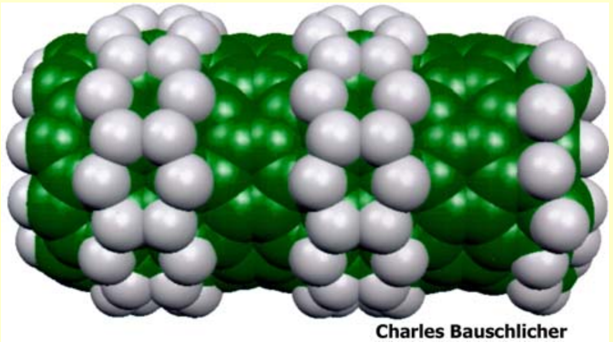
Lecture on Microsystems Design and Manufacture

Chapter 12
Introduction to Nanoscale Engineering



A Futuristic Nanoscale Engineering Product:
an artistic view of a step-shaft built with atoms

"If I were asked for an area of science and engineering that will most likely produce the breakthroughs of tomorrow, I would point to nanoscale science and engineering."
-Neal Lane
Former Assistant to President Clinton for Science and Technology

"Nanotechnology has given us the tools…to play with the ultimate toy box of nature – atoms and molecules. Everything is made from it…..The possibilities to create New things appear limitless." by Horst Stormer, a Nobel Laureate in physics

"the way of ingeniously controlling the building of small and large structures, with intricate properties; it is the way of the future, a way of precise, controlled building, with incidentally, environmental benignness built in by design." by Ronald Hoffmann, a Nobel Laureate in chemistry.

Outline

Part 1

Overview of Nanotechnology

Overview of Nanotechnology

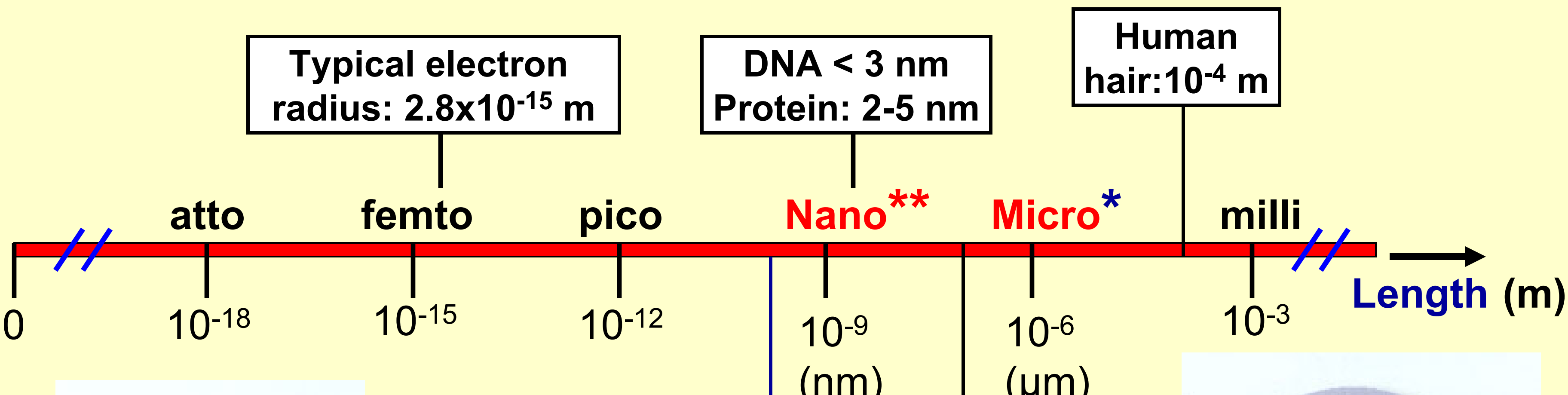
What is Nanotechnology?

Nanotechnology is the creation of:

USEFUL/FUNCTIONAL materials, devices and systems through control of matter on the nanometer length (nm) scale, and exploitation of novel phenomena and properties (physical, chemical, biological) at that length scale to satisfy human needs.

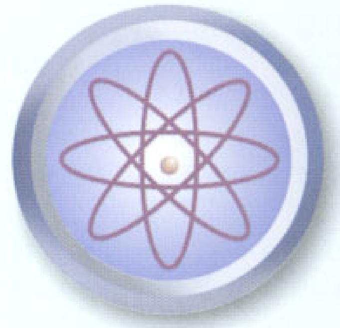
The Perception of Length Scale

- The nanometer (nm)

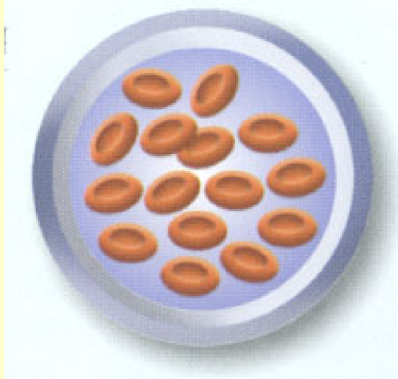


*1 µm = 10^{-6} m ≈ one-tenth of human hair

** **1 nm** = 10^{-9} m ≈ span of 10 shoulder-to -shoulder H_2 atoms



Less than a nanometer
Individual atoms are up to a few angstroms, or up to a few tenths of a nanometer, in diameter.



Thousands of nanometers
Biological cells, like these red blood cells, have diameters in the range of thousands of nanometers.

Why nanotechnology?

All matter that exist in universe are made of atoms or molecules.

The way atoms or molecules of various shapes and surface features organize into patterns on nanoscales determines important material properties, e.g. properties in: electrical and thermal conductivity, optical properties, mechanical strength.

Specifically, two factors can determine the properties of matter:

- The atomic structures (e.g., No. of electrons, as in the periodic table)

  Example: Change electric resistivity of silicon by doping.
- The arrangement of atoms (e.g., molecular structures, like polymers)

Additionally, the size of substances in nanoscale can alter their characterizations in: chemical reactivities, optical reflectivity (e.g., colors), diffusivities, buoyancy, solubility, etc.)

If only we can manipulate the atomic structures and control the arrangement of the atoms in matter, can we then create materials with desirable material properties characterization – e.g., materials with super strength, super electric and thermal conductivities, healthy genomes and biochemical substances in health care, super chemical reactions in drug discovery and productions, etc.

Active R&D in Nanotechnology:

inspired by Richard Feynman's speech in 1959

(1918 - 1988)

A visionary and a Nobel Laureate in Physics, 1965

Feynman, R., **"There's Plenty of Room at the Bottom: An invitation to enter a new field of physics,"** (miniaturization) first presented at the American Physical Society at California Institute of Technology on December 29, 1959. Subsequent publication in 'Engineering and Science', Caltech, February 1960.

Quotations from of Richard Feynman's Speech:

Feynman's vision on a new field of research:

" A field, in which little has been done, but in which an enormous amount can be done in principle."

"This field is **Miniaturization**."

Feynman's view on "The marvelous biological systems":

"In the tiniest cell, all information for the organization of a complex creature such as ourselves can be stored.

All this information - whether we have brown eyes, or whether we think at all, or that in the embryo the jawbone should first develop with a little hole in the side so that later a nerve can grow through it -

- *all this information is contained in a very tiny fraction of the cell in the form of long-chain DNA molecules in which approximately 50 atoms are used for one bit of information about the cell* "

Quotations from Richard Feynman's Speech (Cont'd):

Feynman's view on "The marvelous biological systems"- Cont'd**:**

"Biology is not simply writing information; it is doing something about it."

" Many of the cells are very tiny, but they are active; they manufacture various substances; they walk around; they wiggle; and they do all kinds of marvelous things - all on a very small scale. Also they store information.

Consider the possibility that we too can make a thing very small which does what we want - that we can *manufacture* an object that maneuvers at that level! "

Feynman's vision on "Nanotechnology":

" So, ultimately, when our computer get faster and faster and more and more elaborate, we will have to make them smaller and smaller.

But there is plenty of room to make them smaller.

There is nothing that I can see in the physical laws that say the computer elements cannot be made enormously smaller than they are now "

The Very First Human-Made Nanostructure -
The “Buckyball”

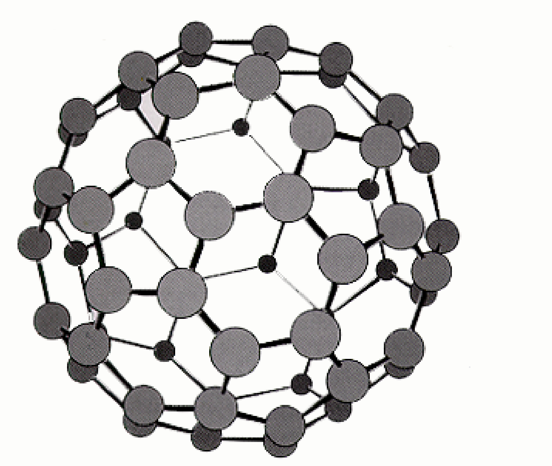
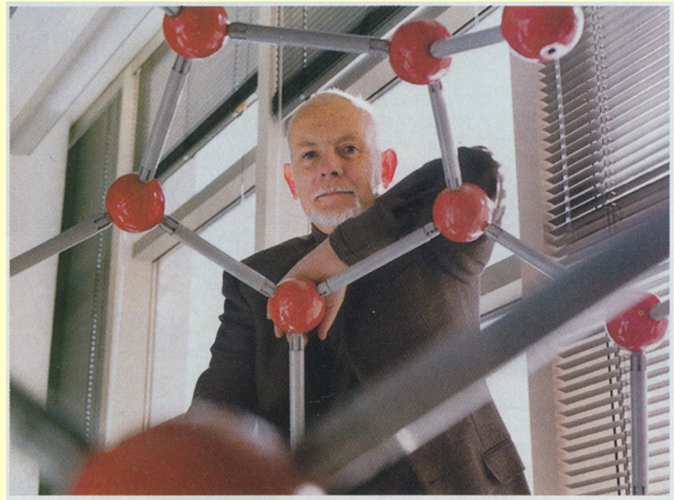


Figure 1.12 Buckminsterfullerene (C_{60}). A third form of pure carbon.

Created in 1985 by a chemistry professor, **Richard Smalley** from Rice University - a Nobel Laureate in 1996.



SMALLEY The buckyballs he discovered can be assembled into shapes that fit onto the receptors of cells

It contained 60 carbon atoms in the shape of a soccer ball with a diameter of 0.7 nanometer.

Made from the Buckminsterfullerene - a third form of pure carbon molecule.

(after the name of a futurist, R. Buckminster Fuller)

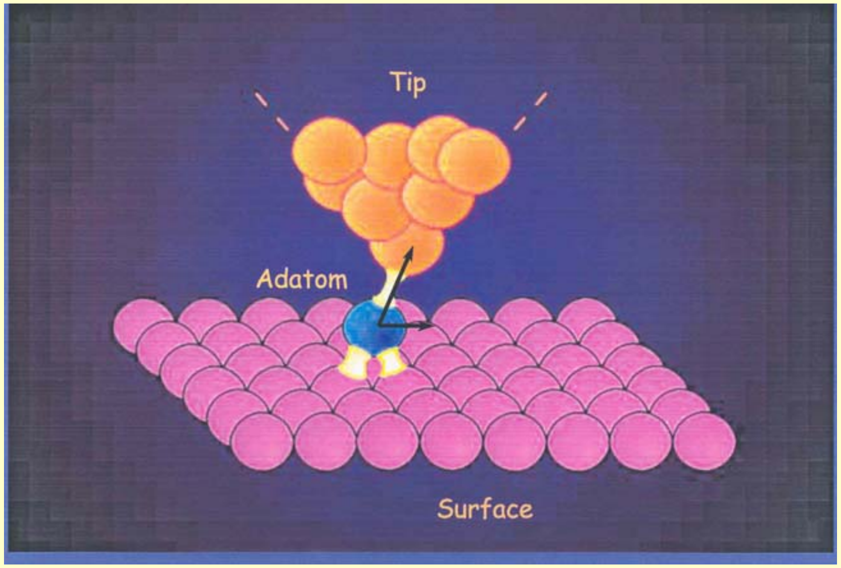
Comparison of Micro- and Nanoscale Technologies

Nanotechnology is NOT a natural outgrowth of MEMS technology!!

Microsystems (MST) Technology	Nanotechnology
Top-down approach	Bottom-up approach
Miniaturization with micrometer and sub-micrometer tolerances	Miniaturization with atomic accuracy
Builds on solid-state physics	Builds on quantum physics and quantum mechanics, e.g. molecular solid and gas dynamics, heat transfer
Evolved from IC fabrication technology	Undefined
Established techniques for producing electromechanical functions	Far from being developed
Established fabrication techniques	Fabrication techniques are in experimental stage
Established manufacturing techniques	Limited to manipulation of atoms only
Proven devices and engineering systems in marketplace	Only a few staionary machine components of simple geometry are produced
Success in commercialization of a few products	A long way to go

Major Impacts of Nanotechnology

(source: Meyya Meyyappan, NASA Ames)



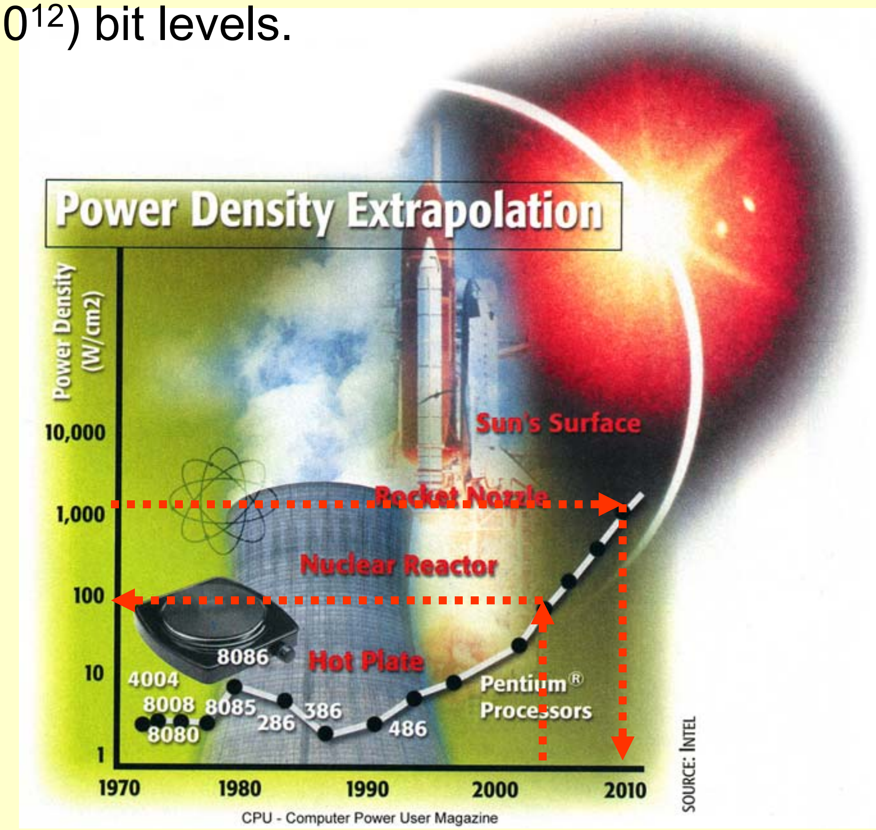
Nanotechnology is an enabling technology

- Electronics, Computing and Data Storage
- Materials and Manufacturing
- Health and Medicine
- Energy and Environment
- Transportation
- National Security
- Space exploration
-
-

Nanotechnology Benefits in Electronics and Computing

(source: Meyya Meyyappan, NASA Ames)

- Processors using molecular electronics with declining energy use and cost per gate, thus increasing efficiency of computer by 10^6.
- Small mass storage devices: multi-tera (10^{12}) bit levels.
- Integrated nanosensors: collecting, processing and communicating massive amounts of data with minimal size, weight, and power consumption.
- Higher transmission frequencies and more efficient utilization of optical spectrum to provide at least 10 times the bandwidth now.
- Display technologies, e.g., TFT.
- Quantum computing, e.g., spinning single electron transistor.



