Fundamentals of nanoscale patterning and manipulation

Lecture by Chung, Jae-Hyun

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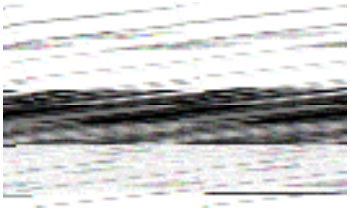
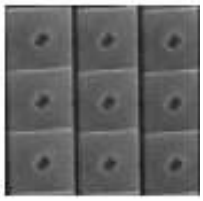
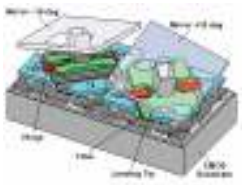
- Introduction to MEMS/Nanotechnology
- Fundamentals for micromachining
- Beam fabrication; Top-down vs. Bottom-up
- Nanodevice; Inverter; Top-down vs. Bottom-up
- Nanowire (nanotube) assembly

UNIVERSITY OF WASHINGTON NanoManufacturing Lab.

MEMS/Nanotechnology

MEMS product




TI mirror array

Ink jet printers

G.T.A. Kovacs, Micromachined Transducers Sourcebook (1998)

Nanotech product

Footwarmers (Shock Doctor/Aerogel Hotbeds)

Northborough, Mass.-based Aspen Aerogels launched a nanotechnology-based footwarmer in March of 2004, which is now used by the 2004 winner of the North Pole Marathon, the Canadian Ski Team and the U.S. Military's Elite Special Forces. Aspen's Pyrogel AR5401 utilizes highly-insulative nanoporous-aerogel technology, providing 5 to 20 times more thermal performance at a given thickness when compared to existing materials. Plymouth, Minn.-based Shock Doctor has developed a product called Hotbeds, which is being used in military boots for improving the level of comfort in cold weather operations. Since the Pyrogel AR5401 is so efficient, the Hotbeds are only 2.5mm thick.

BASF Superhydrophobic Spray

BASF is now wielding its nanotech muscle in the building-material industry, especially in concrete, brick facings, limestone and plasters. In the near future, your home may be coated with Mincor, an additive that helps to improve the hydrophobic effect of building materials. Its extreme water repellence minimizes contact and adhesion among water drops and surfaces, which means rain water pearls up immediately. The nanoparticles in Mincor reduce the adhesion of water and particulate soiling to a minimum. Dirt particles are simply rinsed away by rain water. BASF is currently looking for distributors.

http://www.forbes.com/investmentnewsletters/2005/01/12/cz_jw_0112soapbox.html

Top Ten Nanotech Products, Josh Wolfe, Forbes/Wolfe Nanotech Report,

Nanotech product (cont'd)

3M Dental Adhesive

Having a porcelain veneer, tooth restoration or root canal work soon? Your dentist just may put nanoparticles in your mouth to help your new crown stick better. As we featured in our September story, "3M: Practicing Nanotechnology Without the Hype," 3M ESPE, a 3M subsidiary in dental adhesives, announced a new option in total-etch dental adhesives: Adper Single-Bond Plus Adhesive. The new adhesive incorporates a silica nanofiller technology that forms a stronger bond to tooth enamel and does not need to be shaken by dentists prior to using in order to prevent particle clustering, which can decrease performance.

Golf Balls And The "Nano" Driver

Tokyo-based Maruman & Co. has adopted fullerenes from Hanjo Chemical for use in the top of the line "New Majesty" driver, which went on sale on July 5 of 2004. Compared to conventional titanium, the new driver resists bending 12% better, has a hardness 3.6% better than titanium, a 20% more resilient head and an increased flight distance of 15 yards as compared to their old 360cc class driver.

Buffalo, N.Y.-based NanoDynamics might have a nice accompanying stocking stuffer. NanoDynamics came up with a golf ball that can correct its own flight path. The design of the ball--and the undisclosed nanomaterials it's made of--serve to better channel the energy received from the club head, and thus correct a wobble or slight drift. The ball is expected to hit stores in the spring of 2005.

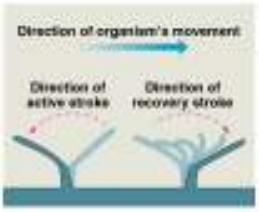
http://www.forbes.com/investmentnewsletters/2005/01/12/cz_jw_0112soapbox.html

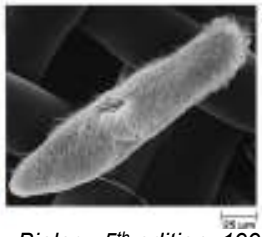
Top Ten Nanotech Products, Josh Wolfe, Forbes/Wolfe Nanotech Report,

Nanodevice?

