Printed RFID: Technology Trends and Outlook

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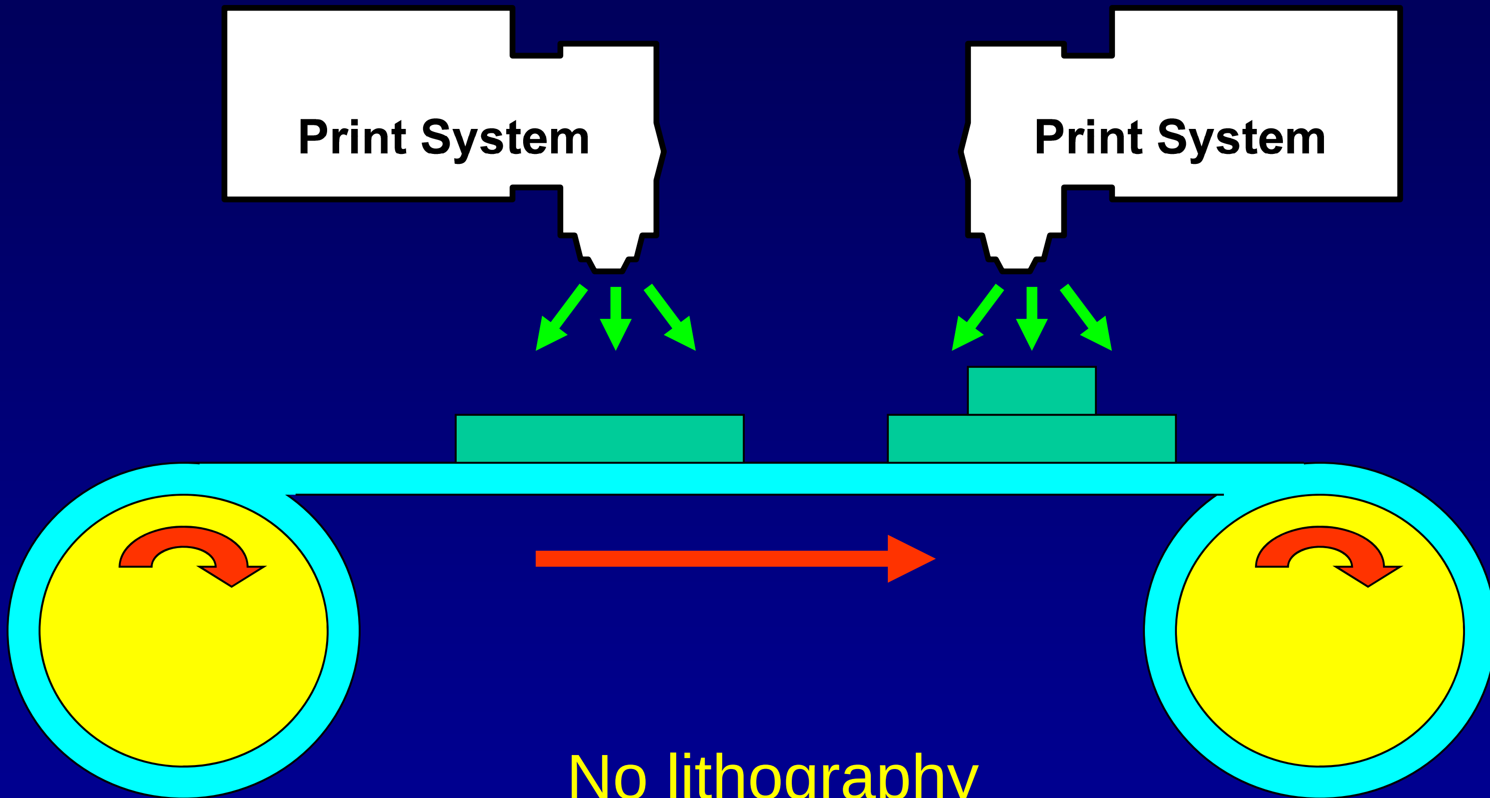
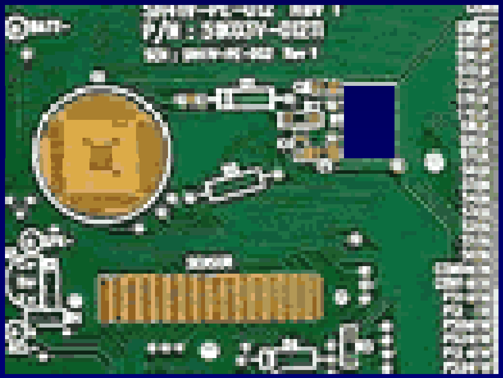
The Cost Holy Grail: Reel-to-Reel Fab



No lithography
No vacuum processing (CVD, PVD, Etch)
Reduced abatement costs
Cheap substrate handling
Reduced packaging costs
Net Result: 20X-200X cost advantage *per unit area*

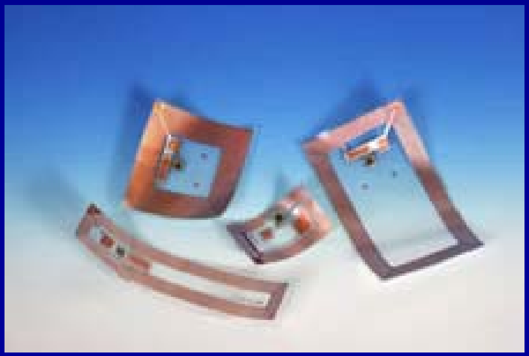
Applications of Printed Electronics

- Near-term
  - Embedded passive components for circuit boards, RFID antennae

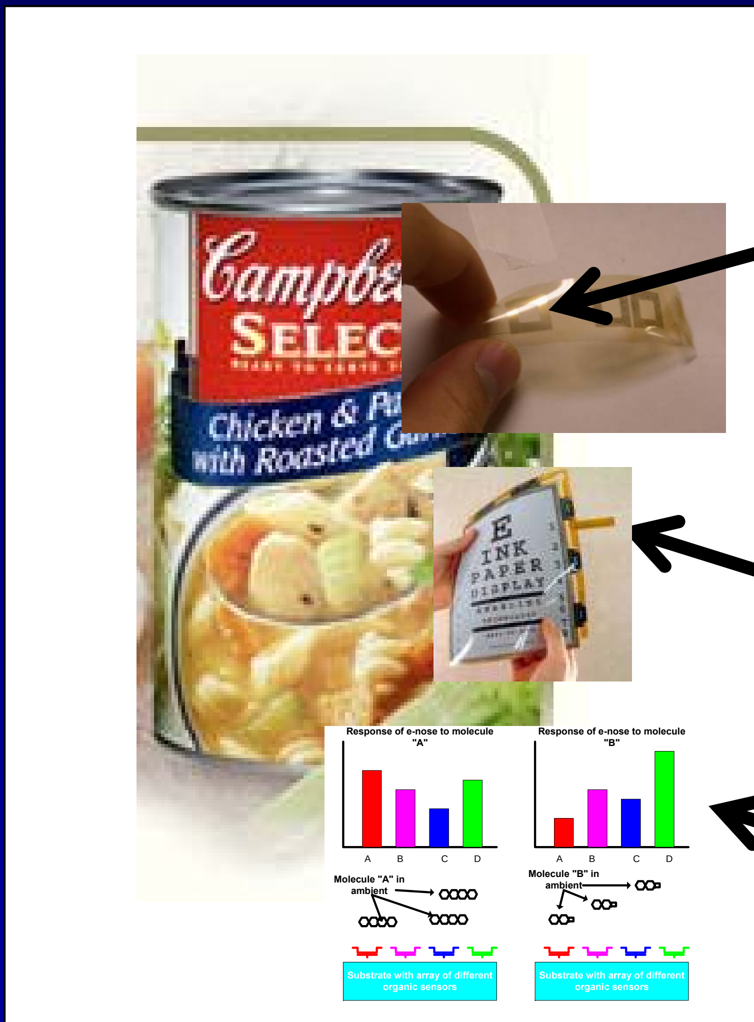


- Intermediate-term
  - Low-cost displays

- Long-term
  - Ultra-low-cost electronics – all-printed RFID, etc.



Driven by applications: smart packaging



Electronic "Bar Code"

Basic RFID functionality

Real-time labeling

Enhanced Interaction

Closed Loop Content Monitoring

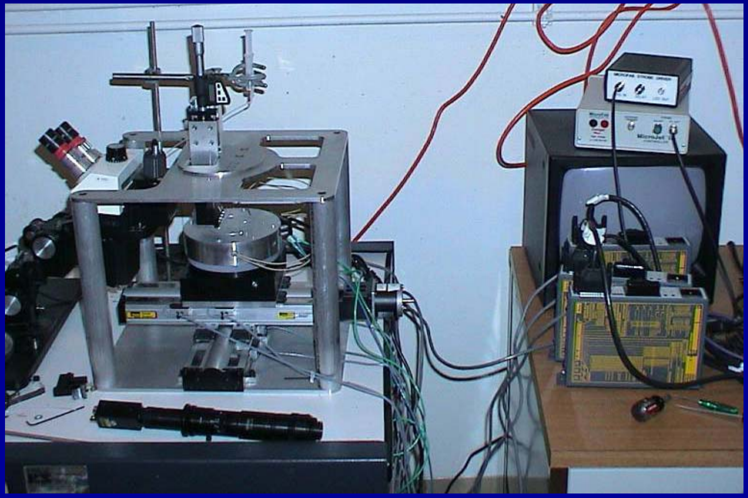
No more expiration dates… the can knows when it has expired!

Progress in Print Technology

Major printing technologies

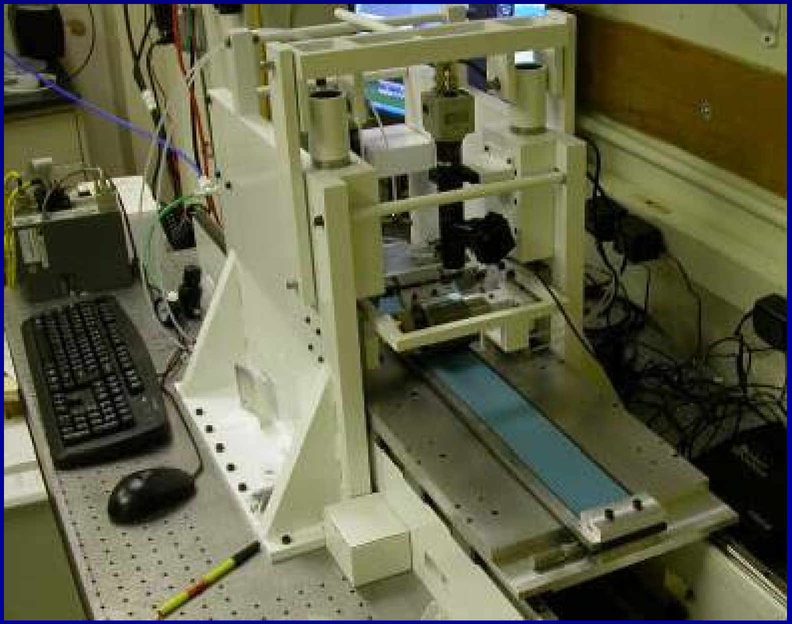
Inkjet

- Advantages
  - Digital input
  - Low-viscosity inks
  - ~10um resolution*
- Disadvantages
  - Pixilated patterns
  - Slow
  - Poor placement accuracy



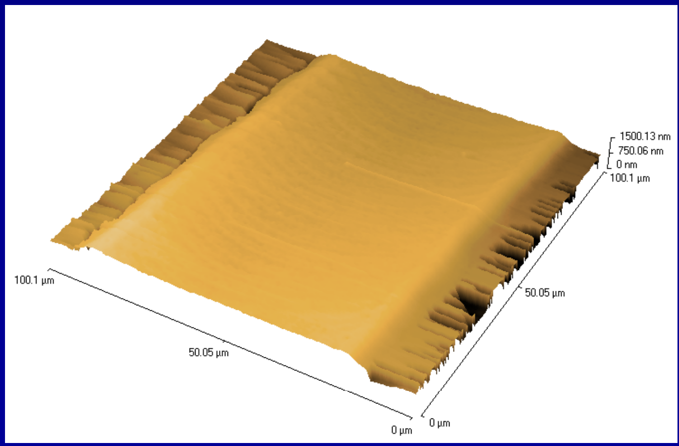
Gravure

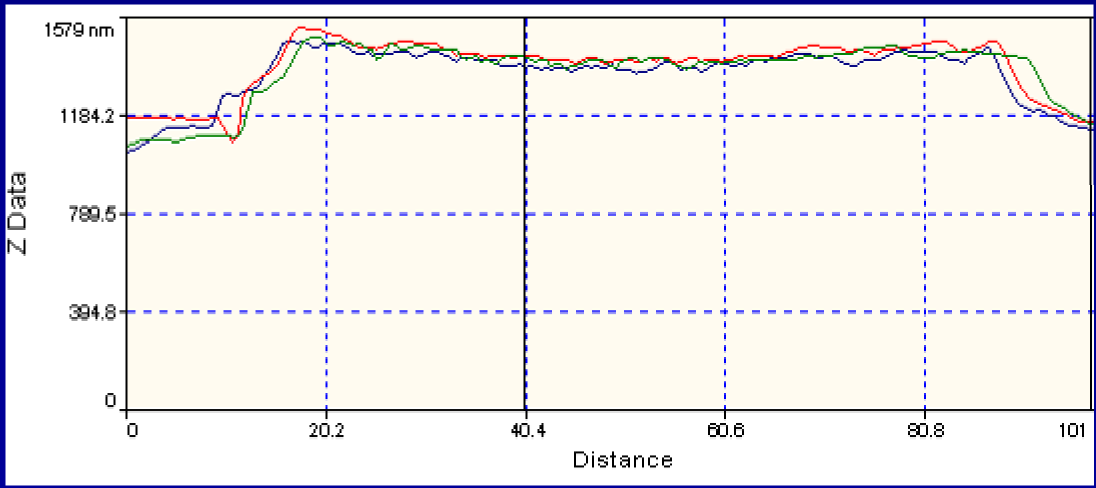
- Advantages
  - Excellent pattern fidelity
  - High throughput
  - ~10um resolution*
- Disadvantages
  - Higher viscosity inks



