Scalable Printing of Nano and Microscale Sensors and Electronics

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High-rate Nanomanufacturing

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www.nanomanufacturing.us

Northeastern University

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

2015 - $15B

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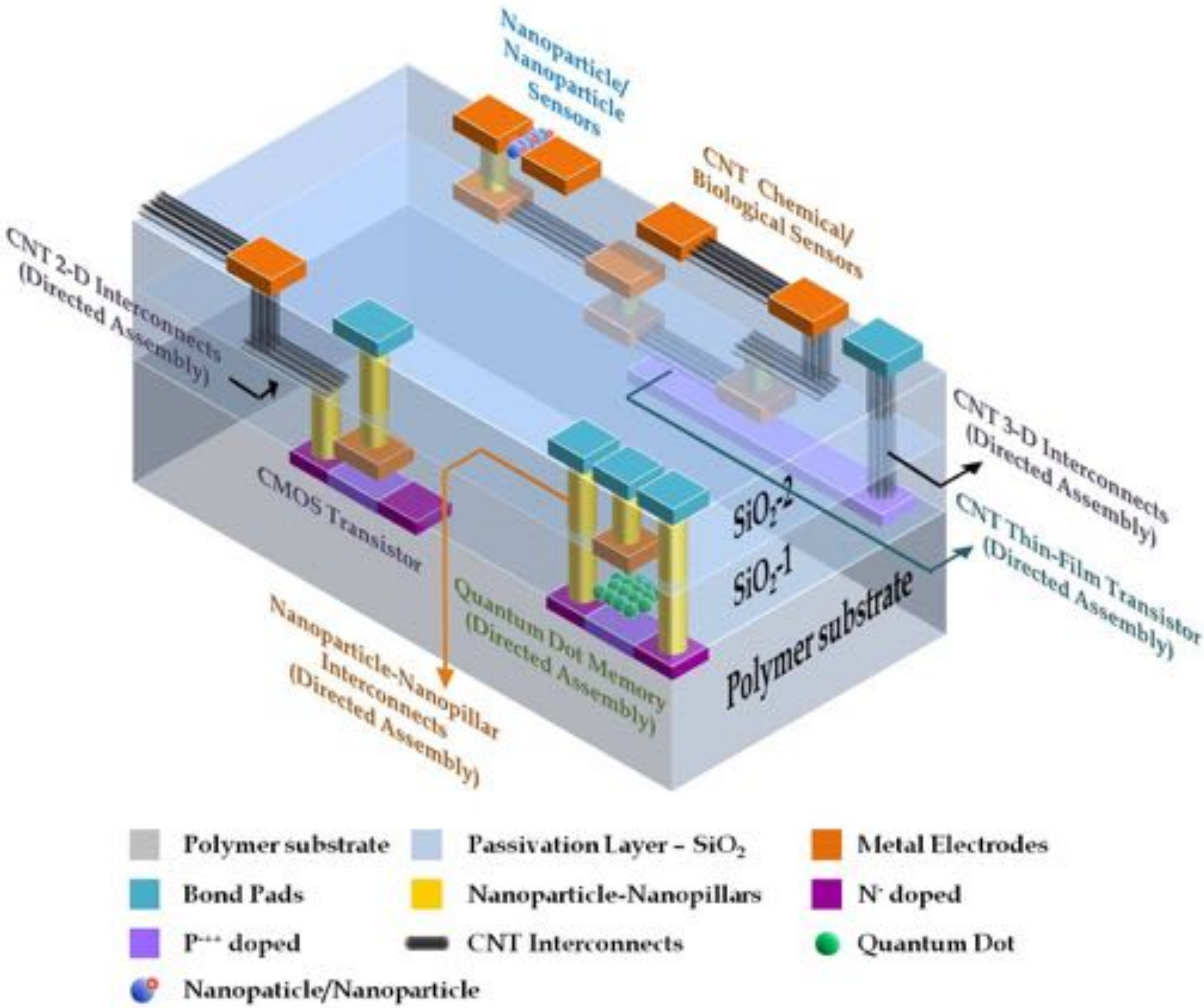
Motivation: Versatility

Can we print any material on any substrate?



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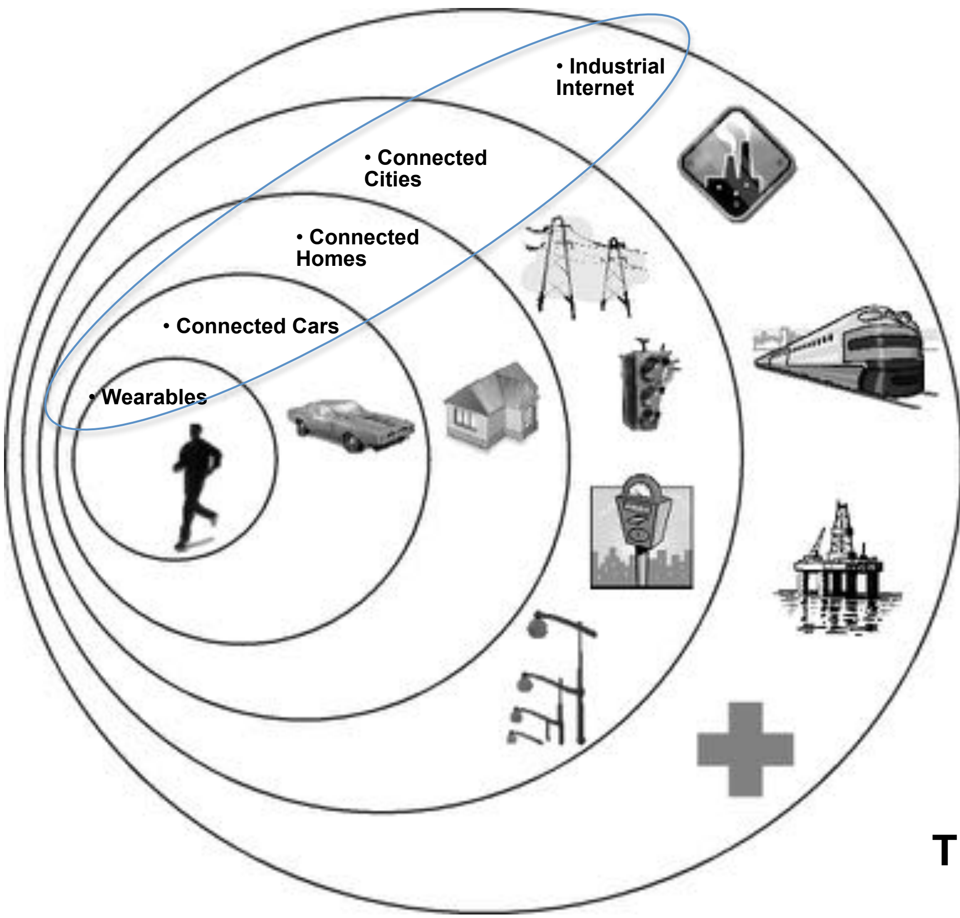
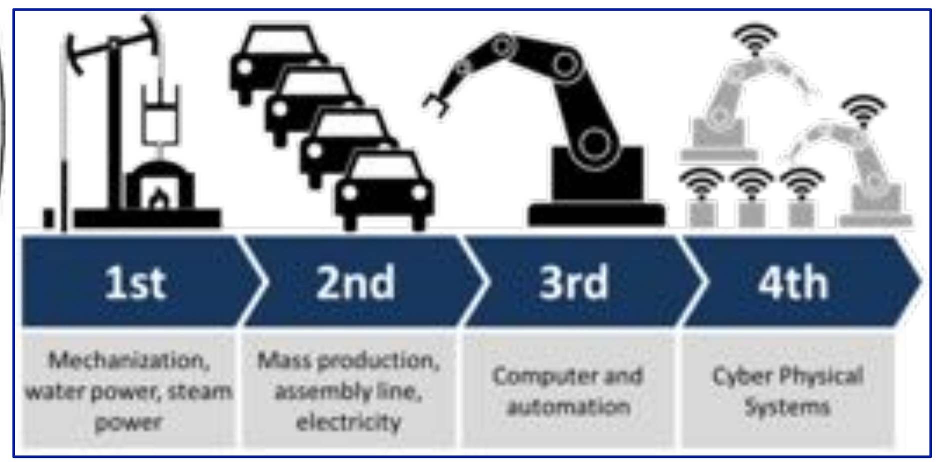
Motivation: IoT Opportunities

IoT has five key verticals: **Connected Wearable Devices, Connected Cars, Connected Homes, Connected Cities**, and the **Industrial Internet.**



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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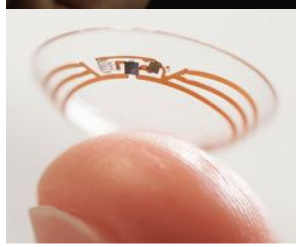
Wearable technology: Impact and Forecasts





Market Sector Size /$ Billions	2015	2016	2020	2025
Health, Medical, Fitness, Wellness -Regulated	8.92	9.61	14.67	28.49
Health, Medical, Fitness, Wellness - UnRegulated	1.61	1.78	1.43	1.01
Infotainment	11.61	14.24	19.00	20.89
Industrial, Commercial, Military	1.37	1.71	4.22	7.58
Fashion & Other	0.70	0.79	2.57	6.31
TOTAL in Billions	24.21	28.13	41.89	64.28

- **The strongest sectors will be health and fitness devices (largest growth) and infotainment (largest size).**
- **Infotainment is likely to suffer from heavy commoditization, similarly to the large, stagnant basic infotainment sectors (including simple accessories like headphones, and basic wristwatches).**

•Source: IDTechEx report **"Wearable Technology 2015-2025"** www.IDTechEx.com

The IoT can only be enabled by breakthroughs in the cost of ubiquitous sensors and Electronics.

This could be accomplished by

Printing Sensors and Electronics

What about the current electronics printing industry?

