

# *Nanotechnology: An Overview*

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Building College-University  
Partnerships for Nanotechnology  
Workforce Development



# *What is Nanotechnology?*



# There's Plenty of Room at the Bottom : An invitation to Enter a New Field of Physics

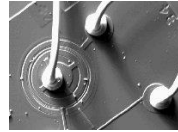


Richard Feynman,  
Caltech 1959

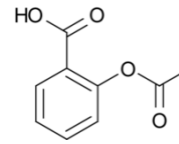
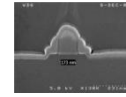
*“People tell me about miniaturization, and how far it has progressed today. They tell me about electric motors that are the size of the nail on your small finger. And there is a device on the market, they tell me, by which you can write the Lord’s Prayer on the head of a pin. But that is nothing; that’s the most primitive, halting step in the direction I intend to discuss. It is a staggeringly small world that is below. In the year 2000, when they look back at this age, they will wonder why it was not until the year 1960 that anybody began seriously to move in this direction. Why cannot we write the entire 24 volumes of the Encyclopedia Britannica on the head of a pin ? ”*

*This goal requires patterning at the 10 nanometer scale and, hence, nanotechnology (NT)*

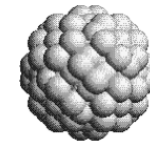
Transistors of 20-30 Years ago



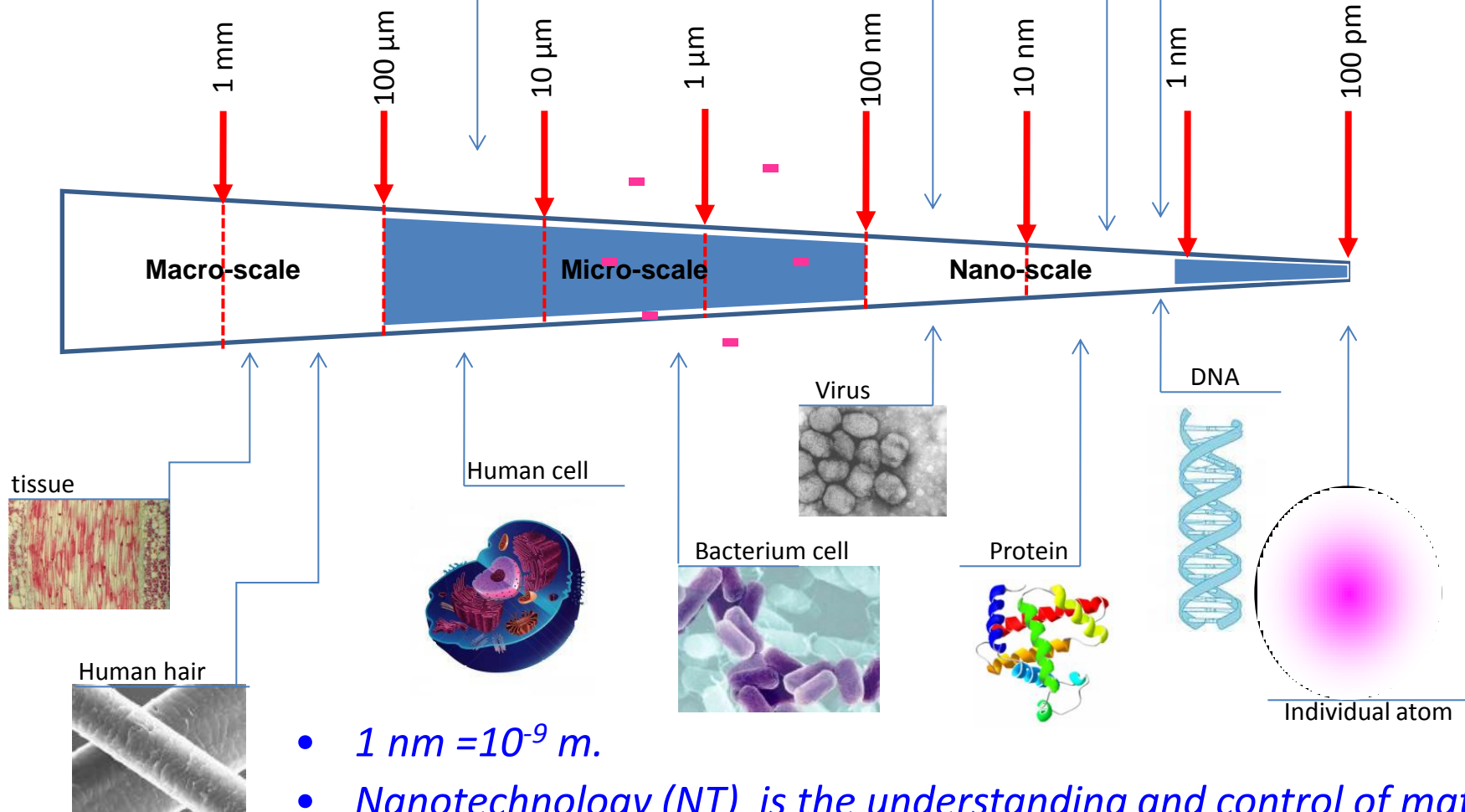
Transistor of 2007



Drug molecule

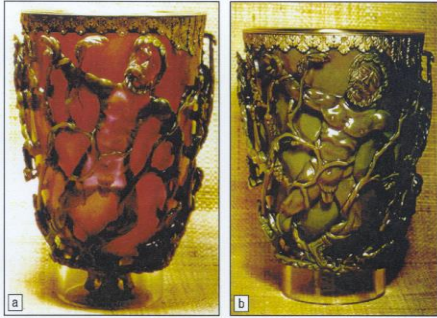


Quantum dot



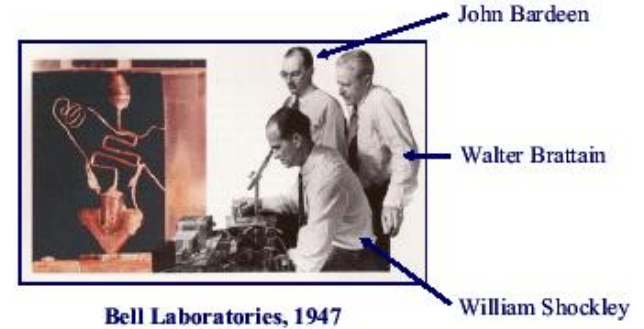
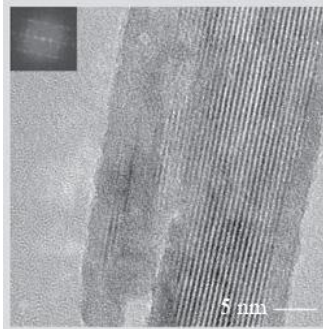
- $1 \text{ nm} = 10^{-9} \text{ m}$ .
- *Nanotechnology (NT) is the understanding and control of matter at dimensions of roughly 1 to 100 nm.*
- *Nanotechnology is not an industry; it is an enabling technology.*

# NT : Historical



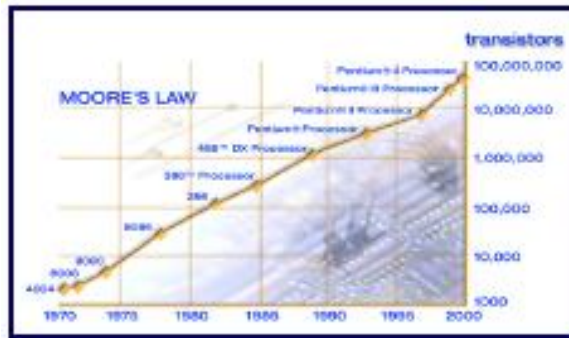
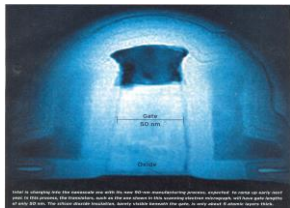
*1000 years ago : carbon nanotubes and nanowires in Damascus steel sword.*

*2000 years ago : the cup is seen in (a) transmitted light, and (b) reflected light.*

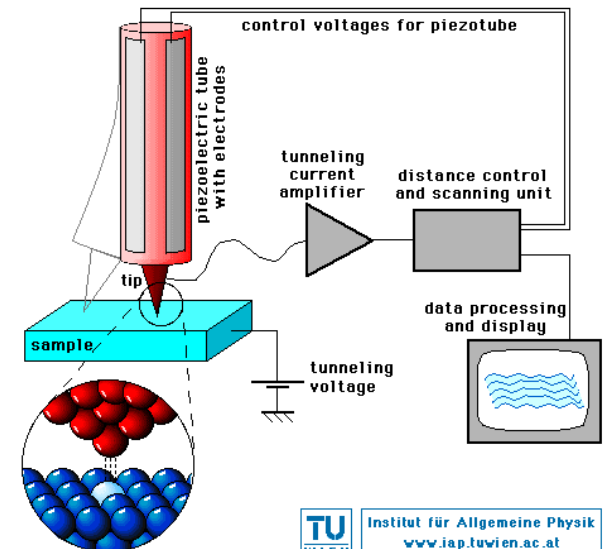


Bell Laboratories, 1947

*1947 Invention of the transistor at Bell Labs.*



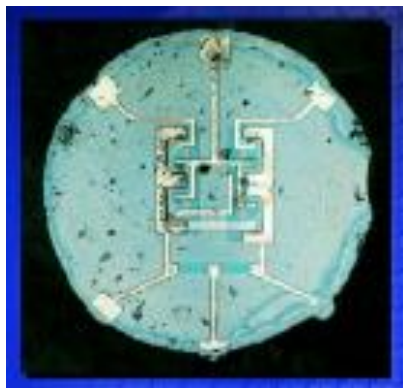
*1965 "Cramming more components onto ICs"*



TU WIEN Institut für Allgemeine Physik [www.iap.tuwien.ac.at](http://www.iap.tuwien.ac.at)

*1981 : Binnig and Rohrer invented the scanning tunneling microscope*

*1961 : the first planar IC*



***If NT has been around for almost 2000 years why is it taking off now?  
Why is it so “big” now?***

***Because we have learned what is going on:***

- *We can now controllably and repeatedly make things in the nano-size range.*
- *And we can now see what we have made.*
- *A whole new technology came to being-  
Nanotechnology.*

# Nanofabrication Approaches:

## (1) Top down

### Deposition

- *Electroplating, spin-on, spray-on.*
- *Physical vapor deposition.*
- *Chemical vapor deposition.*

