Chapter 1

Overview of Semiconductor Materials and Physics

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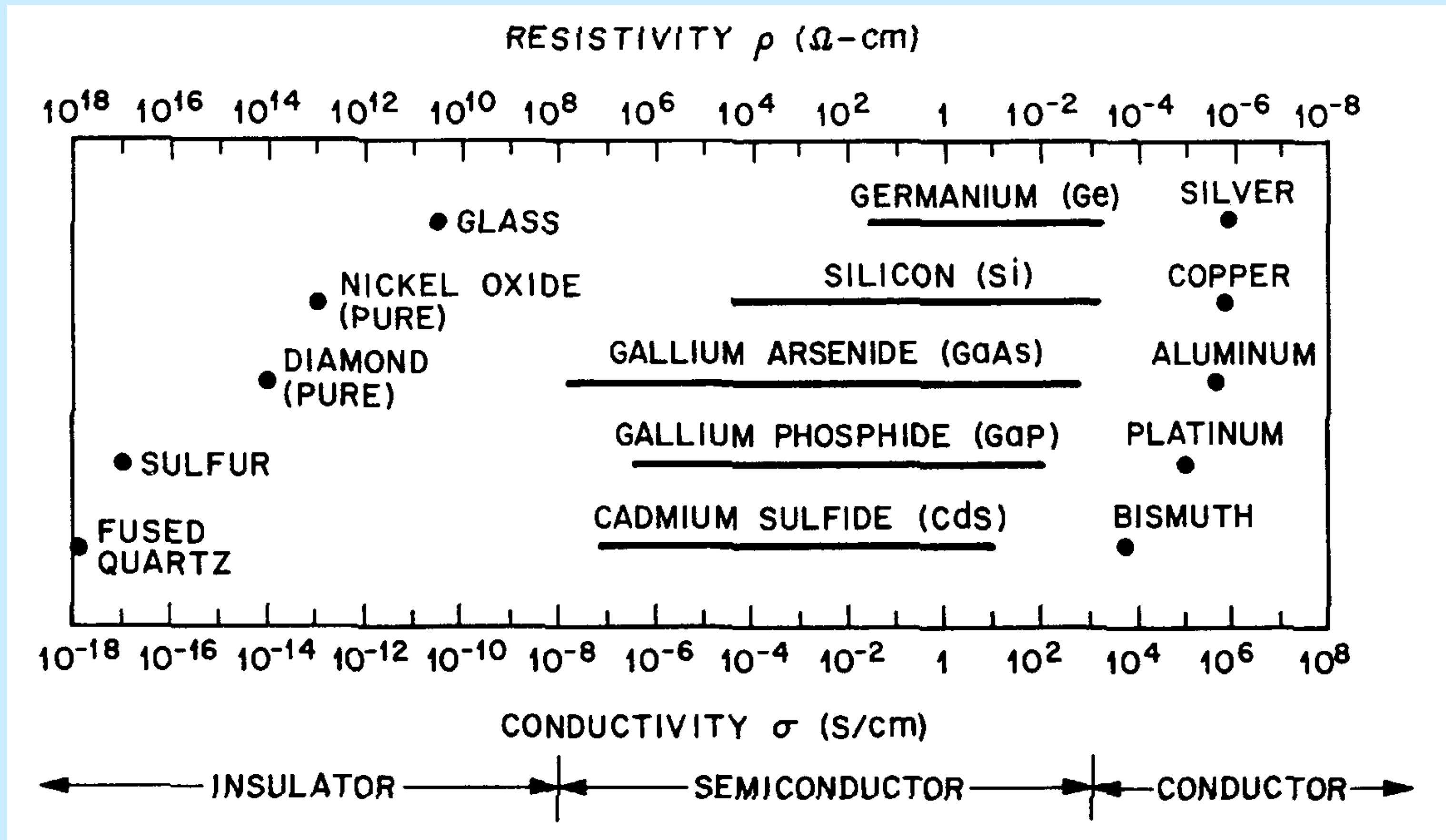
Conductivity / Resistivity of Insulators, Semiconductors, and Conductors



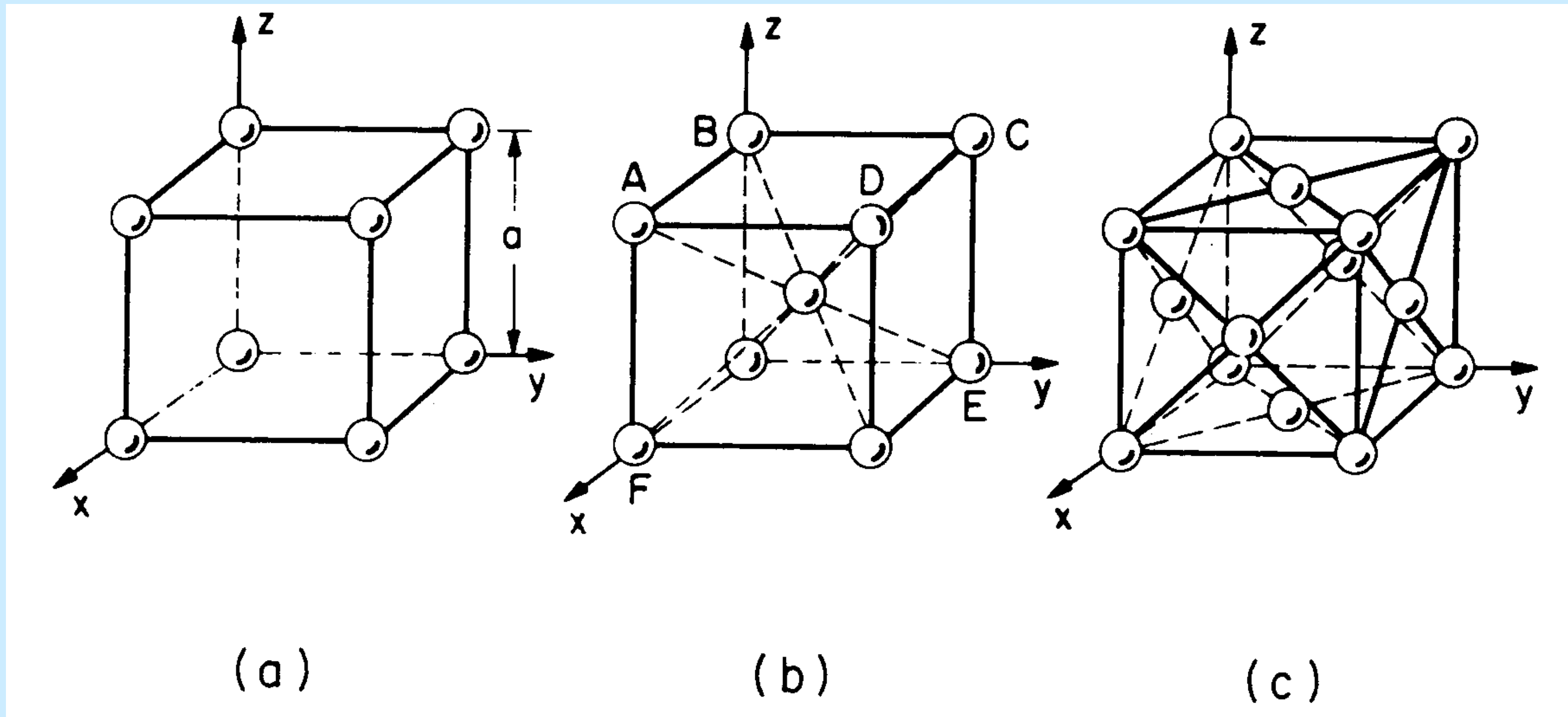
Semiconductor Elements

Period	II	III	IV	V	VI
2		B Boron	C Carbon	N Nitrogen	
3	Mg Magnesium	Al Aluminum	Si Silicon	P Phosphorus	S Sulfur
4	Zn Zinc	Ga Gallium	Ge Germanium	As Arsenic	Se Selenium
5	Cd Cadmium	In Indium	Sn Tin	Sb Antimony	Te Tellurium
6	Hg Mercury		Pb Lead		

