Scalable Printing of Nanoscale Electronics and Sensors
나노 스케일 전자 및 센서의 확장 가능한 인쇄

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www.nano.neu.edu

www.nanomanufacturing.us

Northeastern University

NSF

Center for High-rate Nanomanufacturing

Motivation: Cost

Financial and Environmental Cost

Commercial electronics device manufacturing is still expensive, with fabs costing up to 15 billions and requiring massive quantities of water and power.

1990s - $1B-$2B

2016 - $17B

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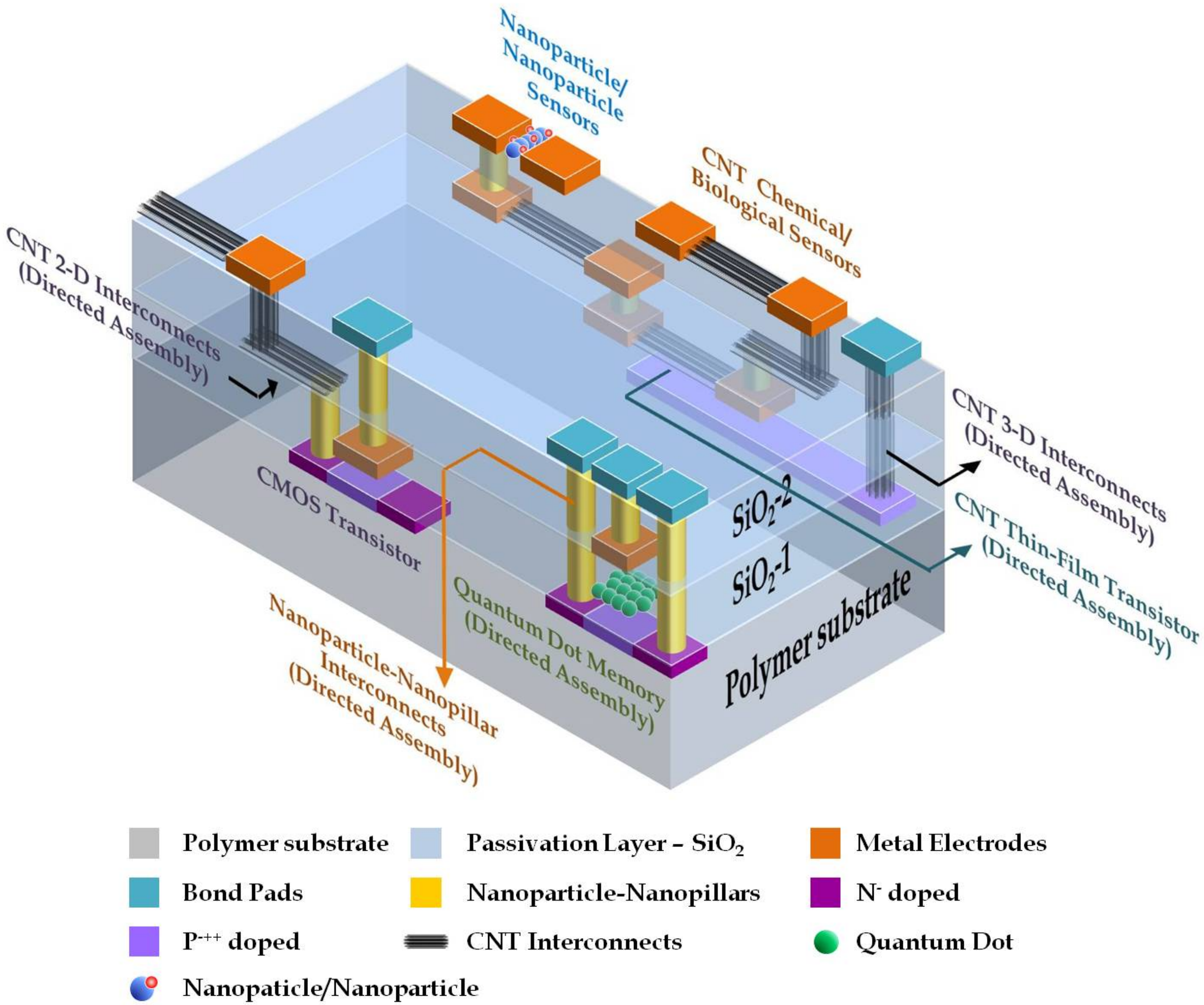
Motivation: Versatility

Can we print any material on any substrate?



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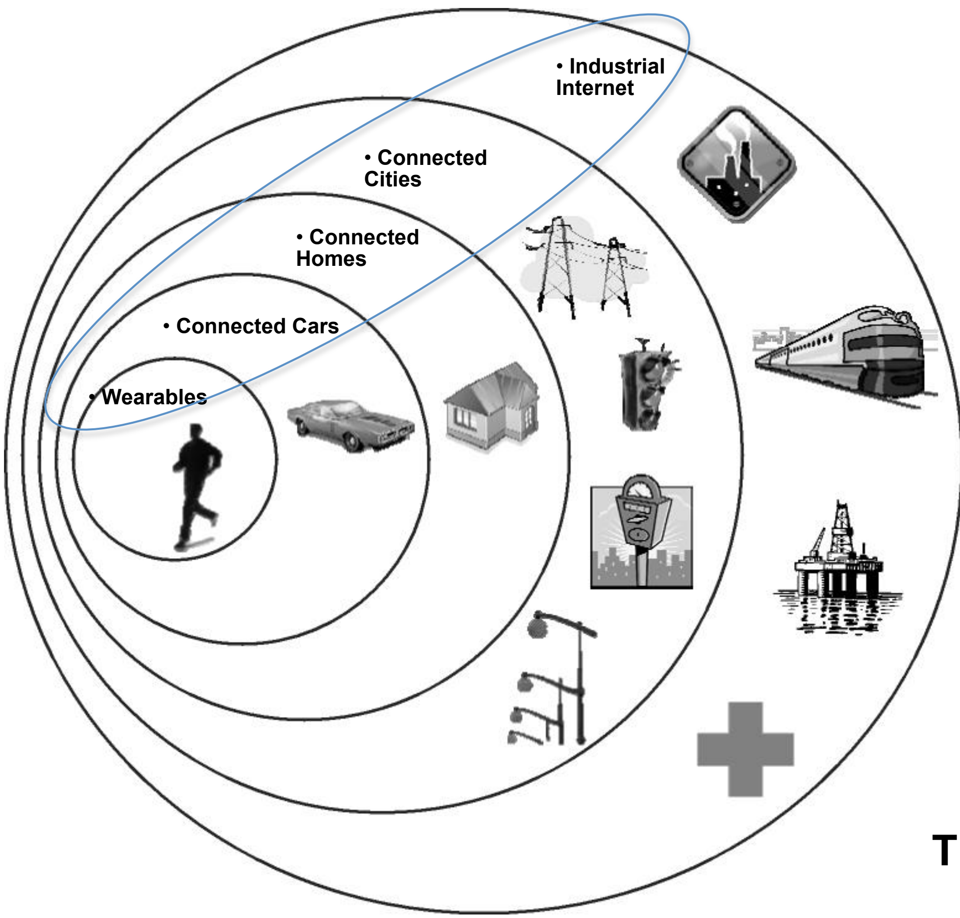
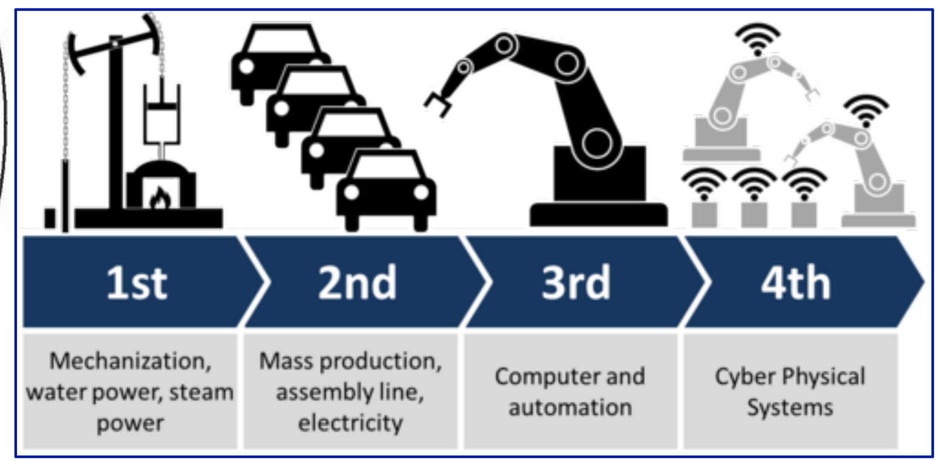
Motivation: IoT Opportunities

IoT has five key verticals: **Wearable Devices, Cars, Homes, Cities**, and the **Industrial Internet. Impact by 2025 is $3.9-$11.1 Trillions.**



The IoT can only be enabled by breakthroughs in the cost of **ubiquitous sensors** for collecting and sharing data



The four industrial revolutions & Industry 4.0; Industrial Internet

The Goldman Sachs Group, Inc. Global Investment Research (2014)

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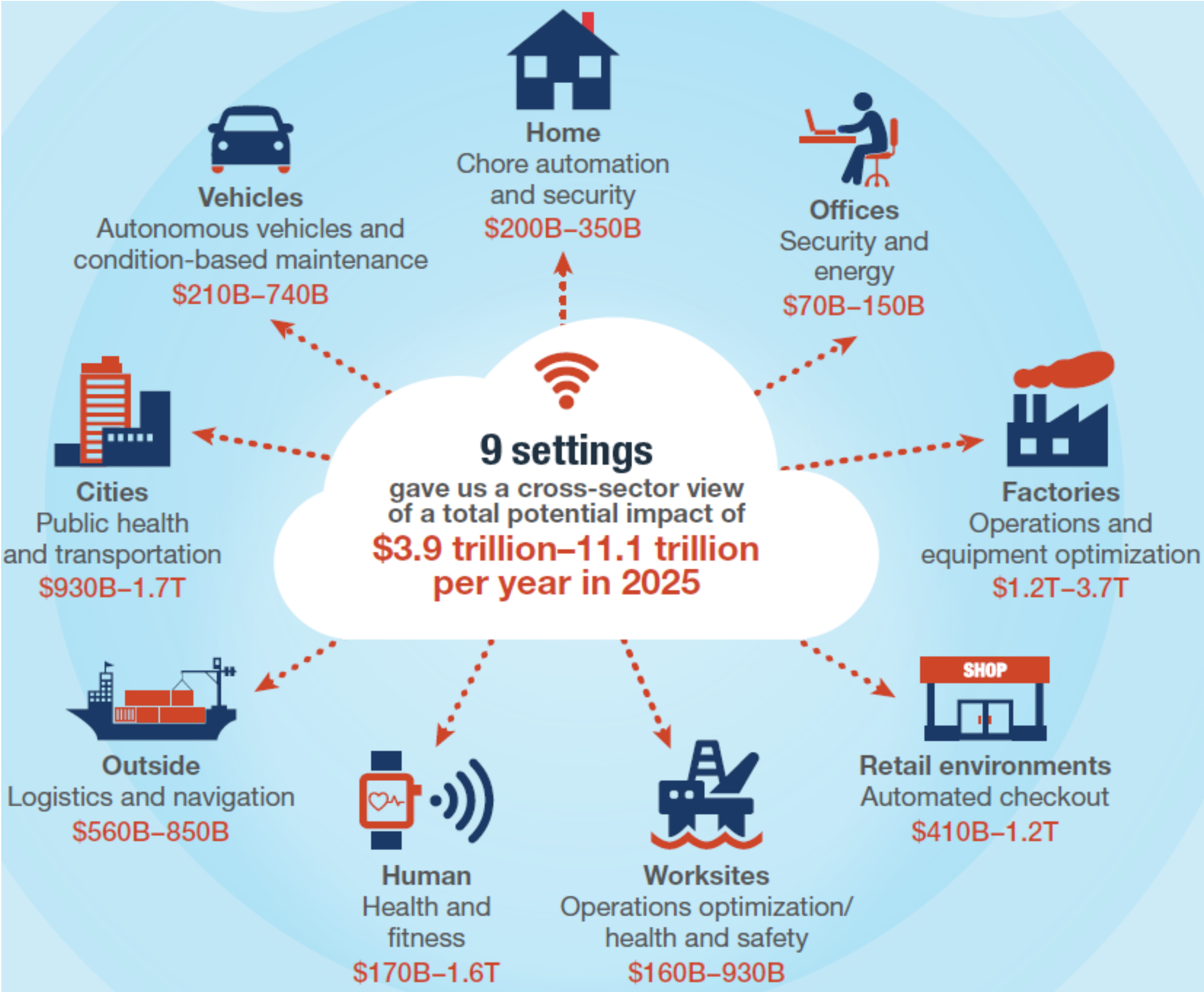
The IoT Nine Applications

Nine key areas where IoT is expected bring up to $11Trillion in 2025.



McKinsey Global Institute, 2016.

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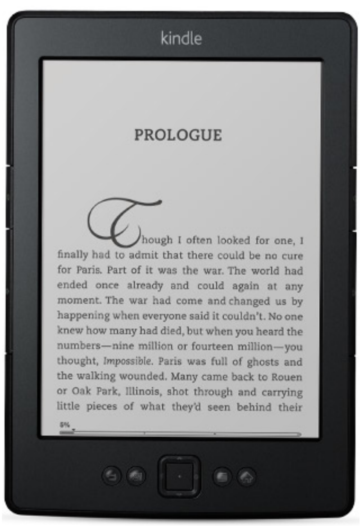
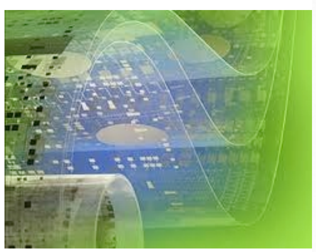
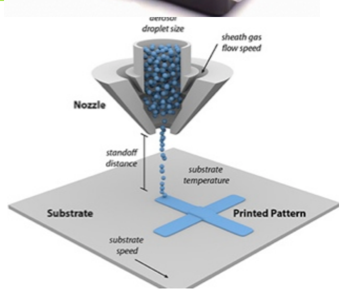
State of the Art - Printing Technologies

- **Current electronics and 3D printing using inkjet technology, used for printing low-end electronics but can only print down to 20 microns (20,000 nanometers).**
- **20 microns was the silicon electronics line width in 1975.**
- **Cost of a currently printed electronics is 10 to 100 times less than the cost of current silicon-based sensors.**







- **A printing technology is needed that can print conductive, semiconducting, and insulating materials (inorganic or organic) down to 20nm and 1000 times faster than inkjet.**
- **There is need to print Inter-connected multilayers.**

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How can electronic printing leap from 1975 to Today?

The NSF Center for High-rate Nanomanufacturing has developed the technology to prints electronics with 20 nm minimum line width or smaller.

However, is nanoscale printing alone enough?