### Lithography (patterning)

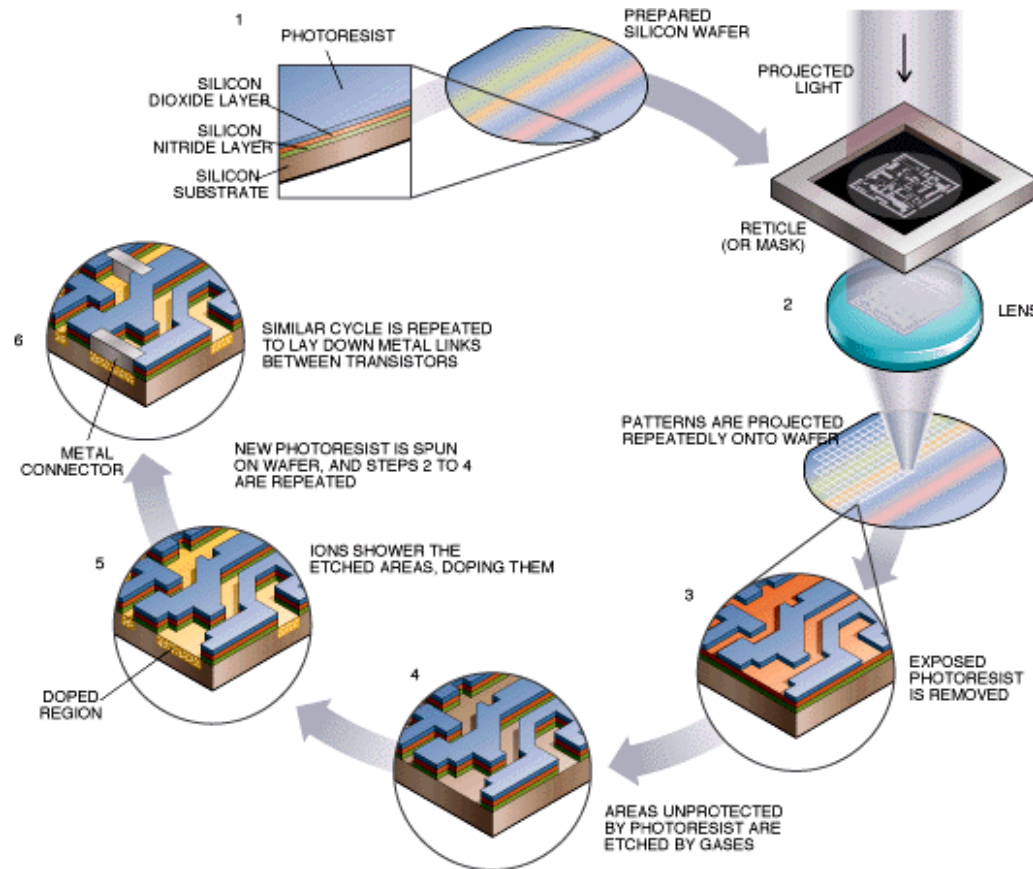
- *Optical (80-193 nm), electron beam (2-10 nm), soft (< 10nm), and scanning probe (< 2 nm).*

### Etching

- *Wet, dry, and focused ion beam milling.*

### Material modification

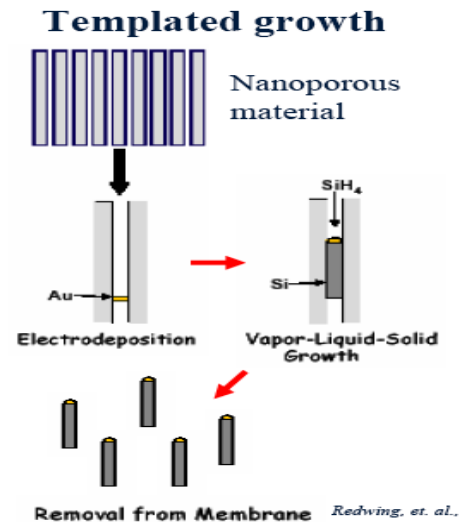
- *Diffusion and ion implantation.*



# Nanofabrication Approaches:

## (2) Bottom up

- **Chemical synthesis**
  - Nanotubes, nanowires, nanoparticles, and quantum dots.
  - Polymers and proteins.
- **Functional arrangements**
  - Self assembly.
  - Assisted assembly (fluidic, field, and surface tension).
  - Templated growth.
- **Scanning probe manipulation**
  - AFM and STM with atomic resolution.

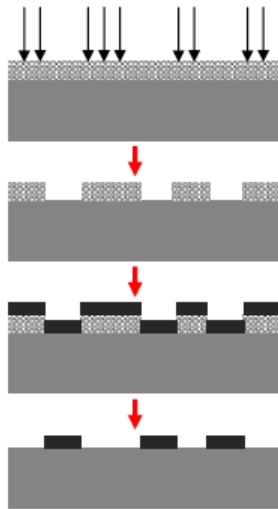




# Nanofabrication Approaches:

## (3) Hybrid - Combined Top down and Bottom up

Lithography,  
deposition, etch, ...



Templated growth, self assembly, ...



**==** New materials,  
devices and  
processes

# Nanotechnology Toolbox

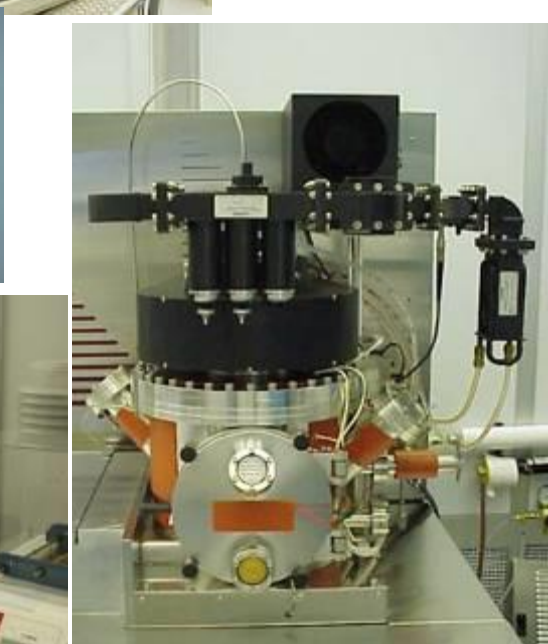
- **Nanofabrication refers to:**

- *Tools*
- *Techniques*
- *Equipment*
- *Processes*

*needed to manufacture micro and nano-scale devices.*

- *Analogous to a (machinists, carpenters, mechanics, etc..) toolbox.*





# *Nanotechnology : Impact on Education and Research*

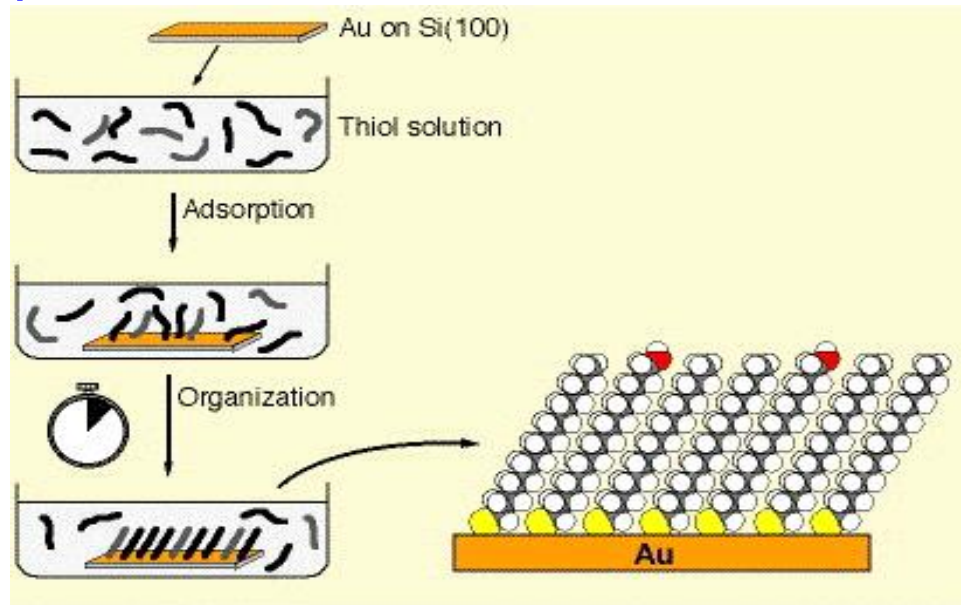


Building College-University  
Partnerships for Nanotechnology  
Workforce Development

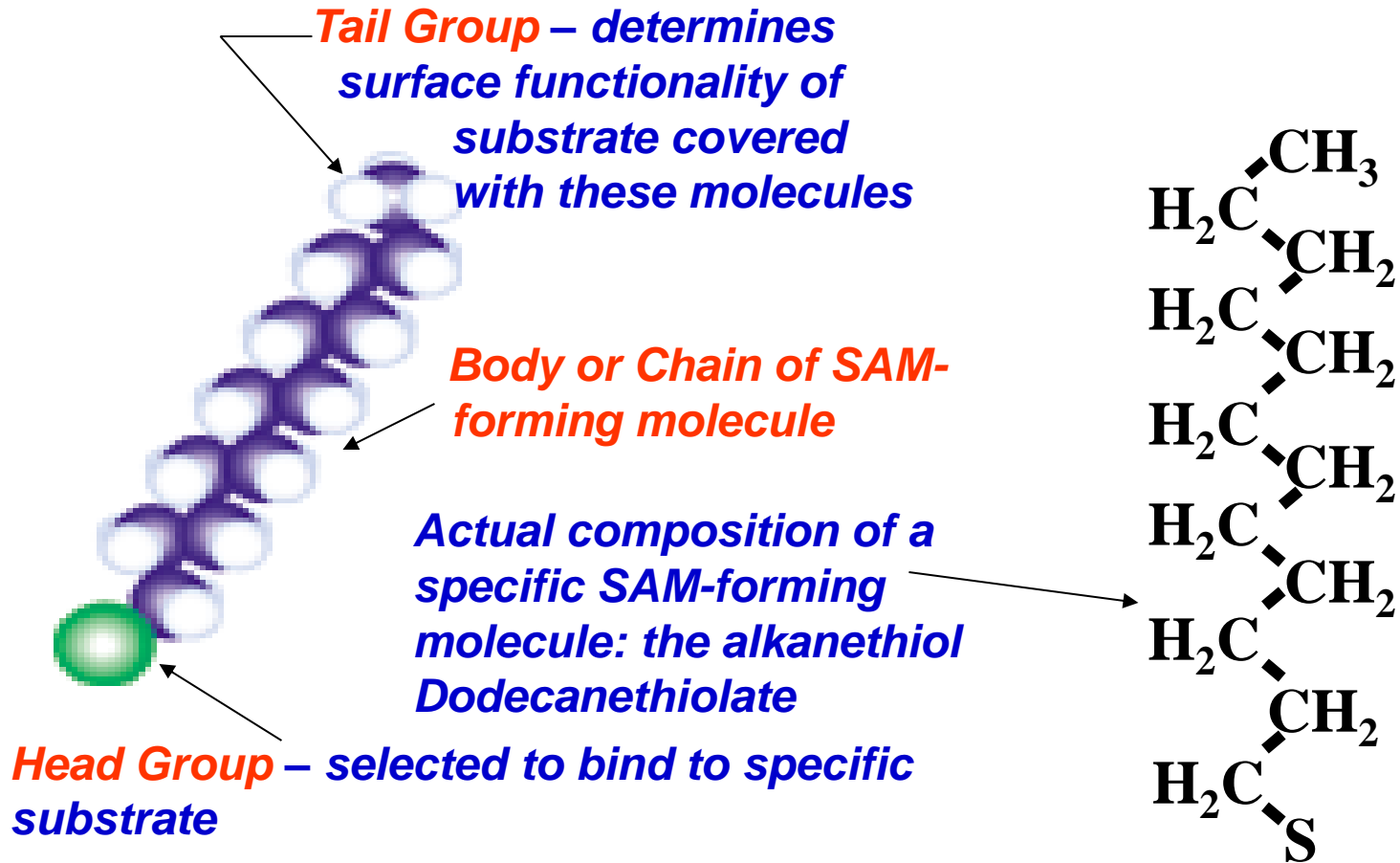
# College of Science

## – Chemistry/Biology and Self Assembly

- Selected molecules can “automatically” link to a surface. They self-assemble into a single monolayer; i.e., they form a self assembled monolayer (SAM) thereby changing the surface properties.
- Molecules can be chosen that bond at their “free end” to other molecules further chemically changing the surface.
- An example: thiolated molecules onto Au



