Continuous and scalable manufacturing of macro-, micro- and nanoscale structures using roll-to-roll processing

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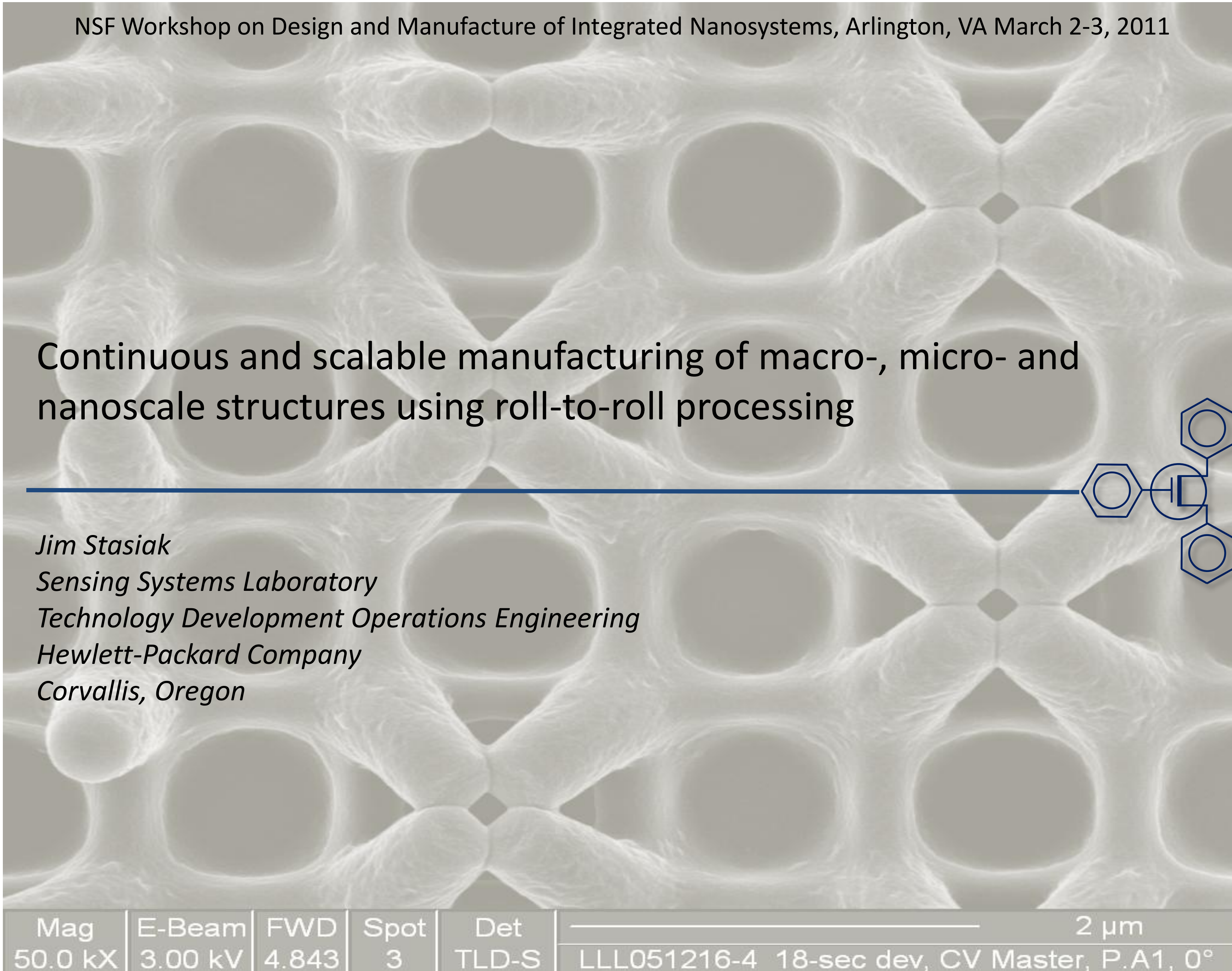

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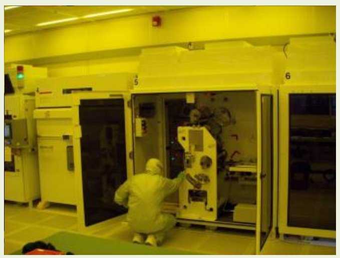


•Plastic Fab/R2R Proto

HP Corvallis, Oregon Site

- HP's largest R&D site
- Began operations in 1976
- 2 million square feet
- Focus on new IJ and Emerging Tech. product development
- ~2,000 people on-site.
- 500 engineers in Technology Platform Dev. (Chemists, Physicists, Mat-Sci, ChemE, EE, CS, ME...)
- Corvallis has 2nd highest patent per capita rate in the United States.

Continuous and scalable manufacturing of macro-, micro- and nanoscale structures using roll-to-roll processing

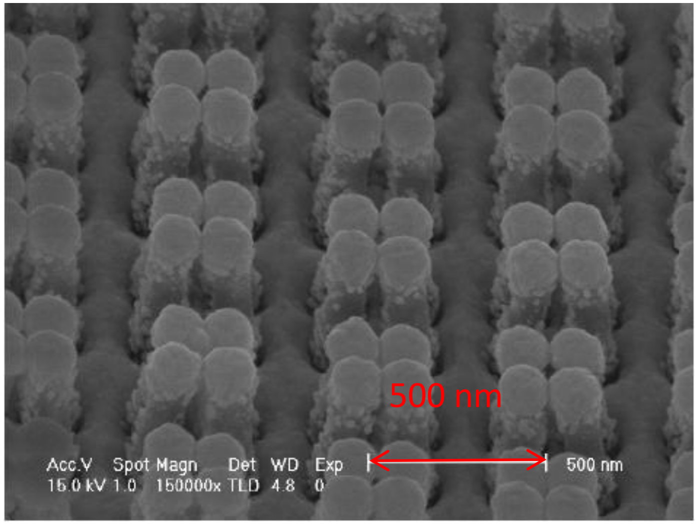
Outline:

1. Motivation

2. Developing Imprinting, Embossing and Roll-to-Roll Manufacturing Methods
   Two examples:
   - Alignment and Registration Tolerant Lithography
   - SERS-based Chemical and Biological Sensors and Sensing Systems