- For printed electronics and devices to compete with current silicon-based nano and microscale electronics, it has to print nanoscale features at:
  - orders of magnitudes faster than inkjet based printers and
  - cost should be fraction of the current cost for making silicon-based electronics

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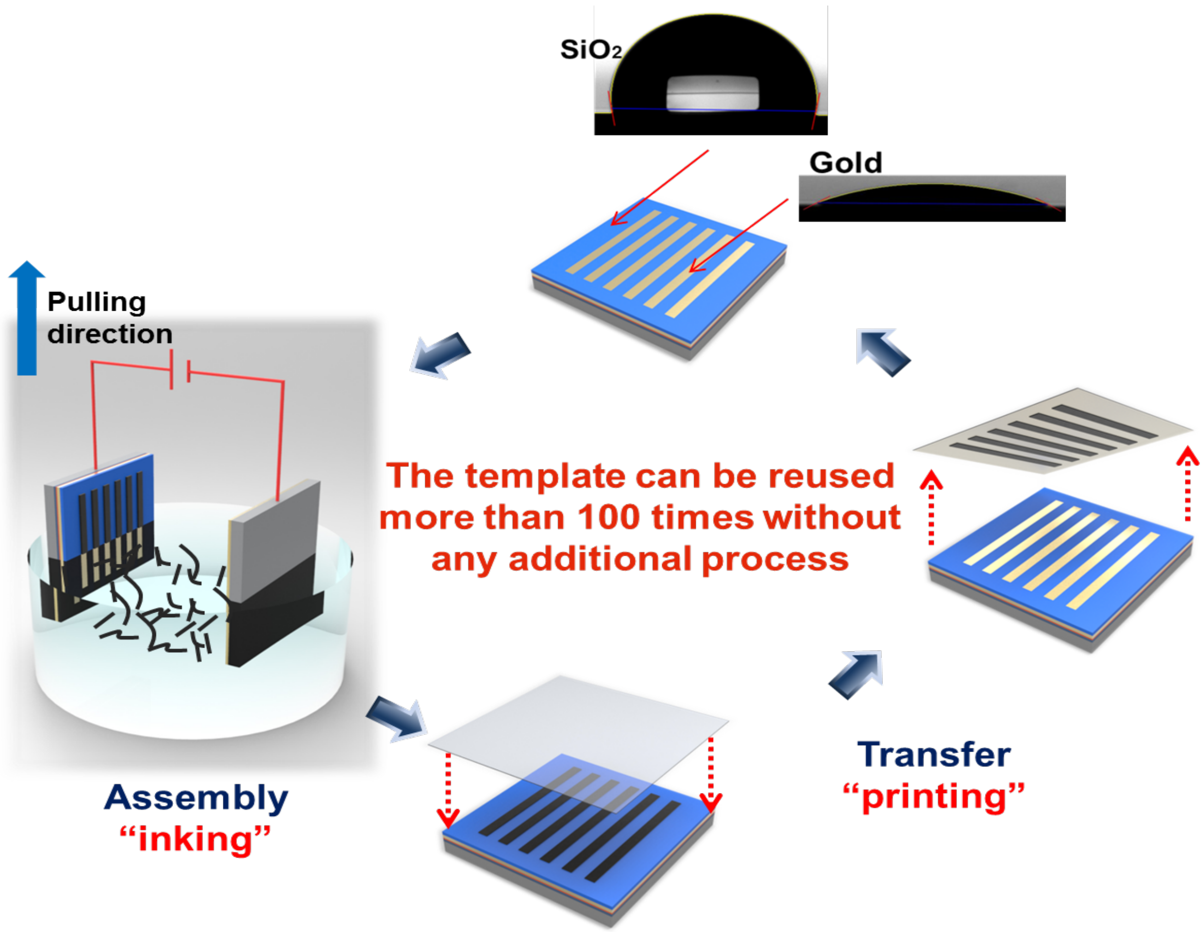
CHN Directed Assembly Toolbox

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,

How does it work?

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



- Additive
- 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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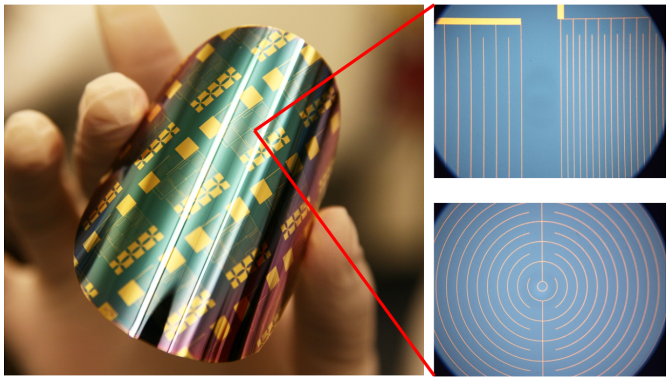
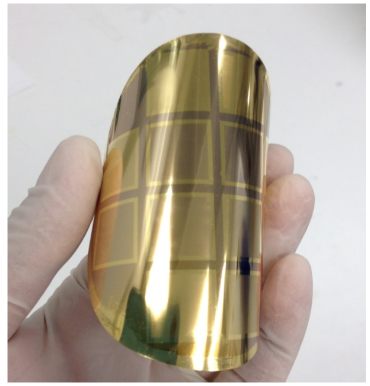
Damascene Templates for Nanoscale Offset Printing

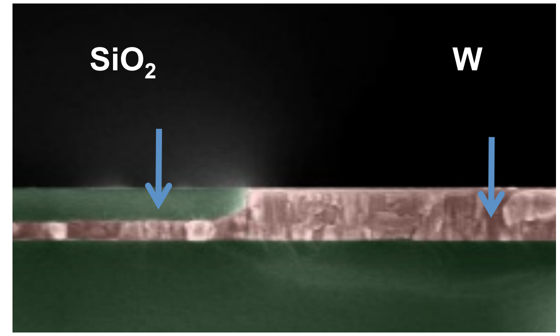


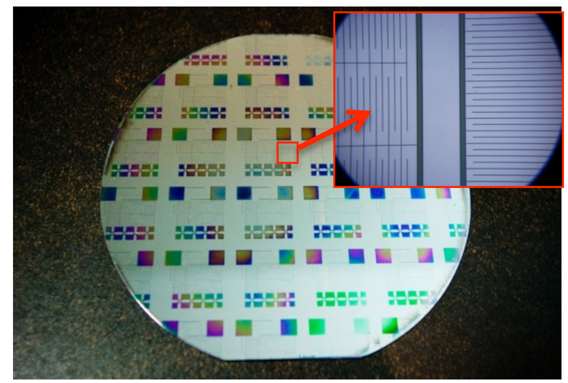


PEN

Polymer-based Templates

PI

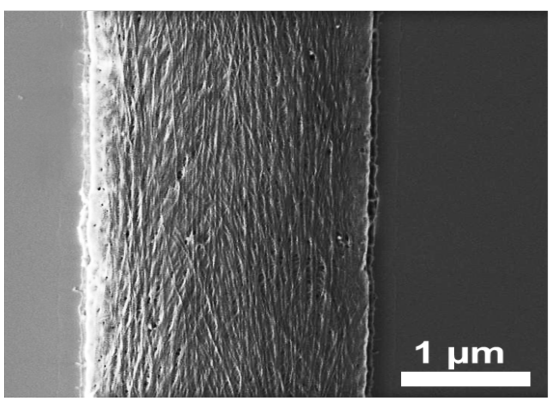




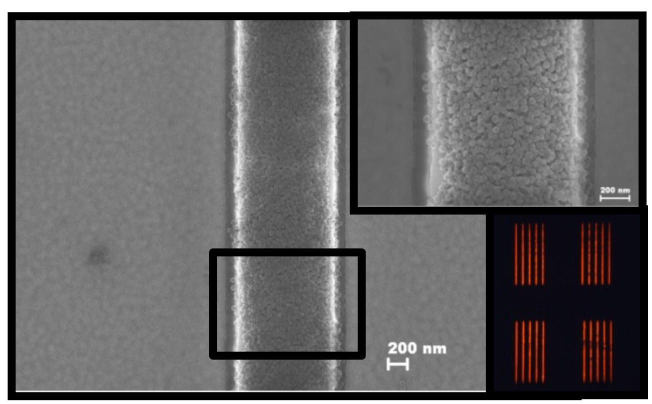
Silicon-based Hard Templates

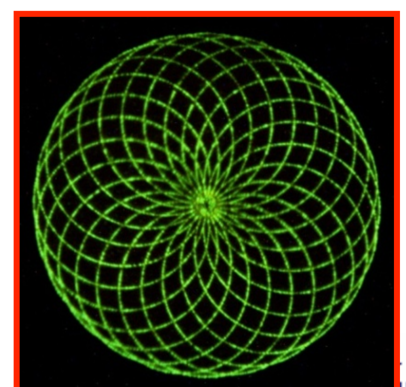
Advanced Materials, 2015

Assembled SWNT



Assembled Particles





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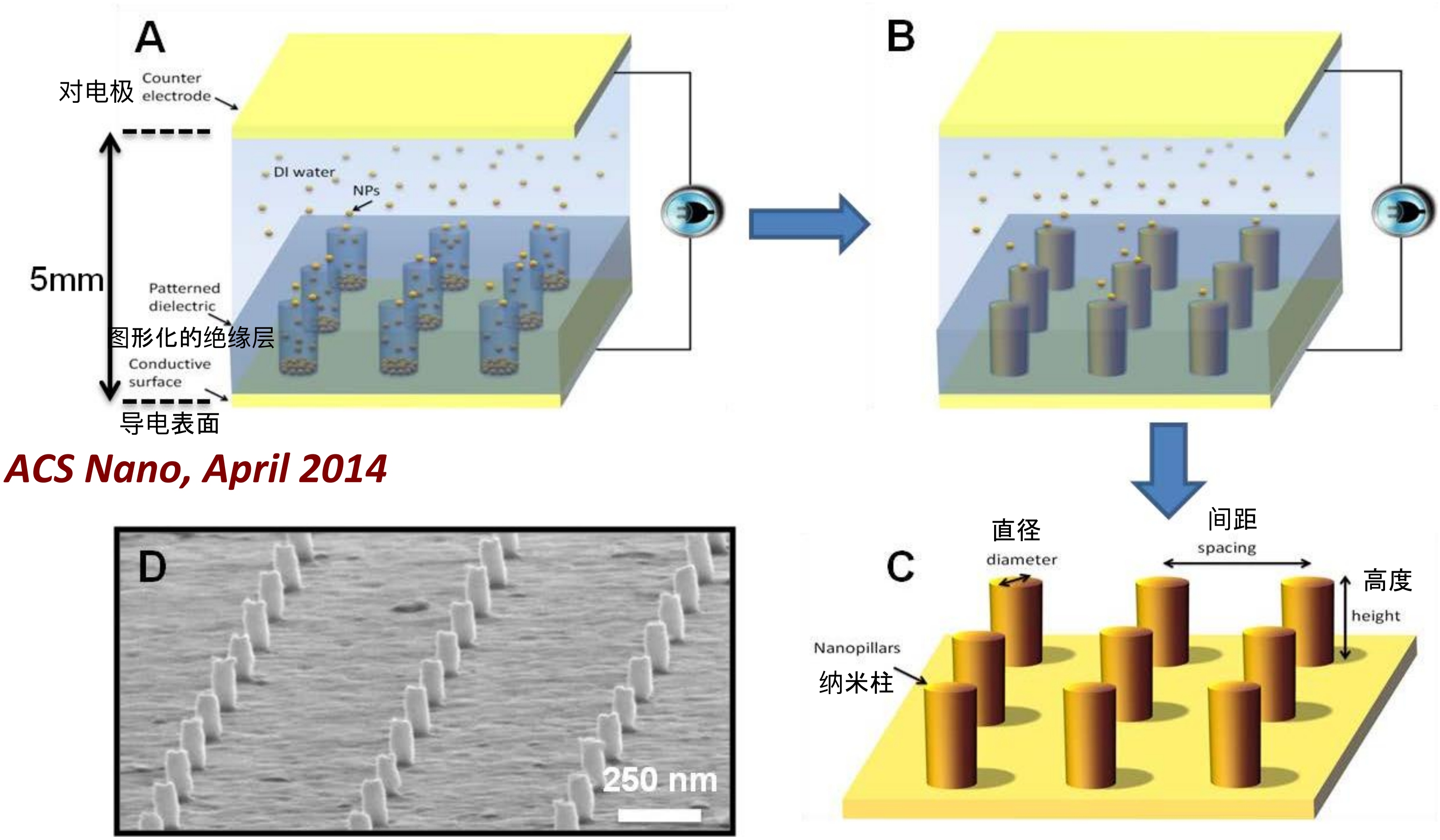
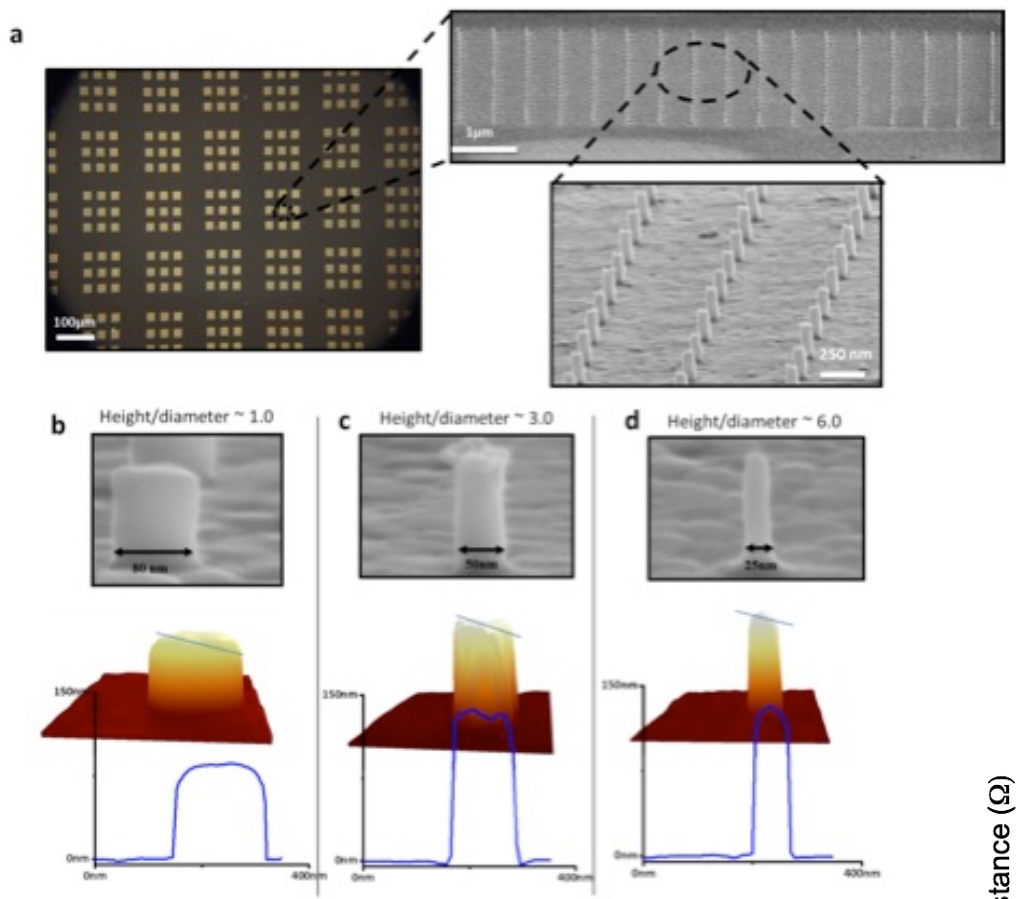
Directed Assembly-based Printing of Interconnects
用于互连的定向自组装

