Nanotechnology in Industry

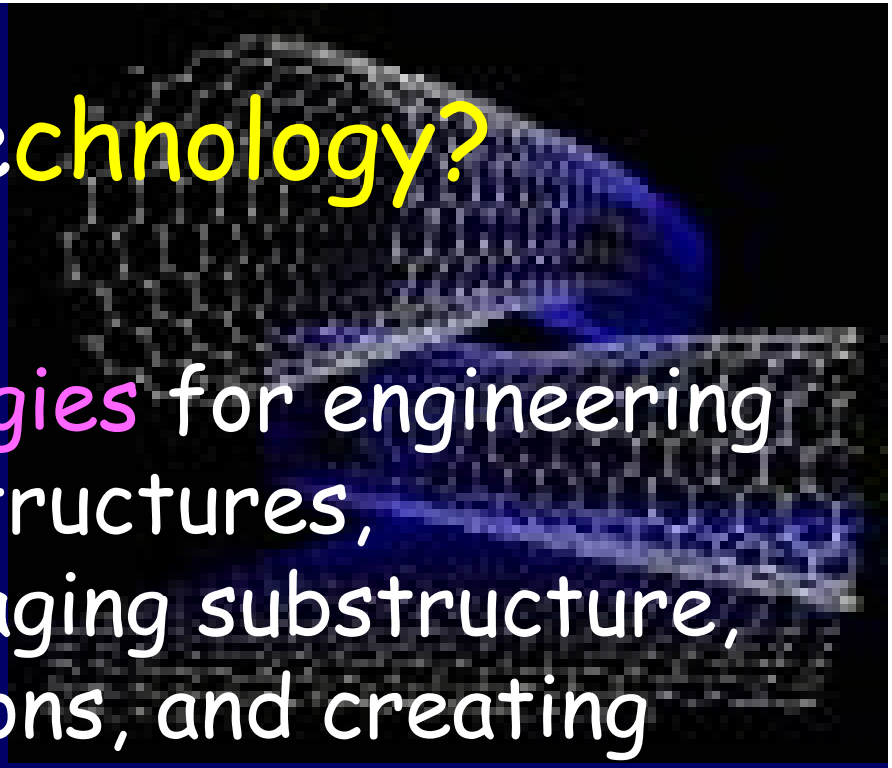
Martin Moskovits, Chief Technology Officer
API Nanotronics Corporation

Nanoscience Opportunities for the High Tech Industry

Center for Functional Nanomaterials
Brookhaven NL

November 13, 2007

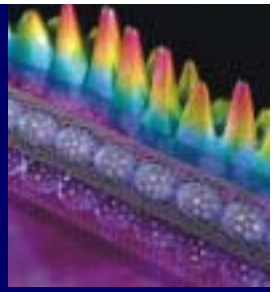
What is Nanotechnology?



It is a suite of technologies for engineering materials, fabricating structures, manipulating matter, imaging substructure, making useful compositions, and creating devices,

that incorporate structural elements a few nanometers in height or width.

SCIENCE VOL 289 25 AUGUST 2000

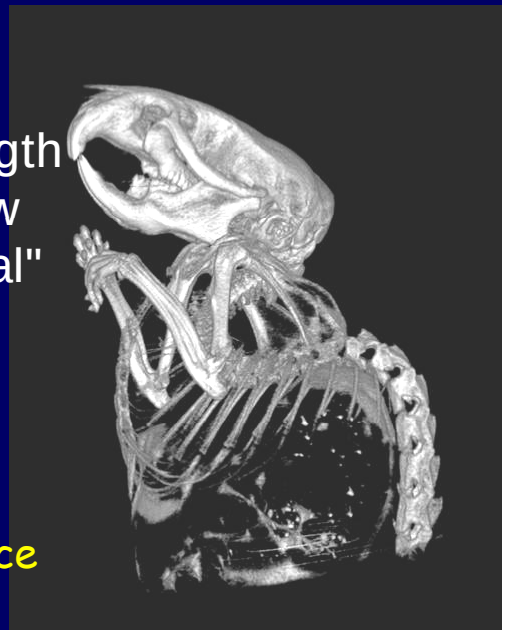


Why is this length scale important?

- Electrons determine chemistry. Confining electrons to a small space imbues the nanostructure with wholly novel properties that are size-dependent. Size becomes a property-tuning parameter.

- Nanostructures such as nanoparticles, nanotubes and nanowires with surface-to-volume ratios can be used as building blocks to create composite materials ultrastrong or ultra-elastic mechanical properties, novel chemistry, unusual and useful electrical and optical behavior.

- Biological systems are organized on the nanometer length scale. Combining nanoscience with biology leads to new bionic devices that engage bio-systems on their "natural" length scale.

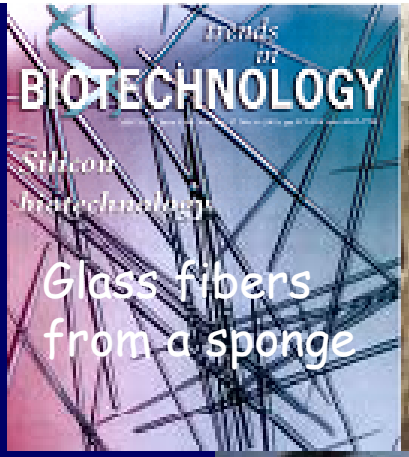


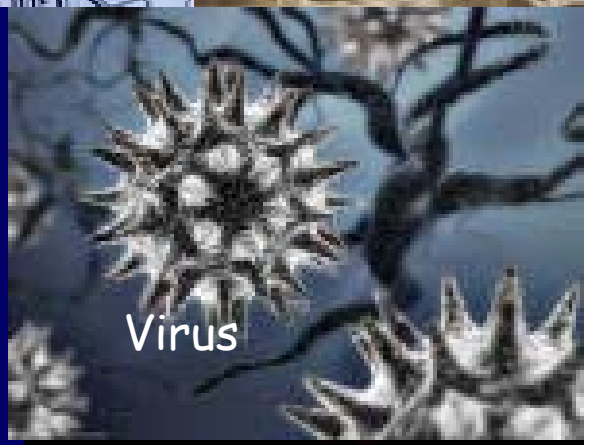
Mouse x-rayed with carbon nanotube-based x-ray source

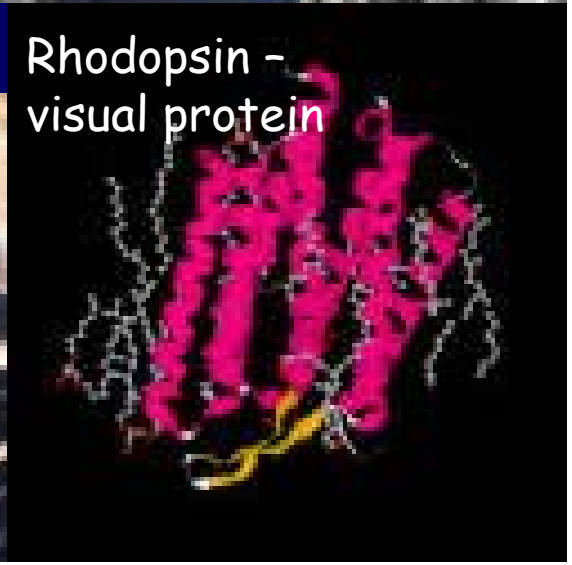
Why is the nanometer scale replete with opportunities ?

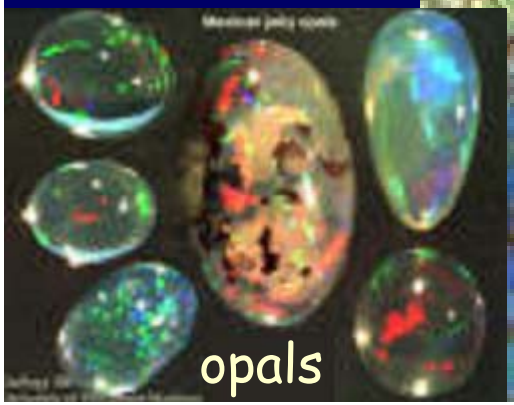
1. Only few examples of nanostructures exist in the inanimate world (e.g. opals, clays)

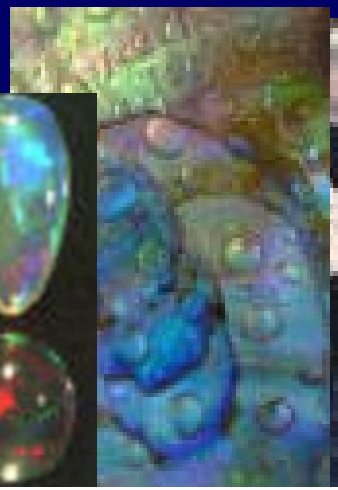
2. Lots of examples exist in the living world: proteins, viruses, milk, bones, shells, corals, allowing technology to engage biology on its "natural" length scale

