Scalable Printing of Nano and Microscale Sensors and Electronics

Ahmed Busnaina, Distinguished University Professor,
William Lincoln Smith Professor and Director,
NSF Nanoscale Science and Engineering center for
High-rate Nanomanufacturing
Northeastern University, Boston, MA, USA

www.nanomanufacturing.us
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
Can we print any material on any substrate?

Motivation: Versatility
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
Wearable technology: Impact and Forecasts

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

- 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).

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?
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).
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
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
Damascene Templates for Nanoscale Offset Printing

Polymer-based Templates

Silicon-based Hard Templates

Advanced Materials, 2015

Assembled SWNT

Assembled Particles
The World’s First Nanoscale Printer for Electronics and Sensors

Printed Electronics Conf., Berlin 2016

The Boston Globe

Herald

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

NanoOPS includes Six Modules:
1. Hexagon Frame Module
2. Template Load Port Module
3. Directed Assembly Module
4. Mask Aligner Module
5. Transfer Module
6. Template Load Port Module

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

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
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.

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**NanoOPS at Northeastern University**
https://www.youtube.com/watch?v=2iEj1cog774

**NanoOPS - A Nanomanufacturing Breakthrough**
https://www.youtube.com/watch?v=J4XupF3Zt5U
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.
What Could We manufacture with Multiscale Offset Printing?

- Assembly of CNTs and NPs for Batteries
- 2-D Assembly of Structural Apps.
- Antennas, EMI Shielding, Radar, Metamaterials
- CNTs for Energy Harvesting
- Flexible Electronics
- SWNT & NP Interconnects
- SWNT NEMS & MoS2 devices
- Multi-biomarker Biosensors
- Drug Delivery
- Materials
- Energy
- Electronics
- Bio/Med

Directed Assembly and Transfer
Nanoscale Science

Center for High-rate Nanomanufacturing
Sensors and Electronics at a Fraction of their Current Cost

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

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

Supporting printed electronics for sensor systems

Band-Aid sensor

Functionalized SWNTs

Sensors for Chemicals
Applications

Electronics
Flexible transparent n-type MoS$_2$ transistors

Heterogeneous SWNTs and MoS$_2$ complimentary invertors through assembly

Rose Bengal Molecular Doping of CNT Transistors

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

*Appl. Phys. Lett. 97, 1 2010.*

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$_2$S, simple alkanes, thiol, etc.

• Working in harsh environment (200°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.

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. $\text{H}_2\text{S}$ gas at 10, 25, 50, 75 and 100 ppm for the functionalized SWCNT sensor.

How does state of the art compares?

<table>
<thead>
<tr>
<th>Commercial Sensors</th>
<th>The Sensors developed by the CHN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight: 5.5 lbs</td>
<td>Weight: 4.15 lbs</td>
</tr>
<tr>
<td><img src="image1" alt="Commercial Chemical Hydrogen Sulfide (H2S) Sensors" /></td>
<td><img src="image2" alt="Our Chemical Hydrogen Sulfide (H2S) Sensors" /></td>
</tr>
<tr>
<td><img src="image4" alt="Commercial Glucose Sensors" /></td>
<td><img src="image5" alt="Our “Band-Aid” sensor uses sweat or tears to detect glucose. And can be used to detect viruses, bacteria, cancer, etc." /></td>
</tr>
<tr>
<td>Commercial Glucose Sensors use blood</td>
<td></td>
</tr>
</tbody>
</table>

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

Fluorescent tag
Secondary Ab
Protein of interest
Primary Ab
Fc of Ab
Entrenched nanoparticle

US Patents: Multiple biomarker biosensor: (US 2011/0117582 A1), 2 more patents pending
Funded by the Keck Foundation, PIs: Ahmed Busnainia 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.
Cancer and Cardiac Disease Biosensors

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

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


US Patents: Multiple biomarker biosensor: (US 2011/0117582 A1), 2 more filed patents
Flexible CNT Bio Sensors for Glucose, Urea and Lactate in Sweat or Tears
Stability of D-glucose/L-lactate/urea detections (2~4 weeks)

(A) D-glucose

(B) L-lactate

(C) Urea
Glucose Detection in Sweat

Mediator-free 3rd generation sensors

Glucose detection from Sweat
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.
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
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.
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?

Prof. Ahmed Busnaina
Northeastern University
busnaina@neu.edu
www.neu.edu/nano
www.nanomanufacturing.us