Printed Electronics:
Technologies, Challenges and Applications

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Palo Alto, CA

International Workshop on Flexible and Printed Electronics (IWFPE 10)
Sept. 8-10, Muju Resort, Korea

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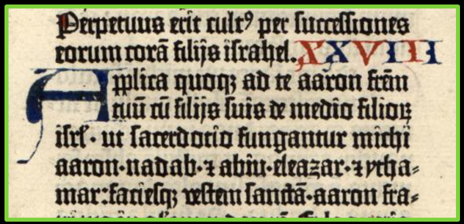
Outline

- Motivations for Printed Electronics
- Printing Technologies
- Printing Materials
- Challenges
- Applications

Motivation

Printed Electronics

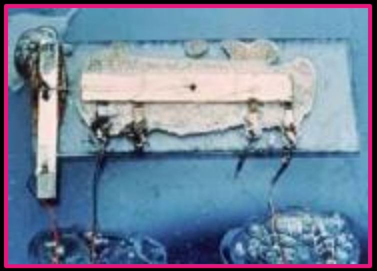
print


Perpetuus erit cult⁹ per successiones
eorum corā filijs israhel. XXVIII
Applica quoq; ad te aaron frēm
tuū cū filijs suis de medio filiorū
isrl · ut sacerdocio fungantur michi
aaron · nadab · et abiu · eleazar · et ytha-
mar: faciesq; vestem sanctā aaron fra-

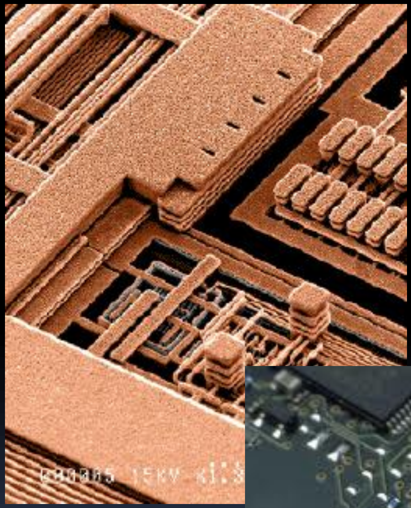
First printed book: Gutenberg

“uniting two worlds”

electronics

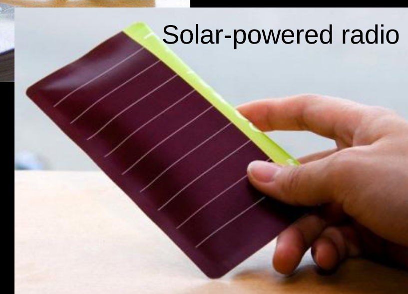


First integrated circuit: Kilby



The Vision of Flexible/Printed Electronics

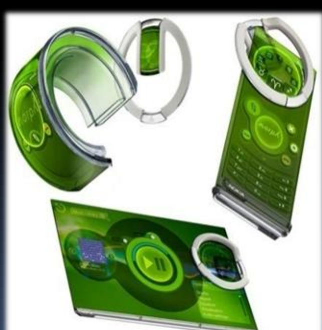
Flexio : Yanko design



Solar-powered radio

e-Drum

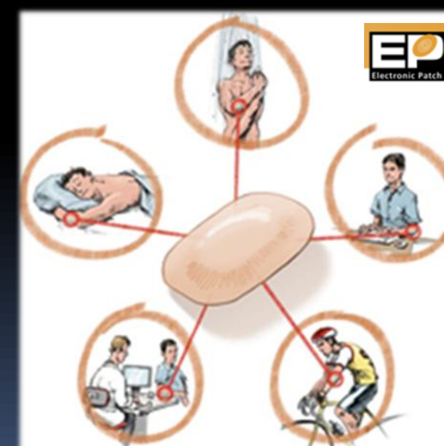
ITRI/ UCSB



Nokia concepts

Antenna Design concept

Freshness sensor (RF, H2S gas)



Electronic Patch Network (DK)

Displays, sensors, RFID, batteries, solar cells, lighting, …

'Printed Electronics' Market

IDTechEx

2250 organisations developing printed electronics: up 50% from two years ago

$1.9 billion 2009 → $57 billion 2019
(~76% printed)

"The market for ***printed electronic devices, components and systems***, according to Hannah ,"(CEO of **$300 billion worldwide within the next 20 years**."
(Printed Electronics Now, Dec 3, 09)

Thin Film/Printable Batteries Market to Reach $5.6 Billion by 2015 According to New NanoMarkets Report

New NanoMarkets Report Predicts Printed Sensors to Generate $5.4 billion in Revenues by 2016

but recently also:

NanoMarkets

Home

Time for a Dose of Market Realism in Printed Electronics

March 01, 2010 •

There is a significant market potential for printed electronics

Key Motivations for Printing Electronics

- Large area or Roll-to-Roll processing
  - Other technologies would be difficult/slow (ex: printed connectors, keypads, PV, lighting,…)
- Difficulty in processing materials otherwise
  - Materials compatibility (ex: glucose sensor strips, OLEDs)
  - Substrate topography/fragility (e.g. thin solar cells, MEMS)
- Thin product form factor
  - Rollable, conformal
- Price:
  - Ultra-low price (ex: battery tester, PV, OLEDs, RFID ?)
    - ->market has to be very large to make money

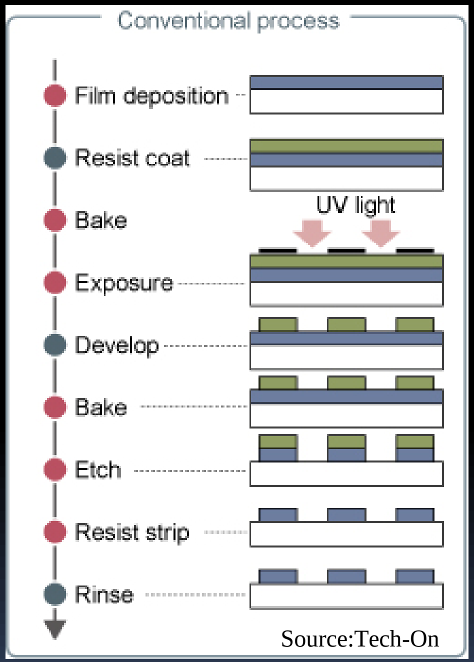
Printing may be used only where it shows a distinct advantage

Printing = Additive Deposition

- 1 step vs 6+ patterning steps

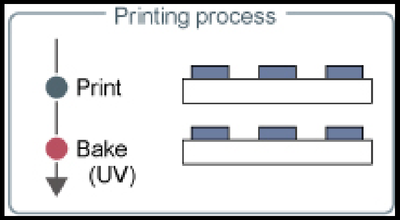
Conventional process

1.
2.
3.
4.
5.
6.



Printing process

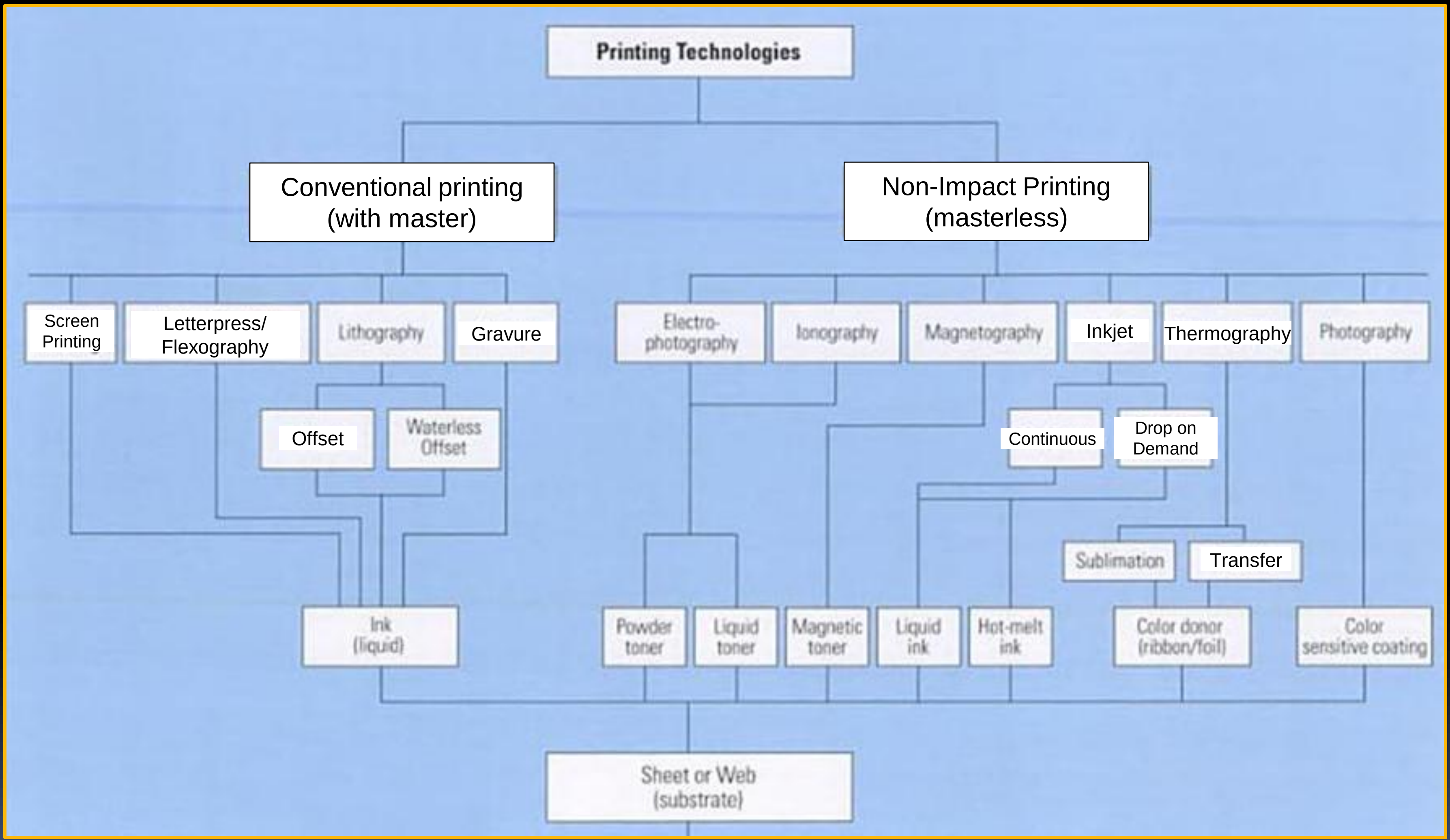
1.



For printing displays: ~50% cost savings is predicted

Printing Technologies

Printing Technologies



after **"Handbook of print media: technologies and production methods"**, Helmut Kipphan

"Printing" for Electronics: Includes a Variety of Processes

- **Inkjet**, gravure, offset, flexo, (rotary) screen, …
- Microcontact, (Nano)imprinting
- (Laser) transfer printing (of high performance circuits)
- Dip-pen nanolithography
- Dry printing (Organic vapor deposition)
- Hot embossing
- Laser processing (cutting sintering, patterning)
- Stamping/die cutting
- Slot-, dip-, spray-coating
- R2R etching, photolithography (!)
- Lamination, …

Consider: The consumer does not care if and how a product is 'printed'

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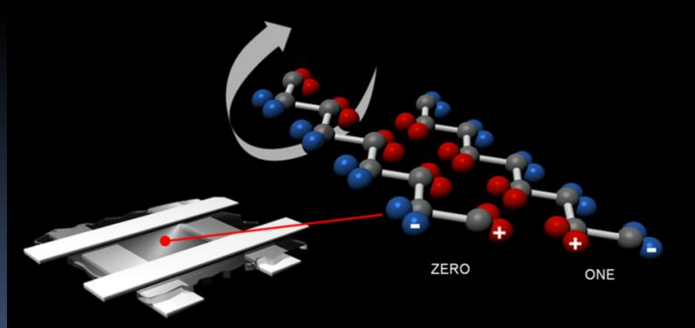
Example R2R Printing Process

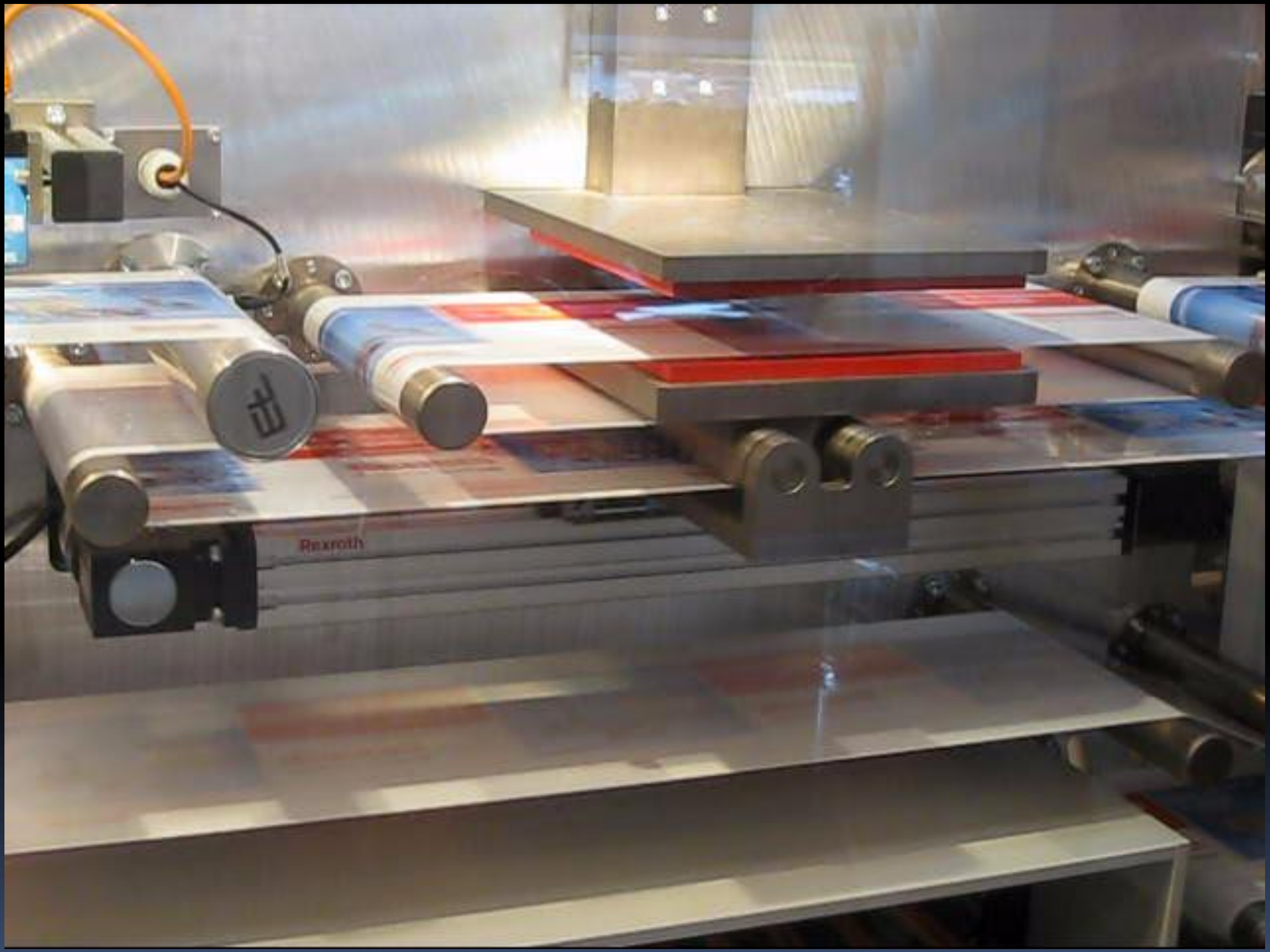
http://www.thinfilm.se/about-us/manufacturing

Ferroelectric polymer memory



Gravure, microgravure, rotary screen printing

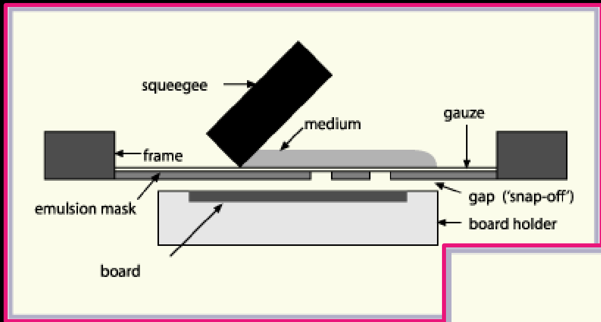
Example of a R2R System with Stationary Step
(Bosch Rexroth)

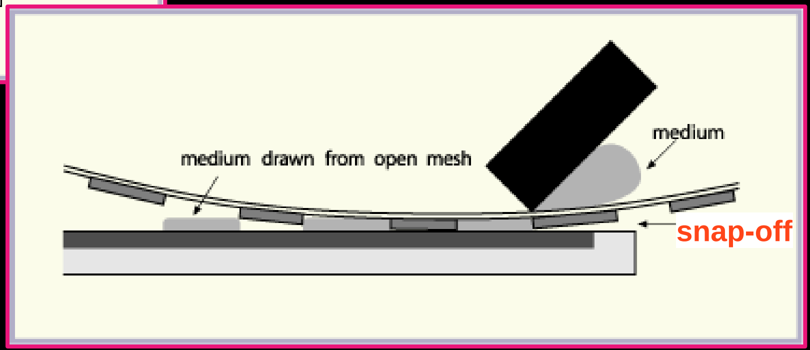


ICFPE09

could enable a roll-to-roll (R2R) photolithography step

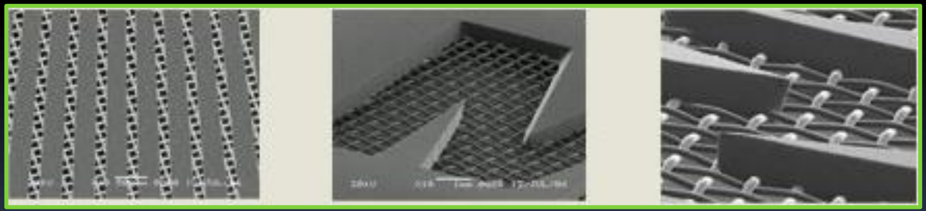
Screen Printing (I)





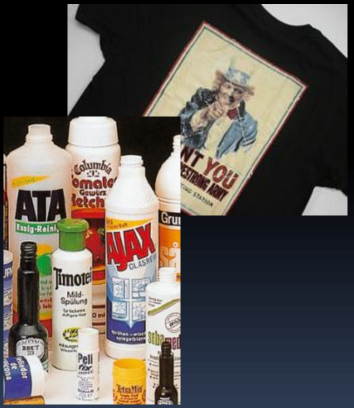
Properties
+ robust
+ simple
(+) thick layers
- large feature size (~100µm)
- high ink viscosity (>10,000cP)
- slower speed (5m/min)

screen printing factors:
- screen parameters
- snap-off distance
- screen tension (N/cm)
- print speed
- squeegee pressure
- squeegee durometer
- angle of contact



