Research Opportunities in Macroelectronics

Motivation, Application Overview

Materials Classes, Challenges

Patterning Techniques, Challenges

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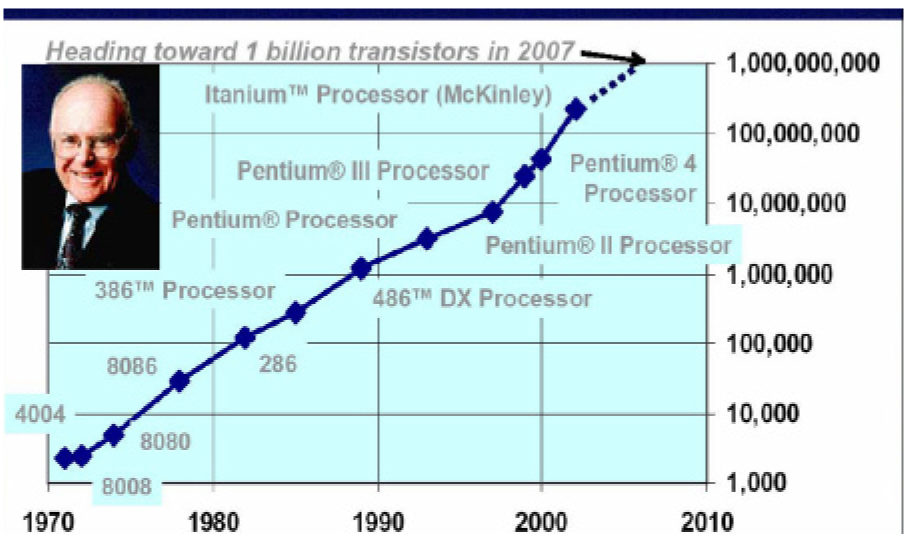
Mechanical and Industrial Engineering and Chemistry
Beckman Institute
Seitz Materials Research Laboratory

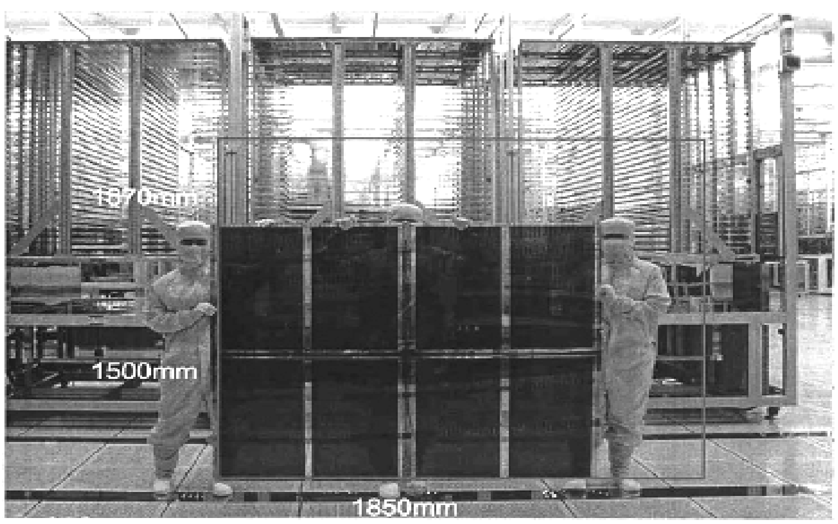
Funding: DARPA, DoE, NSF, DuPont, Dow Corning

Moores Law Continues…



Large Area Displays

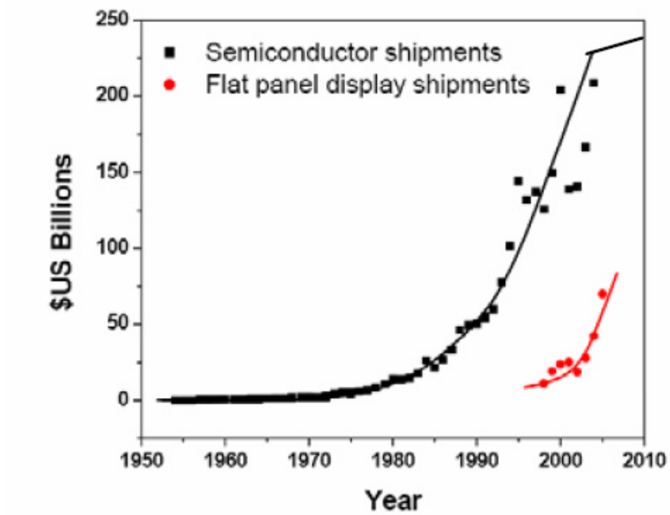
Large Area, Thin Film Electronics -- Macroelectronics



[7th generation (Gen 7) LCD glass substrates]

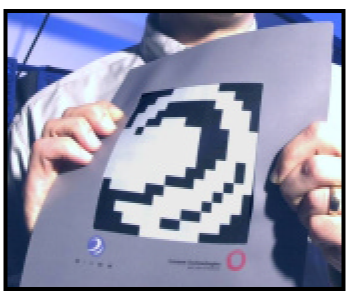
R. H. Reuss et al, IEEE, 93, 1239 (2005)

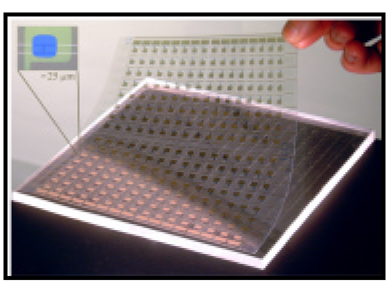
Large Area Electr. May Capture a Dominant Marketshare Position



Data from iSuppli and DisplaySearch

Large, Mechanically Flexible Sheets of Electronic Paper





Plastic Logic, Dec. 2005

PNAS 98(9), 4835 (2001); Science 291, 1502 (2001)

Ultralarge Area Display (Toppan)

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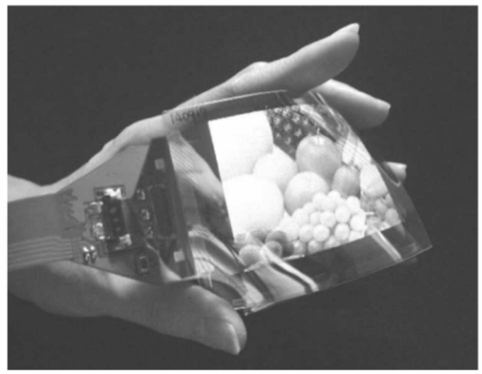
Imaging Materials for Flexible Displays -- OLED



Imaging Materials for Flexible Displays -- Electrofluidic

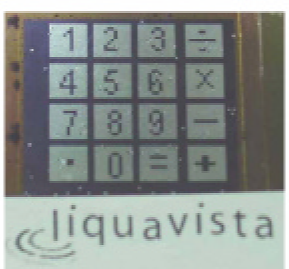
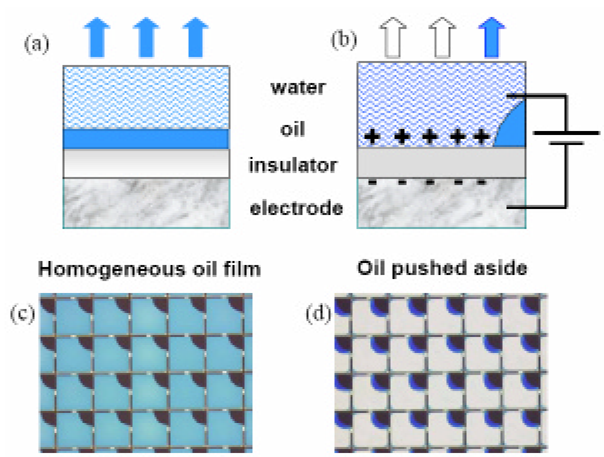


