Scalable Nano and Microscale Printing of Sensors and Electronics

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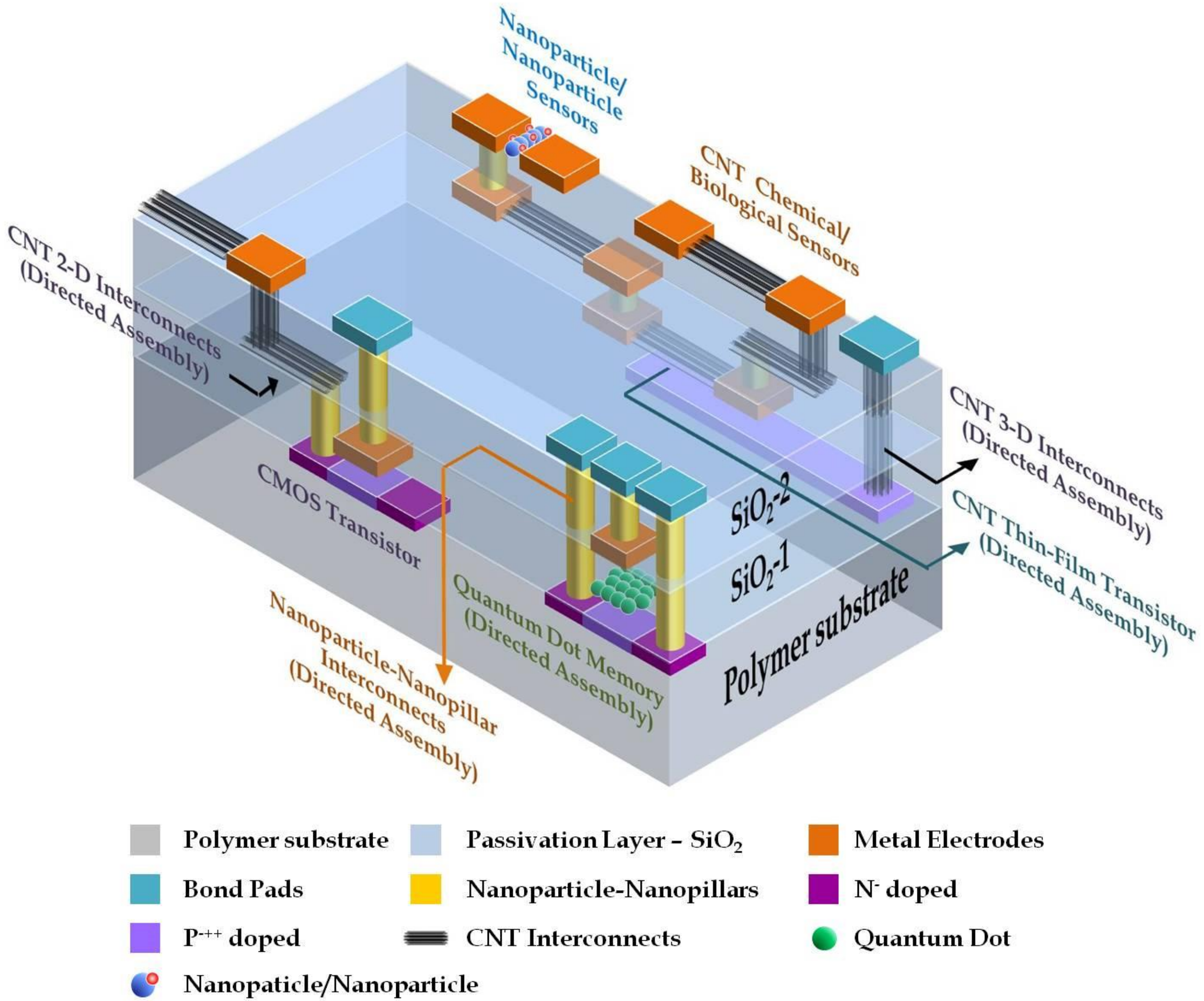
What if designers had complete freedom to use any material or substrate in their devices?



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Introduction

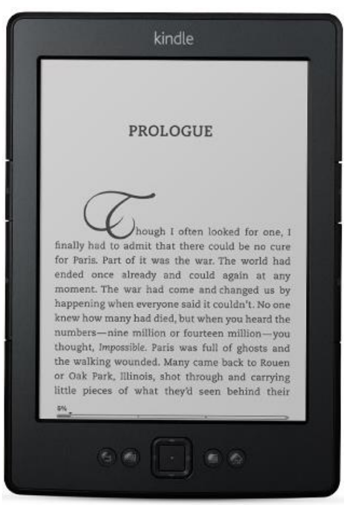
Welcome to the future of manufacturing.

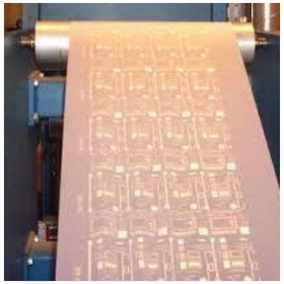
Directed Assembly-based Printing

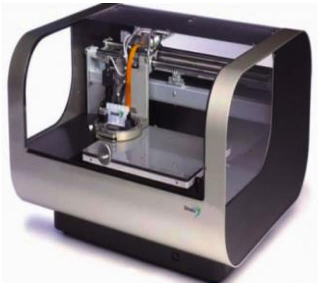
- Build everything bottom up, one molecule or particle at a time using self directed assembly just like Nature.
- Build Things much faster than Nature or present conventional fabrication.
- Build devices and applications using ambient temperature and pressure.
- Build applications on any surface rigid or flexible.
- Build devices at a fraction of their current cost (100 times less)

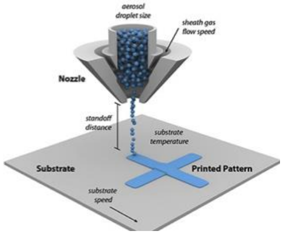
State of the Art - Printing Technologies

- Current electronics and 3D printing using inkjet technology, used for printing low-end electronics, flexible displays, RFIDs, etc. are very slow (not scalable) and **can only print down to 20 microns (20,000 nanometers)**.
- 20 microns was the silicon electronics line width in 1975.
- Lack of CMOS style interconnected multi layers.
- Limitations in the types of materials to be printed.
- Even with these scale limitations, the cost of a currently printed sensor is 1/10th to 1/100th the cost of current silicon-based sensors.









- Printed electronics is $40 billion/year
- Printed sensors are less than $300 million.

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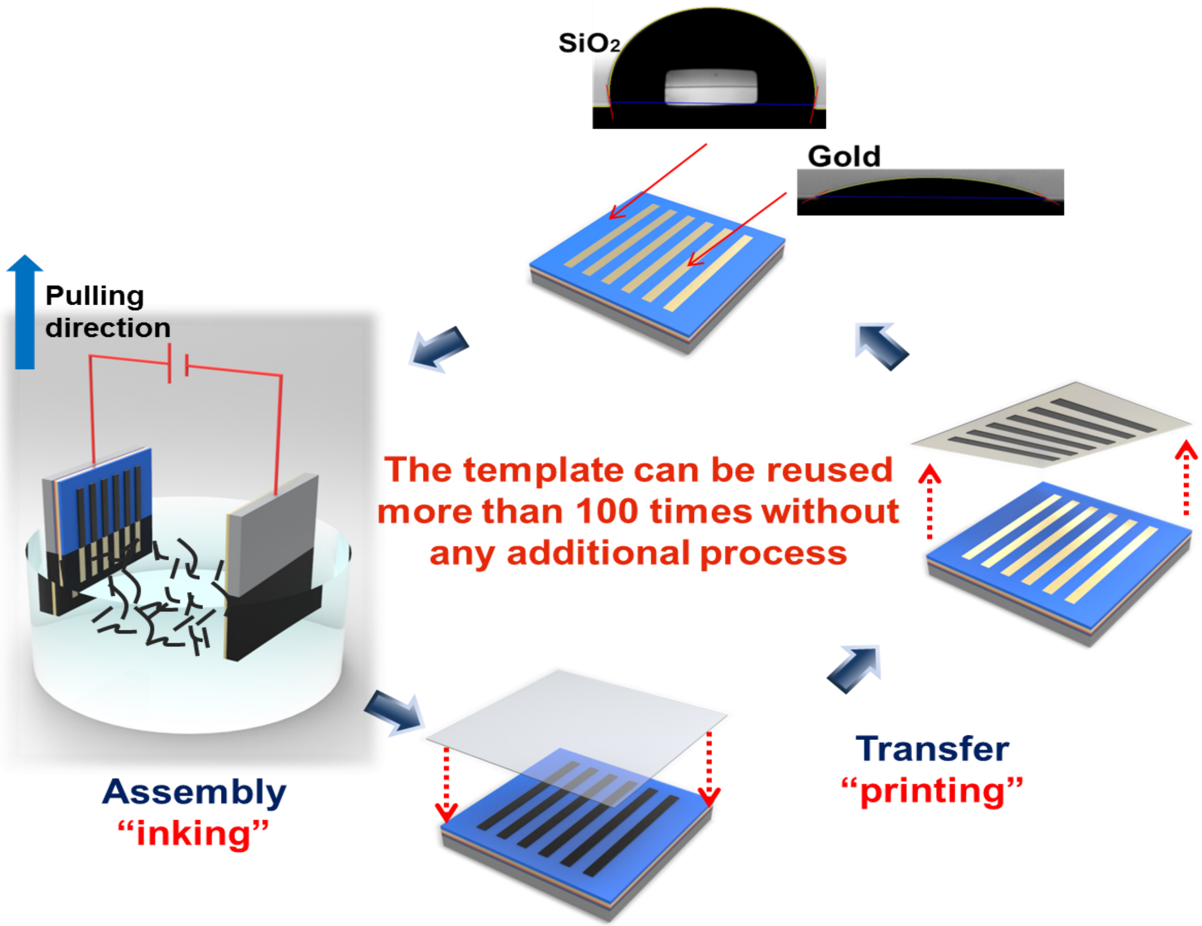
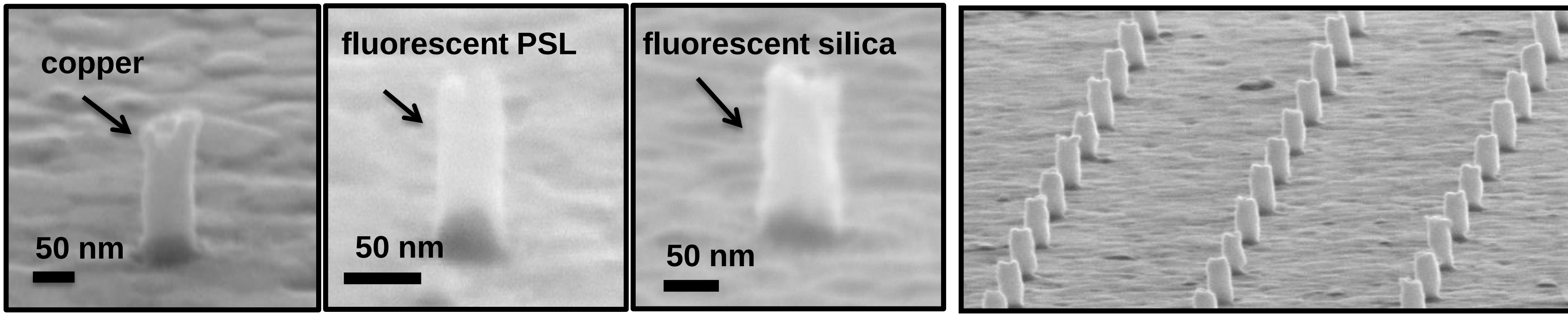
Beyond 3-D & Electronic Printing: Nanoscale Offset Printing Advantages



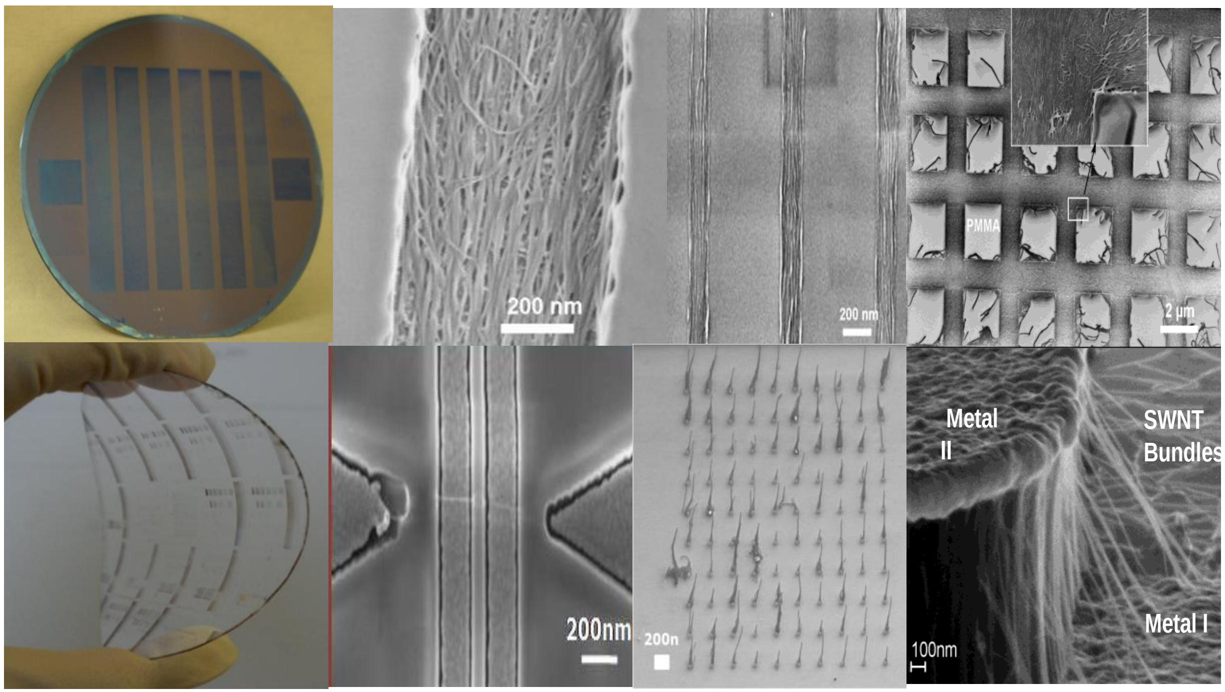
- Additive and parallel
- High throughput
- Prints down to 20nm
- Room temperature and pressure
- Prints on flexible or hard substrates
- Multi-scale; nano to macro
- Material independent
- Very low energy consumption
- Very low capital investment

Advanced Materials, 2015, 27, pp. 1759–1766.

