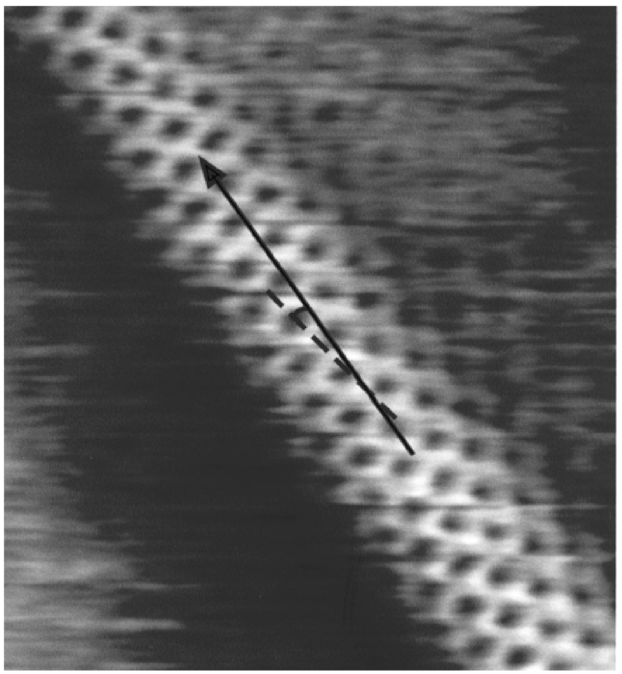
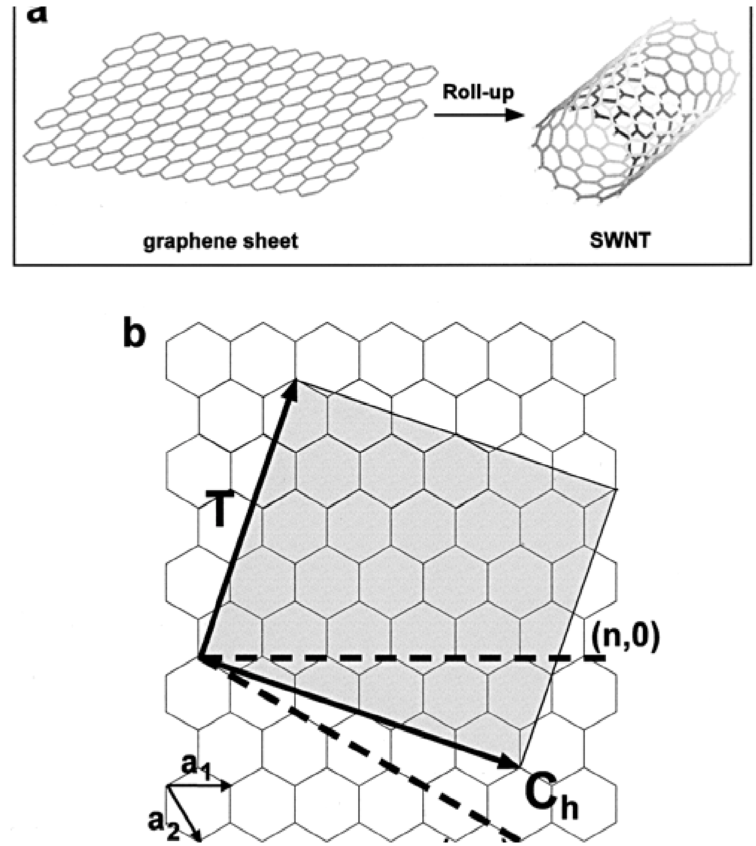
Tubes, Rods, and Wires

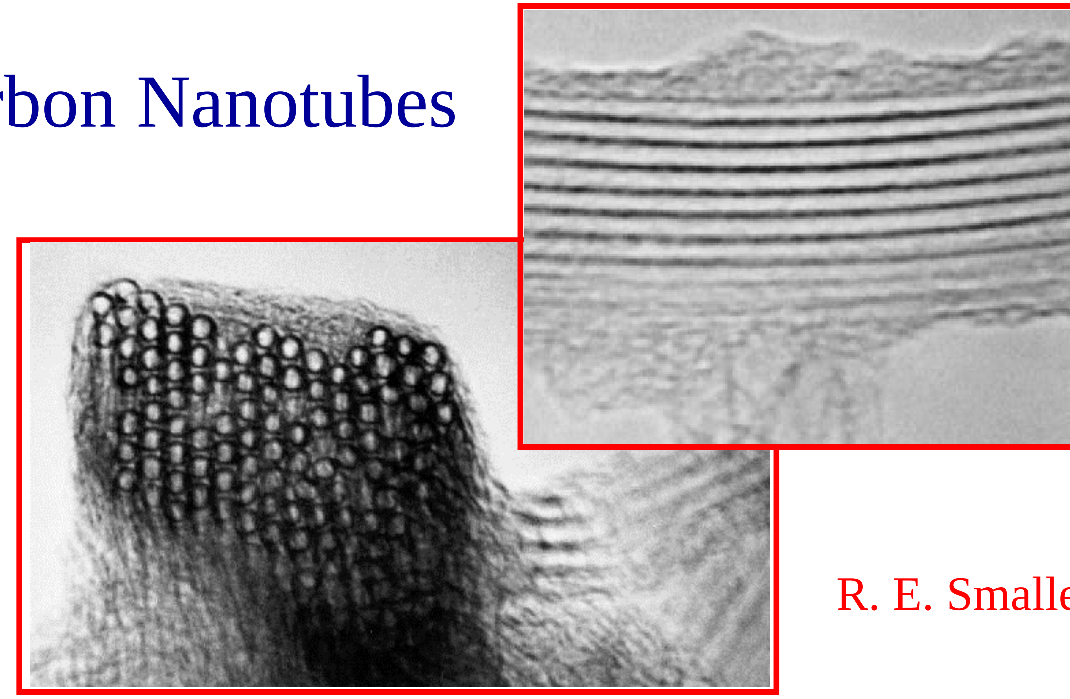
Carbon nanotubes:

- outstanding materials properties
- width, pitch, length and wall/tip chemistry not yet under control





Single-Wall Carbon Nanotubes



R. E. Smalley

Produced as rope bundles by using metal catalysts
Chemical reactions exfoliate bundles and open tube ends

Currently expensive and hard to purify
New $Fe(CO)_5$ synthesis may make kg quantities available

Multi-Wall Carbon Nanotubes - Mechanical Properties

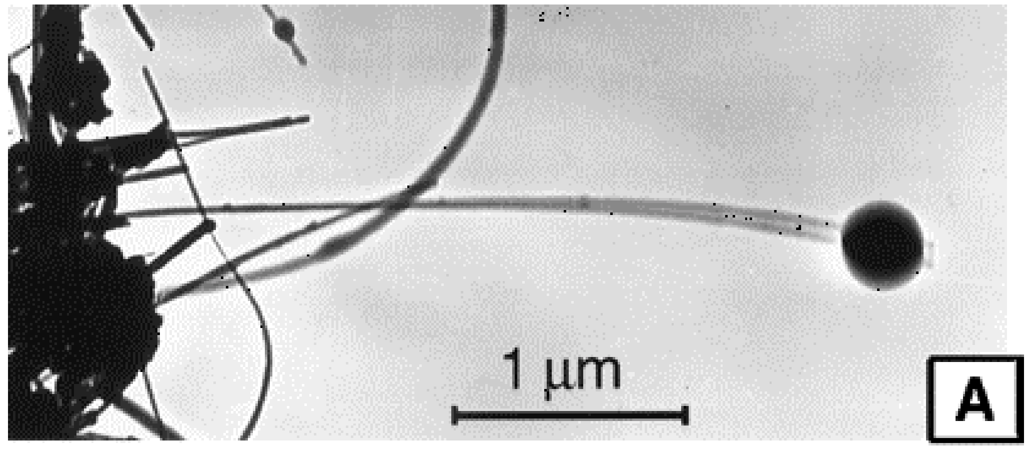
Nano-cantilever

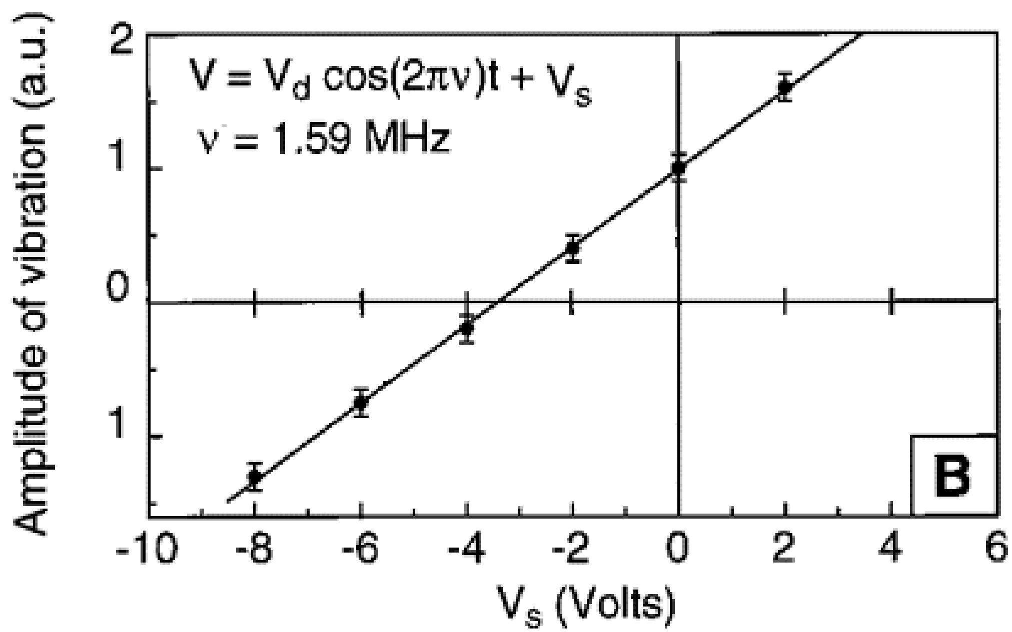
W. de Heer, et al.,
Science 1999, *283*, 1513

Very high Young's modulus (ca. 1 TPa)

Resonance frequency 0.5 - 3 MHz

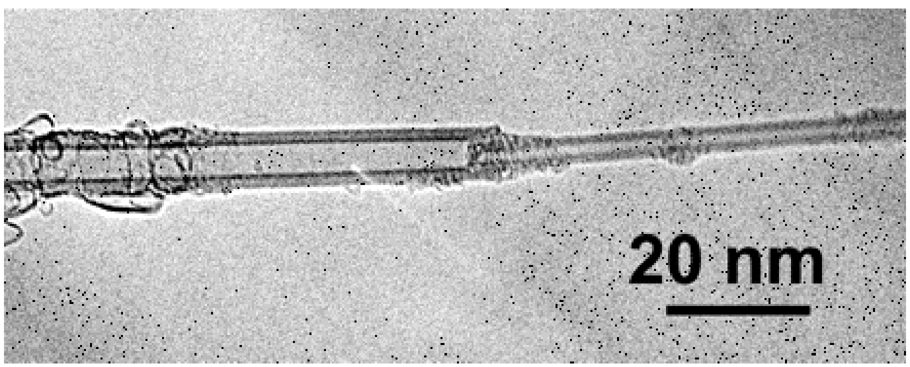
Ultrasensitive cantilever balance

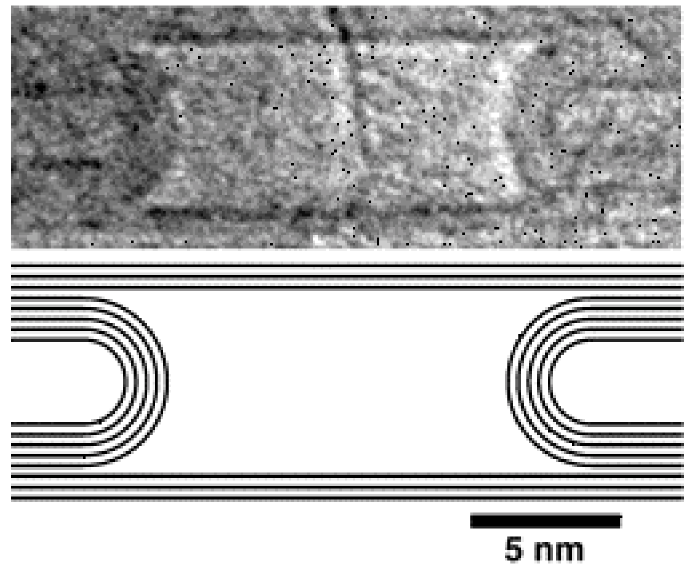




Nanotube Nanobearings

J. Cumings, A. Zettl, *Science* 2000, *289*, 602





Theoretical calculations suggest very soft bearings

Restoring force does not vary with extension

V. H. Crespi, *Phys. Rev. Lett.* 2000, *in press.*

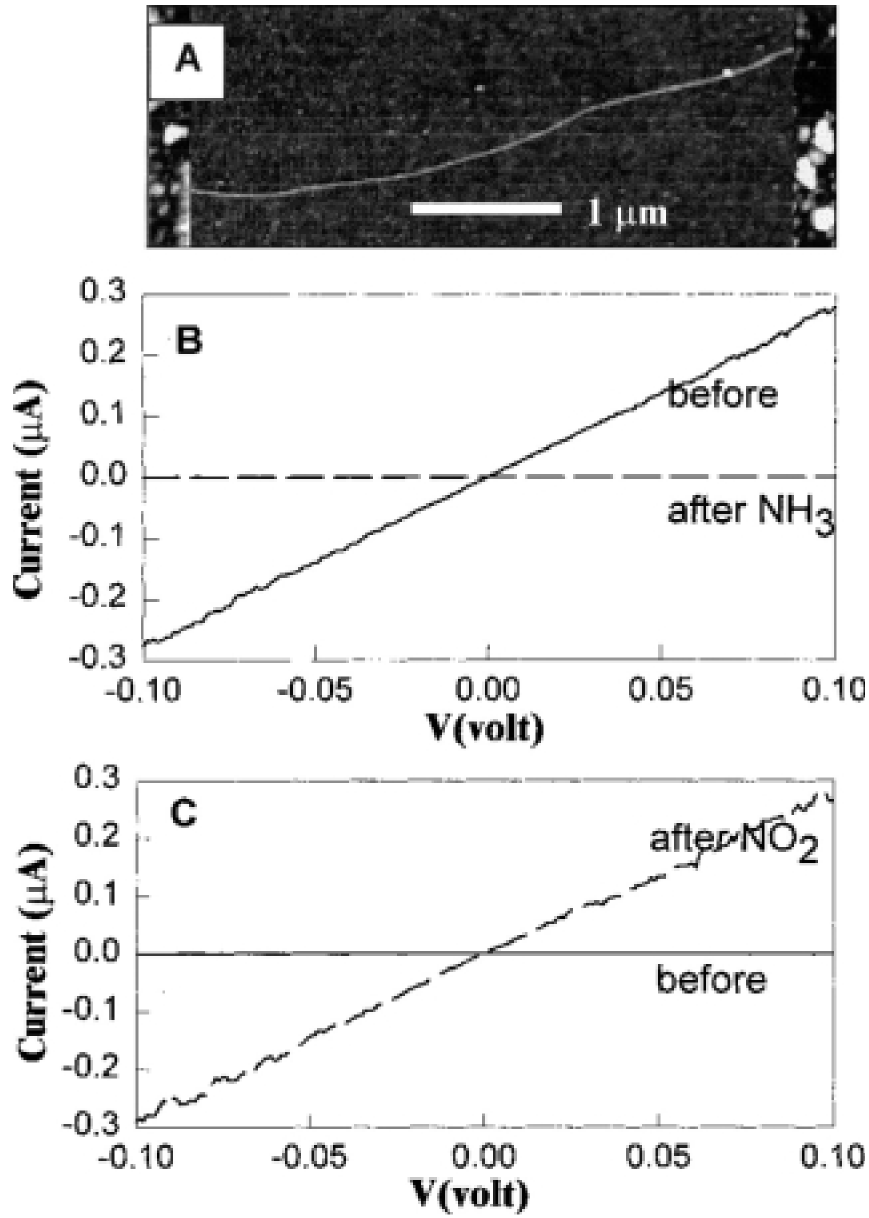
Nanotube Transistors and Sensors

Carbon helix pitch determines conductivity (metal or semiconductor)

Gate lead modulates conductivity

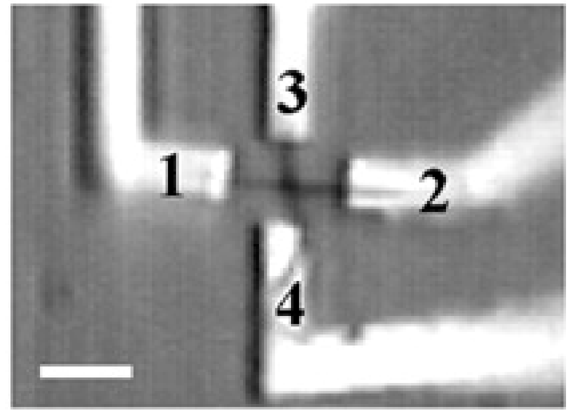
Chemical potential of gate changes with gas adsorption

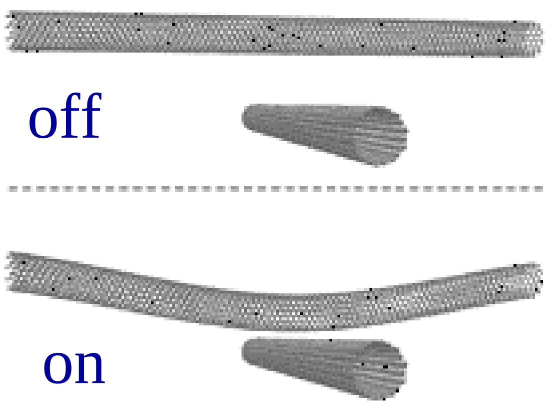
H. Dai, et al., *Science* 2000, *287*, 622.

