Micro and Nanoscale Printing of Sensor Platforms for and Physiological Monitoring, Biomarker and Pathogen Detection

Distinguished University Professor, W. L. Smith
Professor and Director,

NSF Nanoscale Science and Engineering center for

High-rate Nanomanufacturing

Northeastern University, Boston, MA, USA

www.nanomanufacturing.us

Northeastern University

Nano PS©

MILARA

NSF

Center for High-rate Nanomanufacturing

Motivation: Cost

Financial and Environmental Cost

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

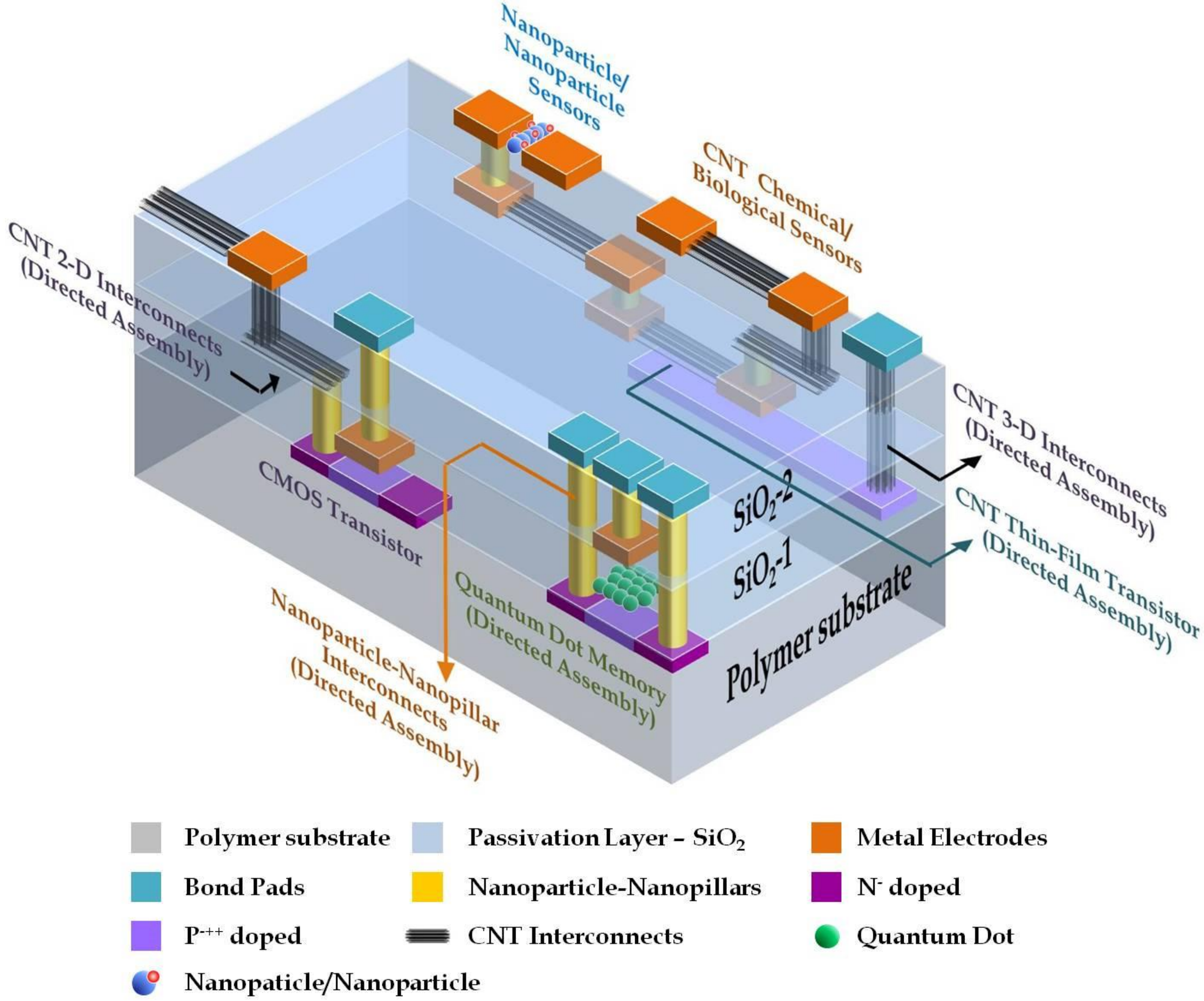
1990s - $1B-$2B

2016 - $17B

Center for High-rate Nanomanufacturing

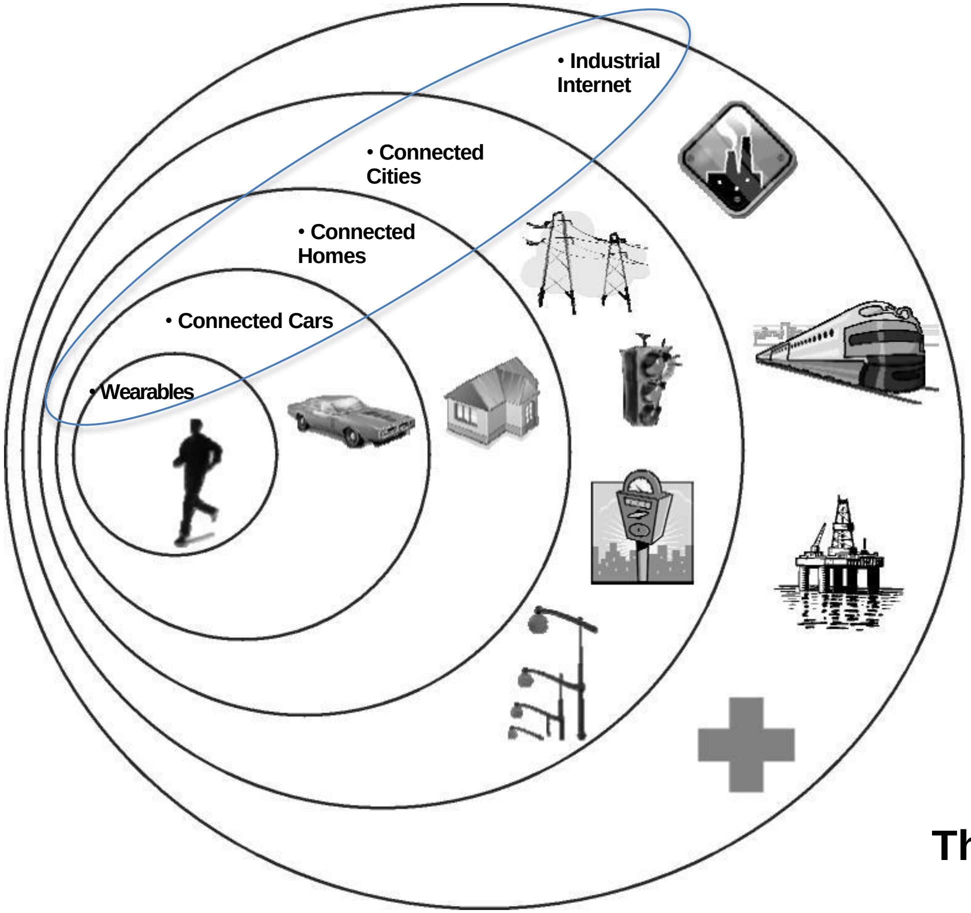
Motivation: Versatility

Can we print any material on any substrate?

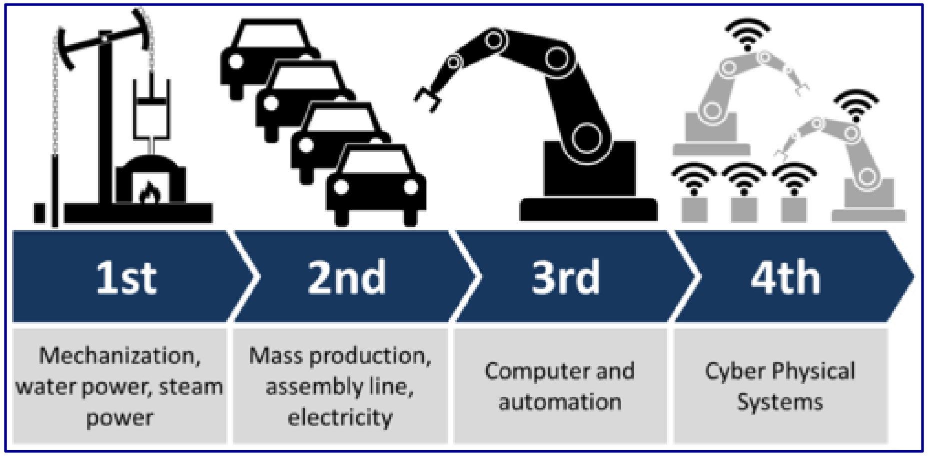


Motivation: IoT (Industry 4.0) Opportunities

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



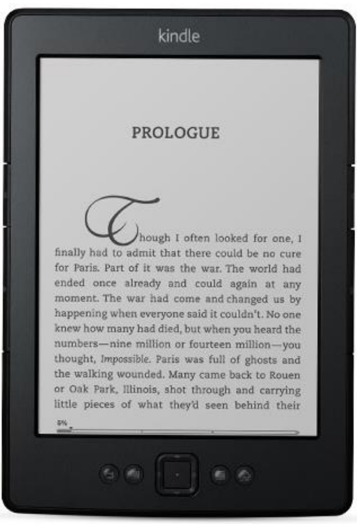
The four industrial revolutions & Industry 4.0; Industrial Internet

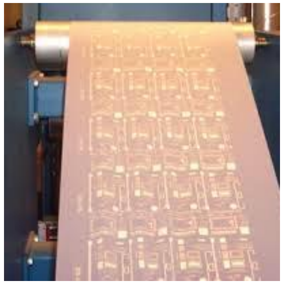
The Goldman Sachs Group, Inc. Global Investment Research (2014)

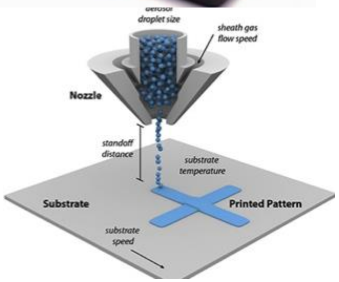
Center for High-rate Nanomanufacturing

What is the State of the Art of the Current Printing Technologies?