3D Shape Control

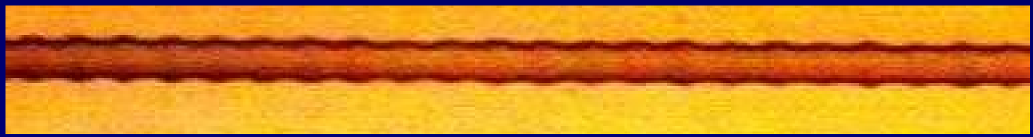
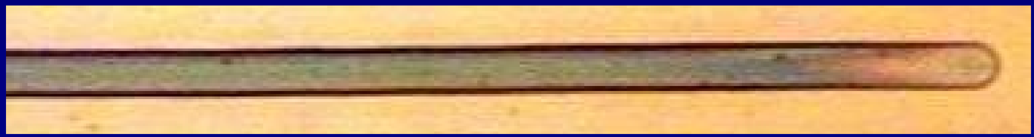
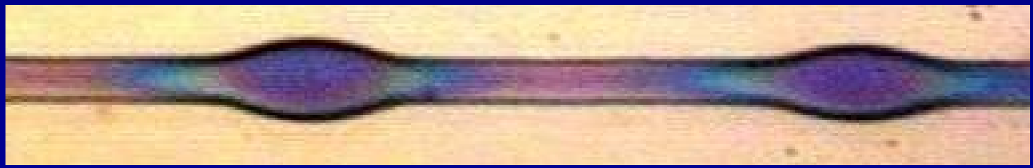
- Morphology of printed films is critical, since poor control results in pinholes in capacitors, shorts and open circuits in transistors, etc.
- Requirement: A smooth, low resistance line with no sharp ridges (which cause pinholes in capacitors and gate dielectrics)





Line Formation Issues

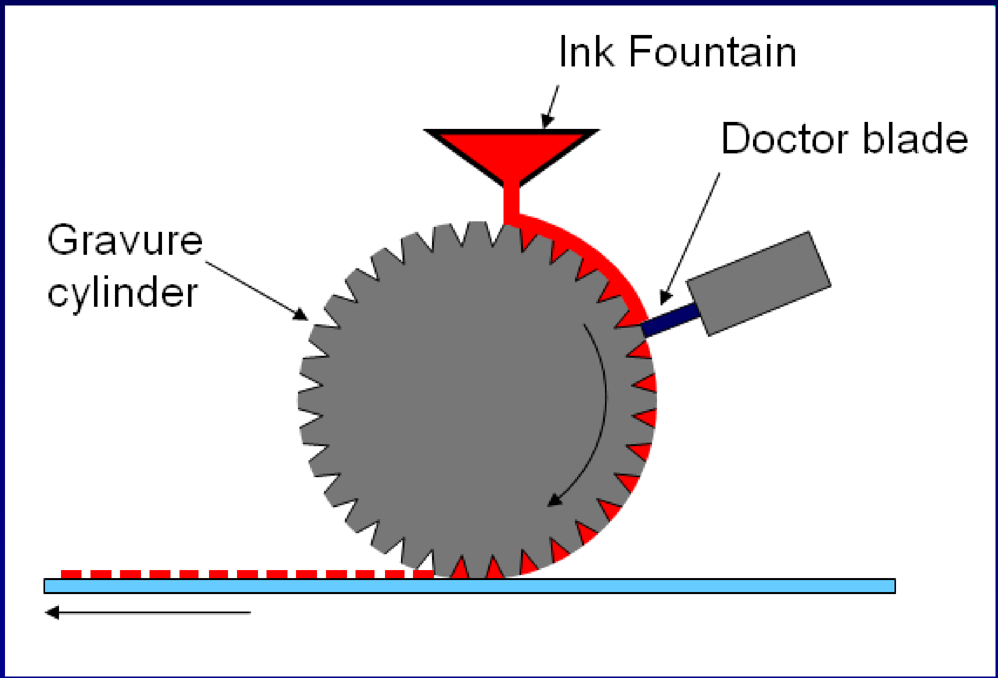
Examples of principal printed line behaviors


1. individual drops
2. scalloped
3. ideal
4. bulging
5. stacked coins

- All effects can be modeled *and controlled*

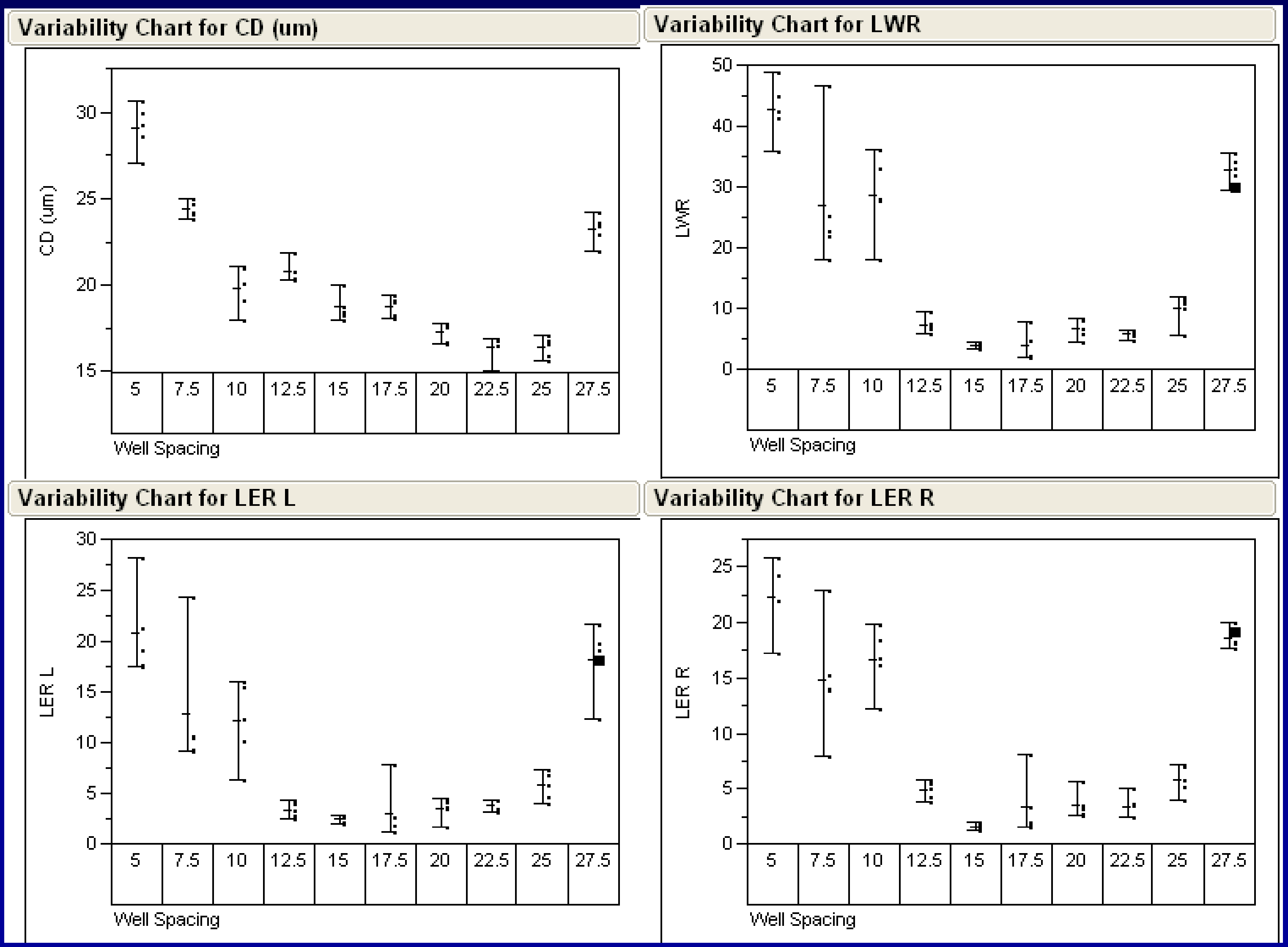
Gravure



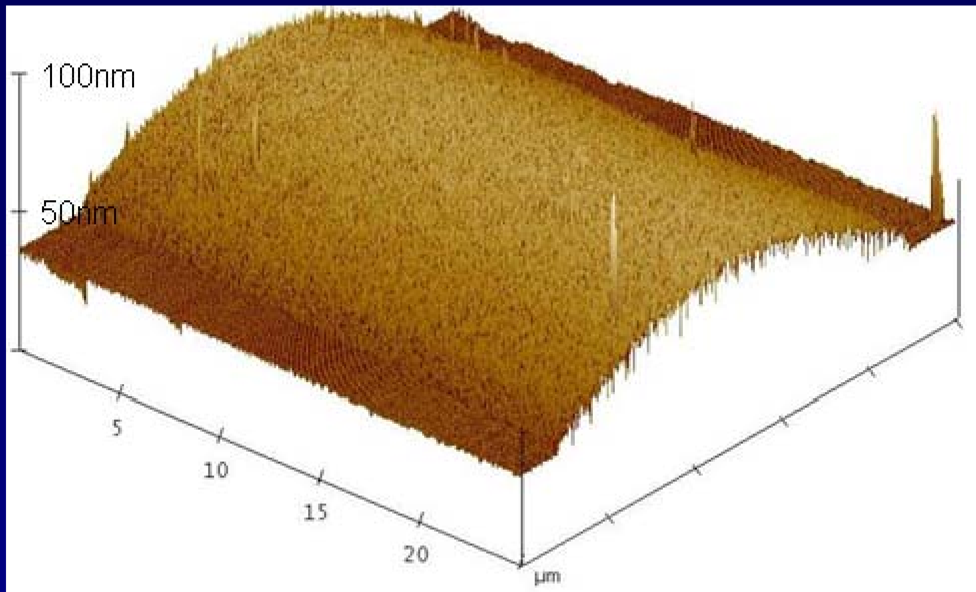
- Chrome coated copper or ceramic gravure rollers
- Steel or plastic doctor blades
- Aqueous and organic inks

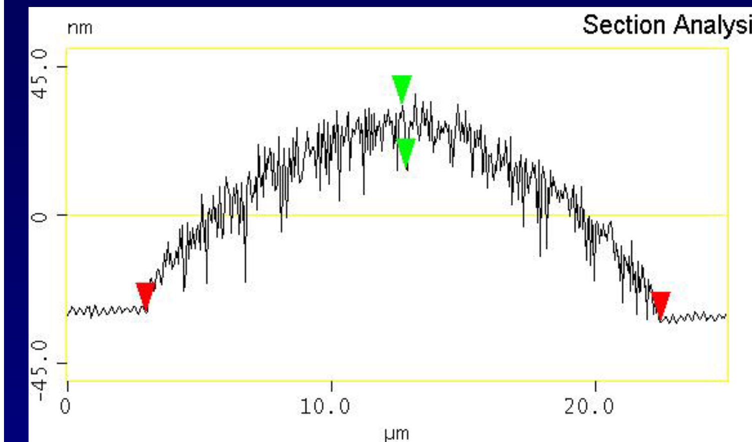
- Commercial use:
  - Magazines
  - Photo-prints
  - Postage Stamps
- Good resolution
- Speed up to 400m/min
- Wide viscosity range (~10cP-1000cP)
- ~10um resolution
- Wide format 2m webs

Shape optimization



State of the art line profiles





Surface distance	19.805 µm
Horiz distance(L)	19.531 µm
Vert distance	2.462 nm
Angle	0.007 °
Surface distance	148.21 nm
Horiz distance	146.48 nm
Vert distance	19.204 nm
Angle	7.469 °
Z range	68.150 nm
Mean	27.475 nm
Rms (Rq)	5.774 nm
Mean roughness (Ra)	4.397 nm

- This line is close to optimal
- Very smooth semi-circular profile
- 20nm pk to pk roughness
- 60nm max thickness

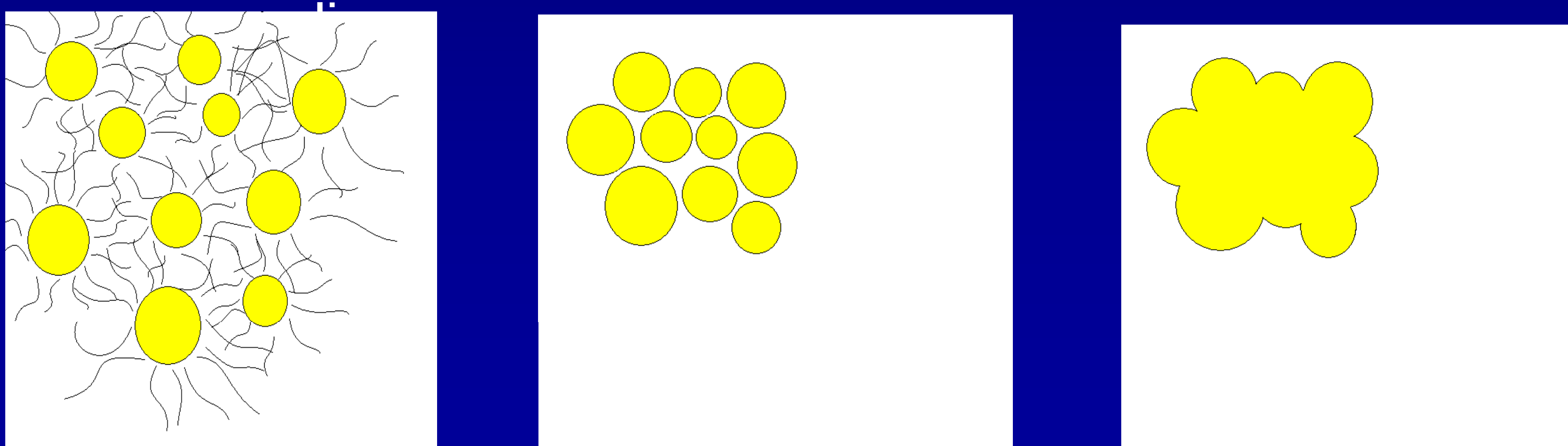
Progress in Materials and Devices

Nanoparticles as printable precursors

- Nanoparticles generally show a reduction in melting point relative to bulk counterparts

$$T_{melt}(R) = T_m^{bulk}(1 - \sigma / R)$$

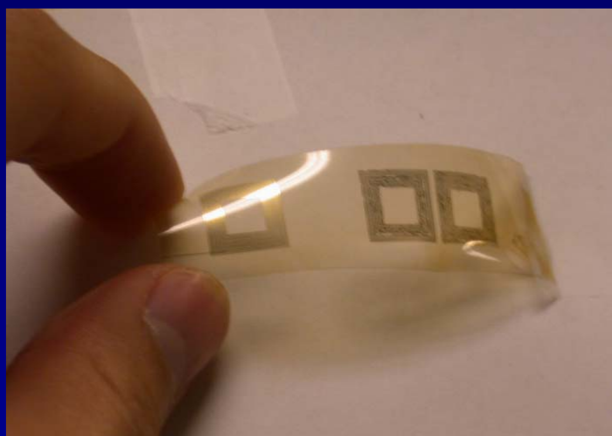
- Additionally, nanoparticles may be stabilized in solution by encapsulating them in organic ligands, which may be removed after printing by subsequent

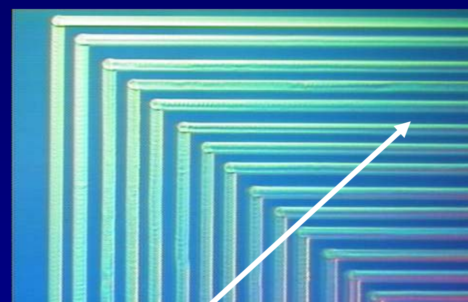


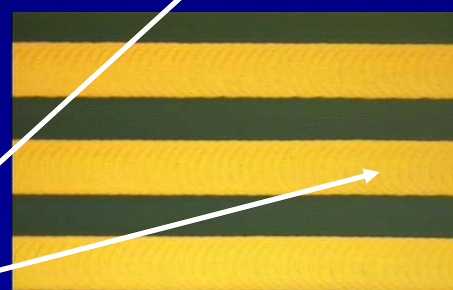
Huang *et al*, J. Electrochem. Soc, 150, 2003

Passive Components

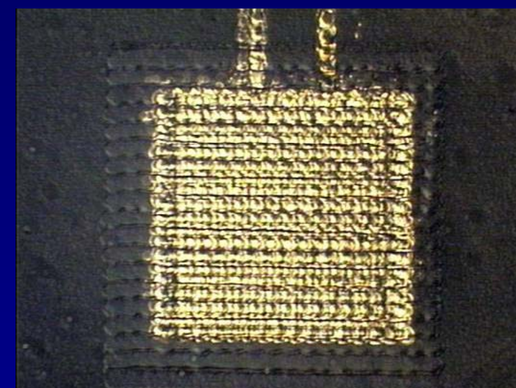
- We have made numerous passive components for use in tagging applications.