•Transistors, memory chips, etc.

The undulating motion enables the cell to swim.





Cilia have a back-and-forth motion, alternating active strokes with recovery strokes.

Biology 5th edition, 1999, Neil A. Campbell et. al, p121

Nanodevice? (cont'd)

Biological cilia

Biomimetic cilia

1) http://pcdprese.tripod.com/index.html

2) PDMS cilia (from NSF supported project)

MEMS market

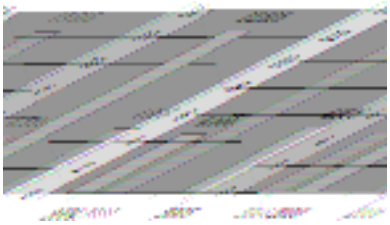
MEMS: devices composed of mechanical elements, sensors, actuators, and electronics on a common silicon substrate.

Market composition: Microfluidic MEMS (inkjet heads)-44%

(2004) Optical MEMS: 20%

Pressure sensors: 18%

Future market: Life science, automotive, and consumer product applications.



Global Forecast of the MEMS Market, AAGRs for 2004, 2005 and 2010 ($ Billions)

Electronics.ca Publications, Inc.

Nanotech market

•Major markets: lithography, fabrication tools, equipment, and semiconductors.

•The total global demand for nanoscale materials, tools, and devices was estimated at $ 7.6 billion in 2003. (1)

•The demand is expected to grow at an average annual growth rate of 30.6% to reach 28.7 billion in 2008. (1)

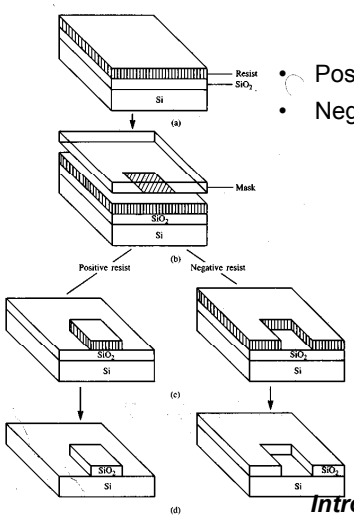
•Electronic News (www.edn.com): the market for semiconductor lithography reached $6.7 billion in 2006, and will grow 11 percent to $7.4 billion in 2007, and 38.2 percent to $10.2 billion in 2008.

•EETimes News (www.eetimes.com): the total spending for fabrication tools in the semiconductor industry alone was $41.95 billion in 2006 that was a 22.9 percent increase compared to that of 2005.

(1) http://www.nanotechbuzz.com/50226711/nanotech_market_to_reach_287_billion_by_2008.php

Fundamentals for micromachining

MEMS: 1. Lithography



- Positive photoresist
- Negative photoresist

- Mask aligner : MA6

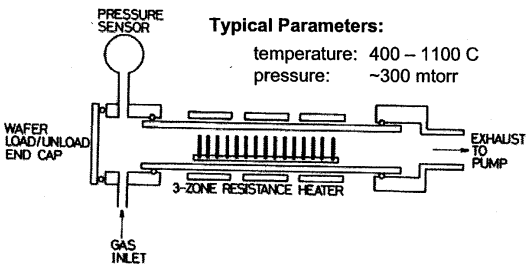
Introduction to Microelectronic Fabrication (by Richard Jaeger)

2. Thermal oxidation

- Oxide layer growing process
- Si (solid) + O_2 (vapor) --> SiO_2 (solid)
- Operating temperature 800~1100ºC

3. Chemical Vapor Deposition (CVD)

- **SiN, Oxide, poly Si, etc**
- **Lower temp. than thermal oxide**
- **Structural layer**



4. Metal deposition

- Electrical connection
- Mask layer
- Sacrificial layer
- Structural layer

- High vacuum operation
  (10^{-6}~10^{-7} torr)
- Cryo-pump or turbo pump

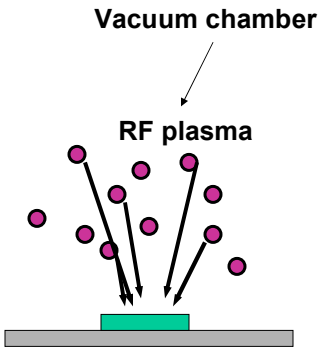
Electron beam evaporator
Washington technology center

5. Etching

- Wet etching
  Anisotropic etching and Isotropic etching
- Gas phase etching
  - Reactive ion etching
  - Deep RIE
  - No surface tension

