Prospects for Organic Semiconductor Devices and Circuits: Applications, Performance and Reliability Considerations

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Why Organics?

- Brighter (OLEDs)
- Thinner (OLEDs)
- Flexible (o-TFTs)

OLEDs offer much better brightness, contrast, viewing angle, and potentially process simplicity than LCDs.

Organic TFTs may be used to drive LCDs and potentially even OLEDs, allowing integration of entire displays on plastic.
Why Organics

• Low-Cost Electronics
  - No vacuum processing (PVD/CVD/Etch)
  - No lithography (printing)
  - Low-cost substrates (plastic, paper, even cloth…)
  - Additive process (lower abatement costs)
  - Direct integration on package (lower insertion costs)

Electronic “Bar Code”
Passive RF circuit that talk to the outside world… no need for scanners
Why Organics

• At the nanoscale, organics may allow us to achieve more, in a manner complementary to silicon:
  - **Functionality** – organic materials may do “more” than silicon
  - **Density** – Molecular-scale devices may be “smaller” than silicon FETs
  - **Integration** – Organic materials can be processed at very low temperatures using localized processing, allowing stacking and heterogeneous integration

In the MARCO MSD center, we focus on the use of organic / molecular devices as evolutionary / complementary alternatives to silicon technology.
Low-cost electronics & displays
Where are we now?

Evaporated films do not offer a compelling cost advantage over silicon.

The best results are all PMOS. No good NMOS candidate exists at this time.

These numbers are MUCH lower than Si, but are good enough for some applications in displays and RFID.
Where are we now?

• Operating voltage
  - Evaporated Pentacene: ~10V (with SiO$_2$ dielectric)
  - Evaporated Pentacene: ~5-10V (with high-K dielectric)
  - Soluble thiophenes: ~20-30V
  - Soluble pentacene precursor: ~10V (with SiO$_2$ dielectric, mobility ~10$^{-1}$)
  - Soluble pentacene precursor: ~5-10V (with soluble high-K dielectric, mobility approaching 10$^{-1}$).

• On-Off ratio
  - 10$^3$ - 10$^8$, highly process dependent

Using a novel printable high-K dielectric, we have reduced operating voltages from 30V to 5V!!!
Circuit Demonstrations

• Solution-processed PMOS Inverters

PEDOT/F8T2/PVP TFT
All solution-processed devices

Circuits ranging from simple invertors to ring oscillators and shift-registers of ~500 gates have been demonstrated, with clock speeds ~200kHz

Sirringhaus et al, 2000
Hybrid Organic / Inorganic Circuits

- $\alpha$-Si NMOS, organic PMOS provides the best of both worlds

Bonse et al, 1998
Kane et al, 2000

This may represent the first application of organic devices to displays, since it will allow the use of CMOS addressing of LCDs
Points to ponder

• Performance is generally similar to or worse than $\alpha$-Si, definitely worse than polySi
• Advantages
  - Solution processed – cost
    • No lithography
    • No vacuum processing
    • Cheaper substrate handling
  - Evaporated
    • Richness of material system – perhaps do “more” than $\alpha$-Si
    • Maybe cheaper substrates
• Disadvantages
  - Inertia
  - Stability
  - Performance
General Applications

• Displays  - Integrate with LCDs/OLEDs to provide pixel addressing.
  • Need more drive current?
  • Operating voltage maybe high?

• RFID
• Sensors
• Distributed / Conformal circuits
RFID

• Applications
  - Smart Cards
  - Barcodes

Courtesy: MIT AutoID Center
RFID Basics

- Standard UPC is 11 digits long: ~52 bits (including 8 bids ECC)
- EPC is 96 bits
- Standard RFID frequencies are 135kHz, 13.56MHz and 900MHz and 2.4GHz (increasing frequency increases range)
- Possible organic electronic communication strategies
  - Direct RF @ 135kHz
  - Sideband @ 135kHz or 13.56MHz (1-100kHz local clock)
  - Direct keying @ baseband
- Anti-collision requires bidirectional communication

049000 indicates a product of the Coca-Cola™ company, 01134 indicates a 3-litre bottle of coke
Needs

We need:

*Really* low-resistance printed metal lines
Printed dielectrics (ideally, both low-K and high-k)
Printed Transistors & Diodes
Printable Conductors


Sheet resistance: <30mΩ/□ for a 1µm thick line
resistivity <3 µΩ-cm (almost 70% of bulk gold conductivity!)