Figure 12 – Active matrix addressed electrowetting display The logo at the bottom off the figure is printed on paper to illustrate the reflective performance of the electrowetting display



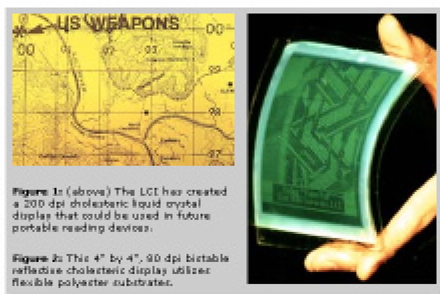
R. A. Hayes and B. J. Feenstra, Nature **425**, 383 (2003).

Imaging Materials for Flexible Displays -- LCs

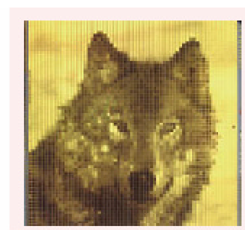
Conv. LC (Toshiba)

Tokyo--Toshiba Corporation today announced that it has developed the world's first large flexible liquid crystal display, opening the way to the display of images on curved screens and moving toward the long-term goal of foldable LCDs. The new display is a full color, 8.4-inch super-slim low-temperature polysilicon active-matrix TFT LCD supporting SVGA resolution.

Cholesterics (LCI)

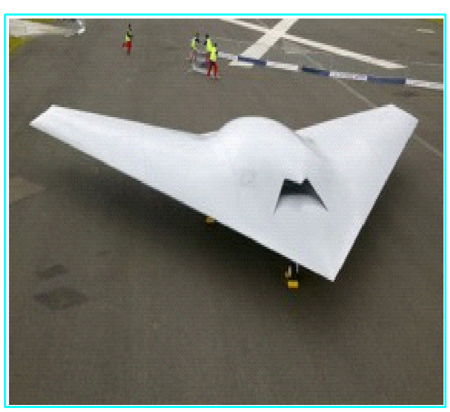


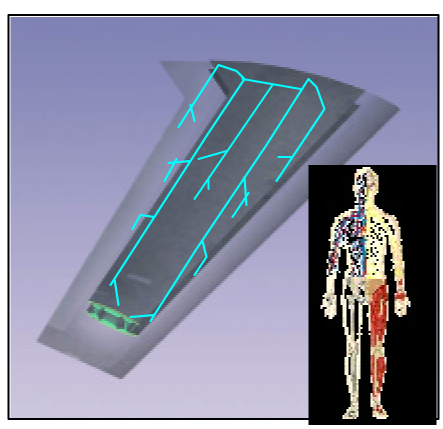
PDLC (Philips)



Structural Health Monitors for Aerospace

The Living Airframe – B. Baron/AFRL





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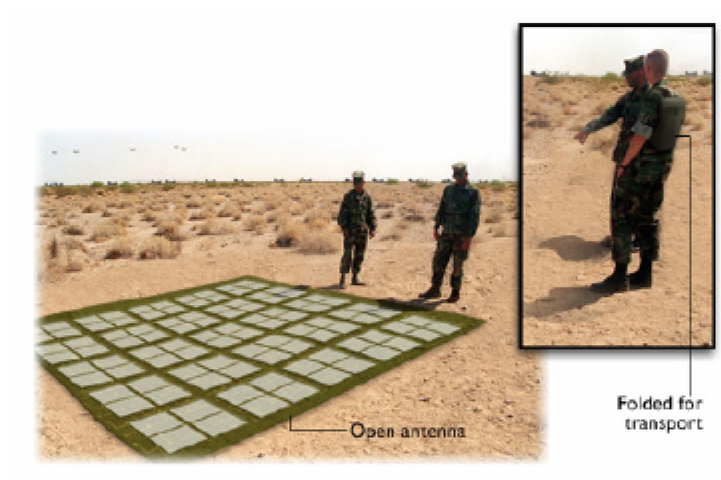
Macroelectronics for Defense Systems

Foldable, Steerable Anntenas for High Speed Communications



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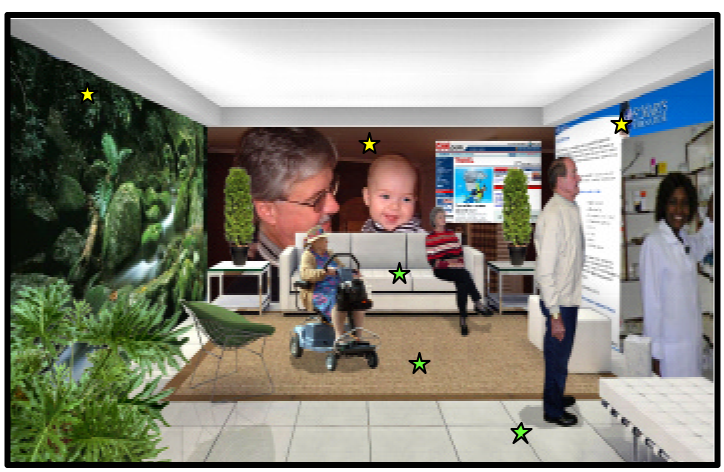
Macroelectronic Systems for Living Environments (w/ Ataman)

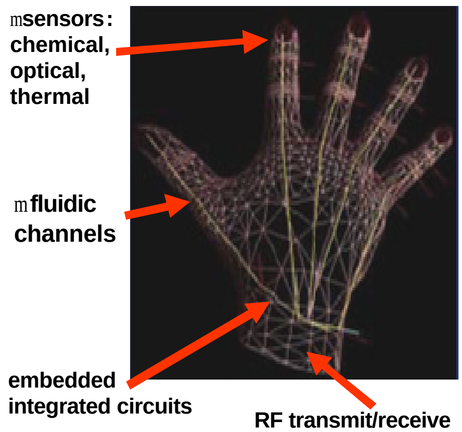
☆ 'Wallscale' Displays ☆ Inhabitant Monitors



Advanced Medical Systems

Intelligent, Wireless Medical Sensors

Smart Surgical Glove



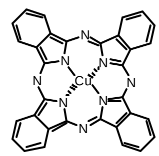
Approaches to Large Area, Printable, Flexible Electronics

