NSF Nanoscale Science and Engineering Center for High-rate Nanomanufacturing (www.nano.neu.edu)

Overcoming Barriers to Nanomanufacturing and Nanomanufacturing Systems at CHN

Director: Ahmed Busnaina, NEU
Deputy Director: Joey Mead, UML, Associate Directors: Carol Barry, UML; Nick McGruer, NEU; Glen Miller, UNH; Jacqueline Isaacs, NEU, Group Leader: David Tomanek, MSU

Collaboration and Outreach: Museum of Science-Boston, City College of New York, Hampton Univ., Rice Univ., Hanyang Univ., Korean Center for Nanoscale Mechatronics and Manufacturing (CNMM), University of Hyogo, Japan
Outline

- Overview
  - Vision
  - Goals and Critical Nanomanufacturing Barriers
  - Applications Roadmap
  - Industrial Partners
  - Process Flow for Nanomanufacturing Systems

- Manufacturing Processes and Applications
  1. Template Directed Assembly and Transfer of Nanoelements
  2. Alignment and Registration (a Concept)
  3. Reliability and Defects
  4. Proof-of-Concept Testbeds (Electronic devices and sensors)
  5. EHS, Life cycle and Societal Implications

- Summary
Past and Present (Nanoscience)

Manipulation of few atoms and SWNTs

STM 1981

AFM 1986

STM manipulation of atoms 1989

AFM manipulation of a SWNT 1999

Molecular logic gate 2002

Source: IBM
Our Mission: To bridge the gap between nanoscale scientific research and the creation of nanotechnology-based commercial products.
What are the Critical Barriers to Nanomanufacturing?

Barrier 1. How can we assemble and connect different nanoscale elements?
   - What are the mechanisms leading to the assembly and orientation of nanoscale structures? and how do we control these mechanisms?

Barrier 2. How can we scale-up assembly processes in a continuous or high rate manner?
   - How do the interfacial behavior and forces required to assemble, detach, and transfer nanoelements differ at high rates and over large areas?

Barrier 3. How can we test for reliability in nanoelements and connections? How can we efficiently detect and remove defects?
   - How can we selectively remove defects without disturbing assembled nanoelements?

Barrier 4. How can nanomanufacturing processes meet existing and future environmental and health regulations?

These Barriers Define CHN Research Thrusts
How Does Directed Assembly and Transfer Work?

- **State of the Art:**
  - Pure self-assembly produces regular patterns

- **Challenge:**
  - Accomplish fast, massive, precise, repeatable, nanoscale directed assembly of Nanoelements.
What does High-rate Nanomanufacturing Mean?

1. **Consistent** nanoscale directed assembly over **large areas** (measured in inches or feet) (over 3 inches)

2. **Fast** nanoscale directed assembly (measured in minutes or seconds) (e.g. 30 seconds)

3. Directed assembly of a **large volume** of nanoelements

4. **Repeatable** and **high yield** assembly processes

5. Assembly of **reliable** structures (testing for nanowires)

What type of products can we make using directed assembly?
CHN Partnerships
Industry (26 companies)

Government Labs
- Lawrence Livermore National Laboratory

Universities and other Outreach
- Hampton University
- Imperial College London
- MicroBioChip Center
- Queen’s University Belfast
- ETH Zürich
- Sabancı Üniversitesi
- University of Ulster
Team Strength and Capability

**NEU:** Directed assembly, MEMS, fabrication, nanoscale contamination control

**UML:** High volume polymer processing and assembly

**UNH:** Synthesis, self-assembly

**Semiconductor & MEMs fab**
- 7,000 ft² class 10 and 100 cleanrooms
- 6 inch completer wafer fab, nanolithography capabilities

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**Plastics processing labs**
- 20,000 ft² +
- Compounding and forming equipment

**Fully-equipped synthetic labs**
- 10,000 ft² +

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**Center for High-Rate Nanomanufacturing**

A unique partnership

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Process Flow for the CHN Testbeds

Level 1
- Thrust 1
  - Synthesize and Functionalize Nanoelements
  - Fabricate Templates

Level 2
- Thrust 2
  - Multi-scale Modeling
  - Transfer Nanoelements to Substrate
  - Assemble Nanoelements at high-rate
  - Reliability, Defects
  - Manufacture & Test Applications

Level 3
- Thrust 3
  - Licensing and partnerships
  - Spin-off companies

Thrust 4
- EHS
- Process & Quality Control
- Economics & Life Cycle
- Regulatory & Ethical Issues

All processes are scalable and integratable with current manufacturing technologies.
Process Flow for the Battery and Nanomaterial Applications

- **SWNT Batteries and Nanomaterials (shielding, etc.)**
  - Manufacture & Test function and reliability
  - Simple manufacturing system that could be manufactured in 10 steps (fits infrastructure)
  - Test component and connection reliability
  - Measure property of CNTs and quality and uniformity of assembly
  - Self Alignment and registration
  - High-rate Directed Assembly
  - Measure template integrity and uniformity
  - Manufacture Templates
  - Monitor solution conductivity, pH, voltage, current, Temp., and humidity

- Passive & active Nanostructures
  - EHS
  - Process & Quality Control
  - Economics & life cycle
  - Regulatory & Ethical Issues
Process Flow for the SWNT Switch for Memory Applications

