

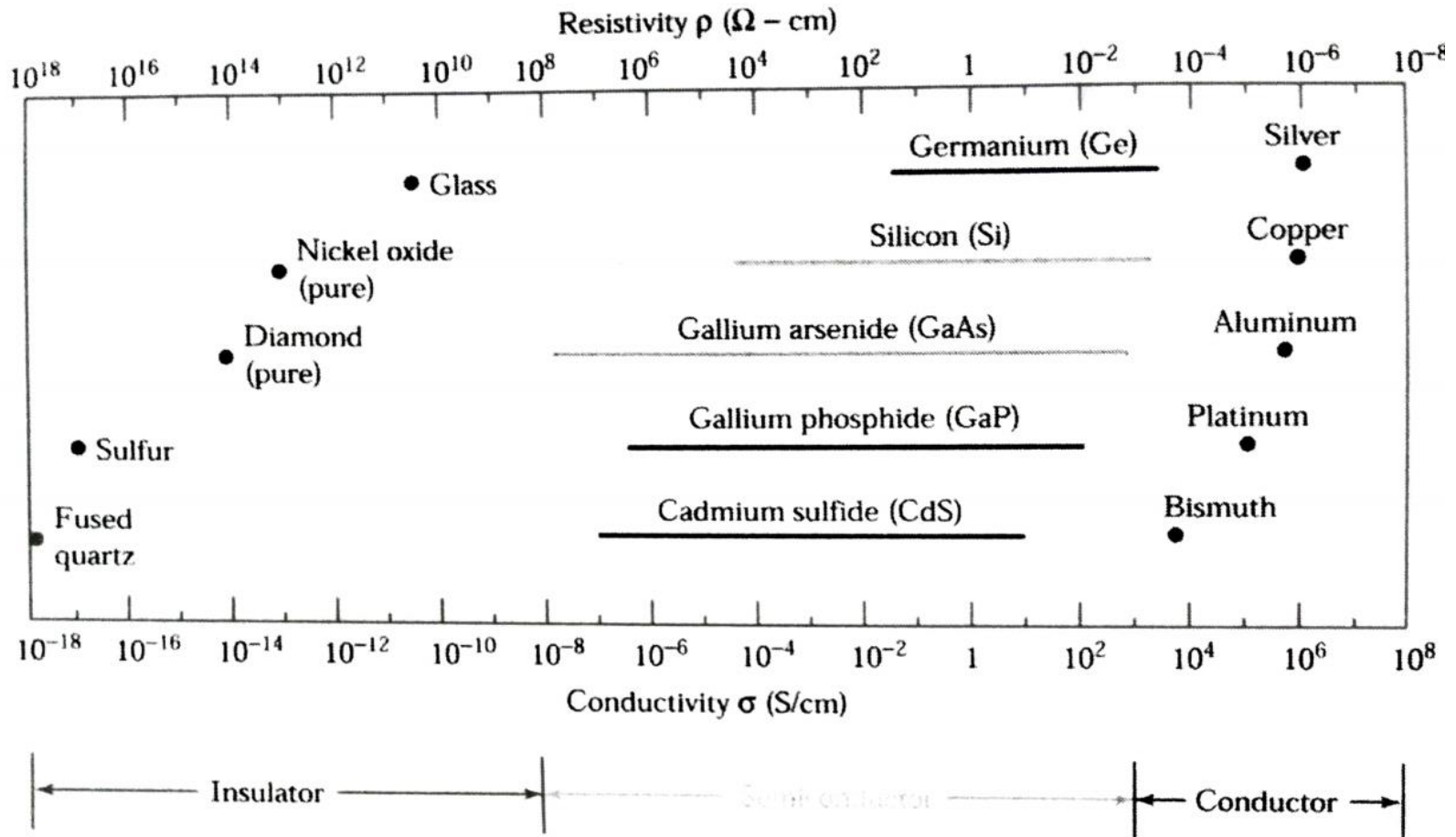
CBCC Course on Electronics

- **Module – 1: Introduction to Semiconductor Physics & Device Fabrication Technology: Introduction, concept of energy bands, Fermi level, intrinsic and extrinsic semiconductors, P-type and N-type semiconductors, energy band diagram, effective mass, carrier transport, mobility, drift and diffusion, carrier recombination, introduction to device fabrication technology.**
- **Module – 2: Junction Diodes: Formation of P-N junction, energy band diagram, depletion region, forward and reverse biased P-N junction diode, I-V characteristics, breakdown mechanisms, Zener breakdown, Avalanche breakdown, Zener diode and its characteristics, junction capacitance and Varactor diode, diode rectifier circuits and Zener voltage regulators.**

Introduction to Electronics

- Electronics deals with the theory and application of a class of devices, called electron devices, in which the electrons are transported through semiconductor, gas and vacuum.
- Semiconductor: solid-state crystalline material.
- Most interesting property of semiconductor: conductivity can be varied over orders of magnitude by varying impurity doping concentration, temperature, and optical excitation.

Conductivity of Semiconductors



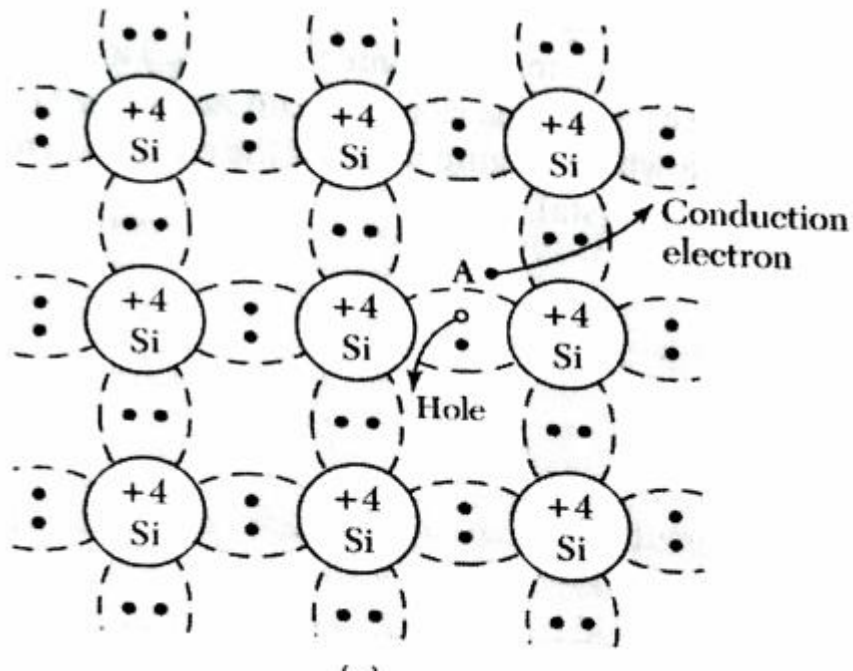
Portion of the Periodic Table Related to Semiconductors

Period	Column II	III	IV	V	VI
2		B Boron	C Carbon	N Nitrogen	O Oxygen
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		

Semiconductor Materials

General Classification	Semiconductor	
	Symbol	Name
Element	Si	Silicon
	Ge	Germanium
Binary compound		
IV-IV -----	SiC	Silicon carbide
III-V -----	AlP	Aluminum phosphide
	AlAs	Aluminum arsenide
	AlSb	Aluminum antimonide
	GaN	Gallium nitride
	GaP	Gallium phosphide
	GaAs	Gallium arsenide
	GaSb	Gallium antimonide
	InP	Indium phosphide
	InAs	Indium arsenide
	InSb	Indium antimonide
II-VI -----	ZnO	Zinc oxide
	ZnS	Zinc sulfide
	ZnSe	Zinc selenide
	ZnTe	Zinc telluride
	CdS	Cadmium sulfide
	CdSe	Cadmium selenide
	CdTe	Cadmium telluride
	HgS	Mercury sulfide
IV-VI -----	PbS	Lead sulfide
	PbSe	Lead selenide
	PbTe	Lead telluride
Ternary compound	$\text{Al}_x\text{Ga}_{1-x}\text{As}$	Aluminum gallium arsenide
	$\text{Al}_x\text{In}_{1-x}\text{As}$	Aluminum indium arsenide
	$\text{GaAs}_{1-x}\text{P}_x$	Gallium arsenic phosphide
	$\text{Ga}_{1-x}\text{In}_x\text{N}$	Gallium indium nitride
	$\text{Ga}_{1-x}\text{In}_x\text{As}$	Gallium indium arsenide
	$\text{Ga}_{1-x}\text{In}_x\text{P}$	Gallium indium phosphide
Quaternary compound	$\text{Al}_x\text{Ga}_{1-x}\text{As}_y\text{Sb}_{1-y}$	Aluminum gallium arsenic antimonide
	$\text{Ga}_x\text{In}_{1-x}\text{As}_y\text{P}_{1-y}$	Gallium indium arsenic phosphide