3. Digital Fabrication, Printable Electronics, MEMS, and Materials

4. Summary



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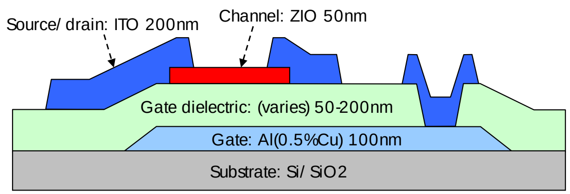
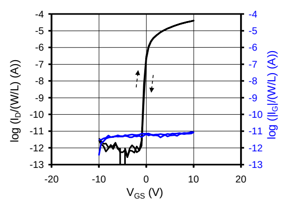
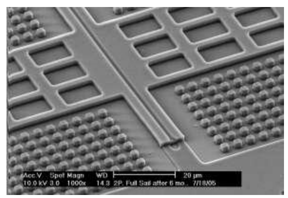
Motivation:

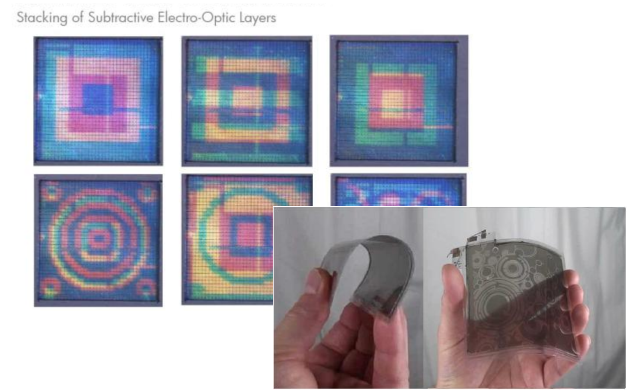
Active research and development programs leveraging multi-scale embossing, novel materials and roll-to-roll processing:





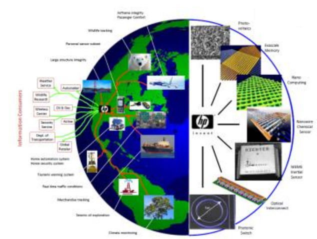


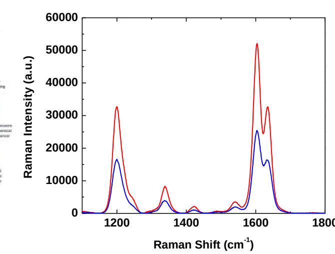
Distortion-tolerant, high performance flexible devices and circuits incorporating metal oxide semiconductor materials.

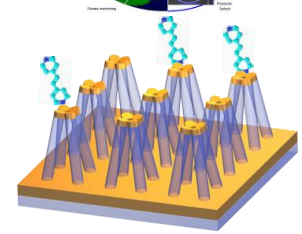


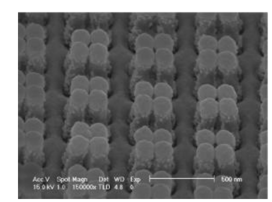
Flexible, active matrix, full-color electrophoretic displays and signage.

Integration of digital printing, digital fabrication and "*functional inks*" enabling Smart Packaging and Smart Labels.









CeNSE: "Central Nervous System for the Earth" e.g. Chemical and biological sensors based on nanofabricated SERS substrates.

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Self-Aligned Imprint Lithography (SAIL)

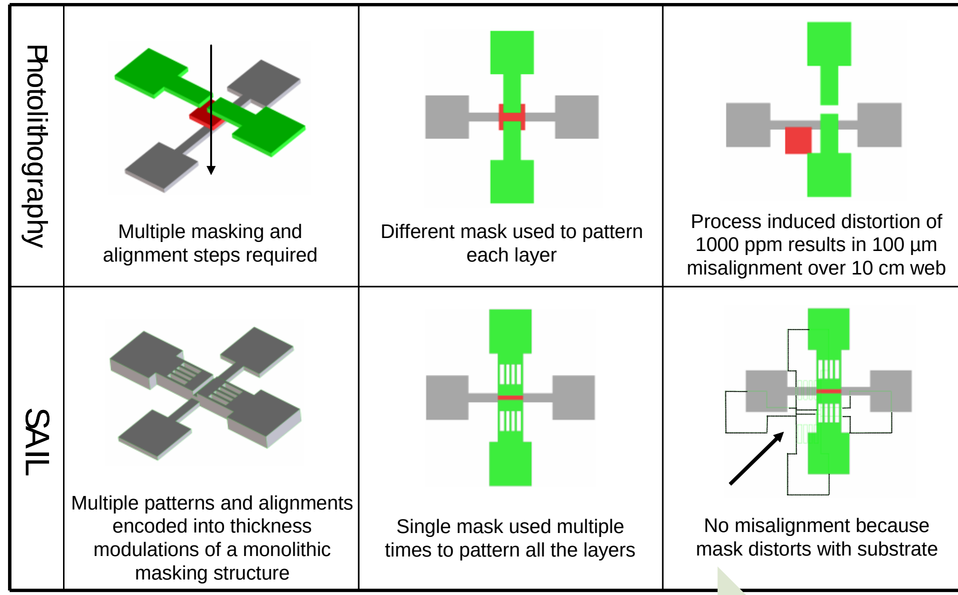
▪Media independence will be a key requirement for integrating electronics, MEMS and microfluidics with Smart Packaging applications.

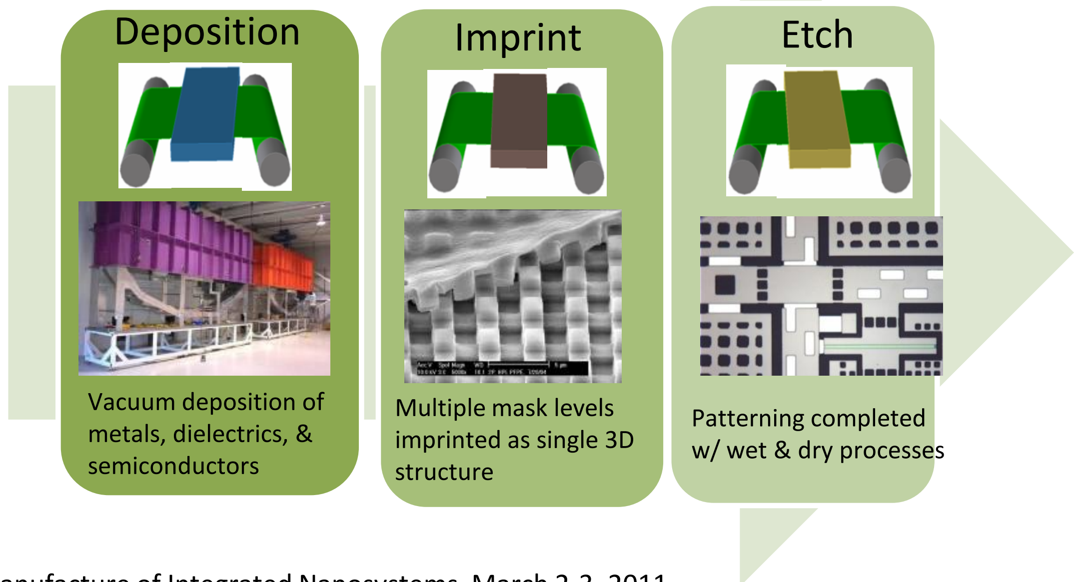
- •Plastics
- •Paper
- •Cardboard
- •Foils
- •…