-> 1) E-Paper Display Example

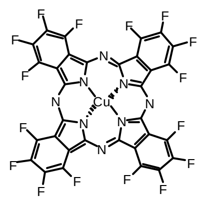
2) Semiconductor Materials

3) Patterning Techniques

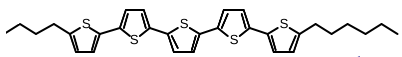
Organic Semiconductors



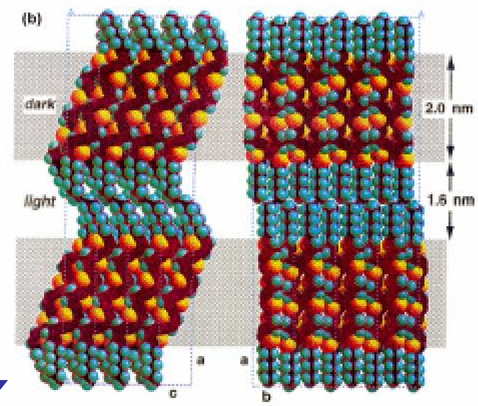
CuPc



FCuPc



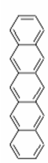
DH-a-5T

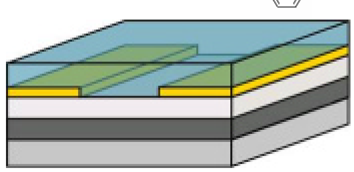


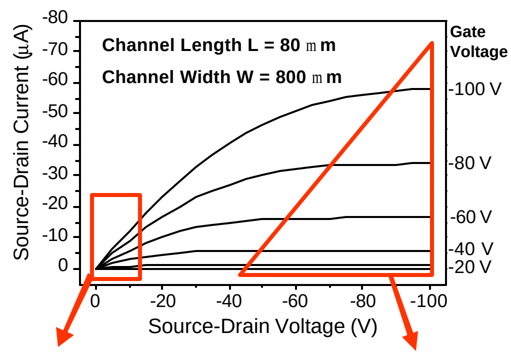
Chem. Mater. 10(11), 3275 (1998).
JACS 120(1), 207 (1998).

Transistor Basics

p-channel pentacene







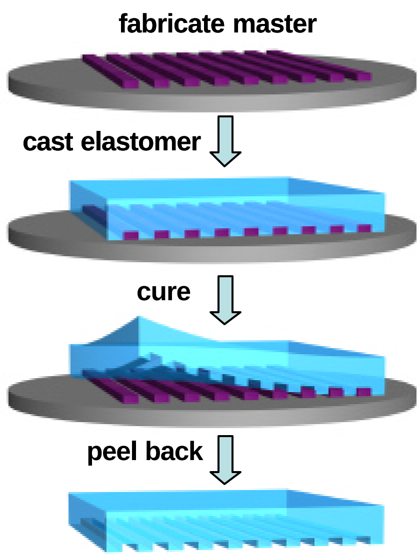
$$I_D = \frac{W}{L} m_{lin} C_i \left(V_G - V_{T,lin}\right) \cdot V_D$$

$$I_{D,sat} = \frac{W}{2L} m_{sat} C_i \left(V_G - V_{T,sat}\right)^2$$

Improvements through:

- **better organic semiconductors (mobility, on/off ratio)**
- **smaller devices , thin or high-k (organic) dielectrics**

Making Elastomeric Stamps, Molds and Phase Masks



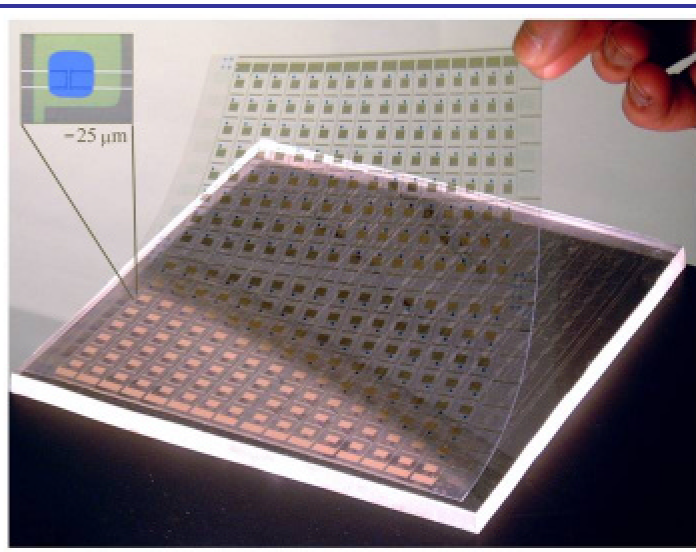
materials developed with Dow Corning

replication fidelity approaching 1 nm !

Nano Lett. **4**, 2467 (2004).

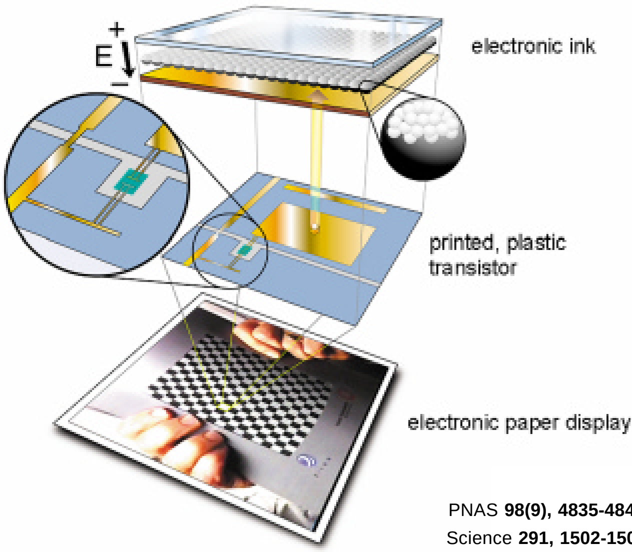
stamp, mold, phase mask

Rubber Stamps and Plastic Circuits for Electronic Paper



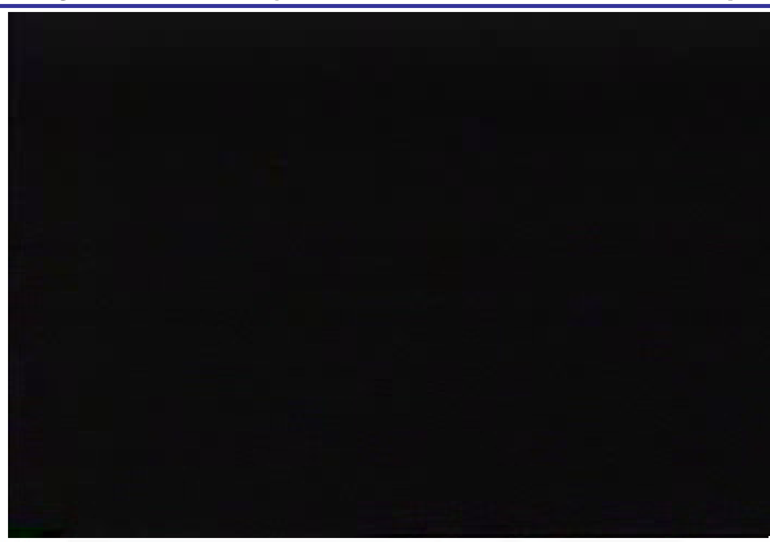
PNAS 98(9), 4835-4840 (2001).
Science 291, 1502-1503 (2001).

Exploded View of a Sheet of Electronic Paper



PNAS **98(9), 4835-4840 (2001).**
Science **291, 1502-1503 (2001).**

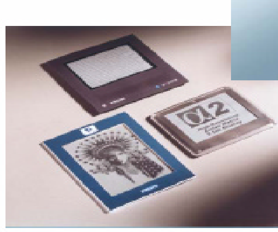
Large, Mechanically Flexible Sheet of Electronic Paper



PNAS 98(9), 4835-4840 (2001).
Science 291, 1502-1503 (2001).

