Scalable Nanoscale Offset Printing System for Electronics, Sensors, Energy and Material Applications

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www.nano.neu.edu

Nanomanufacturing.us

www.nano.neu.edu

NSF Nanoscale Science and Engineering Center (CHN) Team and Capability

NEU: Directed assembly, nanolithography, fabrication, characterization, contamination control

Semiconductor & MEMs fab
- 7,000 ft^2 class 10 and 100 cleanrooms

UML: High volume polymer processing and assembly

Plastics processing labs
- **20,000 ft^2 +**

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A unique partnership

MSU: Molecular Modeling

UNH: Synthesis, self-assembly

Synthetic labs
- **10,000 ft^2 +**

Institution	Faculty	Post-docs	Graduate	Undergrad.	Total
NEU	17	6	31	8	62
UML	14	6	27	13	60
UNH	7	7	15	10	39
MSU	1	1	0	0	2
TOTAL	39	20	73	23	163

Strong Industrial Partnerships

Over 30 Companies

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What is the Current State of Nanomanufacturing?

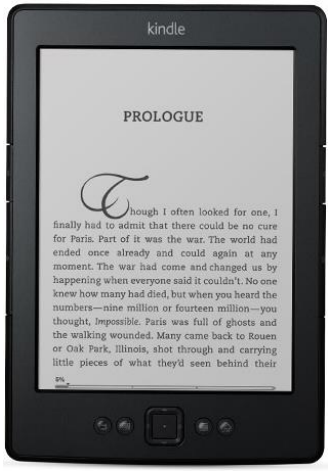
- Considerable investment and progress have been made in nanotechnology, but integration of nanoscale materials and processes into products have been considerably slow.
- However, commercial nanoscale electronics manufacturing is still mostly silicon-based, top-down and expensive, with fabrication facilities cost $7-10 billion each and requiring massive quantities of water and power.

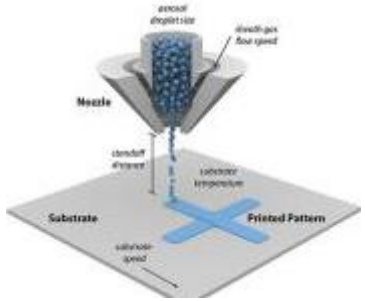
Why?

- Current nanoelectronics manufacturers do not have a technology for making nanostructures (wires, interconnects, etc.) using nanomaterials.
- **There is clearly a need for a new manufacturing technology.**

Can We Use Nanomaterials to Make Electronics?

- Printing offers an excellent approach to making structures and devices using nanomaterials.
- Current electronics and 3D printing using inkjet technology, used for printing low-end electronics, flexible displays, RFIDs, etc. are very slow (not scalable) and provide only micro-scale resolution.
- Screen printing is also used for electronics but can only print microscale or larger patterns.
- **However, even with these scale limitations, the cost of a currently printed sensor is 1/10th to 1/100th the cost of current silicon-based**





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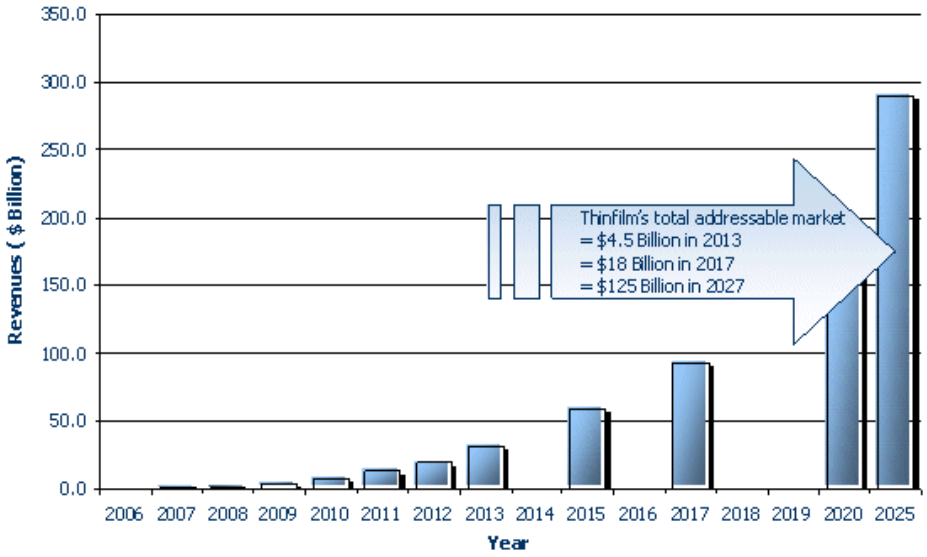
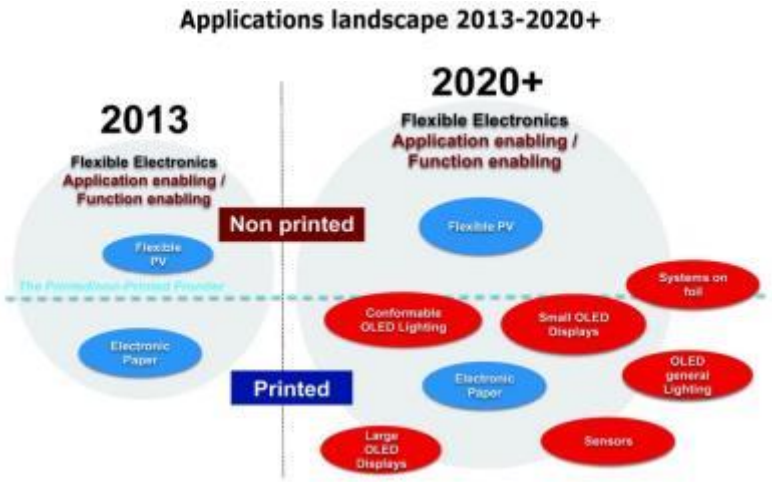
How Large is the Printed Electronics Market?

Printed Electronics - Market forecasts to 2025 - a $250+ billion market



http://www.frost.com/prod/servlet/market-insight-print.pag?docid=108885683



Source: IDTechEx Organic & Printed Electronics Forecasts, Players & Opportunities 2007-2027

Can We Print Nanoscale Electronics?

- For printed electronics and devices to compete with current silicon based nanoscale electronics, it has to print nanoscale features and be:
  - orders of magnitudes faster than inkjet based printers and
  - cost is a small fraction of today's cost of manufacturing Si electronics

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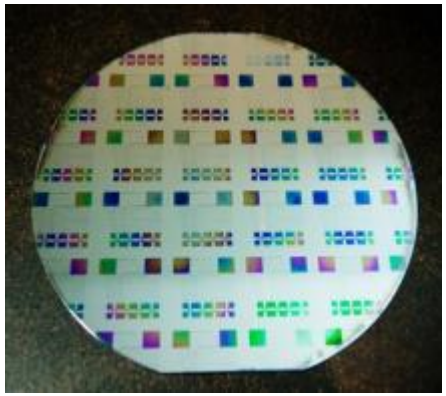
Introducing Nanoscale Offset Printing

- **Leveraging the directed assembly and transfer processes developed at the CHN, Nanoscale Offset Printing has been developed. The system is similar to conventional offset printing.**

- **The ink is made of nanoparticles, nanotubes, polymers or other nanoelements that are attracted to the printing template using directed assembly.**



Nanoscale Offset Printing Template

Nanoscale Offset Printing System

This novel approach offers 1000 times faster printing with a 1000 times higher resolution.