▪…significant challenges arise due to:

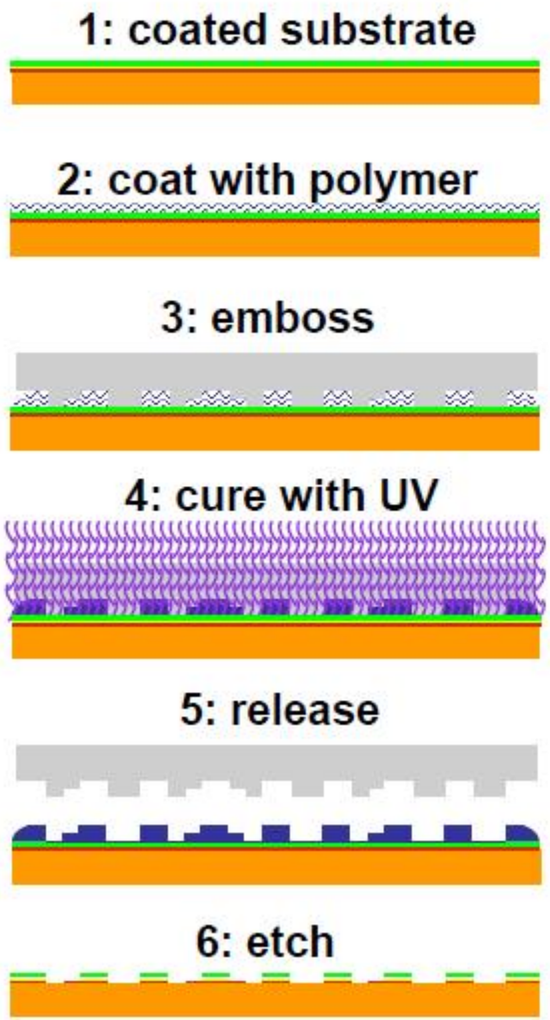
- •Substrate distortion (esp. multi-masking demands for TFTs, etc.)
- •Temperature limitations
- •Surface quality of media
- •Thermal mismatch

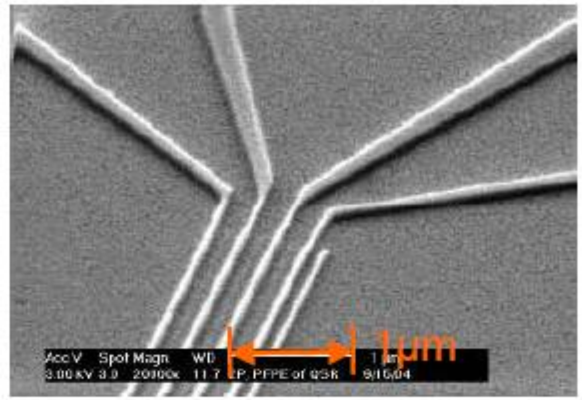
By "trading" lithography and masking operations for a series of etching processes, HP Labs's R2R compatible SAIL lithography process solves layer-to-layer alignment and distortion problems for flexible substrates





Fabrication of TFT's using Self-Aligned Imprint Lithography (SAIL)

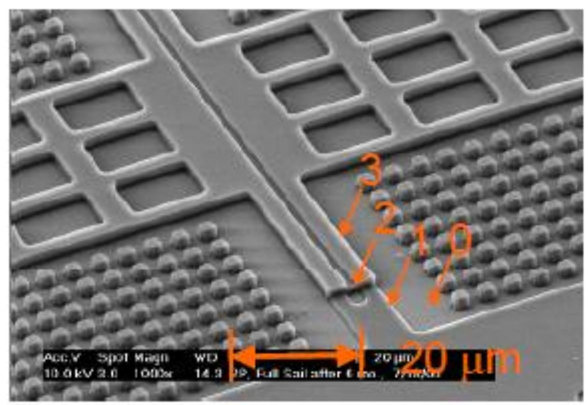




~40nm lines on 50μ polyimide

Pixel speed depends linearly on mobility but inversely with the square of channel length

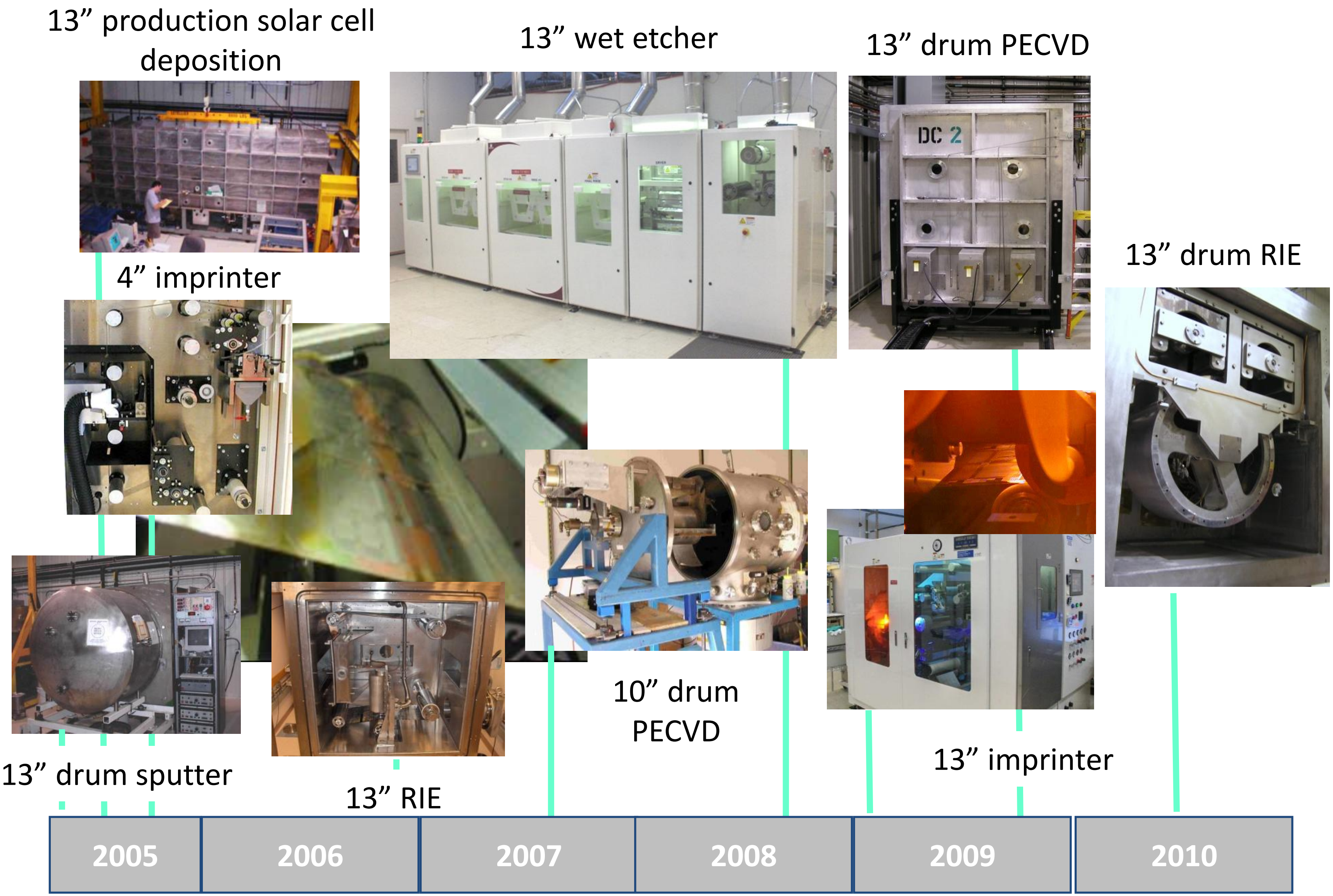
$$t_{pixel} \approx \frac{2L^2}{\mu\,(V_G - V_T)}$$