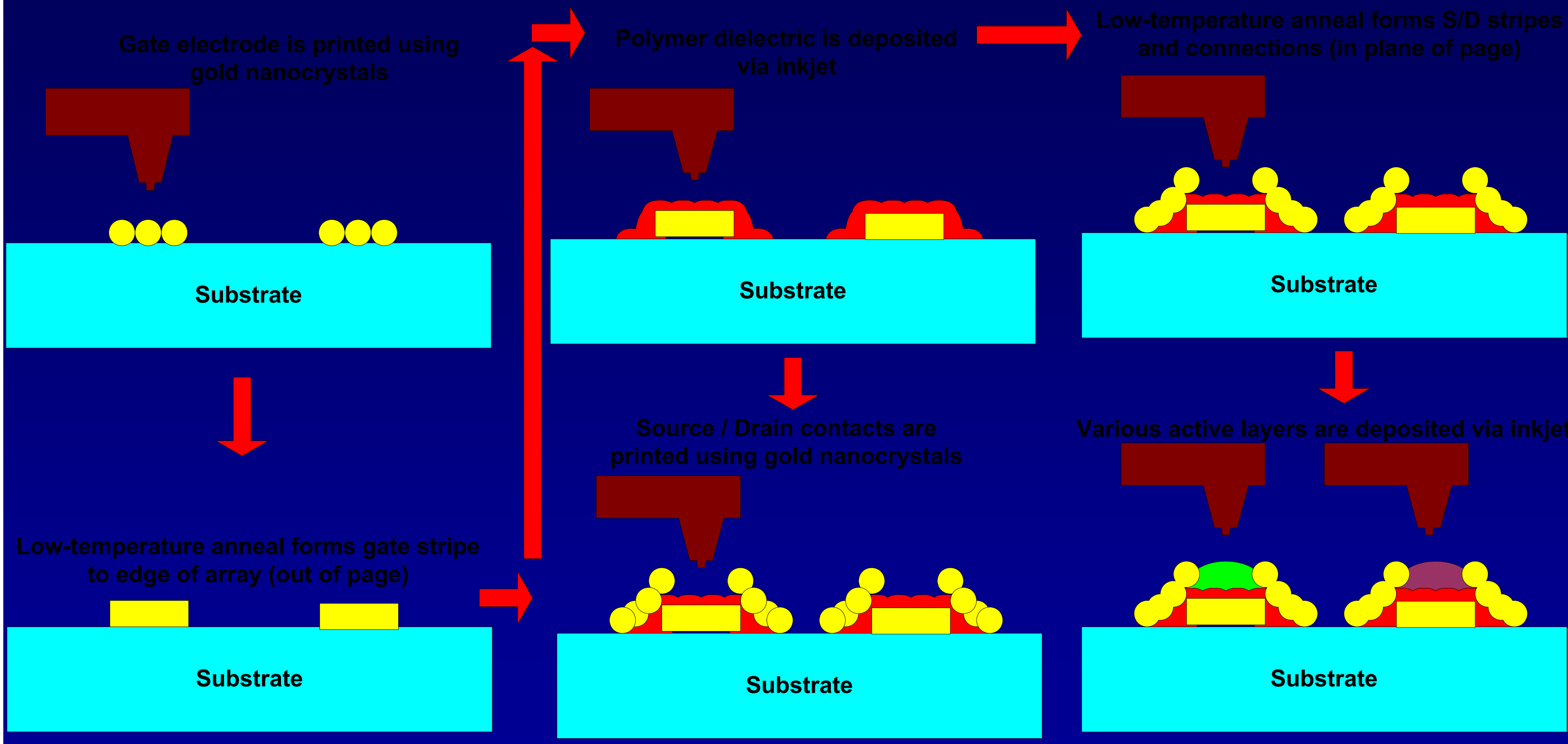
Close-up of inductor on plastic (Q of ~3 @ 13.56MHz)



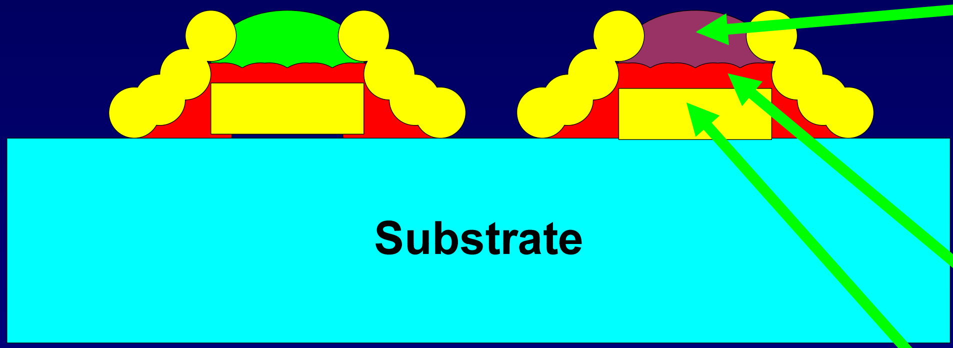
Close-up of capacitor, showing 2 layers of gold separated by 100nm of polyimide. We have also developed a high-K printable material (K ~ 60)

Redinger, *et al*, IEEE Trans. Electron Dev., 51, 2004

Printed Transistors



Materials Needs



Semiconductor (printable, NMOS and PMOS highly desirable)

Gate Dielectric (polymer or even printable high-k)

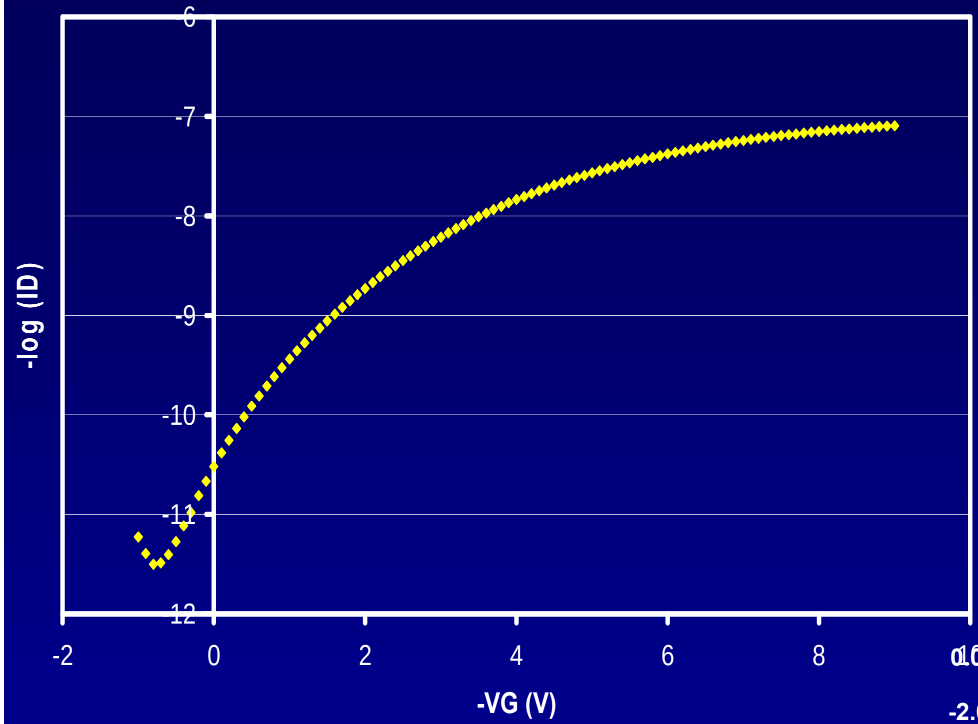
Electrodes (ideally printable metal, so low resistance)

Step-coverage:
Since liquid-based deposition is used, smoothness of lower layers and step coverage are crucial

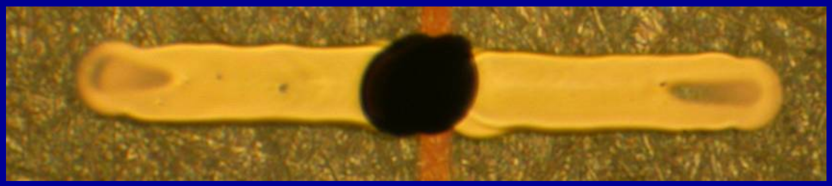
Solvent resistance:
Upper-layer inks shouldn't damage lower layers

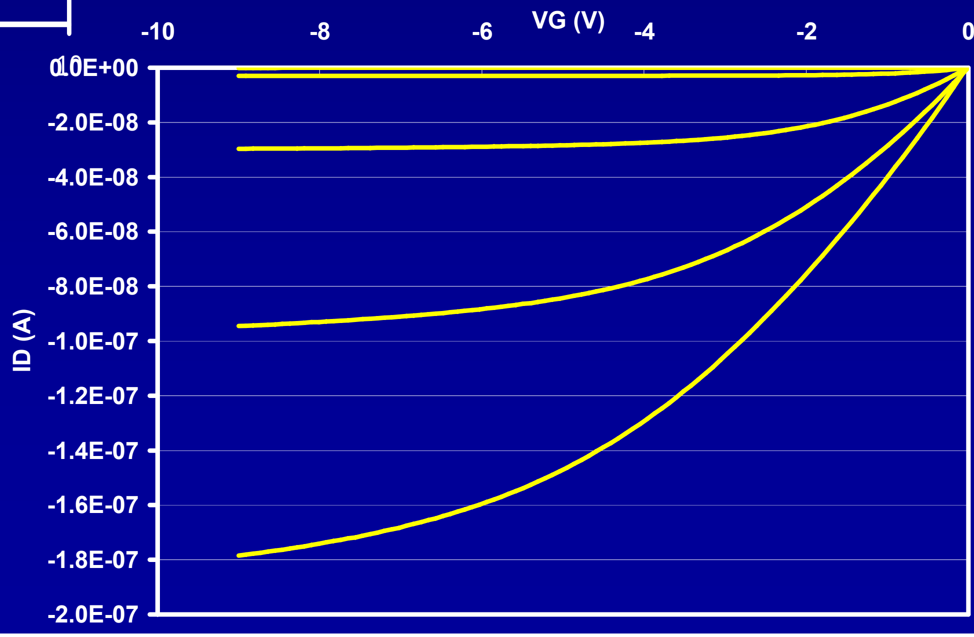
And, it all has to be simple and fast, since process cost and throughput are paramount

Low-voltage printed OFETs

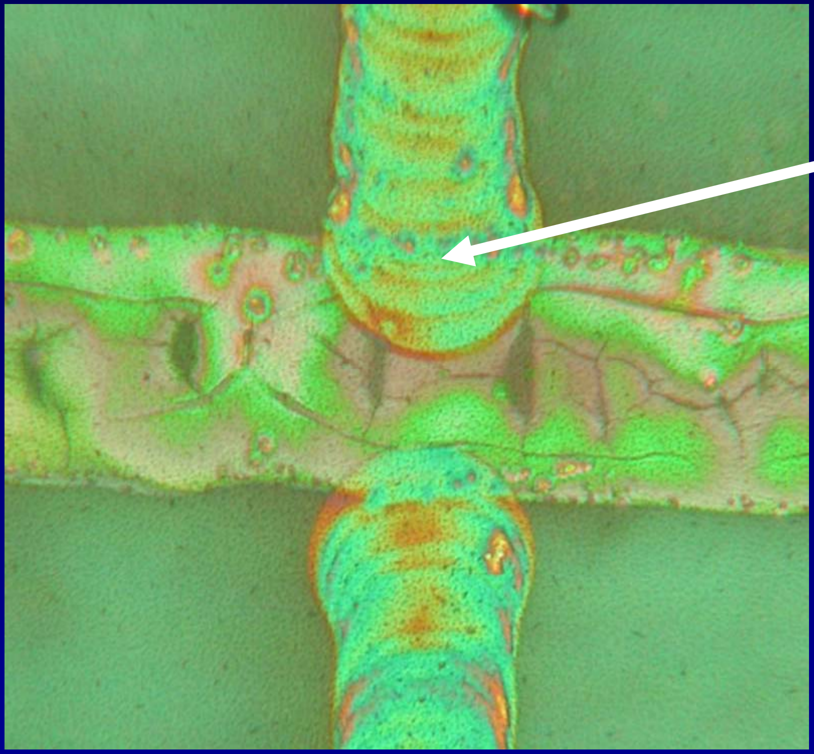


We are routinely able to print transistors with performance approaching a-Si *on low-cost PET plastics!*