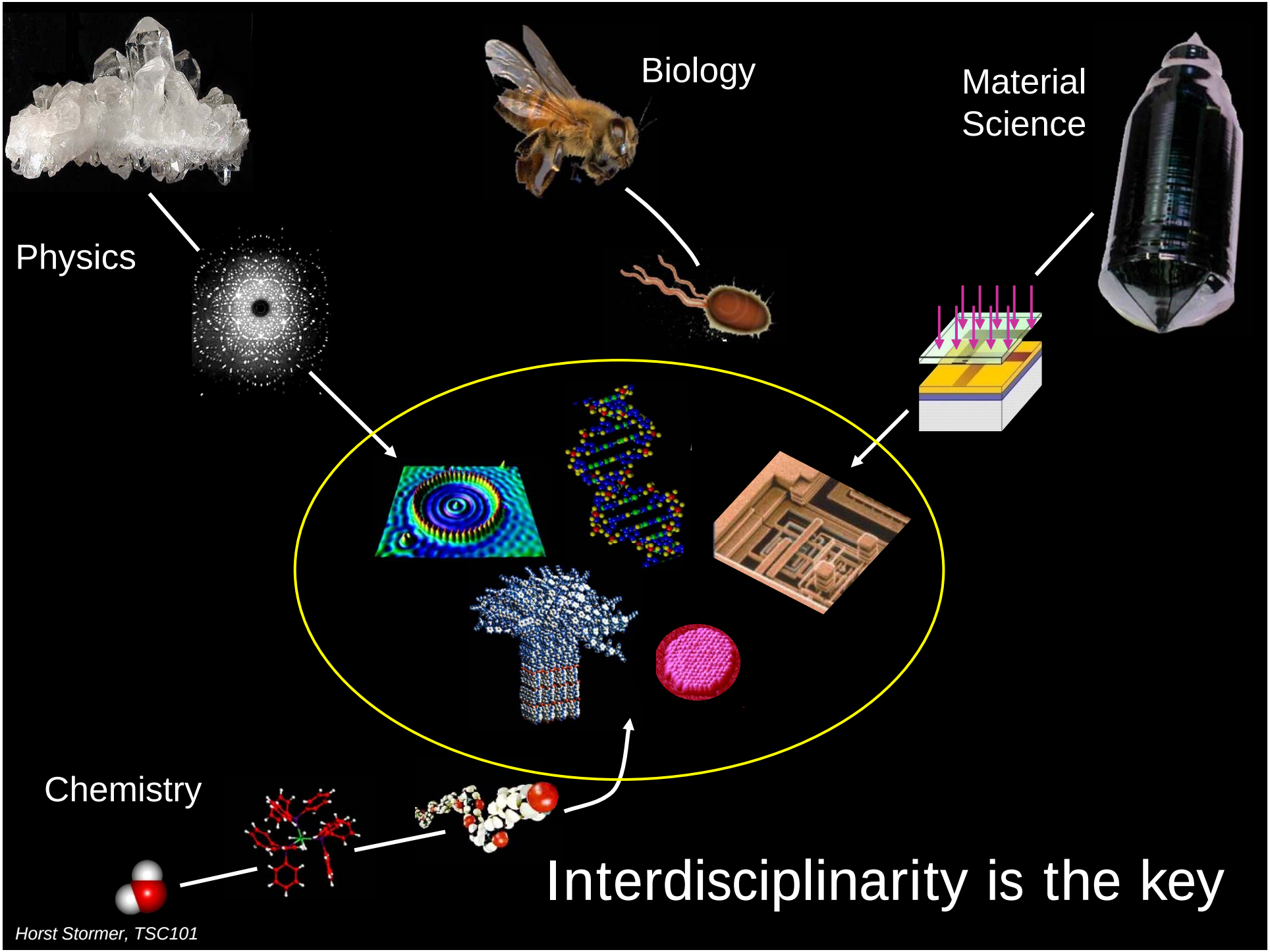











Biology
Material Science
Physics
Chemistry
Interdisciplinarity is the key
Horst Stormer, TSC101

Significant national investment: Nanoscale Science Research Centers: Unique Resources, Unique Capabilities

The Molecular Foundry

Lawrence Berkeley National Laboratory

Unique Resource
- Advanced Light Source
- National Center for Electron Microscopy
- NERSC Computing Center

Scientific Focus
- E-beam nanowriter
- Nanofabrication (lithography and stamping)
- Inorganic nanostructures (crystals and tubes)
- Imaging, manipulation, theory and modeling
- Bio-nanostructures (organic, polymers)

Center for Integrated Nanotechnologies

Sandia National Laboratories

Unique Resource
- Los Alamos Neutron Science Center
- National High Magnetic Field Laboratory

Scientific Focus
- Nano-bio-micro interfaces
- Nanophotonics and nanoelectronics
- Complex functional nanomaterials
- Nanomechanics
- Theory and simulation

Center for Functional Nanomaterials

Los Alamos National Laboratory

Unique Resource
- National Synchrotron Light Source

Scientific Focus
- Nanoscale strongly correlated oxides
- Charge transfer on the nanoscale
- Nanometer-thick organic films
- Nanoscale magnetism
- Nanostructured catalysts
- Nanomaterials applications

Brookhaven National Laboratory

Center for Nanoscale Materials

Argonne National Laboratory

Unique Resource
- Advanced Photon Source
- Electron Microscopy Center

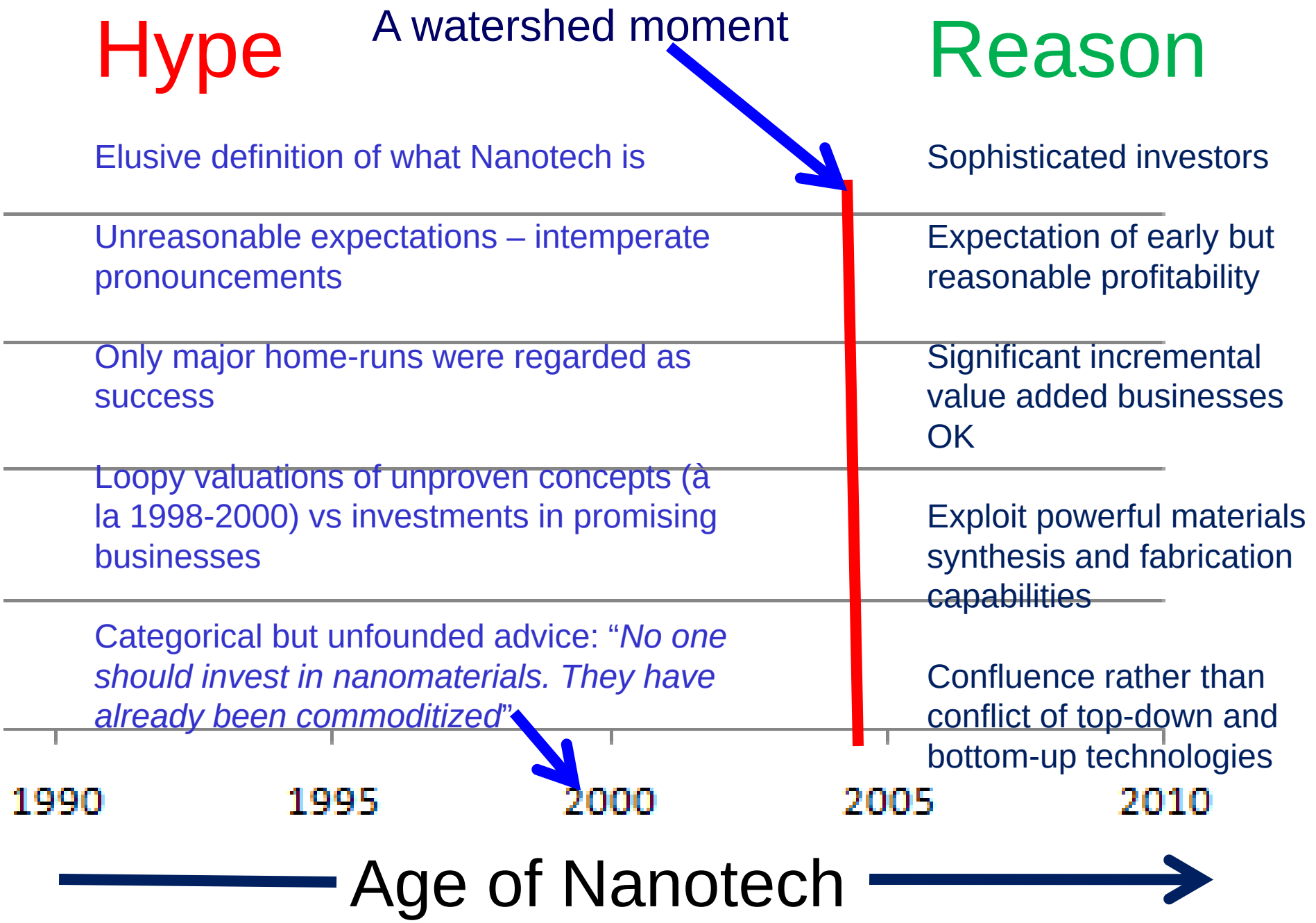
Scientific Focus
- Advanced magnetic materials
- Nanocrystalline diamond
- Complex oxides
- Nanophotonics
- Bio-inorganic hybrids
- X-ray nanoprobe characterization
- Simulations of self-organization

Center for Nanophase Materials Sciences

Unique Resource
- Spallation Neutron Source
- High Flux Isotope Reactor

Scientific Focus
- Neutron scattering to probe materials at the nanoscale, at interfaces, and in complex nanophase materials
- Synthesis and nanofabrication
- Nanomaterials Theory Institute
- Hybrid soft/hard materials
- Organic/inorganic nano-interfaces