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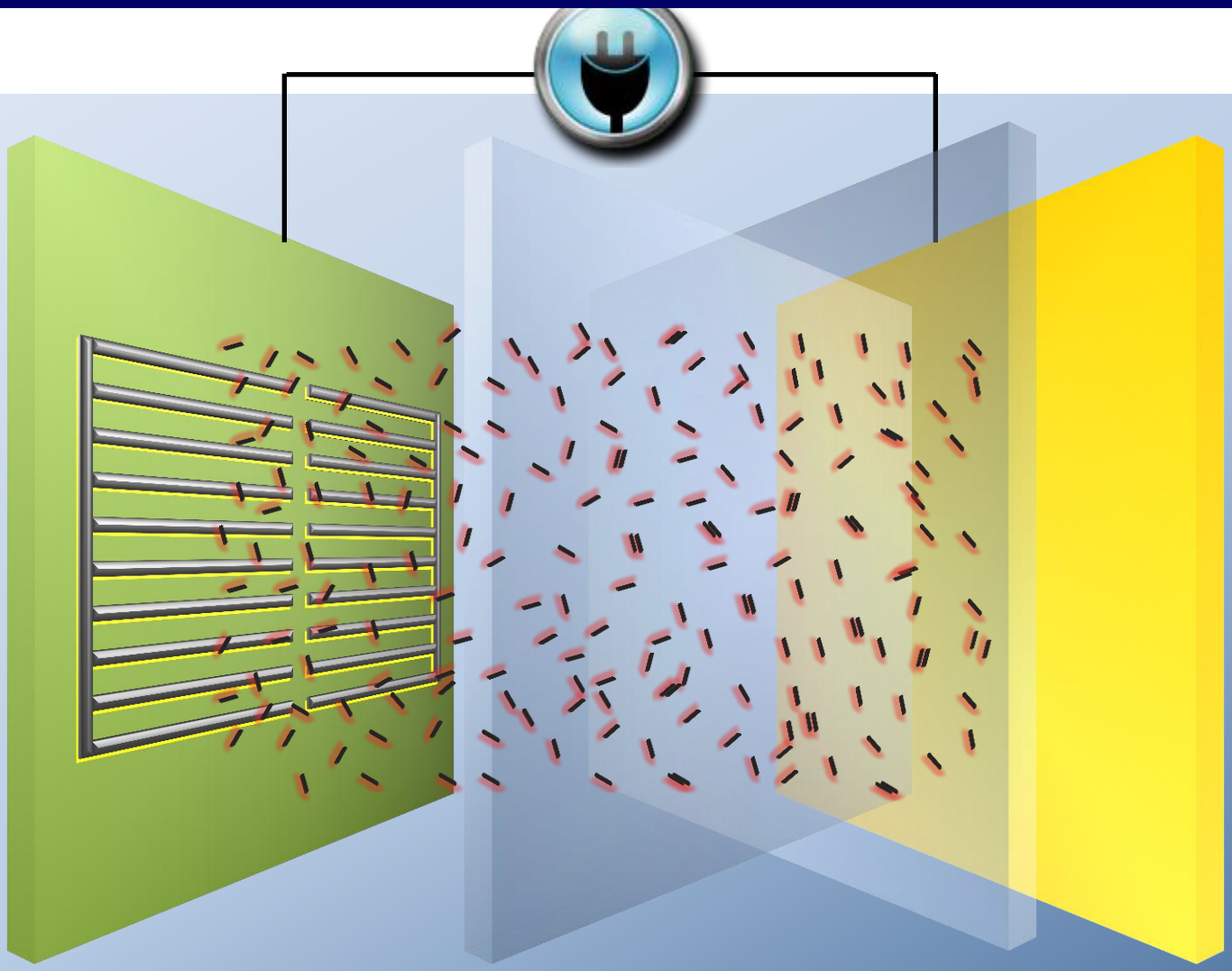
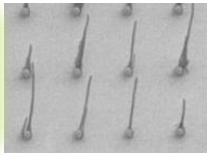
How Does it Work?



What Could We Manufacture with Multiscale Offset Printing?

CNTs for Energy Harvesting

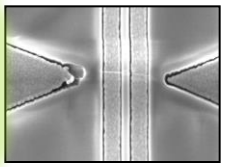
SWNT & NP Interconnects



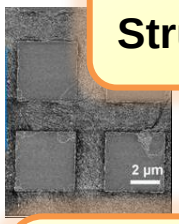
Assembly of CNTs and NPs for Batteries

Flexible Electronics

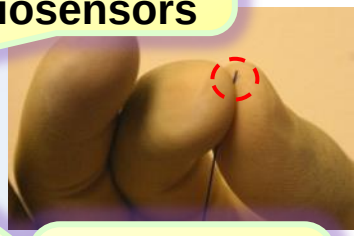
SWNT NEMS & MoS2 devices



2-D Assembly of Structural Apps.



Multi-biomarker Biosensors



Energy

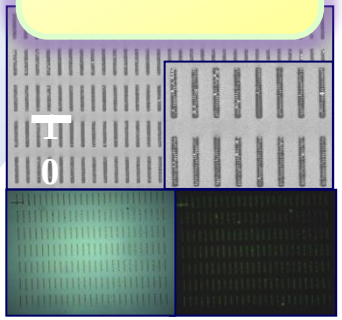
Electronics

Materials

Bio/Med

Antennas, EMI Shielding, Radar, Metamaterials

Drug Delivery



Directed Assembly and Transfer

Nanoscale Science

Center for High-rate Nanomanufacturing

Nanomaterials-based Manufacturing

Nanoscale Offset Printing

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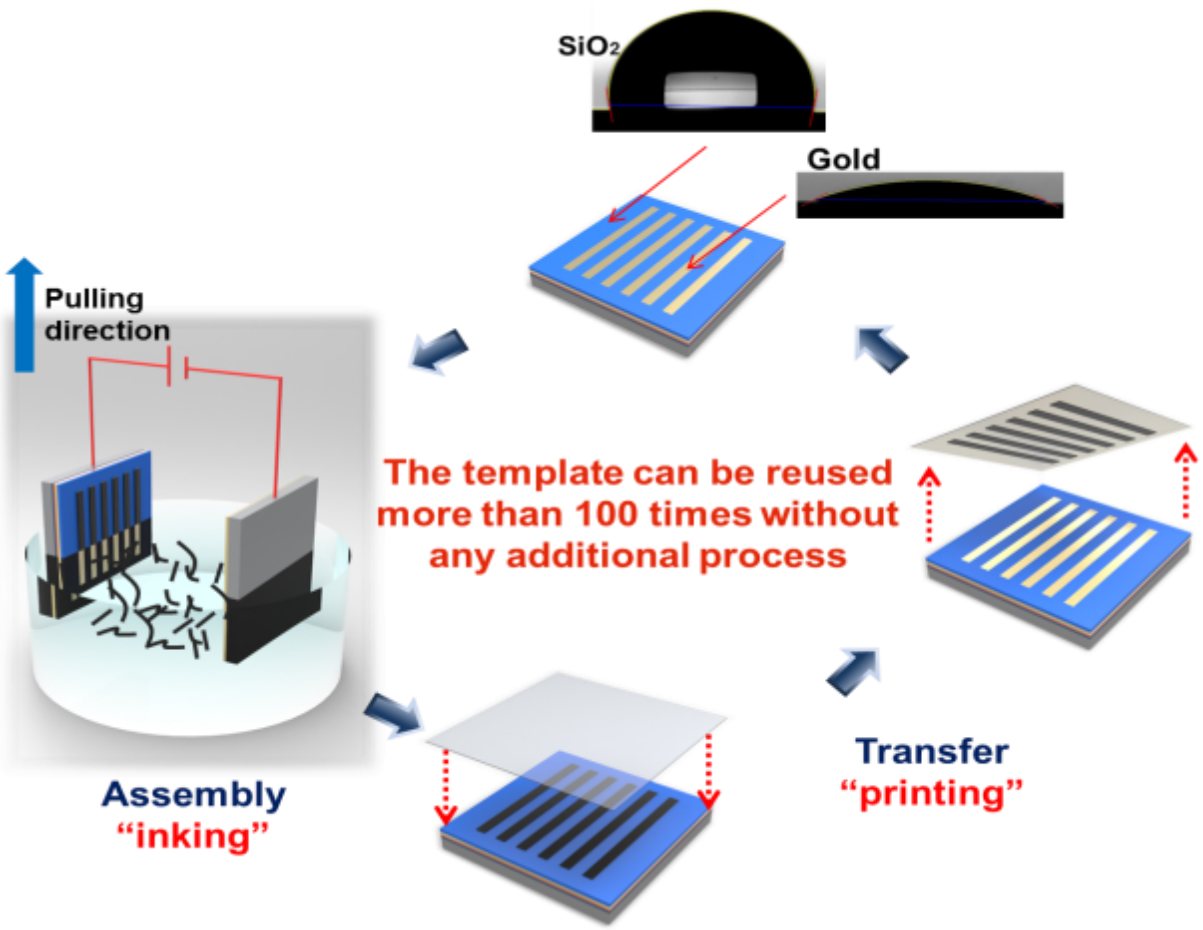
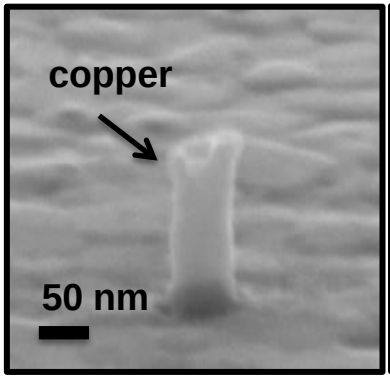
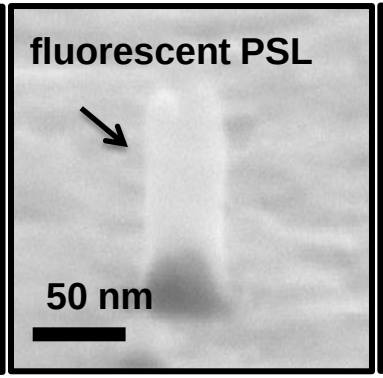
Beyond 3-D & Electronic Printing:
Nanoscale Offset Printing Advantages