Murakami Screen

Screen example:
- Mesh count (per inch): 305
- Thread dia(mu):34
- Mesh opening (mu): 47



Conventional screen printing on clothing, packaging

Screen Printing (II)

- Flat screen or rotary screen printing

Kammann - Flat Screen Head on web printing machine

Mark Andy – Rotary Screen

'kiss printing'
(zero off-contact)

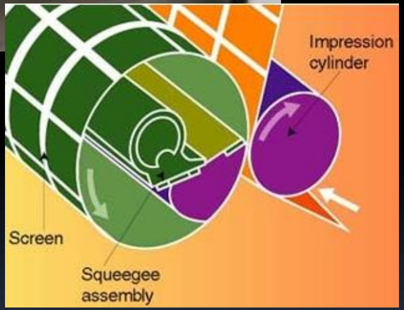
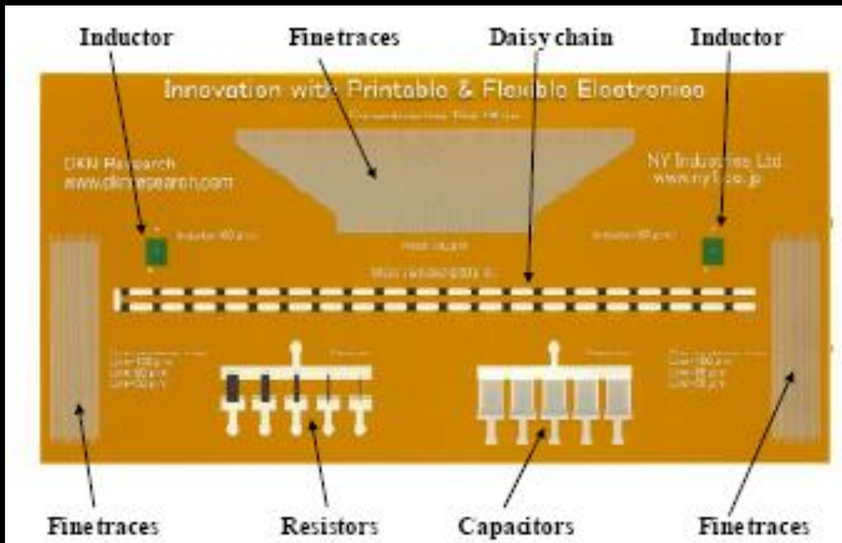


image courtesy of Storck Screens

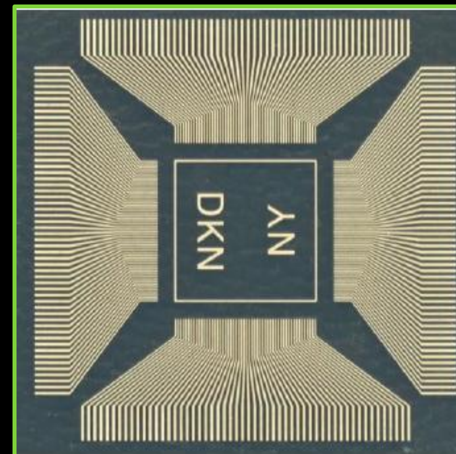
Speed : up to ~20 m/min (R2R)
[up to ~100m/min (~450ft/min)]

Screen Printing (III)

- "Advanced Screen Printing": 30 μm lines/spaces (10-20 μm in development)

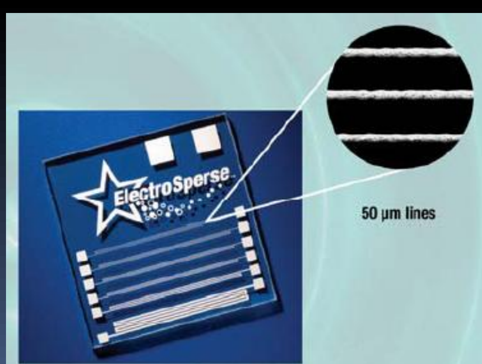


D. Numakura, DKN Research (http://www.dknresearch.com/)



130 μm pitch

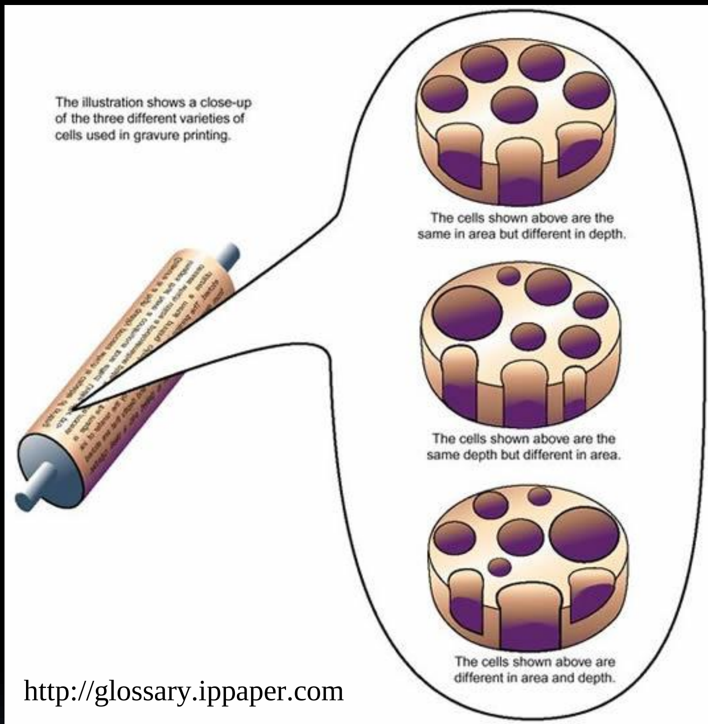
Screen-printed electroluminescent display



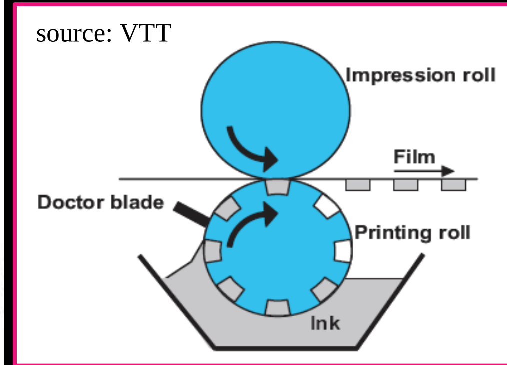
Five Star Technologies, ElectroSperse inks50 μm lines

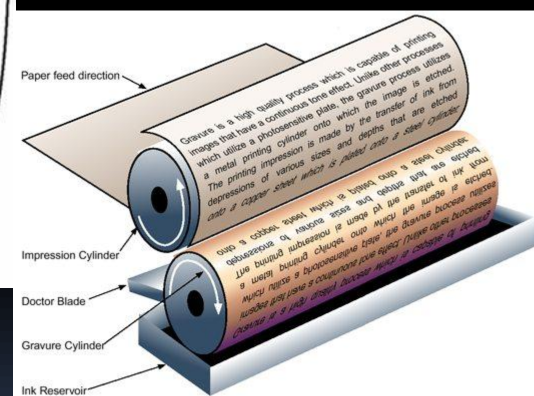
Gravure Printing

Rotogravure



http://glossary.ippaper.com





Daetwyler: Chrome plated cylinder

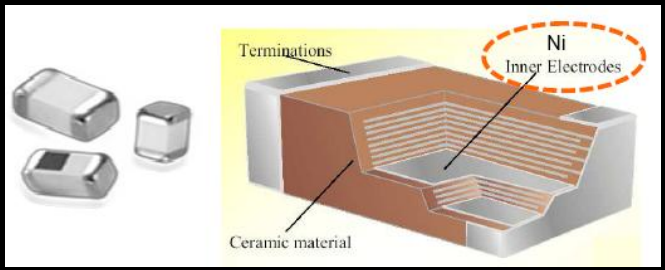
Properties
+ fast printing (50m/min) up to ~3000 ft/min
+ dot thickness variation
+low dot gain
+ High resolution
+use of organic solvents possible
~10-500cp ink viscosity
- relatively high plate cost (metal cylinder)

Gravure printing for high quality print "e.g. National Geographic"

- also MicroGravure (Yasui Seki, Daetwyler R&D)

Gravure Examples

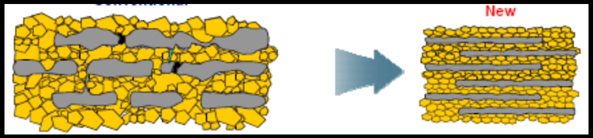
MLCC(Multi-Layer Ceramic Capacitor)



Samsung (SEMCO)

Screen

Gravure



Thinner layers (lower ink viscosity)
Higher speed (50m/min vs 5m/min)

RFID tags

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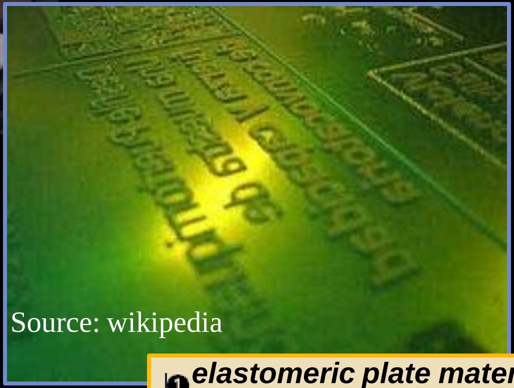
Flexographic Printing

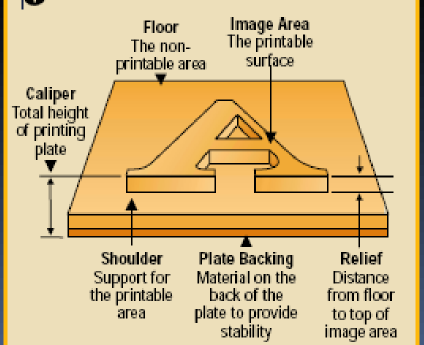
MarkAndy LP3000: 230m/min

Flexo printing plate



Source: wikipedia

elastomeric plate material



Y. Dykes, MacDermid, Inc

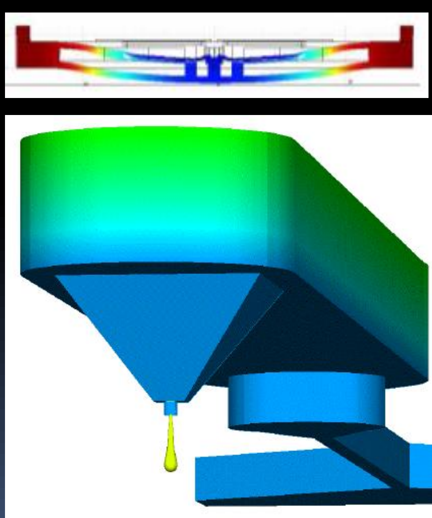
Properties
+ inexpensive plate pattern
+ high throughput
+ thin ink layers / low viscosity inks
- plate degradation due to solvents

Printing on packages: Corrugated cardboard and foil

Inkjet Printing

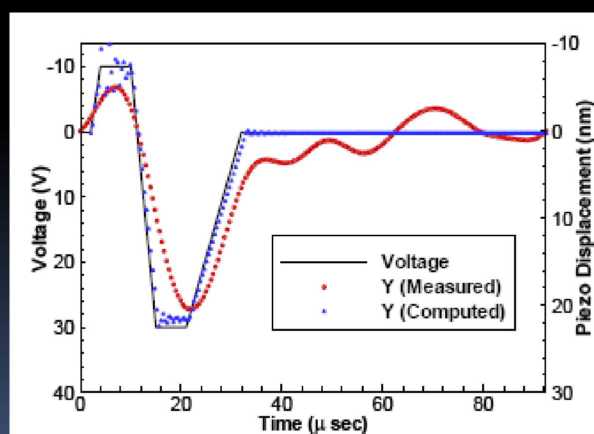
- Piezo
- Thermal
- Electrostatic
- Acoustic
  - Continuous
  - Drop on demand

Properties
+ non-contact
+ small ink quantities required
+ digital printing
+ low viscosity inks ("polymer-free" systems) ~5-50cp
- nozzle reliability
- speed

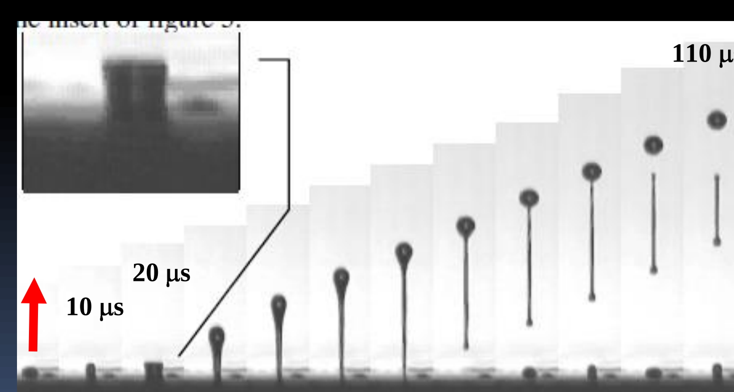


SAMSUNG (SEMCO)

Piezo-inkjet

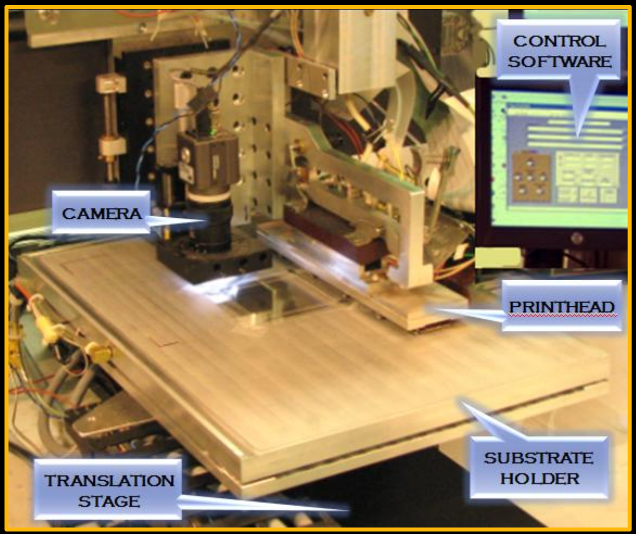


Y.Yoo, ICFPE09

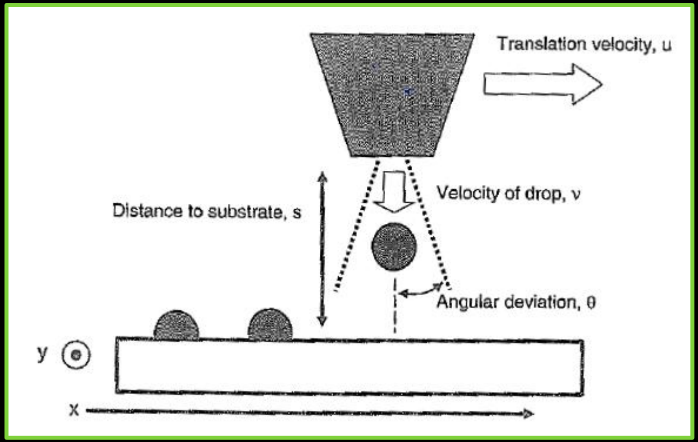


H. Wijshoff, Oce Technologies

Inkjet Printing – Drop Formation

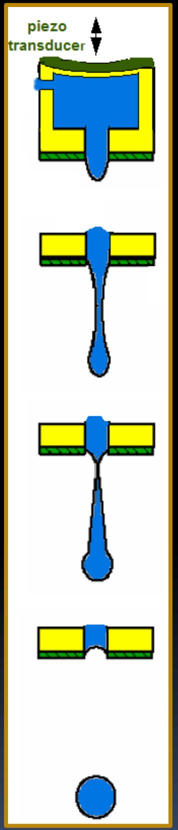


PARC inkjet system



For high accuracy keep distance low !

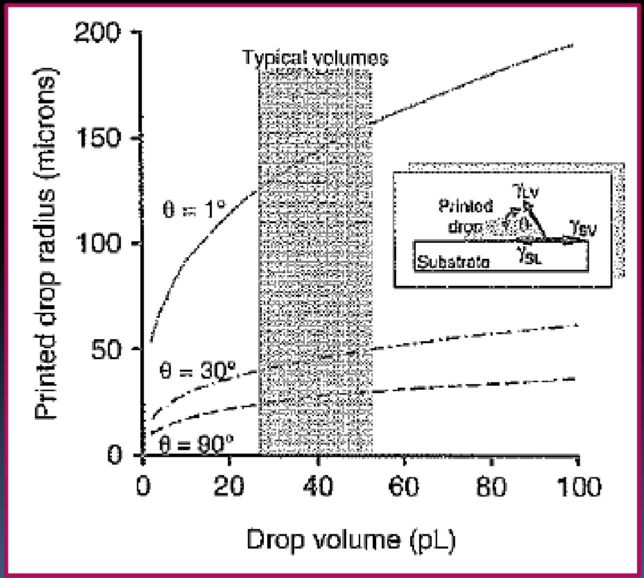
$$\Delta y \sim s \cdot \Delta\theta$$



Piezo-inkjet

Feature size:

depends on printed volume and drop interaction with surface



W. Wong, et al., in 'Flexible Electronics', W. Wong, A. Salleo, edt., Springer

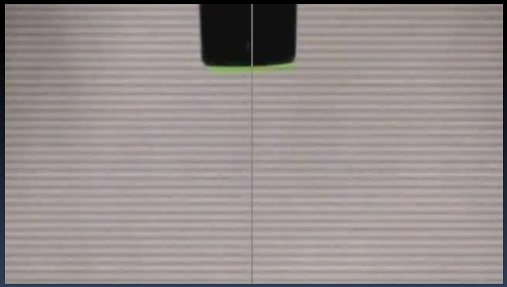
'Jet-printing' - why ?

- Variable digital pattern
- On-the-fly error correction (e.g. on flexible substrates)
- Non-contact printing (substrates with topography, fragile substrates)
- Low operation cost (low ink consumption)
- Wide range of inks (hot-melt wax, solder, bio-materials, low-viscosity inks, …)

why potentially not ?

- limited resolution
- limited printing speed
- jetting reliability issues
- sensitivity to substrate variations

Piezo-inkjet



(PARC)

Jet-printing is excellent for prototyping !