4 levels in 0.5 μ step heights

Multilevel structures on flex at 5m/min

Evolution of R2R Imprint/Emboss Tool Development at HP Labs



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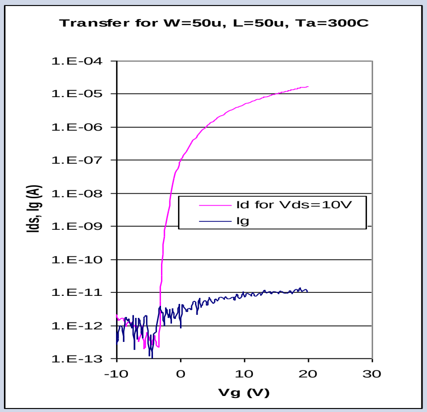
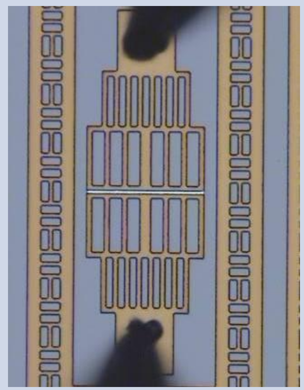
Recent accomplishments:

First MCO-based TFTs fabricated using SAIL

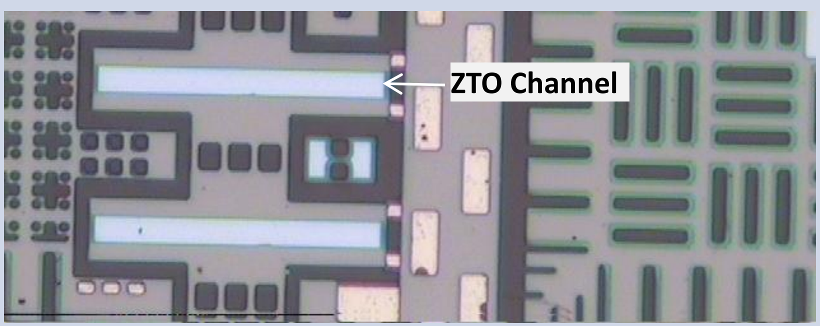
Mobility 10-20 $cm^2 V^{-1} sec^{-1}$

On-off ratio 10^7



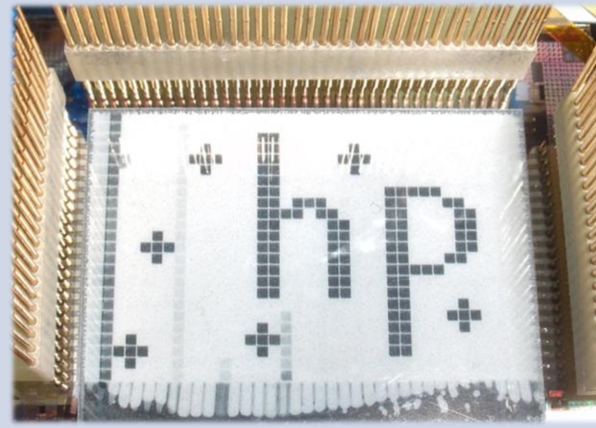


Individual SAIL ZTO Transistors on C-Si-thermal oxide gate dielectric

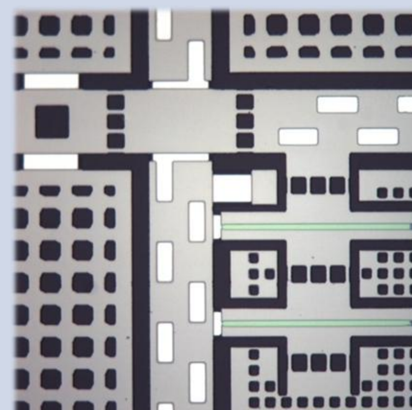


Full SAIL ZTO Transistors on Polyimide

World's first R2R active matrix display



E Ink frontplane and backplane each made with R2R process



SAIL Backplane on flexible substrate pixel detail

Demonstrated at the Flexible Display Conference in Phoenix Arizona, February 2009