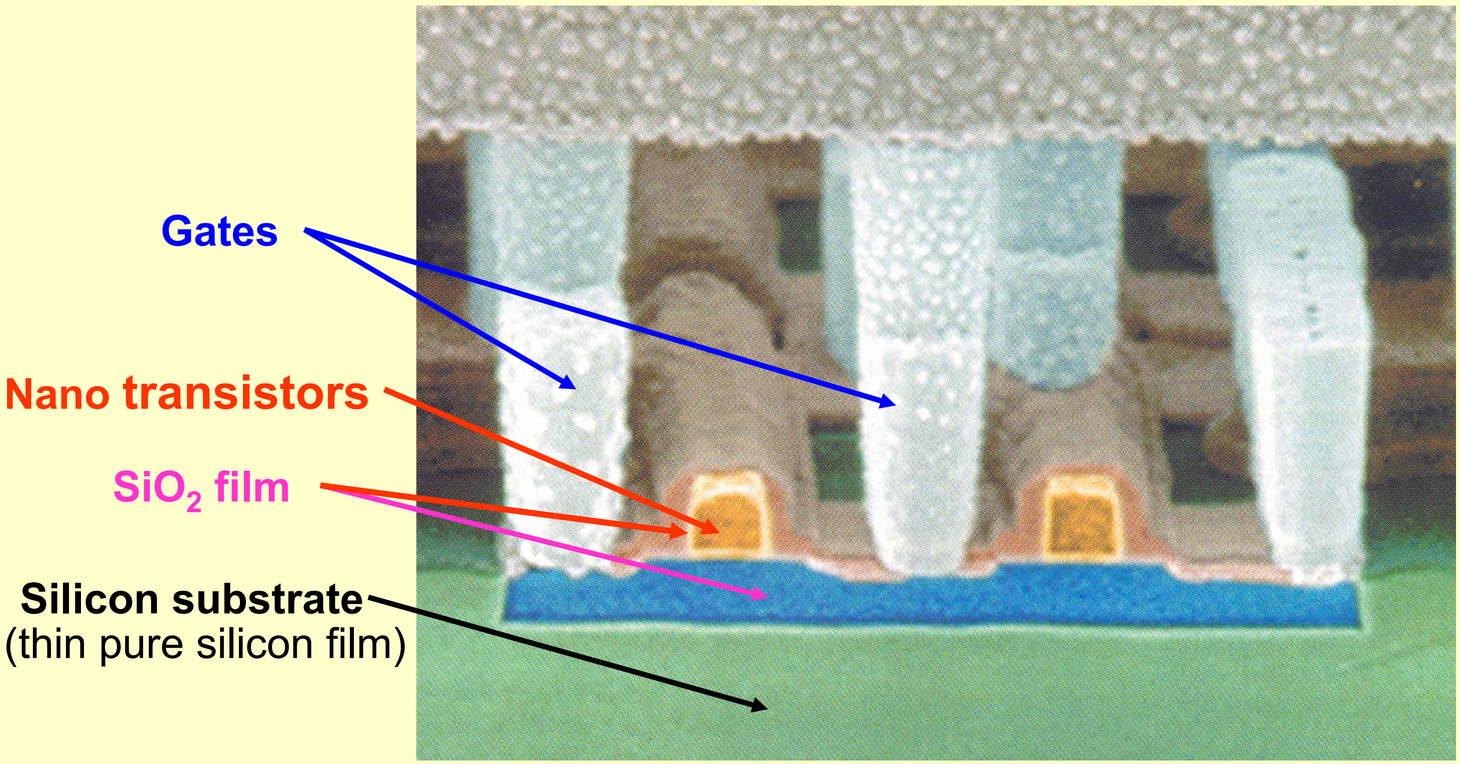
Heat = Horrendous challenge!!

Nanotechnology Benefits in Electronics and Computing-Cont'd

The Nanochip

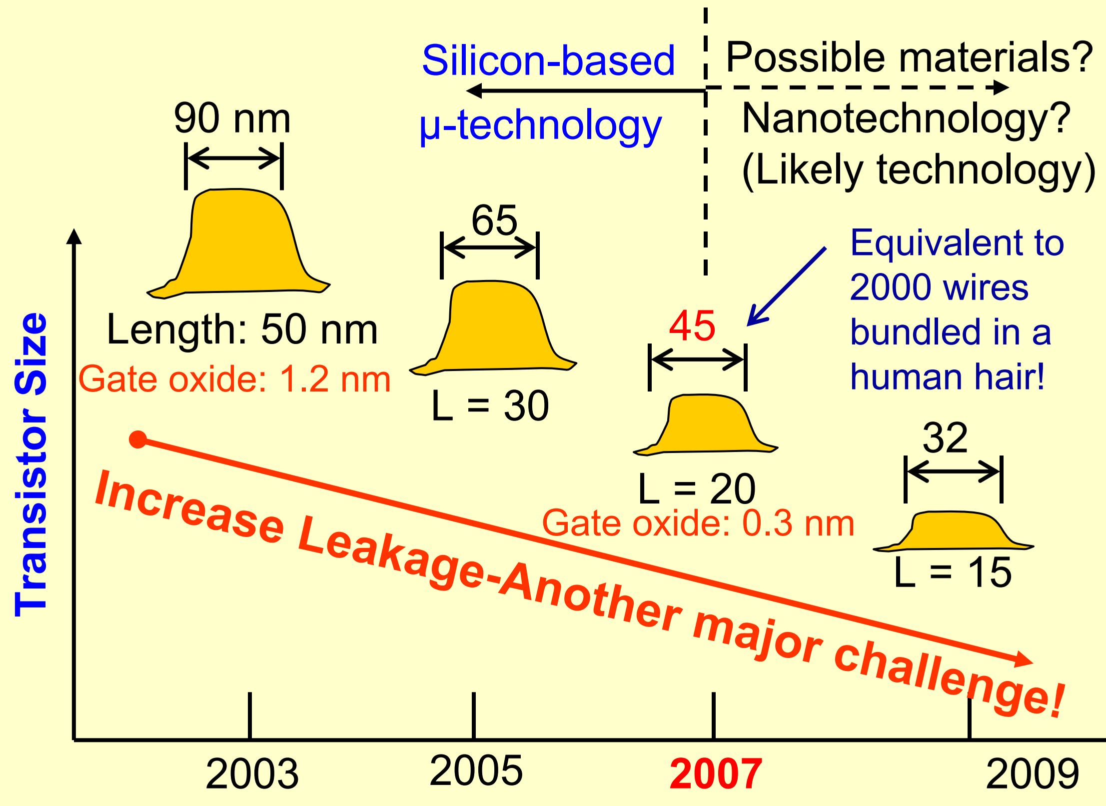
Advantages: **(1) Low unit cost. (2) Narrow gates for faster on-off**

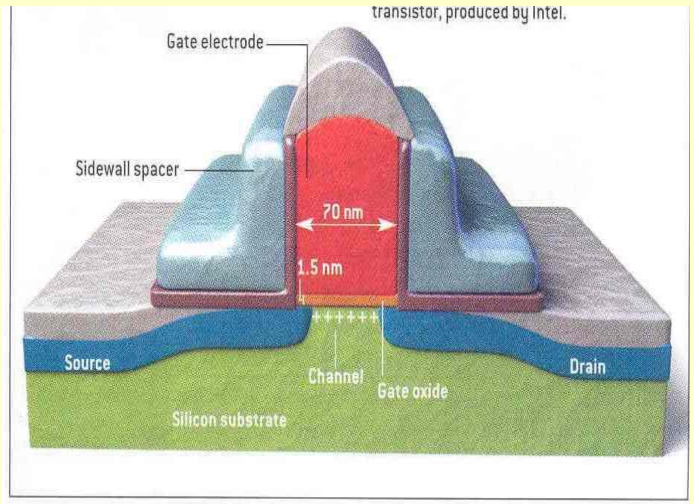
→ boost speed limit of the integrated circuits



Nanotechnology Benefits in Electronics and Computing-Cont'd

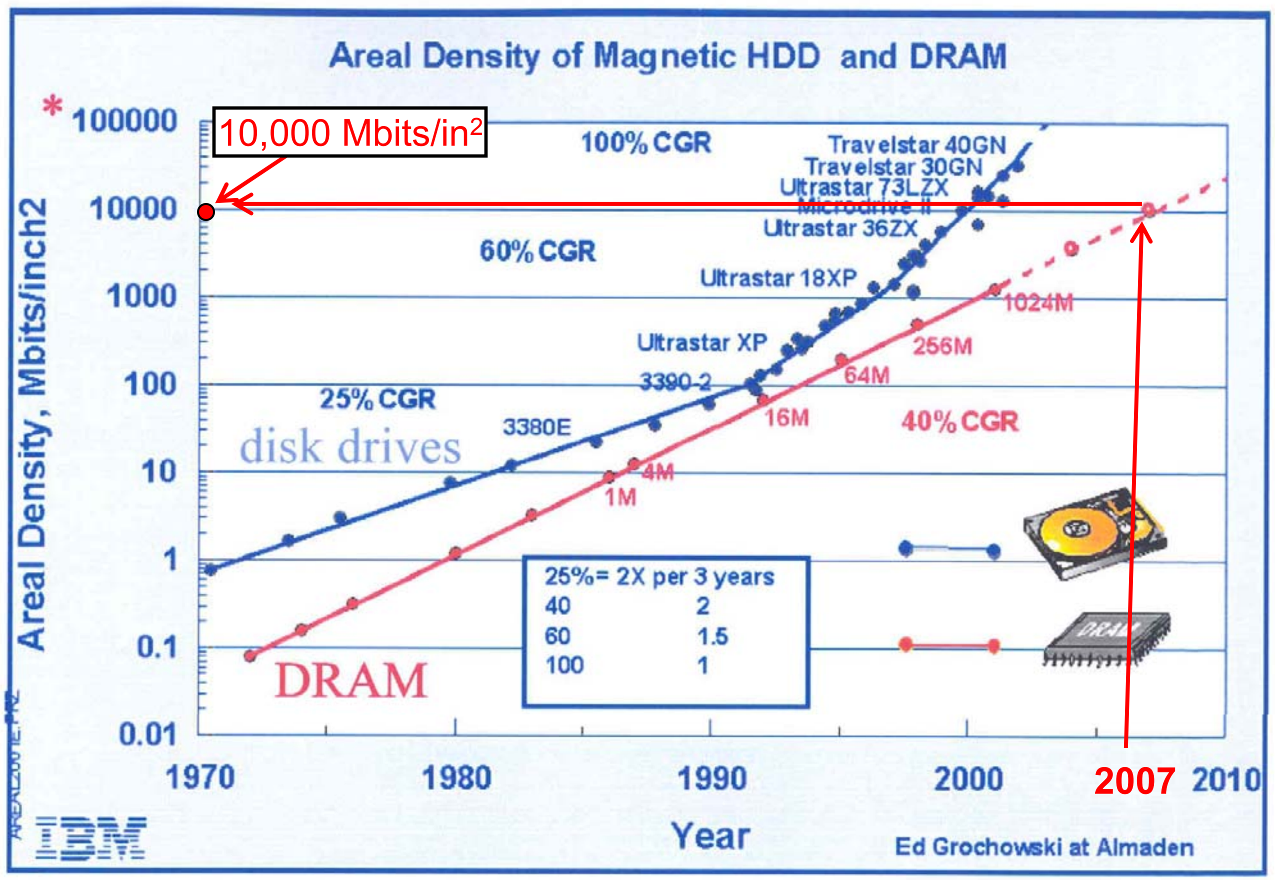
Intel roadmap on nano transistors
using microtechnology:





Nanotechnology Benefits in Data Storage-1

The ever-increasing demand for high density information storage:



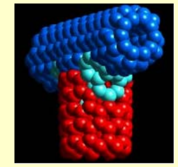
*80 nm ×80 nm bit cell $\Rightarrow 10^5$ Mbit/in²

Nanotechnology Benefits in Data Storage-2

Data Storage Requirements:

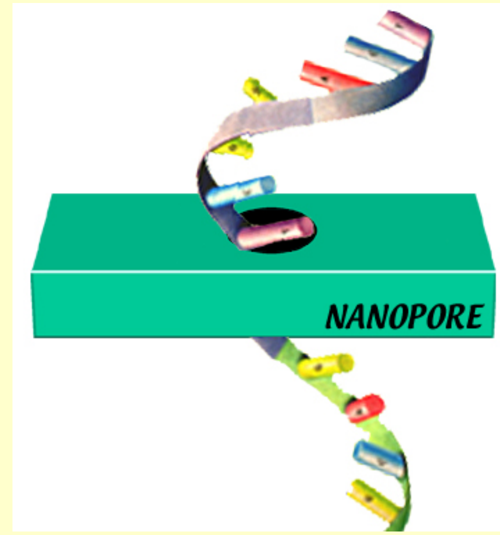
- Density
- Error rate
- Re-writability
- Tracking
- Data rate
- Overall reliability
- Data retention
- Cost

Source: “Scanning Probes Microscope & Their Potential for Data Storage,” John Mamin, IBM Almaden Research Center, San Jose, CA. (Private communication)

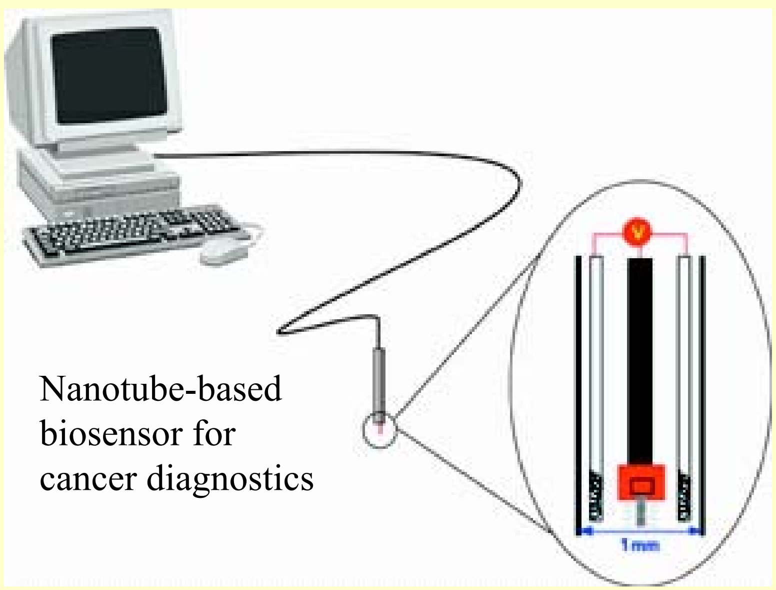


Health and Medicine

Medical testing, diagnosis; Drug discovery and delivery



- Expanding ability to characterize genetic makeup will revolutionize the specificity of diagnostics and therapeutics
  - Nanodevices can make gene sequencing more efficient.
- Effective and less expensive health care using remote and in-vivo devices.



Nanotube-based biosensor for cancer diagnostics

New formulations and routes for drug delivery, optimal drug usage.

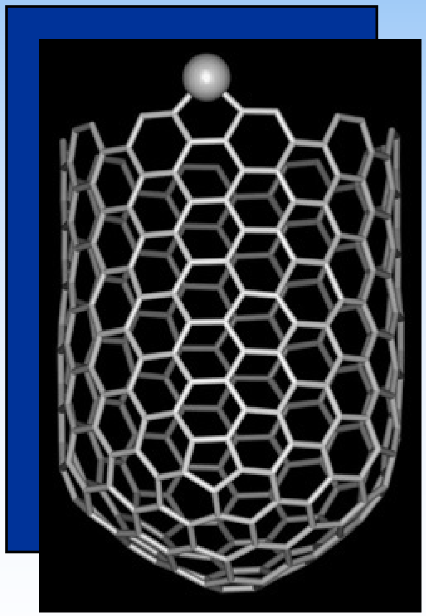
More durable, rejection-resistant artificial tissues and organs.

Sensors for early detection and prevention.

(Source: Meyya Meyya[[an, NASA Ames)

Materials and Manufacturing

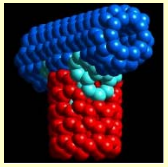
- Ability to synthesize nanoscale building blocks with control on size, composition etc. → further assembling into larger structures with designed properties will revolutionize materials manufacturing:
  - Manufacturing metals, ceramics, polymers, etc. at exact shapes without machining.
  - Lighter, stronger and programmable materials.
  - Lower failure rates and reduced life-cycle costs.
  - Bio-inspired materials.
  - Multifunctional, adaptive materials.
  - Self-healing materials.



(Source: Meyya Meyya[[an, NASA Ames)

Energy and Environment

(Source: Meyya Meyya[[an, NASA Ames)



- **Energy Production**
  - Clean, less expensive sources enabled by novel nanomaterials and processes.

- **Energy Utilization**
  - High efficiency and durable home and industrial lighting.
  - Solid state lighting can reduce total electricity consumption by 10% and cut carbon emission by the equivalent of 28 million tons/year. (Source: Al Romig, Sandia Lab)

- **Materials of construction**, such as paints, sensing changing conditions, e.g., ambient air temperature, and in response, altering their inner structure for optimal property in thermal conductivity.