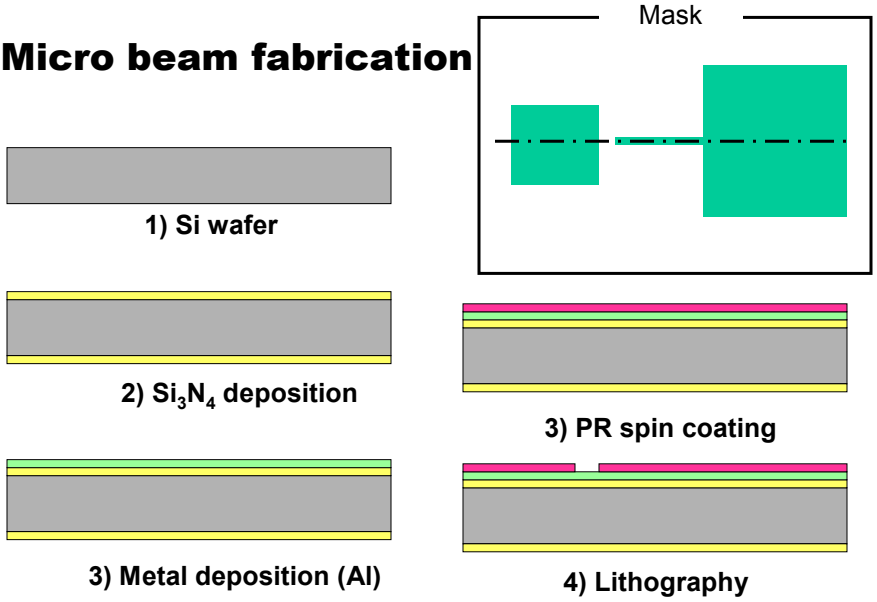
Isotropic etching

Anisotropic etching



Beam fabrication
Top-down vs. Bottom-up

Micro beam fabrication



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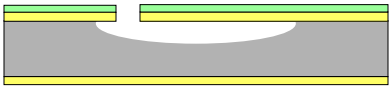
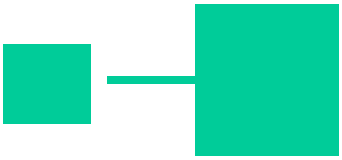
Micro beam fabrication (cont'd)

5) Al etching

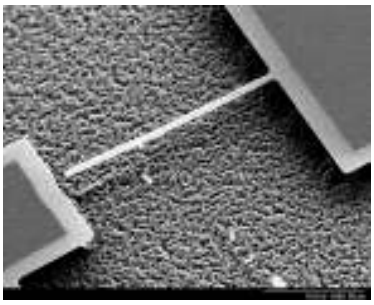
6) PR removal, Si_3N_4 etching



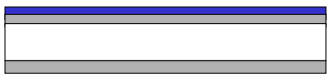
7) Si etching



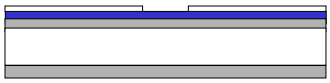
Mask



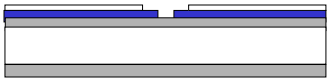
Bottom-up Approach



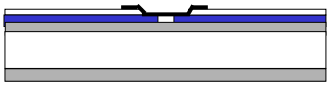
(1) Thermal and PECVD oxide



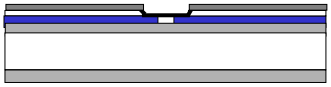
(2) Au electrodes patterning



(3) Patterning and RIE

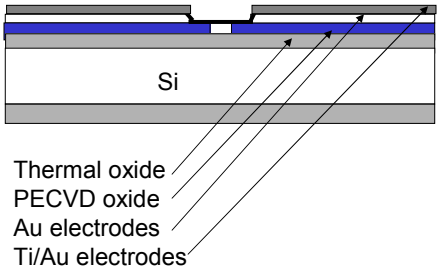


(4) Carbon nanotube assembly



(5) Ti/Au patterning

Bottom-up Approach

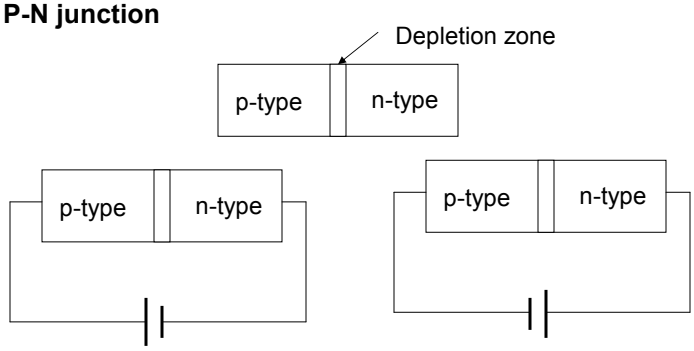


MWCNTs assembled across a trench

Nanodevice; Inverter
Top-down vs. Bottom-up

Inverter: Fundamentals

- **P-N junction**

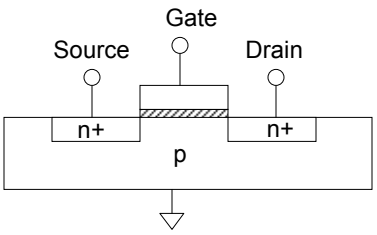


1) Repel holes and electrons
2) Decrease depletion zone
3) ***Electric current Flow***