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



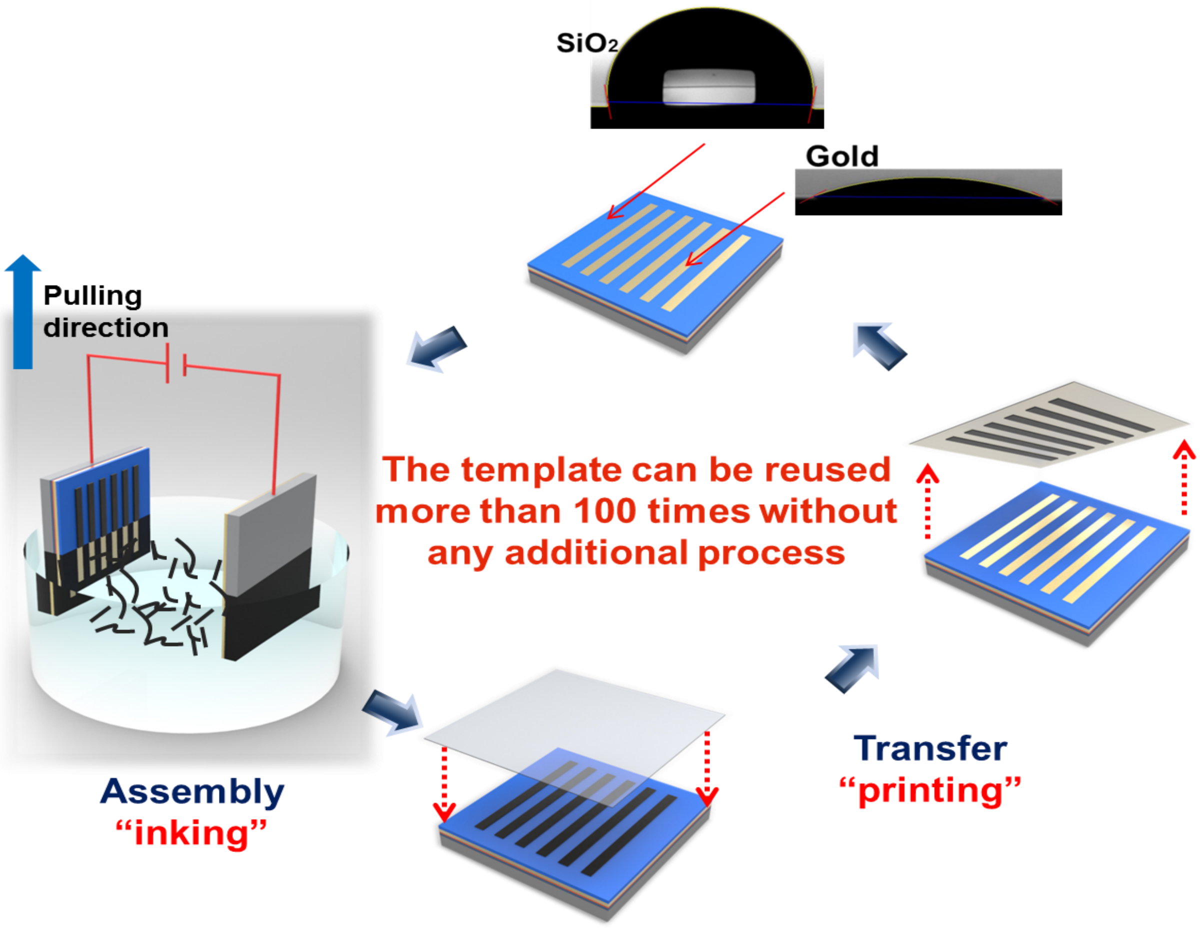




- A printing technology is needed that can print conductive, semiconducting, and insulating materials (inorganic or organic) down to 20nm and 1000 times faster than inkjet.
- There is need to print Inter-connected multilayers.

Center for High-rate Nanomanufacturing

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

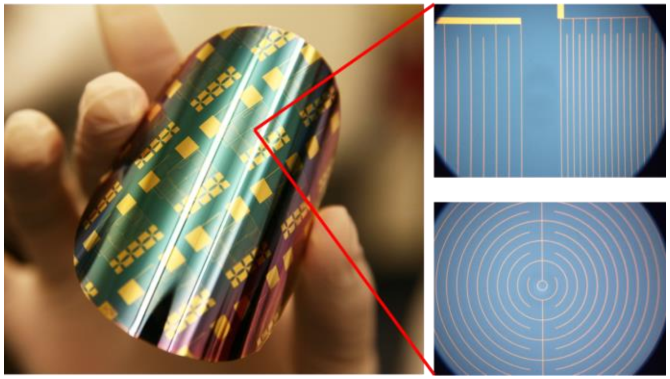


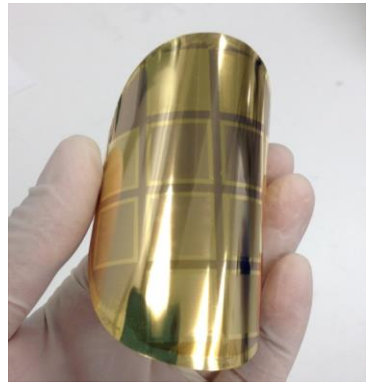
- Additive
- High throughput
- Prints down to 20nm
- Room temperature and pressure
- Prints on flexible or hard substrates
- Multi-scale; nano to macro
- Material independent
- Very low energy consumption
- Very low capital investment