# Self-Assembling Monolayer-Forming Molecules



# Physics and Material Science :

## Carbon Nanotubes

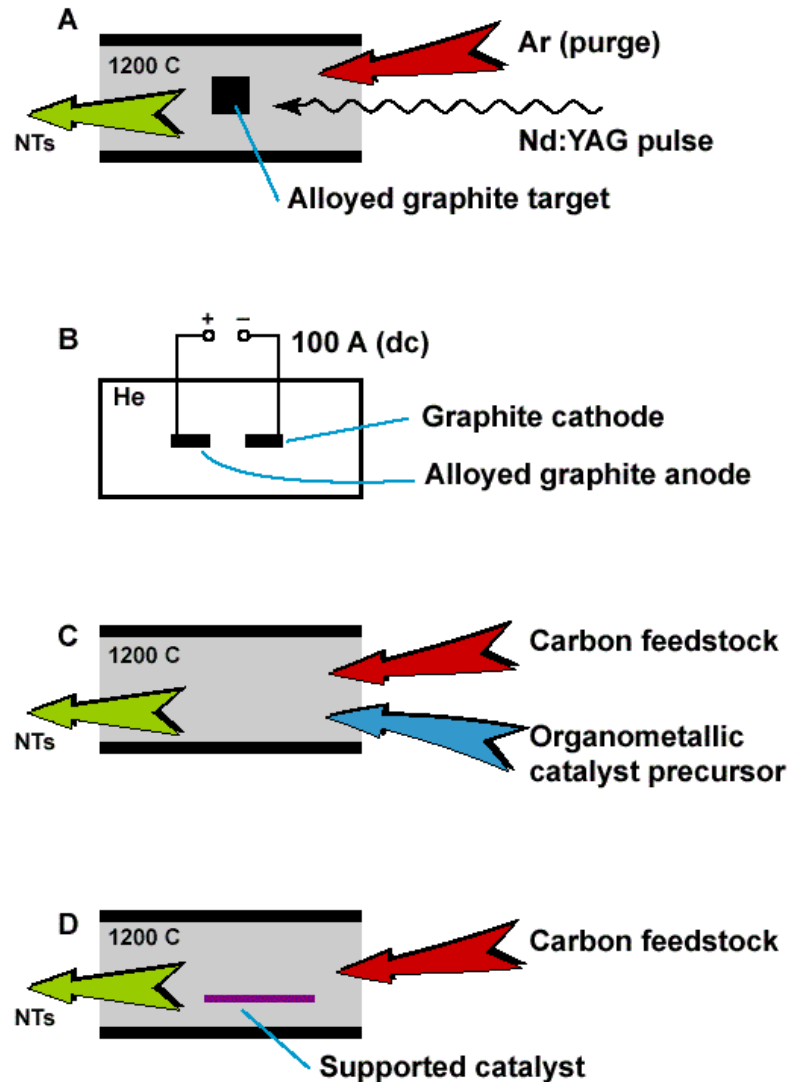
- *Carbon nanotubes (CNTs) belong to the fullerene family. Fullerenes are composed of covalently bonded C atoms arranged to form a closed, convex cage. The first of these molecules C<sub>60</sub> was reported in Nature 1985 by Rice University team (Nobel Prize 1996). C<sub>60</sub> distinctive soccer ball structure resembled architect Buckminster Fuller's geodesic domes winning the name "buckminsterfullerene".*
- *CNT is accredited to Sumio Iijima from NEC Corp. in 1991.*
- *The basic structure of both single wall CNT (SWNT) and multiwall CNT (MWNT) is derived from planar graphene sheet which is composed of sp<sup>2</sup> hybridized C atoms arranged with D<sub>6h</sub> point group symmetry.*
- *SWNT can be imagined to be a sheet that has been wrapped into a seamless cylinder.*
- *A typical SWNT diameter is 1.5 nm. It is less common that SWNT diameter is 1 nm or less, and larger tubes are generally more stable than small ones.*
- *SWNTs might be hundreds of nm long (aspect ratios is on the order of 1000) and are closed at both ends by hemispherical caps. Half of a C<sub>60</sub> molecule is the correct cap for large tubes.*
- *MWNTs are essentially multiple SWNTs of different sizes that have formed in a coaxial configuration.*
- *MWNTs are typically tens of nanometers in diameter and the spacing between the layered shells in the radial direction of the cylindrical nanotube is approximately ~ 0.3 nm.*

# Selected Characteristics of SWNTs

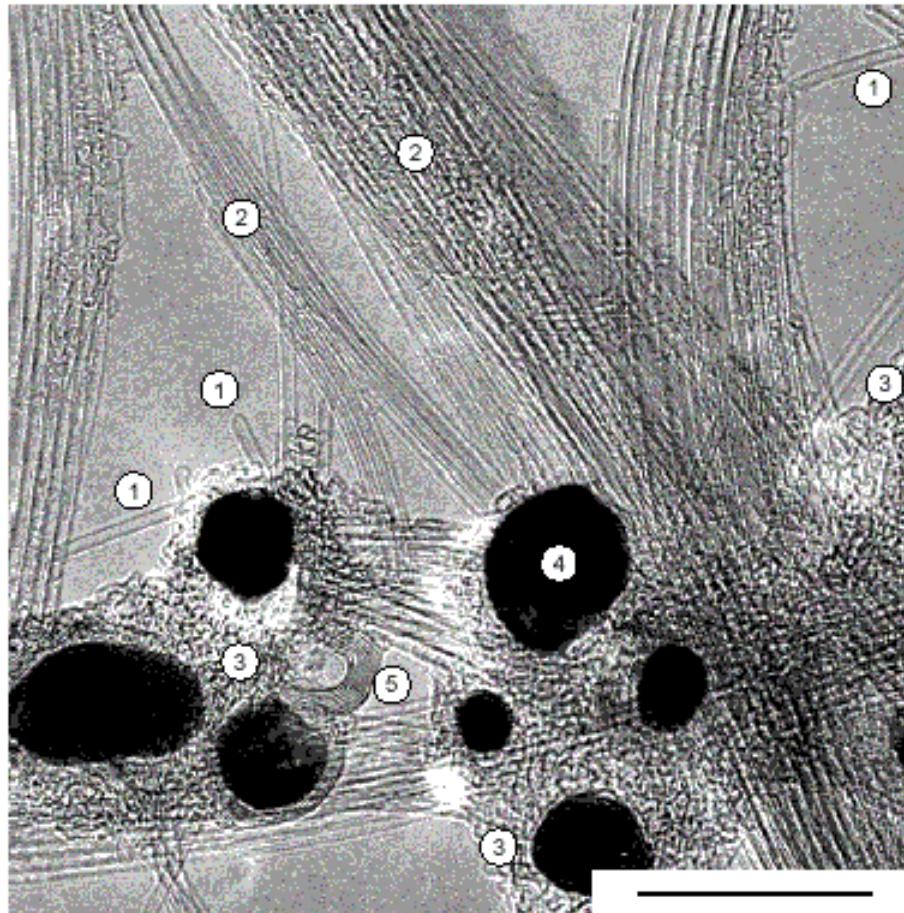
<i>Typical diameter</i>	<i>1-2 nm</i>
<i>Typical length</i>	<i>100-1000 nm</i>
<i>Intrinsic bandgap (metallic/semiconducting)</i>	<i>0 eV/~5 eV</i>
<i>Work function</i>	<i>~ 5 eV</i>
<i>Resistivity at 300 K (metallic/semiconducting)</i>	<i><math>10^{-4}</math>-<math>10^{-3}</math> <math>\Omega\text{cm}</math>/<math>10</math> <math>\Omega\text{cm}</math></i>
<i>Typical field emission current density</i>	<i><math>10</math>-<math>1000</math> <math>\text{mA cm}^{-2}</math></i>
<i>Thermal conductivity at 300 K</i>	<i><math>20</math>-<math>3000</math> <math>\text{W m}^{-1} \text{K}^{-1}</math></i>
<i>Elastic modulus</i>	<i><math>1000</math>-<math>3000</math> <math>\text{GPa}</math></i>



# CNT Synthesis



*Illustration of the four primary approaches for synthesizing carbon nanotubes: (a) pulsed laser vaporization, (b) arc discharge, (c) catalytic decomposition, and (d) chemical vapor deposition.*



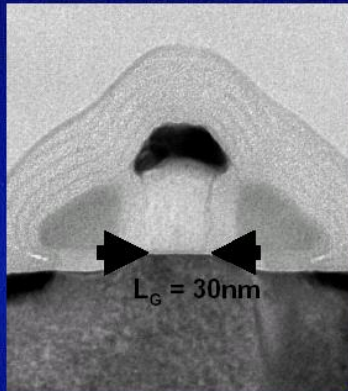
*Transmission electron micrograph of raw nanotube material produced by arc discharge. The multicomponent reaction product includes (1) isolated SWNTs, (2) SWNT ropes, (3) amorphous or uncatalyzed carbons, (4) residual catalyst particles, and (5) polyaromatic graphitic shells.*

# College of Engineering

## Electrical Engineering

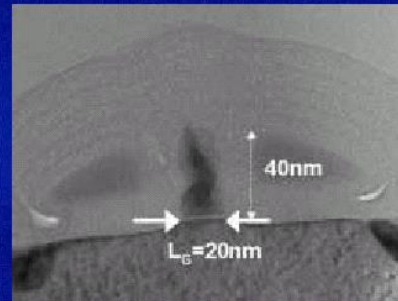
### Intel's Transistors Keep Shrinking *Record small transistors produced in Intel Labs*

30 nm



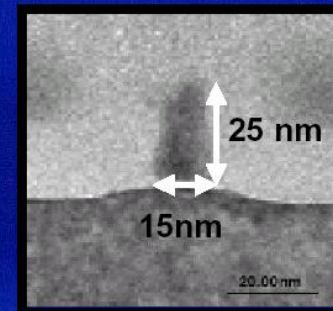
December 2000

20 nm



June 2001

15 nm



Today

7

Intel Labs

Source : Bob  
Trew, NCSU

# Nanoelectronics

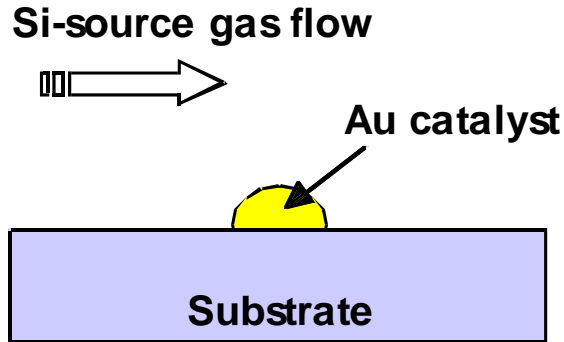
## Solid-State

- *Devices start small*
  - *Nanoparticles are “born” small*
  - *No need for etching*
  - *Position with self-assembly; then no need for lithography*
- *Possible new device physics*
  - *Very small structures possible—this gives rise to quantum confinement effects*
  - *New types of devices possible*

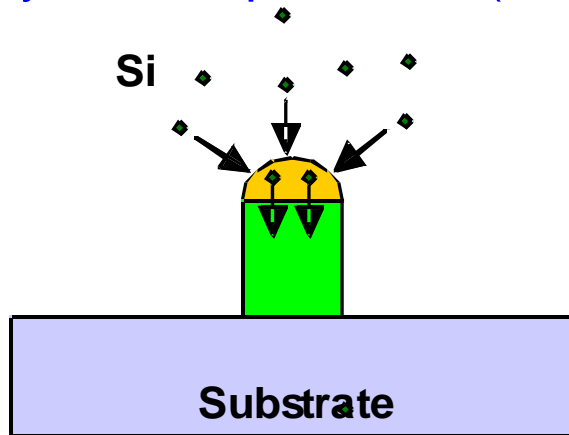
## Molecular Electronics (Moletronics)