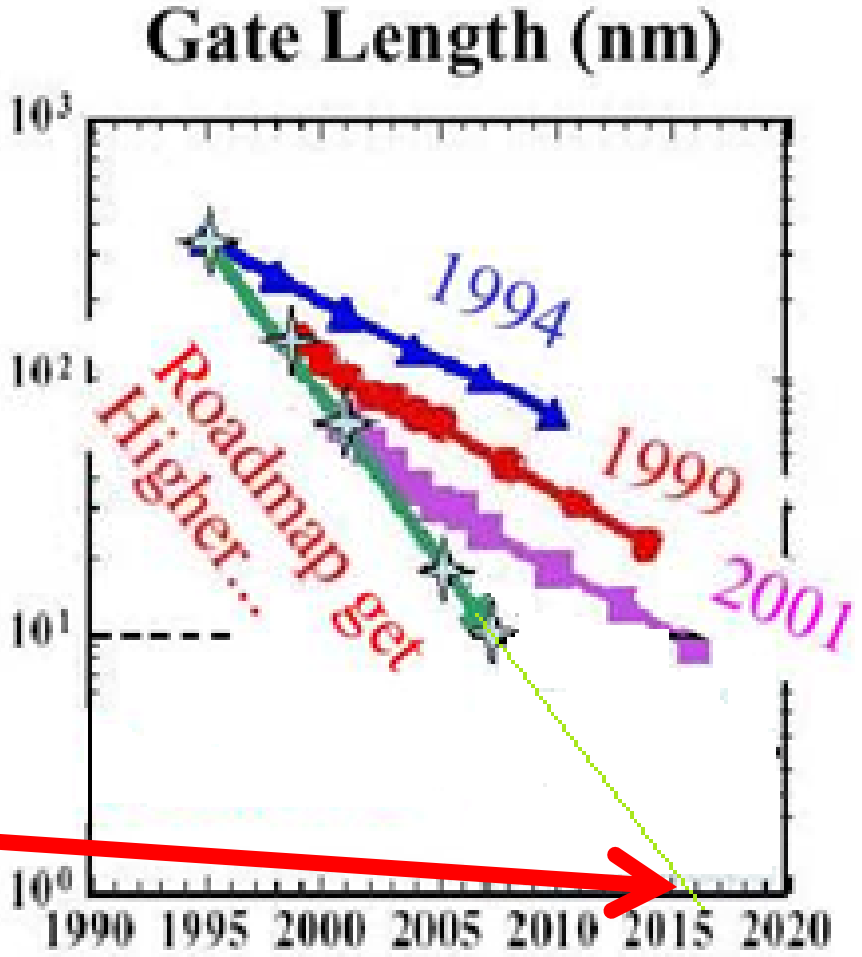
Oak Ridge National Laboratory


Hype
A watershed moment
Reason
Elusive definition of what Nanotech is
Unreasonable expectations – intemperate pronouncements
Only major home-runs were regarded as success
Loopy valuations of unproven concepts (à la 1998-2000) vs investments in promising businesses
Categorical but unfounded advice: "No one should invest in nanomaterials. They have already been commoditized"
Sophisticated investors
Expectation of early but reasonable profitability
Significant incremental value added businesses OK
Exploit powerful materials synthesis and fabrication capabilities
Confluence rather than conflict of top-down and bottom-up technologies
1990
1995
2000
2005
2010
Age of Nanotech

Inexorable convergence of top-down and bottom-up approaches

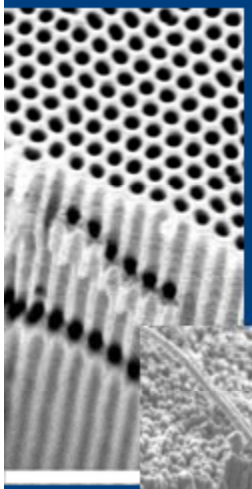
The silicon industry has been “nano” for several years already

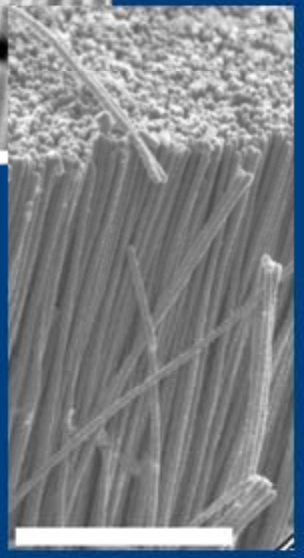
Extrapolating current trends the gate length will achieve molecular dimensions in ~2015

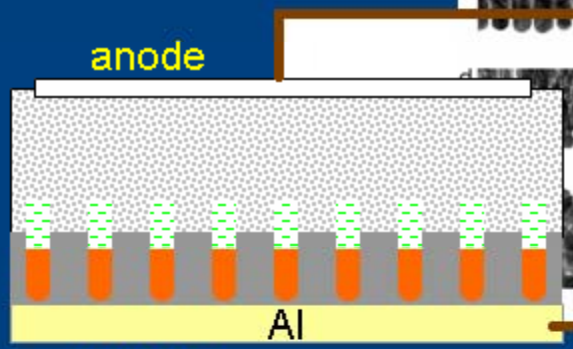


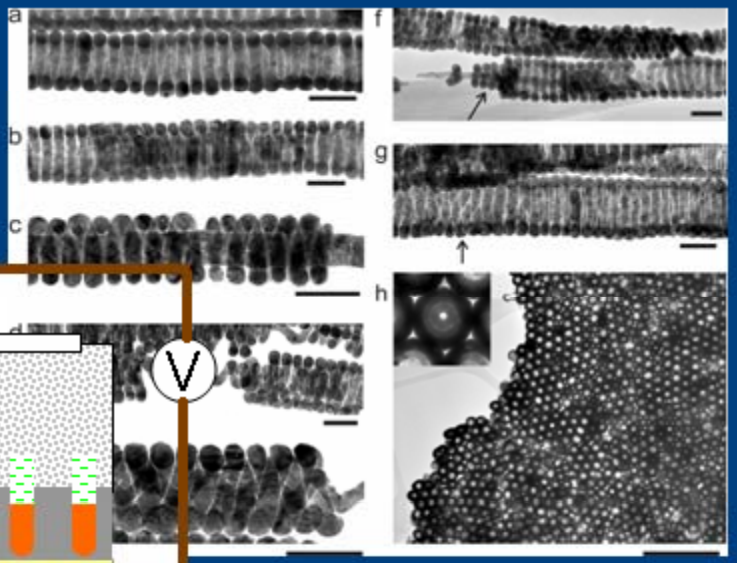
(Intel Corporation Desktop CPU Roadmap)

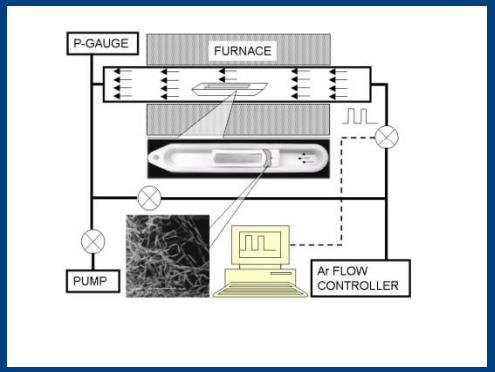
Electronic and photonic applications of nanowires