These Technologies May be Moving Toward Commercialization

Polymer vision (subsidiary of Philips)
Plastic Logic (spinout from Cambridge)
Penn State / Sarnoff (PDLC based system)
E Ink (a-Si drivers)
Samsung
PARC
Infineon,
Etc.



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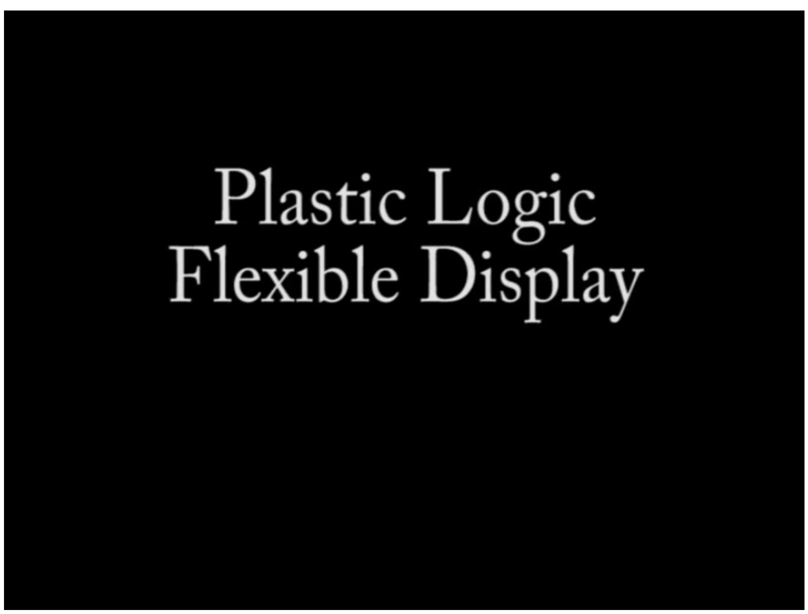
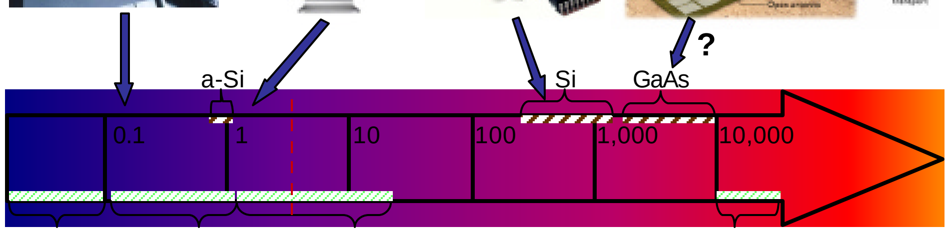


Show polymer vision movie here

Mobilities of ‘Printable Materials’ for Large Area Electronics



Polymers:
Reel-to-reel fabrication, rapid liquid phase deposition (low cost)
Low performance

Small molecules:
Performances competitive with a-Si
High vacuum deposition

Single Crystals:
Study of the intrinsic charge transport
Fragility, Challenging Processing

Carbon nanotubes:
High mobilities
Mechanically and Chemicaly Robust
High temperature growth, mixture of semiconducting and metallic tubes

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Approaches to Large Area, Printable, Flexible Electronics

1) E-Paper Display Example

-> 2) Semiconductor Materials

-> Polymer, Small Molecule Organics

Inorganic Nanomaterials

Carbon Nanotubes, Graphene

3) Patterning Techniques

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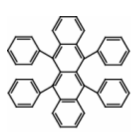
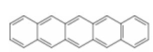
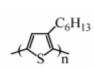
Organic Semiconductors for OTFTs



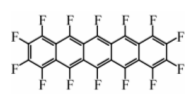
Rubrene



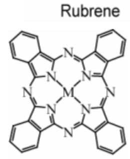
Pentacene



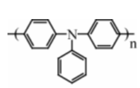
Poly(3-hexylthiophene)



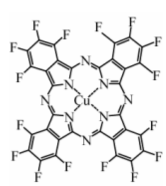
Perfluoropentacene



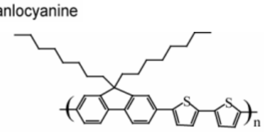
Phthanlocyanine



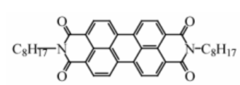
Polytriarylamine



$F_{16}CuPc$



poly-9,9' dioctyl-fluorene-co-bithiophene



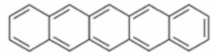
Naphthalenetetracarboxylic diimide

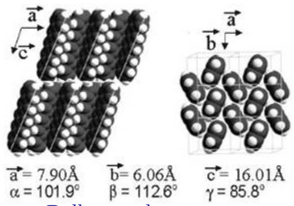
p-type

n-type

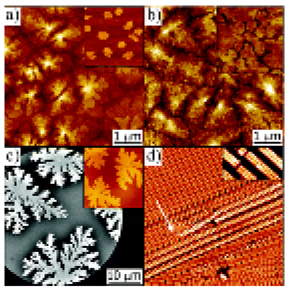
- Conjugated (alternative single and double bonds) small molecules and polymers
- sp^2 hybridization to form three σ bonds and one π bonds
- Gap between LUMO (π^*) and HOMO (π) ~ 1.5-3.5 eV
- π–π overlaps on adjacent molecules are critical to charge transport.
- Disorder plays an important role for charge transport
- p-type behavior is generally observed in organic semiconductors.

Example 1: Pentacene OTFTs

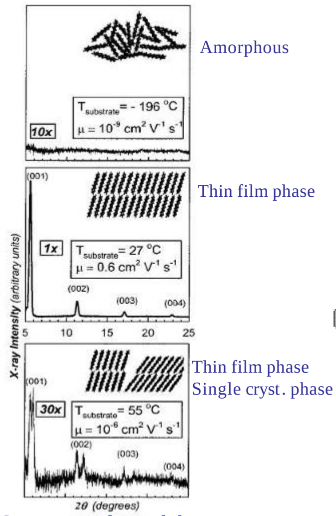




Bulk crystal structure

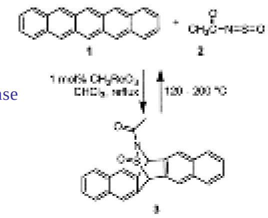


Morphologies of pentacene films on various substrates *(Ruiz et al., Chem. Mater., 16, 4497, (2004)).*



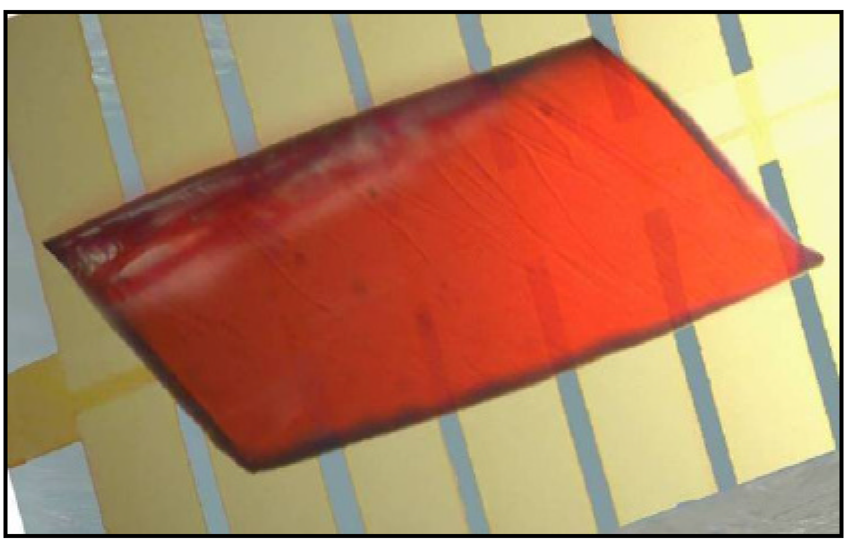
Structure order and device performance *(Dimitrakopoulos et al., Adv. Mater., 14, 99, (2002)).*