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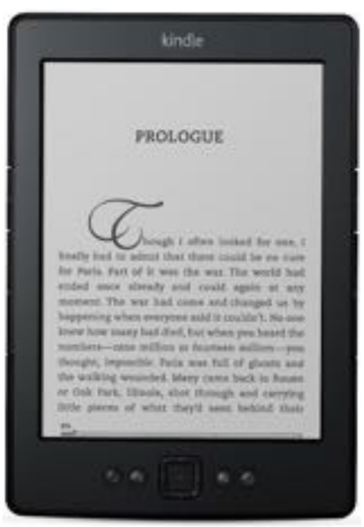
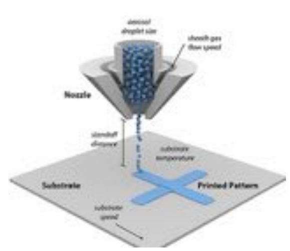
State of the Art - Printing Technologies

- Current electronics and 3D printing using inkjet technology, used for printing low-end electronics, flexible displays, RFIDs, etc. and **can only print down to 20 microns (20,000 nanometers)**.
- 20 microns was the silicon electronics line width in 1975.
- Even with these scale limitations, currently printed sensor cost 10 to 100 times less than conventionally fabricated sensors.





- Can print only one layer
- The largest printed sensors market is about $6 billion (mostly blood glucose strips) (IDTechEx).

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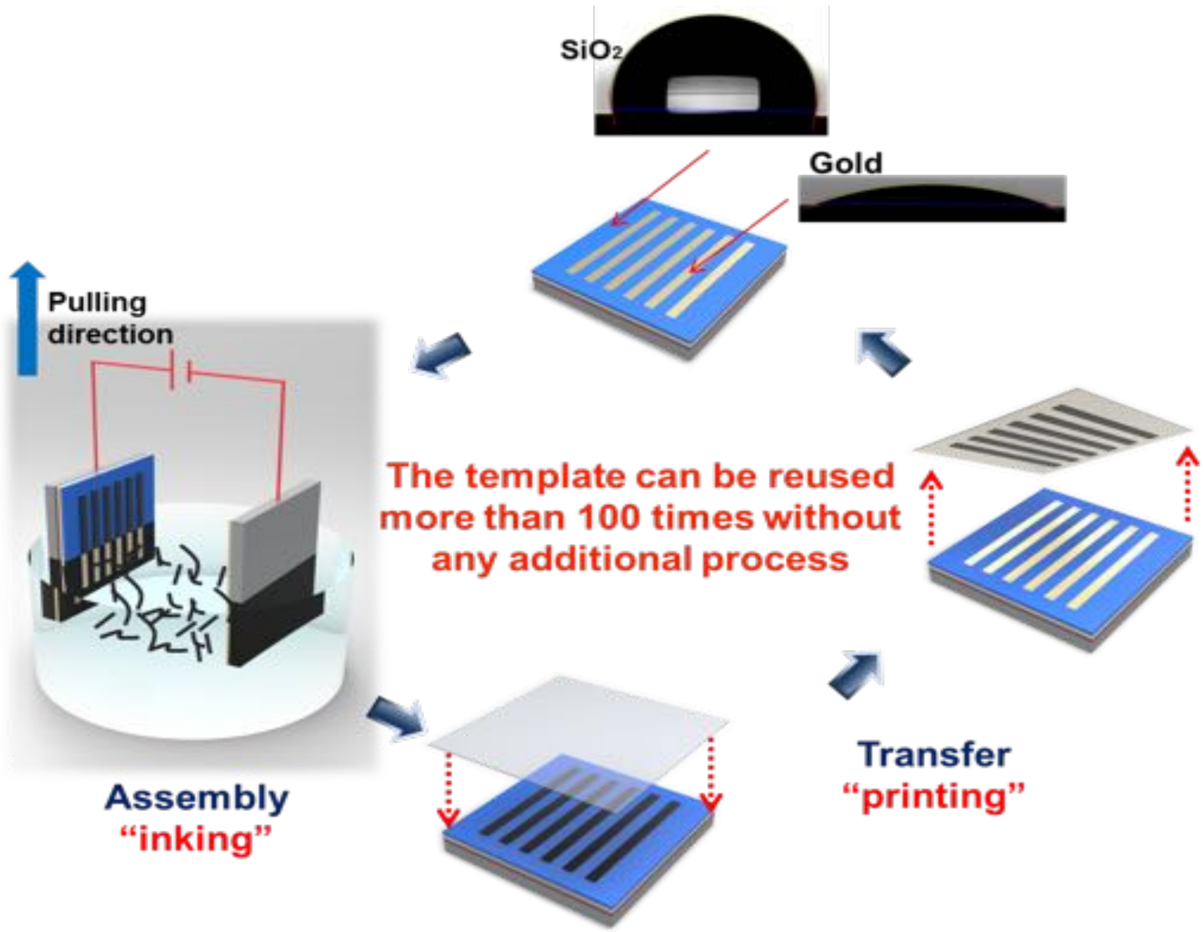
Beyond 3-D & Electronic Printing: Nanoscale Offset Printing Advantages



- 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

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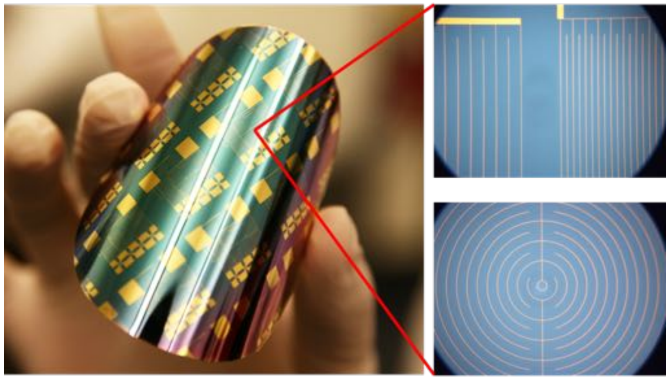
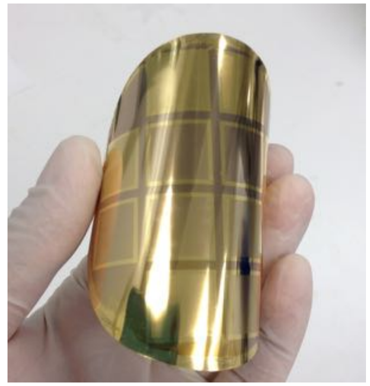
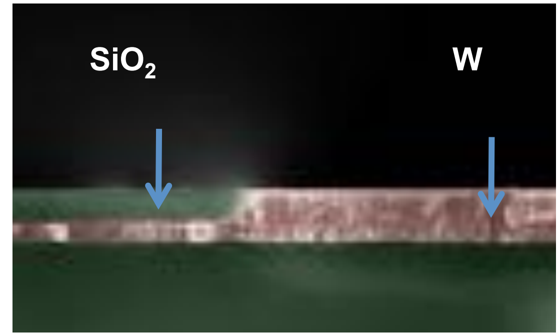
Damascene Templates for Nanoscale Offset Printing