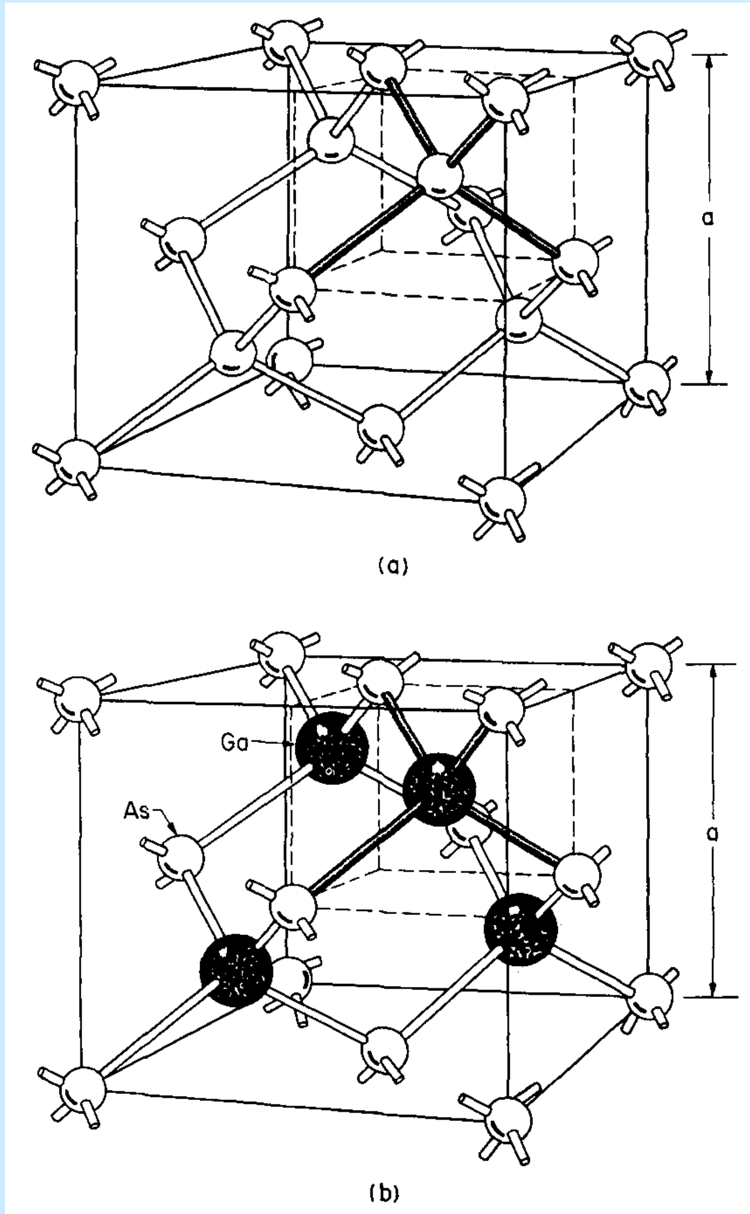
Element and Compound Semiconductors

Elements	Compounds IV-IV	Compounds III-V	Compounds II-VI	Compounds IV-VI
Si	SiC	AlAs	CdS	PbS
Ge	SiGe	AlSb	CdSe	PbTe
	SiCGe	GaN	CdTe	
		GaAs	ZnS	
		GaP	ZnSe	
		GaSb	ZnTe	
		InAs	ZnO	
		InP		
		InSb		

Unit Cells



Simple Cubic **Body-Centered Cubic** **Face-Centered Cubic**



Diamond Lattice

Zincblende Lattice

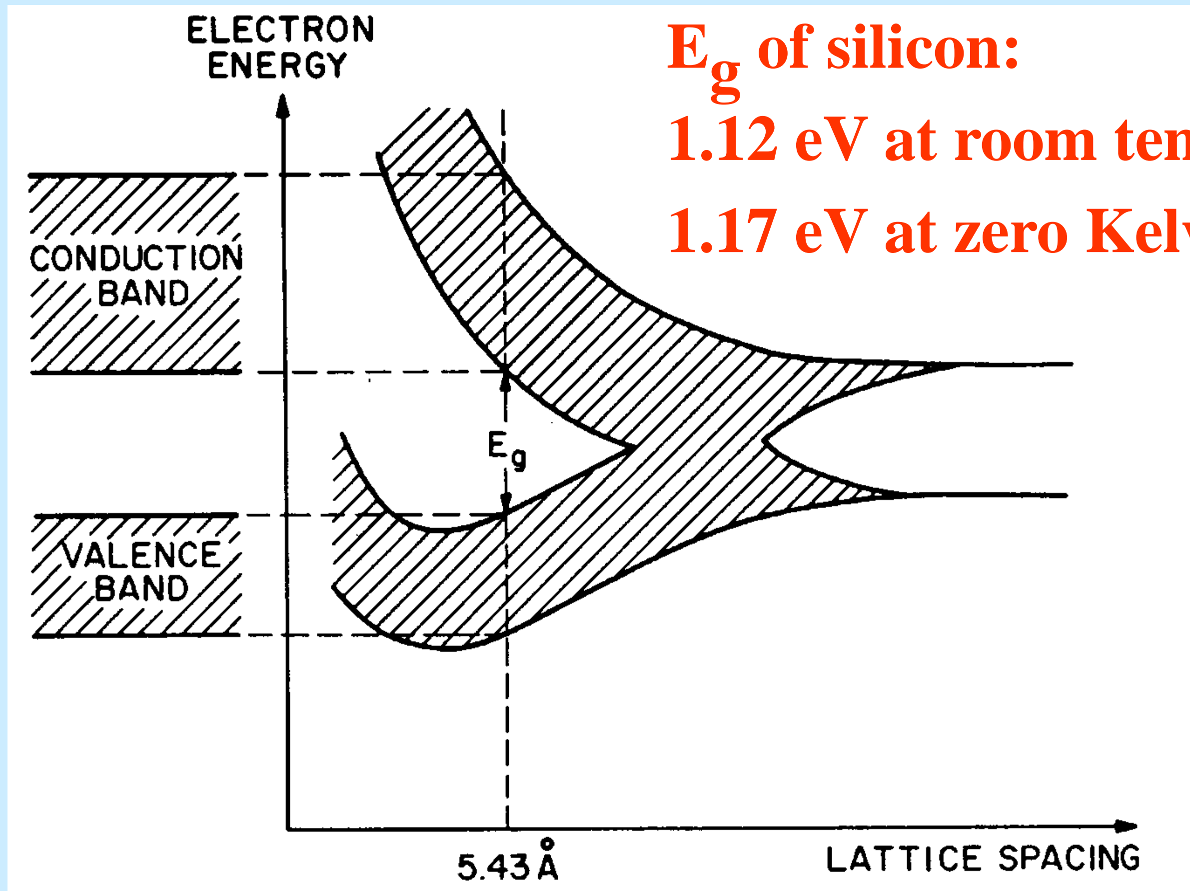
Bohr Hydrogen Model

$$E_H = \frac{-m_o q^4}{8\varepsilon_o^2 h^2 n^2} = \frac{-13.6}{n^2} eV$$

m_o denotes the free electron mass
q denotes the electronic charge
ε_o denotes the free space permittivity
h denotes the Plank constant
n denotes the principal quantum number