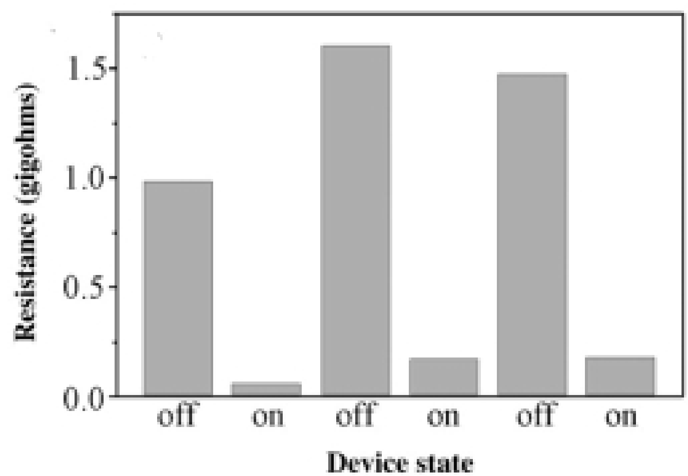


Single-Wall Carbon Nanotube Crosspoint Memory

- On - off state controlled by nanotube contact
- Hysteresis in both states
  - Off - Elastic restoring force
  - On - van der Waals attractive force
- Crosstalk and addressing are still problems

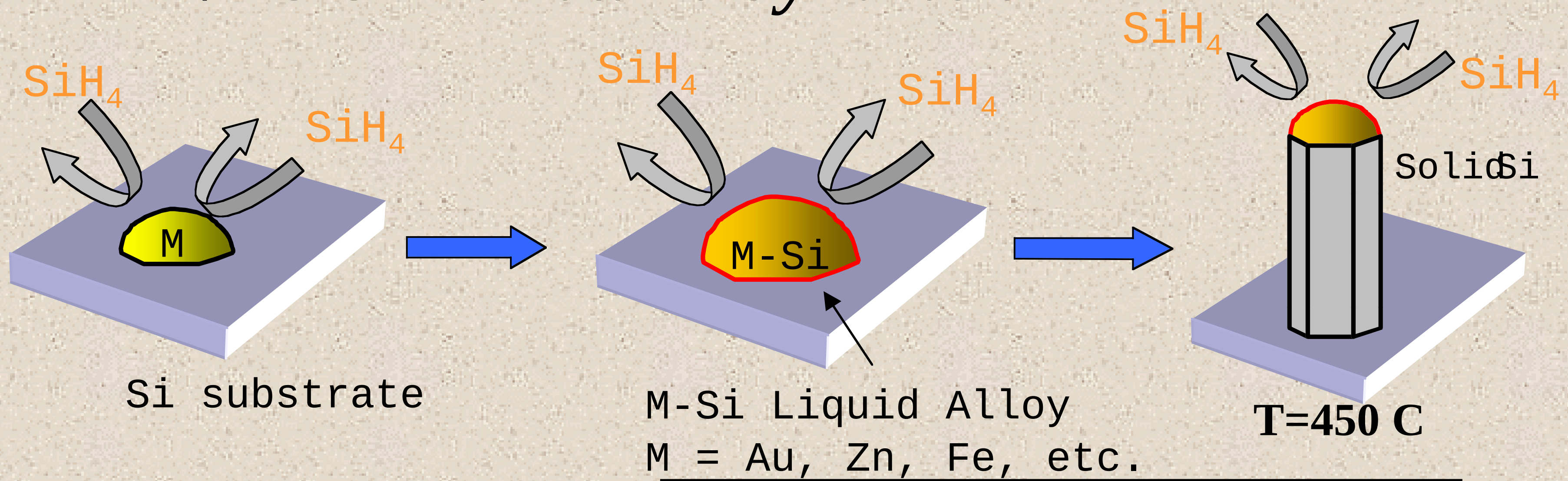


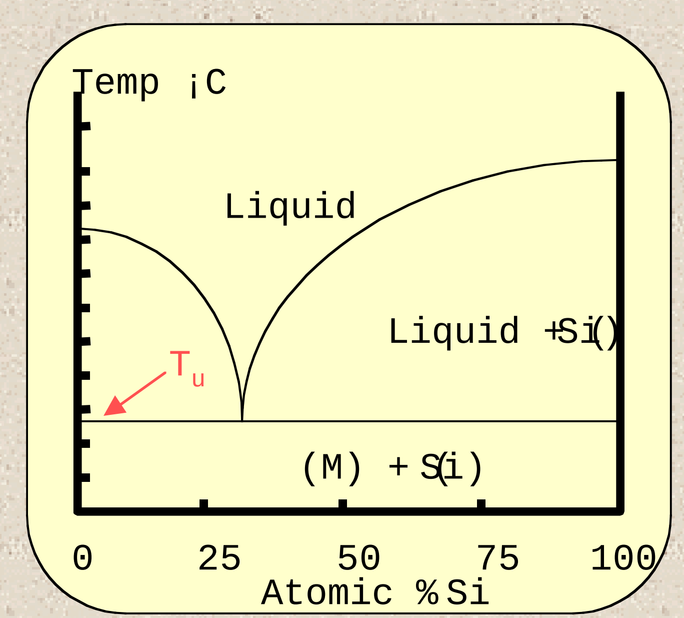


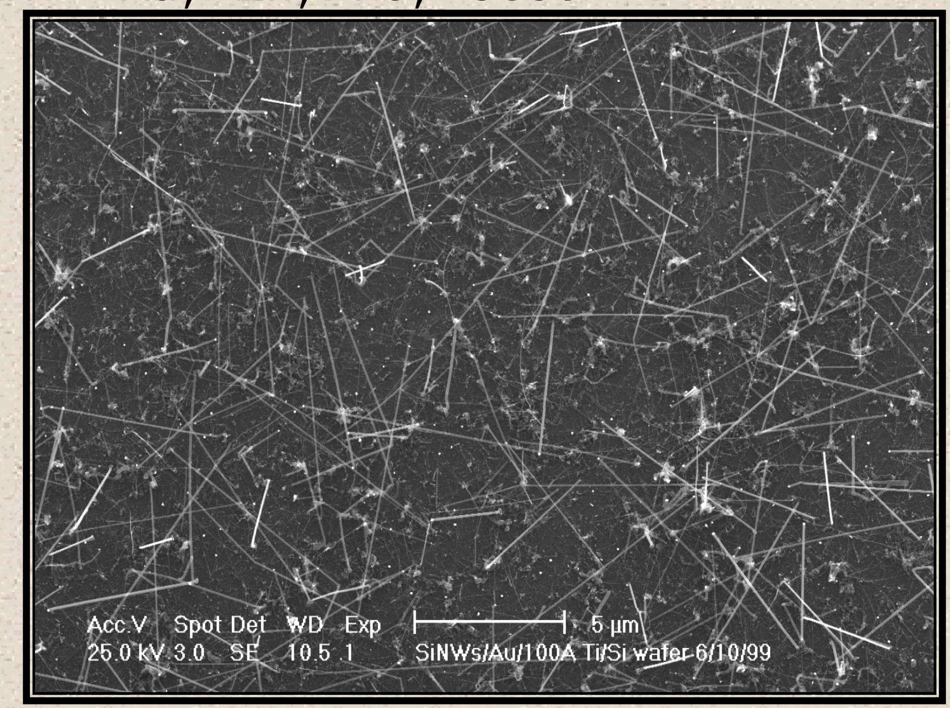


C. Lieber, et al., *Science* 2000, *289*, 94.

VLS Si Nanowire Synthesis

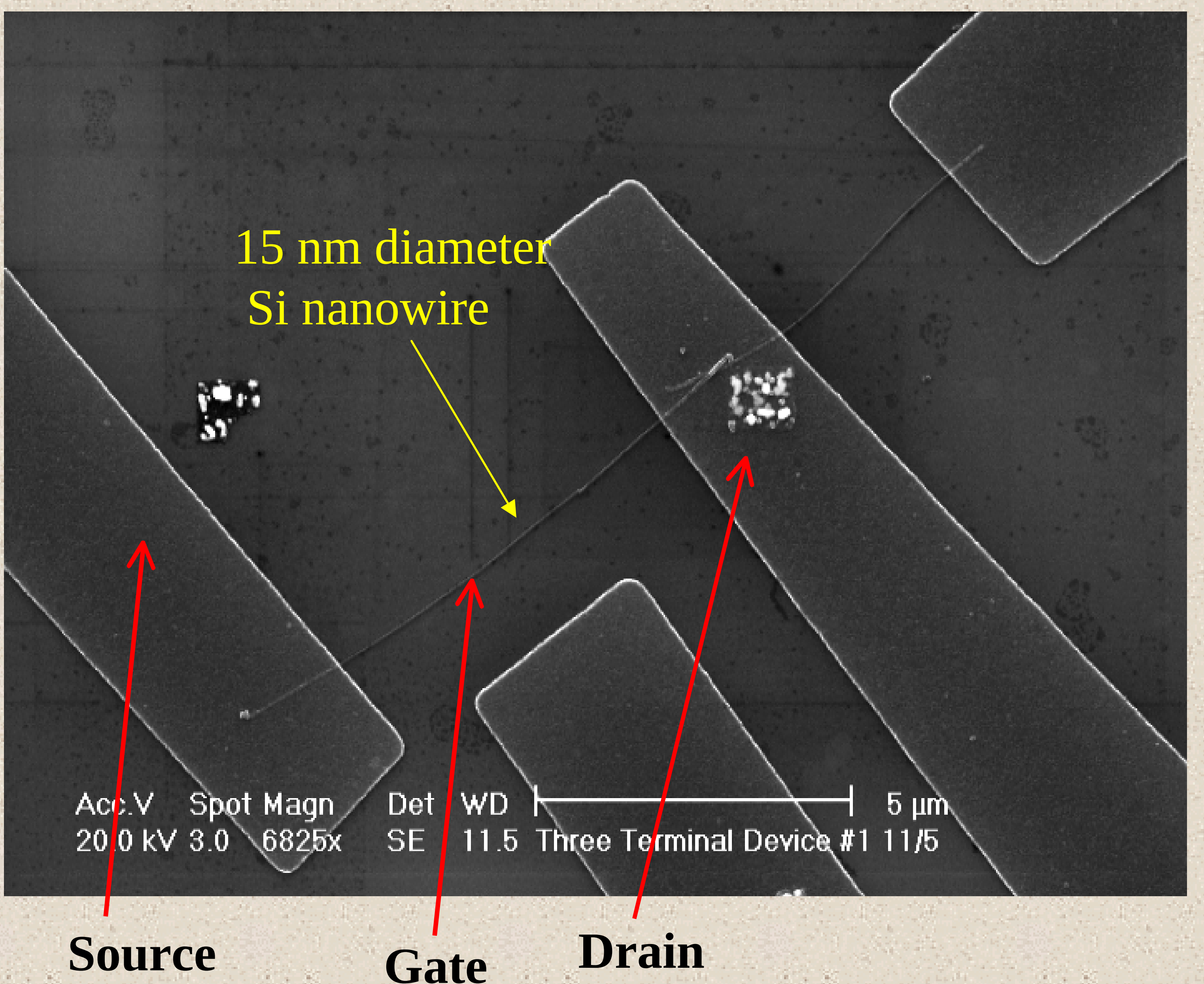






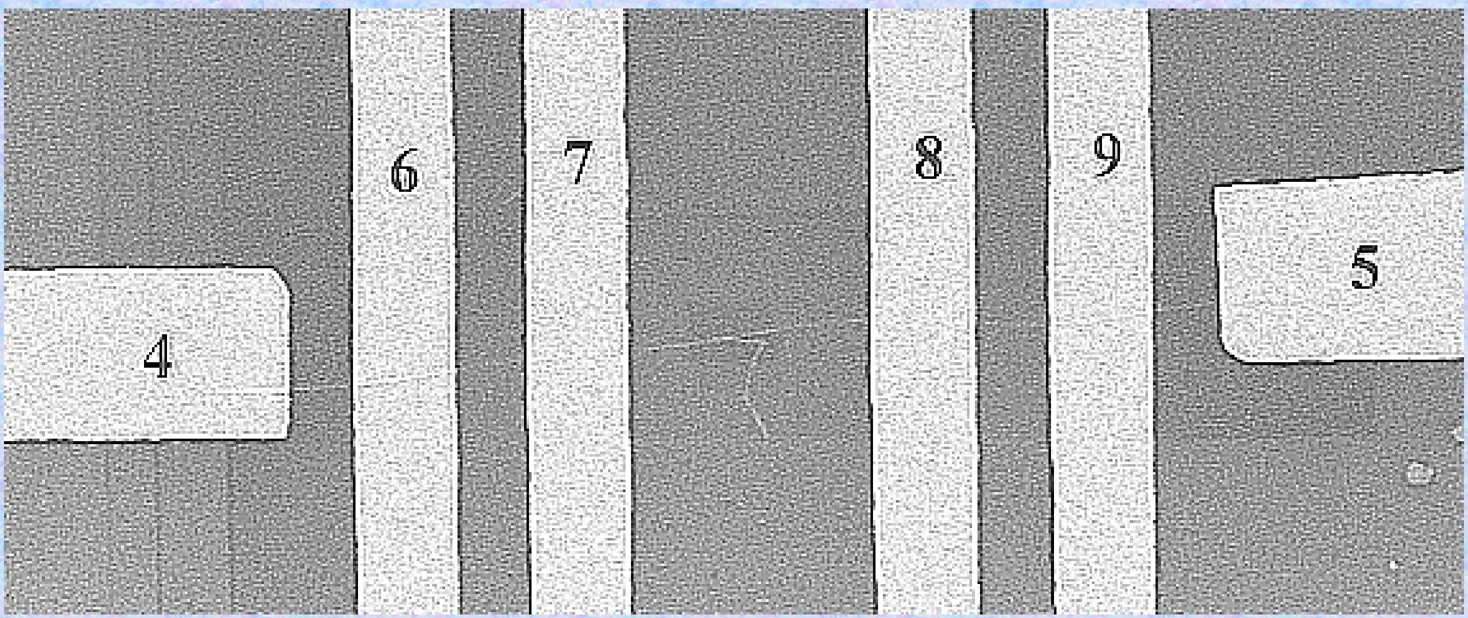
Heath (CPL;1992); Morales & Lieber (Science;1998); Chung, Yu & Heath (APL; 2000)

Si Nanowires: Three Terminal Devices



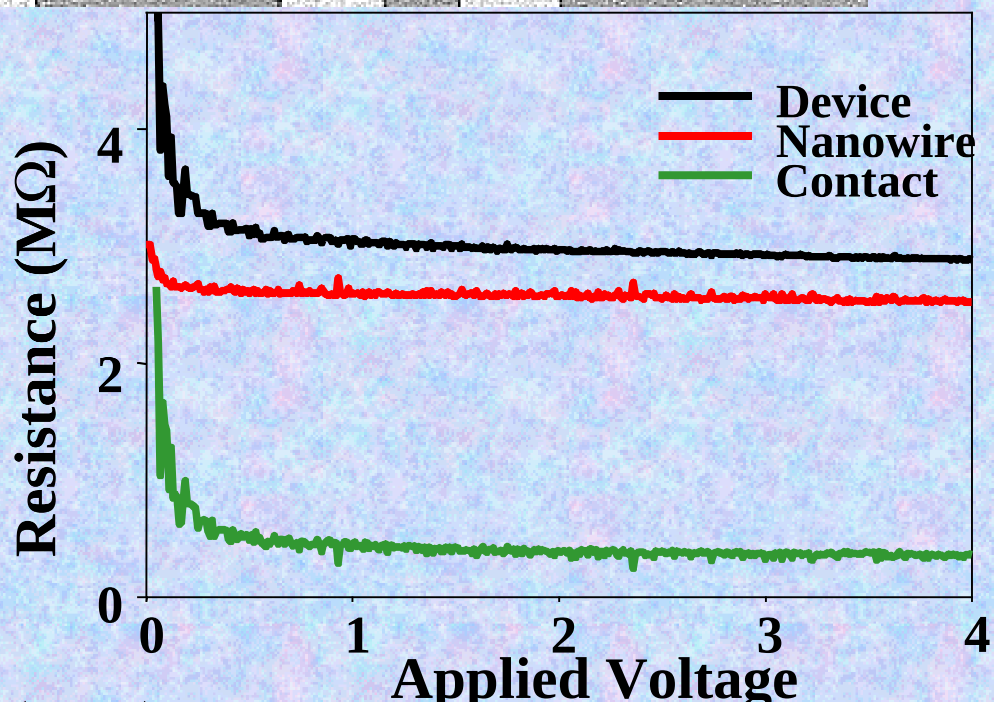
S.W. Chung, J. Yu, J. Heath (1999)