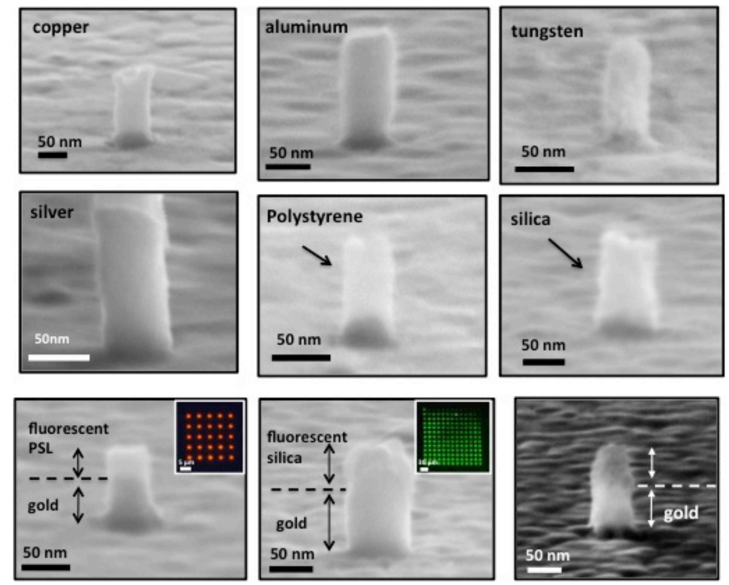


ACS Nano, April 2014

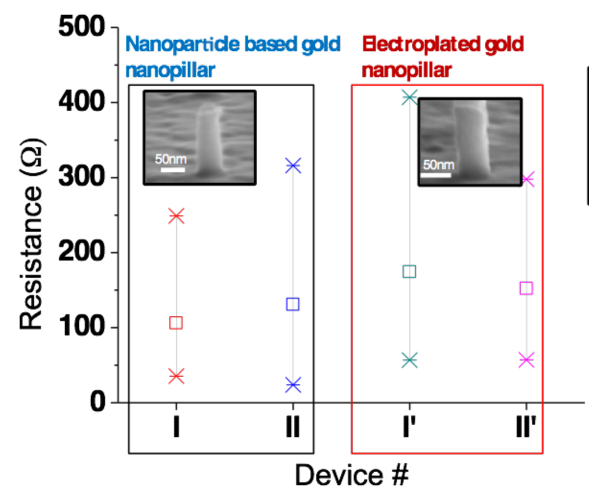
•Manufacturing of 3-D nanostructures using directed nanoparticle assembly process. **(A and B)** NPs suspended in aqueous solution are **(A)** assembled and **(B)** fused in the patterned via geometries under an applied AC electric field. **(C)** Removal of the patterned insulator film after the assembly process produces arrays of 3-D nanostructures on the surface. **(D)** Scanning electron microscopy (SEM) image of gold nanopillar arrays. 使用纳米颗粒定向自组装工艺制造3D纳米结构。（A和B）水溶液中的纳米颗粒在交流电场的作用下被组装（A）到孔形的结构中，并熔化（B）形成纳米柱。（C）组装结束后，去除用于形成孔形结构的绝缘薄膜就会出现成列的3D纳米结构。（D）金纳米柱阵列的扫描电镜图片。

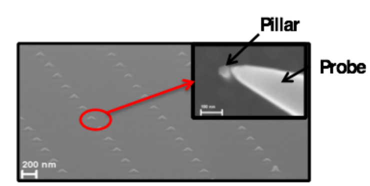
Fabrication of Interconnects with Controlled dimensions
尺寸可控的互连结构制造





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





- ➢ Fabrication over a large area.
- ➢ Controlled, repeatable and reliable fabrication.

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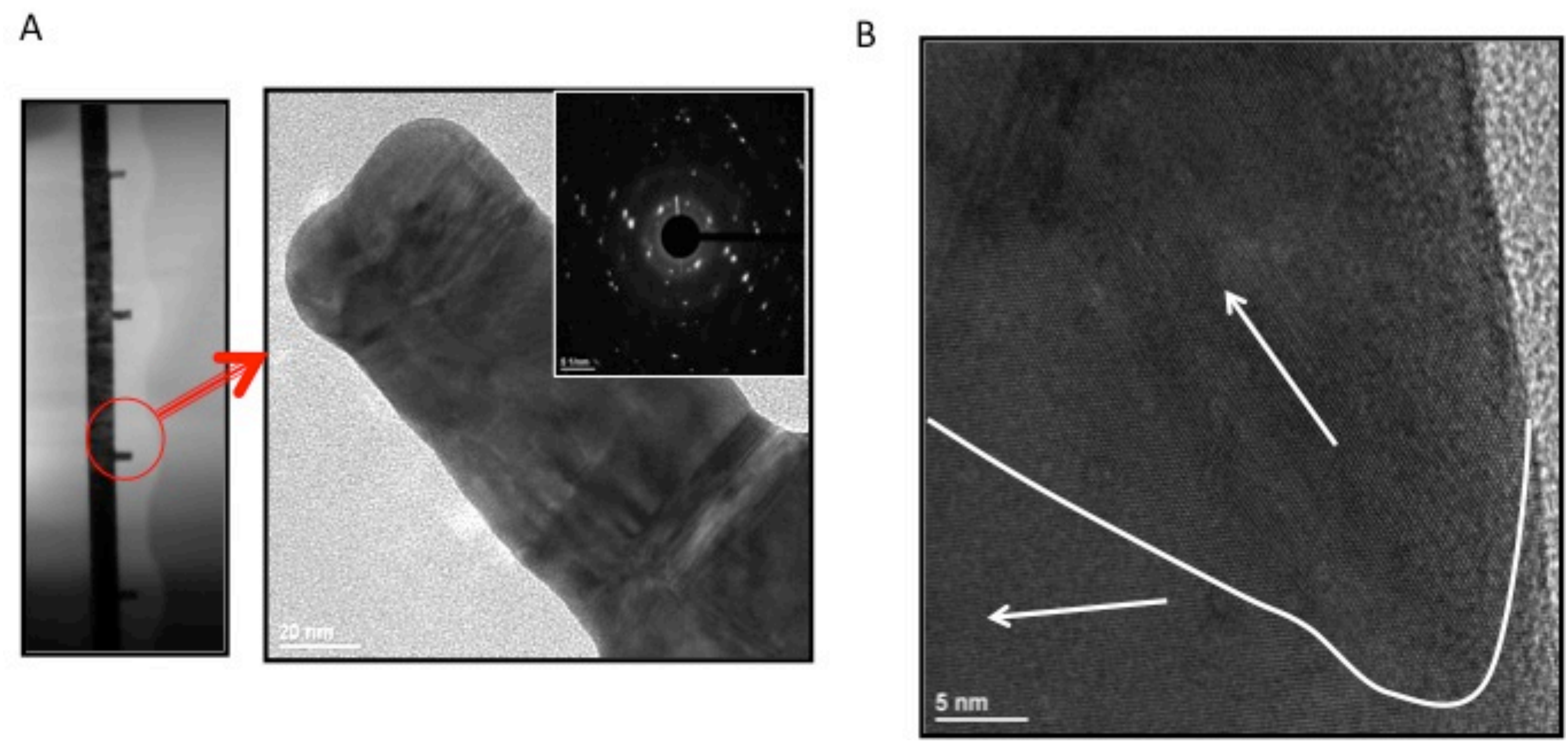
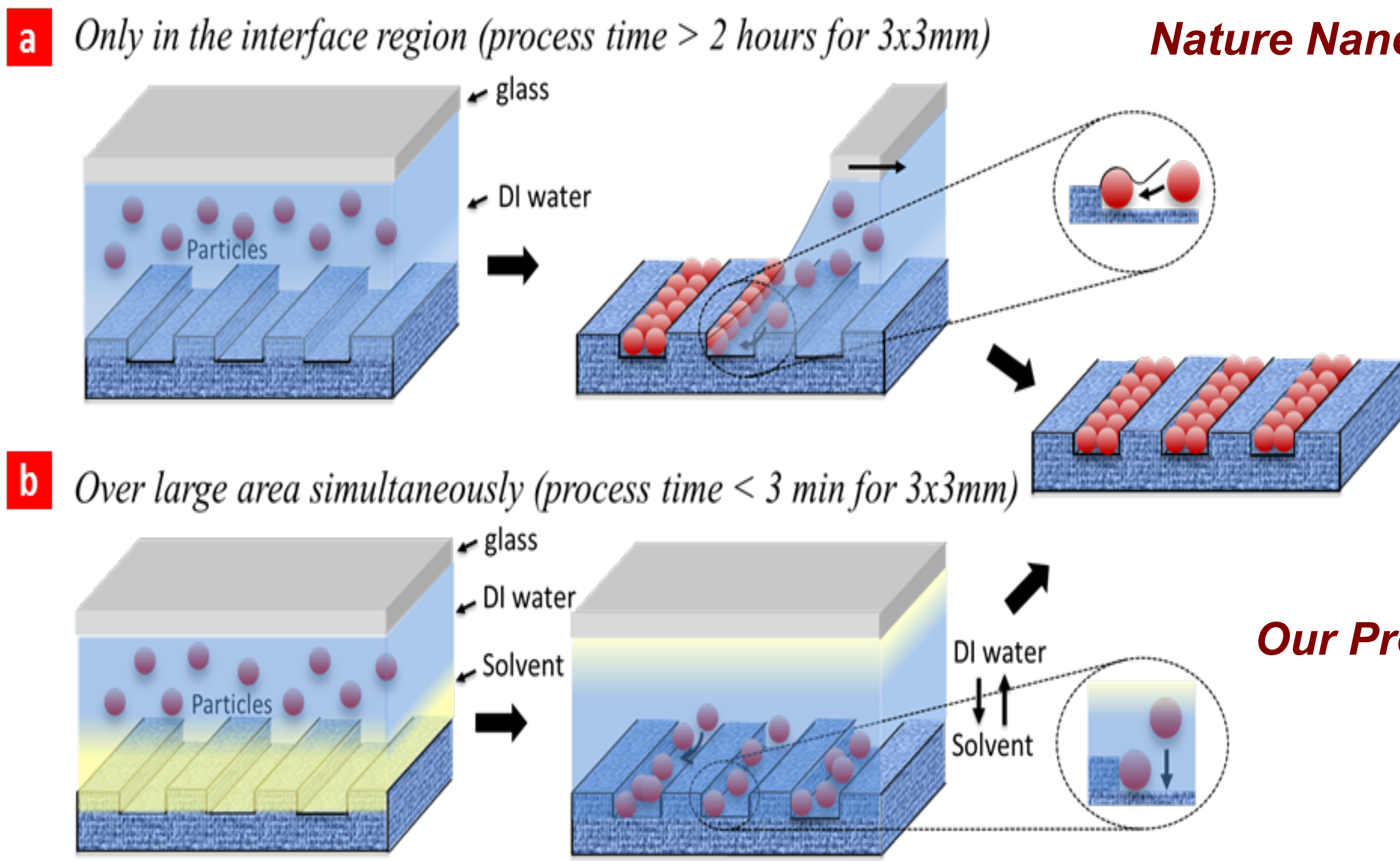
Do particles completely fuse following the assembly?



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

Mechanism of Interfacial Convective Assembly Results

Convective vs interfacial connective assembly

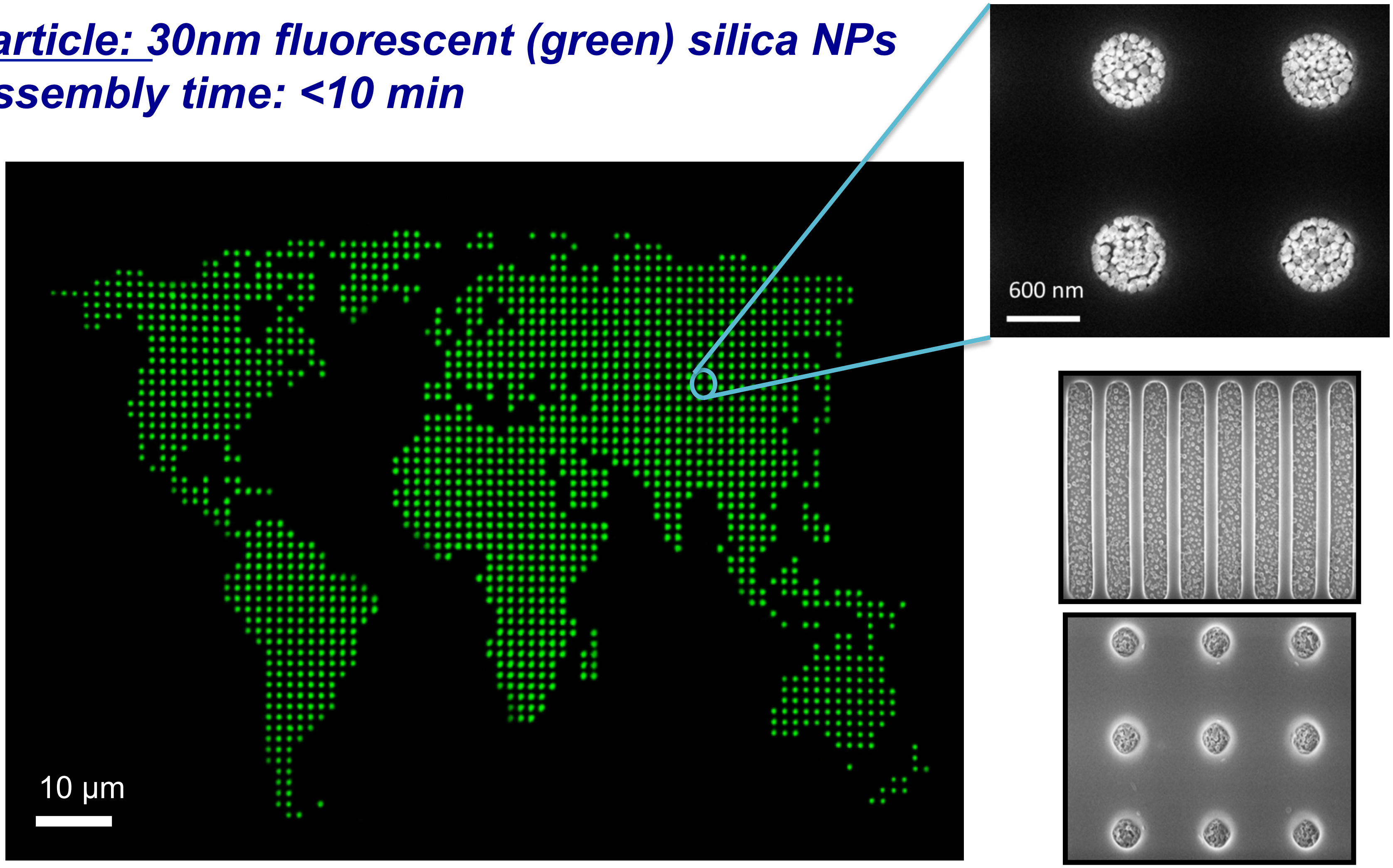


Nature Nano 2007

Our Process

Assembly of NPs into Trench and Vias Over Large Areas

***Particle:* 30nm fluorescent (green) silica NPs**
Assembly time: <10 min



No electrophoretic or Di electrophoretic force is used.