Therefore, for n = 1, that is, ground state, E_H = -13.6 eV

For n = 2, the first excited state, E_H = -3.4 eV

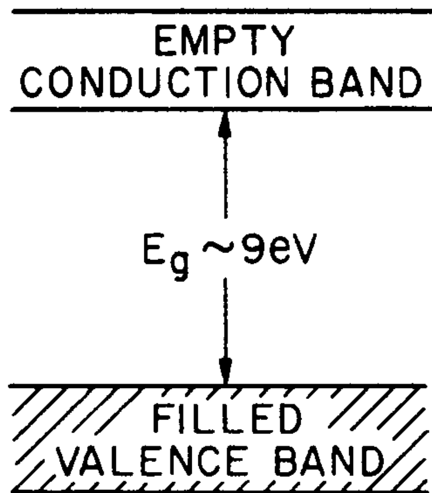


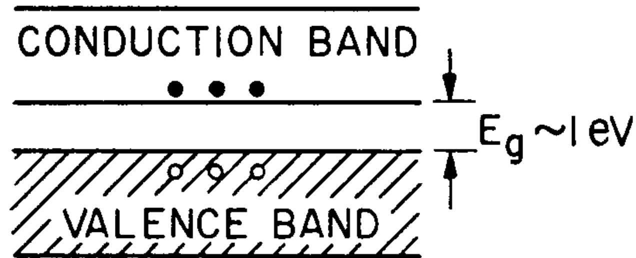
E_g of silicon:

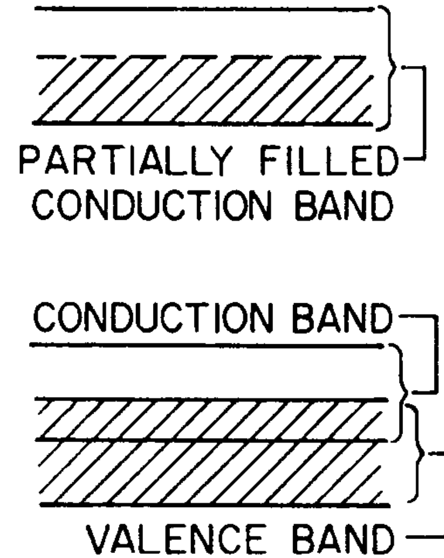
1.12 eV at room temperature

1.17 eV at zero Kelvin

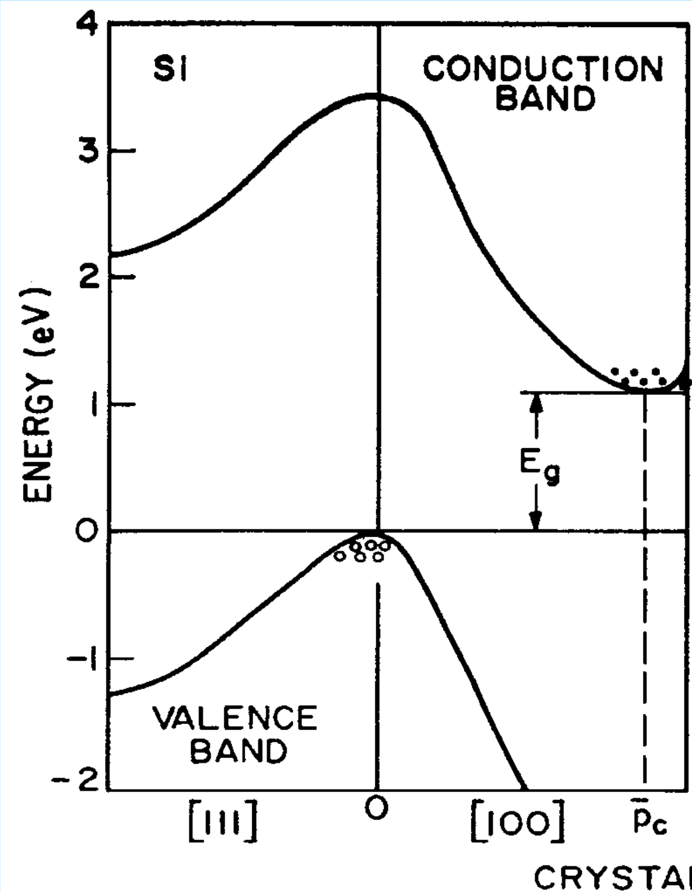
Formation of energy bands as a diamond lattice crystal by bringing together isolated silicon atoms

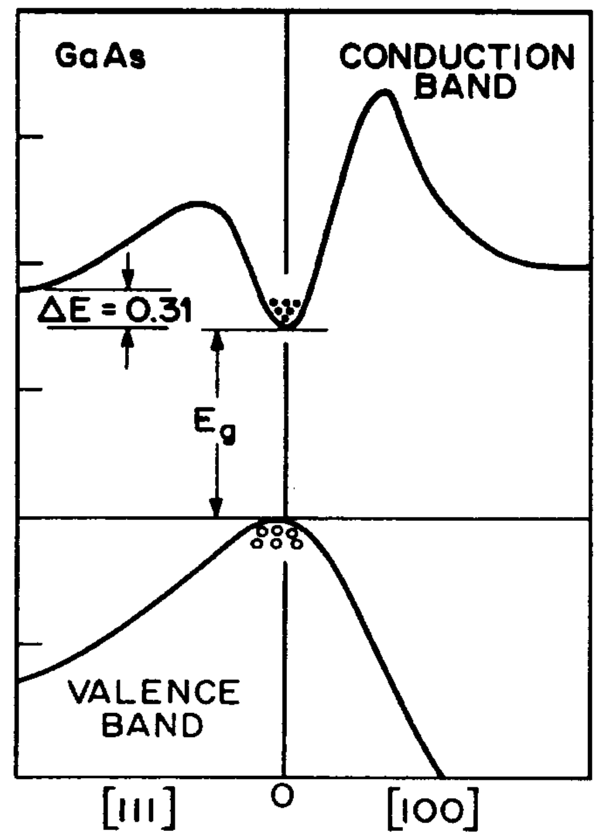






Insulator **Semiconductor** **Conductor**





Indirect Bandgap

Inefficient photon emission, requiring change in crystal momentum

Direct Bandgap

Efficient photon emission

Fermi-Dirac Distribution Function

The probability that an electronic state with energy ***E*** is occupied by an electron is given by the Fermi-Dirac distribution function:

$$f(E) = \frac{1}{1 + e^{(E - E_F)/kT}}$$

E_F is the Fermi level, the energy at which the probability of occupation by an electron is exactly one-half. At room temperature, the intrinsic Fermi level lies very close to the middle of the bandgap.