- Benchmark OTFT material
- Mobility ~0.1 – 1 cm^2/Vs
- Thermal deposited thin film



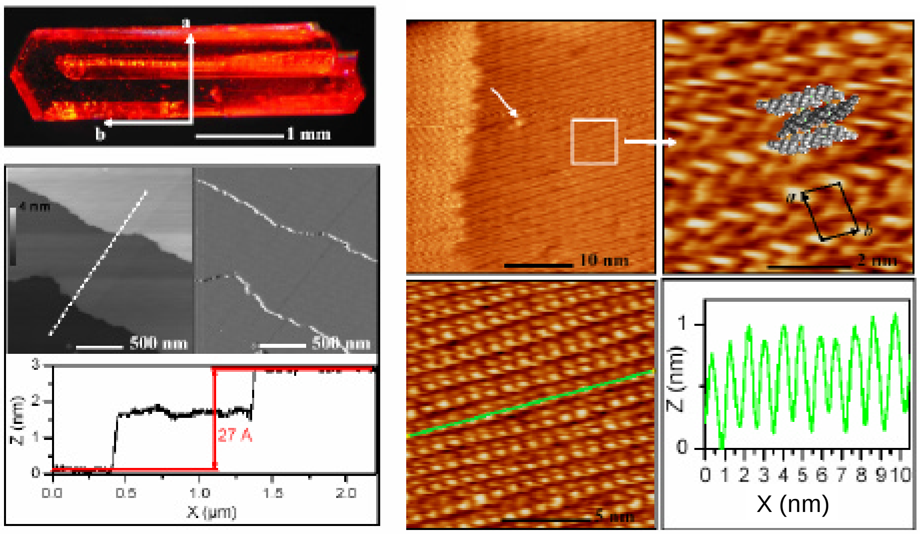
Pentacene Precursor *(Afzali et. al, J. Am. Chem. Soc.* ***124,*** *8812 (2002))*

Micrograph of a Single Crystal Rubrene Transistor



Science 303, 1644-1646 (2004); Adv Mater 16, 2097 (2004)

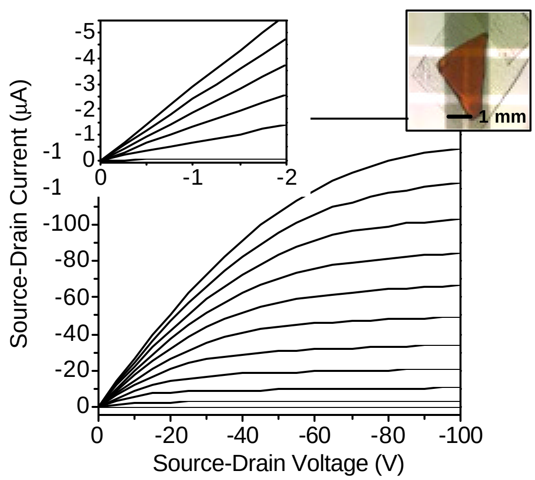
Nanoscale morphology of Rubrene Single Crystal



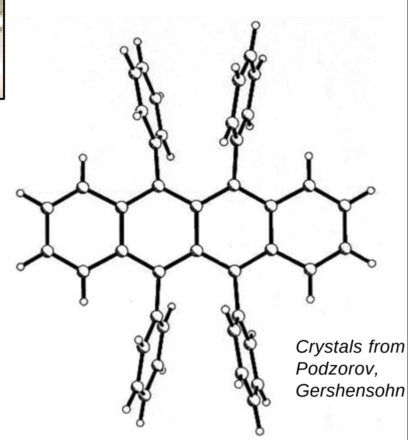
Advanced Materials **18**, 1552-1556 (2006).

Transport in Transistors That Use Single Crystal Rubrene

Device Characteristics



Molecular Structure

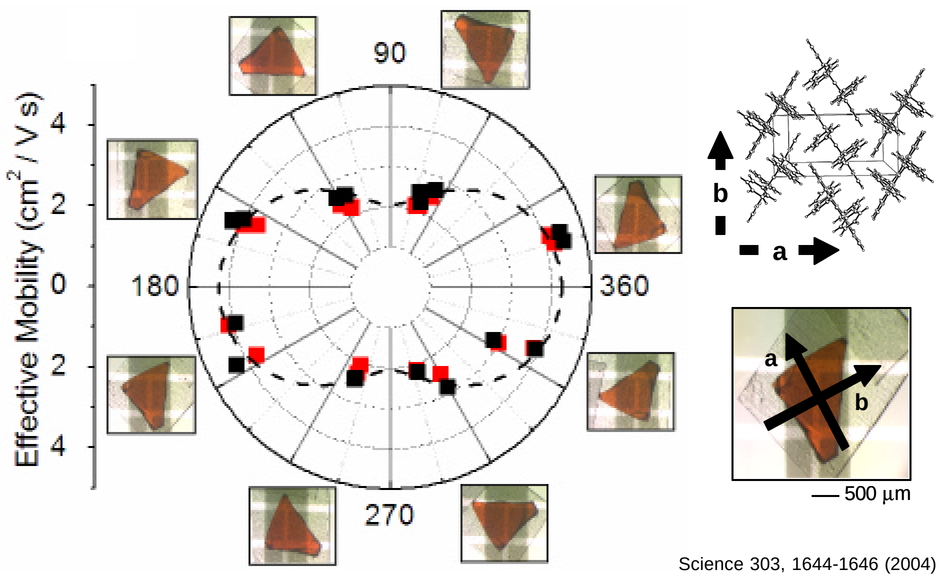


Crystals from Podzorov, Gershensohn

Mobilities as high as 20 cm^2/Vs !!