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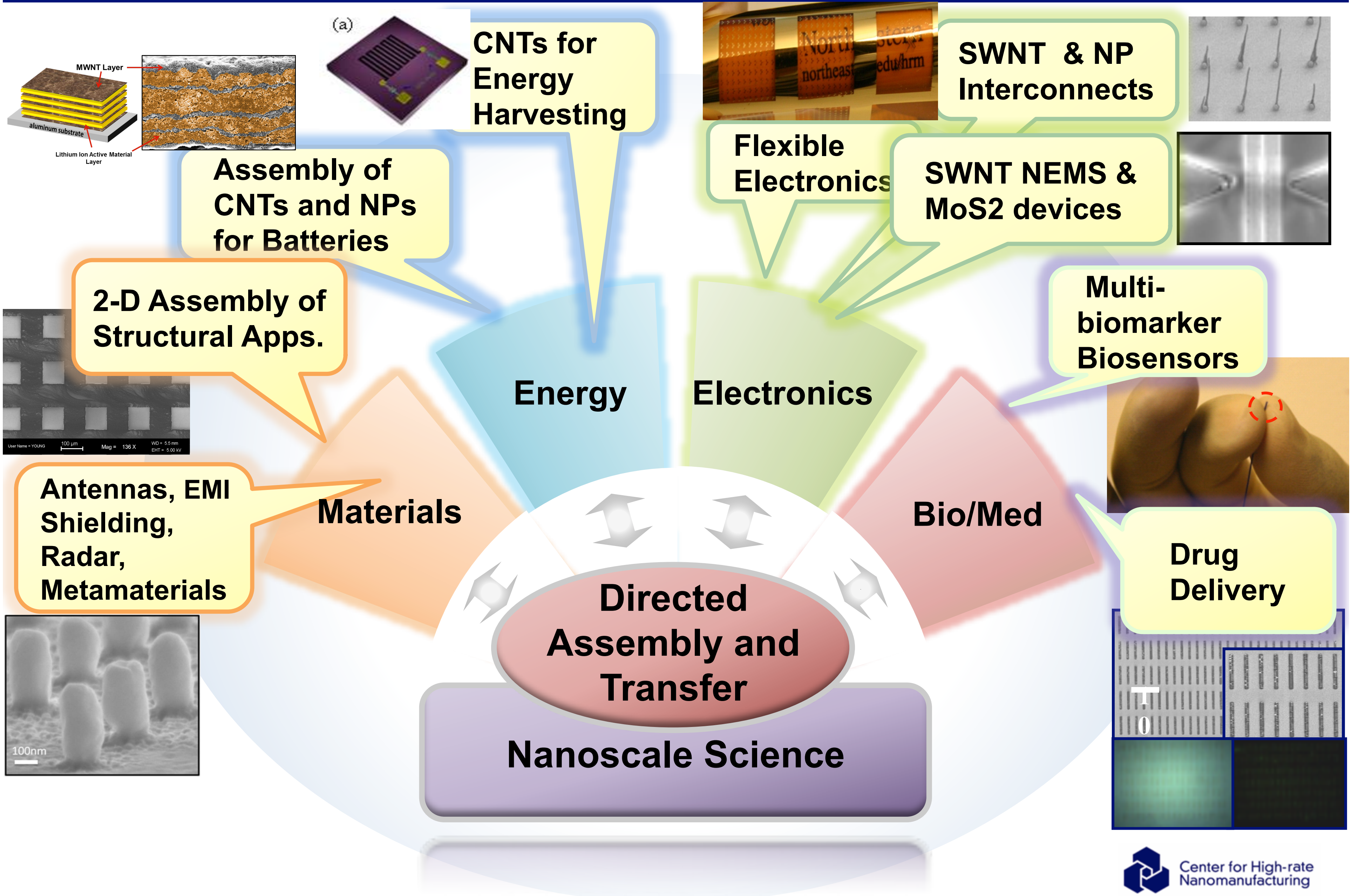
What Could We manufacture with Multiscale Offset Printing?



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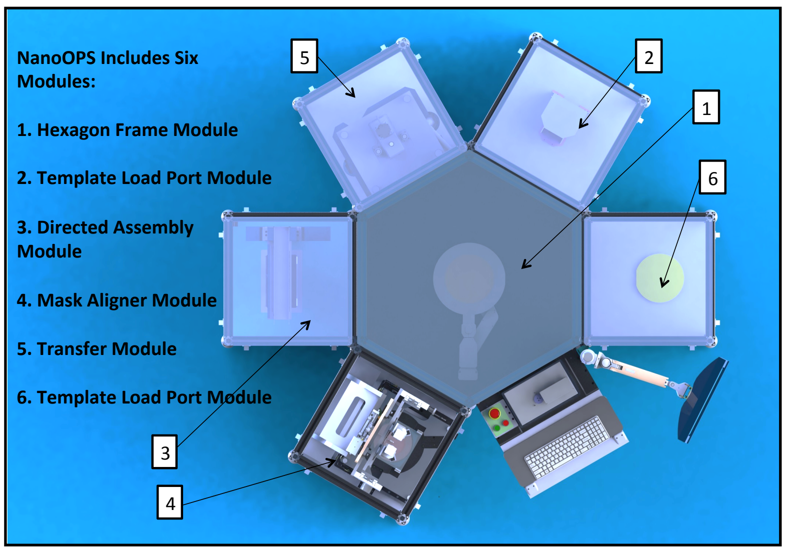
The world's first Printer NanoOPS (Nanoscale Offset Printing System)

- **Capable of printing down to 20nm, 1000 times faster than inkjet and costs 10 to 100 times less than conventional nanofabrication.**
- **Fully automated and integrated registration and alignment.**



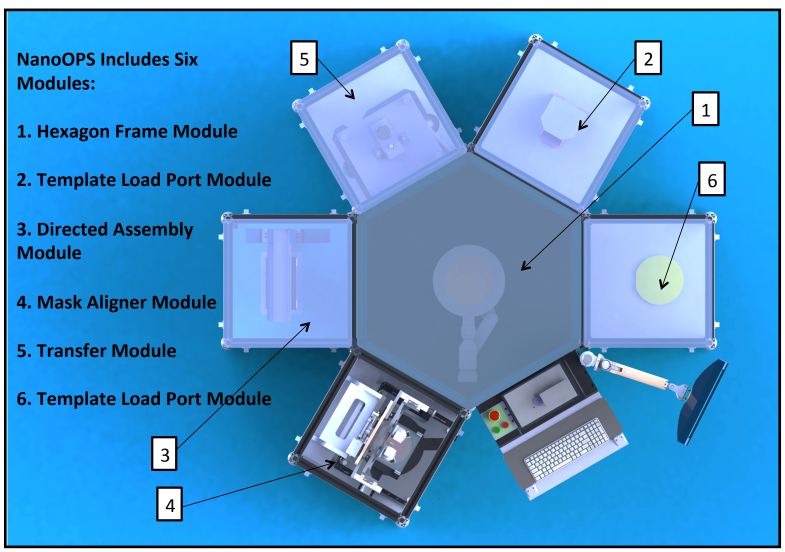
Present: Microelectronics Factory: $10B-$15B >>>>
Future: Nanomanufacturing Factory: $50-$100M

MILARA

Center for High-rate Nanomanufacturing

Fully Automated Nanoscale Offset Printing System (NanoOPS) Prototype was Demonstrated to more than 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=2iEjlcog774

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

MILARA

The World’s First Nanoscale Printer for Electronics Awards and Publicity

2016 FLEXI AWARD

Printed Electronics Conf., Berlin 2016

AWARD WINNER EUROPE 2016

Best Academic R&D Award

IDTechEx Show! EUROPE 2016

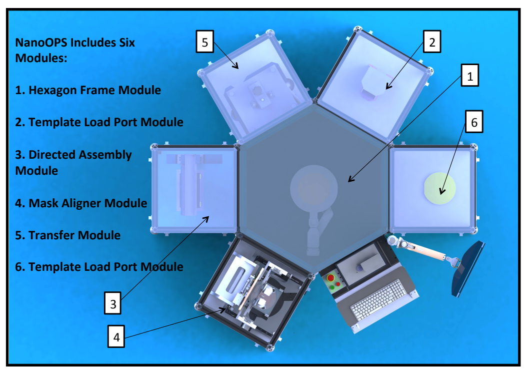
2015 R&D 100 FINALIST

THE WIRED WORLD IN 2015

The Boston Globe

BOSTON Herald WWW.BOSTONHERALD.COM

The world’s first Nanoscale Printing System for electronics and sensors.



1000 times faster printing with a 1000 times smaller features than inkjet or 3D printing.

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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

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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 LABORATORY
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

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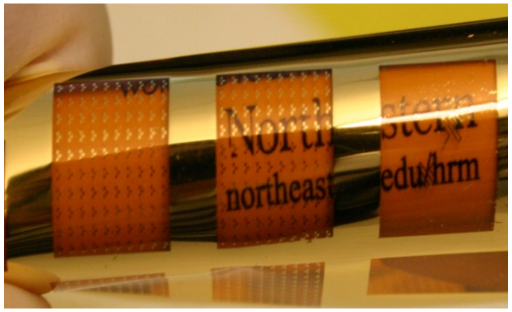
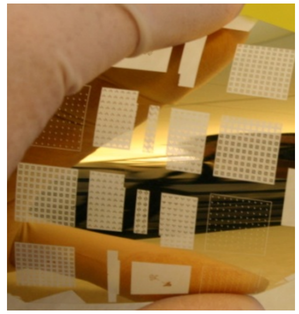
Applications

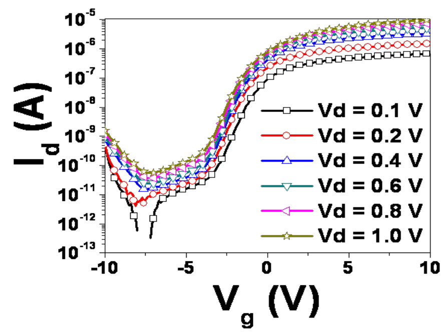
Nanoelectronics
Using 0, 1 and 2 D Nanomaterials, Organic Semiocnductors or Inorganic Narrow or Wide-Bandgap Semiconductors.

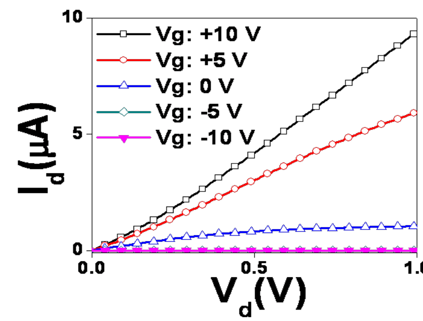
Printed Nanomaterials-based Electronics

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

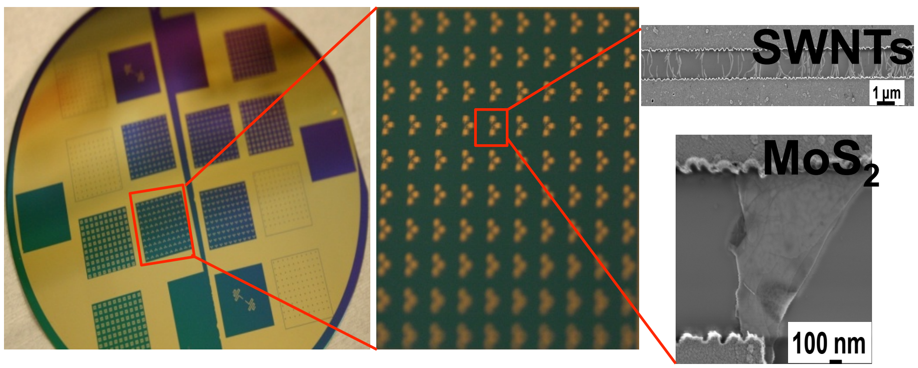


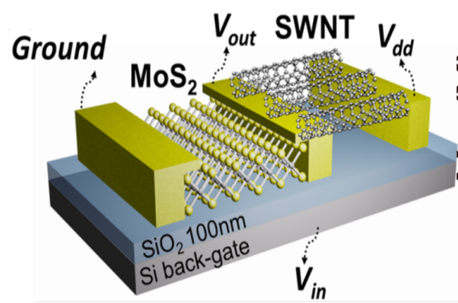


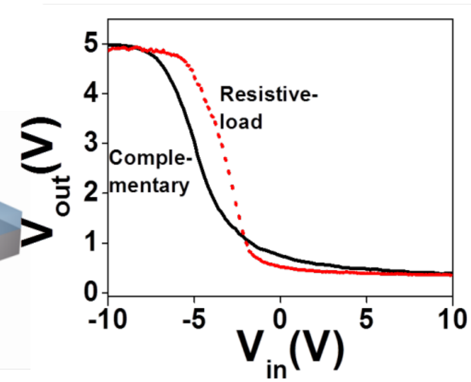




- **Heterogeneous SWNTs and MoS_2 complimentary invertors**



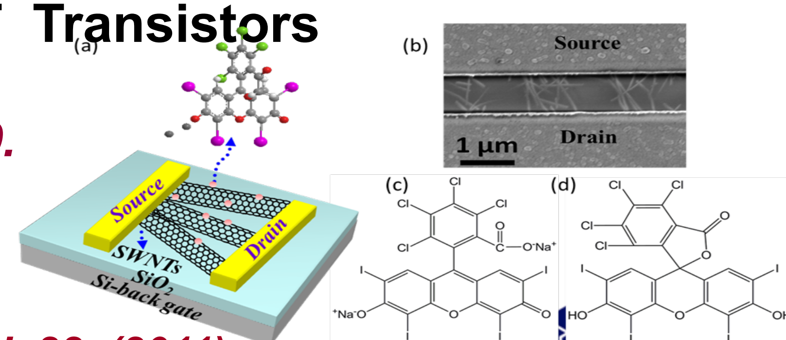




***Nanotechnology**, Vol. 23, (2012).*

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

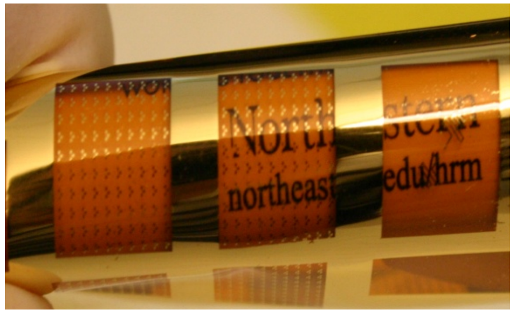
Appl. Phys. Lett. 97, 1 2010.