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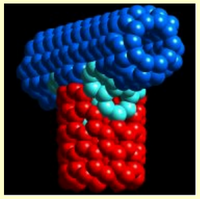
Benefits of Nanotechnology in Transportation



- Thermal barrier and wear resistant coatings.
- High strength, light weight composites for increasing fuel efficiency.
- High temperature sensors for ‘under the hood’.
- Improved displays.
- Battery technology.
- Wear-resistant tires.
- Automated highways.

(Source: Meyya Meyyappan, NASA Ames)

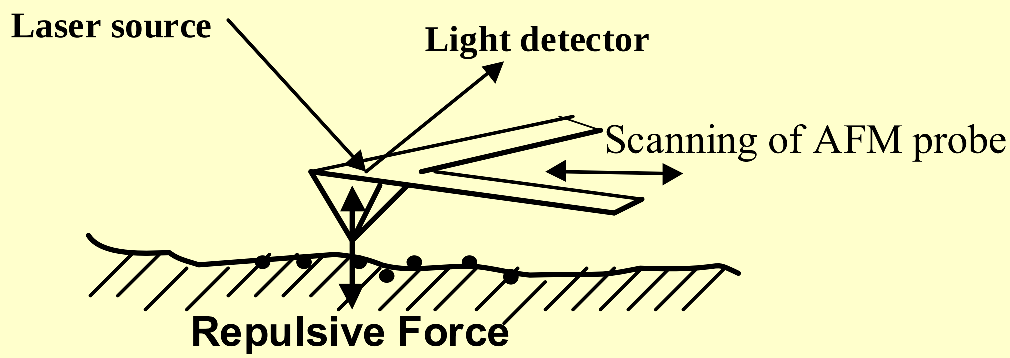
Part 2

Overview of Nanofabrication Techniques

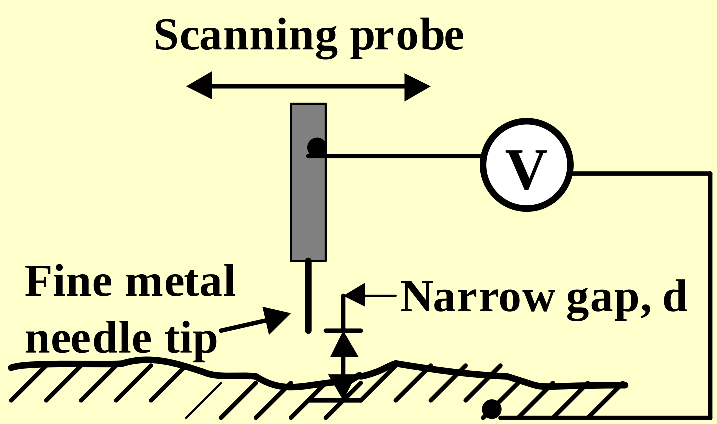
General Principle of Nanofabrication

Step 1 Isolation of atoms or molecules:

1. Mechanical Means- e.g. by Atomic Force Microscope (AFM):



2. Electromechanical Means – e.g. by using scanning tunneling microscope:



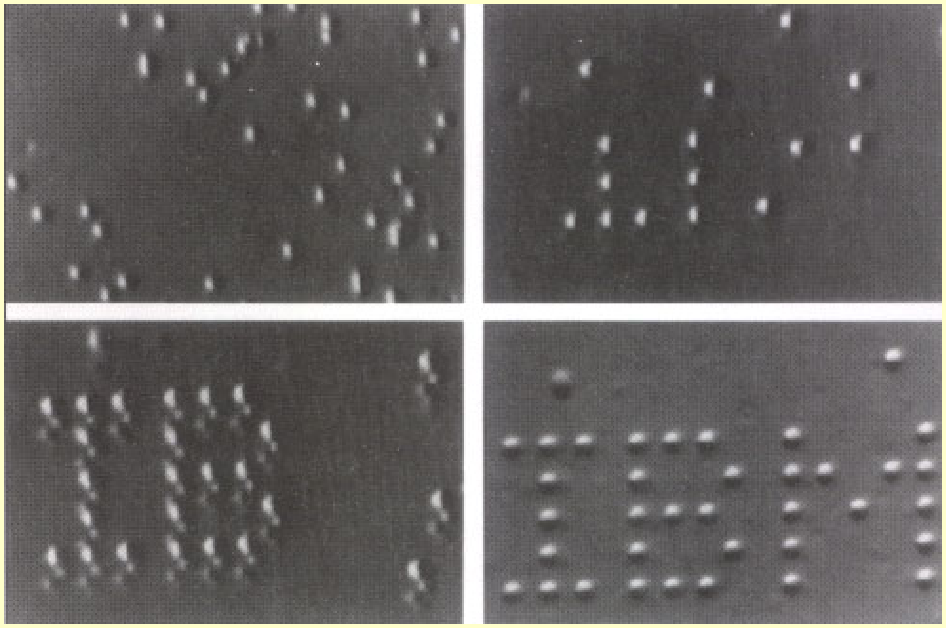
3. High energy physical chemical means: - plasma sputtering (Evaporation) or CVD.

General Principle of Nanofabrication –Cont'd

Step 2 **Assembly of loose atoms or molecules:**

- **Mechanical means** by using special equipment, e.g. AFM-guided nanomachining system (AGN), or by special controlled environment.

  - **Assembled loose gold atoms using STM at IBM:**



Final assembled atoms in "IBM"

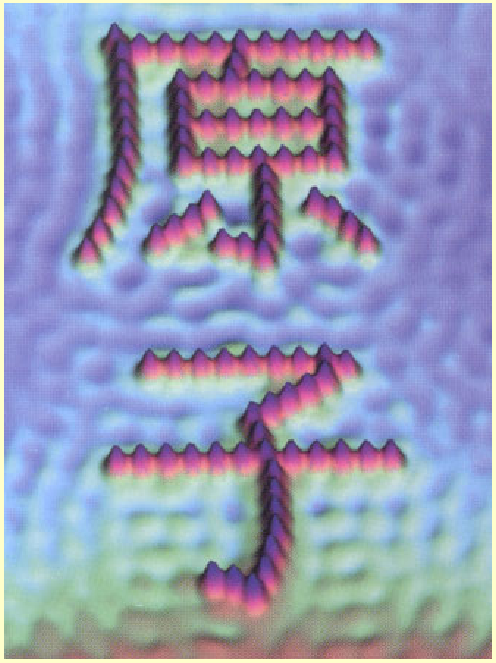
- **Biochemical means** for *self assembler* and *replication*.

General Principle of Nanofabrication-Cont'd

Step 3 **Re-bonding free atoms and molecules (Synthesis):**

- **Mechanical synthesis**, e.g. **vaporizing** free atoms at high temperature in high vacuum, followed by condensations.

(Synthesized Chinese words of "atom" made by atoms) →



- **Chemical synthesis** by diffusion + chemical reactions, e.g. special CVD.

- **Biochemical synthesis**, such as the "natural molecular machines" for "growing" proteins, enzymes and antibodies.

- **There are other methods for producing nanoscale products, e.g. "epitaxial" growth for nanoparticles and nanowires.**

Self Assemblers of Nanoscaled Products Using Biochemistry

- Current R&D activities in self assemblers appear to be on Synthetic processes based chemistry and biochemistry.

- One promising approach is the self repetition and assembly of atoms and molecules such as in the case of biological cells.

- This concept involves the proper assembly of nucleotides in DNA comprise particular genes leading to the production of cellular proteins.

- Many of these proteins are responsible for cellular replication and division.

- Success in the synthesis of these biochemical processes may lead to the self repetition and assembly of atoms or molecules of other substances with industrial applications.

Part 3

Prevalent Nanoscale Products and Applications

Nanoproducts and Market Prospects

- **Prevalent nano scale products are limited to the basic rudimentary types of:**

  - **Nanodots (Quantum dots or Nanoparticles)**
    For smart coatings and paints, cosmetic products, etc.

  - **Nanowires**
    For gates and switches in molecular electronics, sensors, smart composites, fabrics, etc.

  - **Nanotubes**
    For structure supports, nano switches, nanofluidics, etc.

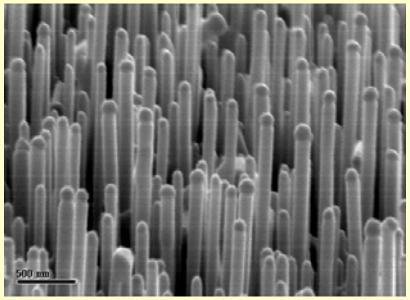
- **Markets and Projected Revenues for Nanotechnology:**

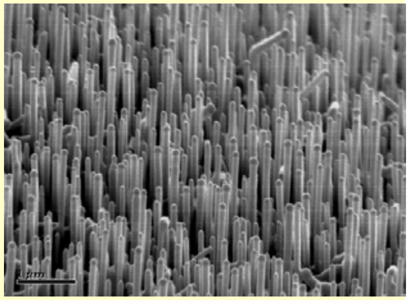
  $50 million in Year 2001
  $26.5 billion in Year 2003
  (if include products involving parts produced by nanotechnology)

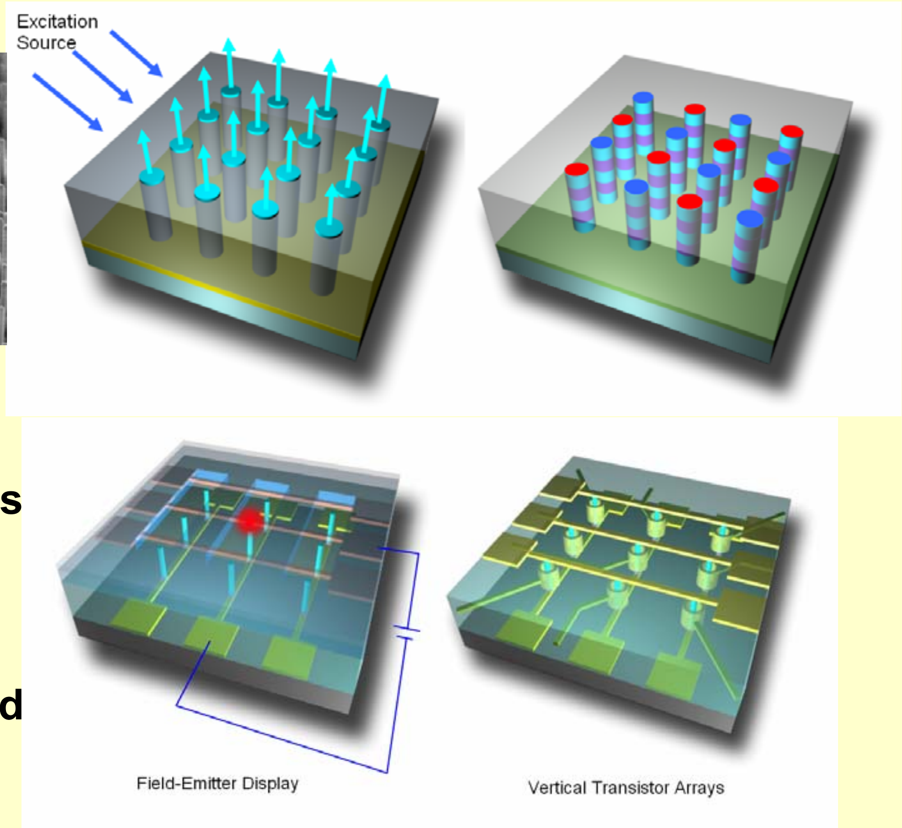
$1 trillion by Year 2015 *(US National Science Foundation)*

An enormous opportunity for manufacturing industry!!

Zinc Oxide Nanowires







Applications:

Used as conducting circuitry wires, and as the gates nanoscale transistors.

Electrical conductivity is usually smaller than bulk material. They can be controlled by surface conditions and doping.

"Epitaxial casting" – An alternative fabrication method

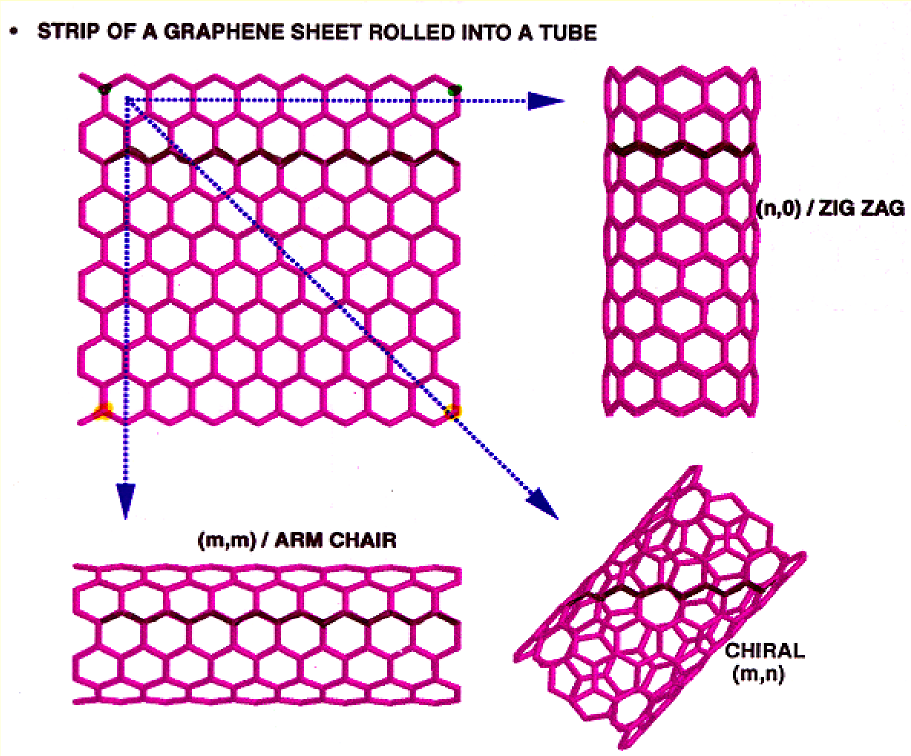
Pure crystal zinc oxide nano wires **1-50 nm** in diameter, that grow vertically in aligned arrays from sapphire wafer. The length of these wires are in the range of **2 to 10 µm** In length (Peidong Yang, Berkeley Lab, 2003).

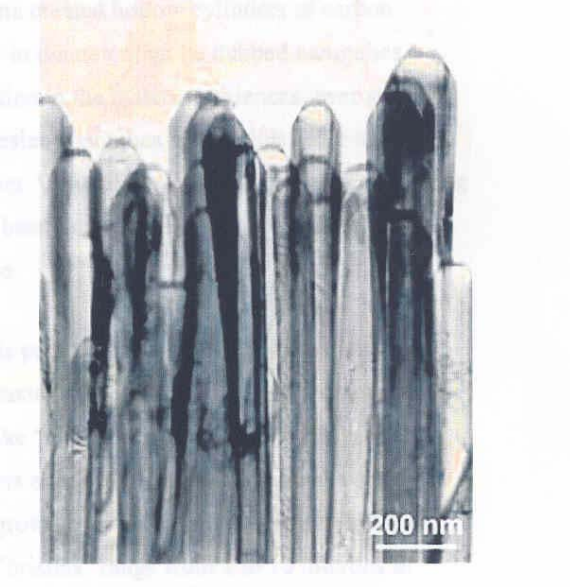
Carbon Nano Tubes (CNT)

(Source: Meyya Meyyappan, NASA Ames)

CNT is a tubular form of carbon with diameter as small as **1 nm** with a few nm to micrometers in length.

CNT is configurationally equivalent to a two dimensional graphene sheet rolled into a tube.



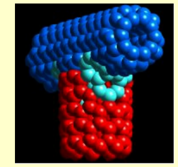


Gallium nitride nanotubes
Courtesy of Peidong Yang, UC-Berkeley

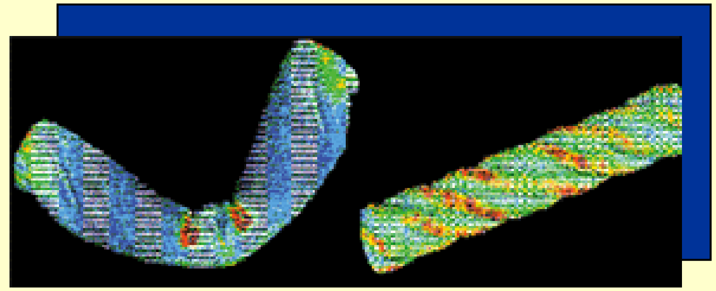
CNT exhibits extraordinary mechanical properties: Young's modulus over 1 Tera Pascal, as stiff as diamond, and tensile strength ~ 200 GPa.

