Chinese University of Hong Kong
Department of Electronic Engineering

Second Term 07/08

ELE2110A Electronic Circuits

Prof. Pun Kong Pang

Email: kppun@ee.cuhk.edu.hk

Course Information

- Homepage: http://asic.ee.cuhk.edu.hk/ele2110a/
  - Lecture notes will be uploaded weekly.
- Newsgroup: cuhk.ee.2110a
- Prerequisite: ELE 1110

- Tutors: Chan Chi Fat/Chen Yan/Ko Chi Tung
  Li Chunxiao/Zheng Yanqi

- Lecture: Wednesday 9:30am – 11:15am, ELB LT3
  Friday 10:30am – 11:15am, ERB LT

Assessment Scheme

- Assignments: 20%

- Test: 30%
  - Three tests;
  - The two highest marks will be counted for each student.

- Final Examination: 50%

Books

Textbook:
Microelectronic Circuit Design, 3e, by Jaeger and Blalock (McGraw Hill 2007)

Reference books:
Microelectronic Circuits, 5e, by Sedra/Smith (Oxford 2004)
Electronic circuit analysis and design, 2e, by D.A. Neamen (McGraw-Hill 2001)

Circuit theories and skills that you have learned …

- – KCL and KVL
- – Nodal and Mesh analysis
- – Linearity and Superposition
- – Source transformation
- – Thevenin and Norton theorems
- – Maximum power transfer
- – AC analysis
- – …

- You should already be able to analyze circuits that consist of R, C and L, i.e., passive circuits.

In this course, you will learn…

- Microelectronic devices that can provide gain (active)
  - Basic semiconductor physics
  - Operation principles, terminal I-V equations and circuit models of
    - PN-junction diode
    - MOS transistor
    - BJT transistor
- Analysis techniques
  - Decompose a signal to DC and AC components
  - DC analysis
  - Small signal AC analysis
- Diode circuits
  - Rectifiers
  - DC-DC converters
  - Clipping & Clamping ckts
- BJT & MOS transistor ckts
  - Single transistor amplifiers
  - Differential pair
  - Multi-stage amplifiers
  - Logic circuits
- Feedback principles
  - Topologies
  - Stability analysis

Problem-Solving Approach

1. Make a clear **problem statement**.
2. List **known information and given data**.
3. Define the **unknowns** required to solve the problem.
4. List **assumptions**.
5. Develop an **approach** to the solution.
6. Perform the **analysis** based on the approach.
7. **Check** the results.
    1. Has the problem been solved? Have all the unknowns been found?
    2. Is the math correct?
8. **Evaluate** the solution.
    1. Do the results satisfy reasonableness constraints?
    2. Are the values realizable?
9. Use computer-aided analysis to **verify** hand analysis.

Week 1: Introduction & Basic Semiconductor Physics

Topics to cover…

- Application of electronic circuits
- Evolution of electronic devices
- Convention of signal notations
- Basic semiconductor physics

Reading Assignment: Chap 1.1-1.5 of Jaeger & Blalock

Application of Electronic Circuits

- Communication
  - Telephone circuits
    - A major driving force of the development of electronic circuits in early 20th century
  - Wireless communication circuits
    - Telegraph, radio, analog television, HDTV, mobile phone, …
- Computer
  - Software functions are executed by electronic circuits (logic gates)
- Consumer electronics
  - Digital camera, iPod, WII, Hi-Fi amplifier, …
- Others, such as biomedical signal acquisition, automobile electronics …

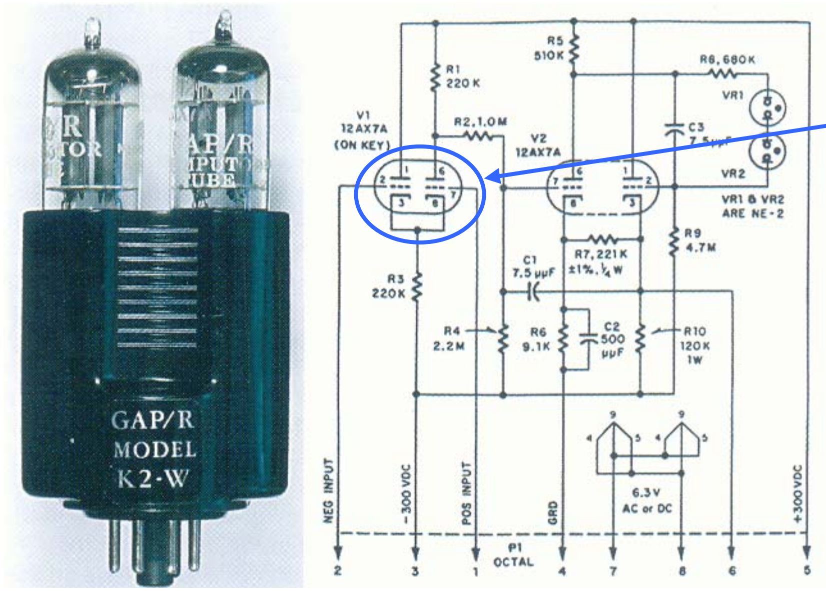
Devices in Electronic Circuits

- Passive components – cannot provide power gain
  - e.g., resistor, capacitor, inductor

- Active devices – can provide power gain and must draw power from a supply
  - e.g., Vacuum tube devices, silicon transistors
  - Enable signal amplification which is a key technology for the success of long distance telephony

Vacuum Tube

- Vacuum tube diode and triode were invented in 1904 and 1906 respectively
- Vacuum tube triode is an extremely important invention, because it enables electronic amplification to take place



Differential pair

K2-W Op-amp built with Vacuum tube

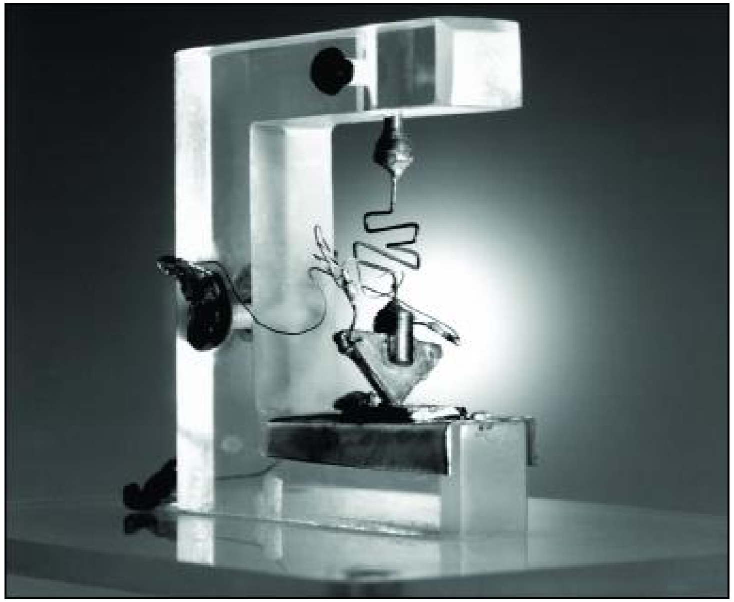
(Source: T.H.Lee, IEEE SSCS News, Fall 2007)

Vacuum Tube

- Early FM radios, television sets, digital computers were built with vacuum tubes
- In modern era, vacuum tubes still find applications in Hi-Fi amplifiers

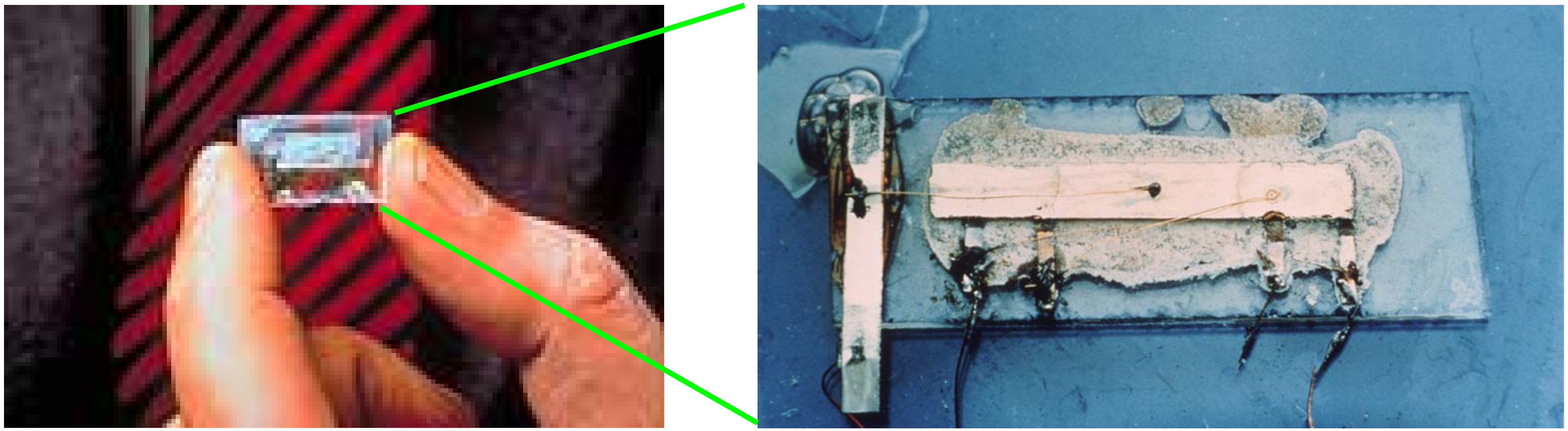
The Start of the Modern Electronics Era

Bardeen, Shockley, and Brattain at Bell Labs - Brattain and Bardeen invented the bipolar transistor in 1947.