Directed Assembly of Nanoparticles, Carbon Nanotubes and Polymers



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



CNTs Rapid, multi-scale Assembly (*Adv. Mat. 2015*)

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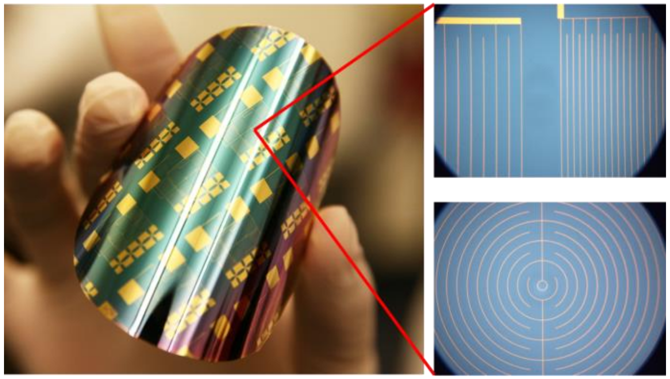
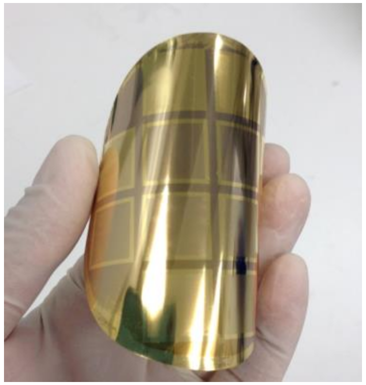
Damascene Templates for Nanoscale Offset Printing

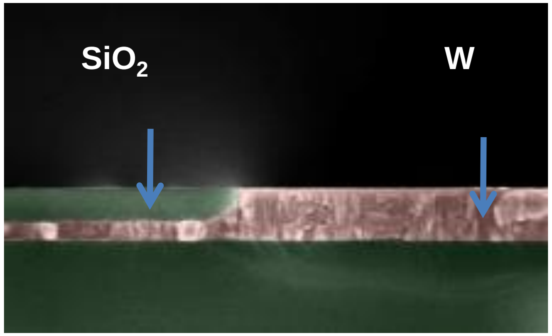




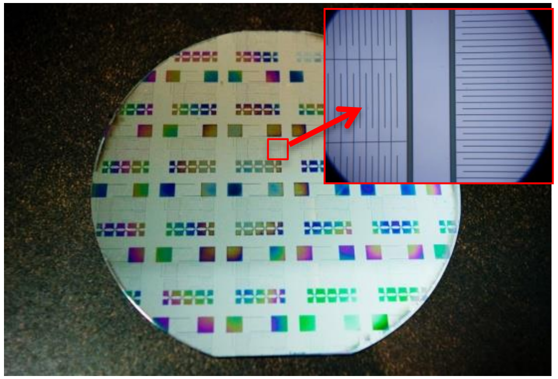
PEN

Polymer-based Templates

PI

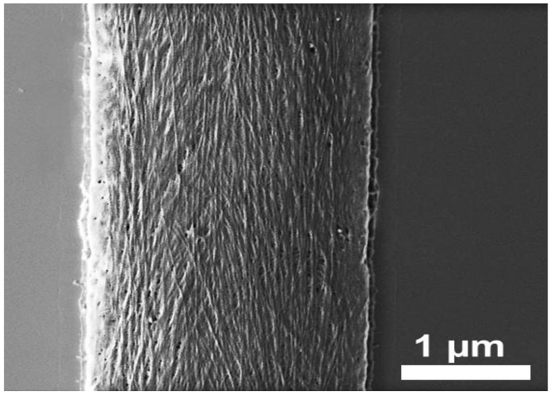


Silicon-based Hard Templates

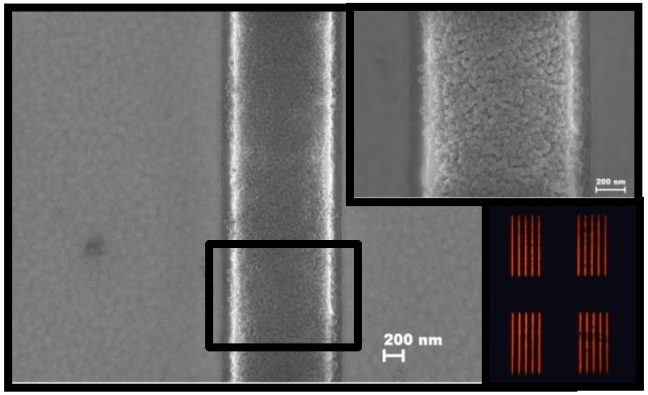


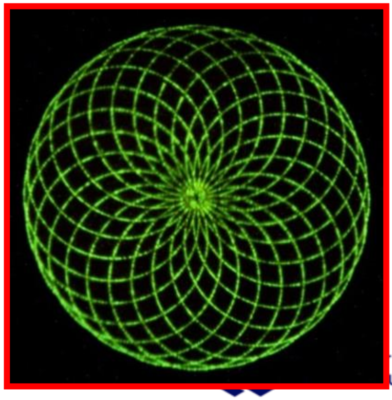
Advanced Materials, 2015, 27, pp. 1759–1766.

Assembled SWNT



Assembled Particles





Directed Assembly-based Printing of Interconnects

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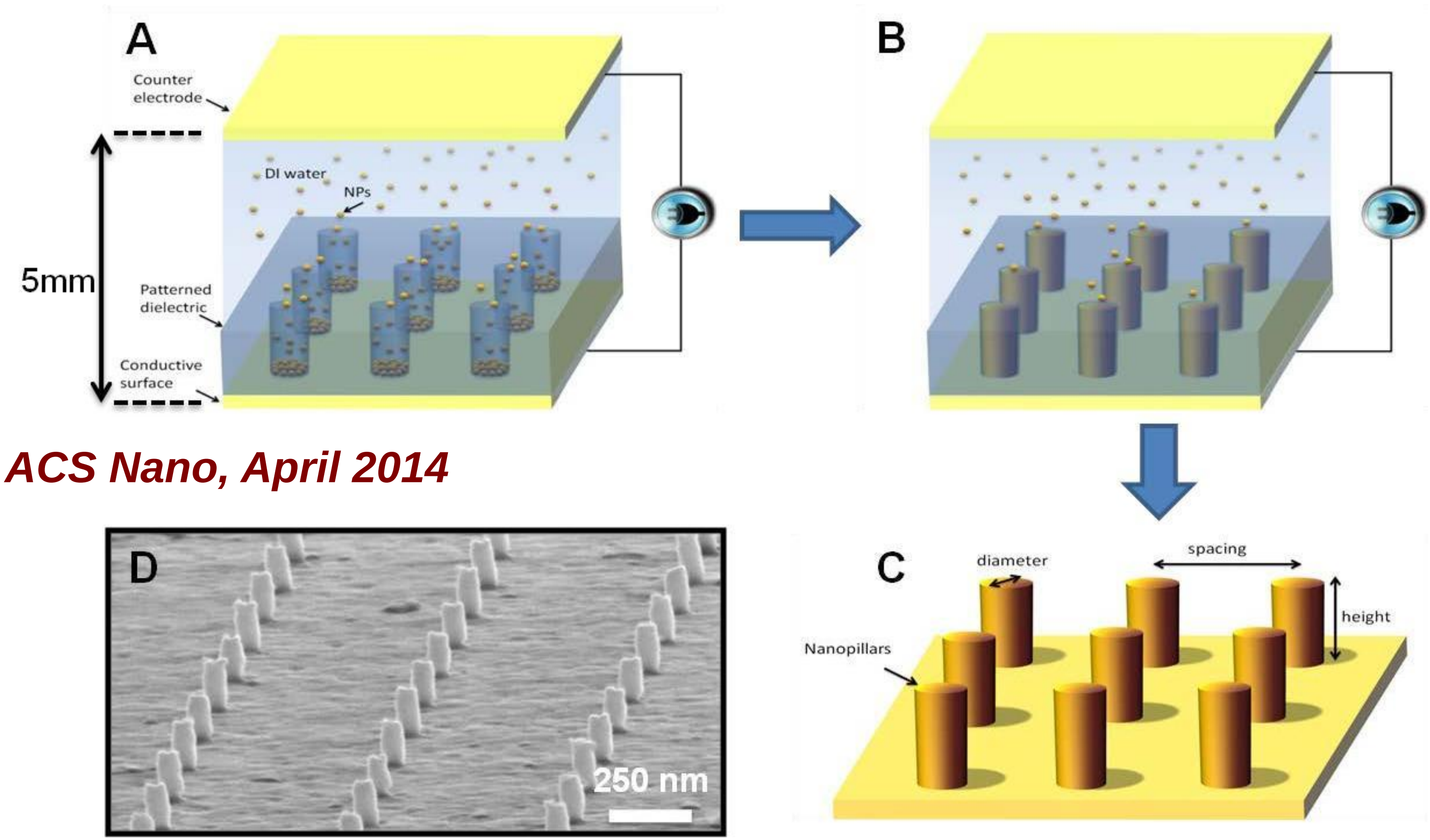
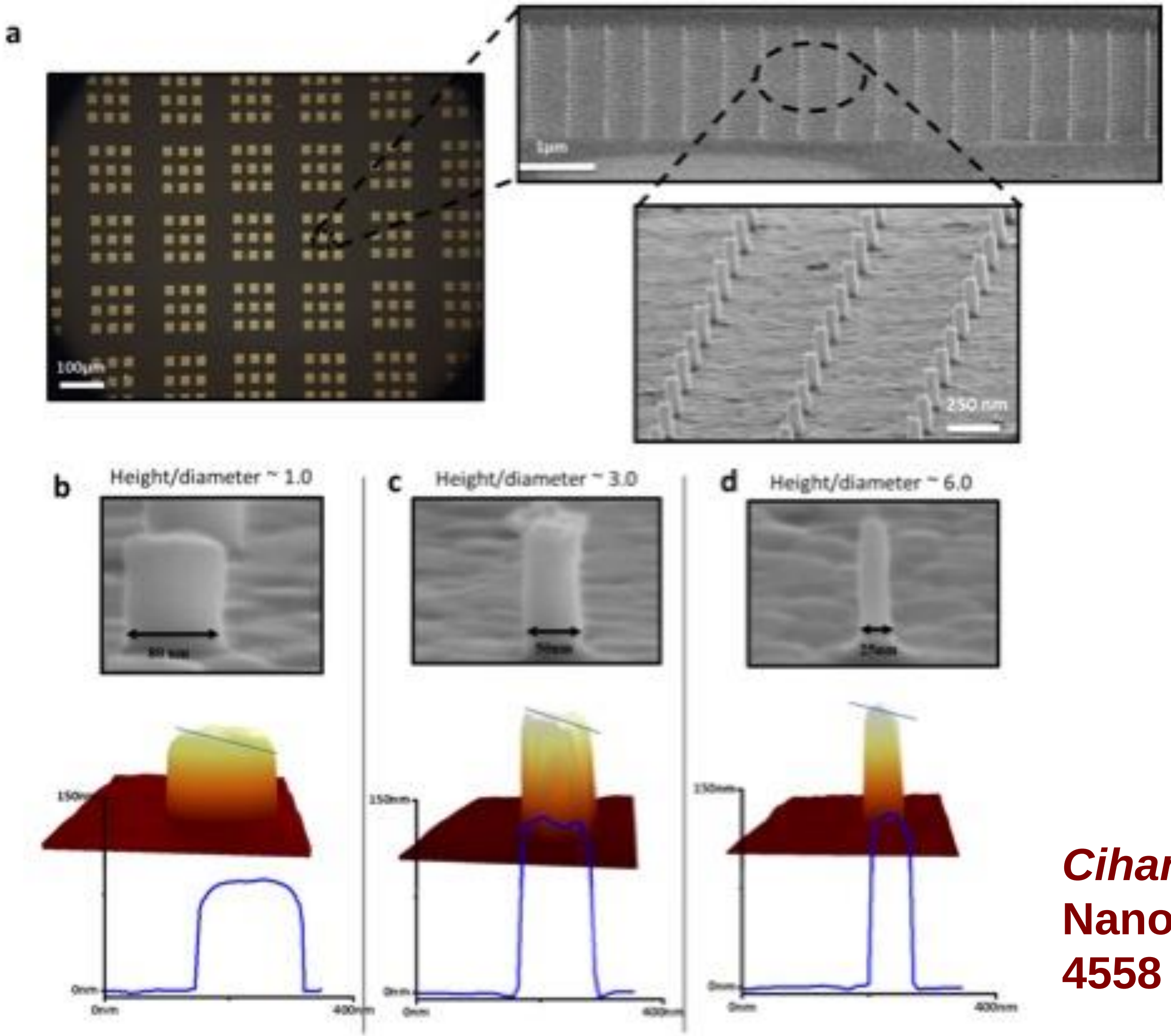


ACS Nano, April 2014

•Manufacturing of 3-D nanostructures using directed nanoparticle assembly process. **(A and B)** NPs suspended in aqueous solution are (**A)** assembled and (**B)** fused in the patterned via geometries under an applied AC electric field. (**C)** Removal of the patterned insulator film after the assembly process produces arrays of 3-D nanostructures on the surface. **(D)** Scanning electron microscopy (SEM) image of gold nanopillar arrays.

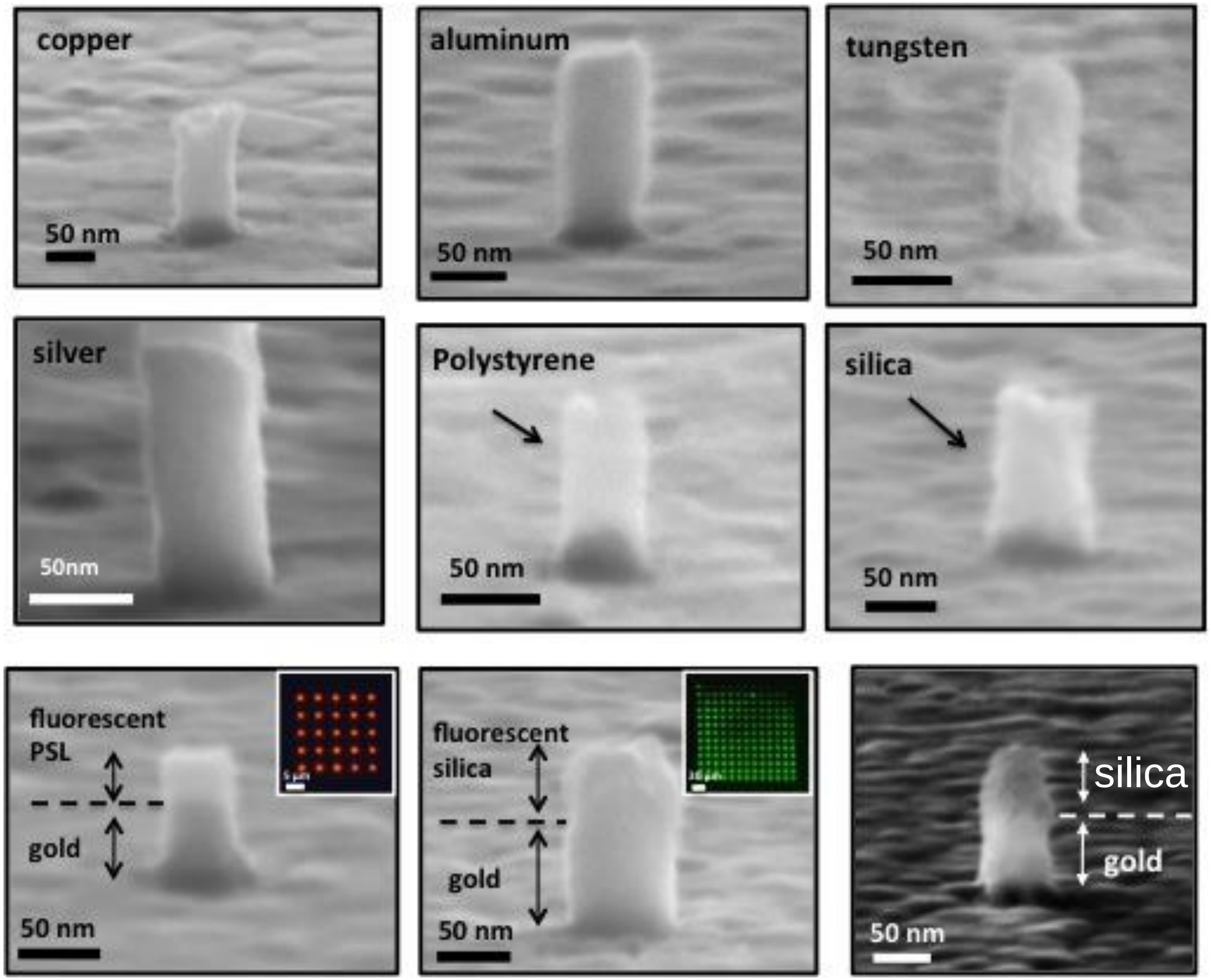
Fabrication of Interconnects with Controlled dimensions