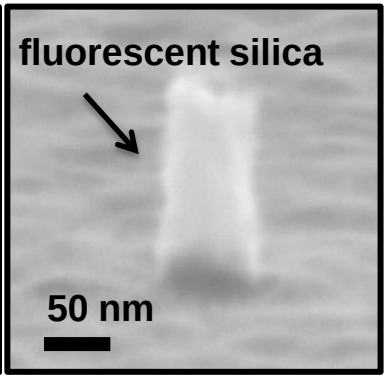


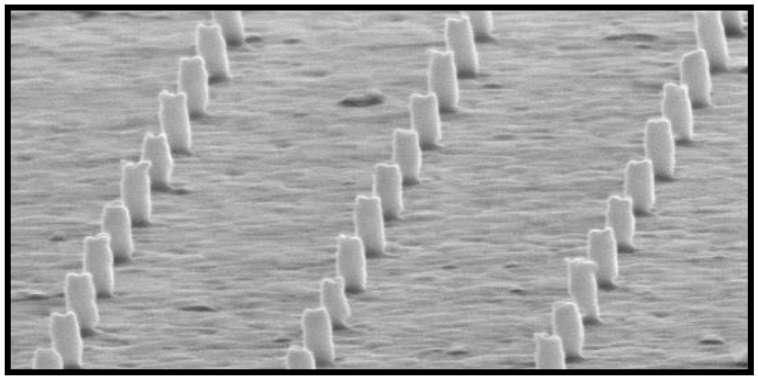
- Additive and parallel
- High throughput
- Prints down to 20nm
- Room temp and pressure
- Prints on flexible or hard substrates
- Multi-scale; nano to macro
- Material independent
- Very low energy consumption
- Very low capital investment

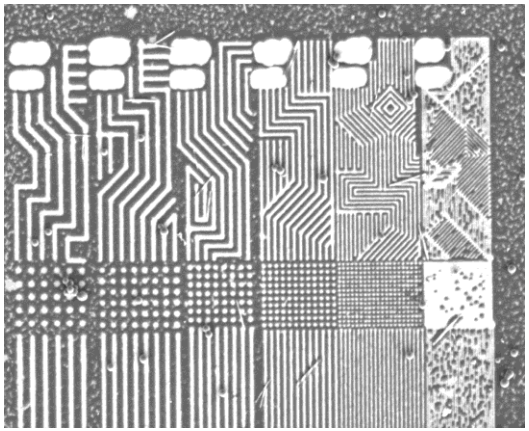
Directed Assembly of Nanoparticles, Carbon Nanotubes and Polymers



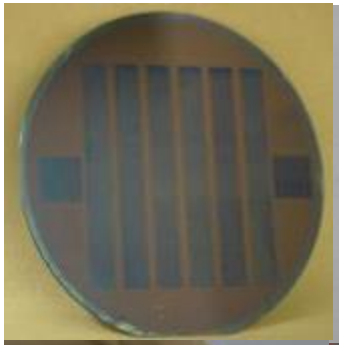


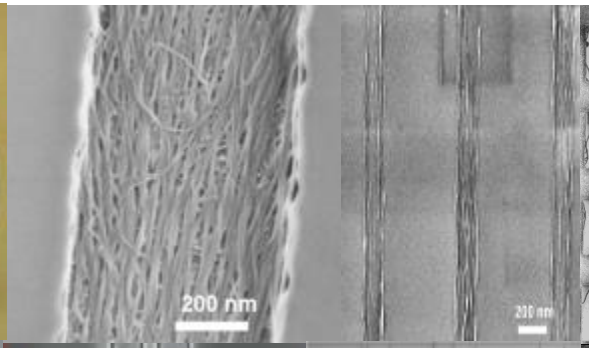


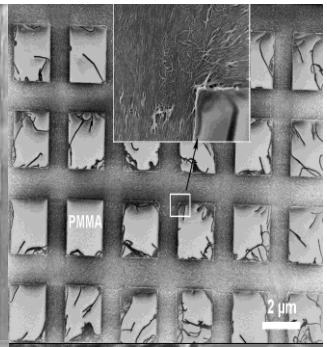


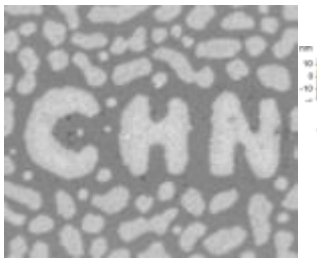


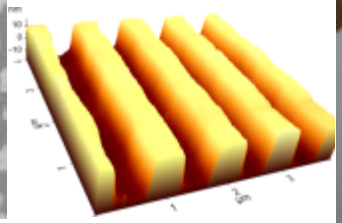
Nanoparticle Rapid, multi-scale Assembly (*ACS Nano 2014*)

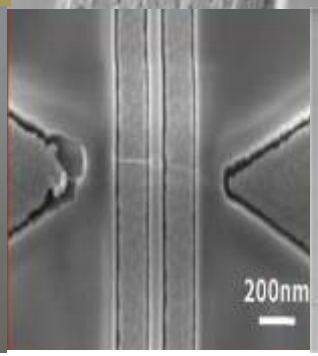


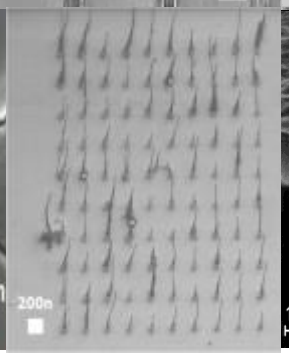


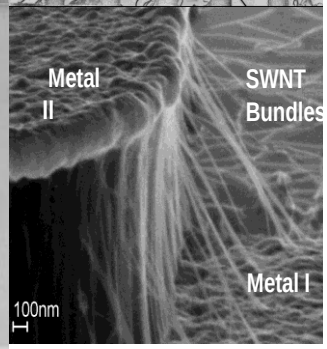












Multiple polymer systems, Rapid Assembly, multi-scales

CNTs Rapid, multi-scale Assembly

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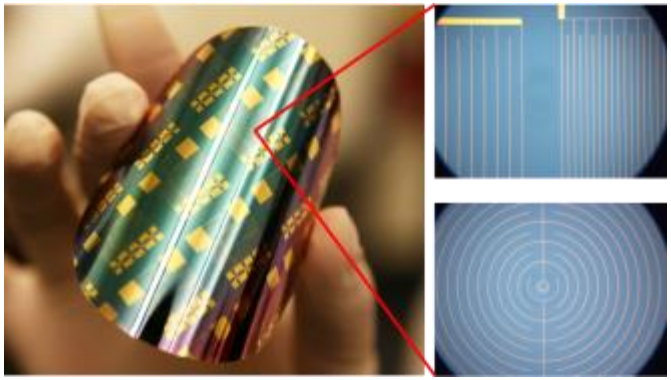
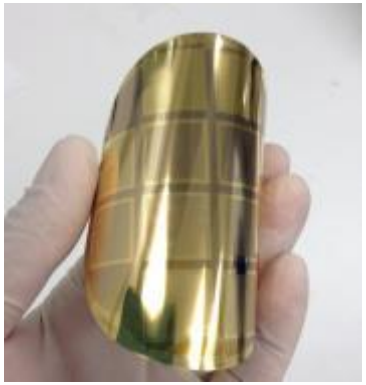
Damascene Templates for Nanoscale Offset Printing