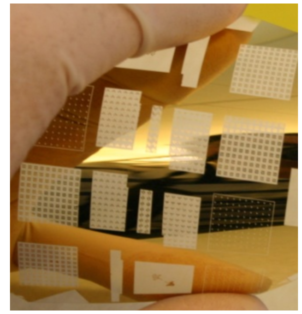


Nanotechnology, Vol. 22, (2011)

Printing Nanomaterials-based Electronics

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





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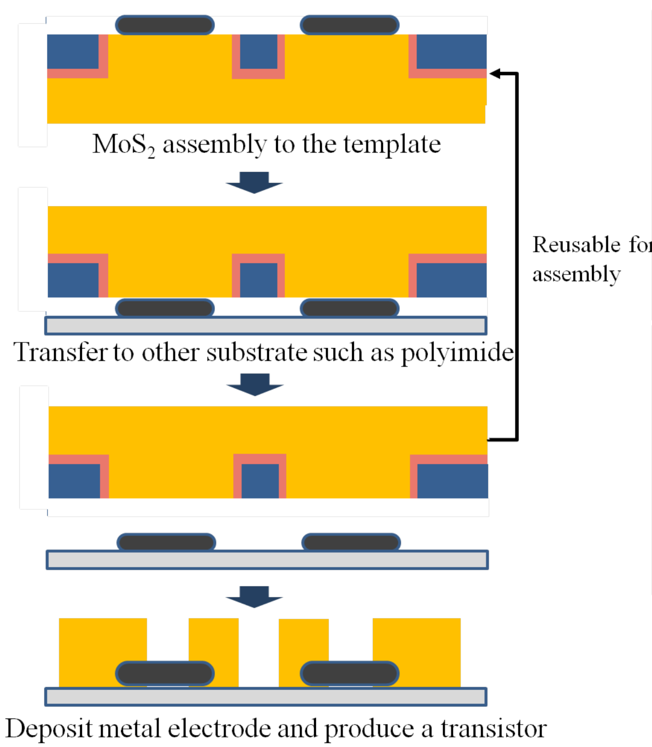

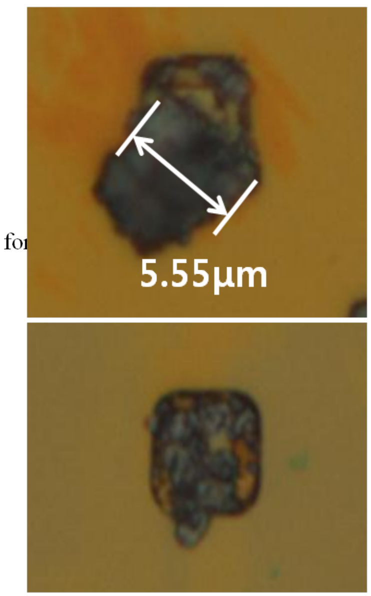

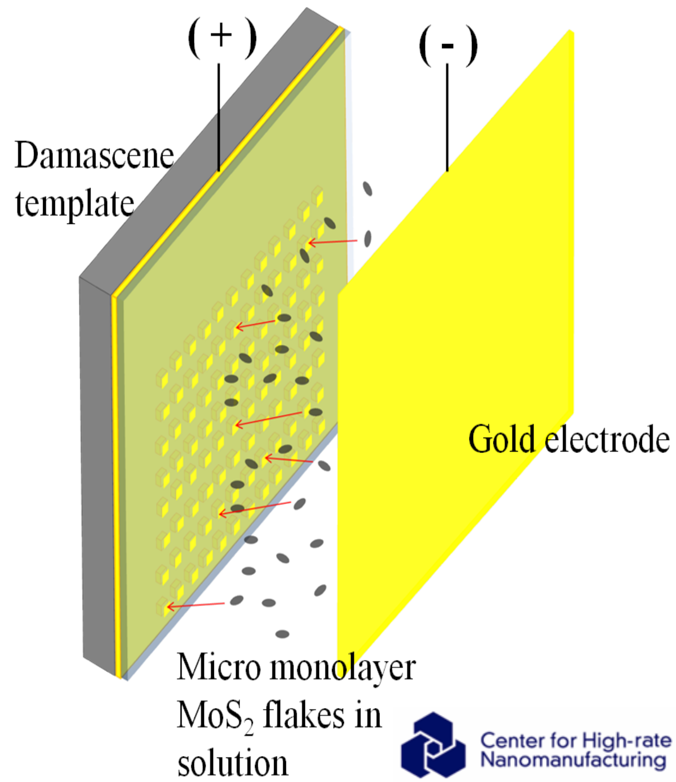

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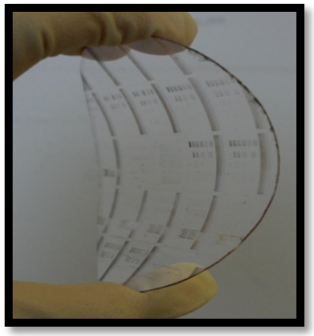
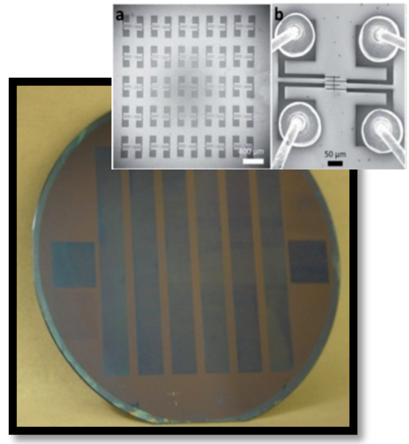
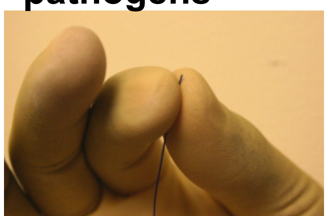
Printing Wireless Sensors and Electronics at a Fraction of their Current Cost

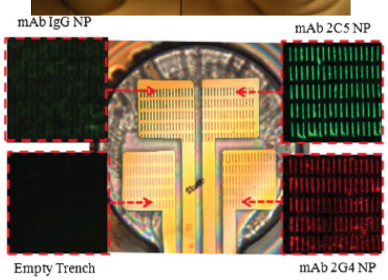




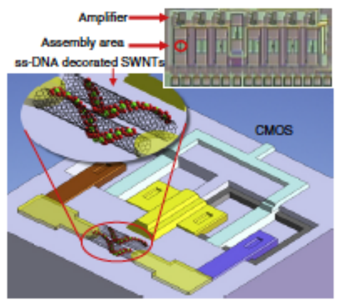
Sensors for Chemicals

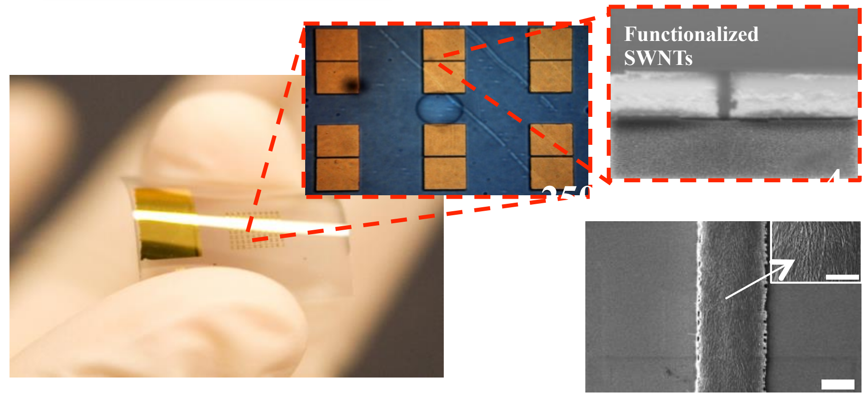
Sensors for E. coli bacteria, viruses, and other pathogens



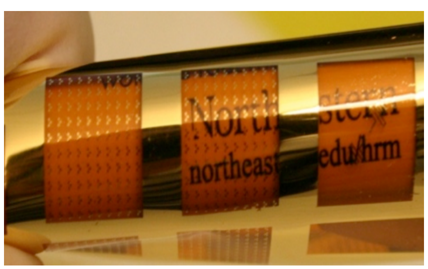


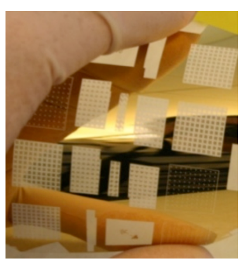
Cancer and cardiac diseases.
Detection limit is 200 times lower than Current technology

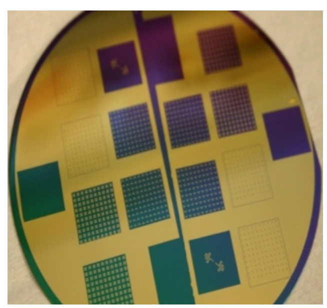




Band-Aid sensor

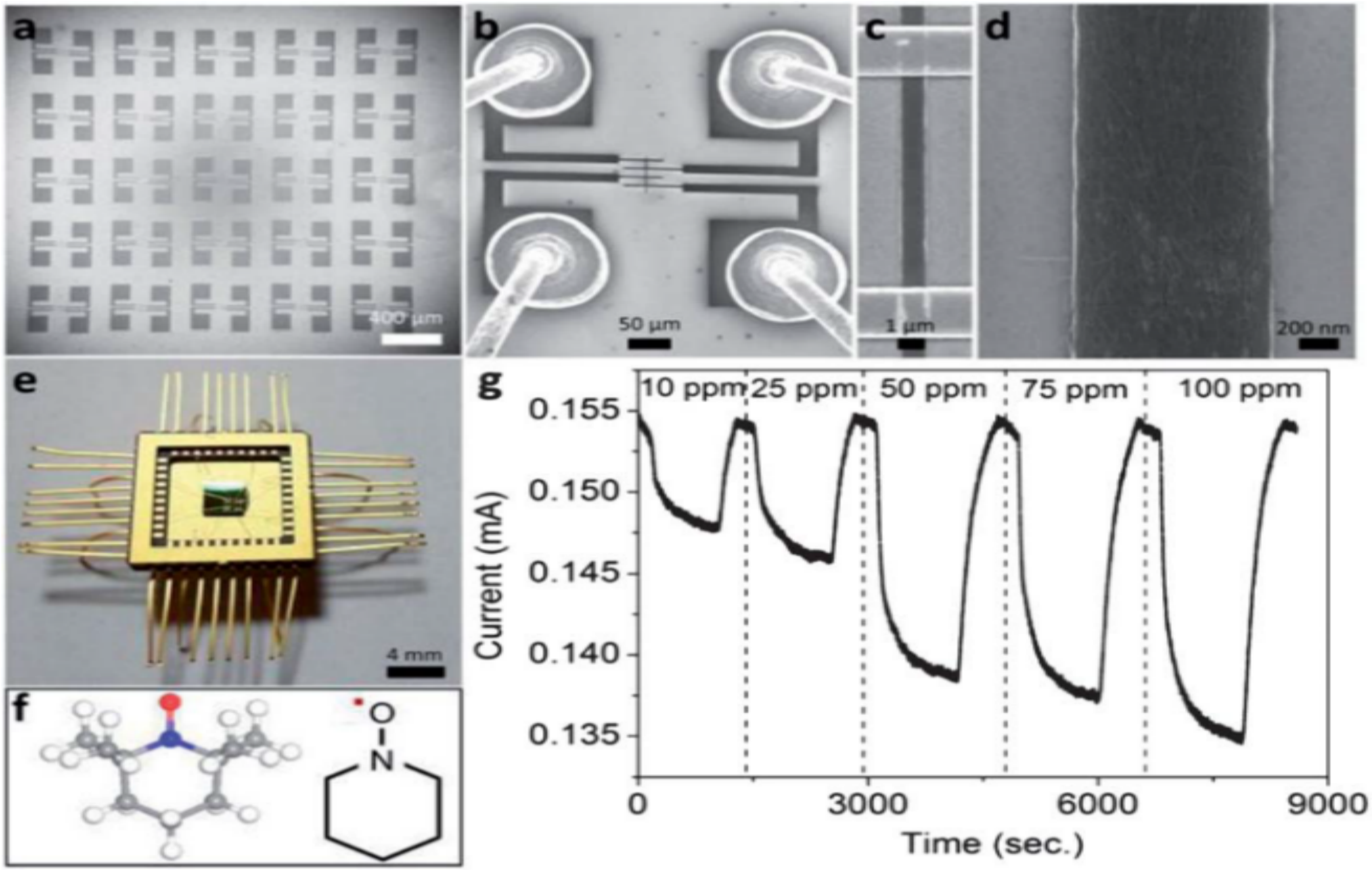






Supporting printed electronics for sensor systems

Printed Chemical Sensors

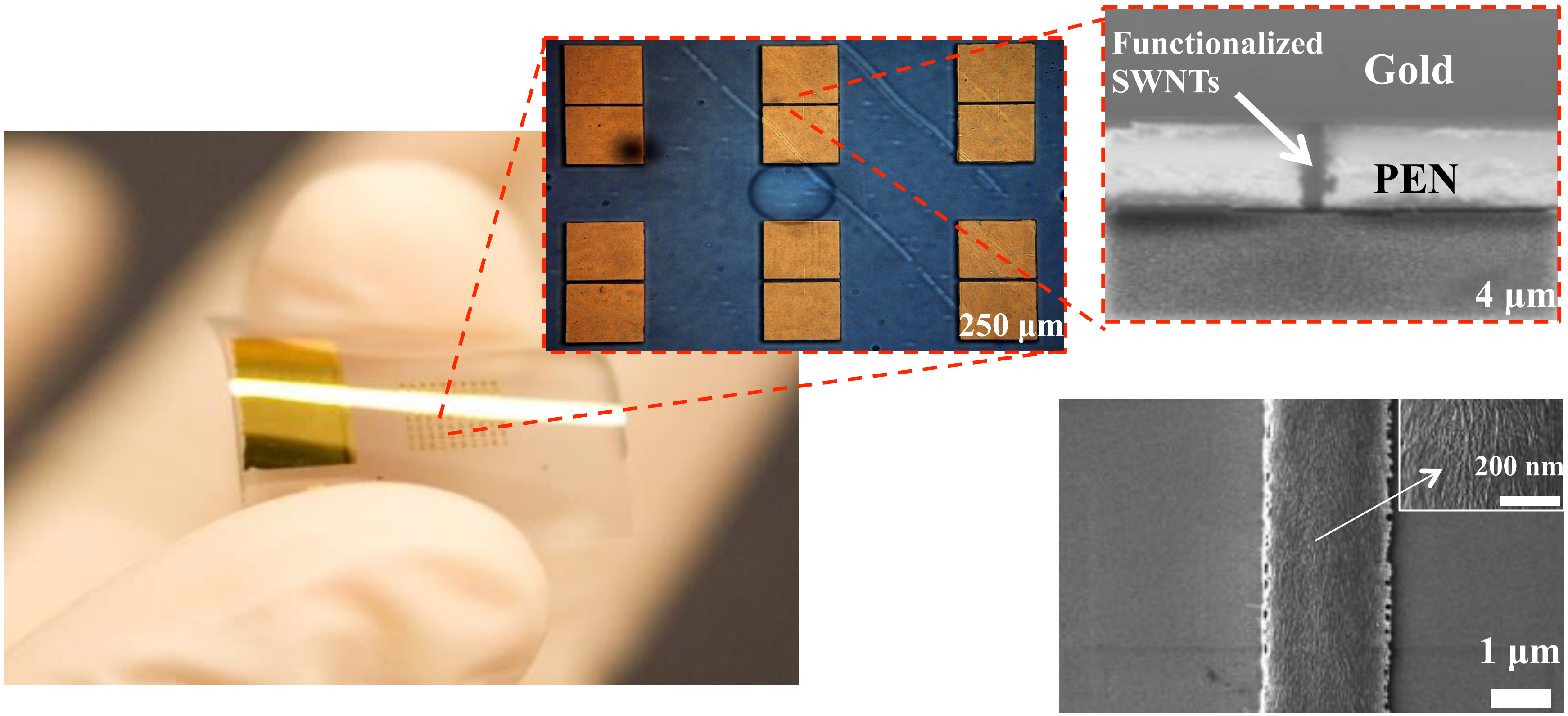


SEM images setup for assembled SWCNT array devices. (e) An optical image of wafer scale sensor devices. (f) Chemical structure of TEMPO molecules. (g) Real-time current changes as a function of conc. H_2S gas at 10, 25, 50, 75 and 100 ppm for the functionalized SWCNT sensor.