***Cihan Yilmaz et al.*, ACS Nano, 2014, 8 (5), pp 4547–4558**

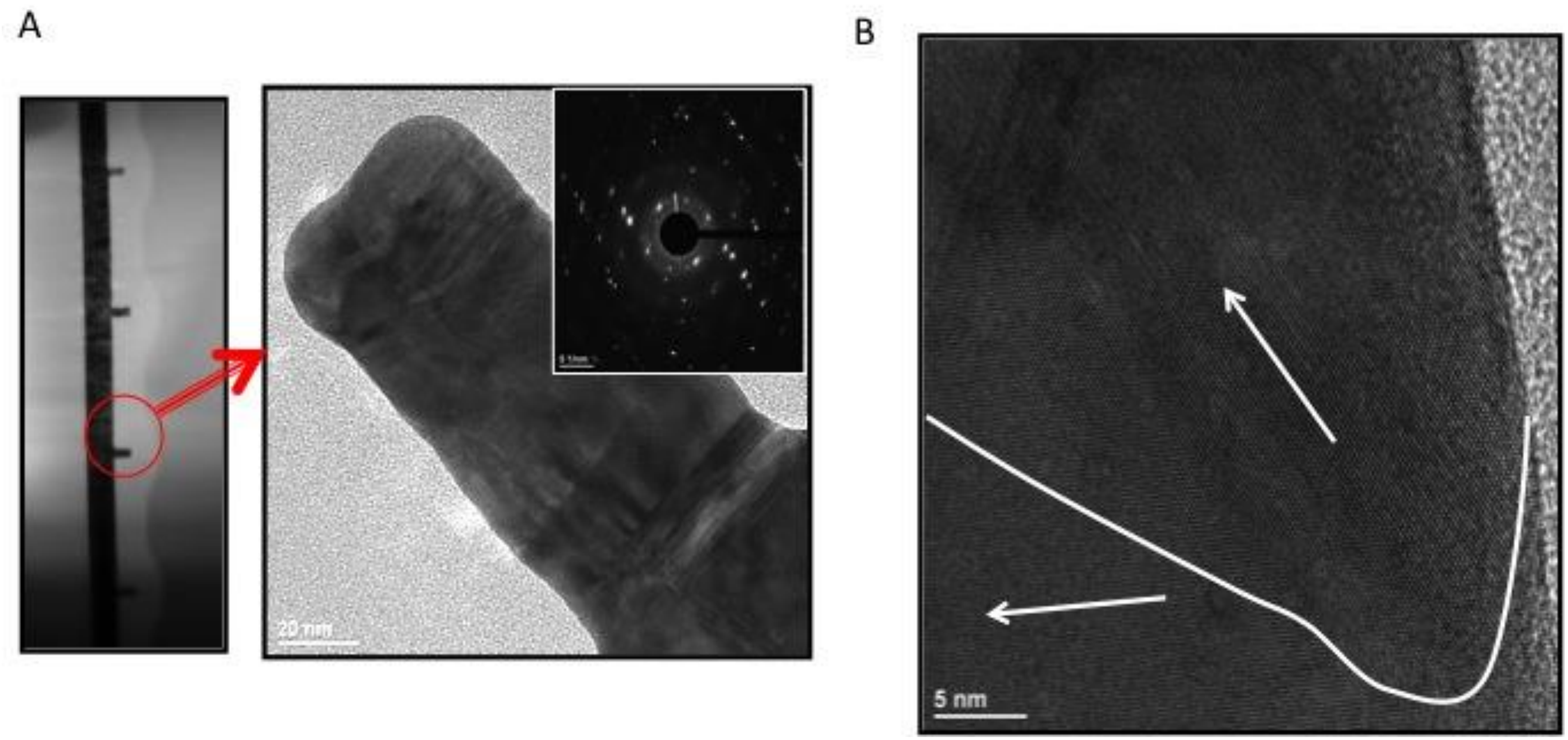
- **Fabrication over a large area. Uniformity is 90.3% over millimeters area.**
- **Controlled, repeatable and reliable fabrication.**

Fabrication of 3-D Homogenous and Heterogenous Nanostructures from Various Different Materials



- Show the potential for the fabrication of interconnect with alternative materials such as tungsten, silver and etc.

Do particles completely fuse following the assembly?



- TEM shows that NPs completely fuse without any voids or gaps.
- Nanopillars have polycrystalline nature.

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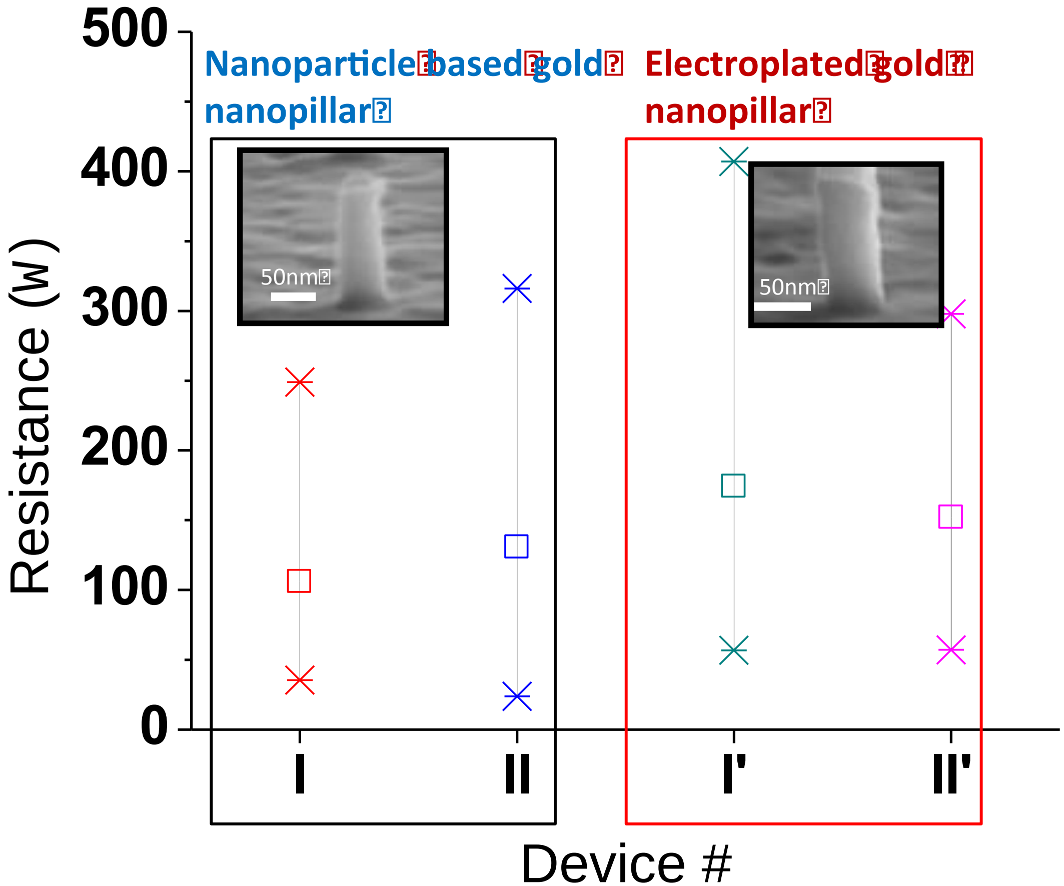
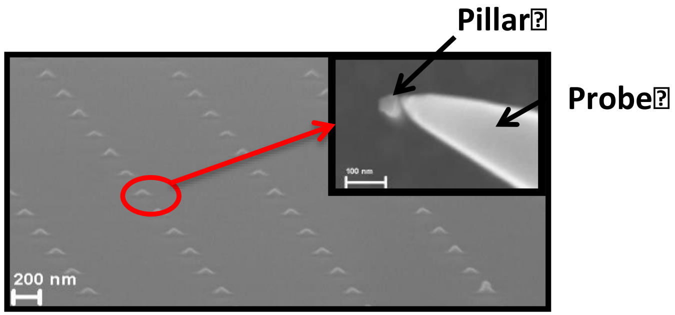
How different the electrical resistivity compared to conventionally fabricated nanostructures?





Measurements were performed using a scanning electron microscopy in-situ nanomanipulator

- **Similar or better resistivity values were observed (~ 10-7 Ω·m) from the nanopillars fabricated by nanoparticles and conventional electroplating.**
- **Tungsten resistivity is similar to CVD tungsten.**

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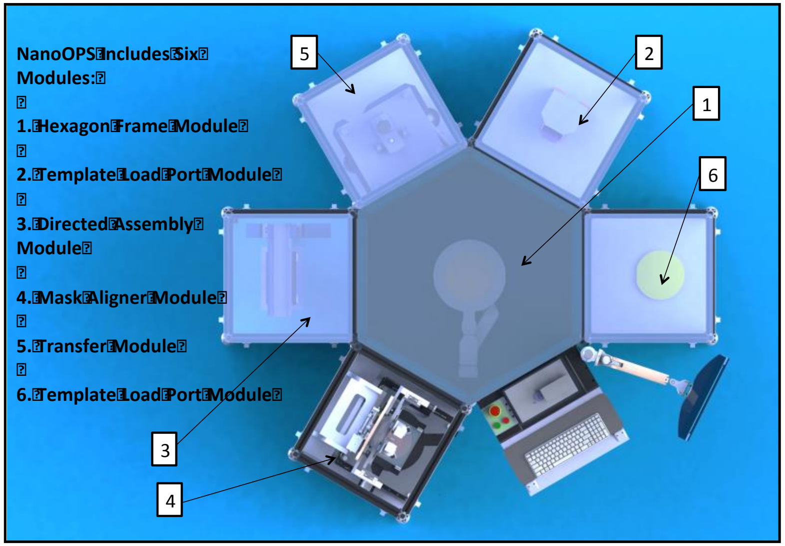
Fully Automated <u>Nano</u>scale <u>O</u>ffset <u>P</u>rinting <u>S</u>ystem (NanoOPS) Prototype was Demonstrated on 9/17/2014 to 58 companies

- **NanoOPS is capable of printing using templates with micro and nanoscale patterns (down to 20nm).**
- **Integrated registration and alignment.**



NanoOPS Videos on Youtube:

From Lab to Fab: Pioneers in Nano-Manufacturing
https://www.youtube.com/watch?v=tZeO9I1KEec

NanoOPS at Northeastern University
https://www.youtube.com/watch?v=2iEjIcog774

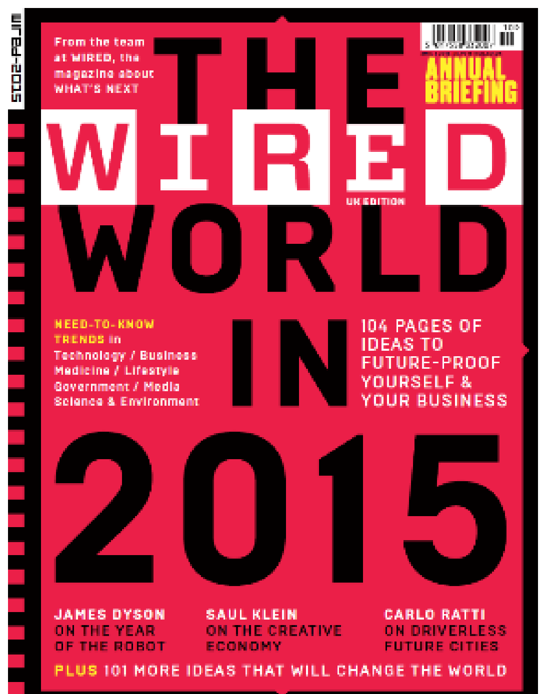
NanoOPS - A Nanomanufacturing Breakthrough
https://www.youtube.com/watch?v=J4XupF3Zt5U

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

Printed Electronics Europe

Best Academic R&D Award 2016

2015 R&D 100 FINALIST



The Boston Globe

Business

September 18, 2014

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

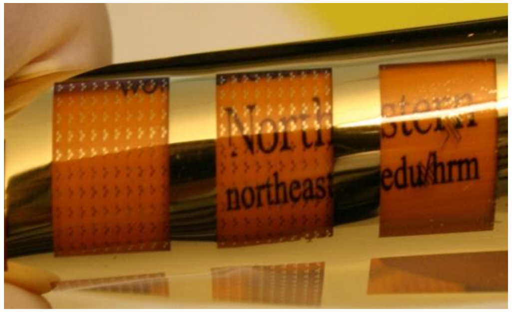
NU envisions vast potential in tiny 3-D printing

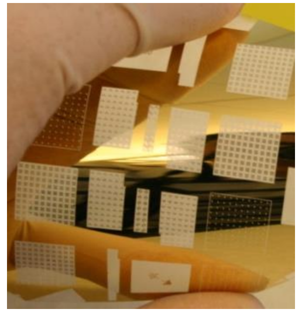
Applications

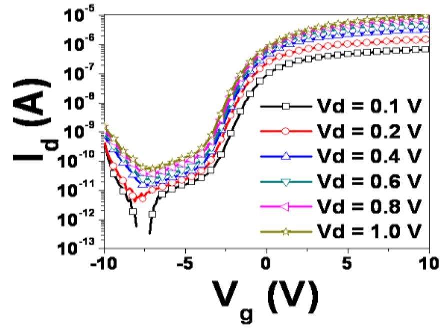
Electronics

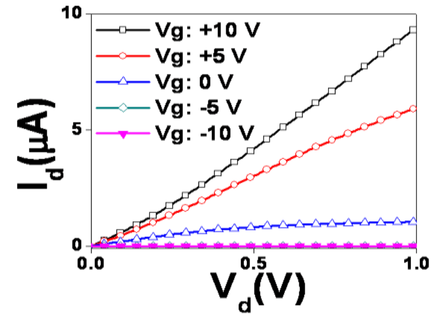
Electronics

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

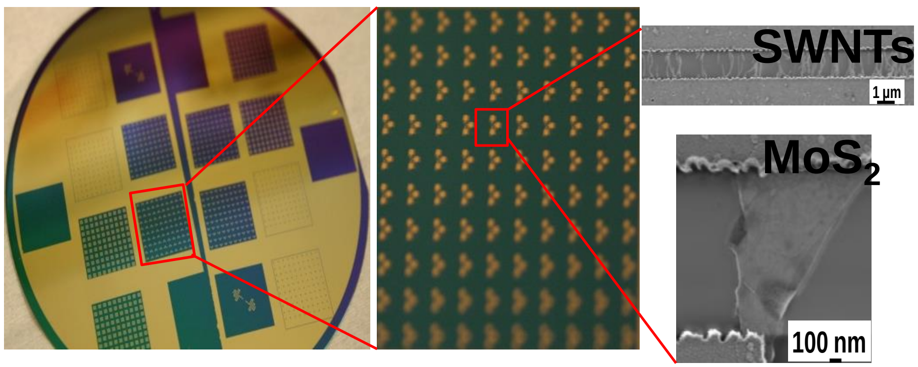


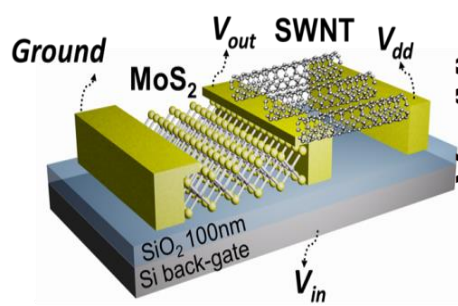


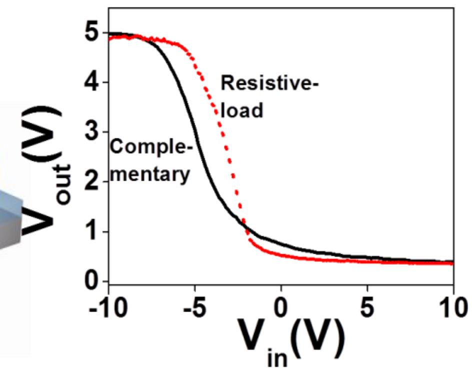




- **Heterogeneous SWNTs and MoS_2 complimentary invertors through assembly**



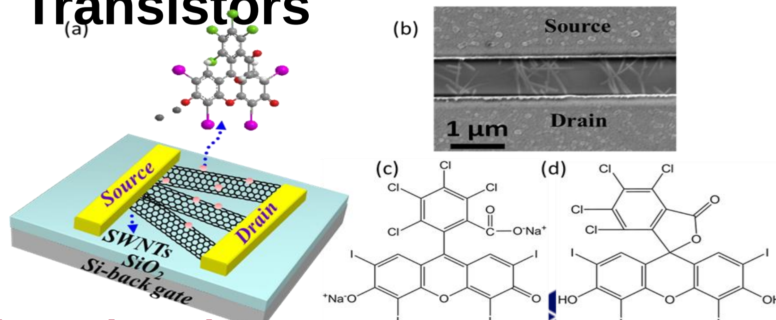




***Nanotechnology**, Vol. 23, (2012).*

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

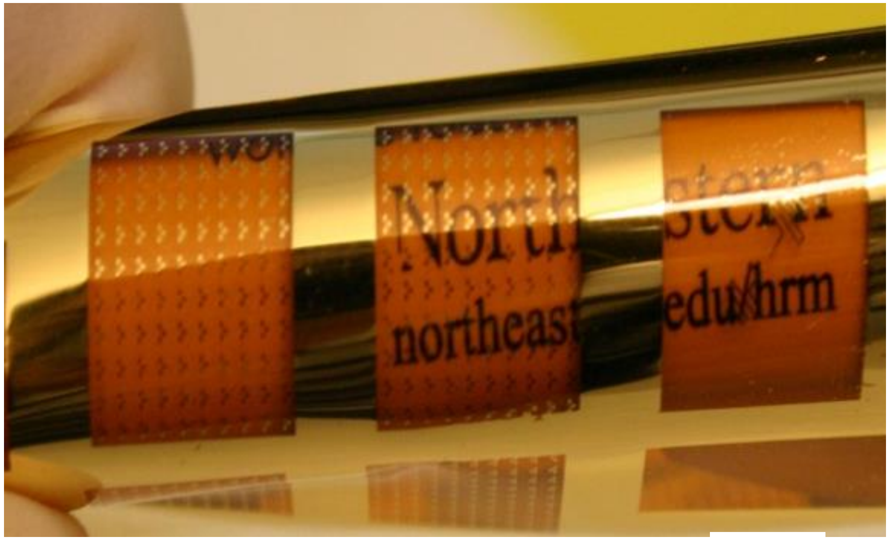
Appl. Phys. Lett. 97, 1 2010.

