NSF Nanoscale Science and Engineering Center for High-rate Nanomanufacturing (CHN)

Rethinking Manufacturing; Directed Assembly Based Nanomanufacturing and the Role of CMP

Ahmed Busnaina, W.L. Smith Professor and Director

Center for High-rate Nanomanufacturing

MICHIGAN STATE UNIVERSITY · UMASS LOWELL · Northeastern University · UNIVERSITY of NEW HAMPSHIRE

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

www.nano.neu.edu

Outline

- Introduction to Nanomanufacturing
- Nanoscale Manufacturing Processes using Directed Assembly (Nanomaterials based Manufacturing)
- The Role of CMP in Directed Assembly
- Applications
- Summary

Center for High-rate Nanomanufacturing

The Vision; Rethinking Manufacturing

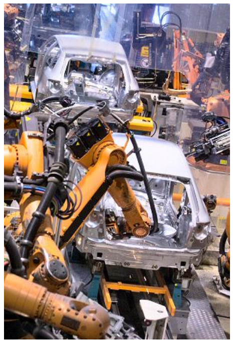
Today, a fabrication facility that manufacture nanoscale devices (such as consumer electronics) costs $5-10 billion US dollars. This high cost entry barrier completely shuts out small, medium and many other large corporations.

Present: Microelectronics Factory: $5B-$10B*
Future Goal: Nanomanufacturing Factory: $25M-$50M

***Sources: * Global foundries, press releases from TSMC, Intel and Samsung; Viking Waters, Inc.**

Rethinking Manufacturing

- Manufacturing is the process of adding or removing materials by means of a large-scale industrial operation, which can take place at macro, micro or nano scales.



- Macro-manufacturing involves cutting, coating, shaping, welding and assembly of various parts.

- Current Micro and nanoscale manufacturing involves deposition (thin film using chemical or physical processes), etching, polishing, assembly, packaging, and wire bonding.

- Directed assembly based Nanomanufacturing involves adding materials selectively such that no material removal is needed, thereby both reducing waste and the number of required processes.

Present: Microelectronics Factory: $5B-$10B >>>> **Future:** Nanomanufacturing Factory: $25-50M

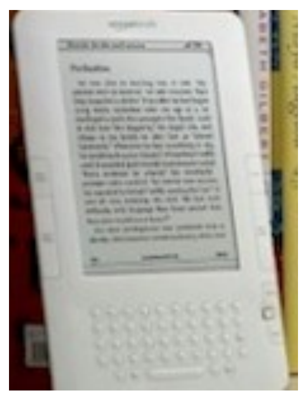
Center for High-rate Nanomanufacturing

Rethinking Manufacturing

Is this possible?

Could nanoscale manufacturing cost be 100 times lower than today's cost?

- **We are already seeing early signs of shifting manufacturing of devices and other products from vacuum-based process. For example, some display applications, already commercialized, using ink-jet or other printing of circuit patterns.**

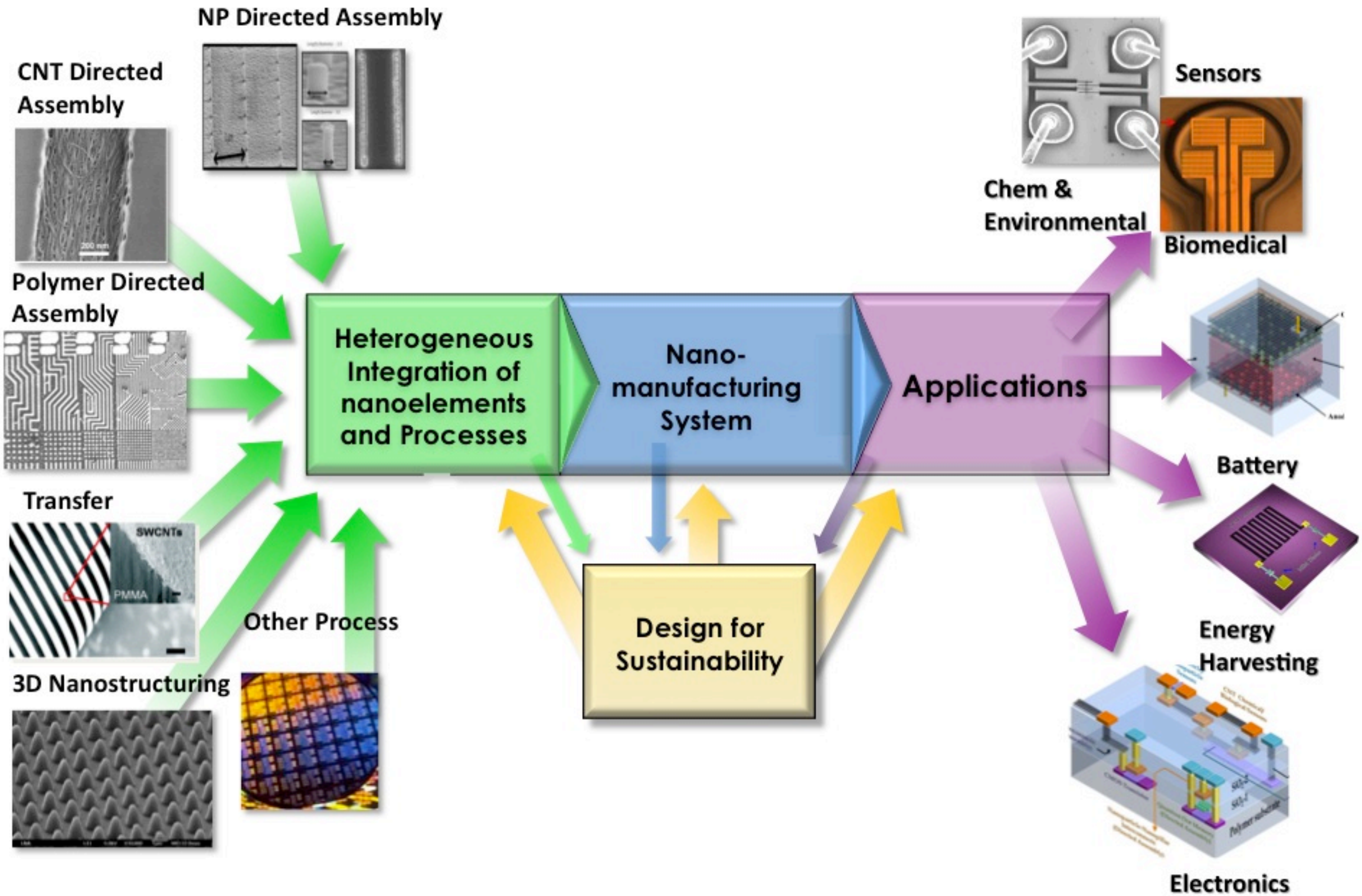


Center for High-rate Nanomanufacturing

Rethinking Manufacturing

- However, these present technologies are all top down and cannot be scaled down to make nanostructures.
- Directed assembly (of Carbon nanotubes, Nanoparticles, polyemers and other nanoelemets) have already been shown to be scalable by the CHN and other researchers.
- In addition, directed assembly based nanomanufacturing processes are operated at room temperature and pressure (no vacuum or high temperature), which will provide a significant cost reduction in equipment, energy, and maintenance costs

Rethinking Manufacturing



Nanomanufacturing Platform

A complimentary set of tools to selectively add and remove material at the nanoscale

Heterogeneous integration of different Nanoelements and processes				
CNT Directed Assembly	NPs Directed Assembly	Polymer Directed Assembly	Transfer	Top Down Processes

Present: Microelectronics Factory: $5B-$10B* >>>> Future: Nano Factory: $25M-$50M

Manufacturing

Microelectronics: Vacuum, high temp. >> Nanomanufacturing: Atmospheric, room temp.

Preliminary Estimate of Manufacturing Cost Comparison

Cost Factor / Platform	Equipment	Raw Wafer	Water/Utility	Chemical/Gas / Consumable	Maintenance	Labor	Total
Microelectronics (300mm)	1000	140	200	300	220	90	$1,950
Nanomanufacturing	16	140	20	30	4	30	$240
% Cost Reduction	99%	0%	90%	90%	98%	66%	88%

The Vision; Rethinking Manufacturing

- Manufacture nanoscale systems and devices at a fraction (one hundredth) of today's cost.
- Unleash a wave of creativity by making nano scale manufacturing accessible and affordable in the same way as the advent of PC technology did to the computing industry.
- Increasing access will lead to increase in innovation and consequently the creation of entirely new industries.

Computing revolution in 1980s	
Mainframe	**PC**
Cost: $0.5M to 5M**	Cost: $1200 to $5000 (1981)
Users: thousands	Users: Billions
Industry: IBM, Unisys, DEC, Burroughs	Industry: Dell, HP, Intel, Microsoft
Jobs: Thousands	Jobs: Millions

Center for High-rate Nanomanufacturing

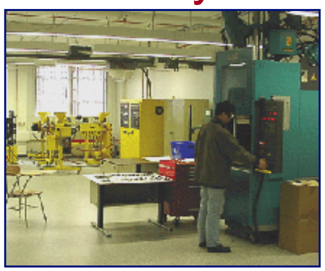
Team Strength and Capability

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

Semiconductor & MEMs fab
- 7,000 ft^2 class 10 and 100 cleanrooms
- 6 inch completer wafer fab, nanolithography capabilities

UML: High volume polymer processing and assembly

UNH: Synthesis, self-assembly



Center for High-Rate Nanomanufacturing

A unique partnership

Plastics processing labs
- **20,000 ft^2 +**
- **Compounding and forming equipment**

Fully-equipped synthetic labs
- **10,000 ft^2 +**

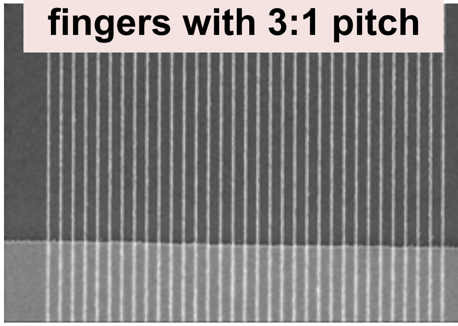
Institution	Faculty	Post-docs	Graduate	Undergrad.	Total
NEU	14	8	19	14	50
UML	18	6	35	16	75
UNH	6	5	12	13	36
MSU	1	1	1	0	3
TOTAL	39	20	67	43	169

Directed Assembly Processes

Process	Nanoelement property	Nanoelements
Electrophoretic Asssembly	Charge	Nanoparticles, CNTs, polymers
Chemical Functionalization	Functionalization	Nanoparticles, CNTs, polymers
Electrophoretic and chemical functionalization	Charge and surface functionalization	Nanoparticles, CNTs, polymers
Dielectrophoretic	Dielectric constant	Nanoparticles, CNTs, polymers
Convective	Surface Functionalization	Nanoparticles, CNTs
Convective interfacial	Surface Functionalization and surface tension	Nanoparticles, CNTs

Making Templates

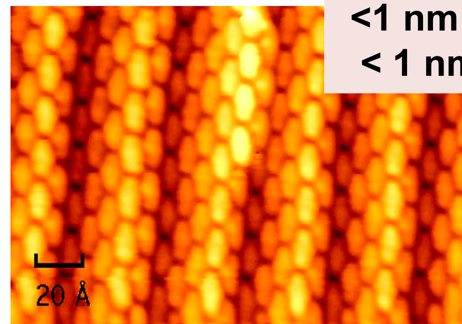
50 nm wide nano-fingers with 3:1 pitch



E-beam nanolithograpy

Low RISK

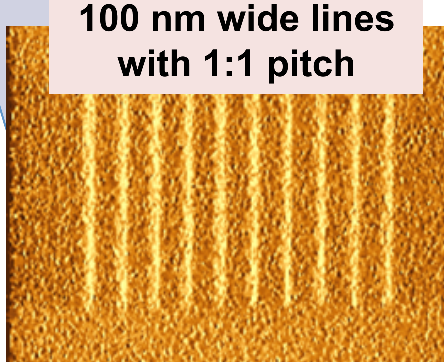
<1 nm rows with < 1 nm spacing



Acene Self-Assembly

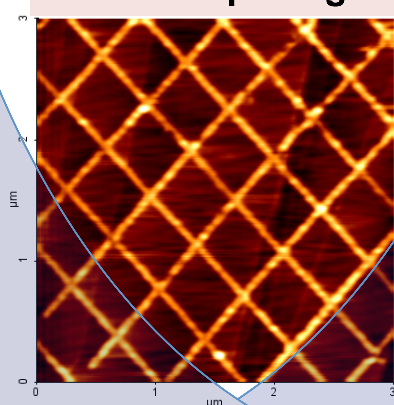
High RISK

100 nm wide lines with 1:1 pitch



Dip-pen nanolithography

15 nm lines with 50 nm spacing

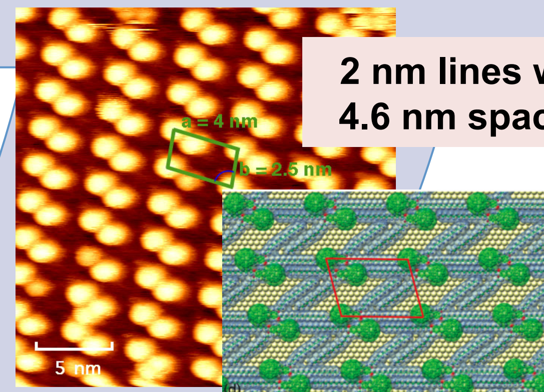


AFM field assisted nanolithography

J. Phy. Chem C111, 10758 (2007)

Nanotechnology, 20, 055303 (2009)