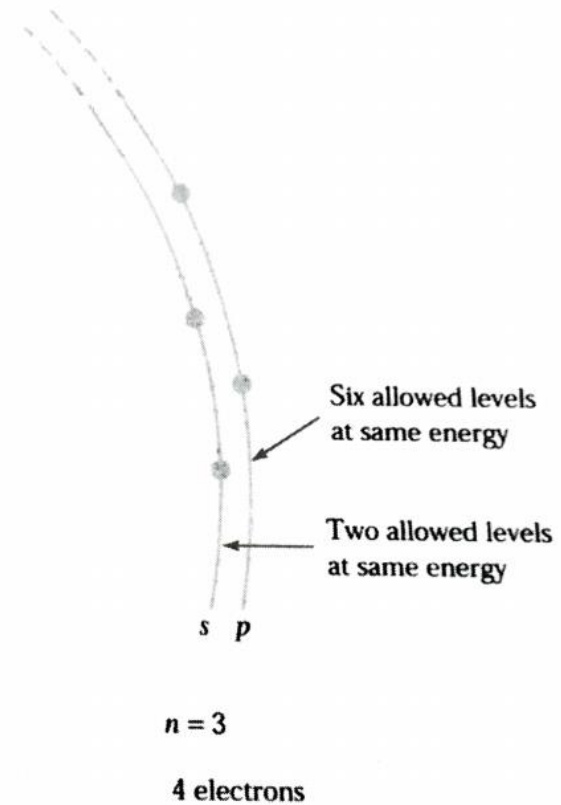
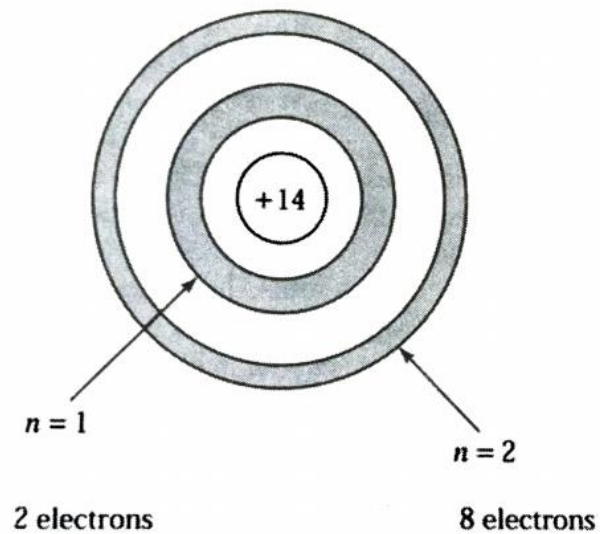
Bond Representation of Intrinsic Silicon



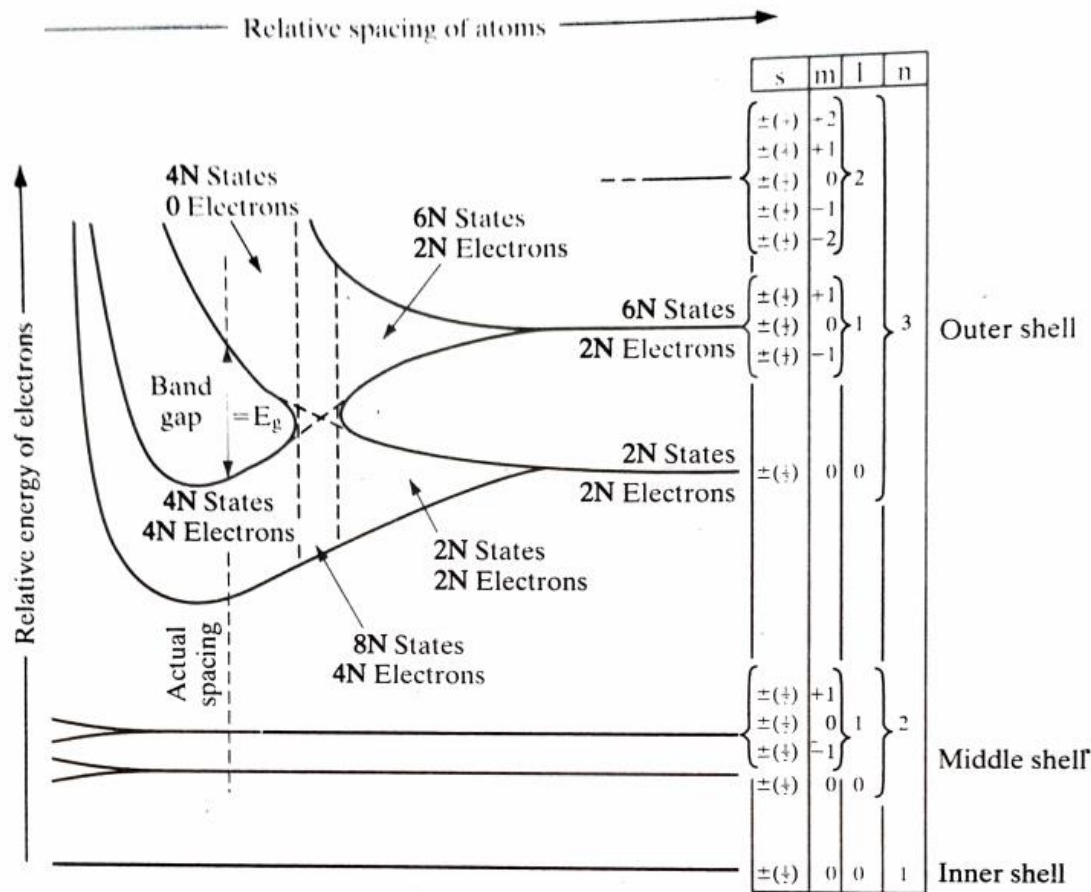
Concepts of Energy Bands

- Bohr's theory predicts that electronic states in an atom are quantized.
- Atoms are characterized by four quantum numbers:
 - (i) principle quantum number; $n = 1, 2, 3 \dots$
 - (ii) angular momentum (orbital) quantum number;
 $l = 0, 1, 2, \dots(n-1)$
 - (iii) magnetic quantum number; $m = -l, \dots -1, 0, +1, \dots +l$
 - (iv) electron spin quantum number; $s = -1/2, +1/2$.
- Pauli exclusion principle (a quantum mechanical principle) states that two or more identical electrons cannot occupy the same quantum state within a quantum system simultaneously.

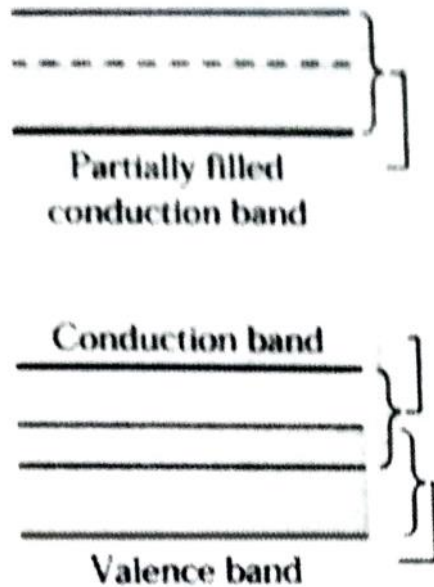
Isolated Silicon Atom



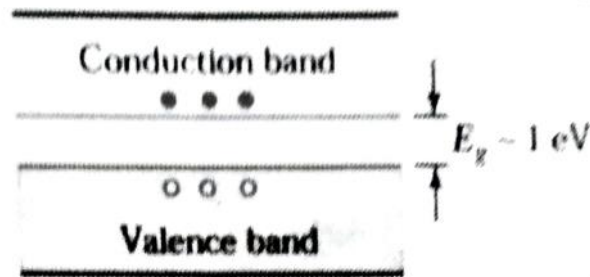
Energy Levels in Silicon as a Function of Interatomic Spacing



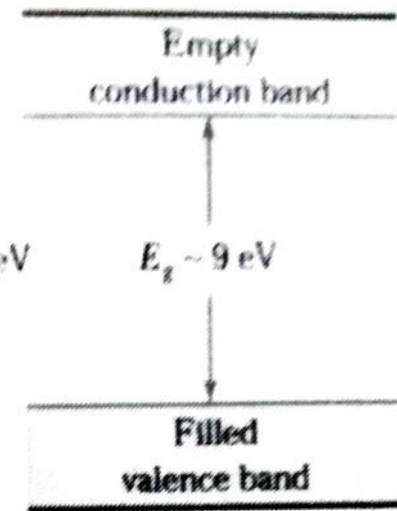
Metal, Insulator and Semiconductor



(a)



(b)

