Introduction to Nanotechnology and Nanoscience – Class#3

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Outline

- Top-down Technologies
- Semiconductor & Silicon
- MOSFET
- HW#1

- (some materials from Professors Lydia Sohn & Tsu-Jae King Liu)

Announcements

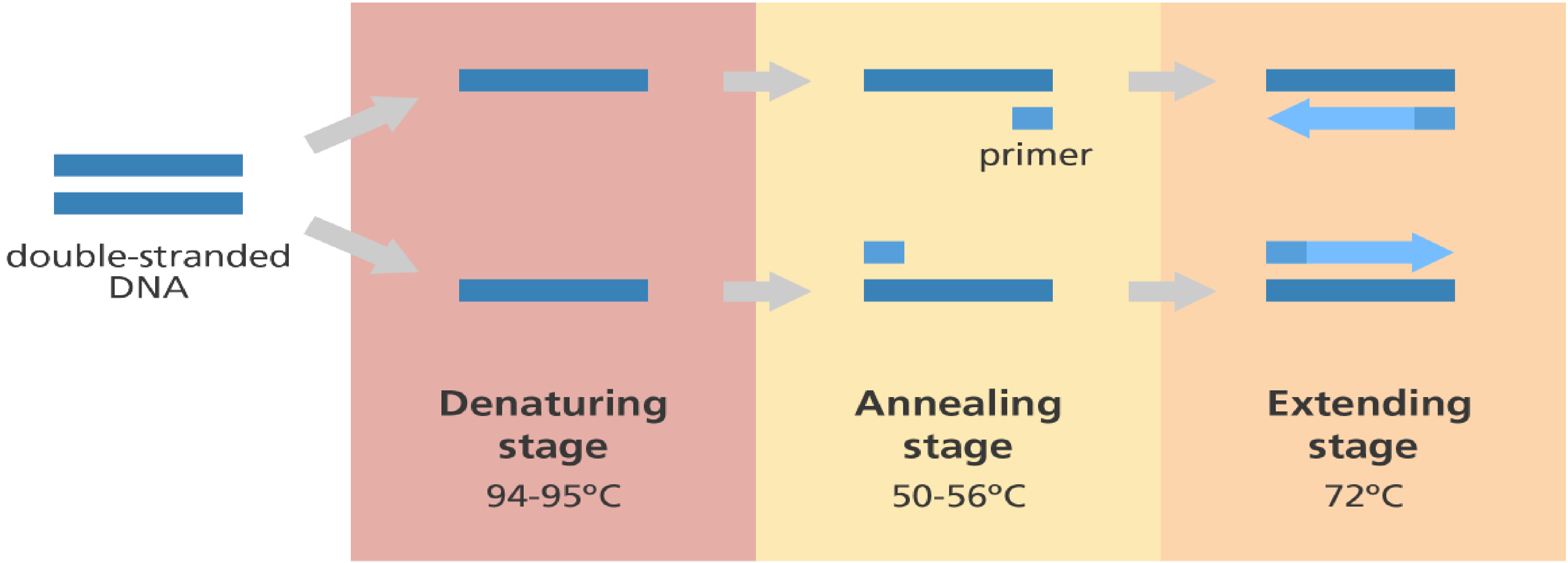
- A fairly "good" textbook:
  - Nanophysics & NanoTechnology, Edward Wolf Wiley-VCH, 2006 (Amazon.com)

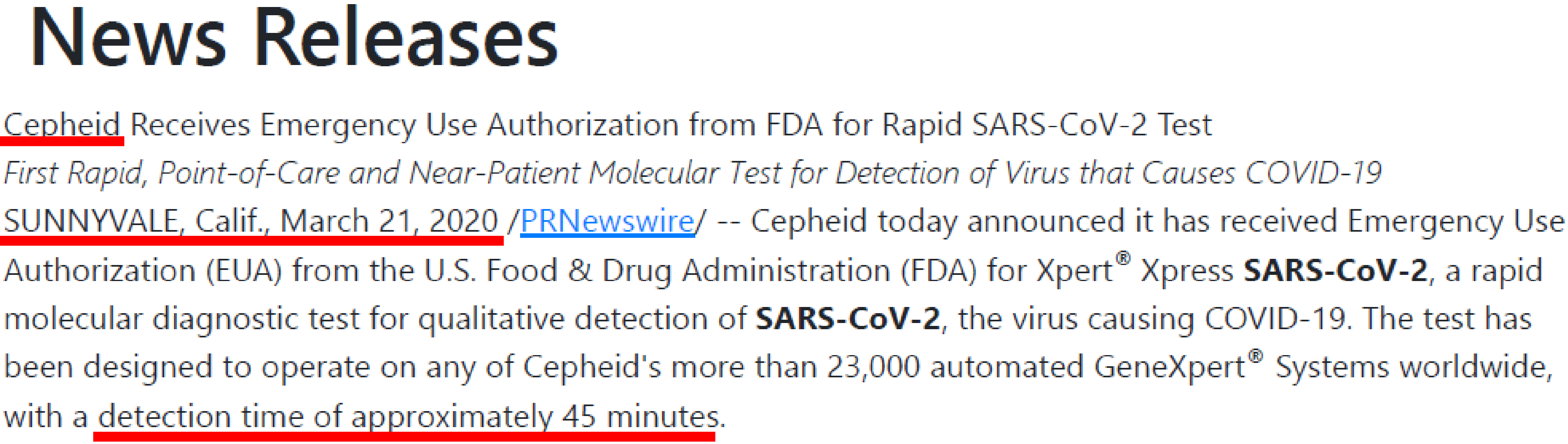
Anal. Chem. **1996**, *68*, 4081−4086

Functional Integration of PCR Amplification and Capillary Electrophoresis in a Microfabricated DNA Analysis Device

Adam T. Woolley,[†] Dean Hadley,[‡] Phoebe Landre,[‡] Andrew J. deMello,[†,§] Richard A. Mathies,[*,†] and M. Allen Northrup[‡]

Department of Chemistry, University of California, Berkeley, California 94720, and Microtechnology Center, L-222, Lawrence Livermore National Laboratory, Livermore, California 94551



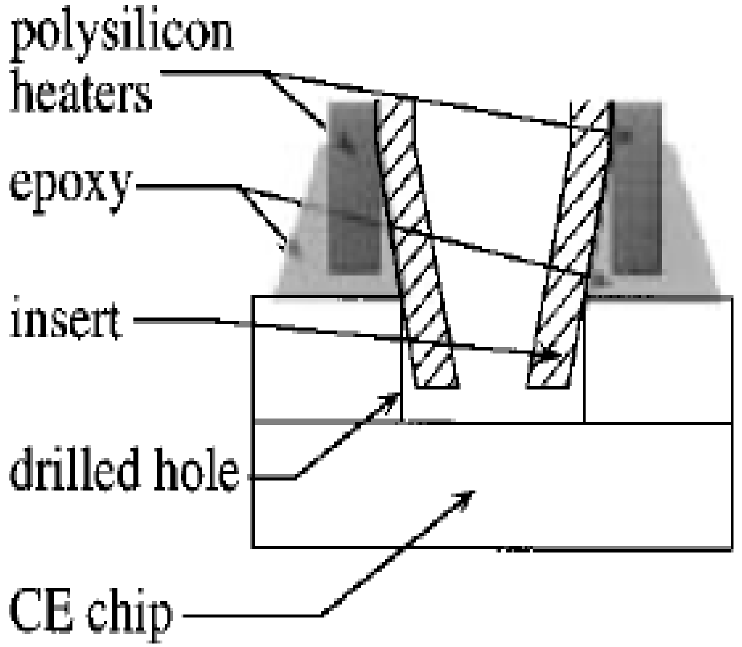


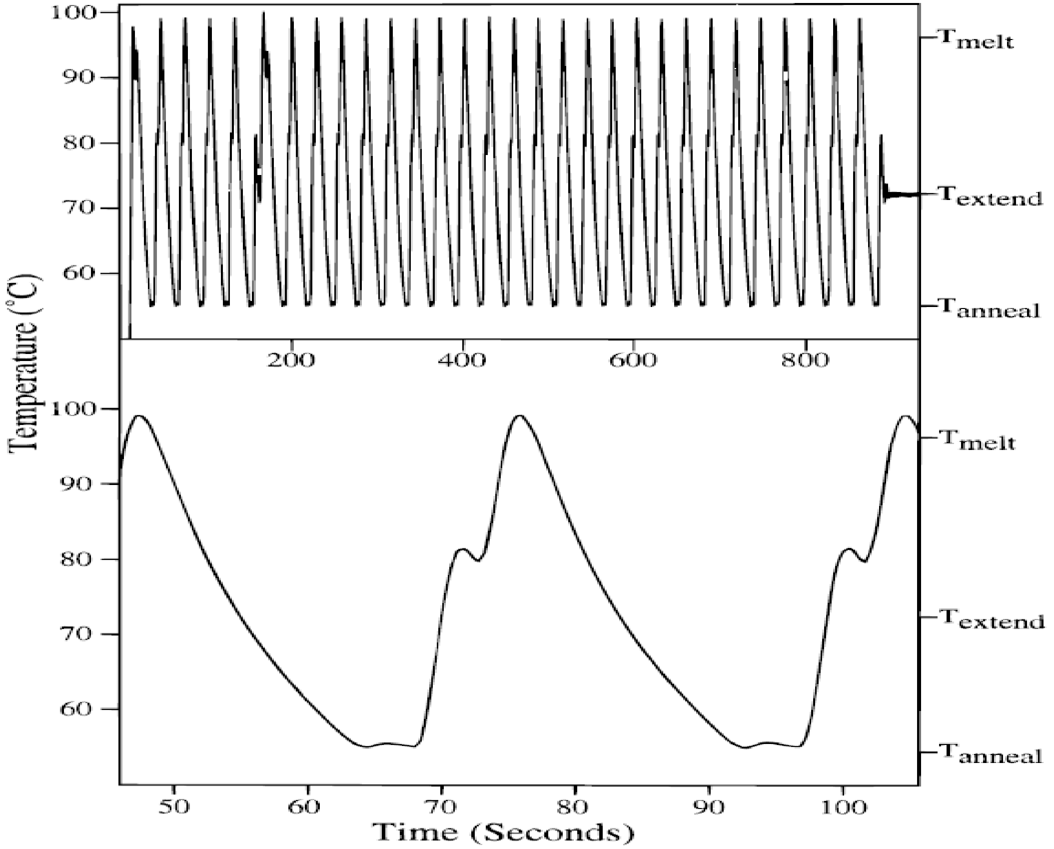
News Releases

Cepheid Receives Emergency Use Authorization from FDA for Rapid SARS-CoV-2 Test

First Rapid, Point-of-Care and Near-Patient Molecular Test for Detection of Virus that Causes COVID-19

SUNNYVALE, Calif., March 21, 2020 /PRNewswire/ -- Cepheid today announced it has received Emergency Use Authorization (EUA) from the U.S. Food & Drug Administration (FDA) for Xpert® Xpress **SARS-CoV-2**, a rapid molecular diagnostic test for qualitative detection of **SARS-CoV-2**, the virus causing COVID-19. The test has been designed to operate on any of Cepheid's more than 23,000 automated GeneXpert® Systems worldwide, with a detection time of approximately 45 minutes.





Cepheid

Cepheid headquarters in Sunnyvale

Type	Subsidiary
Industry	Biotechnology Medical devices
Founded	March 1996
Headquarters	Sunnyvale, California, U.S.