2 nm lines with 4.6 nm spacing

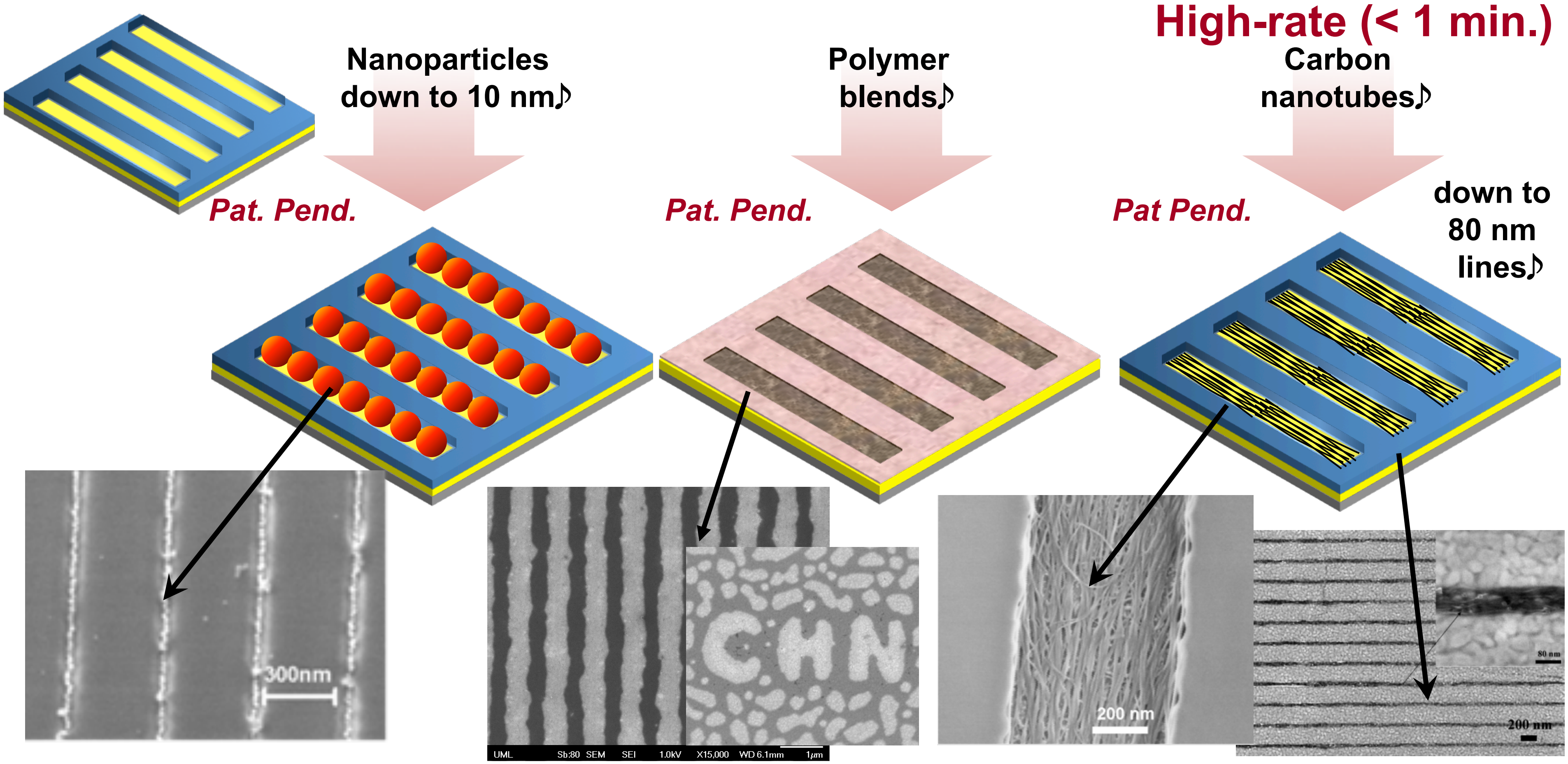


Fullerene Self-Assembly

Phys. Rev. Lett., 102, 056102 (2009)

Center for High-rate Nanomanufacturing

Nanotrench Template Directed Assembly Using Electrophoresis or Chemical Functionalization



Xiong, X, Busnaina, A, et. Al., ***Appl. Phys. Lett. 2007.***

Wei, M. Liang F., Lee, J. Somu, S., Xiong, X, , Barry, C., Busnaina, A., Mead, J, ***Advanced Materials, 2009***.

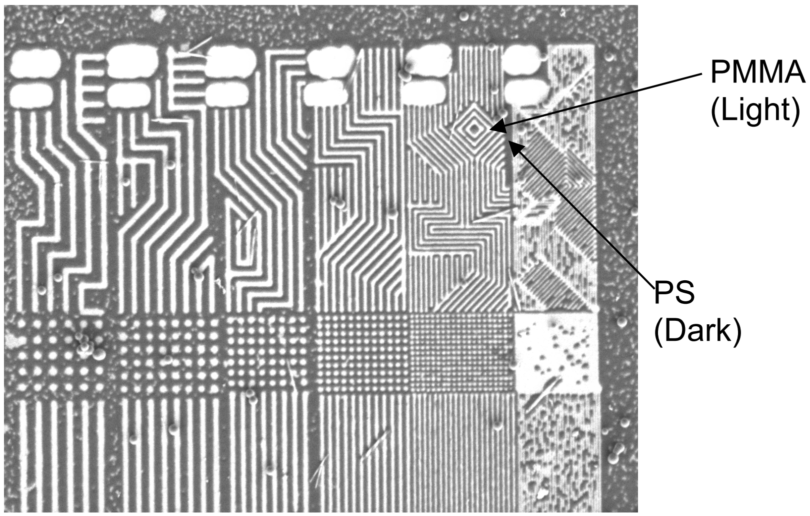
Xiong, X, Jaberabsari, L, Hahm, M G, Busnaina, A, and Jung, Y, J, ***Small, 2007.***

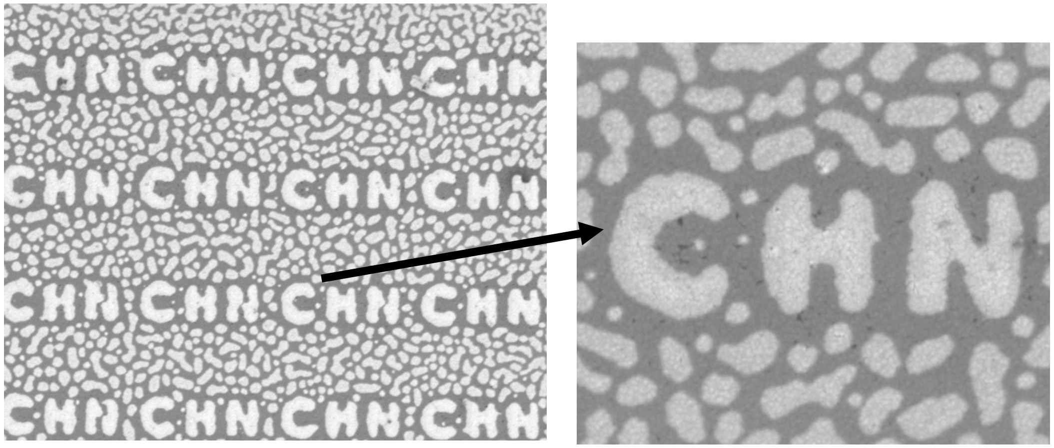
Makaram, P, Somu, S, Xiong, X, Busnaina, A, Jung,Y J, and McGruer, N, ***Appl. Phys. Lett., 2007***.

Last Year: Multi-scale Patterned Polymer Blends

- Chemically functionalized templates assemble PS/ PMMA polymer blends into non-uniform geometries.
- Polymer domains were patterned from 300 nm down to 100 nm on *the same template*.

PS/PMMA (50/50 ratio)



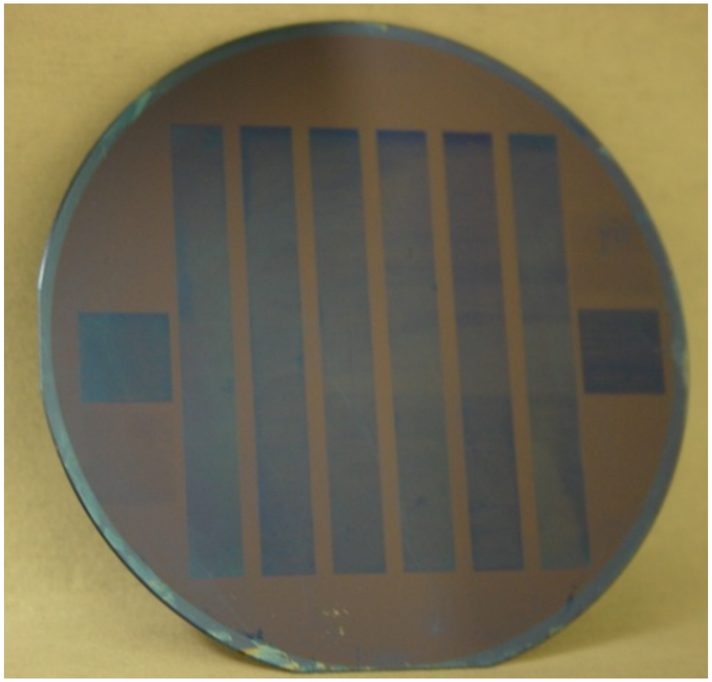


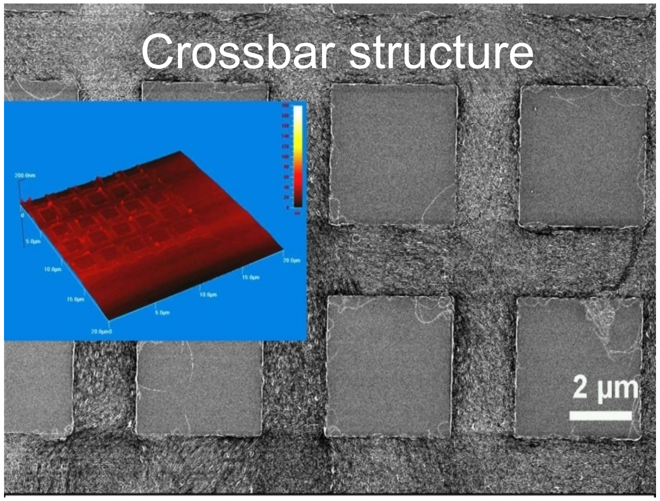
Chiota et al., ***Small,* 2009 Dec;5(24):2788-91**

Center for High-rate Nanomanufacturing

Template Guided Directed Assembly of SWNTs

- Assembly of SWNTs over large areas on templates with different surface energies



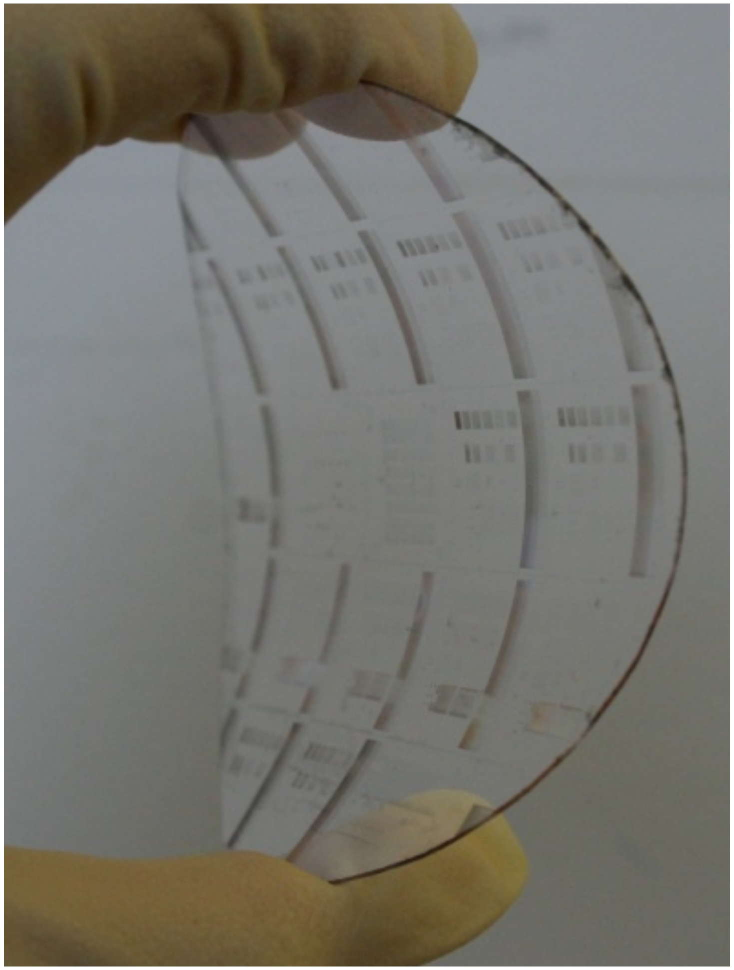


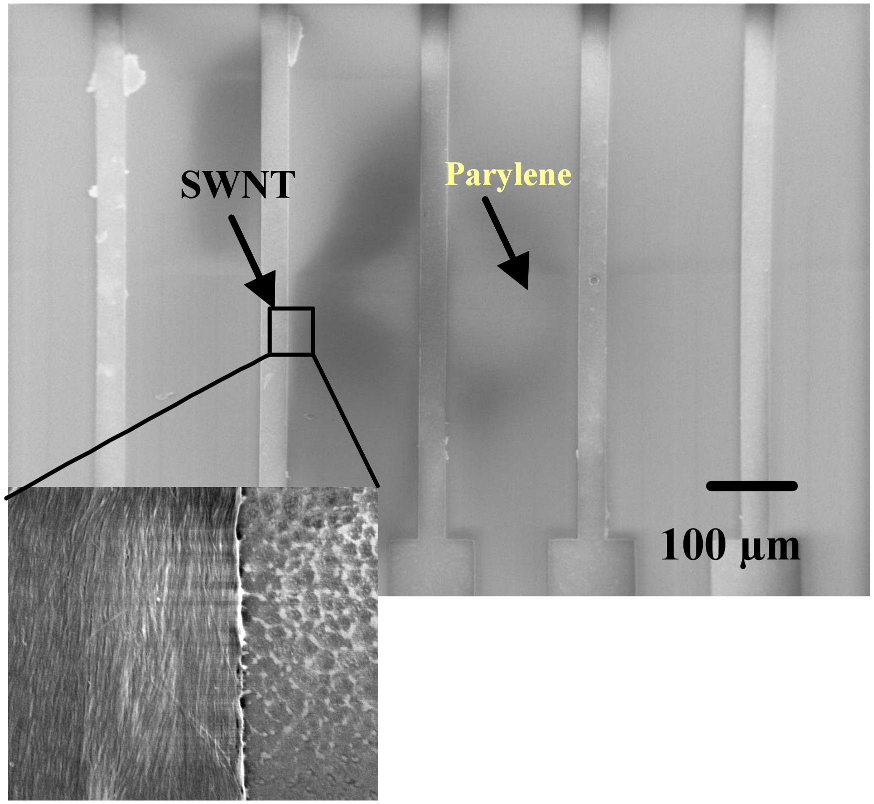
Xiong, X, Jaberabsari, L, Hahm, M G, Busnaina, A, and Jung, Y, J, ***Small*, 3 (12) 2006 (2007)**
Jaber-Ansari, L, Hahm, M G, Somu, S, Echegoyen Sanz, Y, Busnaina, A, and Jung, Y J, ***J. Am. Chem. Soc., 131 (2), pp 804 (2009)***
Jaberasani, L., Somu, S. Hahm, M G, Busnaina, A, and Jung, Y J, ***Appl. Phys. A., 5194 (2009)***

Center for High-rate Nanomanufacturing

Template Guided Directed Assembly

- Large scale assembly on polymer substrates
  - Enables assembly of lines over large areas (i.e., centimeters)





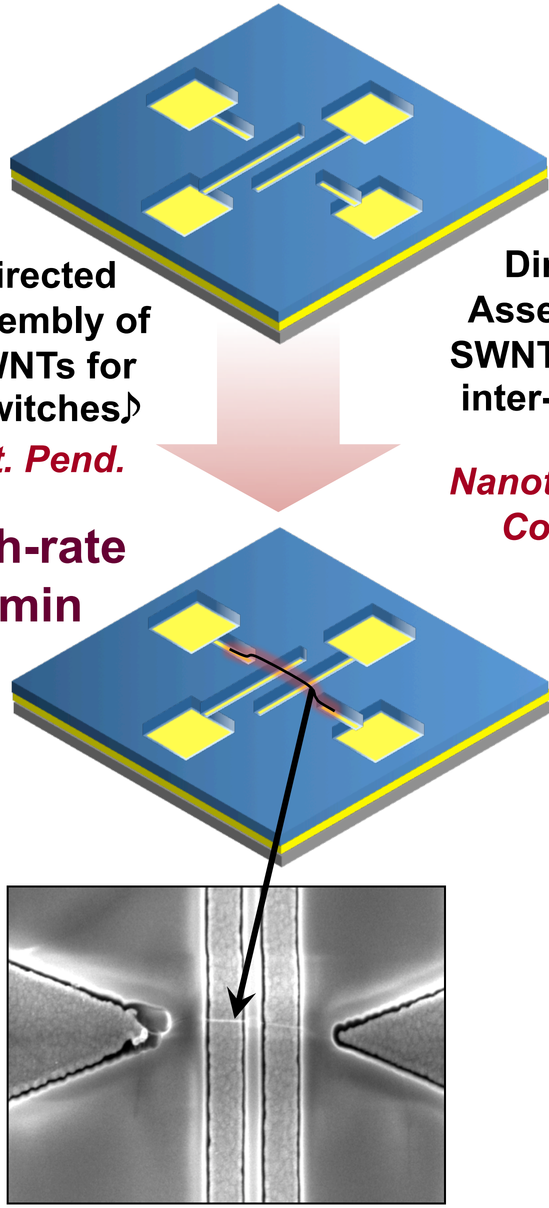
Patterned, aligned CNTs on a parylene, polycarbonate or polystyrene wafers

Nanotechnology 2009

Center for High-rate Nanomanufacturing

Template-free Dielectrophoretic Directed Assembly

Assemble Directly on Devices



Directed assembly of SWNTs for switches♪

Pat. Pend.