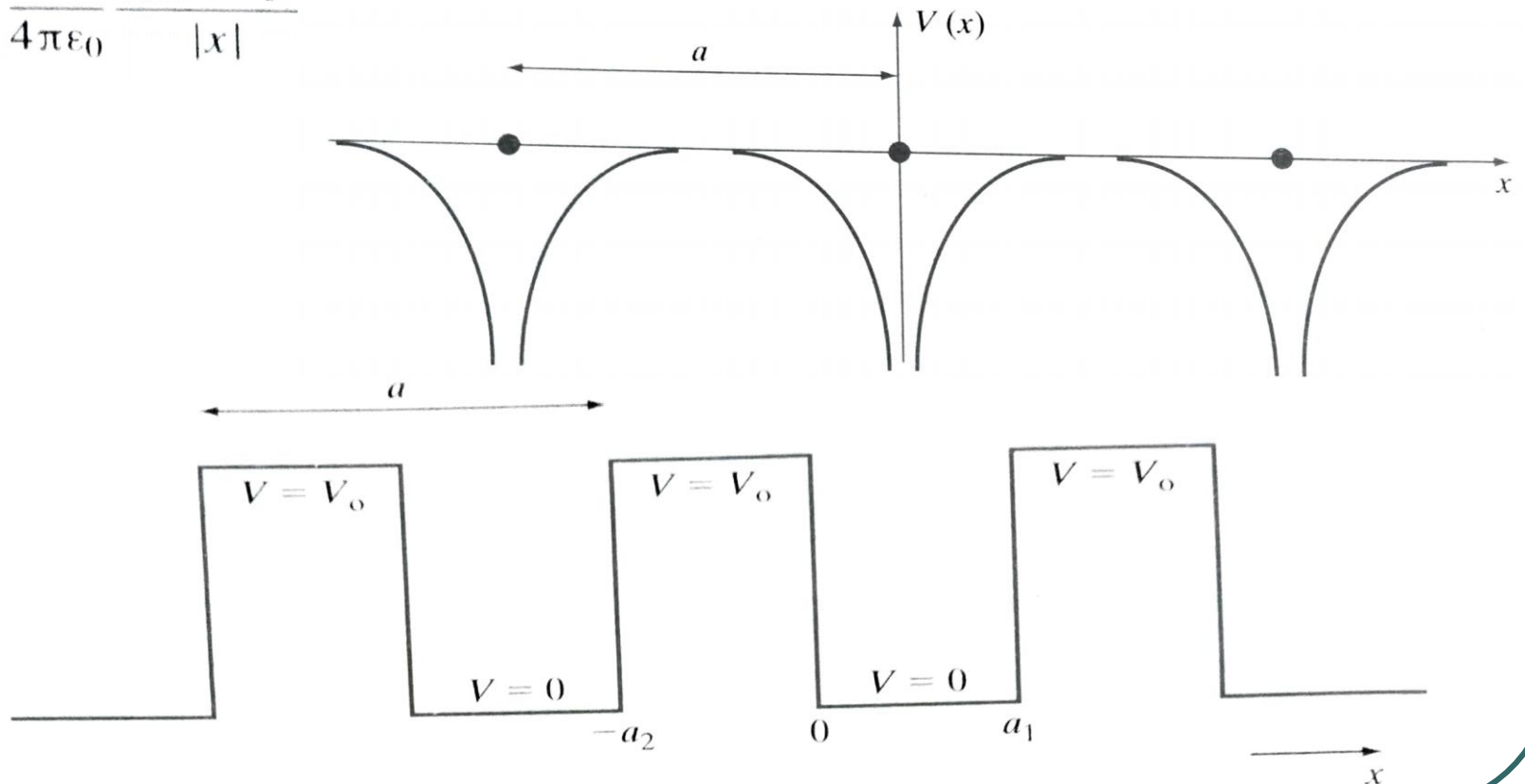


(c)

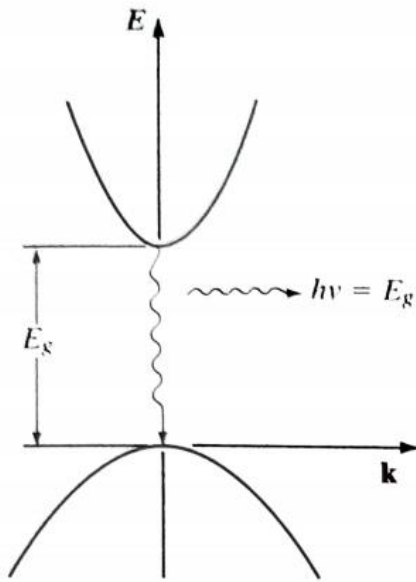
Valence and Conduction Band for (a) Metal, (b) Semiconductor, and (c) Insulator

Periodic Potential and Kronig-Penney Model

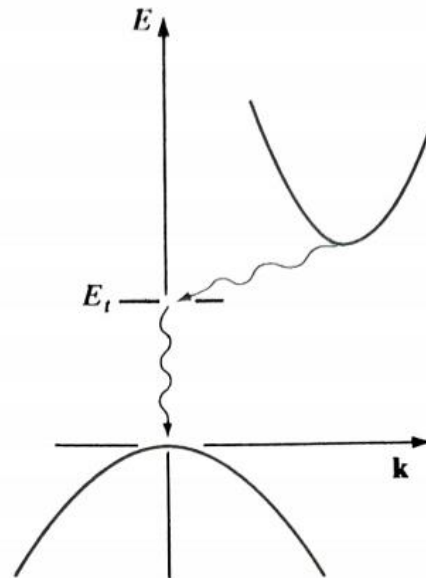
$$V(x) = \frac{1}{4\pi\epsilon_0} \frac{(q_e)(-q_e)}{|x|}$$



Direct and Indirect Bandgap

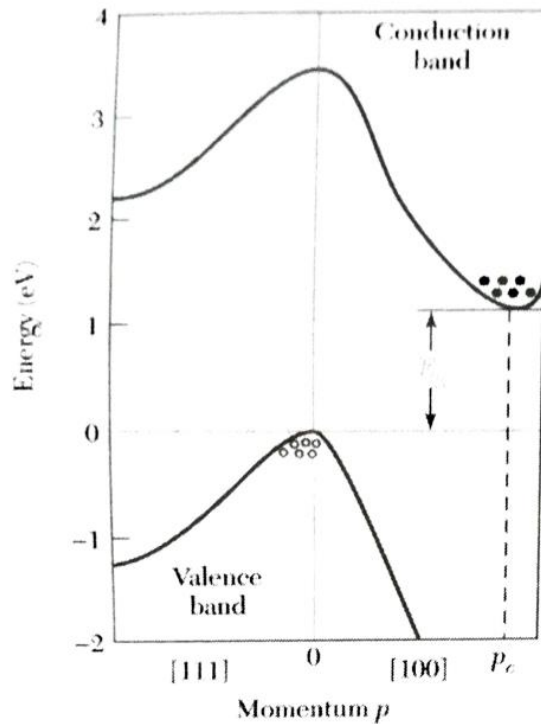


(a) Direct

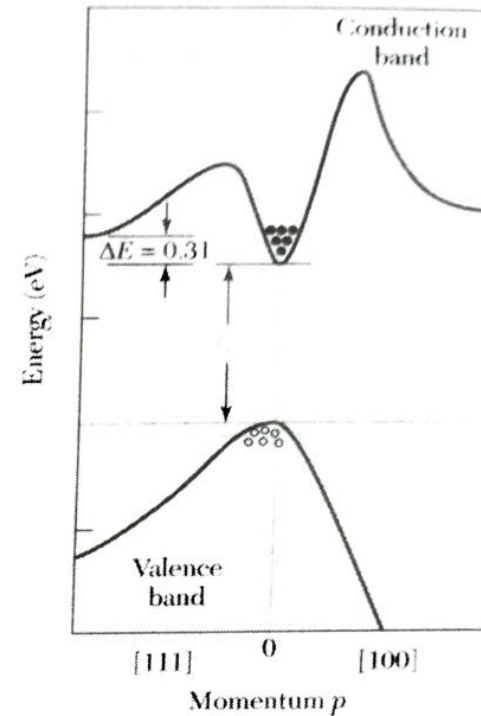


(b) Indirect

E-k Diagram for Si and GaAs



(a)



(b)

(a) Silicon and (b) GaAs

Effective Mass

Electrons in a crystal are not completely free, but instead interact with the periodic potential of the lattice. As a result, their “wave-particle” motion cannot be expected to be the same as that for electrons in free space. Thus, in applying the usual equations of electrodynamics to charge carriers in solids, we must use altered values of particle mass. In doing so, we account for most of the influences of the lattice, so that the electrons and holes can be treated as free particles “almost free” carriers in most computations.

Effective Mass

For a free electron, $\vec{p} = \hbar \vec{k} = m \vec{v}$

$$E = \frac{1}{2} m \vec{v}^2 = \frac{\vec{p}^2}{2m} = \frac{\hbar^2 \vec{k}^2}{2m}$$

$$\Rightarrow \frac{dE}{d\vec{k}} = \frac{\hbar^2 \vec{k}}{m}$$

$$\Rightarrow \frac{d^2E}{d\vec{k}^2} = \frac{\hbar^2}{m} \Rightarrow m = \frac{\hbar^2}{d^2E/d\vec{k}^2}$$

The effective mass of an electron in a band with a given (E, \vec{k}) relationship is

$$m^* = \frac{\hbar^2}{d^2E/d\vec{k}^2}$$

Effective Mass

At the bottom of the conduction band $\frac{d^2E}{dk^2}$ is positive
But at the top of the valence band $\frac{d^2E}{dk^2}$ is negative

$\therefore m^*$ is negative at the (or near the) top of the valence band.