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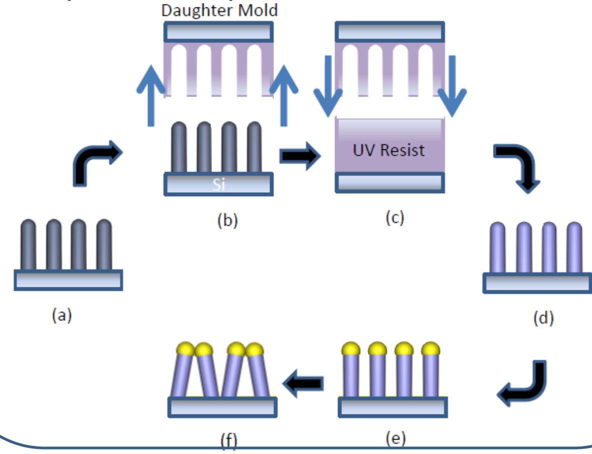
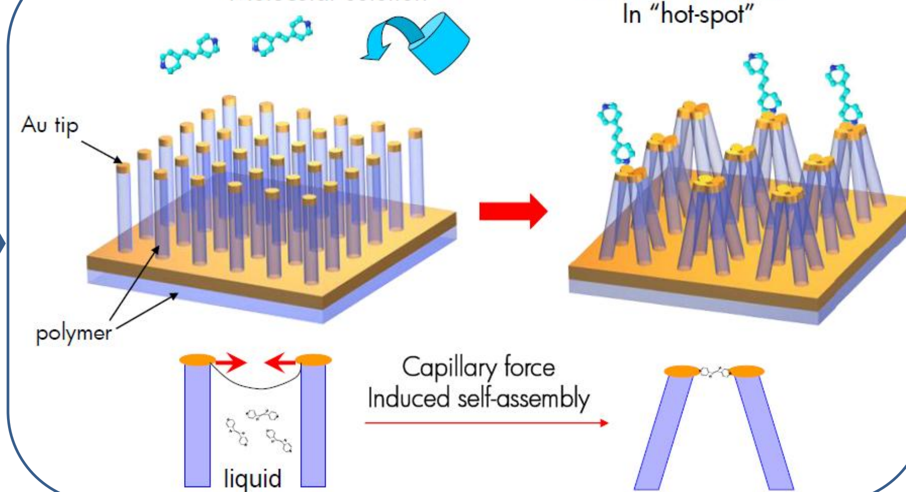
Nano-imprinted "Molecular Tweezers" for SERS sensing:

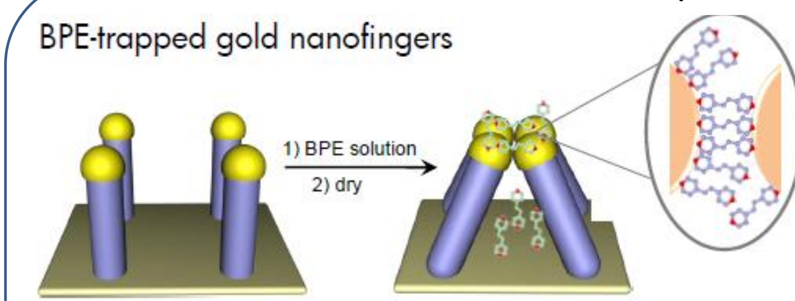
Mastering, stamp fab., imprinting and Au nanoparticle deposition



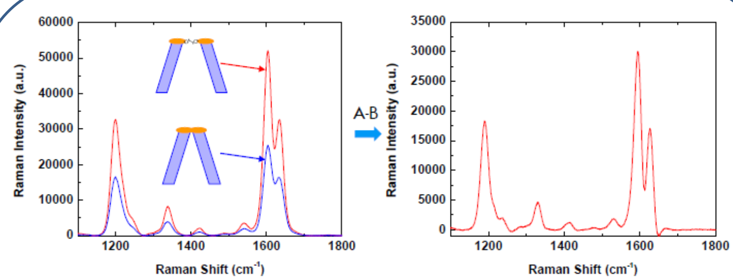


Raman hot-spot

BPE-trapped gold nanofingers



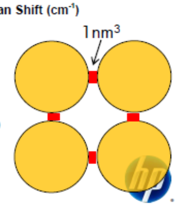
Molecule trapping between the finger tips



Molecules trapped in the fingers contributed **60%** Raman signal!

5molecules/gap, 25 fingers/μm^2, laser spot ~$2\mu m^2$,
∴ 250 molecules trapped between the finger tips

$$EF = \frac{I_{SERS}/N_{SERS}}{I_{bulk}/N_{bulk}} = \frac{30000/250}{40/(125\mu m^3 \times 0.1M \times N_{avogadro})} = 2\times 10^{10}$$



Hu, M. et. al. *J. Am. Chem. Soc.* **2010**, *132*, 12820.

SERS of trapped molecules

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"Lab-scale" fabrication of "molecular tweezer" arrays at HP Labs Palo Alto

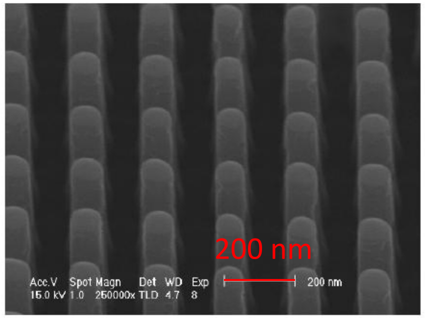


Figure S2: SEM image showing the silicon mold fabricated using nanoimprint lithography

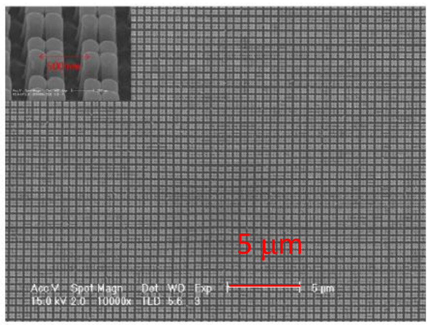


Figure S4: A low magnification top-view SEM image showing the closed gold fingers coated with 80nm sputtered Au film with a pitch of 500 nm. The inset shows a tilted view of the fingers at high magnification.

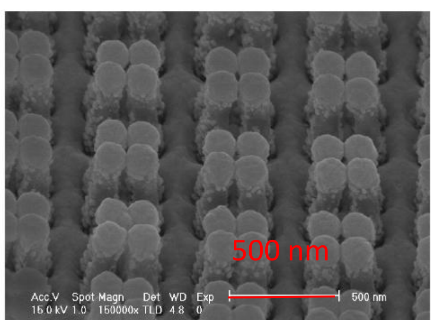


Figure S5. Tilted view SEM image showing the closed fingers coated with 80 nm E-beam evaporated Au film.