Complex system applications that include 400+ manufacturing steps to manufacture and make & test (fits infrastructure)

Self-alignment and registration

Measure property of CNTs and quality and uniformity of assembly

High-rate Directed Assembly

SWNT Switch for Memory Applications

Manufacture & Test function and reliability

Test component, connections and switch Reliability

Monitor solution conductivity, pH, voltage, current, Temp., and humidity

Economics & life cycle

Regulatory & Ethical Issues

Process & Quality Control

EHS

Active nano-structures & systems of nanosystems

Standard fabrication characterization

Manufacture Device
Nanowire Template Directed Assembly Using Electrophoresis or Chemical Functionalization

Nanoparticle directed assembly down to 50 nm particles

Carbon nanotube directed assembly

No Alignment
Nanotrench Template Directed Assembly Using Electrophoresis or Chemical Functionalization

Nanoparticle directed assembly down to 10 nm
APL 2006

Selective directed assembly of nanoparticles

Carbon nanotube directed assembly down to 80 nm lines
APL 2007

- Nanoparticle directed assembly
- Selective directed assembly of nanoparticles
- Carbon nanotube directed assembly
Template-free Dielectrophoretic Directed Assembly

Assemble Directly on Devices

Directed assembly of SWNTs for switches

Directed Assembly of SWNTs for 3-D inter-connect

Nanotechnology Cover 2007

Assemble Directly on Devices Using Circuit Components

Nanotechnology

Cover 2007

IOP Publishing
Large-scale Aligned SWNTS Networks Using Template Guided Fluidic Assembly

Applications
Cabling/Power Distribution, Enhanced Low-Mass/High-Strength Structures, Antennas and EMI Shielding

The Journal Small, 2007
Electrophoretic Assembly and Transfer

Conducting Polymer – Polyaniline (PANI)

Template is Reused

Polymer transfer with heat and pressure

Assembled polymer

Transfer to polyurethane

Template after transfer

J. of Macromolecular Rapid Communications, 27, 2006
Self-registration and Alignment: Concept

- Surface forces must be able to deform substrates by some amount (nm to microns laterally, microns to 10s of microns normal to surface)

- Surface energy associated with the carboxylic acid is approximately 0.4 J/m², which is sufficient with reasonable assumptions.

- Bifunctional spacer (thiol-carboxylic acid here) may also set the template-substrate spacing to promote efficient transfer

Use of chemical “guides” for spacing and alignment during nanotransfer processing
Innovative MEMS devices characterize nanowires (also nanotubes, nanorods and nanofibers) and conduct accelerated lifetime testing allowing rapid mechanical, electrical, and thermal cycling during UHV SPM observation.

Thrust 3 Leader: McGruer, NEU

Test Devices
- Tensile Test
- Bend Test
- Horizontal Resonator
- Angular Resonator
- MicroHotPlate

Moving Structure
Nanowire
Defects and Yield

State of the art in semiconductor fabrication
- Non selective removal of contaminants.
- Removal of contaminants takes 100 out of 400 processing steps.

Current semiconductor technology is not sufficient for nanomanufacturing

State of the Future (Nanomanufacturing needs a different approach?)
- Need selective impurity removal
- Need to understand the adhesion of surfaces, particles, and nanoelements in a variety of conditions and situations
- Chemistry plays a larger role

Photoresist particles trapped in submicron trench (Micron Technology)

Particles generated in a W CVD process

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Applications

Complex System

SWNT NEMS Switch for Memory Devices

Properties: nonvolatile, high speed at <3ns, lifetime (>10^{15} cycles), resistant to heat, cold, magnetism, vibration, and cosmic radiation.

Simple System

Biosensor for Multiple Biomarkers

Properties: increased sensitivity, smaller sample size, detecting of multiple cancers with one device, biocompatible, low cost.
Switches are manufactured using directed assembly with SWNT as the actuation element.

Carbon Nanotube Switch for Non-Volatile Memory Devices

Schematic of state I and II.

FESEM image of the assembled SWNTs on the Nanoswitch.

Switches are manufactured using directed assembly with SWNT as the actuation element.
Nano Biosensor Chip

Goals

- Simultaneous measurement of multiple biomarkers with one device
- Very small size (can be as small as 100 µm x 100 µm)
- Can be made of all biocompatible material
- Low cost
- Future development will lead to a device where drugs are released based on the detected antigen.
- In-vivo measurement
- No issues with sample collection and storage
Size Selective Assembly: 200, 100 and 50nm Nanoparticles

1 μm spaced array of 200nm and 100 nm PSL particles
assembly time: 150 sec

1 μm spaced array of 200nm and 50 nm PSL particles
assembly time: 150 sec


- Create technological feasibility
- Determine best safety practices and screening methods for nanomaterials
- Evaluate EHS/economic tradeoffs and impact of possible releases
- Promote informed policymaking
- Advocate productive public discourse

**Integrated Systems Approach Required for Appropriate and Efficient Commercialization**
There is a need to understand, control and use interdependent nanoscale components in a network interfacing with other nanoscale systems.

Nanomanufacturing systems engineering need to be well integrated (Metrology, monitoring, product driven assembly, etc.).

The challenges are
- Scalability
- Alignment and registration
- In situ metrology and monitoring
- Defects and quality control
- Reliability
- EHS
- Life Cycle
Questions?