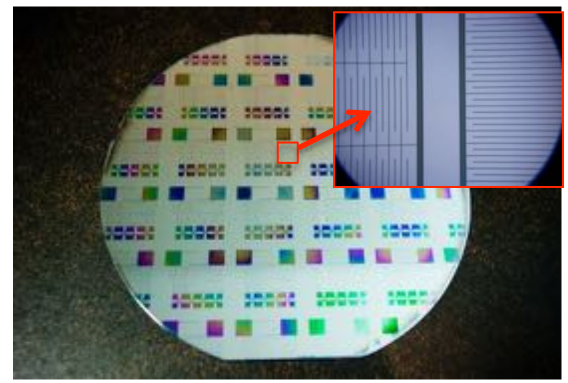


PEN **Polymer-based Templates** **PI**

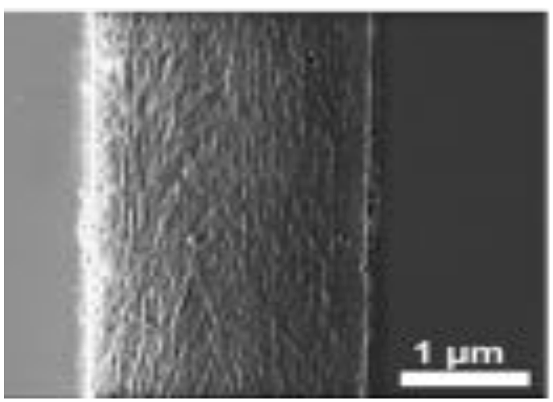
Advanced Materials, 2015



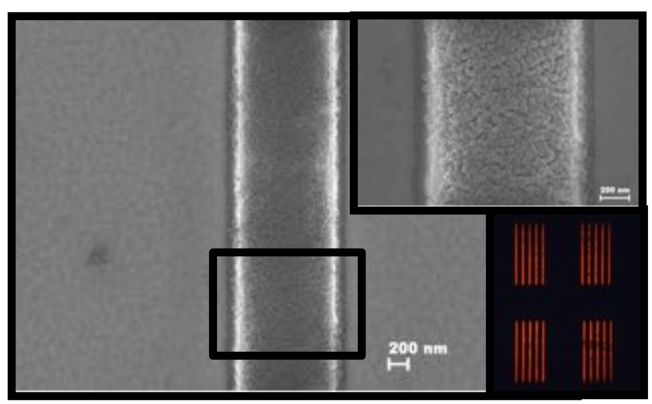
Silicon-based Hard Templates



Assembled SWNT



Assembled Particles



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

Printed Electronics Conf., Berlin 2016

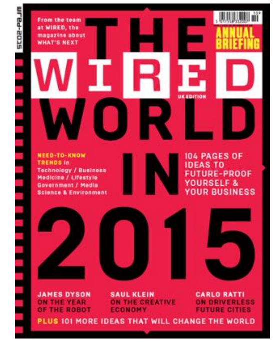
2016 FLEXI AWARD

AWARD WINNER EUROPE 2016

Best Academic R&D Award

IDTechEx Show! EUROPE 2016

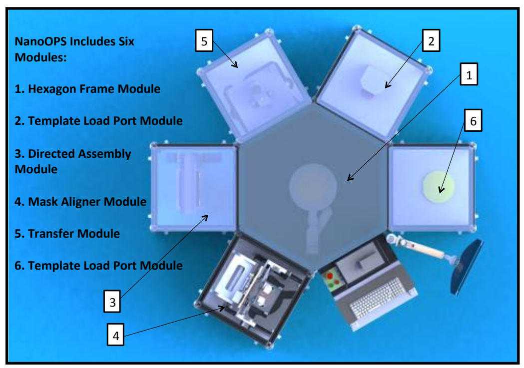
2015 R&D 100 FINALIST



The 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

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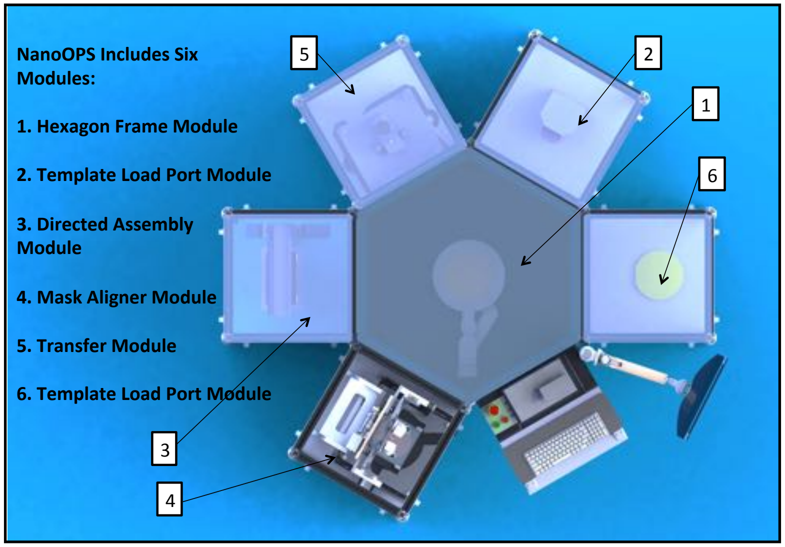
Fully Automated Nanoscale Offset Printing System (NanoOPS) Prototype was Demonstrated on 9/17/2014 to 58 companies

- **NanoOPS is capable of printing using templates with micro and nanoscale patterns (down to 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

Second Generation NanoOPS Printers

The second generation NanoOPS printer is already being built. It will have the ability to print nanoscale sensors and electronics on any polymer substrate. Fully automated with built-in alignment and registration, inspection and annealing.

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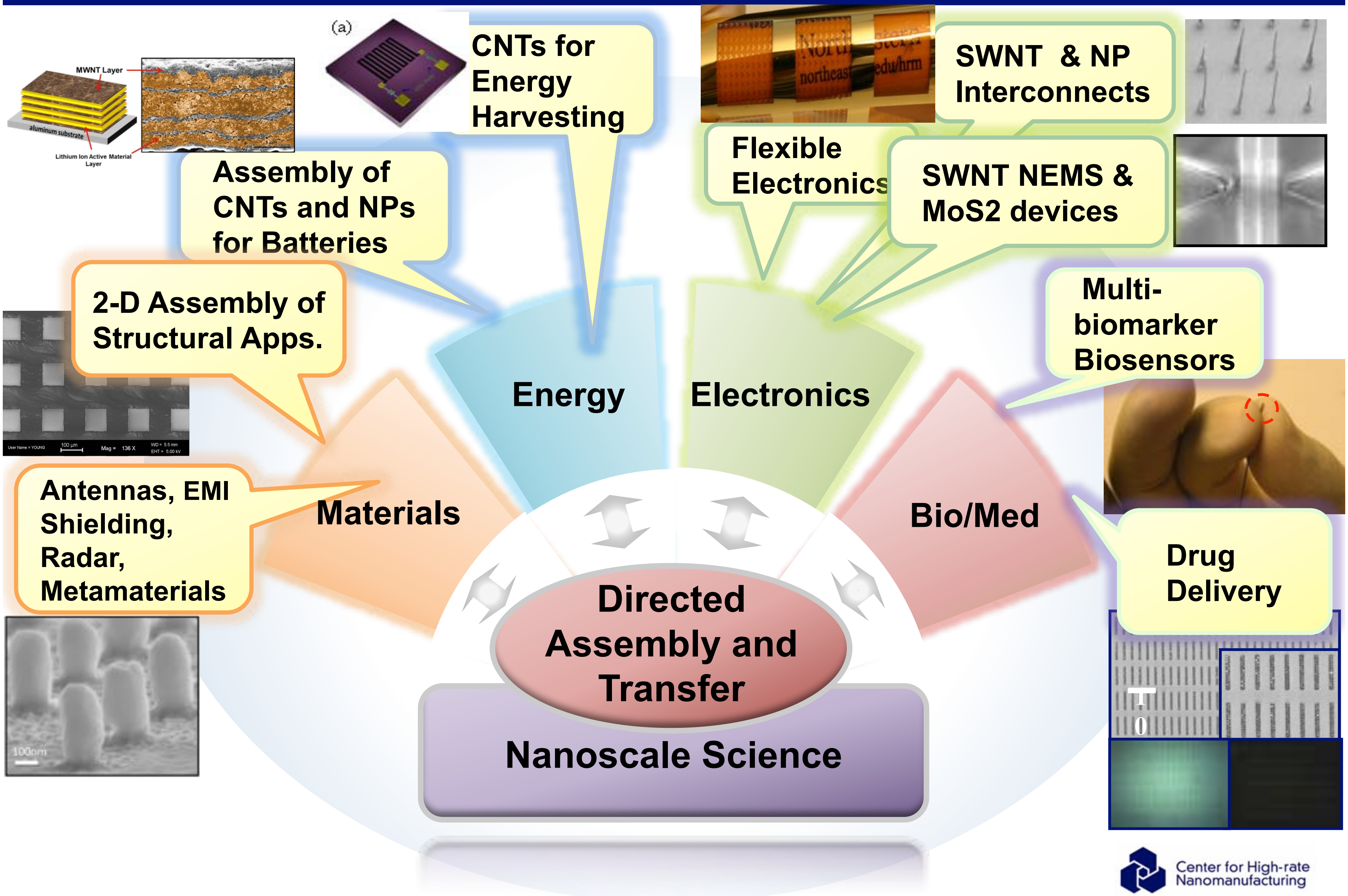
omanufacturing

What Could We manufacture with Multiscale Offset Printing?



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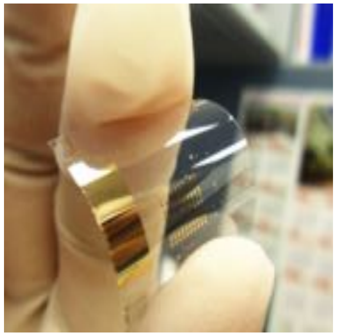
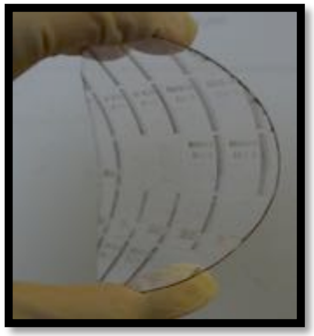
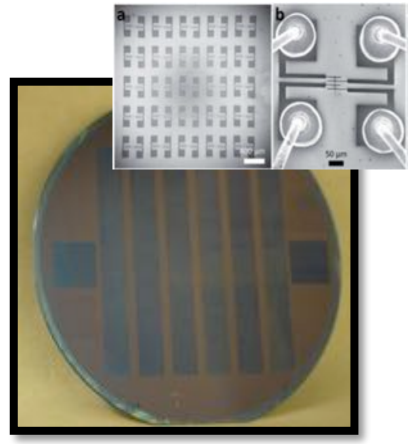
Sensors and Electronics at a Fraction of their Current Cost

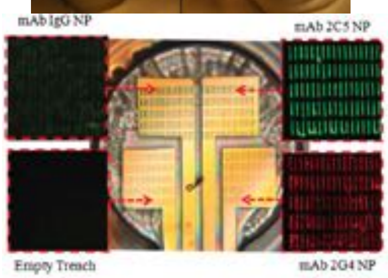




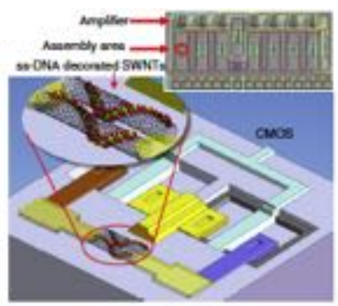


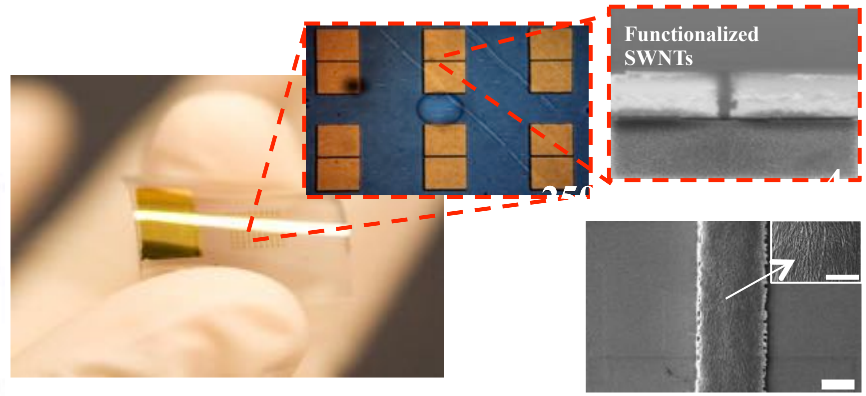
Sensors for Chemicals

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

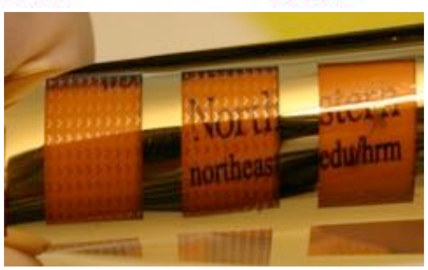


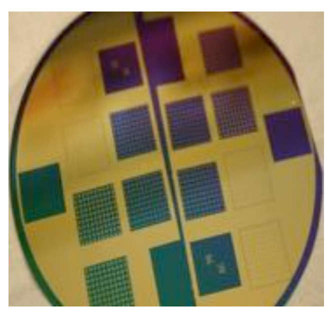
Cancer and cardiac diseases. **Detection limit is 200 times lower than** Current technology