Corporate status

Cepheid was founded in March 1996 by Thomas Gutshall, Bill McMillan, Dr. Kurt Petersen, Dr. Greg Kovacs, Steven Young and Dr. Allen Northrup.

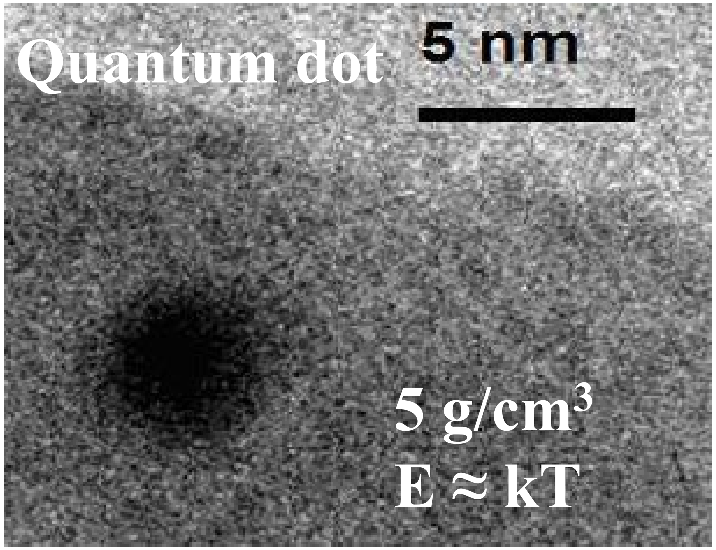
The company went public in 2000.[5] The initial public offering was June 21, 2000 at US$6 per share. Cepheid stock was listed on the Nasdaq under the ticker symbol CPHD until it was acquired by Danaher in 2016.[26]

During the 2001 anthrax attacks, U.S. federal agencies contracted with Cepheid to track the anthrax.[7][5]

During the COVID-19 pandemic, Cepheid began the development of a CRISPR-based diagnostic test for the SARS-CoV-2 (then called "2019-nCov") virus.

Quantum Mechanics

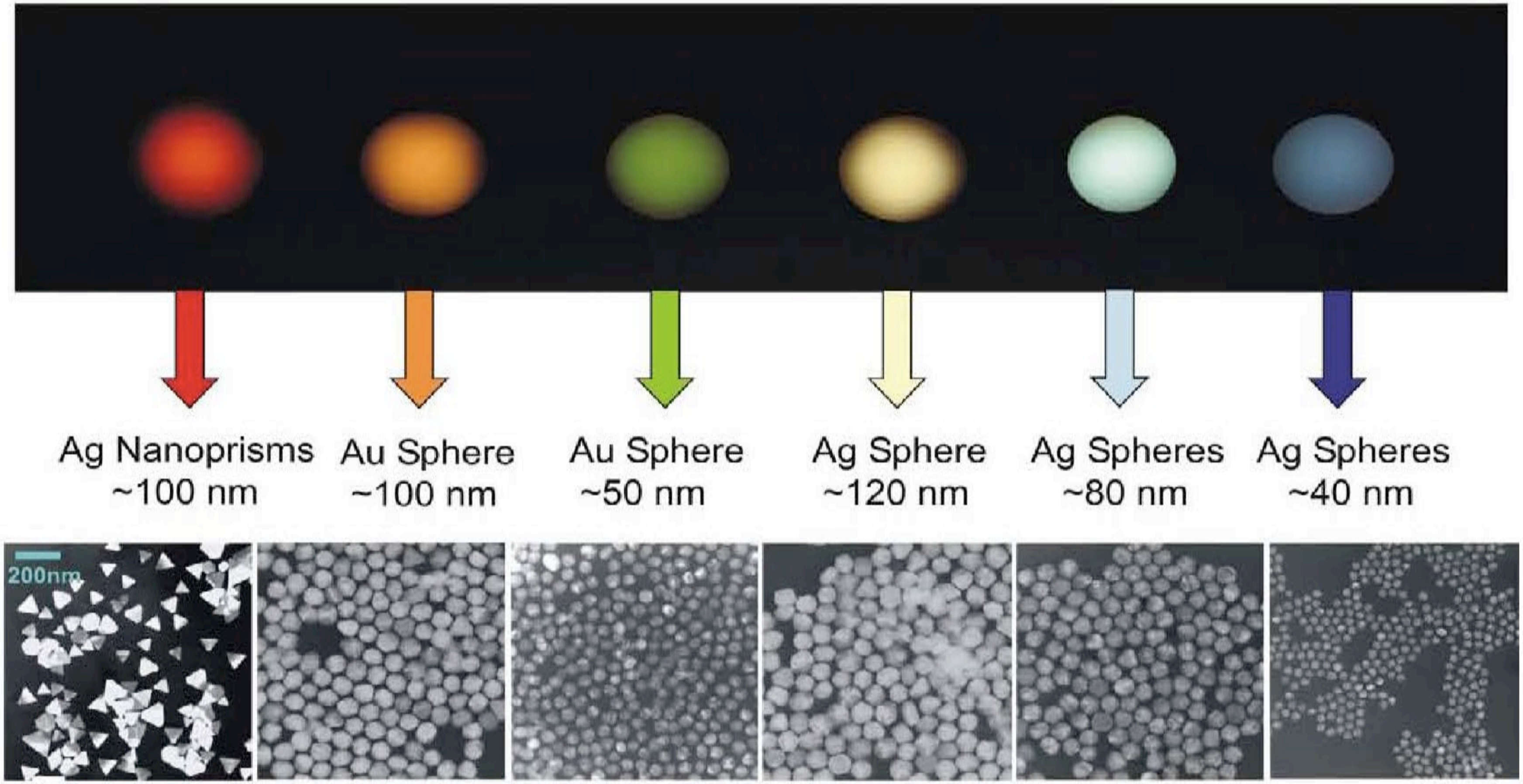
vs



$$\lambda = \frac{\hbar}{\sqrt{2mE}}; \quad \hbar \sim 1x10^{-34} \text{ J-s}$$

Rayleigh Light-Scattering of Nanocrystals

Shape, Size, and Composition Matter



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

Optical Absorption

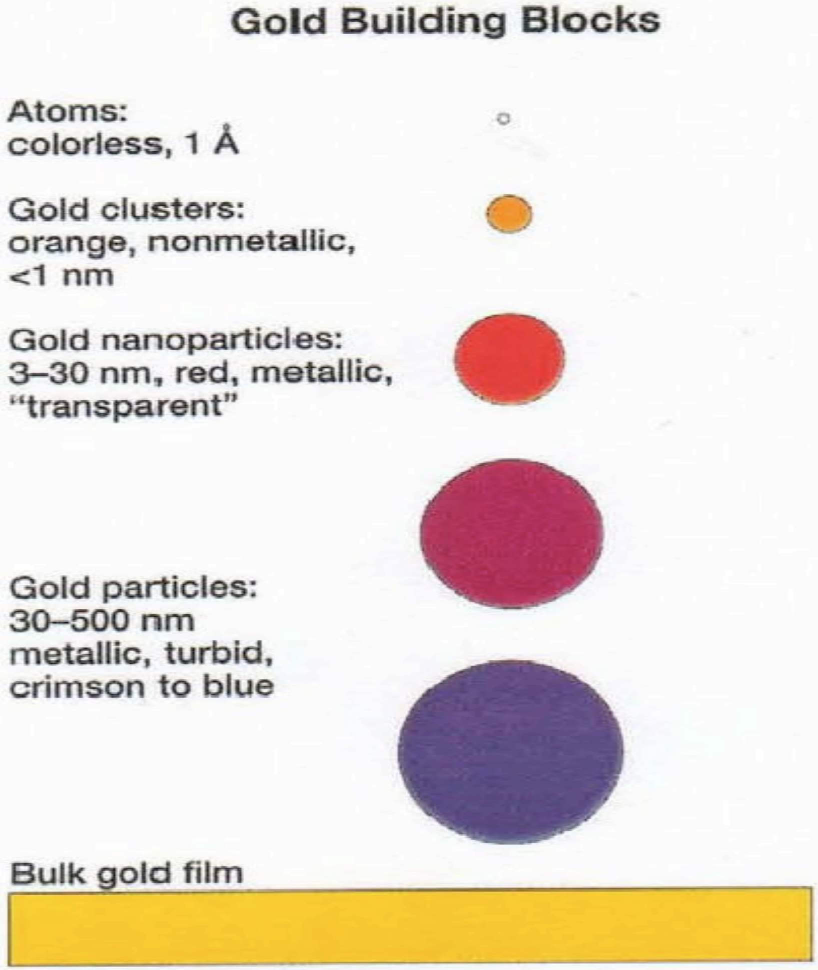


Figure 1. Gold building blocks, from the atomic to the mesoscopic, and their changing colors.