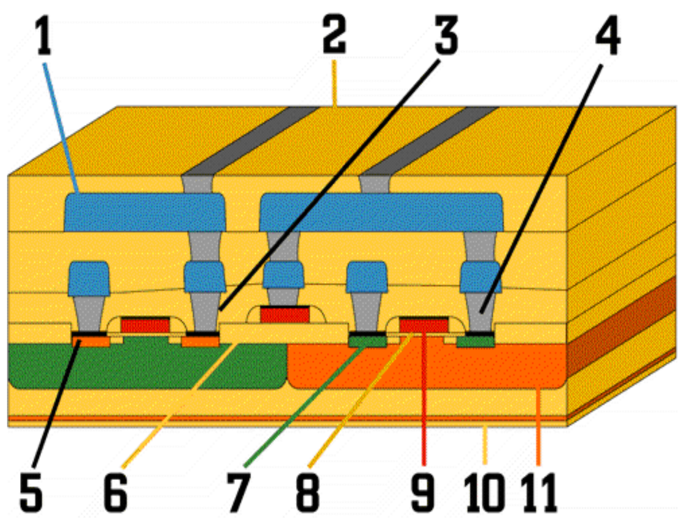
High-rate
< 1 min

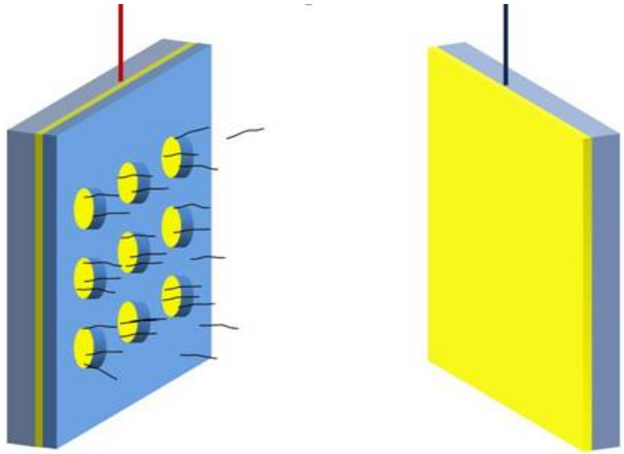
Directed Assembly of SWNTs for 3-D inter-connect♪

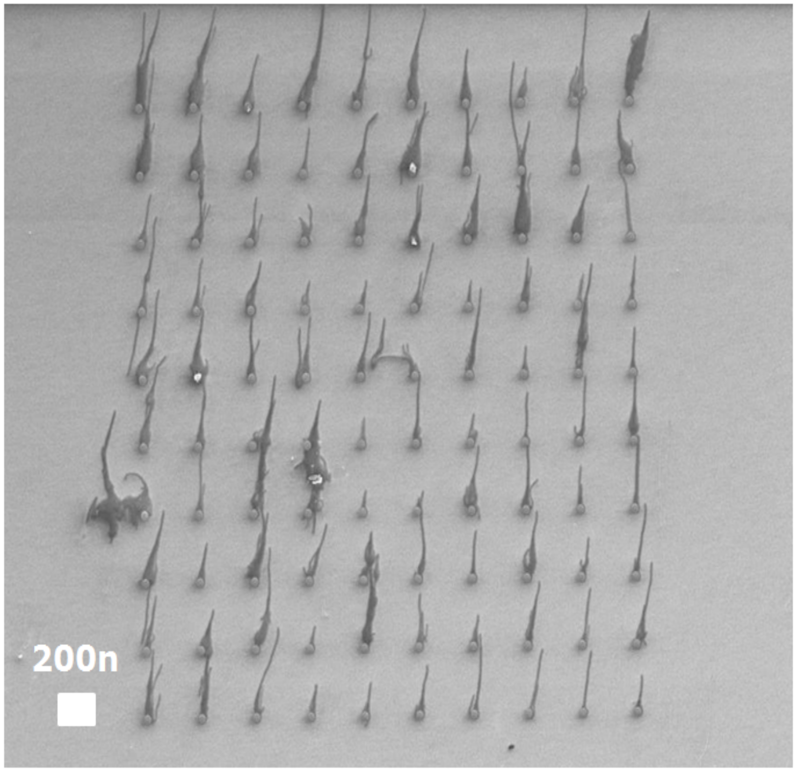
Nanotechnology Cover 2007

CMOS Technology Interconnects

Room temperature 3D assembly of CNTs for CMOS interconnects





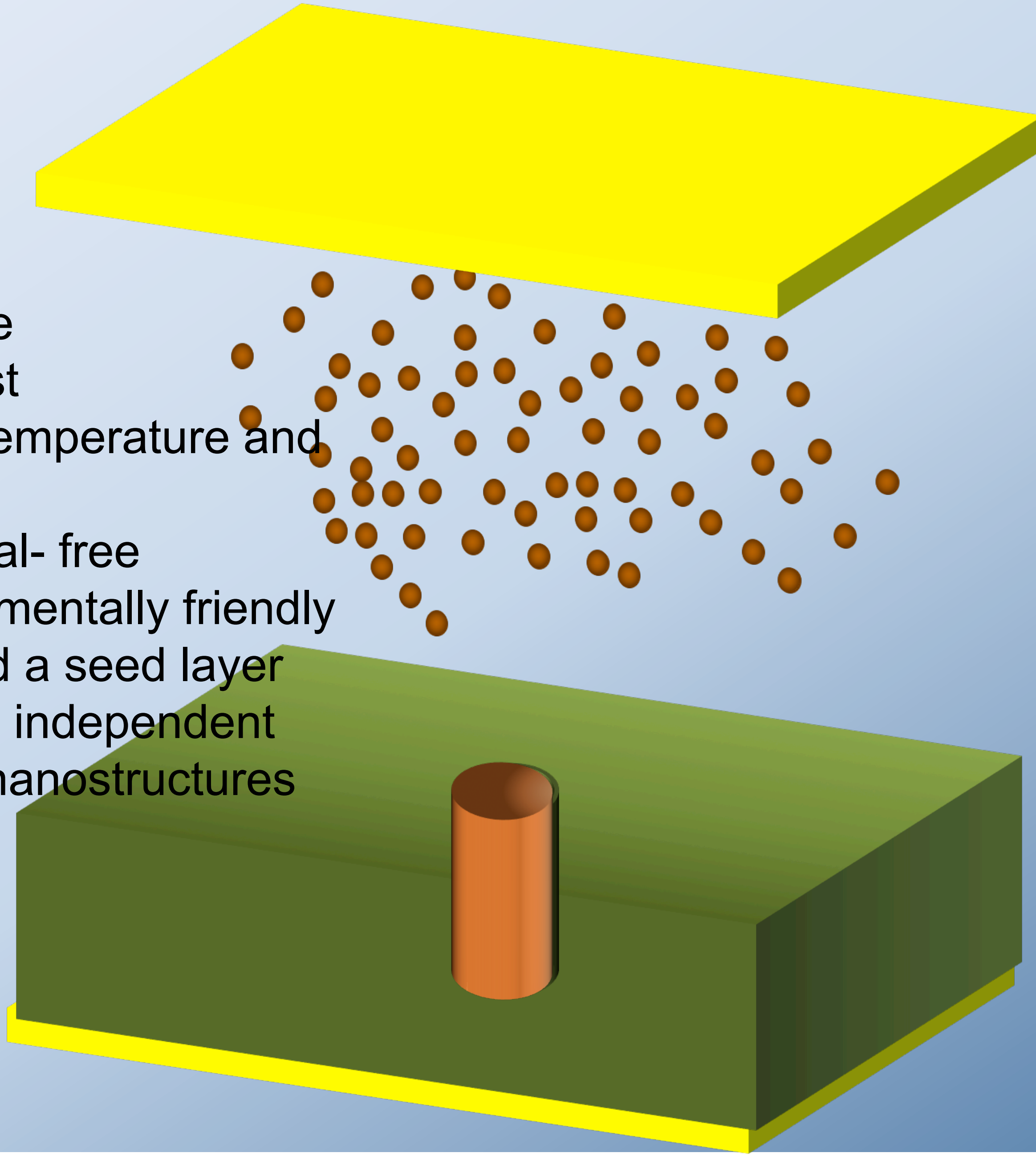


3-D Assembly of SWNT in CMOS vias over a wafer level

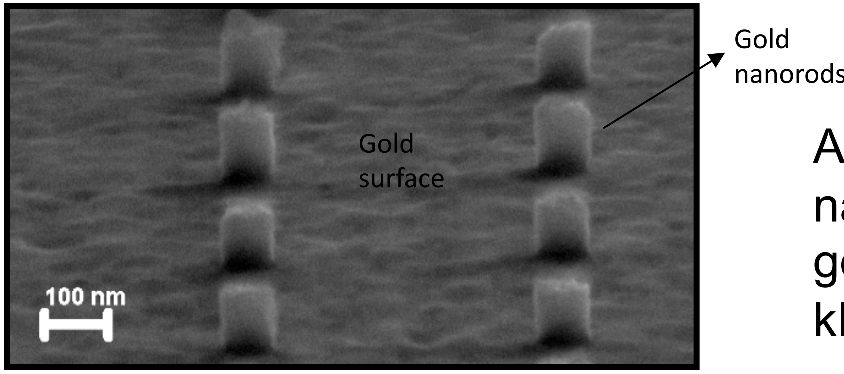
Center for High-rate Nanomanufacturing

Developed Method of Fabricating 3-D Nanostructures

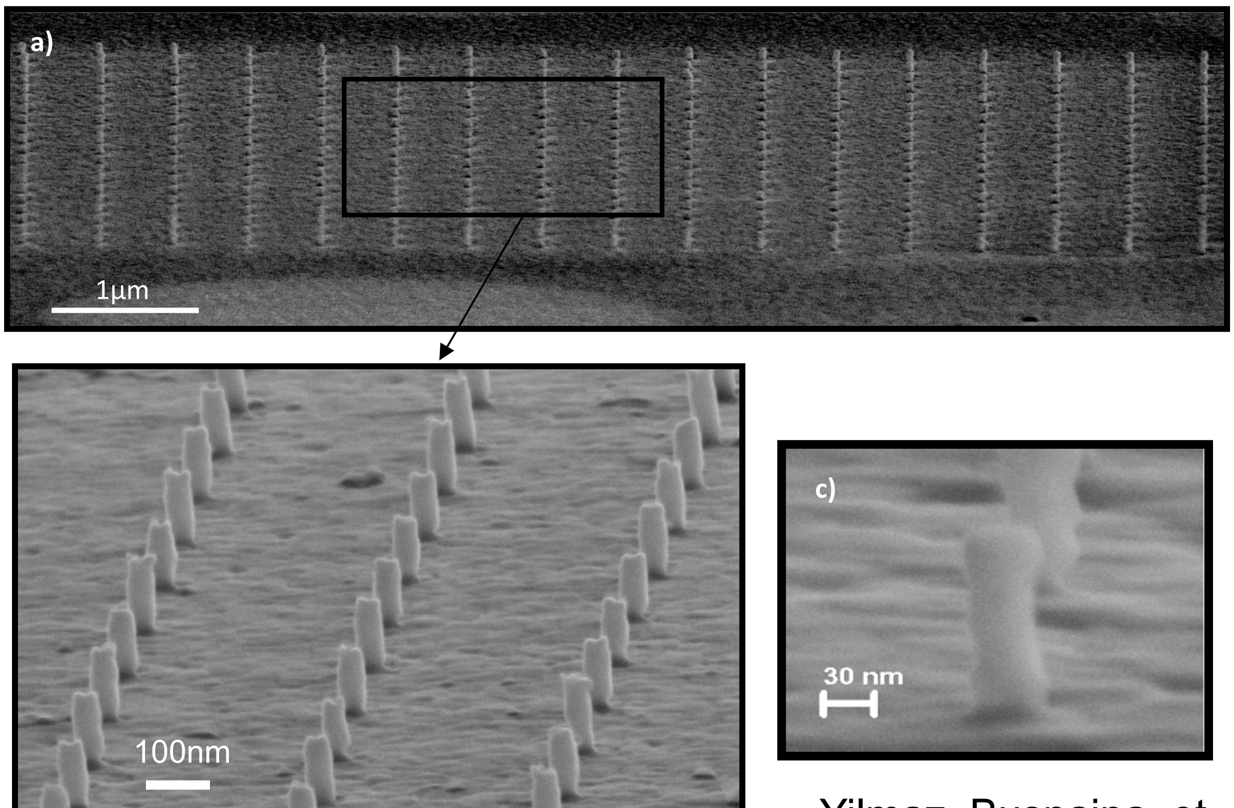
- Fast
- Scalable
- Low cost
- Room-temperature and pressure
- Chemical- free
- Environmentally friendly
- No need a seed layer
- Material independent
- Hybrid nanostructures



Interconnects and Nanorods



A high angle SEM of fabricated 100nm nanorods. 12Vpp was applied to the 5nm gold nanoparticles at the frequency of 10 kHz.



a) SEM image of 50nm nanorods over 10µ x 10µ area.

b) A magnified image of the Nanorods array.