The first germanium bipolar transistor. Roughly 50 years later, electronics account for 10% (4 trillion dollars) of the world GDP.

Invention of Integrated Circuits



Kilby and Noyce from Texas Instruments made in 1958 the world's first IC, consisting of 6 transistors.

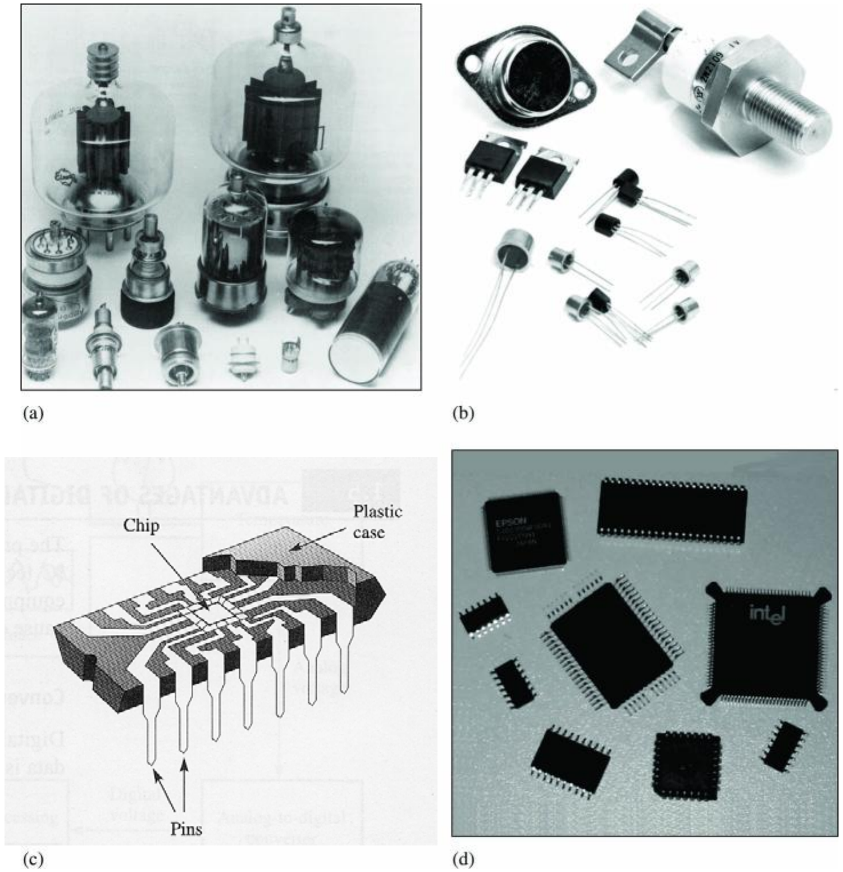
Evolution of Electronics

Vacuum Tubes

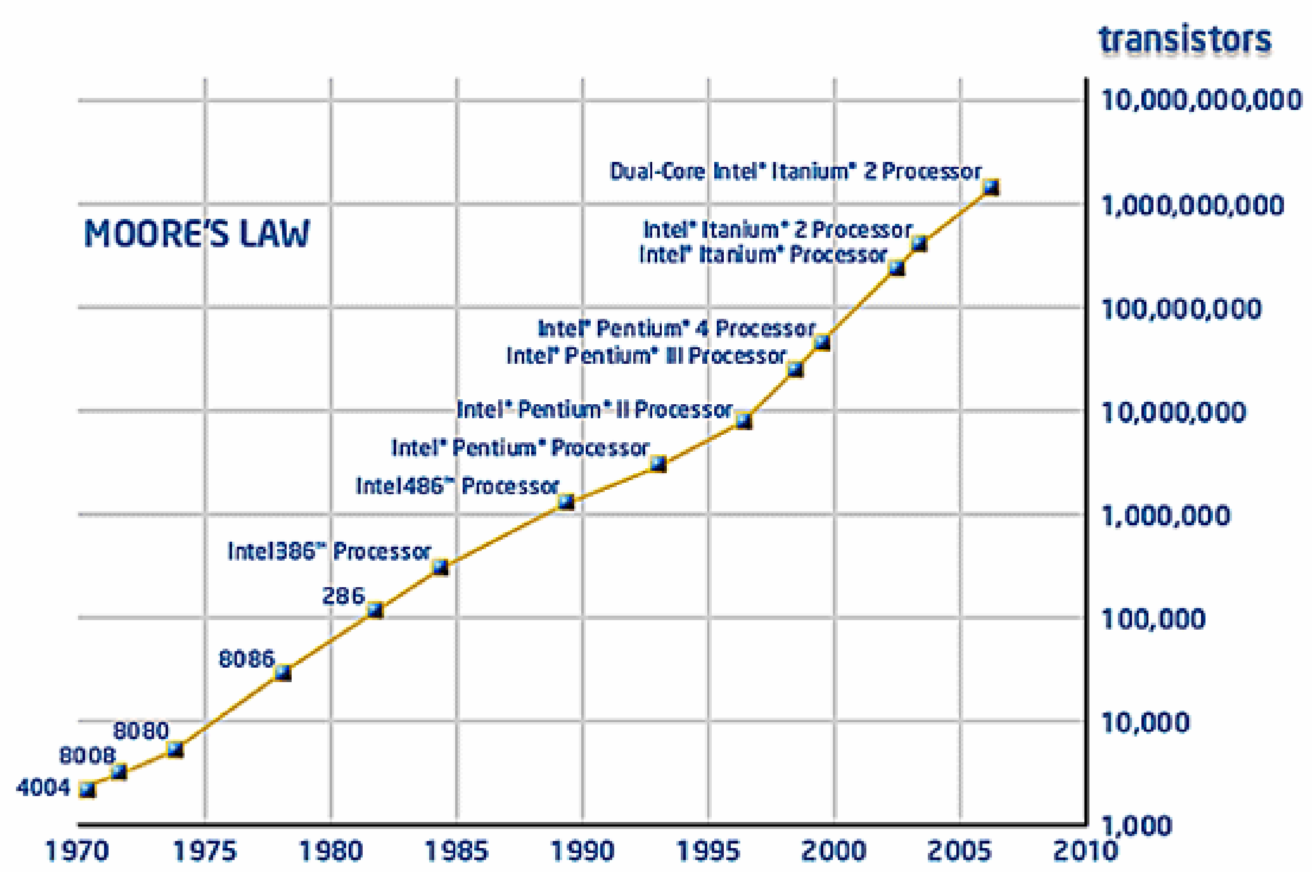
Discrete Transistors

SSI and MSI Integrated Circuits

VLSI Surface-Mount Circuits



Moore's Law

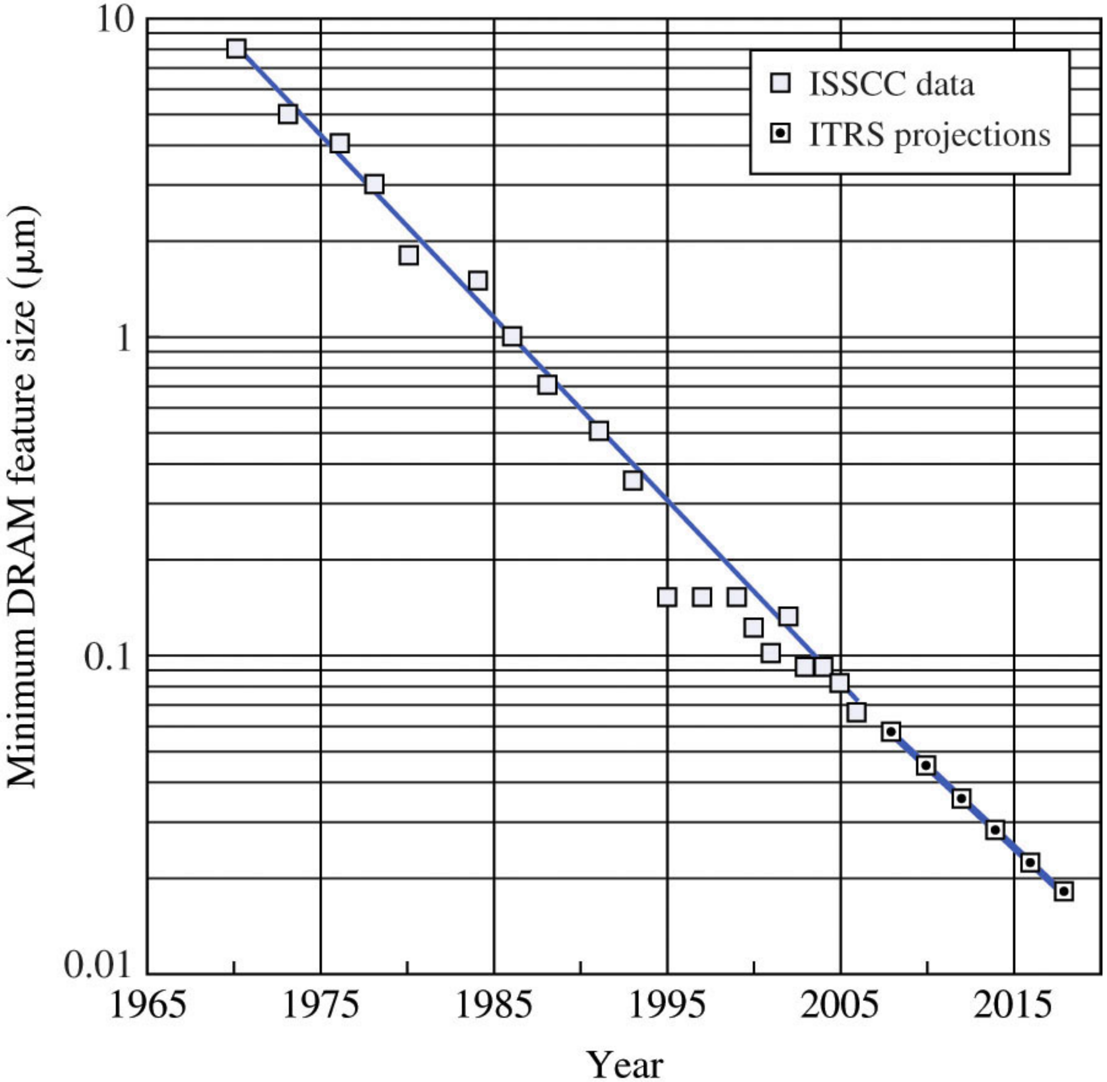


Picture source: inter.com

<u>Moore's Law</u>:
the number of transistors per chip doubles about every 18 months.