1) Pull holes and electrons
2) Increase depletion zone
3) ***No current***

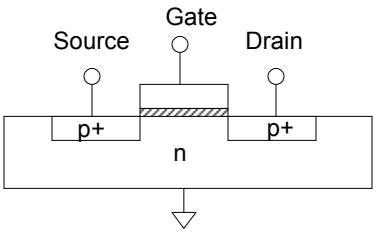
Inverter: Fundamentals

- **nMOS transistor**

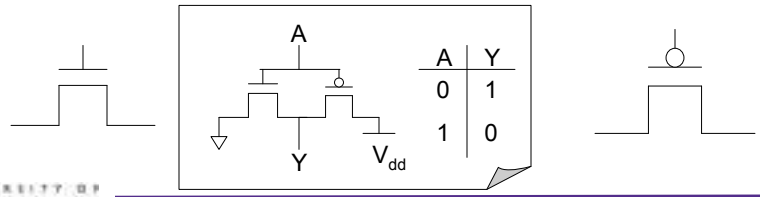


Gate-low : no current – transistor off
Gate-high: current - transistor on

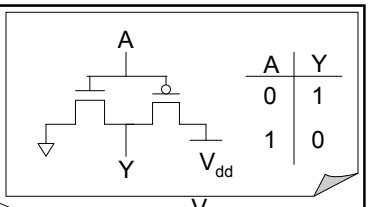
- **pMOS transistor**

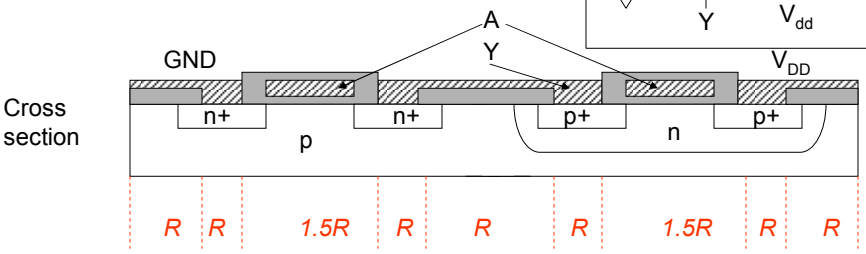


Gate-high : no current – transistor off
Gate-low : current –transistor on



Inverter: by top-down





- Rough approximation of the inverter size

  10R x 6R is required for the area; pattern resolution: R ≅ 4λ (wavelength)

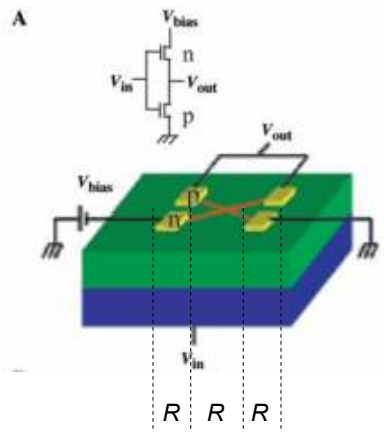
- 6 Mask steps for fabrication

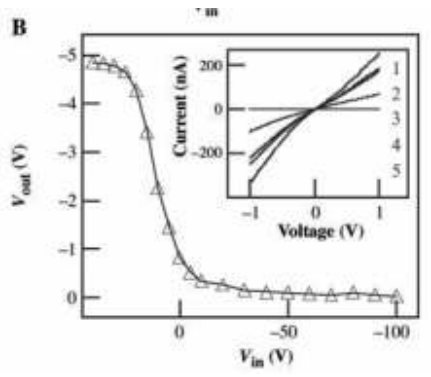
VLSI design techniques for analog and digital circuits, by Randall L. Geiger, et al., McGraw-Hill publishing company.

Intuitive CMOS electronics by Thomas M. Frederiksen, McGraw-Hill series

Inverter: by bottom-up

Inverter using Si nanowires



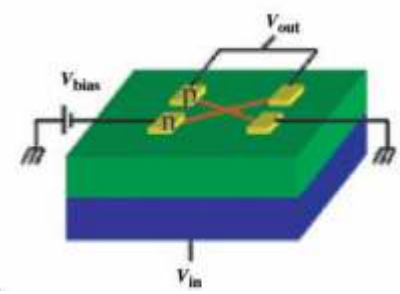


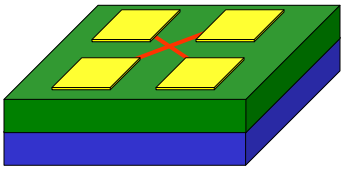
Cui Y and Lieber CM, SCIENCE, 2001.