Overlap Capacitance: A Challenge

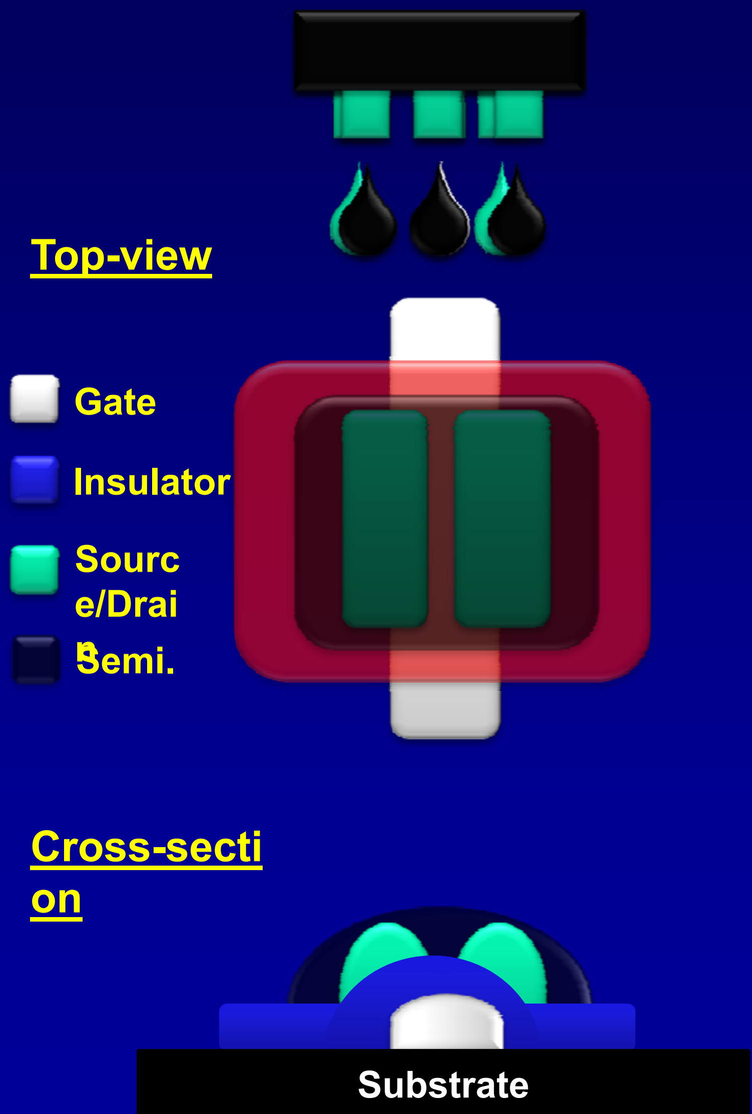


Typical overlap > 20µm
- Resulting parasitic capacitance limits switching speed

Large overlap needed due to:
1. Large physical gate length
2. Expected overlay accuracy in reel-to-reel process

Solutions
1. Shrink gate length and improve placement accuracy
2. Circuit tricks where appropriate
3. Achieve self-alignment

Achieving Self-Alignment



Nanoparticle ink was printed and was then sintered

↓

7.6 wt% of Poly(4-vinylphenol) (PVP) dissolved in hexanol with 0.6% by volume of cross linker poly(melamine-co-formaldehyde) was printed and was then cross linked

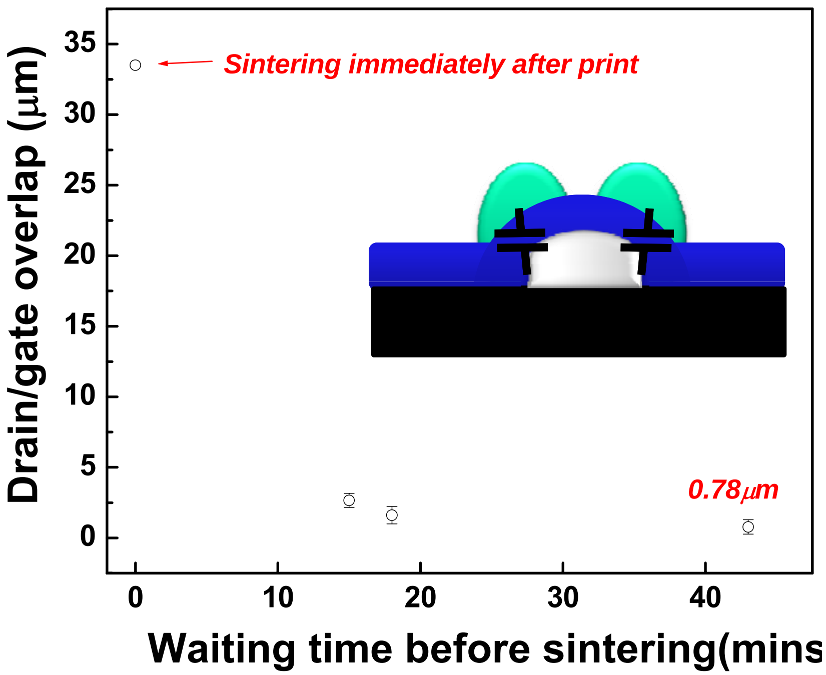
↓

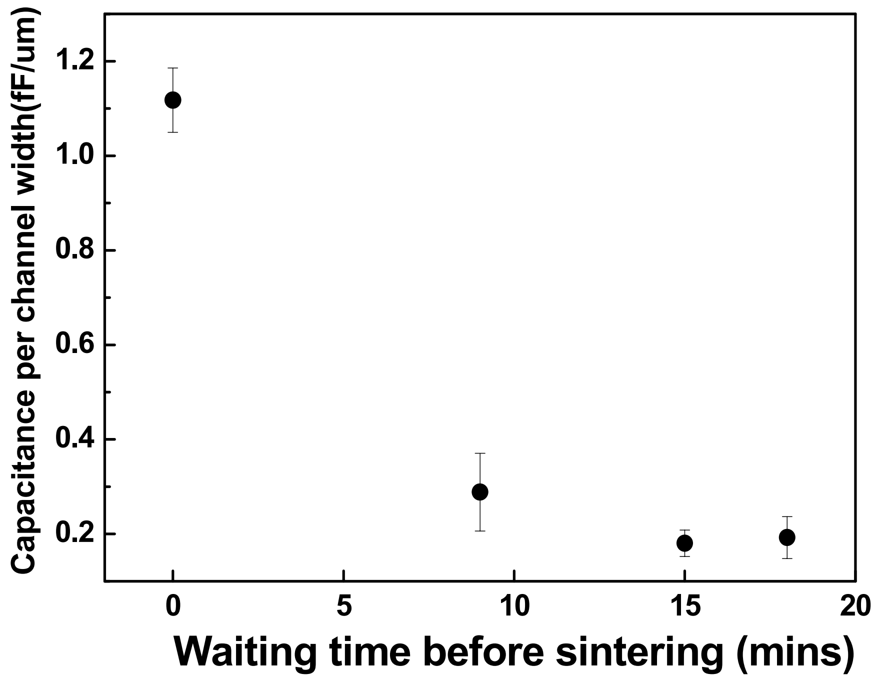
A self-alignment treatment was performed and then the silver ink was then printed as source and drain electrodes

↓

1.5wt% of pentacene precursor (13,6-N-Sulfinylacetamidopentacene, Sigma Aldrich) dissolved in anisole was printed as a p-type semiconductor and was annealed

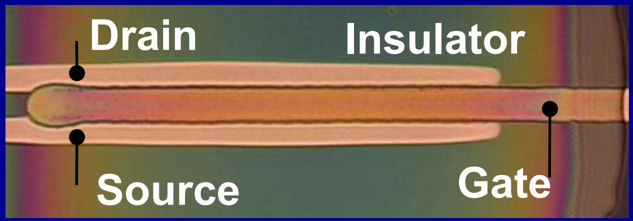
Source and Drain Roll-off Time

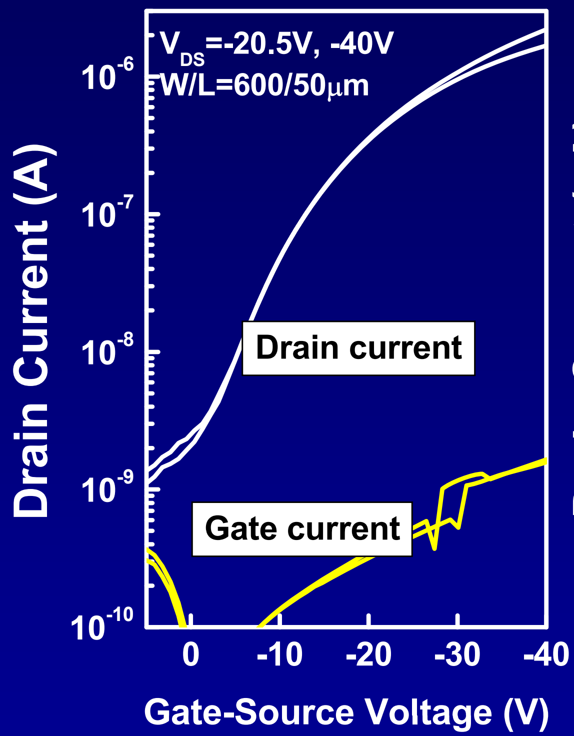


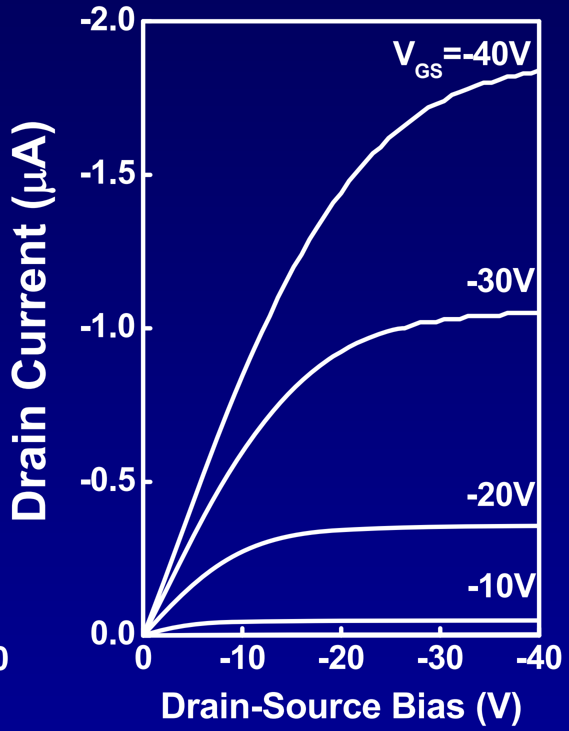


- Minimum overlap of 0.78um was achieved, contrasted to the >10um typically required in conventional printed transistors
- Parasitic capacitance was reduced an order of magnitude