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

Center for High-rate Nanomanufacturing

Damascene Templates for Nanoscale Offset Printing

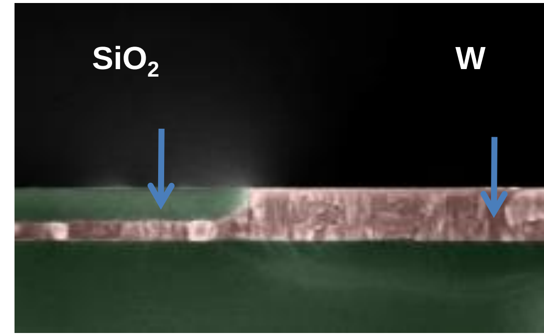


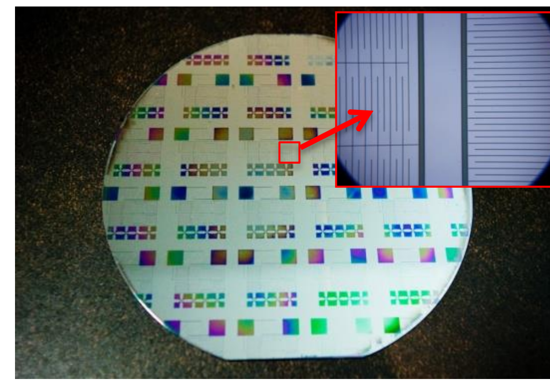


PEN

Polymer-based Templates

PI

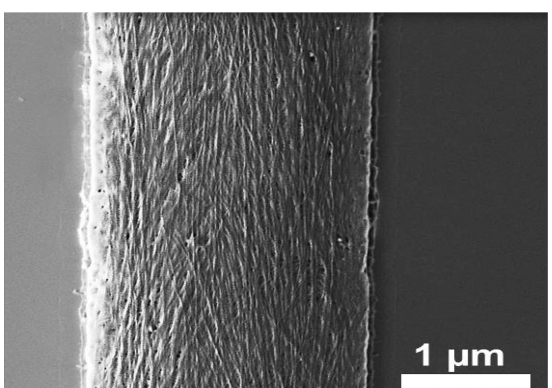




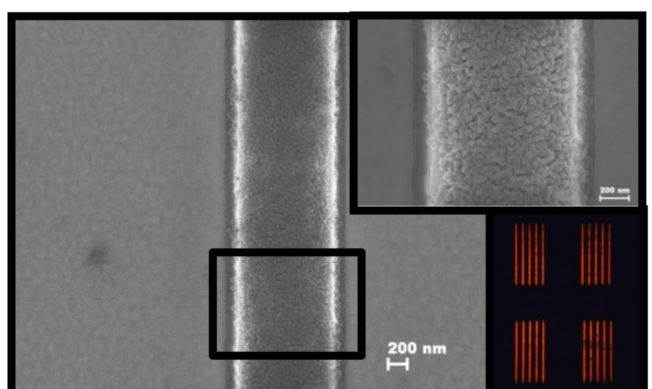
Silicon-based Hard Templates

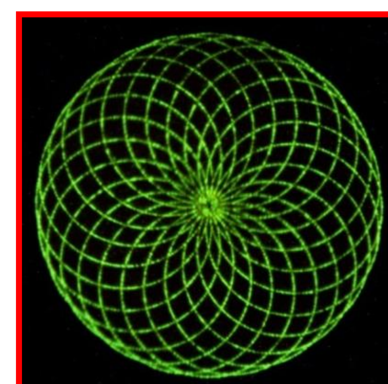
Advanced Materials, 2015

Assembled SWNT

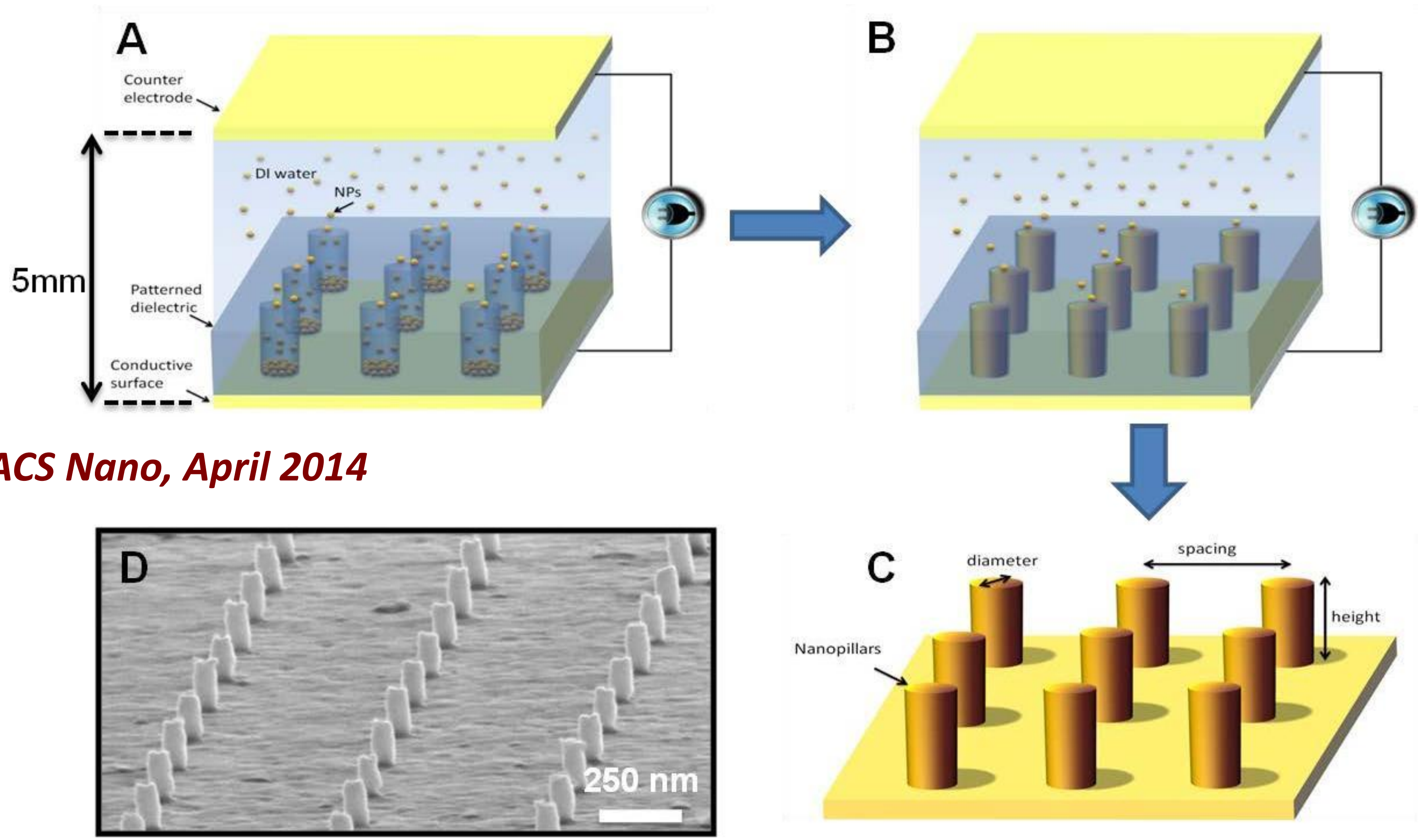


Assembled Particles





Directed Assembly-based Printing of Interconnects

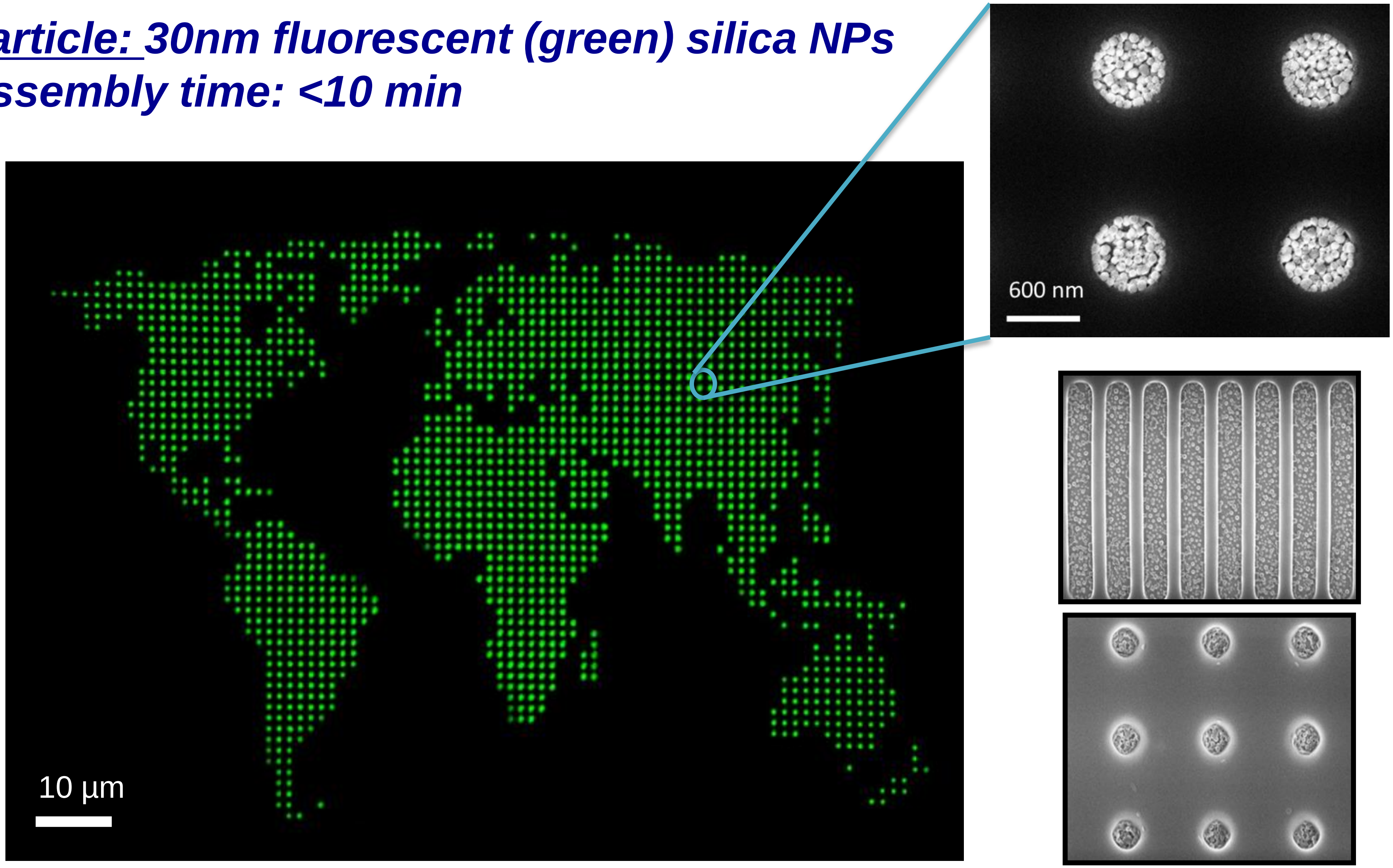


ACS Nano, April 2014

•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。

Assembly of NPs into Trench and Vias Over Large Areas

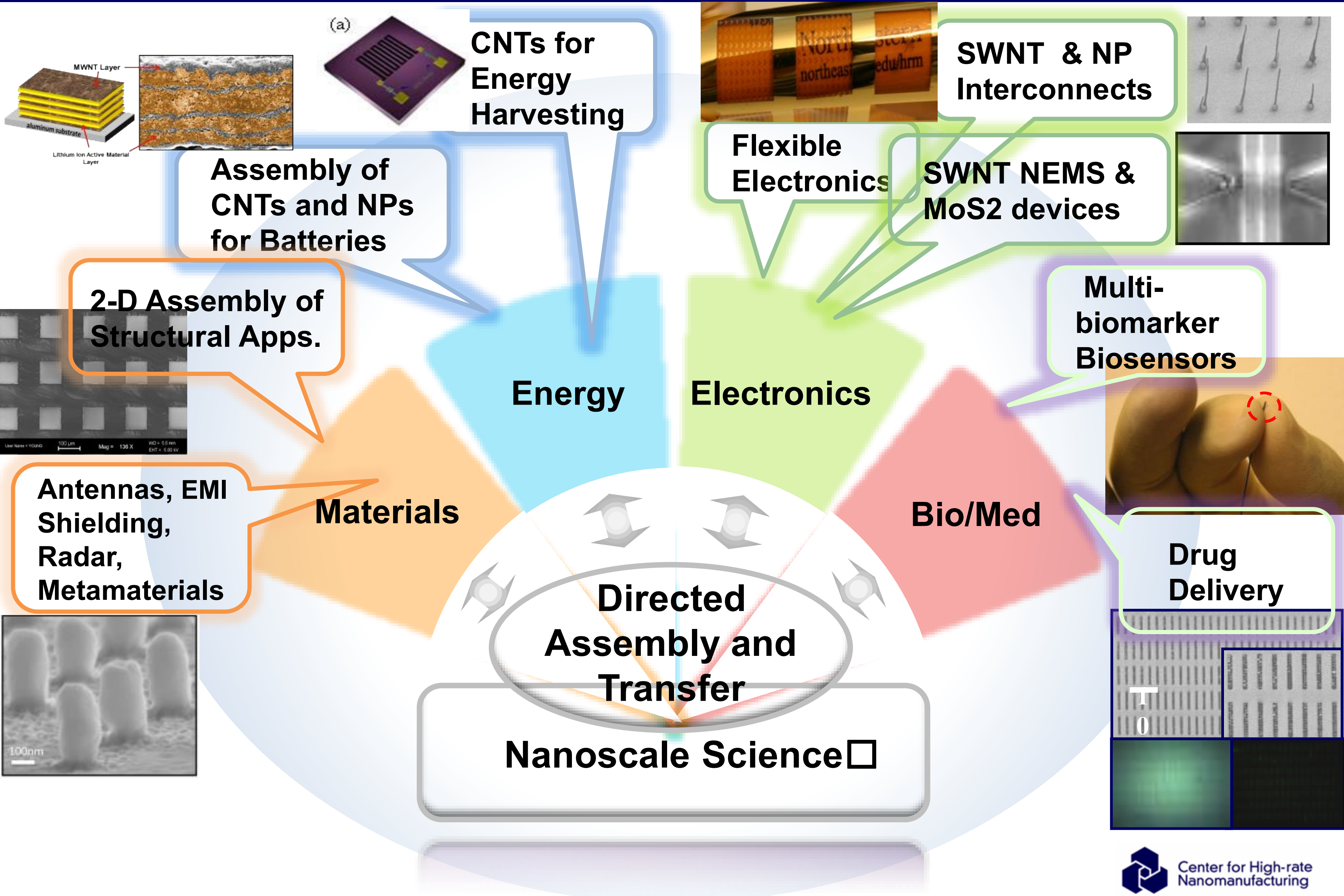
Particle: ***30nm fluorescent (green) silica NPs***
Assembly time: <10 min



No electrophoretic or Di electrophoretic force is used.

Center for High-rate Nanomanufacturing

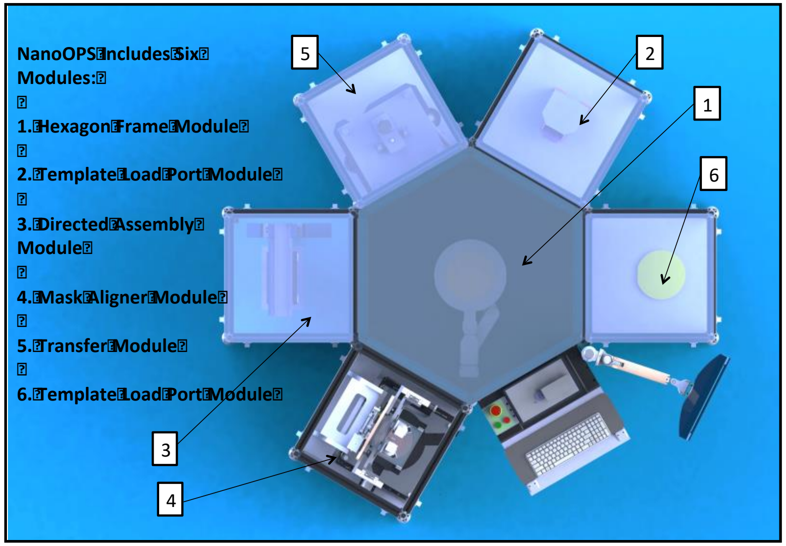
Demonstrated Printed Applications



Center for High-rate Nanomanufacturing

Fully Automated Nanoscale Offset Printing System (NanoOPS) Prototype was Demonstrated to more than 70 companies

- **The World's First Nano Printer with 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

MILARA

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

Printed Electronics Conf., Berlin 2016

2016 FLEXI AWARD

AWARD WINNER EUROPE 2016

Best Academic R&D Award

IDTechEx Show! EUROPE 2016

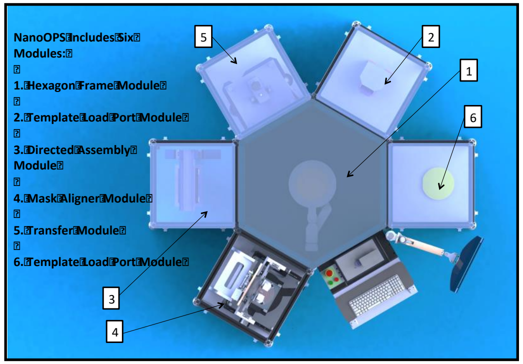
2015 R&D 100 FINALIST

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.

MILARA

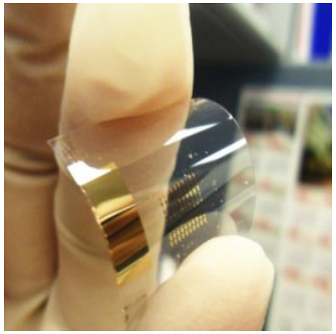
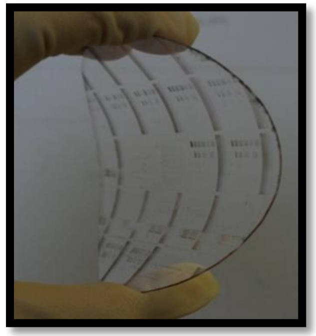
NanoOPS Videos on Youtube:

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

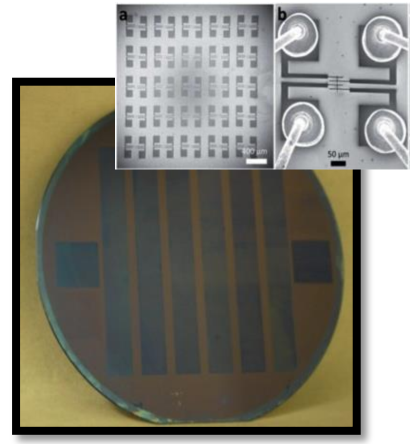
NanoOPS at Northeastern University: https://www.youtube.com/watch?v=2iEjIcog774

Center for High-rate Nanomanufacturing

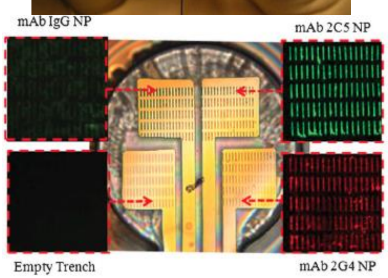
Sensors and Electronics at a Fraction of their Current Cost