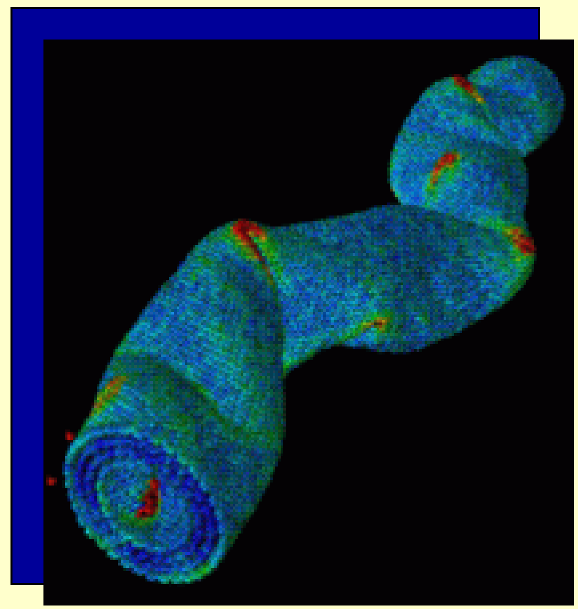
CNT can be metallic or semiconducting, depending on chirality.

CNT Properties



- The **strongest** and most **flexible** molecular material because of C-C covalent bonding and seamless hexagonal network architecture
- **Young's modulus** of over 1 TPa vs 70 GPa for Aluminum, 700 GPA for C-fiber
  - strength to weight ratio 500 time > for Al; similar improvements over steel and titanium; one order of magnitude improvement over graphite/epoxy
- **Maximum strain** ~10% much higher than any material
- **Thermal conductivity** ~ 3000 W/mK in the axial direction with small values in the radial direction





(source: Meyya Meyyappan, NASA Ames)

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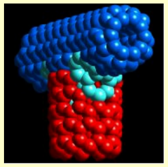
CNT Applications: Structural, Mechanical



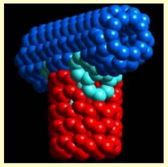
- High strength composites.
- Cables, tethers, beams.
- Multifunctional materials.
- Functionalize and use as polymer back bone
  - plastics with enhanced properties like "blow molded steel".
- Heat exchangers, radiators, thermal barriers, cryotanks.
- Radiation shielding.
- Filter membranes, supports.
- Body armor, space suits.

(Source: Meyya Meyyappan, NASA Ames)

Challenges

- **Control of properties, characterization**
- **Dispersion of CNT homogeneously in host materials**
- **Large scale production**
- **Application development**

CNT Applications: Sensors, (NEMS?), Bio



- CNT based microscopy: AFM, STM…
- Nanotube sensors: force, pressure, chemical…
- Biosensors
- Molecular gears, motors, actuators
- Batteries, Fuel Cells: H_2, Li storage
- Nanoscale reactors, ion channels
- Biomedical
  - in vivo real time crew health monitoring
  - Lab on a chip
  - Drug delivery
  - DNA sequencing
  - Artificial muscles, bone replacement, bionic eye, ear...

Challenges

- **Controlled growth**
- **Functionalization with probe molecules, robustness**
- **Integration, signal processing**
- **Fabrication techniques**

(Source: Meyya Meyyappan, NASA Ames)

Gallium Nitride Nanotubes

Developed by a group lead by Dr. Peidong Yang at Berkeley Laboratory in 2003.

Tube diameters: 30 – 200 nm

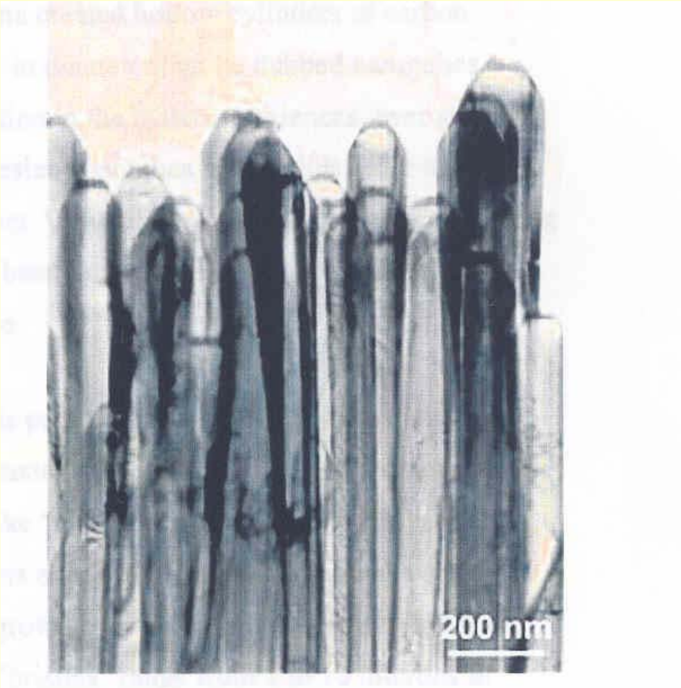
Thickness of tubes: 5 - 50 nm

Unique characteristics:

Single crystal, transparent, electronically and optically active.

Principal application areas:

Chemical sensors, nanofluidics including Nanoelectropheresis.



Gallium nitride nanotubes
Courtesy of Peidong Yang (UC-Berkeley)

Applications of Prevalent Nano Products

The unlimited application of nanotechnology is primarily based on the fact that fundamental properties of materials change with the:

- **Size**
- **Shape**
- **Composition**

that are not observed in any of their corresponding bulk materials

The unique size-dependent properties and characterizations of nanoproducts offer many opportunities for new applications

Size-dependent Properties and Characterization of Materials

- **Mechancial strength** (e.g., Max. tensile strength, Young's modulus, etc.
- **Electrical properties** (e.g., electrical reisitivity)
- **Chemical properties** (e.g., reactivity to chemical reaction-critical in drug discovery and production)
- **Optical properties** (e.g., reactivities to light - nano bar-coding))
- **Thermophysical properties** (e.g., thermal conductivity, thermal diffusivity, coefficient of thermal expansion)
- **Melting point and solubility**
- **Catalytic properties** (e.g., ability to enhance chemical reactions-critical drug discovery and production)
- **Viscosity** for liquids and **surface tension** (important for drug discovery and production)

Biomedicine using Nanoparticles:

- They are extremely sensitive to biological materials - Sensitive disease detectors, e.g., early diagnosis of Alzheimer disease – (diagnosis).

- Used as carriers coated with nanosensors, which could recognize diseased tissues and attach to them, releasing a drug exactly where is needed – (delivery).

- Enter damaged cells and release enzymes that tell the cells to auto-destruct, or could release enzymes to try to repair the cell and return it to normal functioning-(delivery).

- Change color with sizes, can be traced to delivery drug in treating cancerous diseases not to those healthy ones in the surrounding. They are ideal candidates for acting as *biological markers*, or *bio-barcode*, for detecting early stage of major diseases – (diagnosis and drug delivery).

- They can detect various biomarkers comprising nucleic acids or proteins at exceptionally low numbers. It is vital to the practice of diagnostic medicine for neurodegenerative disease, and infection by a virus, and DNA sequencing for dignosing many other diseases – (diagnosis)

- The extremely high surface area to volume ratio also makes them much easier in diffusion process – an critical process in drug manufacturing – (drug discovery)

Molecular Electronics with Nanowires and Nanotubes:

- Nanowires are the basic building blocks for nanoscale electric circuits. They are used in simple switches.

- Nanotubes can be connected in parallel or in junctions. Current passing these tubes can result in change of electrical properties that can serve as permanent memory in a nanoscale data storage system

- A nanoscale transistor using electric conductive molecules to connect the gate and the source and drain. The applied voltage changes the electric properties of these molecules, and thereby regulates the current flow in the transistor.

- Nanotubes with high thermal conductivity (as high as 3000 W/m-K) at room temperature can be used as effective dissipate heat generated by Ohmic heating of nanoscale circuits in molecular electronics.

- The concept of *spintronics* for Quantum computers has become a reality; It involves the development of a data storage system based on the "spin" properties of electrons. Spin can be used as an up-down binary code.

Energy with nanoparticles and nanotubes:

- **Fuel cells**. Fuel cells provide direct conversion of chemical energy to electric energy. Nanoparticles with controlled electrochemical properties are used as catalysts that can enhance the ionization of hydrogen and oxygen in the respective anode and cathode in the cell.

- **Batteries**. These are the only available equipment for storing electrical energy. Nanotechnology allows the design and fabrication of new anodes and cathode made of nanocarbon tubes. These anodes and cathods are able to substantially increase the amount and rate of energy that can be transferred to a battery, and reduce the recharge times significantly.

  Another application is to control the crystal structure of lithium used in the popular lithium-ion (Li-ion) batteries with improved storage efficiency.

- **Solar photovoltaic**. Highly conductive nanowires can be used to maximize the collection of the free electrons generated by the photoelectric conversion with minimum physical space and maximum solar ray exposure. Nanofabrication technique can also be used to produce ultra-thin wafers to minimize the use of expensive silicon wafers.

Environment:

- Nanoparticles can absorb, trap or break down pollutants, make fossil fuels less polluting and coolant more efficient

- Nanotubes can be used to make sensors to detect the presence of dangerous gases. For examples, ZnO film emits visible green light when exposed to UV light. Its grow dims when toxic chemicals such as chlorinated phenols and poly-chlorinated biophenols pass nearby. The pollutants react with the UV-irradiation film and decompose into harmless chemicals

- Nanoparticles ca detoxify a wide variety of common contaminants.

- Nanocomposite material can absorb mercury, and release the absorbed mercury when exposed to heat or vacuum treatment. It is thus an effective tool for recycling mercury

Other Applications with nanoparticles and nanotubes:

- Special coating materials and paints

- Super-strength structural materials

Part 4

Nanoscale Engineering Analysis

Why Nanoscale Engineering Analysis?

- Any device or engineering system, regardless of its size, is an assembly of components. Nanoscale engineering systems are no exception.
- Each component is expected to perform a specific function, e.g. structural support, or as connecting components, or as signal sensing, or as actuating mechanisms.
- Each component must have proper configuration and sufficient physical strength to carry out the intended function(s).
- Components should sustain externally applied forces, heat, chemical and biological attacks.
- Reliable techniques must be available to ensure components' ability to perform the intended functions and survive in hostile environmental conditions.
- Techniques in design, plus reliable fabrication, packaging, assembly, and testing for quality and volume production are called nanoscale engineering.
- Computational nanoscale engineering analysis that ensures the proper design of these components is thus an essential part of nanoscale engineering.

Engineering Analyses in Nano-, Micro-, and Macroscale

- **For structural components in micro- and macroscale (i.e., with linear size > 1 μm):**

- **The laws of physics based on the behavior of "continua" apply in these scales**

- **A continuum = Aggregations of a <u>great many</u> atoms or molecules with no space in between – substance in macroscale**

- **Behavior of a "continuum" = Behavior of aggregation of <u>large number</u> of atoms or molecules**

- **There are differences in behavior of individual atoms or molecules, but the aggregation of large number of these atoms and molecules "average" these differences to give "phenomenological" properties of the aggregated entity in macroscale**

- **Hence, the behavior of individual atoms does not affect the overall behavior of a continuum in macroscale**

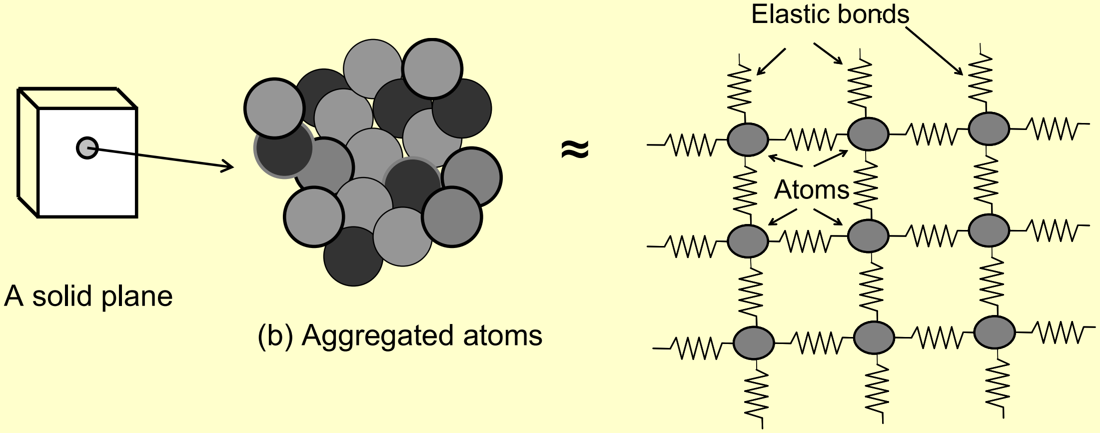
Engineering Analyses in Micro- and Macroscale – Cont'd

- Linear theory of elasticity for stress analysis;
- Newton's 2nd law for rigid-body dynamic analysis;
- Fourier law for heat conduction analysis;
- Newton's cooling law for heat convection analysis;
- Fick's law for diffusion analysis;
- Navier-Stokes's equations for fluid dynamics analysis

- All these analytical formulations are developed on hypotheses of materials being continua, which is not the case for materials at nanometer scale
- Either significant modifications are required to these existing formulations, or new formulations are required for nanoscale engineering analyses

Engineering Analyses in Nanoscale

- **For structural components in nanoscale** (i.e., with linear size < 1 μm):
  - A component at nanoscale contains many fewer atoms or molecules than those in a continuum
  - These atoms or molecules in a nanoscale substance are interconnected by chemical bonds (simulated by elastic springs):



(a) A solid plane

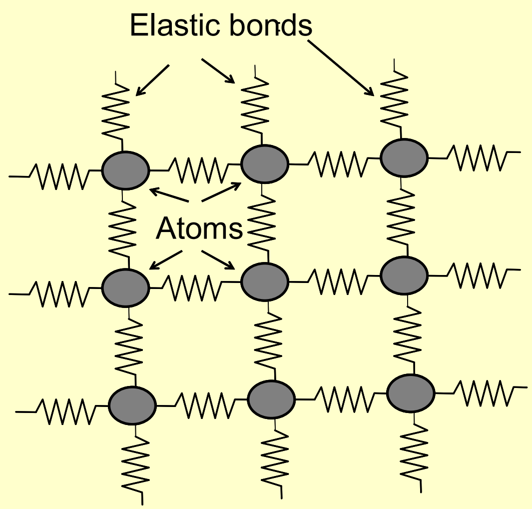
(b) Aggregated atoms

(c) Elastic bonds of atoms

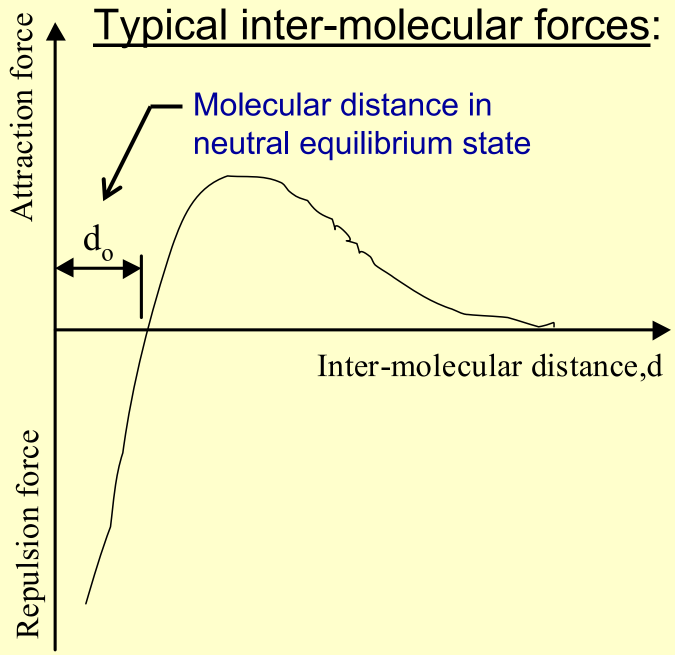
  - Consequently, the behavior of individual atoms plays dominant roles in the overall behavior of the structure
  - Theories derived for continua can no longer be used to model nanoscaled substance
  - **Phenomenological models based on quantum physics and quantum mechanics are used as bases for engineering analyses of components of nanoscale**

Engineering Analyses in Nanoscale – Cont'd

● **Inter-molecular physical-chemical action is another unique aspect of nanoscale engineering analyses**



(c) Elastic bonds of atoms



● **Because the way molecules of various shapes and surface features organize into patterns on nanoscales, and thus the size of the local atomic aggregations,**

● **Size-dependent material properties must be incorporated in nanoscale engineering analysis.**

Size-dependent Properties of Nanoscale Materials

□ **Mechanical strength**, e.g., in maximum tensile strength and Young's modulus.

□ **Electrical properties**, e.g., electrical resistivity.