Jet-printing for Electronics - components

printheads

• . . .

systems

XENNIA innovative inkjet solutions

microdrop TECHNOLOGIES

• . . .

inks

CABOT

Cima NanoTech

HARIMA

H.C.Starck

MERCK

PLEXTRONICS

BASF The Chemical Company

Polyera

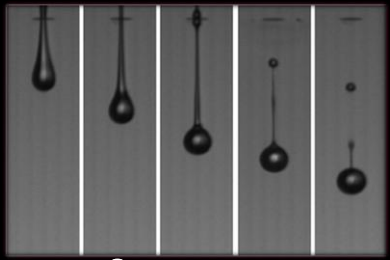
FlexInk

• . . .

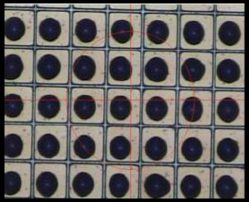
Commercial 'Printing Components'

Applications of Jet-Printing (for electronics)

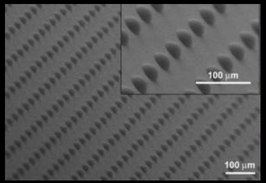
- Color Filters
- LCD Spacers
- Polyimide alignment layer
- Scratch resistant layers
- Back light unit
- LCD materials
- OLED materials
- Electrophoretic media
- Electrowetting fluids
- **Electronic circuits**


source: Samsung

EWD


ITRI

Light guide (BLU)

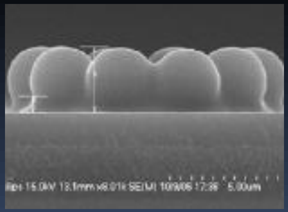


J.Y. Kim, et al, NIP25, '09 (EPFL)

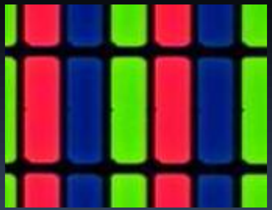
Ch-LCD


ITRI

LCD spacers


LG Display

Color filter


Samsung

Inkjet offers many opportunities, but manufacturing can be challenging

Technology Comparison

Printing method	Viscosity (Pas)	Layer thickness (µm)	Feature size (µm)	Registration (µm)	Throughput (m^2/s)
Gravure printing	0.01-0.2	< 0.1-8	75	> 20	3-60
Flexography printing	0.05-0.5	0.04-2.5	80	< 200	3-30
Offset printing	5-100	0.5-2	10-50	> 10	3-30
Screen printing	0.5-50	0.015-100	20-100	> 25	2-3
Ink jet printing	0.001-0.04	0.05-20	20-50	5-20	0.01-0.5

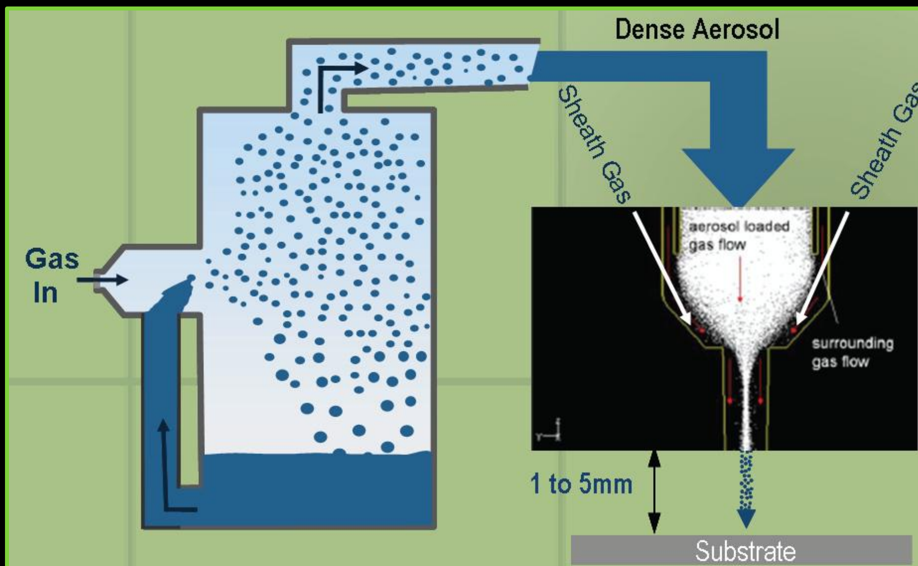
G.E. Jabbour et al (2001), A. Huebler et al (2002), M. Bergsmann et al (2003), T. Kawahara et al (2003), A. Blayo et al (2005), A. Maaninen et al (2005), H. Sirringhaus et al (2006), M. Schrödner et al (2006), Y. Xia et al (2006)

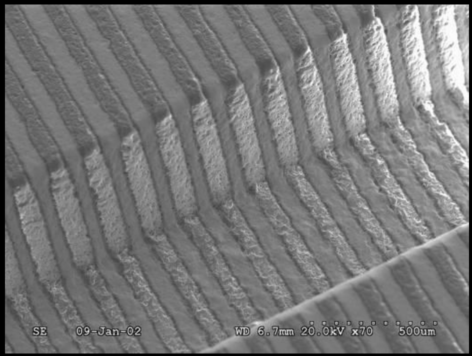
Source: H. Kopola, VTT

Aerosol Jet(R) Printing

http://www.optomec.com

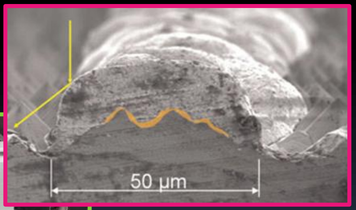
- M3D (Maskless Mesoscale Materials Deposition)

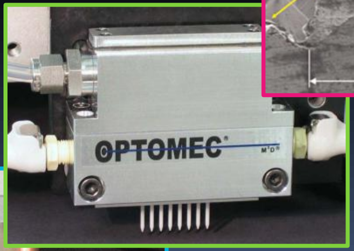


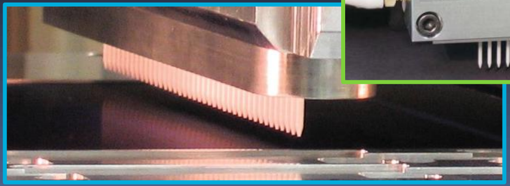


60µm Ag lines written over a 500µm trench.

For solar cell gridlines:
-Combines with light induced plating
- 2% efficiency gain vs screen printed lines (Fraunhofer Inst.)
- up to 40 nozzle head







• Conformal printing on 3D surfaces: 1-5 mm standoff
• Viscosity: 1-2500cP
• Feature size <35mu
• Non-contact
• Thickness: 100nm-5 microns (single layer)
• Write speed: 100mm/sec

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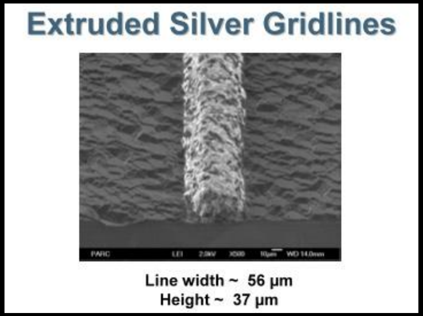
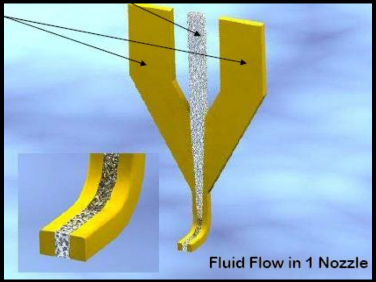
Direct-write Extrusion

- Co-extrusion printing (developed at PARC)





PARC
(http://www.parc.com/)

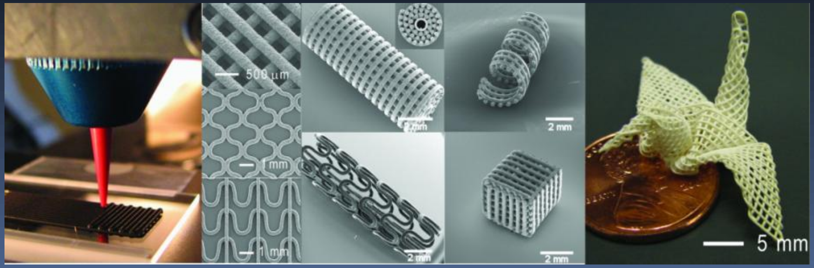
- MDDW (Micro-Dispensing Deposition Write)

- 3D substrates
- Viscosities up to 1mio cP
- ~50-100 mu lines
- Up to 200mm/sec

(http://www.nscryptinc.com/)

3D antenna printed on helmet: N.S. Kim, K.N. Hahn, ICFPE 2009

- Direct Deposition

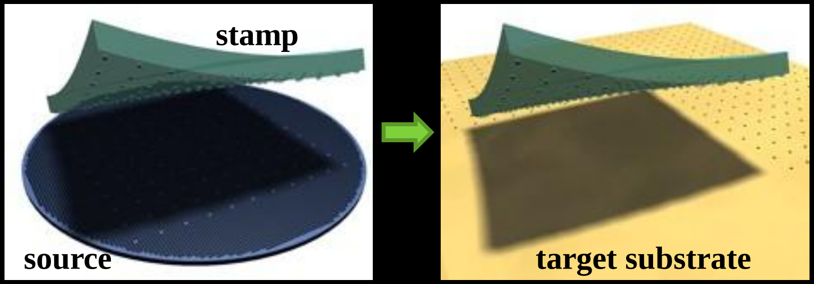


J. Lewis group, U. Illinois, Urbana-Champaign

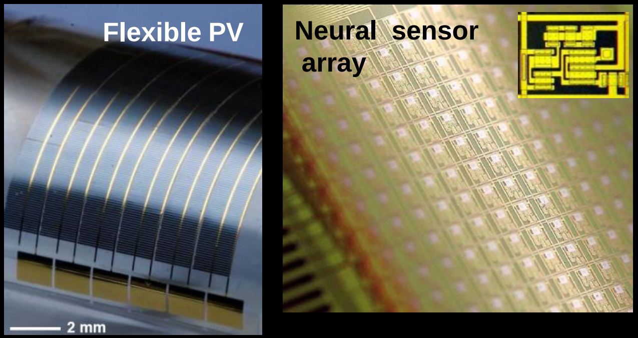
Bok Yeop Ahn , et a., **Advanced Materials**
Volume 22, Issue 20, pages 2251–2254, May 25, 2010

Transfer Printing (I)

- Chip Micro-transfer Printing

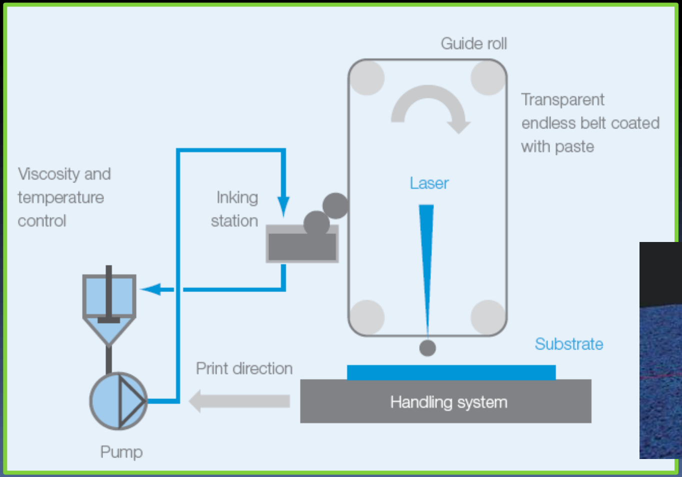


credit: Semprius, Inc.

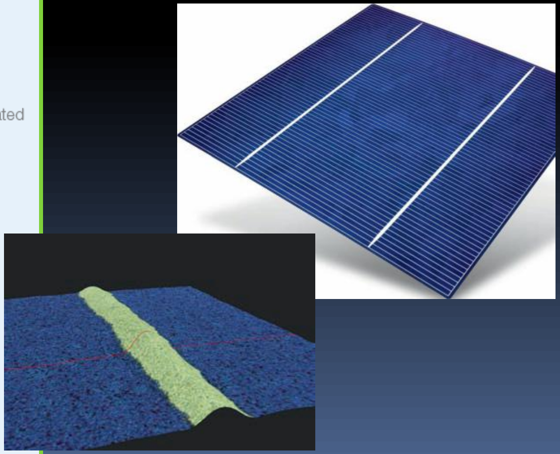


credit: John Rogers, U. Illinois, Urbana

- Laser Transfer



example: **solar cell gridlines**

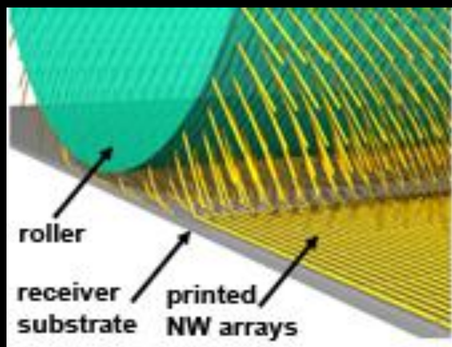


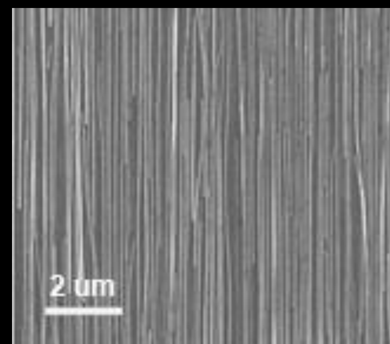
BASF / Schmid Group

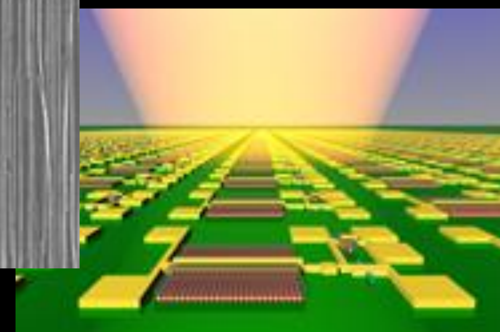
- **Fine line (< 100 mu)**
- **High aspect ratio(>0.3)**
- **Non-contact**

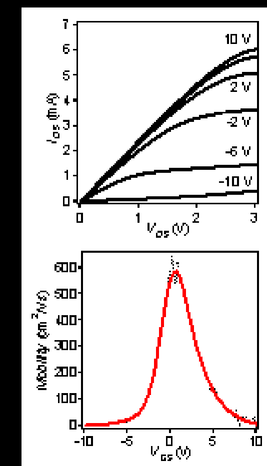
Transfer Printing (II)

- Transfer of nanowires (Javey et al., UC Berkeley)







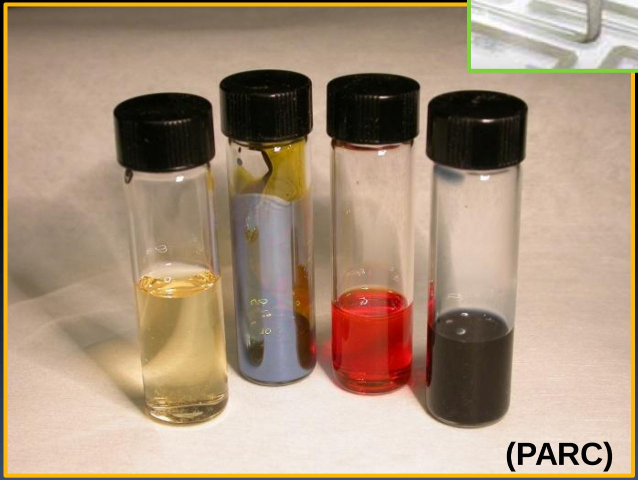


- Thermal transfer of conductive materials

Iimak thermal transfer ribbon:
http://www.iimak.com/

Printing Materials

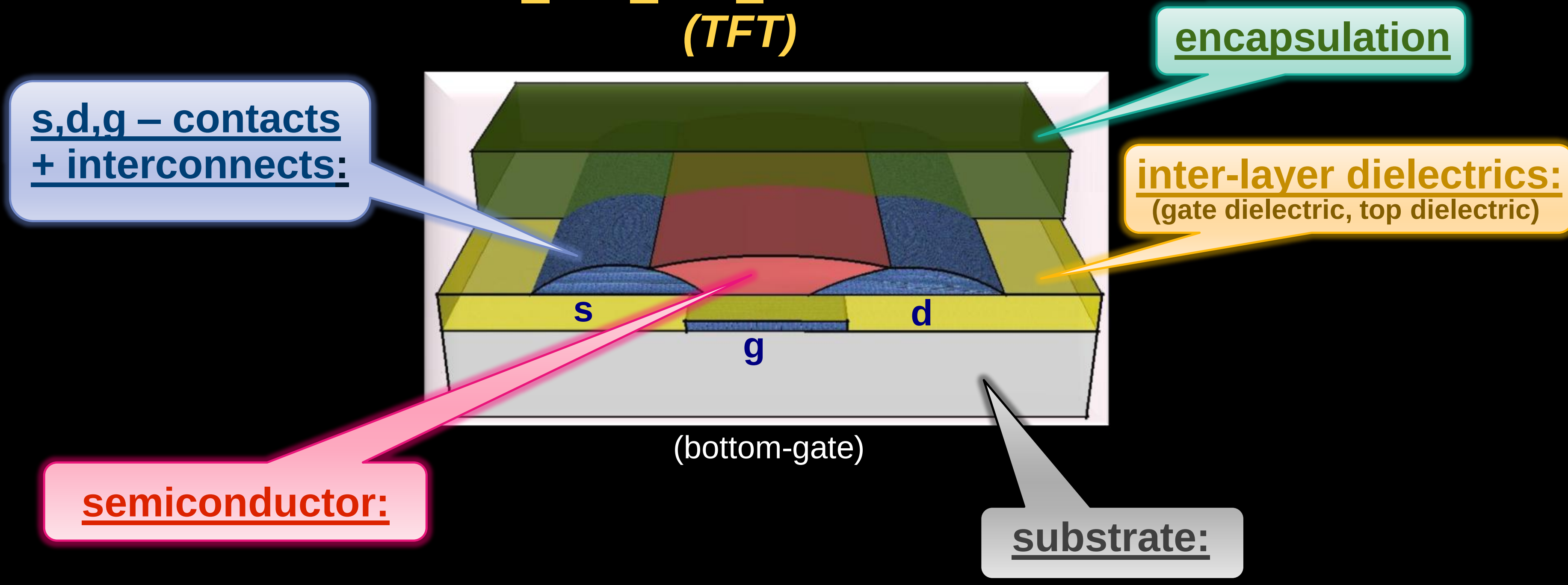
graphic inks

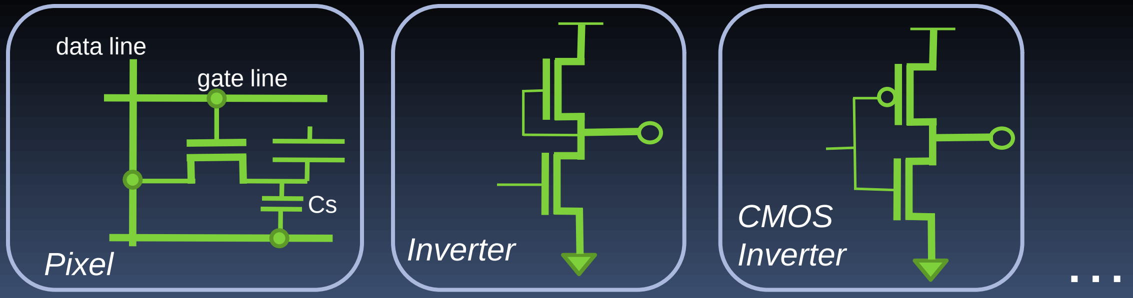


electronic inks

The TFT as the Basic Circuit Element

***Thin Film Transistor* (TFT)**





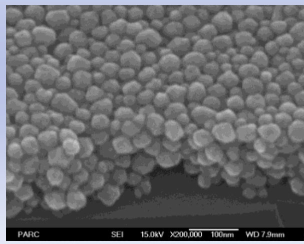
The transistor performance determines the extent of applications