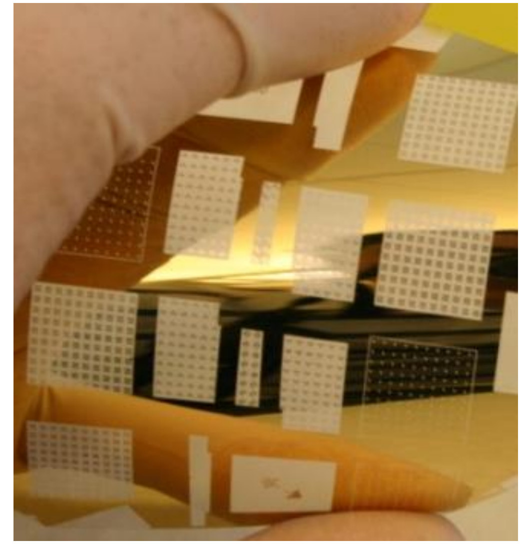


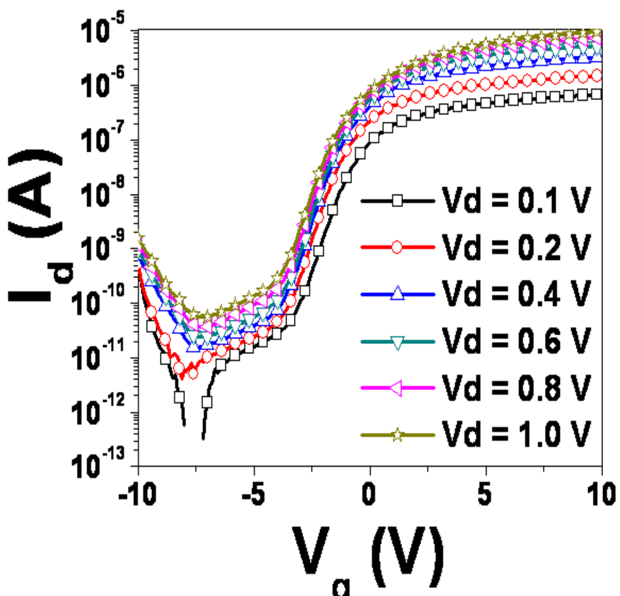
Nanotechnology, Vol. 22, (2011)

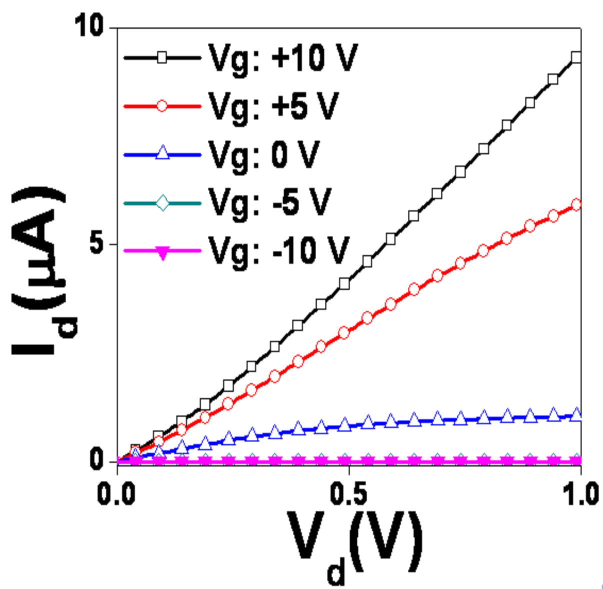
Nanomanufacturing

Flexible transparent n-type MoS2 transistors









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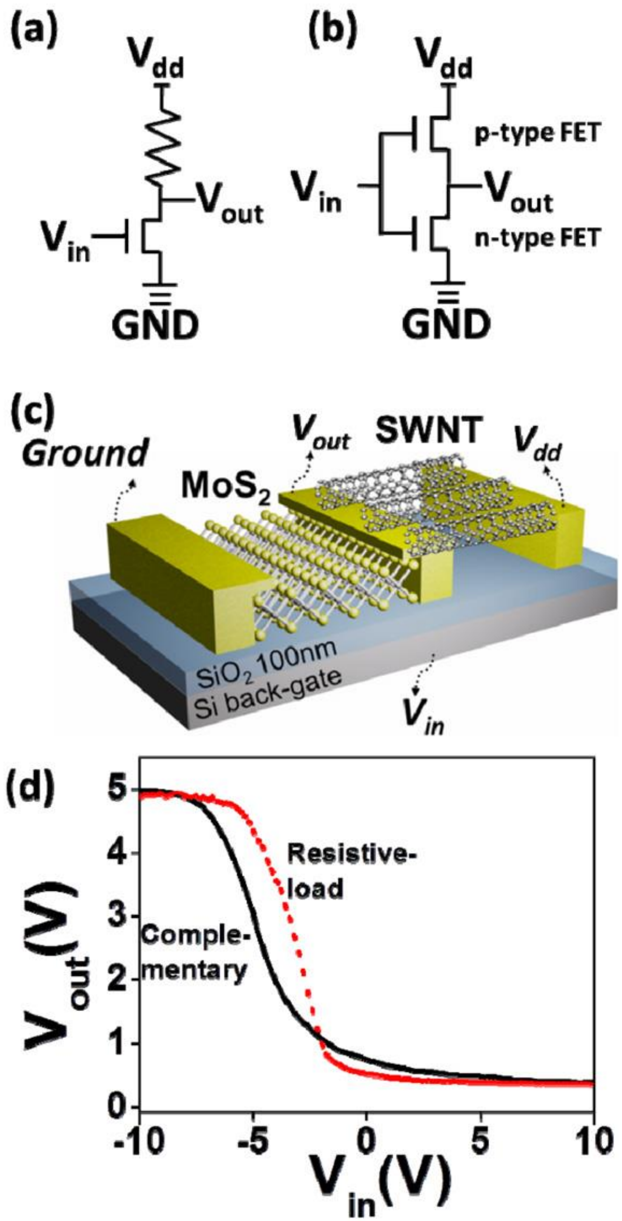
MoS2/SWNT Heterogeneous Complementary Inverter



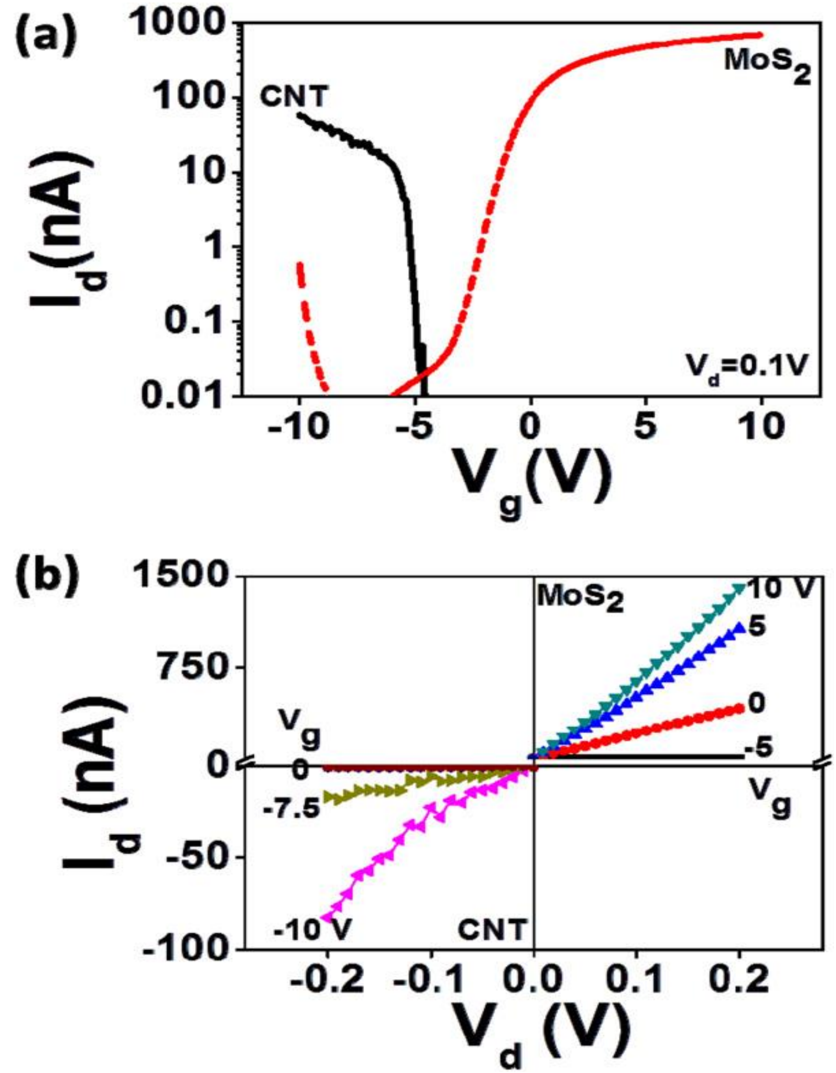


Figure 2. (a) I_d–V_g transfer characteristics of a typical n-type MoS_2 and p-type CNT transistor. (b) I_d-V_d output characteristics of a typical n-type MoS_2 and p-type CNT transistor.

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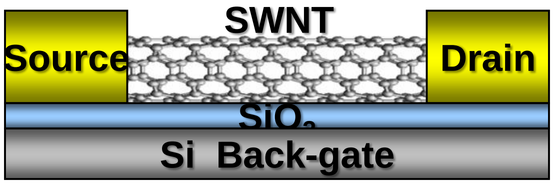
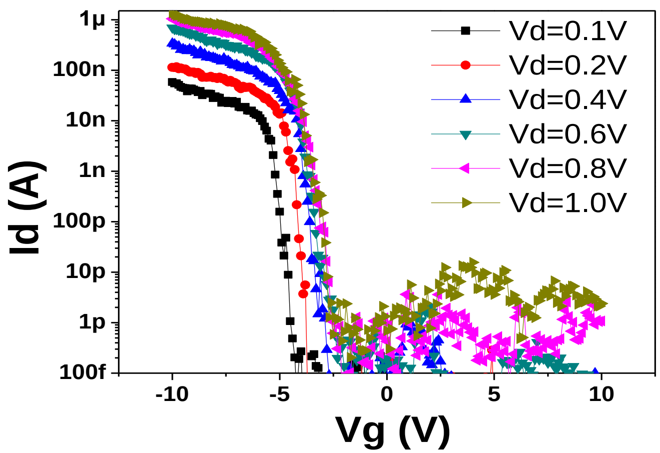
Carbon Nanotube FET

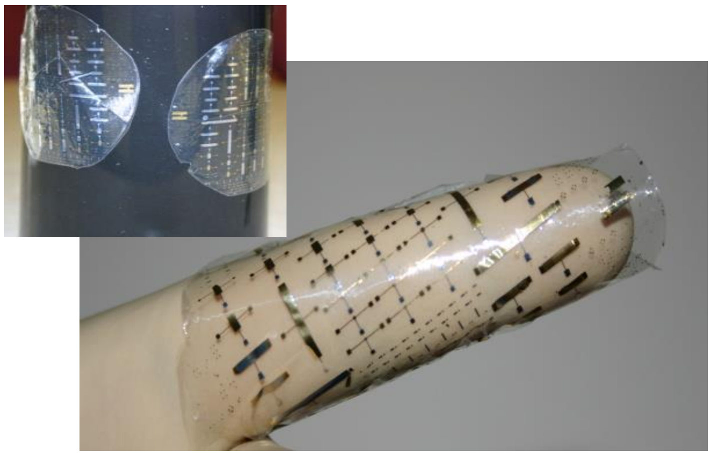




Employs Field Assisted Directed Assembly Technique

Typical p-type behavior, i.e., transistors turn under negative bias.

- **The devices show a high $I_{on/off} > 10^5$**
- **Low off current ~ pA**
- **Sub-threshold swing of ~ 250 mV/dec,**



Applications

High Speed binary transistors ;
Logic gates; Analog devices;
Power amplifiers; Sensors, etc.

Selvarasah, Li, Busnaina, and Dokmeci, ***Appl. Phys. Lett. 97, 1 2010.***

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Nanomechanical Memory Ranked Highly on ITRS

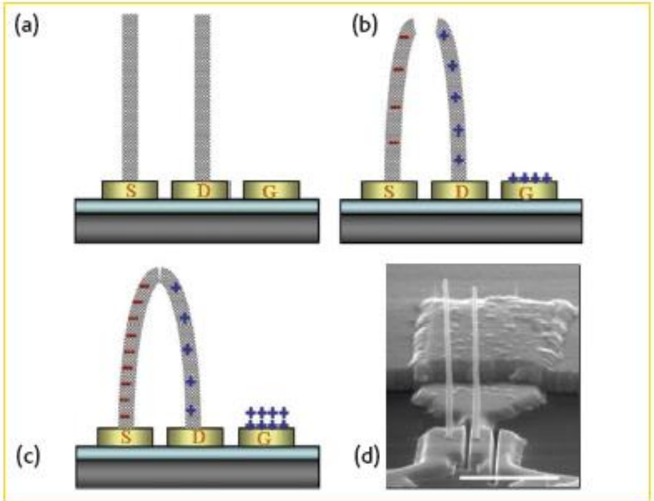
> 20	>16 - 18
>18 - 20	≤ 16

Critical Evaluation Memory

For each Technology Entry (e.g. 1D Structures), sum horizontally over the 8 Criteria
Max Sum = 24
Min Sum = 8

	Scalability	Performance	Energy Efficiency	Off/On ratio	Operational Reliability	Operate Temperature	CMOS Technological Compatibility	CMOS Architectural Compatibility
Engineered Tunnel Barrier Memory	2.4	2.3	2.2	2.0	2.2	2.7	2.7	2.5
Fuse/Anti-fuse Memory	2.6	1.9	2.0	2.2	1.8	2.8	2.7	2.5
Nano Mechanical Memory	1.7	1.9	2.4	2.5	1.9	2.9	2.2	2.2
Electron Injection Memory	2.3	2.2	2.3	2.1	2.0	2.4	2.3	2.4
Ionic Memory	2.6	2.0	2.4	2.1	1.7	2.5	2.1	2.5
Ferroelectric FET Memory	1.8	2.0	1.9	2.1	1.7	2.6	2.3	2.3
Macromolecular Memory	2.1	1.8	2.1	1.8	1.4	2.2	1.9	2.3
Molecular Memory	2.4	1.7	2.4	1.4	1.3	2.2	1.8	1.9

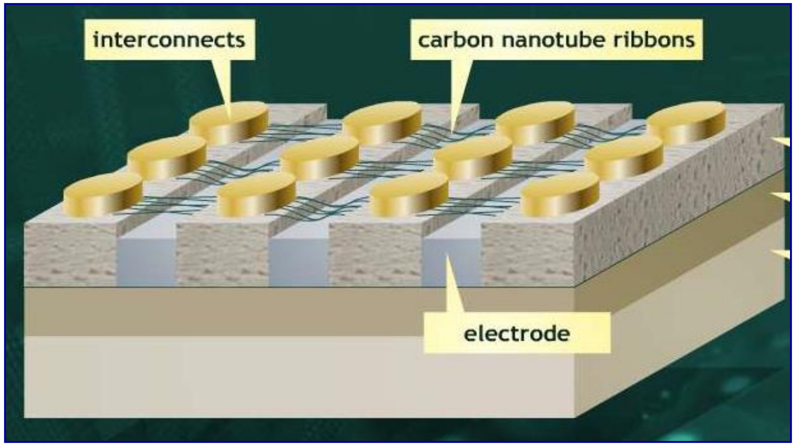
State of the art: Carbon Nanotube Switches



(a-c) Schematics showing NEMS switch being biased from 'off' to 'on' states, and (d) scanning electron micrograph showing nanotubes. (© 2005 American Institute of Physics.)