Thus, valence band electrons with negative mass and negative charge move in an electric field in the same direction as holes with positive mass and positive charge.

\therefore charge transport in the valence band can be fully accounted for by considering hole motion.

	Ge	Si	GaAs
m_n^*	$0.55m_0$	$1.1m_0$	$0.067m_0$
m_p^*	$0.37m_0$	$0.56m_0$	$0.48m_0$

Density of States

$$* N_c(E) = \frac{4\pi}{h^3} (2m_n^*)^{3/2} (E - E_c)^{1/2} \quad \text{for } E > E_c$$

$$* N_v(E) = \frac{4\pi}{h^3} (2m_p^*)^{3/2} (E_v - E)^{1/2} \quad \text{for } E < E_v$$

* $N(E)dE$ is the density of states per unit volume between energy E and $E+dE$.

Occupation Probability: Fermi Dirac Distribution & Fermi Level

* Fermi-Dirac distribution function $f(E)$ gives the probability that an available energy state at E will be occupied by an electron at temperature T .

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

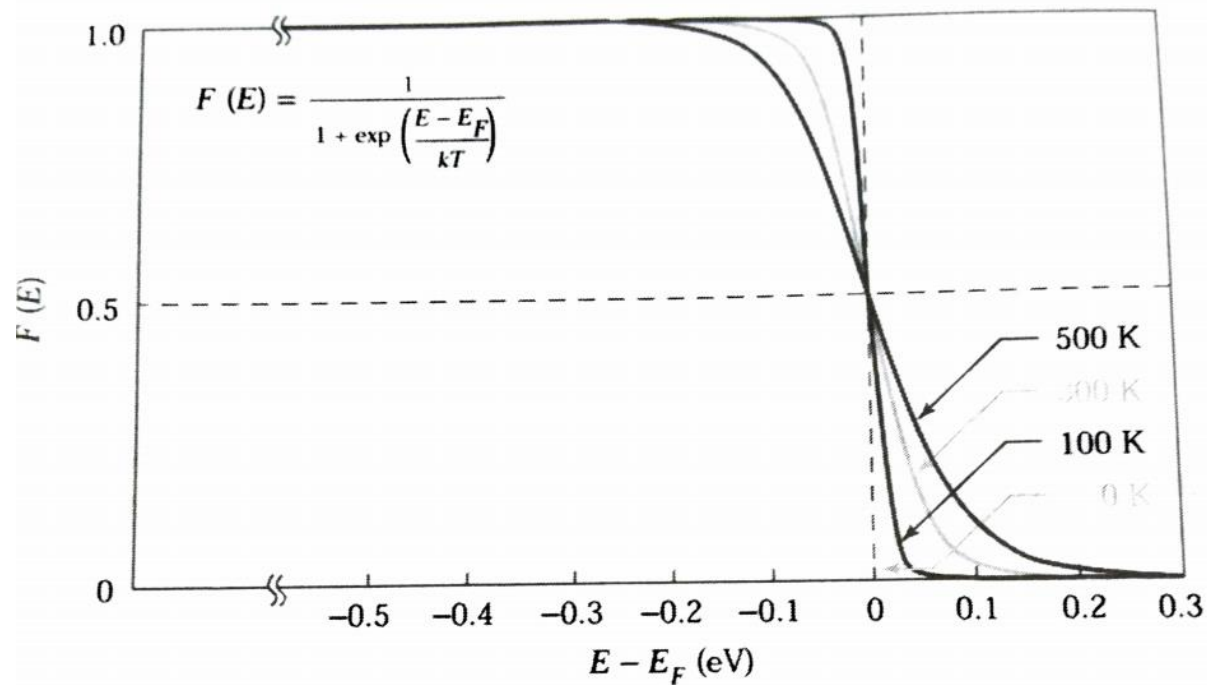
* Properties of $f(E)$:

$$\rightarrow \text{At } T = 0 \text{ \& } E < E_F ; f(E) = \frac{1}{1 + \frac{1}{e^\alpha}} = \frac{1}{1 + 0} = 1$$

$$\rightarrow \text{At } T = 0 \text{ \& } E > E_F ; f(E) = \frac{1}{1 + e^\alpha} = \frac{1}{\infty} = 0$$

$$\rightarrow \text{At } T > 0 \text{ \& } E = E_F ; f(E) = \frac{1}{1 + e^0} = \frac{1}{2}$$

Fermi Dirac Distribution & Fermi Level



Carrier Concentration: Electron

$$n_0 = \int_{E_c}^{\infty} N_c(E) f(E) dE$$

for $E - E_F$ greater than several RT , $f(E) = e^{-(E - E_F)/RT}$

$$\therefore n_0 = \frac{4\pi}{h^3} (2m_n^*)^{3/2} \int_{E_c}^{\infty} (E - E_c)^{1/2} e^{-(E - E_F)/RT} dE.$$

$$= 2 \left(\frac{2\pi m_n^* RT}{h^2} \right)^{3/2} e^{(E_F - E_c)/RT}$$

$$\Rightarrow n_0 = N_c e^{-(E_c - E_F)/RT} \quad \text{where } N_c = 2 \left(\frac{2\pi m_n^* RT}{h^2} \right)^{3/2}$$

& N_c is called effective density of states in the conduction band

Carrier Concentration: Hole

Similarly, $p_0 = \int_{-\infty}^{E_V} N_V(E) [1 - f(E)] dE$

$$= 2 \left(\frac{2\pi m_p^* RT}{h^2} \right)^{3/2} e^{-(E_F - E_V)/RT}$$

$$= N_V e^{-(E_F - E_V)/RT}$$

where $N_V = 2 \left(\frac{2\pi m_p^* RT}{h^2} \right)^{3/2}$ is the effective density of states in the valence band.

Location of Fermi Level in Intrinsic Semiconductor

Location of E_i :

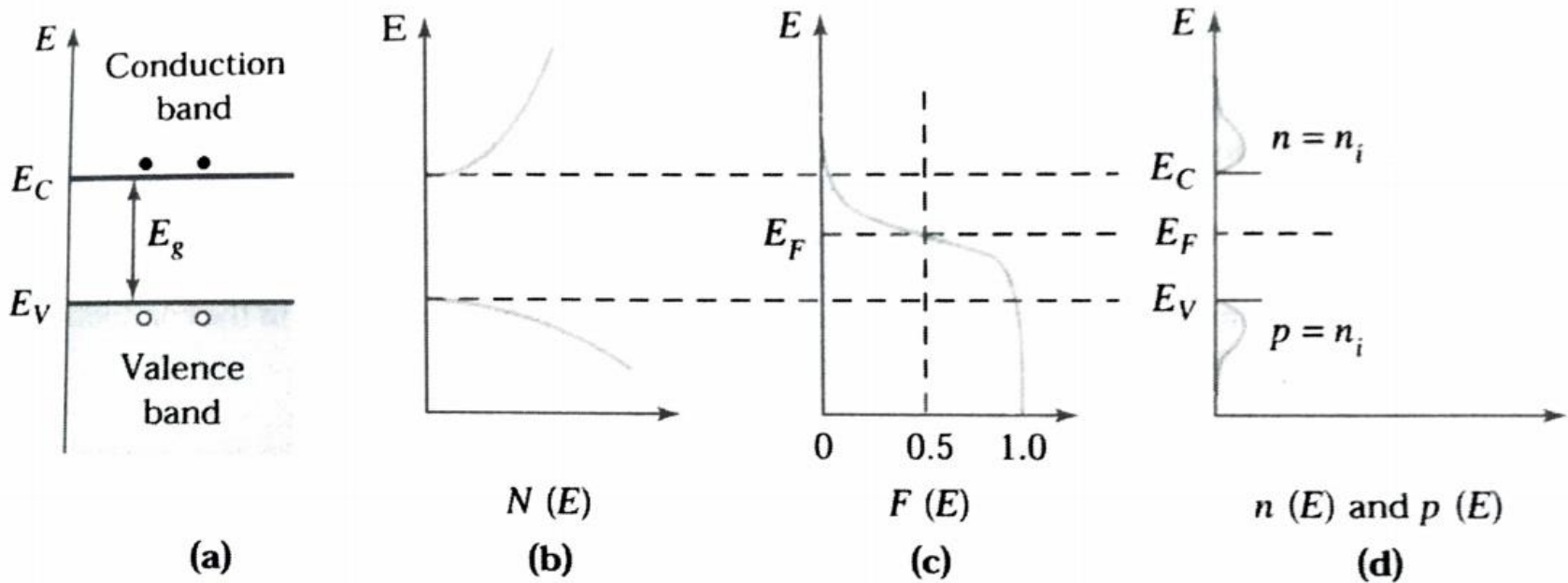
$$n_i = p_i$$

$$\Rightarrow N_c e^{-(E_c - E_F)/RT} = N_v e^{-(E_F - E_v)/RT}$$

$$\Rightarrow E_F = \frac{E_c + E_v}{2} - \frac{RT}{2} \ln \frac{N_c}{N_v}$$

$$= \frac{E_g}{2} - \frac{3RT}{4} \ln \frac{m_n^*}{m_p^*}$$

Carrier Concentration: Intrinsic Semiconductor



Law of Mass Action

$$n_0 = N_c e^{-(E_c - E_F)/kT} \quad \& \quad p_0 = N_v e^{-(E_F - E_v)/kT}$$

$$\therefore n_0 p_0 = N_c N_v e^{-(E_c - E_v)/kT} = N_c N_v e^{-E_g/kT}$$

For intrinsic material, $E_F = E_i$ & $n_i = p_i$

$$\therefore n_i = N_c e^{-(E_c - E_i)/kT} \quad \& \quad p_i = N_v e^{-(E_i - E_v)/kT}$$