The Printed TFT

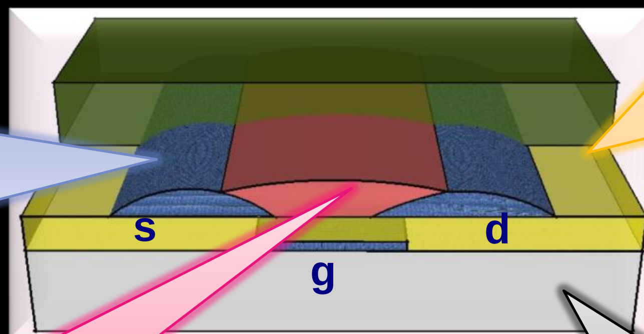
- Materials compatible with solution processing

s,d,g - contacts:

(nanoparticles, polymers,…)



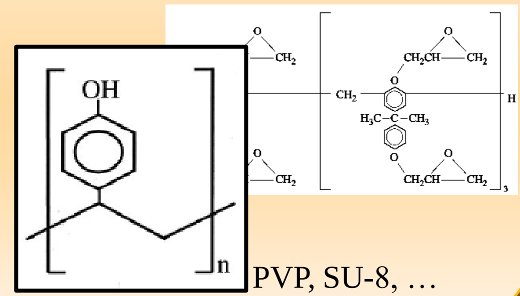
Thin Film Transistor (TFT)



(bottom-gate)

inter-layer dielectrics:

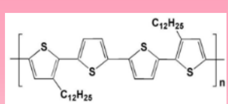
(gate dielectric, top dielectric)

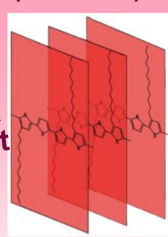


PVP, SU-8, …

semiconductor:

(polymers, oligomers, precursors, nanoparticles)





PQT-12, …

Substrate:

- polyester
- polyimide
- **PEN** (polyethylene naphthalate)
- …

-> performance of the materials has to be optimized and process compatibility ensured

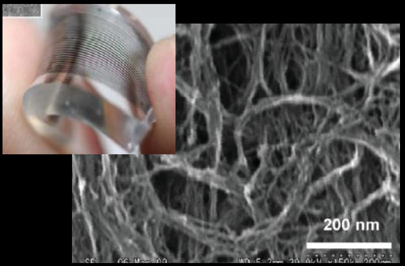
(similar materials sets apply for OPV, OLED, …)

J. Daniel, et al., Mater. Res. Soc. Symp. Proc. Vol. 1114, Fall 2009, 1114-G13-03

Many new materials are introduced into the process

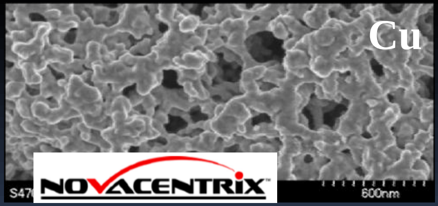
Conductors

- Carbon, silver, aluminum flakes
- Polypyrrole, polyacetylene, thiophenes (PEDOT:PSS)
- Metal nanoparticles (Ag, Au, Cu, Ni - annealing or photonic curing)
- Catalyst printing + plating
- Reduced printed metal salts, metal precursors
- Carbon nanotubes, metal nanowires
- Graphene inks
- Solder
- Elastic Conductors

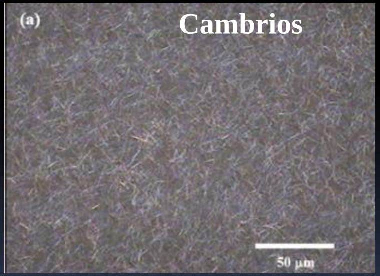


Elastic conductor
(T. Sekitani, T. Someya, Univ. of Tokyo)

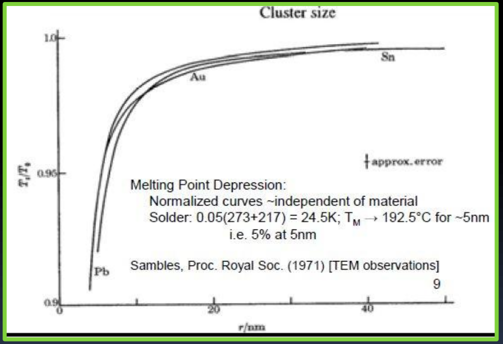
Ag nanoparticles



Photonic cured Cu (~10x bulk)



metallic nanowires



Melting point depression in nanoparticles

‘surface functionalization may be required for TFT s/d electrodes’

High conductivity, low roughness, low process temperature and work function !

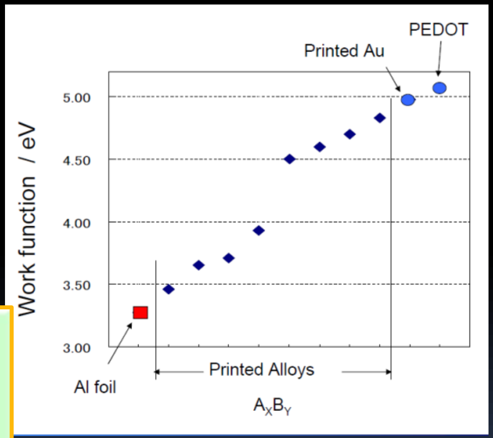
Conductors – selected new developments

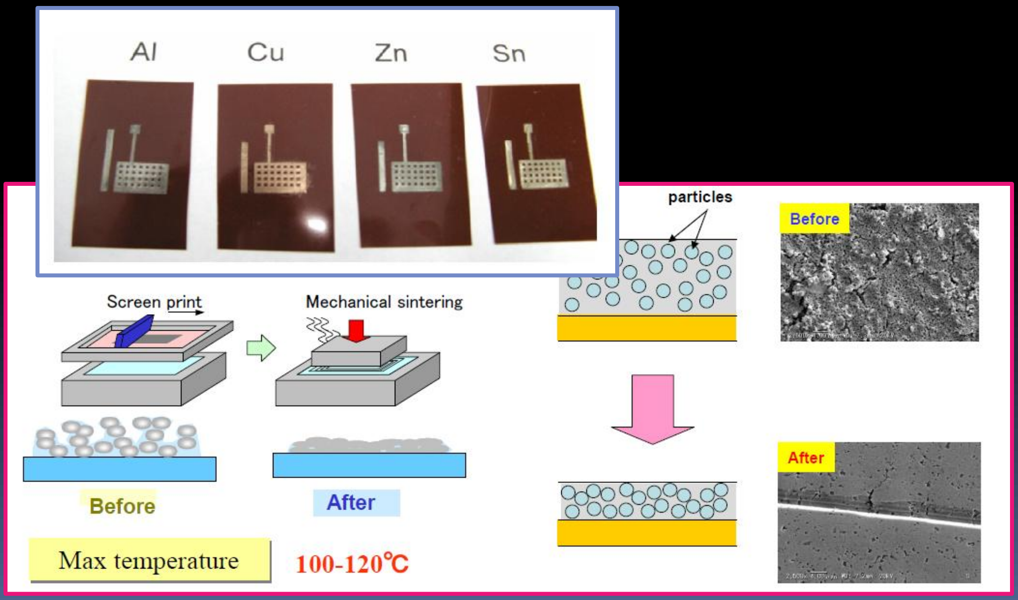
- **Copper deposition**

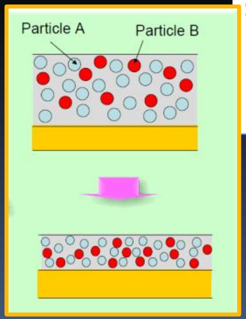
  - in reducing environment (CO, H2, hydrazine)
  - photonic/laser curing

- **Mechanical sintering** (AIST, T. Kamata, Digital Fabrication '09)

  - Alloy sintering -> control of work function
  - Printed oxide semiconductors (NiO, SnO2, In2O3)







Insulators

- Oxides, nitrides
- Al2O3, HfO2 (anodization, atomic layer deposition)
- Polymer dielectrics (PVP, PMMA, …)
- Spin-on-Glass
- Parylene (evaporated)
- Solid electrolytes
- Ion gels
- ….

potential desirable properties

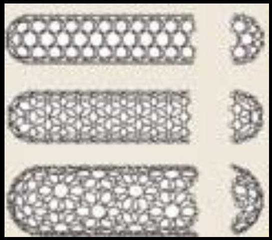
- pinhole-free layer
- high k or low k
- smooth surface
- transparent
- barrier property
- …

'surface functionalization may be required; high-k dielectrics perform poorly with OSCs'

Semiconductor/ insulator interface is crucial for TFTs

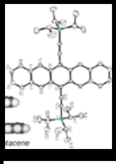
Semiconductors

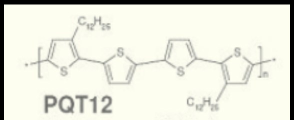
- Organic semiconductors (small molecule, polymer)
- Oxide Semiconductors (ZnO, InGaZnO)
- CNT
- Nanowires, nanoribbons (Si, GaAs)
- Nanoparticles (Si, CdSe, ZnSe)

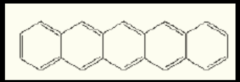


CNT

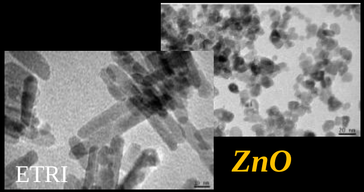
printed Si



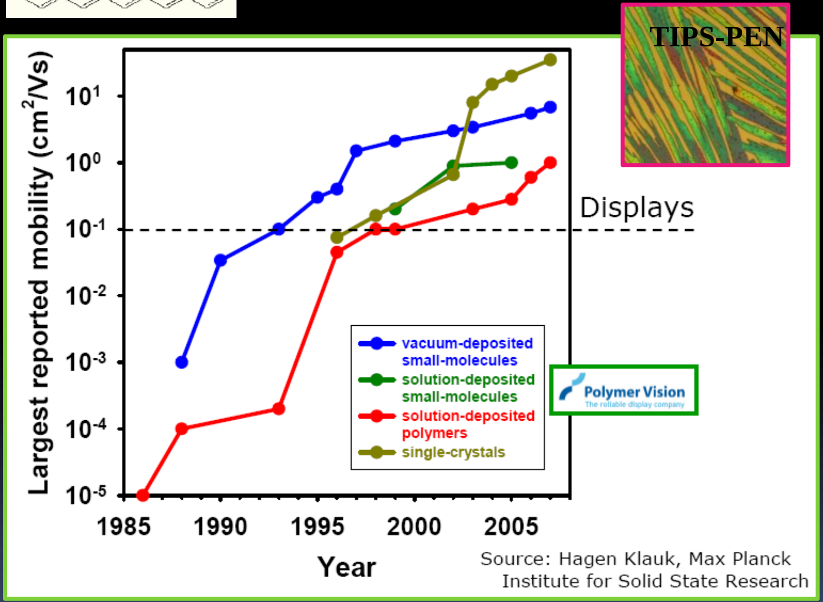




OSC



ZnO



mobilities of organic SC

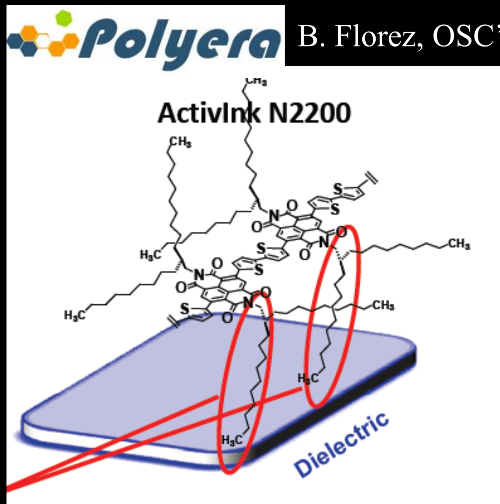
- some processes require annealing steps (e.g. laser or RTP)
- high mobility required for current driven displays (OLED, electrochromic), driver circuit integration and other circuit applications

Organic and inorganic semiconductors are printable

parc A Xerox Company

Semiconductors – organic examples

- Recent developments of printable OSC



B. Florez, OSC'09

Works with high-k dielectics (alkyl chains keep distance from polar interface)

Mobility	On/off	V_{on}
0.2-0.8	10^7	0-5V

ActivInkTM N1500 (Small-Molecule)

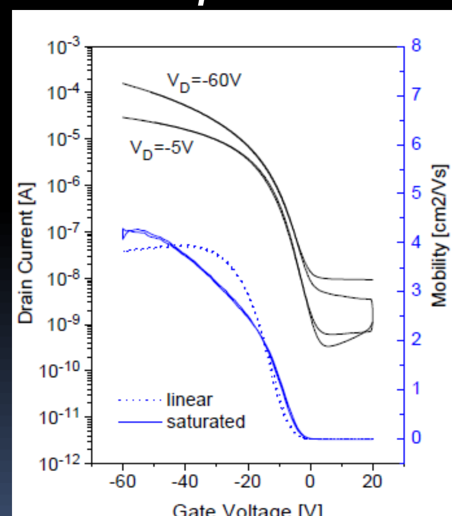
Mobility	On/off	V_{on}
~ 2 cm^2/Vs	$1x10^{6-7}$	<5V

N-type

Mobility	On/off (0V)	V_{on}
~1 cm^2/Vs	$1x10^{5-6}$	0-10V

P-type

multi-component OS ink



Mobility up to ~4cm2/Vs

- also new amorphous polymer with mobility ~0.5cm2/Vs that is easy to process

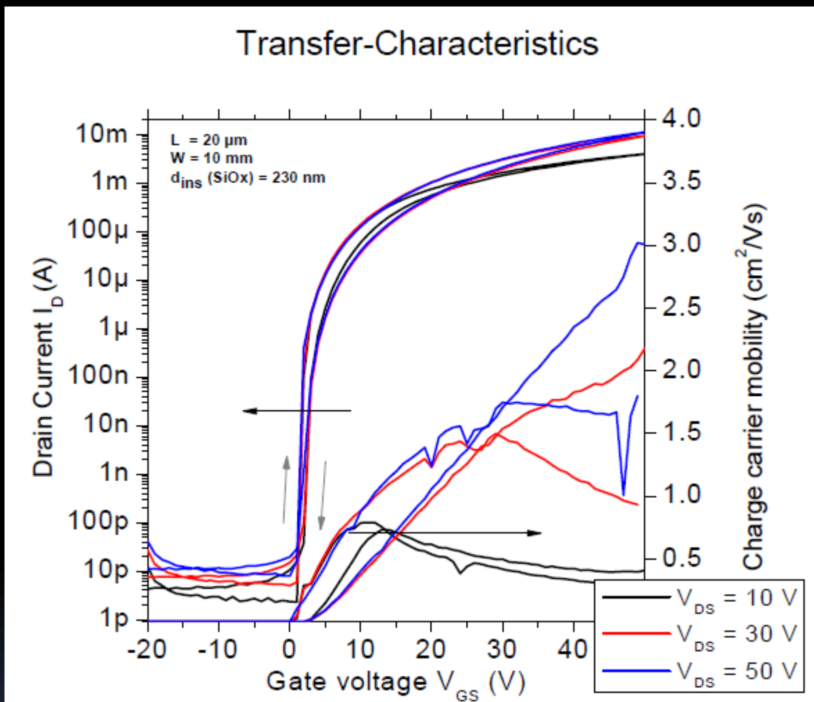
G. Lloyd, OSC'09

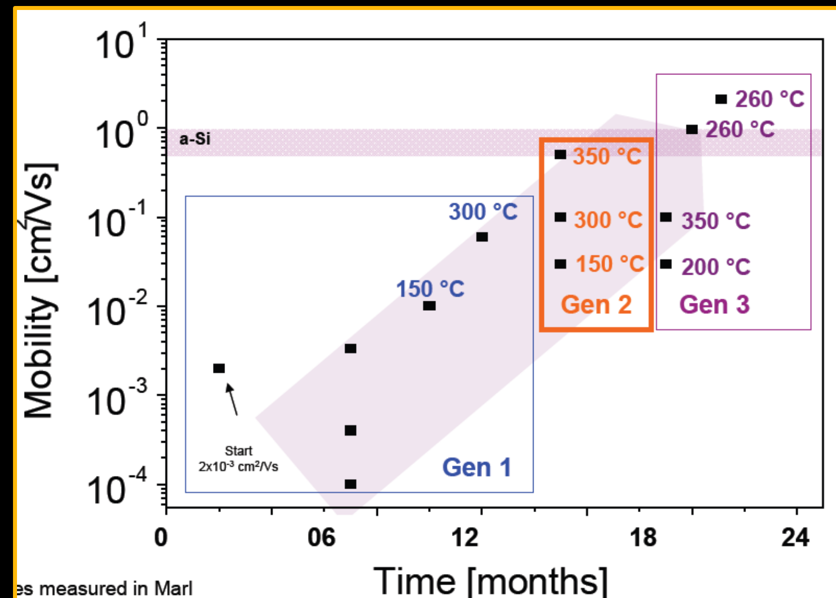
challenge:
-High mobility and uniformity
--> trend towards small molecule precursor / amorphous polymer blend

parc
A Xerox Company

Semiconductors – inorganic example

- Recent development (H. Thiem, OSC09)