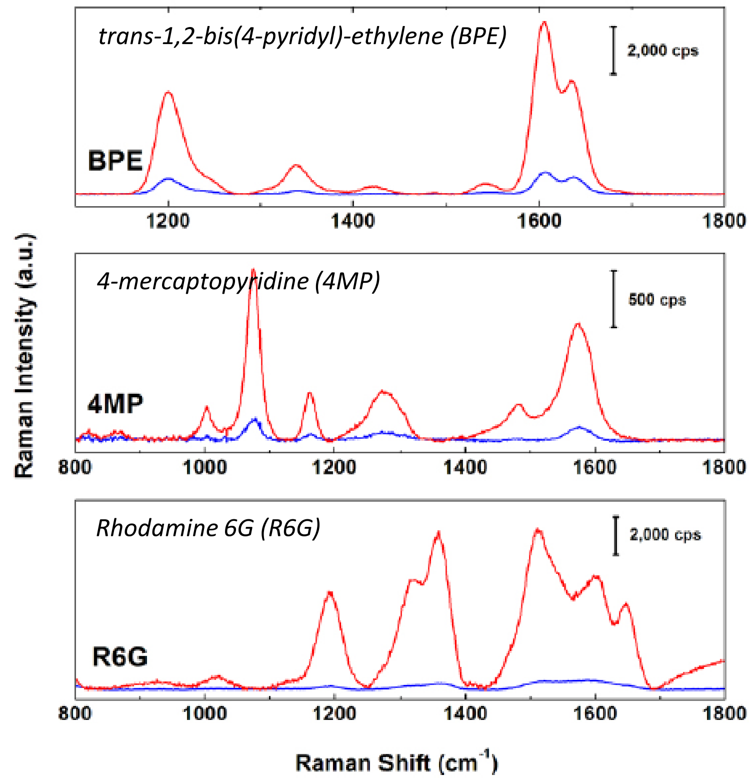


Figure S1: Three different molecules (BPE, 4MP and R6G, from top to bottom) were used in the comparison experiments. Red spectra: Raman spectra collected from the closed-finger samples. Blue spectra: Raman spectra collected from the open-finger samples. The spectral intensity for all three compounds was at least an order of magnitude larger for the closed-finger samples.

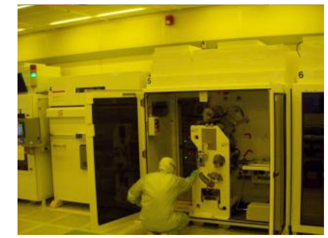
Continuous and scalable manufacturing of macro-, micro- and nanoscale structures using roll-to-roll processing

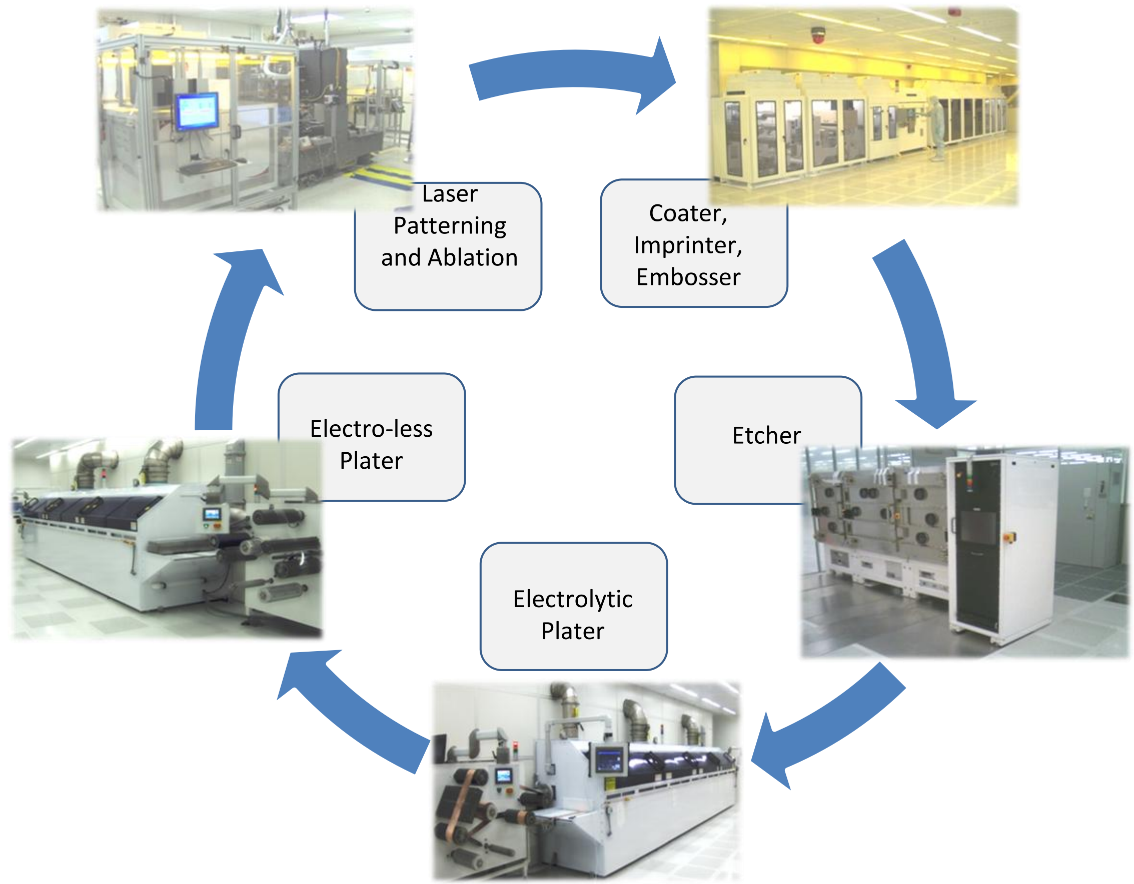
HP Corvallis "Plastic Fab" – 1/3 meter wide web proto-manufacturing facility

- Embossing lithography features < 5μm
- **Compatibility with SAIL patterning and imprinting processes**
- Deposition and plating (both electrolytic and electro-less) of metals and dielectrics
- Laser patterning and template mastering
- Dry etch and plasma treatment

View from Take-up Reel

View from Input Reel





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HP Corvallis "Plastic Fab" – 1/3 meter wide web proto-manufacturing facility

Fabrication of devices continues to push the boundary of size and speed. High precision production of structures to control a range of capabilities enable products such as micro-fluidic devices and optical devices. With high repeatability and process control, the HP embossing technology provides cost-effective methods to pattern flexible substrates such as stainless-steel and PET.

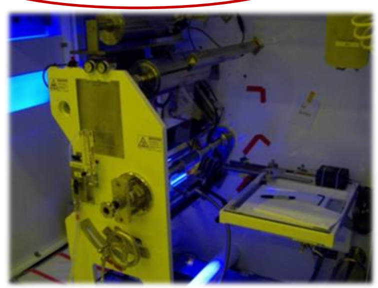
The HP technology includes a range of materials for applications like fluidic management devices or optical filtering or patterning foils.