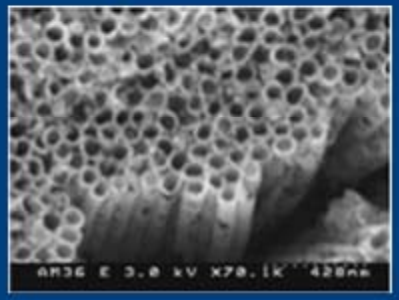


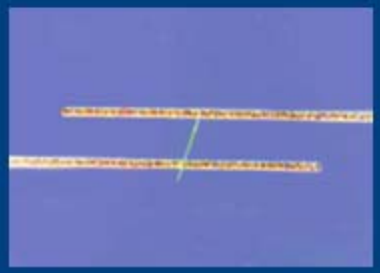


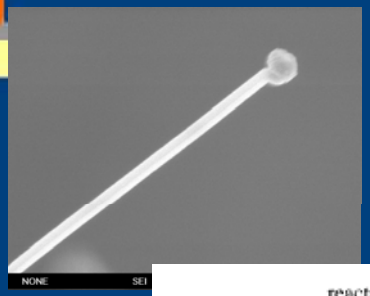


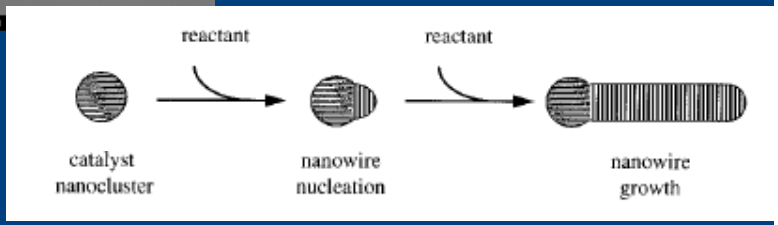




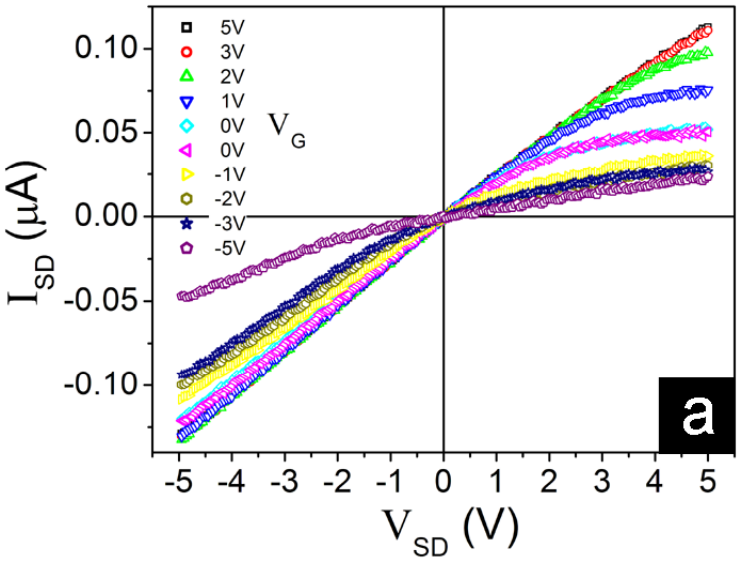


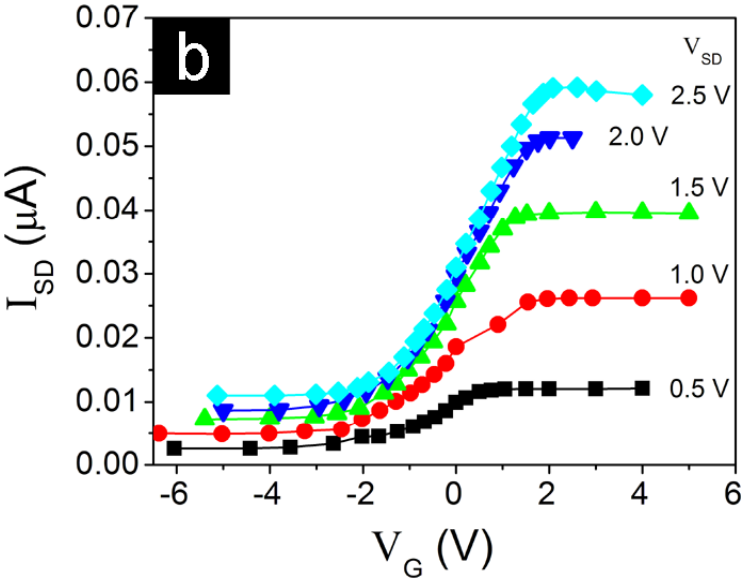


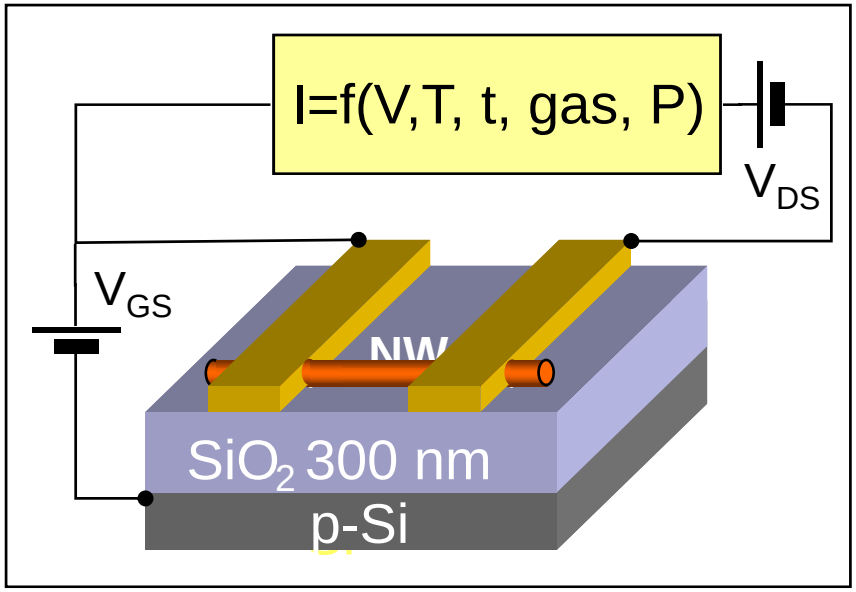


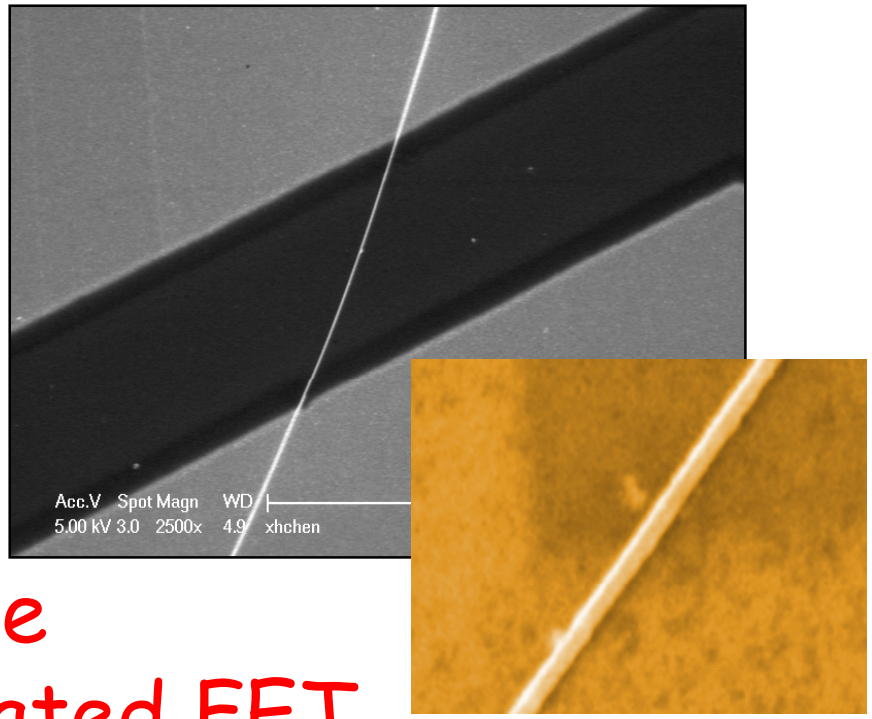


Kolmakov A, Zhang Y, Cheng G, Moskovits M:. *Advanced Materials* 2003, vol.15
Kolmakov A, Zhang Y, Moskovits M: *Nano Letters* 2003, 3(8),1125





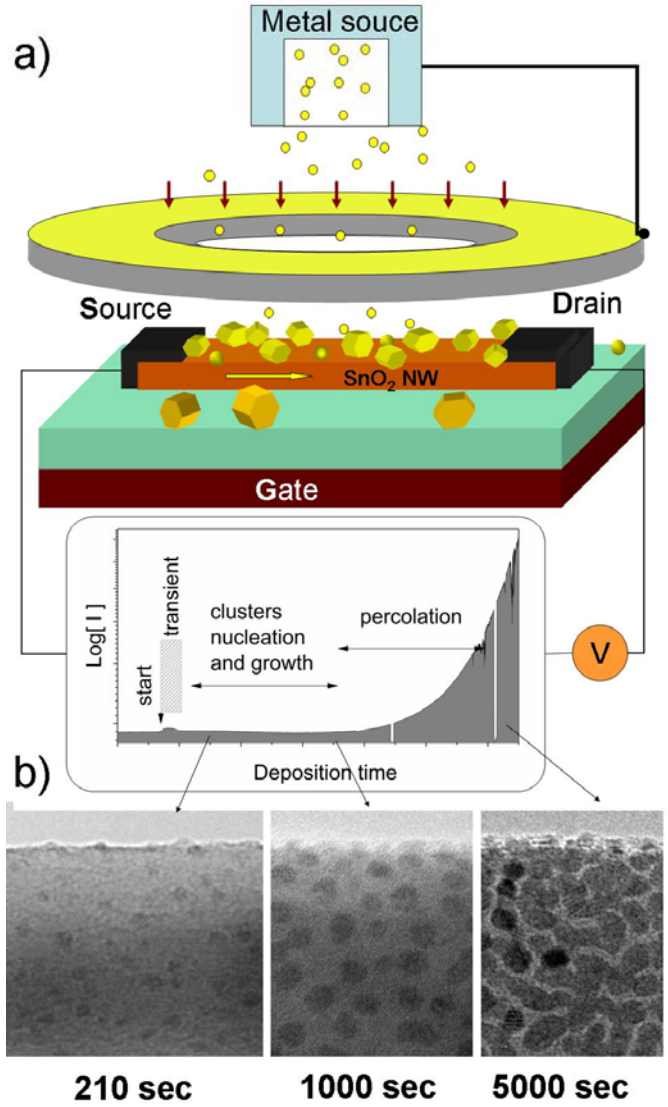


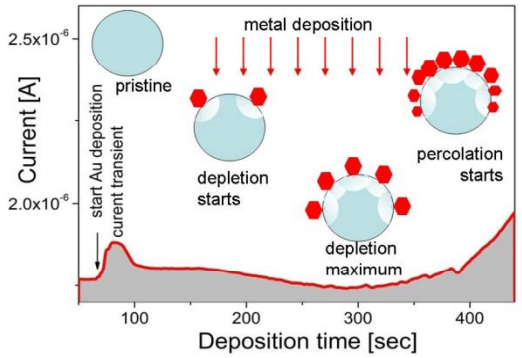


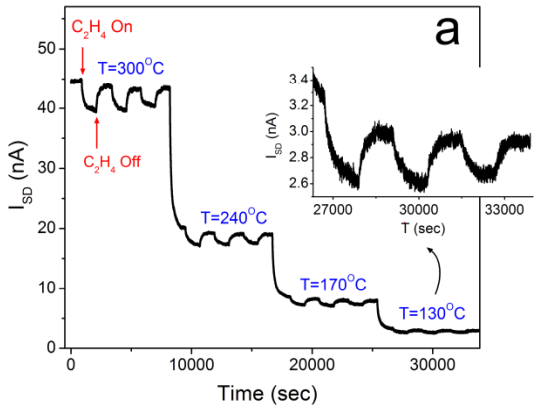
Mn-doped GaN nanowire configured as a back-gated FET