Has been valid for the past 40 years.

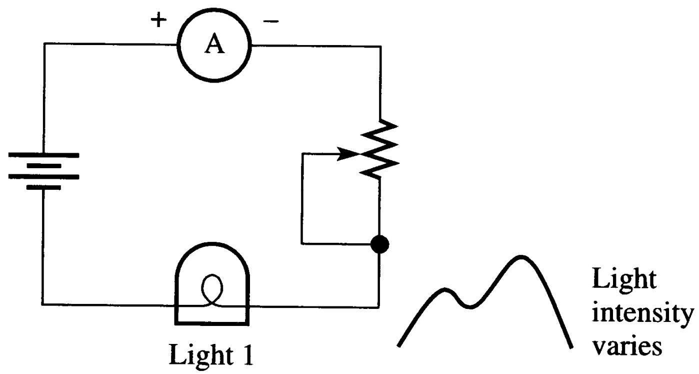
Device Becomes Ever Smaller



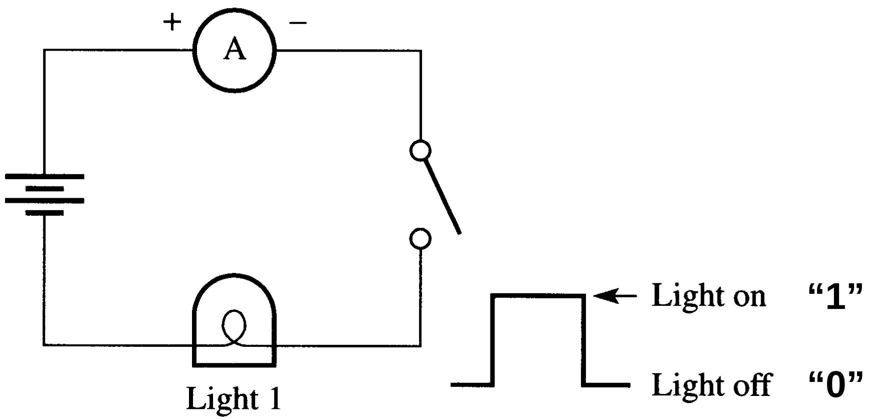
Smaller features lead to more transistors per unit area (higher density) and higher speed

Electrical Signal Types

- An <u>analog</u> signal takes on continuous values. It can be a voltage, current, or sometimes charge.



- A <u>digital</u> signal appears at discrete levels. Usually we use binary signals which utilize only two levels: 0 and 1.



Almost everything is digital now, why analog?

- The “real” or “physical” world is analog.

Egg shell analogy:

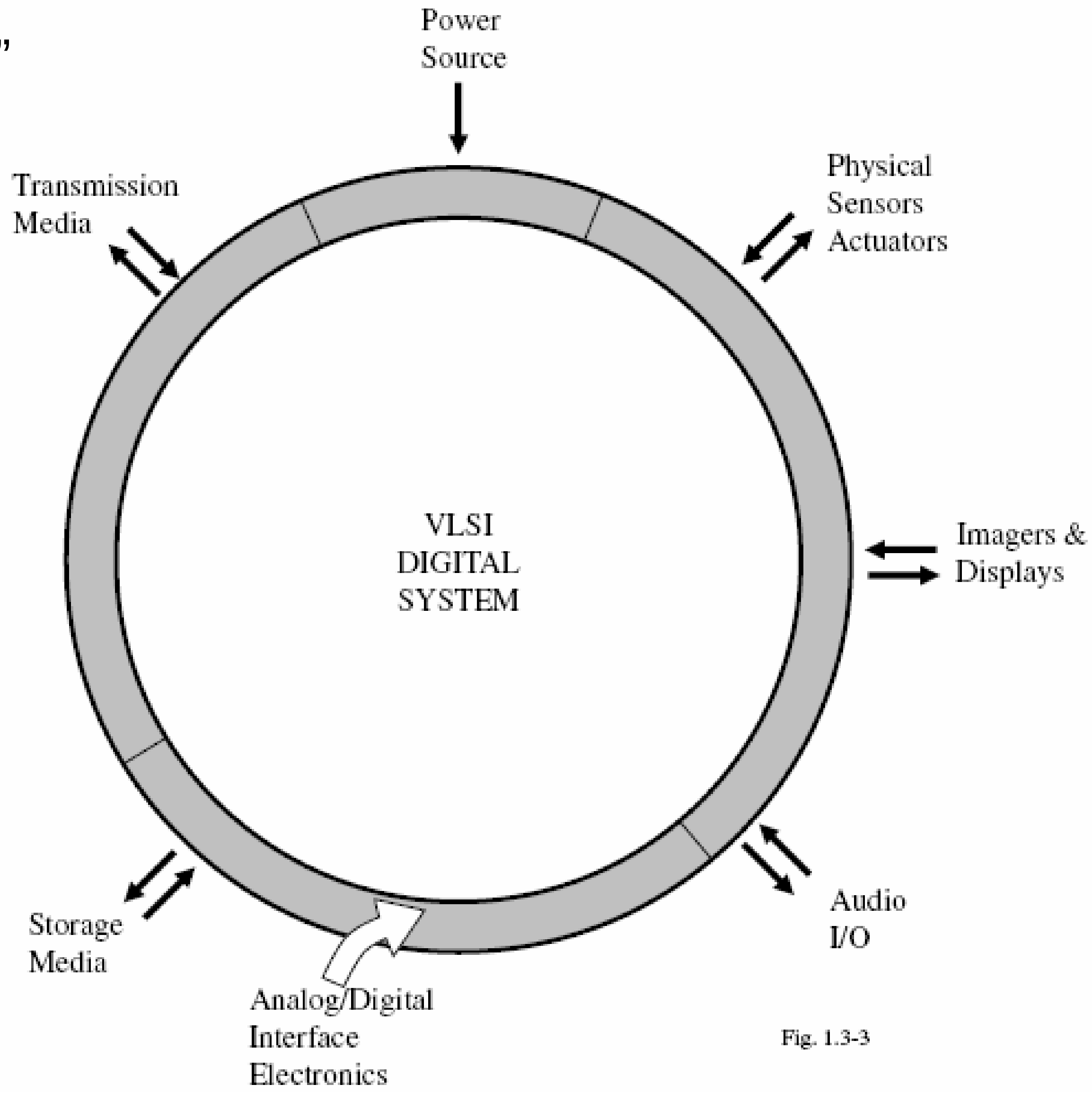
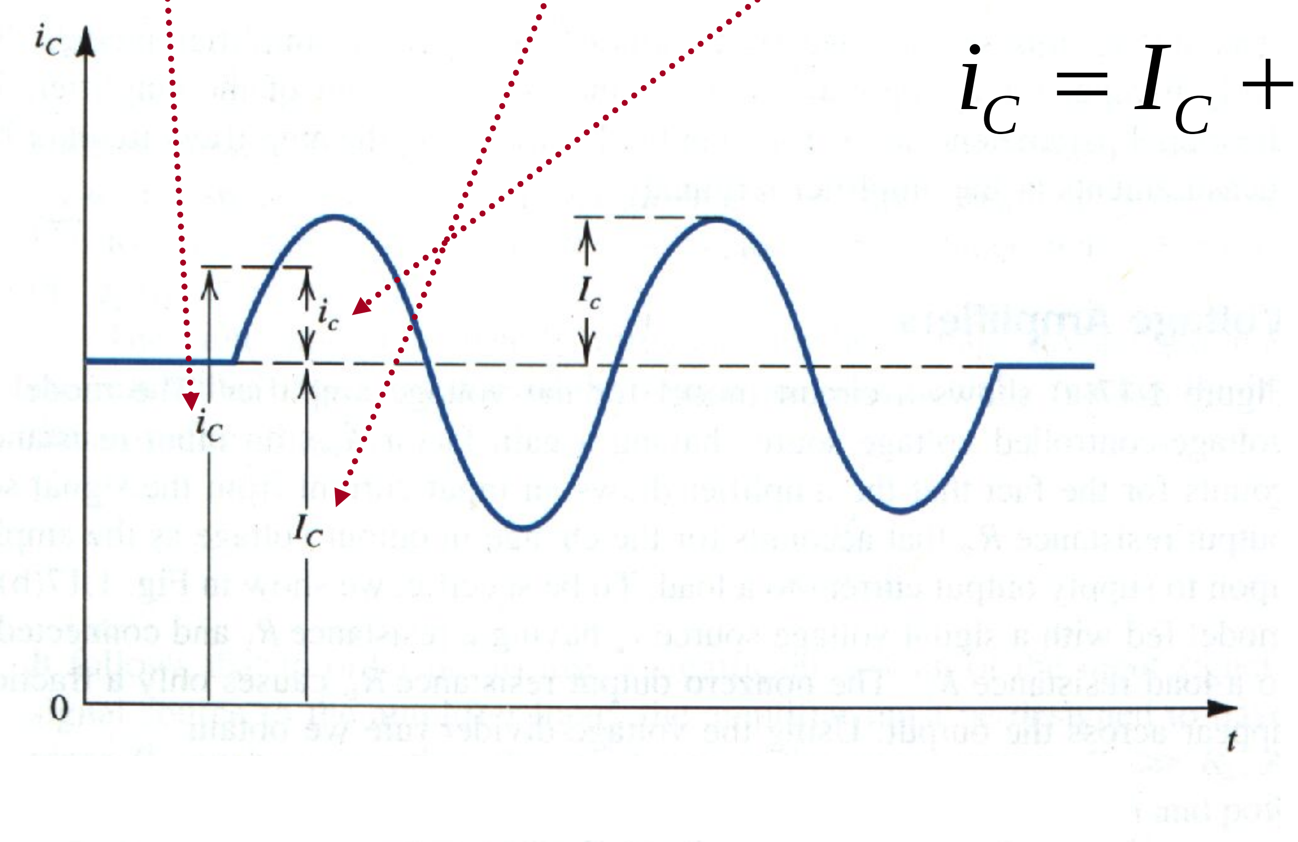


Fig. 1.3-3

Notational Conventions

Total signal = DC component + AC (time varying) component

(V or I)



$$i_C = I_C + i_c$$

Basic Semiconductor Physics

Topics to cover…

- Semiconductor materials
- Energy band models
- Charge carries: electrons and holes
- Types of semiconductors
- Types of currents in semiconductors

- *Reading Assignment: Chap 2 of Jaeger & Blalock*

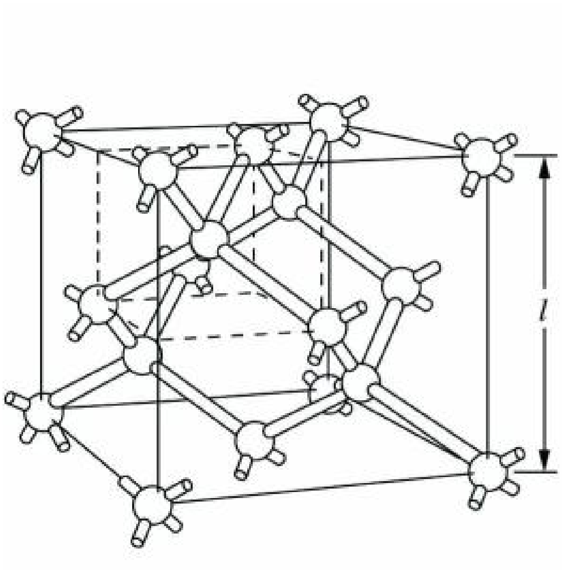
Semiconductor Materials

Semiconductors have a resistivity between 10^{-3} and 10^{5} [Ω-cm]

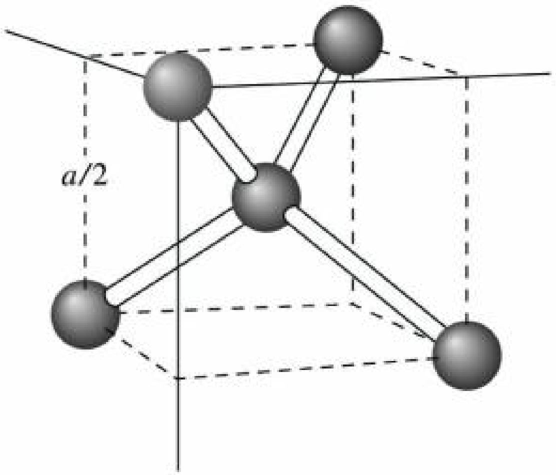
IIB	IIIA	IVA	VA	VIA
	5 **B** Boron 10.811	6 **C** Carbon 12.01115	7 **N** Nitrogen 14.0067	8 **O** Oxygen 15.9994
	13 **Al** Aluminum 26.9815	14 **Si** Silicon 28.086	15 **P** Phosphorus 30.9738	16 **S** Sulfur 32.064
30 **Zn** Zinc 65.37	31 **Ga** Gallium 69.72	32 **Ge** Germanium 72.59	33 **As** Arsenic 74.922	34 **Se** Selenium 78.96
48 **Cd** Cadmium 112.40	49 **In** Indium 114.82	50 **Sn** Tin 118.69	51 **Sb** Antimony 121.75	52 **Te** Tellurium 127.60
80 **Hg** Mercury 200.59	81 **Tl** Thallium 204.37	82 **Pb** Lead 207.19	83 **Bi** Bismuth 208.980	84 **Po** Polonium (210)

- **Ge** is the first semiconductor used.
- **Silicon** is today's most important semiconductor materials
  - low cost
  - easily oxidized to form SiO_2 insulating layers
  - high bandgap energy → can be used in higher-temperature applications
- **GaAs** and **InP** are popular for opto-electronic applications.
- **SiGe** and **GaAs** are good for RF applications

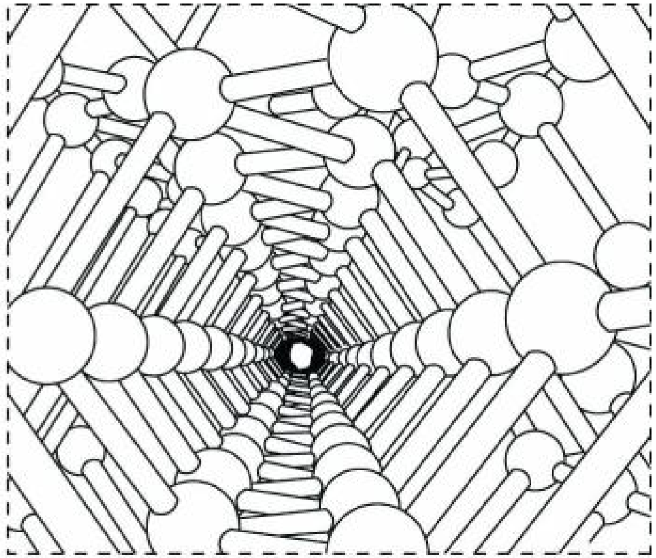
Covalent Bond Model



Silicon diamond lattice unit cell.