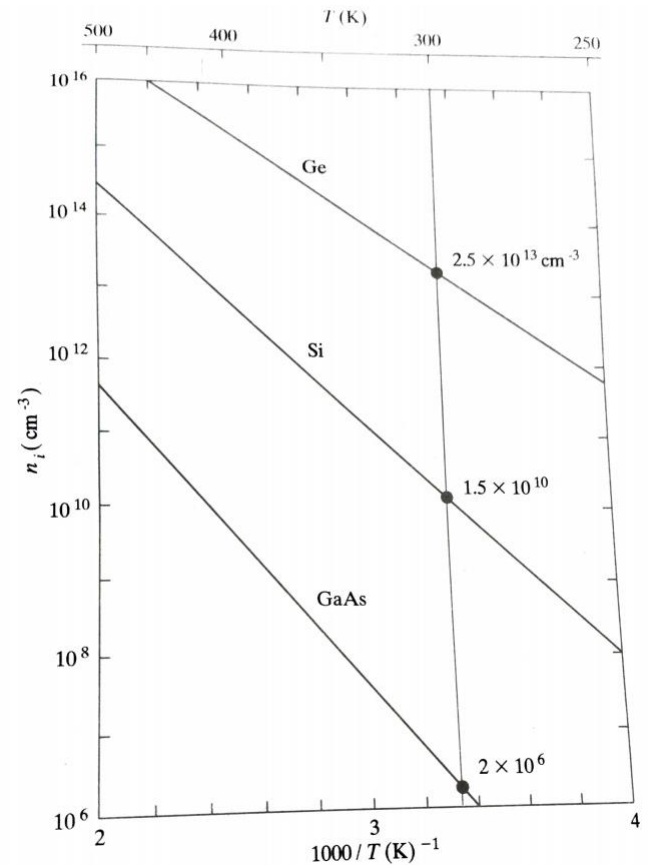
$$\therefore n_i p_i = n_i^2 = N_c N_v e^{-E_g/kT} = n_0 p_0$$

Intrinsic carrier Concentration

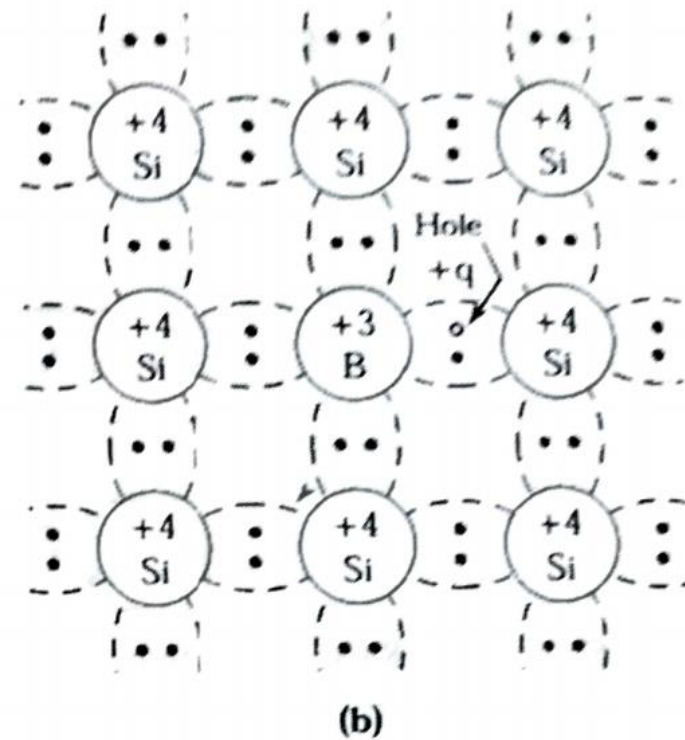
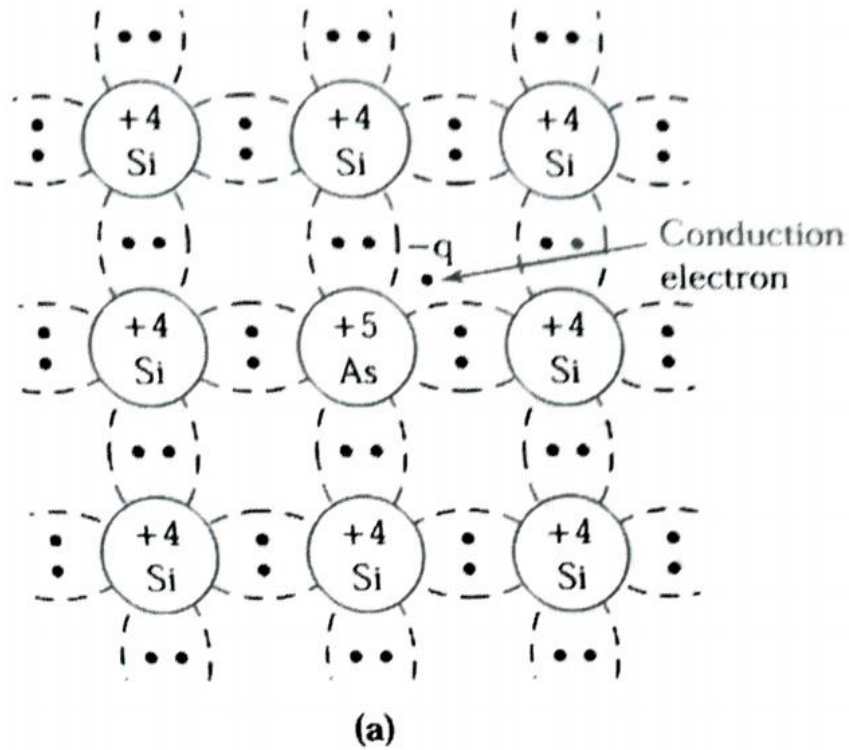
$$n_i p_i = n_i^2 = N_c N_v e^{-E_g/kT} = n_o p_o$$

$$n_i^2 = 2 \left(\frac{2\pi kT}{h^2} \right)^{3/2} (m_n^* m_p^*)^{3/4} e^{-E_g/2kT}$$