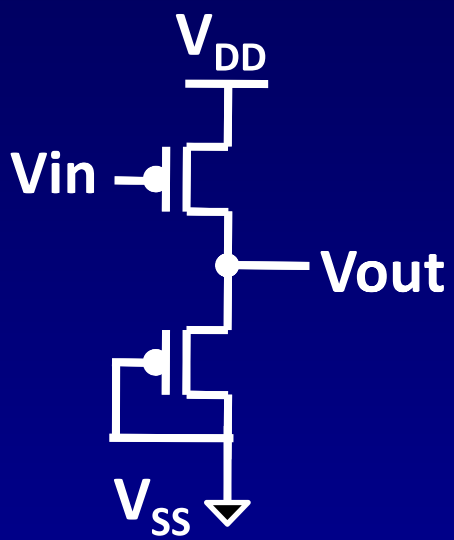
Transistor Characteristics

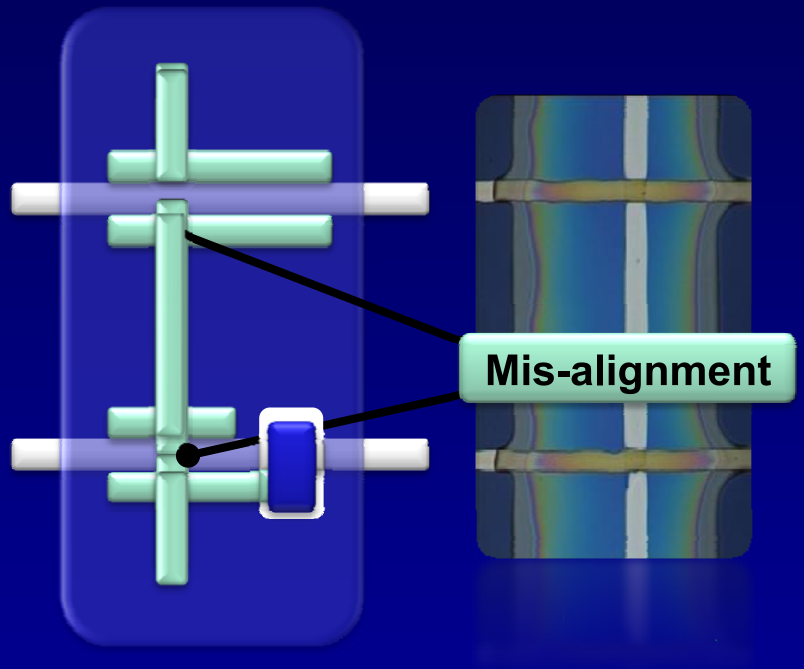






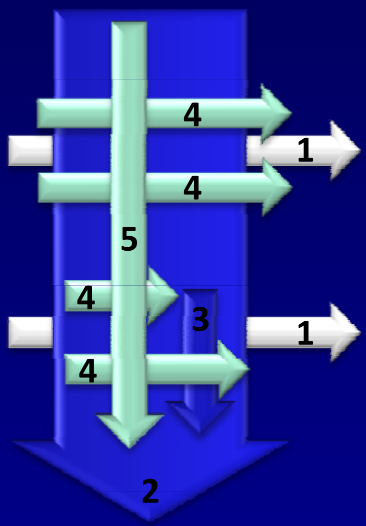
Novel Printed Interconnect

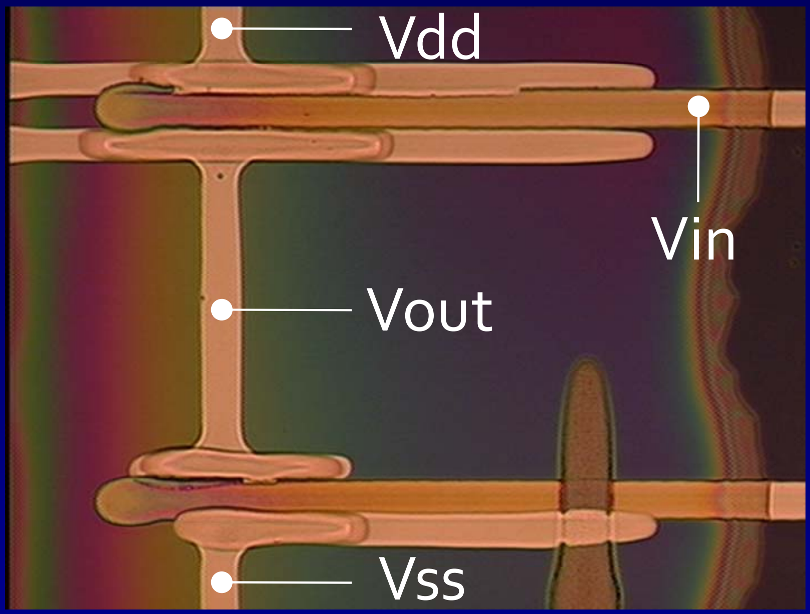


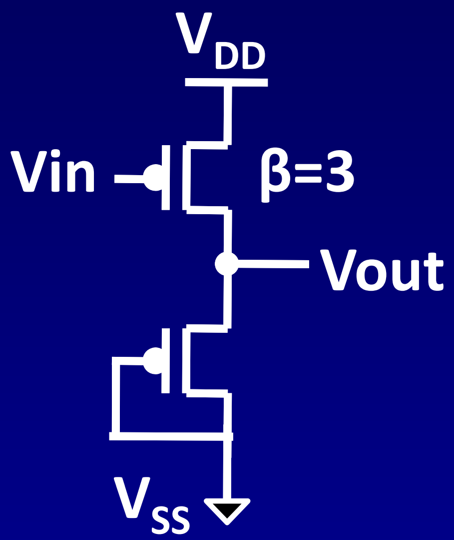


- Self-aligned / self-split interconnect
- Print via and plug

Extending to circuits…

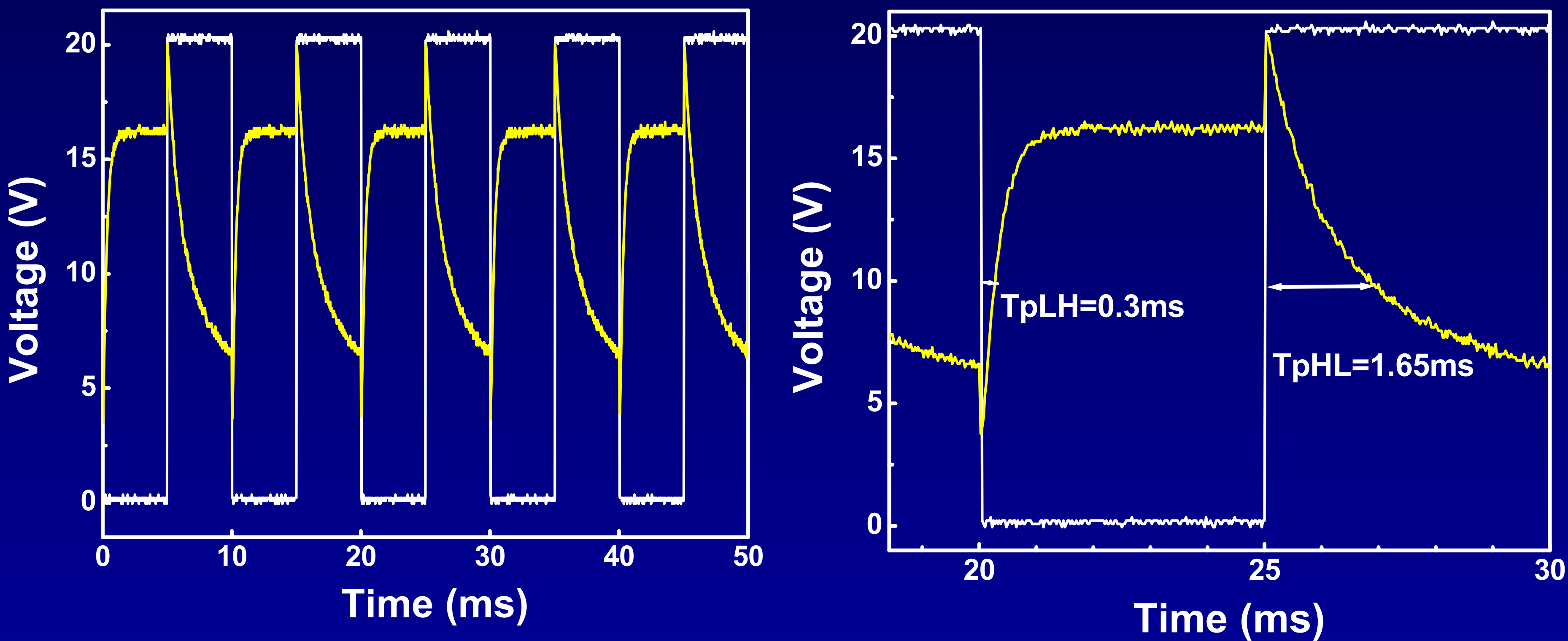






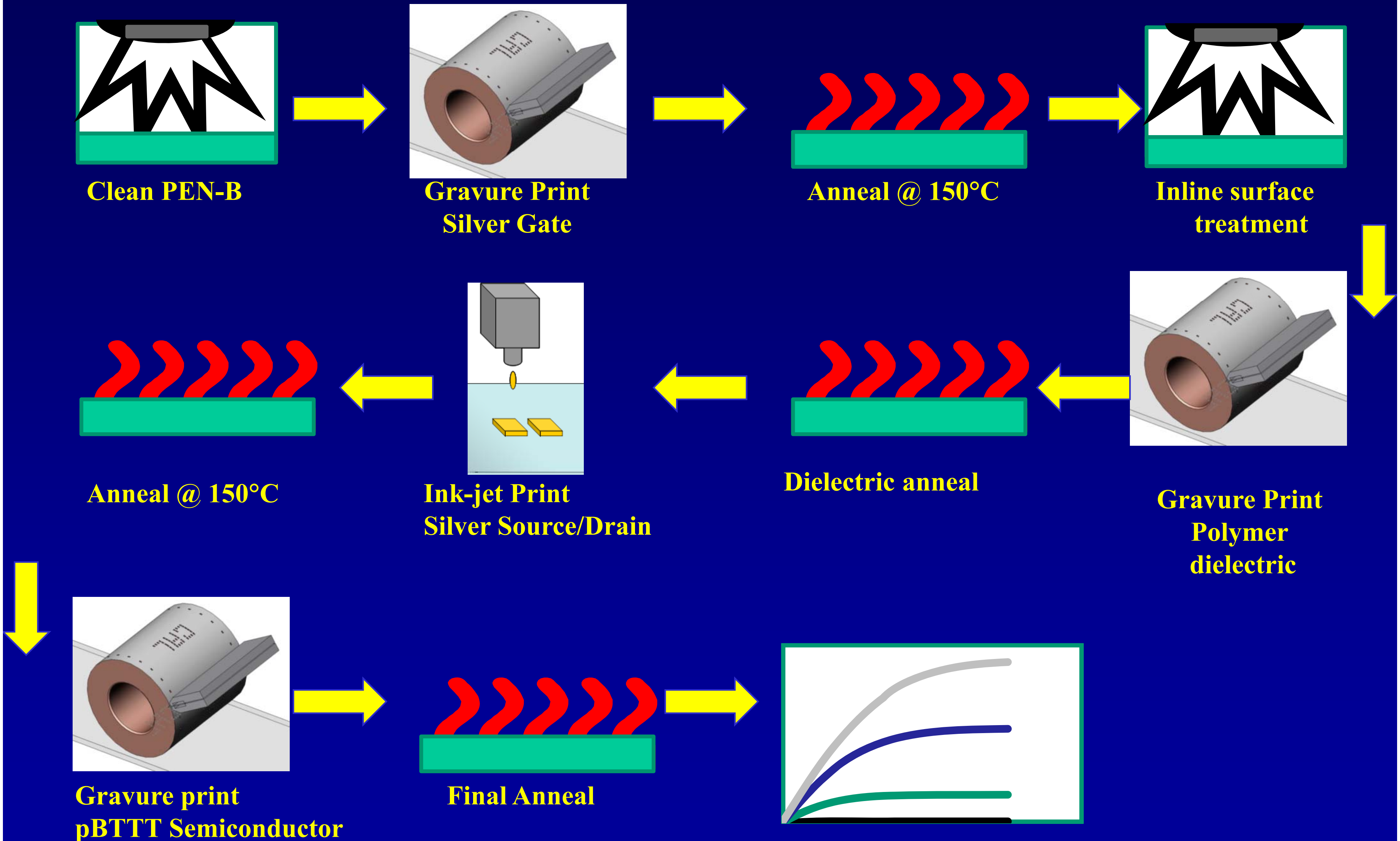
- A printed inverter with a diode-connected load
  - Print via + plug (step 3)
  - Self-aligned S/D (step 4)
  - Self-aligned interconnect (step 5)

Transient output characteristics

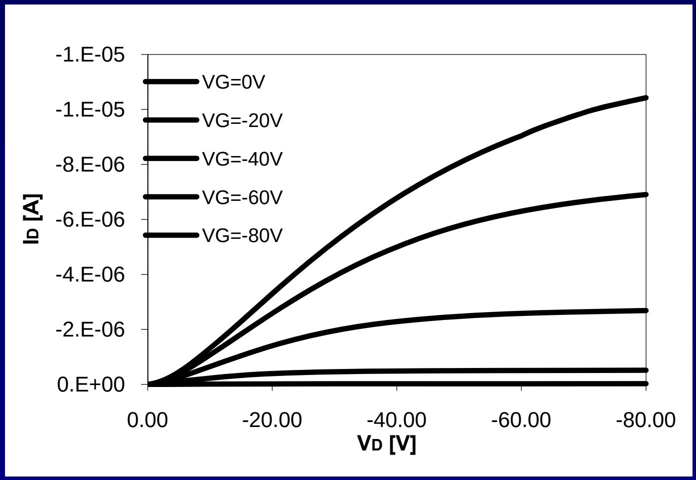


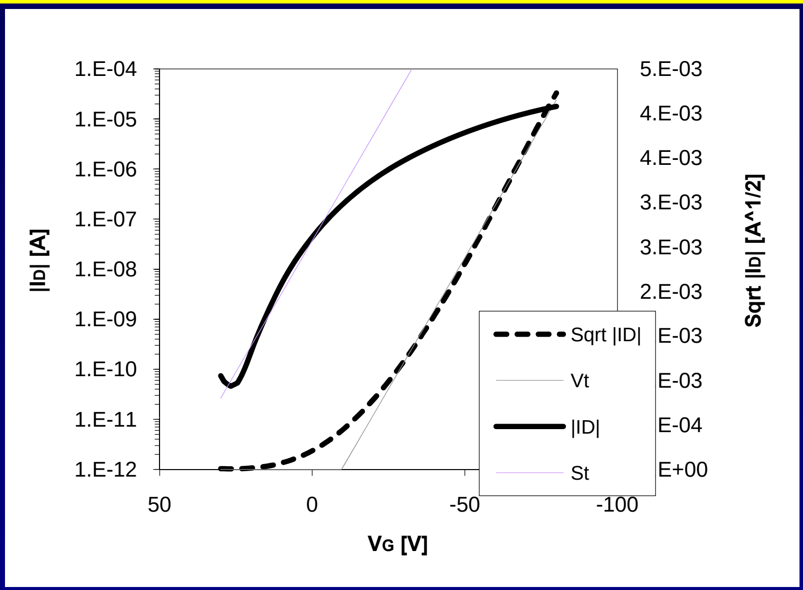
- 10’s of kHz appears feasible in the near term (already at 4kHz with low-performance semiconductor)