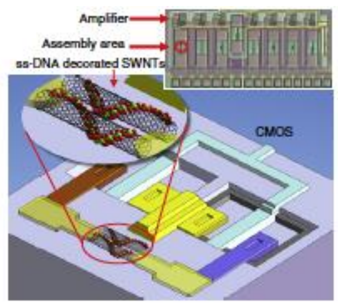
Sensors for E. coli bacteria, viruses, and other pathogens

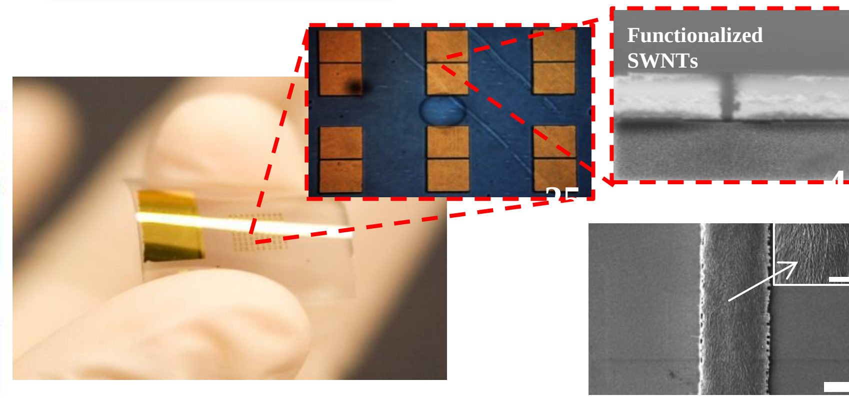


Sensors for Chemicals

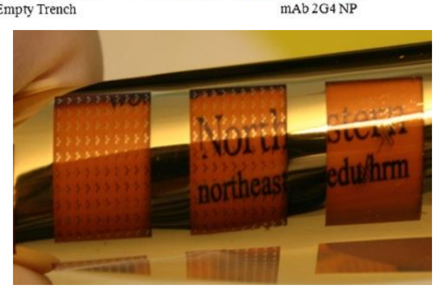


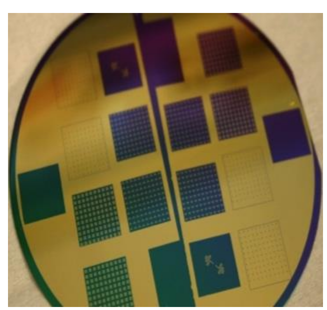
Cancer and cardiac diseases. **Detection limit is 200 times lower than** Current technology





Band-Aid sensor





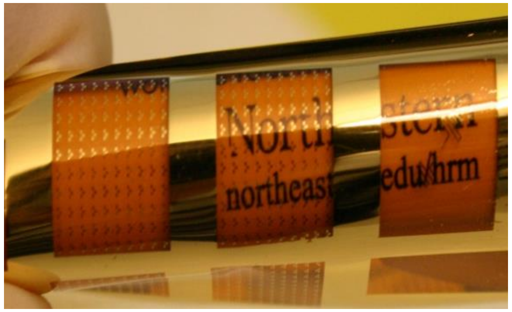
Supporting printed electronics for sensor systems

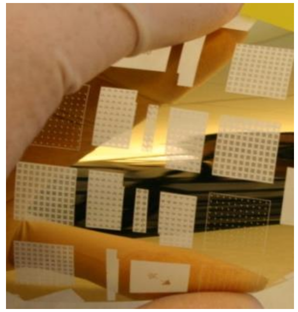
Applications

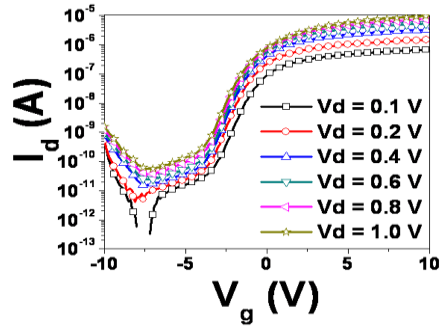
Electronics

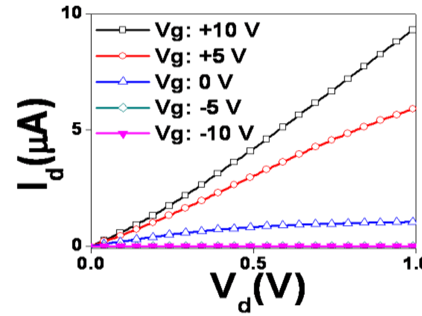
Electronics

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

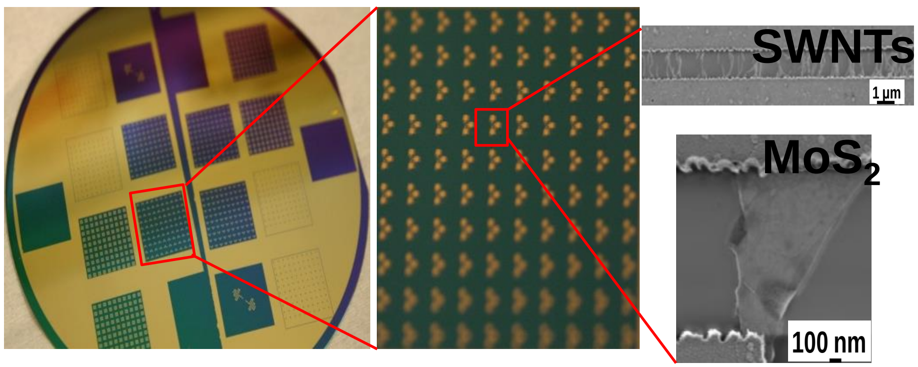


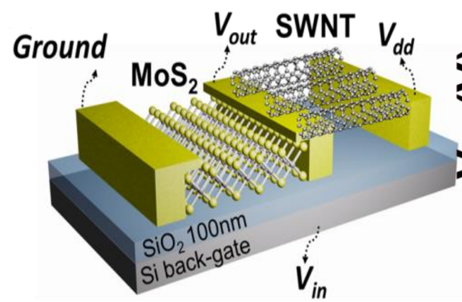


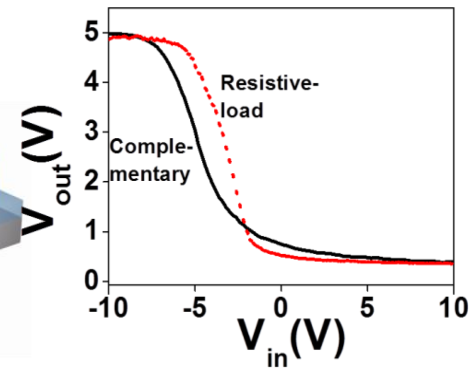




- **Heterogeneous SWNTs and MoS_2 complimentary invertors**



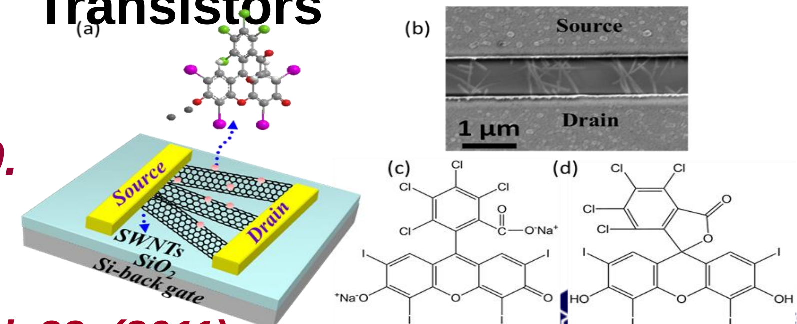




Nanotechnology, *Vol. 23, (2012).*

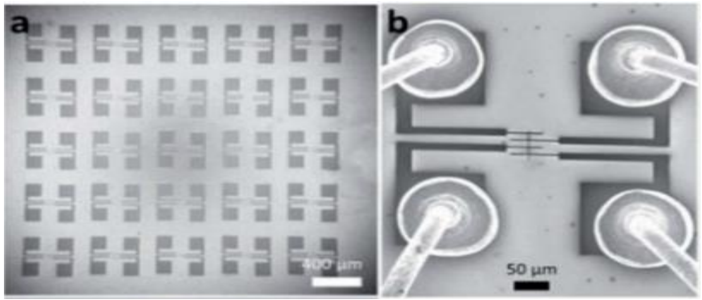
- **Rose Bengal Molecular Doping of CNT Transistors**

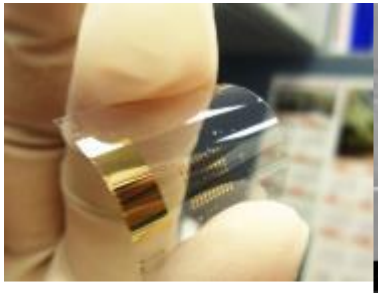
Appl. Phys. Lett. 97, 1 2010.

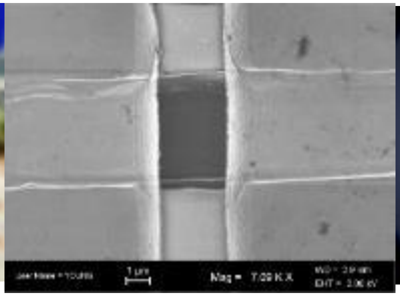


Nanotechnology, Vol. 22, (2011)

Sensors

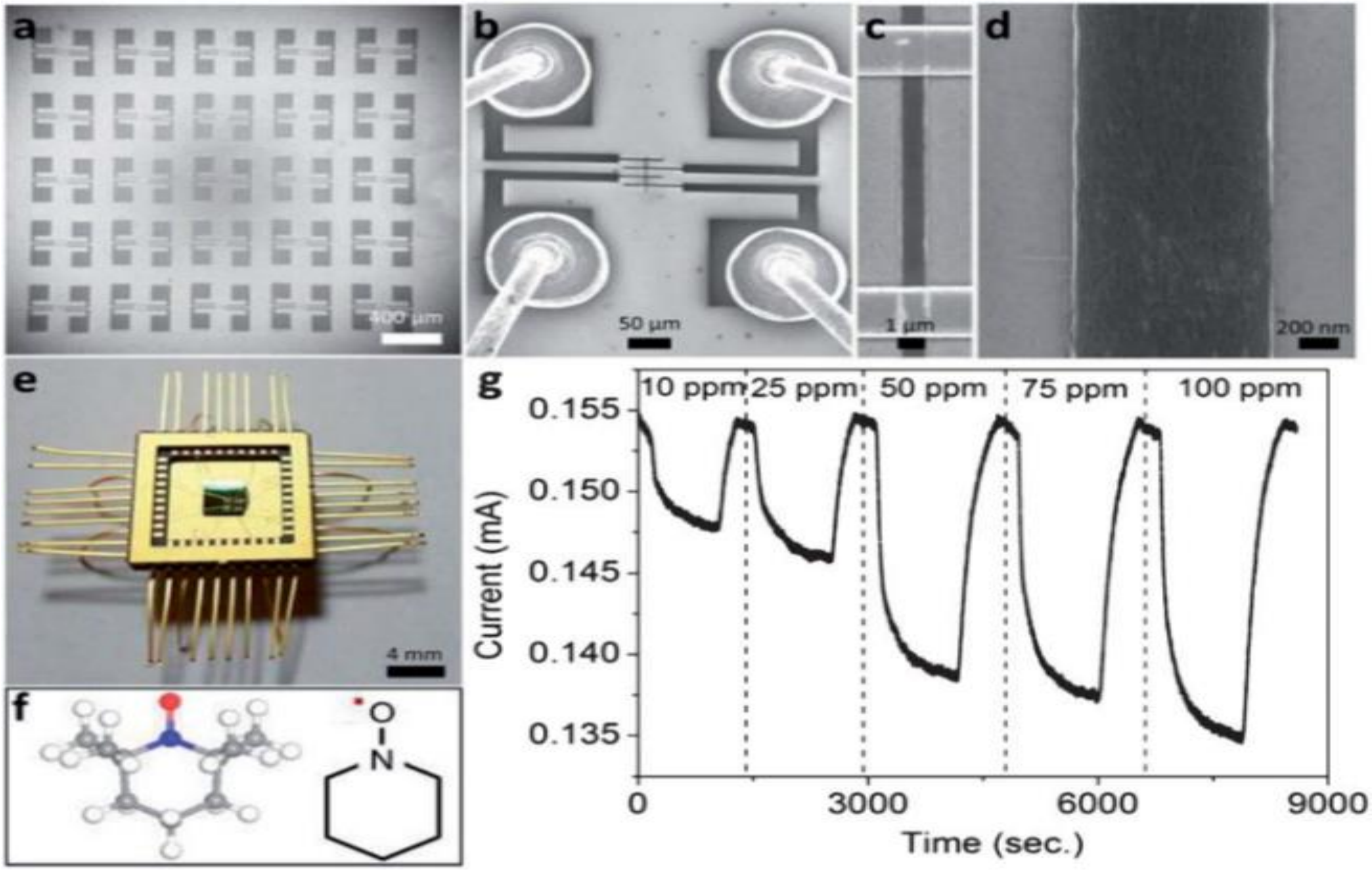






Center for High-rate Nanomanufacturing

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

How does state of the art compares?

