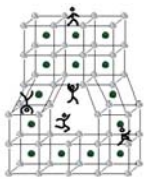
Semiconductor Devices

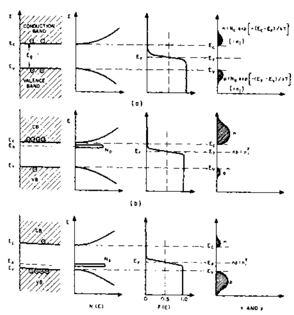


- pn Junctions
- Solar Cells
- Contacts
- Transistors
- Microfabrication and Processing
- Dreams of the Future

**Wednesday,
Nov. 12, 2003**

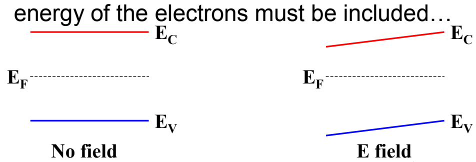
MATS275: INTRODUCTION TO MATERIALS SCIENCE

Changing the Fermi Level

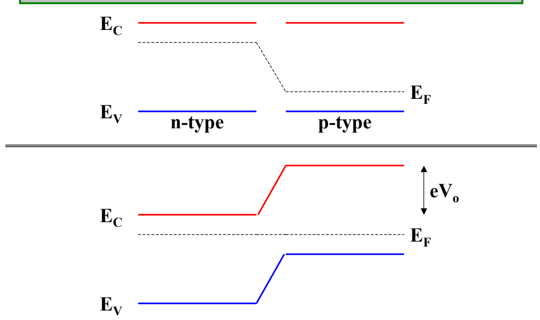


The Effect of an Applied Field

- If an electric field is applied, the potential energy of the electrons must be included…



The pn Junction



The pn Junction

- If the hole concentration on the p side is…

$$N_h = N_v e^{-\frac{E_F - E_v}{kT}} \Rightarrow E_F - E_v = kT\,ln\left(\frac{N_v}{N_h}\right)$$

- And on the n side is…

$$N_e = N_c e^{-\frac{E_c - E_F}{kT}} \Rightarrow E_c - E_F = kT\,ln\left(\frac{N_c}{N_e}\right)$$

- Put these together

$$\left(E_{F_p} - E_v\right) + \left(E_c - E_{F_n}\right) = kT\,ln\left(\frac{N_v}{N_h}\right) + kT\,ln\left(\frac{N_c}{N_e}\right)$$

$$E_g - \left(E_{F_n} - E_{F_p}\right) = kT\,ln\left(\frac{N_v N_c}{N_a N_d}\right)$$

The pn Junction

- So that the contact potential V_0 is…

$$E_g - (eV_0) = kT\,ln\left(\frac{N_v N_c}{N_a N_d}\right)$$

$$V_0 = \frac{E_g}{e} + \frac{kT}{e}\,ln\left(\frac{N_a N_d}{N_v N_c}\right)$$

$$n_i^2 = N_c N_v e^{-\frac{E_g}{kT}}$$

$$ln\left(n_i^2\right) = ln(N_c N_v) - \frac{E_g}{kT}$$

$$\frac{E_g}{e} = \frac{kT}{e}\,ln\left(\frac{N_v N_c}{n_i^2}\right)$$

$$V_0 = \frac{kT}{e}\,ln\left(\frac{N_a N_d}{n_i^2}\right)$$

A Si pn-Junction

- Consider a pn-junction with $N_a=10^{17}$ cm^{-3} and $N_d=10^{16}$cm^{-3}:

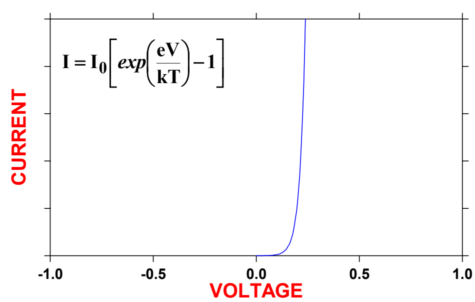
$$n_i = 1.5\times10^{10}\,\mathrm{cm}^{-3}$$

$$V_0 = \frac{kT}{e}\,ln\left(\frac{N_a N_d}{n_i^2}\right)$$

$$V_0 = 300\mathrm{K}\,\frac{1.38\times10^{-23}\,\frac{J}{K}}{1.602\times10^{-19}\,\mathrm{C}}\,ln\left[\frac{\left(10^{17}\,\mathrm{cm}^{-3}\right)\left(10^{16}\,\mathrm{cm}^{-3}\right)}{\left(1.5\times10^{10}\,\mathrm{cm}^{-3}\right)^2}\right]$$