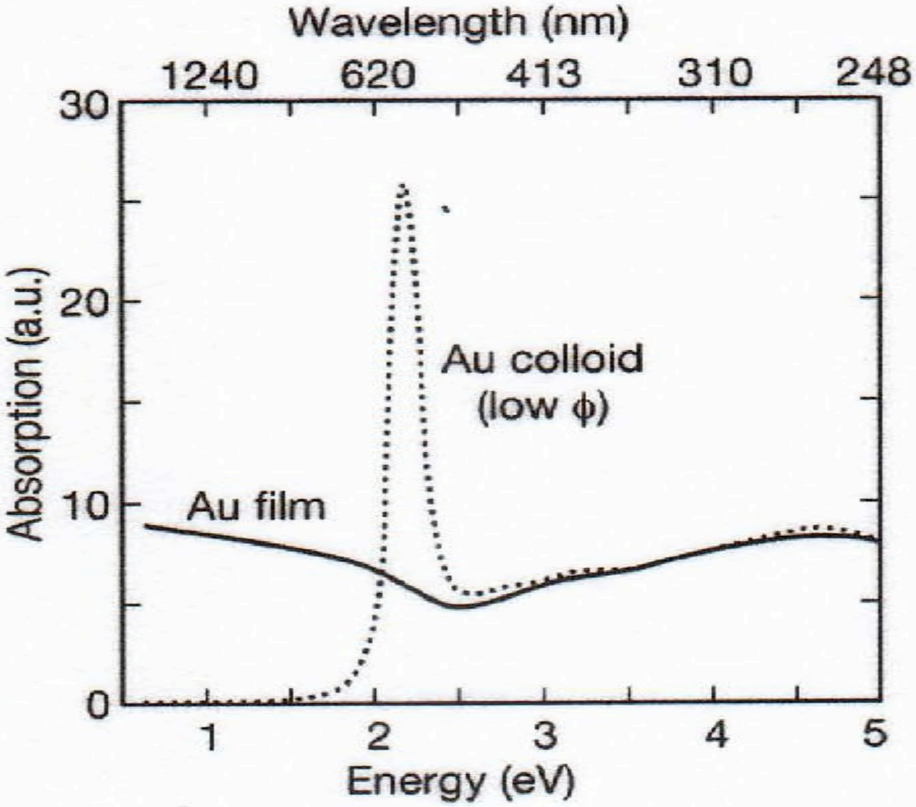
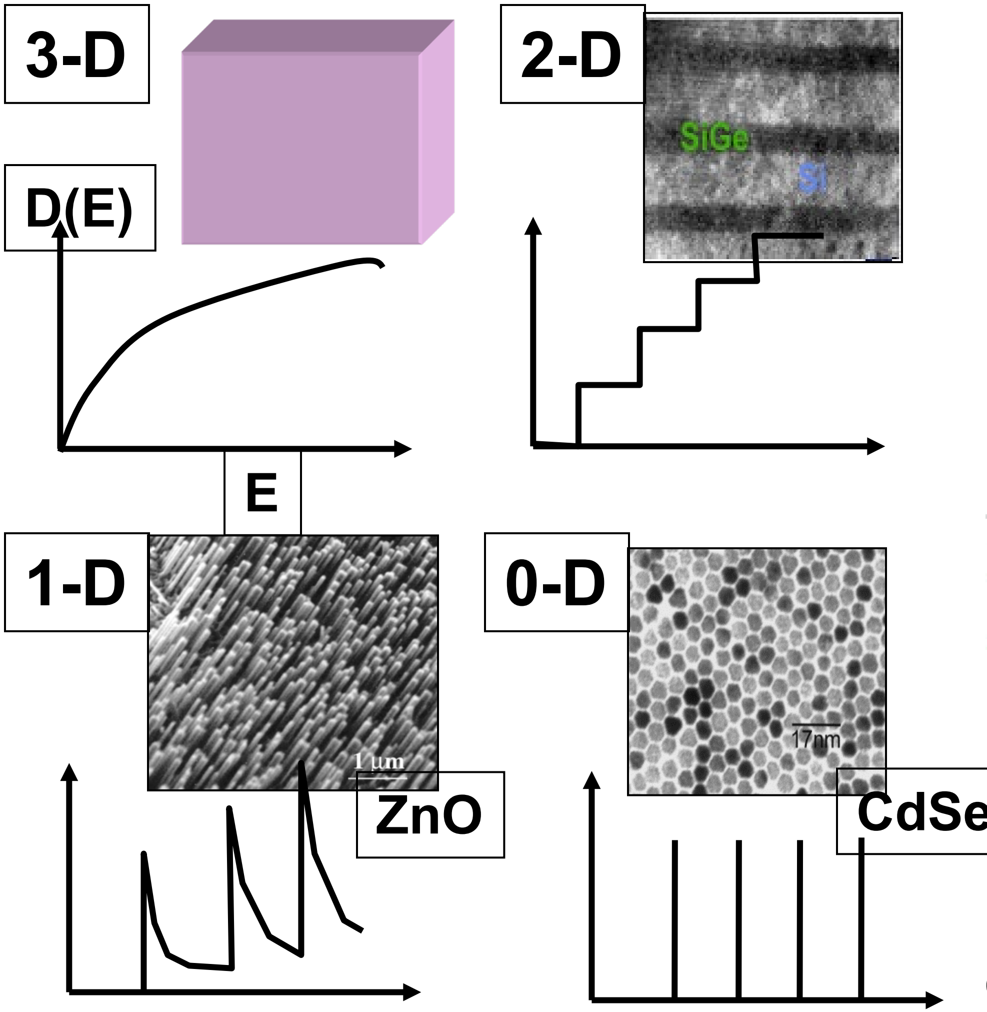
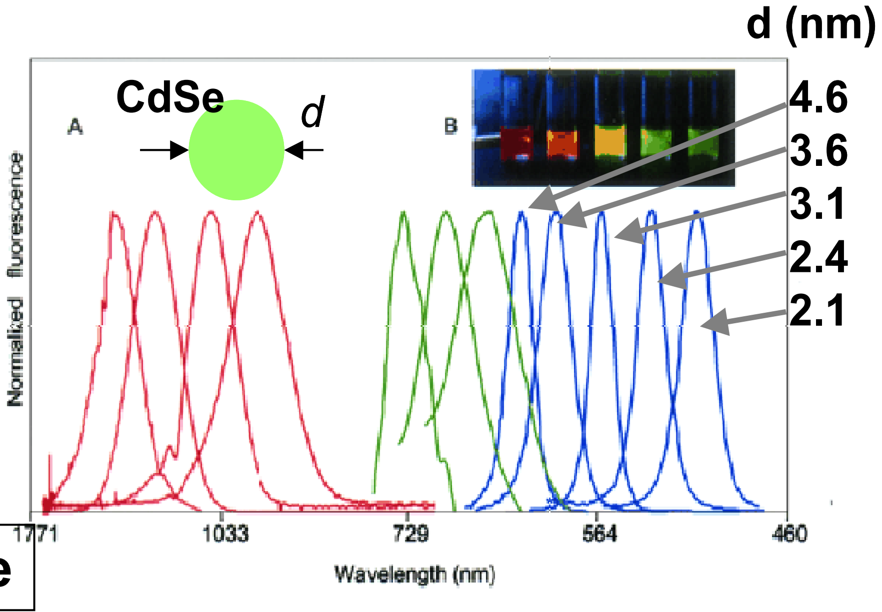


Figure 3. Absorption spectra of a gold nanocrystal film and a thin, bulk gold metal film of equivalent thickness. ϕ is the volume fraction of gold in the sample.

Effects of Confinement of Charge Carriers



Example: CdSe quantum dots Fluoresces vs. wavelength

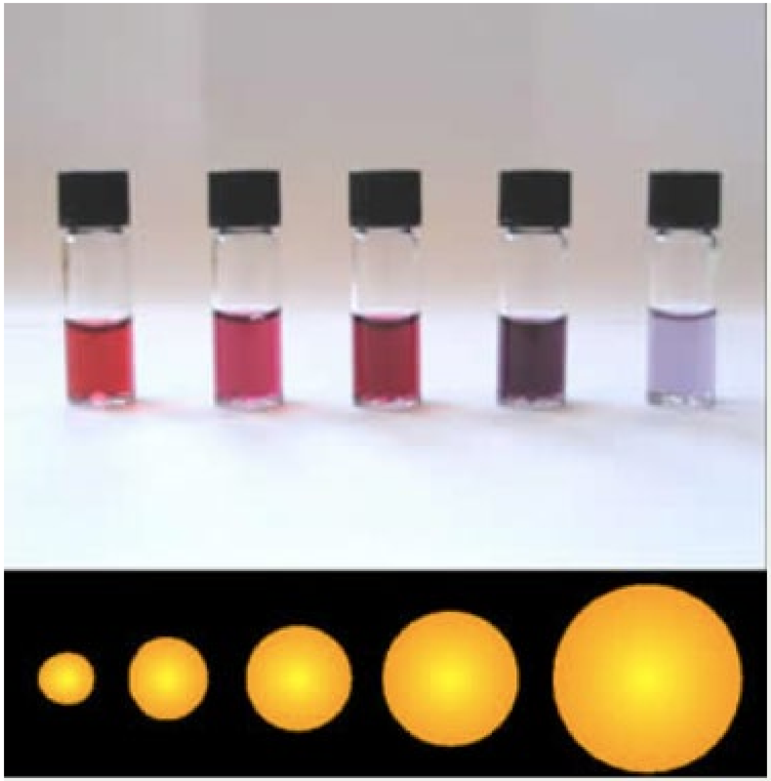


(Paul Alivisatos, UCB)

(After Arum Majumdar, UCB)

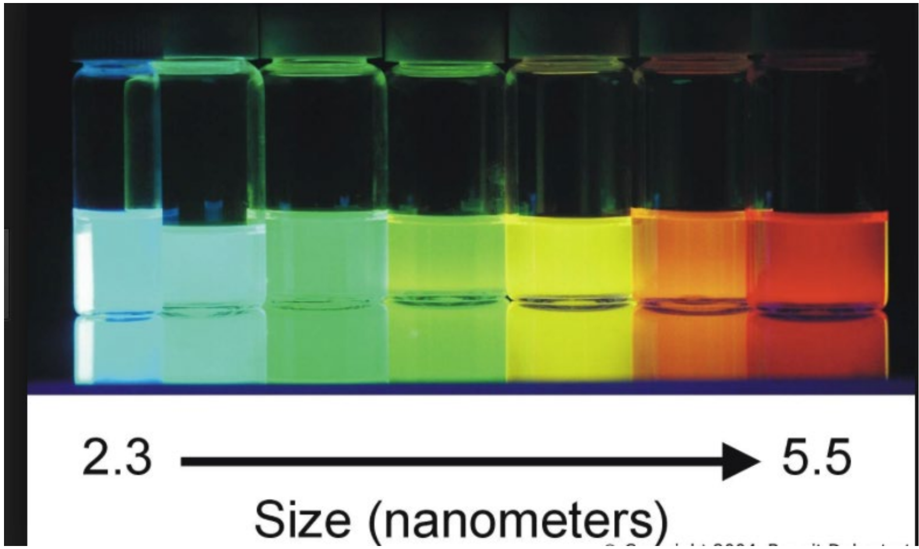
What's going on here?

Gold nanoparticles



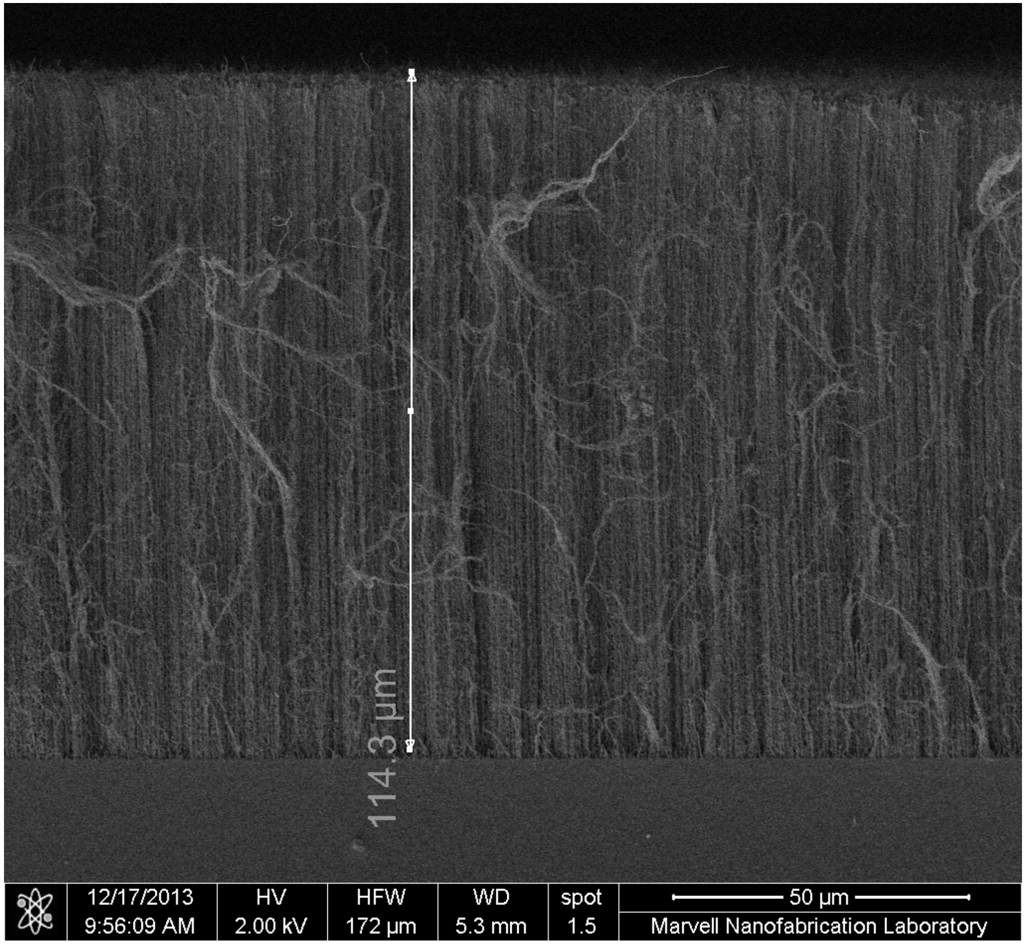
vs.