□ **Chemical properties**, e.g., reactivity to chemical reactions.

□ **Optical properties**, e.g., reactivity to light – same material with different colors depending on its size – a value to drug delivery and medical diagnosis.

□ **Thermophysical properties**, e.g., thermal conductivity, thermal diffusivity, and coefficient of thermal expansion.

□ **Melting points and solubility**.

□ **Magnetic properties**.

□ **Catalytic properties**, e.g., ability to enhance chemical reactions - a vital value to drug discovery processes.

□ **Viscosity** for liquid and **surface tension**.

Computational Nanoscale Engineering Analysis

Computational nano-engineering technology aims at the development of nanometer scale modeling and simulation methods to enable the design and construction of realistic nanometer scale devices and systems.

Computational nanoscale engineering design encompasses:

- **Stress Analysis**
- **Molecular Dynamics**
- **Molecular Heat Transmission**
- **Molecular Gas Dynamics**

Stress Analysis of Solids in Nanoscale

Young's Modulus of Silicon:

Miller index for orientation	Young's modulus of bulk material	Young's modulus of nanocantilever at 3 nm thick	% Change
<100>	129.5	75	42.1
<110>	168.0	110	34.5
<111>	186.5	130	30.3

Unit: GPa

Significant size-dependent Young's modulus of nanoscale materials has <u>invalidated</u> the linear generalized Hooke's law:

$$\{\sigma\} = [C(E,\upsilon)]\{\varepsilon\}$$

in which {σ} = stress tensor, {ε} = strain tensor, $[C(E,\upsilon)]$ = the elasticity matrix with E = Young's modulus and ν = Poisson's ratio.

Significant modifications of the constitutive relations of materials at this scale because the values of both **E** and ν vary with the size of the structure

Modifications for finite element analysis of nanoscale solids:

The constitutive equations for incremental stress and strain components for a conventional elastoplastic stress analysis of solids with temperature and strain rate-dependent properties:

("The Finite Element Method for Thermomechanics," T.R. Hsu, 1986)

$$\{d\sigma\} = \left[C_{ep}\right]\{d\varepsilon\} - \left[C_{ep}\right]\left(\{\alpha\}dT + \{D^T\}dT + \{D^{\dot{\varepsilon}}\}d\dot{\varepsilon}\right) - \frac{1}{S}\left[C_e\right]\{\bar{\sigma}^*\}\left(\frac{\partial F}{\partial T}dT + \frac{\partial F}{\partial \dot{\varepsilon}}d\dot{\varepsilon}\right)$$

where $S = 6\left\{\bar{\sigma}^*\right\}\left\{\bar{\sigma}^*\right\}C(T,\dot{\varepsilon}) + 6\left\{\bar{\sigma}^*\right\}\left[C_e\right]\left\{\bar{\sigma}^*\right\}$

$[C_e]$ = elasticity matrix; $[C_{ep}]$ = elastic-plasticity matrix; $\{D^T\}$ and

$[Ce\}$ = respective temperature-dependent and strain rate-dependent elasticity matrix.

α = coefficient of thermal expansion; F = plastic yield function; T = temperature

$\{D^{\dot{\varepsilon}}\}$ and $\{D^T\}$ = respective coefficient matrices relating to the strain rate and temperature T

$\bar{\sigma}^*$ = translated deviatoric stress following von-Mises plastic potential function

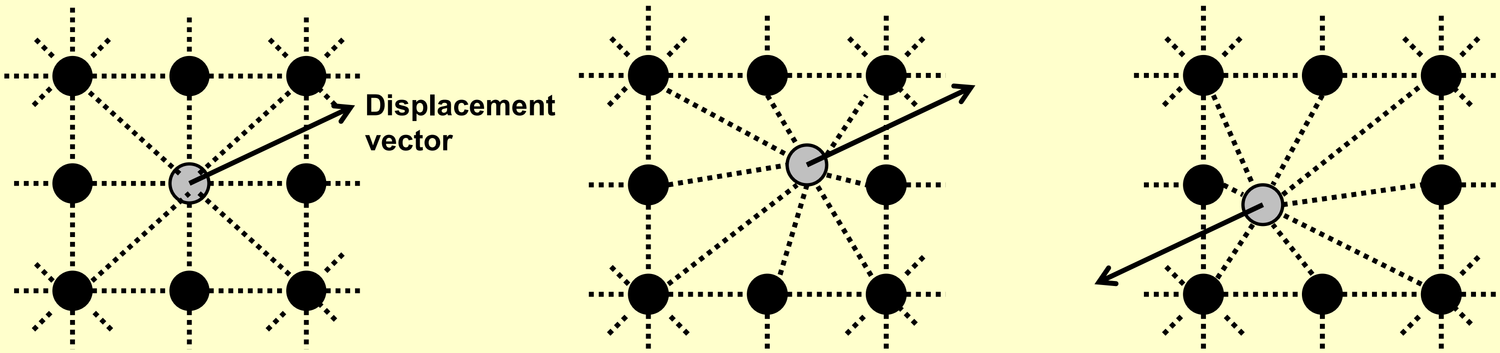
Significant modifications on the above constitutive equations are required to accommodate <u>size-dependant material properties</u> and the <u>inter-molecular mechanistic behavior</u>.

- **Commercial Finite element analysis codes developed for macroscale solids/fluids are no longer applicable for those in nanoscale without proper modifications in theoretical formulations.**

Overview of
Molecular Dynamics

- **Deformation of any matter, whether it is solid or fluid, result in movement of atoms or molecules within the matter.**

Atoms with elastic bonds:



(a) Initial equilibrium position (b) Position at time t_1 (c) Position at time t_2

Oscillatory motions of an atom subject to external disturbance

- **At molecular level, i.e. nanoscale, such movement of atoms or molecules may contribute significantly to the overall physical consequences.**
- **One thus needs to treat EVERY problem in nanoscale as a TRANSIENT problem. The name "static mechanics" does not exist in nano-mechanics.**
- **Every mechanics analysis is thus related to Molecular Dynamics.**

Principle of Molecular Dynamic Simulation

- It computes the *MOTION* of individual molecules in solids, liquids and gases.

- Motion of molecules includes: *position*, *velocities* and orientations with time (*trajectories*)

- All molecules are subject to *inter-molecular force field* and thus the *potential energy* that includes: static force, kinetic energy, electromagnetic, thermal, etc.

Simulation methods covers the spectrum of:

Stochastic ↔ **Deterministic**

Metropolis Monte Carlo

Force-biased Monte Carlo

Brownian dynamics

General Langevin dynamics

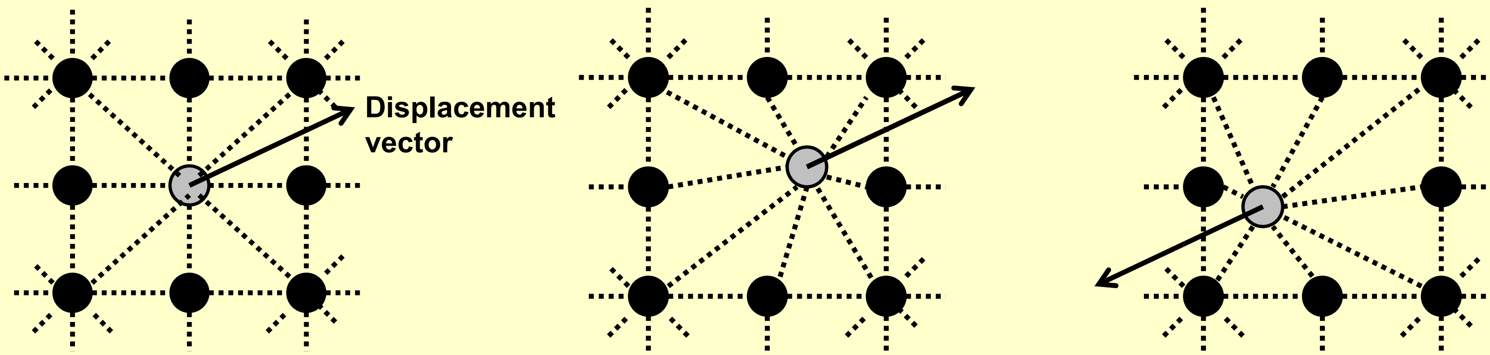
Molecular dynamics

Molecular Dynamics in
Engineering Design of Nanoscale Structures

It determines:

(1) The required forces (or energy) to move single atoms (or molecules) in a molecular force field.

Atoms with elastic bonds:



(a) Initial equilibrium position

(b) Position at time t_1

(c) Position at time t_2

(2) The motion of individual atoms (or molecules):
Trajectories (Positions, Velocities and Orientations) when subject to external force field.

(3) The Schrodinger's equation (1926) is used as the basic governing equation for the "deterministic" molecular dynamics.

The Schrodinger Equation

for Nonrelativistic Quantum Mechanics (1926)

The position of a charged particle, $\phi(\vec{r},t)$ **in a force field of N-charged particles with masses,** m_0, m_1, m_2,…, m_{N-1} **can be obtained from the following equation:**

$$-\frac{h^2}{2}\sum_j \frac{1}{m_j}\frac{\partial^2\phi(\vec{r},t)}{\partial r_j^2} + U(\vec{r},t)\phi(\vec{r},t) = ih\frac{\partial\phi(\vec{r},t)}{\partial t}$$

where $\vec{r}$ = position vector, or the coordinates

$U(\vec{r},t)$ = potential energy function

h = the Planck constant **= 6.626076 x 10^{-34} J-s**

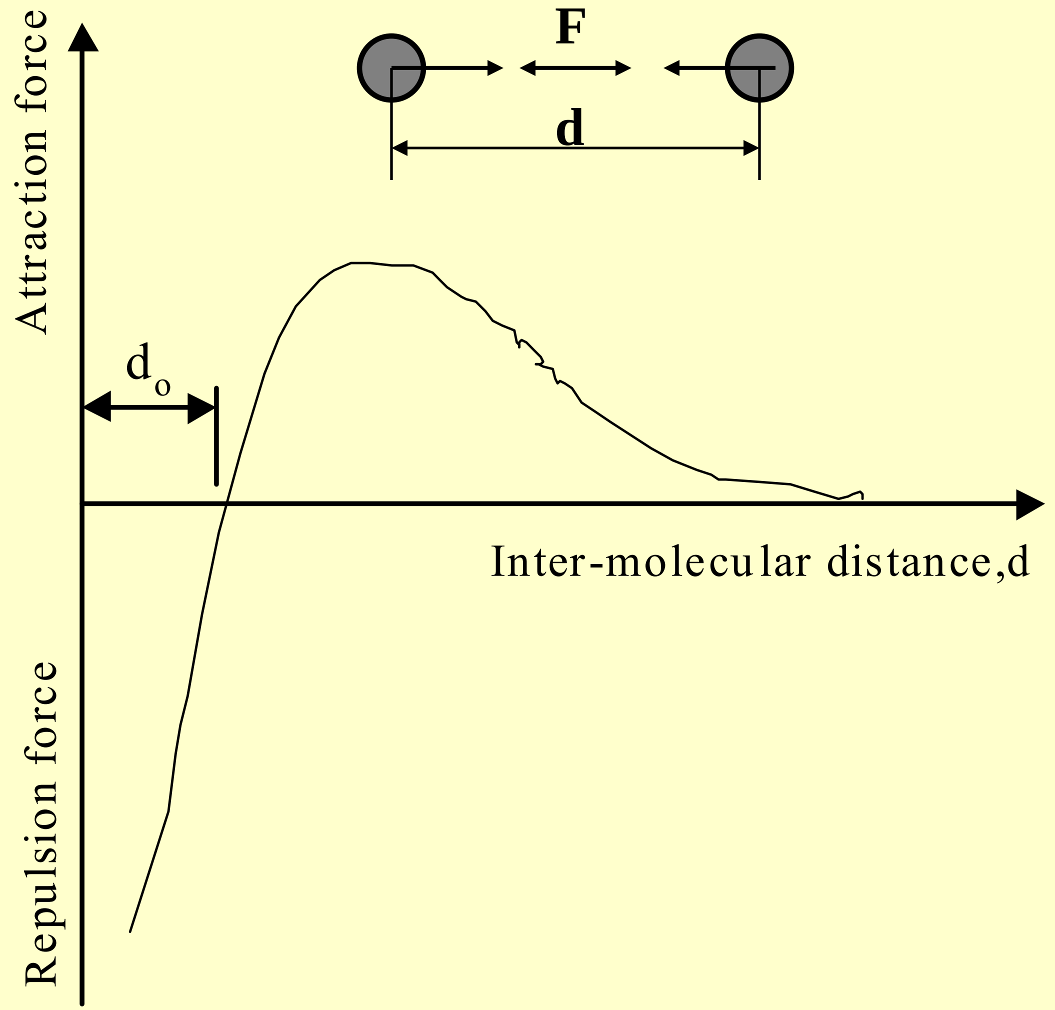
$i = \sqrt{-1}$

The inter-molecular force on molecule i caused by N-1 other molecules is:

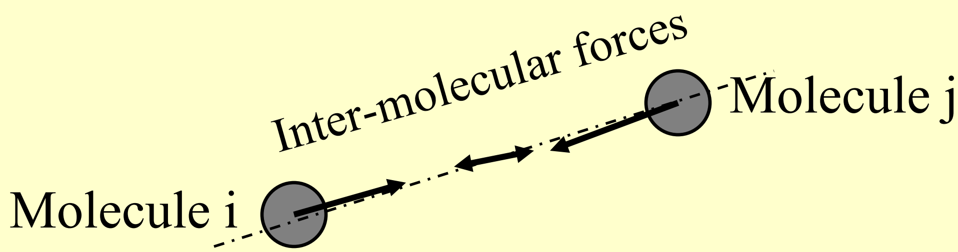
$$\vec{F}_i = -\frac{\partial\phi(\vec{r},t)}{\partial\vec{r}}$$

Molecular Dynamics

Inter-Molecular Forces with Separation:



Potential Energy Function in Schrodinger Equation



$$U(\vec{r}) = \sum_{i<j} \frac{q_i q_j}{4\pi \varepsilon_0 d_{ij}}$$

where

q_i, q_j = respective charge intensities of Particle i and j

d_{ij} = distance between Particle i and j

ε_o = permittivity of the free space.

Elements of Molecular Dynamic Simulation

Principal Modules:

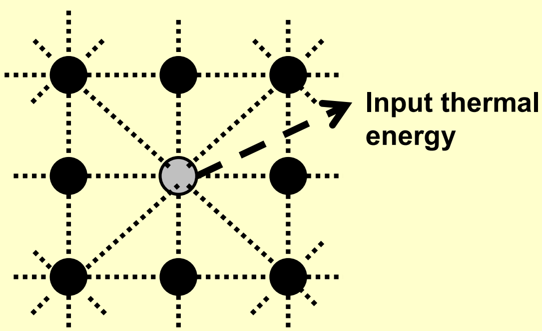
- **Equation of Motion**
- **Environmental Interactions**
- **Molecular Interactions**

Sub-modules:

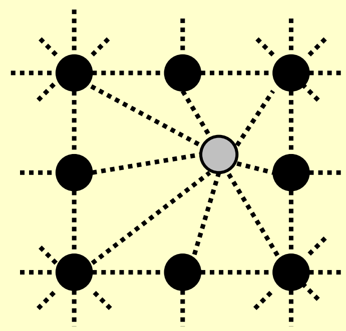
- **Dynamic equilibrium with applied forces and energies**
- **Dynamic and static properties**
- **Molecular trajectories (soft or hard sphere collision)**
- **Phase-space trajectories for vibrating molecules**
- **Distribution functions of sample molecules in 2-D and 3-D (velocities, properties, etc.)**
- **Periodic boundary conditions**

Overview of
Molecular Heat Transmission in nanoscale

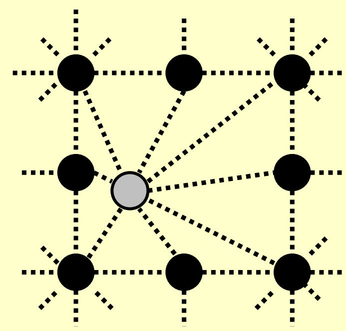
Any input of thermal energy to a substance from an external source can cause a disturbance to the energy equilibrium in its natural state.



(a) Initial state



(b) Lattice movement at time t_1



(c) Lattice movement at time t_2

This input energy can cause the LATTICES that connect atoms to deform (extend or contract) depending on the form of the input energy.

Because lattices are considered as elastic bonds, any extension or contraction of any lattice will result in a series of vibrations of lattices.

Vibration of lattices are always associated with energy.