6-Terminal Measurement on 10 nm diam. Au-SiNW



μAmps of Current

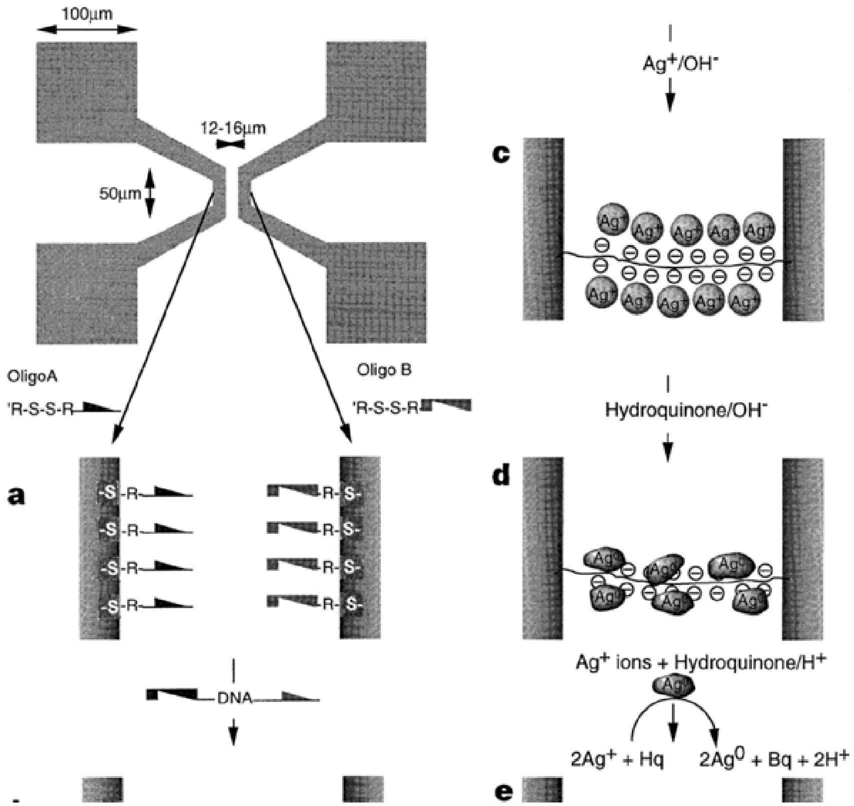
- Ohmic Contacts
- Doped from VLS metal particle

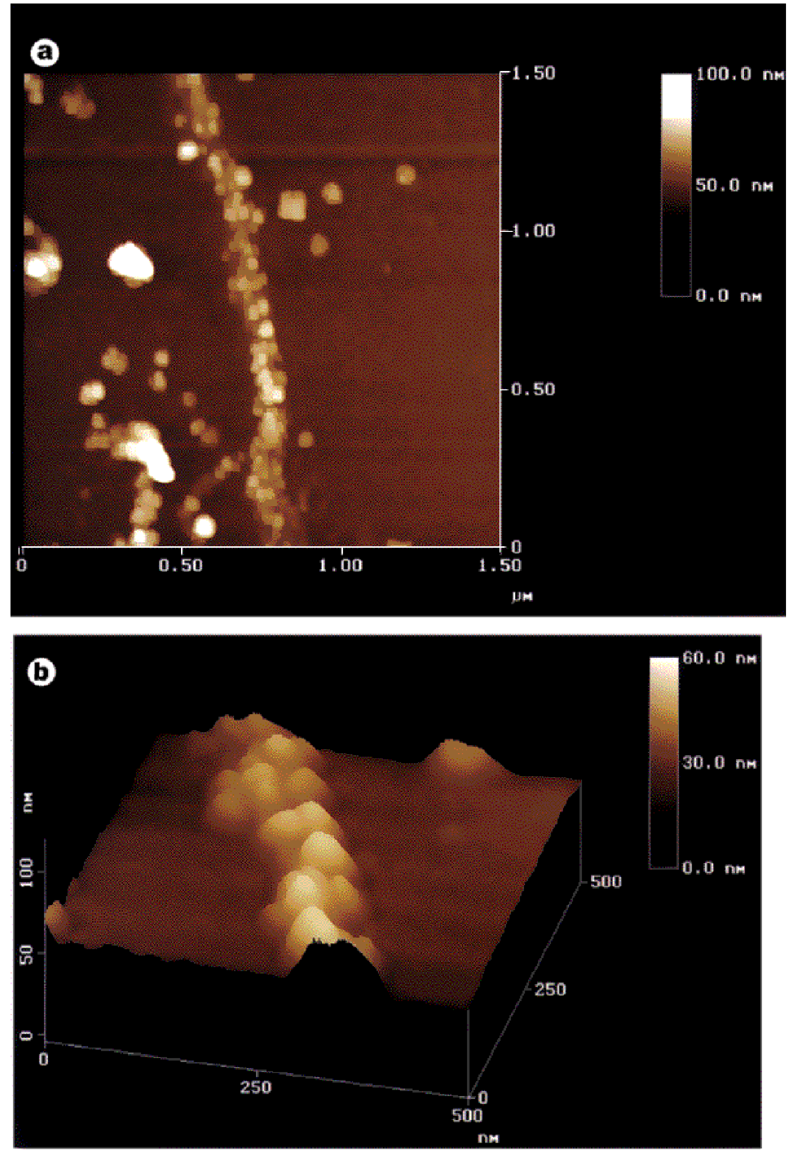


J. Yu, S.W. Chung, Heath Appl. Phys. Lett. (4/2000)

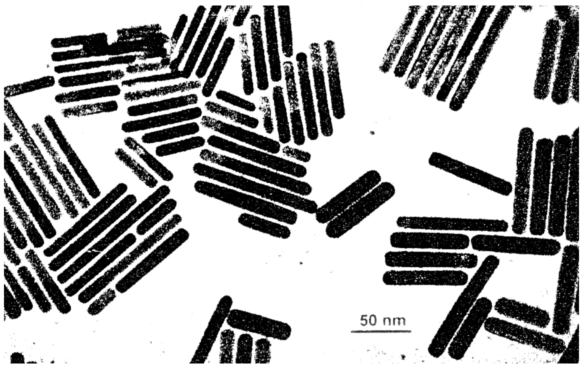
Electroless deposition of 100 nm dia. Ag “wires” on DNA strands

E. Braun, et al., *Nature* **1998**, *391*, 775.





Template synthesis of metallic nanowires

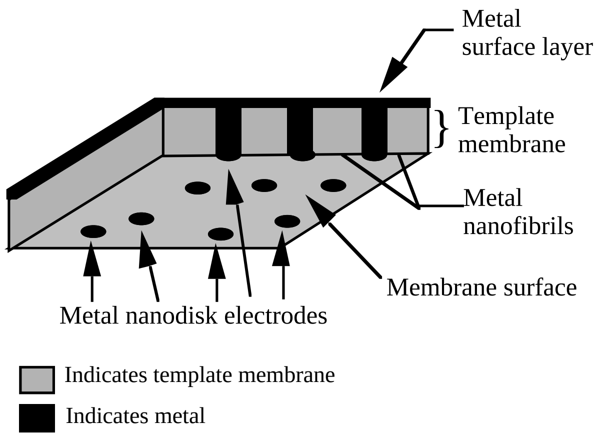


Electrochemical synthesis of Au rods in micelles

C. R. C. Wang, et al., J. Phys. Chem. 101, 6661 (1997).

Electroless plating of phospholipid tubules

J. M. Schnur, et al., Thin Solid Films 152, 181 (1987).

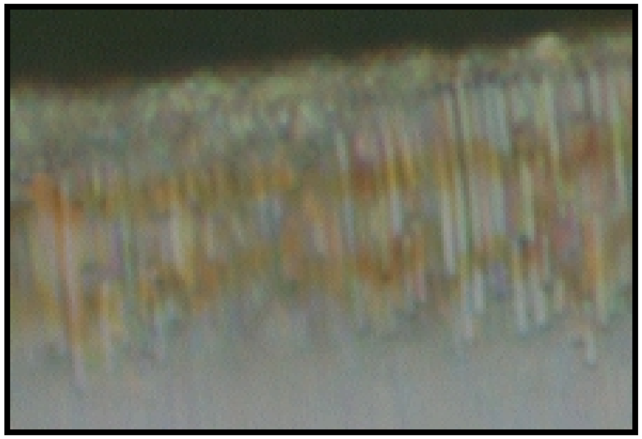


Replication of polycarbonate and alumina membranes

C. K. Preston and M. Moskovitz, J. Phys. Chem. 97, 8495 (1993).

C. R. Martin, Chem. Mater. 8, 1739 (1996).

Template synthesis of “striped” nanowires



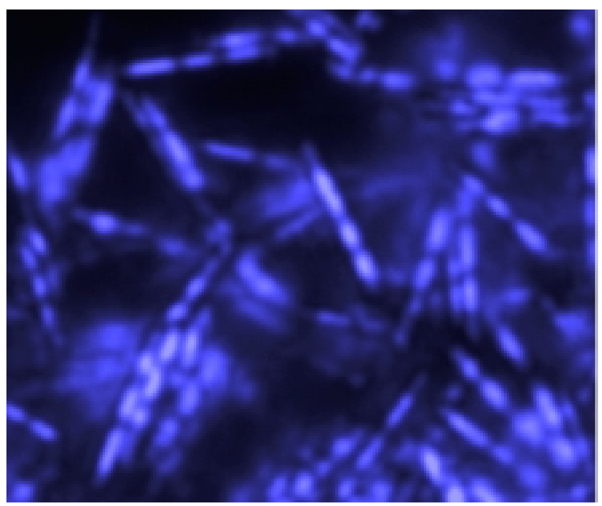
5-stripe Au-Ag rods in membrane

Monodisperse nanowires containing Au, Ag, Pt, Pd, Ni, Co, Cu, Pb, Sn, Se segments fabricated by electrochemical replication of porous membranes

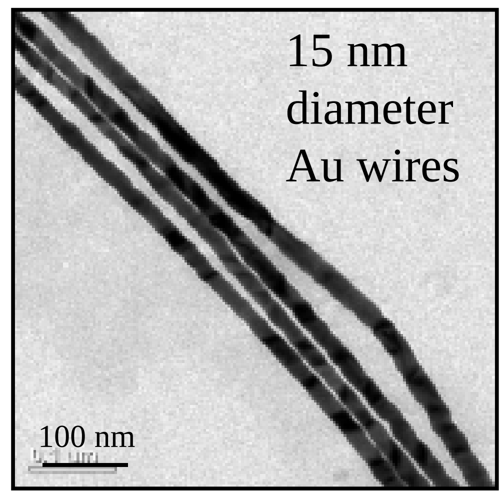
– 60 nm -10 µm long, 15 - 200 nm diameter
– Sequence of stripes controlled by electroplating and self-assembly
– 10^8 - 10^9 wires per membrane

Base etch

Red-filtered optical image



← 5 µm →

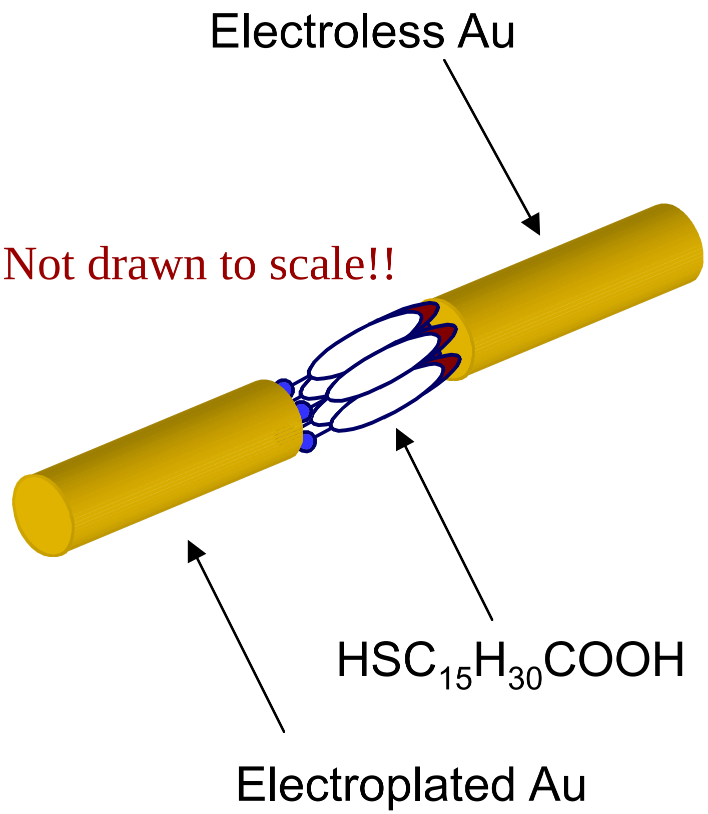


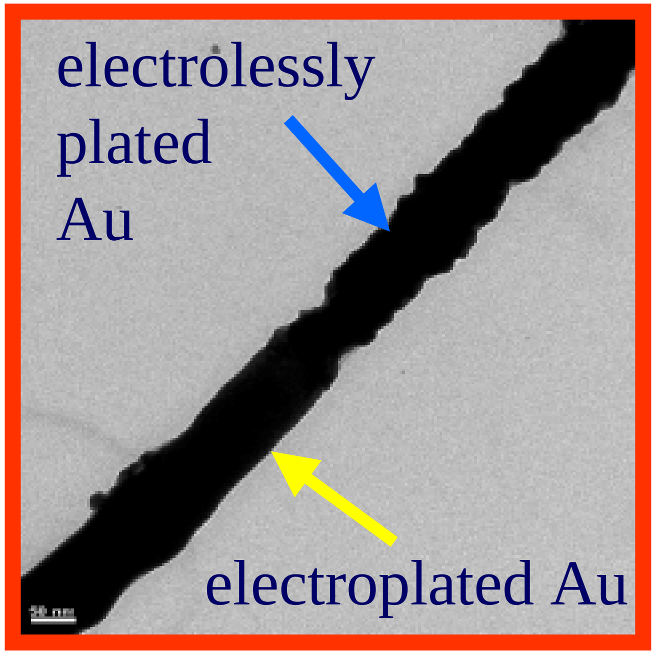
Au-CdSe-Au (~3:1:3 μm) rods with hexane-dithiol adhesion layer between Au and CdSe.