Mastering Generation
Several methods are available for master stamp generation including cast polymer stamp, laser ablated roller, photo defined features

Coating
Coatings can be applied in a number of ways such as gravure, slot die, or needle dispense

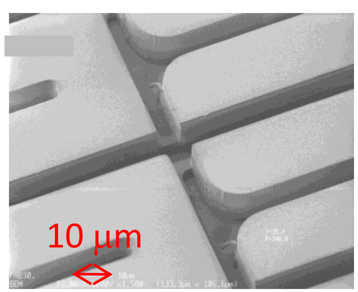
Embossing/Curing
The integrated emboss/cure step assures maximum fidelity

SAIL Compatible

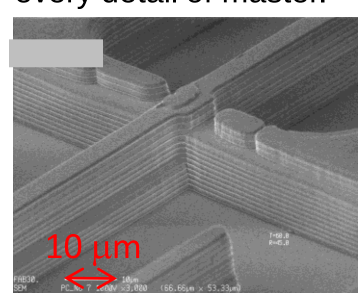


Feature	Min	Max	Units
Web Width	100	330	mm
Continuous patterned area	10 x 10	100 x 150	mm
# levels	1	4	levels
Depth	0.5	17	µm
Width	4	500	µm
Spacing	0.004	100	mm
Aspect Ratio	0.3	3.6	
Angle between lines and imprint direction	0	60	Degrees
Layer to layer overlap	0.5	--	µm
Transport rate	0.2	0.8	m/minute
Substrate thickness	20	250	µm
Substrates	PET, PEN, SS, ITO/PET, SS/PET		

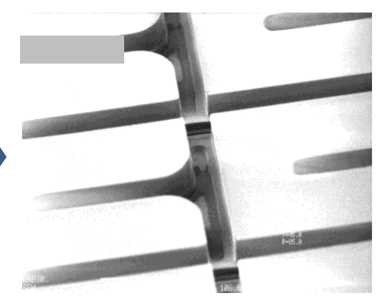
Three level Master



Stamp: Stamp resin shows every detail of master.



Final embossed feature



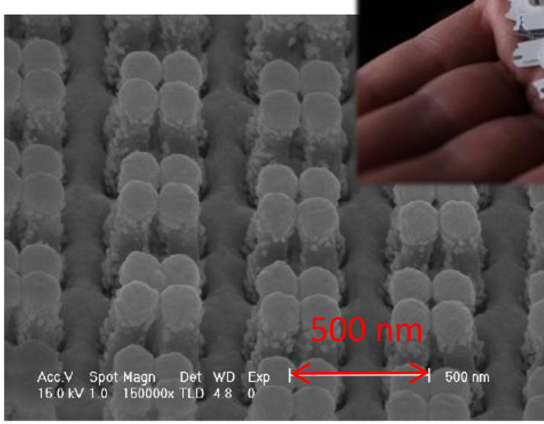
Transferring lab-scale imprinting and embossing processes to Corvallis R2R proto line

Starting R2R Scale-up of SERS substrates in Corvallis:

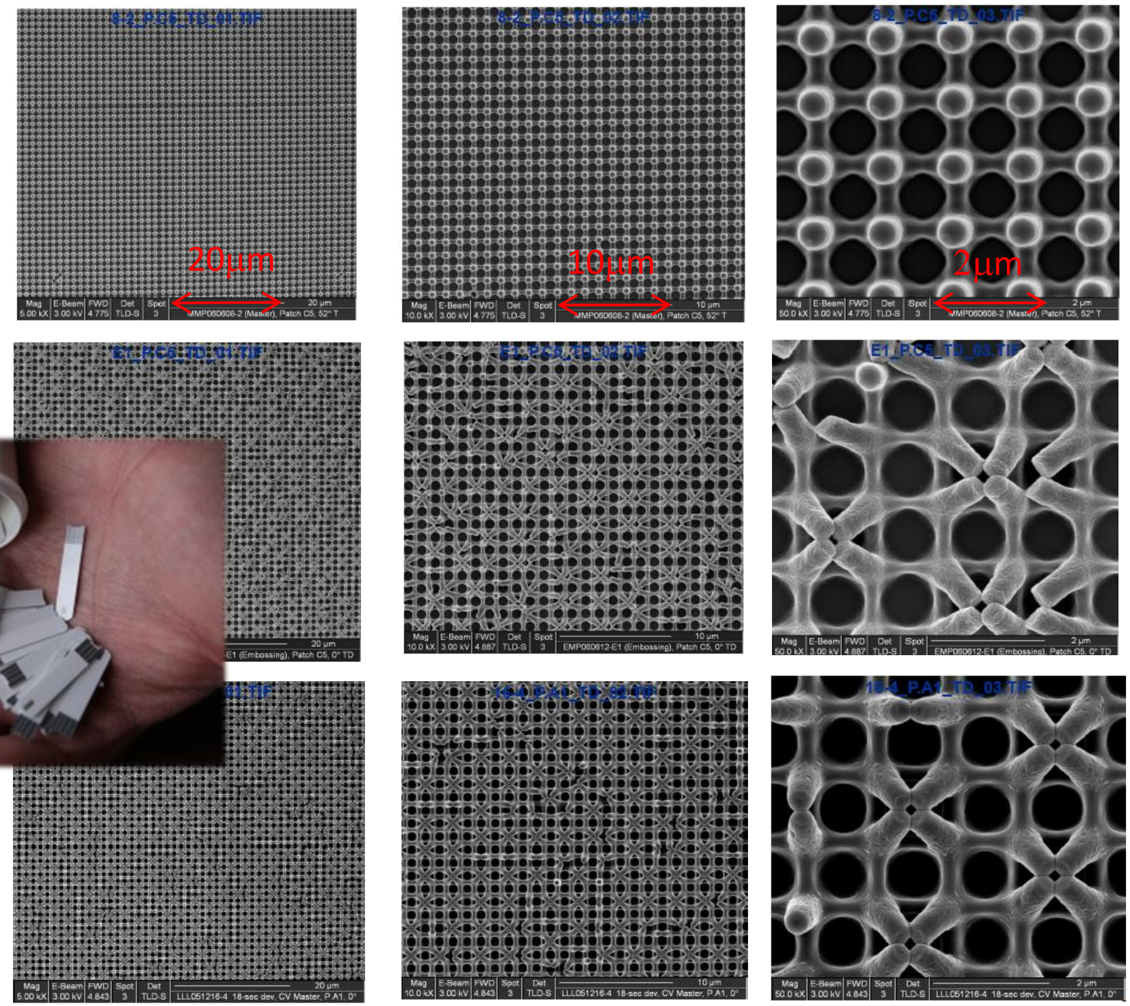
Masters formed via photolithography on glass substrates. (E-beam mastering will reduce feature size)

Embossed features are formed using cured embossing resins

Scale provides a path to high volume and low costs



Master | Embossed arrays on plastic substrates | Magnified images



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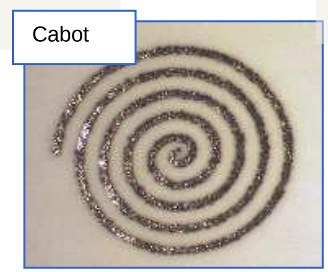
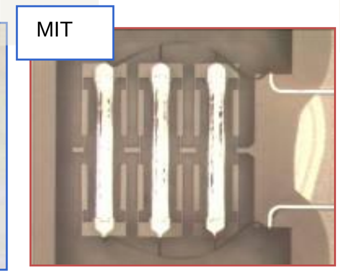
Digital Fabrication, Printable Electronics, MEMS, and Materials

The development of new "functional inks" and drop-on-demand (both thermal and piezo inkjet) printing processes – enabling the "printing of things".