The energy associated with local lattice vibration is called "**ENERGY CARRIER**"

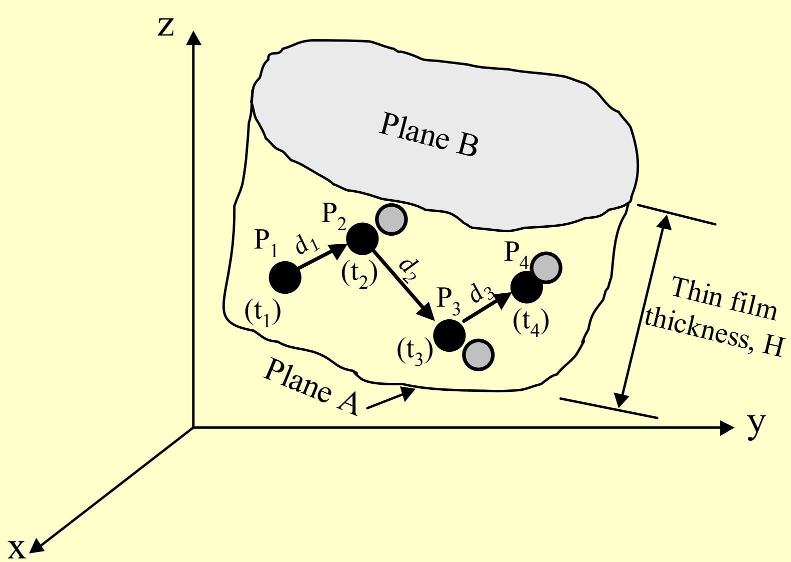
Molecular Heat Transmission

A. Energy Carrier:

Heat conduction in solids requires *carriers*.

Heat transportation in solids of in sub-micrometeer and nanoscales is predominantly done by the "flow" of phonons.

There are *collisions and scattering* of free-phonons take place at all times during heat transmission:



The average "mean free path" (MFP):

$$\lambda = \frac{d_1 + d_2 + d_3}{3}$$

The average "mean free time" (MFT):

$$\tau = \frac{(t_2 - t_1) + (t_3 - t_2) + (t_4 - t_3)}{3} = \frac{t_4 - t_1}{3}$$

Molecular Heat Transmission – Cont'd

(For solid size, H < 7λ)

B. Size-dependent Thermophysical Properties

The thermal conductivity, $$k = \frac{1}{3} C V \lambda$$

Parameters for Thermal Conductivity of Thin Films
[Flik et.al. 1992 and Tien and Chen 1994]

	Materials	Dielectric and semiconductors
Specific heats, C	Specific heat of electrons, C_e	Specific heat of phonons, C_s
Molecular velocity, V	Electron Fermi velocity, $V_e \simeq 1.4 \times 10^6$ m/sec	Velocity of phonons (sound velocity), $V_s \simeq 10^3$ m/sec
Average mean free path, λ	Electron mean free path, $\lambda_e \simeq 10^{-8}$ m	Phonon mean free path, $\lambda_s \simeq$ from 10^{-7} m and up

Example: With an average value of $\lambda = 10^{-7}$ m for phonons, the k for 200 nm thick silicon film is only 83% of the same property of silicon in macroscale.

Molecular Heat Transmission –Cont'd

C. Modified Heat Conduction Equation

The heat conduction equation carries additional term for energy carrier's movement:

$$\nabla^2 T(\vec{r},t) + \frac{Q}{k} = \frac{1}{\alpha}\frac{\partial T(\vec{r},t)}{\partial t} + \frac{\tau}{\alpha}\frac{\partial^2 T(\vec{r},t)}{\partial t^2}$$

where the "relaxation time, τ is:

$$\tau = \frac{\lambda}{V}$$

in which V is the average velocity of the heat carrier.

The value of $\tau \approx 10^{-10}$ seconds is used for semiconducting materials.

Overview of Molecular Gas Dynamics

- Gas dynamics derived from continuum theory breaks down at scale less than 1 μm (or < 1000 nm).

- Molecular physics governs.

- Gas flow in this scale is "rarefied".

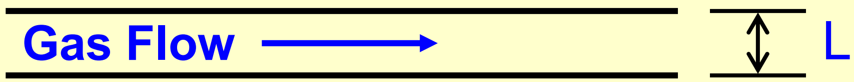
"Mean free path" (MFP) and "Mean free time" (MFT) dominate in energy transportation.

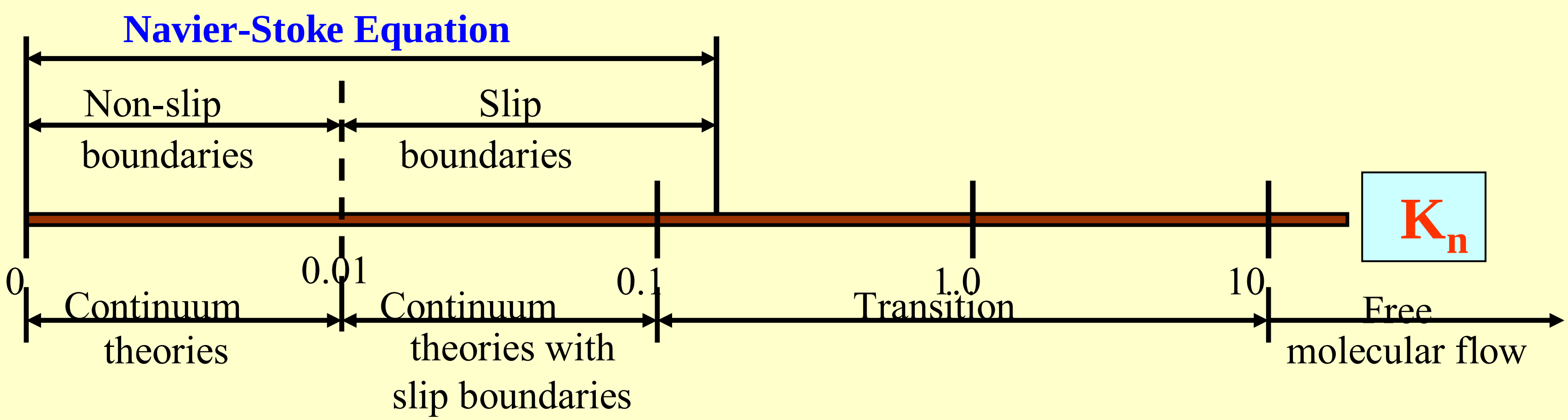
Knudson number (Kn) and Mach number (Ma) characterize the flow.

- Kn = MFP (λ)/Characteristic length (L); $\lambda \approx 65$ nm
  Ma = Speed of sound in the rarefied gas/
  Speed of sound at standard conditions (Ma < 0.3)

Modeling of Molecular Gas Dynamics

- K_n = MFP (λ)/Characteristic length (L); $\lambda \approx 65$ nm for most gases
  M_a = Speed of sound in the rarefied gas/Speed of sound at standard conditions

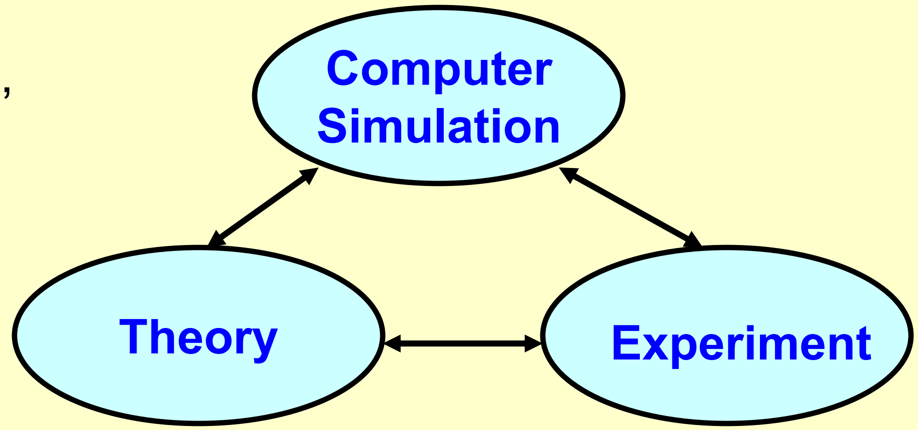




- Modified Navier-Stokes equation can be used for $0.01 < Kn < 0.13$.
- New gas dynamics theory and formulations need to be developed for nano scale gas flow with $Kn > 0.13$.

Summary on Nanoscale Engineering Analysis

- R&D on computational nanoscale engineering so far has been sporadic and has not received support as it deserves.
- It is a matter of time that industry (and thus the government funding agencies) will recognize its essential value in the design of nano-scale devices and nano-microscale systems.
- Computational nanoscale engineering presents enormous challenge to researchers due to the extreme complexity in the bridging the quantum and continuum mechanics.
- Because of this extreme complexity, the following inter-play relationship will play a major role in the overall development of nanoscale engineering design.



Part 5

Measurements of Selected Nanoscale Material Properties

We have learned a unique feature of nanotechnology
- the properties of nanoscaled substance change with its sizes

- Take for example, the **color** of silver nanoparticles begins with a light pink color at the size of 120 nm. It turns to light blue at 80 nm, and dark blue at 40 nm

  Gold nanoparticles change color from orange at 100 nm to olive green at 50 nm

- Significant change of **thermophysical properties** of substances with sizes at nanoscale as presented before

- Measurement of material properties at nanoscale is extremely difficult because of the minute size of the samples, coupled by the accuracy of the measurement instruments

- We will illustrate one particular kind of property measurement –
  the **thermal conductivity** (k) of semiconductors and insulators

Principle of k- Measurements

- **Thermal conductivity** of solids **k** is usually determined by measuring the <u>temperature gradient</u> produced by a <u>steady flow of heat</u> in a <u>one-dimensional geometry</u>

- **Reliable and accurate measurements of k rely on the one-dimensional heat flow**

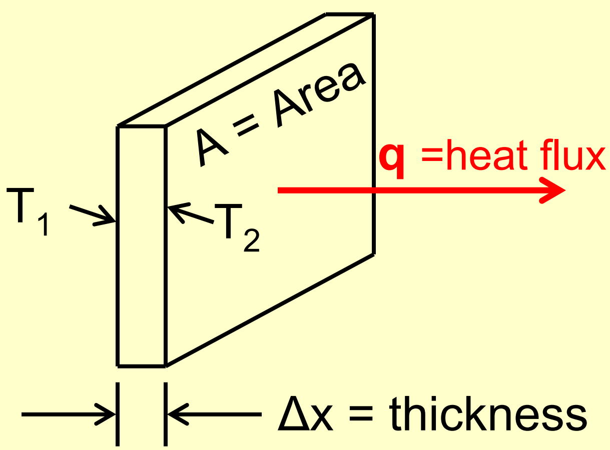
Theoretical Background

Heat conduction in solids is governed by
Fourier law of heat conduction:

$$q_x = -kA\frac{\partial T(x,y,z)}{\partial x}$$

where q_x = heat conduction rate, BTU/h, or Watt
A = area through which the heat is transferred, ft^2 or m^2
k = thermal conductivity of the material, BTU/h-ft-^{o}F or W/m-^{o}C
$\frac{\partial T}{\partial x}$ = Temperature gradient in the direction of heat flow, ^{o}F/ft or ^{o}C/m

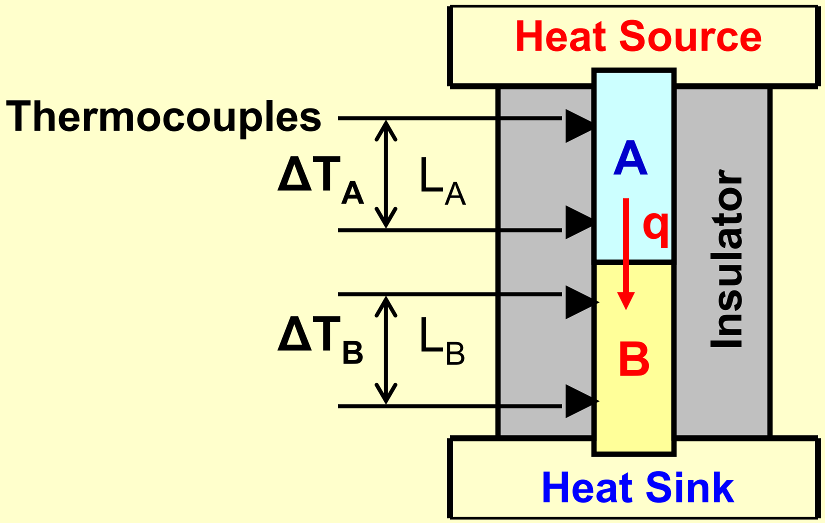
Measurement of k may be conducted on a flat slab:



$$k = \frac{q\,\Delta x}{A(T_1 - T_2)}$$

where T_1 and T_2 are temperature of the rear and front surfaces respectively

Measurement of k of Conductors, e.g. Metals in Macroscale



Two metal rod samples:

Sample A with known k_A

Sample B with K_B to be determined.

From Fourier law of heat conduction:

$$q = \frac{k_A A_A \Delta T_A}{L_A} = \frac{k_B A_B \Delta T_B}{L_B}$$

where $A_A = A_B$ = cross-section of the Sample A and B.
$L_A = L_B$ = the distances between thermocouples in Sample A and B
ΔT_A, ΔT_B = measured temperature differences in Sample A and B respectively.

Hence the thermal conductivity of Sample B is determined by:

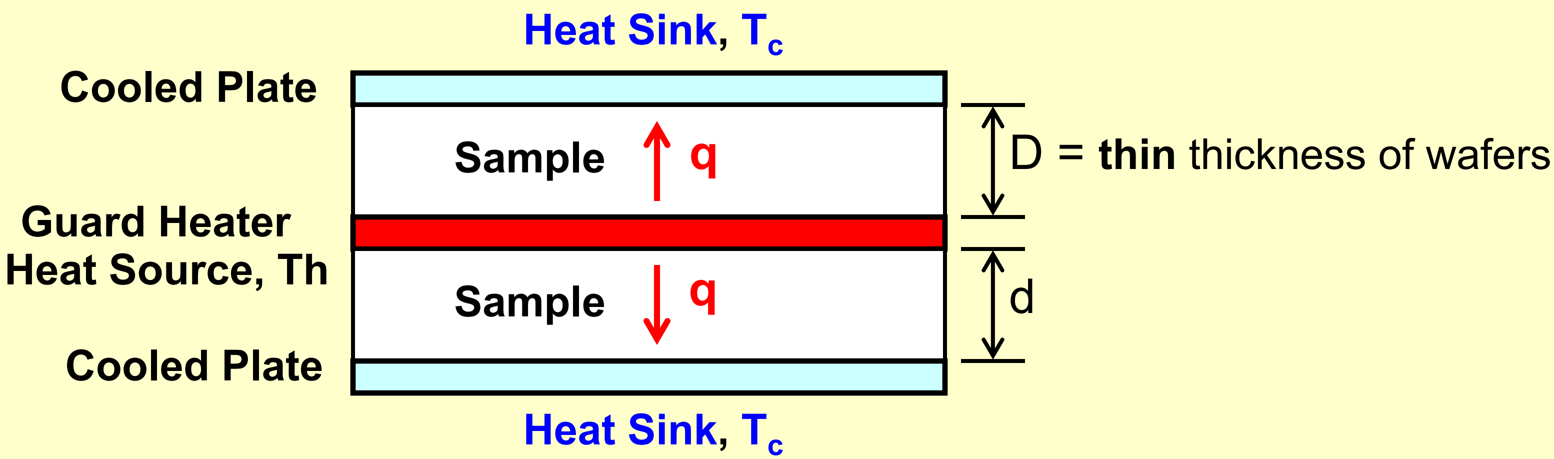
$$k_B = \frac{\Delta T_A}{\Delta T_B} k_A$$

Measurement of k of Semiconductors and Insulators

These materials typically have low aspect ratios and low k-value.
Maintaining one-dimensional flow of heat in the samples is a major issue

Measurement set-up requires strict control of temperatures in both heat source (guard hot plate) T_h and heat sink T_c

One-dimensional heat flow is ensured by the difference of T_h and T_c



The thermal conductivity of the samples $$k = \frac{d}{A(T_h - T_c)} q$$

where A = cross-sectional area for heat flow; q = heat output of the heater

Measurement of k of Semiconductors or Insulators in Sub-micrometer and Nanometer Scale

Major issues

- These materials have low k-values. Consequently, require high precision measurement techniques with high resolutions
- Samples are normally thin and small in size. Proper positioning and stationing in the fixture are difficult
- Being thin in sample size (e.g. silicon wafers), it is not possible to ensuring one-dimensional heat flow
- The temperature gradient along the sample thickness is too small to be measurable
- There is no place for thermocouples in the samples