3R x 3R is required.

Inverter: by bottom-up

Inverter Fabrication using Si nanowires



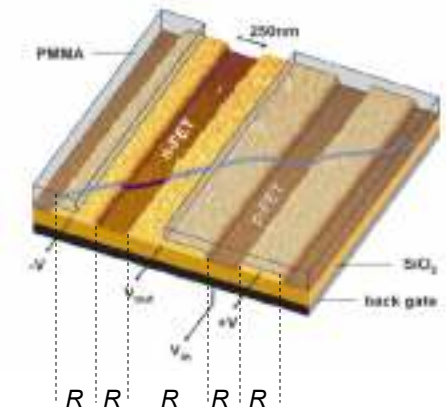


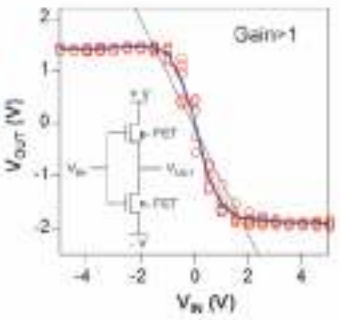
Fabrication process:

Si wafer - oxidation - *1st Si nanowire assembly* - *2nd Si nanowire* - electrode patterning

Inverter: by bottom-up

Inverter using carbon nanotubes





5R x 1R is required.

Derycke V, et al., NANO LETTERS, 2001.

Inverter: by top-down vs. bottom-up

Inverter	Top-down	Bottom-up (Si nanowire)	Bottom-up (CNT)
Area	10R x 6R	3R x 3R	5R x 1R
Limited by	Wavelength	Assembly process	
Mask steps	6 mask process	1 mask process	2 mask process
Pros	Well established	Simple structures and fabrication	
Cons	Complicated fabrication	Low yield for assembly processes	
Future	Resolution can be 30 nm.	? (may be dominant under 10nm)	

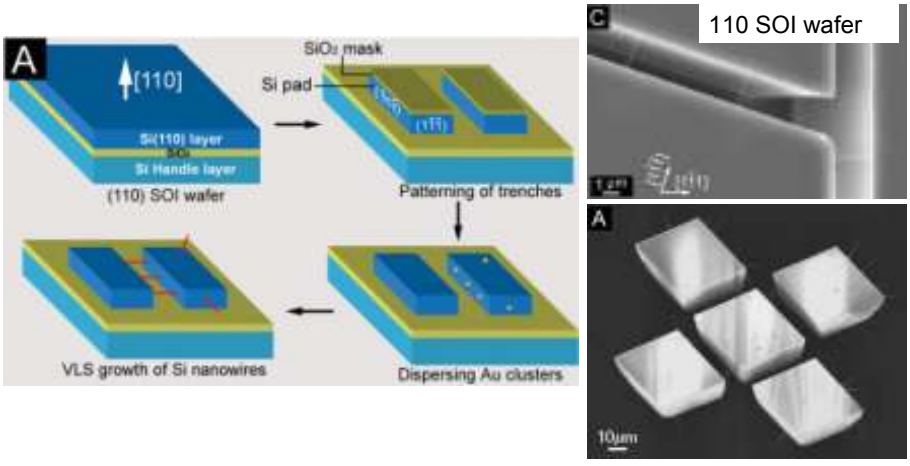
Nanowire assembly is key to the future!

Nanowire (nanotube) assembly

Assembly Methods

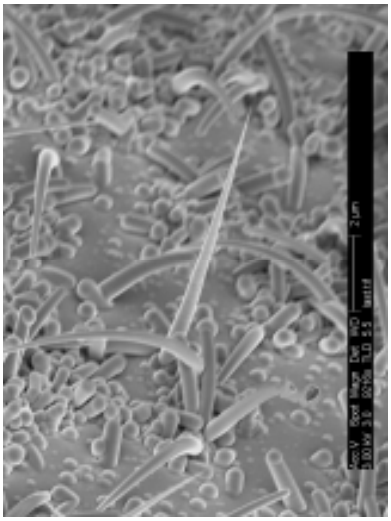
- **Growth methods** : Chemical vapor deposition (CVD), Plasma enhanced vapor deposition (PECVD), Vapor-liquid-solid growth, etc.
- **Chemical patterning**: assembly using an electrostatic attraction of nanowires (nanotubes) suspended in solution.
- **Electric field guided assembly**: dielectrophoresis and electrophoresis.
- Other methods:
  - •Manipulation using either a micromanipulator or an atomic force microscope (AFM)
  - •Magnetic and optical fields
  - •Shear force in viscous solution (ex: spin coating and fluid flow)