CdSe quantum dots



Aspect Ratio

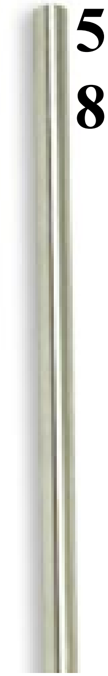
vs



Electrical Properties: Tunneling Current

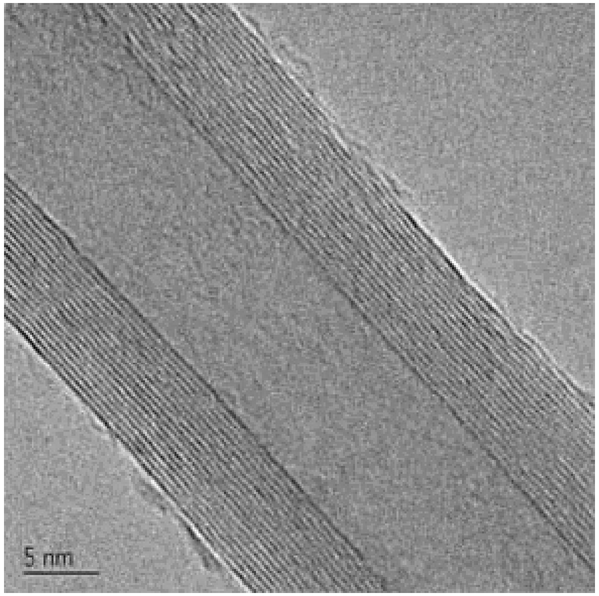
- At the nanometer scale, electrical insulators begin to fail to block current flow
- Quantum mechanical effect known as tunneling
- Tunneling current increases exponentially as the thickness of the insulator is decreased
- Tunneling is the basis of the scanning tunneling microscope and covalent chemical bonding

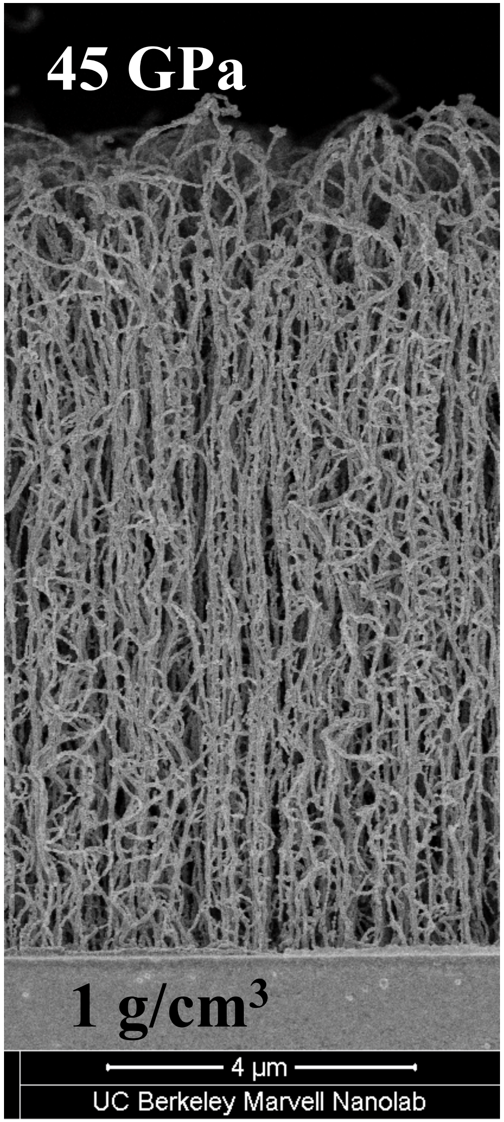
Strength-to-weight ratio



520 MPa
8 g/cm^3

vs.





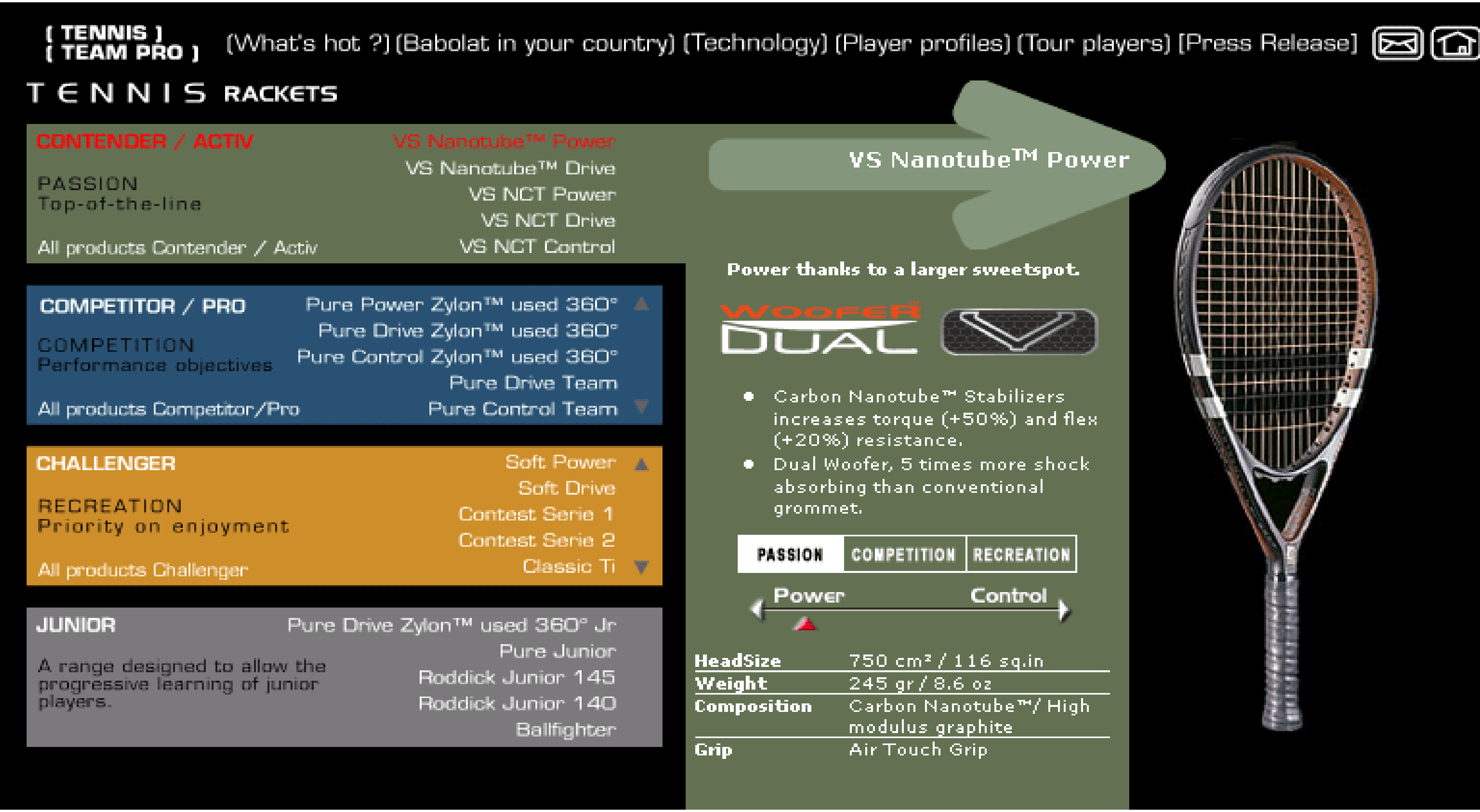
45 GPa

1 g/cm^3

Pa/(kg/m^3)

http://www.owlnet.rice.edu/~biy/Selected%20papers/01TAPhys.pdf
http://cnx.org/contents/f3abd155-e65d-4155-bd2c-9b435b6d2f6a@4/Carbon_Nanomaterials

Nanotube Composite



TENNIS RACKETS

CONTENDER / ACTIV

PASSION
Top-of-the-line

All products Contender / Activ

VS Nanotube™ Power
VS Nanotube™ Drive
VS NCT Power
VS NCT Drive
VS NCT Control

COMPETITOR / PRO

COMPETITION
Performance objectives

All products Competitor/Pro

Pure Power Zylon™ used 360°
Pure Drive Zylon™ used 360°
Pure Control Zylon™ used 360°
Pure Drive Team
Pure Control Team

CHALLENGER

RECREATION
Priority on enjoyment

All products Challenger

Soft Power
Soft Drive
Contest Serie 1
Contest Serie 2
Classic Ti

JUNIOR

A range designed to allow the progressive learning of junior players.

Pure Drive Zylon™ used 360° Jr
Pure Junior
Roddick Junior 145
Roddick Junior 140
Ballfighter

VS Nanotube™ Power

Power thanks to a larger sweetspot.

- Carbon Nanotube™ Stabilizers increases torque (+50%) and flex (+20%) resistance.
- Dual Woofer, 5 times more shock absorbing than conventional grommet.

HeadSize	750 cm² / 116 sq.in
Weight	245 gr / 8.6 oz
Composition	Carbon Nanotube™/ High modulus graphite
Grip	Air Touch Grip

Size-Dependent Properties

At the nanometer scale, properties become size dependent!

For example,

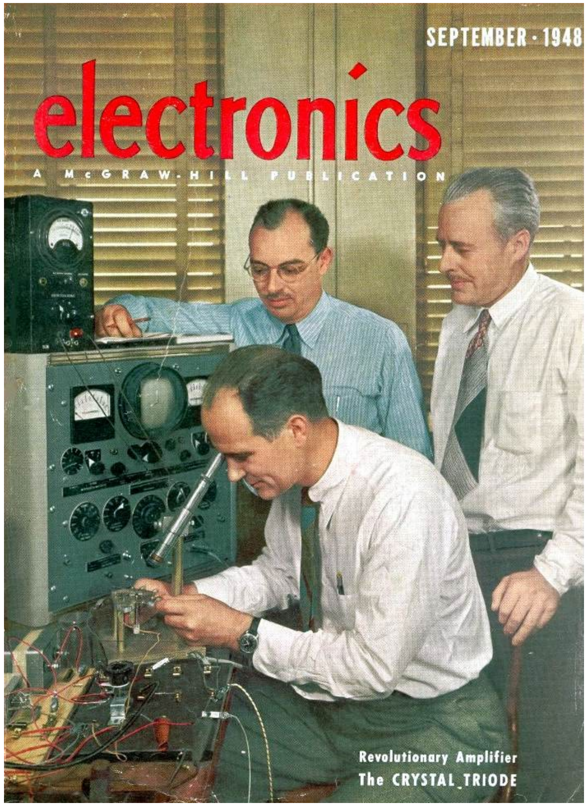
- Thermal properties — melting temperature
- Mechanical properties — adhesion, capillary forces
- Optical properties — absorption and scattering of light
- Electrical properties — tunneling current
- Magnetic properties — superparamagnetic effect

New properties enable new applications

Invention of the Transistor

The Greatest Motivation

http://www.bellsystemmemorial.com/belllabs_transistor.html



The first transistor was invented in 1947 by Bardeen, Brattain, and Shockley at Bell Laboratories. BBS won the Nobel Prize in 1956