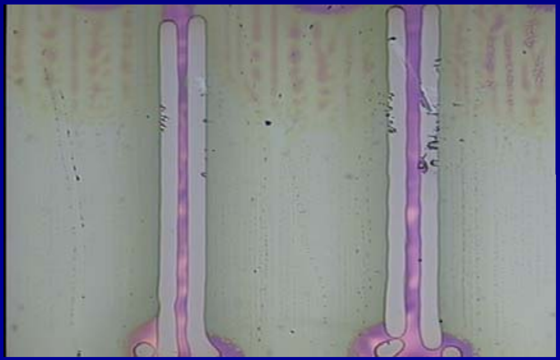
Gravure printed transistors

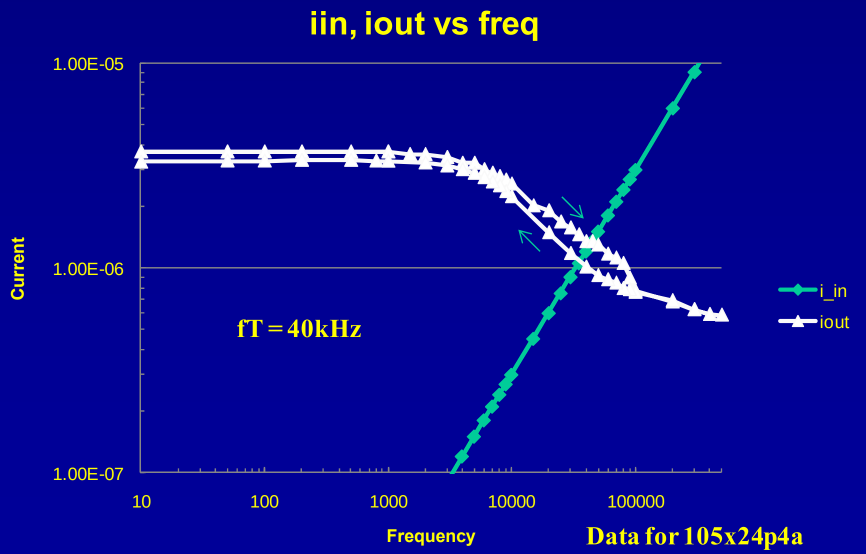


State of the art switching



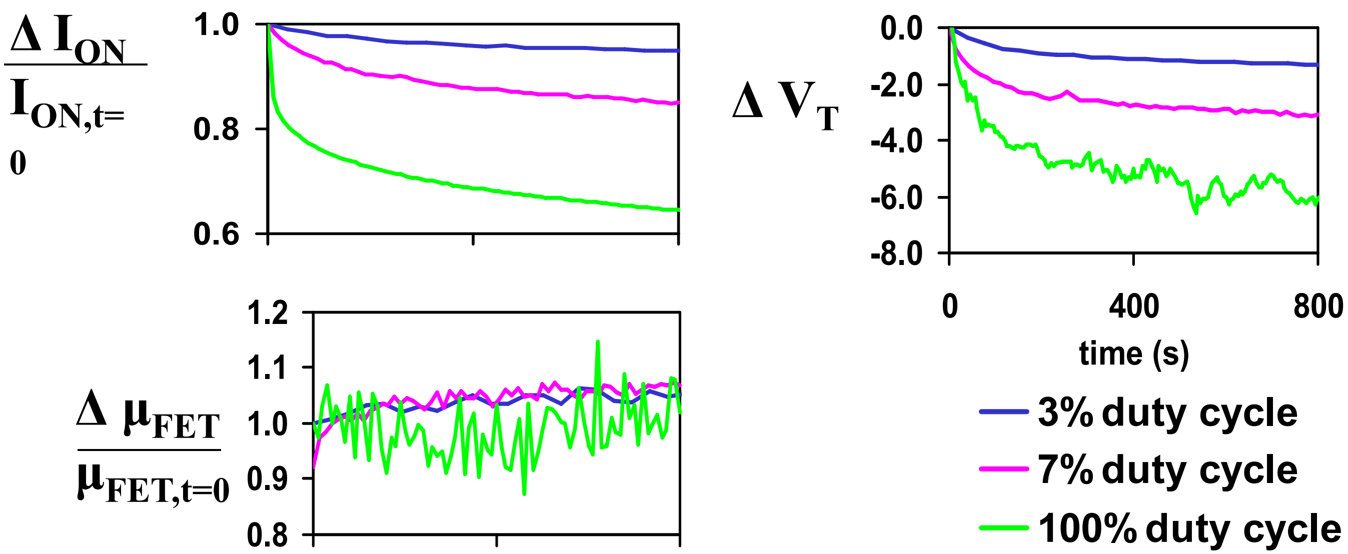




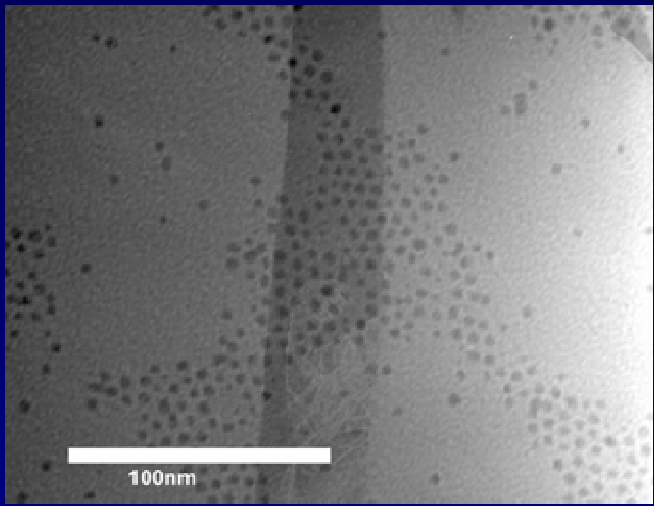


Bias stress and degradation

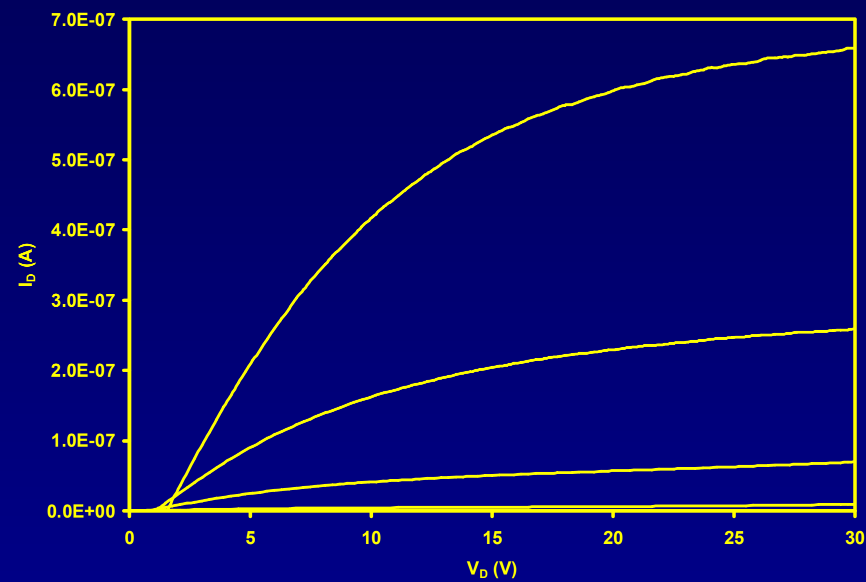
- OTFTs show substantial degradation
  1. Environmental exposure – *oxidation, etc., of organic semiconductors; requires significant investment in encapsulation research*
  2. Bias stress – *due to trapping behavior in organic semiconductors; reversible, but must be considered*



ZnO nanoparticle-based TFTs



Nanoparticles



Transparent transistor:

$\mu_{FE} > 0.2 cm^2/V\text{-}s$

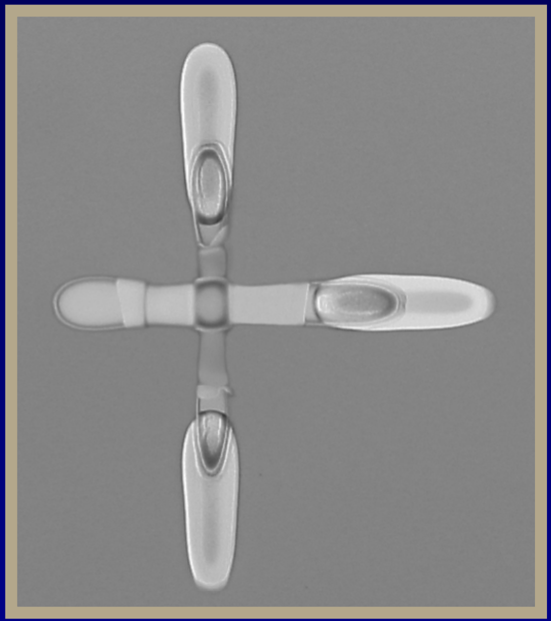
Transparency > 93%

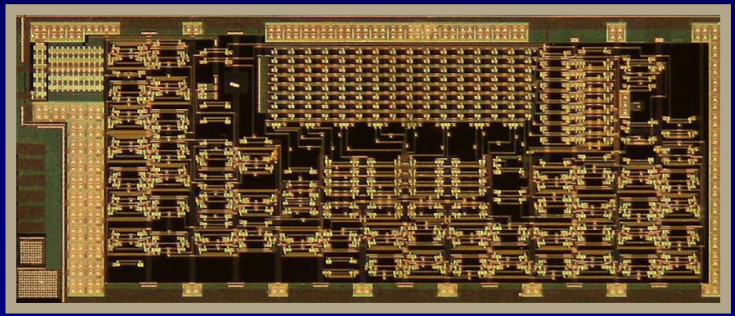
Formed out of solution

On glass, mobilities of ~$10 cm^2/V\text{-}s$ have been achieved

Volkman *et al*, IEEE IEDM, 2004

Printed Silicon (Kovio)





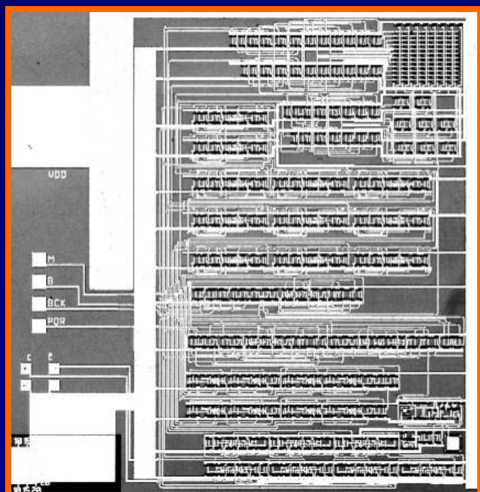
2007
Transistor

2008
RF Barcode

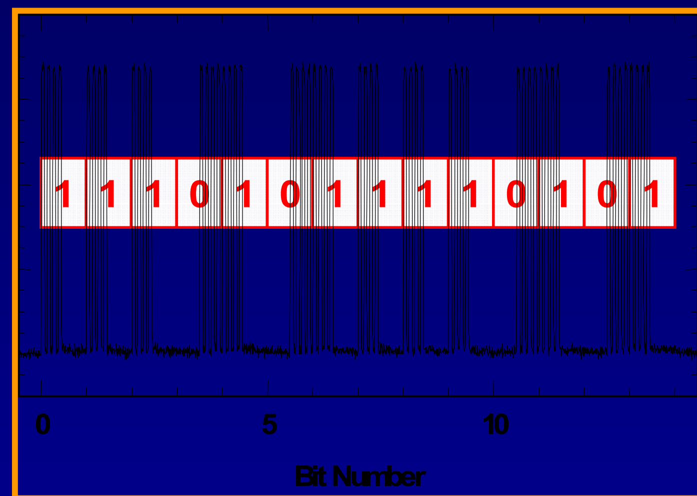
Inks	• Printable silicon with µ > 300 on steel • Various metal inks, dopant inks & dielectrics
Print	• Inkjet printing to 10µ • Screen & extrusion printing for high volume

Silicon Ink Performance (Kovio)

Silicon Ink RFIC



13.56MHz, 96b, 106kbps

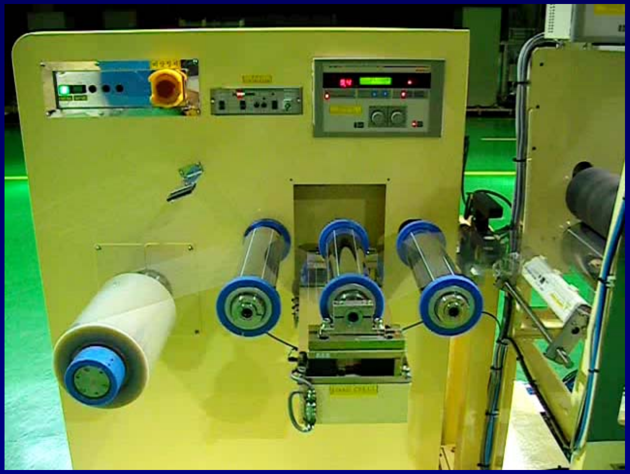


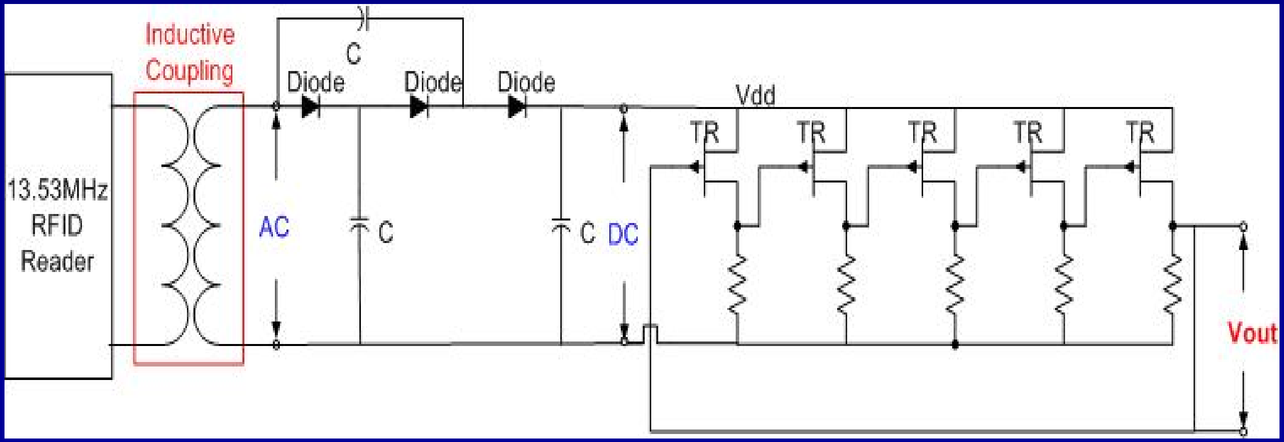
- **Low Power CMOS Design**
- **Adheres to ISO HF RFID Protocol → 96b, 106kbps, Anti-Collision,….**

Fully-printed nanotube devices (Sunchon)

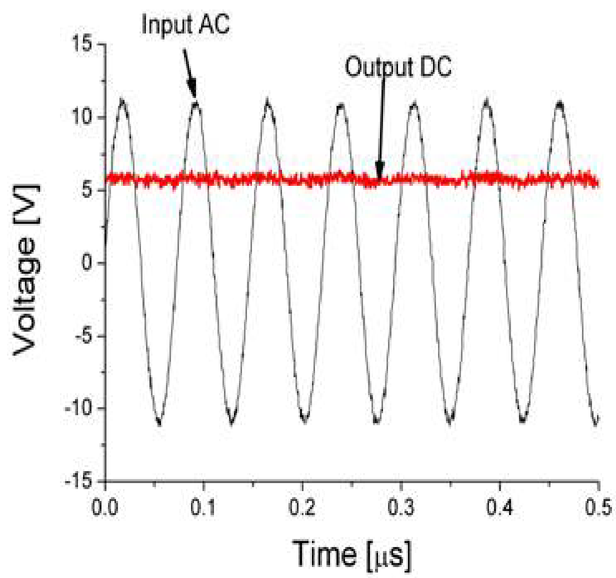
2 color units

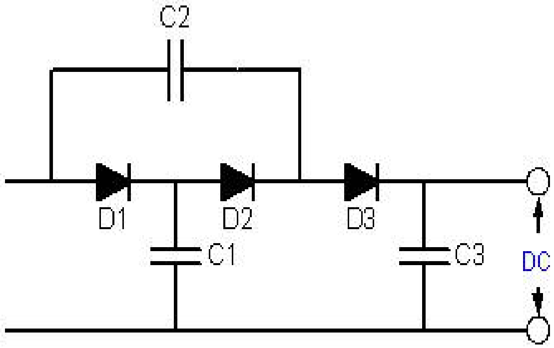
4 color units

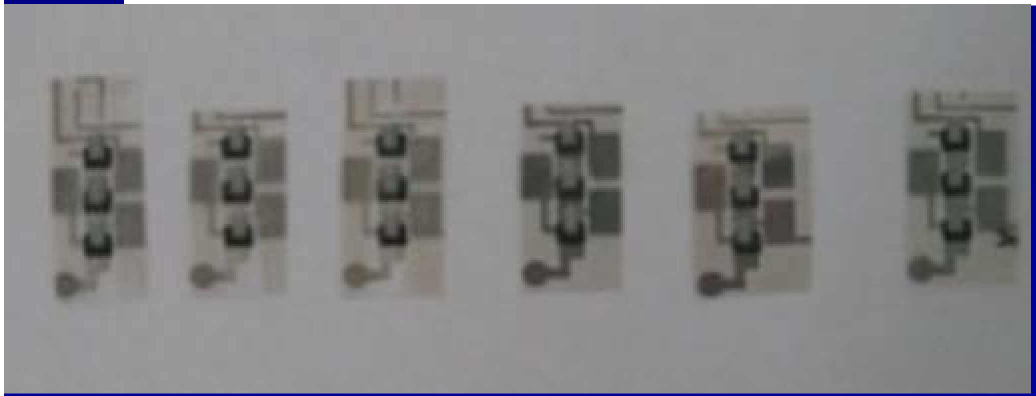




Printed rectifiers (Sunchon)