By syncopating in X and Y, we can create smooth surfaces suitable for use as capacitor plates, bottom gates, etc.
Passive Components

Using a gold/polyimide interconnect technology, we have successfully fabricated 3-level interconnected systems entirely using printing. Demonstration circuits include 5-pole filters, single-bit passive RF tags, transformers, and baluns.

Close-up of inductor on plastic – estimated Q of 40 @ 2GHz

Close-up of capacitor, showing 2 layers of gold separated by 100nm of polyimide
Power Harvesting

L1 (inductor on reader)

R2 (resistance of L2)

C2 (Tuning Capacitor)

D1-D4 (Bridge Rectifier)

C3 (Smoothing Capacitor)

D5 (clamping diode)

R3

Q1 (regulating FET)

Vout

Polyimide

Bottom contact - Au Nanocrystals

Plastic Substrate

Top Contact - Au Nanocrystals

L2 (inductor on tag)

Vdiode (Volts)

Idiode (Amps)

Diameter (microns)

45um pixels (1.5mPa-s) on 45um pitch

60um pixels (3.2mPa-s) on 45um pitch
Reliability

• While the performance of organic devices is nearly good enough for our target applications, little work has been done on reliability
  - Environmental Stability
  - Temperature instability / Bias Temperature Stress

BTS has been related to movement of moisture (which acts as a dopant), resulting in large shifts.

Zilker et al, 2001
Environmental Stability

- Many organic materials are extremely sensitive to oxygen and moisture.

Problem: while we talk about forming circuits on plastic and paper, these are notoriously poor barrier materials. This has prevented the reliable implementation of OLEDs and o-TFTs on plastic.
Thermal Exposure

- Organic materials have low processing temperatures
  - Advantage: can fabricate on low-T substrates
  - Disadvantage: devices have poor temperature stability

Mobility degrades irreversibly above 60°C

De-doping occurs at elevated temperatures, reducing conductivity and raising on-off ratio
Molecular-scale Organic Devices
Molecular memories

- Single molecule / cell stores information
- Extremely fine pitch ($>10^{11}$ cells / cm$^2$)
Self-assembly through synthesis

- Custom molecules form “molecular” FETs through self-assembly on specific surfaces

Self assembles on SiO₂
Self assembles on Au
Organic Semiconductor molecules have poor ordering as deposited, resulting in low carrier mobility.

Use of self-organizing terminal chain ensures proper ordering of molecules, increasing mobility.

Hydrophobic

Hydrophilic

Substrate

Substrate

![Graph showing current (I) vs. gate voltage (Vg) for different surface areas per monomer](image)

- 7 Å²/monomer
- 10 Å²/monomer

- y-axis: log(I) in µA
- x-axis: Vg in V

- 1.0E+00
- 1.0E-01
- 1.0E-02
- 1.0E-03
- 1.0E-04
- 1.0E-05
- 1.0E-06
- 1.0E-07
- 1.0E-08
- 1.0E-09

- -30 -20 -10 0 10

- 7 Å²/monomer
- 10 Å²/monomer
Summary

- Organics are extremely promising materials with applications in
  - Low cost electronics / displays
  - High-performance, dense molecular-scale systems
- Significant challenges remain
  - Thermal Stability
  - Environmental Stability
  - Reliability
- However, we should remember that similar problems existed in Si and were solved... by investing in reliability studies early, we may enable a quantum leap in the technology and applications of these versatile materials.
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