Band-Aid sensor





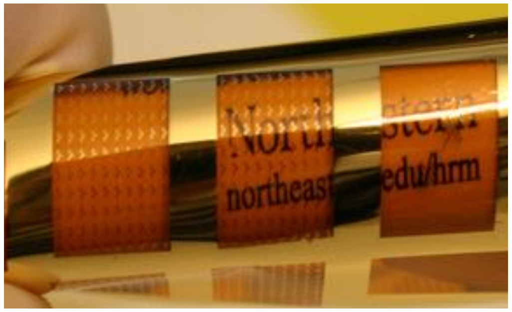
Supporting printed electronics for sensor systems

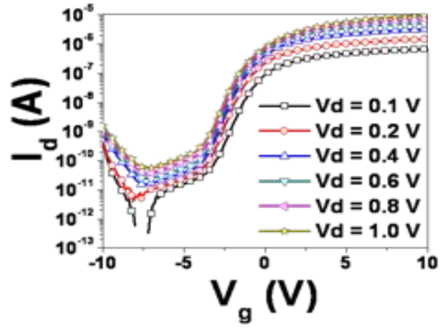
Applications

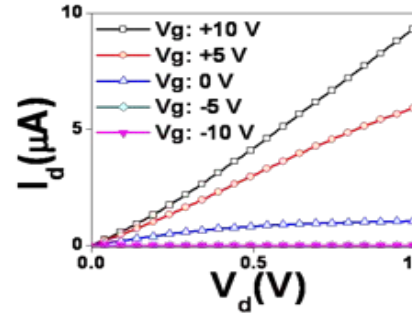
Electronics

Electronics

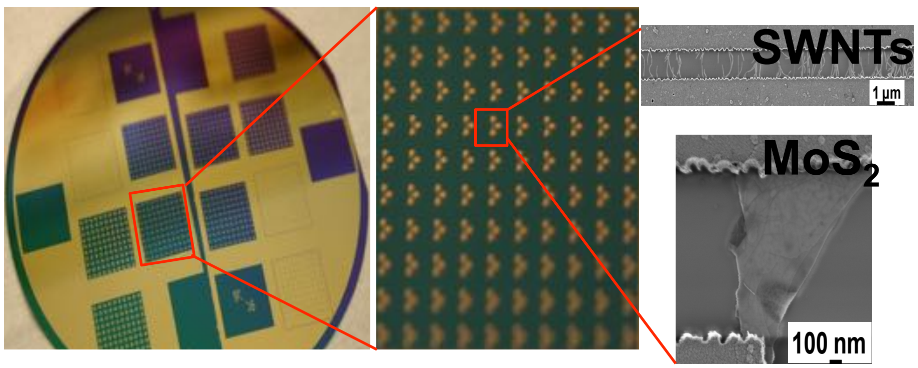
- Flexible transparent n-type MoS_2 transistors

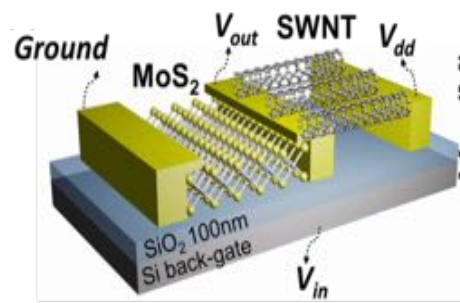


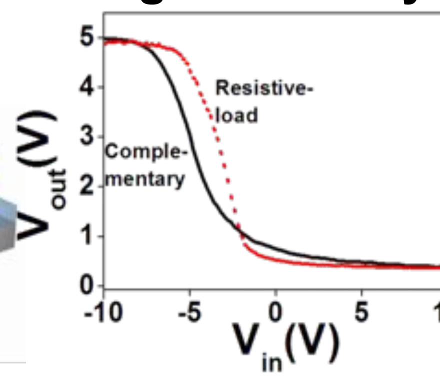




- Heterogeneous SWNTs and MoS_2 complimentary invertors through assembly



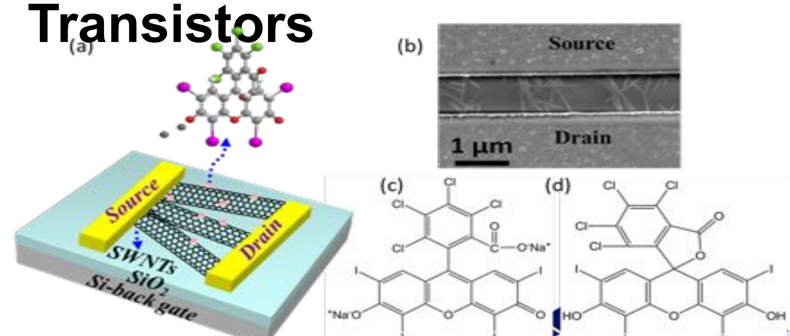




Nanotechnology, Vol. 23, (2012).

- Rose Bengal Molecular Doping of CNT Transistors

Appl. Phys. Lett. 97, 1 2010.



Nanotechnology, Vol. 22, (2011)

Applications

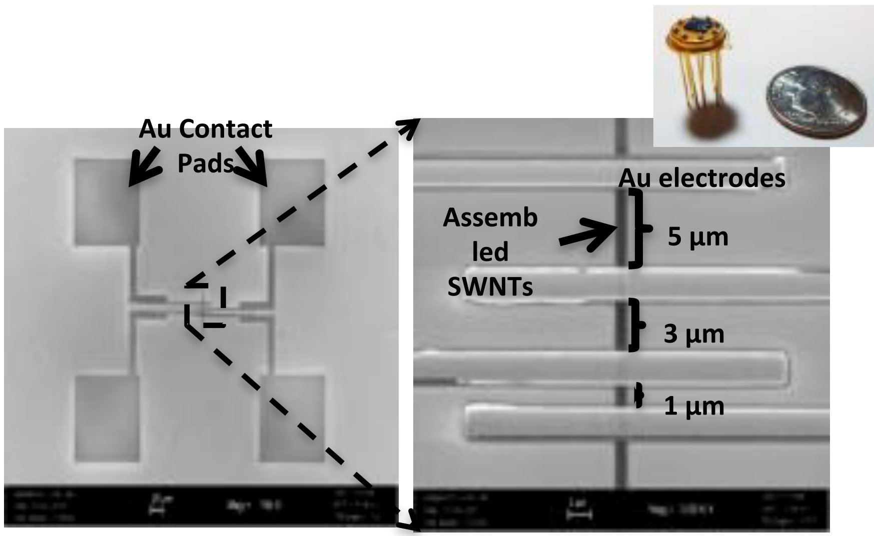
Sensors

Sensor Manufacturing Major Issues

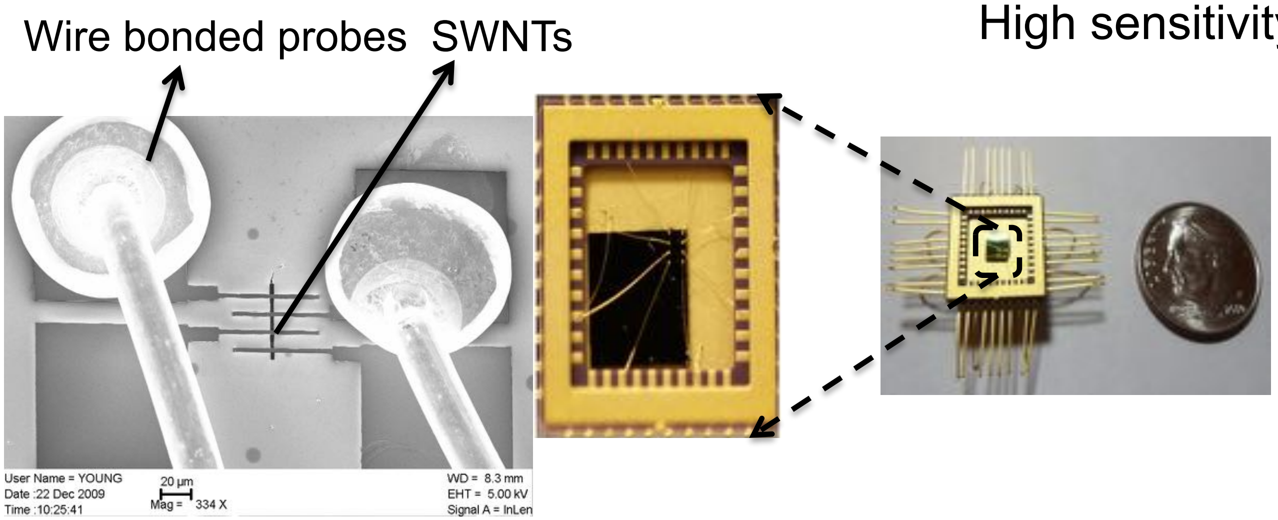
- **Printing (Manufacturing)**
  - Scalability, reproducibility, raw material (supply chain), yield and life cycle.
  - Packaging (is it supposed to deliver liquids to the sensor?)
  - Sensor system (supporting electronics)
- **Sensors**
  - Specificity
  - Repeatability and stability (from batch to batch and in different environments)
  - Regeneration (how many times a sensor could be used?)
  - Response time
  - Signal Strength (how much stronger than background noise?)
  - Testing and characterization Protocols

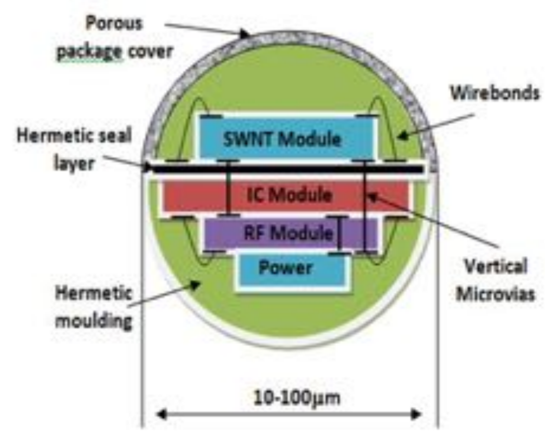
Chemical Sensors

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.