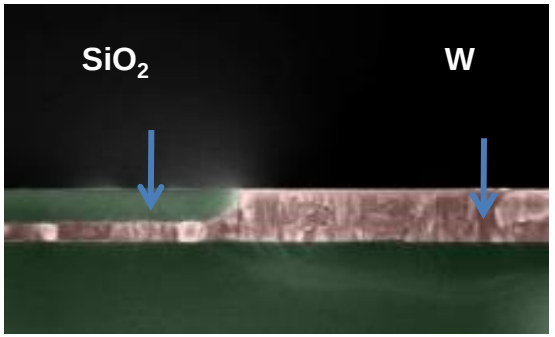


PEN

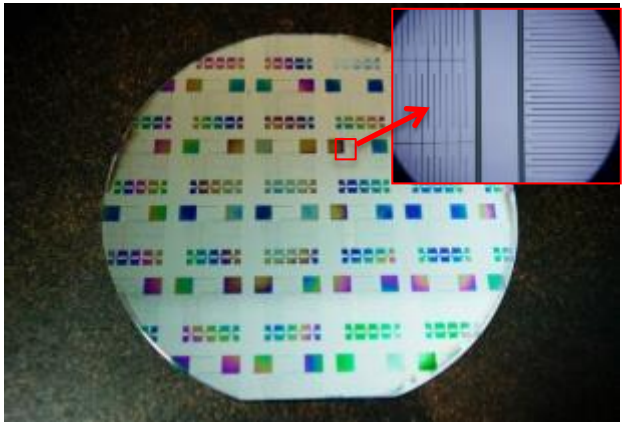
Polymer-based Templates



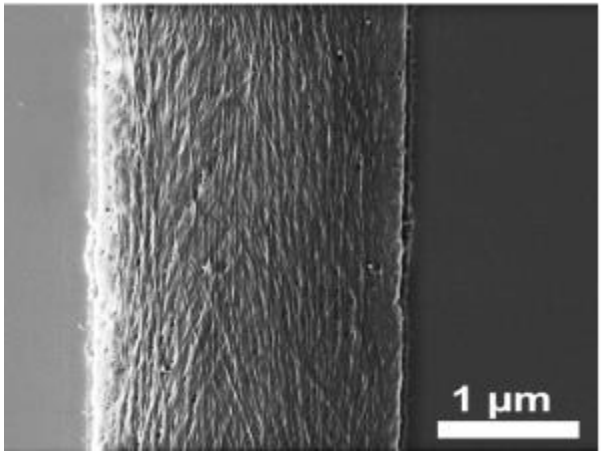
PI



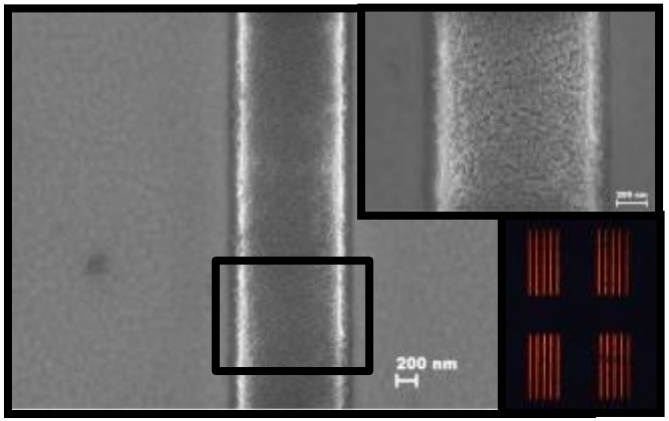
Silicon-based Hard Templates

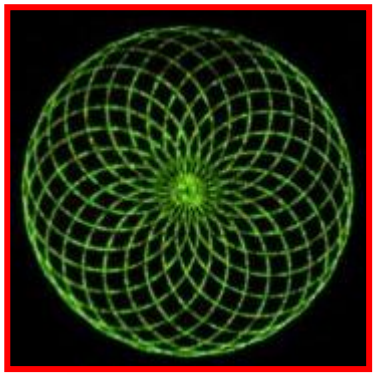


Assembled SWNT

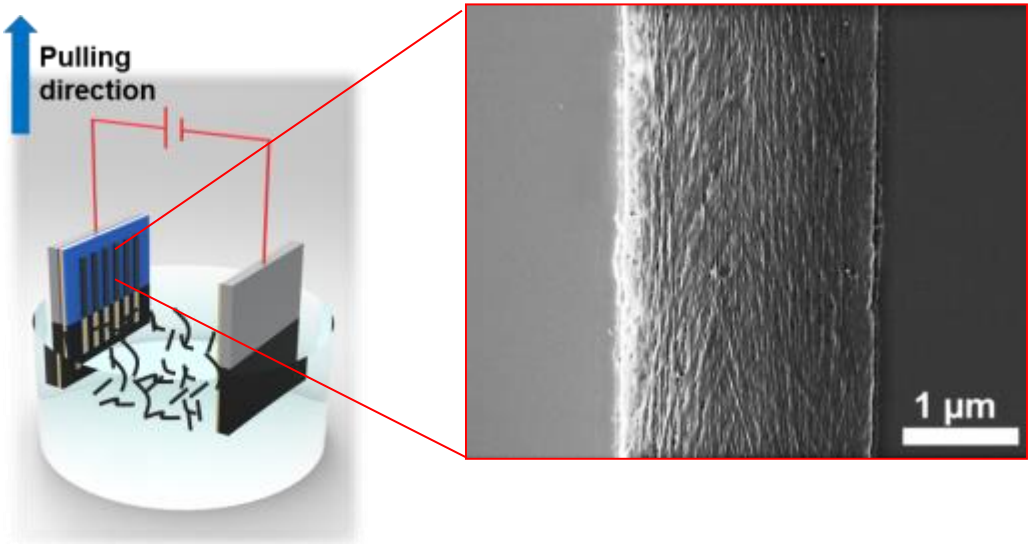


Assembled Particles

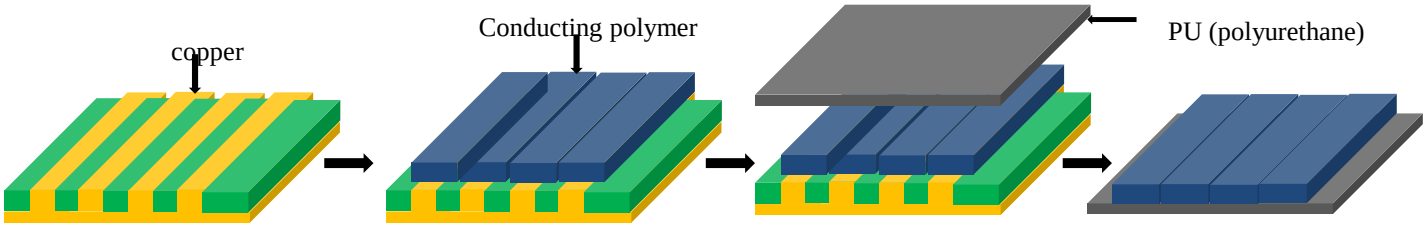


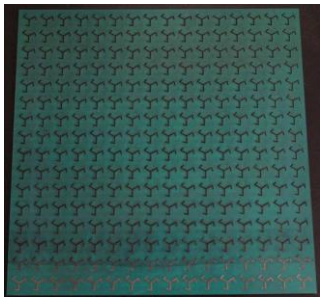


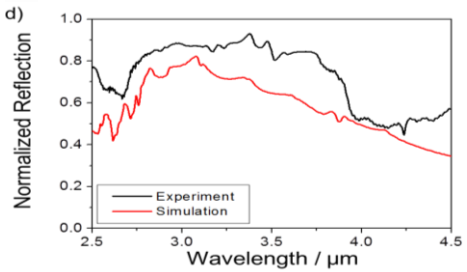
Alignment and Scalability



- ✓ Alignment of Single Walled Carbon Nanotubes can be controlled during printing process







Printing of mm Scale Chiral Metamaterial

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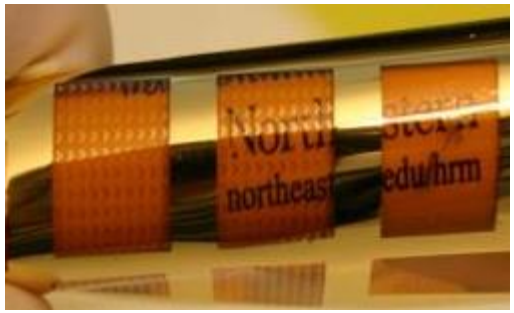
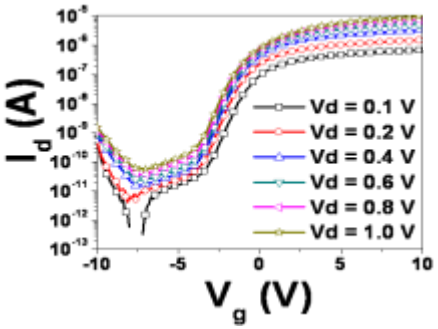
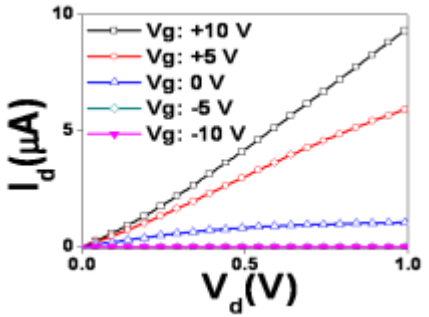
Applications