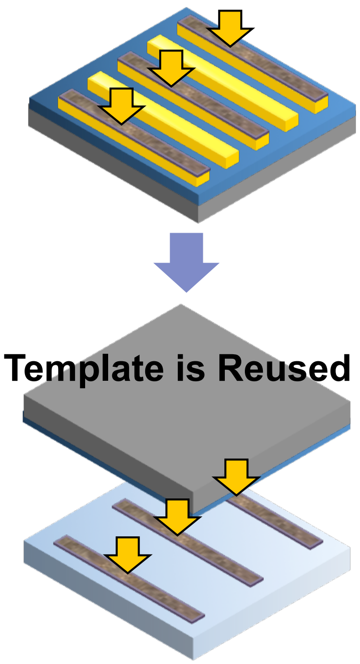
c) High magnification image of a single rod.

Yilmaz, Busnaina, et. Al, ***IEEE Trans on Nanotechnology 2010***

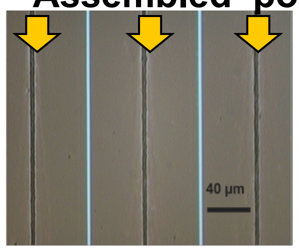
Center for High-rate Nanomanufacturing

High-rate Transfer (< 1 min)

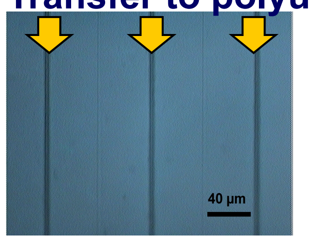
Transfer of conductive polymer wires



Assembled polymer



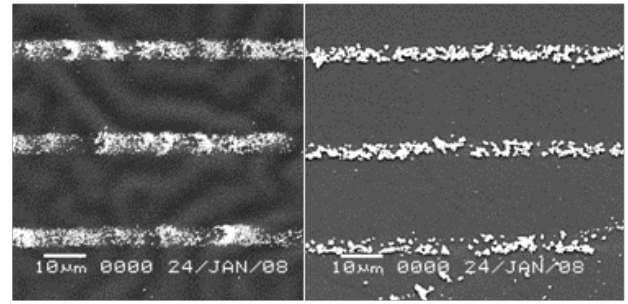
Transfer to polyurethane



Template after transfer

J. of Macromolecular Rapid Comm, 2006

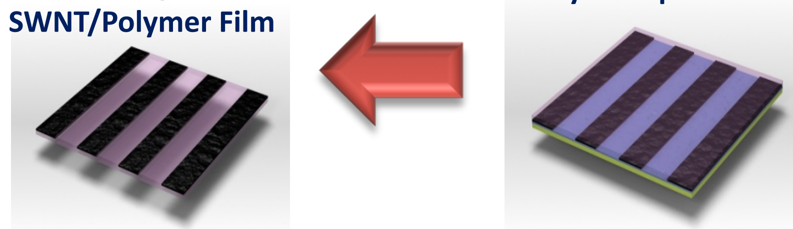
Transfer of assembled nanoparticles



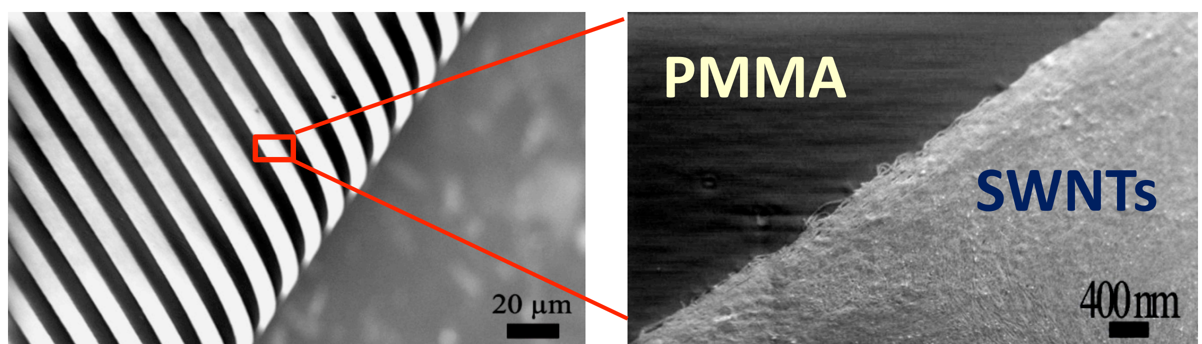
Langmuir, 2009

Peeling Off
SWNT/Polymer Film

Polymer Spin Coating



Transfer of assembled S
WNT Wires



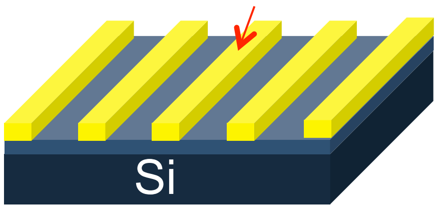
Role of CMP

The Role of CMP in Directed Assembly

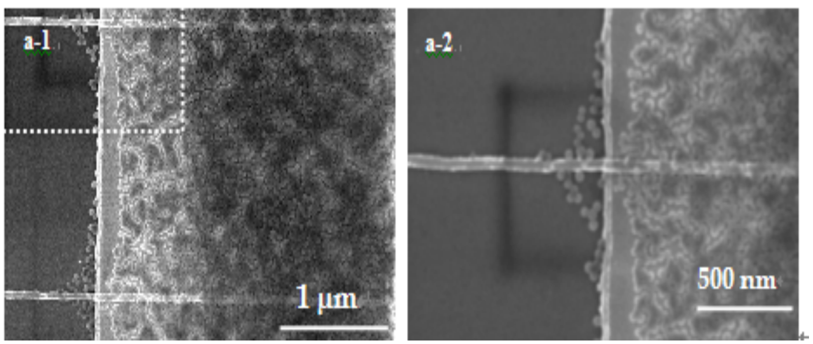
Damascene Nanowire Templates; Motivation

Previous Nanowire Template

Metal nanowire



DC assembly, microwires attract most of the nanoparticles compared with nanowires

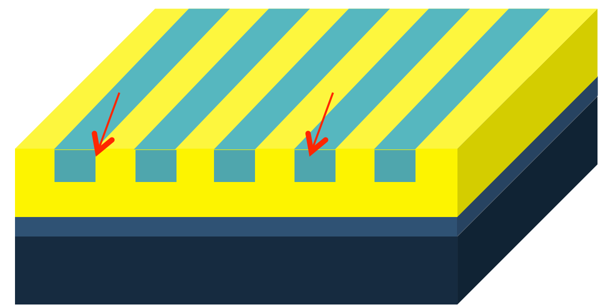


Disadvantage

- **Huge potential drop → Nonuniform assembly.**
- **Nanowires burning.**
- **Poor adhesion → Nanowire peel off**
- **Non-uniform topography**

Damascene Nanowire Template

Metal Nanowire SiO2

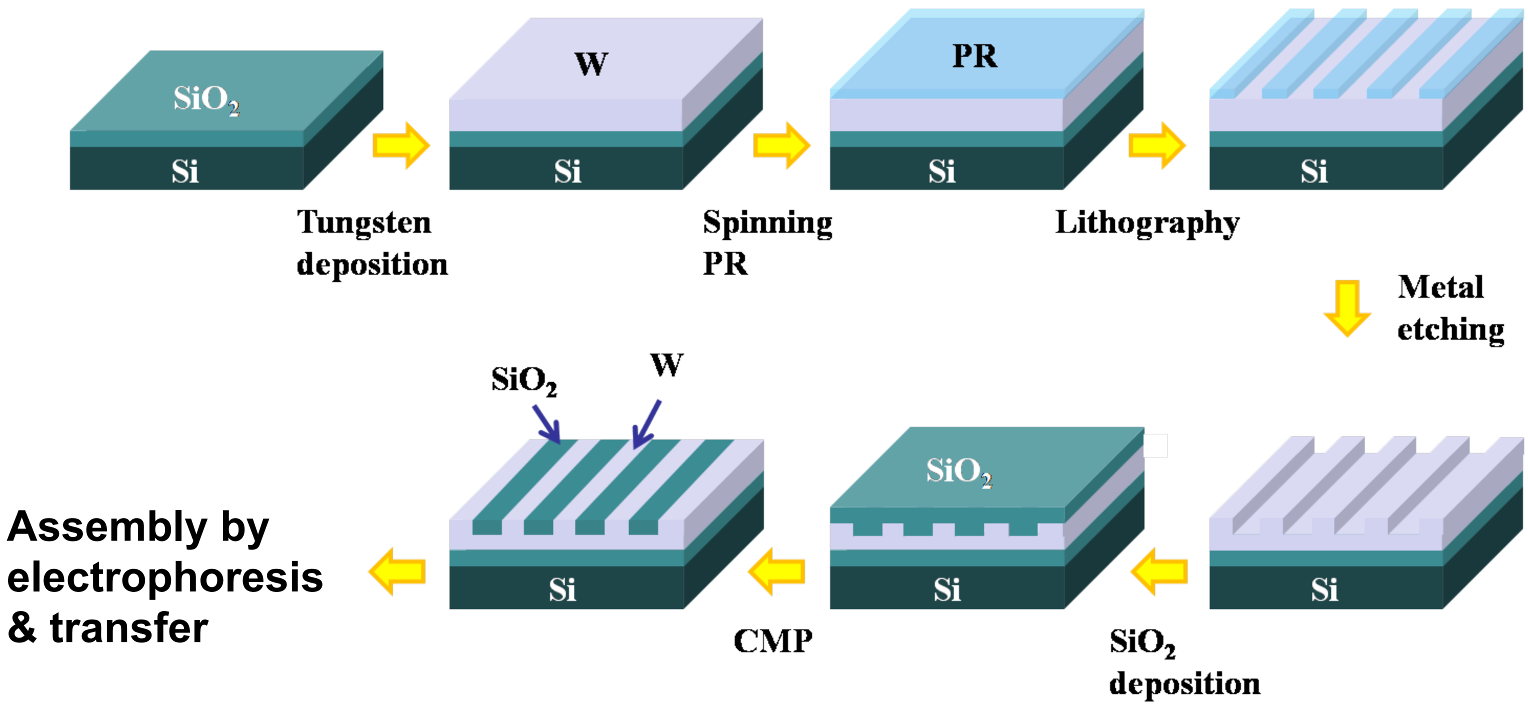


Advantages

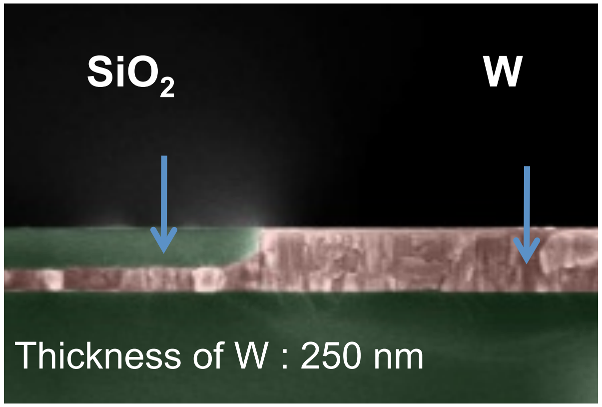
- **Equipotential on all the nano and microwires.**
- **High rate assembly with good uniformity.**
- **Strong adhesion**
- **Completely flat surface.**

Center for High-rate Nanomanufacturing

Fabrication of the Damascene Nanowire Templates



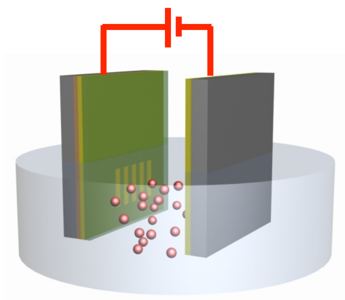
: Schematics of damascene template fabrication



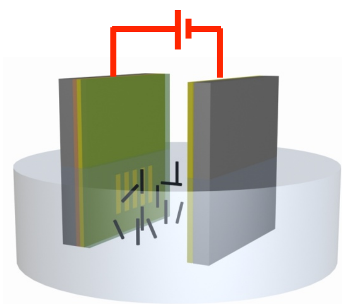
FESEM image of damascene template cross section

Center for High-rate Nanomanufacturing

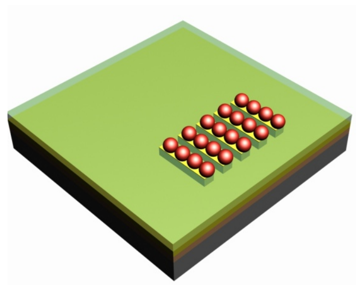
Electrophoertic Assembly and Transfer



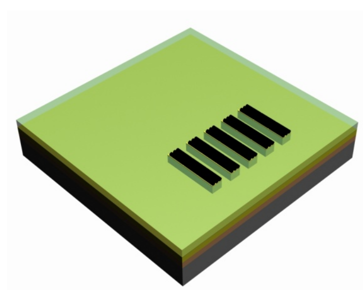
Electrophoresis assembly of nanoparticles



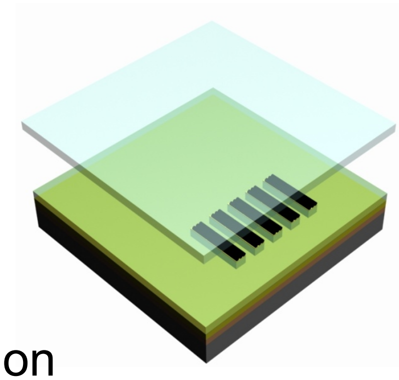
Electrophoresis assembly of carbon nanotubes