David Peña
Jeremiah Mbindyo
Chris Keating

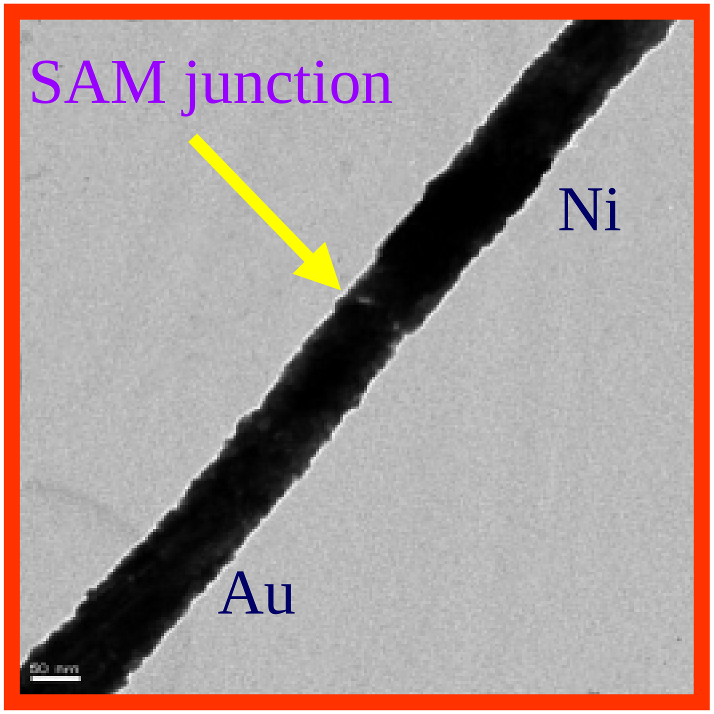
Monolayer Junctions

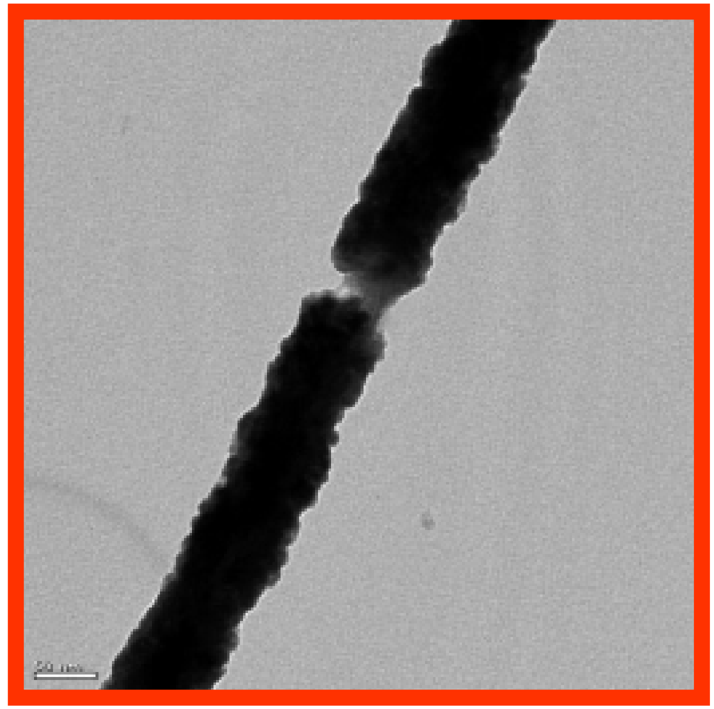
- Molecular junctions assembled in 70 nm diameter nanowires
  - Au / $HSC_{15}H_{30}COOH$ / Au, Ag, or Ni





Monolayer Junctions

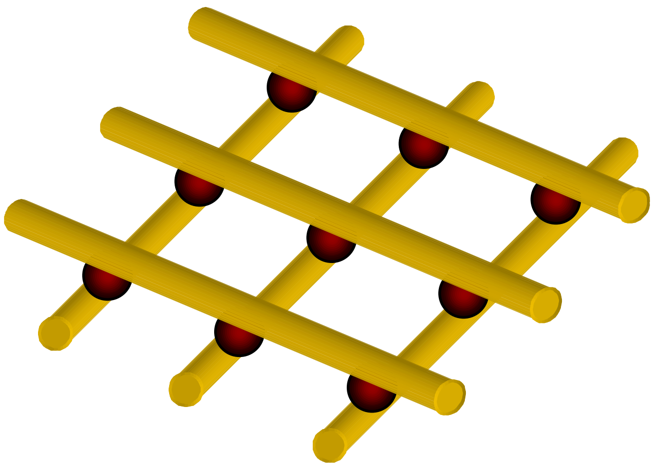




Differential expansion of Au and Ni, under the intense electron beam, reveals junction details

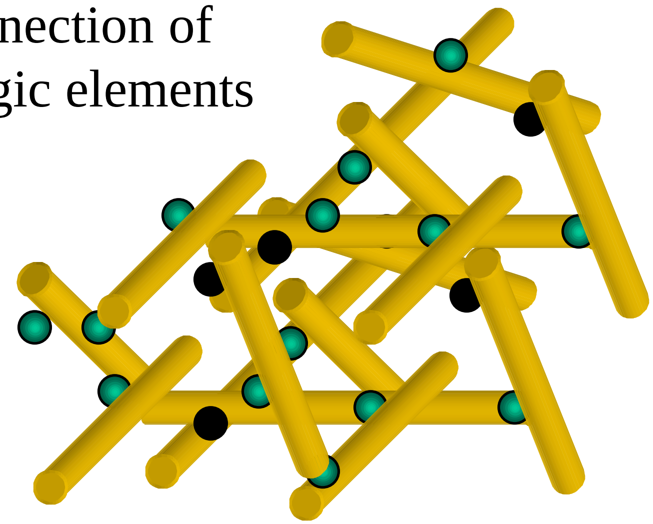
Connecting Molecular-Scale Devices

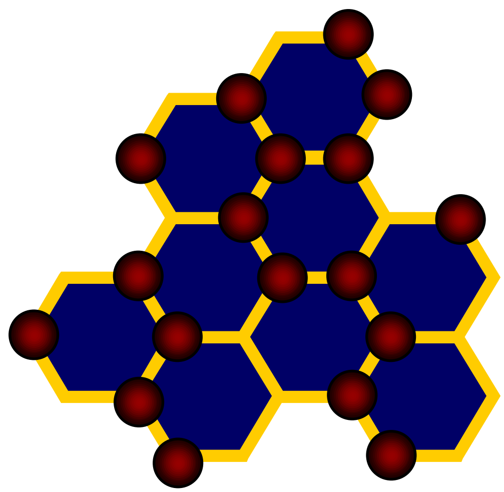
- Robust connection strategies are needed for assembling molecules and nanoparticles into functional circuits



Periodic crossbar array of wires and memory elements

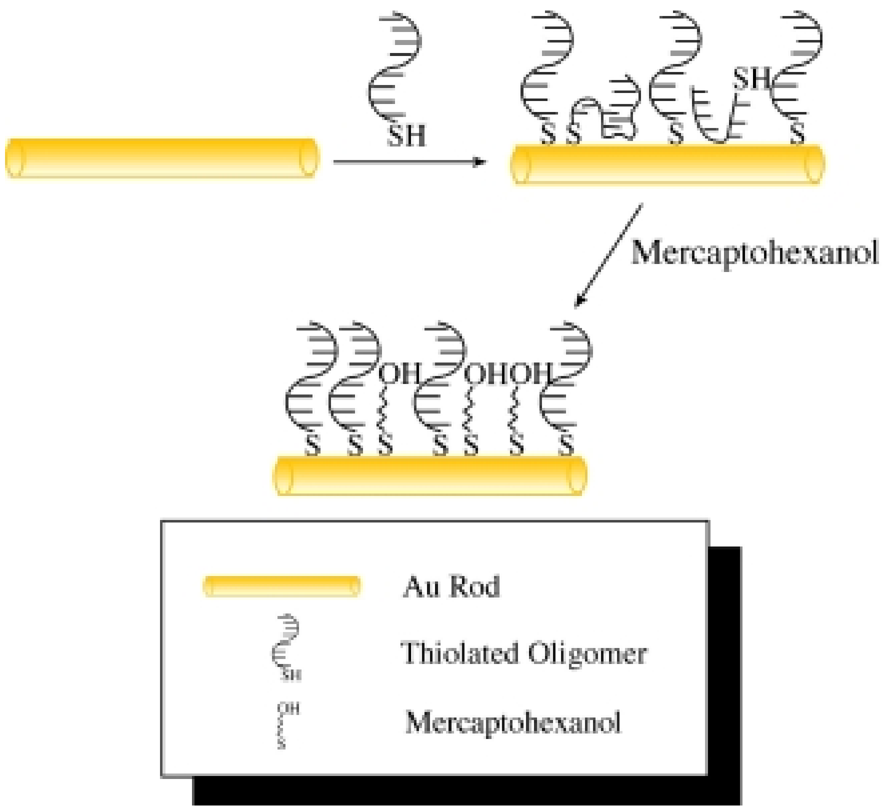
Random connection of wires and logic elements





Disordered circuit elements on a periodic wire grid

DNA Monolayers on Au Nanowires



Surface Coverage of 36-mer Oligo

Thiol-tagged ~1 x 10^{13} oligos/cm^2

W/out thiol ~1 x 10^{12} oligos/cm^2

After treatment with $HS(CH_2)_6OH$

Thiol-tagged ~7.9 x 10^{12} oligos/cm^2

Hybridization efficiencies

Thiol-tagged 63%

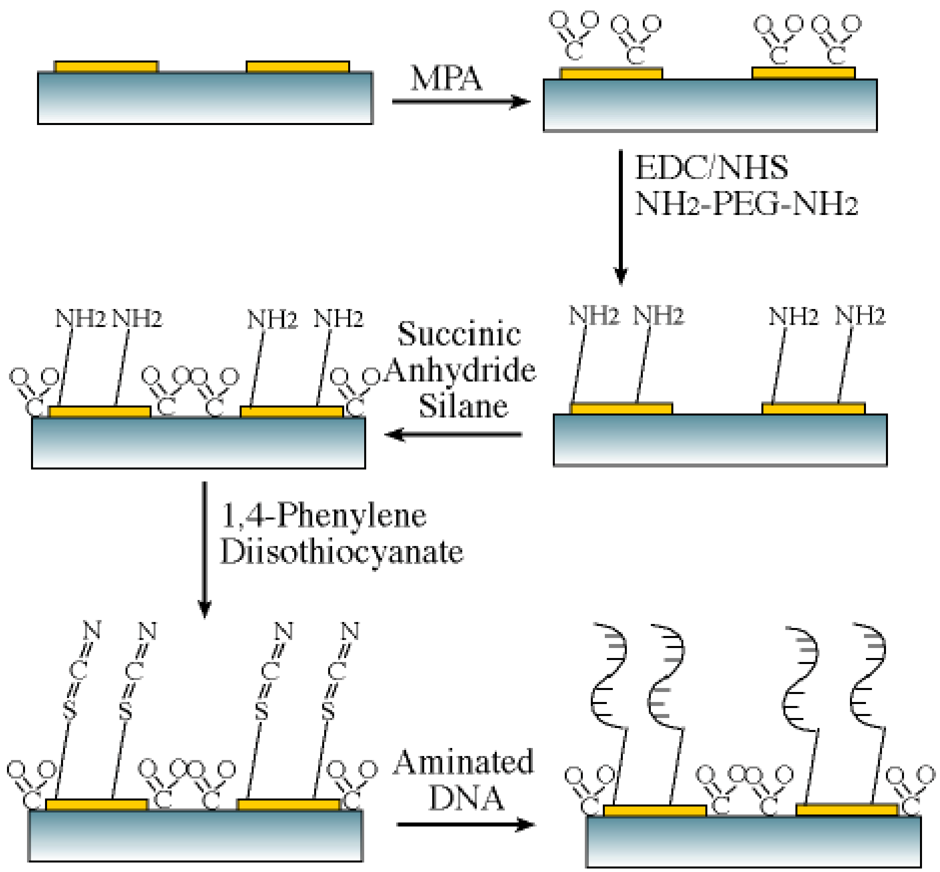
W/out thiol 21%

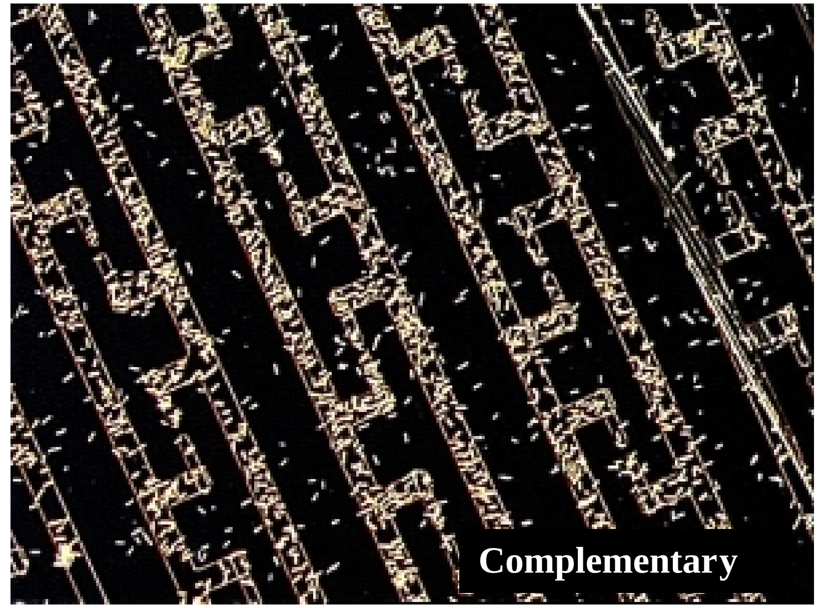
$$\theta = KC/1+KC$$

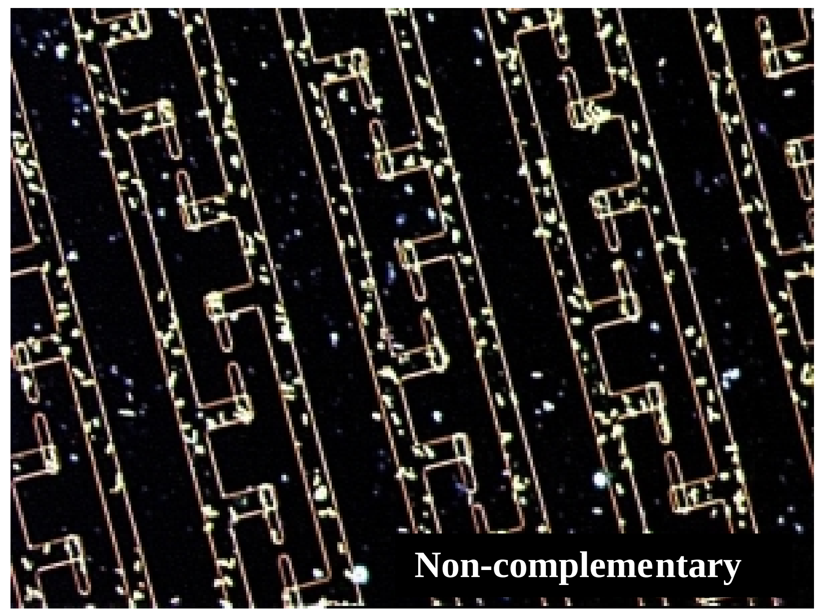
thiol: $K_{eq} = 1.8 \times 10^5\ M^{-1}$

nonthiol: $K_{eq} = 3.7 \times 10^4\ M^{-1}$

DNA linking of Au nanowires to complementary surfaces

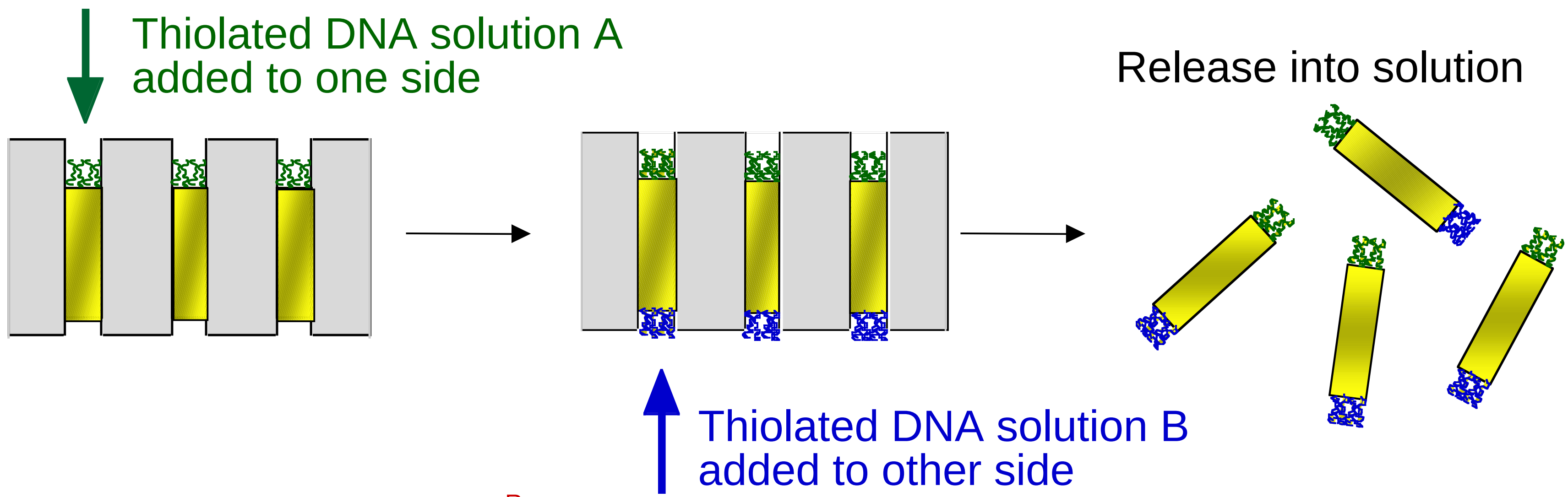


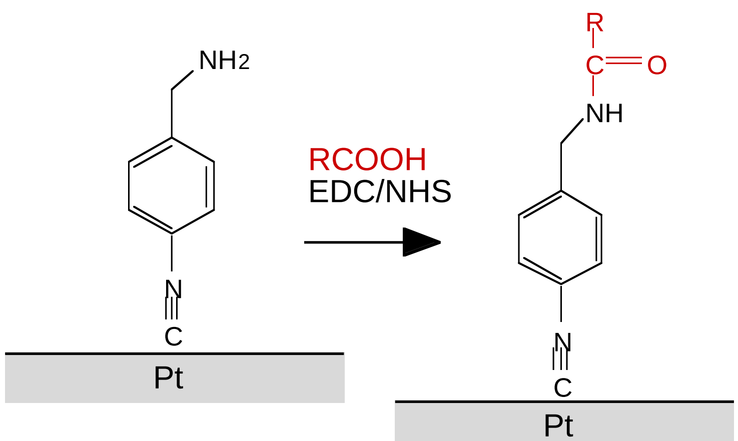




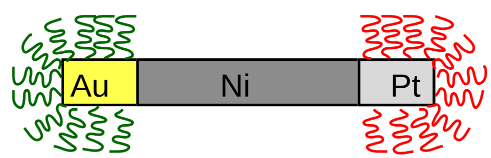
Brian Reiss
Chris Keating
(Penn State)