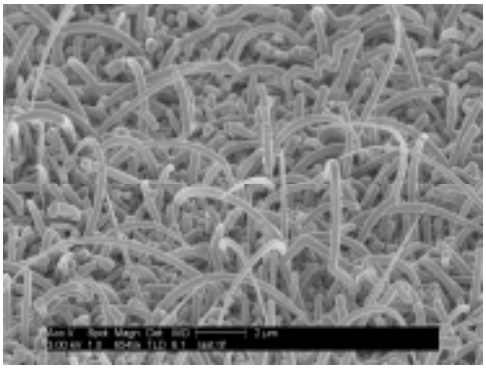
Growth (Si nanowires; VLS CVD)



He RR et al., ADVANCED MATERIALS, 2005

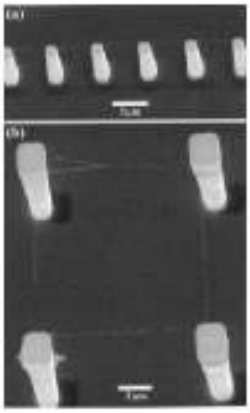
Growth (Si nanowires; PECVD)





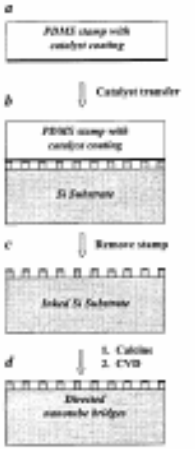
Washington Technology Center
Process temp: 500ºC

Growth (SWCNT; Chemical vapor deposition)



•*SEM image*

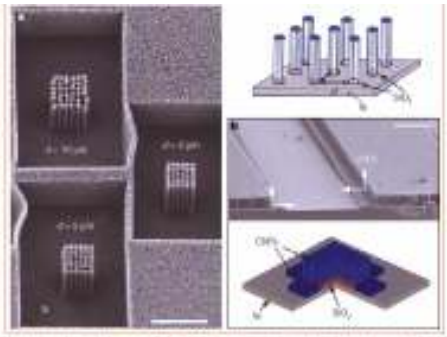
•*TEM image*



•*Procedure for CVD growth*

• *Cassell AM, et al. JACS 1999*

Growth (MWCNT; Chemical vapor deposition)



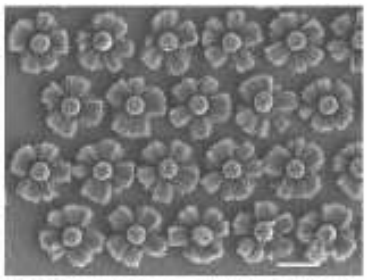


Figure 2 Repeating patterns containing mutually orthogonal nanotube arrays produced on deep (about 5 μm) silica features (circular cross-section) machined on silicon substrates. Growth in the vertical direction occurs from the top silica surface (seen as arrays emanating from the centre of each pattern); growth on the sides occurs as horizontal arrays (sideways growth seen on each pattern). Scale bar, 50 μm.

• *Wei BQ, et al., NATURE, 2002*

Chemical patterning (MWCNT)

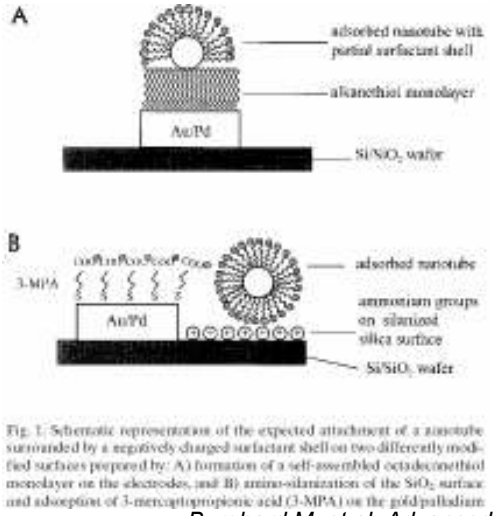


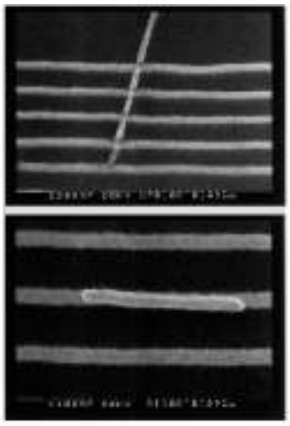
Fig. 1. Schematic representations of the expected attachment of a nanotube surrounded by a negatively charged surfactant shell on two differently modified surfaces prepared by: A) formation of a self-assembled octadecanethiol monolayer on the electrodes, and B) amino-silanization of the SiO_2 surface and adsorption of 3-mercaptopropionic acid (3-MPA) on the gold/palladium

Burghard M, et al. Advanced Materials, 1998.