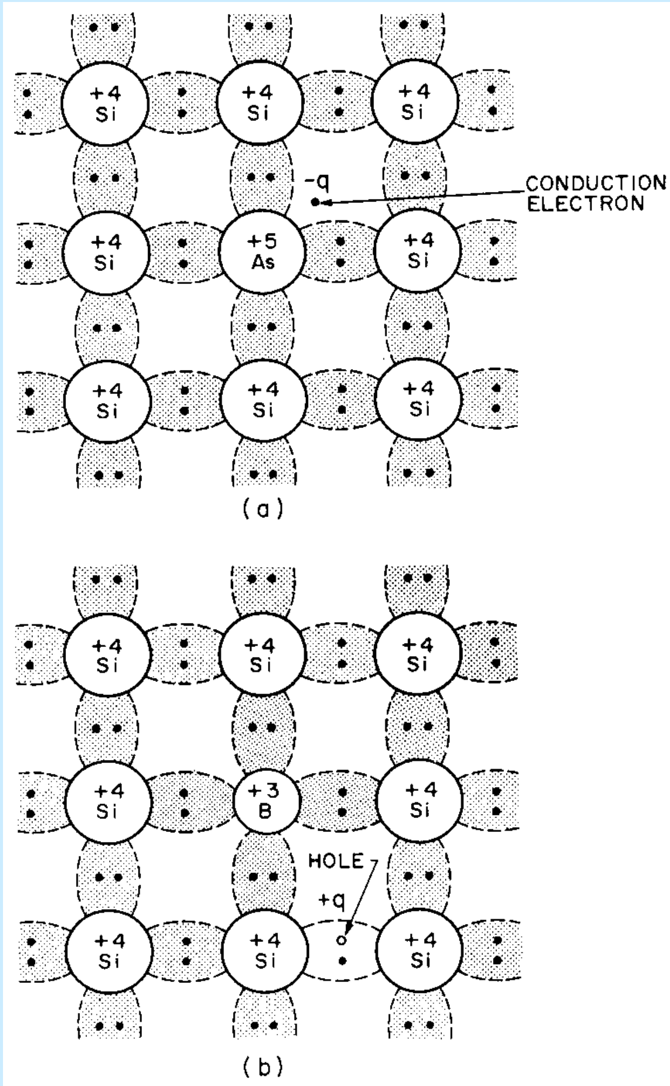
The effective density of states in the conduction band N_C is equal to $2[2\pi m_n kT/h^2]^{3/2}$. Similarly, the effective density of states in the valence band N_V is $2[2\pi m_p kT/h^2]^{3/2}$. At room temperature, N_C for silicon is 2.8 x 10^{19} atoms/cm^3.

For an intrinsic semiconductor, the number of electrons per unit volume in the conduction band is equal to the number of holes per unit volume in the valence band. That is, $n = p = n_i$ where n_i is the intrinsic carrier density.

- For a doped, or extrinsic, semiconductor, the increase of one type of carriers reduces the number of the other type. Thus, the product of the two types of carriers remains constant at a given temperature

- For Si, $n_i = 1.45 \times 10^{10}$ cm^{-3} and for GaAs, $n_i = 1.79 \times 10^{6}$ cm^{-3}. GaAs has a lower intrinsic carrier density on account of its larger bandgap

n-type Si with donor (arsenic)

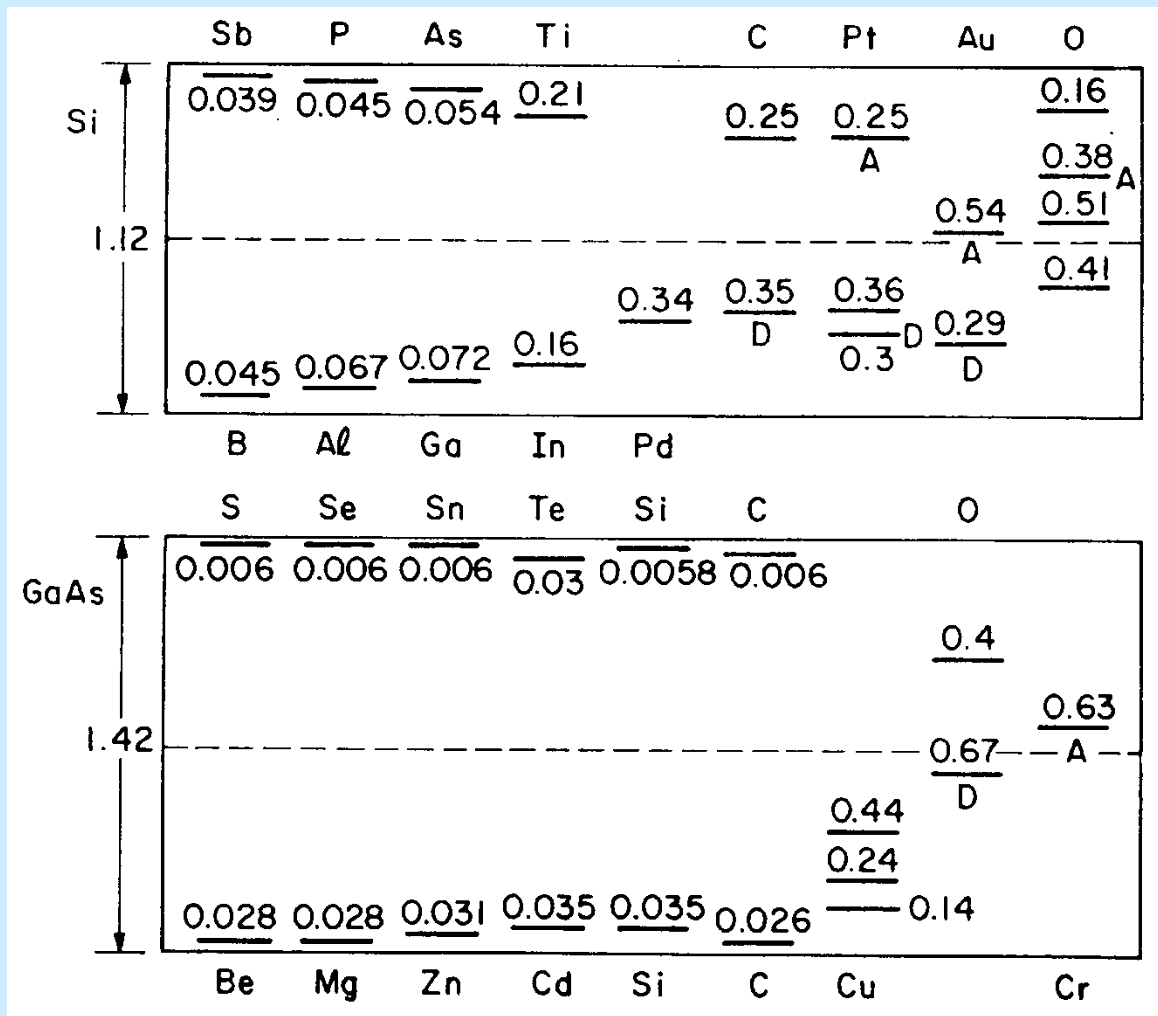


p-type Si with acceptor (boron)

The arsenic atom forms covalent bonds with its four neighboring silicon atoms, and the fifth electron becomes a conduction electron, thereby giving rise to a positively charged arsenic atom. The silicon crystal becomes n-type and arsenic is called a donor.

Boron has only three outer shell electrons and is an acceptor in silicon.

Impurities such as arsenic and boron have energy levels very close to the conduction band and valence band, respectively



Shallow donors or acceptors exist in ionized form at room temperature because thermal energy is sufficient to ionize them.

This condition is called complete ionization, that is, $n = N_A$ or N_D

Since $n = N_C \exp\{-(E_C - E_F)/kT\}$,

$N_D = N_C \exp\{-(E_C - E_F)/kT\}$ and $E_C - E_F = kT \ln[N_C/N_D]$.