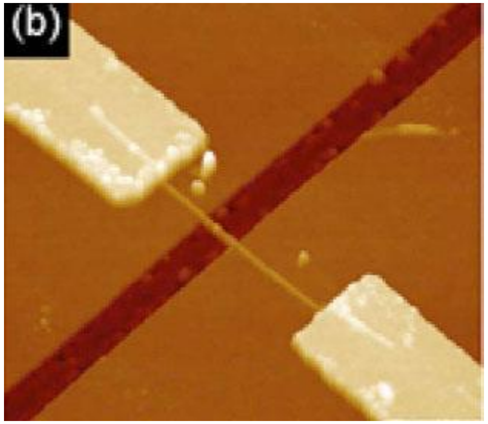
MWNT Mechanical Switch

Jang et al., Appl. Phys. Lett. (2005) 87, 163114.



Carbon Nanotube Non-Volatile Memory Device,

Ward, J.W.; Meinhold, M.; Segal, B.M.; Berg, J.; Sen, R.; Sivarajan, R.; Brock, D.K.; Rueckes, T. *IEEE,* 2004, 34-38.



Chemically-assembled switches based on electroactuated multiwalled nanotubes

E. Dujardin,a V. Derycke,b M. F. Goffman, R. Lefèvre, and J. P. Bourgoin Applied Physics Letters 87, 193107 2005.

Goal: High-rate, large area directed assembly of swnt switches.

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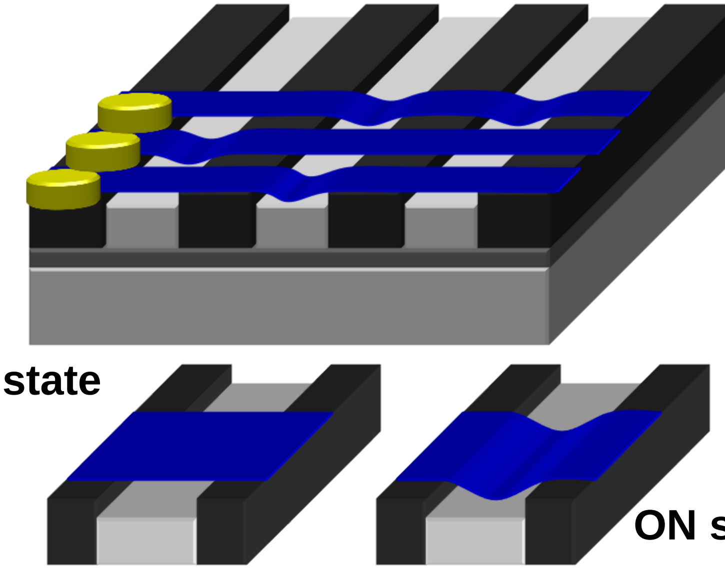
SWNTs NEMS Nonvolatile Memory Chip

Current process

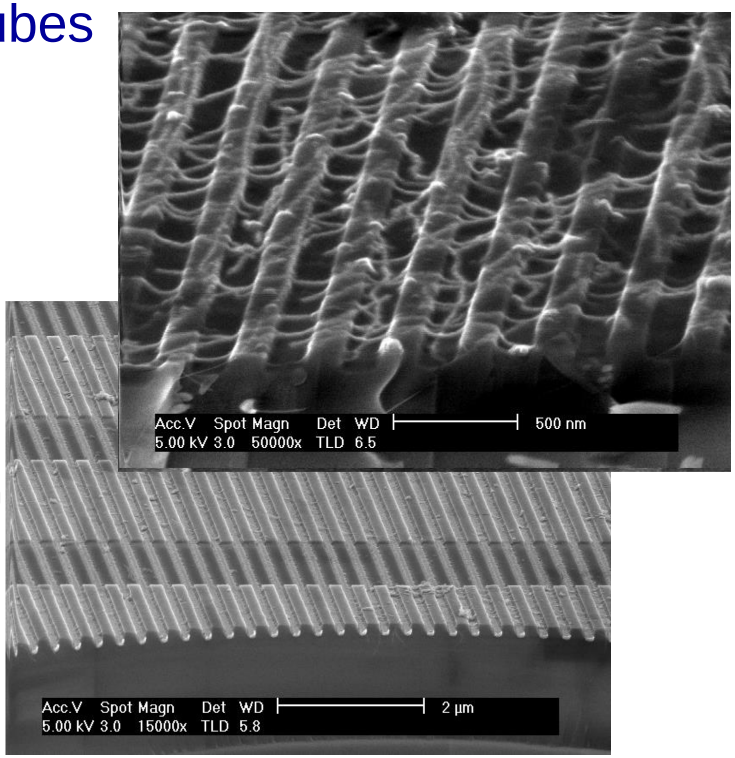
- ➢ Uses conventional optical lithography to pattern carbon nanotube films
- ➢ Switches are made from belts of nanotubes



OFF state

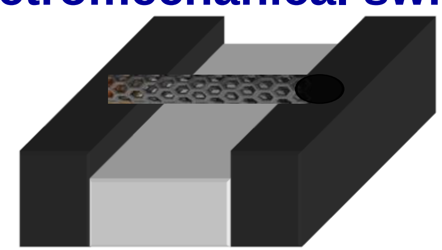
ON state

Electrodes (~100nm with 300 nm period)



(Nantero, 2004)

Nanotemplate will enable single CNT electromechanical switch



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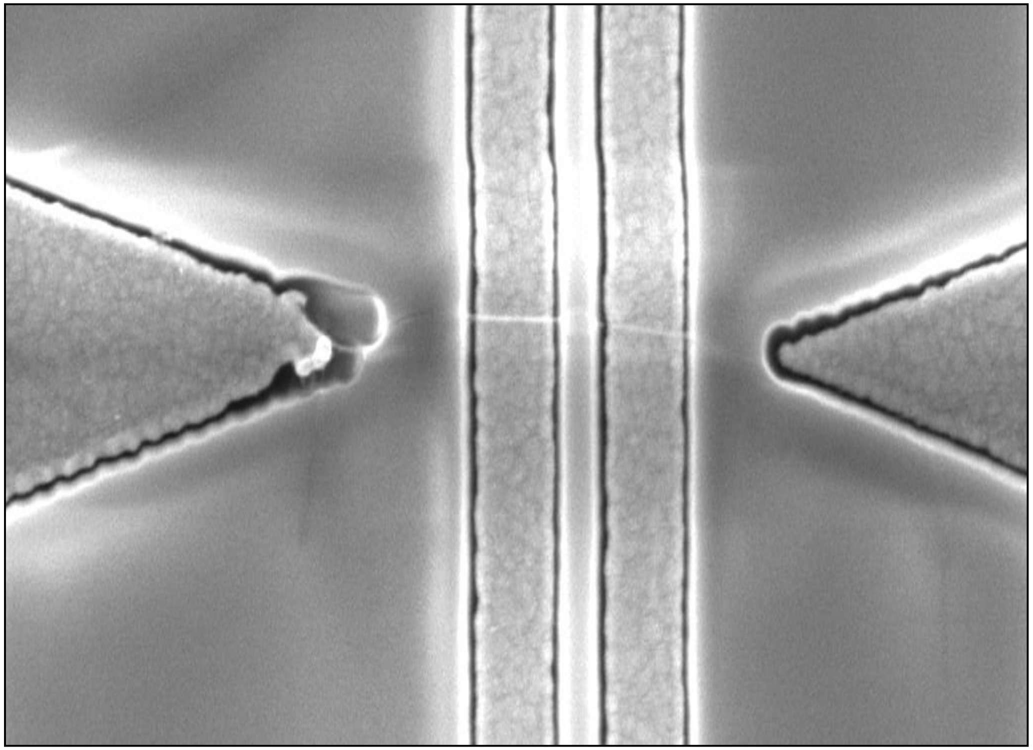
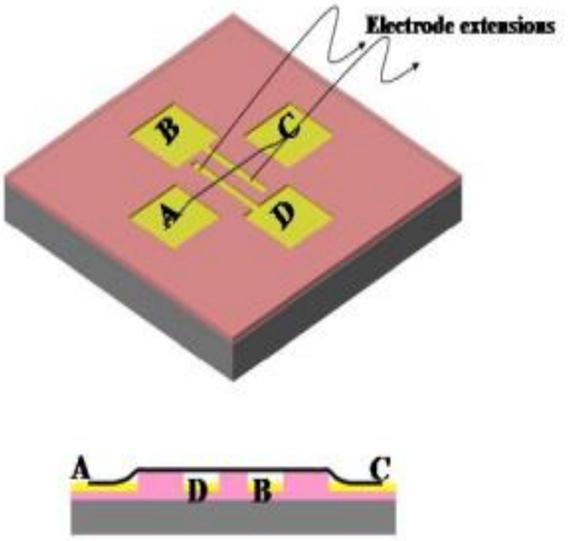
Single-Walled Carbon Nanotube Switch for Non-Volatile Memory Devices



FESEM image of the assembled SWNTs on the Nanoswitch.



Schematic of bi-stable switch.

A switch was designed and fabricated using directed assembly to assemble one single wall carbon nanotube per switch as the actuation element on a wafer level

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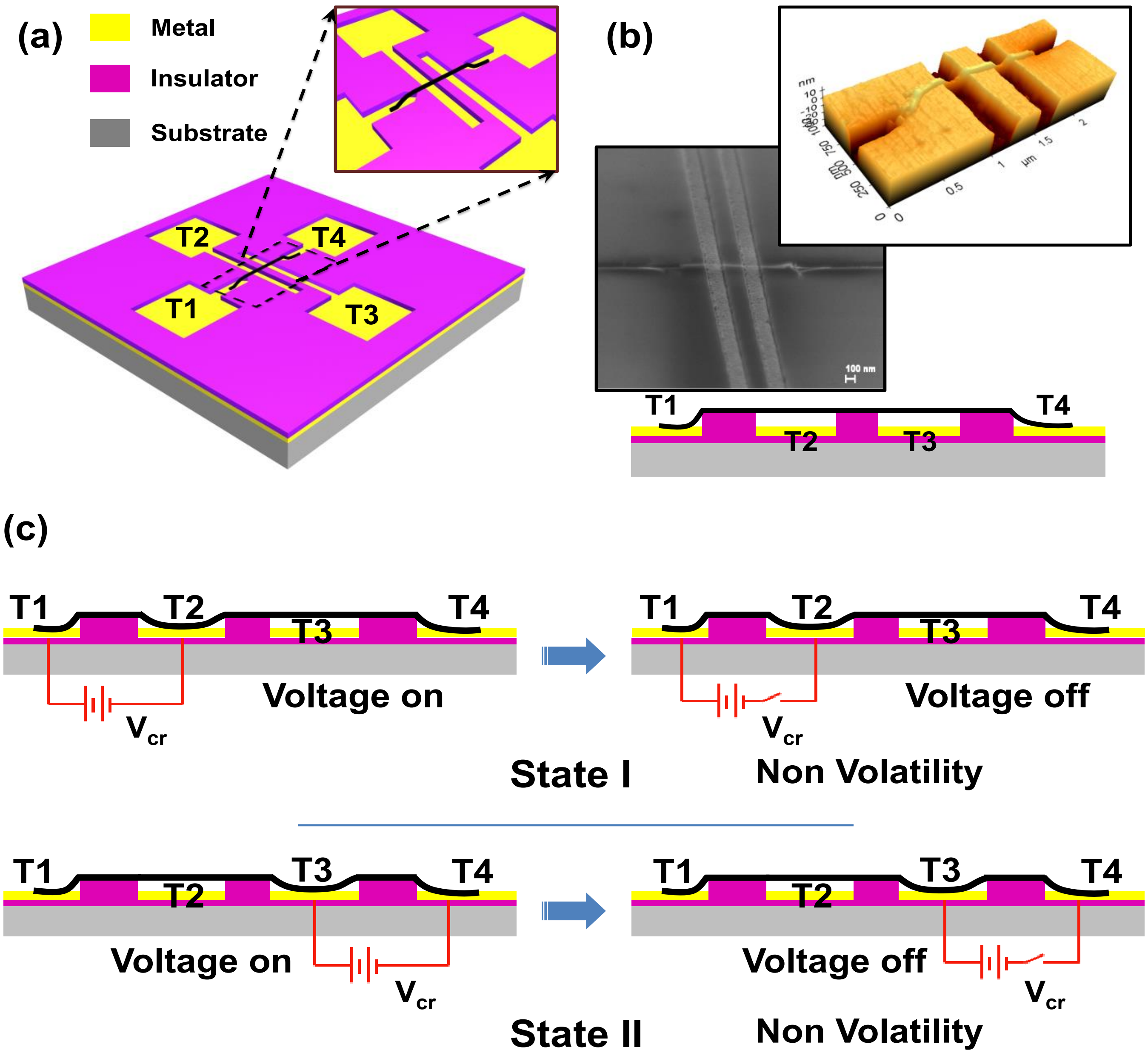
NEMS Bi-stable SWNT Switch