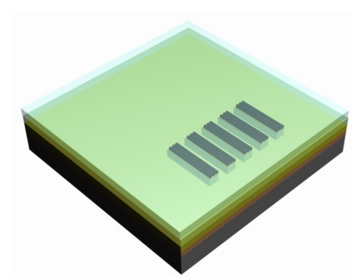


Nanoparticles assembly on metallic wires

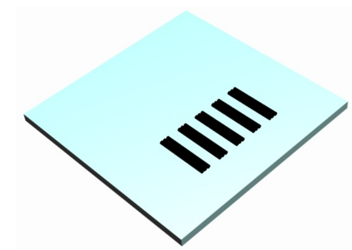


Carbon nanotubes assembly on metallic wires





Heat and pressure apply for transfer onto flexible substrate



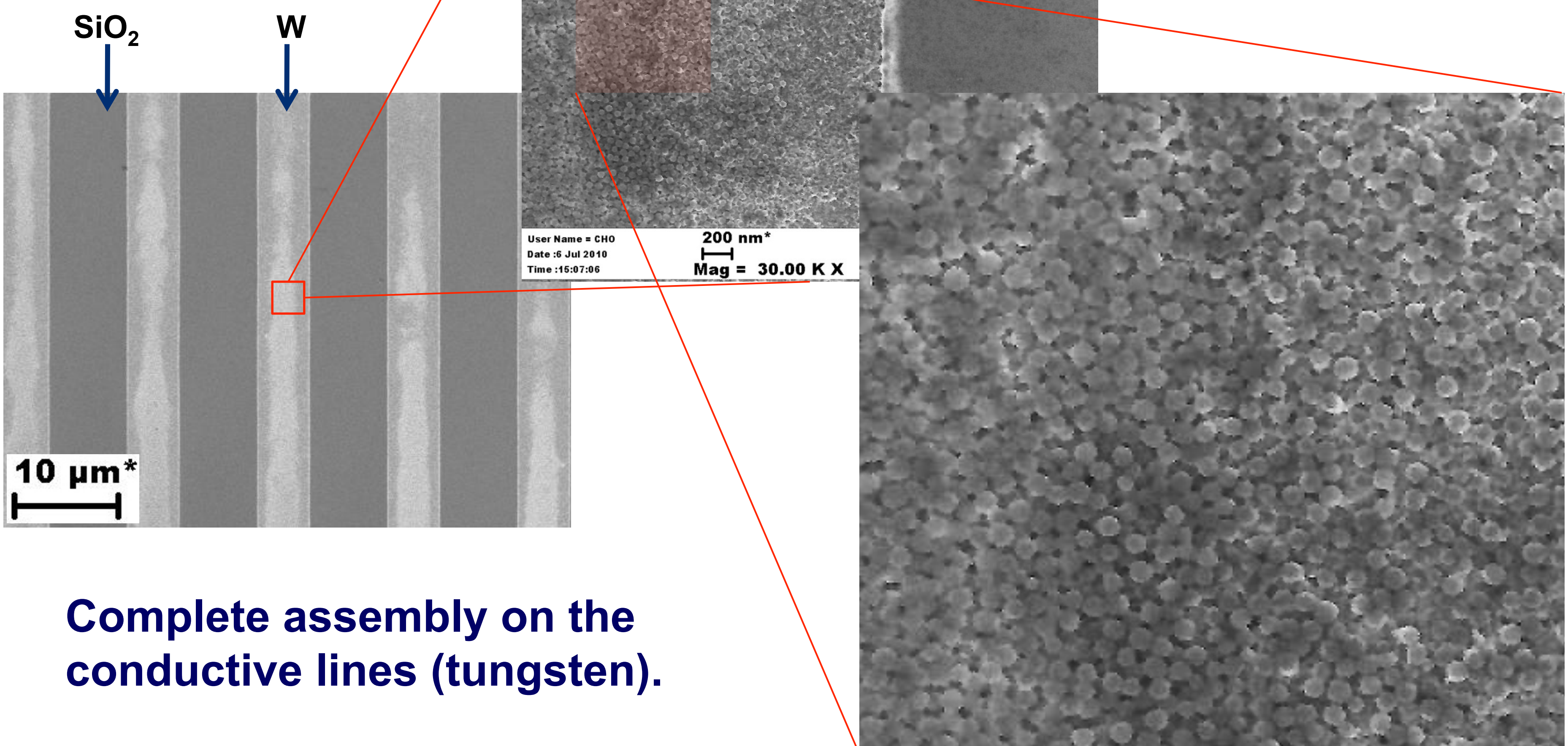
Nanoelements transfer onto flexible substrate

Center for High-rate Nanomanufacturing

Nanoparticle Assembly by Electrophoresis on Damascene Templates

Assembly condition

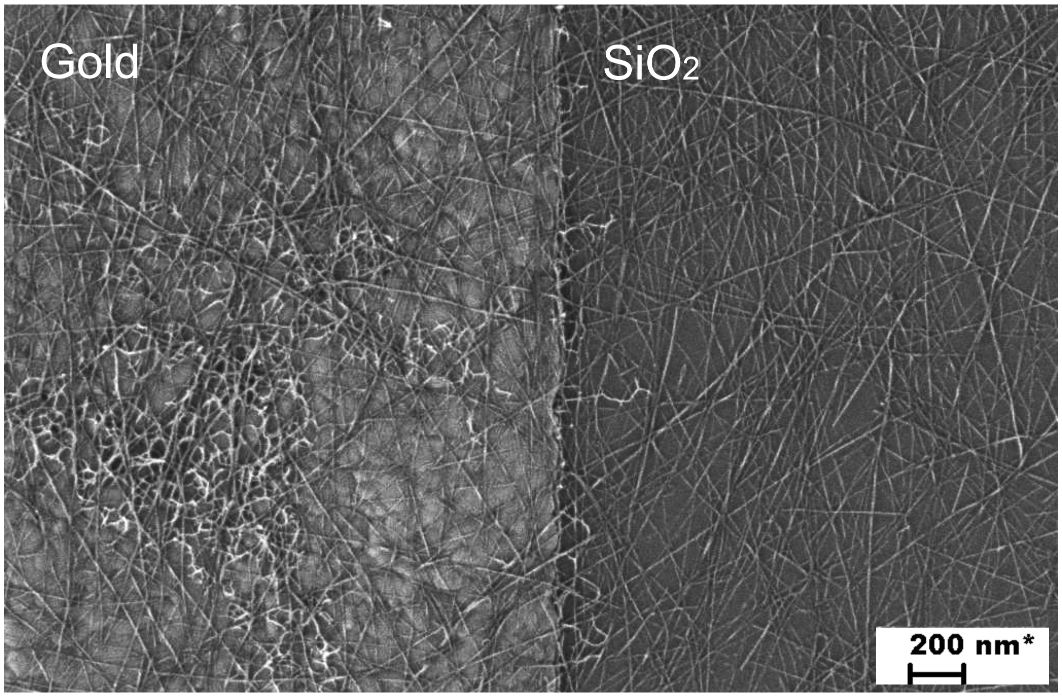
50 nm particles
1 min assembly time



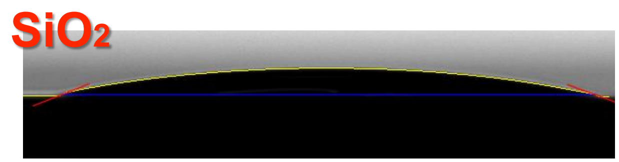
Complete assembly on the conductive lines (tungsten).

SWNT Assembly by Electrophoresis on Damascene Templates

SWNTs were assembled on gold and even on SiO_2 lines



Contact angle: 15°

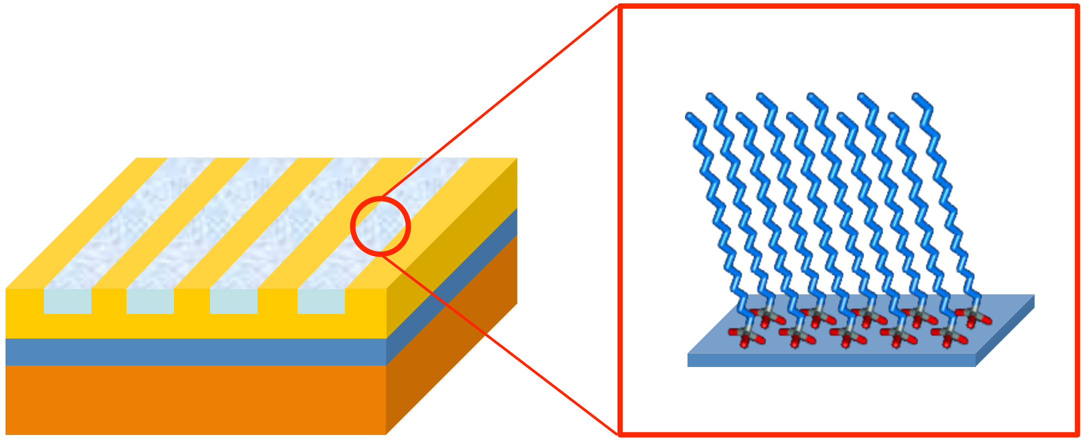


Contact angle: 10°

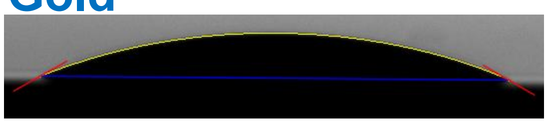
Self assembled monolayer (SAM) need to be used to change the surface energy.

Center for High-rate Nanomanufacturing

Wetability Control using SAM

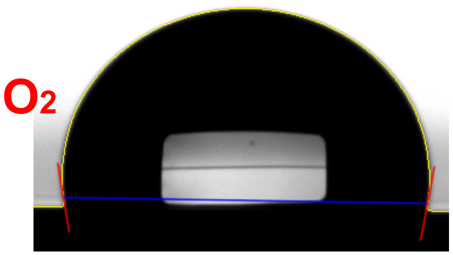


Gold



Contact angle: 18°

SiO_2



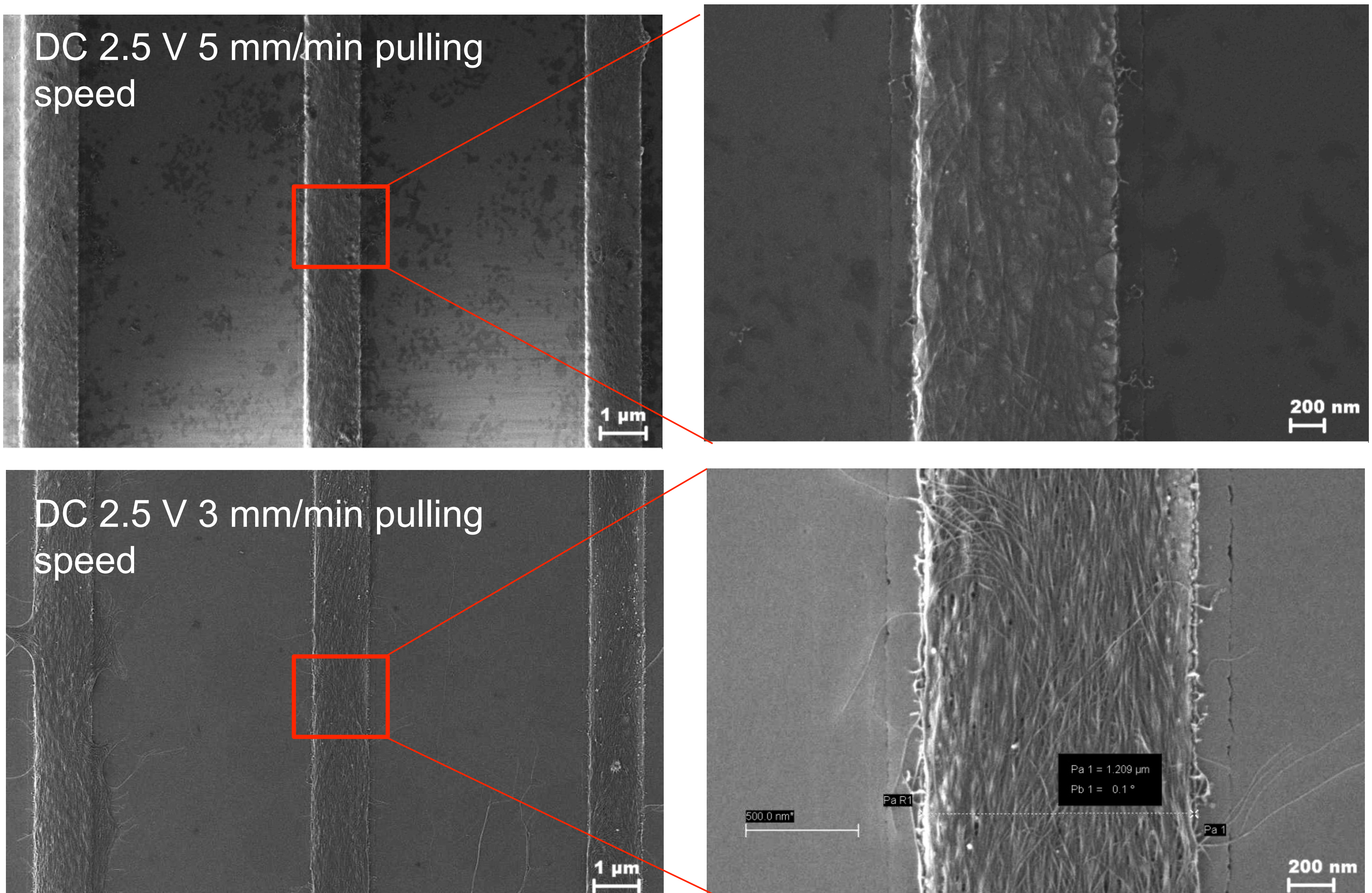
Contact angle: 100°

OTS self assembled monolayer

⇨ **SiO2 becomes hydrophobic**

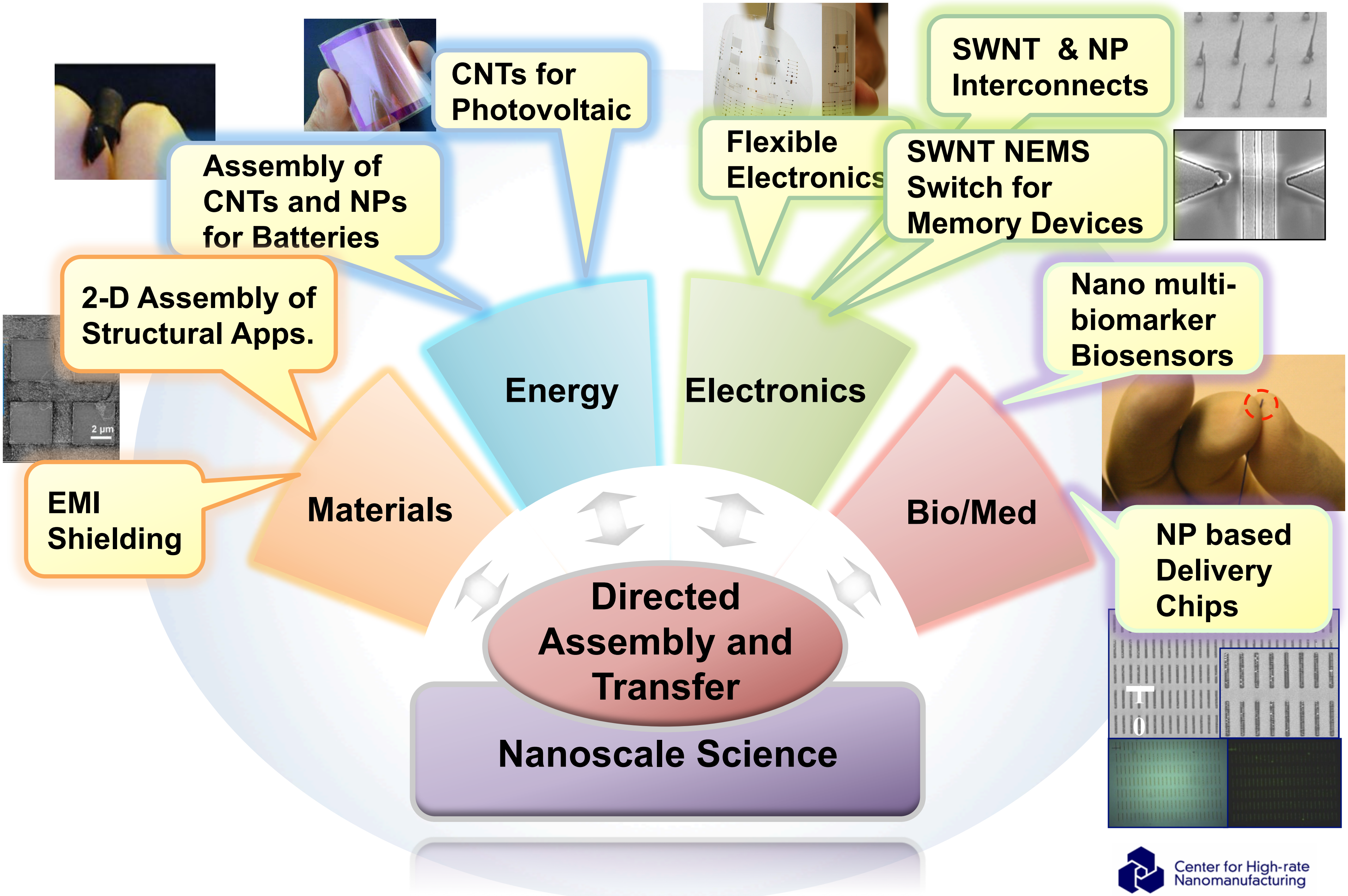
⇨ **Will prevent SWNTs from being assembled**