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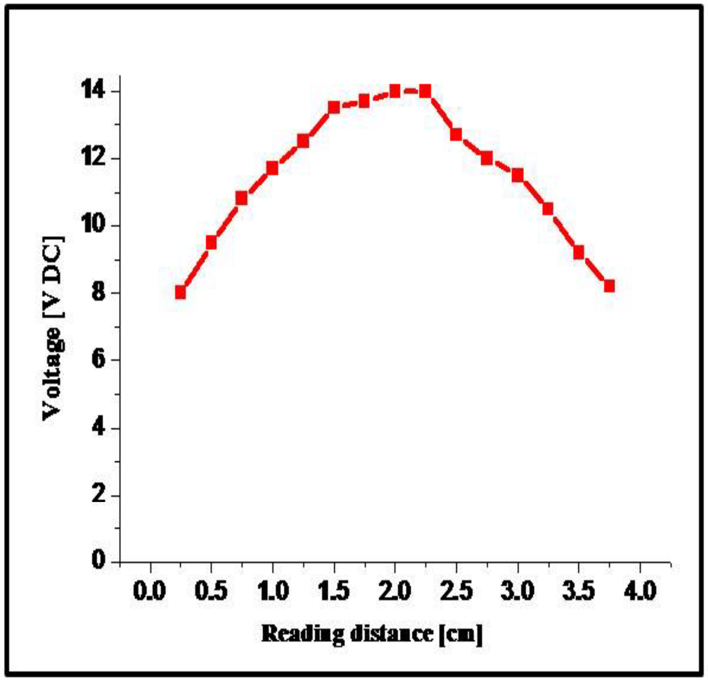
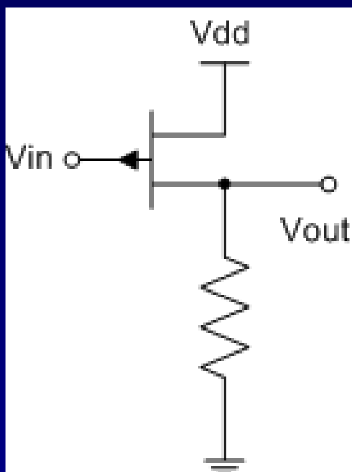
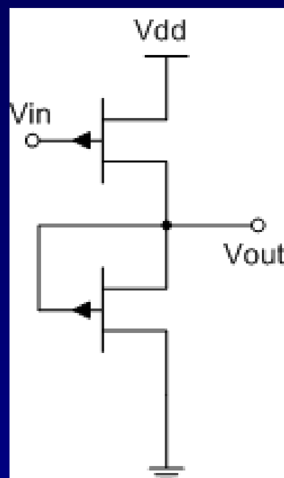
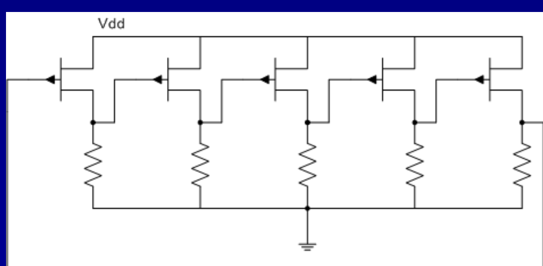
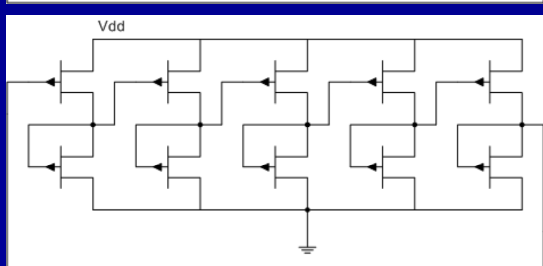


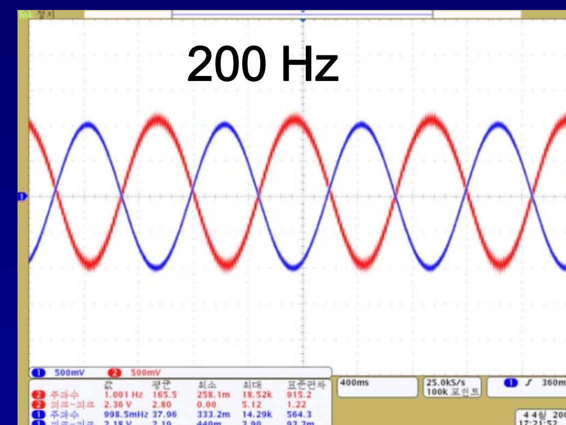
Fully-printed ring oscillator (Sunchon)











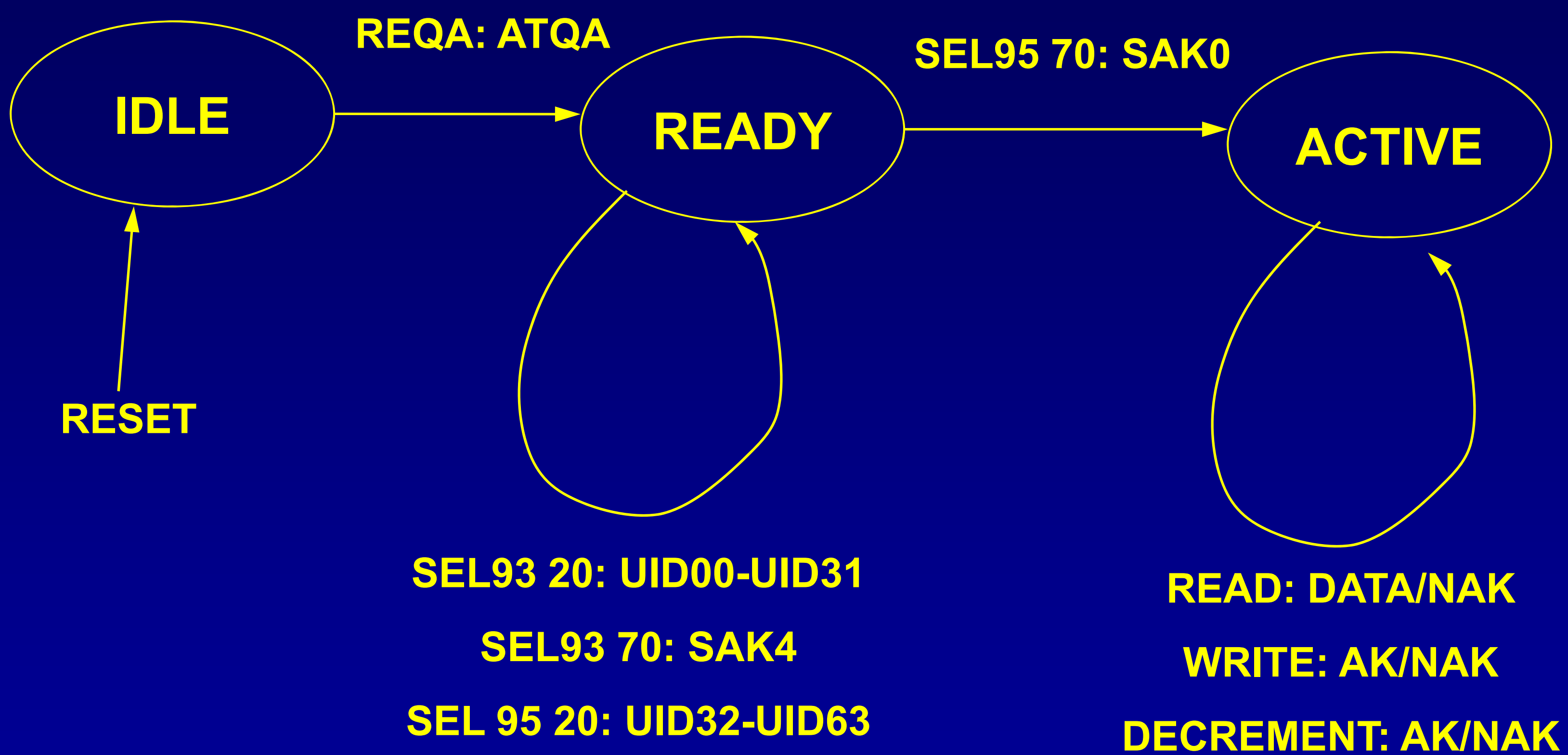
Demonstration of all printed ~200Hz ring oscillator operated under DC 10 V

Status: Printed Devices

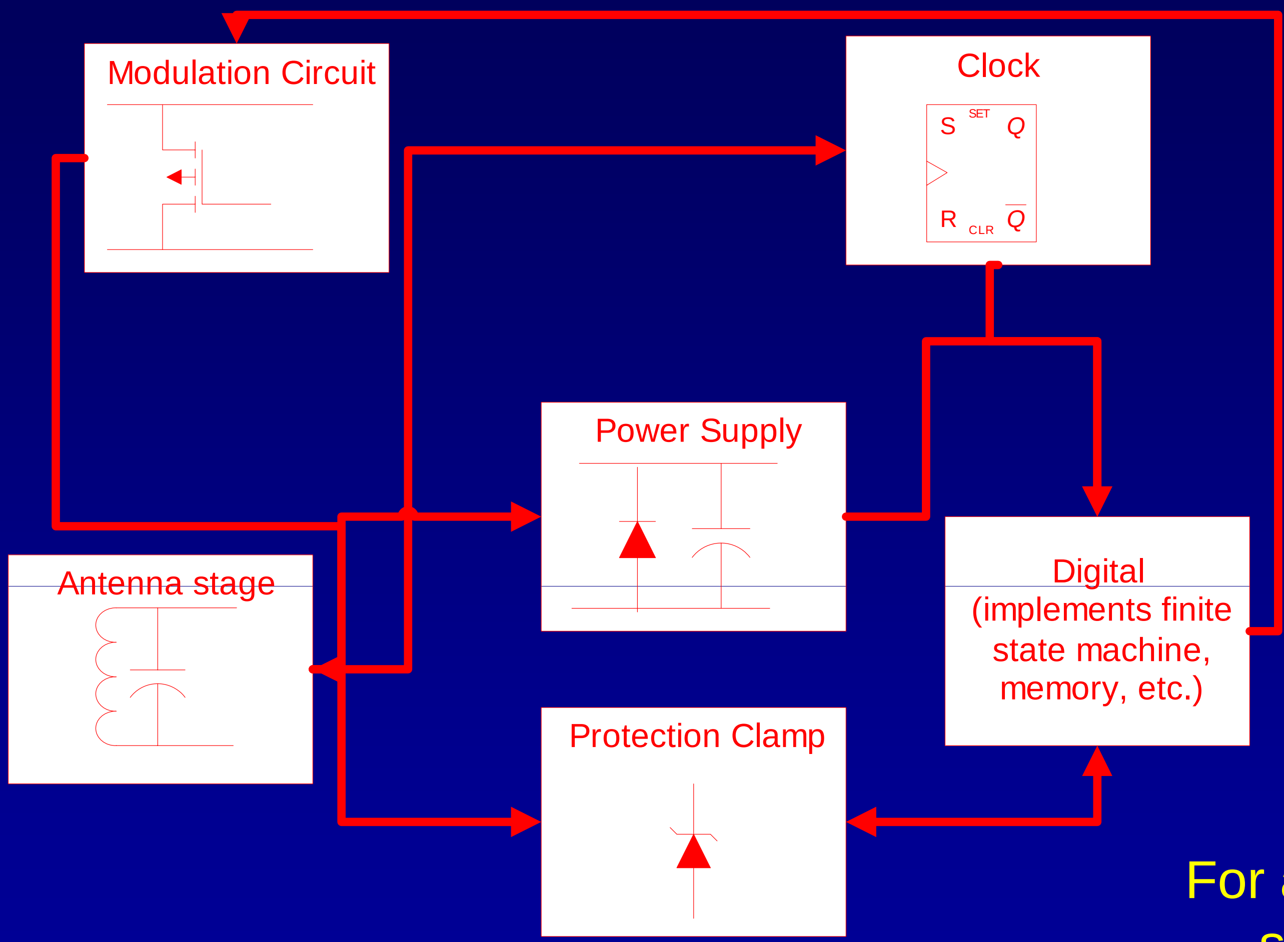
- Organics:
  - Low mobility
  - Easy to process
  - Plastic compatible
  - Only simple demonstrations by printing; more complex demonstrations are NOT printed
- Printed Silicon:
  - Very high performance
  - Requires careful processing
  - Steel
  - Fairly complex demonstrations using hybrid processes
- Nano
  - High up-side, but very immature
  - Plastic compatible
  - Fully-printed demonstrations have been made

So what does all this mean?