$$E_g = E_{g0} - \beta T ; E_{g0} \text{ is } E_g \text{ at } T = 0^\circ K$$

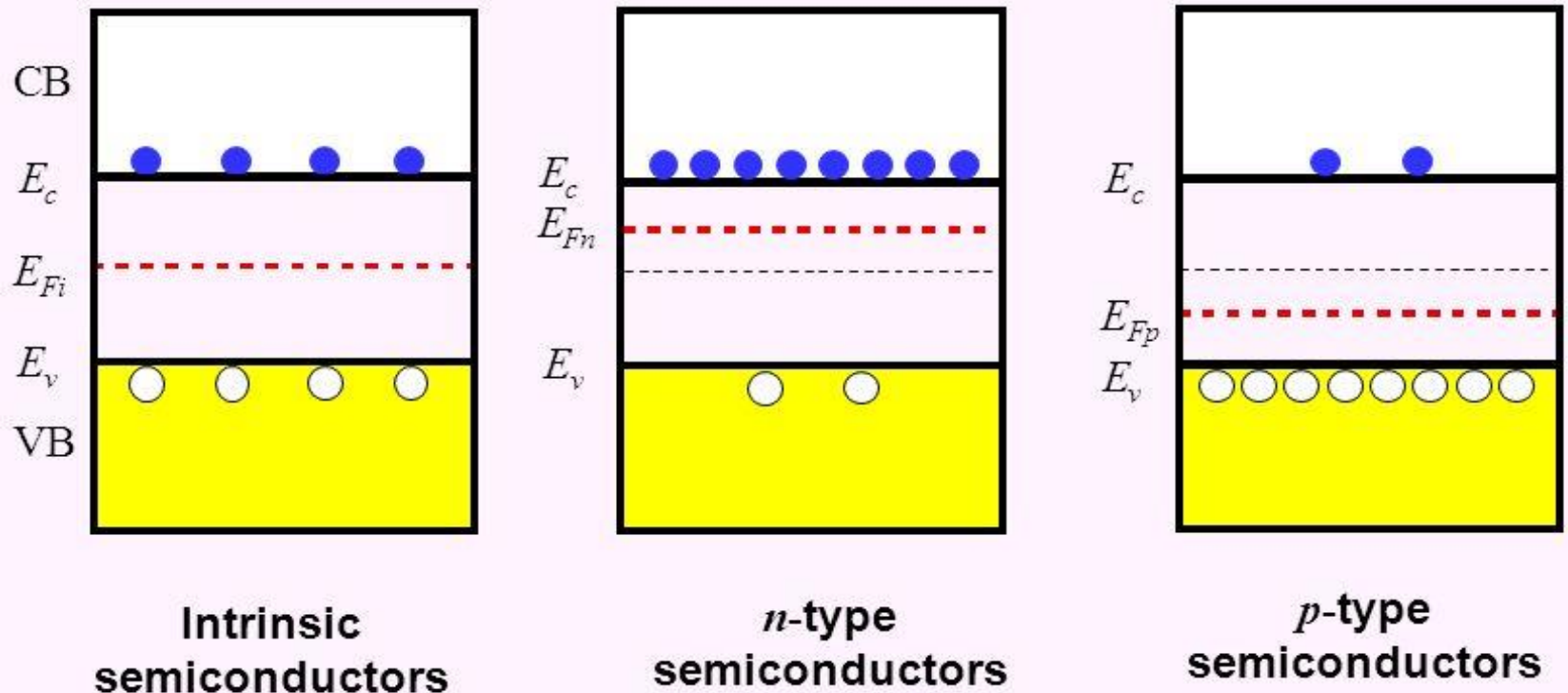


Impurity Doping



Intrinsic, n-Type, p-Type Semiconductors

□ Energy band diagrams



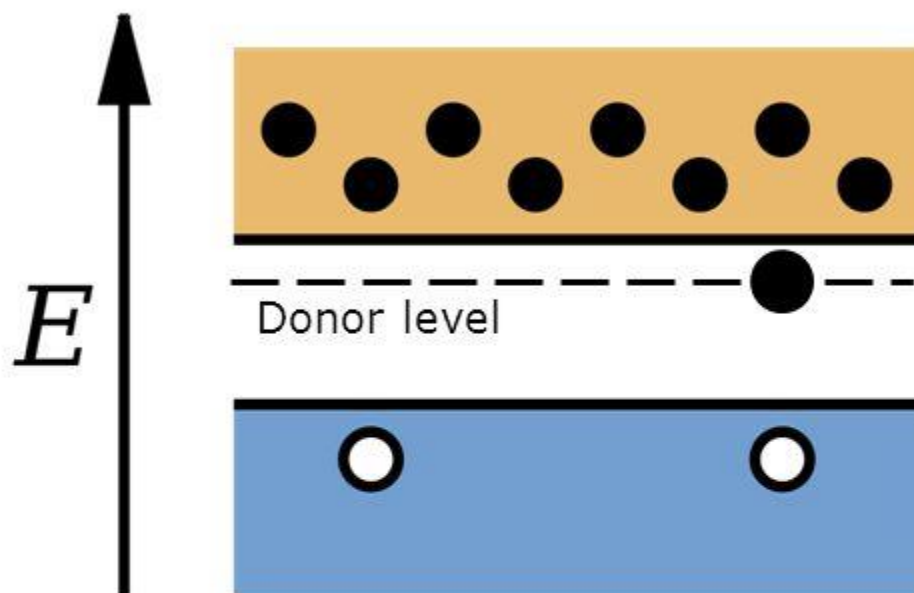
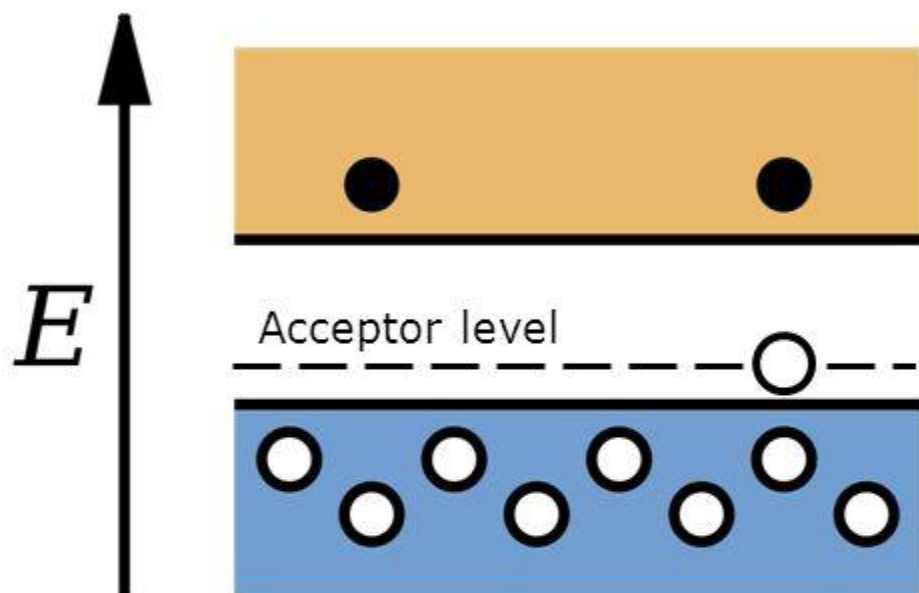
- In all cases, $np = n_i^2$
- Note that donor and acceptor energy levels are not shown.



Extrinsic Semiconductors

p -type band structures :

n -type band structures :



Group IV semiconductors:

Si and Ge

Acceptors: B and Al

Group IV semiconductors:

Si and Ge

Donors: P and As

Group III-V semiconductors:

GaAs and GaN

Acceptors: Be, Zn, Cd and Ge

Group III-V semiconductors:

GaAs and GaN

Donors: Se, Te, Si and Ge

Carrier Concentration and Doping

Since the semiconductor is charge neutral

$$\rho = -q n_0 + q p_0 - q N_a + q N_d = 0$$

$$\Rightarrow q(p_0 - n_0 + N_d - N_a) = 0$$

$$\Rightarrow n_0^2 - (N_d - N_a)n_0 - n_i^2 = 0 \text{ as } p_0 = \frac{n_i^2}{n_0} \text{ for } N_d > N_a$$

$$\Rightarrow n_0 = \frac{N_d - N_a}{2} + \frac{N_d - N_a}{2} \sqrt{1 + \frac{4n_i^2}{(N_d - N_a)^2}}$$

$$= N_d - N_a \text{ as } N_d - N_a \gg n_i$$

$$= N_d \text{ if } N_a = 0.$$

$$\therefore n_0 = N_d \text{ \& } p_0 = \frac{n_i^2}{N_d}$$

$$\text{For p-type, } p_0 = N_a \text{ \& } n_0 = \frac{n_i^2}{N_a}$$

Carrier Concentration, Fermi Level & Quasi Fermi Level

$$n_0 = N_c e^{-(E_c - E_F)/RT} = N_c e^{-(E_c - E_i)/RT} \cdot e^{(E_F - E_i)/RT} = n_i e^{(E_F - E_i)/RT}$$

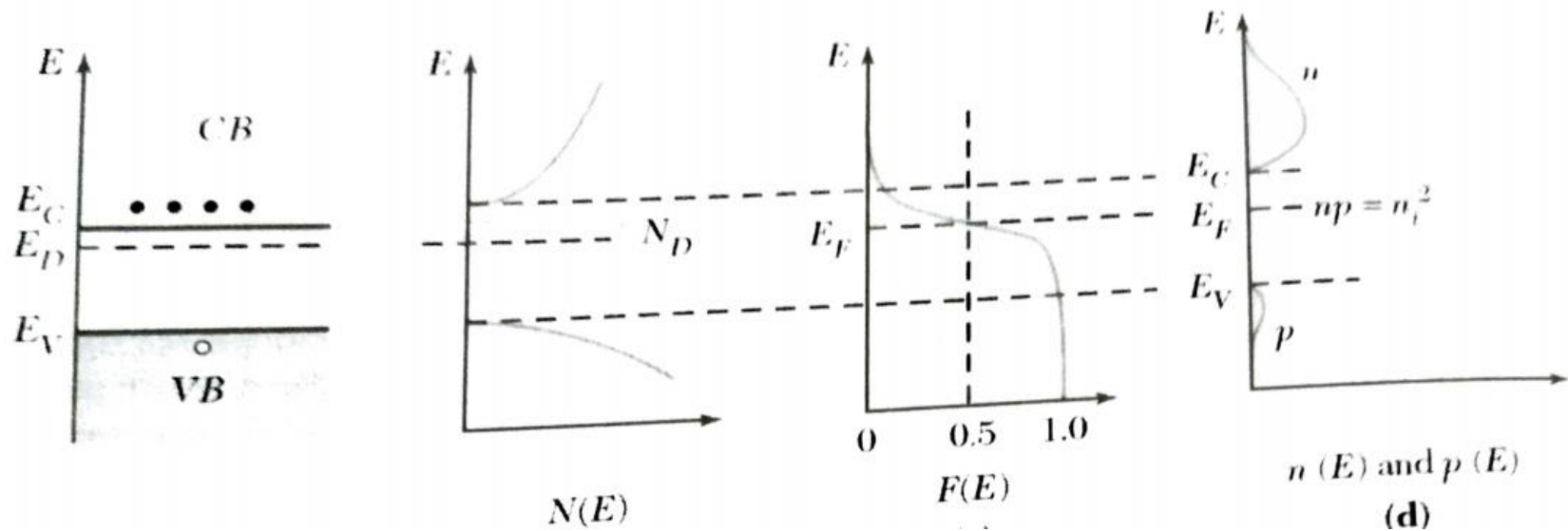
$$p_0 = N_v e^{-(E_F - E_v)/RT} = N_v e^{-(E_i - E_v)/RT} \cdot e^{(E_i - E_F)/RT} = n_i e^{(E_i - E_F)/RT}$$