Chemical patterning (MWCNT)

Experimental procedure
1) CNT
Growth
Dispersion in surfactant by sonication
2) Au lines
Si wafer
Oxidation
Au patterning
Alkanethiol growth (SAM) in solution or with evaporation
3) CNT assembly by self-assembly
Single drop of CNT suspension
Dry
4) Imaging

Case A

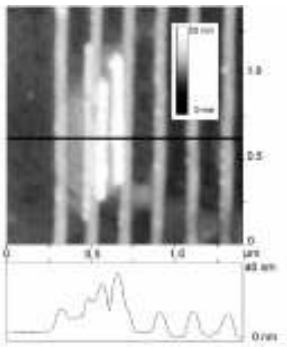


Burghard M, et al. Advanced Materials, 1998.

Chemical patterning (MWCNT)

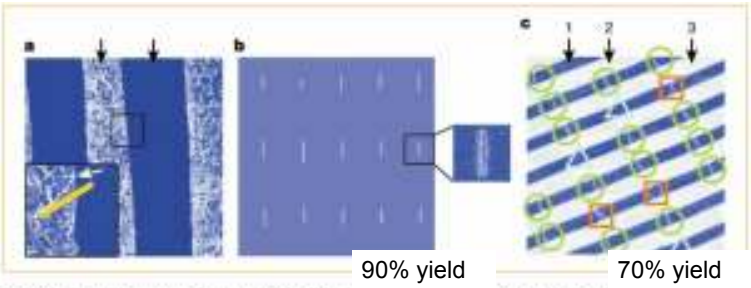
Experimental procedure
1) CNT
Growth
Dispersion in surfactant by sonication
2) Au lines
Si wafer
Oxidation
Au patterning
Amino-silanization on oxide layer
3mercaptopropionic acid (3-MPA) on electrodes
3) CNT assembly by self-assembly
Single drop of CNT suspension
Dry
4) Imaging

Case B



Burghard M, et al. Advanced Materials, 1998.

Chemical patterning (SWCNTs)



90% yield 70% yield

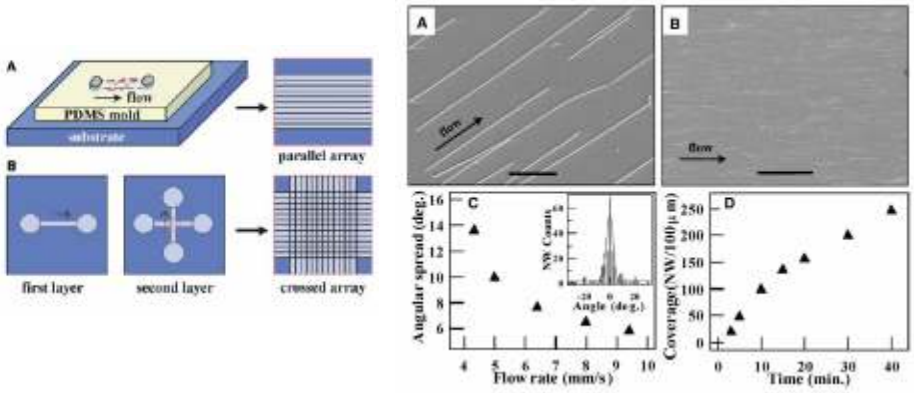
Figure 1 Atomic force micrographs showing large-scale self-assembly of single-walled carbon nanotubes (swCNTs). **a**, Image (12 × 12 μm²) showing the topography of swCNTs near the boundary (white arrow, inset) between polar (cysteamine; left arrow) and non-polar (1-octadecanethiol (ODT); right arrow) molecular patterns on gold. No swCNTs are evident in ODT regions. Yellow box represents a tangent to a bent swCNT, showing the extent of bending due to lateral–directional force. **b**, Topography (30 × 30 μm²) of an array of individual swCNTs covering about 1 cm² of gold surface. Thin friction-force image (inset) shows a single swCNT (dark line), and the regions containing 2-mercaptoimidazole (bright area) and ODT (dark area). **c**, Topography (20 × 20 μm²) of an array of junctions with no swCNTs (triangles), one swCNT (circles) or two swCNTs (squares), covering an area of about 1 cm². Arrows 1, 2 and 3 indicate octadecyltrichlorosilane (used to passivate the Si O_2 surface), 2-mercaptoimidazole on gold, and ODT on gold, respectively.