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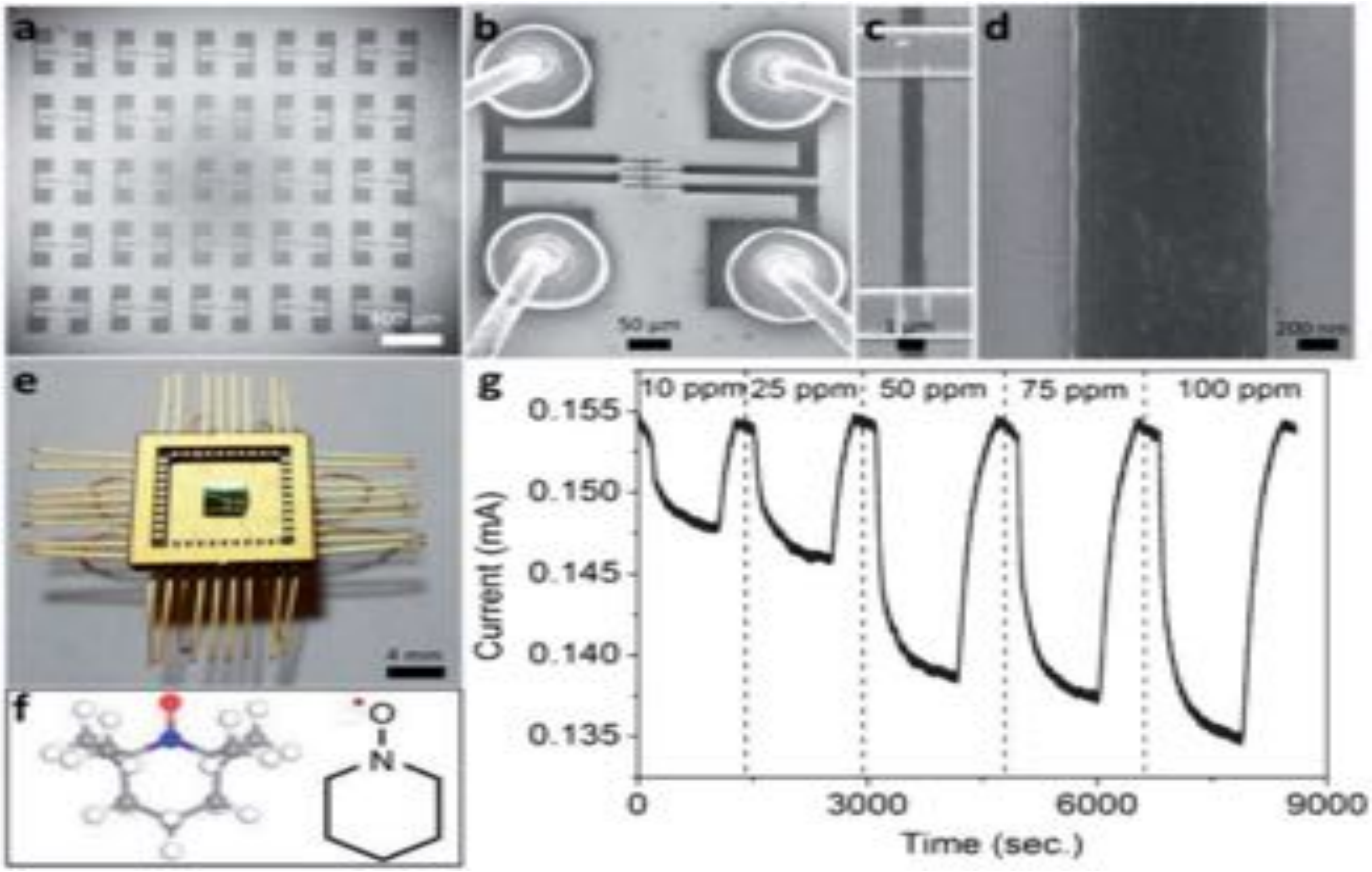
Chemical Sensors



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

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How does state of the art compares?

Commercial Sensors

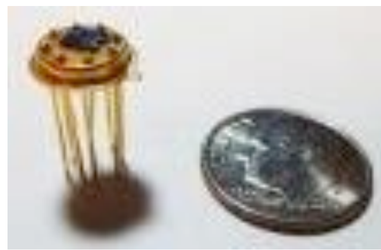
Weight: 5.5 lbs **Weight: 4.15 lbs**

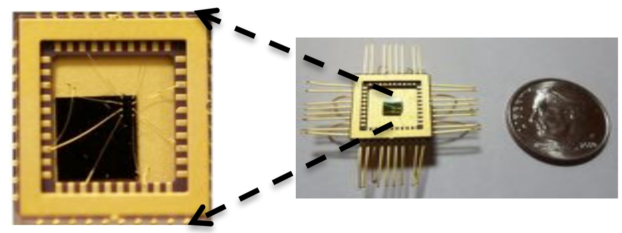
Commercial Chemical Hydrogen Sulfide (H2S) Sensors

Commercial Glucose Sensors use blood

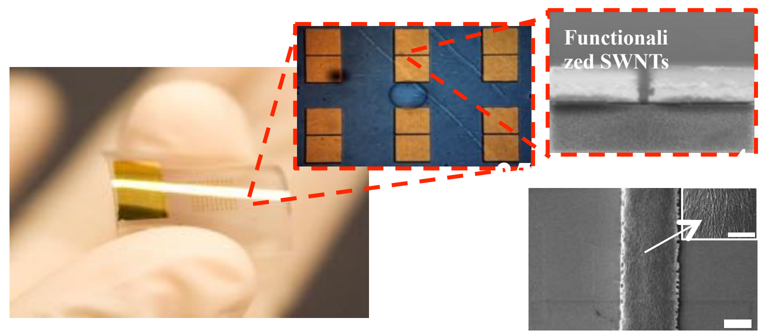
The Sensors developed by the CHN

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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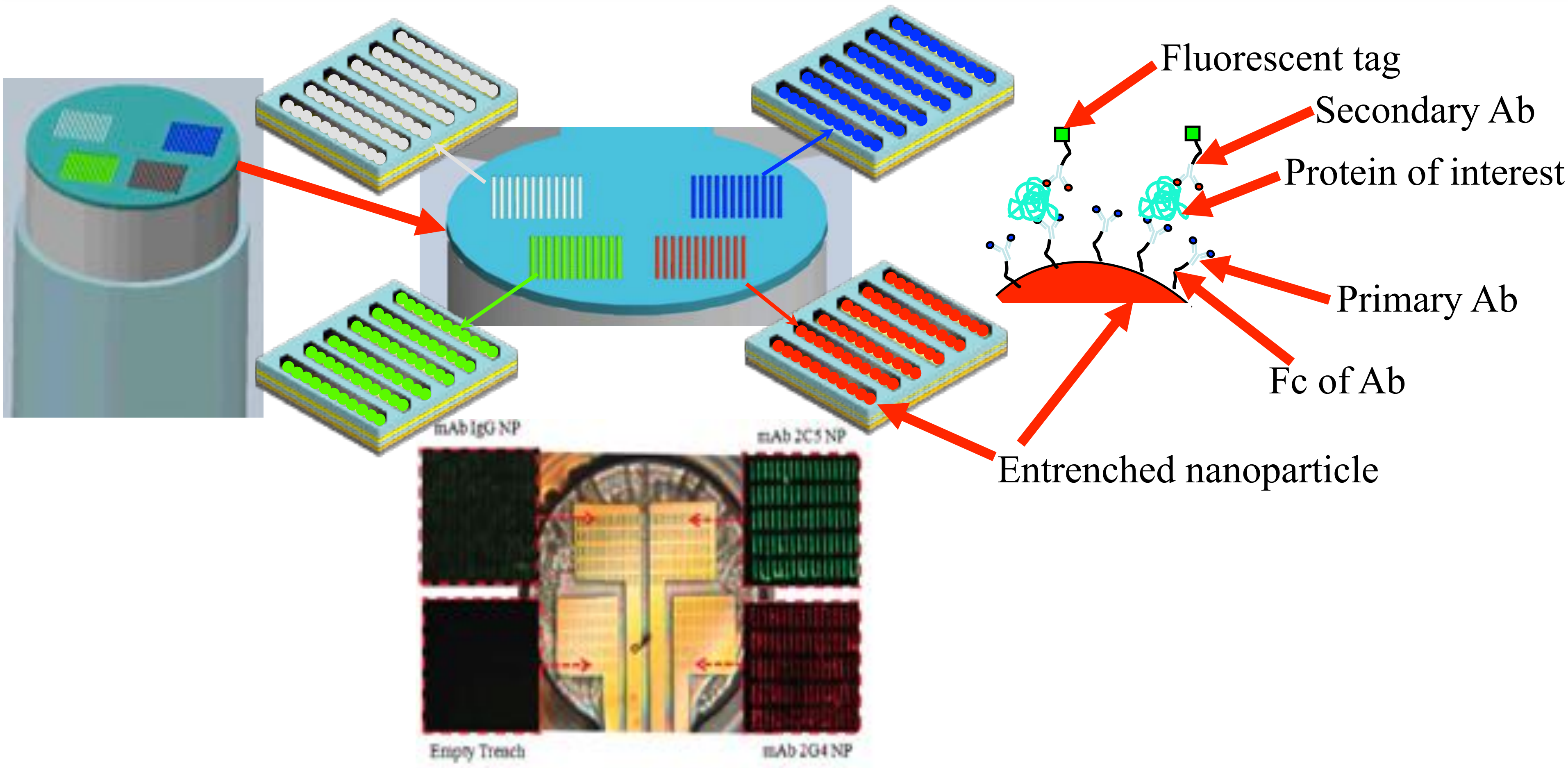
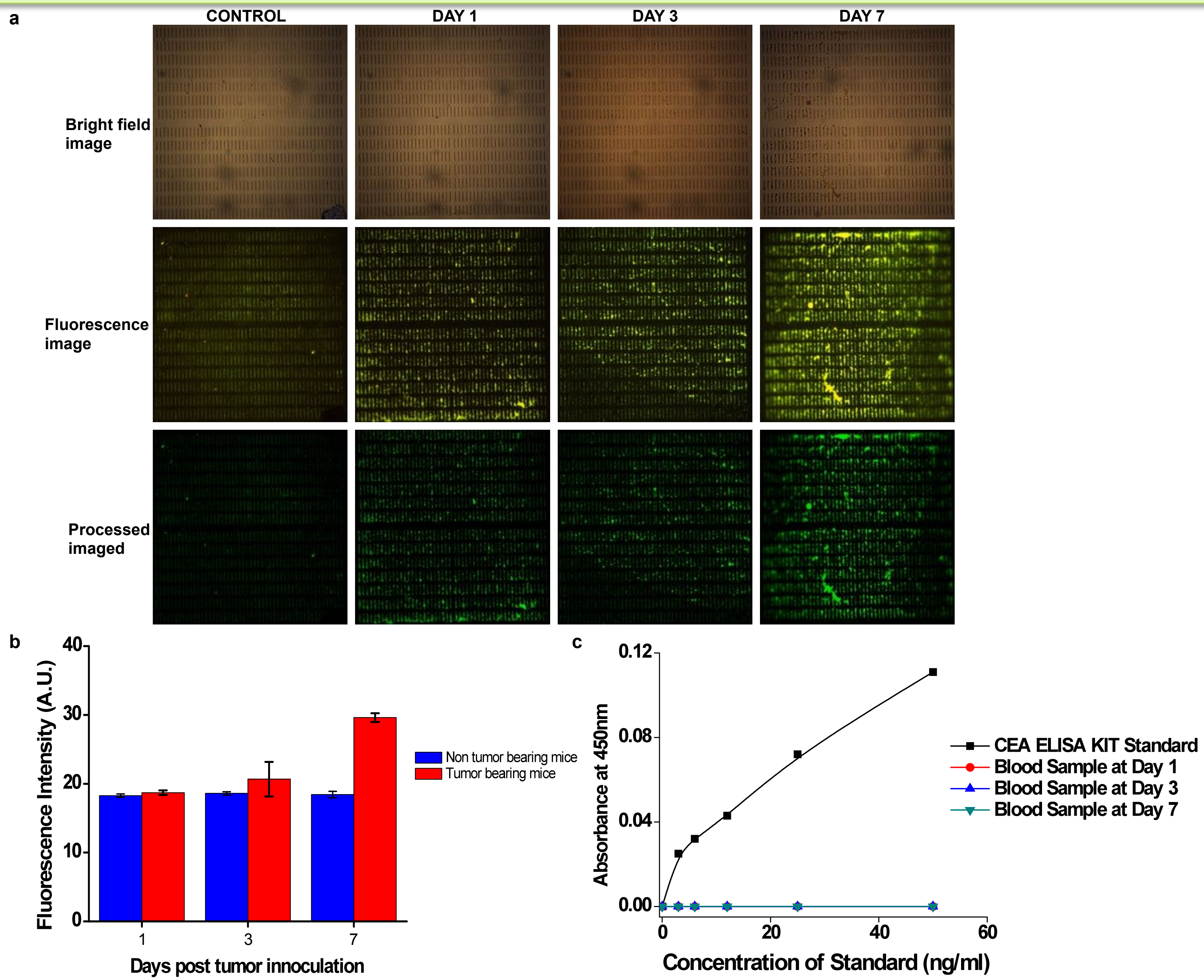
Biolom Platform Technology Solution