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

Center for High-rate Nanomanufacturing

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



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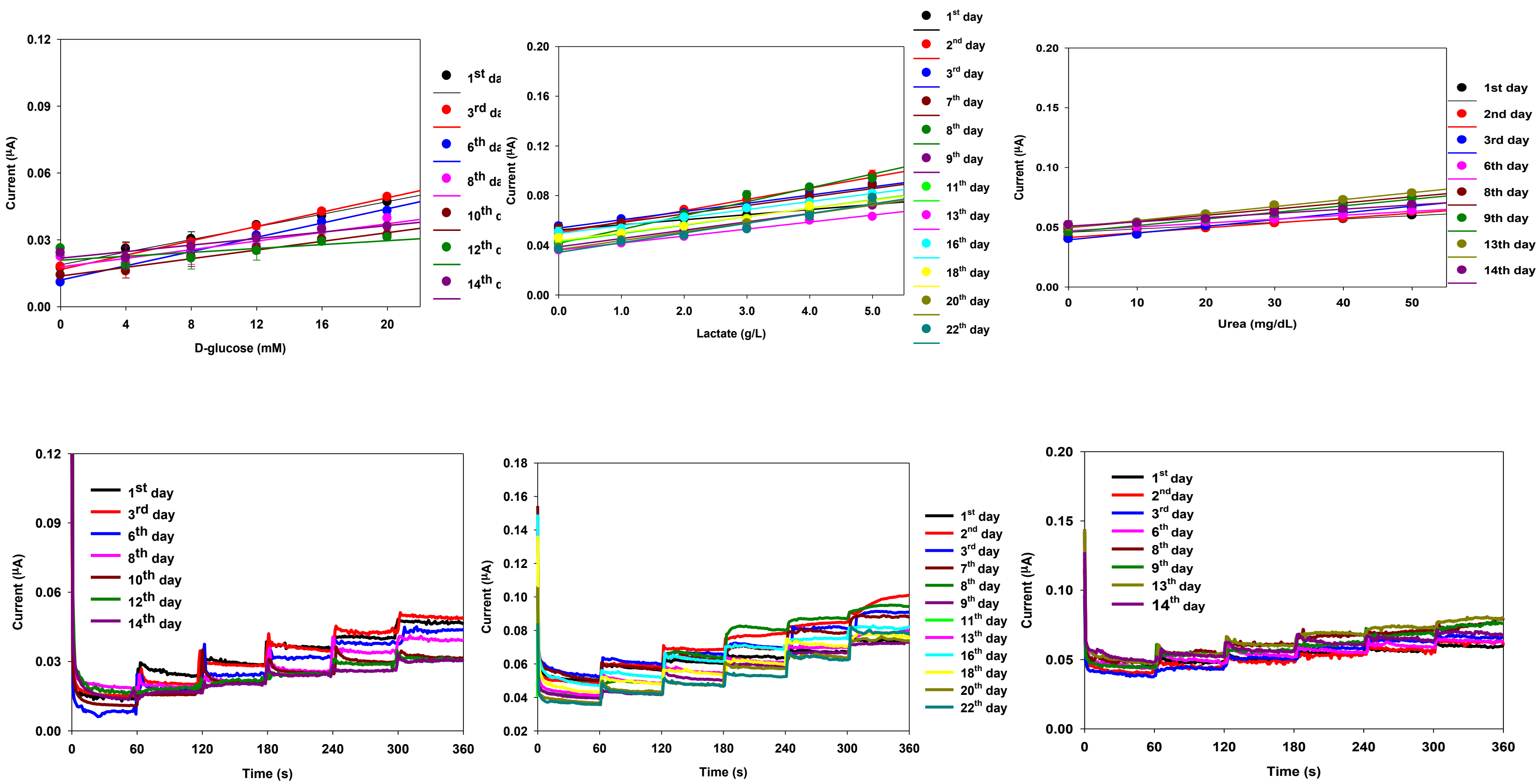
Stability of D-glucose/L-lactate/urea detections (2~4 weeks)

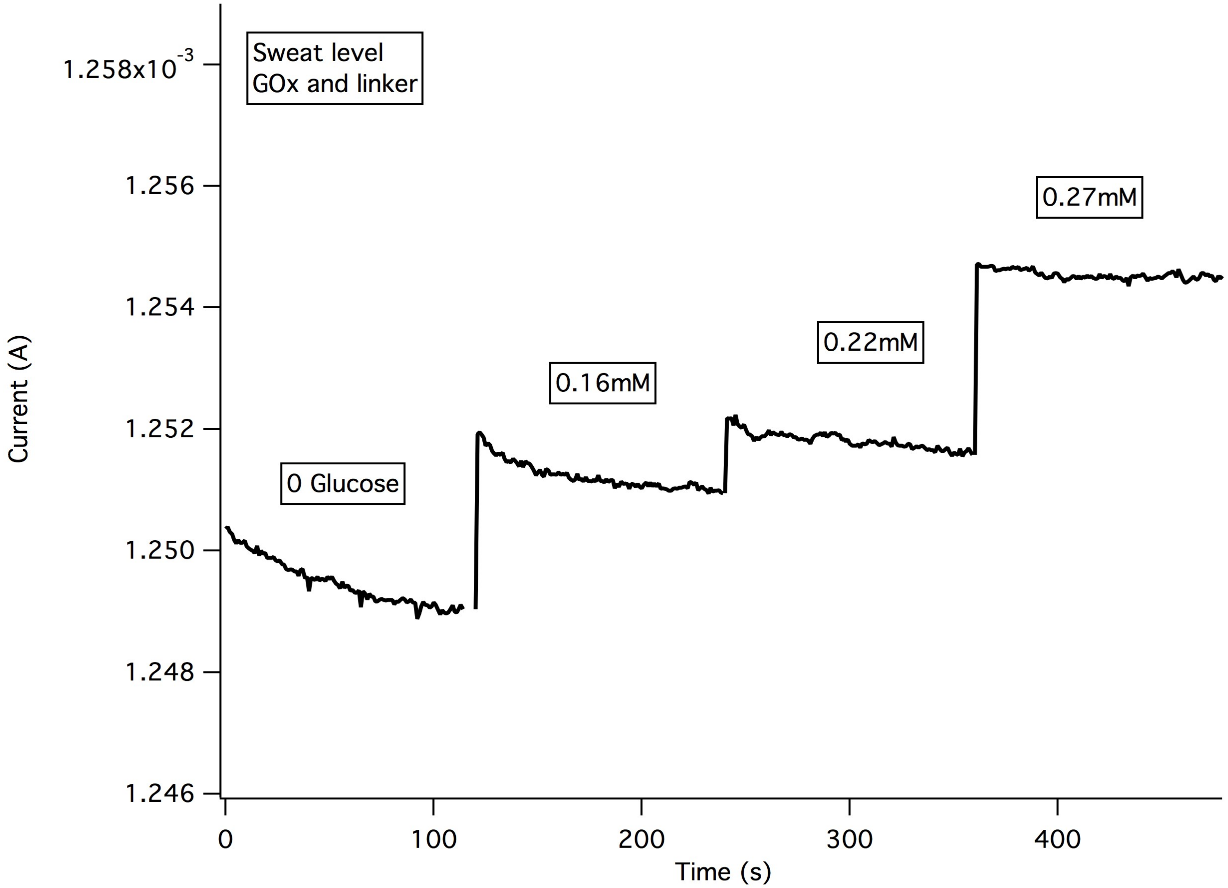


(A) D-glucose (B) L-lactate (C) Urea

Printed Sensor for Glucose Detection in Sweat

Mediator-free 3rd generation sensors

Glucose detection from Sweat



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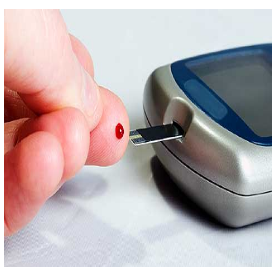
How does state of the art compares?

Commercial Sensors

Weight: 5.5 lbs **Weight: 4.15 lbs**

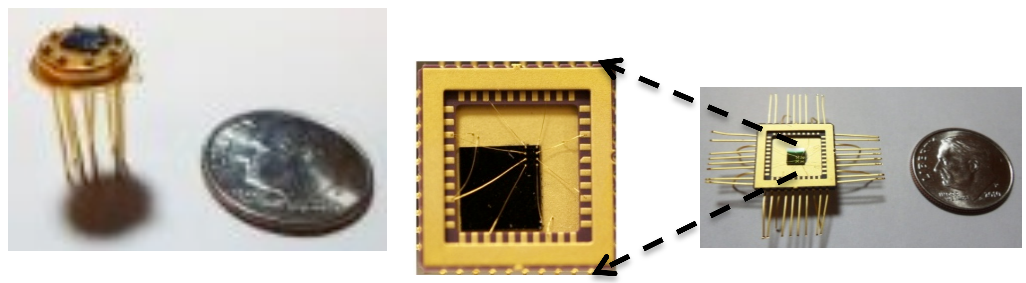
Commercial Chemical Hydrogen Sulfide (H2S) Sensors



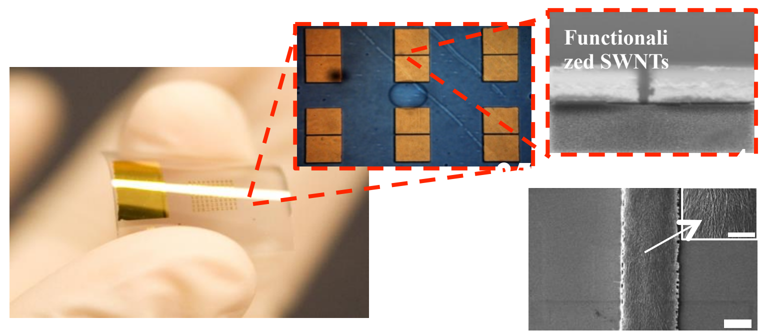
Commercial Glucose Sensors use blood

The Sensors developed by the CHN

Weight: 0.000220462 lbs



Our Chemical Hydrogen Sulfide (H2S) Sensors



Our "Band-Aid" sensor uses sweat or tears to detect glucose. And can be used to detect viruses, bacteria, cancer, etc.

- Current Sensors are large and consume more energy
- Most sensors are not wearable, flexible or wireless

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A New Spinout to Make the Nanoscale Printing Systems Available to Industry and Researchers

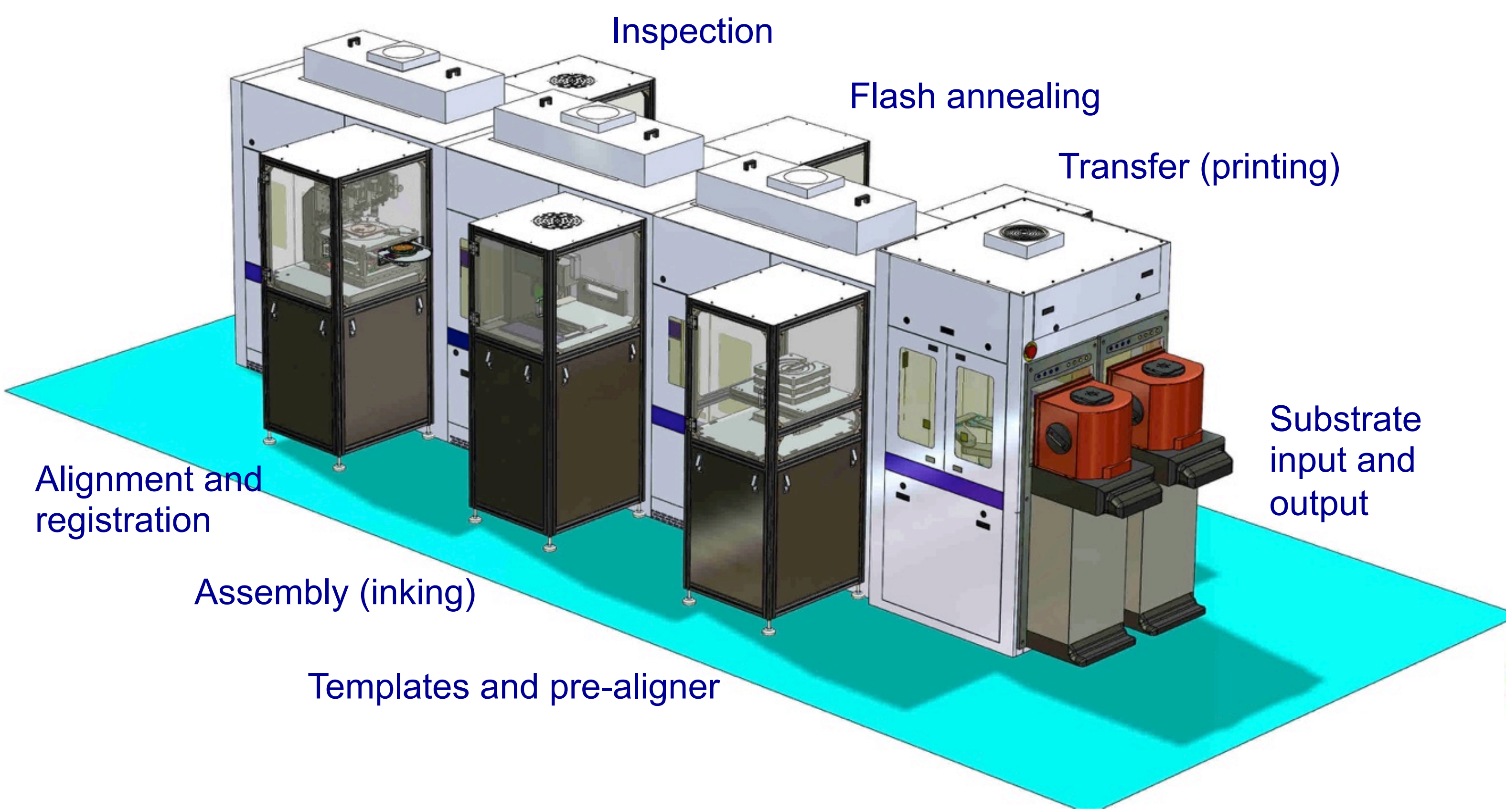
www.nano-ops.net

1. Core Nanoprinting Equipment
2. 35 patents
3. Core Experienced Team
4. Products:

- Electronics (power or consumer electronics)
- Chemical Sensors,
- BioSensors: Cancer, Antibiotics, Physical and Fitness Indicator
- Display applications

Gen 2 NanoOPS Printing System

The second generation NanoOPS printing System, currently being built, has the ability to print nanoscale sensors and electronics on any polymer substrate. The system is fully automated with built-in alignment and registration, inspection and annealing.