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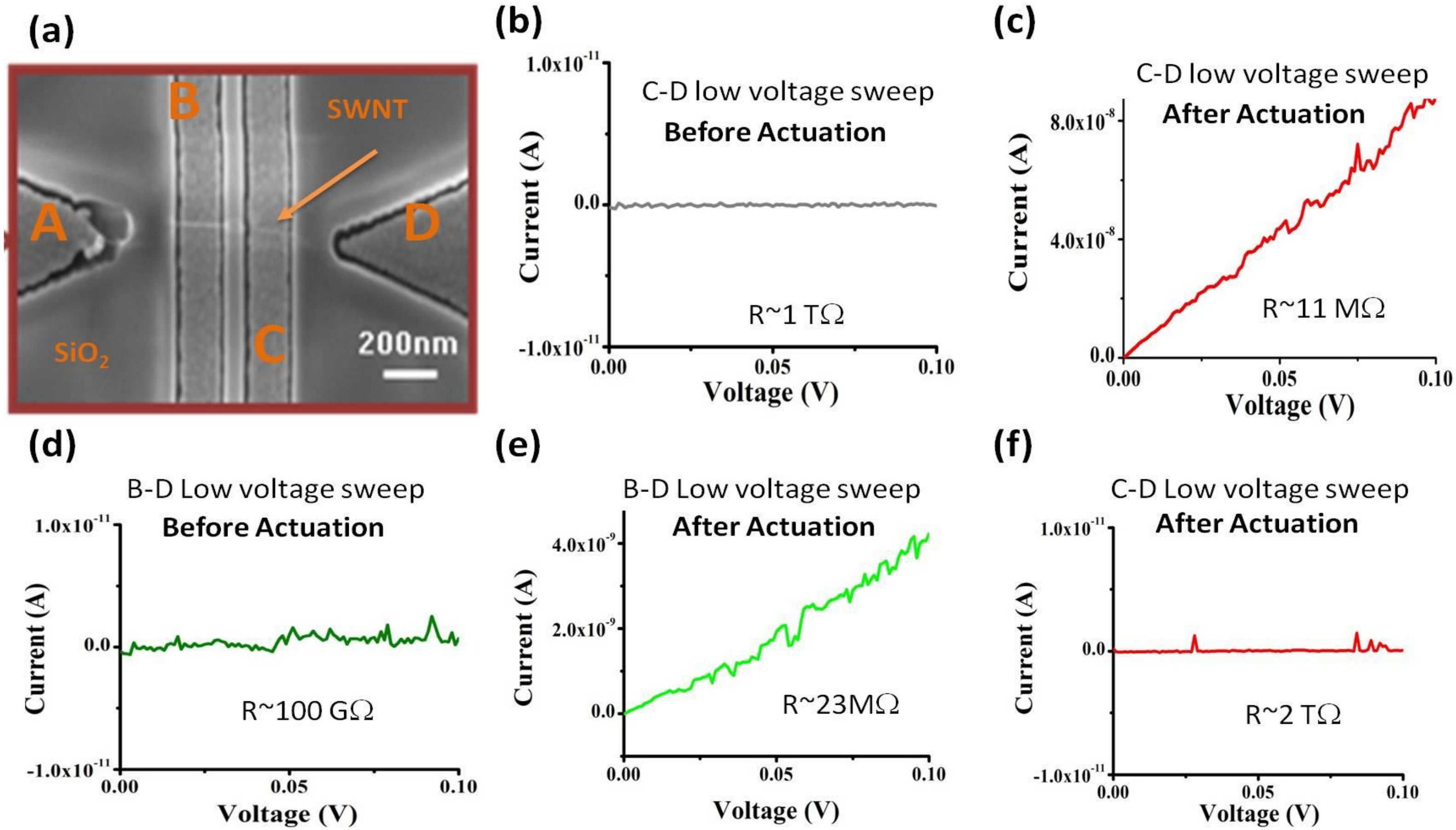
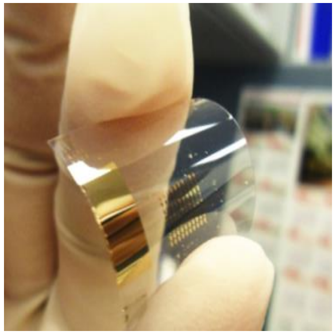
NEMS Bi-stable SWNT Switch

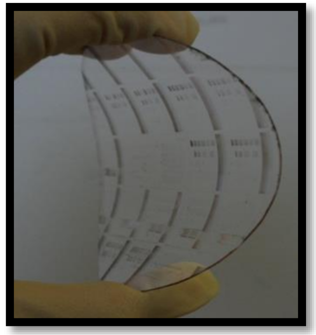


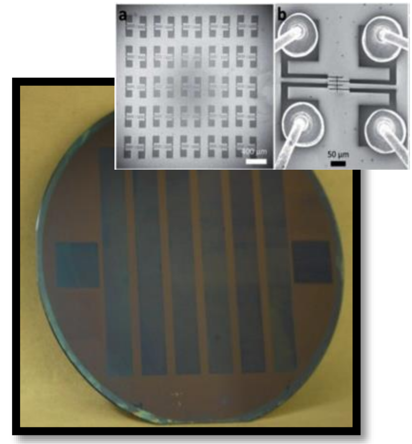
(b) continuity testing before actuation of the first trench, showing open circuit **(c)** continuity testing after actuation of the first trench, showing closed circuit **(d)** continuity testing before actuation of the second trench, showing open circuit **(e)** continuity testing after actuation of the second trench, showing closed circuit **(f)** continuity testing of the first trench after actuation of the second trench, showing open circuit.

Sensors

Faster, smaller, more efficient, more accurate and cost a fraction of current sensors prices.

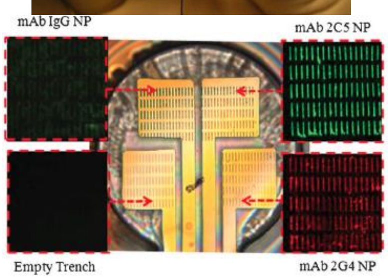




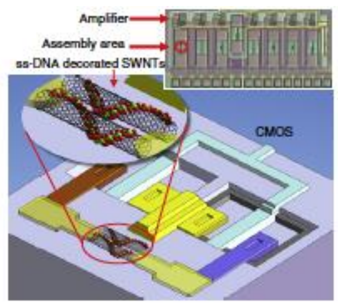


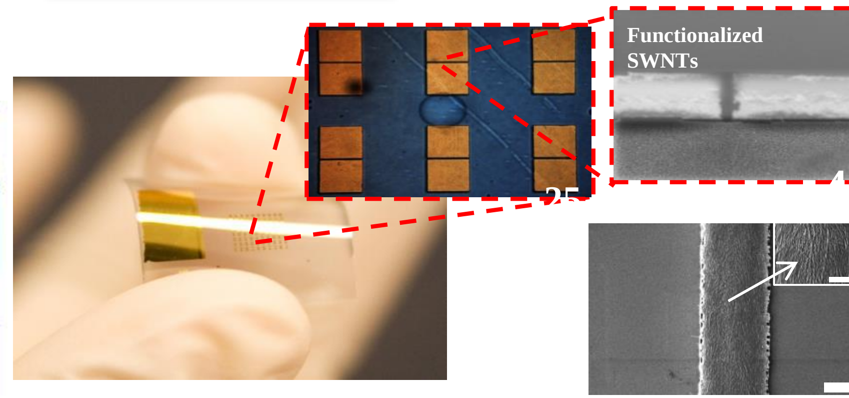
Sensors for Chemicals

Sensors for E. coli bacteria, viruses, and other pathogens

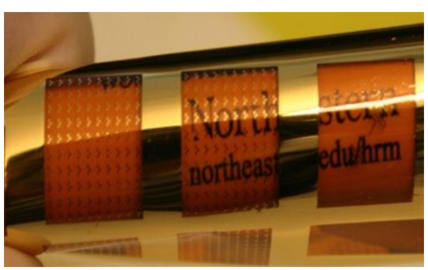


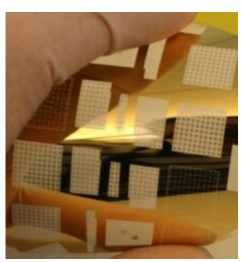
Cancer and cardiac diseases. Detection limit is 200 times lower than Current technology

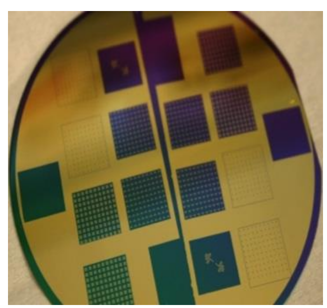




Band-Aid sensor

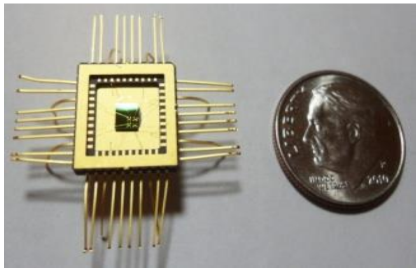


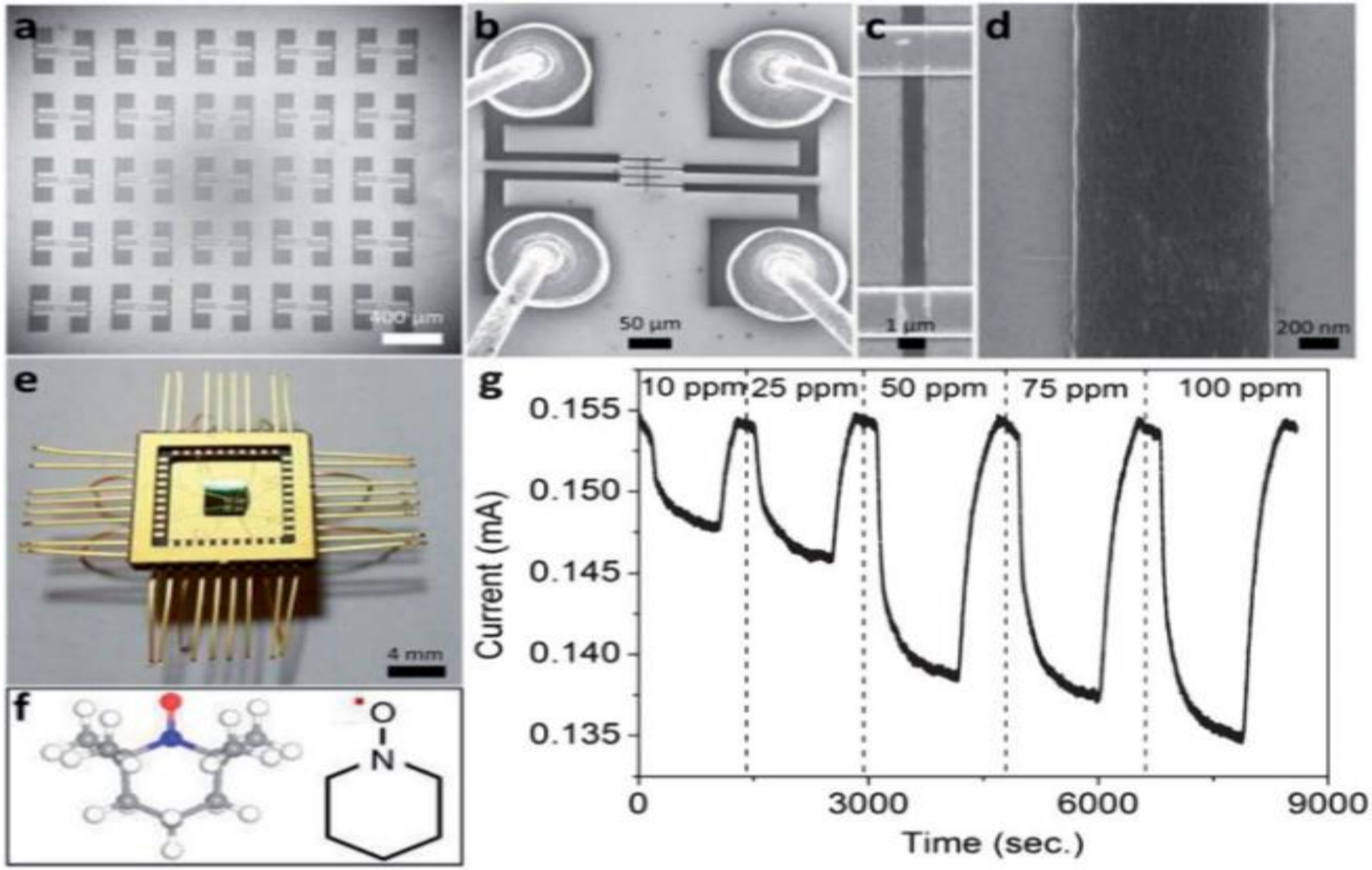




Supporting printed electronics for sensor systems

Chemical Sensors

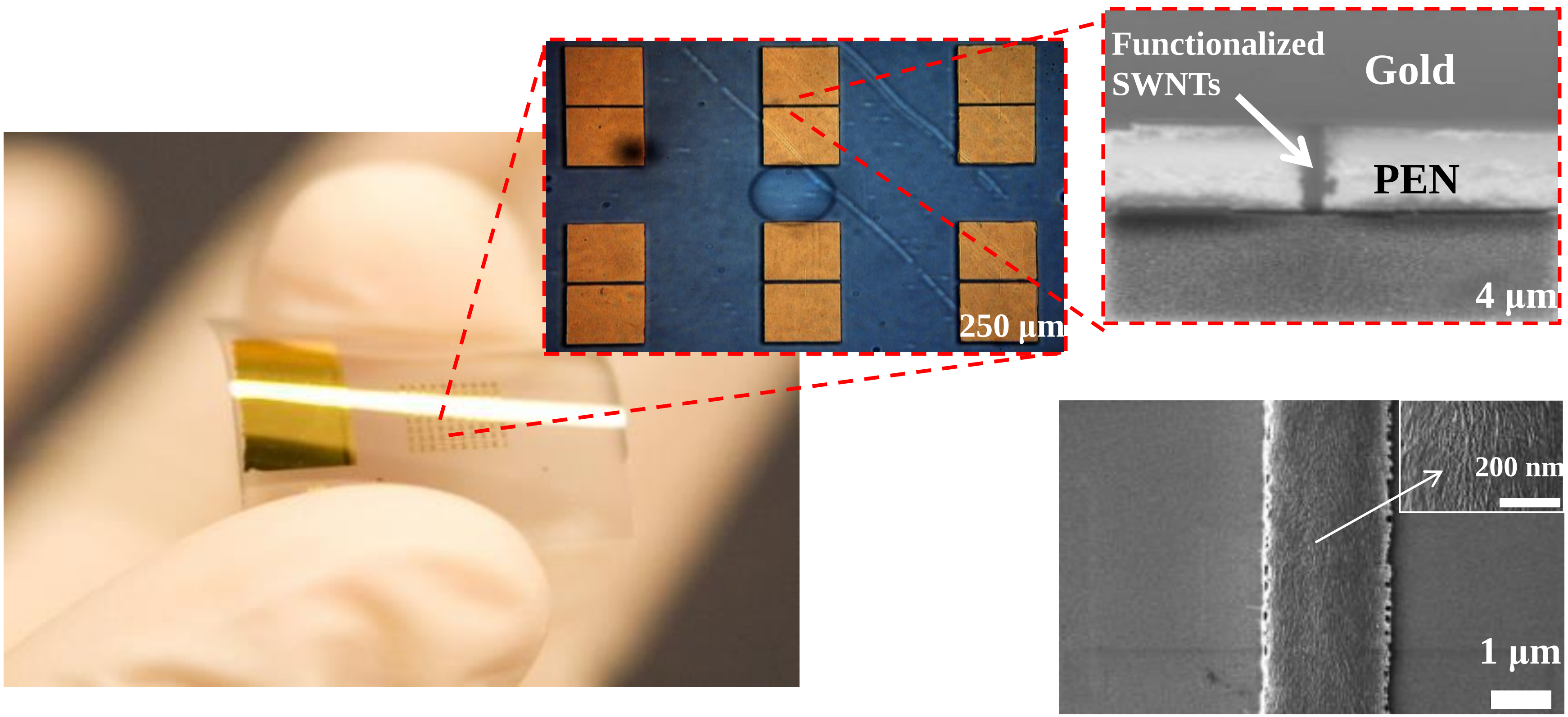




SEM images setup for assembled SWCNT array devices. (e) An optical image of wafer scale sensor devices. (f) Chemical structure of TEMPO molecules. (g) Real-time current changes as a function of conc. H_2S gas at 10, 25, 50, 75 and 100 ppm for the functionalized SWCNT sensor.