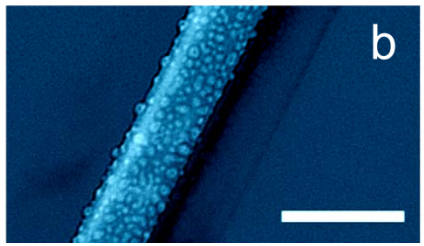
X.H. Chen et al

A. Kolmakov et al., X. H. Chen et al.









Metal Nanoparticle – semiconductor nanowire Schottky junction sensing device

Nano-wire grid polarizers and related optical devices

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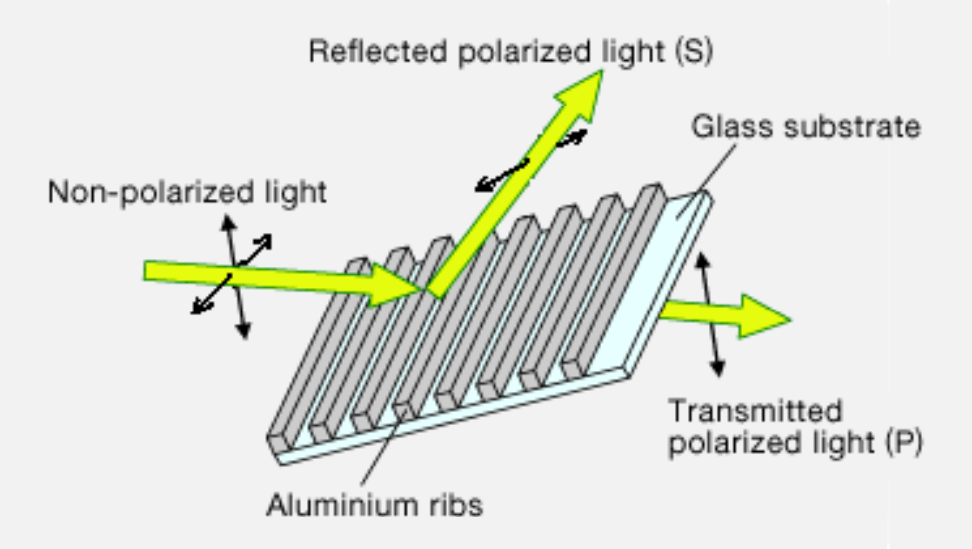
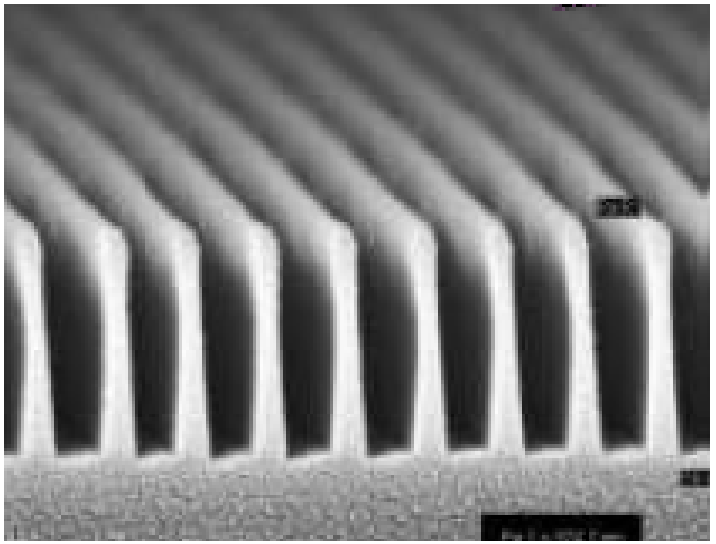
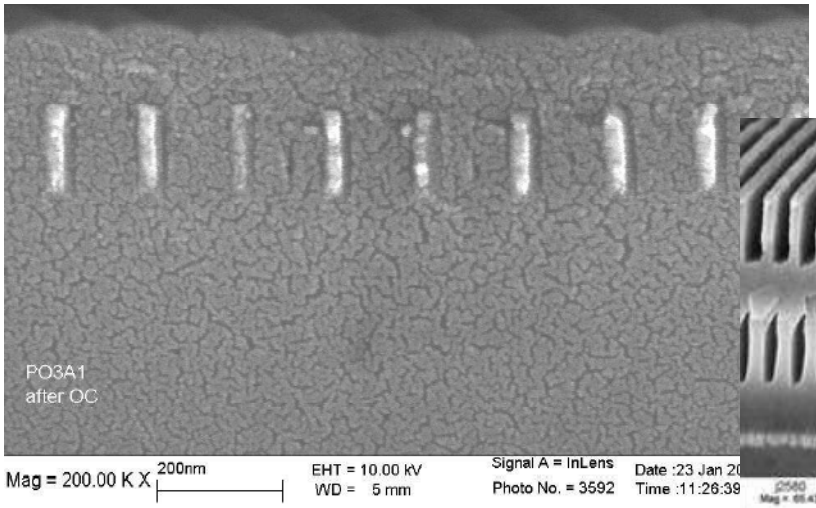
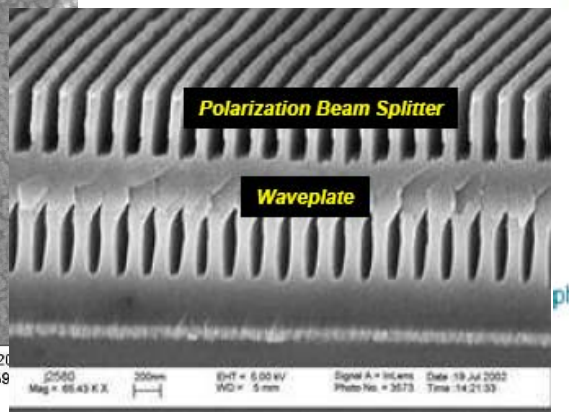
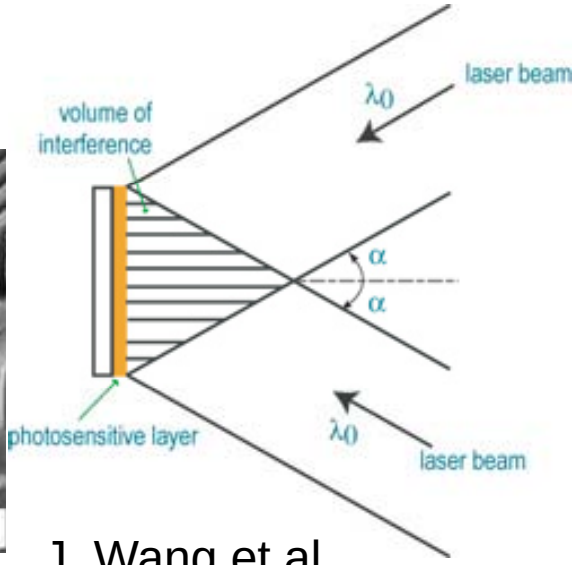






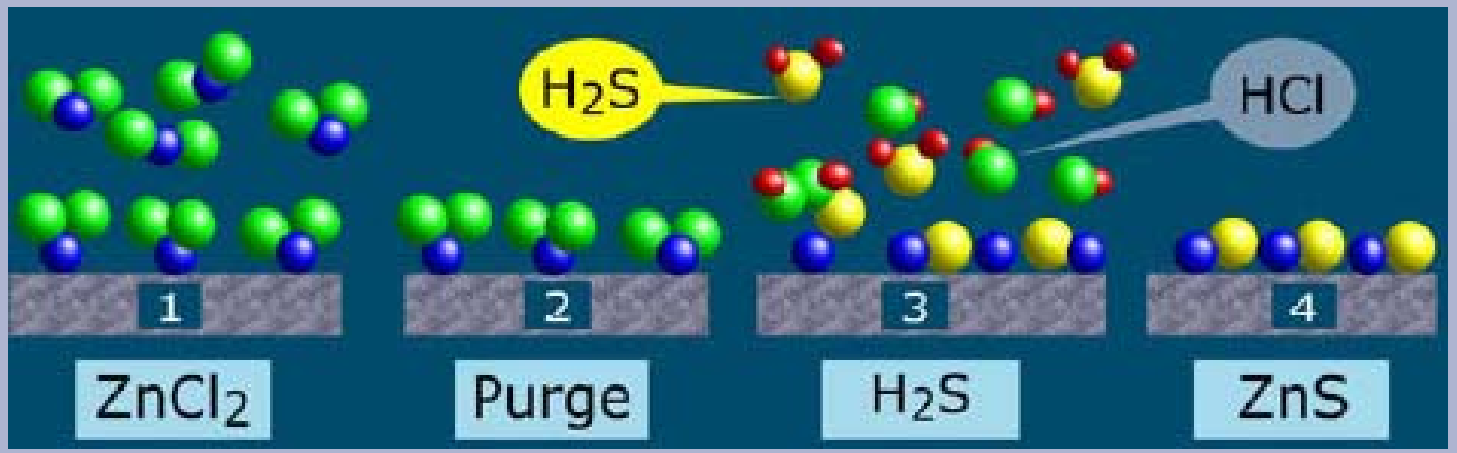




J. Wang et al.

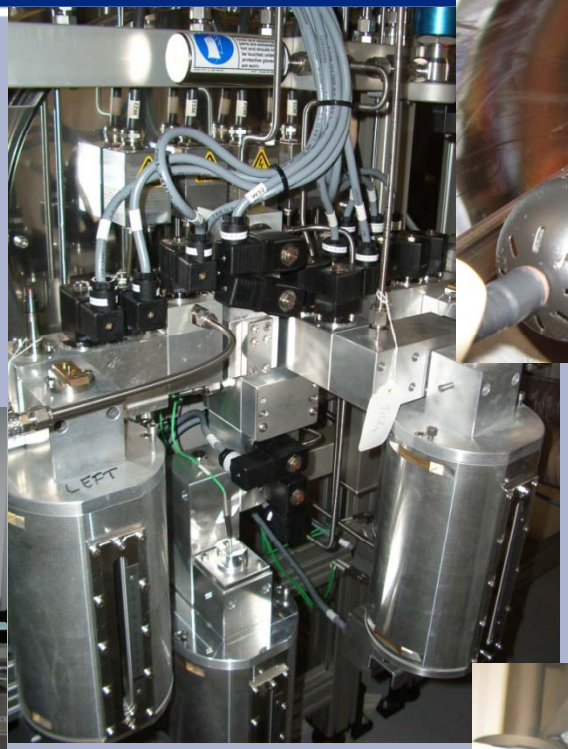
Conformal nanolaminates by Atomic Layer Deposition