Commercial Sensors

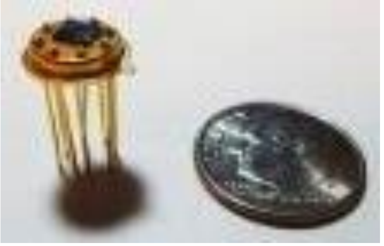
The Sensors developed by the CHN

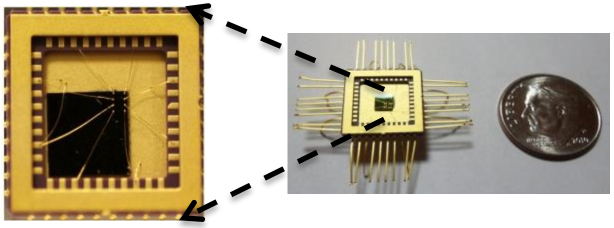
Weight: 5.5 lbs

Weight: 4.15 lbs

Commercial Chemical Hydrogen Sulfide (H2S) Sensors ($400-$500)

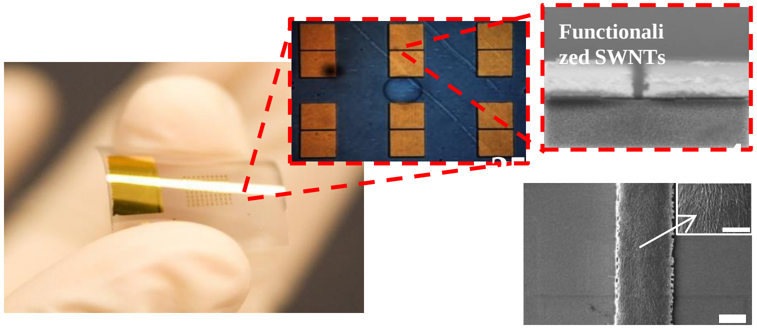
Weight: 0.000220462 lbs ($0.5)





Our Chemical Hydrogen Sulfide (H2S) Sensors

Commercial Glucose Sensors use blood



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

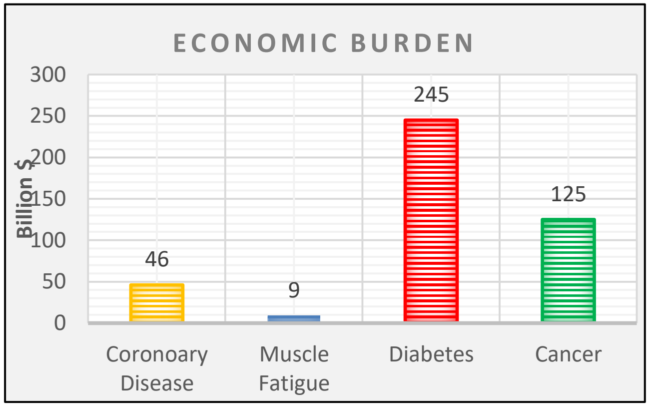
- **Current Sensors are large and consume more energy**
- **Most sensors are not wearable, flexible or wireless**

Center for High-rate Nanomanufacturing

Benefits of continuous glucose sensing

Biomarker	Associated disorder
High muscle lactate levels	Muscle fatigue, ischemia
High blood glucose levels	Diabetes

- ➢ Diabetes requires strict monitoring of blood glucose levels.
- ➢ Non-invasive, continuous monitoring can provide keen measurement and therapy.
- ➢ Sweat provides a good pathway for non-invasive sensing.
- ➢ Sensors can also be used to aid adopt a healthier lifestyle.

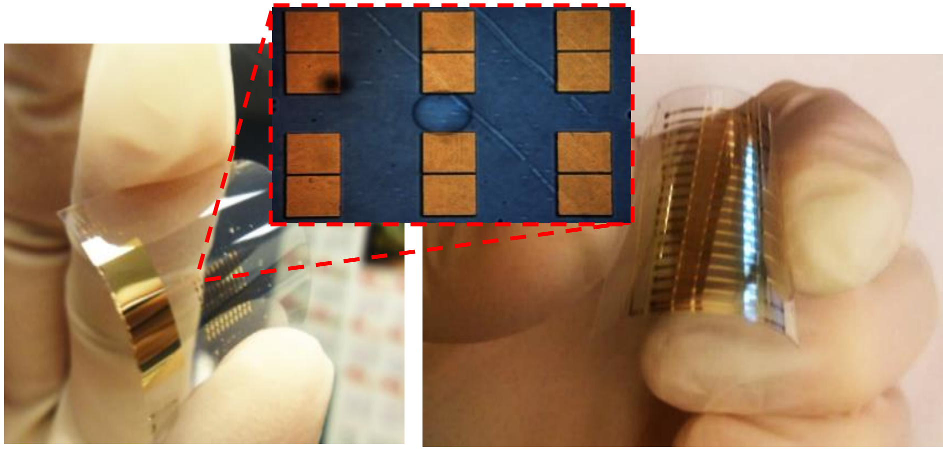


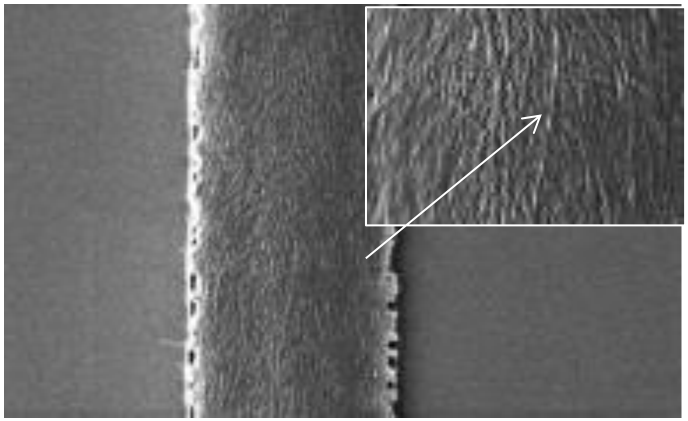
Source: FAQ How

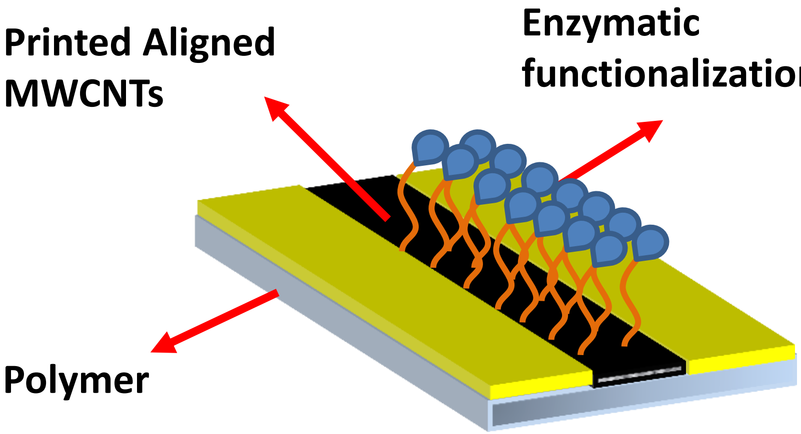
Chao Chen, RSC Adv., 2013,3, 4473-4491

Center for High-rate Nanomanufacturing

Lactate Sensor Design







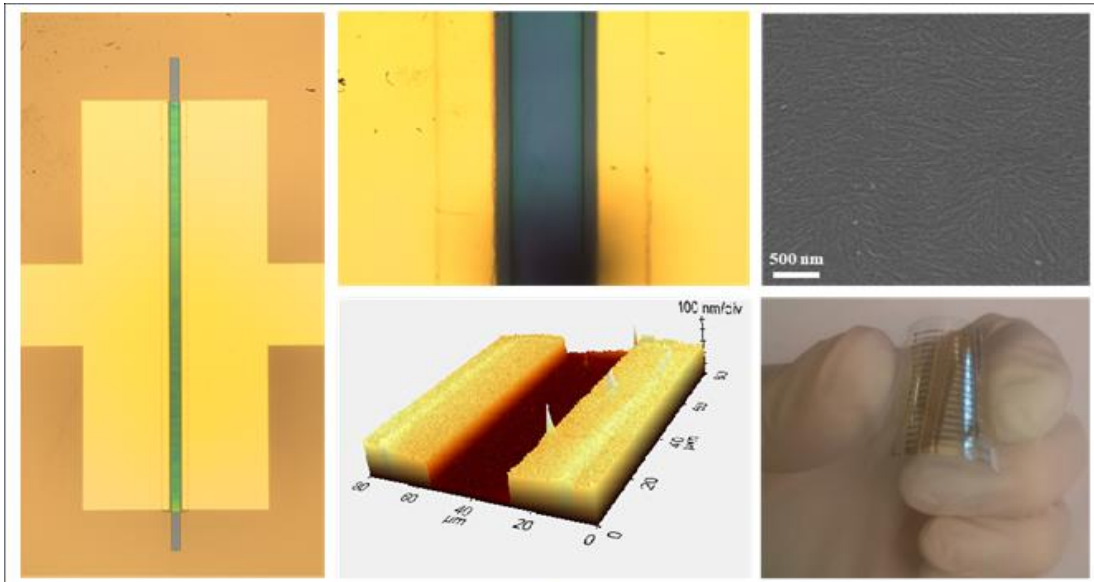
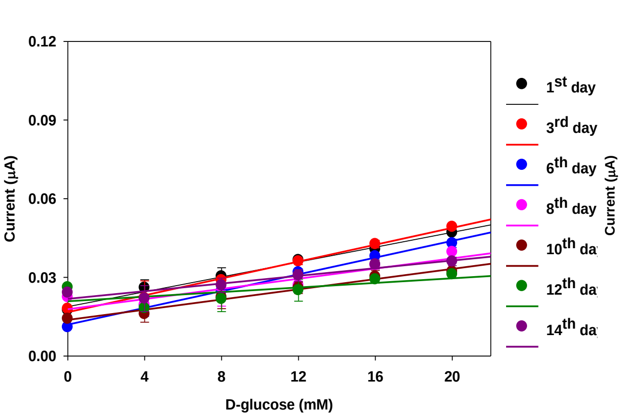
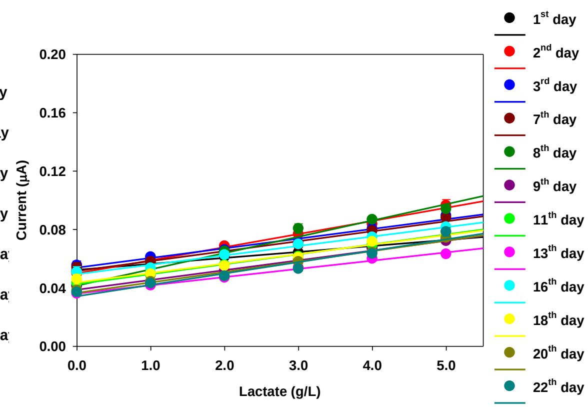


Figure 1. The sensor channel (a) and the open window shown in (b). An AFM image of the channel is shown in (c). The assembled carbon nanotubes are seen in (d) and (e) shows an array of sensors on a 20 mm x 20 mm PET substrate.