- *Devices start very small*
  - *Molecules are inherently small*
  - *No need for etching*
  - *Position with self-assembly; then no need for lithography*
- *Possible new device physics and chemistry*
  - *New types of devices possible*

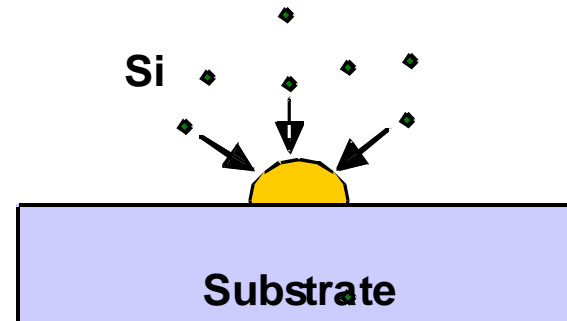
# Vapor-Liquid-Solid Growth of Silicon Nanowires



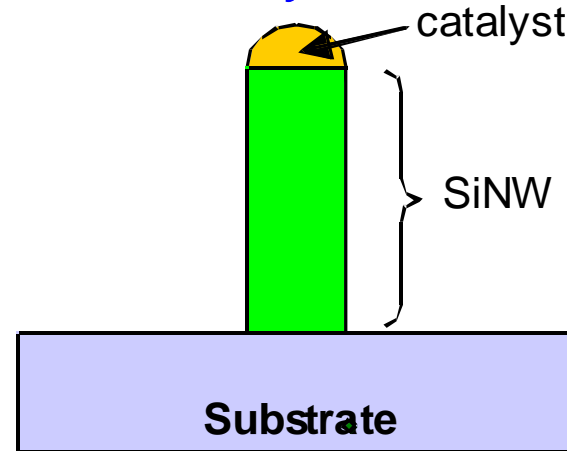
Molten eutectic alloy droplet at relatively low temperatures (363°C)



Eutectic liquid become supersaturated and Si precipitates out at a solid-liquid interface

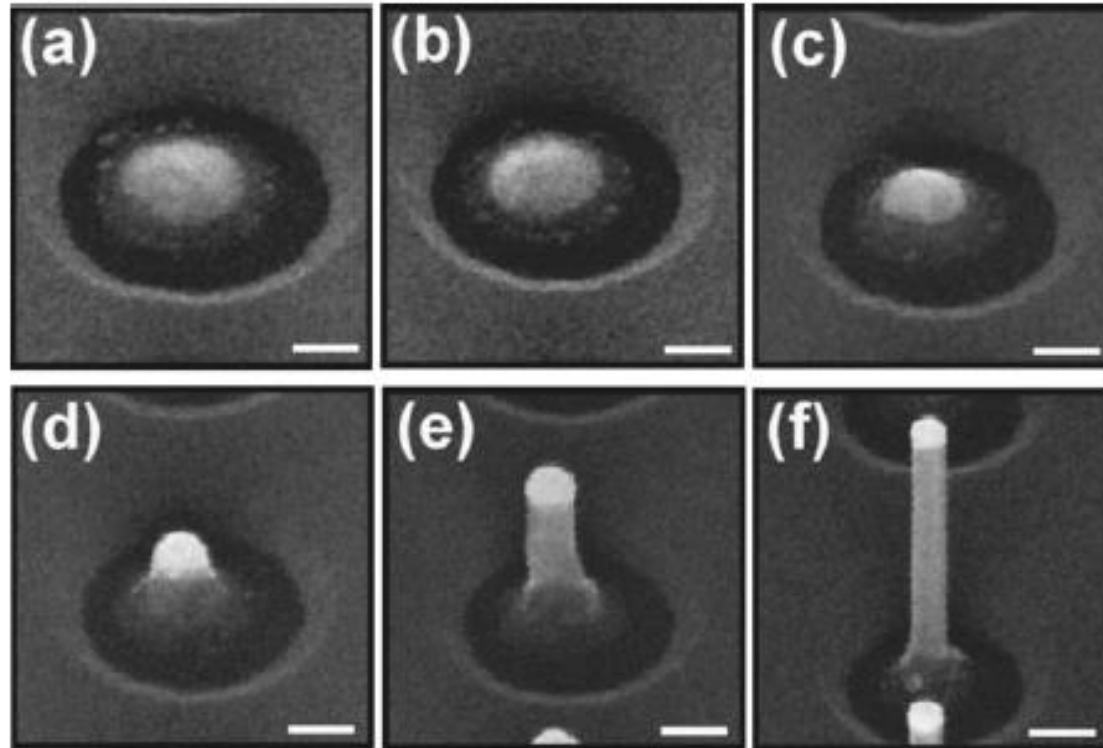


Liquid alloy acts as a preferred sink or catalyst for arriving vapor



Nanowire grown by VLS

# SiNW growth by CVD-VLS process

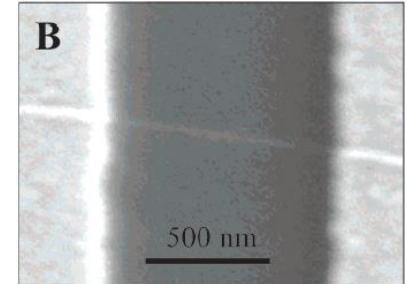
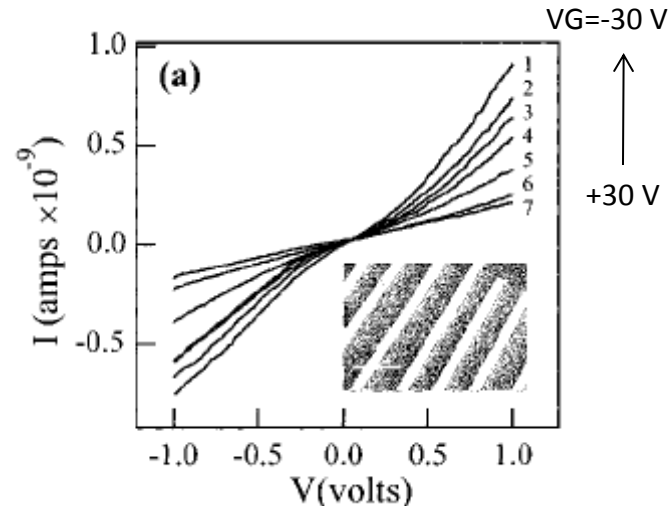


*(J. Appl. Phys. 103, 2008, p. 024304)*

# The first silicon nanowire field-effect transistor

## Fabrication Process

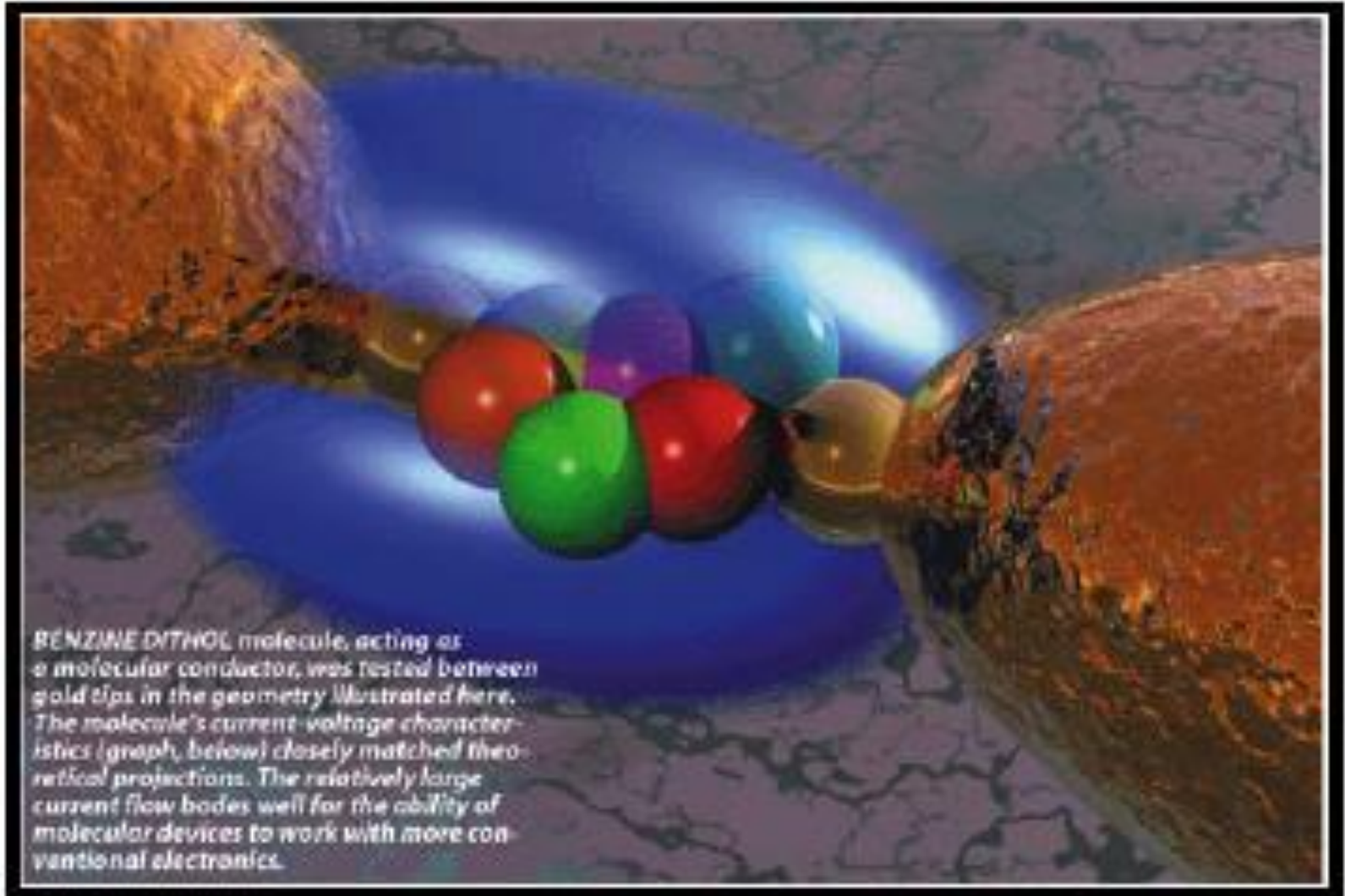
- A SiNW is placed on a Si/SiO<sub>2</sub> substrate.
- Source/Drain contacts are defined by conventional lithography technique.
- The back side of the substrate was used as the gate. SiO<sub>2</sub> was used as the gate oxide