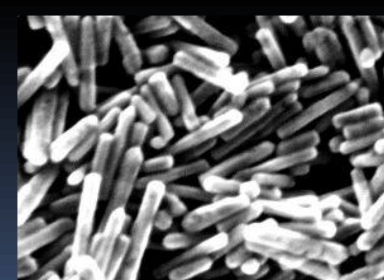


μ_{sat} = 2.2 cm²/Vs

V_{th} = 2 V

$I_{on}/I_{off} = 10^7$

Mobilities up to 5 cm2/Vs (350degC)



ZnO

- Solution processed (jet-printed) inorganics
- Targeting 150degC process temperatures

Challenges in Printed Electronics (with focus on inkjet)

Printing process challenges

- Registration
- Chemical compatibility of materials (orthogonal solvents)
- Physical compatibility (step coverage, work function, etc.)
- Curing/drying of inks within thermal tolerances/time
- Online quality control to optimize process yield
- Controlled atmosphere for sensitive materials

Materials challenges

- Ink viscosity
- Printability
- Ink stability (e.g. particle agglomeration, settling,…)
- Material lifetime (moisture, oxygen, ozone, etc.)
- Cost (e.g. Au, Ag vs Cu)
- Uniformity (e.g. OSC, nanowires, thickness)
- Performance (e.g. OSC mobility)
- Process/solvent compatibility
- Wetting properties (surface tension, surface energy)

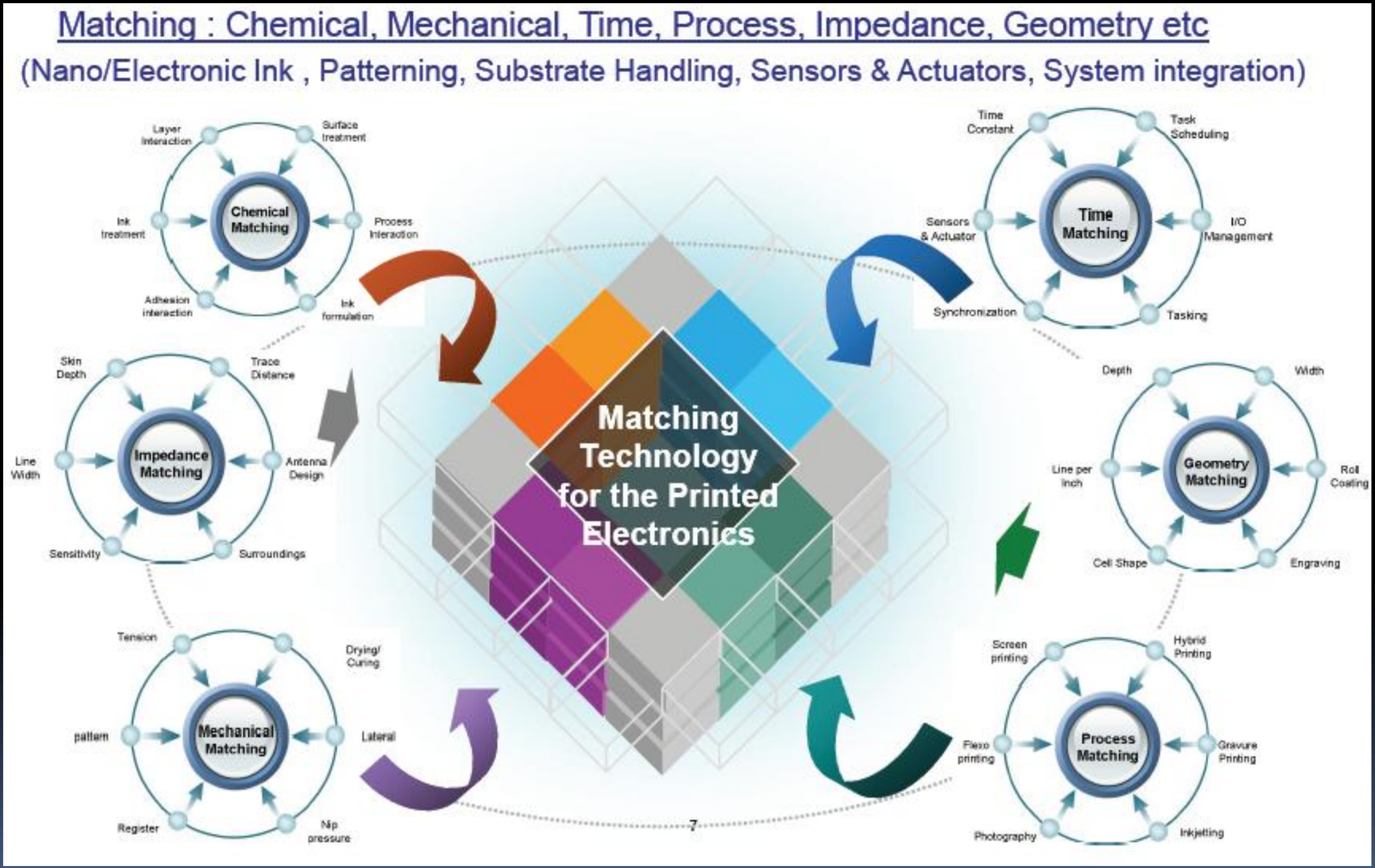
Challenges – from the lab to the fab

- Manufacturing challenges:
  - Environmental impact / disposability
    - e.g. are nanoparticles ‘safe’ ?, disposable batteries ?
  - Health & safety
    - benign solvents
  - Process time/ TACT time/ print speed
    - Curing -> UV (photonic curing , laser sintering ?)
  - Temperature Budget
    - Low-T curing or photonic curing ?
  - Process parameters: substrate tension, layer thickness
  - Yield/ uniformity/process monitoring
  - Packaging
    - operation in air, elevated temperatures (e.g. in car in summer ?)

Device challenges

- Parasitic capacitance (affecting device speed)
- Feature size (affecting device area)
- Uniformity (device to device)
- Reliability (pinholes, roughness)
- Yield
- Encapsulation (for longer lifetime)
- Process compatibility of device layers
- Performance tradeoffs (top gate vs bottom gate)

Challenges – from the lab to the fab



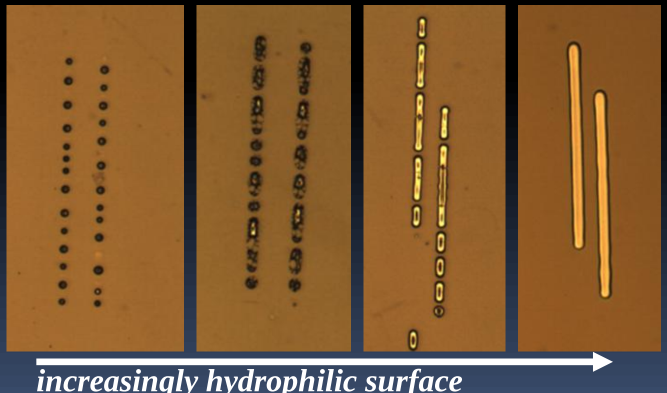
K.H. Shin, Konkuk Univ., Seoul, Korea

parc A Xerox Company

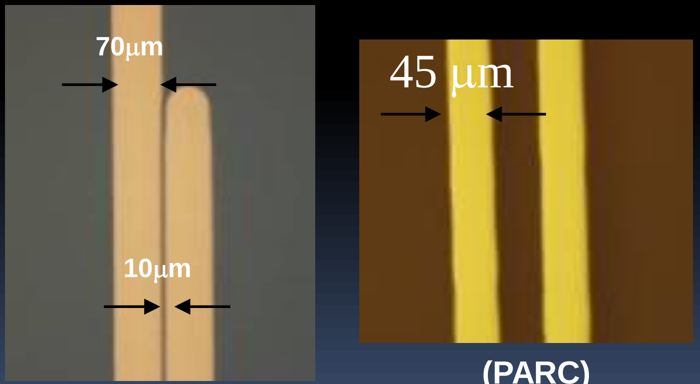
Challenges in (Jet)-Printing Circuits

- Ink formulation (-> adjusted viscosity, surface tension, evaporation rate)
- Substrate quality (-> surface energy, roughness control)
- Layer to layer registration (-> self-alignment)
- Jetting-reliability (-> monitoring, redundancy)
- Ejector-to-ejector variations (->monitoring, redundancy)
- **Print resolution** (-> surface energy adjustment or patterning, laser assist, novel print-heads)

Influence of Substrate surface



Examples of printed silver lines



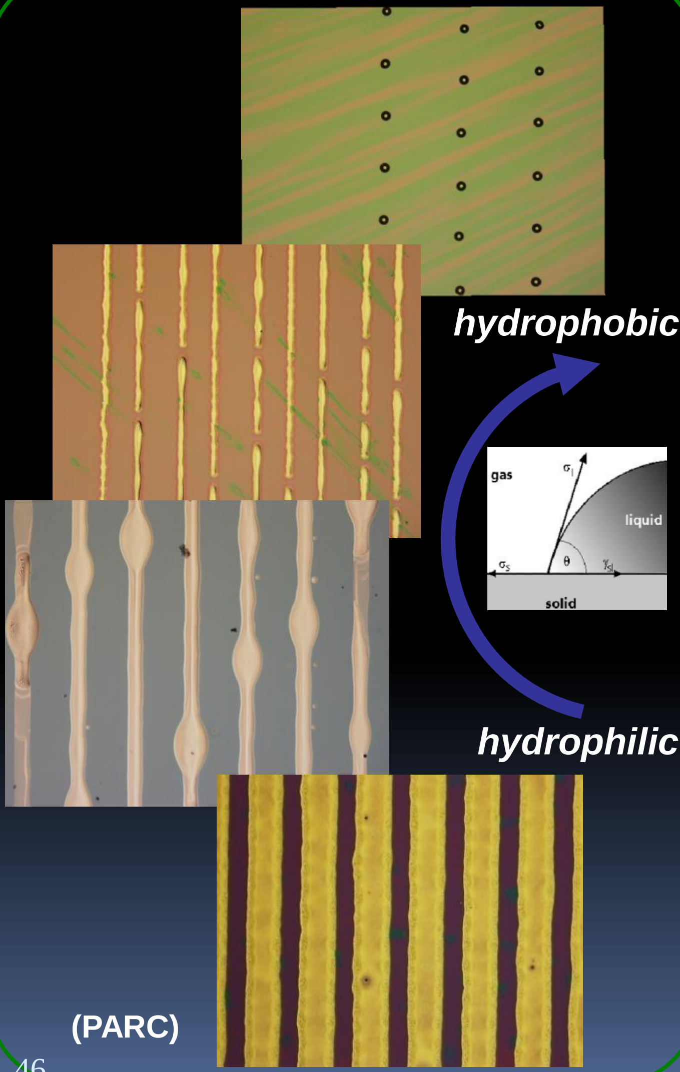
Printing challenges offer opportunity for R&D

A.C. Arias, et al., J. of the SID, 15/7 (2007) 485
J. Daniel, et al., NIP25/ Dig. Fab. 2009, 599-602

parc A Xerox Company

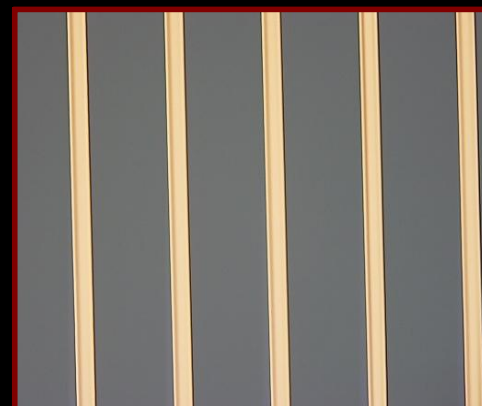
Jet-printing challenges - nanosilver

ink-surface interaction



(PARC)

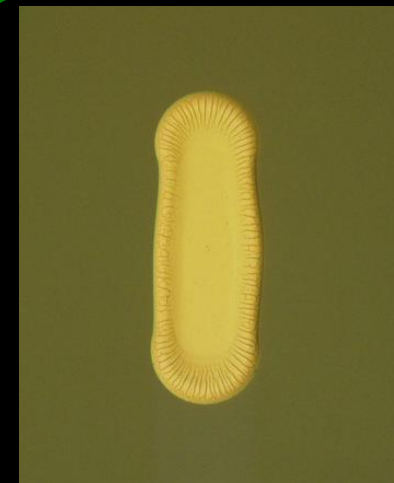
optimized process

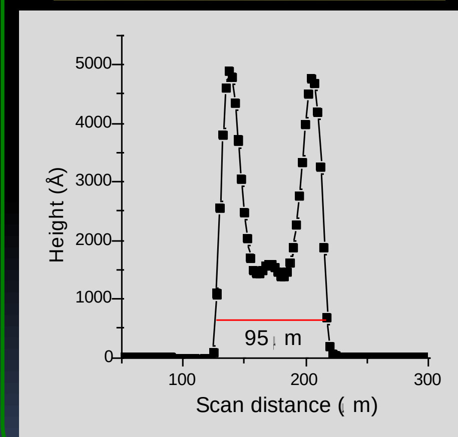


~140 micron lines

~65 micron lines
on polyimide
(smaller drop size)

coffee-ring effects

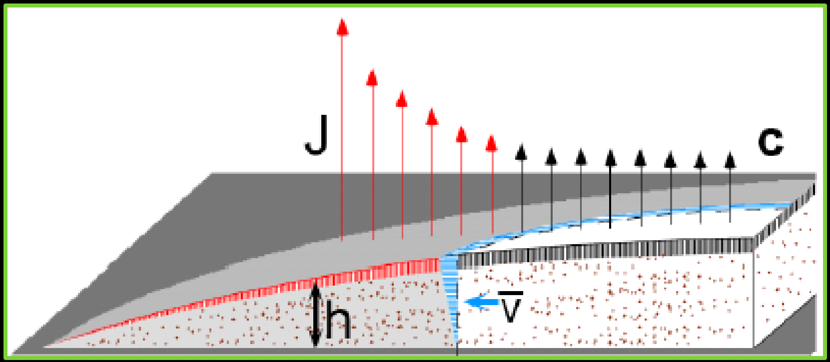




A.C. Arias, et al., J. of the SID, 15/7 (2007) 485
J. Daniel, et al., Jpn. J. Appl. Phys., Vol 46, No 3B (2007) 1363-1369

Coffee Stain Effect

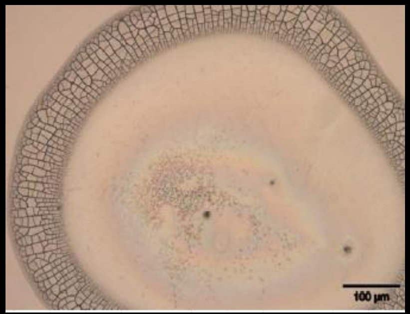
- Typical for inkjet printing: result of the uneven evaporation of a liquid over a droplet's liquid-air interface

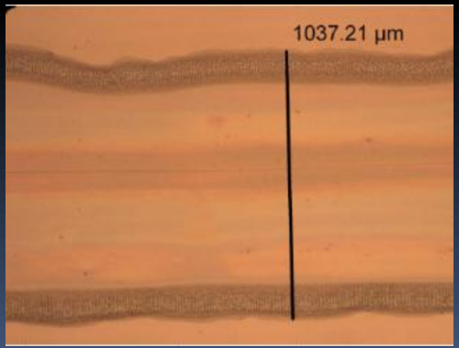


Pinned contact line

• the free surface, constrained by a pinned contact line, squeezes the fluid outwards to compensate for evaporative losses.

Dynamics of the "coffee stain" effect:
The evaporation rate J is larger at the edge of a droplet due to the curvature of the droplet leading to a flow of fluid and nanoparticles with a velocity v.



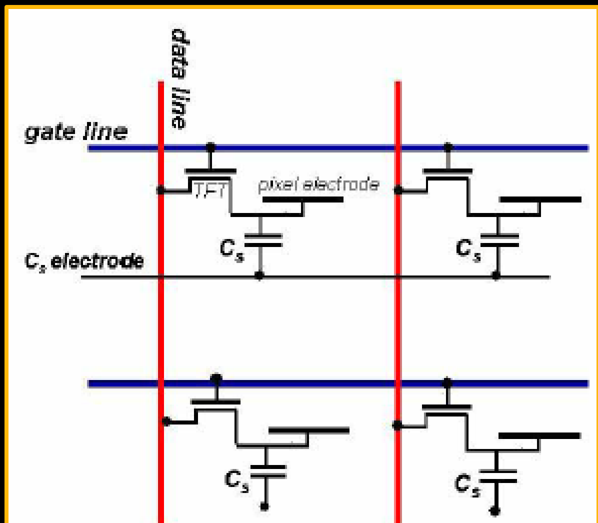


Source: U Illinois

'Circulating flows driven by surface-tension gradients (Marangoni flows) can counteract coffee stain: Marangoni flow can be induced by mixing two solvents with different boiling point and different surface tension.'