Langmuir Journal, 27, 2011 and Lab on a Chip Journal, 2012
US Patents: Multiple biomarker biosensor: (US 2011/0117582 A1), 2 more patents pending
Funded by the Keck Foundation, PIs: Ahmed Busnaina and Vladimir Torchilin

Experiments with Tumor Bearing Mice



(a)Optical images (b) results showing early detection of CEA relative to (c) ELISA test. ELISA was not able to detect CEA in tumor bearing mice

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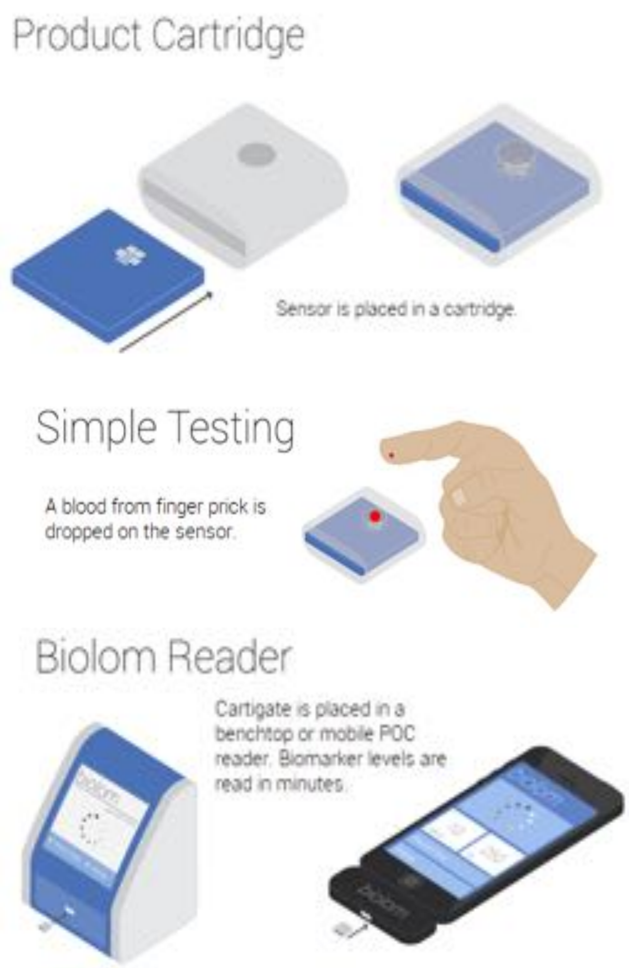
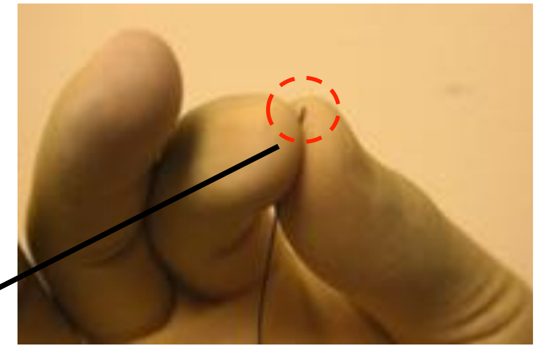
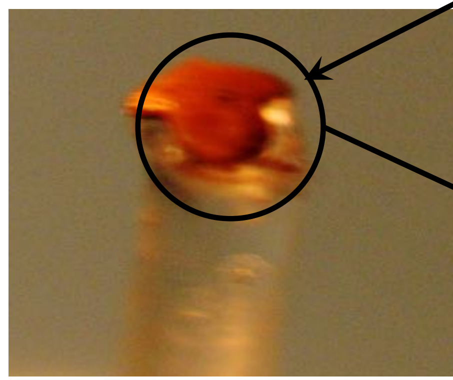
Cancer and Cardiac Disease Biosensors



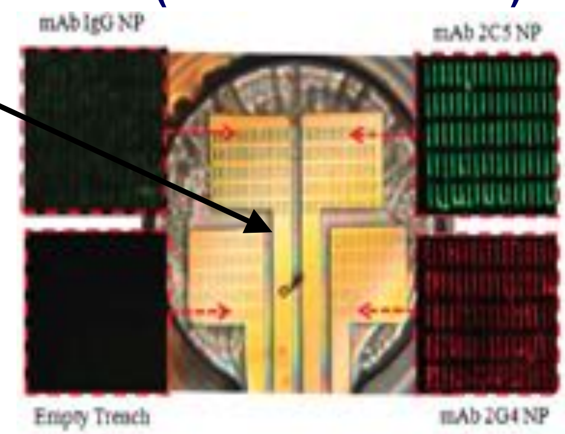
biolom

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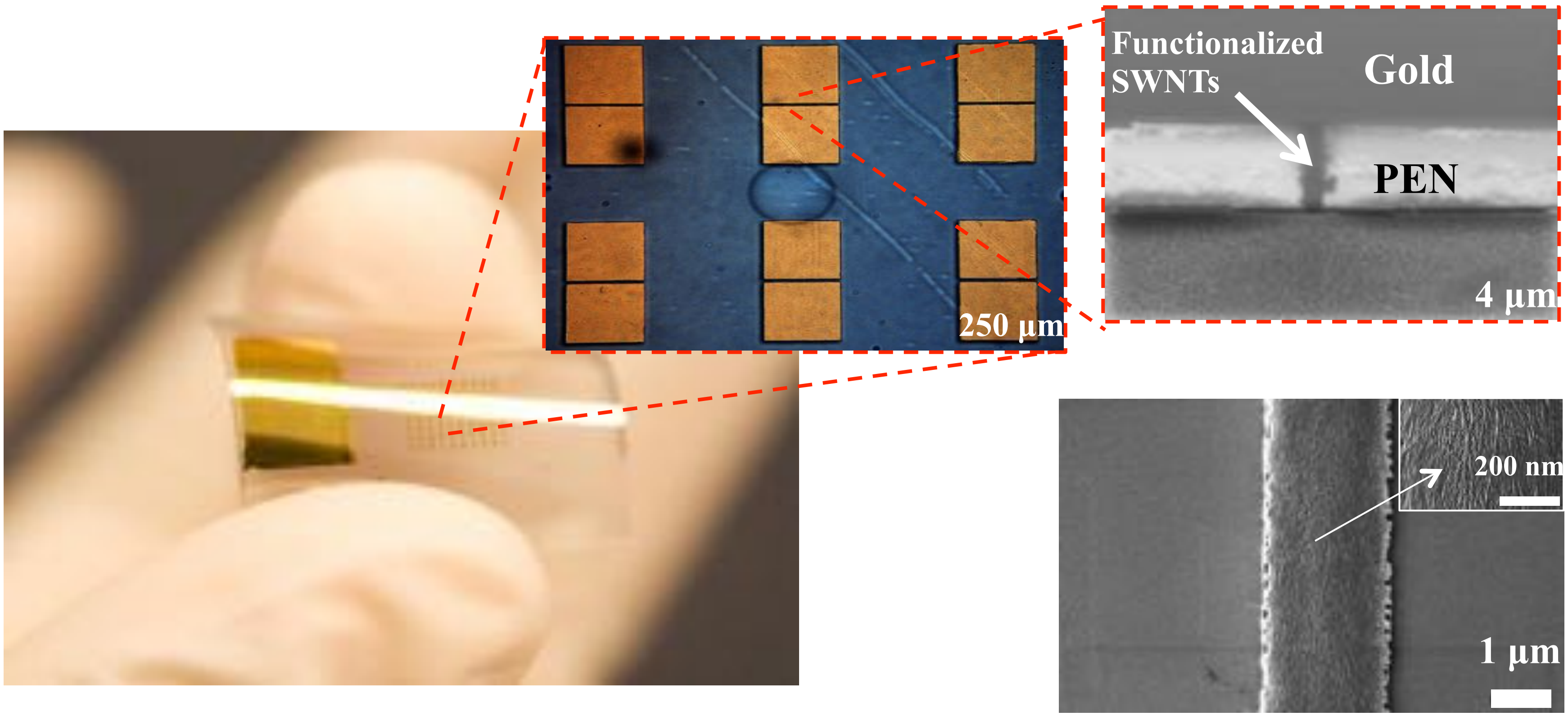
Flexible CNT Bio Sensors for Glucose, Urea and Lactate in Sweat or Tears