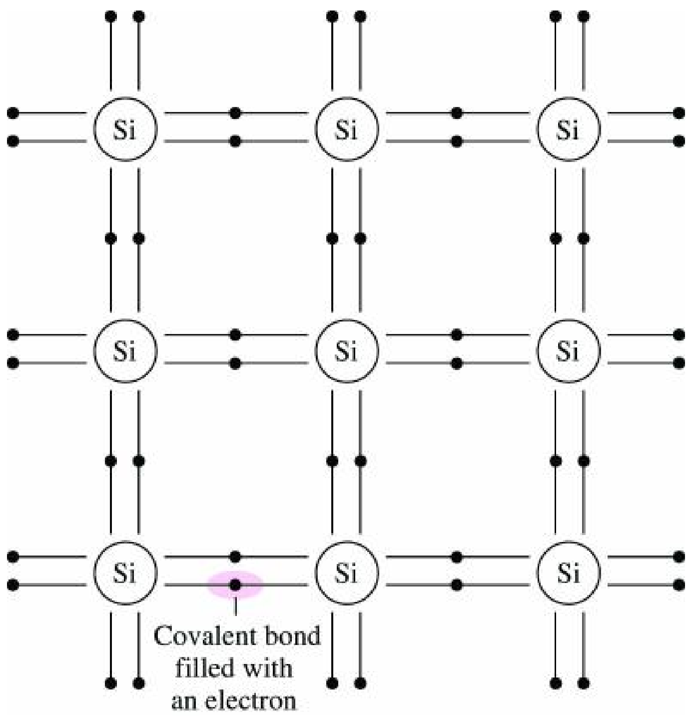


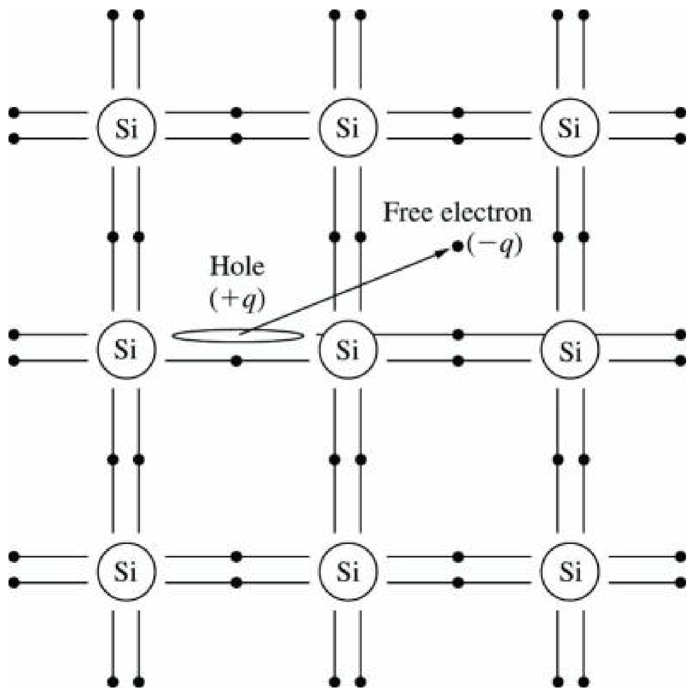
Corner of diamond lattice showing four nearest neighbor bonding.



View of crystal lattice along a crystallographic axis.

Silicon Covalent Bond Model

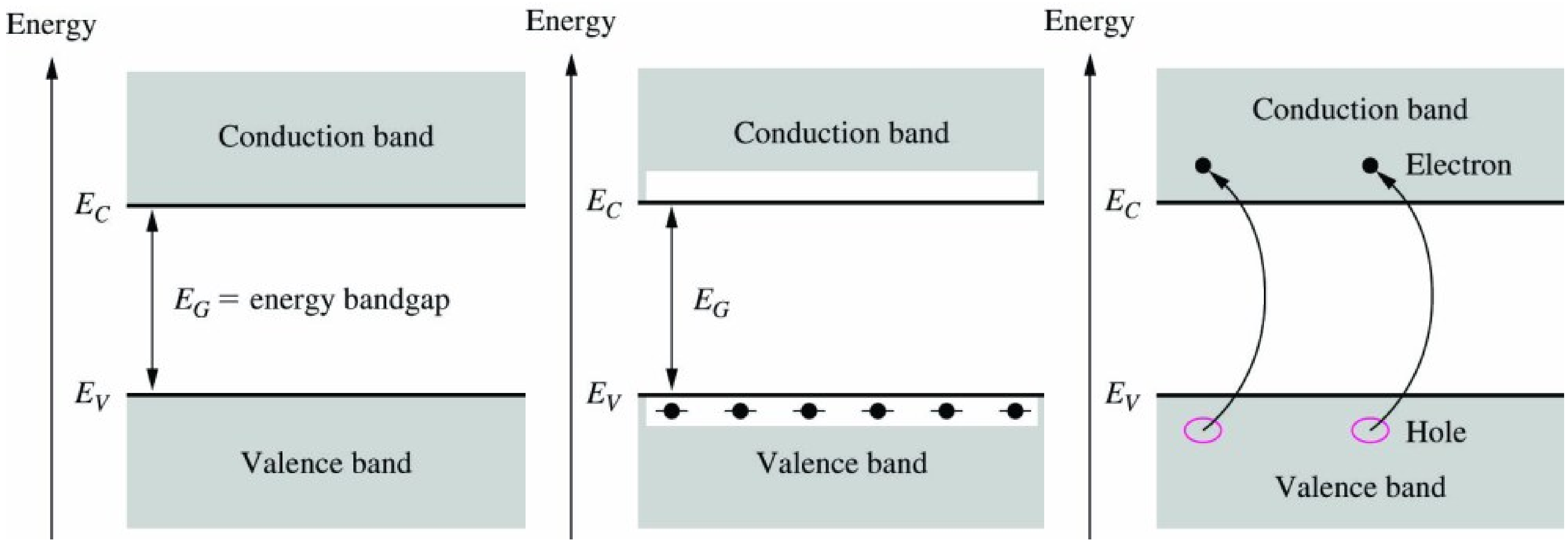




Near absolute zero, all bonds are complete. Each Si atom contributes one electron to each of the four bond pairs.

Increasing temperature adds energy to the system and breaks bonds in the lattice, generating electron-hole pairs.

Semiconductor Energy Band Model



E_C and E_V are energy levels at the edge of the conduction and valence bands.

Electron participating in a covalent bond is in a lower energy state in the valence band. This diagram represents 0 K.

Thermal energy breaks covalent bonds and moves the electrons up into the conduction band.

Bandgap Energy

Semiconductor	Bandgap Energy E_G [eV]
Carbon (diamond)	5.47
Silicon	1.12
Germanium	0.66
Tin	0.082
Gallium arsenide	1.42
Gallium nitride	3.49
Indium phosphide	1.35
Boron nitride	7.50
Silicon carbide	3.26
Cadmium selenide	1.70

<u>Bandgap energy</u> is the minimum energy needed to free an electron by breaking a covalent bond in the semiconductor crystal.