SWNT Assembly on Functionalized on Damascene Templates



Center for High-rate Nanomanufacturing

Nanomanufacturing Applications Roadmap



Center for High-rate Nanomanufacturing

CHN Toolbox
Connects Research to Applications

Templates	Nanoelements	Assembly Processes	Transfer Processes	Substrates	Applications
Microwires template	Nanoparticles	Electrophoretic 2-D and 3-D	Direct transfer (no functionalization)	Silicon	SWNT switch for memory devices
Nanowires templates	Carbon nanotubes (SWNTs and MWNTs)	Chemical Functionalization	Direct transfer with chemical functionalization	Polymer	Polymer-based Biosensors
Nanotrench template	Conductive polymers (PANi)	Electrophoretic and chemical functionalization	No transfer needed	Metal	Nanoparticle-based Biosensors
Template-free	Polymer blends	Dielectrophoretic 2-D and 3-D	Reel-to-reel transfer		SWNT Batteries
Damascene Template	***Fullerenes***	***Convective***	***Switchable functionalization***		Photovoltaics
	Acenes	***Convective interfacial***			SWNT Chem Sensors
	Graphene	***Self assembly***			EMI Shielding

Process Flow for SWNT Chemical Sensors

Templates	Nanoelements	Assembly Processes	Transfer Processes	Substrates	Applications
Microwires template	Nanoparticles	Electrophoretic	Direct transfer (no functionalization)	Silicon	SWNT switch for memory devices
Nanowires templates	Carbon nanotubes (SWNTs and MWNTs)	Chemical Functionalization	Direct transfer with chemical functionalization	Polymer	Polymer-based Biosensors
Nanotrench template	Conductive polymers (PANi)	Electrophoretic and chemical functionalization	No transfer needed	Metal	Nanoparticle-based Biosensors
Template-free	Polymer blends	Dielectrophoretic	Reel-to-reel transfer		SWNT Batteries
Damascene Templates	Fullerenes	Convective	Switchable functionalization		Photovoltaics
	Acenes	Convective interfacial			SWNT Chem Sensors
	Graphene	Self assembly			EMI Shielding

Center for High-rate Nanomanufacturing

Process Flow for Nanoparticle-based Biosensors

Templates	Nanoelements	Assembly Processes	Transfer Processes	Substrates	Applications
Microwires template	Nanoparticles	Electrophoretic	Direct transfer (no functionalization)	Silicon	SWNT switch for memory devices
Nanowires templates	Carbon nanotubes (SWNTs and MWNTs)	Chemical Functionalization	Direct transfer with chemical functionalization	Polymer	Polymer-based Biosensors
Nanotrench template	Conductive polymers (PANi)	Electrophoretic and chemical functionalization	No transfer needed	Metal	Nanoparticle-based Biosensors
Template-free	Polymer blends	Dielectrophoretic	Reel-to-reel transfer		SWNT Batteries
Damascene Templates	Fullerenes	Convective	Switchable functionalization		Photovoltaics
	Acenes	Convective interfacial			SWNT Chem Sensors
	Graphene	Self assembly			EMI Shielding

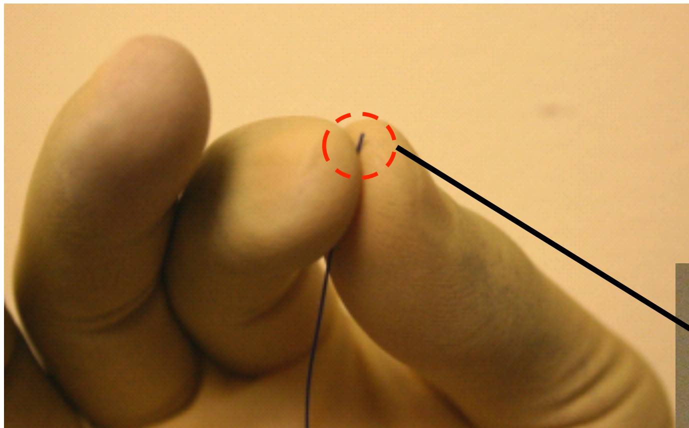
Center for High-rate Nanomanufacturing

CHN Directed Assembly Toolbox

Process	Speed	Scalability	Nanoelement property	Mechanism	Nanoelements
Electrophoretic Asssembly	Fast	Yes	Charge	Electrophoresis	Nanoparticles, CNTs, polymers
Chemical Functionalization	Fast/ slow	Yes	Functionalization	Chemistry	Nanoparticles, CNTs, polymers
Electrophoretic and chemical functionalization	Fast	Yes	Charge and surface functionalization	Electrophoresis and surface energy	Nanoparticles, CNTs, polymers
Dielectrophoretic	Fast	Yes/No	Dielectric constant	Dielectrophoresis	Nanoparticles, CNTs, polymers
Convective	Slow	No	Surface Functionalization	Convection	Nanoparticles, CNTs
Convective interfacial	Fast	Yes	Surface Functionalization and surface tension	Convection and interfacial force	Nanoparticles, CNTs

In vivo Nano Biosensor

S. Siavoshi, C. Yilmaz, S. Somu, T. Musacchio, J. Upponi, V. Torchilin, and A. Busnaina, Langmuir, 27, (2011).



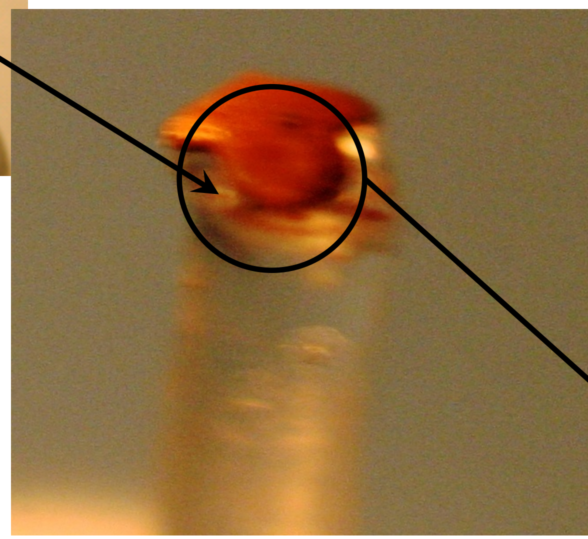
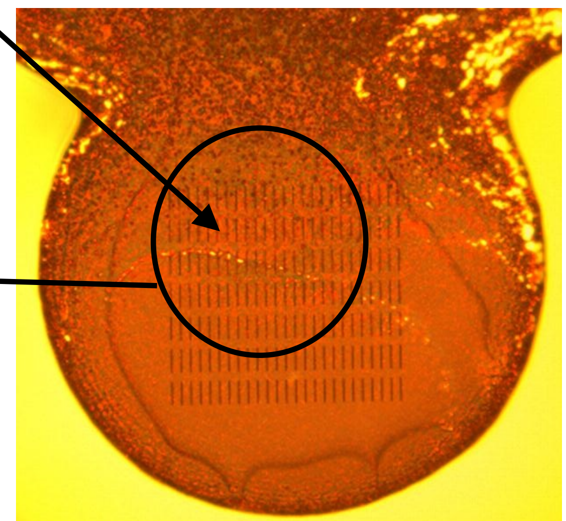
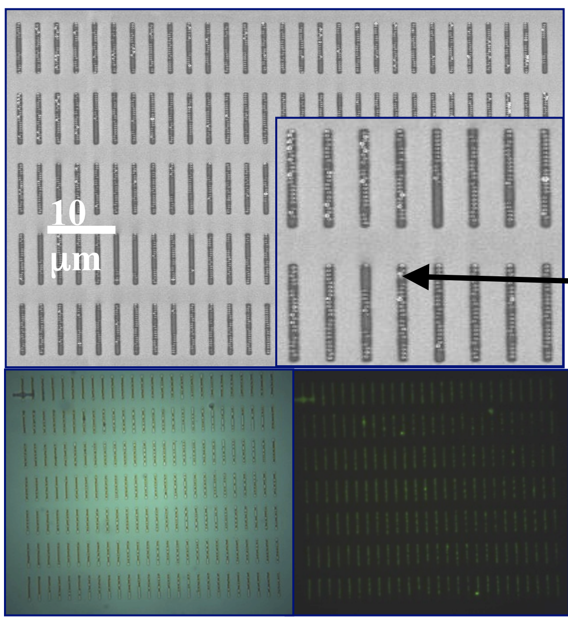


Image of the *in-vivo* biosensor (0.1 mm x 0.1 mm) after animal testing

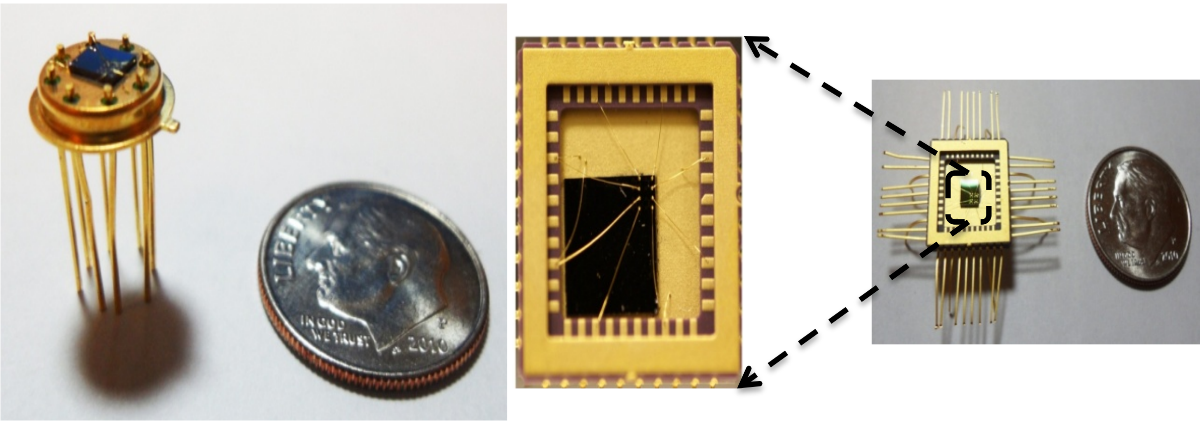


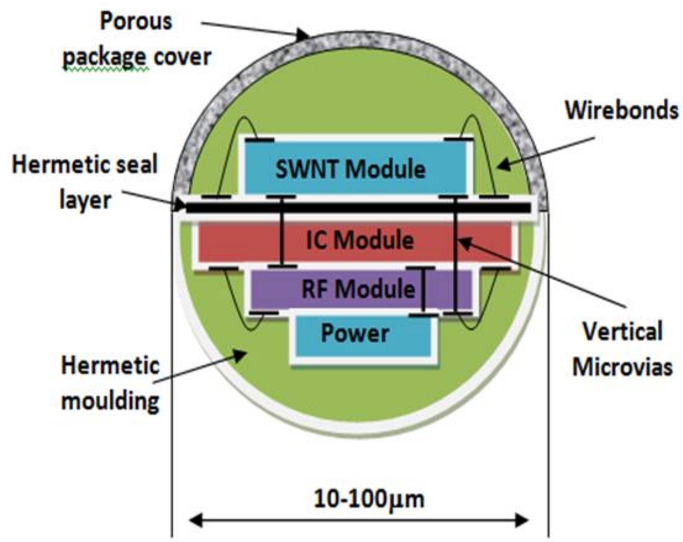


Incubated with human plasma spiked with CEA
Detection limit: 15 pg/ml
Current technology detection limit is 3000 pg/ml