Lieber Group  
Harvard

*Phys. Chem. B* **2000**, 104, 5213, *Nano Letters*. 3 2003, 149

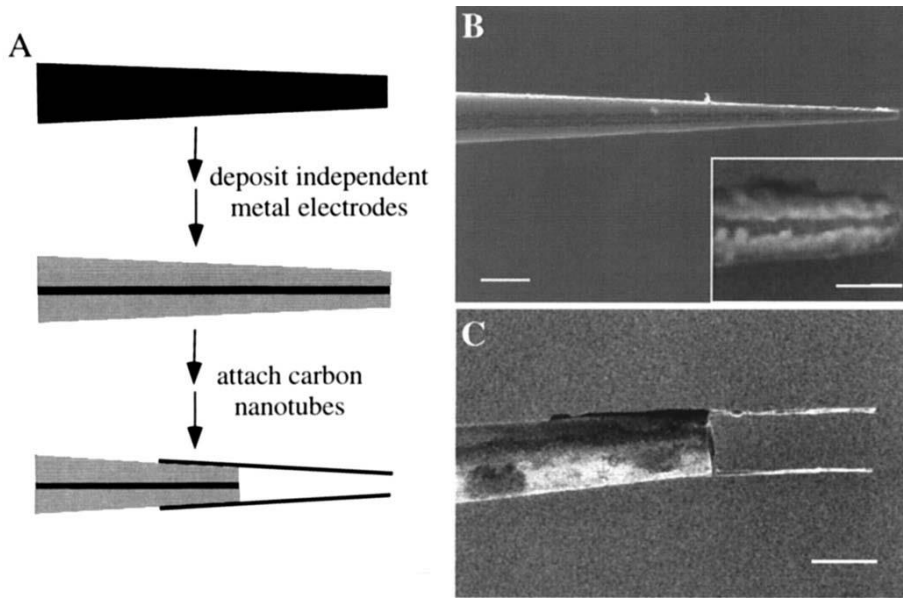
# Moletronics



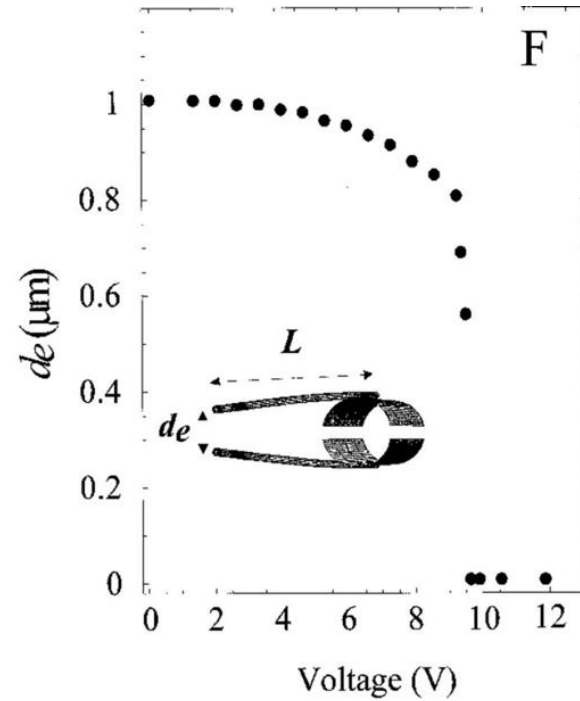
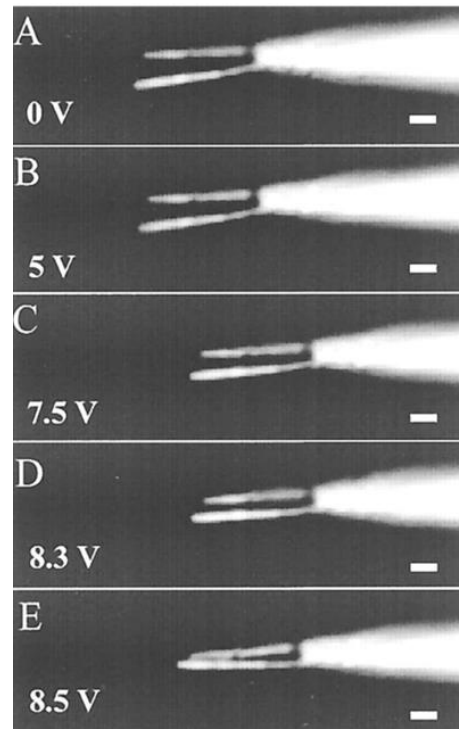


# Mechanical Engineering

- *At the nanoscale, surface and interface forces become dominant.*
  - *Adhesion forces*
  - *Capillary forces*
  - *Strain forces*
- *These forces can exceed forces that are often dominant in macroscopic structures, e. g., gravity.*
- *Surface coating is, therefore, very important in inhibiting forces of adhesion in nanoelectromechanical systems (NEMS).*
- *With reduced size, mechanical motion can proceed much faster.*
  - *Resonant frequency for a mass on a spring is inversely proportional to the square root of the mass.*
  - *Therefore molecular motors will have exceptionally high resonant frequencies, could be as high as 100 GHz.*

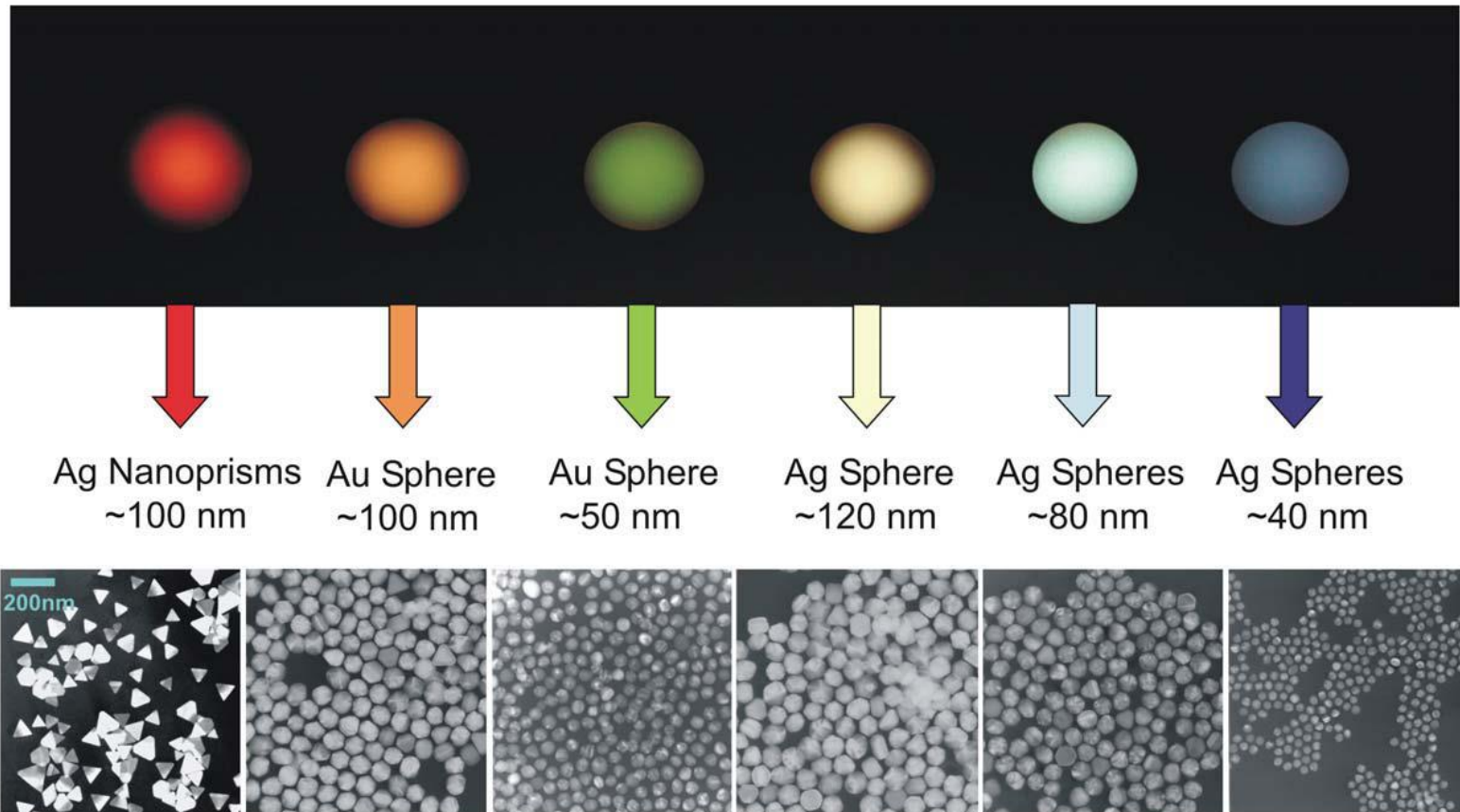


## *Carbon nanotube tweezers*



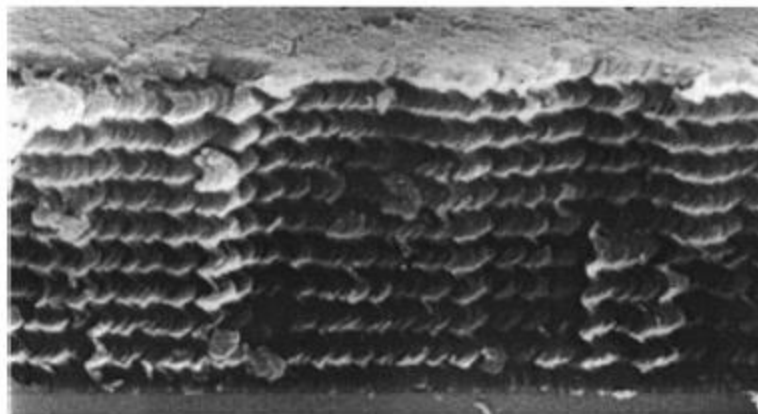
# Chemical/Material Engineering

## Rayleigh Light-Scattering of Nanocrystals: Shape, Size, and Composition Matter



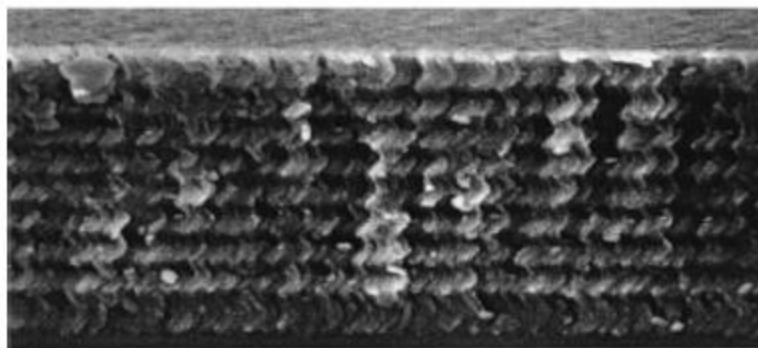
\* The scale bar is the same for all the images.

# Sculptured Thin Films (STFs)



(a)

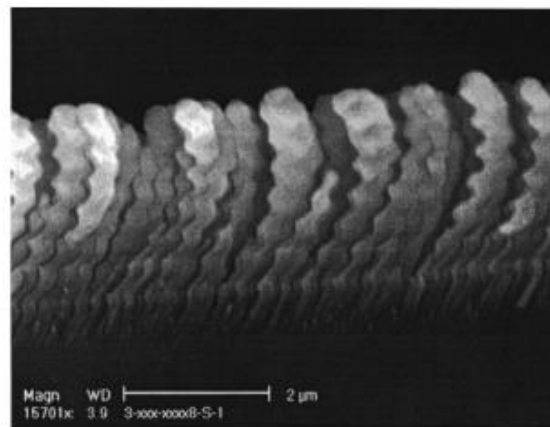
1 μm



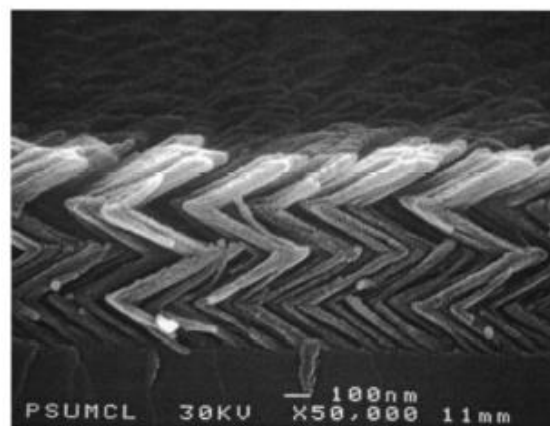
(b)

1 μm

FIG. 2. (a) Ten-turn TFHBM prepared by evaporation of SiO;  $\chi_V=8^\circ$ . (b) Nine-turn TFHBM prepared by reactive sputtering of SiO<sub>2</sub>;  $\chi_V=25^\circ$ .