Patterning organic molecules by dip-pen nanolithography and microcontact printing followed by CNT patterning

Rao SG, et al., Nature, 2003.

Chemical patterning (Si nanowires)

Chemical patterning was combined with fluid flow for nanowire assembly.



Huang Y, et al., SCIENCE, 2001

Chemical patterning (3-d structures)
Metal-Polymer Amphiphiles

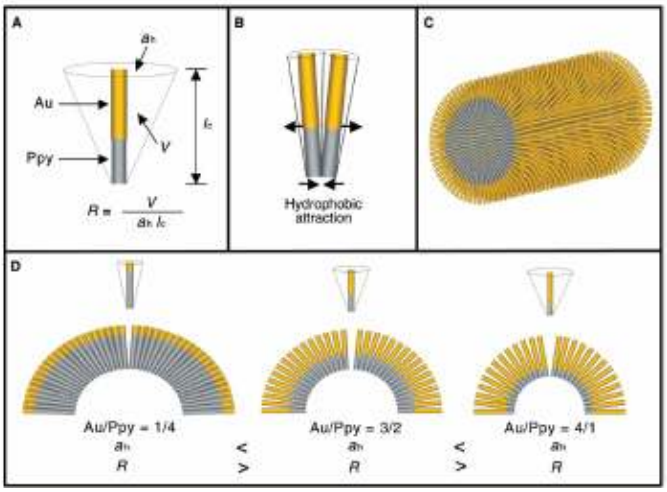
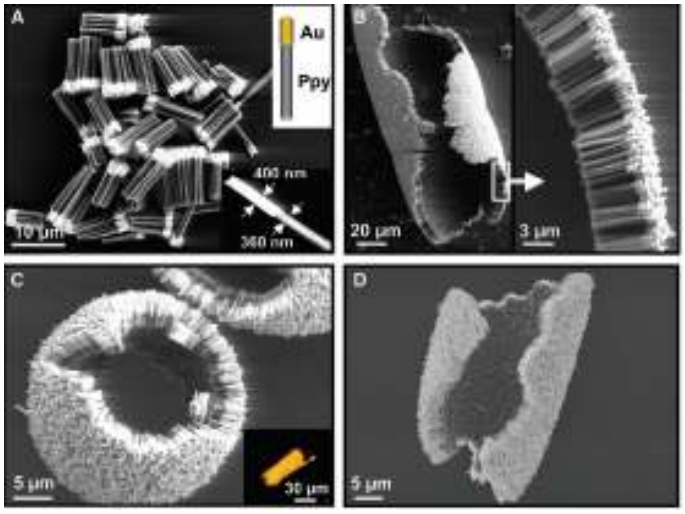


Fig. 2. Schematic representations of the corresponding Au-Ppy rod assemblies described in Fig. 1, B to D. (A) Geometric packing parameters (where V is the volume of rods, a_h is the average rod head area, and l_c is the rod length), calculated by assuming a truncated cone. (B) The estimated a_h can be acquired from a first-order approximation of the average area occupied by the gold end of each rod in the microtubular structure, which is defined by the perimeter area of the tube divided by the total number of rods that make up the superstructure. (C) A three-dimensional bilayer structure composed of rod-like building blocks. (D) Cross-sectional views of tubes of various diameters formed from specific rod compositions with well-defined block-length ratios.

Park S, et al., SCIENCE, 2004

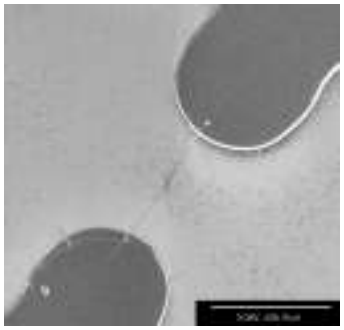
Chemical patterning (3-d structures)
Metal-Polymer Amphiphiles



Park S, et al., SCIENCE, 2004

Electric Field Guided Assembly

Parallel Assembly



One dimensional assembly

•Electrodes are required for assembly.
•Electric fields (AC, DC, and composite fields).
•Electrophoresis, Dielectrophoresis, Electrokinetic flow, etc.
We will more discuss electric field guided methods in this lecture.

Comparison for assembly methods

	Growth	Chemical patterning	E-field
Purity demand	High	High	Low
Patterning	Catalyst	Deposition area	Electrodes
Temp./ time	>500°C/ ~hrs.	room temp./ 1min	room temp./ 1min
Sorting	Yes	No	Yes (electrical property & physical size)
Potential for Waferscale fab.	Yes	Yes	Yes

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