Nanomaterials Based Electronics

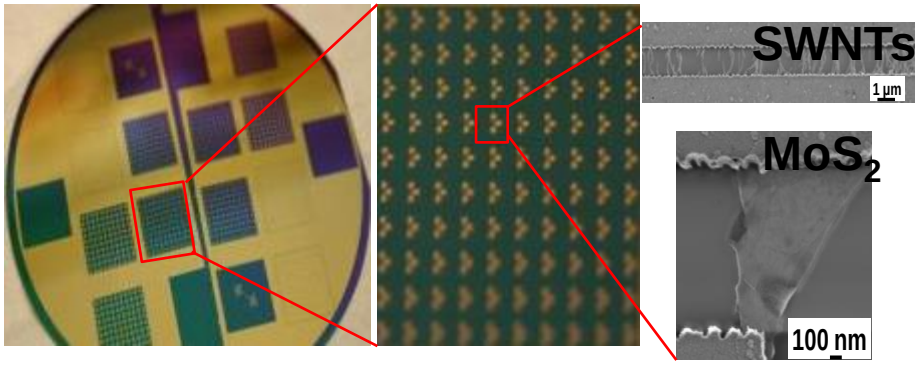
- **Flexible transparent n-type MoS_2 transistors**

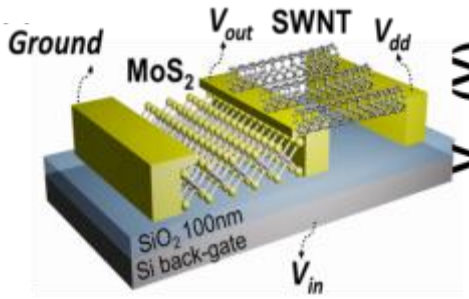


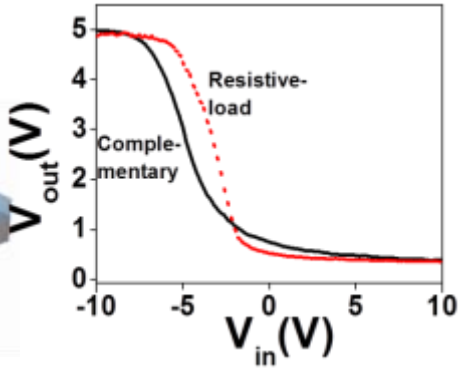




- **Heterogeneous SWNTs and MoS_2 complimentary invertors through assembly**



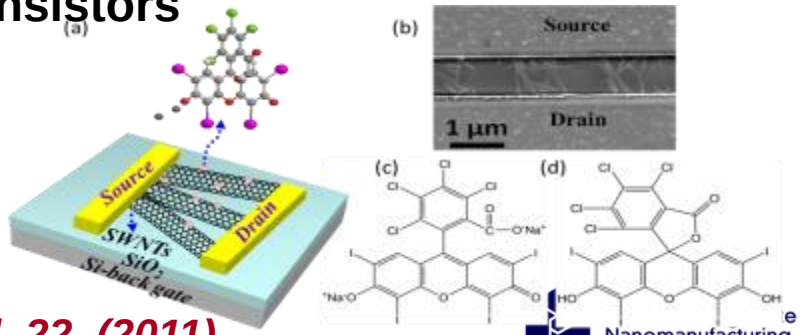




***Nanotechnology**, Vol. 23, (2012).*

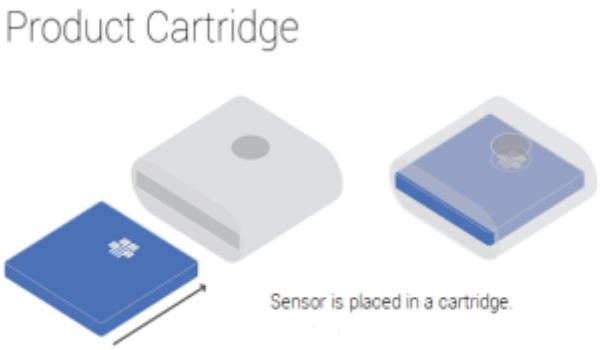
- **Rose Bengal Molecular Doping of CNT Transistors**

Appl. Phys. Lett. 97, 1 2010.



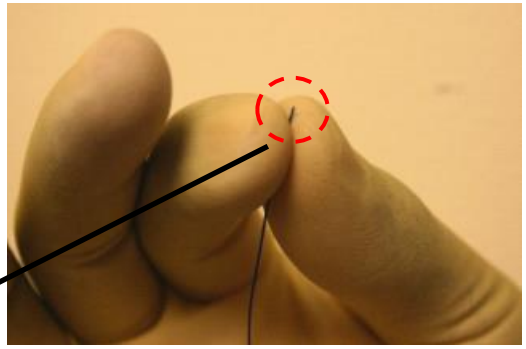
Nanotechnology, Vol. 22, (2011)

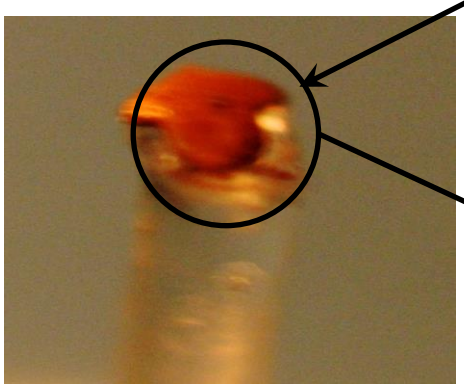
Cancer and Cardiac Disease Biosensors



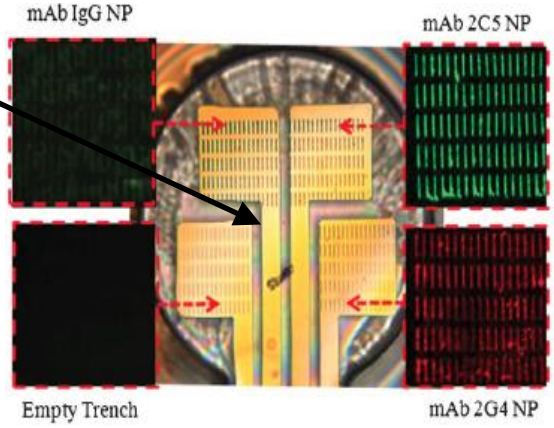
biolom

- ✓ **Multiple-biomarker detection**
- ✓ **High sensitivity**
- ✓ **Low cost**
- ✓ **Low sample volume**
- ✓ **In-vitro and In-vivo testing**





***in-vivo* biosensor (0.1 mm x 0.1 mm)**



Tested for detected with biomarkers for prostate (PSA), colorectal (CEA), ovarian (CA125) and cardiac diseases.

Detection limit: 15 pg/ml

Current technology detection limit is 3000 pg/ml

Publications: Langmuir Journal, 27, 2011 and Lab on a Chip Journal, 2012

US Patents: Multiple biomarker biosensor: (US 2011/0117582 A1), 2 more filed patents