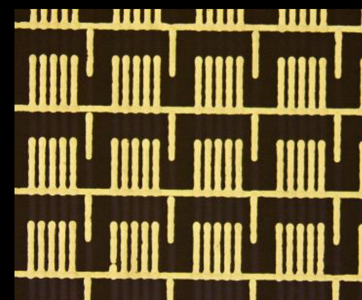
Deegan, R.D., et al, "Capillary Flow as the Cause of Ring Stains from Dried Liquid Drops" , Nature 389, 1997

Jet-Printed Active-Matrix Backplanes

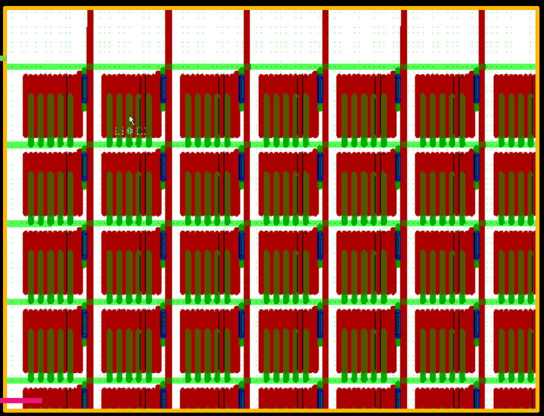


printed

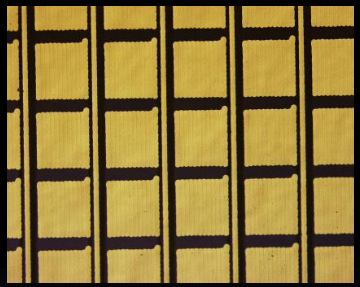
Gate layer



Pixel design

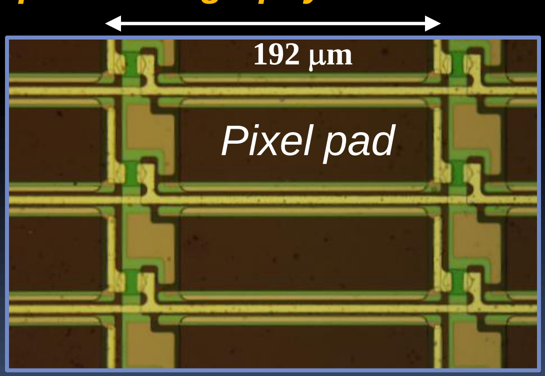


Data layer

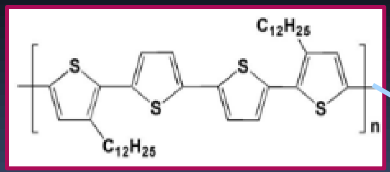


Jet-printed nano-silver

photolithography

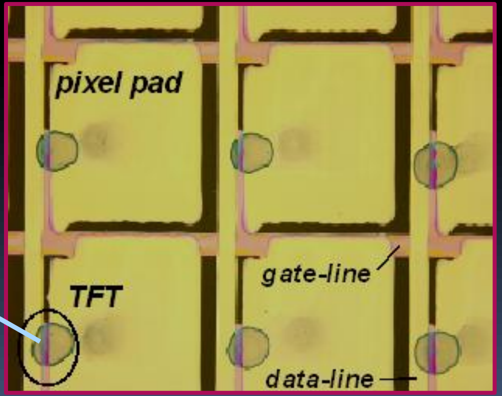


Commercial backplane
(smallest features ~5 μm)



PQT-12 jet-printed OSC

Printed pixels (PQT TFT)



680 μm (37ppi)

(PARC)

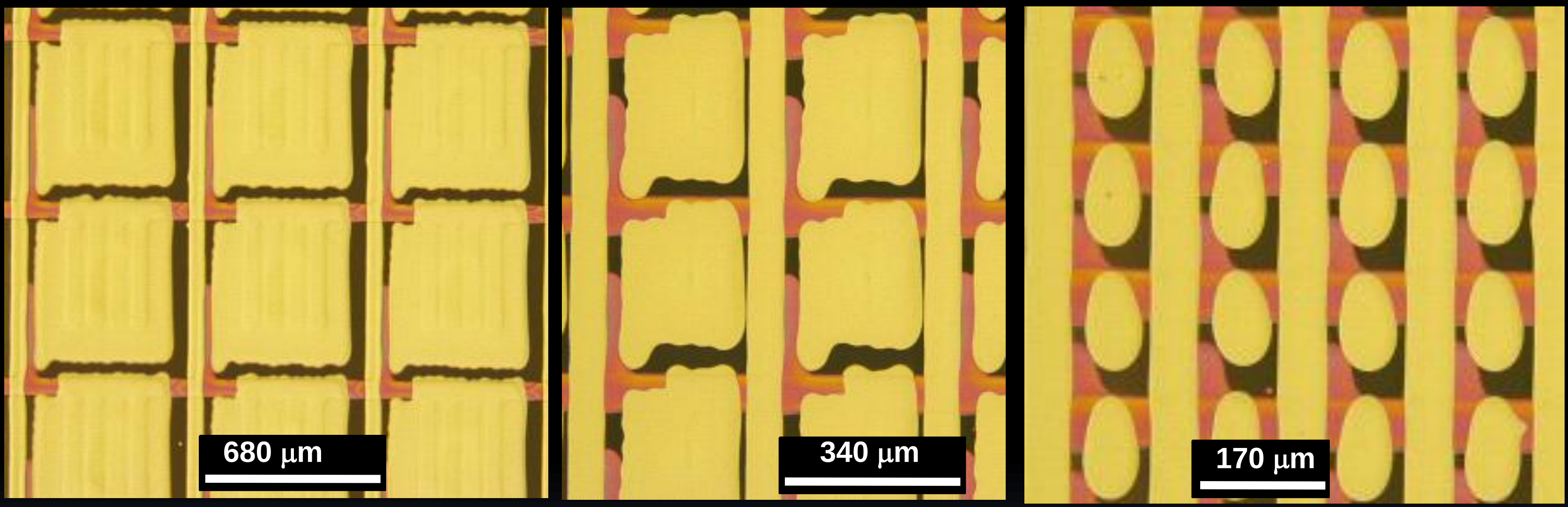
A.C. Arias, et al., J. of the SID, 15/7 (2007) 485
J. Daniel, et al., SID 07 Digest, P-21, 249-251

parc
A Xerox Company

Challenge: Higher Resolution

- *Higher display resolution requires smaller pixels*

Fill factor: ~72% **~58%** **~32%**



(PARC)

increasing pixel count

decreasing fill factor

solutions

- **improve printing process (line width / spaces)**
- **multi-layer pixel design**

J. Daniel, et al., Proc. NIP25 and Digital Fabrication 2009, 599

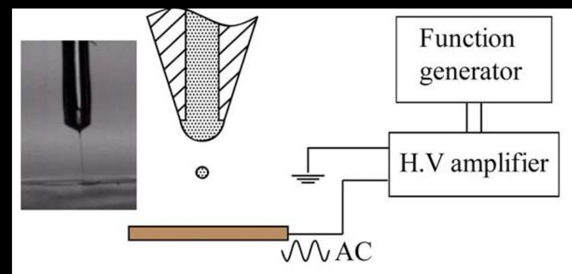
parc A Xerox Company

Higher Resolution

Printheads with 1pl drops for ~20 micron features

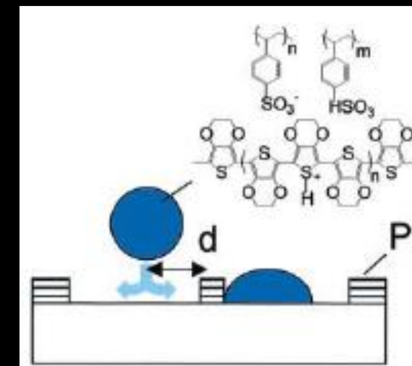
Brownian motion, electrostatics !

Electrohydrodynamic printing



Droplets smaller than nozzle size possible

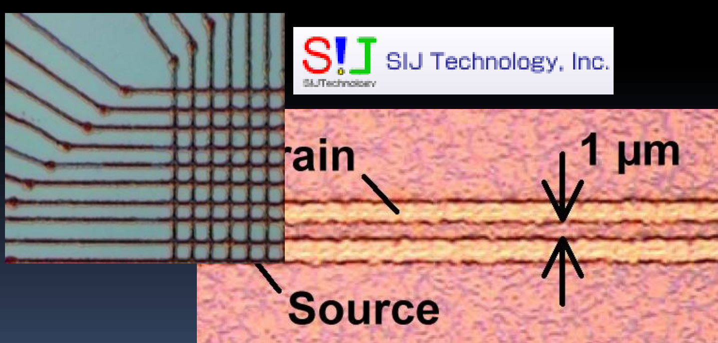
Surface energy patterning of substrate



Sirringhaus, et al., Science, 290 (2000), 2123

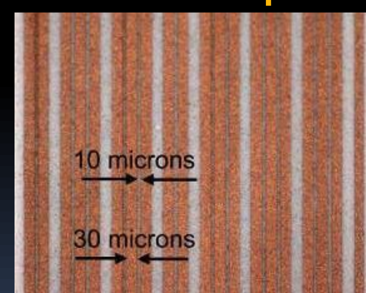
T. Tano, Ricoh Co., NIP25, '09

Superfine inkjet printing



Sekitani, *Proc. Nat. Acad. Sci. 105 4976 (2008)*

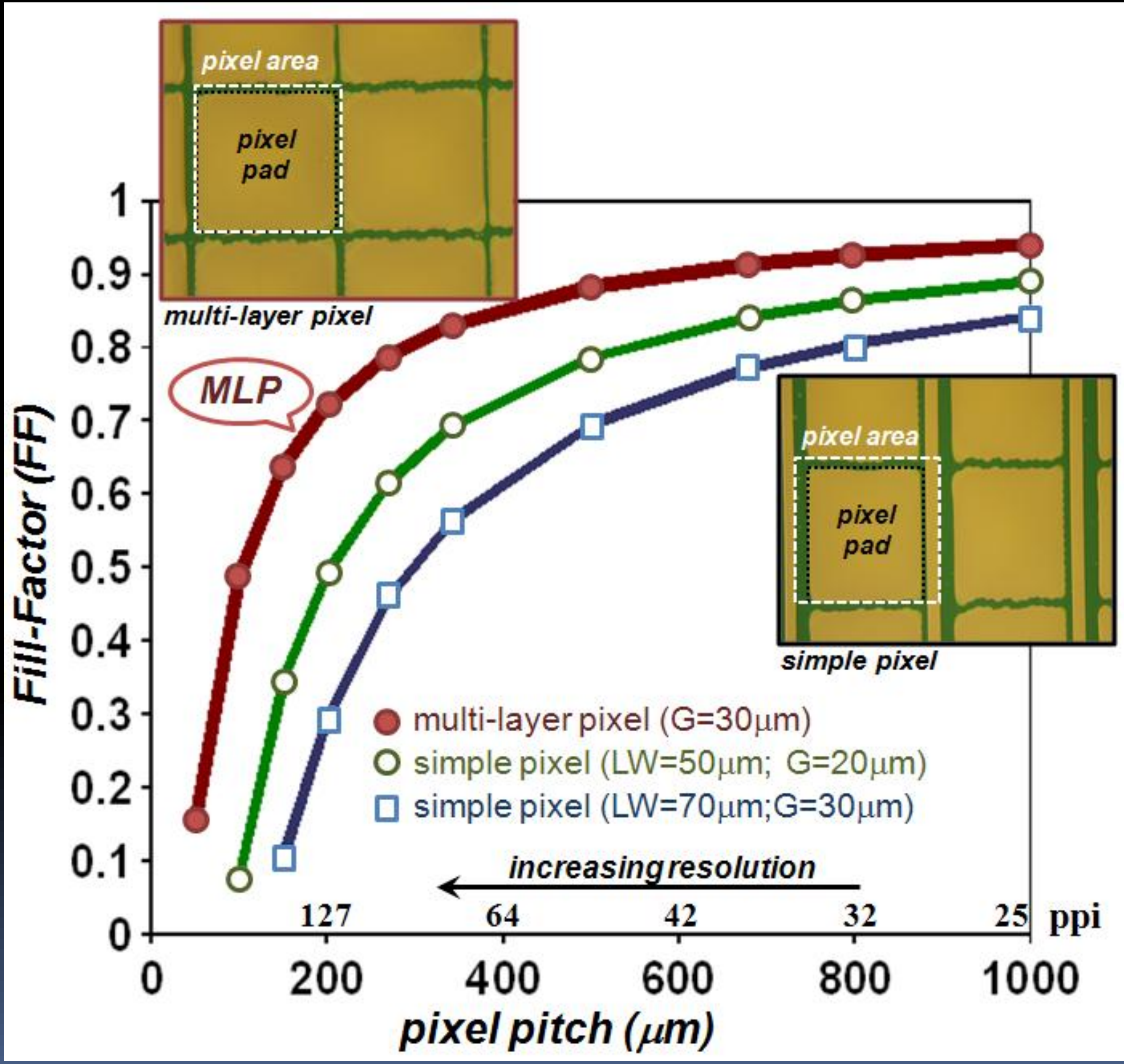
Laser assisted printing

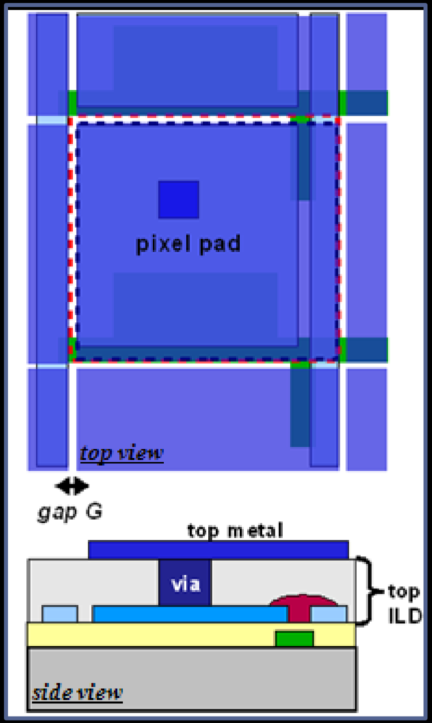


Conductive Inkjet Technology (CIJ)

Brownian motion and electrostatics are crucial at small drop sizes

Pixel Fill-Factor





Multi-layer pixel (MLP)

Requires via formation

J. Daniel, et al., SID 09 Digest, 44.3, p660-663

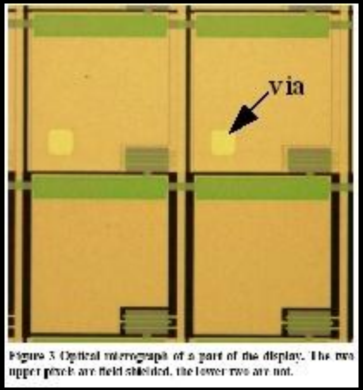
(PARC)

parc
A Xerox Company

Via Formation in Printed Electronics

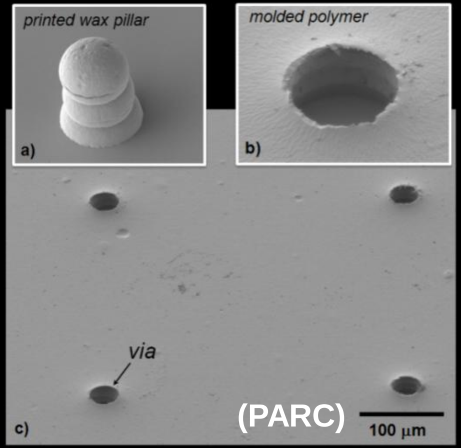
- Vias in dielectrics are essential for multi-layer pixels and for most other electronic circuits

Photolithography



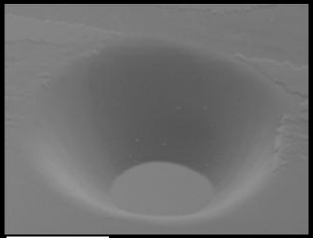
Gelinck, et al., SID 05 Digest, 3.1
(Polymer Vision / Philips)

Molding process

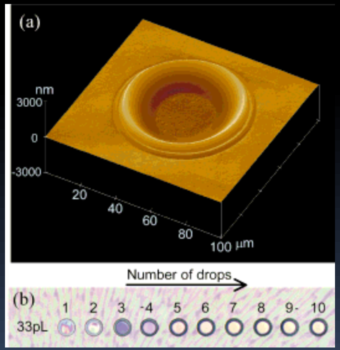


J. Daniel, et al., SID 09 Digest, 44.3, p660-663

Laser ablation

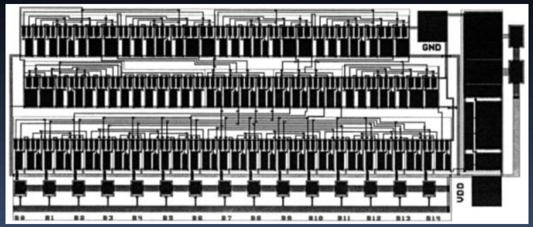


Solvent Printing



Kawase, Sirringhaus, et al.,
Adv. Mater. 2001, 13, 1601
(Seiko-Epson/ Univ. Cambr.)

Hole Punching

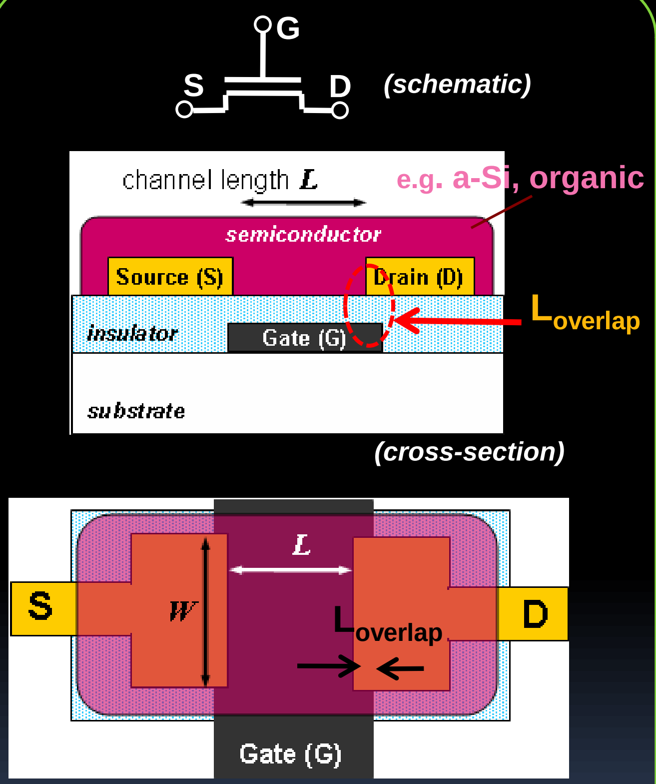


Drury, et al., Appl. Phys. Lett., 73, 1998, 108
(PhilipsRes. Lab)

Via formation process is still challenging

Overlap capacitance in Printed TFTs

- Larger print tolerances cause greater overlap capacitance



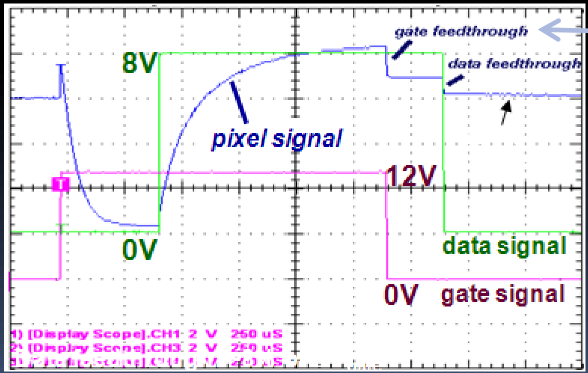
typical bottom-gate TFT

$$f = \mu \cdot (V_{gs} - V_t) / 2\pi L(L+2L_{overlap})$$

High overlap capacitance -> ***low switching frequency***

$$\Delta V_{pixel} = \Delta V_{gate} \cdot C_p/(C_p+C_{st})$$

High overlap capacitance -> ***high feedthrough voltages***
(unless compensated by large storage capacitor)



(PARC)

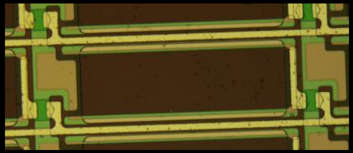
Feedthrough voltage

(can negatively affect appearance of a display)

Reduce overlap capacitance, e.g. with self-alignment techniques

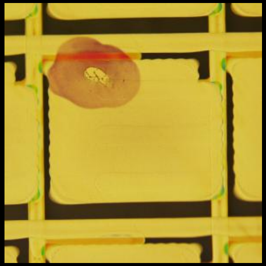
Speed of Display – video rate ?