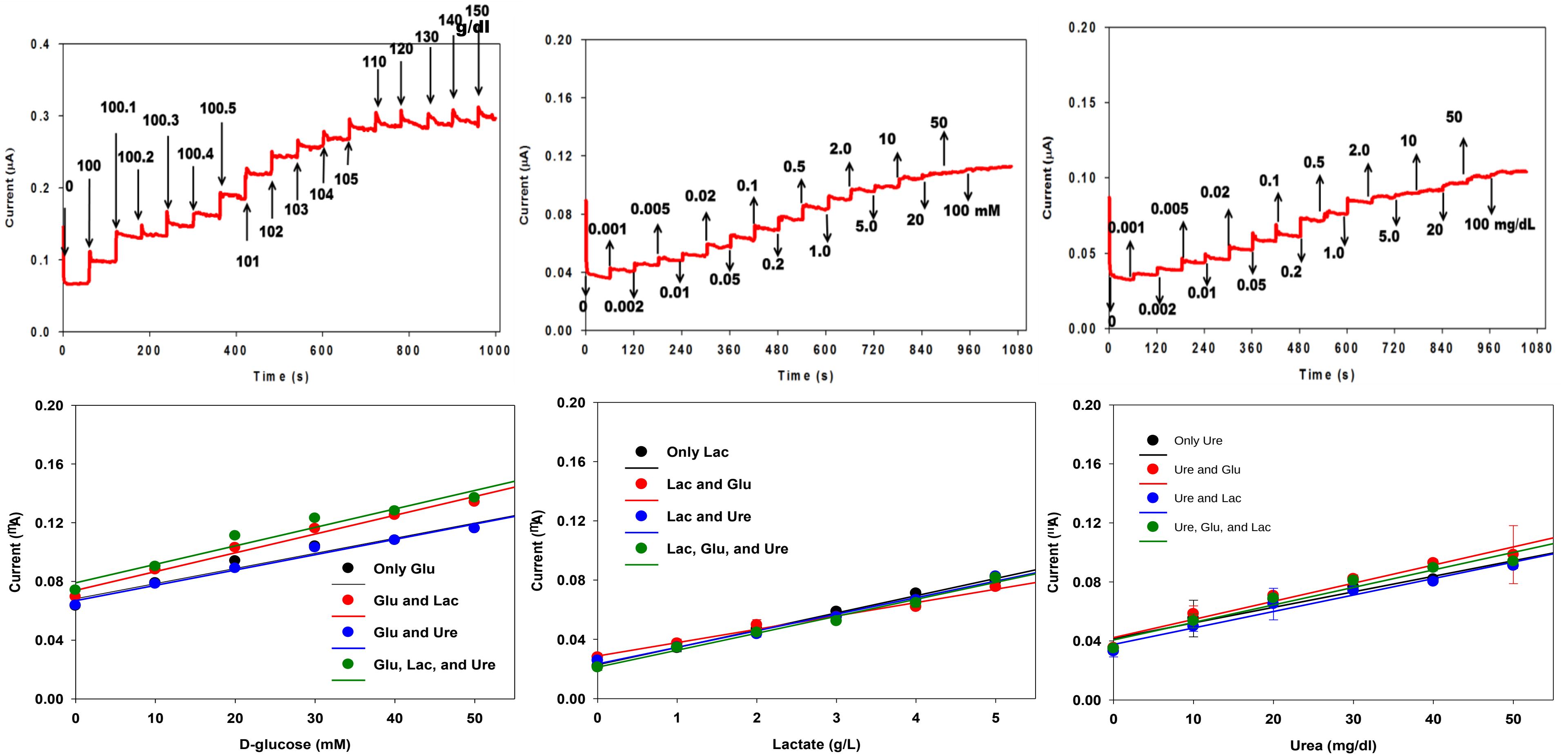
Analyst, 138, December 2013, Issue 23, pp.7206-7211

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



CNT Sensors for Biological Detection

Glucose **Lactate** **Urea**



Capable of detecting these analytes in both blood and sweat

Submitted to *Biosensors*

Center for High-rate Nanomanufacturing

Summary

- Directed assembly based nanoscale printing approach gives designers complete freedom in choosing materials for their devices without worrying about the fabrication process (materials independent printing process).

- The nanoscale printing process represent a new green nanomanufacturing technology with room temperature and pressure for printing electronic devices using a variety of semiconductors (organic or inorganics) including CNT and 2D materials and a variety of conductors and insulators.

- A nanofabrication facility could be built for $50 million, a small fraction of today's cost, making nanotechnology accessible to millions of new innovators and entrepreneurs.

Questions?

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www.nano.neu.edu
www.nanomanufacturing.us

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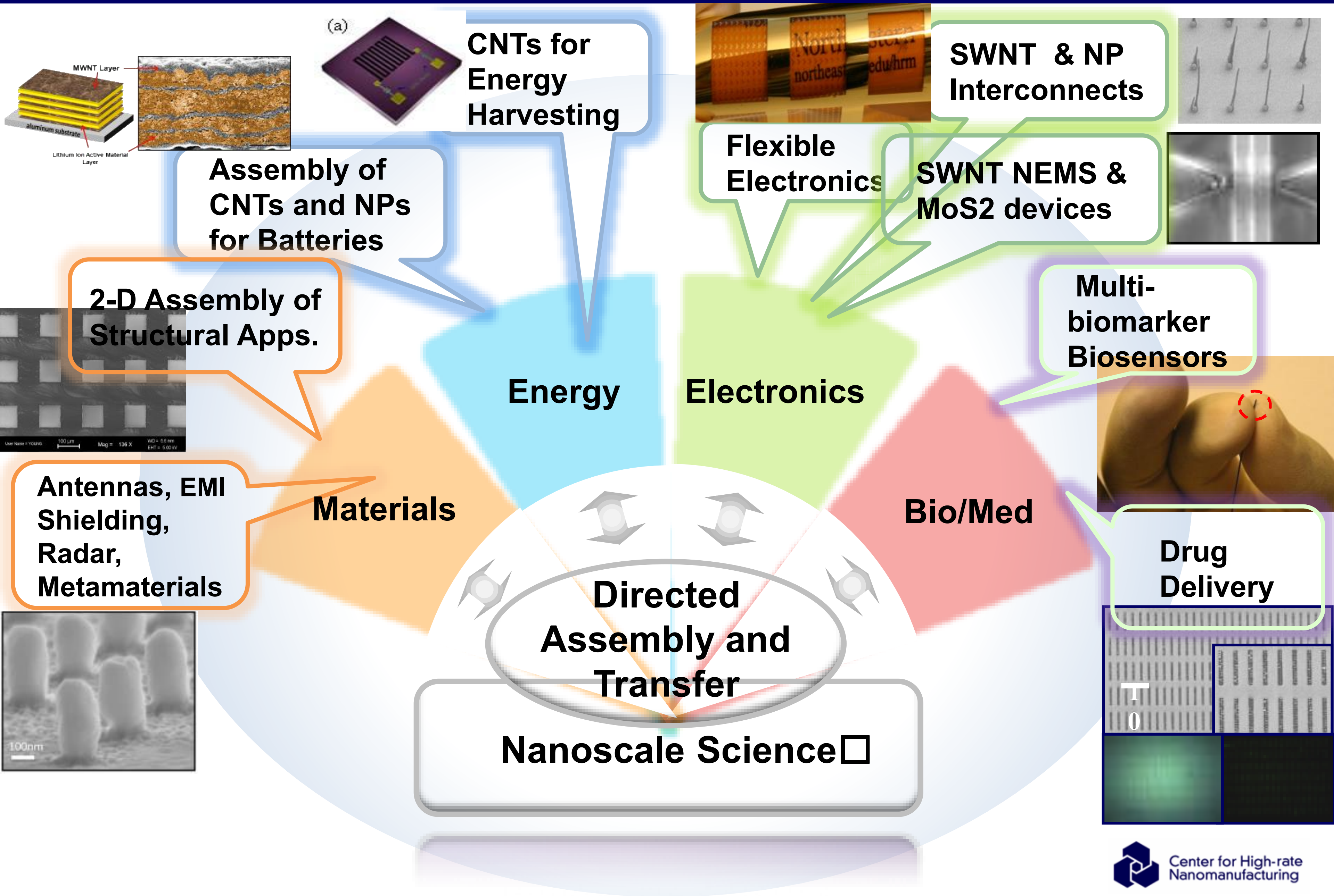
What Could We manufacture with Multiscale Offset Printing?



Strong Industrial Partnerships

varian
MILARA
Schlumberger
Ticona ENGINEERING POLYMERS
kuraray
Veeco
H.C.Starck
TERADYNE
AEC
Nypro
AMBERWAVE
zyvex
nanocomp TECHNOLOGIES, INC.
TIAX
TEXTRON
VELCRO
QinetiQ North America
Foster-Miller
BAE SYSTEMS
Raytheon
EMC²
MOTOROLA intelligence everywhere
DRAPER
LOCKHEED MARTIN We never forget who we're working for
CORNING
intel
IBM
NANTERO
Microfluidics
BASF The Chemical Company
Kodak
GE
SWeNT SouthWest NanoTechnologies
tsi
CABOT
brewer science
SOLOPOWER
ROGERS CORPORATION
A Division of the Massachusetts Technology Collaborative

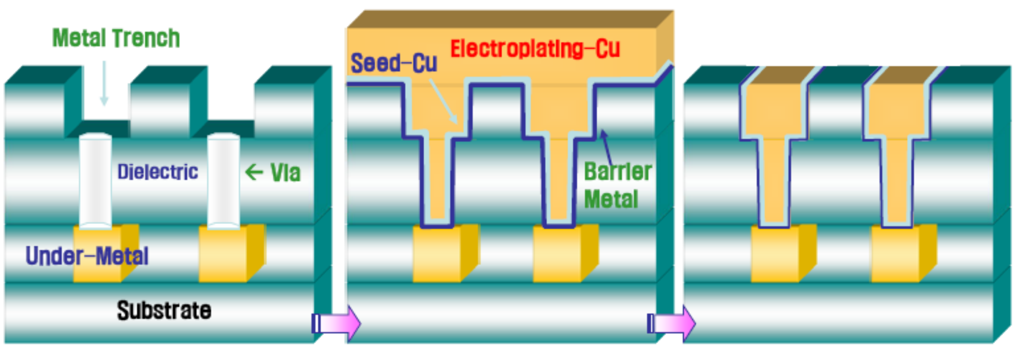
Over 30 Companies

What is Damascene?

Damascene structures more than a 1000 years ago.

- The concept comes from metalwork in Damascus starting in the 3rd century A.D.
- Damascene steel swords could split a feather in midair, yet retain their edge through many a battles.

Damascene structures in the 1990s.



- IBM introduced the copper damascene process for interconnect in 1990s.
- Semiconductor industries use damascene structure for copper interconnect on all electronics we use today.

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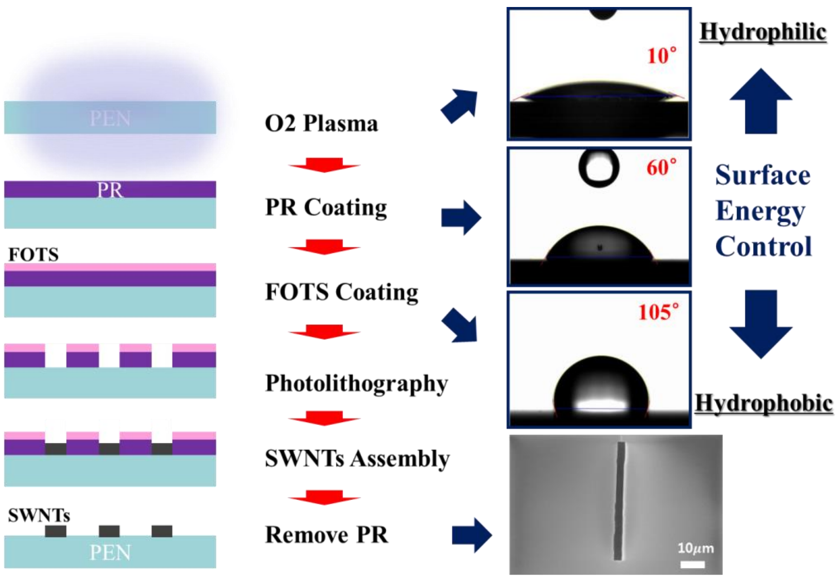
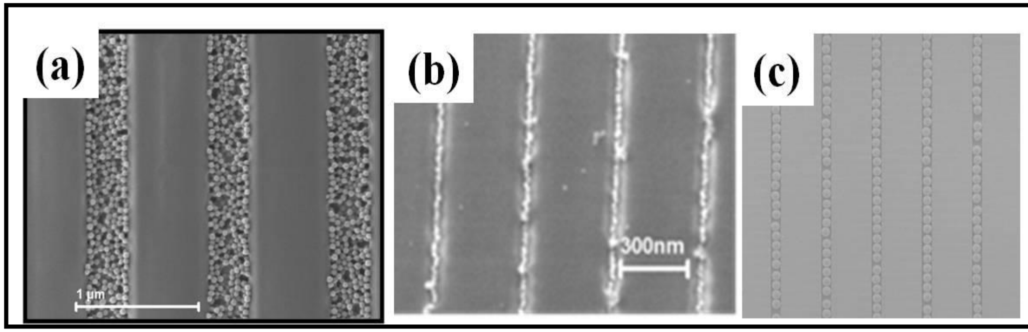
CHN Directed Assembly Toolbox

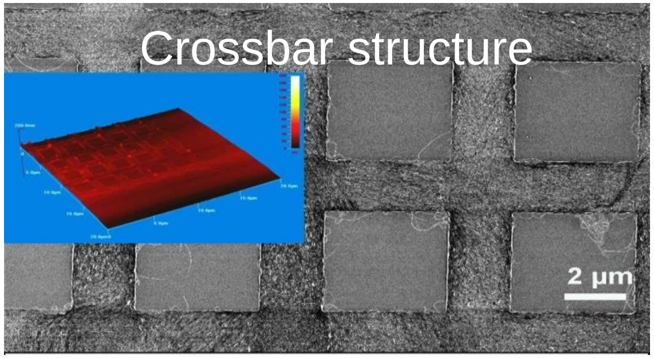
Process	Speed	Scalability	Nanoelement property	Mechanism	Demonstrated assembly of
Convective	Slow	No	Surface Functionalization	Convection	Nanoparticles
Convective interfacial	Fast	Yes	Surface functionalization and surface tension	Convection and interfacial force	Nanoparticles, 2D materials
Chemical functionalization/ fluidic	Fast/ slow	Yes	Functionalization	Chemistry	Nanoparticles, CNTs, polymers, 2D materials
Electrophoretic and chemical functionalization (NanoOPS)	Fast	Yes	Charge and surface functionalization	Electrophoresis and surface energy	Nanoparticles, CNTs, polymers, 2D materials
Electrophoretic Assembly on Conductors or Insulators	Fast	Yes	Charge	Electrophoresis	Nanoparticles, CNTs, polymers, 2D materials
Dielectrophoretic	Fast	Yes/No	Dielectric constant	Dielectrophoresis	Nanoparticles, CNTs, 2D materials, polymers,

Template Guided Chemical/Fluidic Assembly

- **Assembly of CNTs over large areas on templates with different surface energies**
  - **Hydrophobic and hydrophilic regions assist fluidic assembly**







Small, 3(12) 2006 (2007). *J. Am. Chem. Soc.*, 131 (2), pp 804 (2009).
Appl. Phys. A., 5194 (2009), *Nanotechnology*, 20, pp. 295302-308, July 2009.