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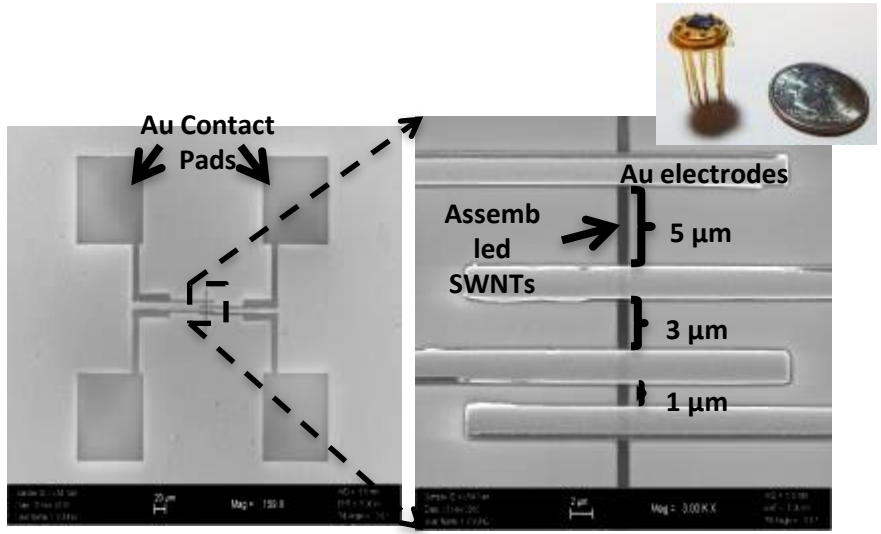
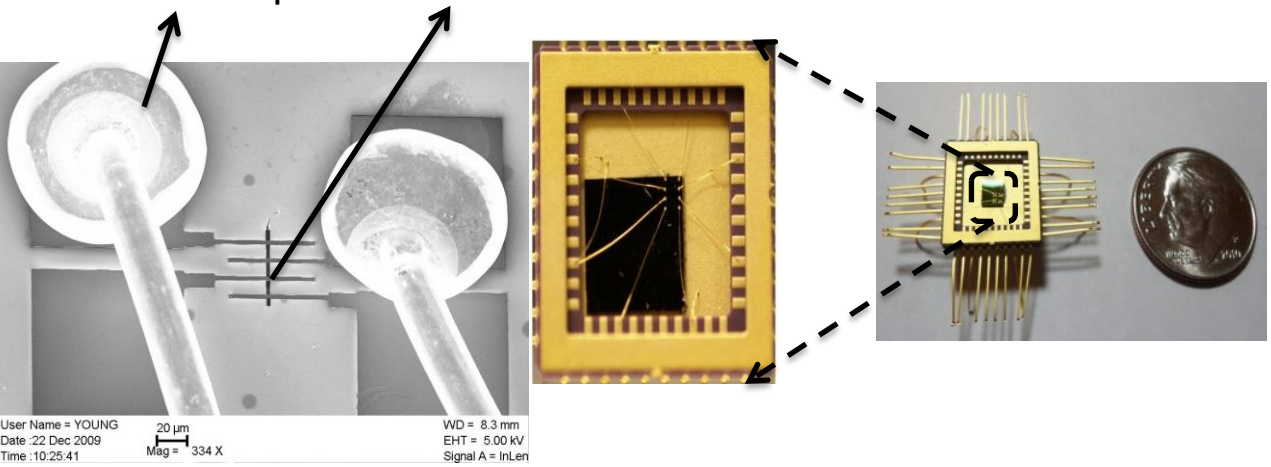
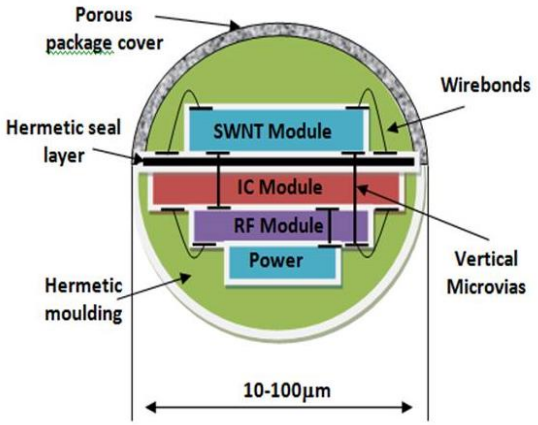
CNT Chemical Sensors

Functionalized SWNT Chemical sensor



- Developed, fabricated and tested a micro-scale robust semiconducting SWNT based sensor for the detection of H_2S, simple alkanes, thiol, etc.
- Working in harsh environment (200^{o}C; 2500Psi).
- Specific in various environments (N_2, Air, Water vapor, Water, alkanes, etc.)
- Resistance based operation
- Simple inexpensive 2-terminal device
  High sensitivity ~ppm.

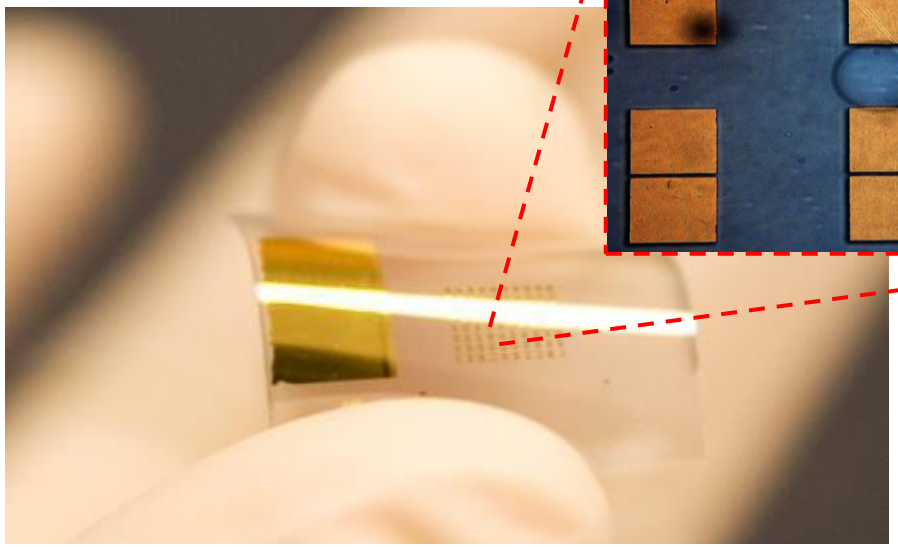


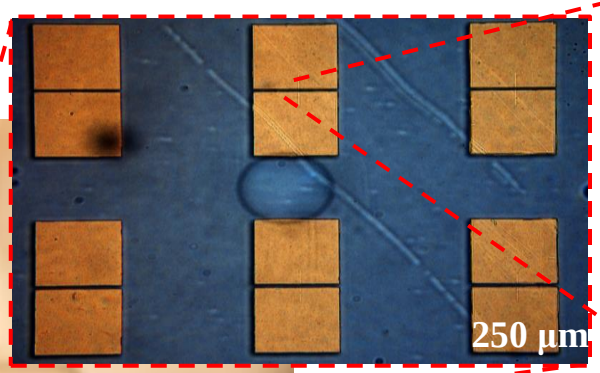


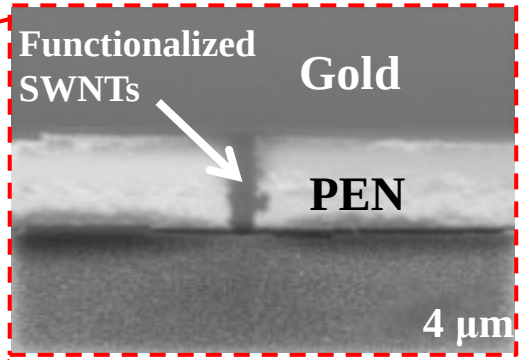
Analyst, 138, December 2013, Issue 23.

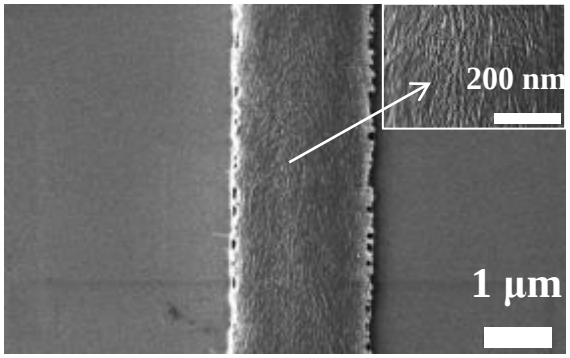
Center for High-rate Nanomanufacturing

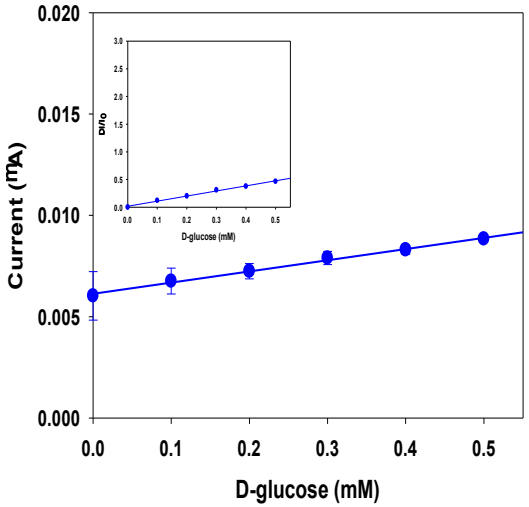
Flexible CNT Bio Sensors for Glucose, Urea and Lactate in Sweat or Tears