Orthogonal DNA Assembly

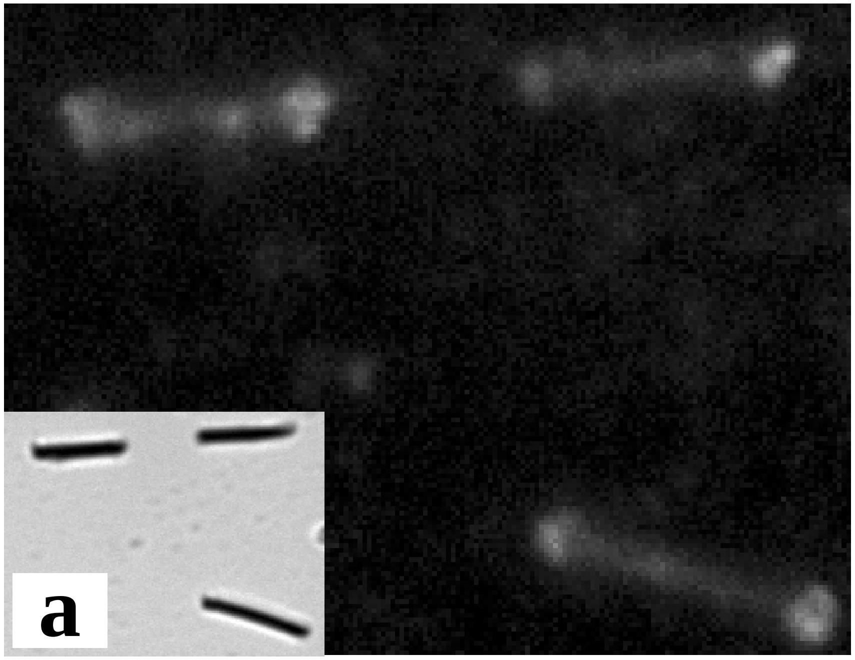




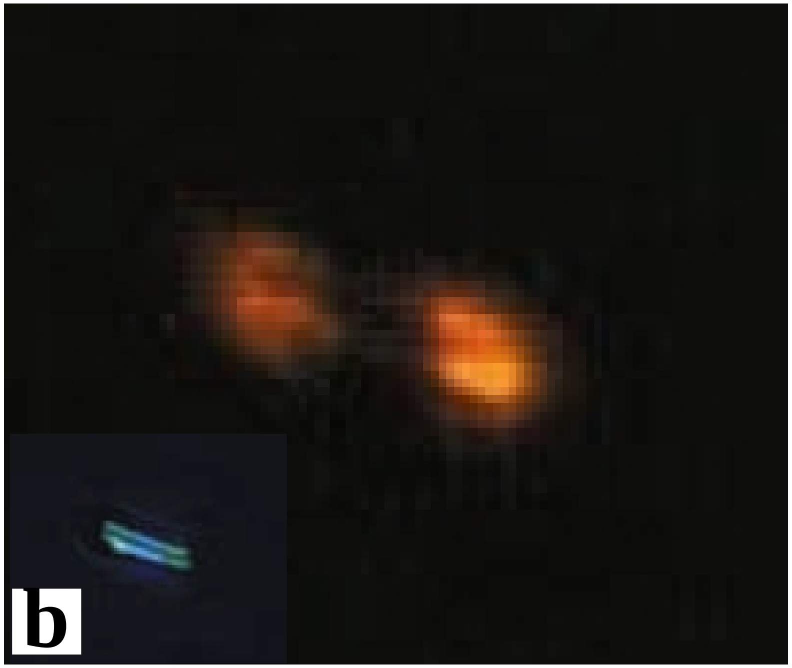
Expose Au/Ni/Pt solution to isocyanide
Exchange isocyande with thiolated DNA **A**
Couple carboxylated DNA **B** to the isocyande