(a)

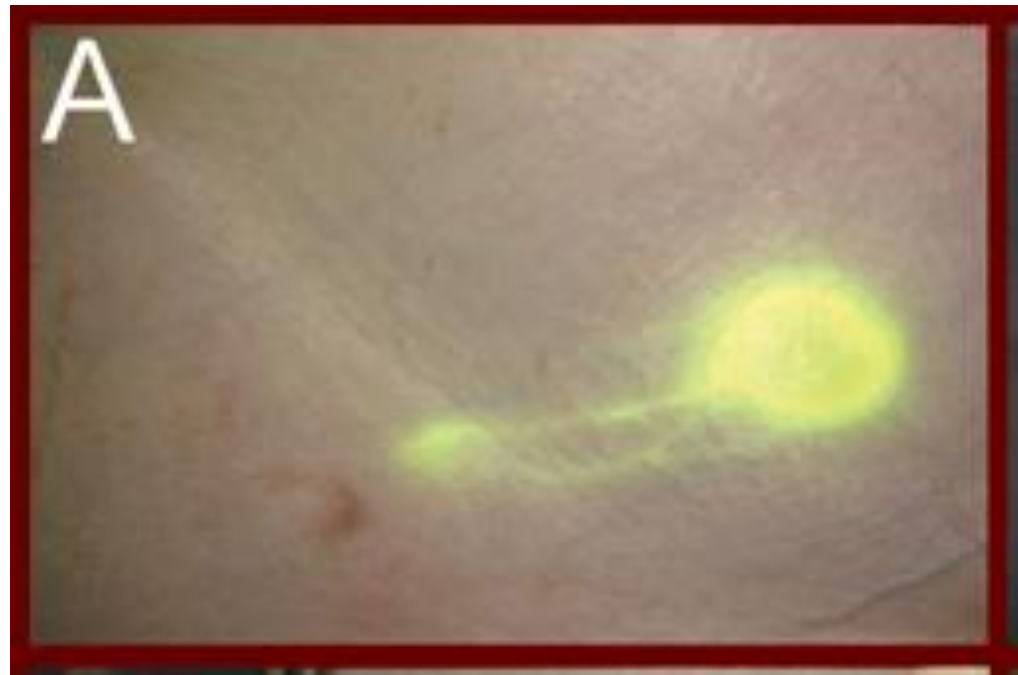


(b)

FIG. 3. (a) Superhelical STF prepared by MgF<sub>2</sub> evaporation at  $\chi_V=8^\circ$ ,  $\Delta=20^\circ$ , nine turns. (b) Double zigzag STF prepared by MgF<sub>2</sub> evaporation at  $\chi_V=5^\circ$  and  $175^\circ$ .

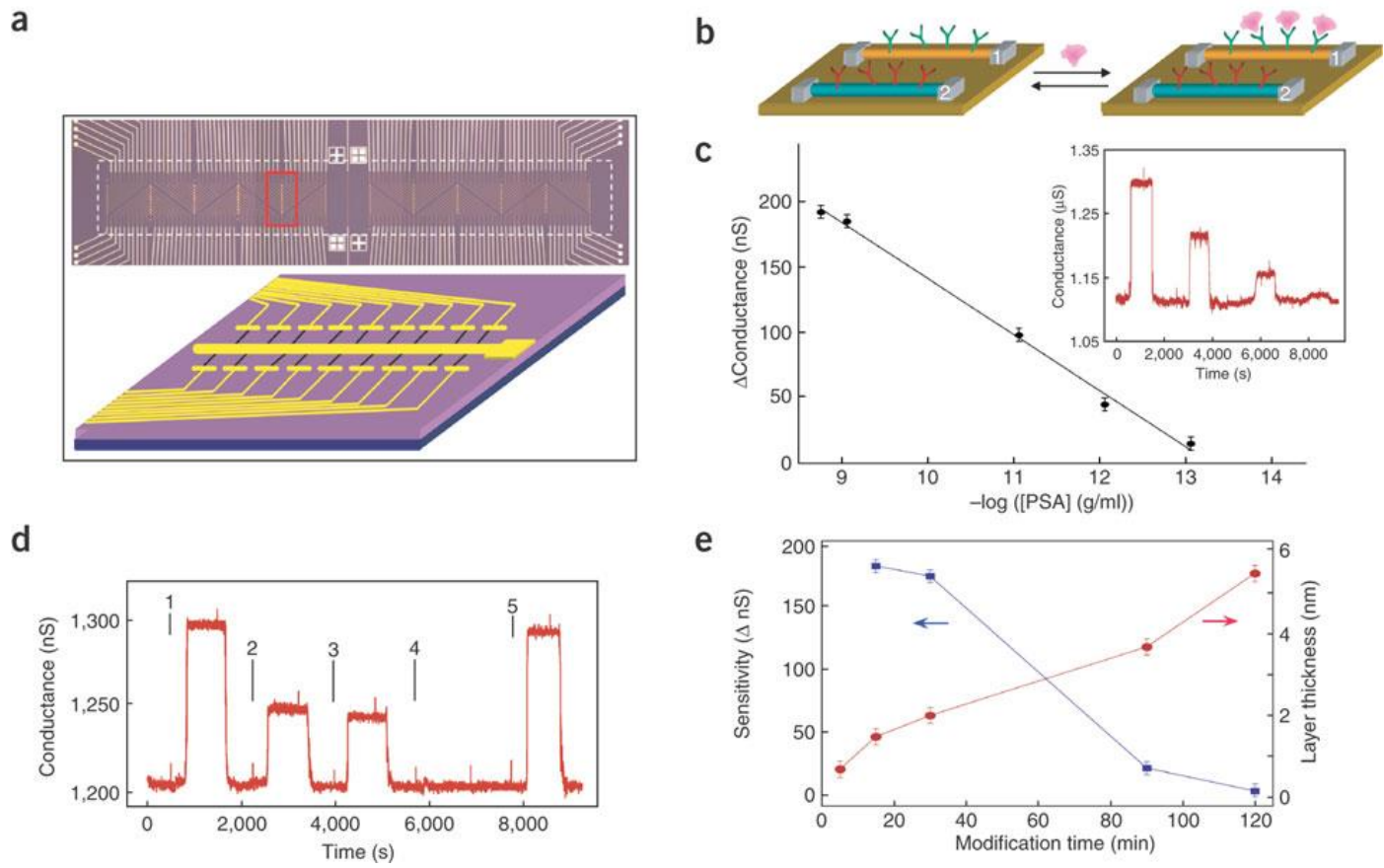
# College of Medicine

- *Quantum dots were injected into a primary tumor in a near-human sized pig (large green region at right).*
- *The color image clearly shows transport of the quantum dots through lymph vessels to a nearby lymph node (smaller green area at left) even when imaged non-invasively through the skin.*
- *This use of quantum dots allows a physician to see the tumor and its interaction with the lymph system – all non-invasively*



# Multiplexed electrical detection of cancer markers with nanowire sensor arrays

Gengfeng Zheng, Fernando Patolsky, Yi Cui, Wayne U Wang & Charles M Lieber



*Essentially, the binding of the biomolecule to the receptor behaves as a field effect (it changes the surface charge profile and the surface potential). The conductance and the I-V characteristics of the nanowire can therefore be used to characterize biomolecular binding.”*

# *Nanotechnology : Applications*



Building College-University  
Partnerships for Nanotechnology  
Workforce Development

# Application Areas for Nanotechnology

Medicine  
and  
Health

Information  
Technology

Energy  
Production  
/ Storage

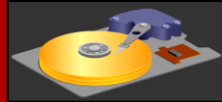
Materials  
Science

Food, Water  
and the  
Environment

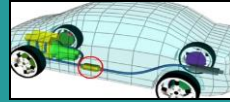
Instruments



Drug  
delivery



GMR Hard  
Disk



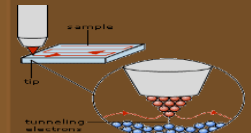
Hydrogen  
Fuel Cells



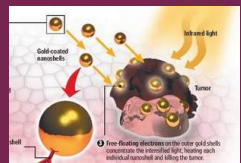
Lightweight &  
strong matls.



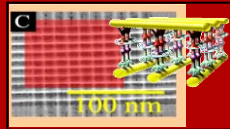
Remediation  
methods



Tunneling  
microscopy



Treatments  
for Cancer



Molecular  
Switches



Solar Cells



City-Sized  
Skyscrapers



“Smart”  
Membranes



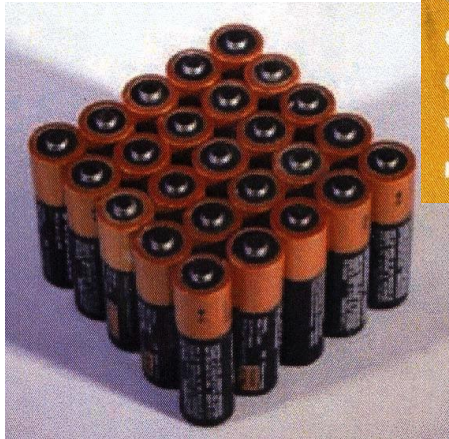
Nano  
Manipulators

*Expected to impact virtually all technological sectors as an “enabling” or “key” technology*



# Energy

- *Energy production, storage, and conversion.*
- *Photovoltaic cells and organic light-emitting devices based on quantum dots.*
- *Carbon nanotubes in composite coatings for solar cells.*
- *Long lasting rechargeable batteries.*
- *Nanocatalysts for hydrogen generation.*
- *Novel hydrogen storage systems based on carbon nanotubes and other lightweight nanomaterials.*



Batteries as a common means of energy storage are lasting longer with advances in nanotechnology

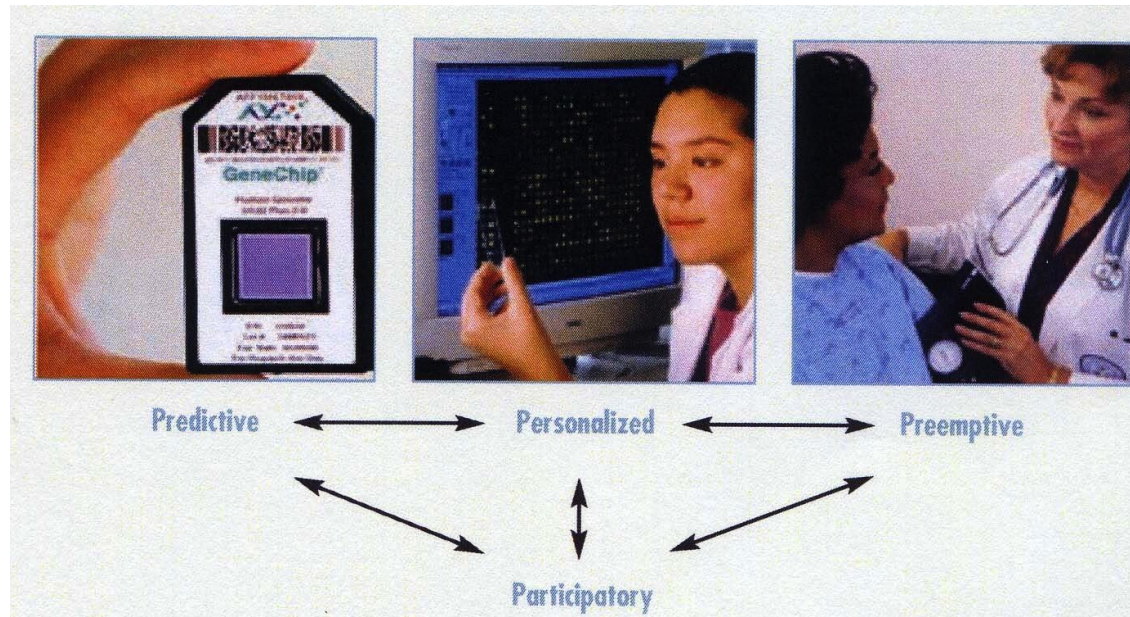


Solar panels can become more energy efficient using nanotechnology

# Nanomedicine

## Disease Diagnosis and Drug Delivery

- *New methods for disease diagnosis based on nanotools for imaging tissues and for analyzing blood.*
- *Lab-on-a-chip (nanoliter systems).*
- *Nanoparticles/nanocapsules as selective drug release systems for cancer treatment.*