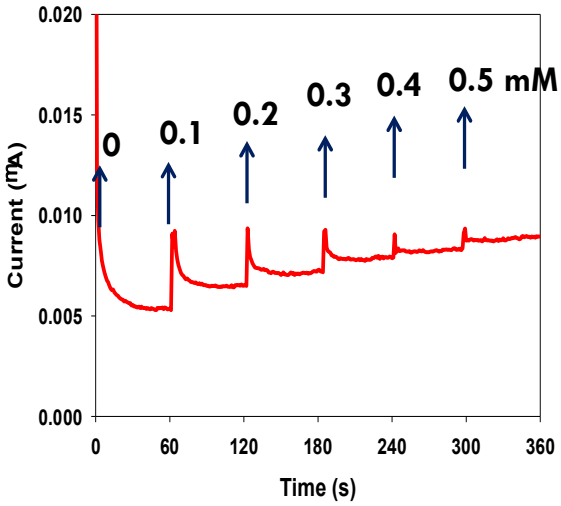












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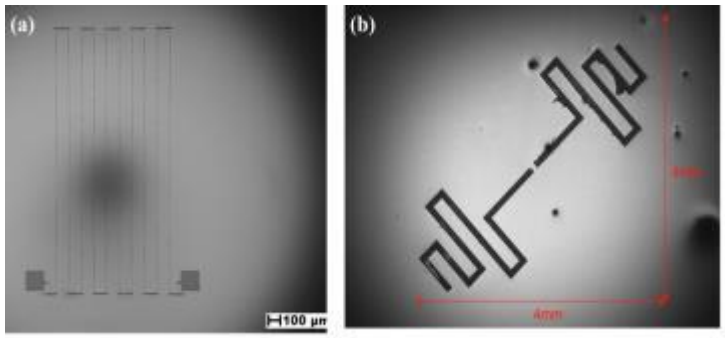
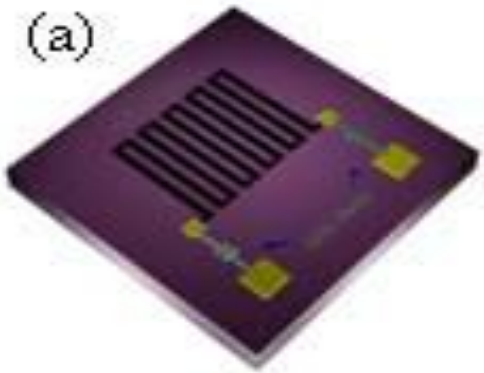
Energy Harvesting: CNT Antenna

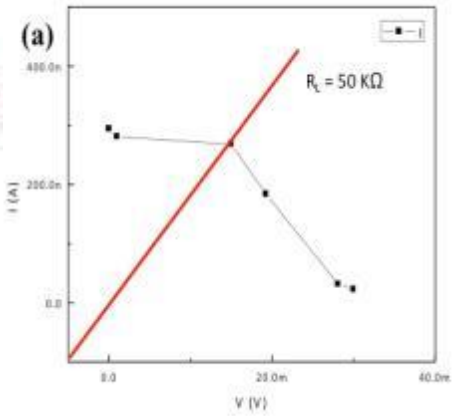
SWNT based infrared energy harvesting device

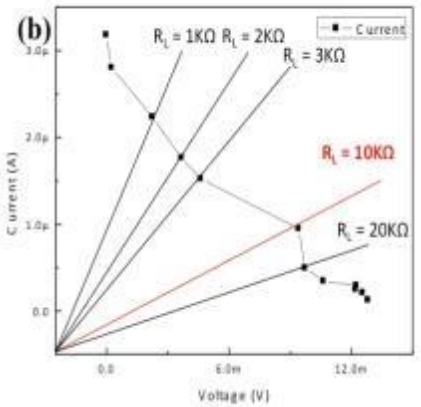


- Developed rectifying SWNT antennas having the potential for absorption of far and mid-Infra red incident light.
- Developed both Zig-Zag and linear designs.
- Rectifying circuit consists of commercially available MIM diodes operating in the W band.
- Harvesting energy wherever there is temperature difference larger than 5 degrees

CNT Infrared Energy Harvester







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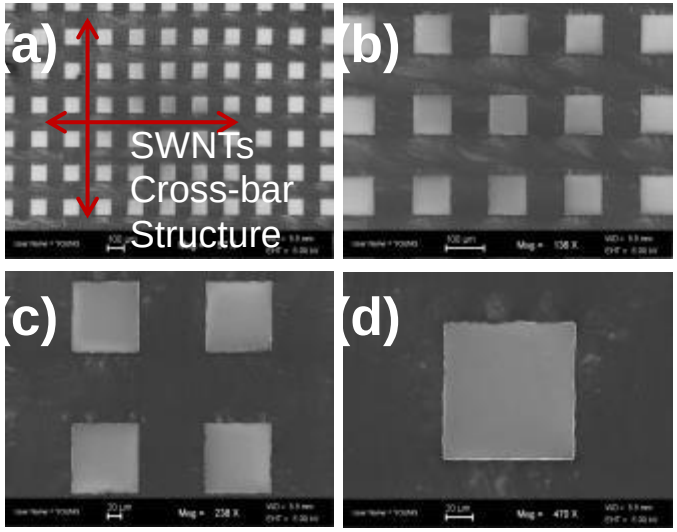
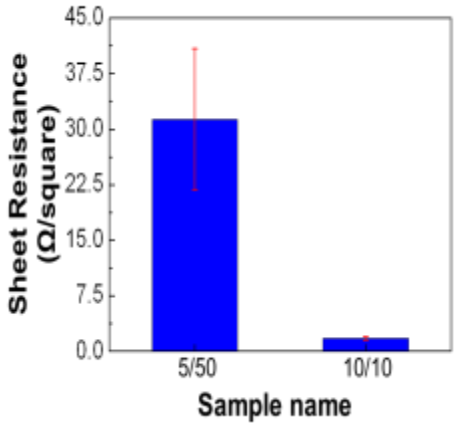
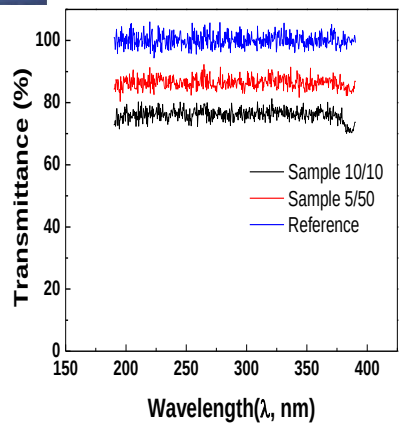
Multifunctional Structures and Surfaces

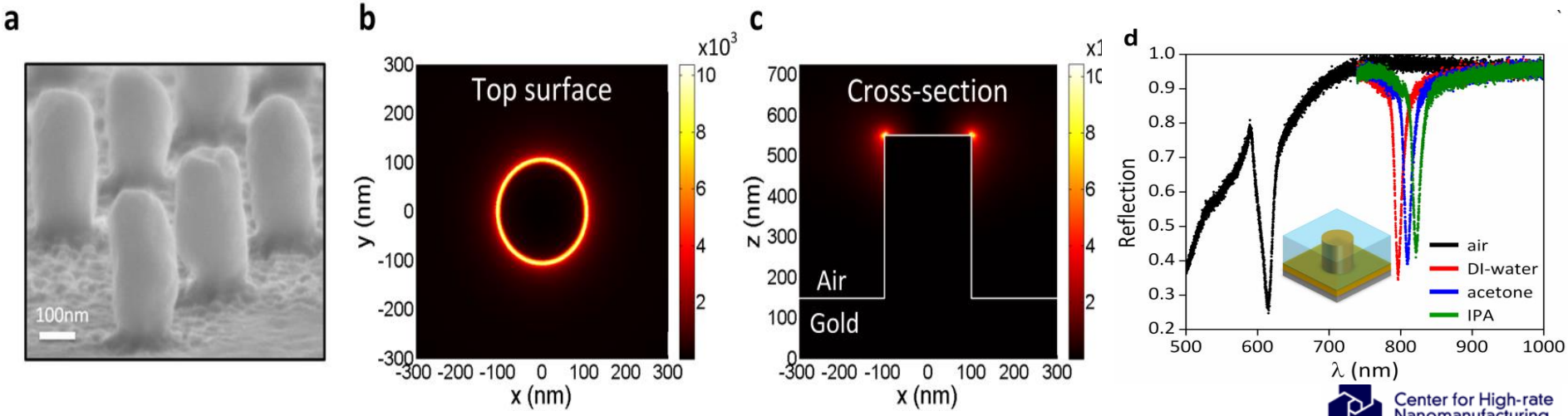
- **Ordered CNT materials for EMI shielding ➔ Excellent conductivity and transparency**







- **Active camouflage ➔ Designed structures for very good absorption in the visible (red) and near infrared regime**