Free Electron Density in Intrinsic Semiconductor

- Intrinsic semiconductor = pure semiconductor
- The density of free electrons in an intrinsic semiconductor is:

$$n_i^2 = \mathrm{B} \cdot T^3 \exp\left(-\frac{E_G}{kT}\right) \quad [\mathrm{cm}^{-6}]$$

E_G = semiconductor bandgap energy in [eV] (electron volts)

k = Boltzmann's constant, 8.62 x 10^{-5} [eV/K]

T = absolute termperature, [K]

B = material-dependent parameter, 1.08 x 10^{31} [K^{-3} cm^{-6}] for Si

- $n_i \approx 10^{10}$ cm^{-3} for Silicon at room temperature

A Second Charge Carrier - Hole

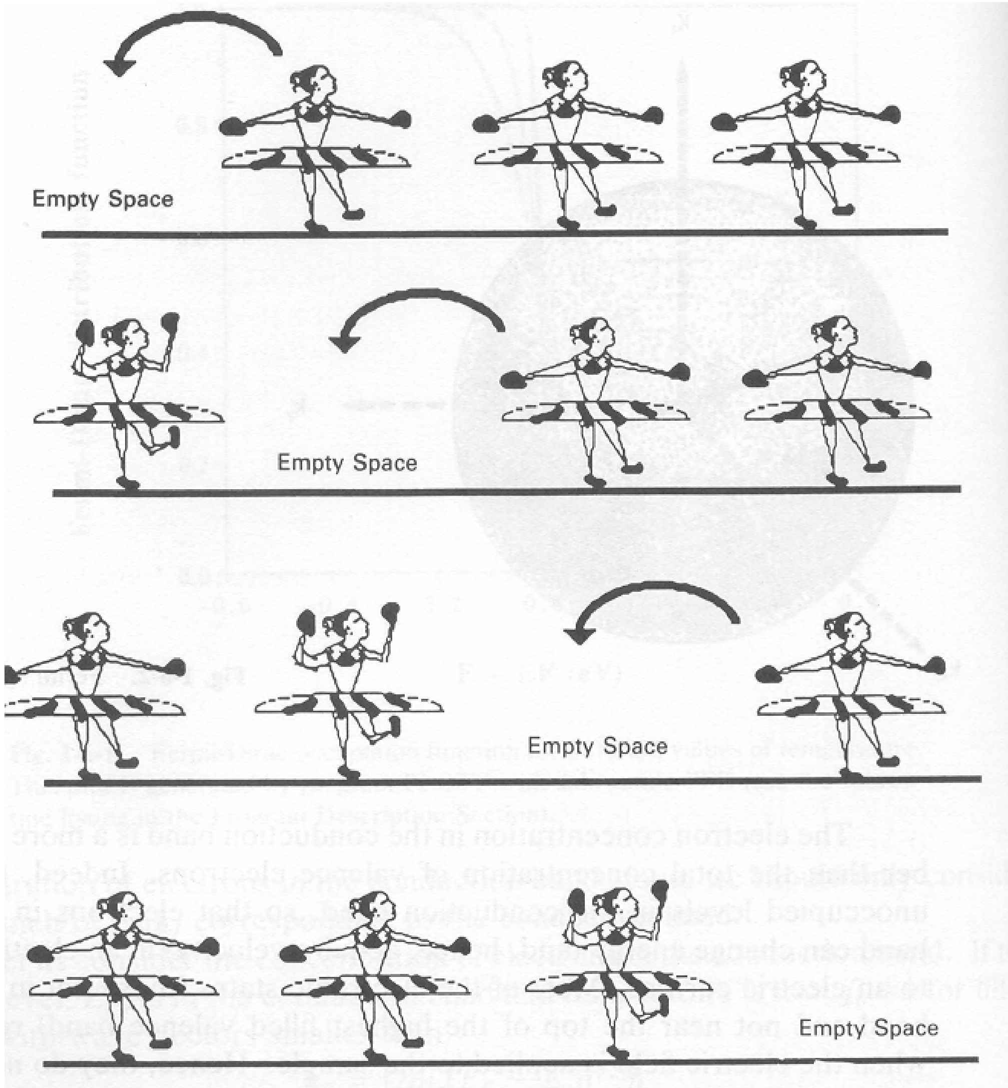
- A vacancy is left when a covalent bond is broken
- The vacancy is left with an effective charge of +q
- The vacancy is called a hole
- A hole moves when the vacancy is filled by an electron from a nearby broken bond. This motion of charge carrier is called hole current

- Hole density *p* for intrinsic semiconductor is $p = n_i$

$$\boxed{pn = n_i^2}$$

- The *pn* product above holds when a semiconductor, not limited to intrinsic ones, is in thermal equilibrium (when no external excitation is applied)

Concept of a Hole



Drift Current

- When an electric field is applied to a material, charged particles will move or *drift*.

- Carrier drift velocity $\boldsymbol{v}$ [cm/s] is proportional to electric field $\mathbf{E}$ [V/cm] at low fields:

$$\boldsymbol{v}_n = -\mu_n \mathbf{E} \quad \text{and} \quad \boldsymbol{v}_p = \mu_p \mathbf{E} \,,$$

  where

  $\boldsymbol{v}_n$ and $\boldsymbol{v}_p$ = electron and hole velocity [cm/s],

  μ_n and μ_p = electron and hole *mobility* [cm^2 / V·s]

  – $\mu_p < \mu_n$ since holes are localized to move through the covalent bond structure, while electrons can move freely in the crystal

- The resulting current is called *drift current*.

Drift Current

- The current through a unit area is defined as the *current density*:

$$\boldsymbol{j} = Q\boldsymbol{v} \quad [(\mathrm{C/cm^3})(\mathrm{cm/s})] = [\mathrm{A/cm^2}]$$

where
$\boldsymbol{j}$ = current density [A/cm^2]
Q = charge density (amount of charge in a unit volume)
$\boldsymbol{v}$ = velocity of charge in an electric field

- Drift current densities:

$$\boldsymbol{j}_n^{drift} = Q_n \boldsymbol{v}_n = (-qn)(-\mu_n \boldsymbol{E}) = qn\,\mu_n \boldsymbol{E} \quad [\mathrm{A/cm^2}]$$
$$\boldsymbol{j}_p^{drift} = Q_p \boldsymbol{v}_p = (+qp)(+\mu_p \boldsymbol{E}) = qp\,\mu_p \boldsymbol{E} \quad [\mathrm{A/cm^2}]$$

$$\boldsymbol{j}_T^{drift} = \boldsymbol{j}_n + \boldsymbol{j}_p = q(n\,\mu_n + p\,\mu_p)\boldsymbol{E} = \sigma \boldsymbol{E}$$

- This defines electrical conductivity:

$$\sigma = q(n\,\mu_n + p\,\mu_p) \qquad [1/(\Omega\cdot\mathrm{cm})]$$

Resistivity ρ is the reciprocal of conductivity:

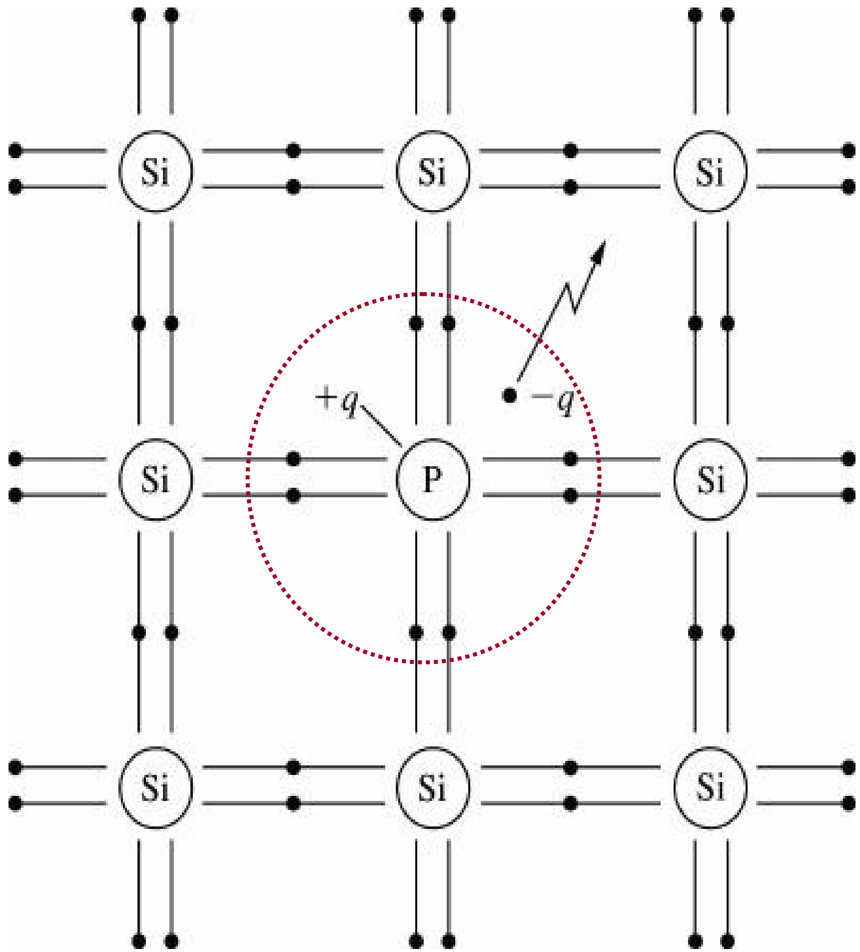
$$\rho = 1/\sigma \qquad [\Omega\cdot\mathrm{cm}]$$