Au and Au-Pt-Au nanowires with DNA-modified tips

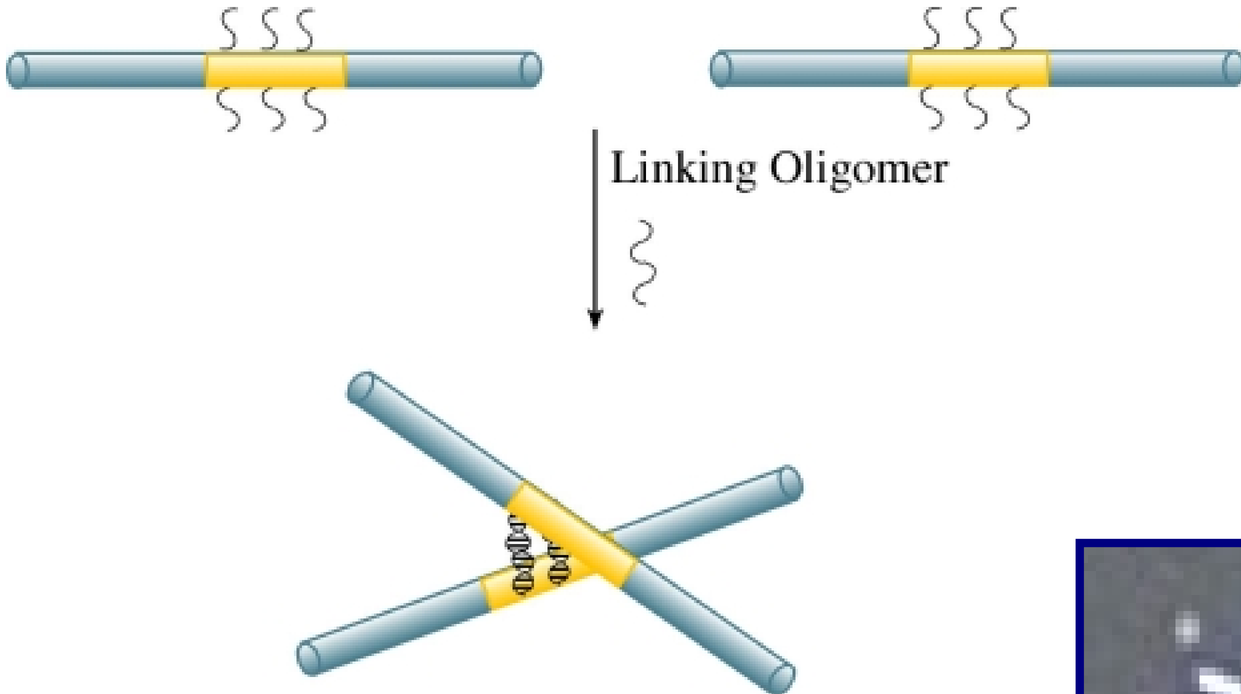


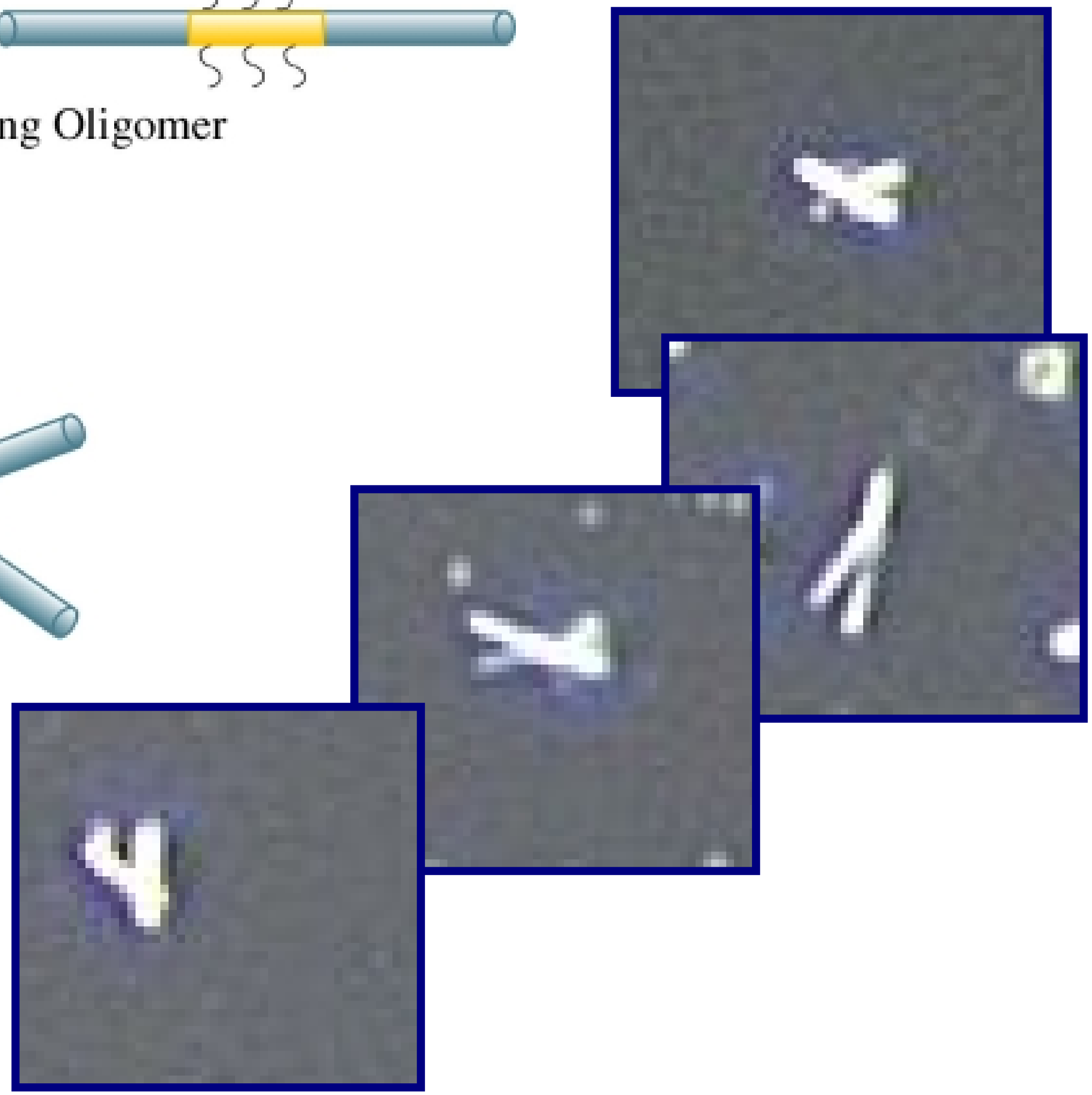
Au wires derivatized in membrane



Au-Pt-Au wires derivatized by orthogonal self-assembly

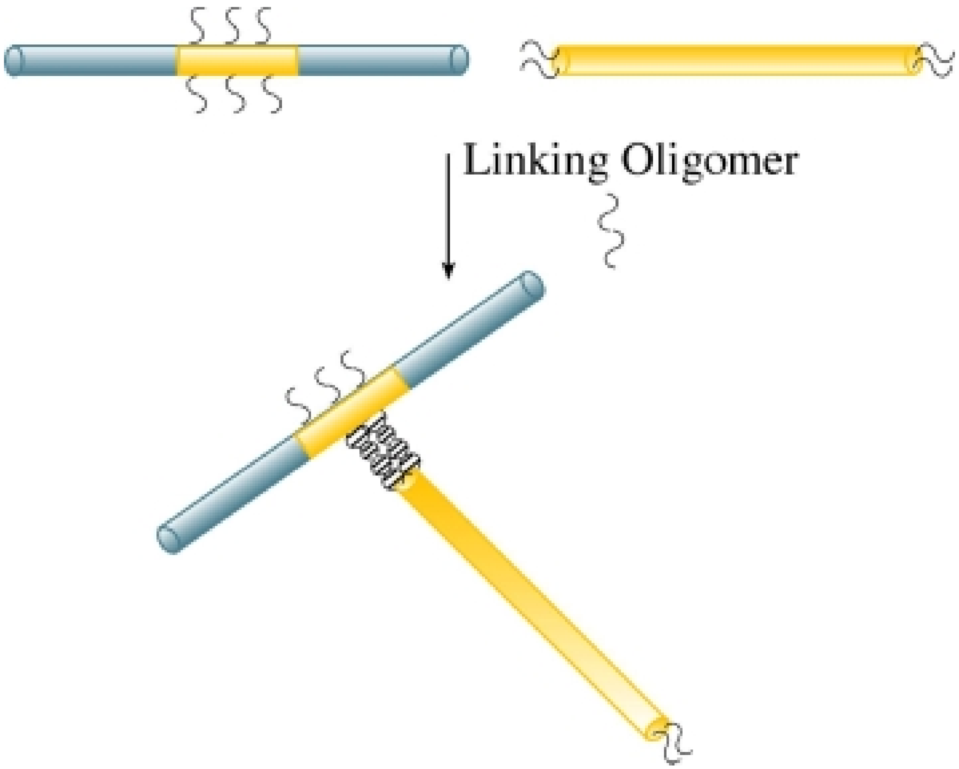
DNA-linked crossbars

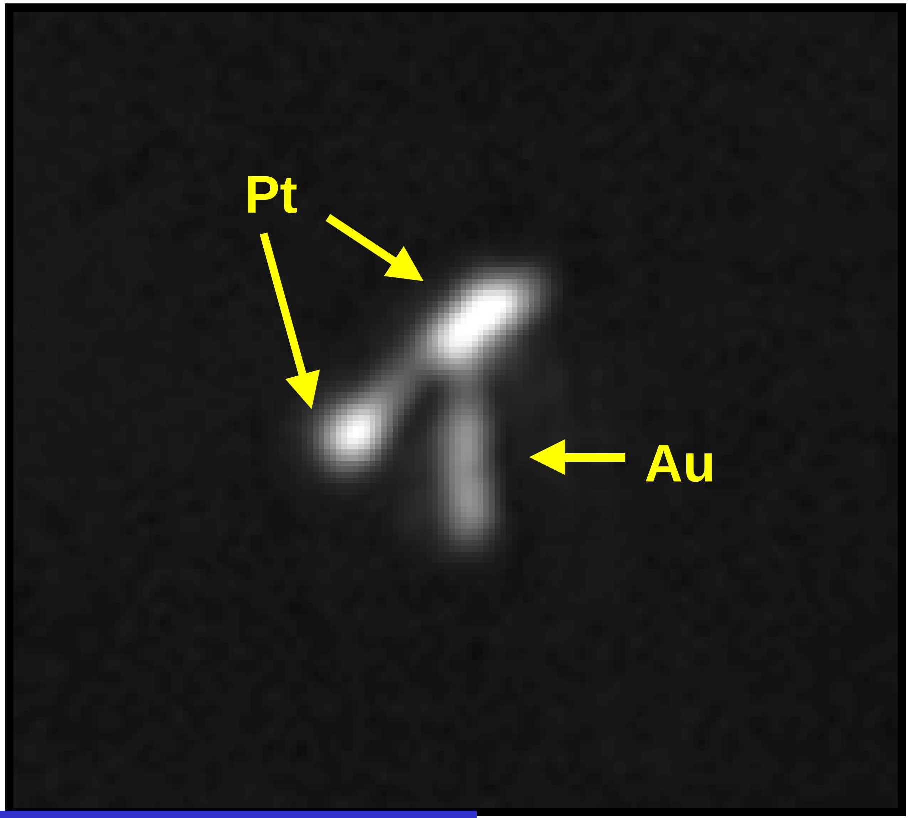




Brian Reiss
Chris Keating

DNA-directed T-assembly





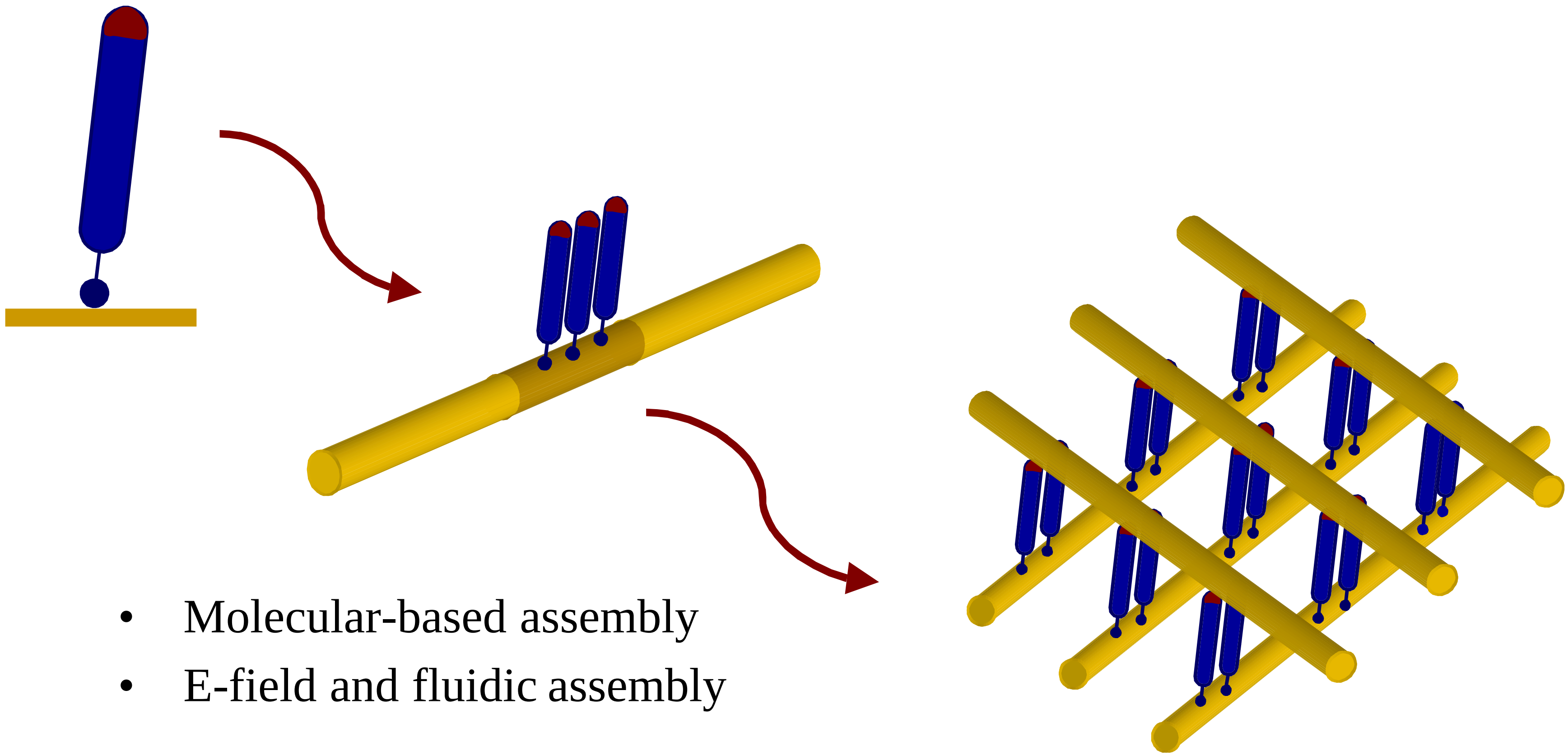
Brian Reiss
Chris Keating

52% of rods are in T's

27% in controls

Interfacing Nanoscale Circuits

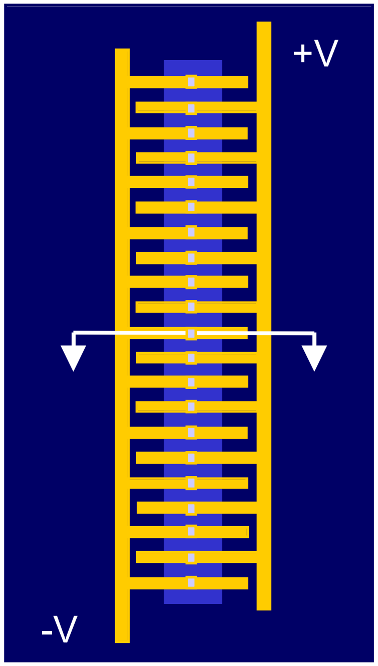
- Exploiting the power of molecular-scale devices also requires a suitable interface between the *nano* world and the *macro* world



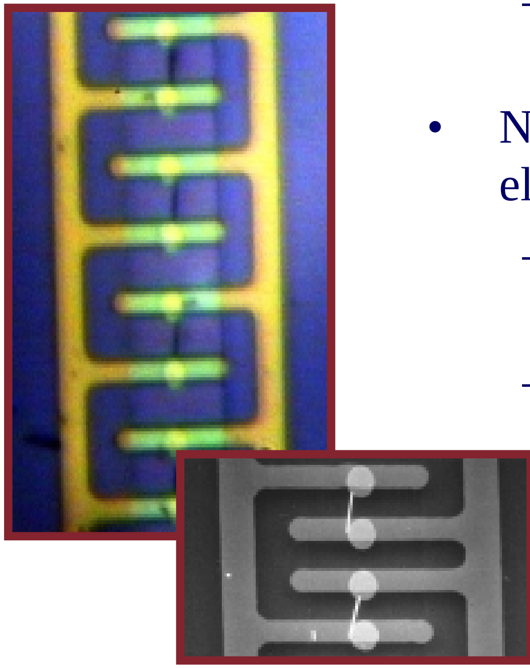
- Molecular-based assembly
- E-field and fluidic assembly

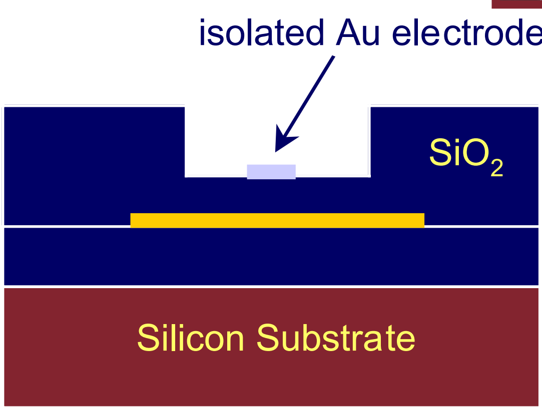
Electrofluidic assembly of nanowires

- AC electric field used to align nanowires
  - balances force due to net charge on the metallic nanowire
- Nanowires are attracted and aligned to electrically isolated electrodes
  - long-range force due to charge separation in metallic nanowires
  - short-range alignment due to capacitance maximization across isolated electrodes

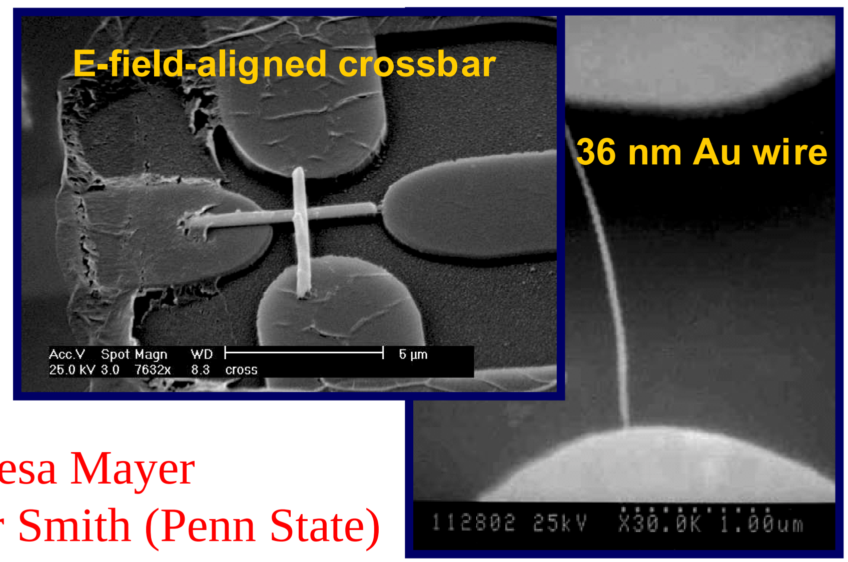


Top View



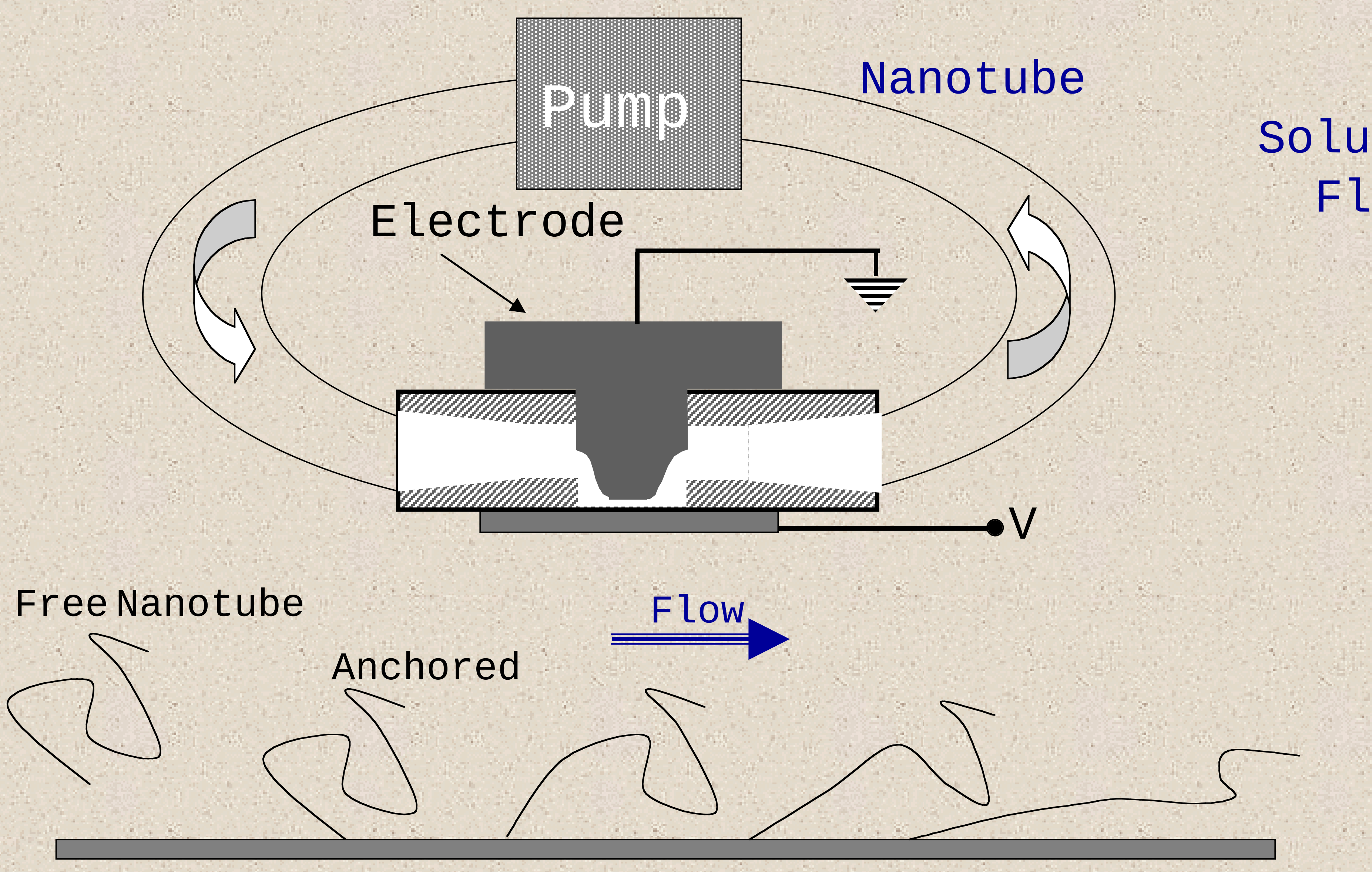


Cross Section



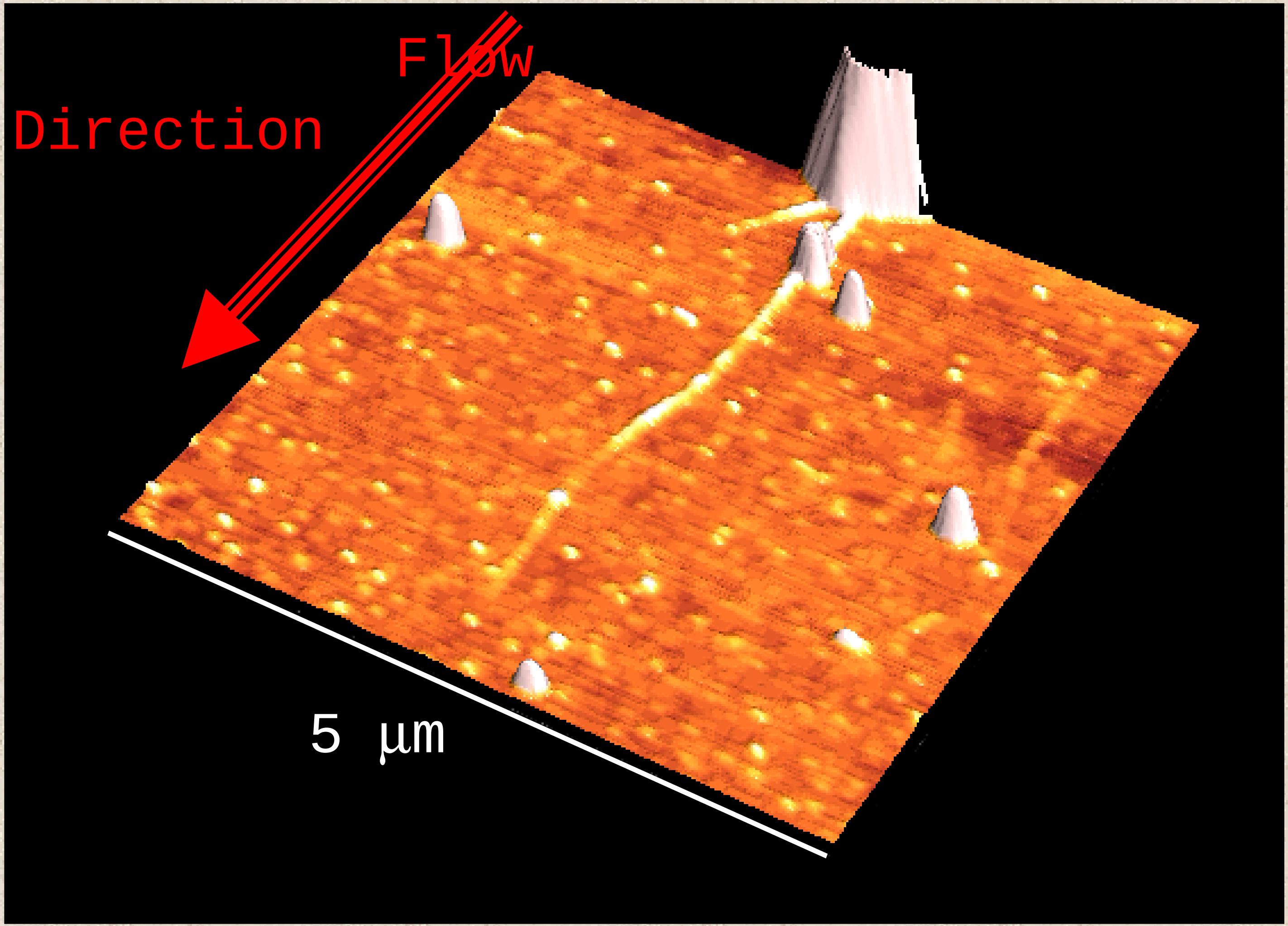
Theresa Mayer
Peter Smith (Penn State)

Electrochemical Flow Cell



Wong, Heath (2000)