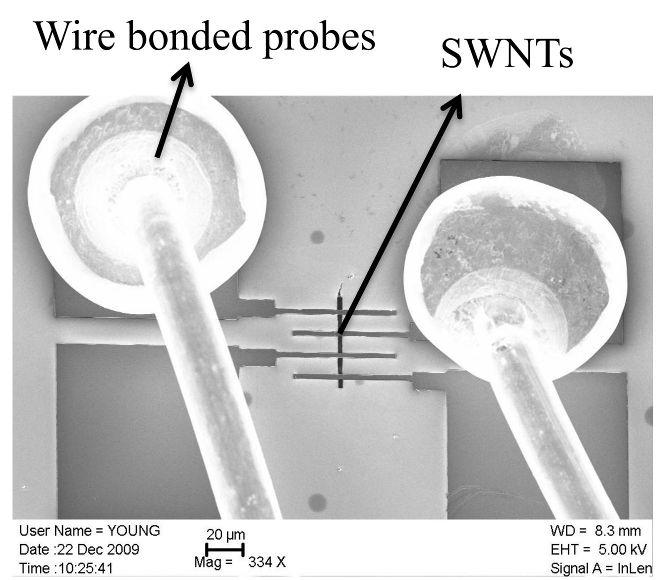
Center for High-rate Nanomanufacturing

Chemical Sensors I



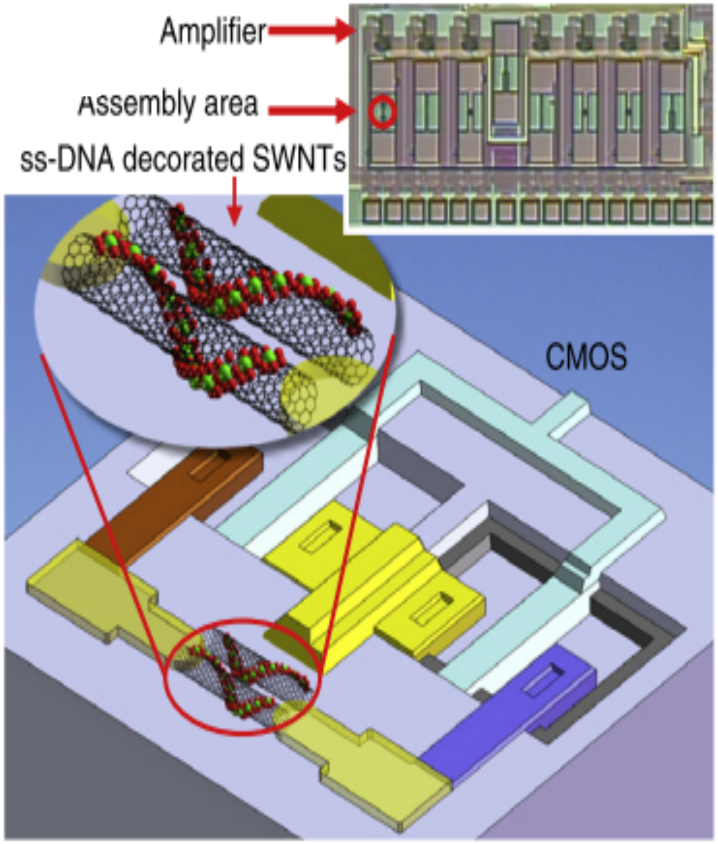


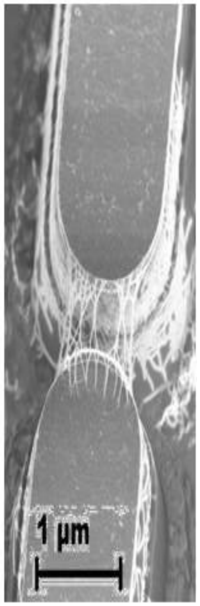
- Sensor active area is less than 10 micron squared;
- Resistance based; Very high sensitivity ~ppm
- Fast, specific Multiple species Detection
- Working in harsh environment (~250C and 25 Kpsi) already tested for 600psi and 200C
- When combined with peripheral components, data storage and communication is possible
- Potential Robust platform for low cost, sensitive sensor With durability to withstand reservoir injection.



Center for High-rate Nanomanufacturing

Chemical Sensors II





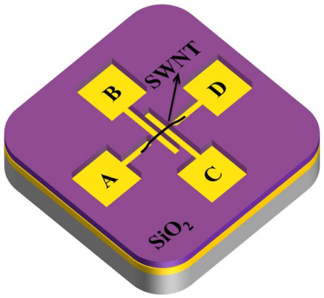
- Sensor active area is 2 micron squared or less
- Employs directed assembly
- Resistance based
- CMOS integrated
- Alcohol sensors
- Fast detection
- Highly portable
- High sensitivity
- When combined with peripheral components, data storage and position identification is possible

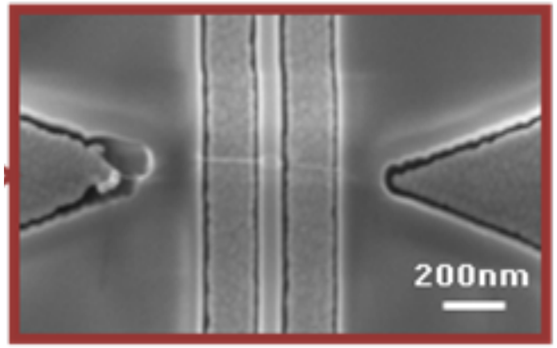
Application
Organic solvent Chemical sensors; Bio sensors
Modifications can lead to organic vapor sensors

Kim, Sonkusale, Busnaina, Dokmeci, et al. ***Nanotechnology, 21 (2010)***

Center for High-rate Nanomanufacturing

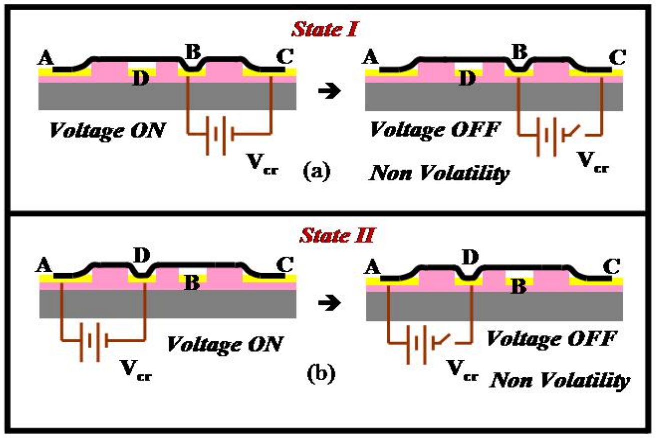
Carbon Nanotube NEMS Switch





Applications

- Memory element
- Logic gates
- Latches; Registries
- Analog devices
- Operational Amplifiers
- Sensors



Schematic of states I and II.

- Nano electromechanical Switch
- Non-voaltile
- Bistable Latch
- Position –Alternative state variable
- Novel State Variable Based Logic
- Fabrication employs field assisted directed assembly technique & a single mask process
- CMOS compatible

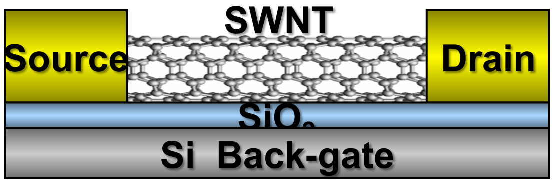
Characteristics:

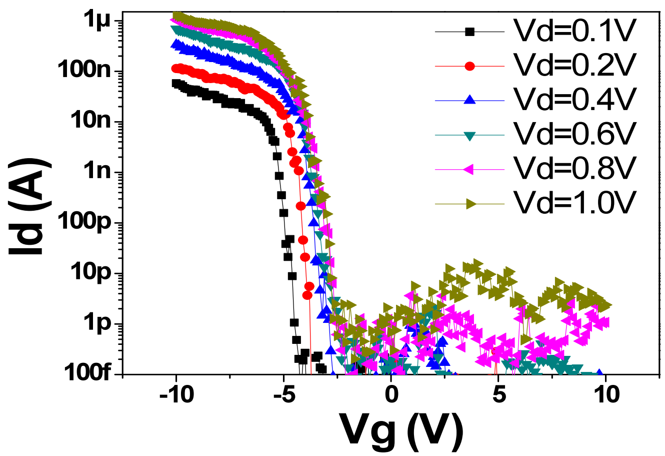
- Read write erase time ~ns
- Read write erase power ~ 100nW
- Infinite sub-threshold slope
- Zero leakage current
- Performance increases with scaling down

Center for High-rate Nanomanufacturing

Carbon Nanotube FET

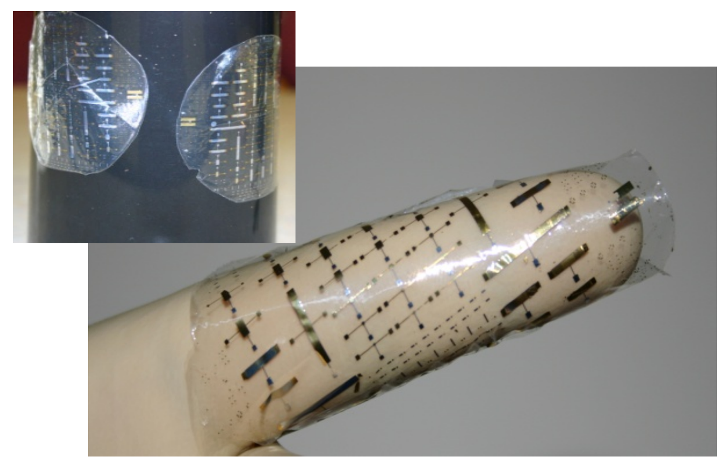
Employs Field Assisted Directed Assembly Technique





Typical p-type behavior, i.e., transistors turn under negative bias.

- The devices show a high $I_{on/off} > 10^5$
- Low off current ~ pA
- Sub-threshold swing of ~ 250 mV/dec,



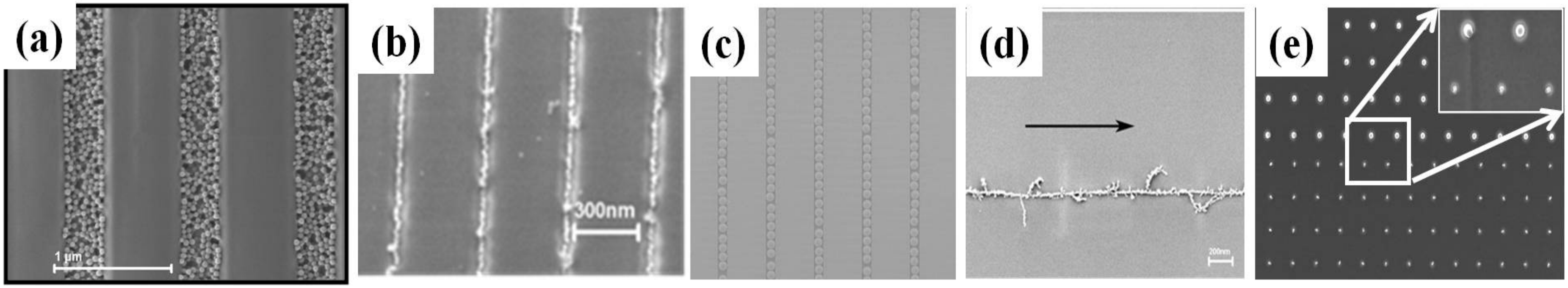
Applications

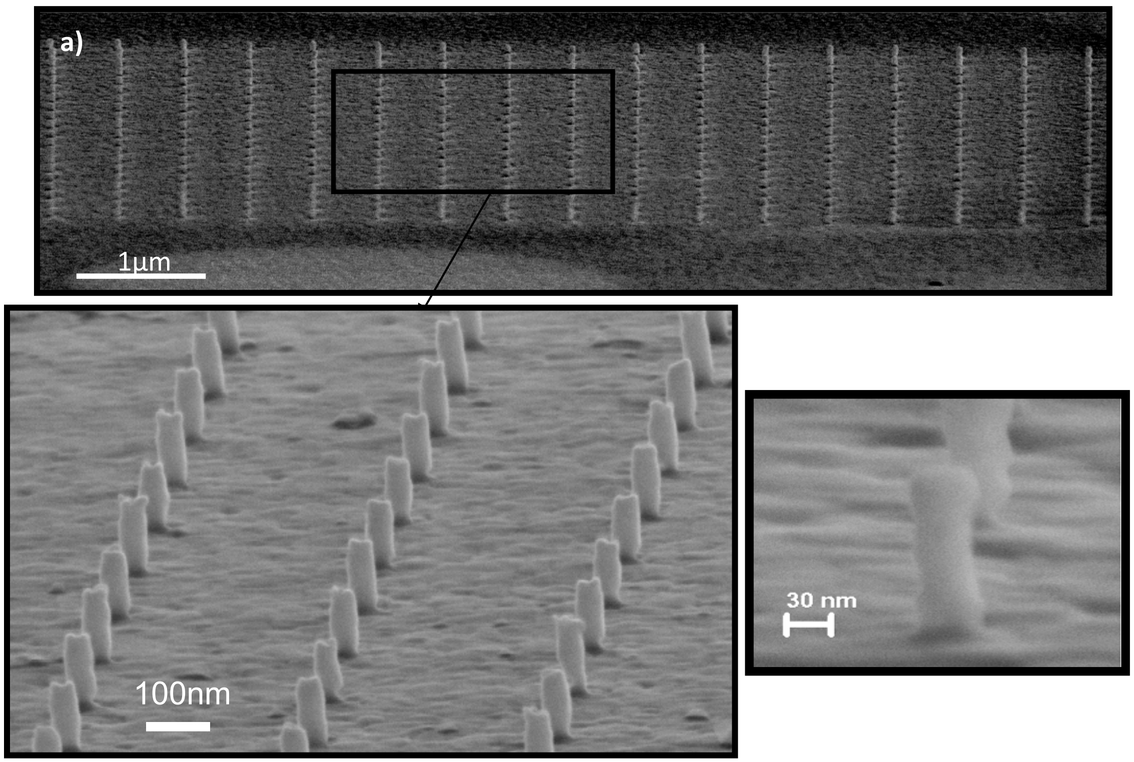
High Speed binary transistors ;
Logic gates; Analog devices;
Power amplifiers; Sensors, etc.