- **Conventional LCD display pixels:**



190x64 µm,
Cst ~0.2pF,
Cp ~0.03pF

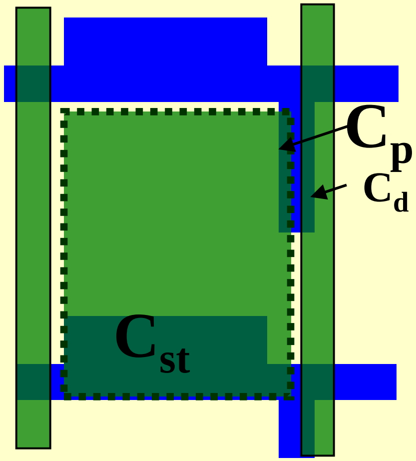
- **Printed pixels:**



680x680 µm,
Cst ~pF,
Cp ~pF

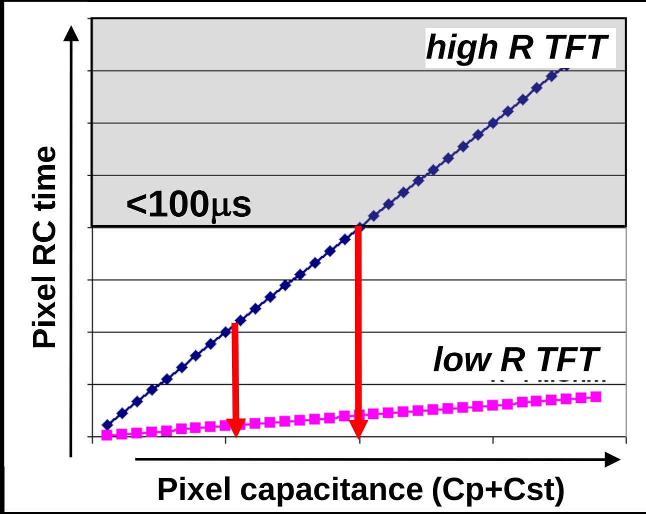
typically larger feature size !

Pixel capacitances and feedthrough voltage



$$V_{ft} = V_s \cdot \frac{C_p}{C_{st}+C_p}$$

Pixel charging speed



(PARC)

"Fast pixel response requires careful balancing of feedthrough voltage and pixel capacitances"

- high mobility semiconductor is desirable (+ high W/L)
- good control over printing process to reduce parasitics
- ~ 30 fps may be sufficient for many applications
- for e-paper, faster display media is under development (E-ink, SID'05)

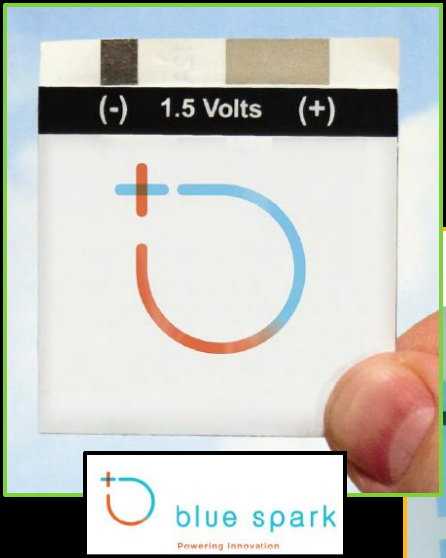
Applications

Printed Battery 'Energy Strip'

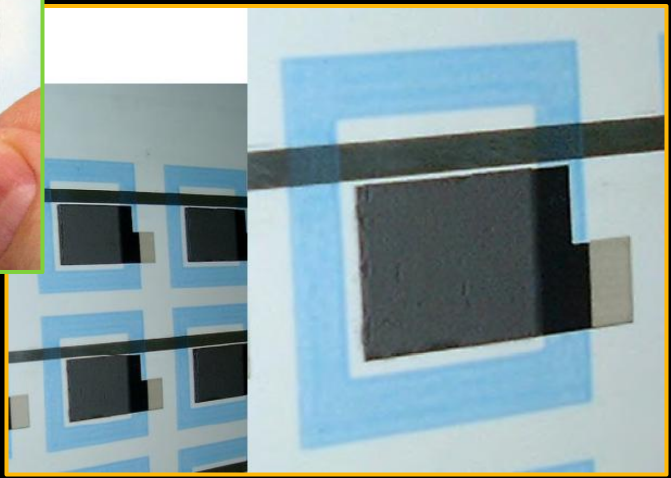
Printed
- conductor
- insulator
- thermochromic dye

Nice to have, but consumer probably would not want to pay extra for it

Printed Battery



- 1.5V/cell carbon-zinc MnO2 chemistry
- R2R process



printed Li polymer battery

printed Zn/MnO2
– ZnCl2 electrolyte

potential applications:

- Battery-assisted RFID
- RF-enabled sensor systems and data loggers
- RFID smart cards and ID badges
- Medical care devices
- Cosmetic patches
- Interactive consumer goods packaging

Printing enables battery integration with other devices on one substrate

Printed RFID tags

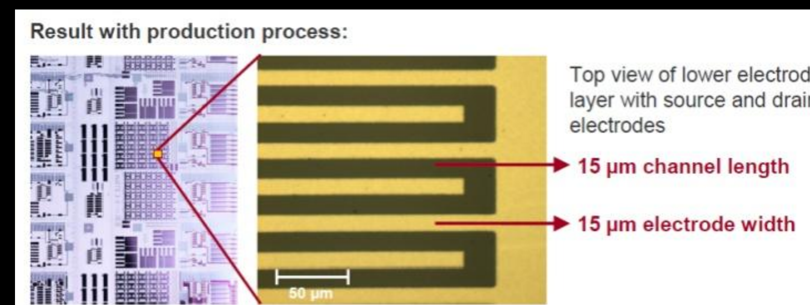
- Organic semiconductor on plastic foil

•Item-Level Tracking
•Smart Packaging for Healthcare Applications
•Brand Protection
•Inventory and Tracking
•Transit Cards and Smart Cards

TFT mobilitiies <0.1 cm2/Vs

Web speed: ~30m/min

- 13.56 MHz voltage rectifier
- ~100Hz ring oscillator,
- 4 bit Manchester chip (64-bit tags in lab)
- Antenna is not printed

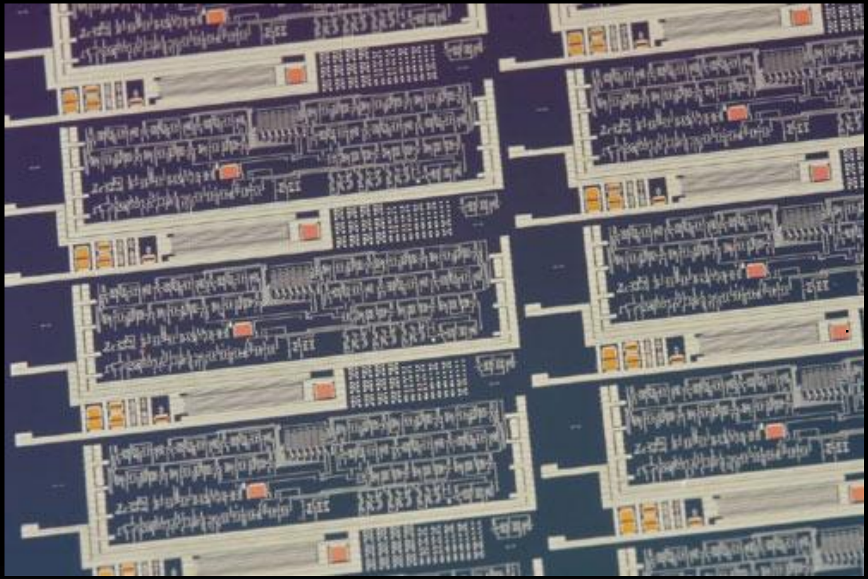


re-writable memory (for toys/games):
PolyIC and Thin Film Electronics ASA

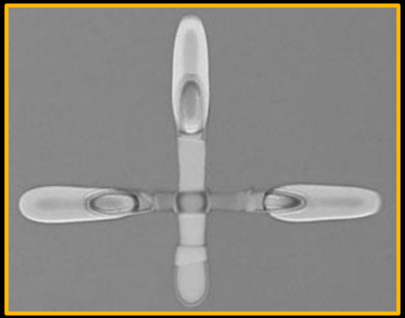
For ultra-cheap RFID tag applications

Printed RFID tags

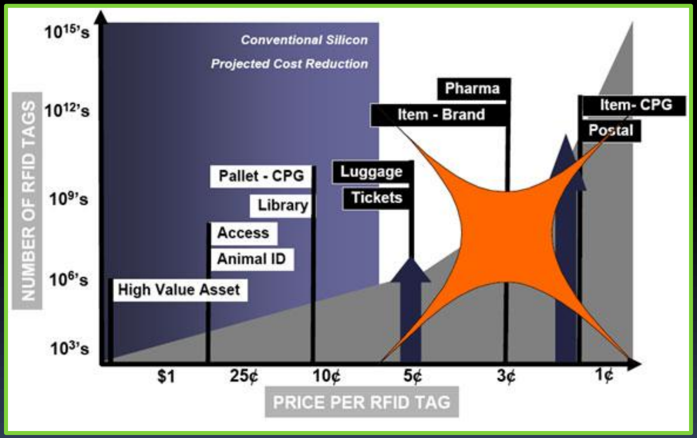
- Silicon ink semiconductor on metal substrate



Kovio's RFID chips are printed on a 16 x 16 in. sheet of metal.



nFET thin-film transistors (TFT) with electron mobilities of 80 cm^2/Vs.



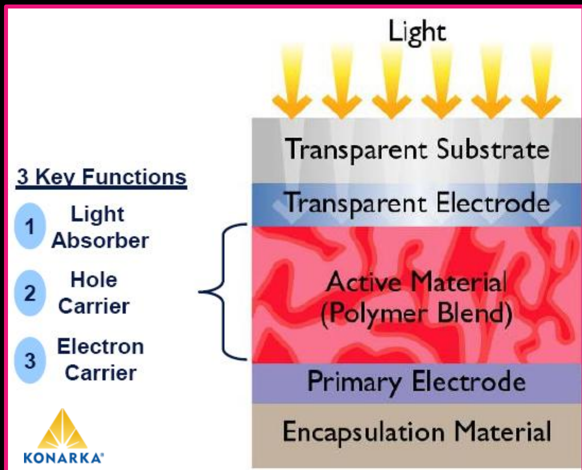
IDTechEx: market size for item-level RFID tags by 2015 will grow to 163 billion units, valued at $5.3B. By then, the average sales price will be cents per tag.

(source: Semiconductor International)

For ultra-cheap RFID tag applications

Printed Organic PV

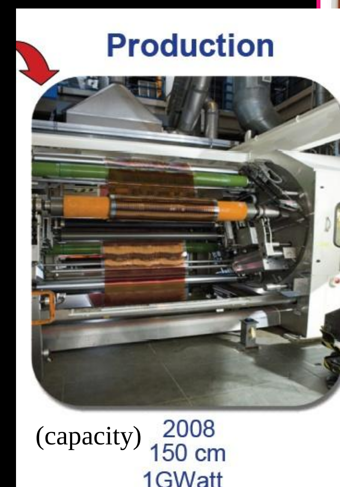
Bulk Heterojunction Polymer / Fullerene

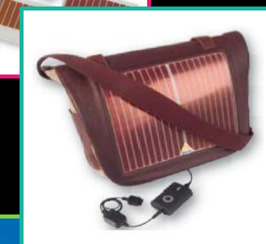


J. Hauch, OSC09

100feet/min; 250-1500mm width

KONARKA





Konarka/Lundberg Design

- 6.39% efficiency (0.8cm^2)
- T80 lifetime ~8000h (>3yrs)

- commercial OPV modules: ~3-5%

SOLARMER Energy, Inc

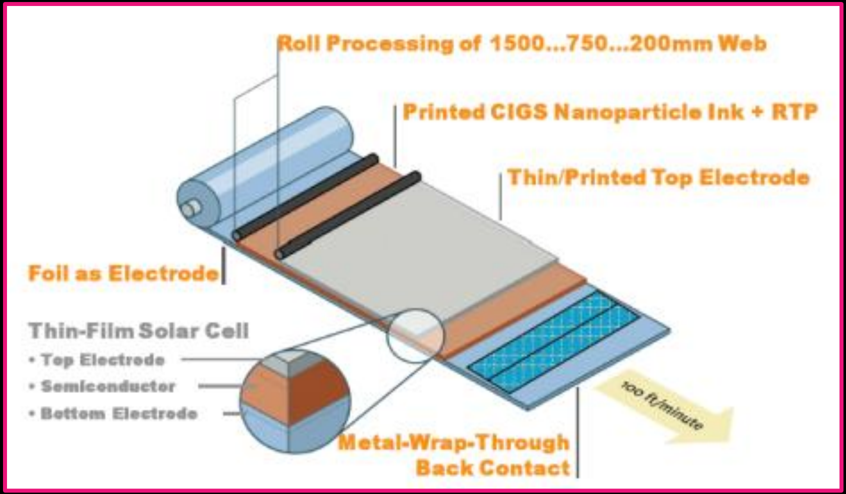
8.13% record efficiency (size ?)

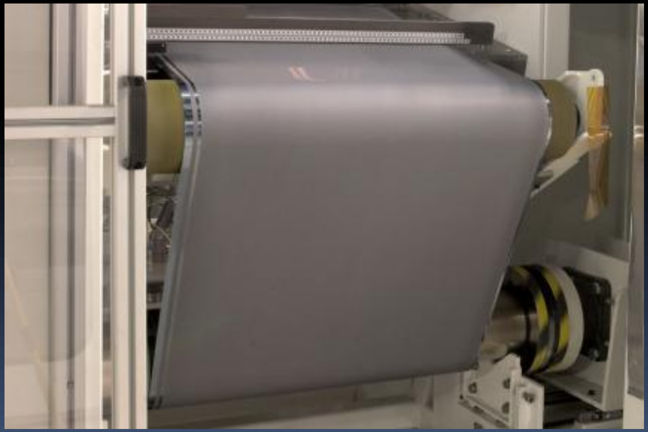
Promising for ultra-low cost, partial transparency and high flexibility

parc A Xerox Company

Printed Inorganic PV

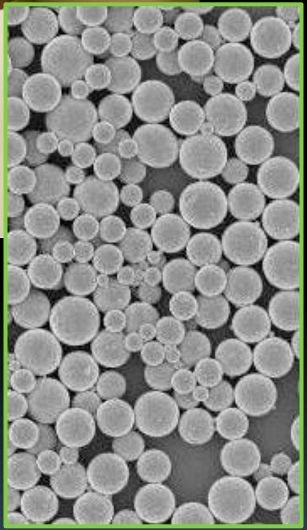
- ‘Printed’ CIGS solar cell





nanosolar

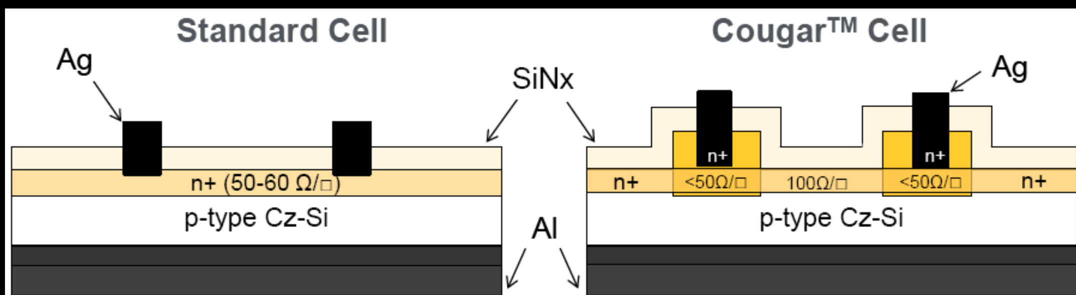
CIGS (copper-indium-gallium selenide)

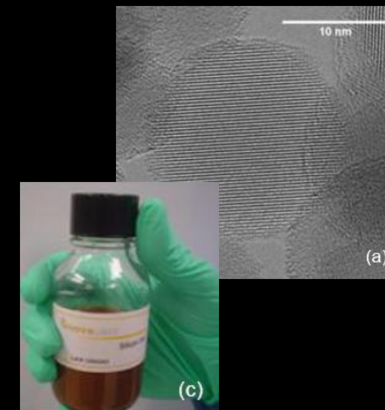


R2R (non-vacuum) process enables low cost

Printed Selective Emitter Process

- Innovalight





Si -nanoparticle ink

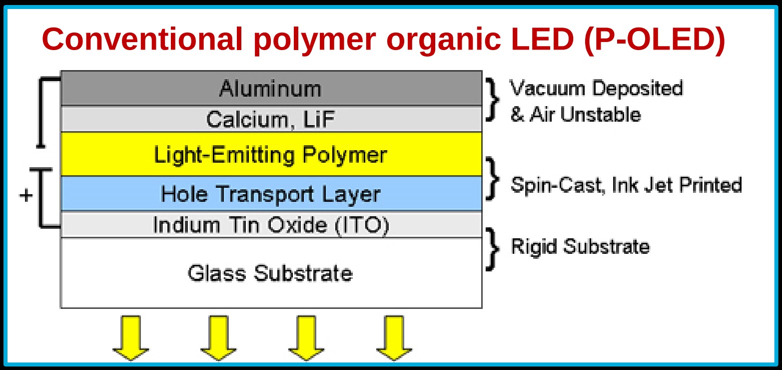
Printed n-type Silicon ink (screen or inkjet)
One step added to a conventional cell line (retrofitable)

Efficiency improvement

H. Antoniadis: 34th IEEE Photovoltaic Specialist Conference, 7-12 June 2009, Philadelphia, PA, USA

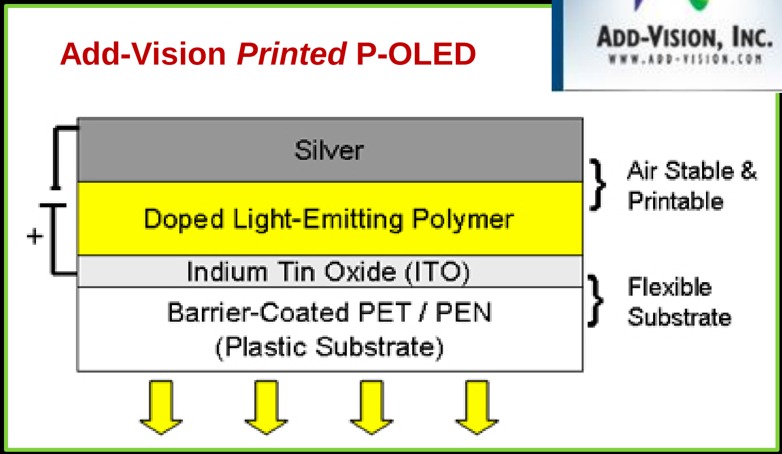
OLED Displays / Lighting

- Fully printed OLED



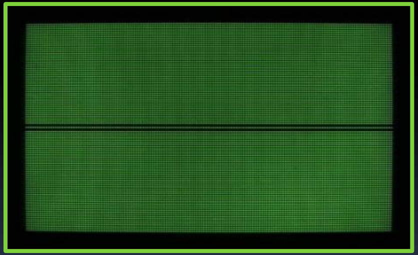
evaporated cathode material !