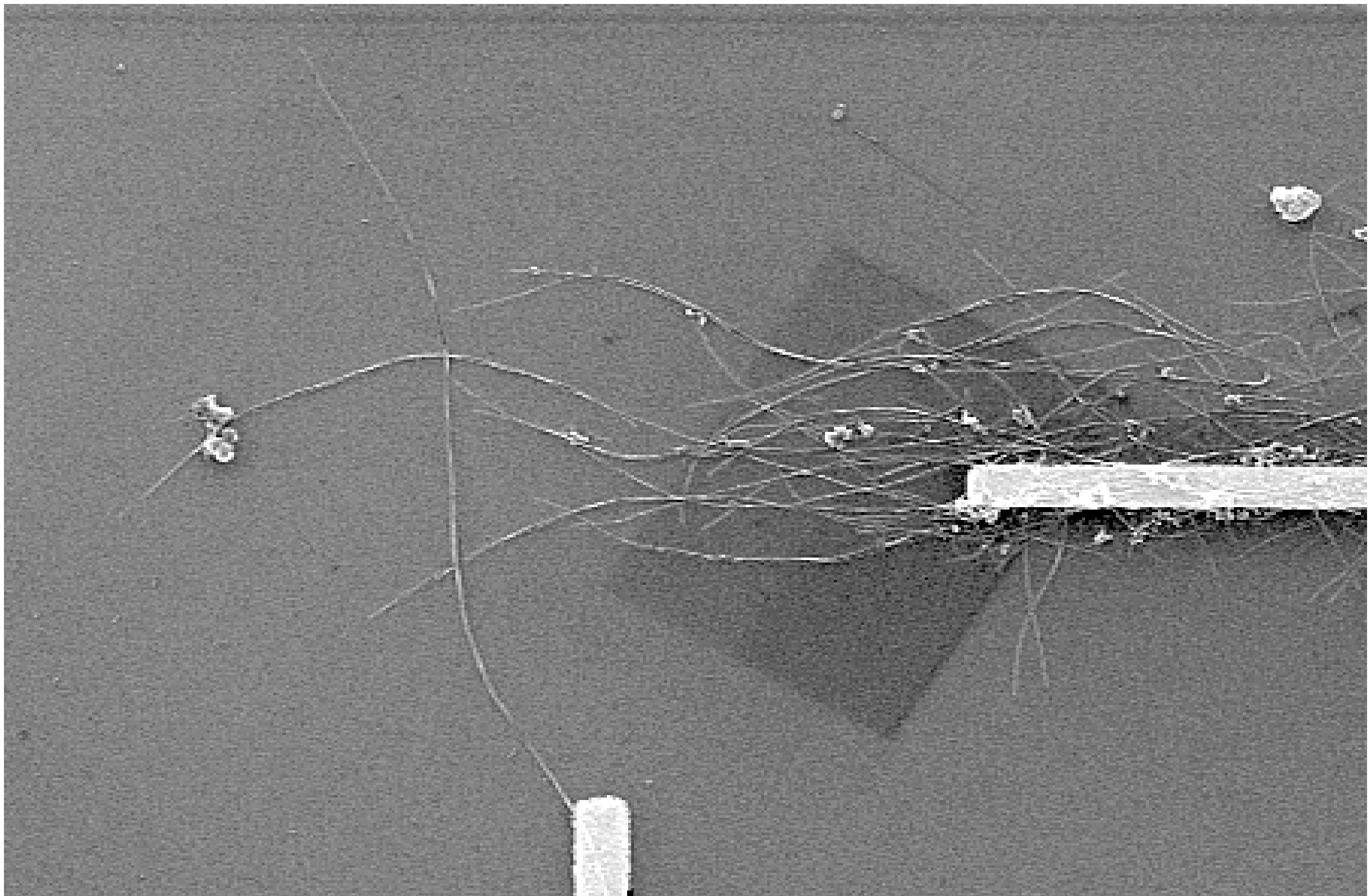
One Rope One Electrode



Bias=+2V Rate=1000 cm/sec Time=30 minutes

Diameter=1.8 nm

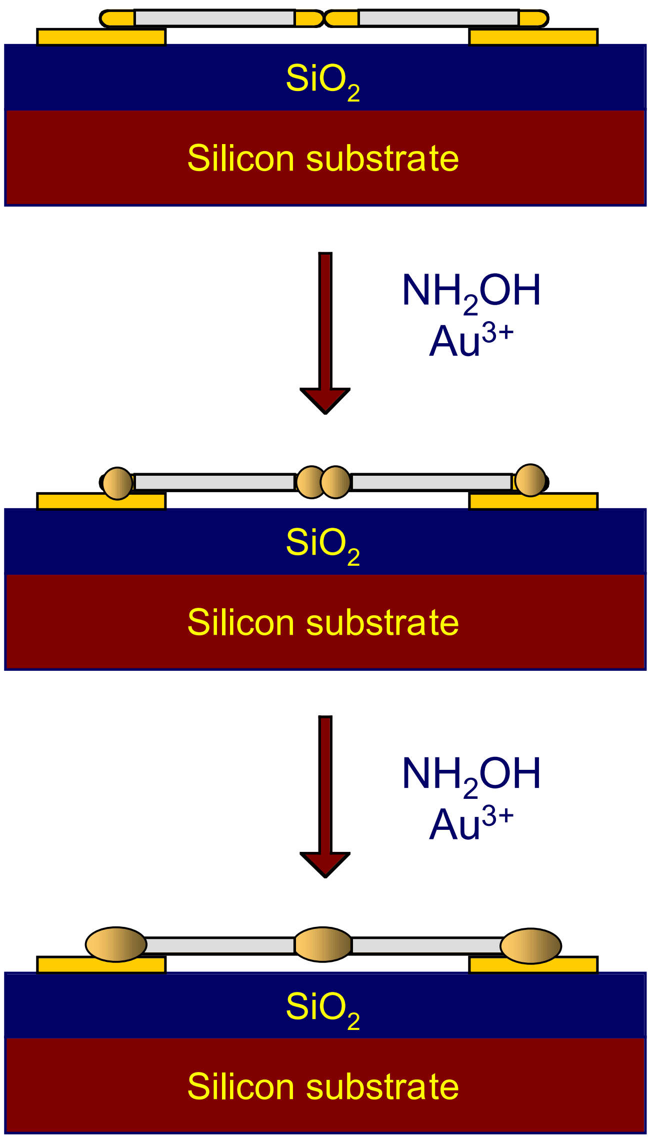
Fluidic Assembly of Single-Wall Nanotube Crossbars

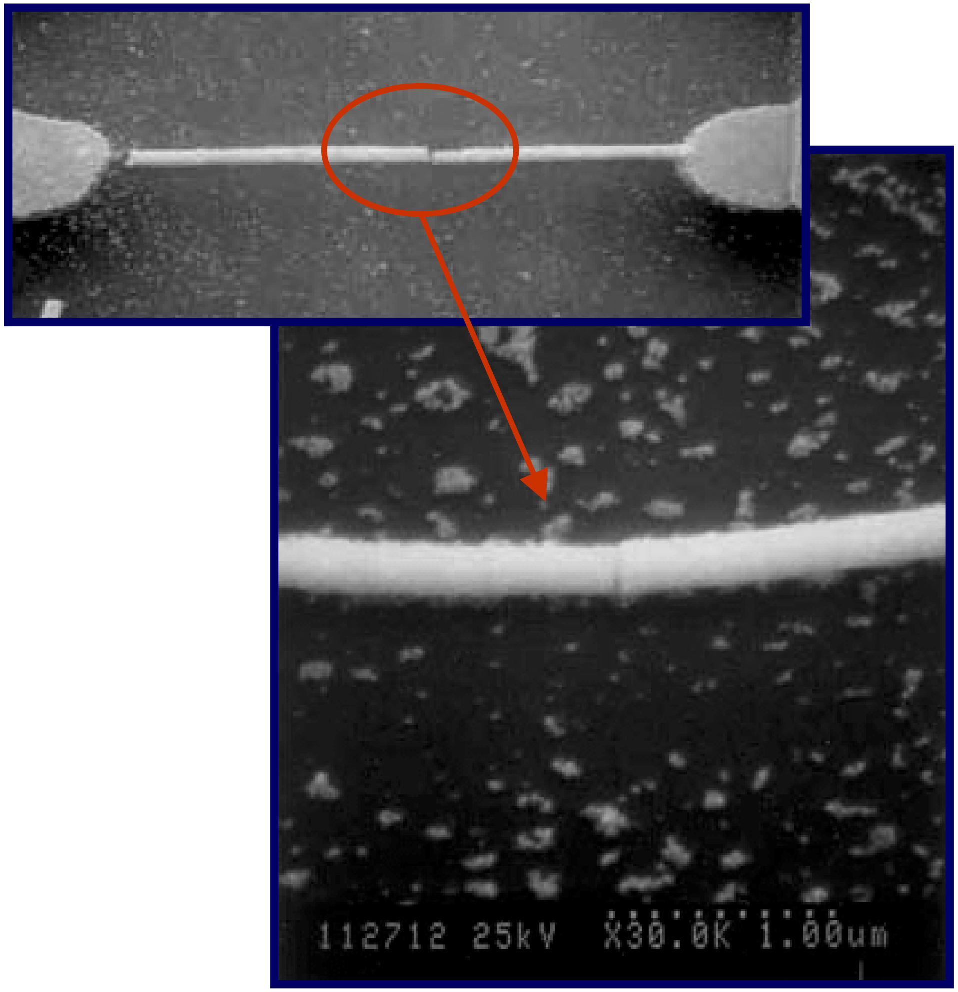


300 nm

Wong,Boukai, Heath
w/ Stoddart group SWNTs (2000)

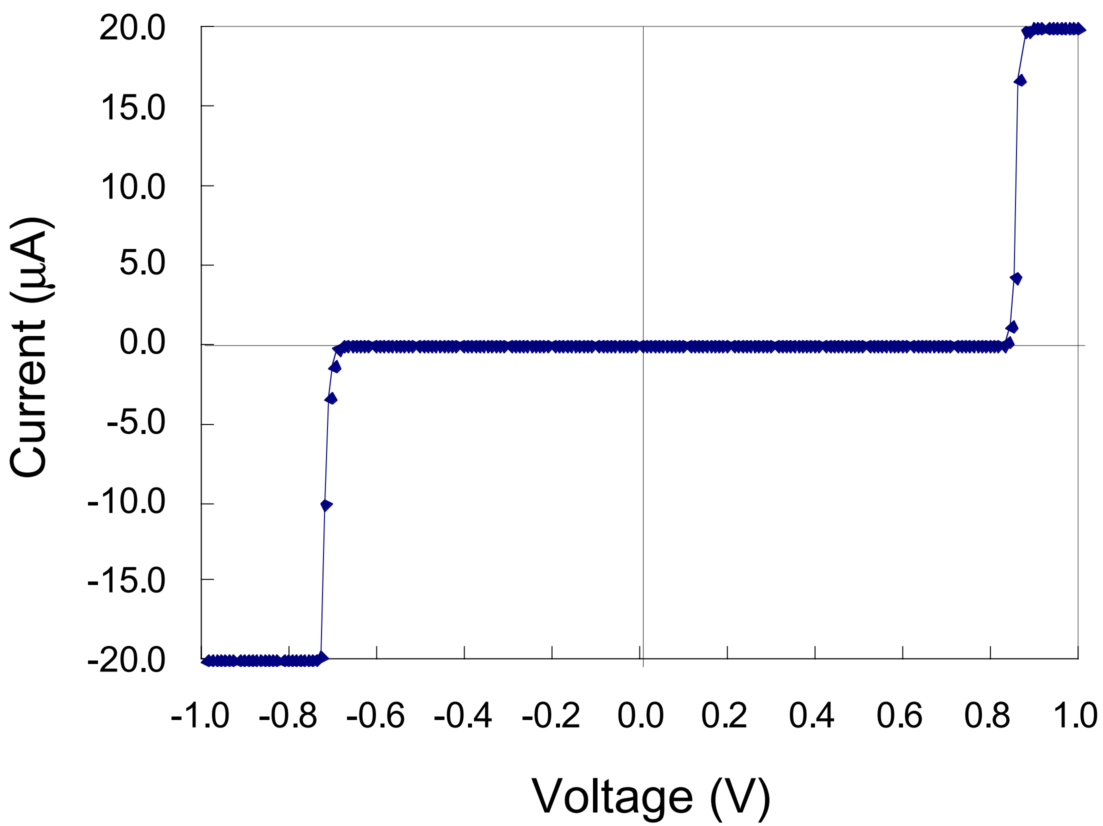
Electroless soldering of nanowires

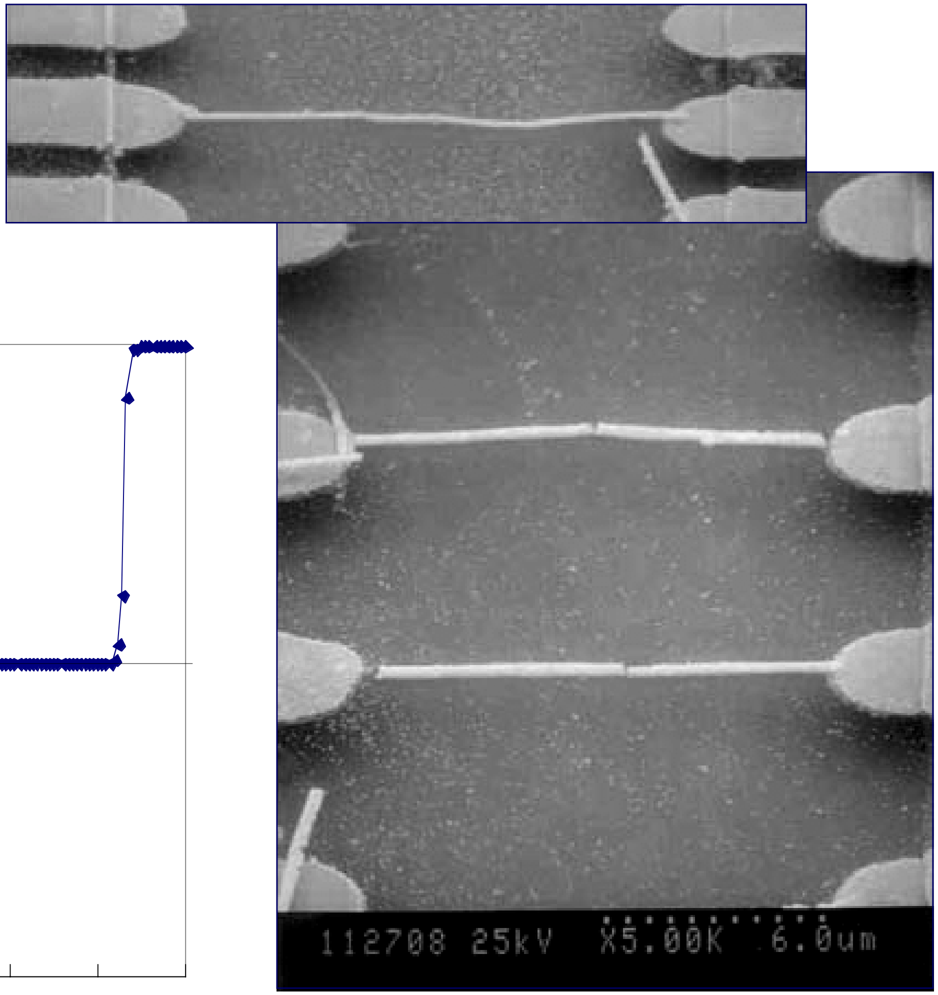




Dan Dermody, Ben Martin,
Chris Keating (Penn State)

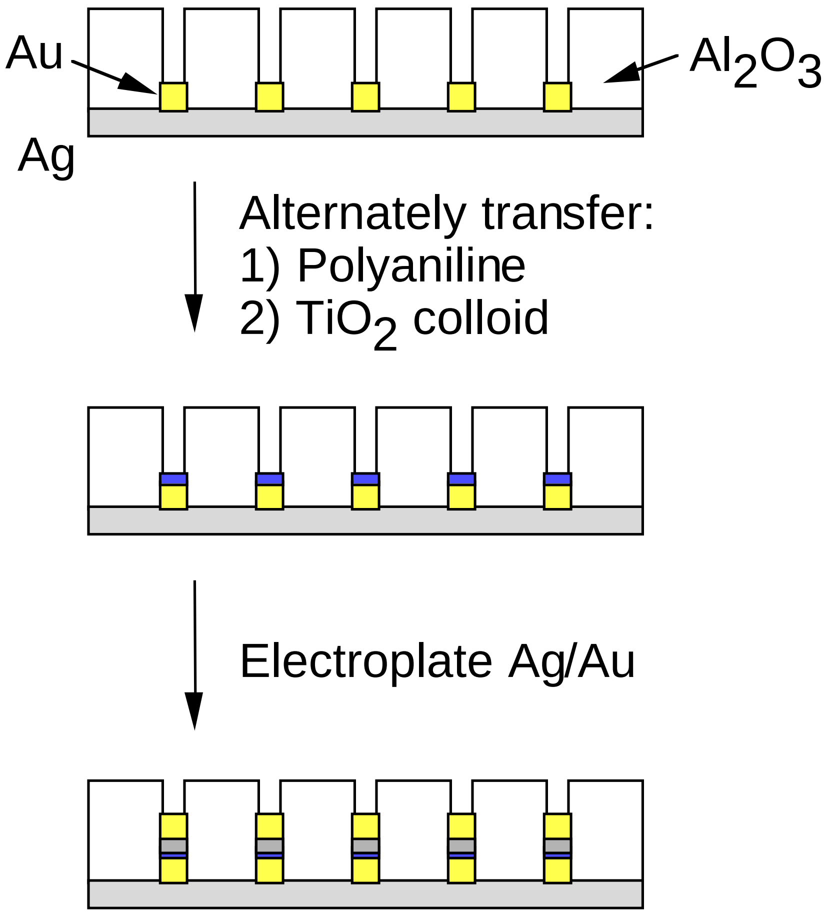
- Field assisted assembly can be used to form nanowires chains
  - Electroless plating used to lower junction contact resistance