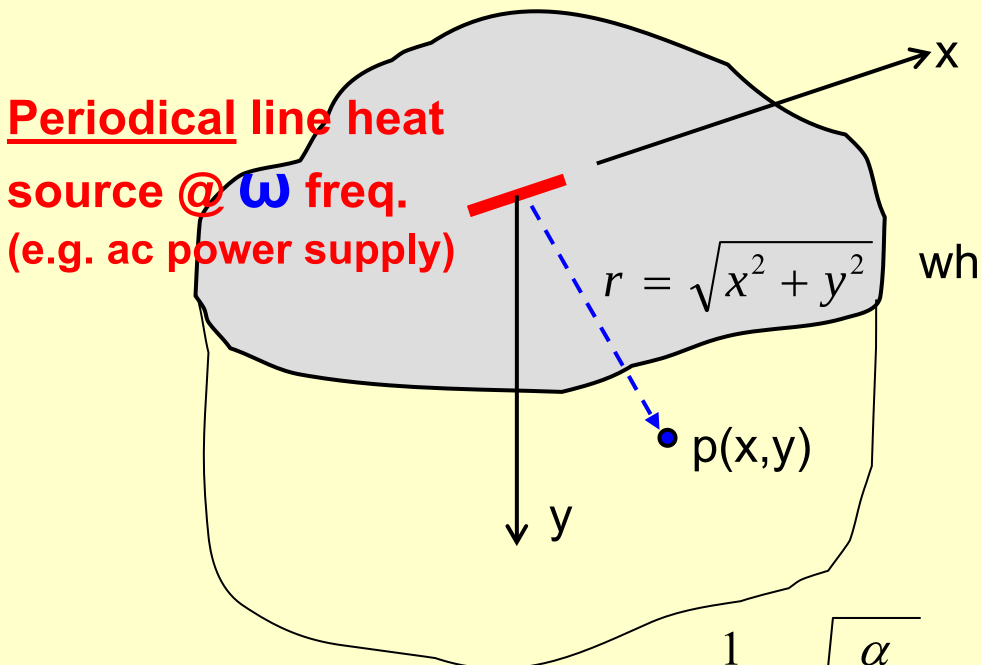
Two Principal Techniques for Measurements of k in Thin Films of Semiconductors and Insulators

- **The 3 – Omega Method**
- **Scanning Thermal Microscope**

The 3-Omega Method for Semiconductors and Dielectric Materials

Theoretical basis of 3-Omega method [Cahill 1990]:

Temperature distribution of a semi-infinite solid induced by a finite line heat source [Carslaw and Jaeger 1959]



The temperature rise at point P inside the half-volume is:

$$\Delta T(r) = \frac{1}{\pi k}\left(\frac{P}{L}\right) K_o(qr)$$

where P = the amplitude of the power generated at a angular frequency ω in the line source.

L = length of the line heat source

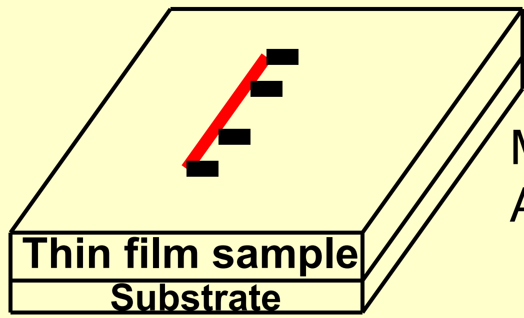
k = thermal conductivity of the solid

$K_o(r)$ = Modified Bessel function of second kind at zeroth order

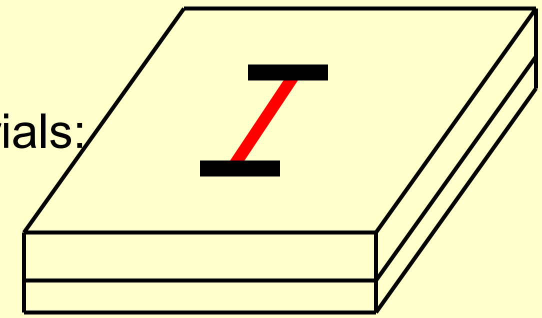
$\frac{1}{q} = \sqrt{\frac{\alpha}{i2\omega}}$ = wavelength of the diffusive thermal wave with α to be the diffusivity of the solid

The thermal conductivity k may be calculated from the measured temperature rise as shown above

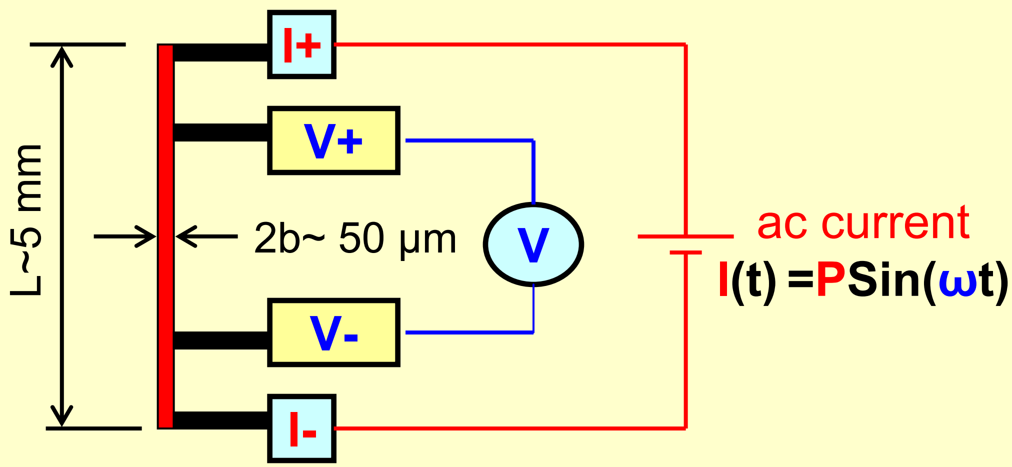
The 3-Omega Method –
Experimental Set-up



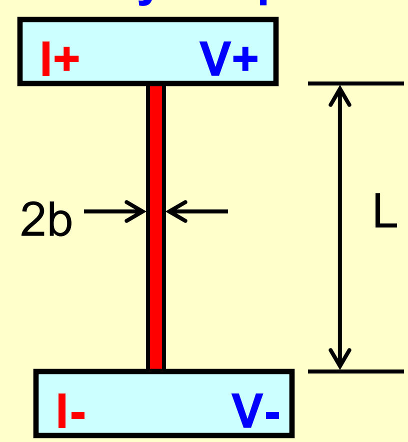
Metal line materials:
Au, Ag, Pt, etc.



Metal line by photolithography:

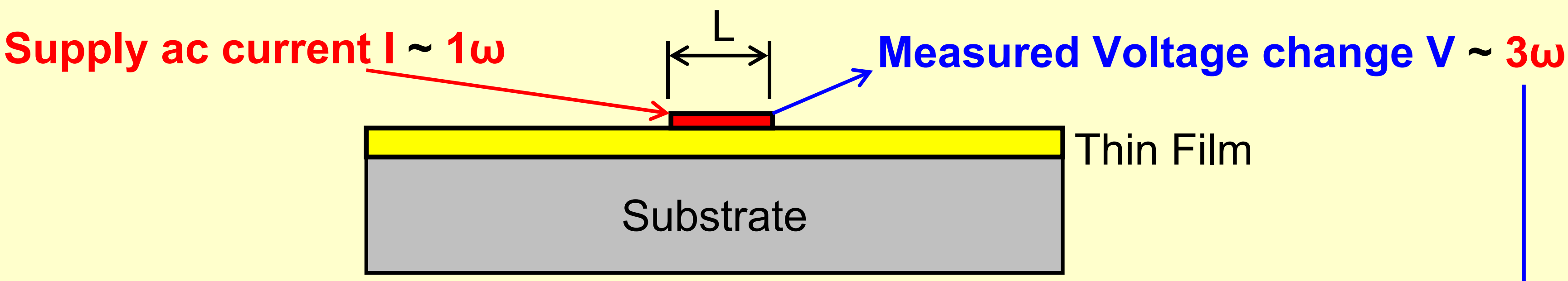


Metal line by evaporation:



- **Supply current I ~ 1ω**
- **Temperature rise T ~ I^2 ~ <u>2ω</u>**
- **Resistance in metal line R ~ T ~ 2ω**
- **<u>Measured</u> voltage output V ~ IR ~ 3ω**

The 3-Omega Method
k-Measurements



2ω ~ Temperature rise ΔT with calibration
2ω ~ Resistance change ΔR with calibration

The thermal conductivity of the thin film is:

$$k = \frac{V^3 \, \ell n\left(\frac{\omega_2}{\omega_1}\right)}{4\pi L R^2 \left(V_{3,1} - V_{3,2}\right)} \frac{\Delta R \; (\leftrightarrow 2\omega)}{\Delta T \; (\leftrightarrow 2\omega)}$$

ω_1, ω_2 = Measurements with two angular frequencies of supply current
R = resistance in the line heat source
V = voltage across metal line at ω
$V_{3,1}$ and $V_{3,2}$ = measured voltages across the heater @ 3ω
with ω_1 and ω_2 power supplies respectively

Thermal Microscopy of Micro- and Nanodevices

Techniques	Spatial Resolution
Infrared thermometry	1-10 μm
Laser Surface Reflectance	1 μm
Raman Spectroscopy	1 μm
Liquid Crystals	1 μm
Near-Field Optical Thermometry	< 1 μm
Scanning Thermal Microscopy	< 100 nm (= 0.1 μm)

Scanning Thermal Microscope

- For measuring k for thin films in the thickness range of 10 nm to 10 μm
- The method is based on heated tip that scan across the surface of the sample
- The heat flowing into sample is correlated to local thermal conductivity of the sample
- Modified version of scanning thermal microscope – called thermoreflectance thermometry can measure k of thin films in both normal and lateral directions
- Atomic force microscope (AFM), laser beam, photo- and thermal sensors are major components in this type of measurement systems

Atomic Force Microscope (AFM)

- The **AFM** consists of a microscale cantilever with a sharp tip (probe)

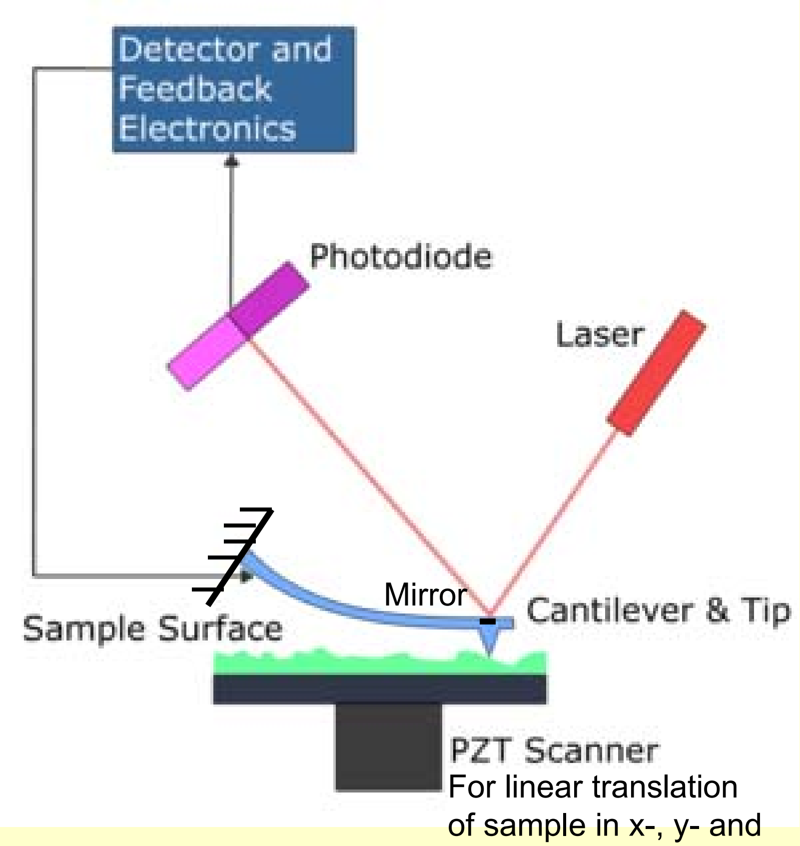
- Its end is used to scan the specimen surface

- The cantilever is typically silicon or silicon nitride with a tip radius of curvature on the order of nanometers

- When the tip is brought into proximity of a sample surface, forces between the tip and the sample lead to a deflection of the cantilever by Hooke's law

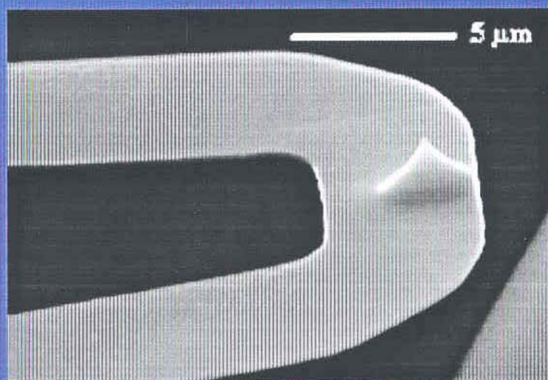
- Depending on the situation, forces that are measured in AFM include:
  - mechanical contact force
  - Van der Waals forces, capillary forces
  - chemical bonding, electrostatic forces
  - magnetic forces,etc

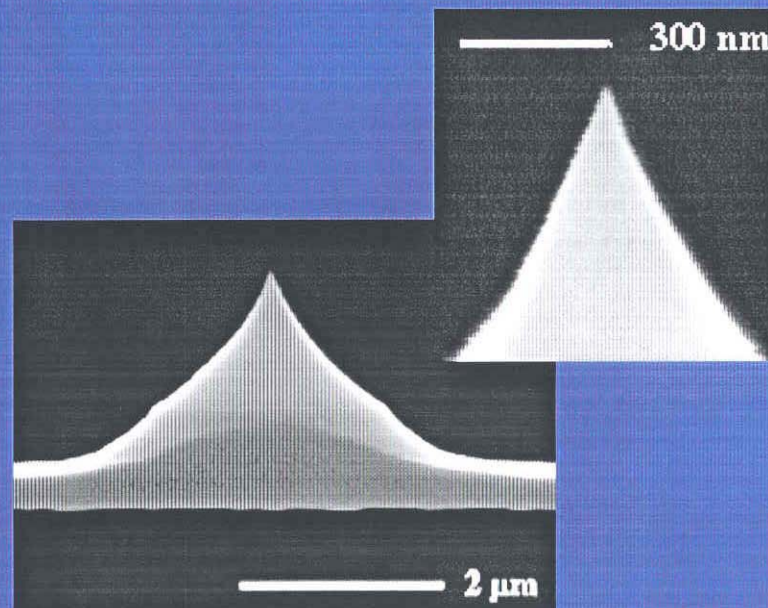
- Typically, the deflection is measured using a laser spot reflected from the top of the cantilever into an array of photodiodes