The Ever-Shrinking Transistor

1st Transistor

1947

Bell Lab -

Bardeen, Brattain, Shockley

TI

Jack Kilby

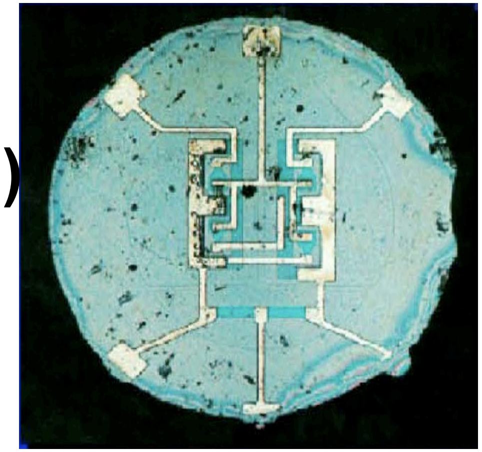
Nobel Prize @2000

1st Integrated Circuit (IC)

1958

Fairchild

Robert Noyce

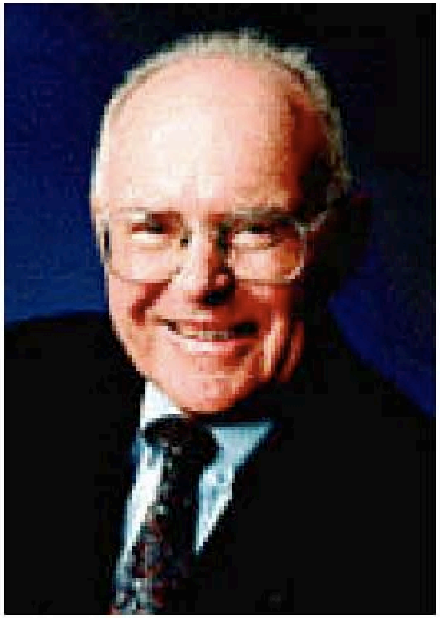


1st Planar IC

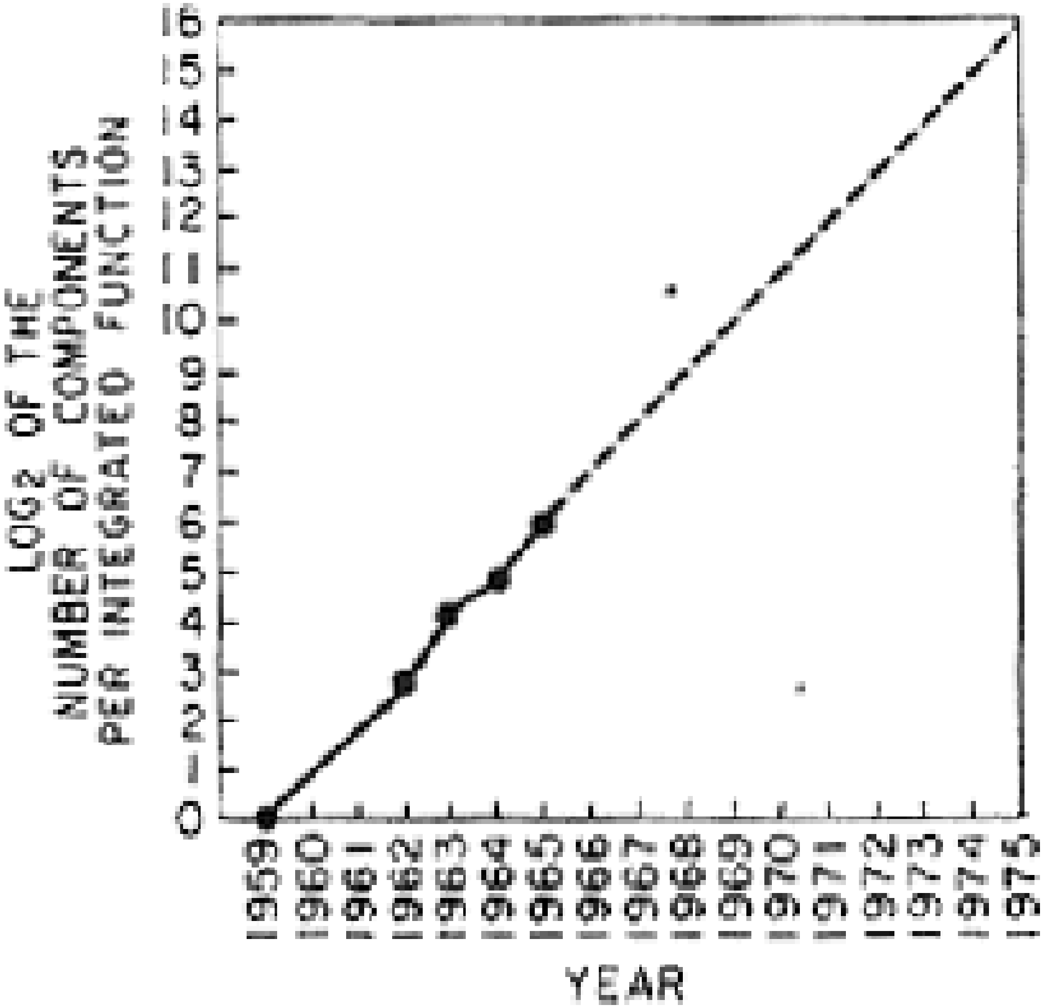
1961

"Moore's Law"

Not a Law, Just a Roadmap!