Quasi Fermi-Level;

$$n = n_i e^{(E_{Fn} - E_i)/kT}$$

$$\text{and } p = n_i e^{(E_i - E_{Fp})/kT}$$

Carrier Concentration and Fermi Level in Extrinsic Semiconductor



Summary of Previous Lecture

Effective mass, $m^* = \frac{\hbar^2}{d^2 E / dk^2}$

Intrinsic carrier concentration, $n_i = 2 \left(\frac{2\pi kT}{h^2} \right)^{3/2} (m_p^* m_n^*)^{3/4} e^{-\frac{E_g}{2kT}}$

Location of E_i ; $E_i = \frac{E_g}{2} - \frac{3kT}{4} \ln \frac{m_n^*}{m_p^*}$

Carrier concentration in doped semiconductor:

P-type: $p_0 = N_A$, $n_0 = \frac{n_i^2}{N_A}$, n-type: $n_0 = N_D$, $p_0 = \frac{n_i^2}{N_D}$

$$n_0 = N_c e^{-(E_c - E_F)/kT} = n_i e^{(E_F - E_i)/kT}$$

$$p_0 = N_v e^{-(E - E_v)/kT} = n_i e^{(E_i - E_F)/kT}$$

Quasi-Fermi Level: $n = n_i e^{(E_{Fn} - E_i)/kT}$ & $p = n_i e^{(E_i - E_{Fp})/kT}$

Degenerate Semiconductor

When $N_D \geq N_c$ or $N_A \geq N_v$,

One cannot use approximation $f(E) = e^{-(E-E_F)/RT}$

$$\therefore n_0 = \int_{E_c}^{\infty} N_c(E) f(E) dE$$

$$\text{or } p_0 = \int_{-\infty}^{E_v} N_v(E) [1 - f(E)] dE$$

is to be evaluated numerically.

For heavily doped n- or p-type semiconductor,

E_F will be above E_c or below E_v .

Such semiconductor is referred to as degenerate semiconductor.

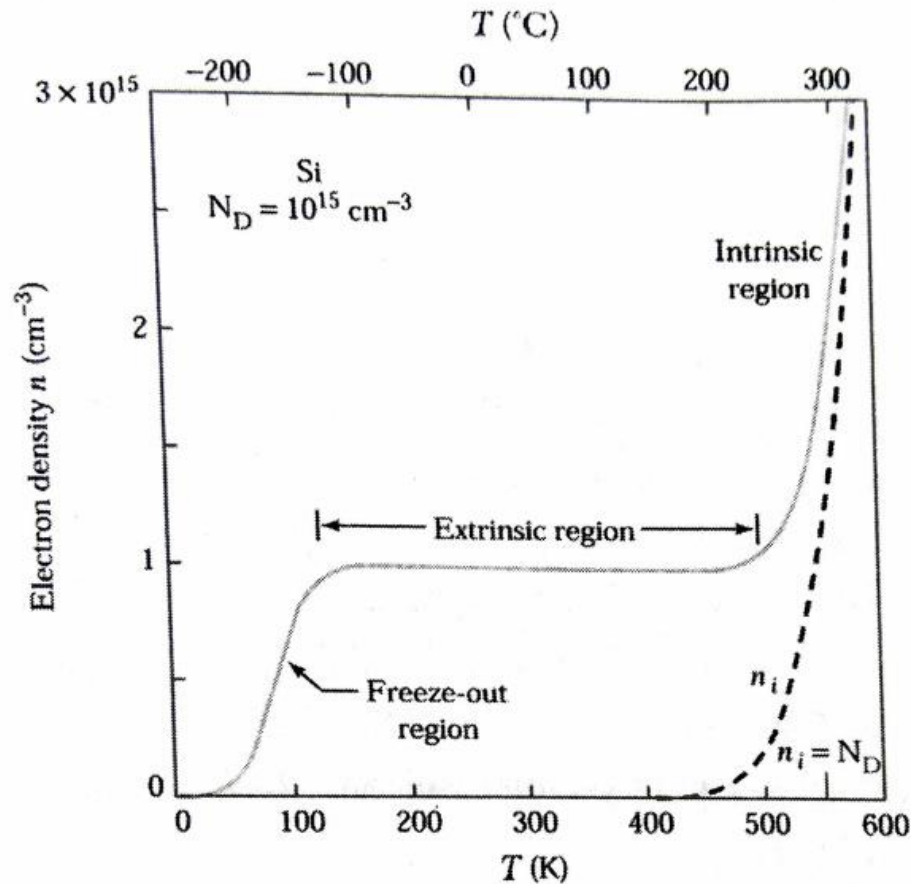
Carrier Density vs. Temperature

At low T : thermal energy is not sufficient to ionize all the donor impurity atoms and therefore $n_0 < N_D$. Also n_0 increases as T increases (Freeze-out or ionization region)

As T increases ; at some temperature, the condition of complete ionization is reached and $n_0 = N_D$.
 n_0 remains constant for a wide range of T .
(Extrinsic region)

As T increases further : a point is reached when $n_i \approx N_D$.
Beyond this point, the semiconductor becomes intrinsic.

Carrier Density vs. Temperature



Thermal Velocity, Mean Free Path & Mean Free Time

Electrons in conduction band or holes in valence band are considered as free particles. The influence of crystal lattice is incorporated in the effective mass.

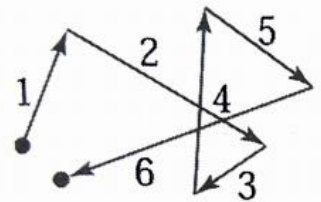
As per theorem for equipartition of energy, average thermal energy is $\frac{1}{2} kT$ per degree of freedom.

$$\therefore \text{K.E. of electron } \frac{1}{2} m_n^* v_{th}^2 = \frac{3}{2} kT$$

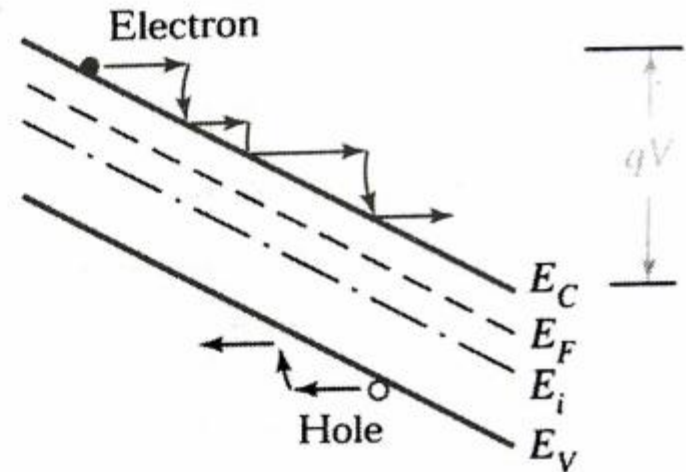
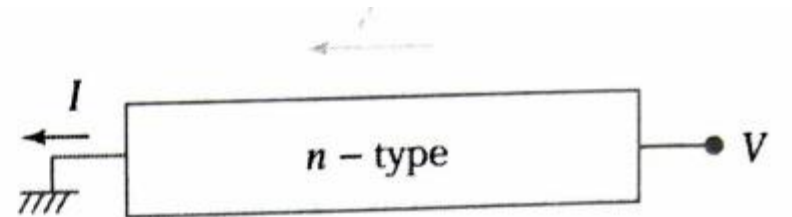
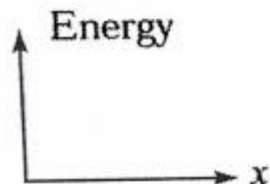
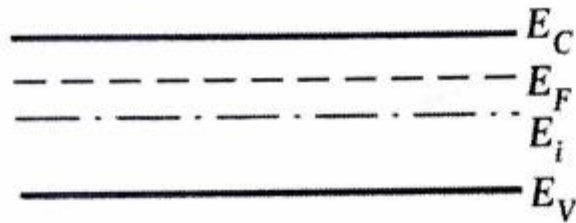
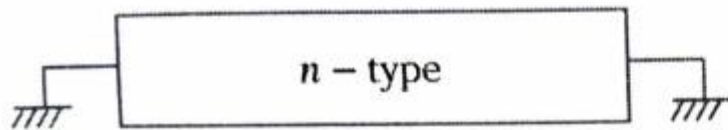
$$\Rightarrow v_{th} = \sqrt{\frac{3kT}{m_n^*}} \sim 10^7 \text{ cm/s for Si \& GaAs}$$

The electron therefore move rapidly in all directions and suffer random scattering from collisions with lattice atoms, impurity ions and other scattering centers resulting in zero net displacement over a sufficiently long period of time.