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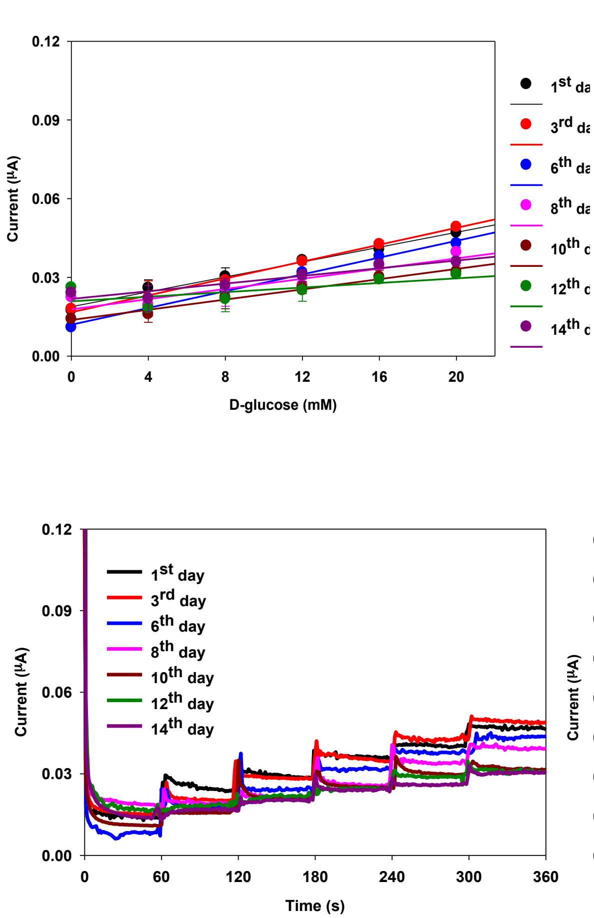
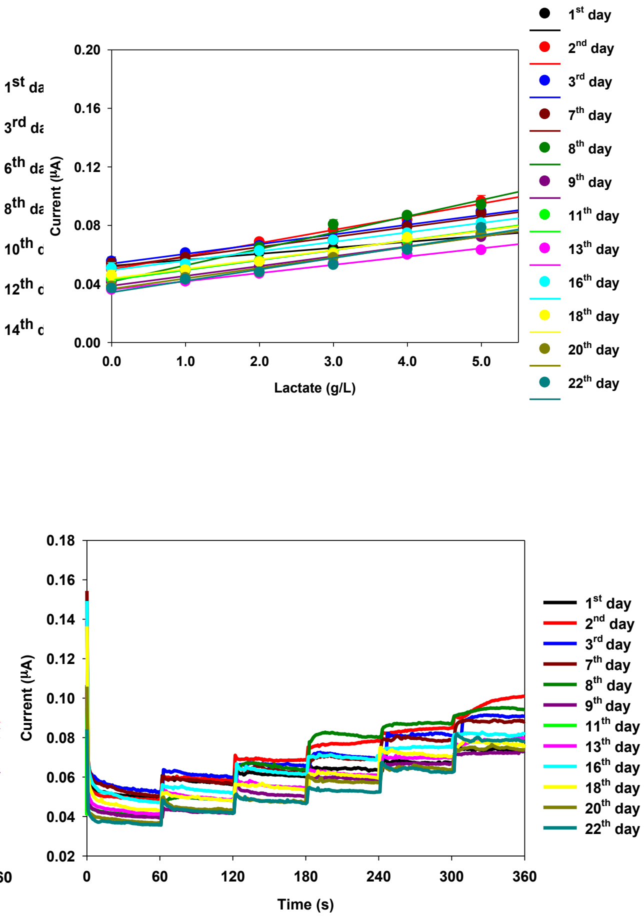
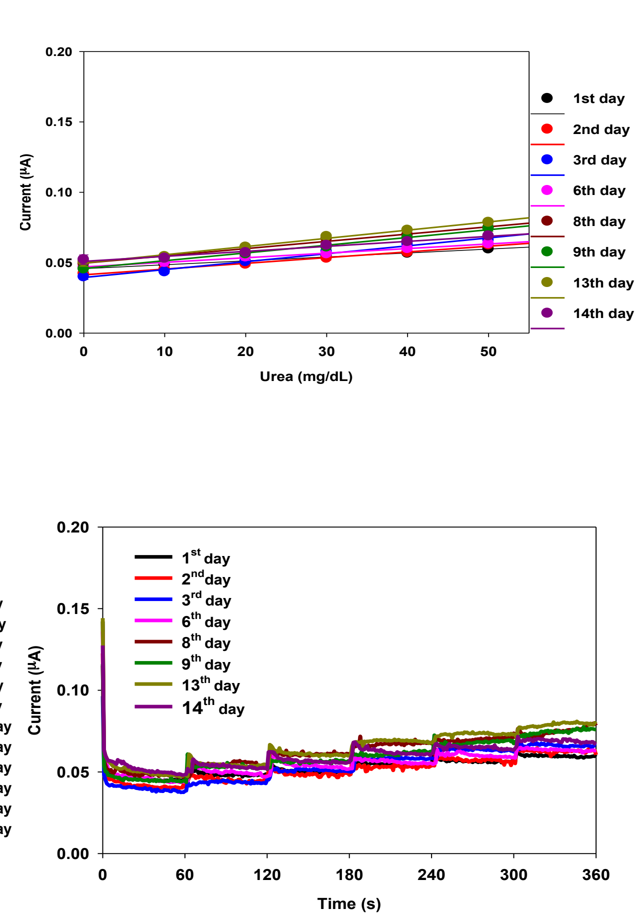
Stability of D-glucose/L-lactate/urea detections (2~4 weeks)



(A) D-glucose



(B) L-lactate



(C) Urea

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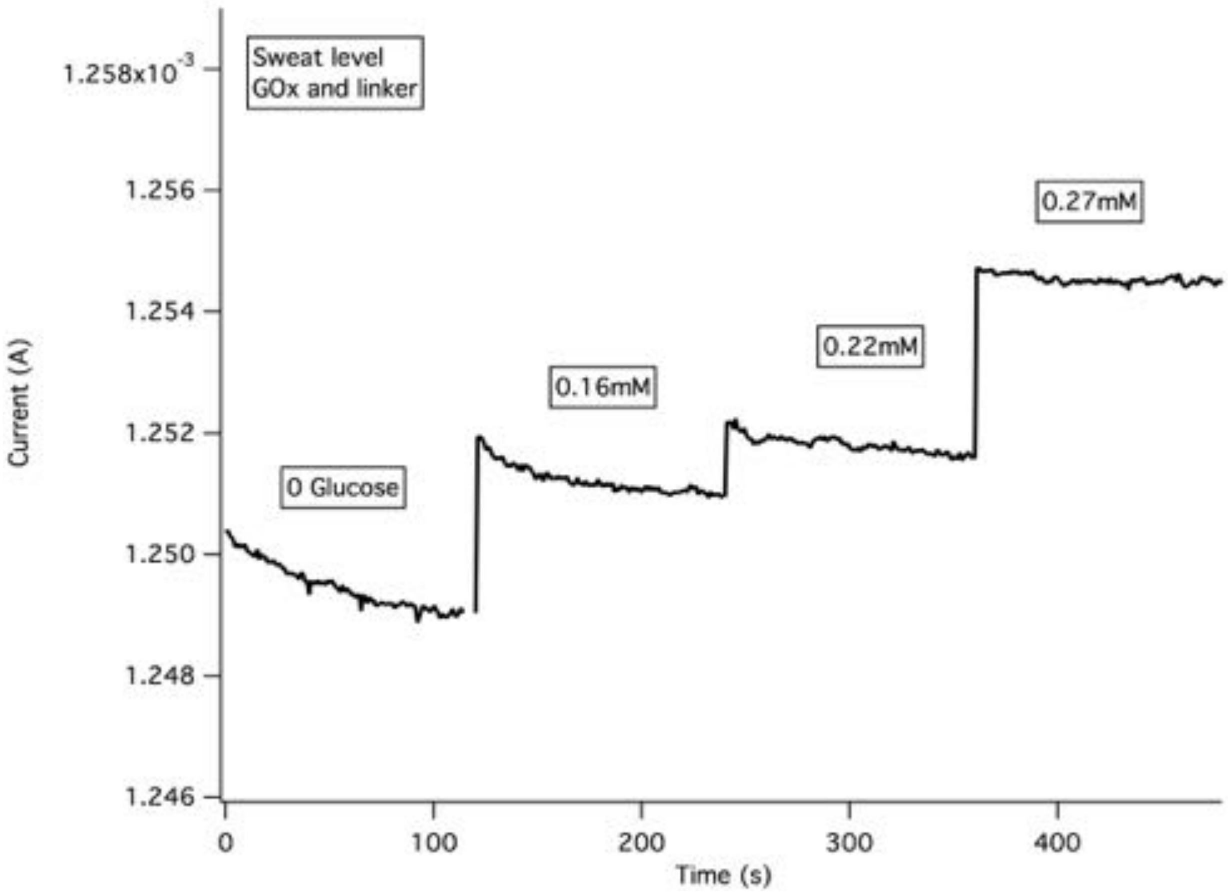
Glucose Detection in Sweat