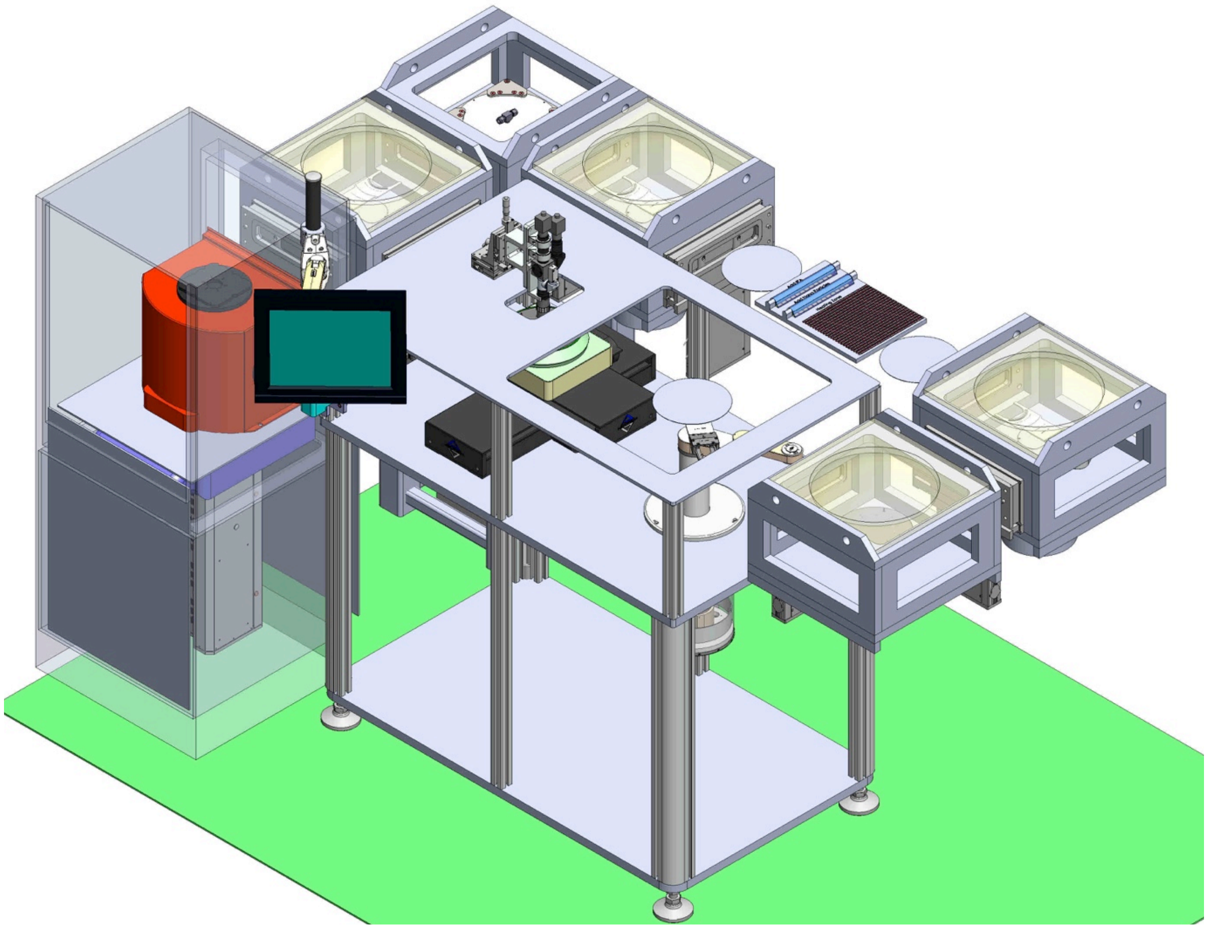
NanoOPS

MILARA

Center for High-rate Nanomanufacturing

Gen 3 NanoOPS Printing System

Designing and Building the third generation NanoOPS printer that has the ability to print nano and microscale patterns and structures on any substrate (silicon, glass, ceramic, or metal) is underway.



NanoOPS
MILARA
Center for High-rate Nanomanufacturing

Summary

- Printing at the nanoscale introduces a disruptive technology for making nano and microelectronics that will change the electronics and sensor landscape.
- Printing nano and micro electronics costs 10 to 100 times less than conventional fabrication.
- 1000 times faster printing with a 1000 times smaller patterns than inkjet or 3D printing.
- Electronics are printed at ambient temperature and pressure, on any rigid or flexible substrate, using any conductive, semiconducting or insulating materials (organic or inorganic).
- Other benefits of printed electronics and sensors are: sustainable manufacturing, improved performance and the use of any existing and new nanomaterials, etc.
- This will open the door to many new and innovative applications.

Thank you, 감사합니다

Questions and Discussion?

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www.northeastern.edu/nano
www.nanomanufacturing.us

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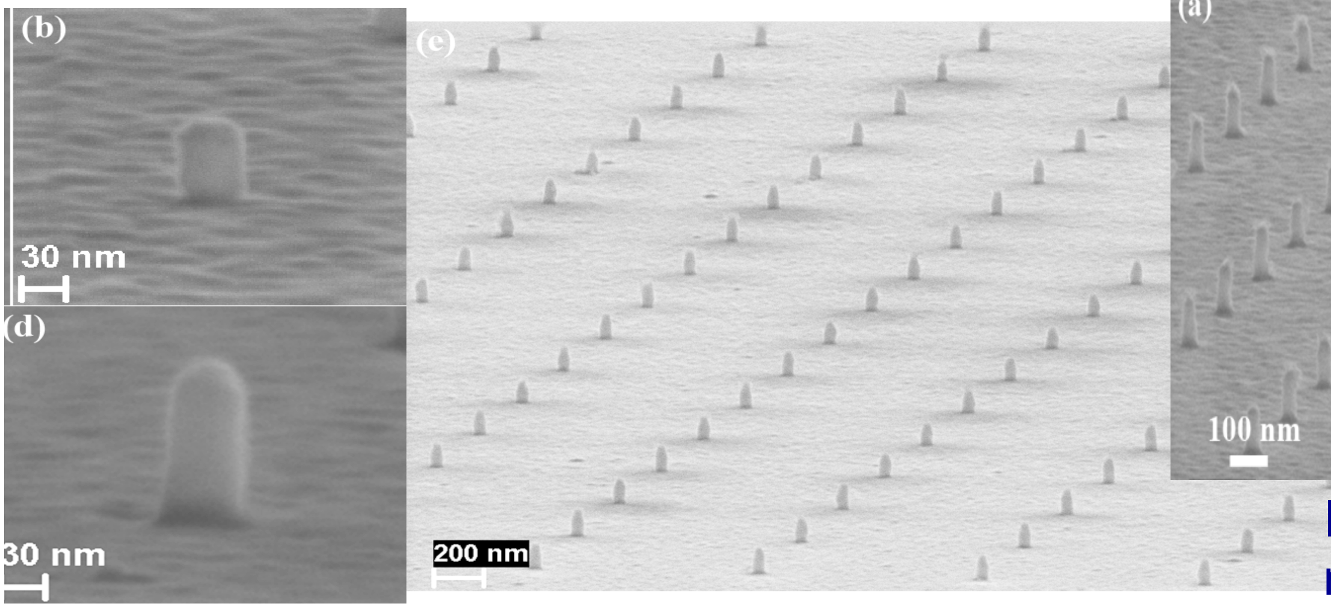
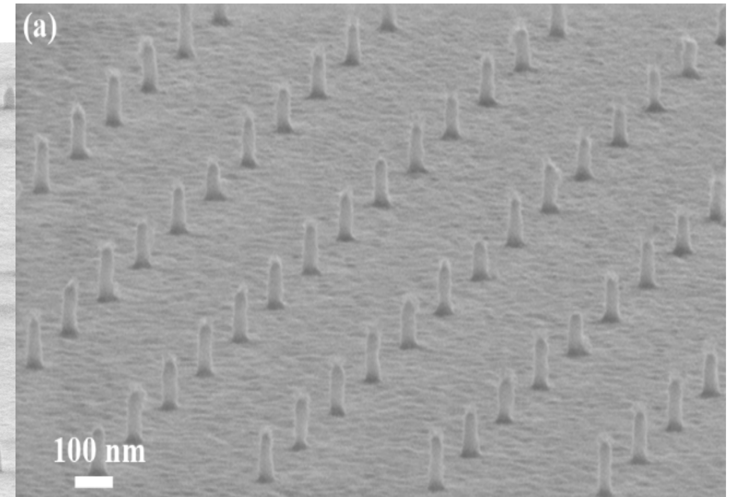
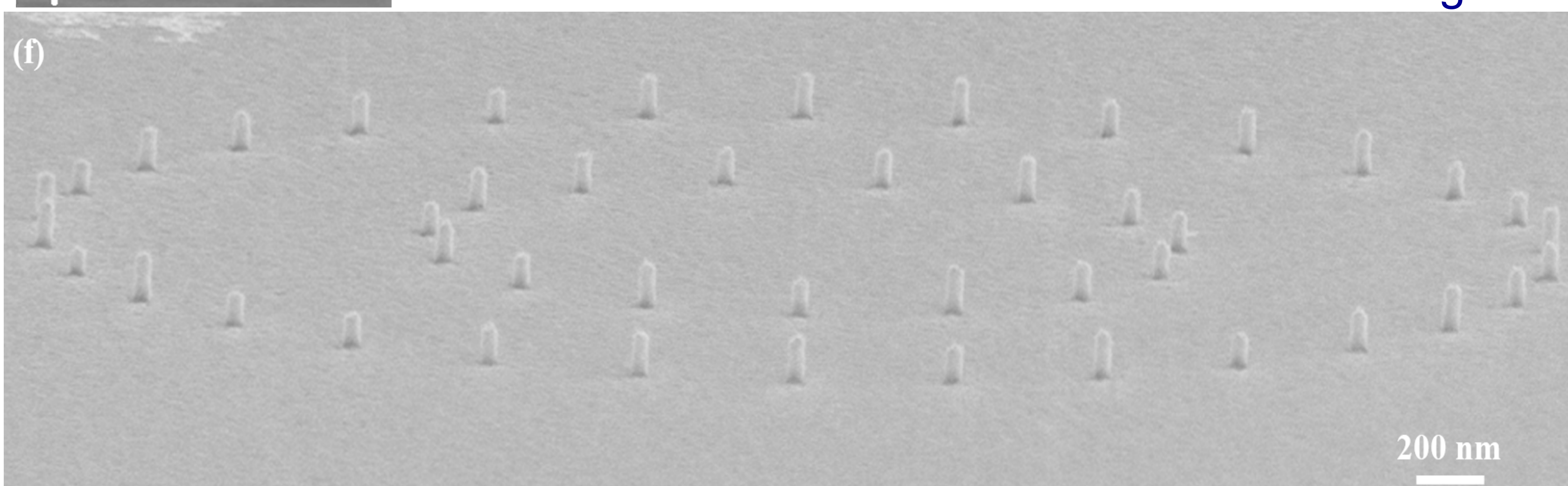
Printing Nano Structures





Images of Printed nano rods using 20 nm



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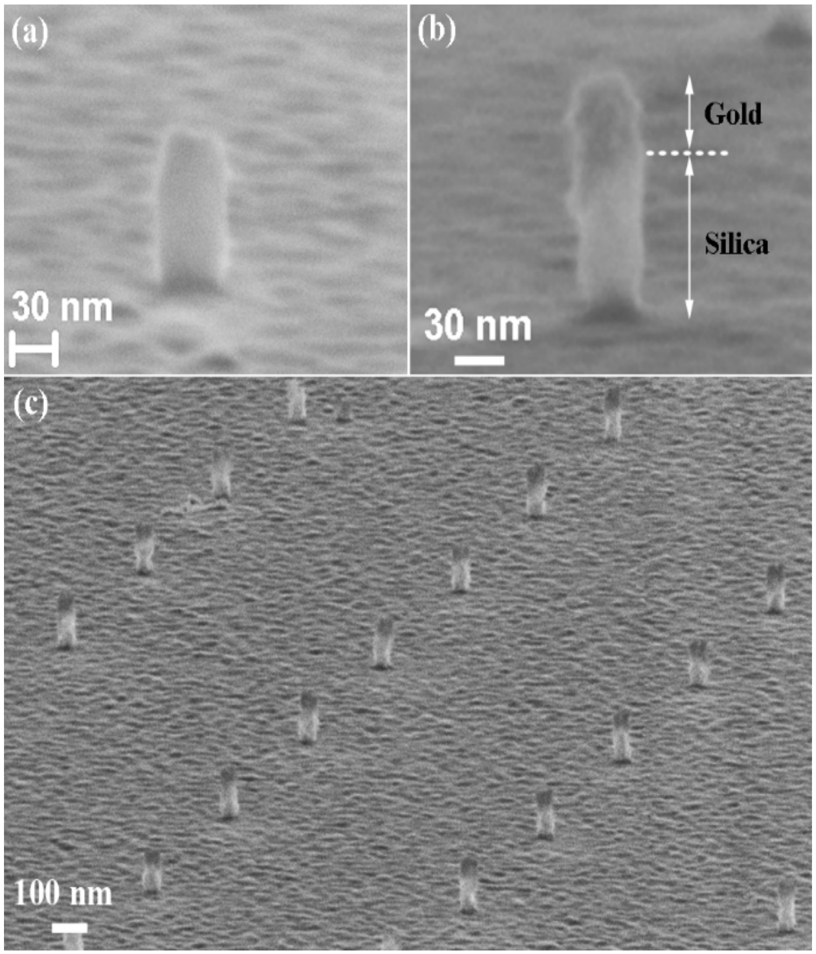
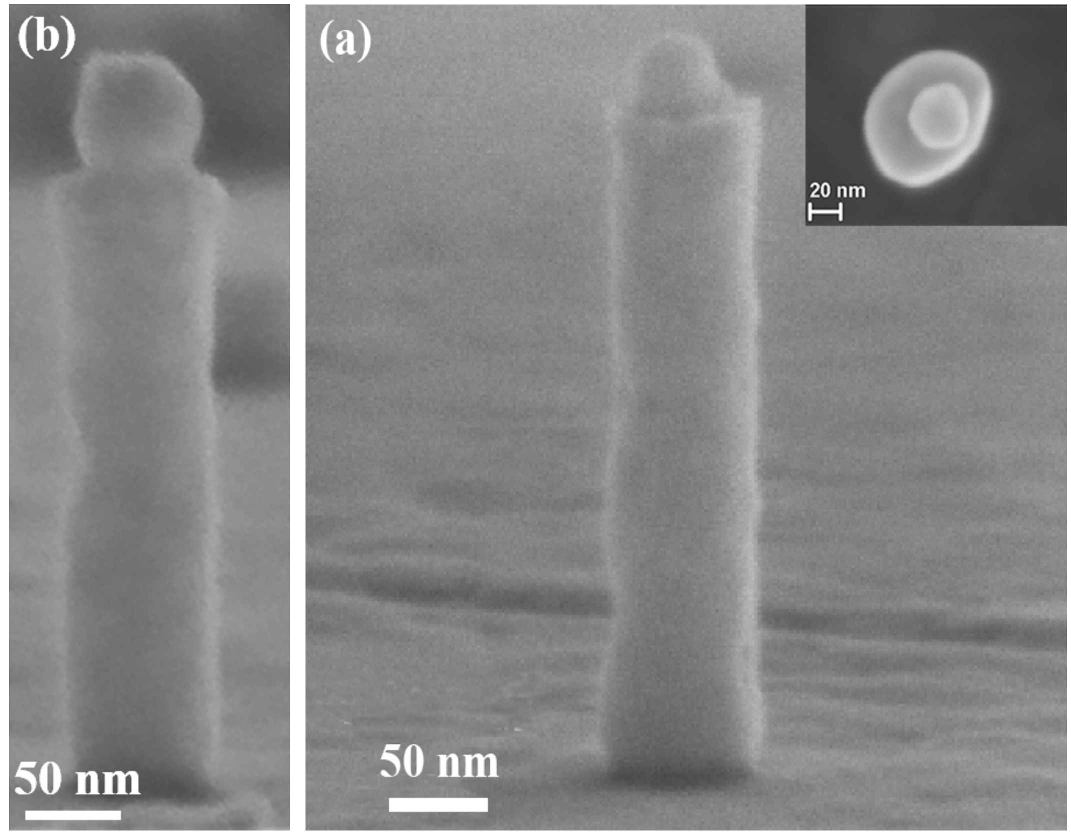
What we can do with printing LEDs Structures



Printed hybrid silica-gold nano rods over a large area.