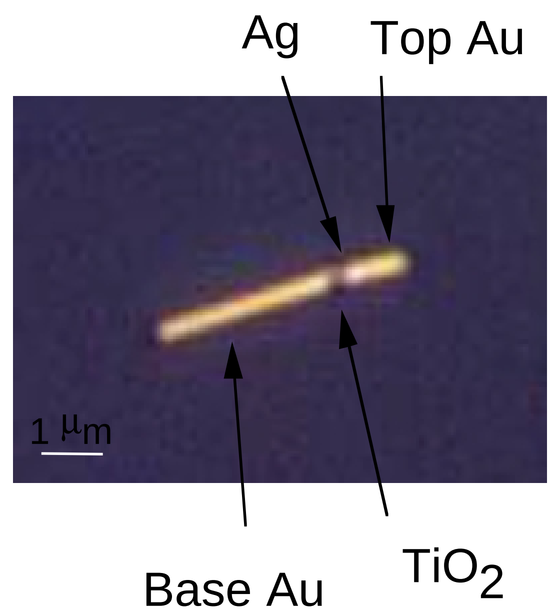




Nanowire Diode Synthesis

Electroplate Au in porous alumina

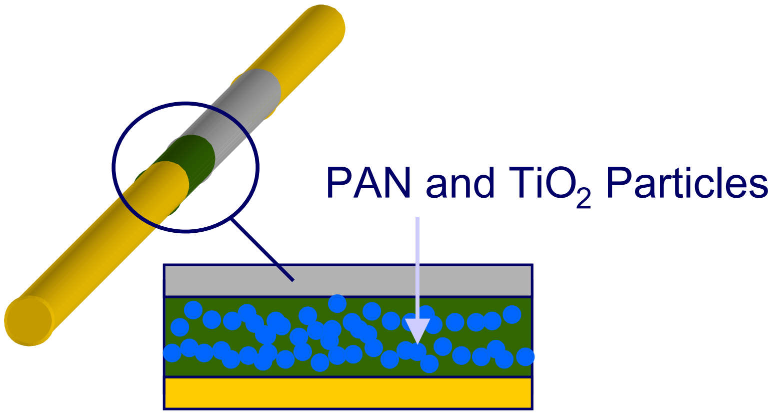


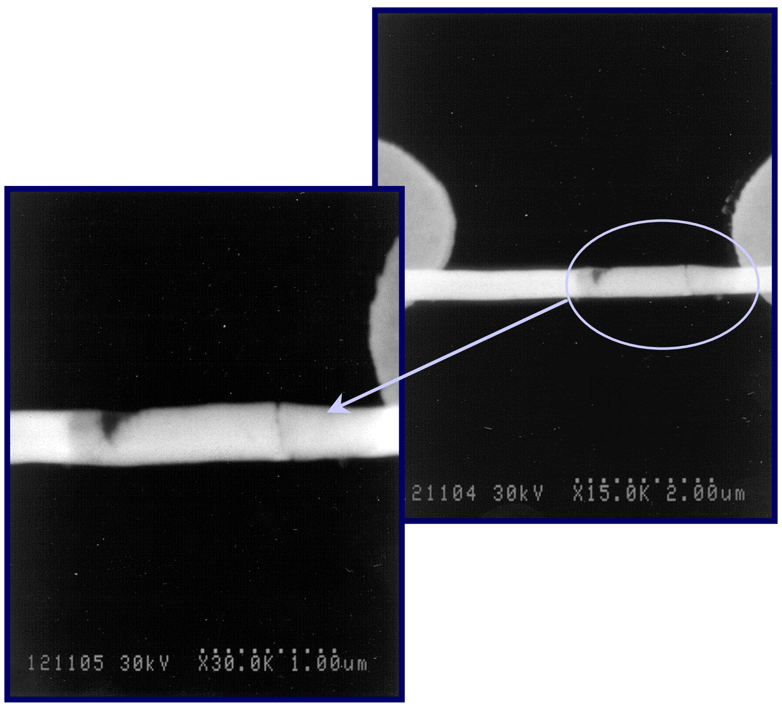


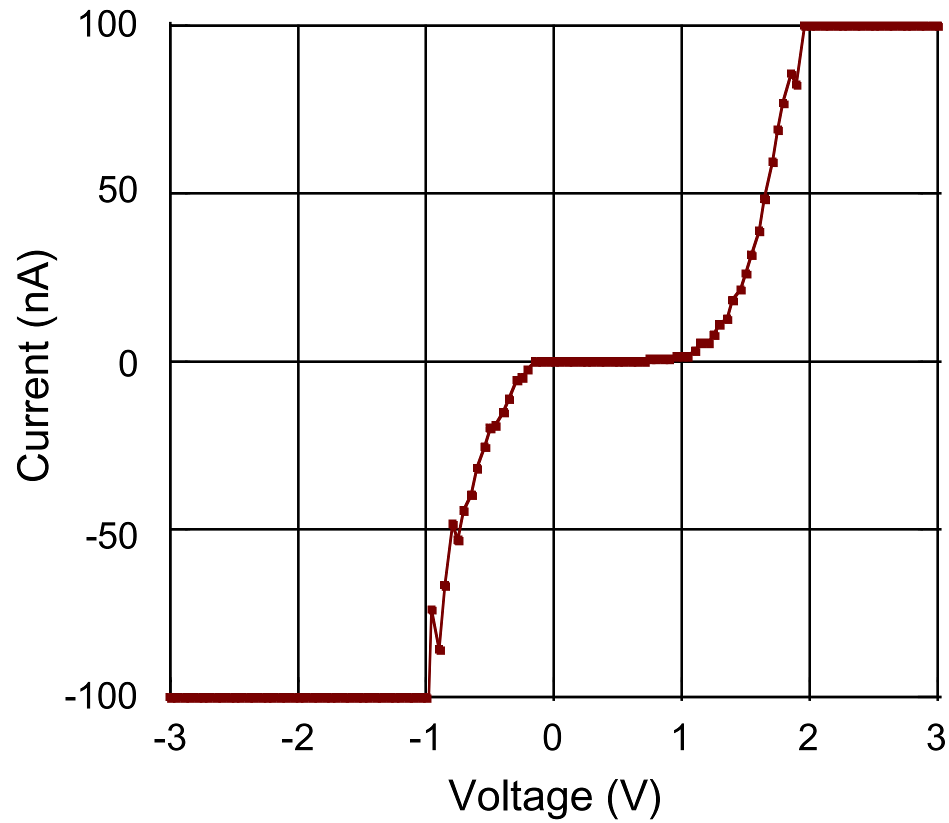
asymmetric top and bottom Au

Nina Kovtyukhova
Ben Martin (Penn State)

Nanowire Diode i-V Curve





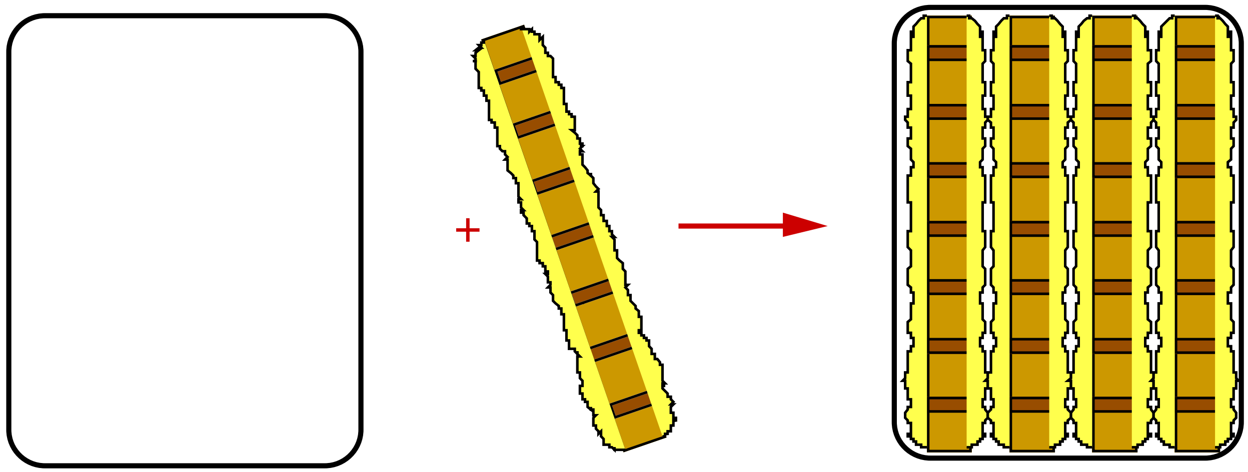


Theresa Mayer
Peter Smith (Penn State)

Assembly of Function Blocks from Pseudo-1D Objects

Concept:

Lithographic-scale patterning directs the
assembly of sub-lithographic components



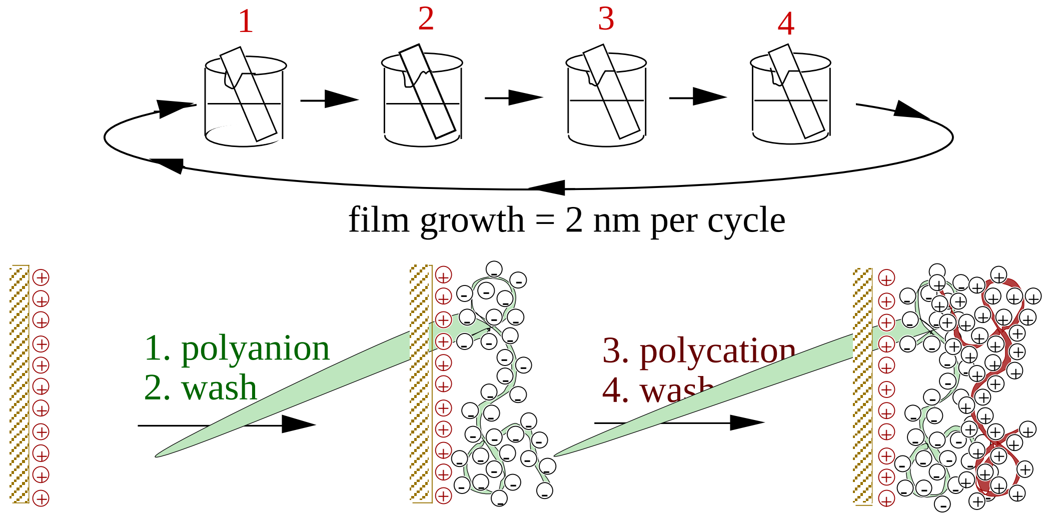
Advantages:

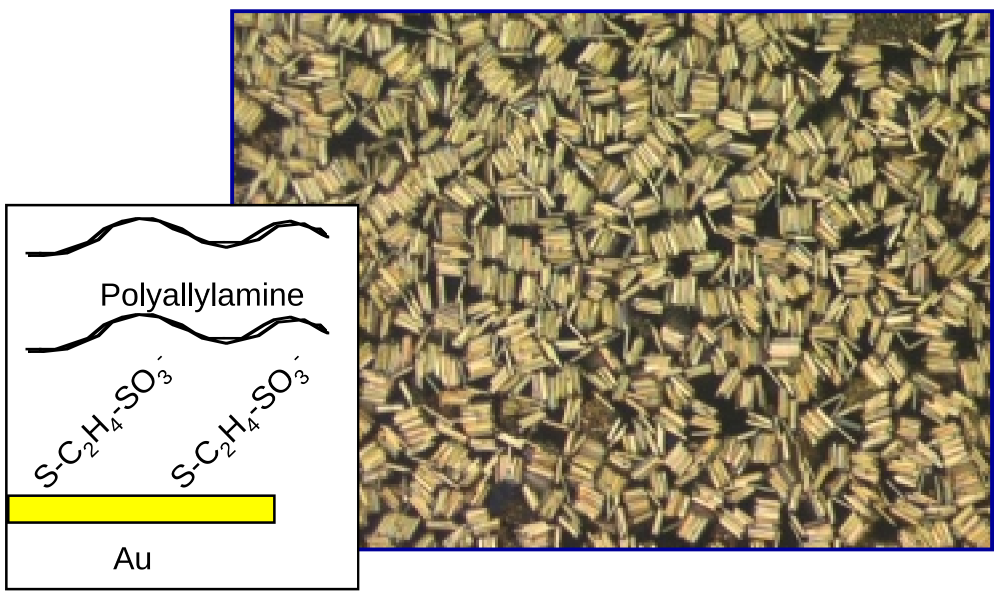
-- Defect free structures over small areas

-- On-chip assembly of dense memory with low-density interconnects

-- Addressing/interconnection becomes a local problem

Chemical assembly at the liquid-liquid interface

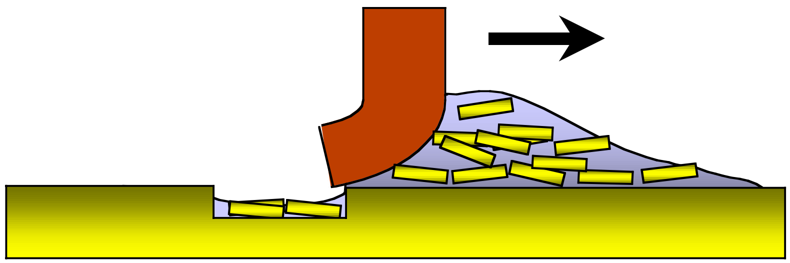




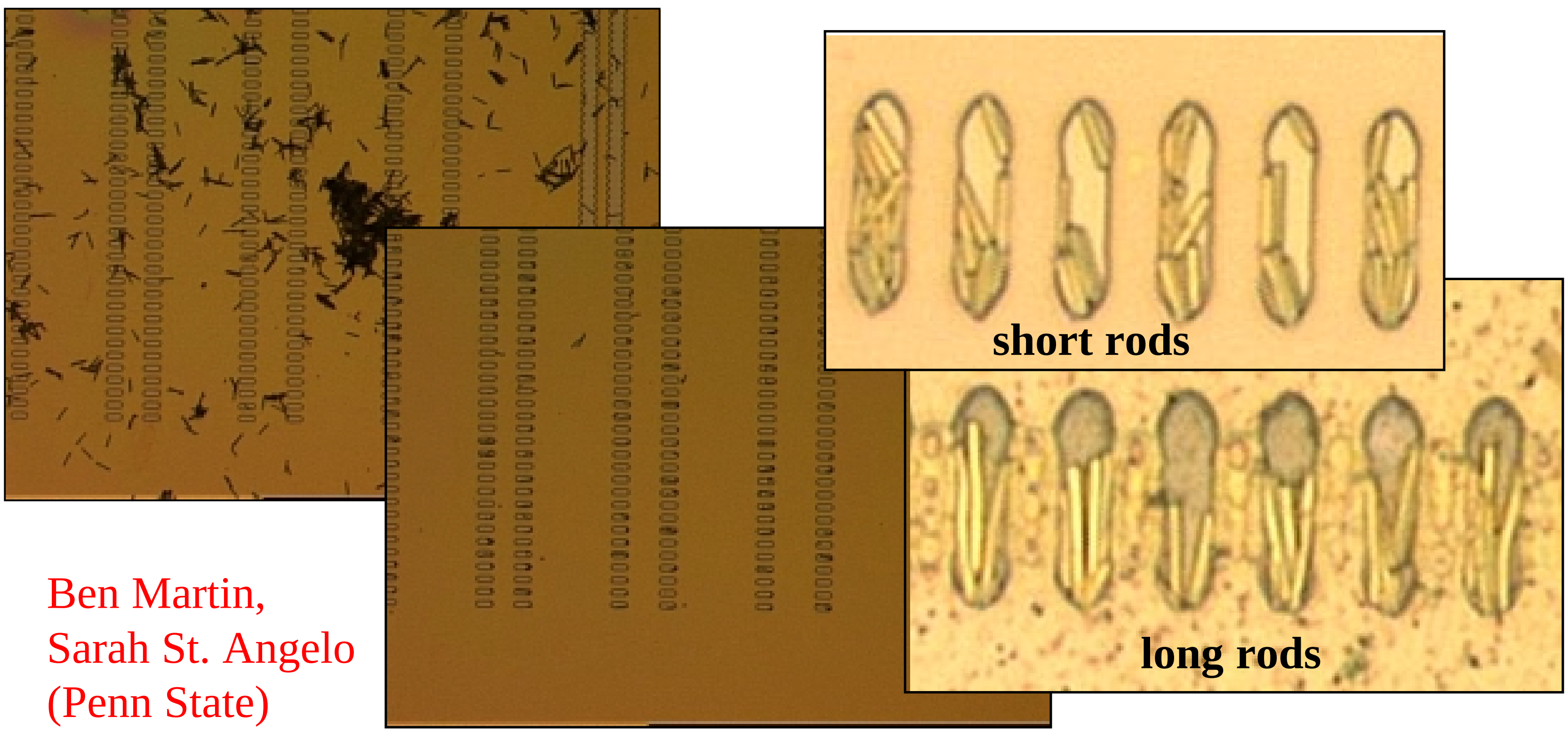
Self-assembled smectic bundles of surface-modified Au nanowires

Dan Dermody, Ben Martin, Sarah St. Angelo (Penn State)

Fluidic alignment of function blocks



Nanowires are aligned and concentrated in surface depressions using directional fluidic force



Ben Martin,
Sarah St. Angelo
(Penn State)

Conclusions and Outlook

- Inorganic nanoscale building blocks include polyhedra, sheets, spheres, tubes, and rods.

- Excellent structural and electronic properties.

- Better synthetic control needed for controlled asymmetry
  ⇒ programmed assembly of functional devices.

- Specific noncovalent linking needed to control assembly (A-T/G-C, hydrophobic/hydrophilic, steric interactions).
  Examples: rods of controlled length and sequence
  T-joints, triangles, polyhedra….

- Combination of electrofluidic alignment and function block approach should give functional circuits and other nano-assemblies in the near term.

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