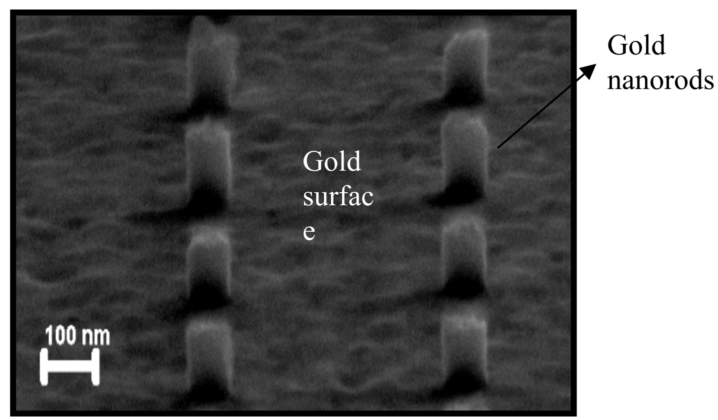
Selvarasah, Li, Busnaina, and Dokmeci, ***Appl. Phys. Lett. 97, 1 2010.***

Center for High-rate Nanomanufacturing

Assembly of Nanoparticles



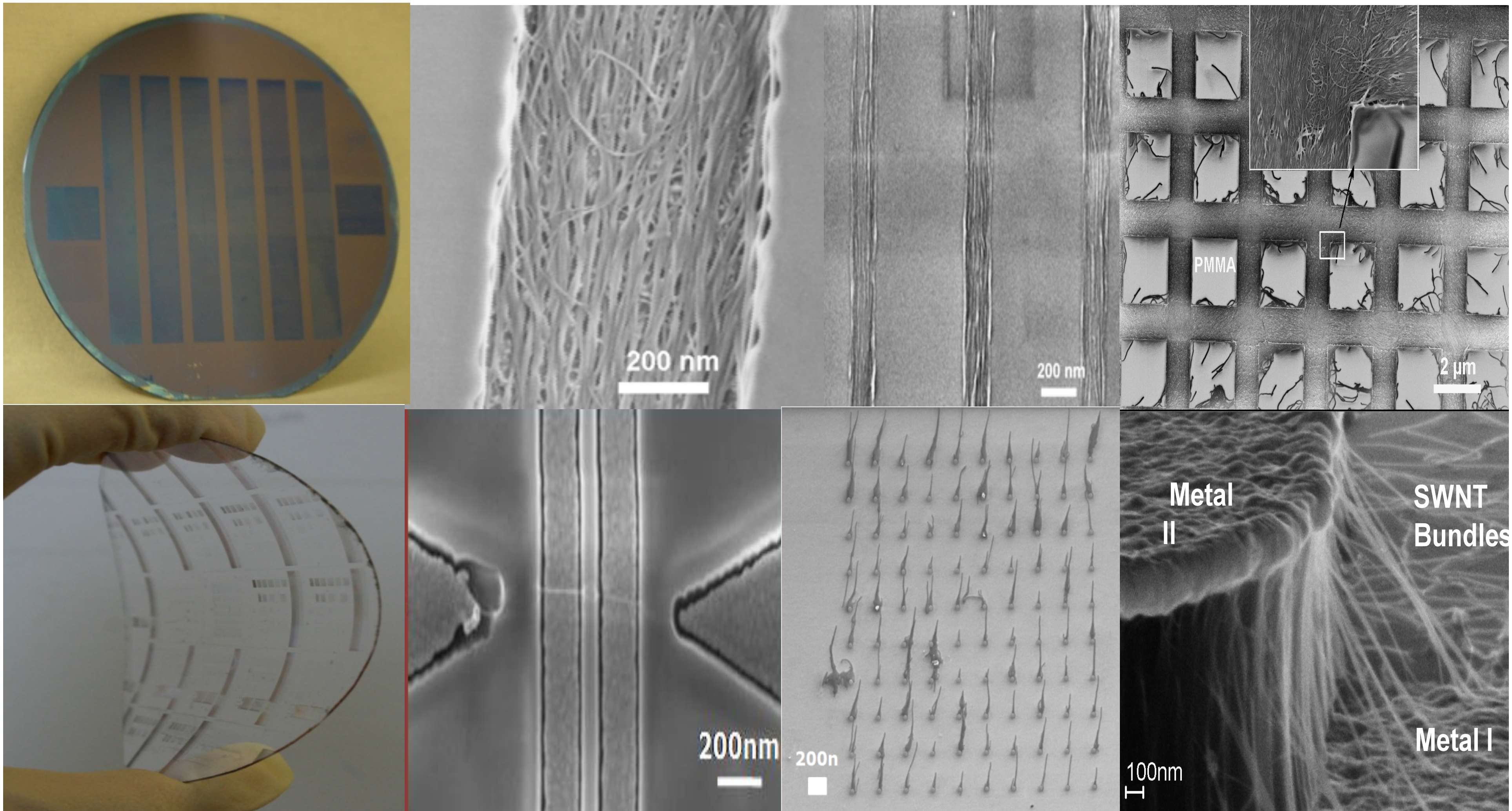




Center for High-rate Nanomanufacturing

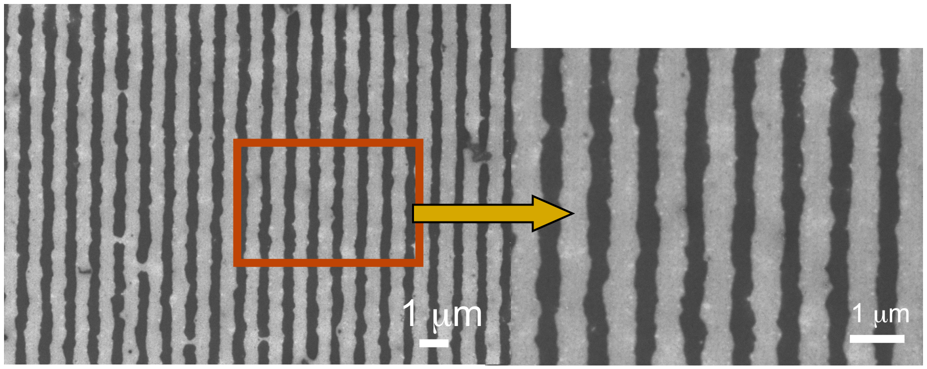
Assembly of Carbon Nanotubes

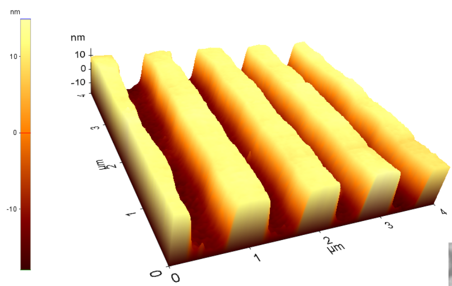
Carbon nanotubes assembled in various configuration via various assembly methods

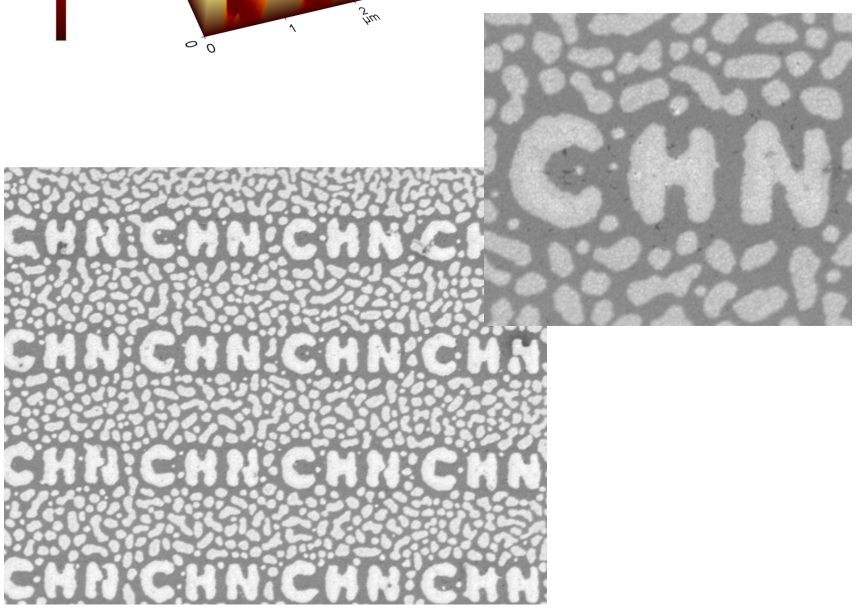


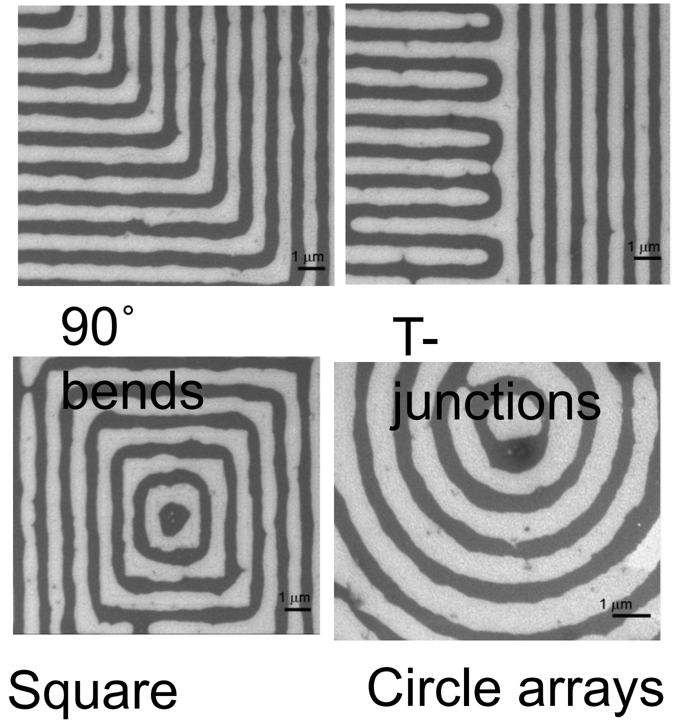
Center for High-rate Nanomanufacturing

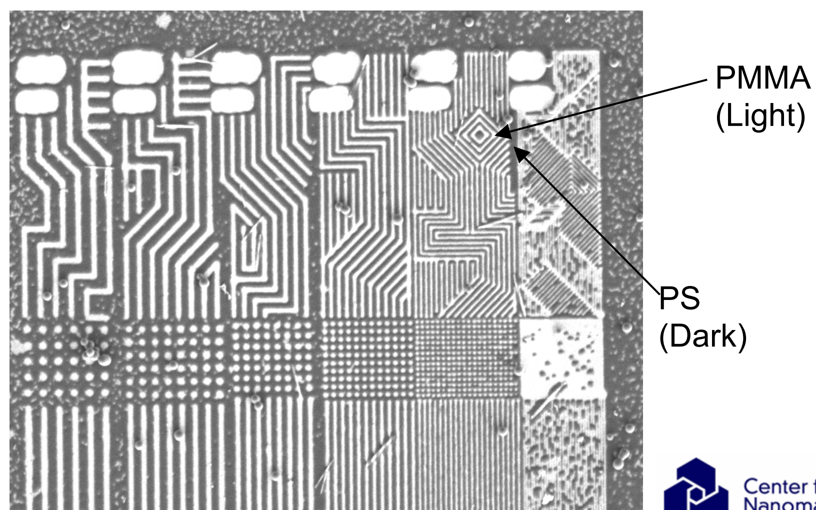
Directed Heterogeneous Assembly of Polymers





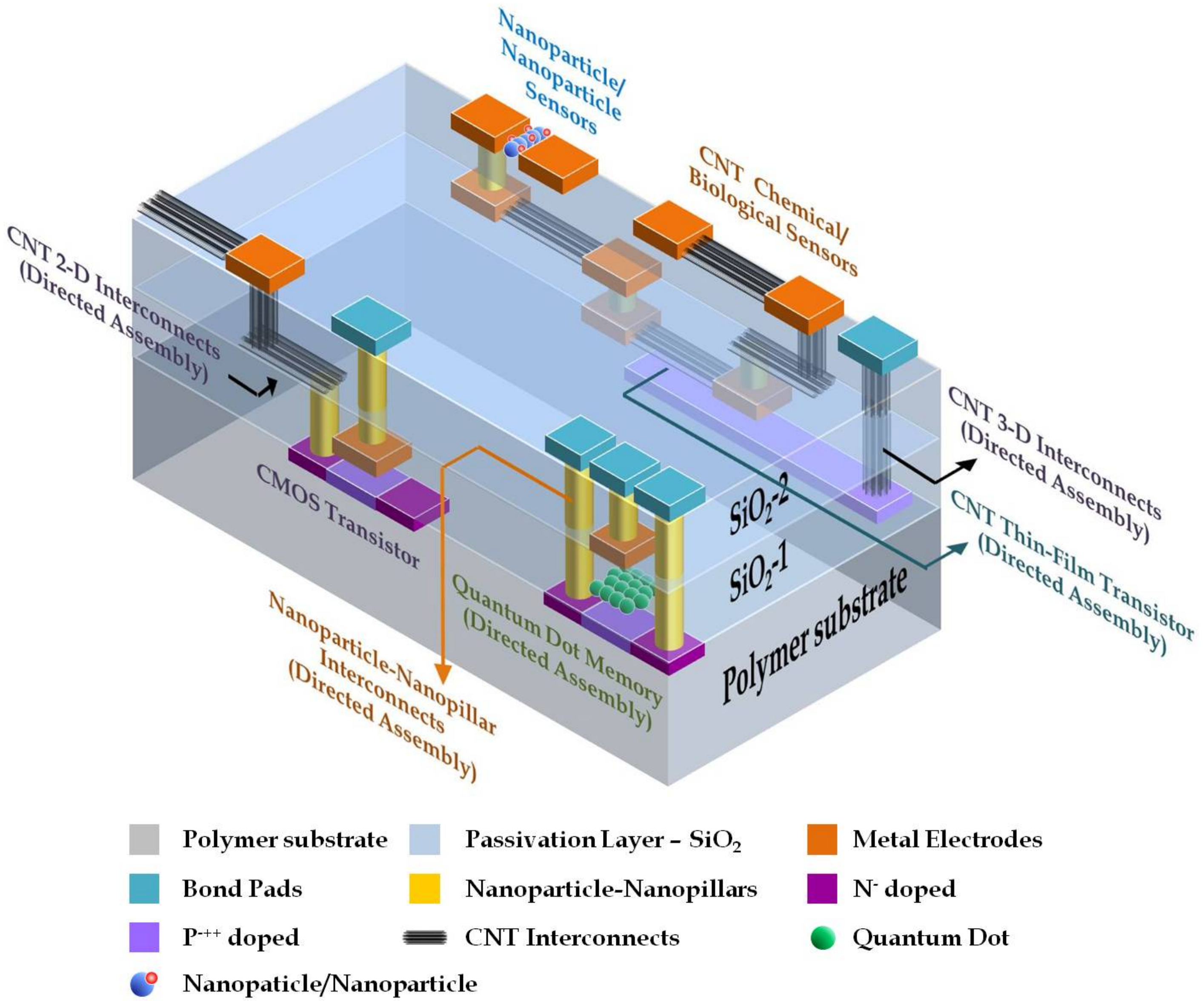






Center for High-rate Nanomanufacturing

Monolithic Flexible IC - Directed Assembly – Reel to Reel or Batch



Center for High-rate Nanomanufacturing

Strong Industrial Partnerships

varian
nanodynamics
TEXTRON
Ticona ENGINEERING POLYMERS
kuraray
Schlumberger
TERADYNE
tsi
zyvex
Veeco
TIAX
VELCRO
BAE SYSTEMS
nanocomp TECHNOLOGIES, INC.
AEC
QinetiQ North America
Foster-Miller
PI
ENVIRON
CORNING
DRAPER LABORATORY
AMBERWAVE
Raytheon
Nypro
MOTOROLA intelligence everywhere
intel
brewer science
NANTERO
EMC²
Microfluidics
BASF The Chemical Company
CABOT
Konarka technologies
IBM
LOCKHEED MARTIN We never forget who we're working for
SOLOPOWER
Kodak
GE
A Division of the Massachusetts Technology Collaborative

Over 30 companies

Center for High-rate Nanomanufacturing

Summary

- Directed assembly based nanomanufacturing will spur growth by drastically lowering the entry barrier to the fabrication of nanoscale devices.
- Many of the potential products that utilize nanomaterials (nanotubes, nanowires, nanoparticles) cannot be commercialized without nanoscale directed assembly.
- A nanofactory could be built for $25-$50 million, a small fraction of today's cost, making nanotechnology accessible to millions of new innovators and entrepreneurs and unleash a wave of creativity in the same way as the advent of the PC did for computing.
- Dramatically lowering such barriers would lead to the creation of entirely new industries.

Questions?

Center for High-rate Nanomanufacturing