Printed silica-gold nanorods with 40 and 80 nm gold nanoparticles on top.

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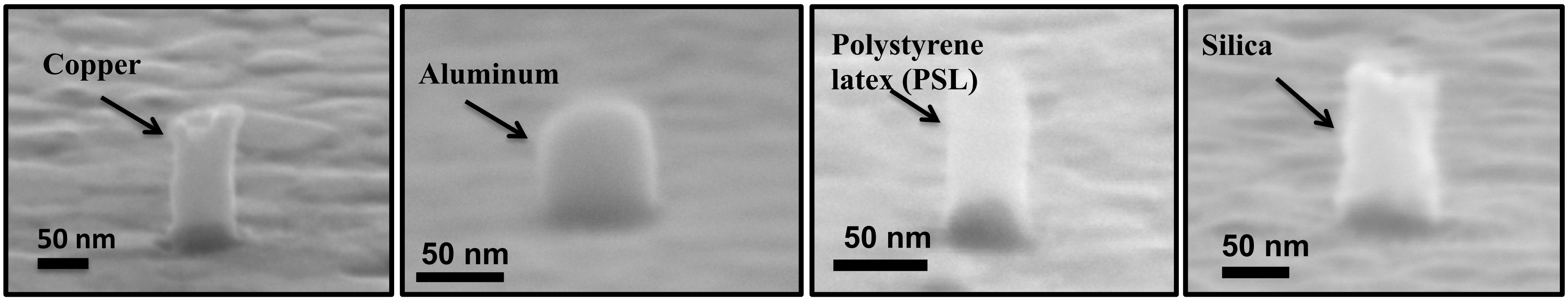
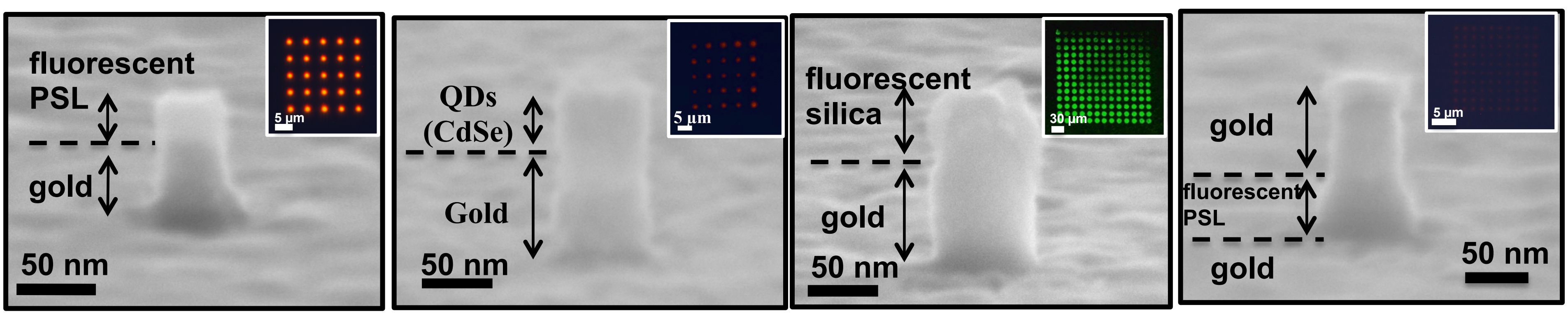
What we can do with printing LEDs Structure

Homogenous nanopillars:

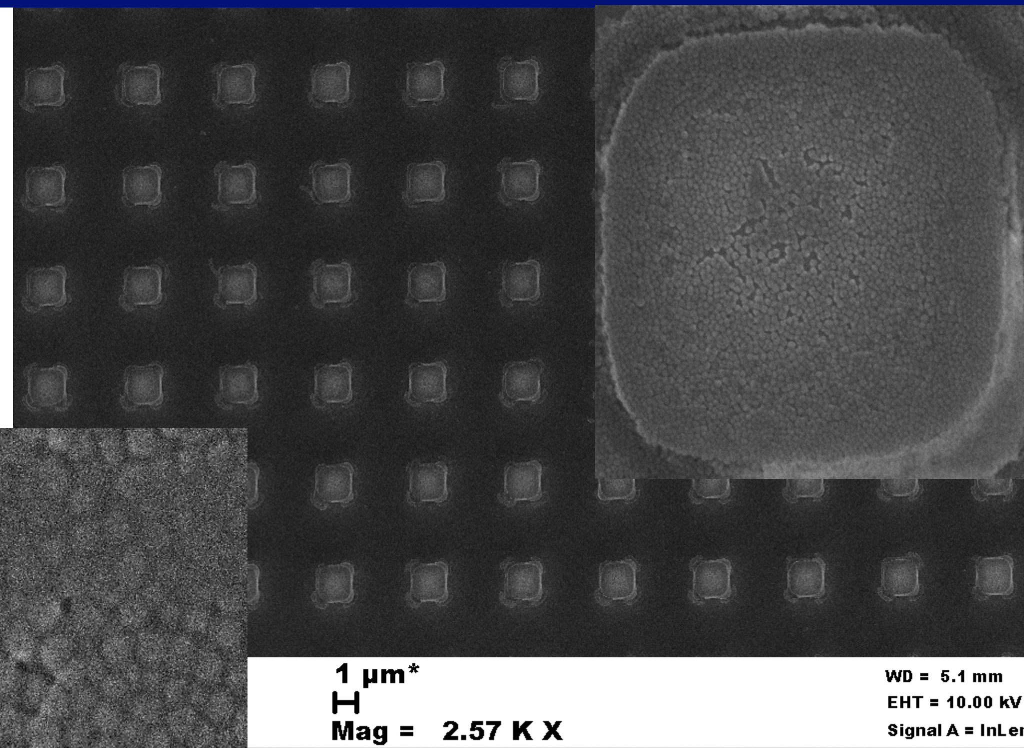


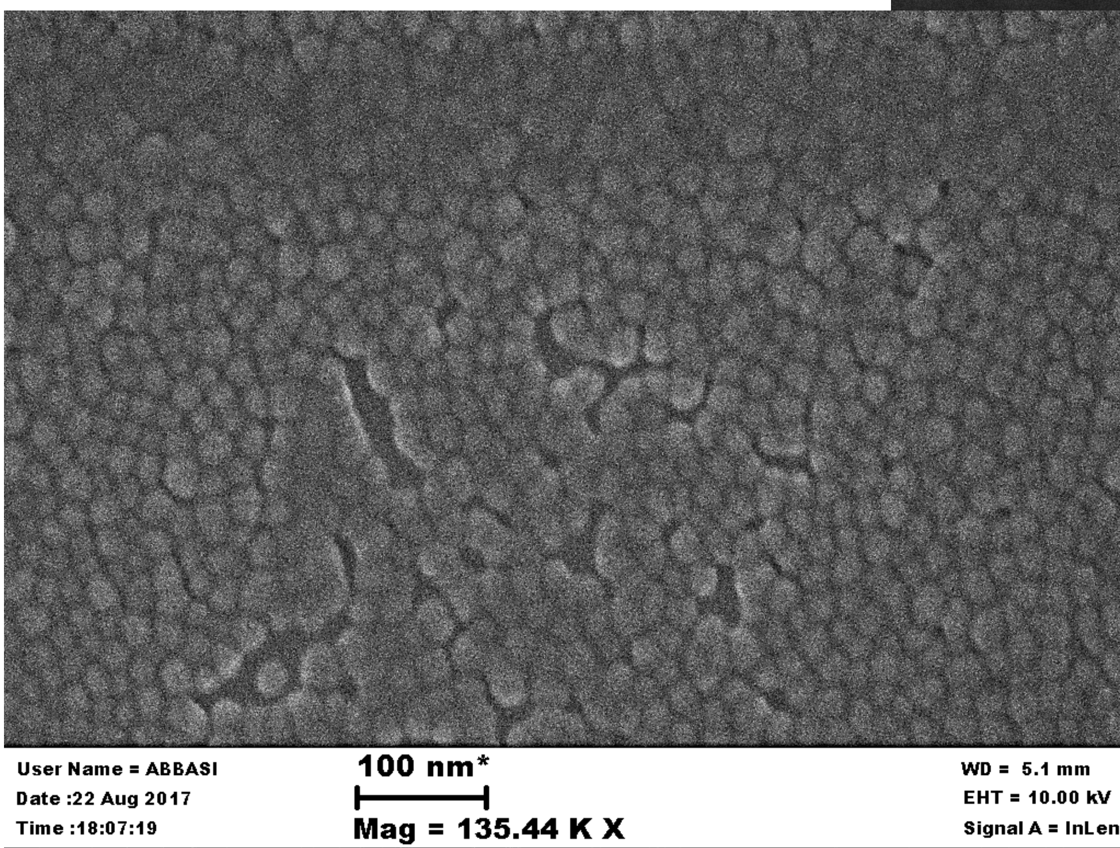
Hybrid nanopillars:

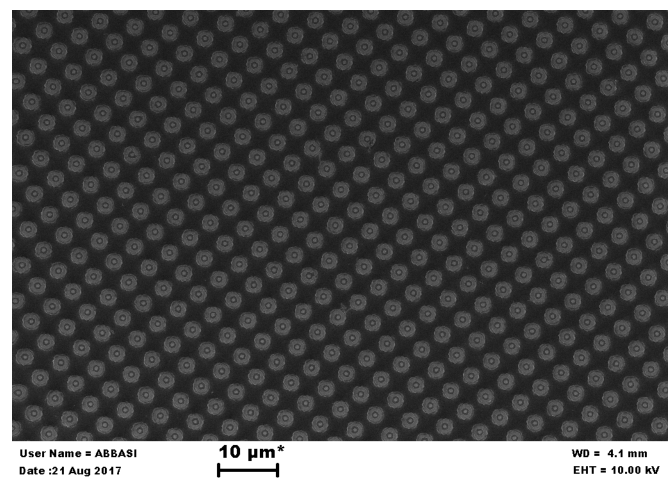


What we can do with precise printing of QDs?

- Large scale printing of a single layer 20nm silica nano particles.

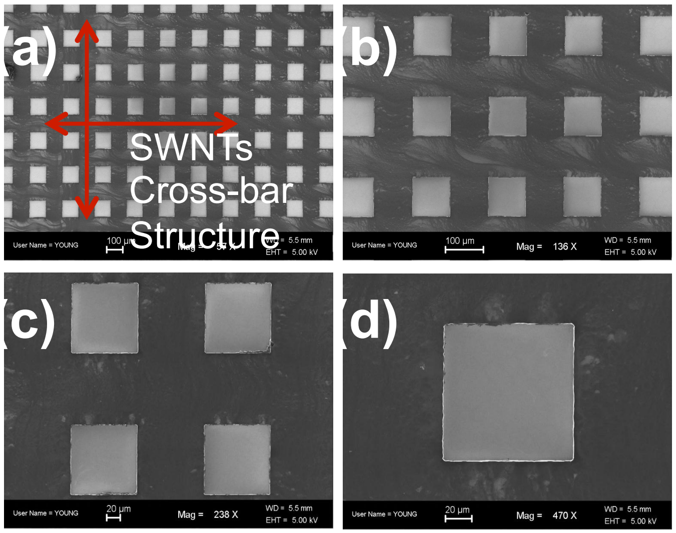


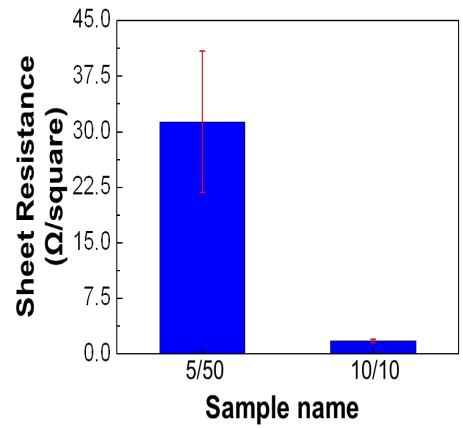


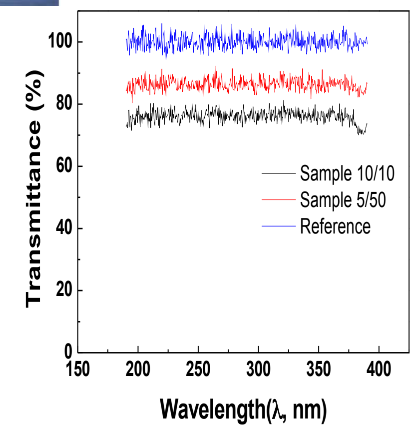


Functional Materials and Surfaces

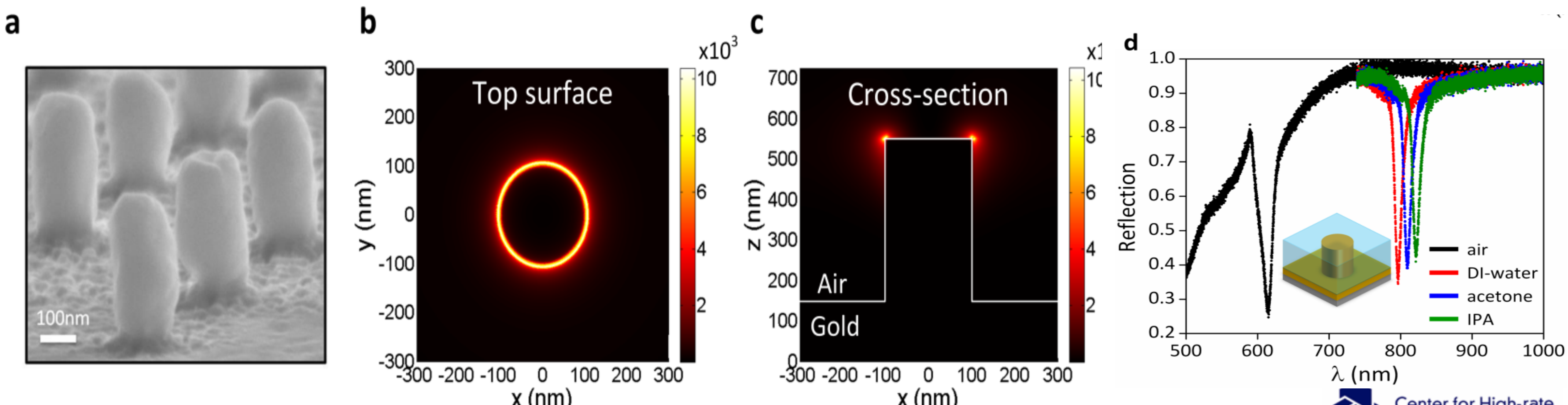
- Ordered CNT materials for EMI shielding ➔ Excellent conductivity and transparency







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



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