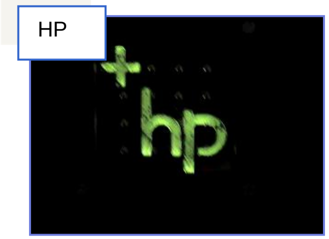
Precision drop-on-demand materials printing tools



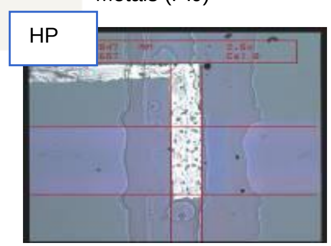
Metals (PIJ)



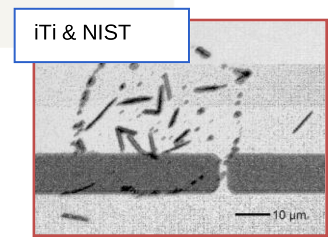
PZT actuators (TIJ)



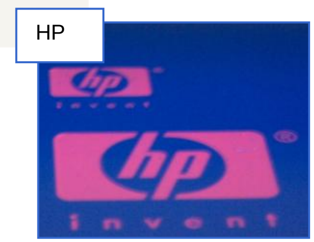
OLED (TIJ)



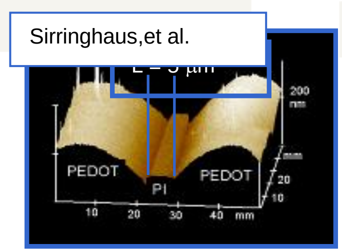
Inorganic TFT



Nanowires (TIJ)

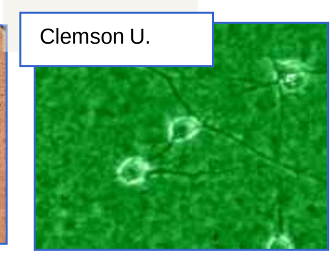


Quantum dots (TIJ)



Organic TFT (PIJ)

CNT's on paper (TIJ)



Printed neurons (TIJ)

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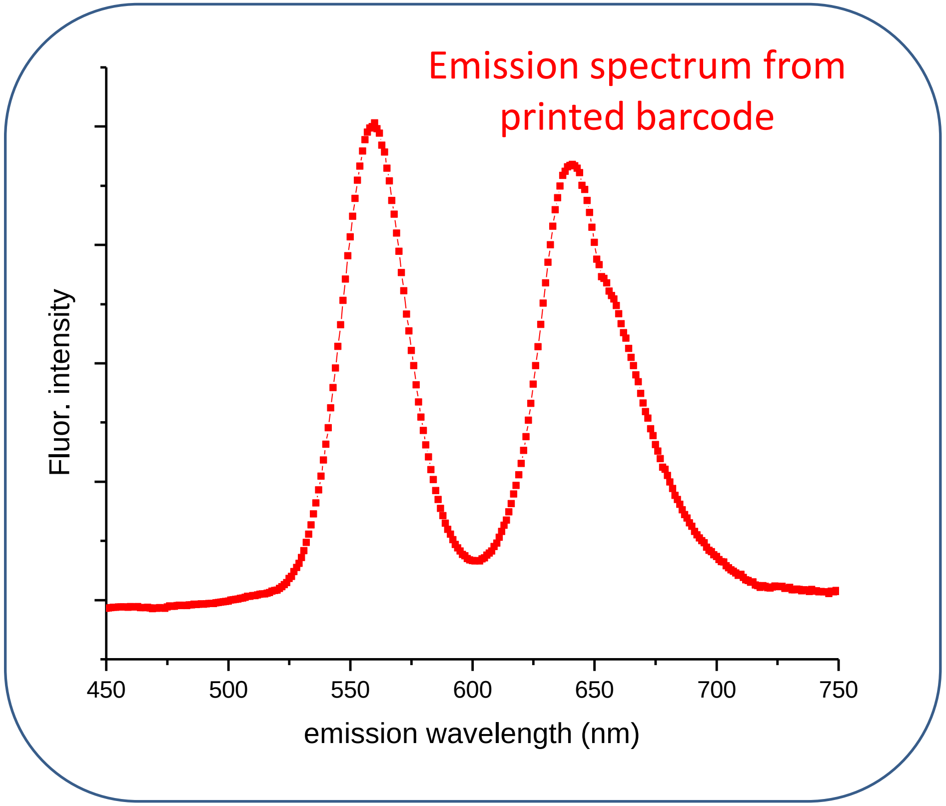
Inkjet printing and patterning of quantum dots:

- 2-D barcode printed with two QD "colors"
- Relative peak areas depend on sample position (spot sampled is larger than barcode pixels)
- Sharp, well-resolved peaks allow precise specification of emission wavelength and amplitude to generate covert "signature" (independent of positional information contained in 2-D barcode)



Barcode printed with QD-containing ink shown under UV (254 nm) illumination

- **Ink** = Water + humectant + surfactant
- **Print System** = HP 95 cartridge in DeskJet 6540 TIJ printer
- **Quantum Dots** = blue- and red-emitting CdSe:ZnS with TOPO ligand
- **Media** = Low-fluorescence office paper

Summary:

HP's current research and development programs in flexible electronics, flexible displays, chem/bio sensing and other emerging technologies are:

- Leveraging existing and new nanoimprinting, embossing, and roll-to-roll manufacturing investments.
- Driving the development of new R2R-compatible patterning and processing approaches at all length scales (e.g. SAIL).
- Enabling the development of new devices and structures (e.g. flexible circuits and high enhancement factor SERS substrates).
- Providing a new continuous and scalable manufacturing platform for emerging technologies and new businesses.

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Stan Williams (HPL)

Peidong Yang (UC Berkeley)

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This work was partly supported by DARPA


Questions?
Acc.V Spot Magn Det WD Exp
15.0 kV 2.0 50000x TLD 5.5 3
1 µm