$(E_C - E_F)$ becomes smaller with increasing N_D, or the Fermi level moves closer to the bottom of the conduction band

For p-type semiconductors, the Fermi level moves towards the top of the valence band with increasing acceptor concentration

- When both donors and acceptors are present simultaneously, the impurity which is present at a higher concentration determines the type of conductivity in the semiconductor

- The electron in an n-type semiconductor is called the majority carrier, whereas the hole in n-type semiconductor is termed the minority carrier

- In a p-type semiconductor, holes are majority carriers and electrons are minority carriers

Carrier Mobility

- Using the theorem of equipartition of energy, $m_n v_{th}^2/2 = 3kT/2$, where m_n is the electron effective mass and v_{th} is the average thermal velocity

- Electrons in the semiconductor therefore move rapidly in all directions

- The thermal motion of an individual electron can be visualized as a succession of random scattering from collisions with lattice atoms, impurity atoms, and other scattering centers

- The average distance between collisions is called the mean free path, and the average time between collisions is termed the mean free time, τ_c

- When a small electric field, ε, is applied to the semiconductor, each electron will experience a force equal to $-q\varepsilon$ and will be accelerated in opposite direction to the electric field with a drift velocity, v_n. By Newtonian physics, the momentum of the electron is force times time, that is, equal to $-q\varepsilon\tau_c$. Therefore, $m_n v_n = -q\varepsilon\tau_c$, or $v_n = -[q\tau_c/m_n]\,\varepsilon$

- The drift velocity is proportional to the applied electric field. The proportionality factor is called the electron mobility, μ_n, in units of $cm^2/V\text{-}s$. Hence, $v_n = -\mu_n\varepsilon$ where $\mu_n = q\tau_c/m_n$

- A similar expression can be written for holes: $v_p = \mu_p\varepsilon$. The negative sign is removed here because holes drift in the same direction as the electric field

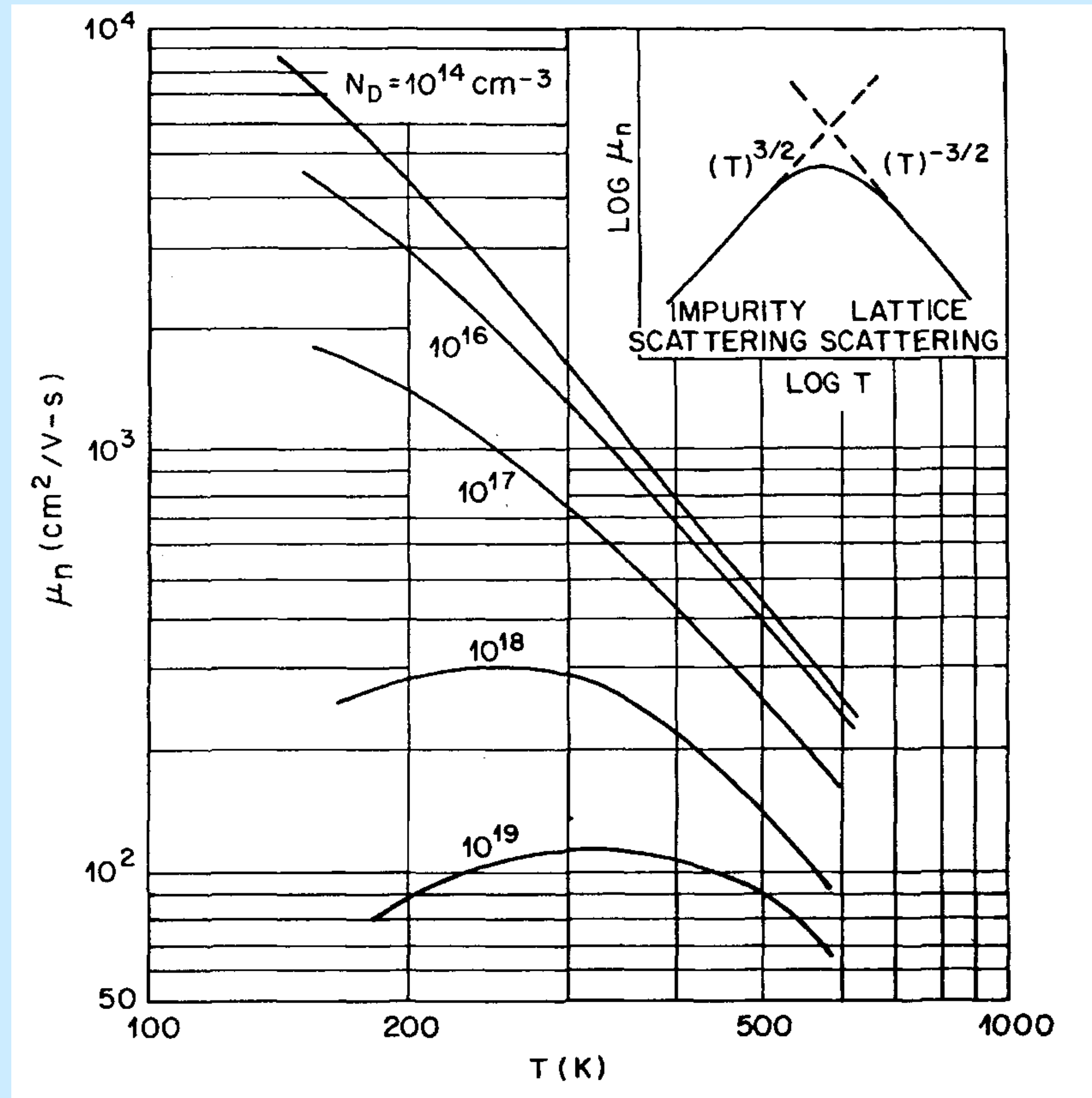
- Carrier mobility depends on lattice scattering and impurity scattering

- Lattice scattering results from thermal vibrations of the lattice atoms. As lattice vibration is more significant with increasing temperature, mobility decreases. At high temperature, lattice vibration dominates

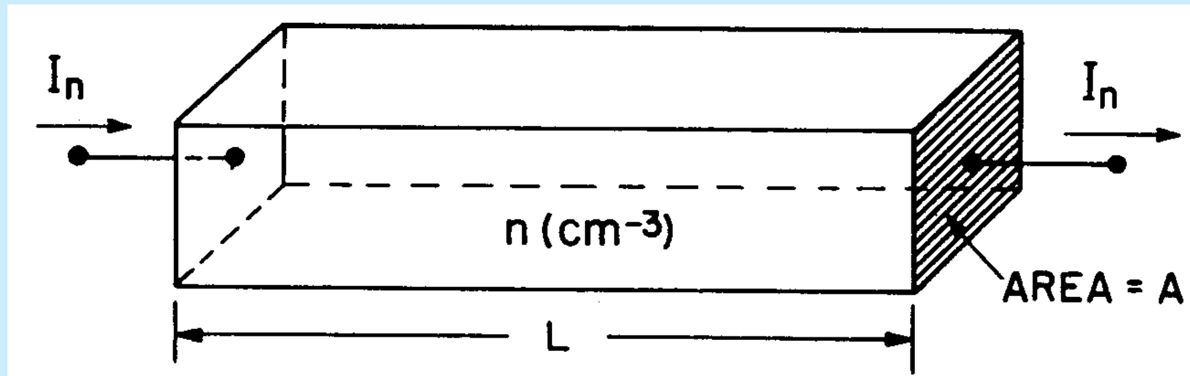
- Impurity scattering results when a charge carrier travels past an ionized donor or acceptor. The probability of impurity scattering depends on the total impurity concentration. Unlike lattice scattering, impurity scattering becomes less significant at high temperatures because the carriers move faster and are less effectively scattered