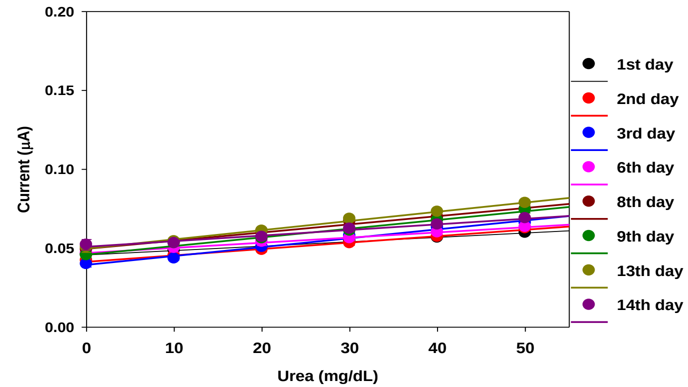
Monitoring Glucose, Lactate and Urea in Sweat



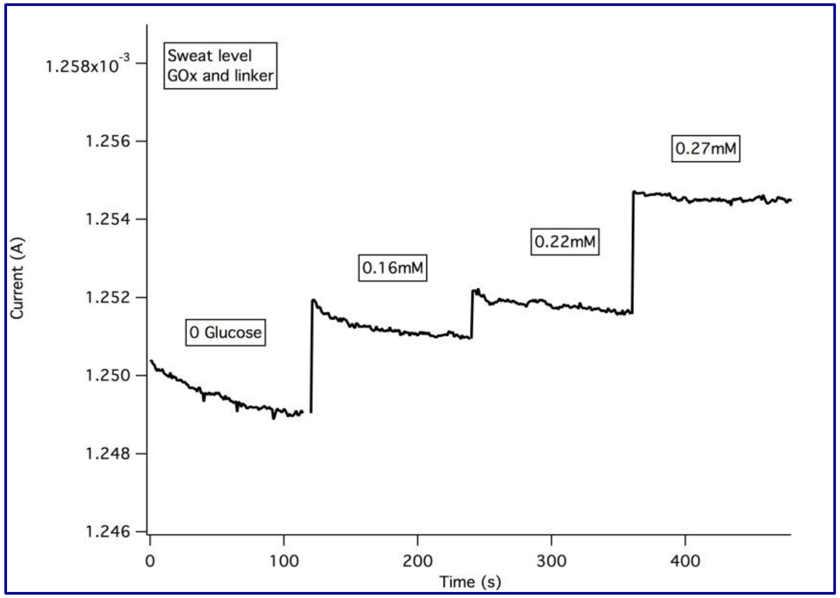
D-glucose



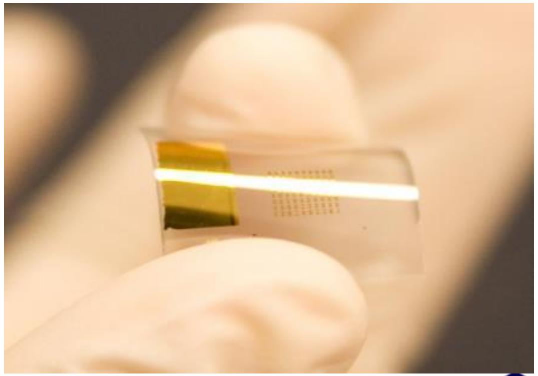
L-lactate



Urea

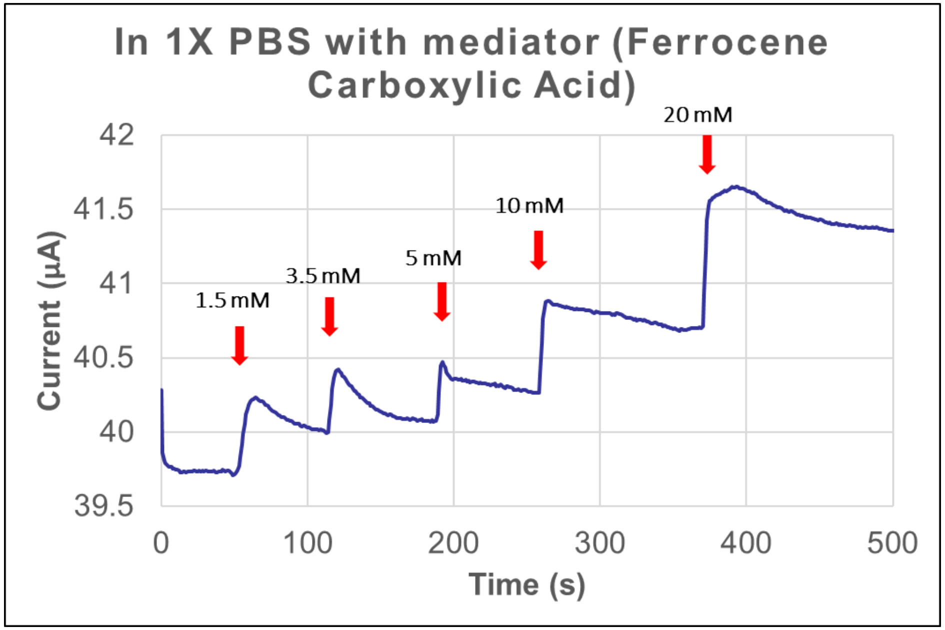


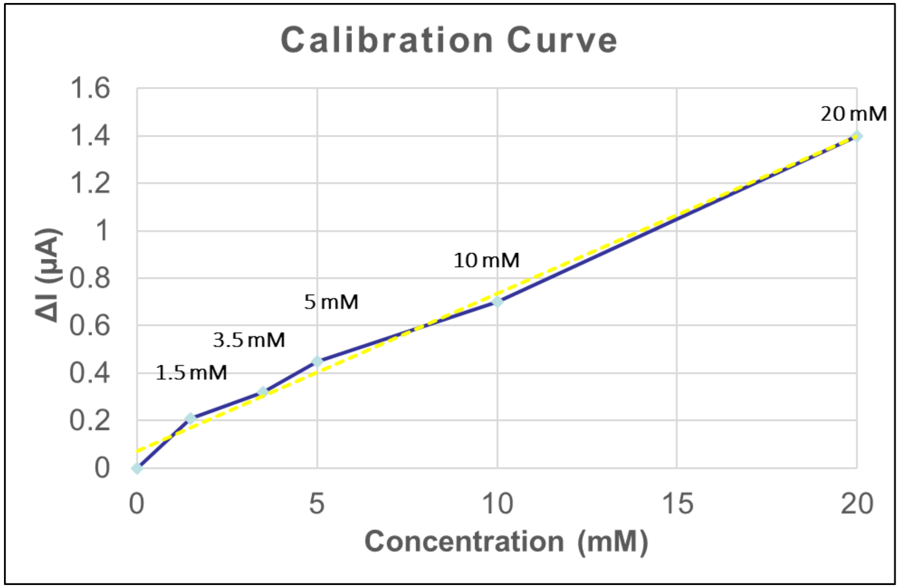
Redesigned glucose sensor for detection in sweat