Semiconductor Doping

- Doping is the process of adding very small well-controlled amounts of impurities into a pure semiconductor
- Doping enables the control of the resistivity and other properties over a wide range of values
- For silicon, impurities are from columns III and V of the periodic table

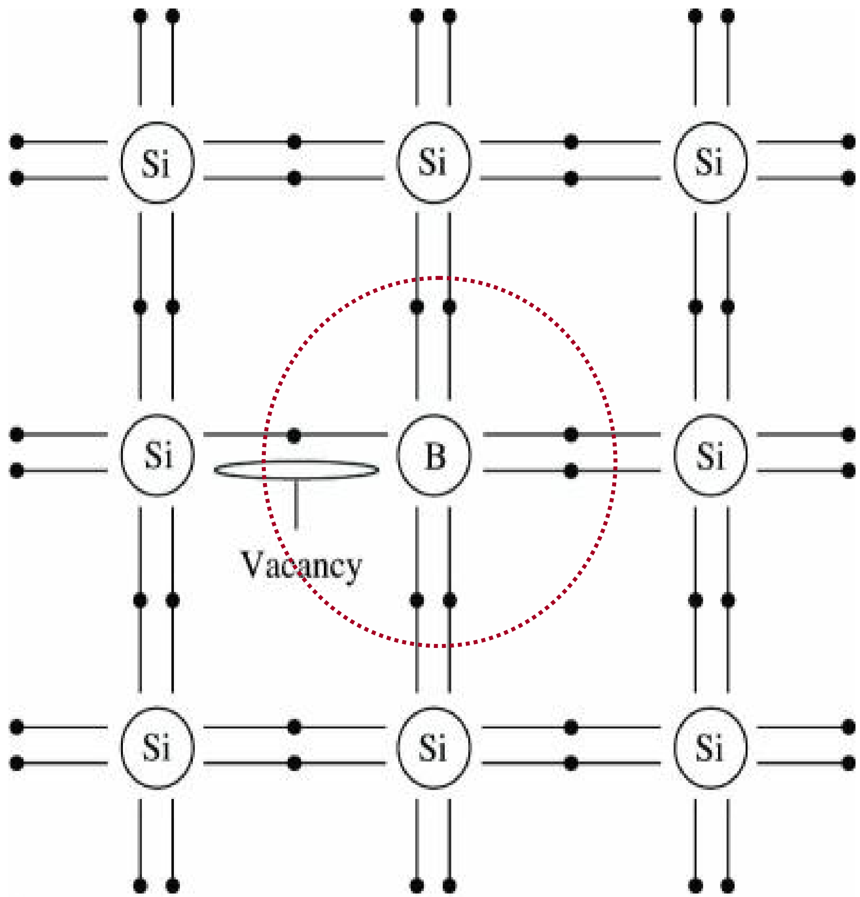
<u>Donor</u> Impurities in Silicon

- Phosphorous (or other column V element) atom replaces silicon atom in crystal lattice
- Since phosphorous has five outer shell electrons, there is now an 'extra' electron in the structure
- Material is still charge neutral, but very little energy is required to free the electron for conduction since it is not participating in a bond



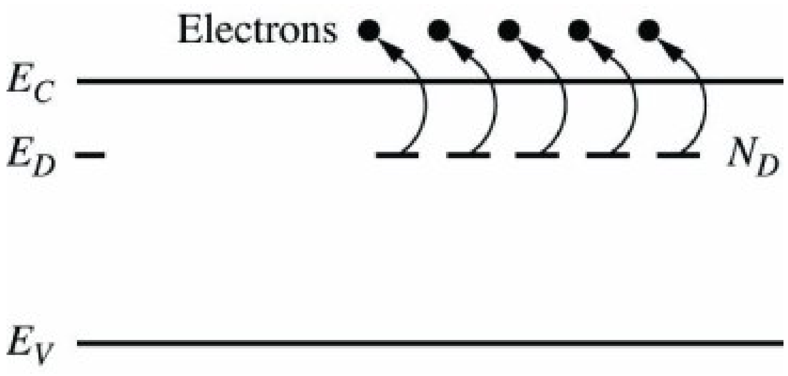
<u>Acceptor</u> Impurities in Silicon

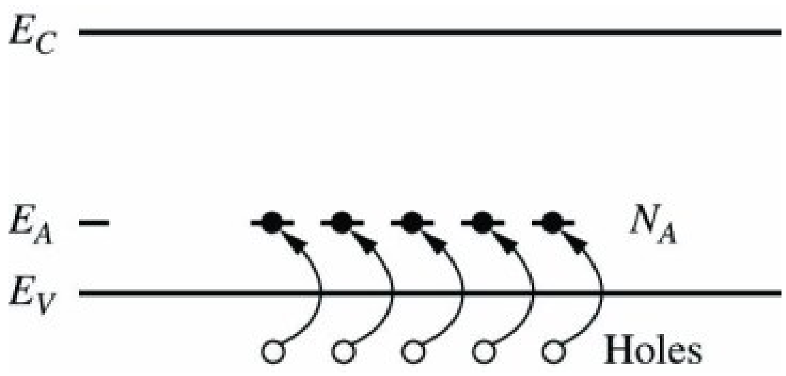
- Boron (column III element) has been added to silicon
- There is now an incomplete bond pair, creating a vacancy for an electron
- Little energy is required to move a nearby electron into the vacancy
- As the 'hole' propagates, charge is moved across the silicon



(a)

Energy Band Model for Doped Semiconductors





Semiconductor with donor or n-type dopants. The donor atoms have free electrons with energy E_D. Since E_D is close to E_C, (about 0.045 eV for phosphorous), it is easy for electrons in an n-type material to move up into the conduction band.

Semiconductor with acceptor or p-type dopants. The donor atoms have unfilled covalent bonds with energy state E_A. Since E_A is close to E_V, (about 0.044 eV for boron), it is easy for electrons in the valence band to move up into the acceptor sites and complete covalent bond pairs.

Doped Silicon Carrier Concentrations

- If $n > p$, the material is n-type.
  If $p > n$, the material is p-type.

- The carrier with the larger density is the majority carrier, the smaller is the minority carrier

- N_D = donor impurity concentration [atoms/cm^3]
  N_A = acceptor impurity concentration [atoms/cm^3]

  Typical doping ranges are 10^{14}/cm^3 to 10^{21}/cm^3

- Charge neutrality requires $q(N_D + p - N_A - n) = 0$

- It can also be shown that

  $$pn = n_i^2$$

  even for doped semiconductors in thermal equilibrium

Doped Silicon Carrier Concentrations

- For n-type silicon:

  Substituting $p=n_i^2/n$ into $q(N_D + p - N_A - n) = 0$ yields

  $$n^2 - (N_D - N_A)n - n_i^2 = 0.$$

  Solving for n

  Highly temp. dependent

  $$n = \frac{(N_D - N_A) \pm \sqrt{(N_D - N_A)^2 + 4n_i^2}}{2} \quad \text{and} \quad p = \frac{n_i^2}{n}$$

  For $(N_D - N_A) >> 2n_i$, $n \approx (N_D - N_A)$.