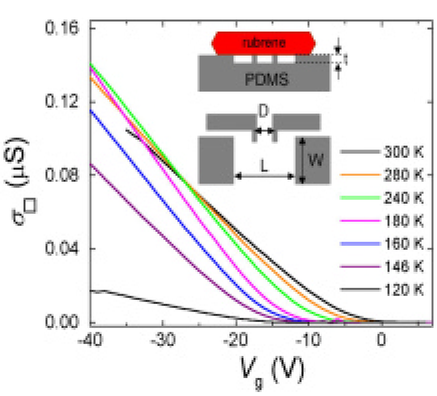
Science 303, 1644-1646 (2004)

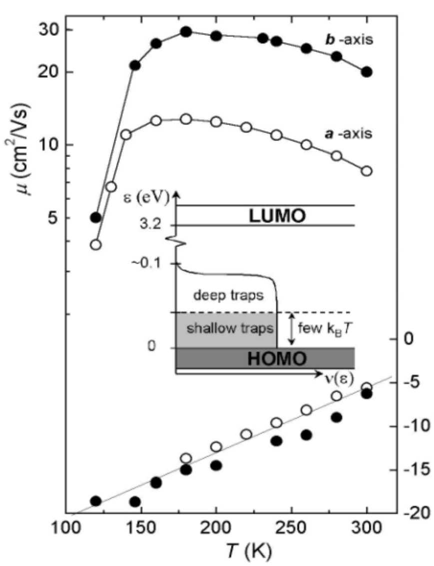
Large In-Plane Anisotropy in the Mobility



Science 303, 1644-1646 (2004)

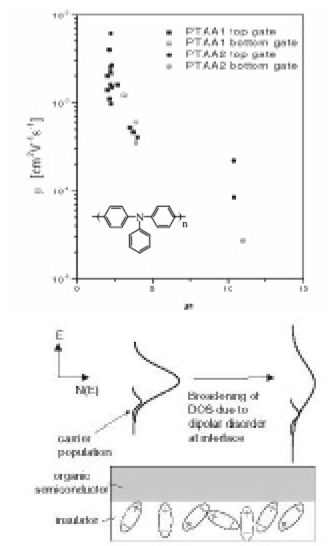
Temperature Dependent Transport in Single Crystal Rubrene



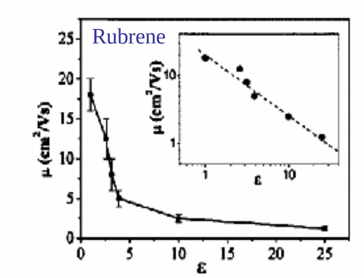


Phys. Rev. Lett., 93, 086602 (2004)

Effect of Dielectric Constant on Mobility



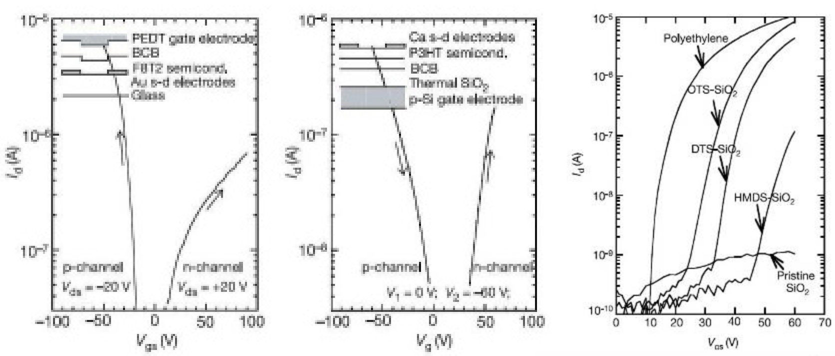
Veres et. al, Adv. Fun. Mater., 13, 199 (2003).

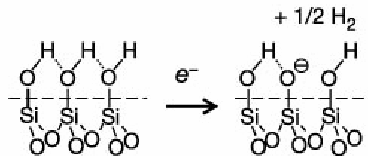


Stassen et. al, Appl. Phys. Lett., 85, 3899(2004)
Morpurgo et al, Nature Materials, 5 982 (2006)

- High-k dielectric layer decreases the mobility
- The polar groups of high-k dielectrics induce energetic disorder.
- High energetic disorder affects charge transport.

Effect of Dielectric on Transport





- N-type and ambipolar behaviors are observed in many conjugated polymer transistors with hydroxy-free dielectric materials.
- Only p-type behavior is generally observed with SiO_2 as dielectric layer.
- -OH groups on SiO_2 surface traps the electrons, preventing the electron transport.

Chua et. al, Nature, 434, 194 (2005).

Organic Semiconductor Design

Molecular Structures

HOMO/LUMO levels
HOMO/LUMO gap
Redox properties
Molecular weight
Regioregularity

Processing

Solution process
(spincoating, printing, etc.)
Thermal evaporation
Precursor/conversion
Dielectric surface/interface

OTFT characterizations

Device type
Mobility
On/off ratio
Contacts

Morphology

Crystal Packing
Herringbone/ π-stacks
Intermolecular interactions
π-stacking directions
Grain size
Defects/disorders

Approaches to Large Area, Printable, Flexible Electronics

1) E-Paper Display Example

-> 2) Semiconductor Materials

Polymer, Small Molecule Organics

->Inorganic Nanomaterials

Carbon Nanotubes, Graphene

3) Patterning Techniques

Device Application of NC Solids: Thin Film Transistors

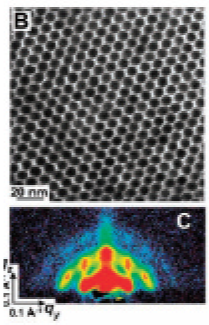


Fig. 1. (A) Optical absorption spectrum of a colloidal solution of 8-nm PbSe nanocrystals in tetrachloroethylene. a.u., arbitrary units; fwhm, full width at half-maximum. (B) TEM image of an array of 8-nm PbSe nanocrystals. q_x and q_y are the lateral and vertical components of the momentum transfer, respectively. (C) GISAXS pattern of PbSe nanocrystal film (16).

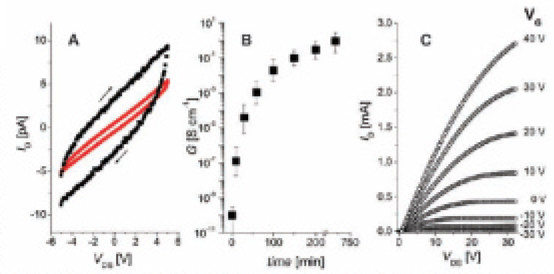


Fig. 2. (A) I-V scans for a film of 8-nm oleic acid capped PbSe nanocrystals in which the voltage scan rate is 0.5 V s^{-1} (black) and 0.025 V s^{-1} (red) and the channel length L and width W are 6 μm and 5000 μm, respectively. (B) Conductance G of a PbSe nanocrystal film versus time of exposure to a 1 M solution of N_2H_4 in acetonitrile. The error bars show the spread in data from five samples. (C) Plot of drain current I_D versus drain-source voltage V_{DS} as a function of V_G for a nanocrystal FET with a channel composed of 8-nm PbSe nanocrystals treated with hydrazine solution for 12 hours (L = 10 μm, W = 2000 μm, with a 100-nm-thick SiO_2 gate dielectric).

Murray et al, Science **310**, 86 (2006).

Solution Si Precursors For Laser Annealed TFTs

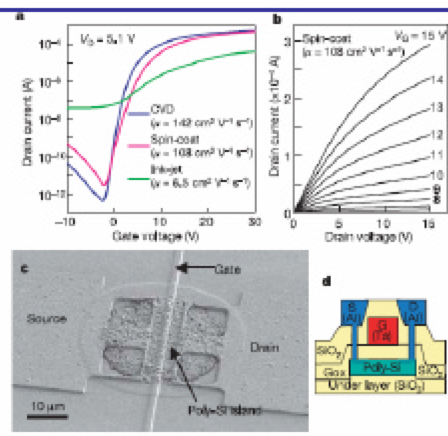


Figure 4 | The structure and characteristics of solution-processed LTPS TFTs. a, The transfer characteristics of LTPS TFTs, whose silicon film was formedby CVD (blue), spin-coating (magenta) and ink-jet printing (green), respectively. The drain current of the ink-jetted TFT is normalized to have the same channel width and length as the CVD-formed and spin-coated TFTs, for comparison. **b,** The output characteristics of the TFT using spin-coated silicon film whose transfer properties are shown in **a. c,** An SEM image of the TFT made from ink-jetted silicon film, whose transfer characteristics are shown in **a. d,** A cross-sectional schematic of a fabricated TFT. Gox, SiO_2 gate insulator.