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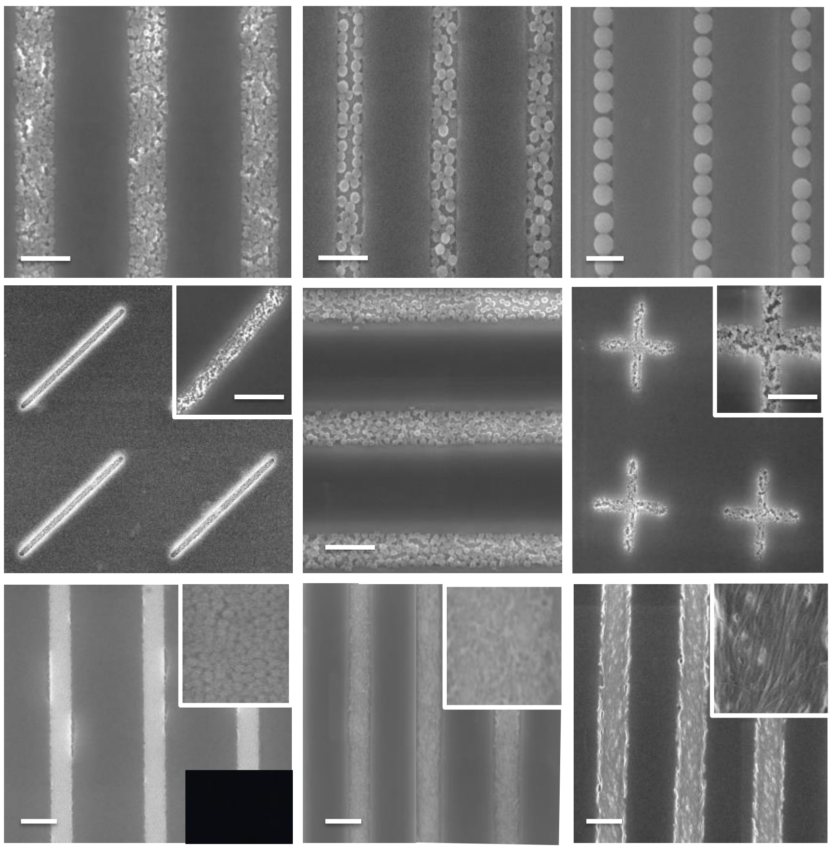
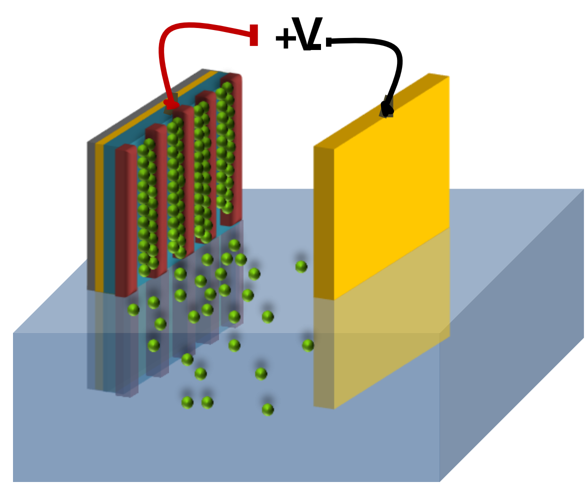
High-rate Electrofluidic Directed Assembly of Nanoelements on Insulating Surfaces



Assembly Capabilities of Electrofluidic Directed Assembly

- **Electrophoretic directed assembly on insulating substrates.**
- **Nanoparticles of multiple sizes (50nm, 100nm and 200nm) assembled into patterns at various angles to pulling direction.**
- **Silica particles, quantum dots and single-walled carbon nanotubes were successfully assembled.**



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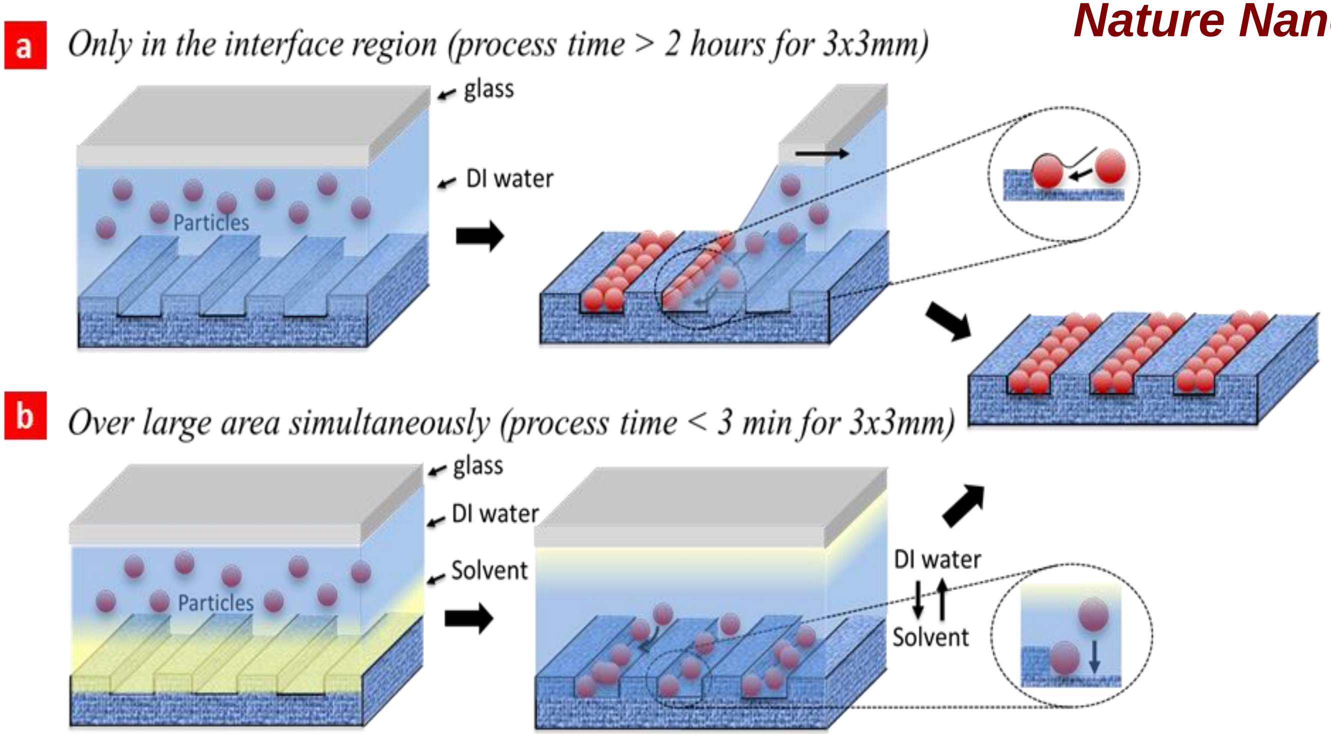
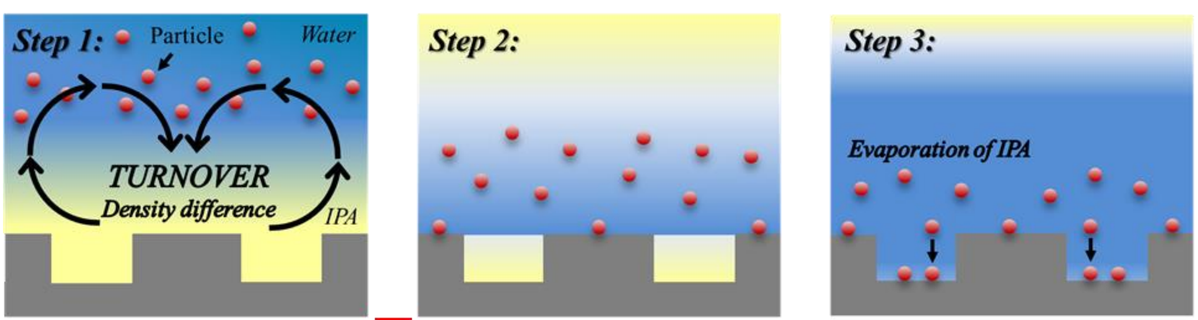
Mechanism of Interfacial Convective Assembly Results

Convective vs. interfacial connective assembly

Nature Nanotechnology, 2007.

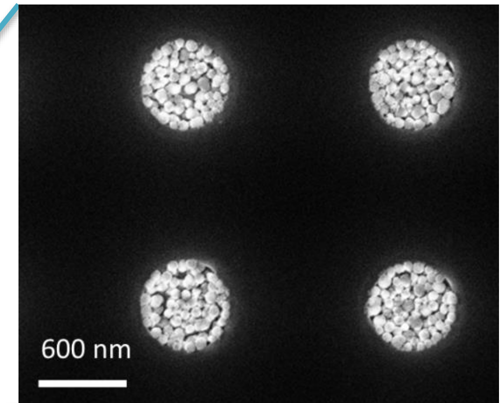


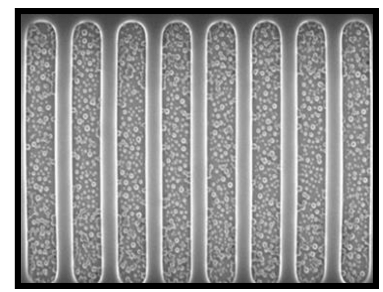
Mechanism

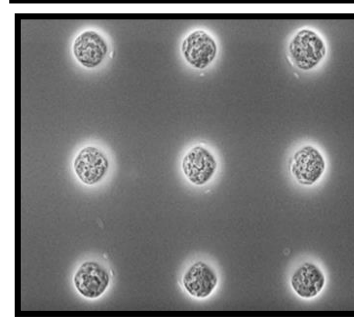


Assembly of NPs into Trench and Vias Over Large Areas

<u>Particle:</u> 30nm fluorescent (green) silica NPs
Assembly time: <10 min







<u>No electrophoretic or Di electrophoretic force is used.</u>

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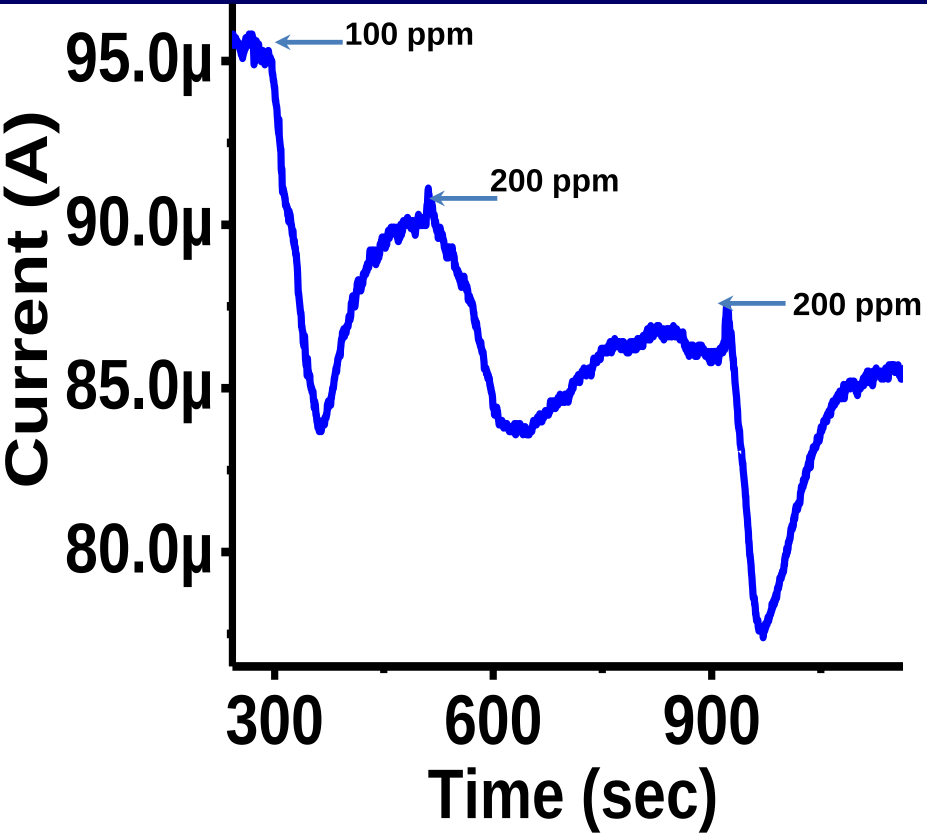
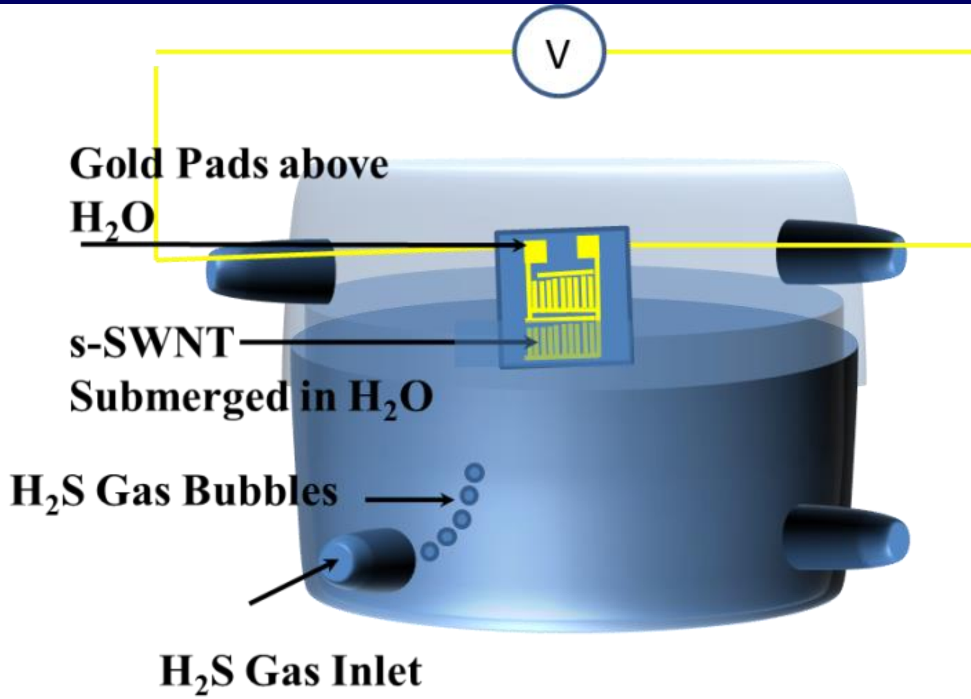
H_2S Detection in Water (Liquid)





➔ Sensor didn't recover to the baseline resistance similar to continuous testing in environments other than air

➔ The response was faster than other environments

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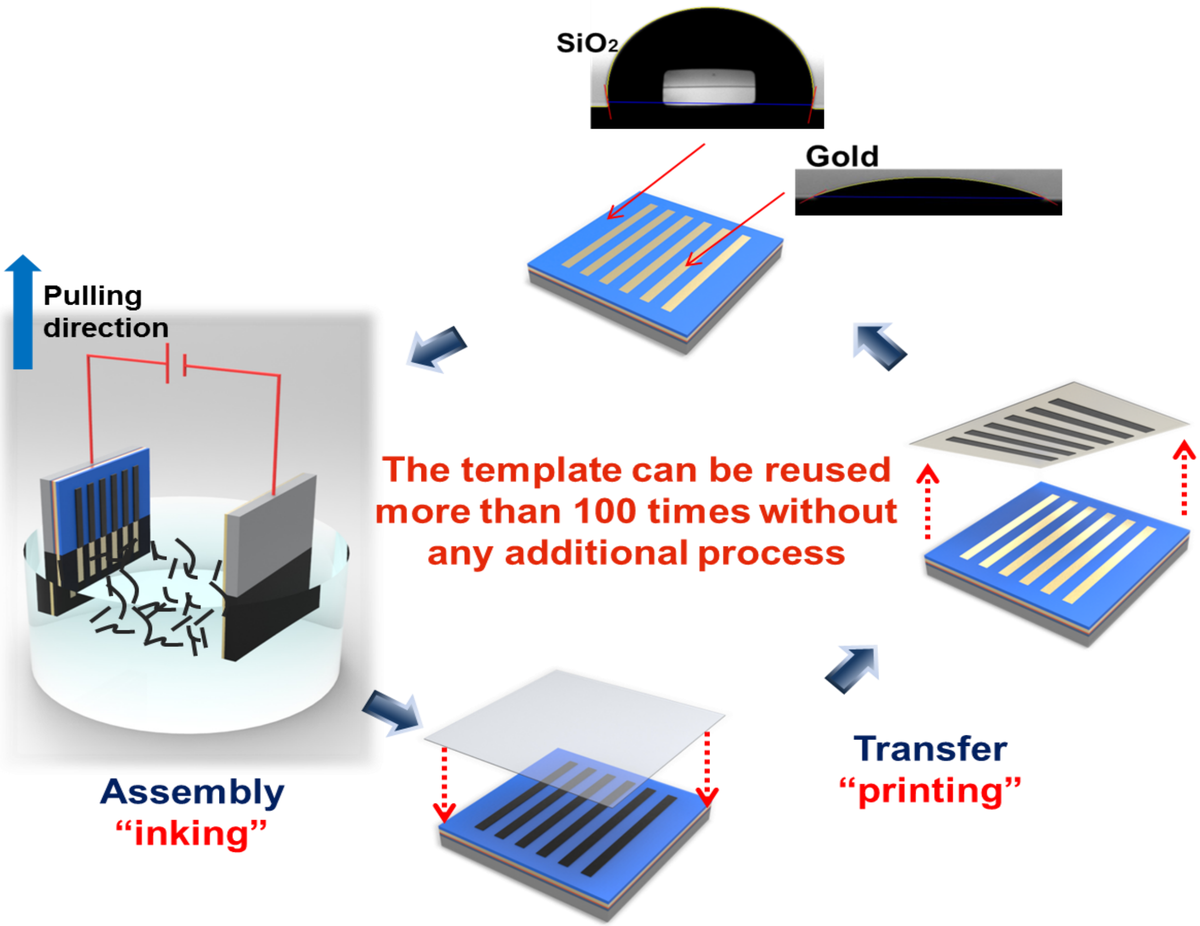
Beyond 3-D & Electronic Printing:
Nanoscale Offset Printing Advantages



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

Advanced Materials, 2015, 27, pp. 1759–1766.

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