Electron Mobility Versus Temperature

Insert shows the theoretical temperature dependence of electron mobility



Resistivity and Conductivity

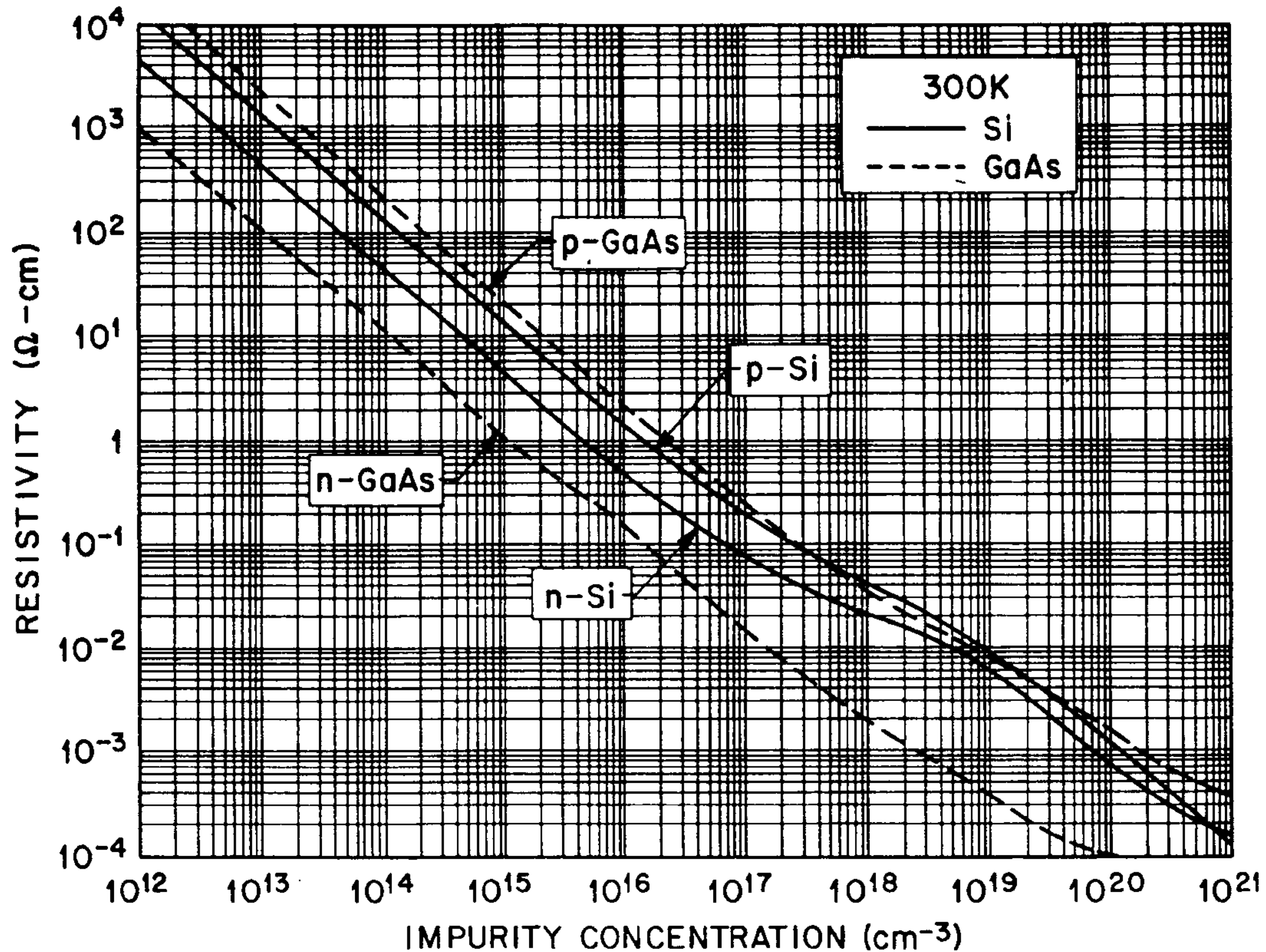


The electron current density, J_n, flowing in the sample can be calculated by summing the product of the charge on each electron times the electron's velocity over all electrons per unit volume n

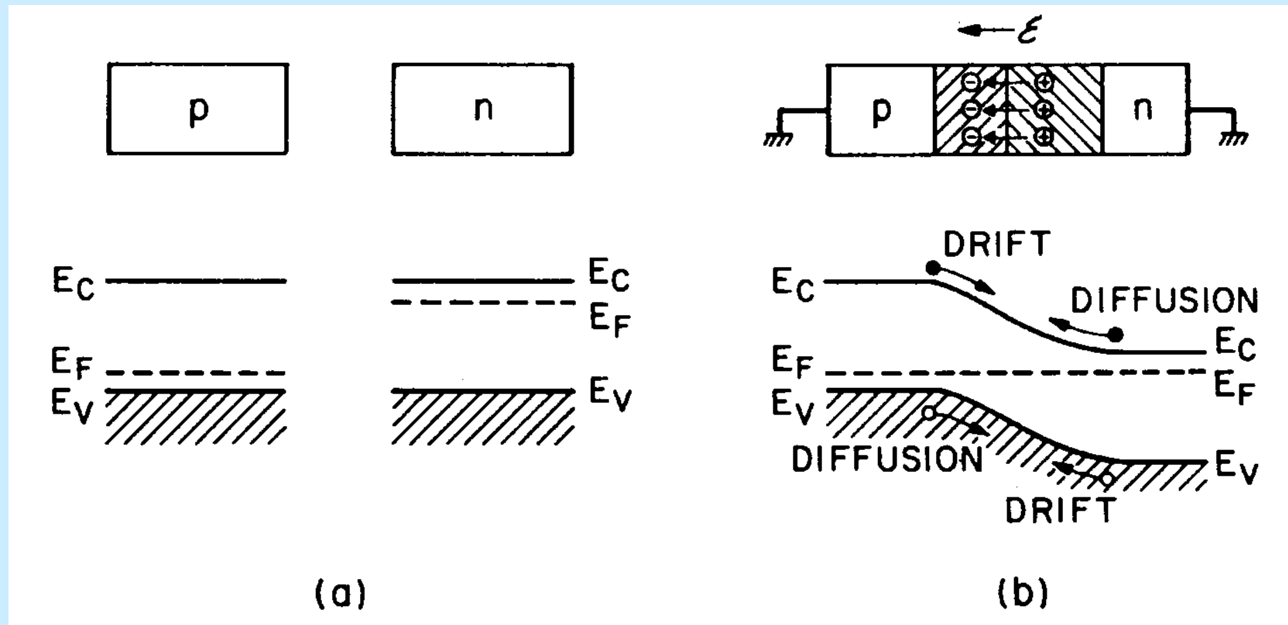
$$J_n = I_n/A = \Sigma(-qv_i) = -qnv_n = qn\mu_n\varepsilon$$

- The total current, $J = J_n$ **(electrons)** $+ J_p$ **(holes)** and $J = (qn\mu_n + qp\mu_p)\varepsilon$
- The proportionality constant is known as the conductivity, σ. A more commonly used term is the resistivity, ρ, which is the reciprocal of the conductivity. Thus, $\rho = \sigma^{-1} = [q(n\mu_n + p\mu_p)]^{-1}$
- Generally, in extrinsic semiconductors, one of the two components is dominant. Therefore, for n-type semiconductors, $\rho = (qn\mu_n)^{-1}$ and for p-type semiconductors, $\rho = (qp\mu_p)^{-1}$