*Nanotechnology could be used to make medicine more predictive, pre-emptive, personalized and participatory.*

# Agriculture and Food

## Agricultural

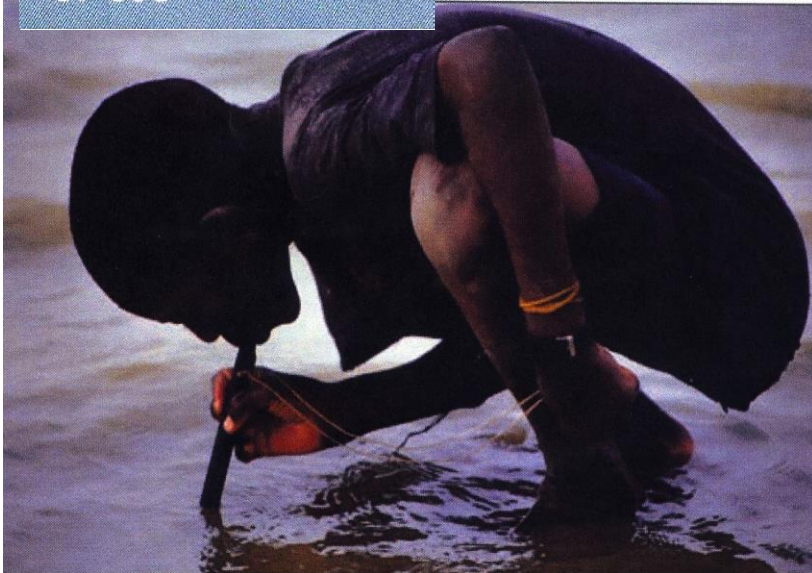
- *Productivity and enhancement.*
- *Nanoporous zeolites for slow-release and efficient dosage of water and fertilizers for plants, and of nutrients and drugs for livestock.*
- *Nanoparticles/nanocapsules for herbicide delivery.*
- *Nanosensors for soil quality and for plant health monitoring.*

## Food Processing and Storage

- *Nanocomposites for plastic coatings used in food packaging.*
- *Antimicrobial nanoemulsions for applications in decontamination of food equipment, packaging, or food.*
- *Nanotechnology-based antigen detecting biosensors for identification of pathogen contamination.*

# Environment and Water

Nano-enhanced technologies can generate clean water for safe drinking at point of use



## Water Treatment and Remediation

- *Nanomembranes for water purification, desalination, and detoxification.*
- *Nanosensors for the detection of contaminants and pathogens.*
- *Nanoporous zeolites, nanoporous polymers for water purification.*
- *Magnetic nanoparticles for water treatment and remediation.*
- *TiO<sub>2</sub> nanoparticles for the catalytic degradation of water pollutants.*

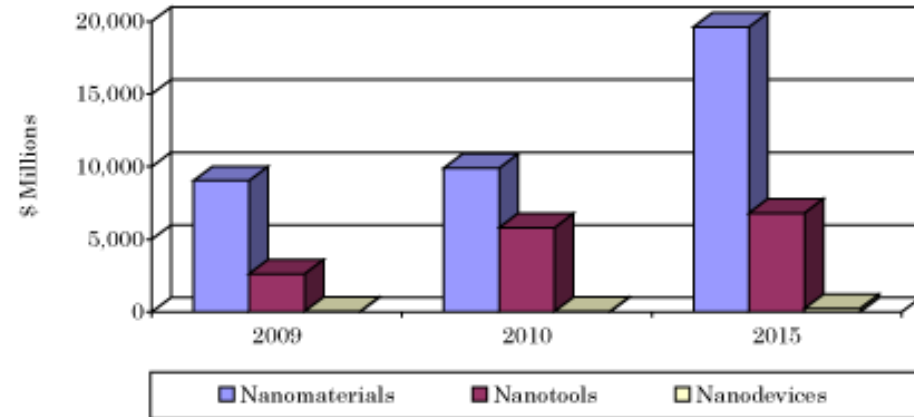
# *Nanotechnology : Economics*



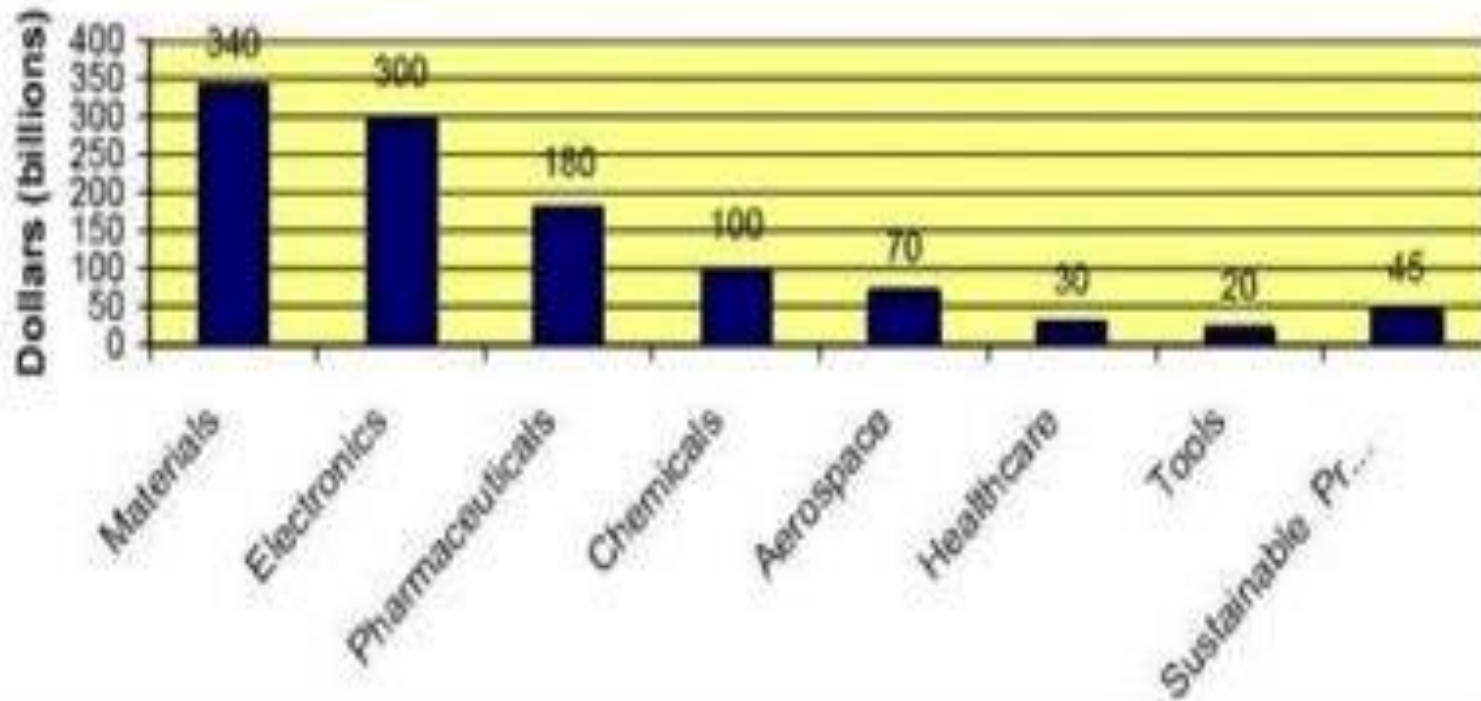
Building College-University  
Partnerships for Nanotechnology  
Workforce Development

# Worldwide NT Market

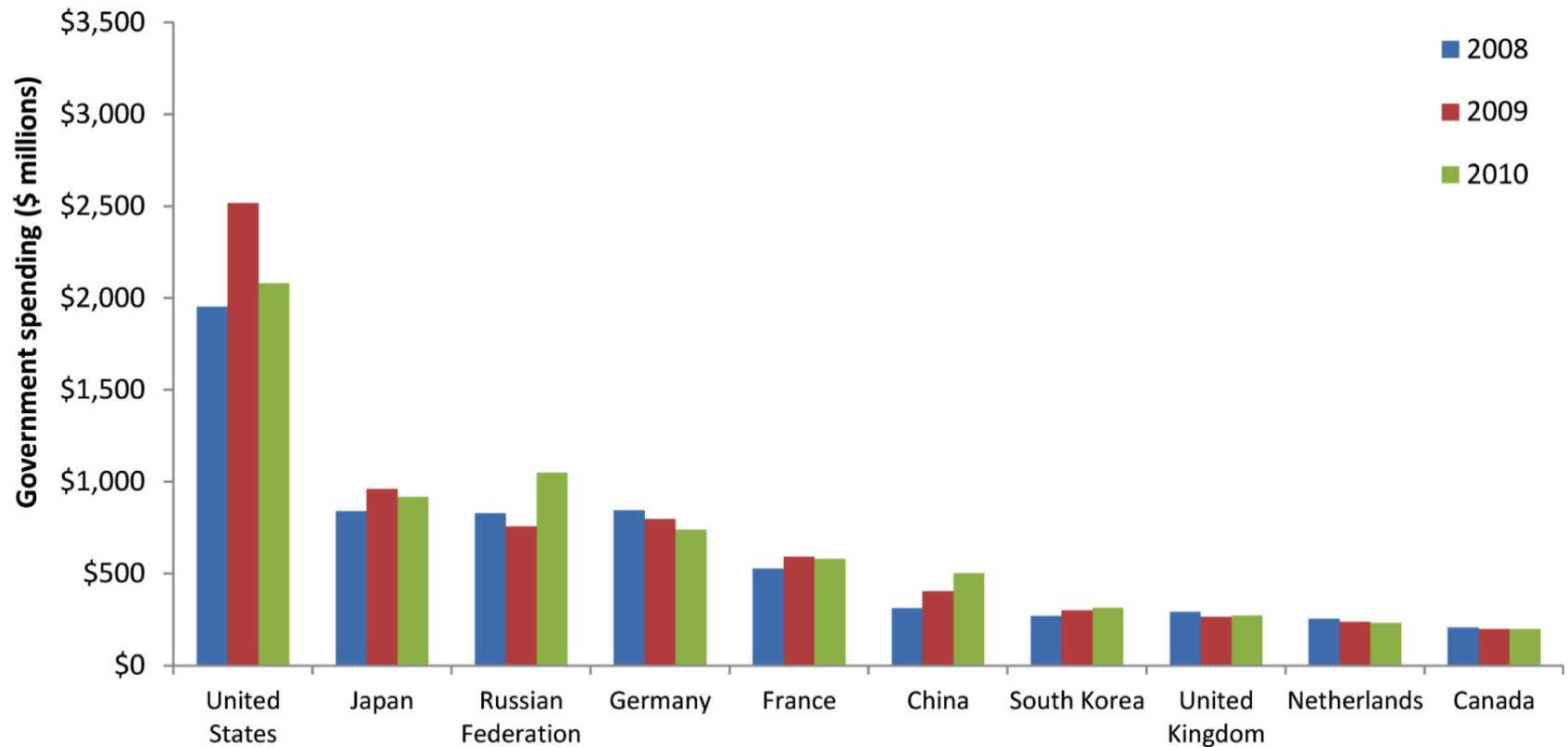
SUMMARY FIGURE  
GLOBAL NANOTECHNOLOGY MARKET, 2009-2015  
(\$ MILLIONS)