Intel Co-Founder
Gordon E. Moore

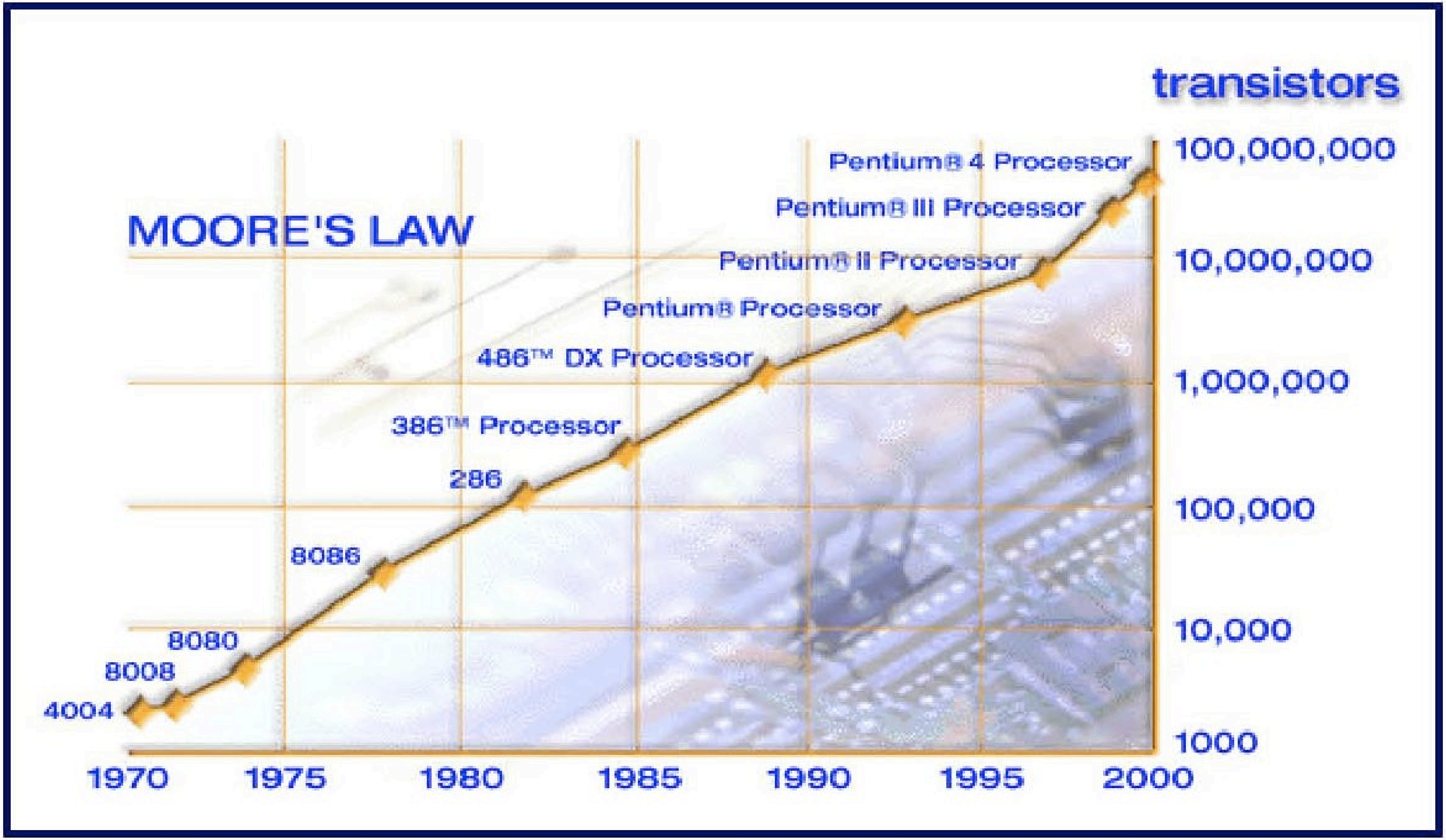


Moore, Electronics **38**, 1965

640K ought to be enough for anybody…

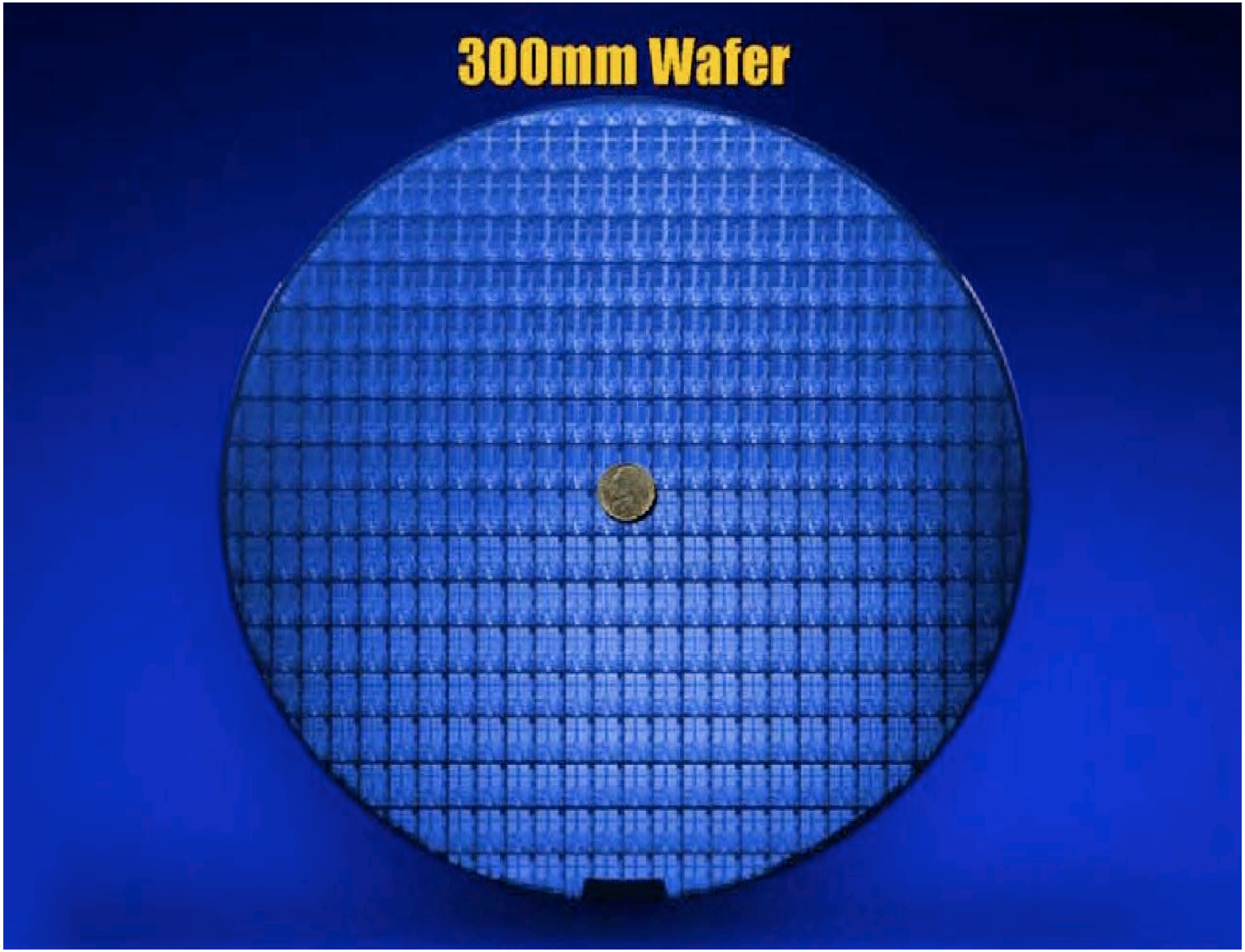
Bill Gates, 1981

Where Are We Now?

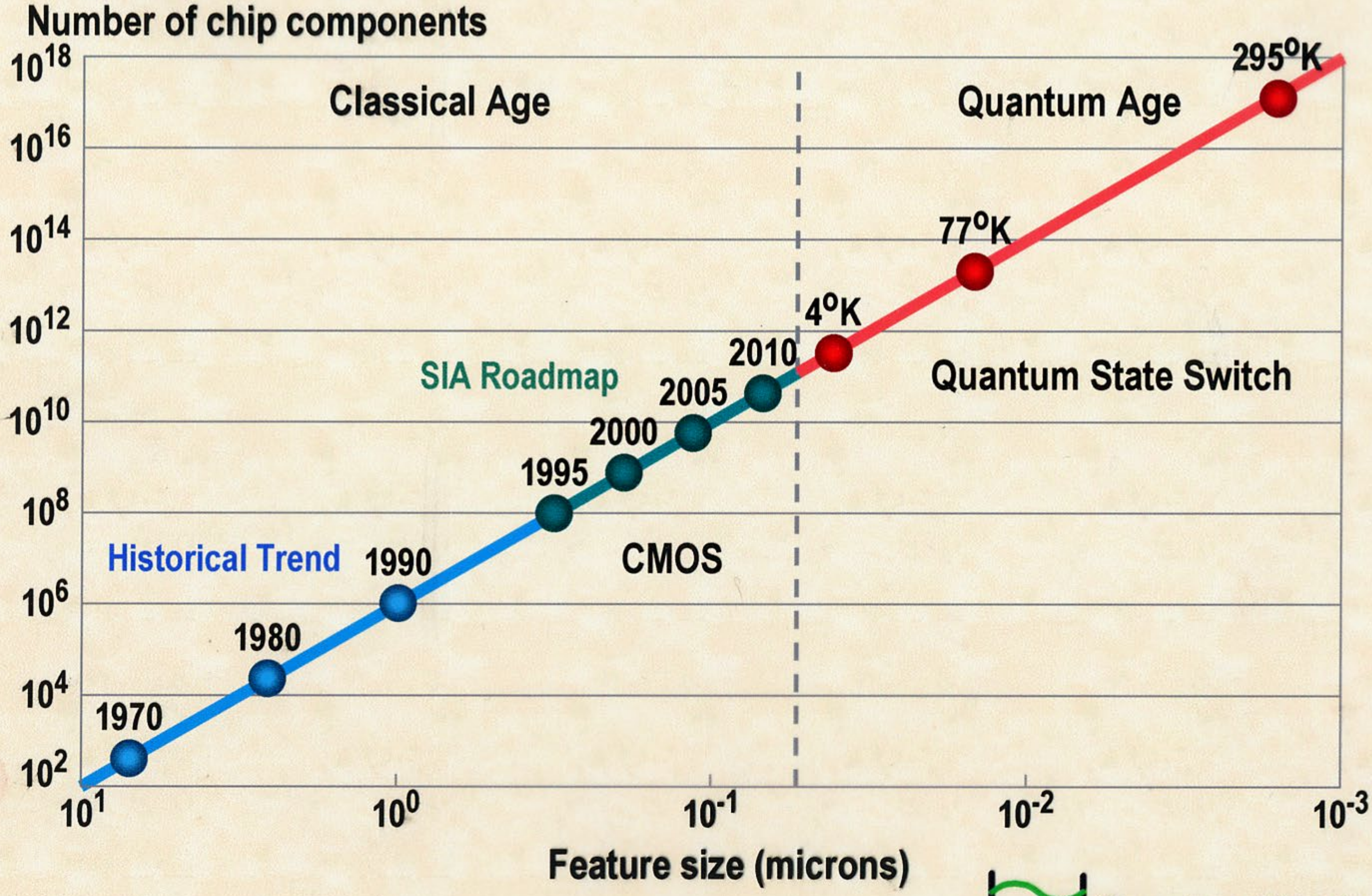


No exponential is forever…but we delay “Forever.”

G. Moore, 2003


300mm Wafer

Scaling of electronic devices



Quantum Structures
Research Initiative

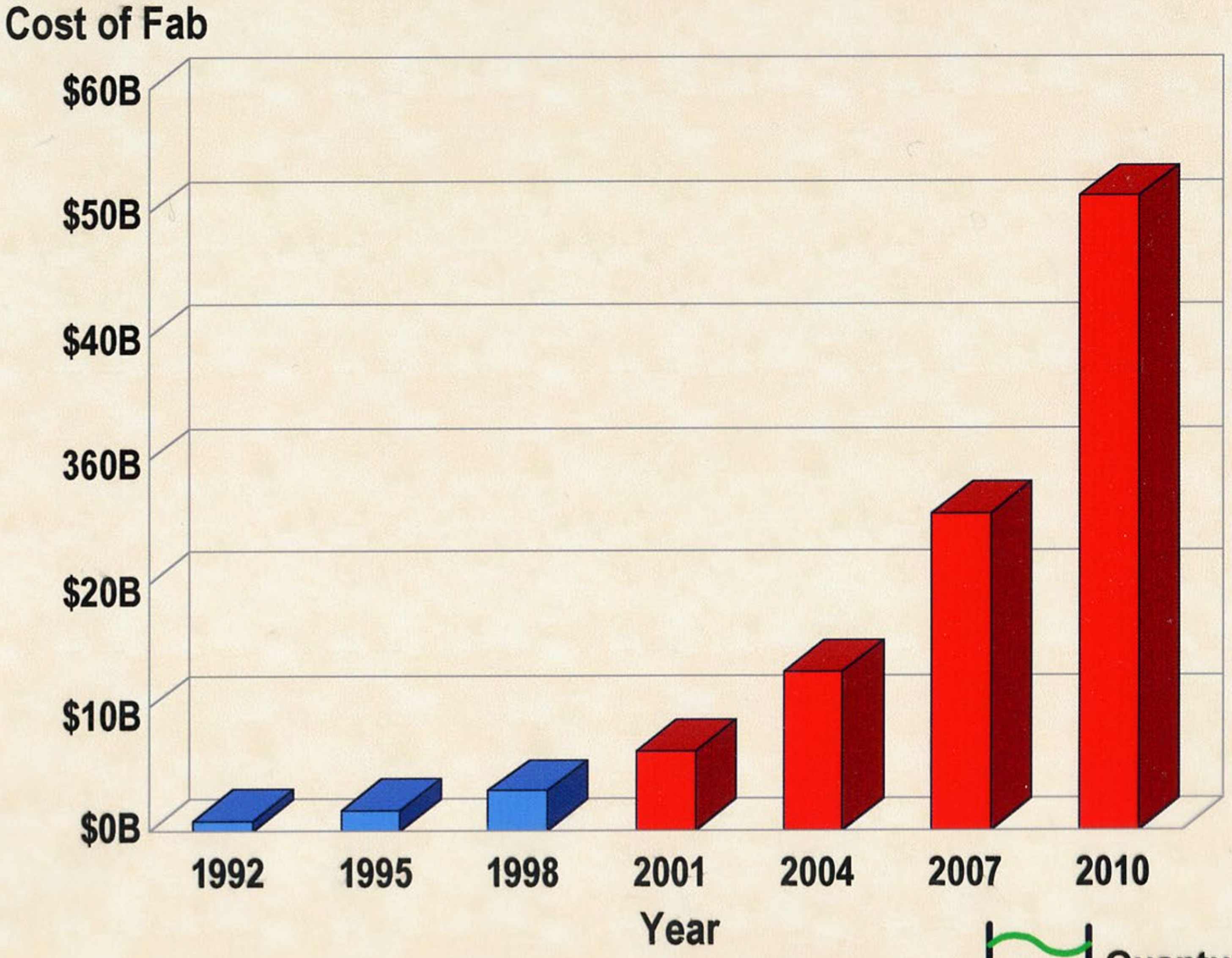
Nanofabrication

- Top Down:
"Chisel" away material to make nanoscale object

- Bottom Up:
Assemble nanoscale object using even smaller units (atoms and molecules)

Ultimate Goal: "Dial in" properties that you want by designing and building at the scale of nature (I.e. the nanoscale)

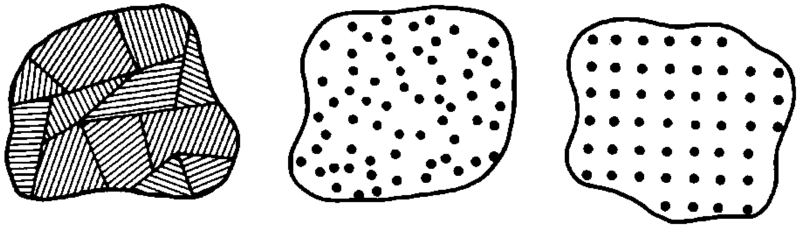
Moore's Second Law



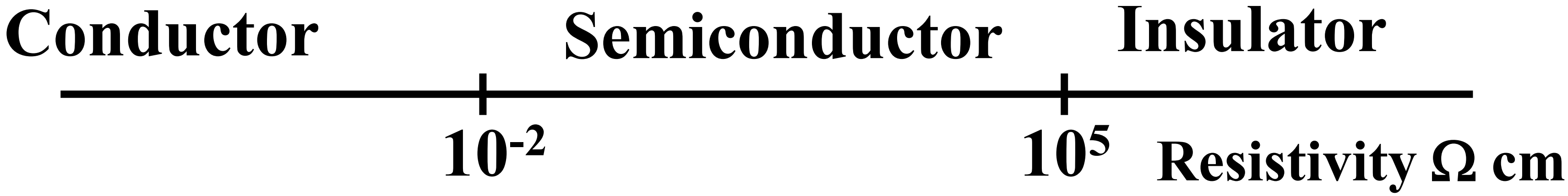
Quantum Structures
Research Initiative

What is a Semiconductor?