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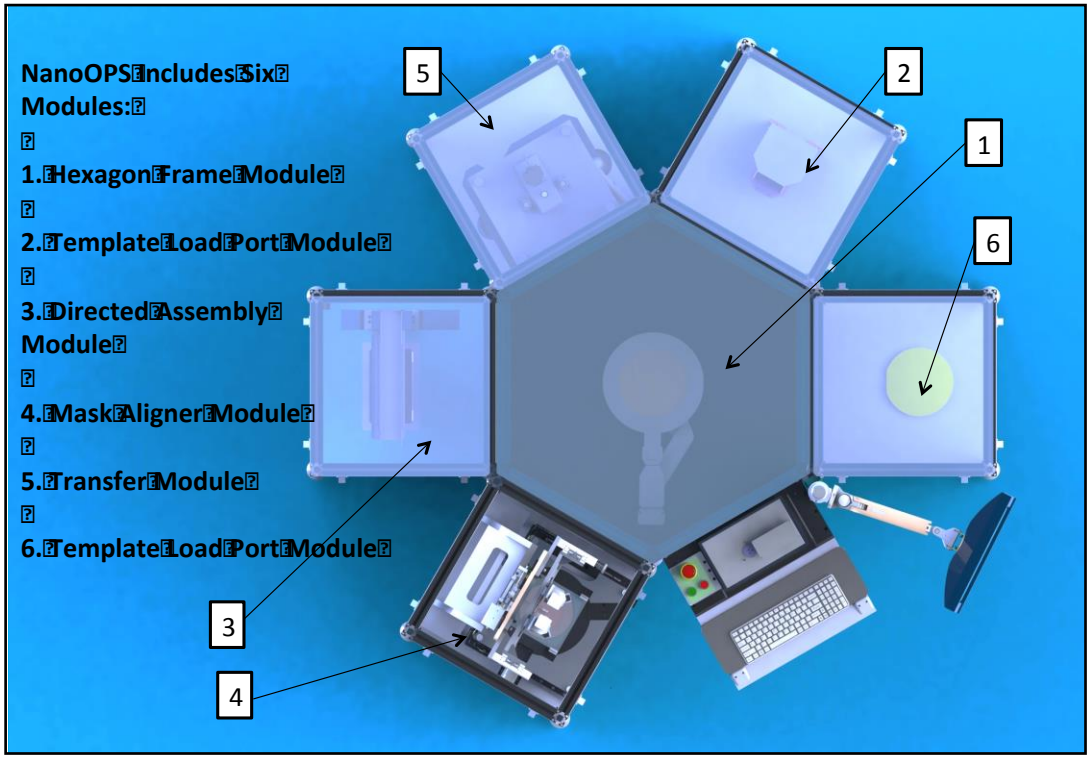
Where do we go from here?

Automated Nanoscale Offset Printing System (NanoOPS) Prototype was Demonstrated on 9/17/2014 to 58 companies

- **NanoOPS is capable of printing using templates with micro and nanoscale patterns (down to 25nm).**
- **This year's system will have registration and alignment.**



- **A nanofactory could be built for under $50 million, a small fraction of today's cost**
- **Nanotechnology accessible to millions of innovators and entrepreneurs**

Center for High-rate Nanomanufacturing

Automated Nanoscale Offset Printing System (NanoOPS) Prototype was Demonstrated on 9/17/2014 to 58 companies

The Boston Globe

Business

September 18, 2014

Northeastern University's nano printer molds ultra-thin layers into objects.

NU envisions vast potential in tiny 3-D printing

http://www.bostonglobe.com/business/2014/09/17/northeastern-printer-next-big-thing-using-tiny-particles/1loul6zn3D5LaWqU6XkaNN/story.html

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Questions?

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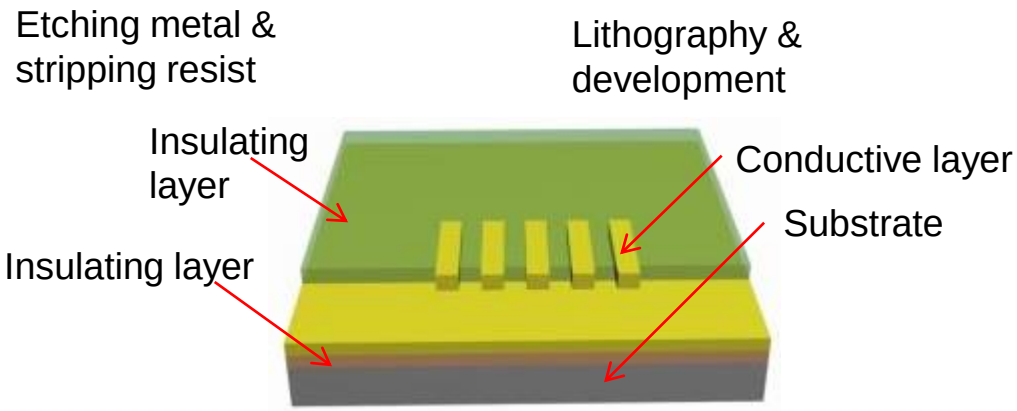
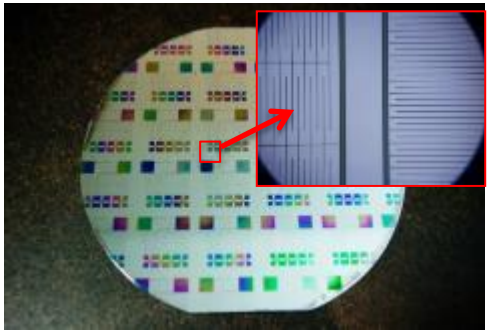
What Could We manufacture with Multiscale Offset Printing?

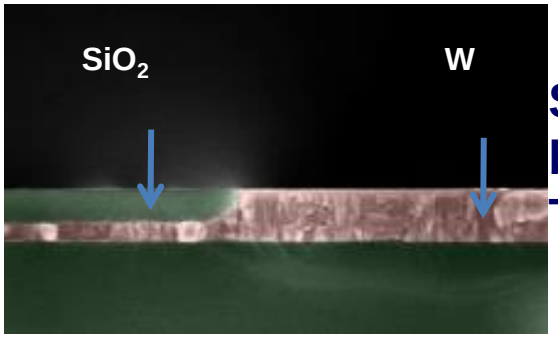
- Nanosensors and devices for early detection of cancer and cardiac diseases
- A Band-Aid that could read your glucose level using sweat and text it to your phone
- Eliminate certain injectable drugs by replacing them with printed oral medications
- High performance flexible electronics at a fraction of the cost
- Wallpaper that doubles as a flexible, high-resolution television screen
- Lightweight, durable materials to replace metal components in aircraft
- Thin, flexible, lightweight and fast-charging batteries
- Flexible energy-harvesting fabrics that could power laptops or phones anywhere

Damascene Templates for Nanoscale Offset Printing



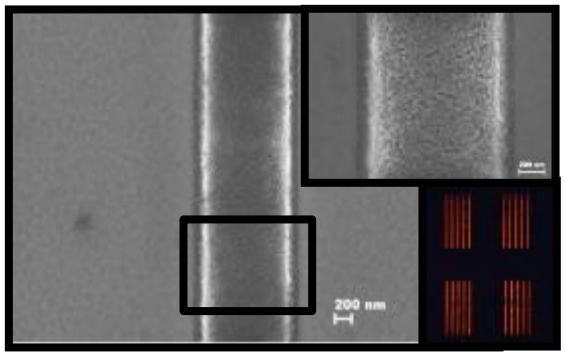
Cross section of damascene template

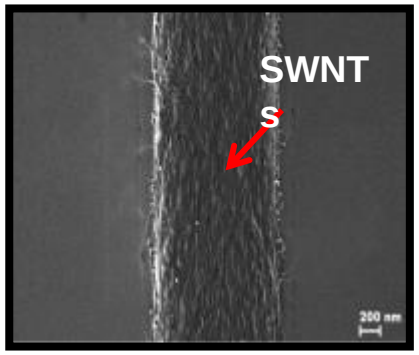


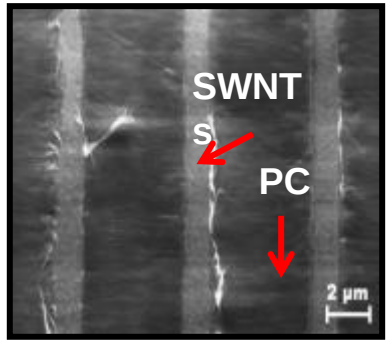


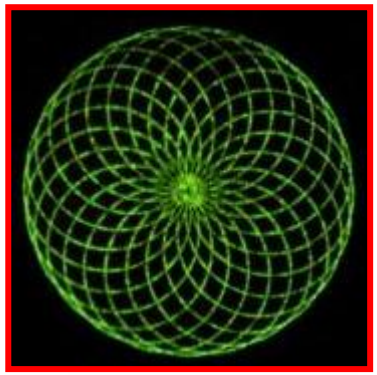
Silicon-based Hard Templates

Flexible Templates for Roll-to-Roll Manufacturing









Exposure Assessment with NIOSH

- Established MOU between CHN and NIOSH in September 2010
- Led to CHN collaborations with NIOSH team at several academic and industry facilitates
- Published NIOSH/CHN Safe Practices document for ENMs
  - Methodology for risk management and exposure assessment
  - Techniques and guidance for exposure control including local exhaust ventilation and other engineering and administrative controls