- Monolayer by monolayer deposition – self limiting
- Sequentially introduce reactants
- Nanolaminates – alternating material layers (e.g. ABAB, ABCABC) where one or both have nm scale thicknesses
- Precise and controlled deposition technique, sequential deposition of multiple materials, fully conformal coating, reduced/no pinholes or defects, very high quality films



api nanotronics

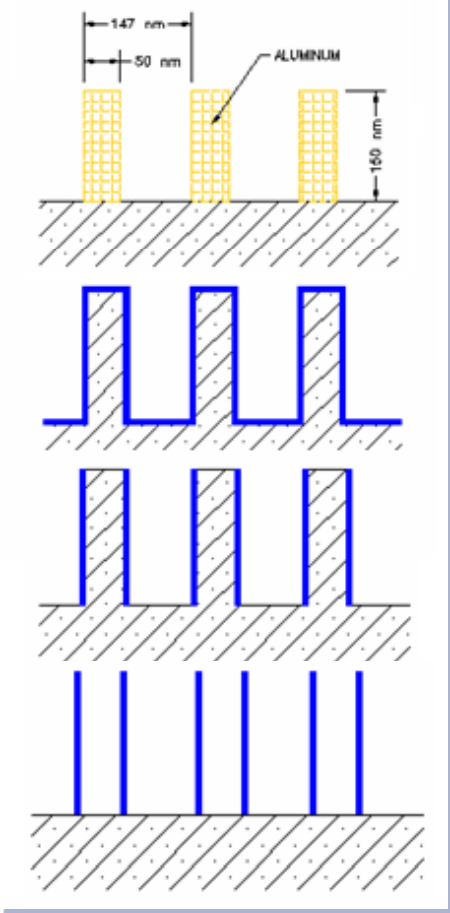
Three ALD machines, fully equipped nanofab



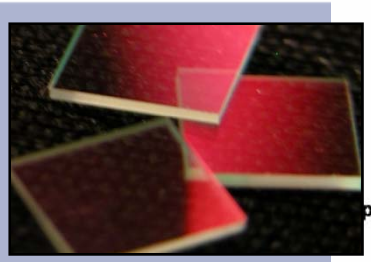
nanoopto

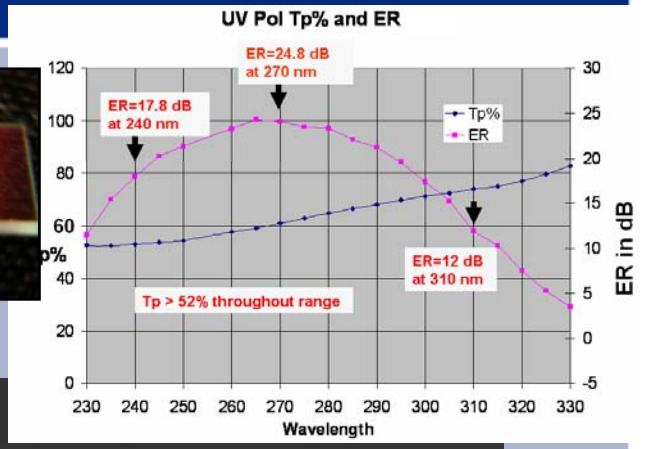
Division of API Nanofabrication and Research Corp.

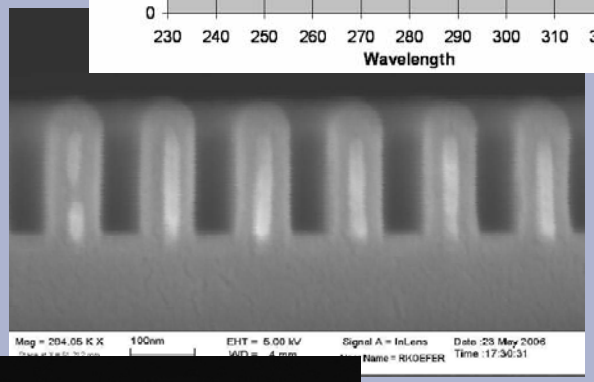
Allows us to create products no one else can – such as a deep UV polarizer

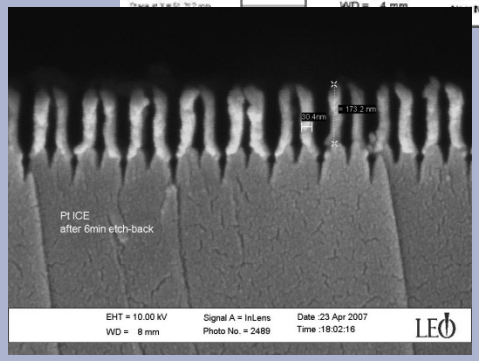


1. Fabricate nanowire grid polarizer using UV hollography
2. Conformally deposit TiO_2 using ALD
3. Dry etch the top TiO_2 layers using fluorine RIE
4. Wet-etch aluminum, leave behind TiO_2 nanograting with half the pitch









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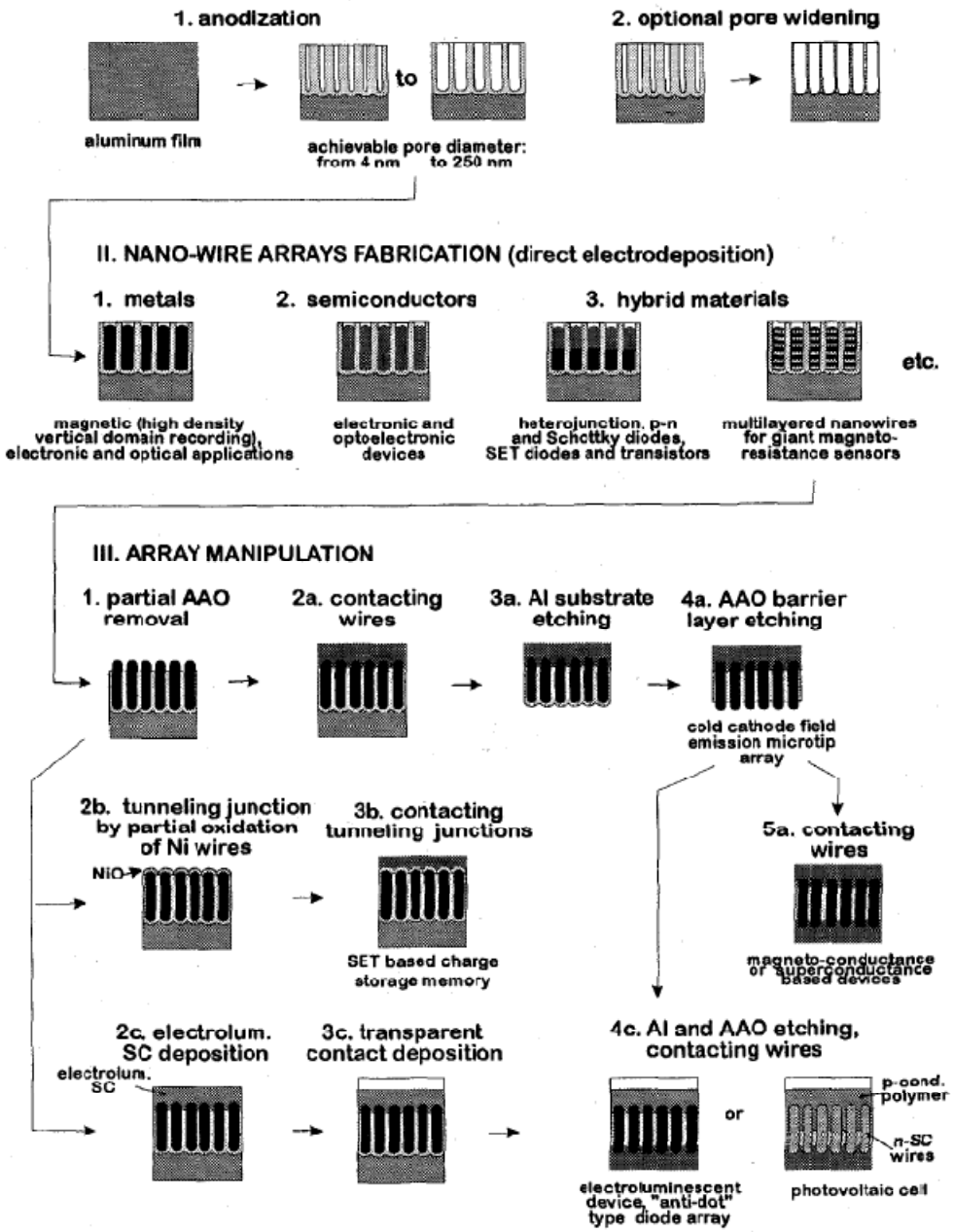
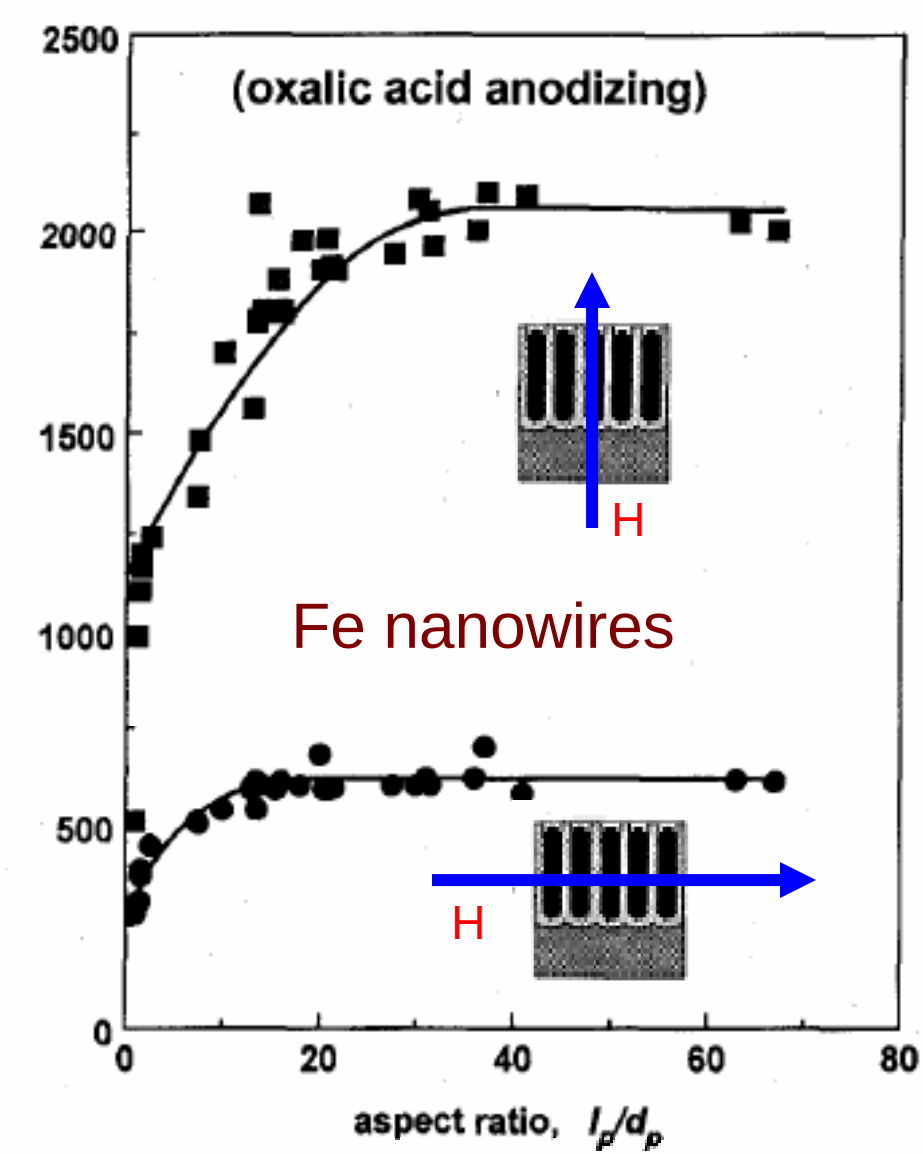
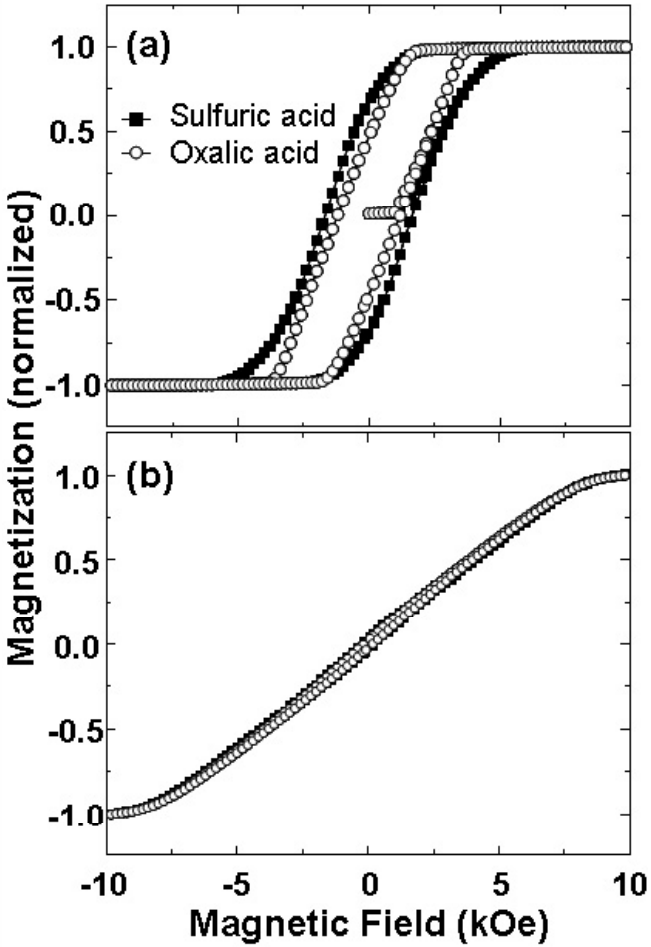
Riff on technologies based on Nanowires