ISO14443 – State Machine



Standards-based issues



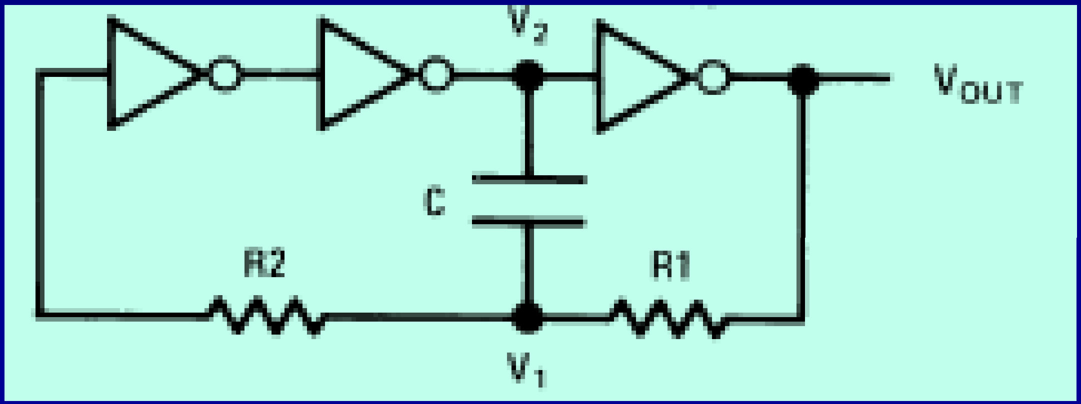
Clock is divided down from 13.56MHz carrier

The need for RTF dramatically increases complexity, particularly due to CRCs

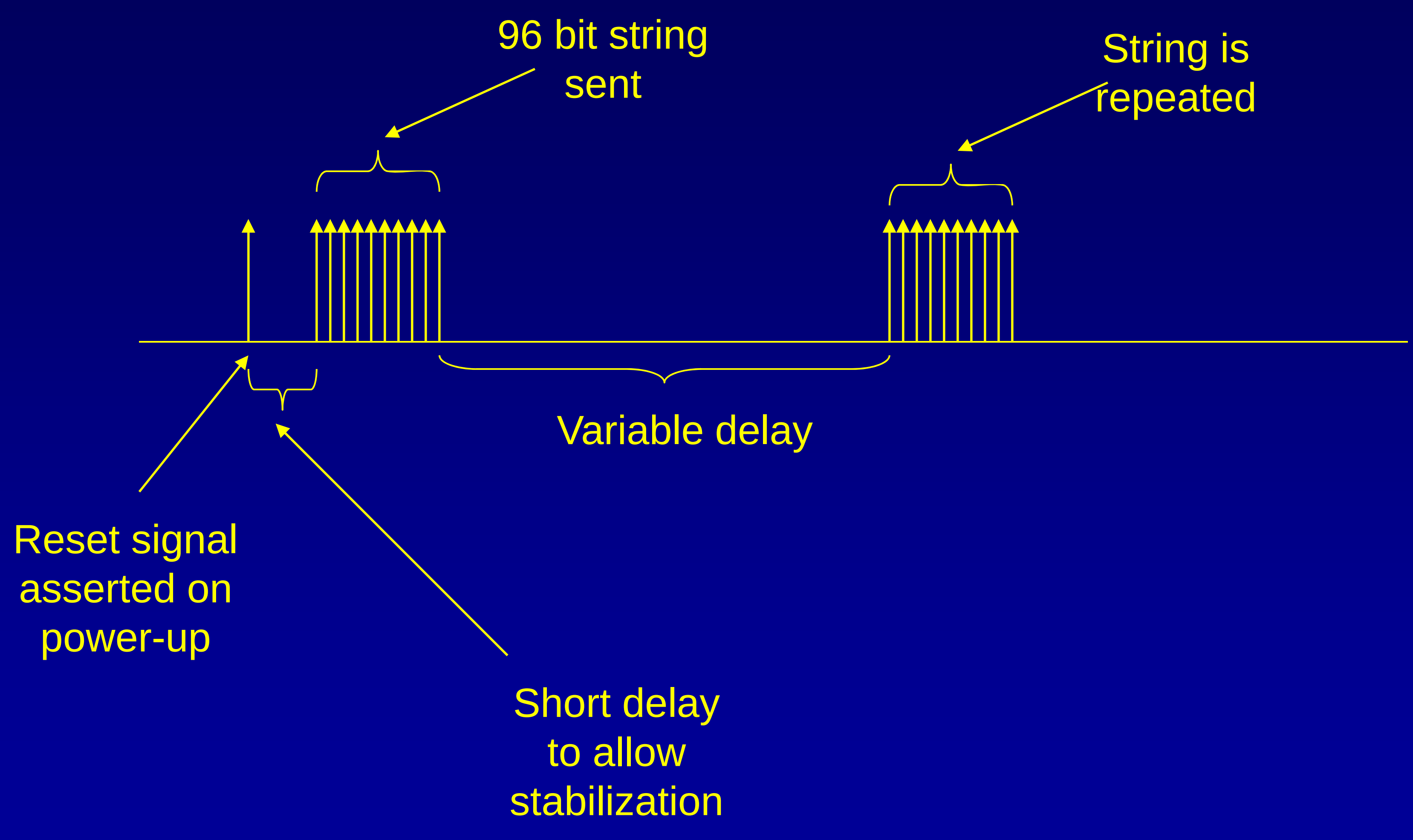
For anything more than simple barcodes, transistor counts may blow out cost models

Clocking architectures

- Could divide 13.56MHz carrier, but OTFTs cannot do this due to f_T constraints
- Can generate clock locally, but need smart reader to deal with drift due to on-resistance variation of OTFTs with supply voltage, drift, and degradation



TTF: A low-cost entry for barcodes



Performance Expectations

- Standards
  - Let's be realistic… costs, yield, and performance limitations will place the following bounding boxes on printed RFID in the near future

Transistor count <5K

Range <5cm

Async, <1kb/s for organics

Sync, 200kb/s for inorganics

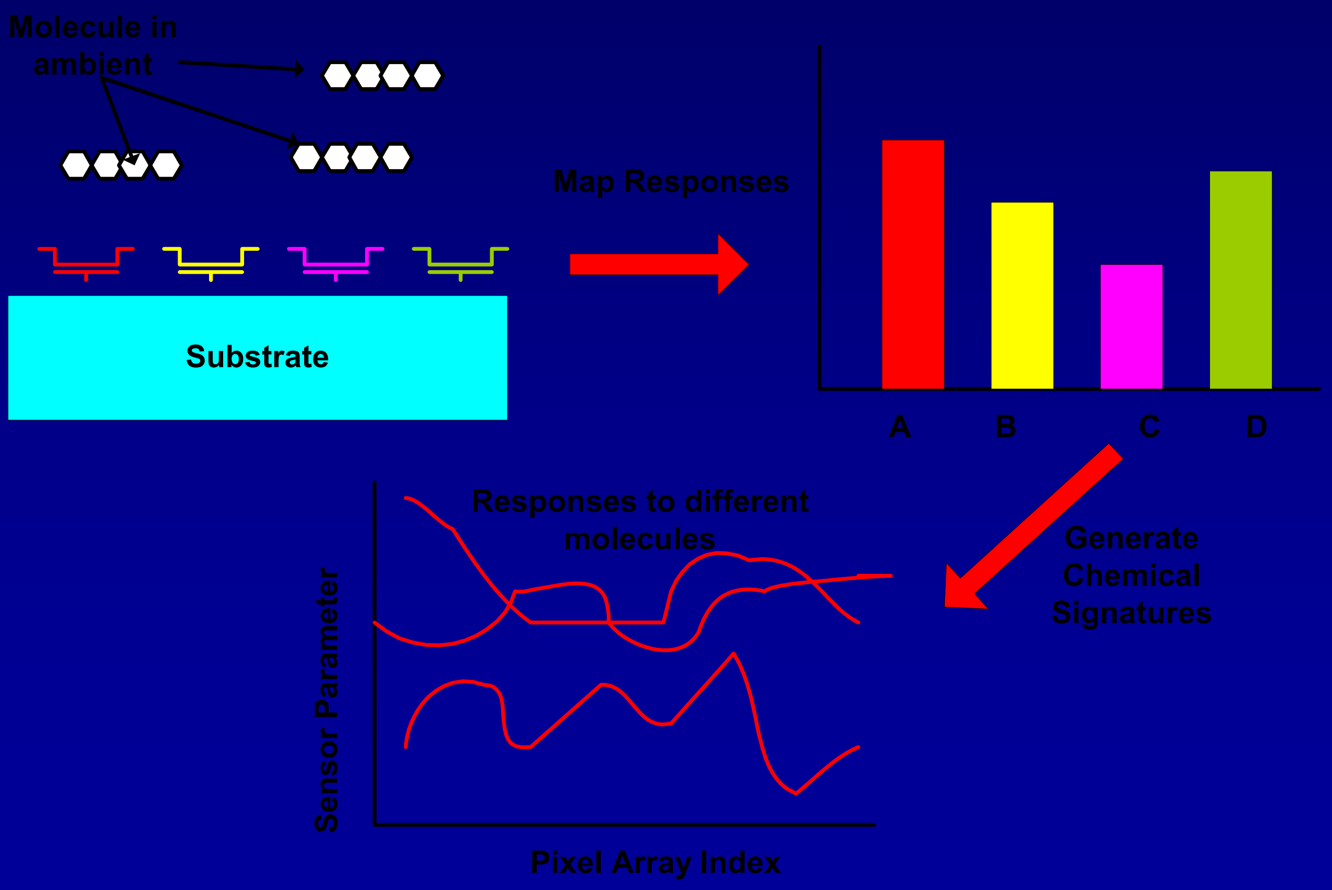
The need for an eco-system

- Standards
  - Low transistor counts dictate the need for simple protocols (e.g., TTF, or reduced-complexity RTF protocols)
  - Continuum of choices may be needed, based on material performance (data rates, sync. Vs. async, etc.)
- Readers
  - High-performance materials enable compatibility with existing reader chips (e.g., simple firmware changes)
  - Low-cost electronics on plastic may need new ASICs
- Eco-system
  - Need tool suppliers, material suppliers to align

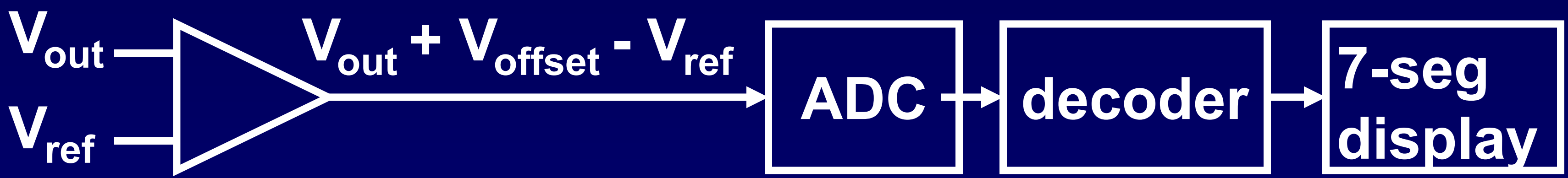
What else can printing bring to the table?

Spatially-specific deposition: Sensors

Can we exploit the ease of spatially-specific deposition offered by inkjet to realize novel functionality?



Integrated Vapor Sensor



<u>Sensor in Air</u>
Reading: 6

<u>Sensor in Ethanol vapor</u>
Reading: 7

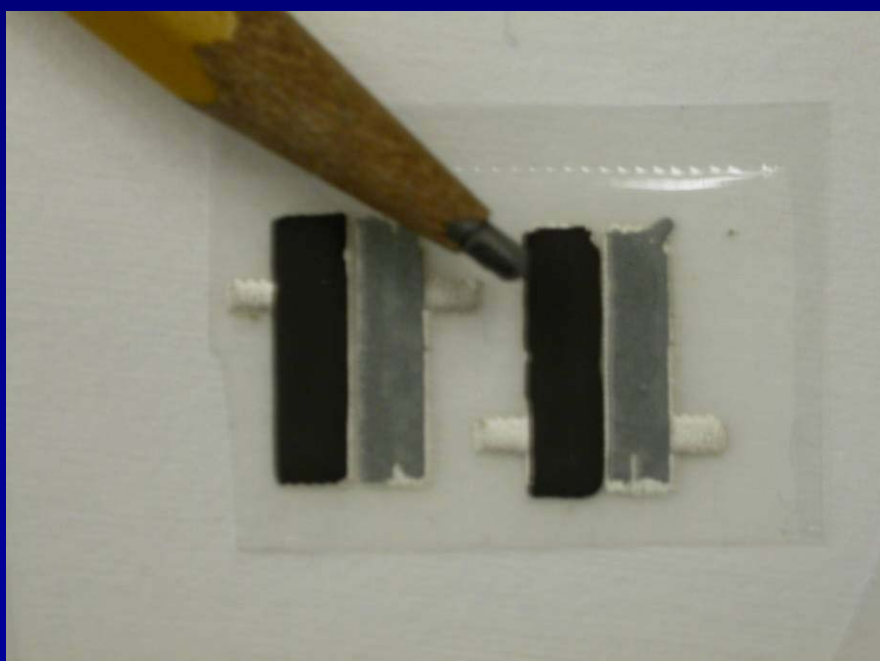
<u>Sensor in Ethanol with 10% -COOH vapor</u>
Reading: 4

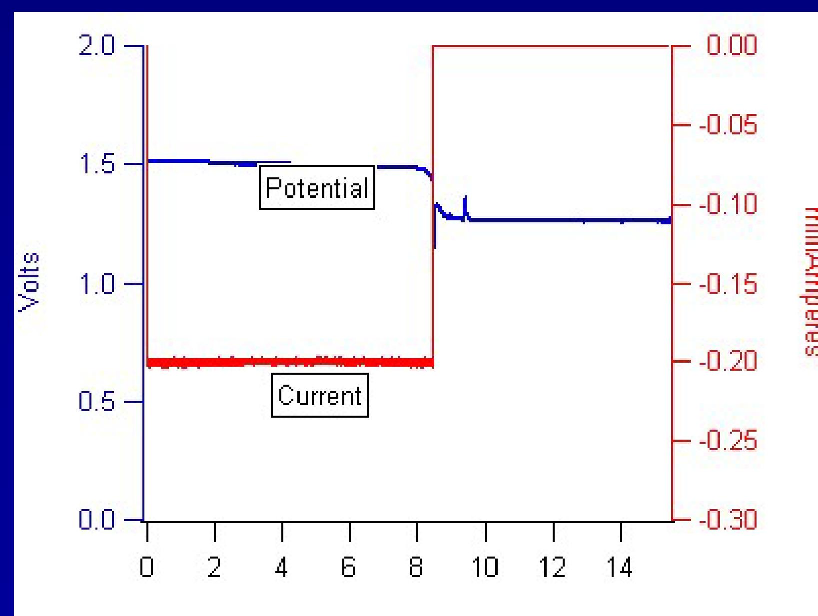
Sensor recovers completely, and can be cycled hundreds of times without failure, maintaining consistent values

Chang, *et al* J. Appl. Phys. 100, 014506 (2006)

Printed Batteries

- We have recently developed a printed battery technology that is air-stable (i.e., not Li-based), but offers energy densities on par with Li cells (>3.5mAhr/cm^2 for cells <100μm thick)





So what is the future?

- Opportunities probably exist for integrated systems including sensors, batteries, authentication circuits, etc.
- Inkjet and gravure allow tremendous flexibility of fabrication, and we should exploit this at a system level
- It is all about the eco-system….