Shimoda et al, Nature 440, 783 (2006)

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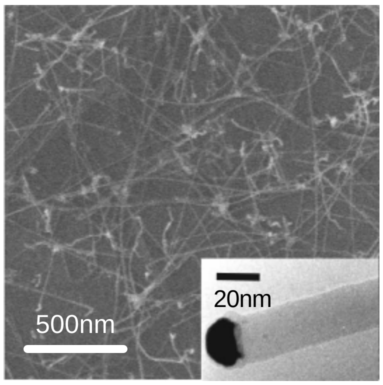
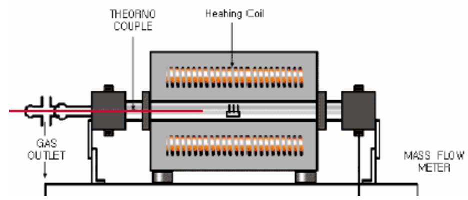
Chemical Vapor Deposition Synthesis



SEM / TEM Images of
Si NWs on SiO_2/Si wafer



CVD Growth

Catalyst: Au Nanoclusters (Ted Pella)
Gas: SiH_4 + H_2
Temperature: 435 °C

Cui, Y. *et al. Appl. Phys. Lett.* **78**, 2214 (2001)

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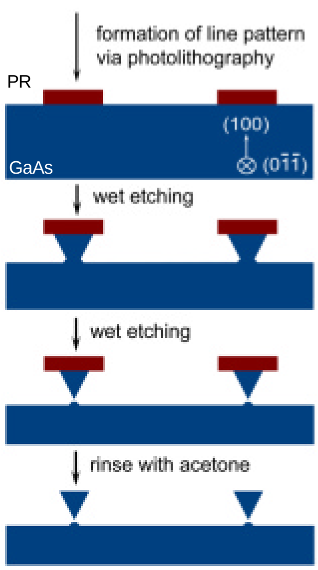
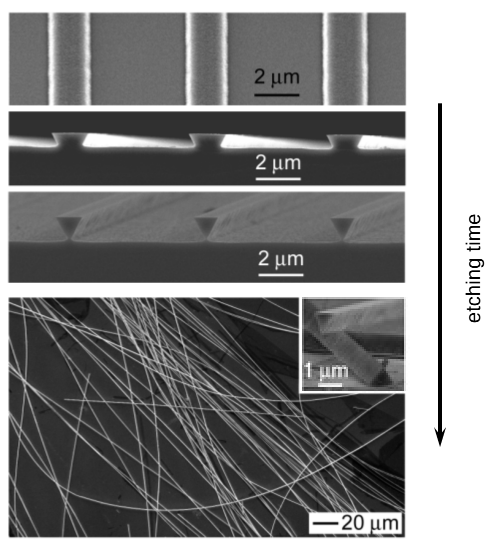
GaAs Wires from Bulk Single Crystal Wafers





Nano Lett, **4**(10), 1953-1959 (2004).

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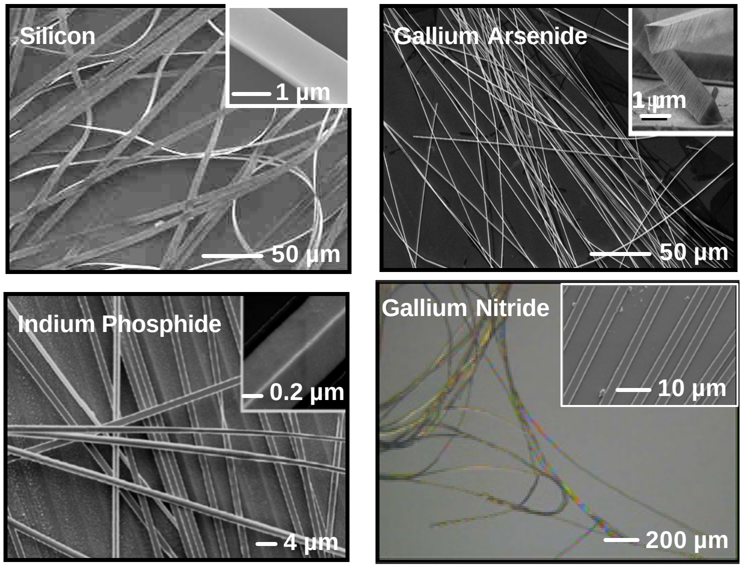
Semiconductor Wires/Ribbons from Bulk Wafers



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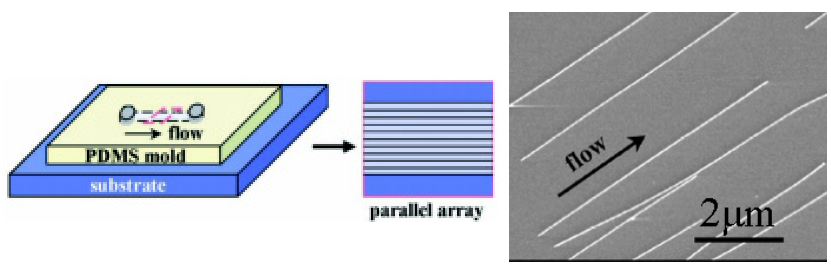
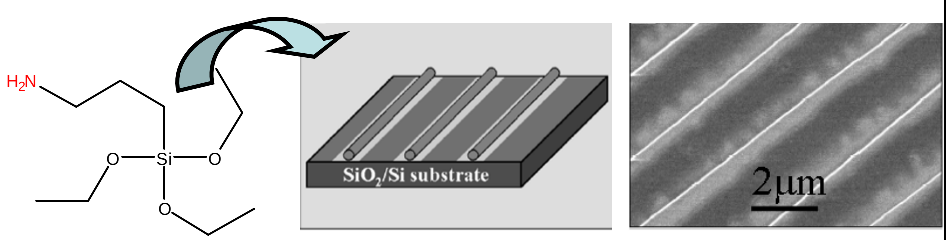
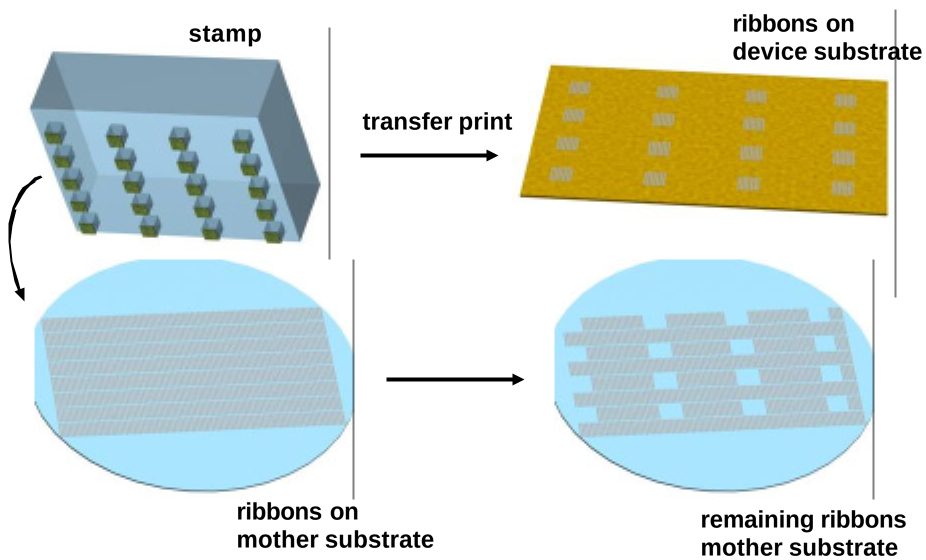
Alignment Techniques