Center for High-rate Nanomanufacturing

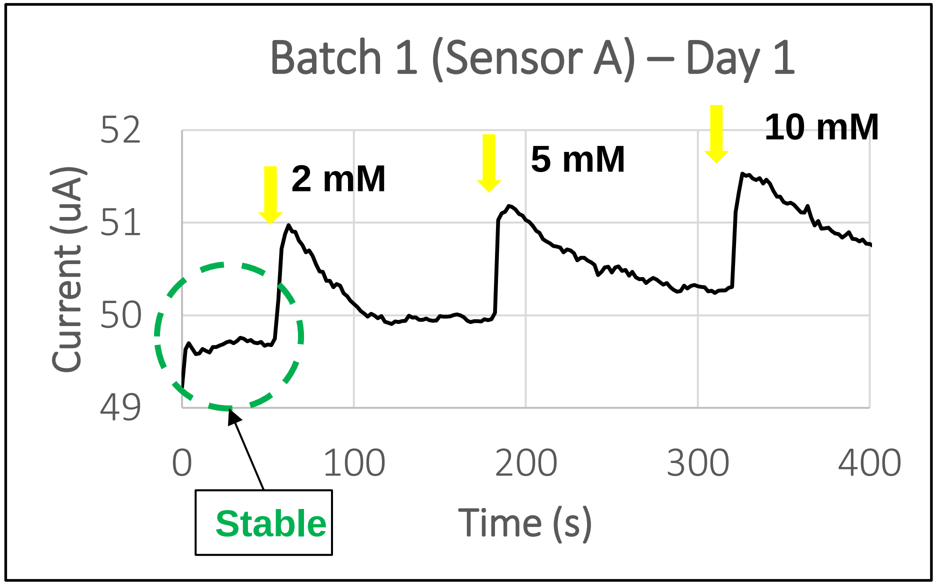
Lactate Sensor Calibration and Testing

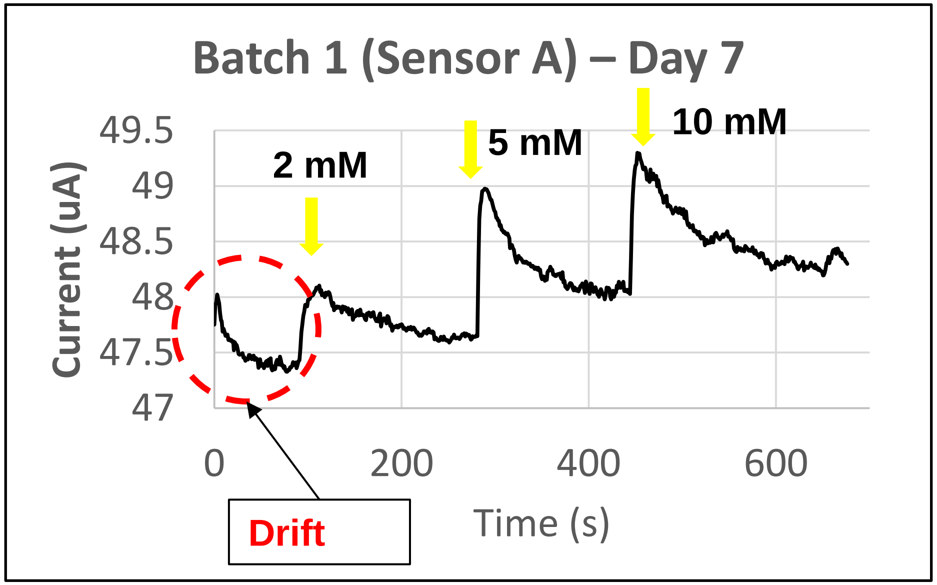


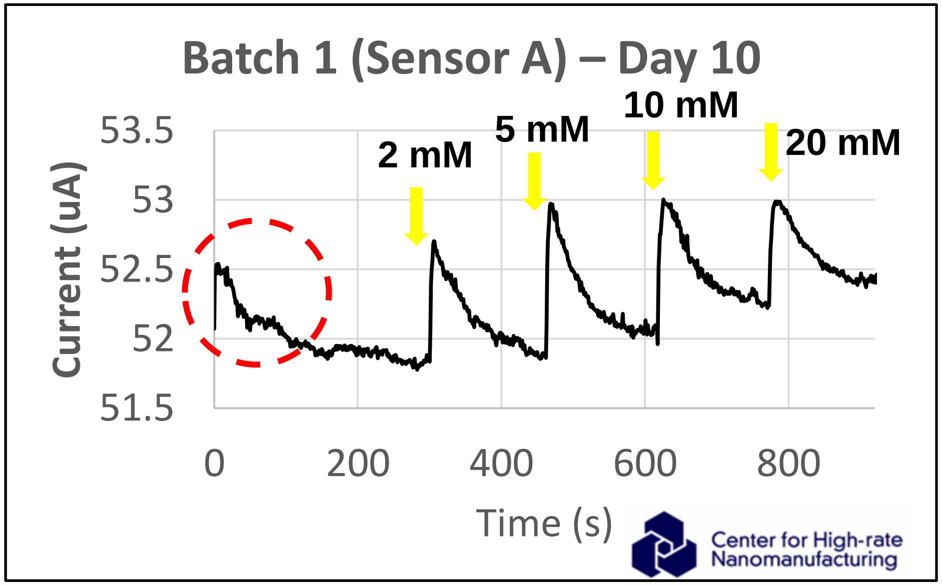


*** Sensor was used over a week before these results were obtained.**

Lactate Testing in 1X PBS:
Baseline stability decreases over a week

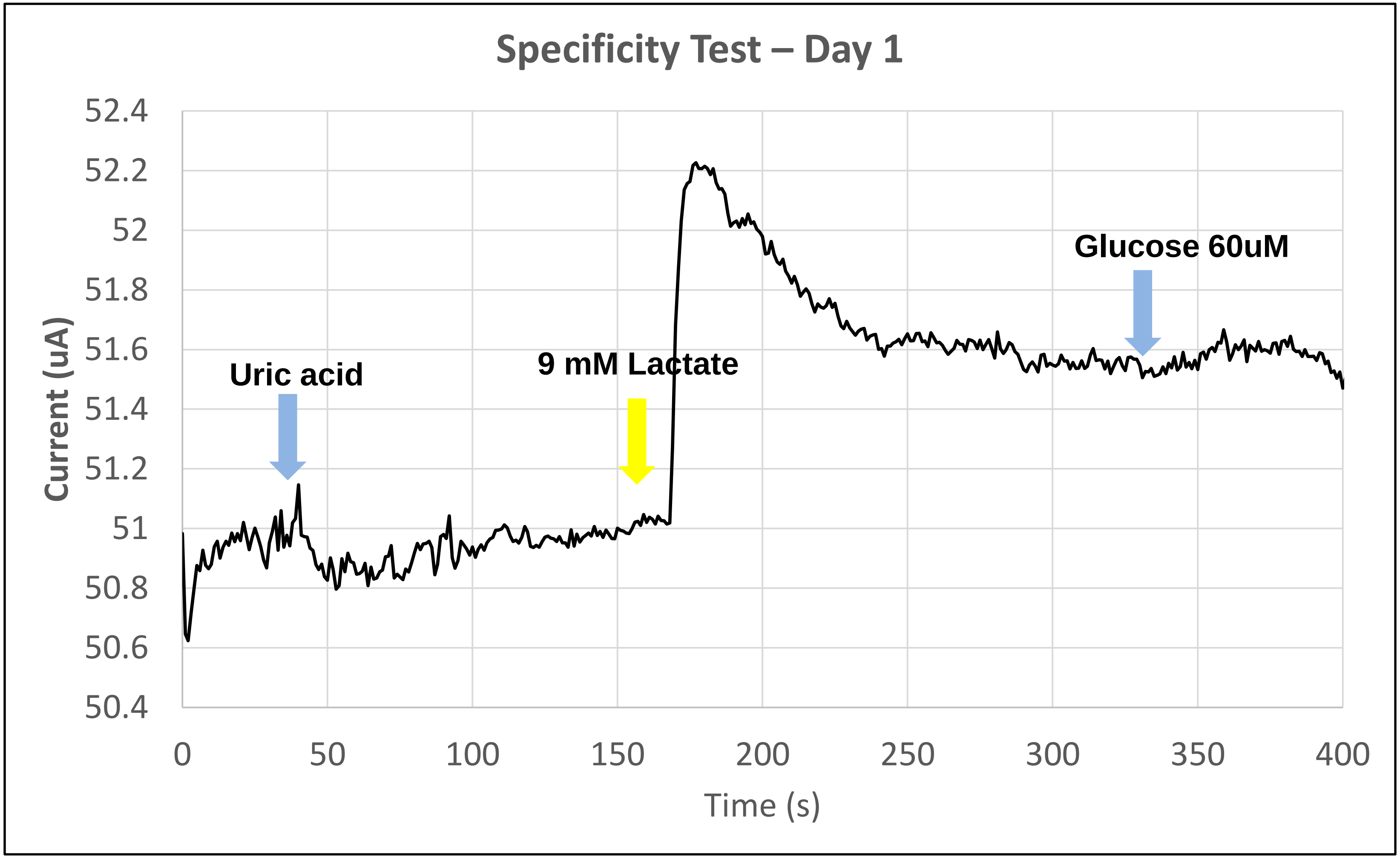






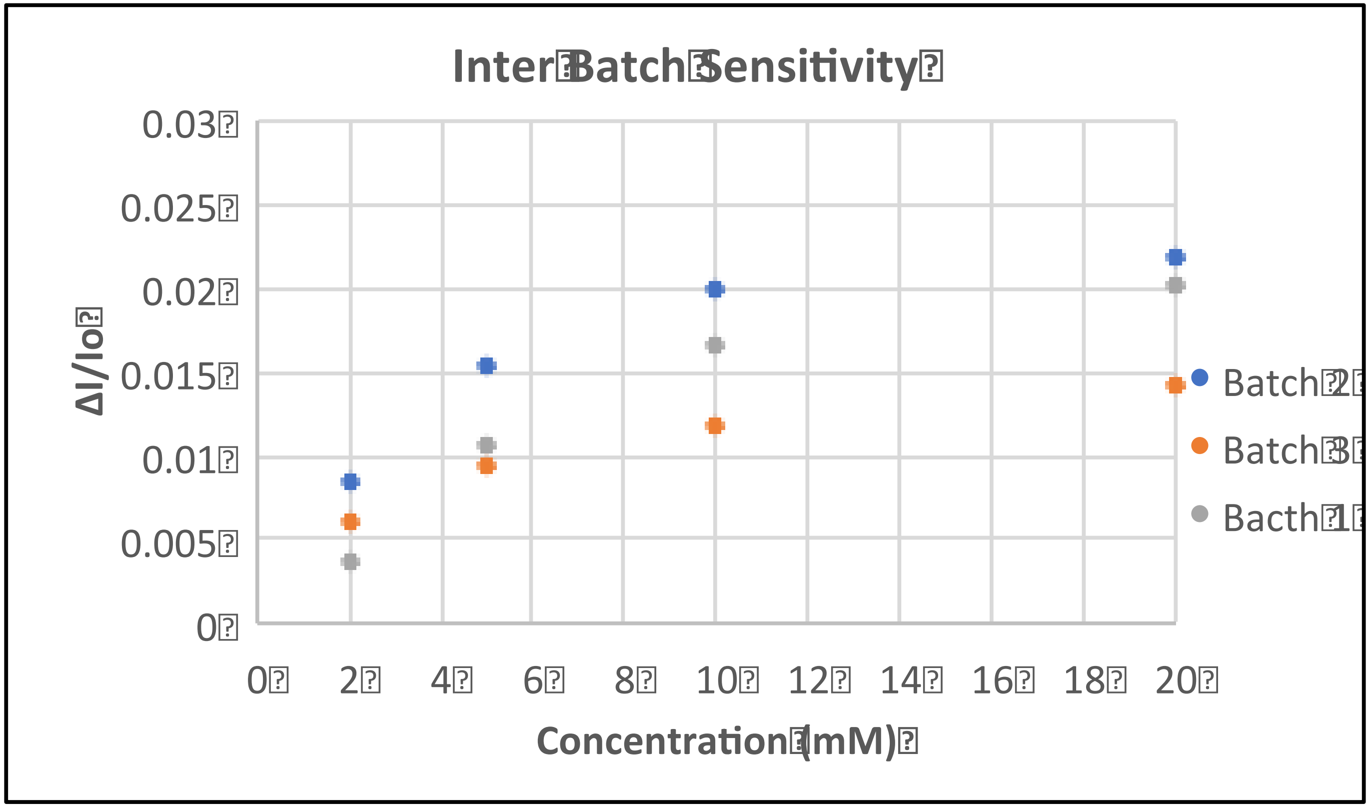
Center for High-rate Nanomanufacturing

Lactate Sensor Specificity (1X PBS)



Center for High-rate Nanomanufacturing

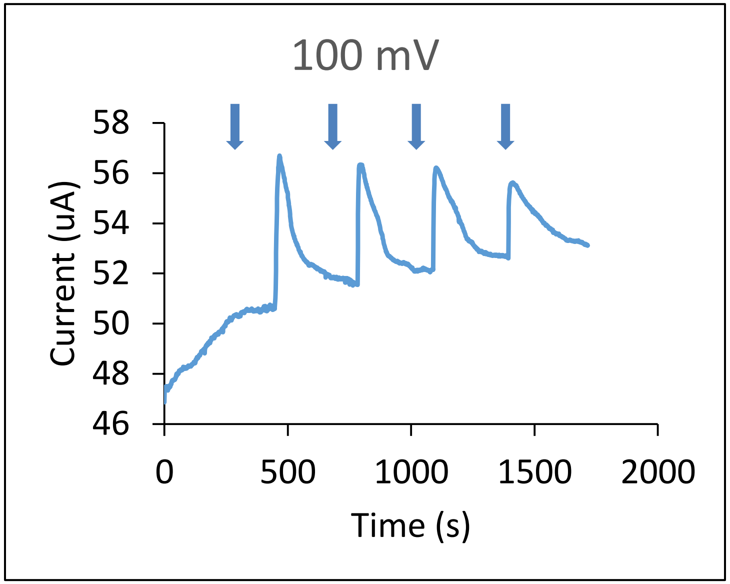
Inter-Batch Sensitivity Characterization

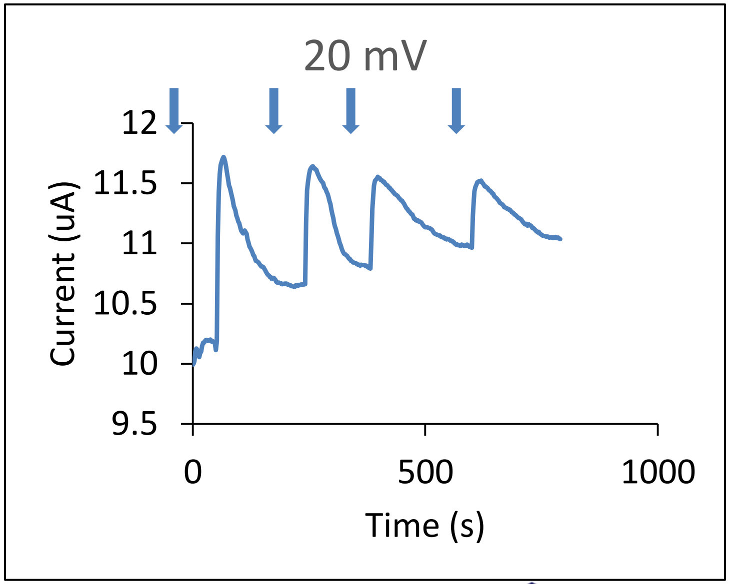


- Characterization shows Inter-batch sensitivity
- Batches were made few weeks apart.
- Multiple reasons, including difference in CNT assembly, functionalization, and the thickness of the Ppy\mediator layer affect the error margin.