D. Routkevitch et al

AlMawlawi et al, J.M. Baik et al.





Tuning magnetic properties using size

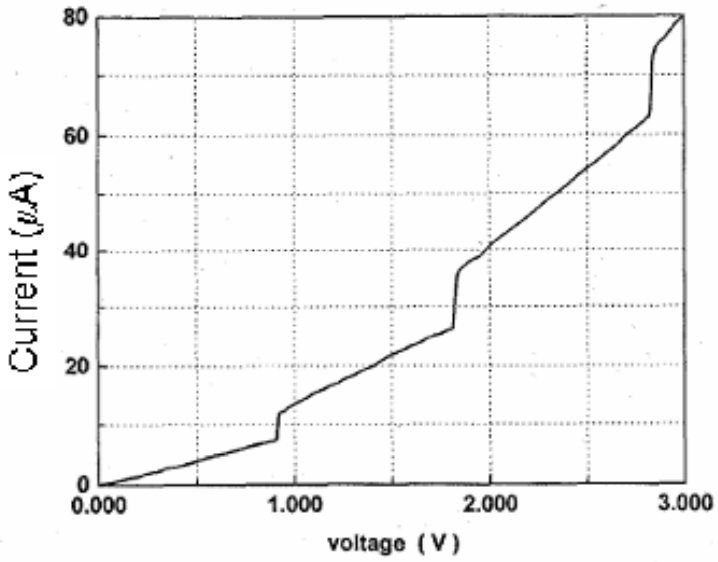
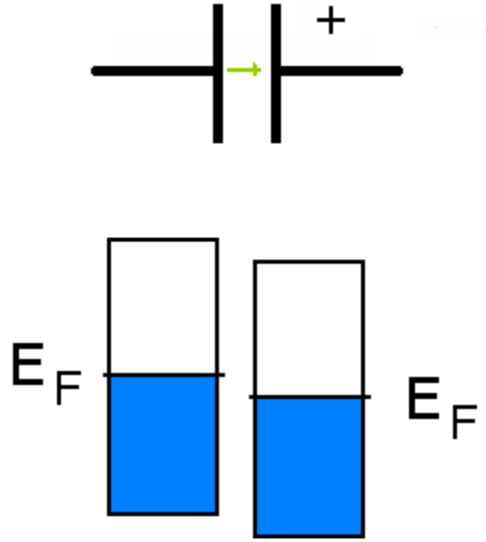
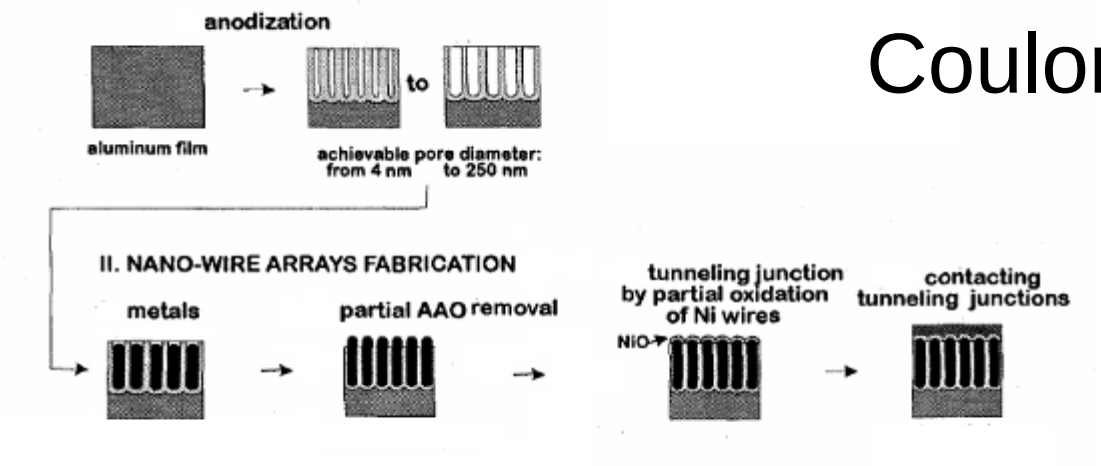


Fig. 13. Current-voltage characteristics of a double tunnel junction array Al\AAO $_{BL}$\Ni-wires\NiO\Ag obtained (in the dark) at 300 K.