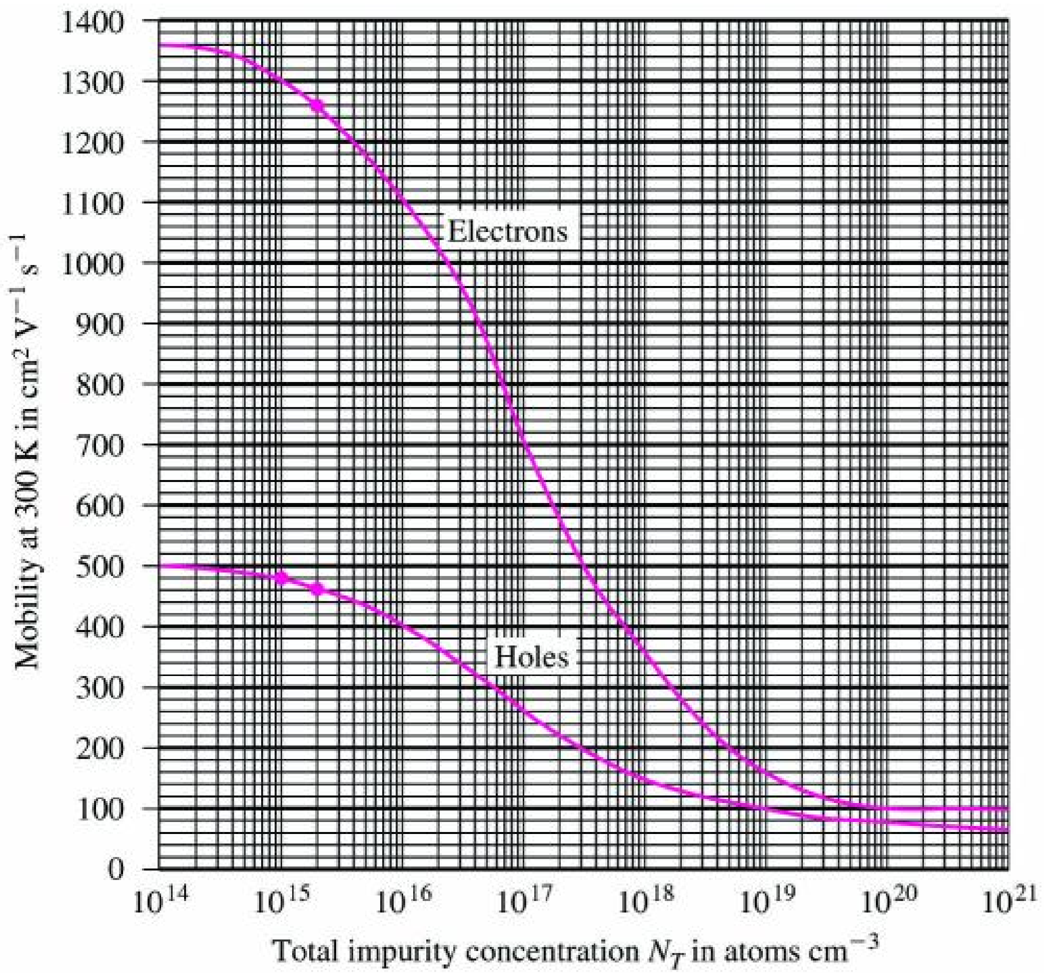
  Temperature INdependent

- Similarly, for p-type silicon we have:

  $$p = \frac{(N_A - N_D) \pm \sqrt{(N_A - N_D)^2 + 4n_i^2}}{2} \quad \text{and} \quad n = \frac{n_i^2}{p}$$

  For $(N_A - N_D) >> 2n_i$, $p \approx (N_A - N_D)$.

Mobility in Doped Silicon



Mobility drops as doping level increases due to

- Impurity atoms have different size than silicon and hence disrupt the periodicity of crystal lattice
- Impurity atoms represents localized charges.

Mobility approximations

$$\mu_n = 92 + \frac{1270}{1 + \left(\frac{N_T}{1.3 \times 10^{17}}\right)^{0.91}}$$

$$\mu_p = 48 + \frac{447}{1 + \left(\frac{N_T}{6.3 \times 10^{16}}\right)^{0.76}}$$

$$N_T = N_A + N_D$$

Example: Resistivity of Doped Silicon

Problem: Calculate the resistivity of silicon doped with a density $N_D = 2\text{x}10^{15}$ cm^{-3} . What is the material type? Classify the sample as an insulator, semiconductor or conductor.

Approach: Use N_D to find *n* and *p* and μ_n and μ_p; substitute these values into the expression for σ.

Assumptions: $N_A = 0$. Assume room temperature with $n_i = 10^{10}$ cm^{-3}

Analysis: $n = N_D = 2\times10^{15}\ \text{cm}^{-3}$

$$p = \frac{n_i^2}{n} = 10^{20}/(2\times10^{15}) = 5\times10^{4}\ \ \text{cm}^{-3}$$

Because *n* > *p* , the silicon is *n*-type. From previous slide, we have

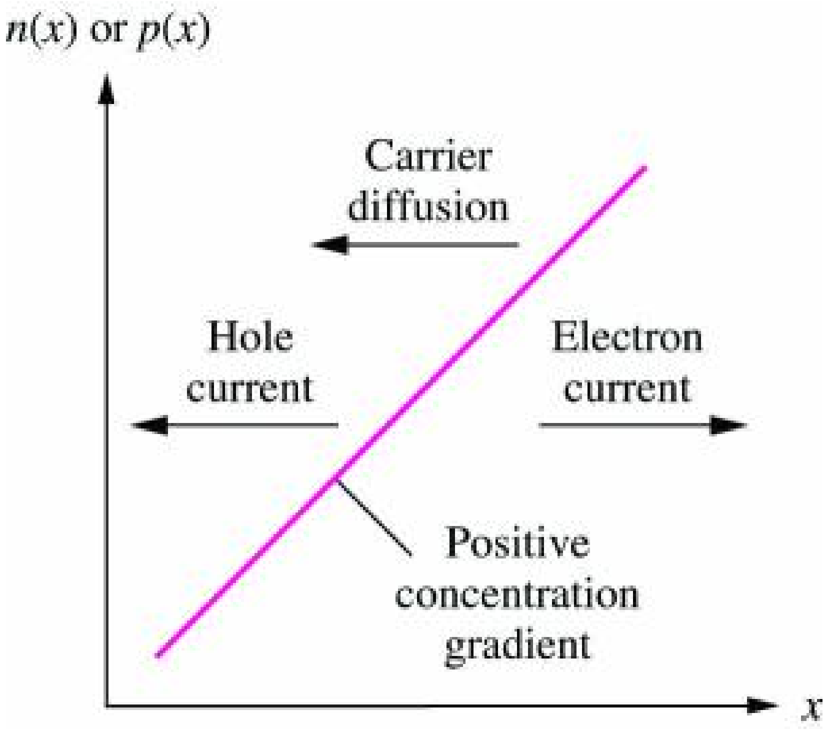
$$\mu_n = 1260\ \ \text{cm}^2/\text{V}\cdot\text{s} \qquad \mu_p = 460\ \ \text{cm}^2/\text{V}\cdot\text{s}$$

$$\therefore\ \ \sigma = q(n\mu_n + p\mu_p) = 1.6\times10^{19}[(1260)(2\times10^{15}) + (460)(5\times10^{4})] = 0.403\ \ (\Omega\cdot\text{cm})^{-1}$$

$\rho = 1/\sigma = 2.48\ \ (\Omega\cdot\text{cm})$ This silicon sample is a semiconductor.

Diffusion Current

In the presence of a concentration gradient, free carriers have a natural tendency of moving from high concentration regions to low concentration regions. The resulted current is called *diffusion current*.



This current is proportional to the concentration gradient:

$$\mathbf{j}_p^{diff} = (+q)D_p\left(-\frac{\partial p}{\partial x}\right) = -qD_p\frac{\partial p}{\partial x} \quad [\mathrm{A/cm^2}]$$

$$\mathbf{j}_n^{diff} = (-q)D_n\left(-\frac{\partial n}{\partial x}\right) = +qD_n\frac{\partial n}{\partial x} \quad [\mathrm{A/cm^2}]$$

The proportionality constants D_p and D_n are called the hole and electron *diffusivities*.

Total Current in a Semiconductor

- Total current is the sum of *drift* and *diffusion* current:

$$\begin{cases} \mathbf{j}_n^T = q\mu_n n\mathbf{E} + qD_n \dfrac{\partial n}{\partial x} \\ \mathbf{j}_p^T = q\mu_p p\mathbf{E} - qD_p \dfrac{\partial p}{\partial x} \end{cases}$$

- *Mobility* and *Diffusivity* are related by Einsteins's relationship:

$$\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = \frac{kT}{q} = V_T \text{ (Thermal voltage)}$$

$V_T \approx 25$ mV at room temp.

$$\Rightarrow \begin{cases} \mathbf{j}_n^T = q\mu_n n\left(\mathbf{E} + V_T \dfrac{1}{n}\dfrac{\partial n}{\partial x}\right) \\ \mathbf{j}_p^T = q\mu_p p\left(\mathbf{E} - V_T \dfrac{1}{p}\dfrac{\partial p}{\partial x}\right) \end{cases}$$