Low Power Requirement

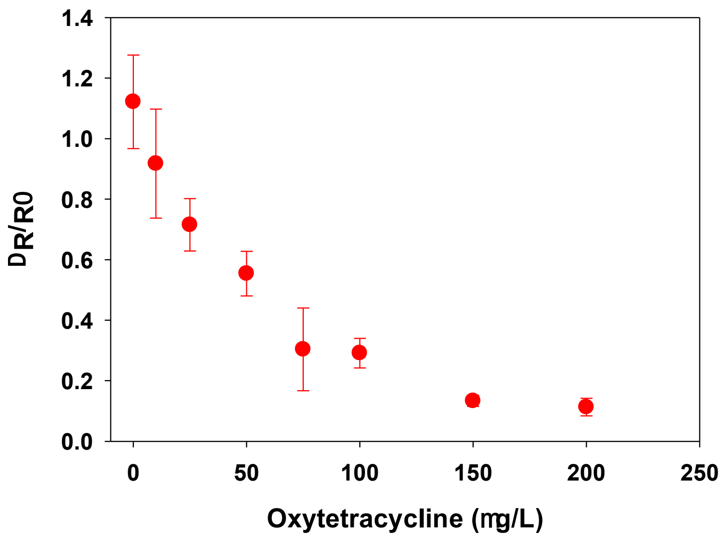
- Power is only needed when a measurement is conducted. If a measurement is needed every minute or five minutes, then the voltage is only turned on at that time.
- Lactate range: 2- 20 mM.
- 20 – 100 mV applied.
- A suitable catalytic reaction mediator can reduce or eliminate the need for constant power.

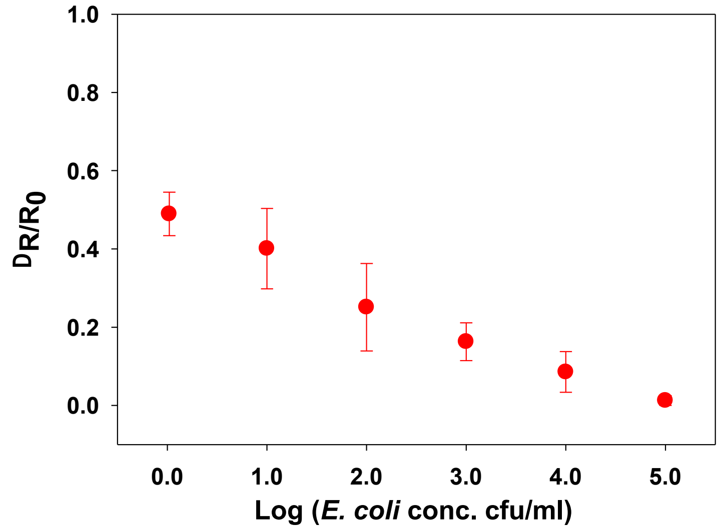


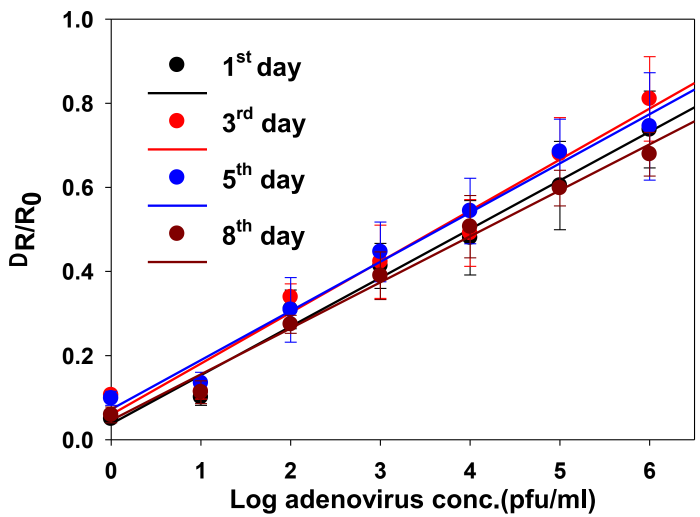


Center for High-rate Nanomanufacturing

CNT Sensors for Viruses, Bacteria, Antibiotics in Water







- Sensors work in both air and liquid environments
- Very high specificity
- Very high repeatability
- Possible regeneration
- Instantaneous response

Nano OPS, Inc.

The Future of Nanomanufacturing

www.nano-ops.net

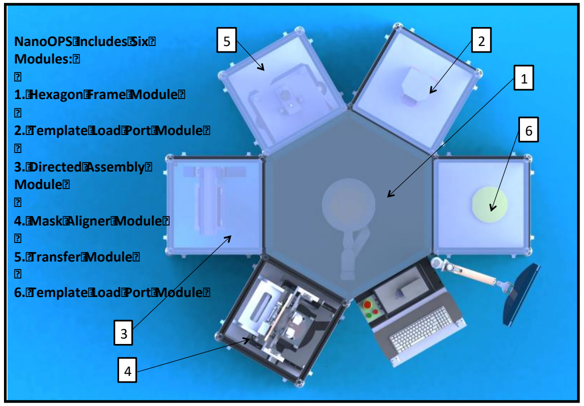
Nano OPS, Inc. IP Portfolio

Nano OPS, Inc. has an exclusive license for 30 patents that cover printing processes, printing templates and sensors:

1. Core nanoprinting process technology
2. Core equipment automation technology
3. Core experienced team
2. Printed products expertise:
   - ➢ Electronics
   - ➢ Chemical Sensors,
   - ➢ Bio Sensors for: cancer, antibiotics, physical & fitness indicator
   - ➢ Display applications

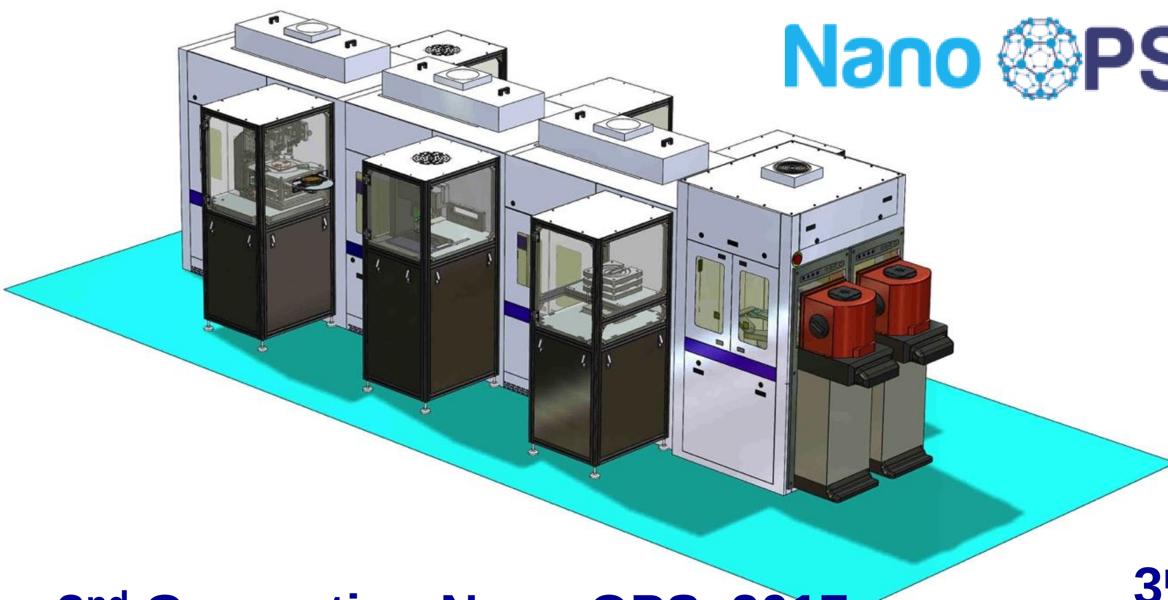
Center for High-rate Nanomanufacturing

2nd and 3rd Generation Nano OPS, Inc. Printers

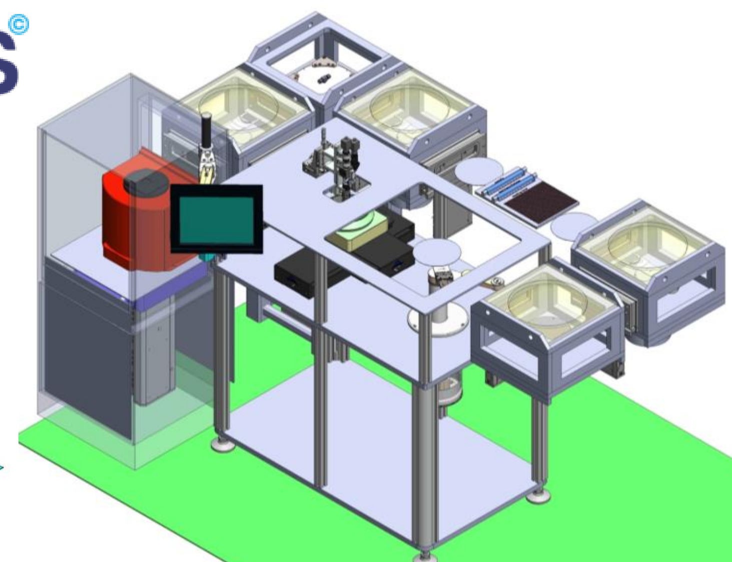


First Generation Nano OPS, 2014

Nano OPS ©



2nd Generation Nano OPS, 2017



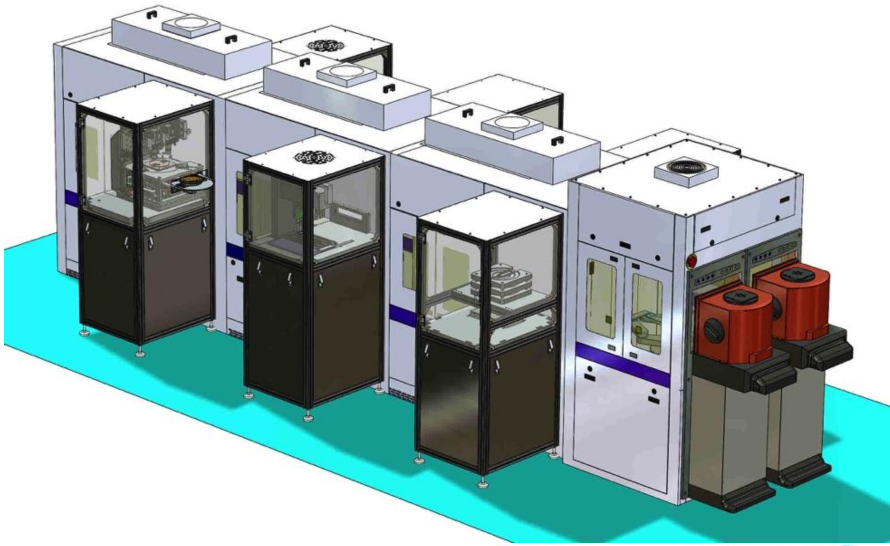
3rd Generation Nano OPS, 2018

MILARA

Center for High-rate Nanomanufacturing

Gen 2 Nano OPS 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.



Nano OPS©

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.

Summary

- We demonstrate simple yet scalable methods for the printing and functionalization of CNT enabled sensors on flexible substrates for detecting lactate in human sweat.
- The sensors are capable of real-time continuous monitoring of lactate in ionic solutions and are active for at least ten days.
- The sensors also show minimal intra-batch variation, which points to the reproducibility and practicality of the technique.
- Baseline stability of CNT-based biosensors has been thoroughly discussed in the Supplementary Information section.
- The directed assembly-based printing method can easily be extended to the manufacture of sensors for the detection of other metabolites such as glucose, urea and creatinine, etc.

Thank you

Questions and Discussion?

Prof. and Director Ahmed Busnaina
Northeastern University
a.busnaina@northeastern.edu
www.nano.neu.edu
www.nanomanufacturing.us

Center for High-rate Nanomanufacturing