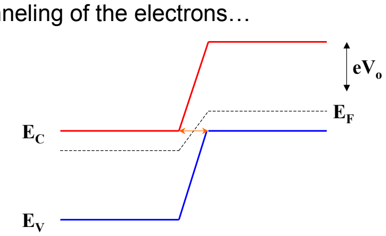
$$V_0 = 300\mathrm{K}\left(8.614\times10^{-5}\,\mathrm{eV/K}\right)\left(29.12\right) = 0.752\,\mathrm{V}$$

The Diode Equation

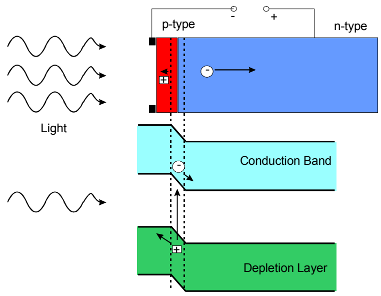


The Zener Diode

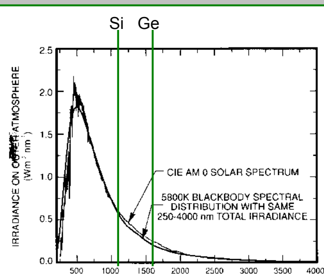
- If we heavily reverse bias, we can get tunneling of the electrons…



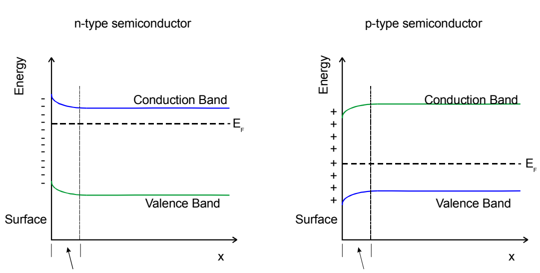
Solar Cell (a.k.a. Photodiode)



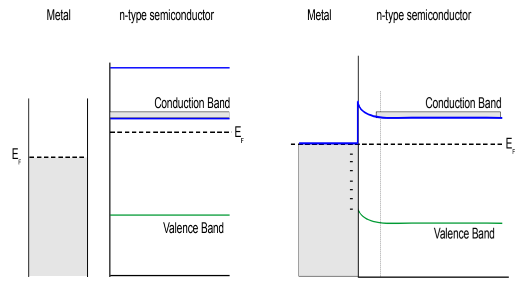
Solar Cell Design Consideration



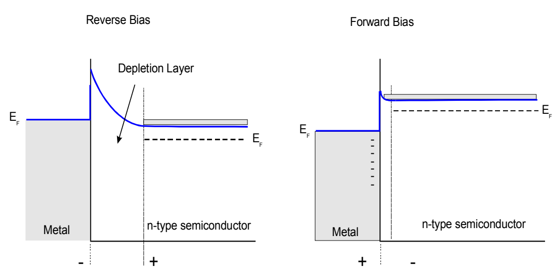
Band Bending



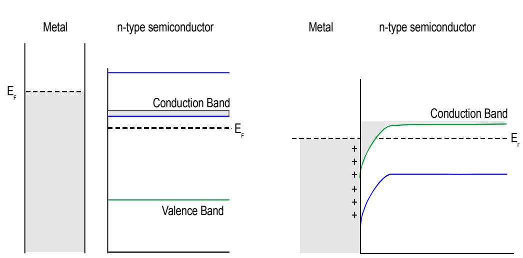
Rectifying (Schottky Barrier) Contact



Rectifying Contact (Diode)



Ohmic Contact



The Transistor (circa 1947)

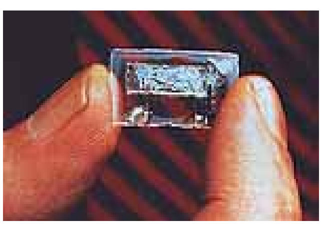
First transistor invented at Bell Labs in 1947 by Walter Brattain, William Shockley and John Bardeen

The first device was fabricated from Ge not Si!

Figure from: *The Solid State Century, The Past, Present and Future of the Transistor*, Scientific American Special Issue January 22, 1998

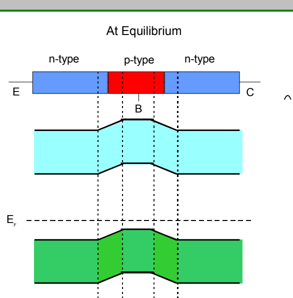
Nobel Prize Physics 2000

Dr. Jack Kilby Texas Instruments “For his part in the invention of the integrated circuit”

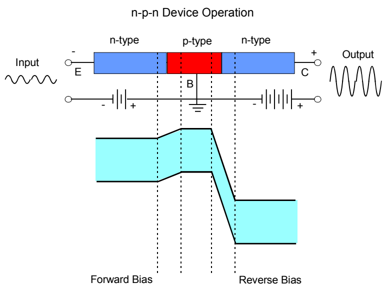


1st IC circa 1958 (again made out of Ge not Si!)