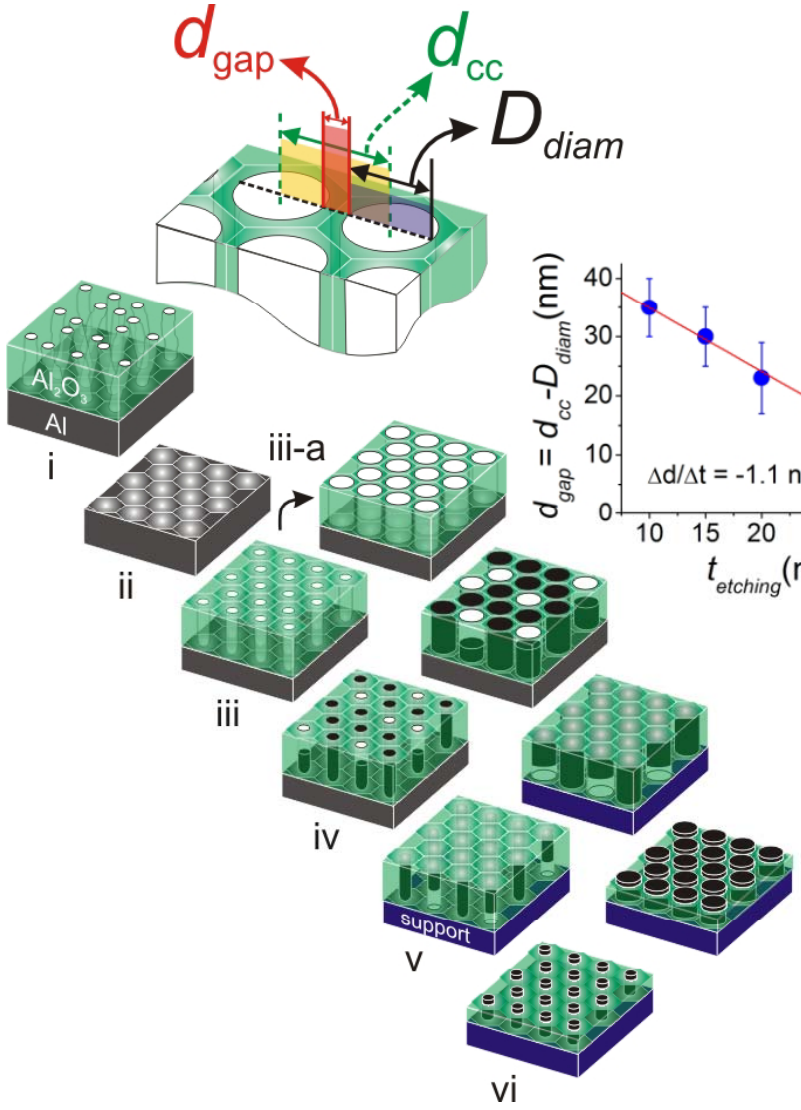


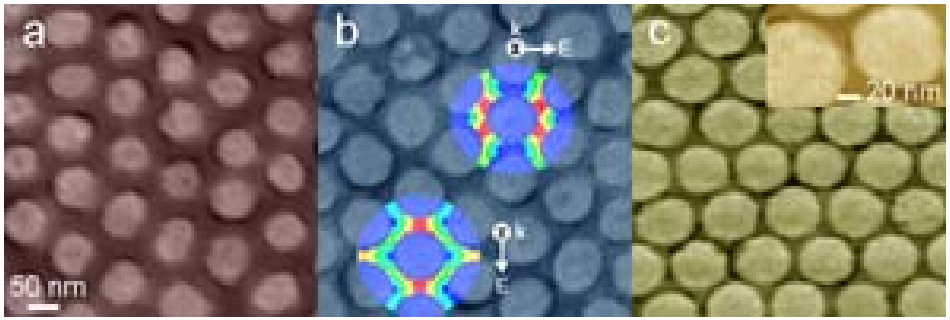


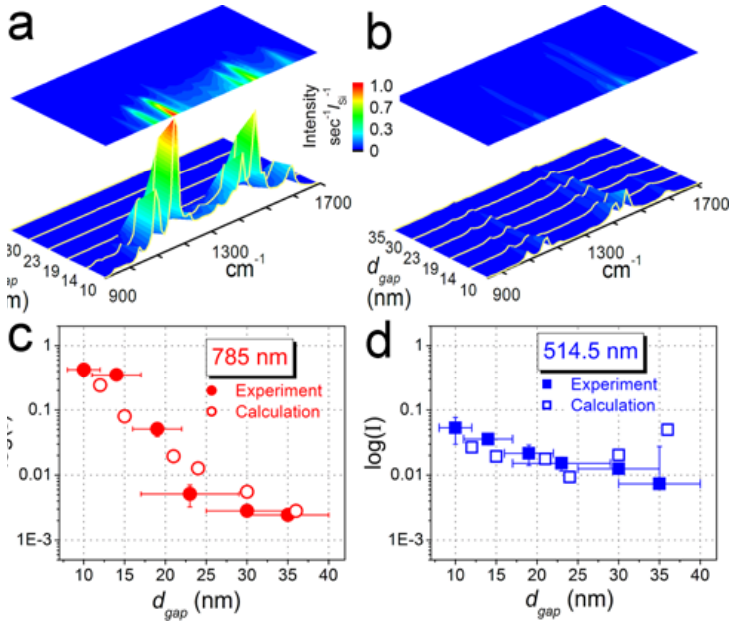
Coulomb Blockade

D. AlMawlawi, J-M Xu et al.

S. J. Lee et al







Silver Nanowire arrays for Chemical and bio-sensing using surface-enhanced Raman

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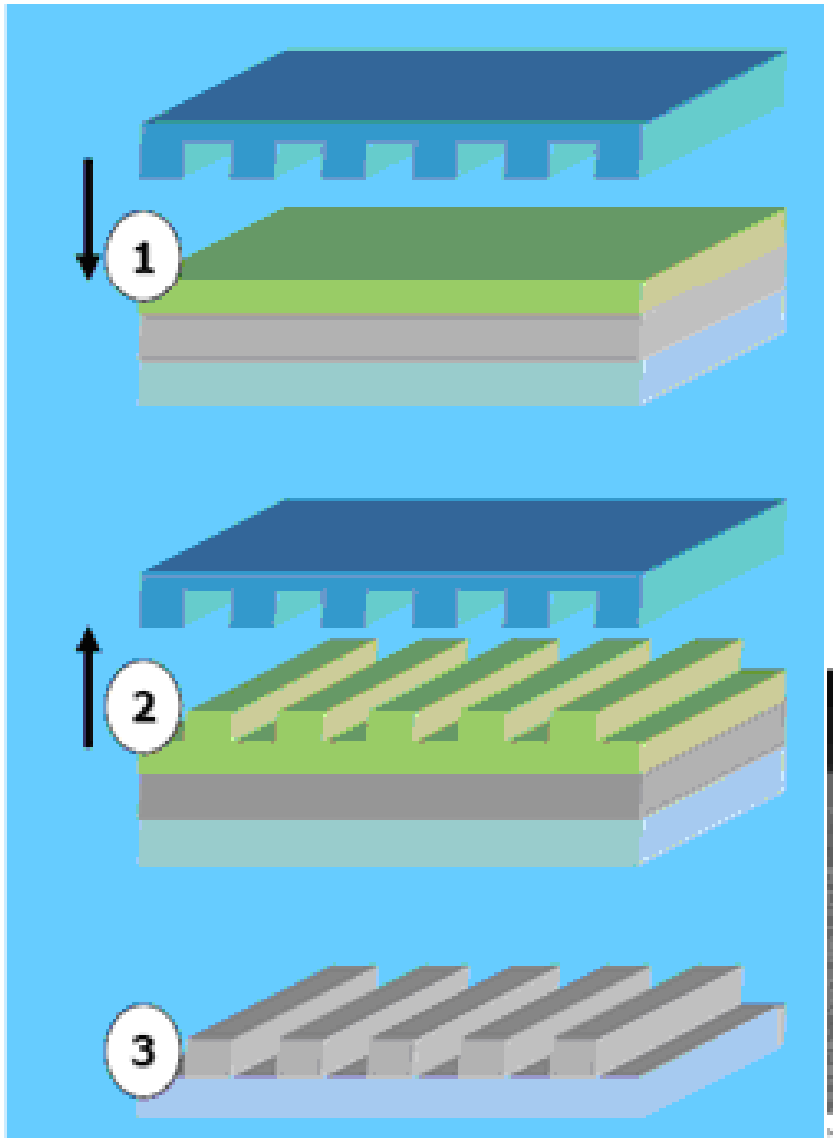
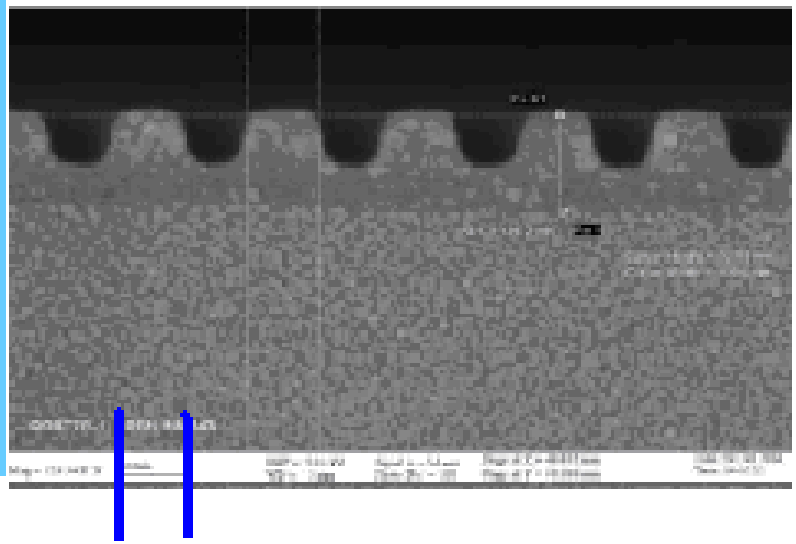


Nano-imprint Lithography, Developed by Steve Chou et al, Princeton U



Summarizing: Nanotech is

- A suite of fabrication approaches that integrates improvements in existing device fabrication (so-called top-down) technologies developed for microelectronics, with wholly novel and adaptations of existing materials synthesis and fabrication technologies (bottom-up techniques) expanding the scope of present day materials, electronics and optics.
- A powerful approach for integrating technology into biology and medicine.
- It is ready to impact today's business through incremental added value to products and processes impacting communication, computation, electronics and photonics, sensor and diagnostic technologies, catalysis, drug delivery, imaging…