For linear translation of sample in x-, y- and Z-direction

Tip Characteristics





Tip Height: ~1.7µm

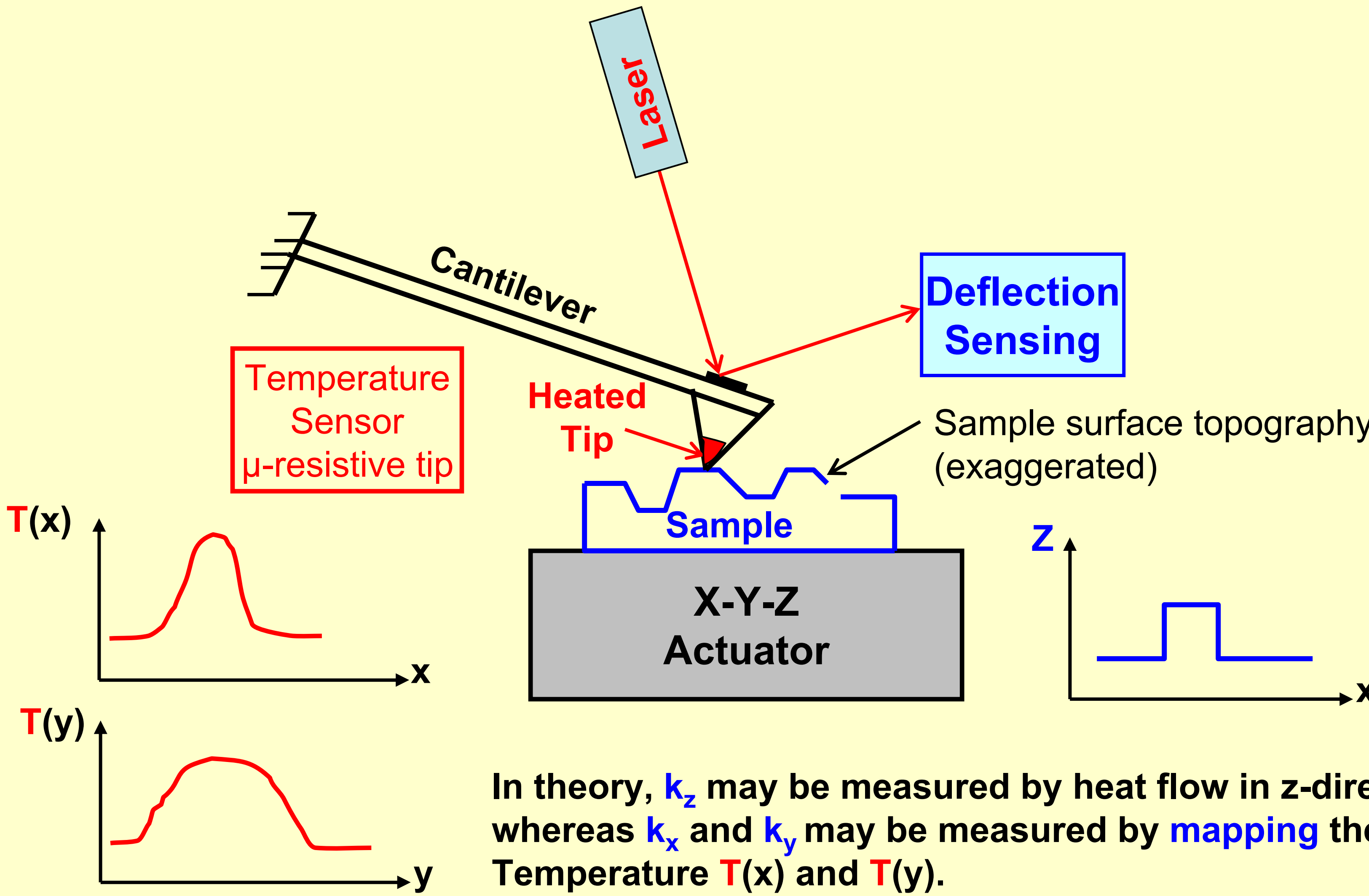
Tip Height Homogeneity in an Array: ± 50 nm (± 0.5%)

Tip Radius: <20 nm

Zurich Research Laboratory
Micro- and Nanomechanics Team

Major Components of Scanning Thermal Microscope

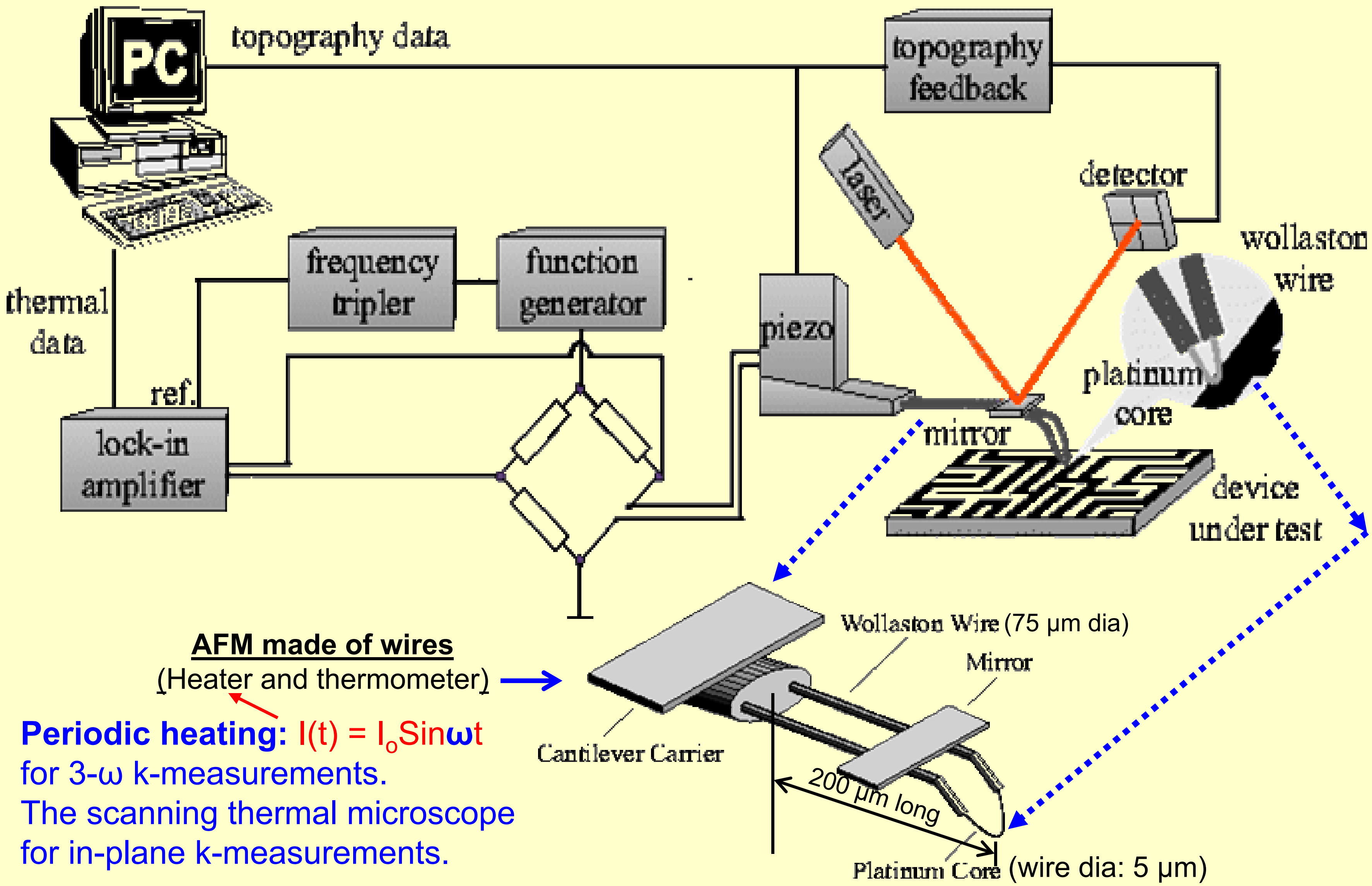
AFM + Thermal Probe



In theory, k_z may be measured by heat flow in z-direction whereas k_x and k_y may be measured by mapping the Temperature T(x) and T(y).

Measurement of k of Thin Film Using 3-Omega Method and Scanning Thermal Microscope

Fiege, G.B.M, Altes, A., Heiderhoff and Balk, L.J. “Quantative thermal Conductivity Measurements with Nano Resolution,” J. Physics D: Applied Physics, vol. 32, No. 5, 1999.



AFM made of wires

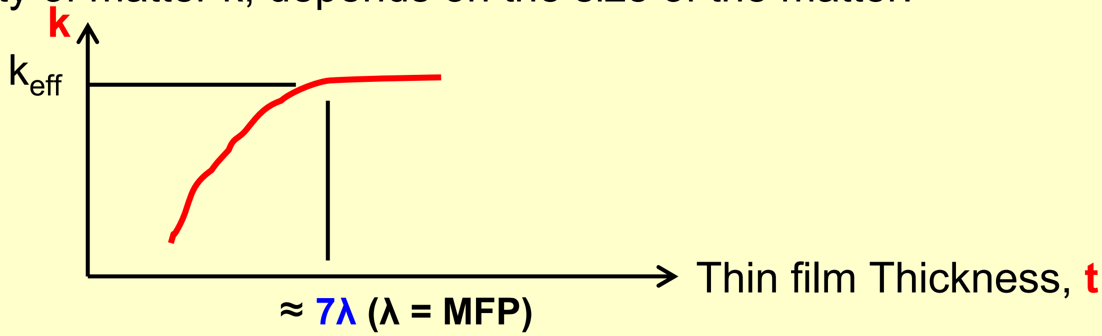
(Heater and thermometer)

Periodic heating: $I(t) = I_o \mathrm{Sin}\omega t$ for 3-ω k-measurements.

The scanning thermal microscope for in-plane k-measurements.

Summary on Thermal Conductivity Measurements of Thin Films

- Thermal conductivity is an important material characteristic in micro and nanoscale device design
- Heat transmission in matter rely on the traveling of energy carriers, such as phonons, electrons and photons
- The ability of conducting heat by matter, i.e. thermal conductivity, depends on how free these energy carriers can travel in the matter
- Thermal conductivity of matter k, depends on the size of the matter:



- Measurements of k for thin films presents a major challenge to engineers
- Two principal methods for measuring k of thin films are:
    - The 3-Omega method using periodic line heat source, and
    - Scanning thermal microscope using scanning AFM with heated contact tips
- Combined 3-Omega method and scanning thermal microscopy was used to measure the k-values of thin films of 30 nm thick in both normal and lateral directions

Part 6

Challenges in Nanoscale Engineering

- Nanotechnology has, and will bring to humankind enormous benefits and wealth.

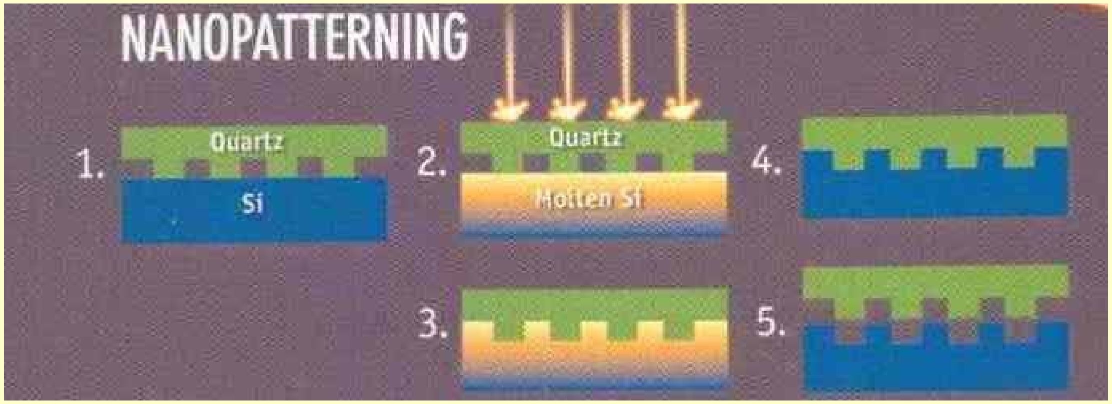
- The potentials and possibilities of what this technology can do to us appear limitless.

- However, many of these unthinkable possibilities could bring to human much unprecedented and irreversible negative socio-ethical consequences to human civilization

- While no one can stop the rapid advances of this emerging technology in the New century, it is a colossal challenge to scientists and engineers to only capitalize the benefits of nanotechnology but reject those that would bring disaster to our society

Nano-Patterning for Nanoscaled Devices

- **Photolithography has been extensively used in microscale patterning.**
- **The requirements for line sizes in nanometers and the line definition in the same scale has exceeded the limits of photolithographic technique due to:**
  - **The availability of adequate light source with sufficiently short wavelength,**
  - **Free from diffraction of the light beam for clear edge definition.**
- **New technique in patterning substrates in nanoscale is thus necessary.**
- **Current development of nano-patterning is termed as "Nano-imprint":**



General Procedures:

1. Nano-patterns in master quartz wafer. **2.** Heat up silicon substrate close to melting point.
3. Press quartz wafer into the Si substrate. **4.** Indent the "soft" silicon with the nano-patterns.
5. Retract the master quartz wafer.

Nanoscale Engineering Design

- Lack of materials that can be produced in nanoscale

- There is lack of electro-mechanical convertible materials, such as nanoscale piezoelectric crystals. This makes **NEMS** (Nanoelectromechanical systems) a misleading terminology widely used by researchers

- Lack of available mechanical and thermophysical material properties for mechanical and structural design

- Size-dependent material properties invalidated most established theories and physical laws used in design, .e.g., the Hooke's law, heat conduction equations, etc.

- Quantum physics and quantum mechanics are the fundamental phenomenological models available for describing molecular behavior, which is basically statistical of nature – the need to develop **stochastic models** for engineering design.

- Much effort is required in R&D of "computational stochastically mechanics" - the likely tool for engineering design of nanoscale devices

Nanoscale Engineering- Production and Manufacturing

There are several issues in transforming NT from scientific discoveries in the laboratory to commercial production by industry:

- **Facility for volume production:**

  - Self-assembly technology.
  - Reel-to-reel fabrication facility.
  - Robust tools and processes.
  - Low capital and operating costs.

- **Production systems** e.g. **"Flexible process-oriented manufacturing systems"** for nanoscale products of: high volume-low variety; medium volume-medium variety, or low volume-high variety of high value**.**

- **Reliability and testing techniques and standards.**

- **Integration of nanoscale structures and devices into micro-, meso- and macroscale products – packaging and interconnect.**

- **Production management.**

Part 7

Future Outlook of Nanotechnology and Negative Social Impacts

Before we look forward to what the ultimate benefits nanotechnology can bring to humankind, let us look back what are great technological breakthroughs in the past Century of human civilization:

Greatest Engineering Achievements of the 20th Century

As selected by the US Academy of Engineering

1. **Electrification***
2. **Automobile***
3. **Airplane***
4. **Water supply and distribution**
5. **Electronics**
6. **Radio and television**
7. **Agriculture mechanization***
8. **Computers**
9. **Telephone**
10. **Air conditioning and refrigeration***
11. **Highways**
12. **Spacecraft***
13. **Internet**
14. **Imaging**
15. **Household appliances***
16. **Health technologies**
17. **Petroleum and petrochemical technologies**
18. **Laser and fiber optics**
19. **Nuclear technology***
20. **High performance materials**

*** with significant mechanical engineering involvement**

Futuristic Industrial Products in the 21st Century by Nanotechnology

Near-term Products	"Dream" Products
• New vaccines and medicines that cure many incurable diseases. • Synthetic antibody-like nanoscale drugs and devices seeking out to destroy malignant cells in human or animal bodies. • In-vivo medical diagnostic and drug delivery systems. • Smart surface coating materials with self-adjusting thermal conductance for buildings and refrigeration systems. • Smart fabrics for self-cleaning clothe. • Super-strong materials for light weight airplanes, vehicles and structures. • Clean energy conversion systems and super-long life batteries. • New breed of crops and domestic animals that can feed entire world population.	• "Dust" sized super-intelligent computers. • "Needle-tip" sized robots for biomedical applications and for search and rescue. • Spacecraft weighing less than today's family cars. • Biomedicine, e.g. in-vivo systems and surgery that can sustain human lives to 150 years and longer. • Robots with artificial human intelligence becoming the mainstream workforce in our Society. • Unlimited supply of clean renewable energies that replace all fossil fuel produced energies on the Earth. • Tele-transportation systems that can transport human anywhere on Earth in seconds. • Spacecraft for human/cargo inter-planet traveling.

HSU-2005

Negative Social Impacts by Nanotechnology

- Nanotechnology could be used to produce devastating products for humankind:
  - Deadly vaccines that create pandemic diseases
  - Mass destruction weapons
- Unethical human cloning and duplication

A VC's Perception on Timeline for Commercialization of NT

(Steve T. Jurvestson, Managing Director, Draper Fischer Jurvetson, Menlo Park, CA)

♦ **Early Revenue** (next 5 years)
- Tools for bulk materials (e.g. powders, composites, etc.) fabrications.
- 1-D chemical and biological sensors, e.g. out-of-body medical sensors and diagnostic.
- Larger MEMS-scale devices.

♦ **Medium Term** (5 to 10 years)
- 2-D nanoelectronics: memory, displays, solar cells, etc,
- Hierarchically-structured nanomaterials.
- Passive drug delivery & diagnostics, improved implantable medical devices.

♦ **Long Term** (10 years and beyond)
- 3-D nanoelectronics.
- Nanomedicine, therapeutics, and artificial chromosomes.
- Quantum computers used in small molecule design.
- Machine-phase manufacturing.
- Something that we cannot predict today.

SUMMARY

- There has been unprecedented interests (and expectations) expressed by the scientific community, and colossal amount of investments in R&D by governments of leading industrialized nations in the world.
- Current state of nanotechnology appears focused on "scientific discovery" with rudimentary products at laboratory scale.
- Near term breakthroughs in significant commercial applications of nanotechnology appear in the new superior materials and disruptive biomedical applications.
- R&D on creative and novel micro/nano scale products that have identified global market potentials is a sensible direction to follow.
- Nanoscale engineering is a necessary vehicle to reach this goal.
- Related "soft nanotechnology", e.g. commercialization and global marketing for nano scale products, and volume production technologies should be encouraged and supported.

End of

Chapter 12

Thank You