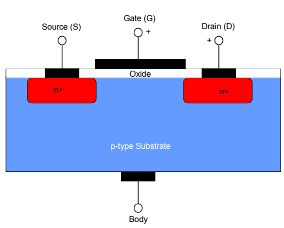
n-p-n Bipolar Junction Transistor

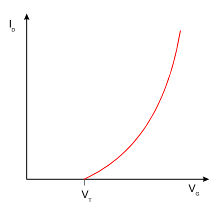


Bipolar Signal Amplification

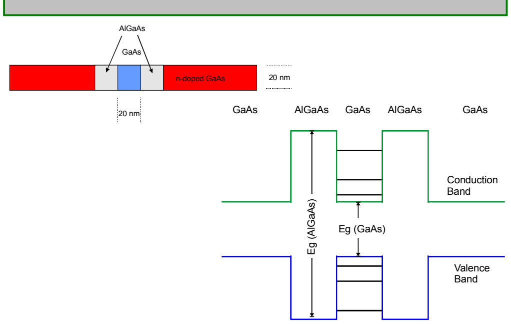


Metal Oxide Semiconductor Field Effect Transistor (MOSFET)

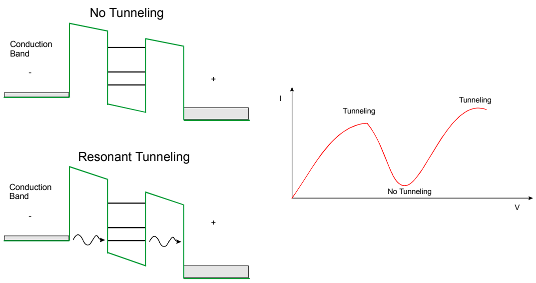




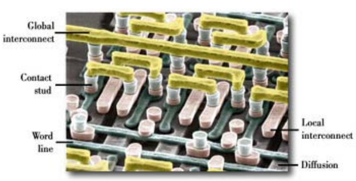
Semiconductor Quantum Well Device



Resonance Tunneling



Microfabrication



Year	Minimum Feature Size (μm)
1985	1.00 (1000 nm)
1990	0.50 (500 nm)
1995	0.35 (350 nm)
2000	0.20 (200 nm)
2005	0.10 (100 nm)

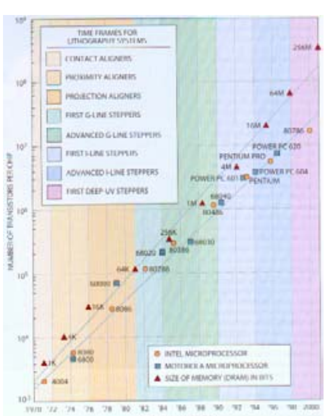


Figure from: *The Solid State Century, The Past, Present and Future of the Transistor*, Scientific American Special Issue January 22, 1998

Numbers…Big and Small

If a digital cell-phone was made with vacuum tubes instead of transistors, it would occupy a building larger than the Washington Monument…

1,000,000,000

transistors on a chip by the turn of the century (2000-2001)
The patterns etched onto these chips will be as complicated as a road map of the entire planet shrunk to the size of a fingernail.

500,000,000

transistors manufactured every second last year

5,000,000

transistors in a typical integrated circuit

0.000001 cents

price of a transistor today

During the 1950's, the cost went from $45 to $2. Do you recognize that curve?

Microfabrication Process Flow

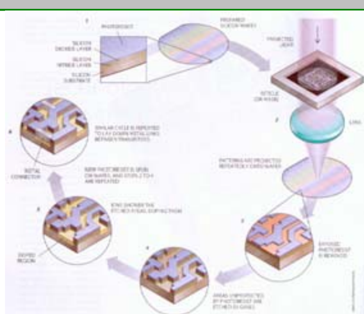
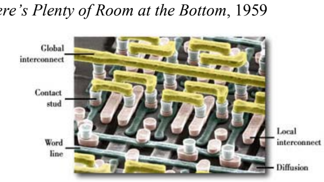


Figure from: *The Solid State Century, The Past, Present and Future of the Transistor*, Scientific American Special Issue January 22, 1998

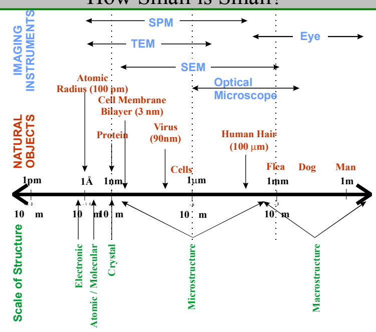
Microelectronics from the Bottom Up

"When we get to the very, very small world--say circuits of seven atoms--we have a lot of new things that would happen that represent completely new opportunities for design. Atoms on a small scale behave like *nothing* on a large scale, for they satisfy the laws of quantum mechanics."
Richard Feynman, *There's Plenty of Room at the Bottom*, 1959



What is Nanotechnology?