Resistivity versus impurity concentration



P-N Junction



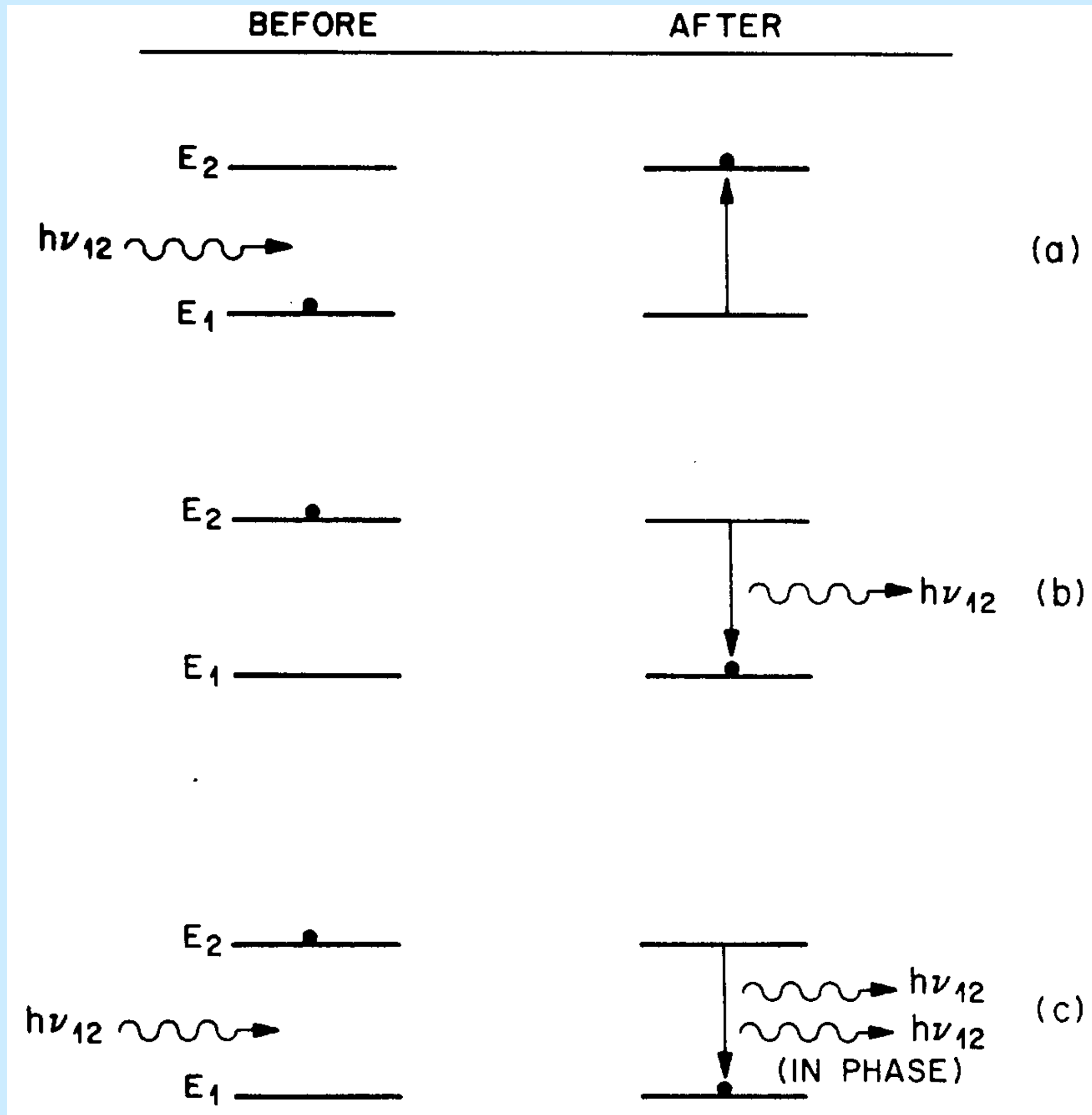
The large carrier concentration gradients at a p-n junction cause carrier diffusion. Holes from the p-side diffuse into the n-side, and electrons from the n-side diffuse into the p-side. This sets up an electric field, which in equilibrium, exactly counteracts these diffusion tendencies and thus permits no net transport of electrons or holes across the junction.

- When a small positive voltage is applied to the p-side, there will be a net movement of holes flowing from the p-side to the n-side, thereby creating a forward bias situation

- If a negative voltage is applied to the p-side, i.e. reverse bias condition, the p-n junction becomes an open circuit. A p-n junction therefore acts as a diode

Recombination Processes

- When the thermal equilibrium in a semiconductor is perturbed, that is, the product, **np**, is no longer equal to n_i^2, by injection of excess carriers, processes exist to restore the system back to equilibrium ($np = n_i^2$)
- If the released energy results in the emission of a photon, the process is called radiative recombination, otherwise it is called nonradiative recombination
- When excess carriers are introduced to a direct-bandgap semiconductor such as GaAs, the probability is high that electrons and holes will recombine directly and a photon is emitted



Absorption

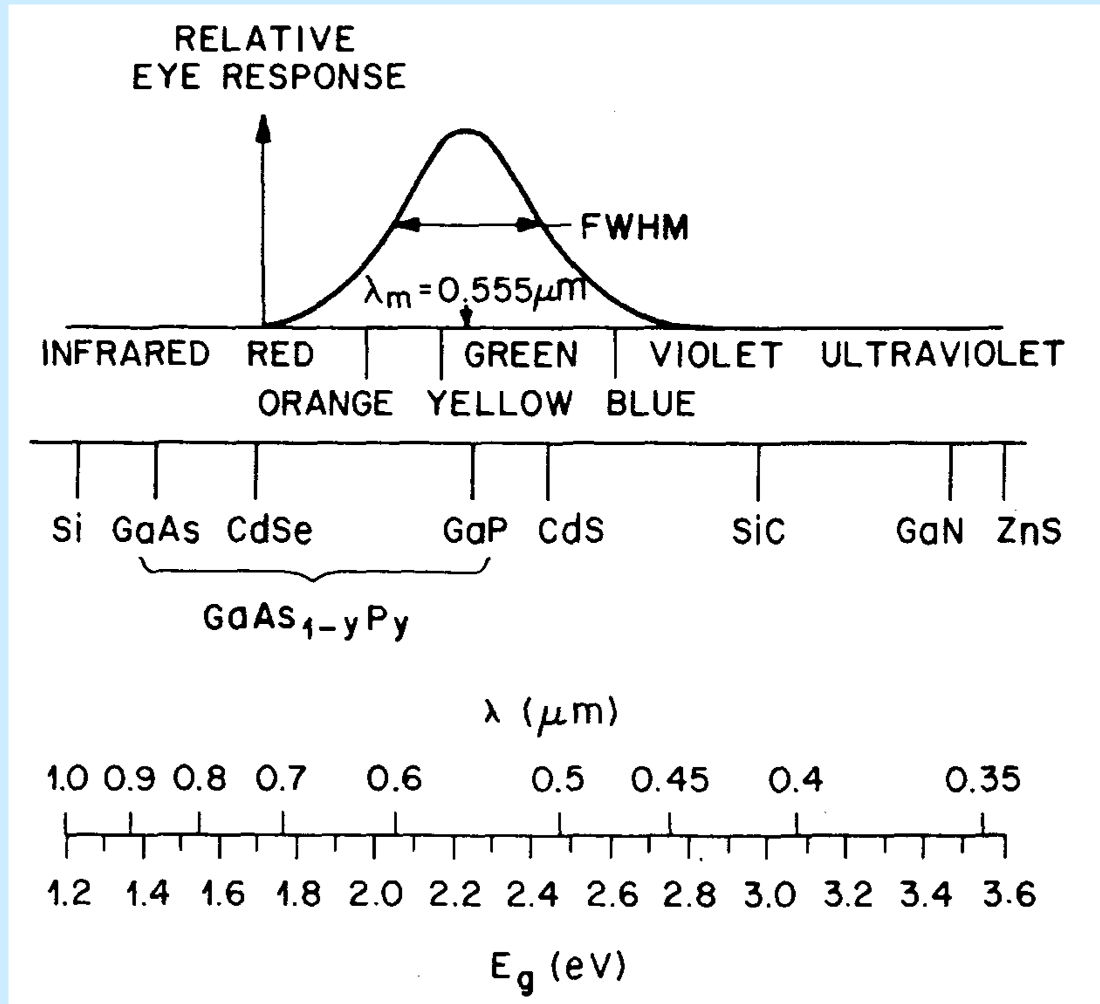
Spontaneous Emission

Stimulated Emission
(laser)