- ☐ Low resistivity => “conductor”
- ☐ High resistivity => “insulator”
- ☐ Intermediate resistivity => “semiconductor”
  - conductivity lies between that of conductors and insulators
  - generally crystalline in structure for IC devices
    - In recent years, however, non-crystalline semiconductors have become commercially very important


polycrystalline amorphous crystalline

Semiconductor



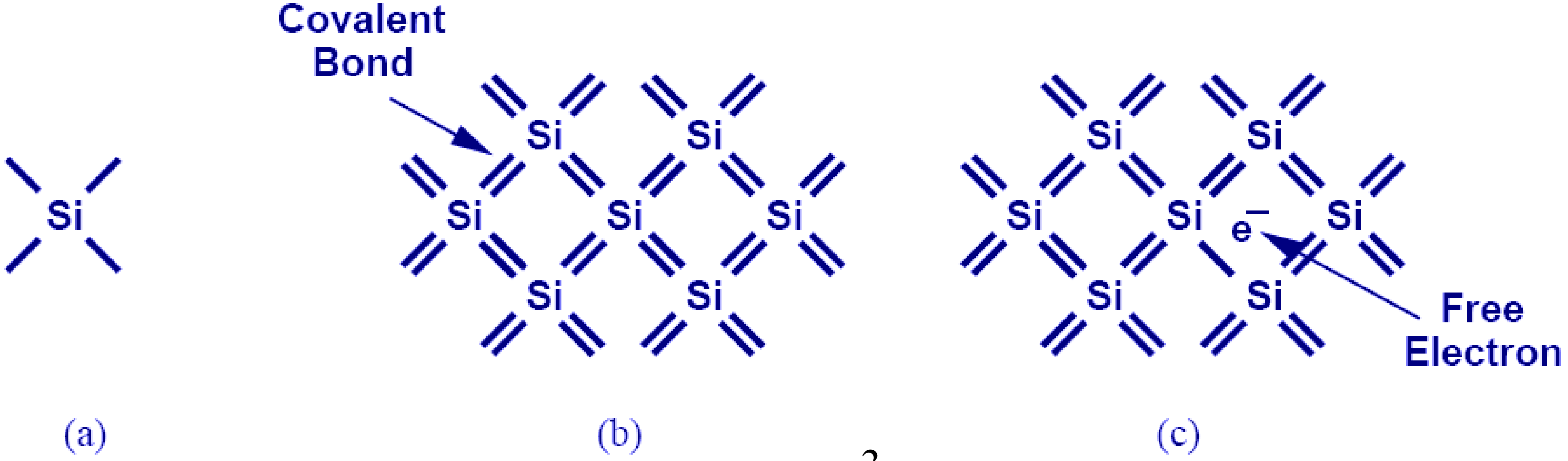
- ☐ Examples:
  - Aluminum = 10^{-6} Ω cm
  - $SiO_2 = 10^{16}$ Ω cm
- ☐ Dopant concentration
  - Electron (hole) concentration → n (p)

Semiconductor Materials

	III	IV	V	
	Boron (B)	Carbon (C)		
• • •	Aluminum (Al)	Silicon (Si)	Phosphorous (P)	• • •
	Galium (Al)	Germanium (Ge)	Arsenic (As)	
		• • •		

Silicon

- ☐ Atomic density: 5×10^{22} atoms/cm^3
- ☐ Si has four valence electrons. Therefore, it can form covalent bonds with four of its nearest neighbors.
- ☐ When temperature goes up, electrons can become free to move about the Si lattice.



Intrinsic Si $n_i = 3.87x10^{16} T^{\frac{3}{2}} \exp[\frac{-7014}{T}]$

$1.45x10^{10}$ at room temperature

Electronic Properties of Si

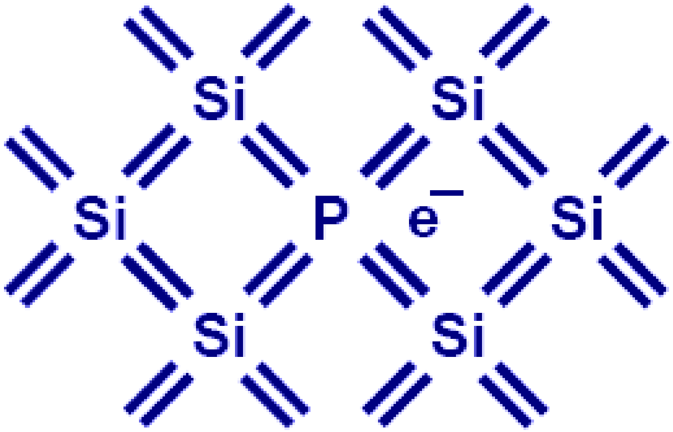
- **Silicon is a semiconductor material.**
  - Pure Si has a relatively high electrical resistivity at room temperature.

- **There are 2 types of mobile charge-carriers in Si:**
  - ***Conduction electrons*** are negatively charged;
  - ***Holes*** are positively charged.

- **The concentration (#/cm^3) of conduction electrons & holes in a semiconductor can be modulated in several ways:**
  1. **by adding special impurity atoms (*dopants*)**
  2. **by applying an electric field**
  3. **by changing the temperature**
  4. **by irradiation**

Doping (N type)

- ☐ Si can be "doped" with other elements to change its electrical properties.
- ☐ For example, if Si is doped with phosphorus (P), each P atom can contribute a conduction electron, so that the Si lattice has more electrons than holes, *i.e.* it becomes "N type":

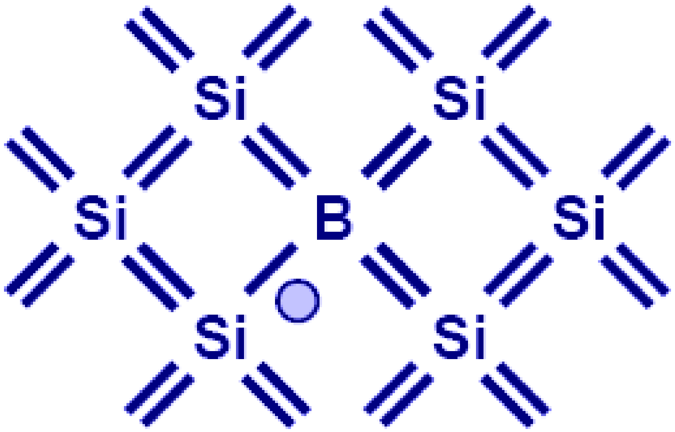


Notation:
n = conduction electron concentration

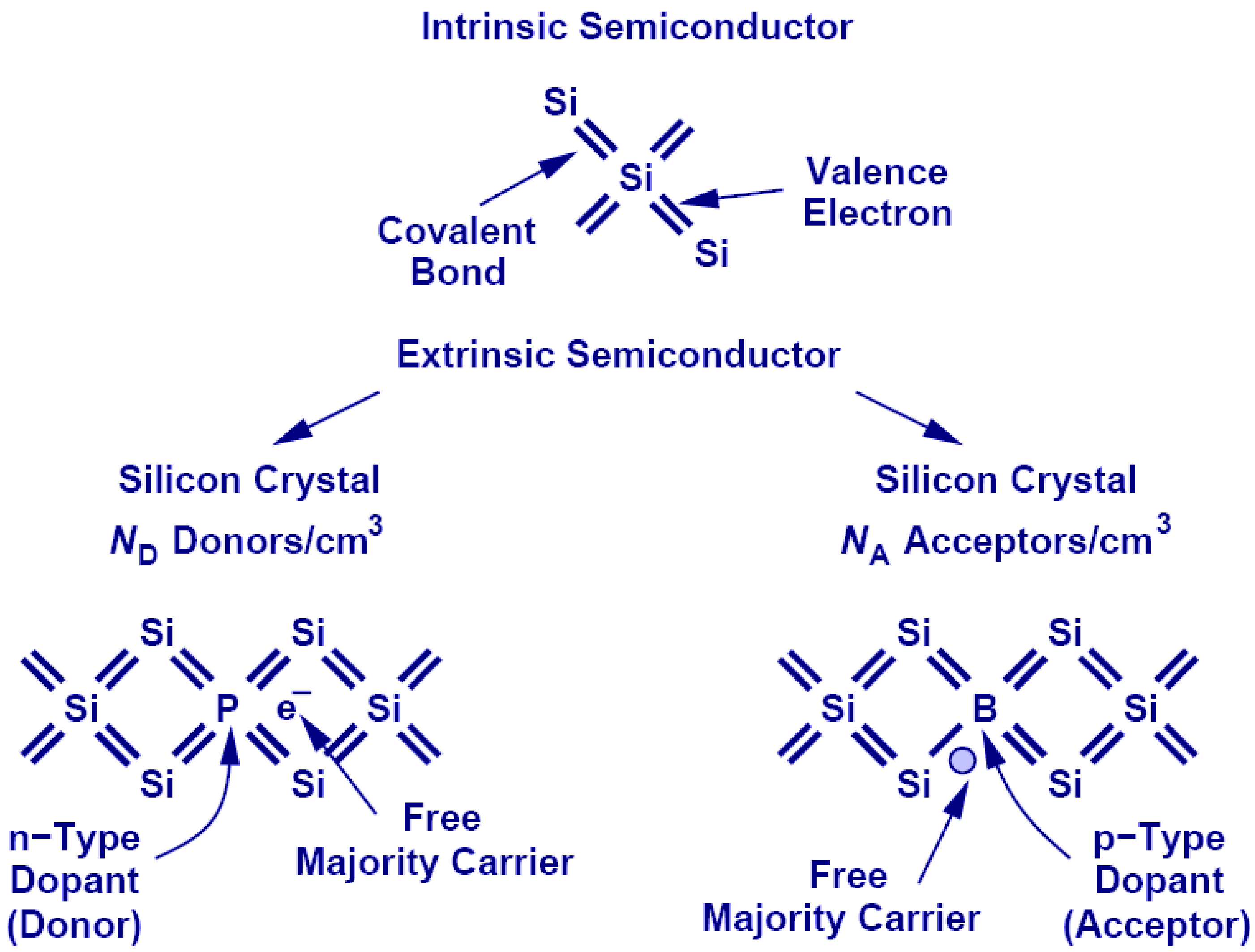
Doping (P type)

- ☐ If Si is doped with Boron (B), each B atom can contribute a hole, so that the Si lattice has more holes than electrons, *i.e.* it becomes “P type”:

Notation:
p = hole concentration



Charge Carriers



Intrinsic Semiconductor

Covalent Bond

Valence Electron

Extrinsic Semiconductor

Silicon Crystal

N_D Donors/cm^3

n−Type Dopant (Donor)

Free Majority Carrier

Silicon Crystal

N_A Acceptors/cm^3

Free Majority Carrier

p−Type Dopant (Acceptor)

