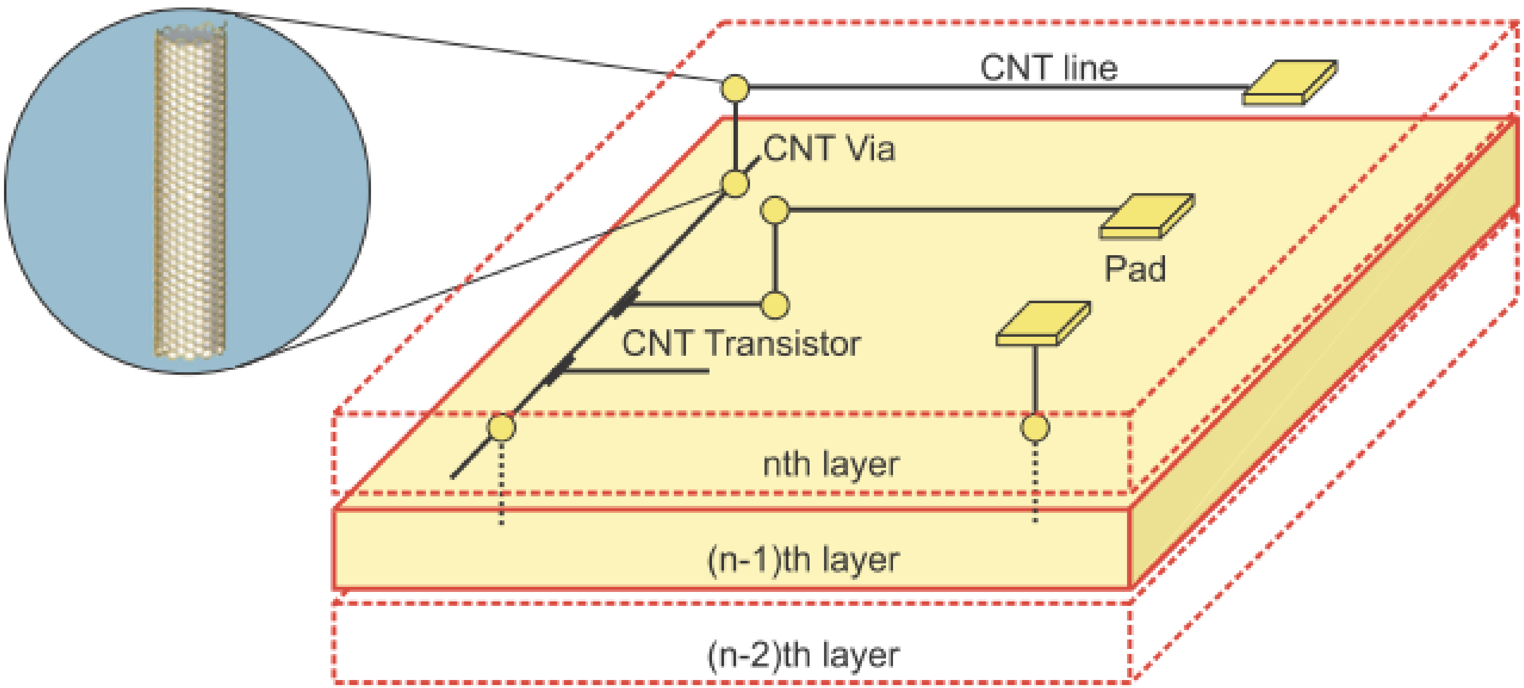


Fig. 3: Theoretical resistance for via fillings with Cu and an array of SWCNTs or one MWCNT with varying diameter. The array of SWCNTs would give the lowest resistance.

All-CNT Nanoelectronics



Concept for an all-CNT-based microelectronics technology. All active elements and interconnects are made out of nanotubes. Due to the quasi-crystalline nature of the nanotubes high quality devices are possible without the need for a single crystal silicon substrate. By the application of well known back-end-of-line techniques cost-effective stacking of a real 3-dimensional structure is feasible.

In Conclusion…

- There are many unique properties
- Further investigation of toxicity is needed
- There are many ways to synthesize
- Method of synthesis depends on financial needs and amount of product desired
- There are many exciting applications of carbon nanotubes

Questions?

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