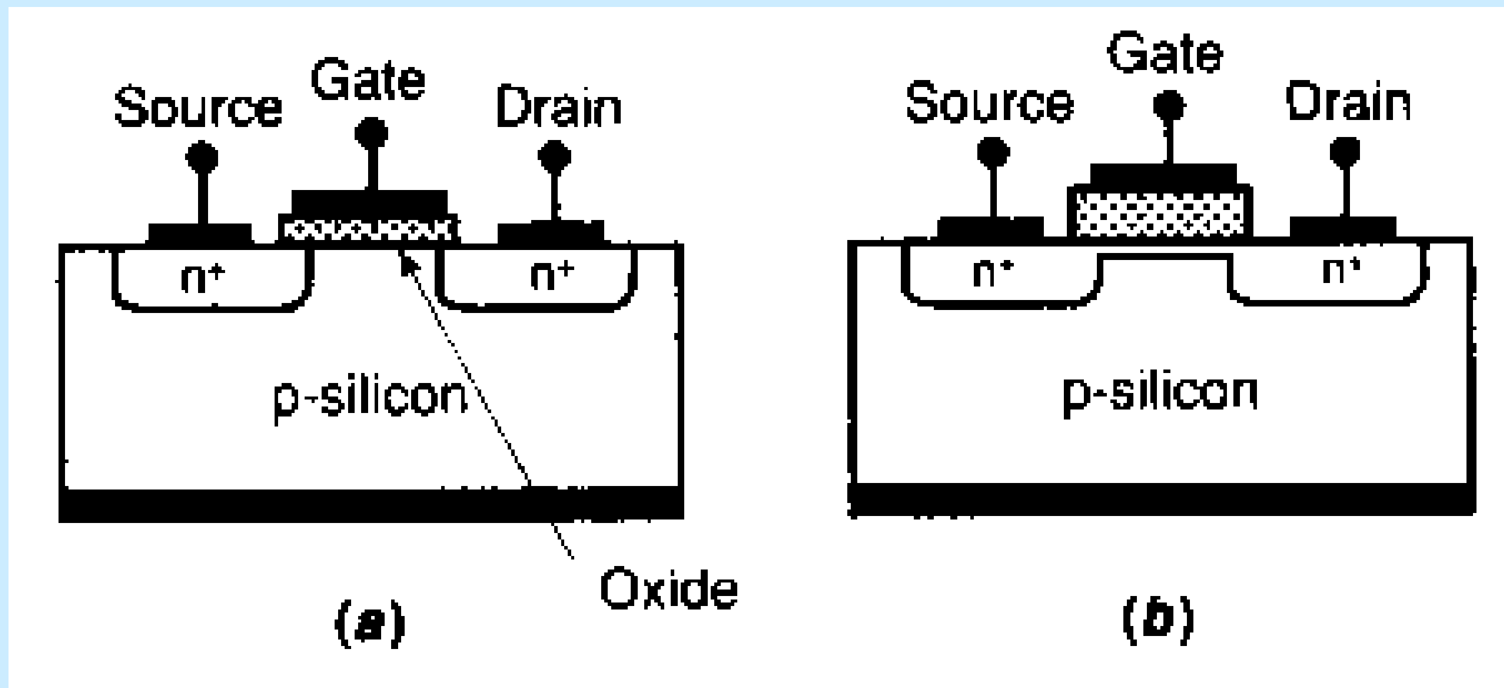
Light-Emitting Diodes

Light emitting diodes (LEDs) are p-n junctions that emit spontaneous radiation in ultraviolet, visible, or infrared region under bias. The most common visible LEDs are made of alloys of $GaAs_{1-y}P_y$, where y is the atomic fraction. The bandgap of the alloy depends on its composition, i.e. y, thus implying that the emitted light frequency can be tailored by altering y.

Semiconductors of interest as visible LEDs

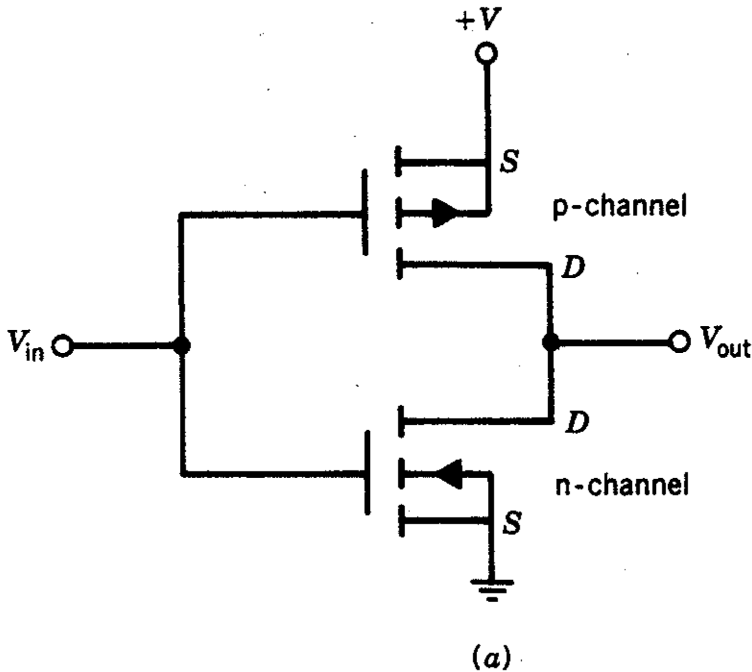


Metal-Oxide Semiconductor Field Effect Transistor (MOSFET)

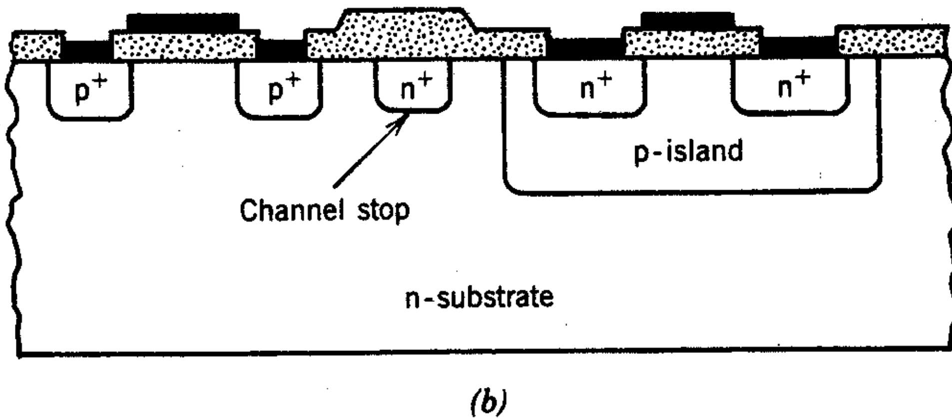


Enhancement Mode

Depletion Mode



(a)



(b)

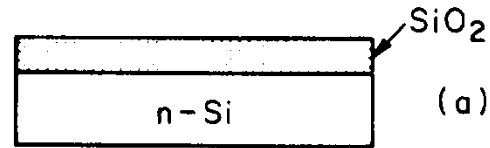
Complementary MOS (CMOS)

- low current
- low power consumption

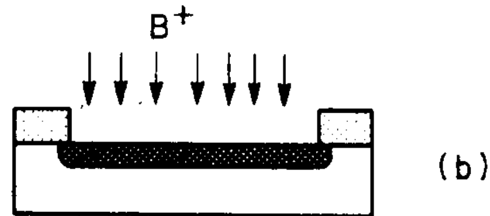
Fabrication steps of an MOS capacitor

MOS CAPACITOR

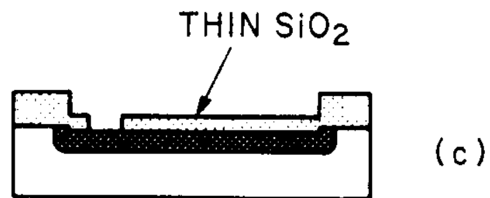
GROW 4000Å OXIDE ON
N-TYPE SILICON MATERIAL



PATTERN AND ETCH OXIDE, THEN
ION IMPLANT 50 KeV BORON
TO FORM P^+ REGION.



GROW THIN OXIDE (200Å),
PATTERN AND ETCH OXIDE TO
FORM CONTACT.



DEPOSIT 5000Å ALUMINUM,
PATTERN AND ETCH ALUMINUM.