(Superior power efficiency brightness and lifetime)



screen printed air-stable printed cathode material

Seiko Epson, CDT, …



panel with ink volume correction

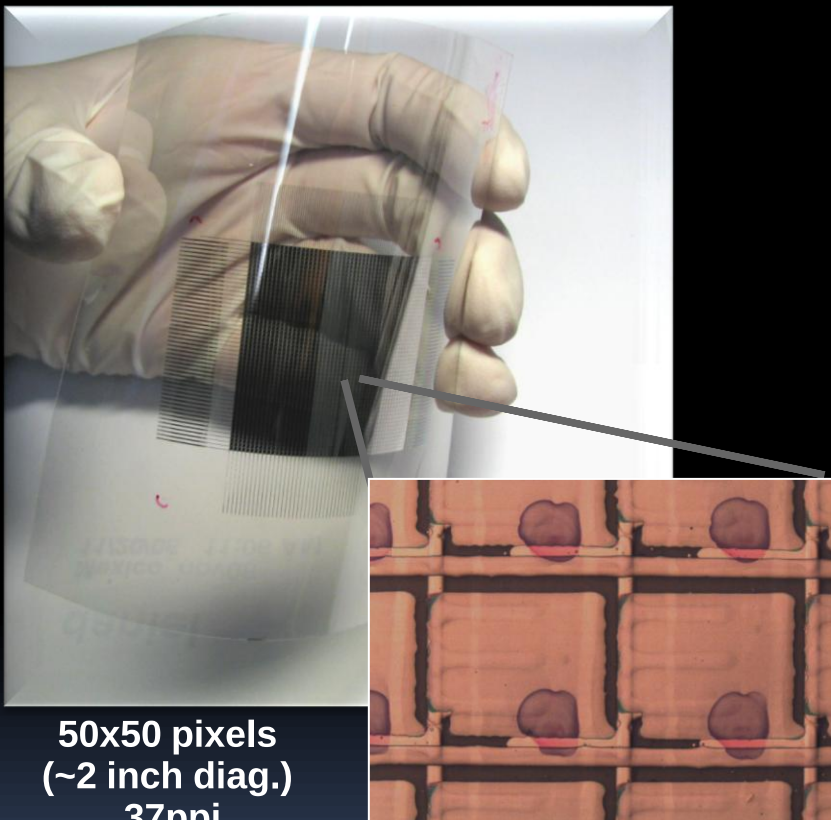
S.Skai, et al., NIP 25, 2009 (Seiko Epson)

http://www.add-vision.com/

inkjet printed displays – volume averaging required for uniformity (Mura reduction)

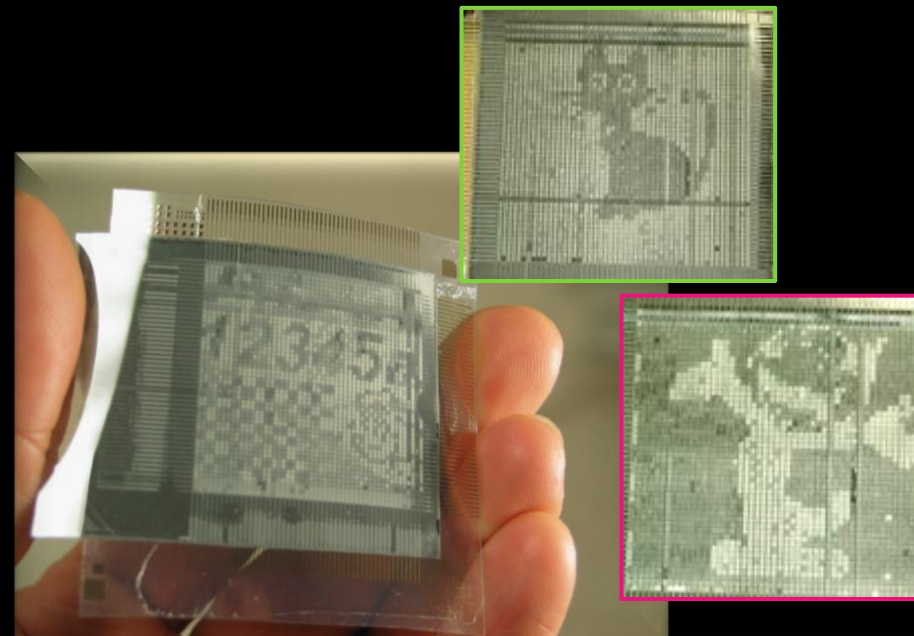
Flexible Displays with Printed Backplane

'active-Matrix pixel circuits for electrophoretic media (PARC)'



50x50 pixels
(~2 inch diag.)
37ppi

680 μm pixels; PQT-12 jet-printed Semiconductor



Display medium: ***E-ink*** *electrophoretic imaging film*

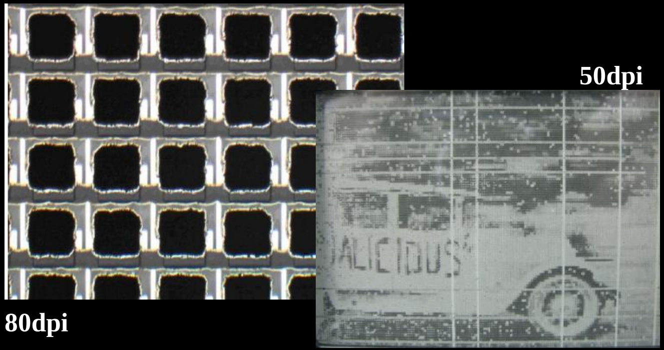
- ***PEN substrate***
- ***PVP gate dielectric***
- ***Printed Ag***
- ***PQT semiconductor***

All-additive solution process

A.C. Arias, et al., J. of the SID, 15/7 (2007) 485
J. Daniel, et al., SID 09, 44.3, 660

Printed Displays - further examples

Dai Nippon Printing

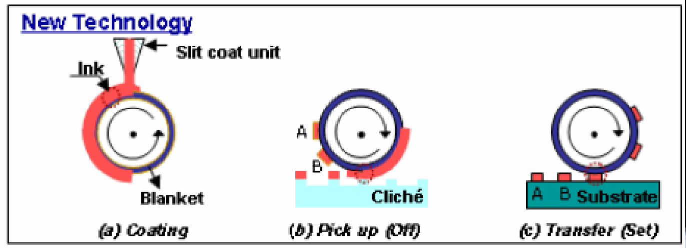


50dpi

80dpi

- screen printing+ solution processing
- pentacene OSC
- QR-power display

LG



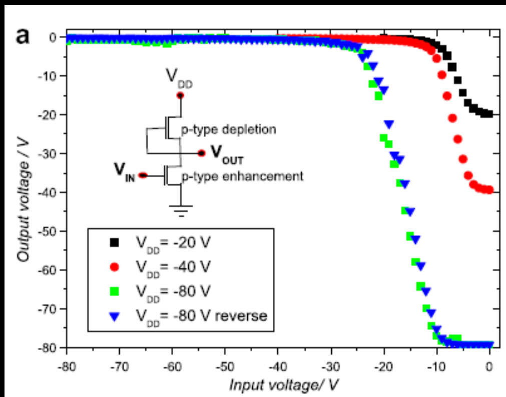
- roll printed resist for all layers
- 15 inch display

Samsung

parc
A Xerox Company

Printed Electronics Circuits

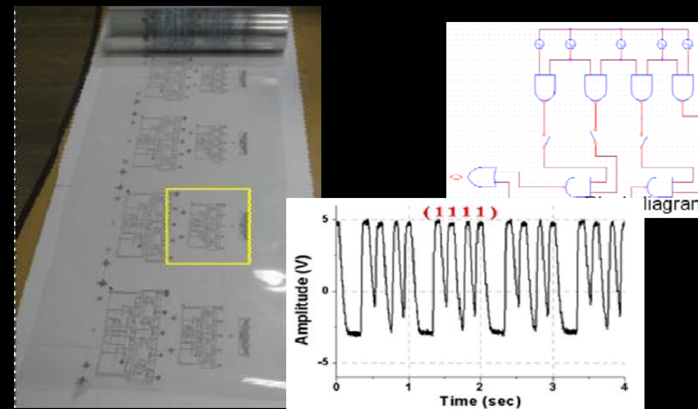
Gravure/Flexo printed inverter



(Chemnitz Univ./Johns Hopkins Univ)
K. Reuter, et al., Organic Electronics 11 (2010) 95-99

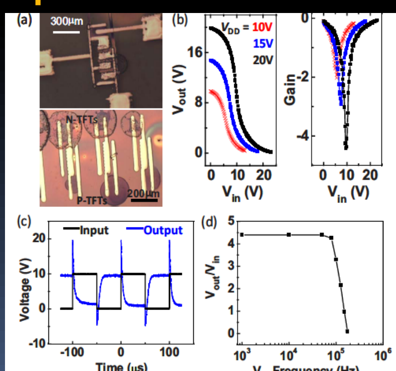
- Contact charging of Cytop dielectric for depletion/accumulation TFTs

Gravure printed 4-bit logic



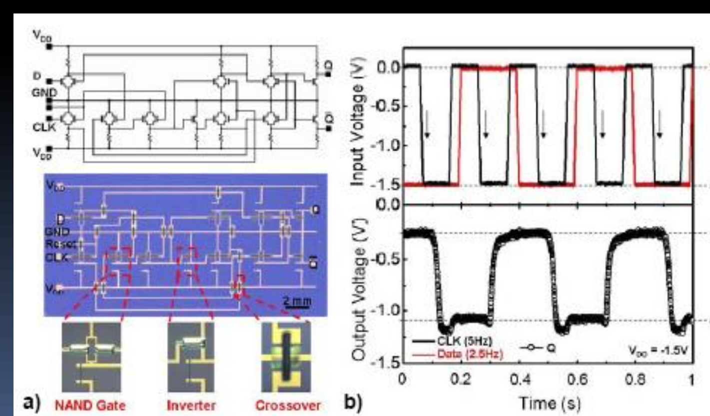
(Sunchon National Univ.)
M. Jung, G. Cho, et al. ICFPE09

Jet printed inverter



(PARC)
T. Ng, et al., Appl. Phys. Lett., 94, 233307 (2009)

Printed D-Flipflop (printed ion gel gated circuit)



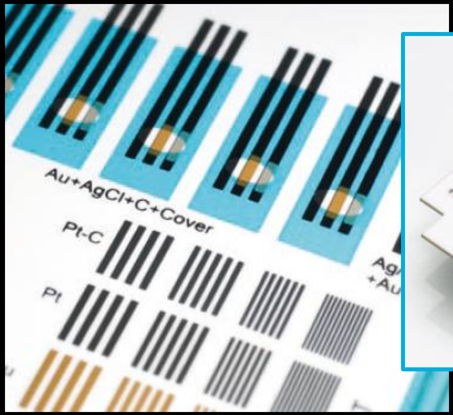
Y. Xia, D.Frisbie, U. Minnesota

Other Printed Electronic Devices

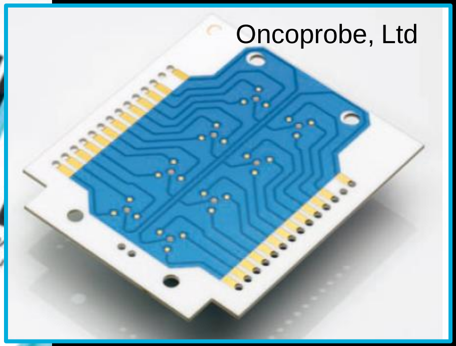
Antennas

Source: Dupont

Biosensors



Printed sensors for glucose meters: ~2.2 billion sold each year



Oncoprobe, Ltd

Source: Dupont

Electroluminescent Lamps

GSI technologies

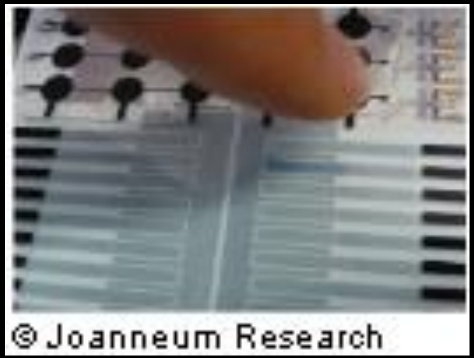
Electrochromic Displays

GSI technologies + NTera

Relatively simple printed devices are already on the market

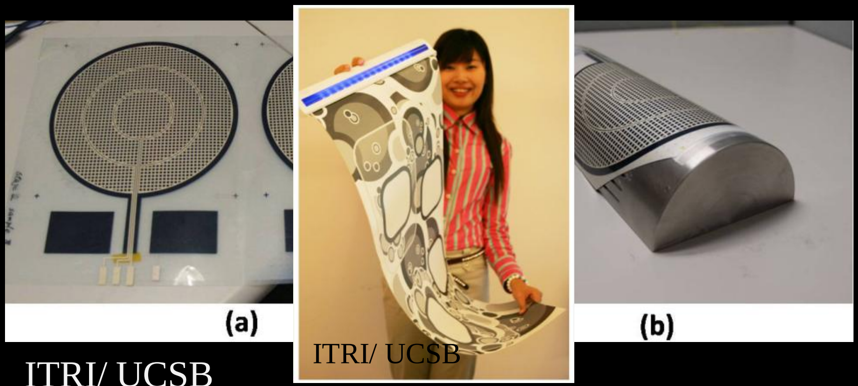
Examples of Printed Sensors

screen printed piezo/pyro sensors



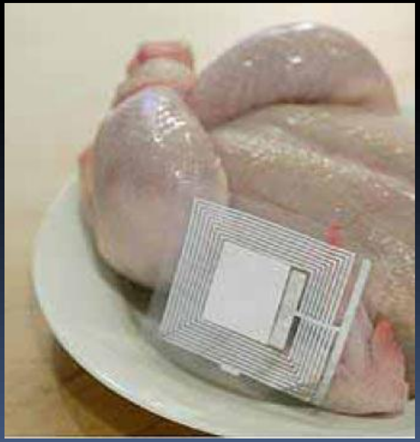
3PLAST project

screen printed piezoresistive pressure sensor (e-Drum)



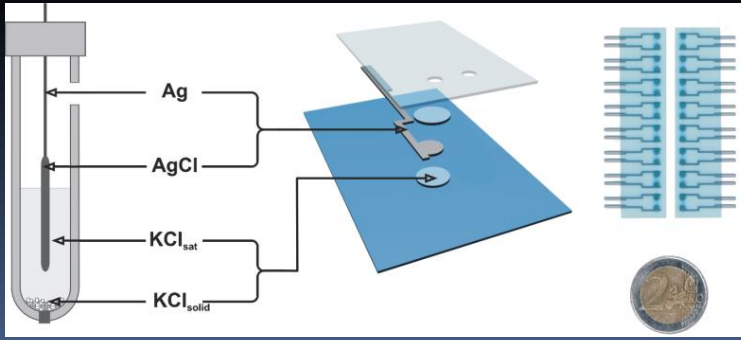
ITRI/ UCSB

detection of H2S gas



VTT

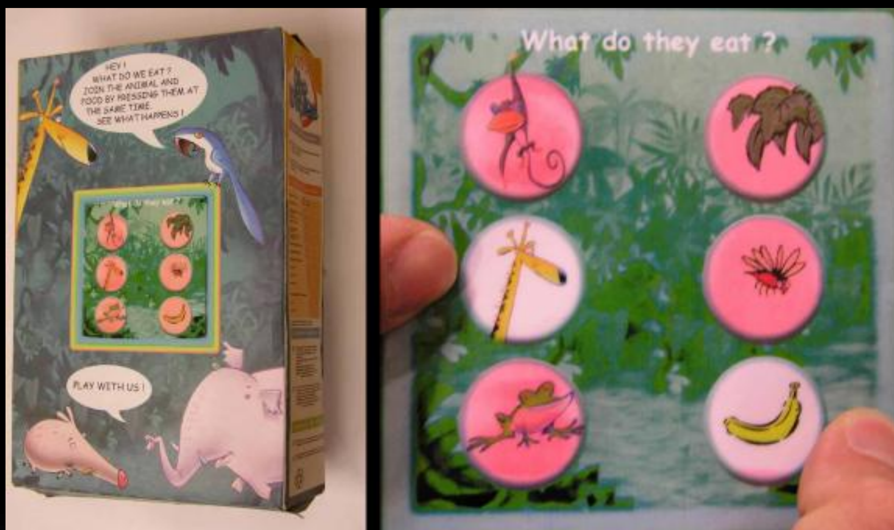
Screen printed Ion-selective sensor electrodes



L. Tymecki, et al, Sensors ***2006, 6, 390-396***

Demonstrators

Interactive package:
Conductors, dielectrics, thermochromic ink



Interactive cards (gaming cards) –
batteries, conductors, push buttons

Printed Electronics - demonstrators

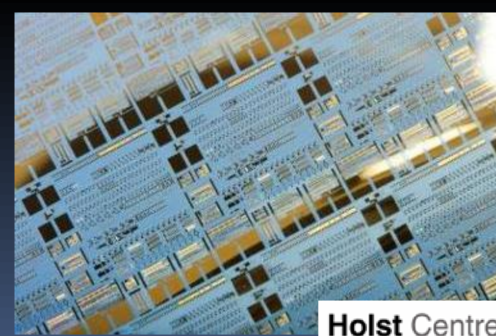
- Demonstrator kits by OE-A


Game board

Demonstrators may enable designers to have new application ideas

Alternatives to Printed Circuits

- SAIL (HP)
- Lift-off processes (PVI)
- Hetero-integration – pick and place (Muehlbauer)
- Fluidic self-assembly (Alien Technology)
- R2R vacuum deposition and patterning
- Lithography + OSC (Holst Centre, ITRI, …)



Acknowledgment

- For work performed at PARC:
  - A.C. Arias, T. Ng, S.E Ready, R.A. Street, B. Krusor, B. Russo
  - Xerox Research Center of Canada
  - DuPont Teijin
  - NIST
  - DARPA (contr. # W81XWH-08-C-0065)

A Xerox Company

Thank you !