Electron and Hole Concentrations

- ☐ Under thermal equilibrium conditions, the product of the conduction-electron density and the hole density is ALWAYS equal to the square of n_i:

$$np = n_i^2$$

<u>N-type material</u>

$$n \approx N_D$$

$$p \approx \frac{n_i^2}{N_D}$$

<u>P-type material</u>

$$p \approx N_A$$

$$n \approx \frac{n_i^2}{N_A}$$

Terminology

donor: impurity atom that increases n

acceptor: impurity atom that increases p

N-type material: contains more electrons than holes

P-type material: contains more holes than electrons

majority carrier: the most abundant carrier

minority carrier: the least abundant carrier

intrinsic semiconductor: $n = p = n_i$

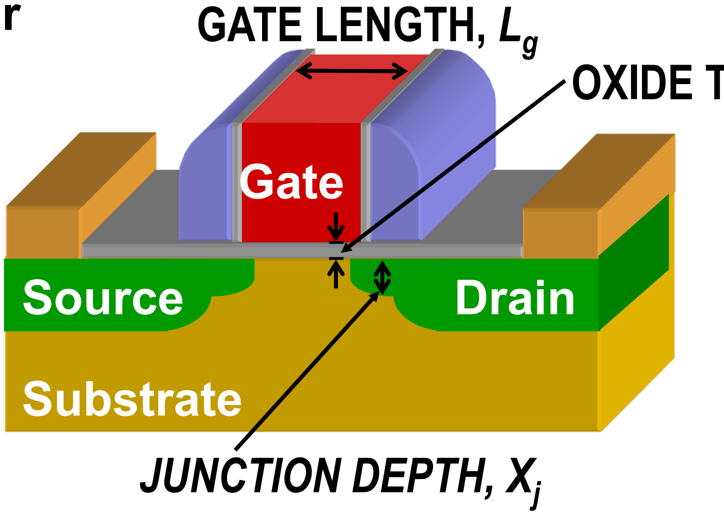
extrinsic semiconductor: doped semiconductor

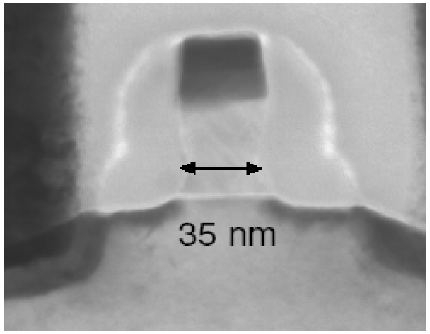
Facts

- The band gap energy is the energy required to free an electron from a covalent bond.
  - E_g for Si at 300K = 1.12eV
- In a pure Si crystal, conduction electrons and holes are formed in pairs.
  - Holes can be considered as positively charged mobile particles which exist inside a semiconductor.
  - Both holes and electrons can conduct current.
- Substitutional dopants in Si:
  - Group-V elements (***donors***) contribute conduction electrons
  - Group-III elements (***acceptors***) contribute holes

The MOSFET

Metal-Oxide-Semiconductor Field-Effect Transistor:



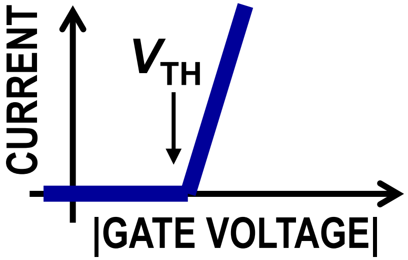


M. Bohr, *Intel Developer Forum*, September 2004

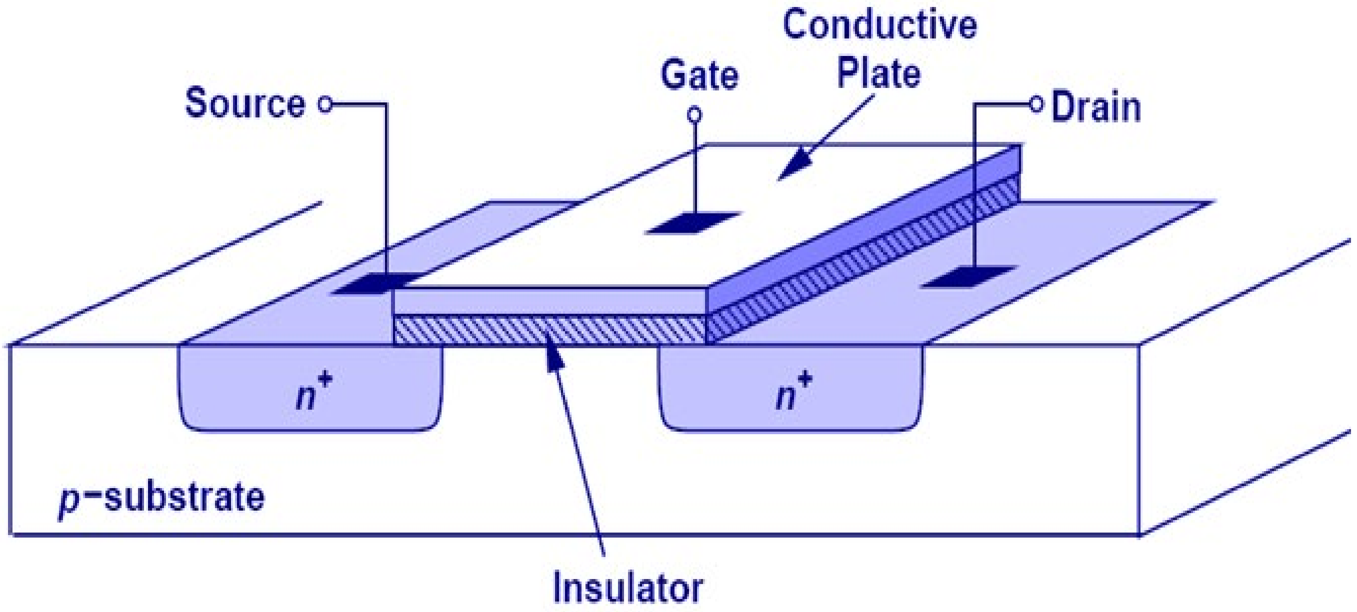
- Current flowing through the **channel** between the **source** and **drain** is controlled by the **gate** voltage.

- **"N-channel" & "P-channel" MOSFETs operate in a complementary manner**

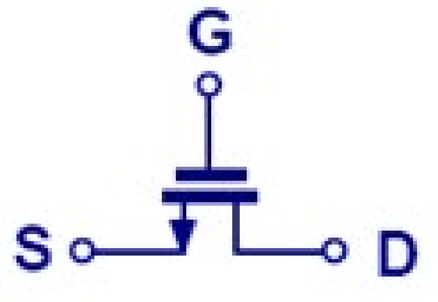
  "CMOS" = Complementary MOS



N-Channel MOSFET Structure

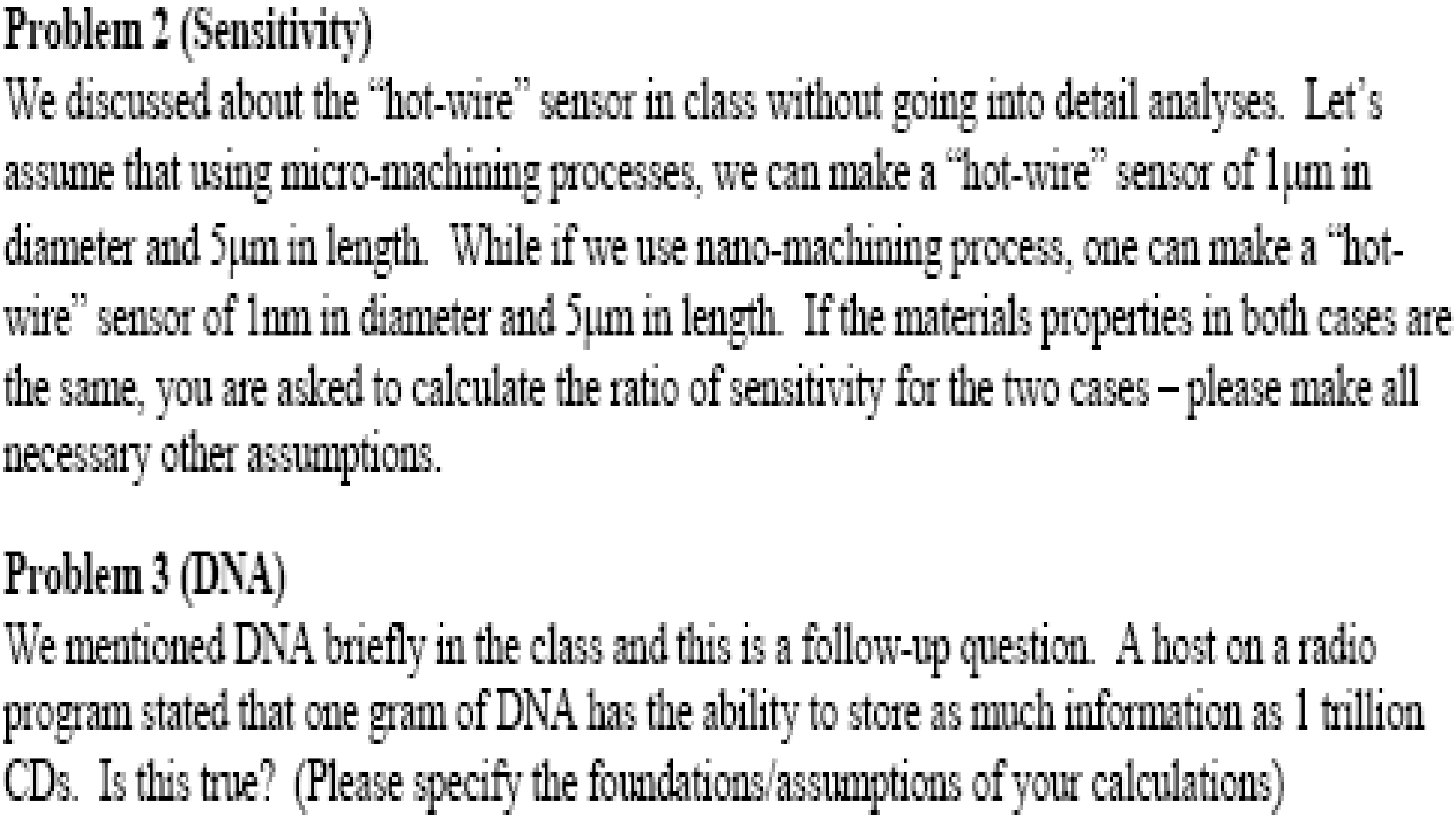


Circuit symbol



- The conventional gate material is heavily doped polycrystalline silicon (referred to as “polysilicon” or “poly-Si” or “poly”)
  - Note that the gate is usually doped the same type as the source/drain, *i.e.* the gate and the substrate are of opposite types.
- The conventional gate insulator material is SiO_2.
- To minimize current flow between the substrate (or “body”) and the source/drain regions, the p-type substrate is grounded.

HW#1 – Problem 2&3



Problem 2 (Sensitivity)

We discussed about the "hot-wire" sensor in class without going into detail analyses. Let's assume that using micro-machining processes, we can make a "hot-wire" sensor of 1μm in diameter and 5μm in length. While if we use nano-machining process, one can make a "hot-wire" sensor of 1nm in diameter and 5μm in length. If the materials properties in both cases are the same, you are asked to calculate the ratio of sensitivity for the two cases – please make all necessary other assumptions.

Problem 3 (DNA)

We mentioned DNA briefly in the class and this is a follow-up question. A host on a radio program stated that one gram of DNA has the ability to store as much information as 1 trillion CDs. Is this true? (Please specify the foundations/assumptions of your calculations)

HW#1 – Problem 4

Problem 4 (MOSFET)

The diagram shows a standard MOSFET. (1) Draw the cross-sectional view diagram in the areas under the two dash lines. (2) Assuming that that the drawing in scale and the minimum feature size is 45nm for the gate length. Calculate how many MOSFET can be placed in an area of 1"x1"