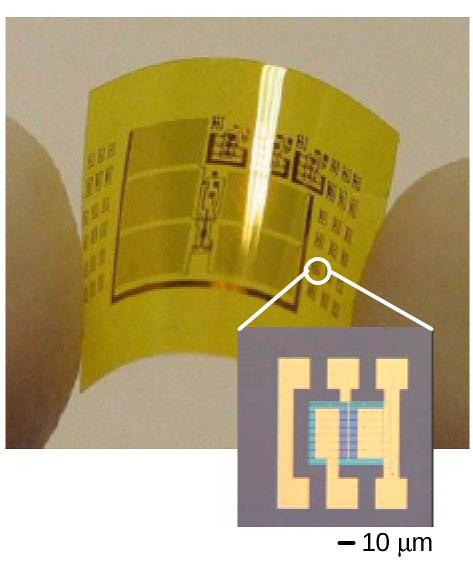
Huang, Y. *et al. Science* **291**, 630 (2001)

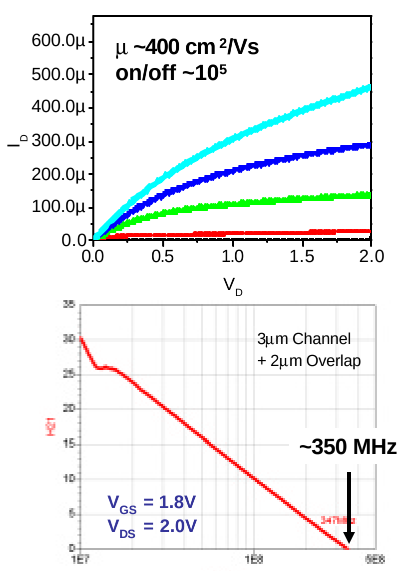


Transfer Printing Wires/Ribbons – ‘Stick and Place’



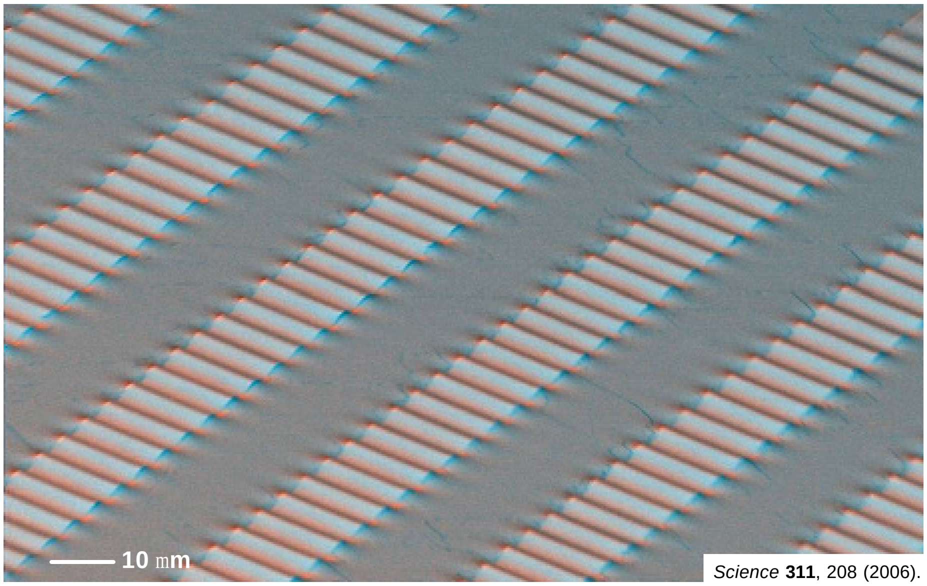
Single Crystal Silicon TFTs and Circuits on Plastic





IEEE Electron Dev. Lett., **27**(6) 460 (2006).

Stretchable Single Crystal Silicon – ‘Wavy’ Si on Rubber



Science **311**, 208 (2006).

Approaches to Large Area, Printable, Flexible Electronics

1) E-Paper Display Example

-> 2) Semiconductor Materials

Polymer, Small Molecule Organics

Inorganic Nanomaterials

->Carbon Nanotubes, Graphene

3) Patterning Techniques

Graphene: 1D Tubes and 2D Sheets

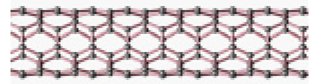
Single Tube Transistors:

Mobility: 10,000 cm^2/Vs
McEuen *et al*., **PRL 95**, 146805 (2005)

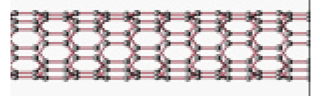
Transconductance: 3 mS/mm
Dai *et al*., **Nat. Mater. 1**, 241 (2002)

On/Off: ~10^6
Dai *et al*., **Nat. Mater. 1**, 241 (2002)

Metal



Semiconductor



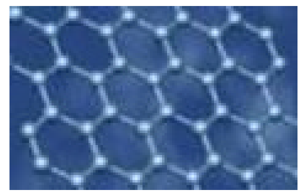
Challenges: Integration, electronic uniformity, narrow channels

Sheet Transistors:

Mobility: 50,000 cm^2/Vs
Geim *et al*., **Science 306**, 666 (2004)
Kim *et al.,* **Nature** 438, 201 (2005)

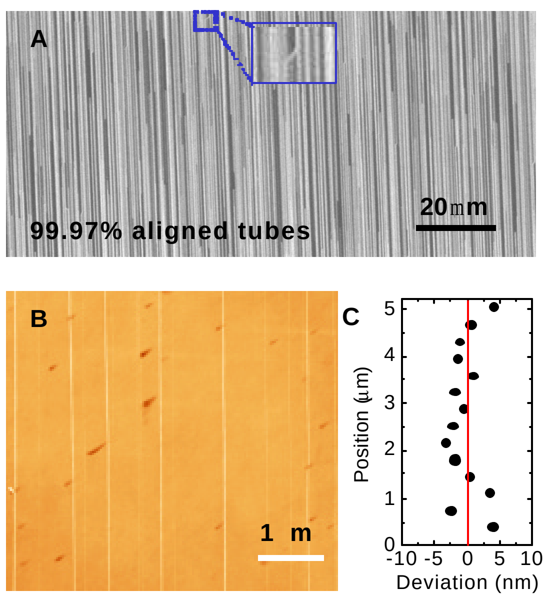
On/Off: ~30
Geim *et al*., **Science 306**, 666 (2004)

Semimetal



Challenges: Integration, on/off

Statistics of Aligned Arrays of SWNTs



Horizontally Aligned Arrays

Nature Nanotechn. 2, 230 (2007).