Mediator-free 3rd generation sensors

Glucose detection from Sweat



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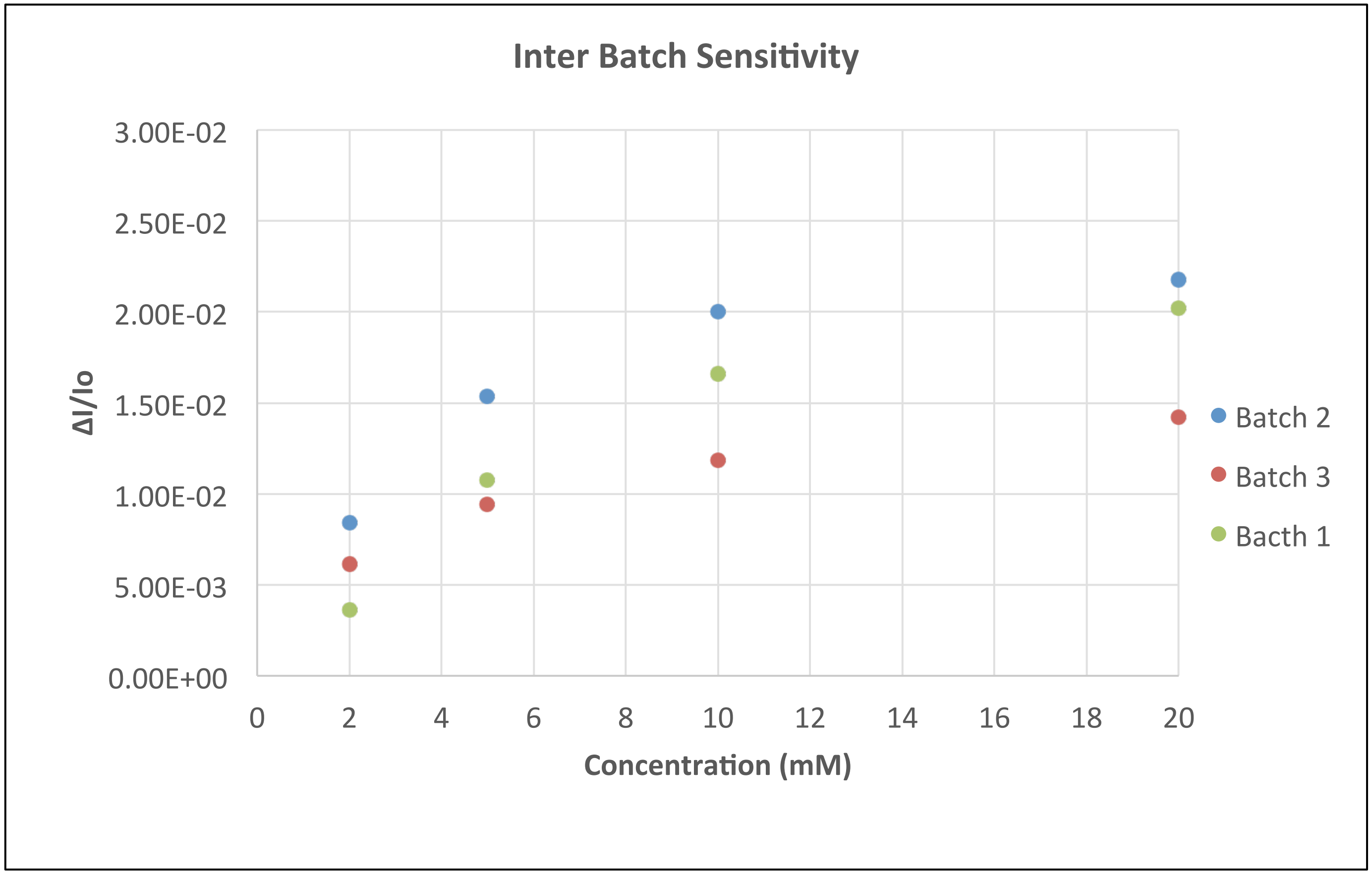
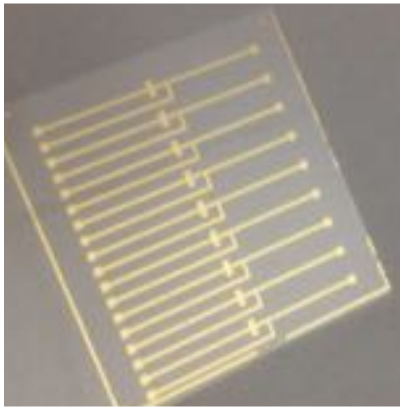
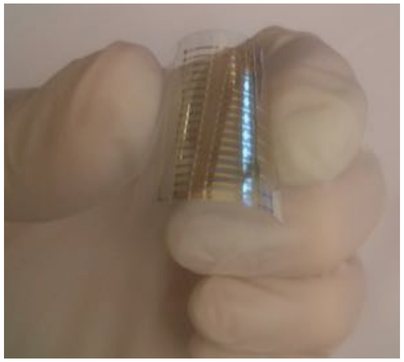
Inter-Batch Sensitivity for Sweat-based Lactate Sensor







- ➢ **Variation in inter-batch sensitivity has multiple reasons, including difference in CNT assembly, functionalization, and the thickness of the Ppy\mediator layer affect the error margin.**

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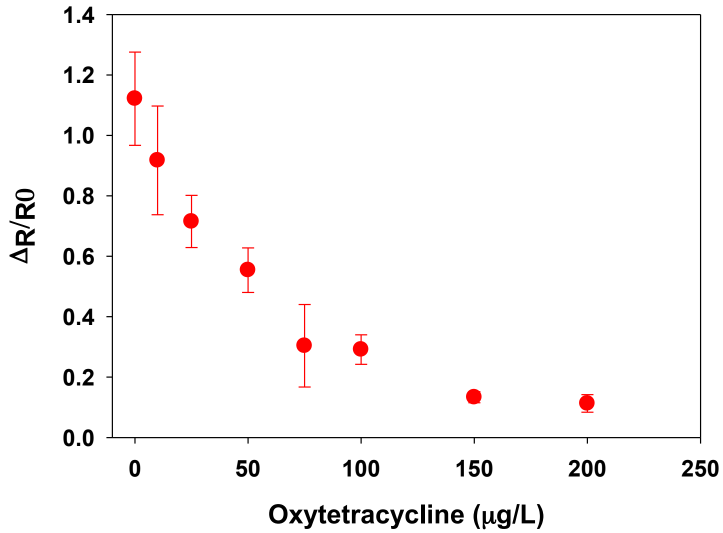
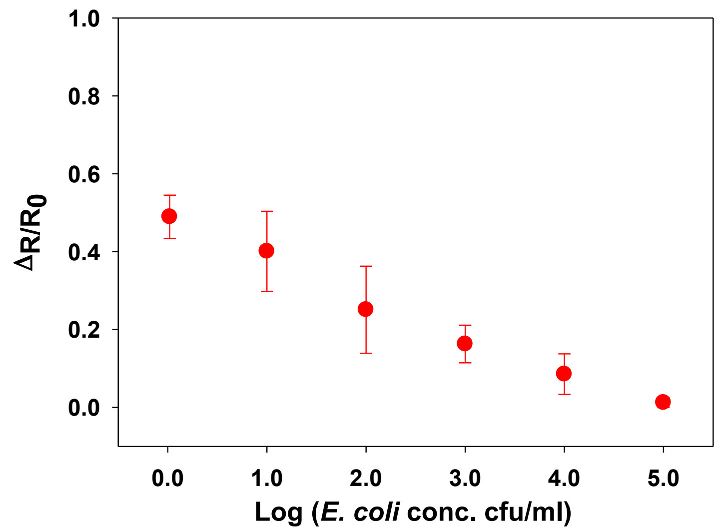
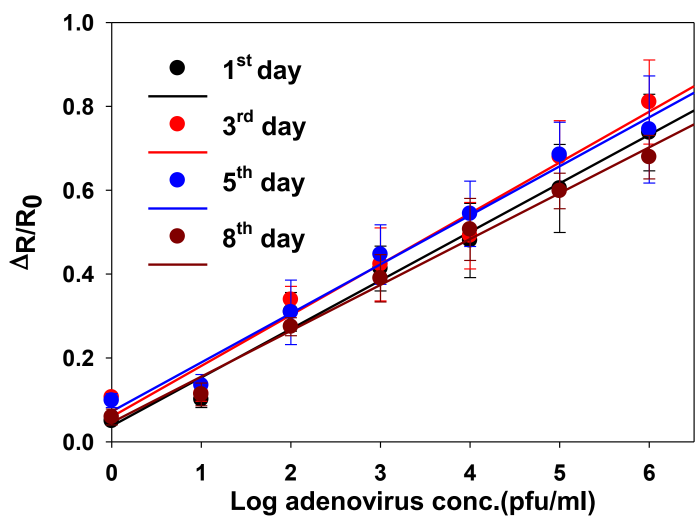
CNT Sensors for Viruses, Bacteria, Antibiotics in Water







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

Prof. April Gu's Group

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Summary

- Printing nano and micro electronics **costs 10 to 100 times less** than conventional fabrication.
- Prints a **1000 times faster** and **1000 times smaller** circuits 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, flexibility, transparency and the use of new materials, etc.
- Printed sensors have been shown selectivity, specificity and quick response for the detection of glucose, lactate, urea, viruses, bacteria, antibiotics, H2S, Methane, NOx, etc.

Summary

- The NanoOPS printer is at a TRL 7 and MRL 7.
- The printed sensors are at a TRL 6 and a MRL 6.
- 35 patents (20 awarded) that cover the printing process, sensors and electronics.
- **Our start-up Nano OPS, Inc. is making nano and micro scale printers available to industry and research labs.**
- **The company is developing wireless and wearable sensors prototypes (including electronics and software) for licensing.**
- **Currently, printing wireless sensors prototypes for small, medium and multi billion dollar corporations.**

Questions?

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