Source: BCC Research

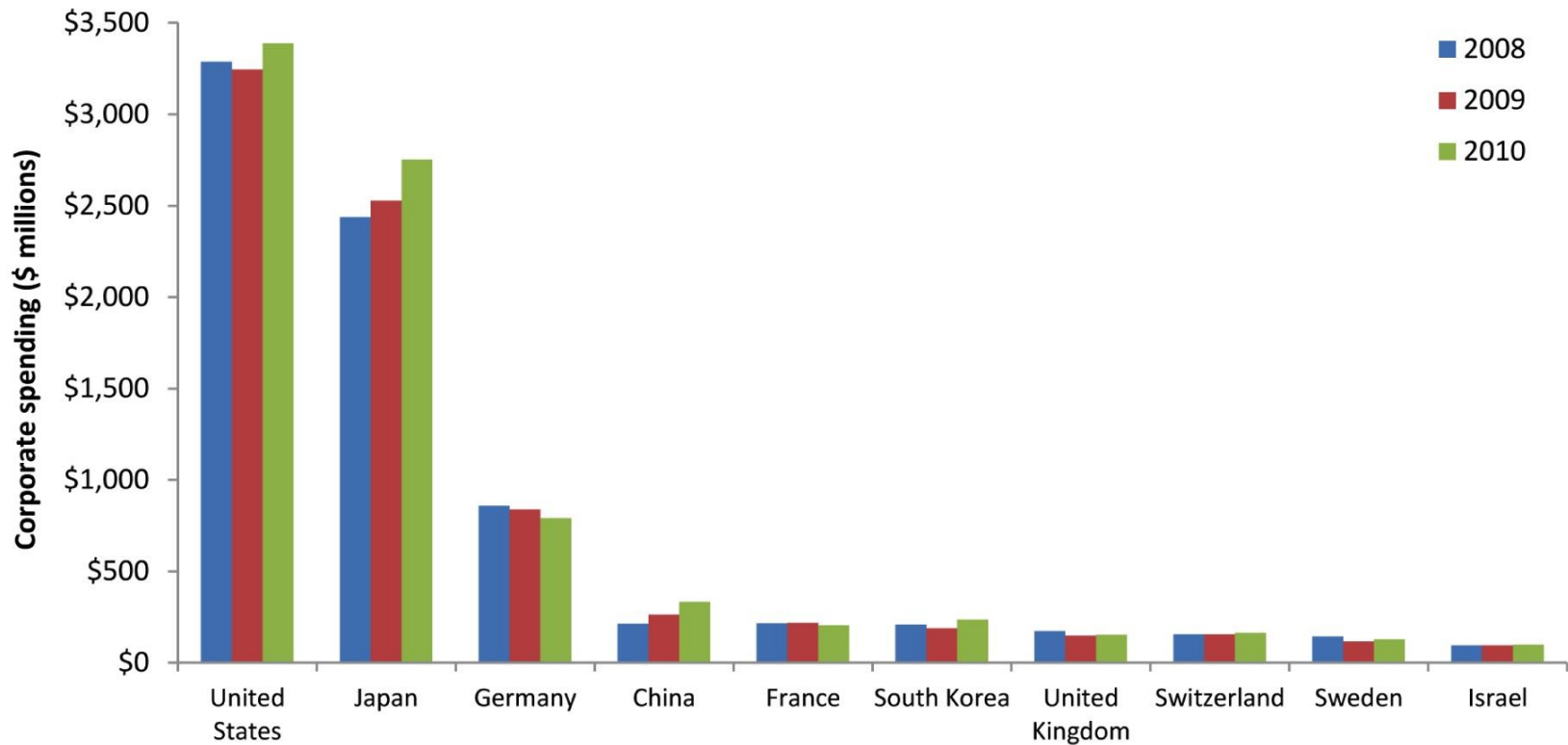


# Global Governmental Nanotechnology Spending: Top Ten Countries



Source: A. Xue and D. Hwang, "Nanotechnology Funding: Corporations Grab the Reins," *Lux Research*, April 2011.

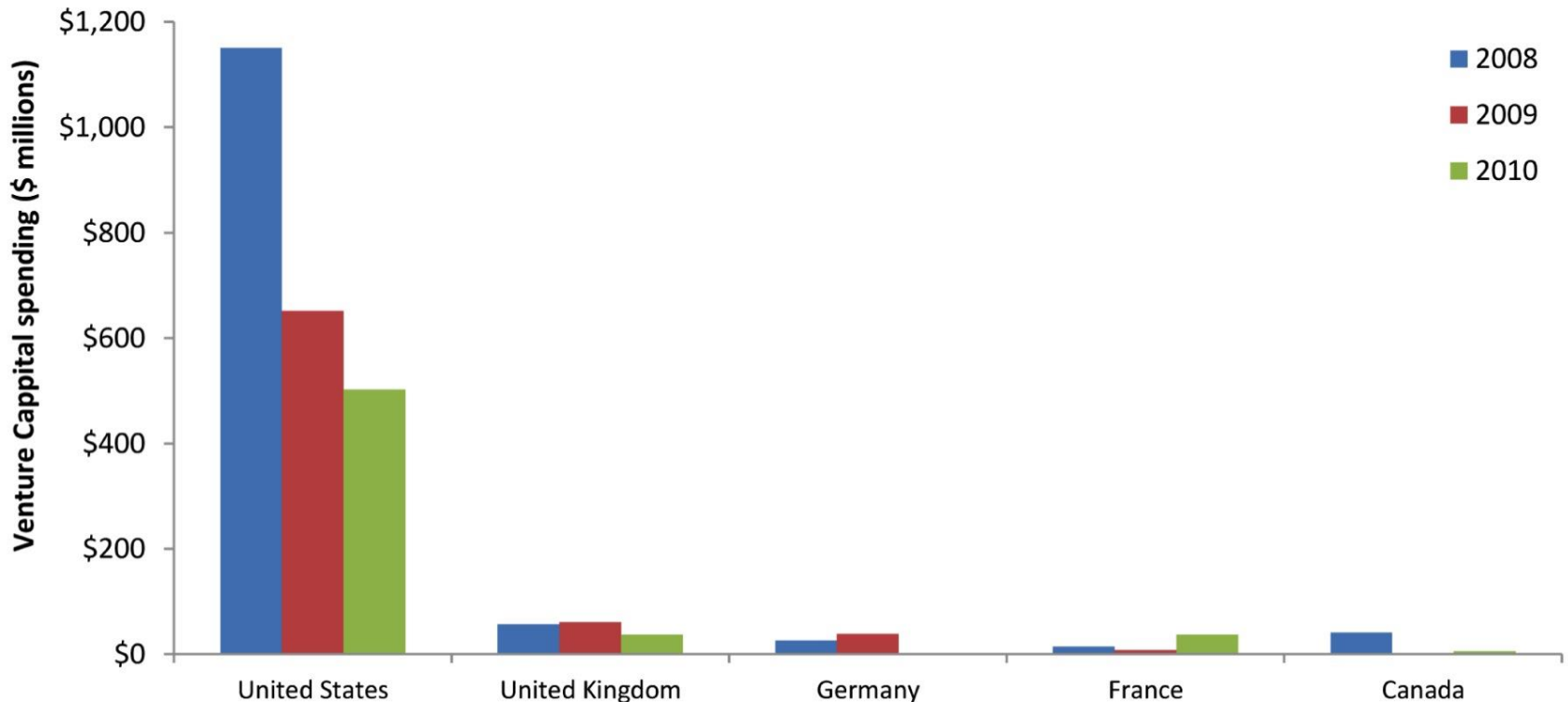
# Corporate Nanotechnology Spending: Top Ten Countries



Source: A. Xue and D. Hwang, "Nanotechnology Funding: Corporations Grab the Reins," *Lux Research*, April 2011.



# Venture Capital Nanotechnology Spending: Top Five Countries



Source: A. Xue and D. Hwang, "Nanotechnology Funding: Corporations Grab the Reins," *Lux Research*, April 2011.

Note: No data were available for Germany's Venture Capital spending for 2010.

# More Products Mean a Growing Need for a Trained Nanotechnology Workforce

## Workforce Demand:

- *By 2015:*
  - **2 million** *nanotechnology workers needed worldwide*
    - *Mihail C Roco, Nature Biotechnology Vol. 21, No. 10, Oct. 2003*
  - *Potentially **5 million** additional “infrastructure” support jobs needed in the global market by 2015.*
    - *Mihail C Roco, Nature Biotechnology Vol. 21, No. 10, Oct. 2003*
- *However, only very few states in the US have seriously addressed the issue of workforce development*
  - *Jack Uldrich, Smalltimes Magazine, April 22, 2005*

# *Nanotechnology : Workforce Development*



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# Nanotechnology Research Workforce Development : Training Existing Researchers

- *Training Existing Personnel in NT Research: University Professors and Research Staff in Governmental and Industry Laboratories*
  - *NT must be accessible to researchers in a wide range of research expertise : physical, chemical, and biological sciences and their engineering applications; medicine, agriculture; environment etc.*
  - *Short/long-duration fellowships, workshops, symposia etc. in institutions with advanced NT facilities and research: e. g., public and private universities, national labs, and industry would be of help in this respect.*
  - *National Nanotechnology Infrastructure Network (NNIN) is assisting in this front.*

# Nanotechnology University-Level Workforce Development

- **Graduate Level**
  - *Development of M. S. and Ph. D. programs focusing on NT.*
  - *Development of NT-related courses in different graduate degrees.*
  - *Promote interdisciplinary research and course offerings: NT is highly interdisciplinary.*
- **Undergraduate Level**
  - *Interdisciplinary degree offerings.*
  - *Development of new majors.*
  - *Development of concentrations and minors in NT coupled to different majors.*
- *Overall, there may be a need for redefining borders between colleges and departments in newly established institutes of technology and universities.*

# Nanotechnology Technical Workforce Development

- *The goals are to develop a workforce for existing and emerging nano- and microtechnology-based industries.*
- *Two-year Associate Level Degrees focusing on NT : Technology degrees and Science degrees.*
- *Broad education—not directed toward one industry.*
- *Bottom-up and top-down nanofabrication.*
- ***Hands-on total immersion in nanofabrication and characterization.***
- *Incumbent worker training and workshops for industry technicians.*
- *You will be introduced to NACK's approach in this aspect of education in this workshop.*

# High School and Secondary Level Education

- *Integrate nanotechnology into biology, physics, chemistry, and general science curricula.*
- *Inject nanotechnology into the curriculum (Use kits, modules, remote web-access to equipment).*
- *More student exposure--nanotechnology Camps.*
- *More teacher exposure--Workshops for Educators.*
- *You will be introduced to NACK's approach in this aspect of education in this workshop.*

THANK YOU