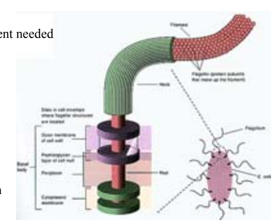
How Small is Small?



Microelectromechanical Systems
(MEMS)

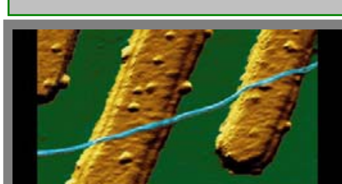
MEMS Electrostatic Motor
- CW, CCW Rotation
- 50,000 rpm
- 300 μm in size
- ~ $500 M investment needed to fabricate

E. Coli Bacteria
- Simple organism
- Electrostatic Motor
- CW, CCW Rotation
- Internal switch
- 15,000 rpm
- 50 nm in size

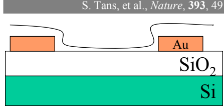


Microbiology - A Human Perspective by Nester, Roberts, Pearsall, Anderson, Nester. 2nd Addition. McGraw-Hill

Nanoelectronics--Molecular Switches



S. Tans, et al., *Nature*, **393**, 49 (1998)



R. Martel, et al., *Appl. Phys. Lett.*, **73**, 2447 (1998)

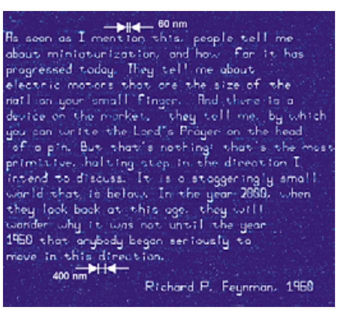
SWNT, R. Smalley's Group, Rice U.

Feynman Again…

"I have estimated how many letters there are in the *Encyclopaedia*, and I have assumed that each of my 24 million books is as big as an *Encyclopaedia* volume, and have calculated, then, how many bits of information there are (10^{15}). For each bit I allow 100 atoms. And it turns out that all of the information that man has carefully accumulated in all of the books in the world can be written in this form of a cube of material one two-hundreths of an inch wide—which is the barest piece of dust that can be made out by the human eye. So there is *plenty* of room at the bottom! Don't tell me about microfilm!"

R. P. Feynman, *There's Plenty of Room at the Bottom*, 1959

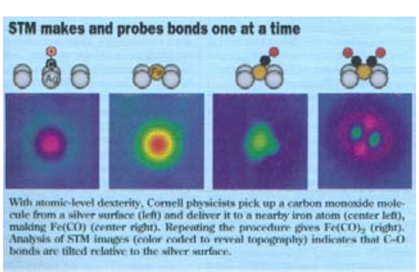
Feynman's Challenge



Chad Mirkin's group at Northwestern University takes on Feynman's famous challenge with 60 nm letters using alkanethiol "inks"

White: MHA
Blue: Octadecanethiol (ODT)

Molecular Chemistry



With atomic-level dexterity, Cornell physicists pick up a carbon monoxide molecule from a silver surface (left) and deliver it to a nearby iron atom (center left), making Fe(CO) (center right). Repeating the procedure gives $Fe(CO)_2$ (right). Analysis of STM images (color coded to reveal topography) indicates that C-O bonds are tilted relative to the silver surface.

H. Lee and W. Ho, *Science*, **286**, 1719 (1999)

Molecular Chemistry Part II

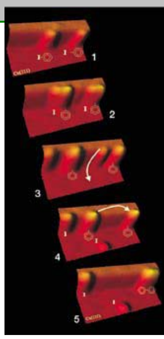
A.

B.

C.

D.

E.



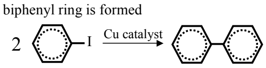
A. Two iodobenzene molecules sit at the step edge of a copper surface.

B. The STM is used to break the iodine off of the benzene ring

C. The iodine atoms are dragged away from the reaction

D. The phenyl ring is dragged towards each other

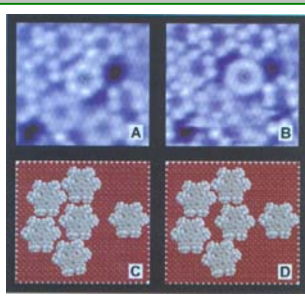
E. A biphenyl ring is formed



Karl-Heinz Rieder, Saw-Wai Hla, et al.

Free University of Berlin (2000)

Molecular Bearings and Motors



J.K. Gimzewski and C. Joachim, *Science*, **283**, 1683 (1999)