The average distance between collisions is called ~~free~~ mean free path and the average time between collisions is known as mean free time.



Conduction Process: Drift of Carriers



Drift Velocity and Carrier Mobility

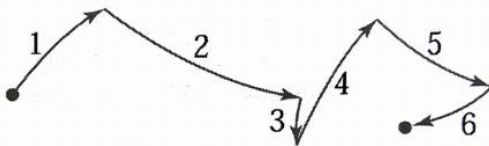
When a small electric field \vec{E} is applied to the semiconductor, electrons will experience a force $-q\vec{E}$ that will accelerate them along the field during the time between collisions. Therefore, an additional velocity component v_d , called drift velocity, will be superimposed upon v_{th} resulting in a net displacement of electrons in the direction opposite to the field.

The momentum (force \times time) applied to an electron during free flight between collisions will be equal to the momentum gain (mass \times velocity) by the electron.

$$\therefore -q\vec{E} \tau_{cn} = m_n^* v_{d,n} ; \tau_c \text{ mean free time of electron}$$

$$\Rightarrow v_{d,n} = - \frac{q\tau_{cn}}{m_n^*} \cdot \vec{E} = -\mu_n \vec{E} \text{ where } \mu_n \equiv \frac{q\tau_{cn}}{m_n^*}$$

$$\text{Similarly, } v_{d,p} = \mu_p \vec{E} ; \mu_p = \frac{q\tau_{cp}}{m_p^*}$$



Carrier Scattering

Mean free time is determined by various scattering mechanisms, such as lattice scattering, impurity scattering, etc.

Lattice scattering results from thermal vibrations of lattice atoms at $T > 0^\circ\text{K}$. Such vibrations disturb the periodic potential of the lattice and allow energy transfer between carriers and lattice. As lattice vibrations increase with temperature, mobility is reduced following $\mu_L \propto T^{-3/2}$.

Impurity scattering results from Coulombic force interaction when a charge carrier travels past an ionized dopant impurity. The probability of such scattering depends on the total concentration of ions. Impurity scattering decreases with increasing temperature as a fast moving carrier is likely to be scattered less than a carrier with less momentum. Hence, $\mu_I \propto T^{3/2}$.

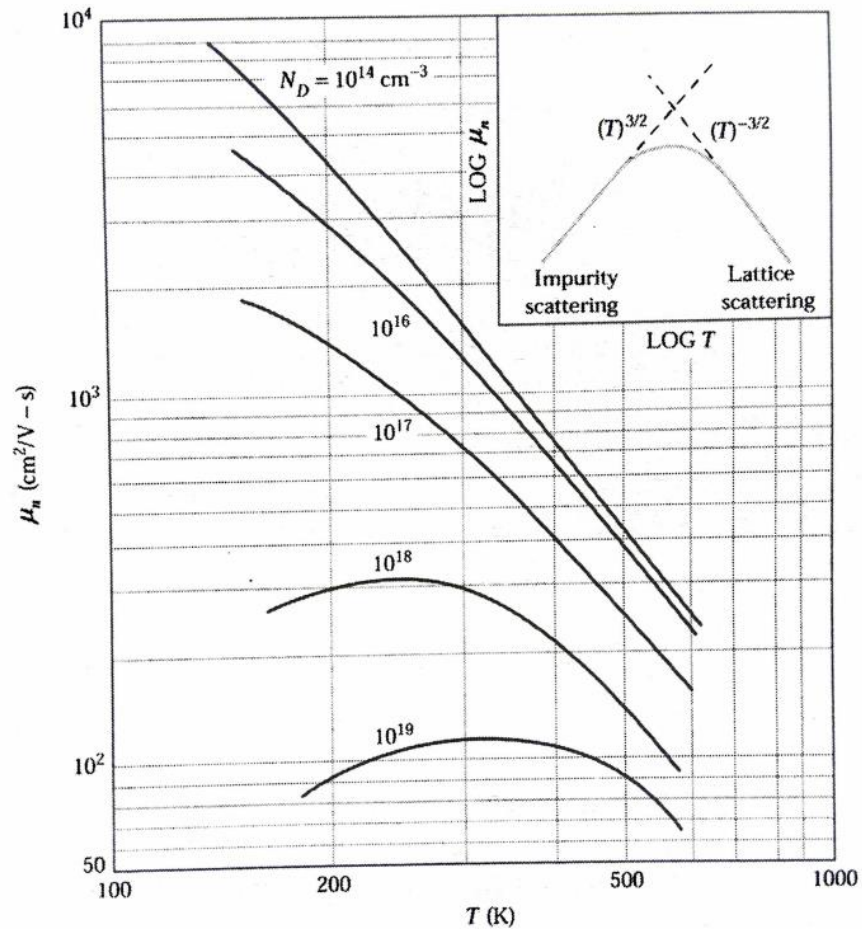
Scattering and Mobility

The number of collisions taking place in unit time, $\frac{1}{\tau_c}$, is the sum of the numbers of collisions due to various scattering mechanisms :

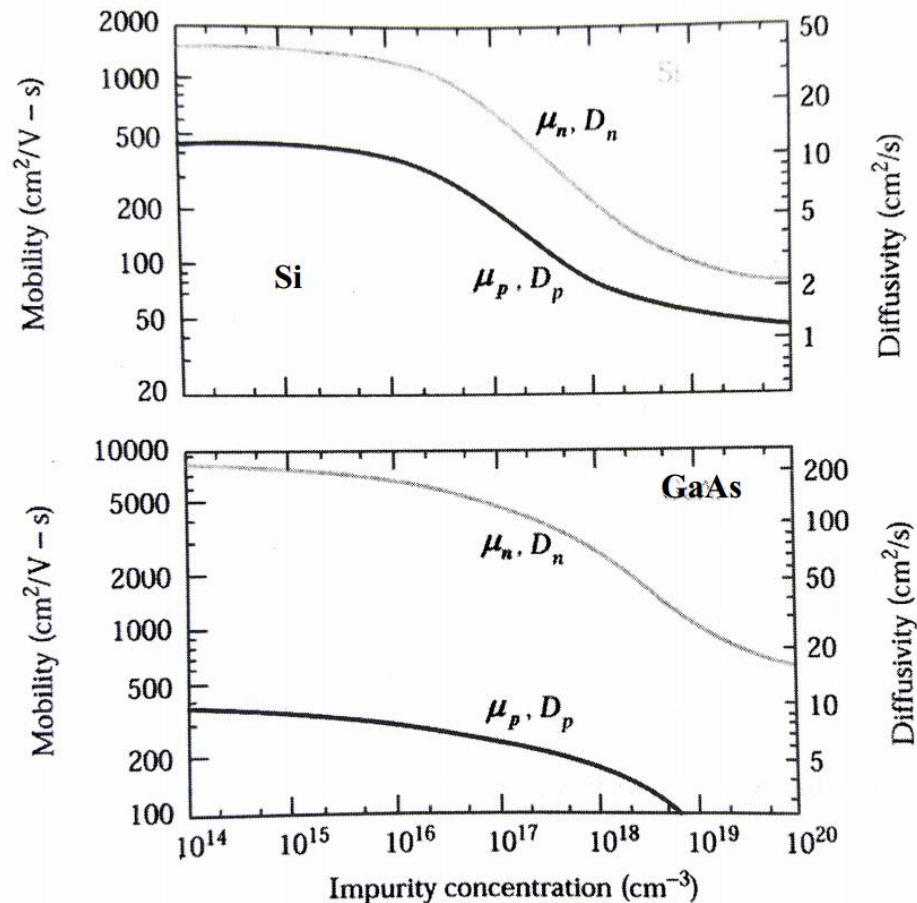
$$\frac{1}{\tau_c} = \frac{1}{\tau_{c, \text{lattice}}} + \frac{1}{\tau_{c, \text{impurity}}}$$

$$\text{or, } \frac{1}{\mu} = \frac{1}{\mu_L} + \frac{1}{\mu_I}$$

Mobility vs. Temperature



Mobility vs. Doping Concentration



Drift Current Density and Resistance

Application of an electric field results in drift current.

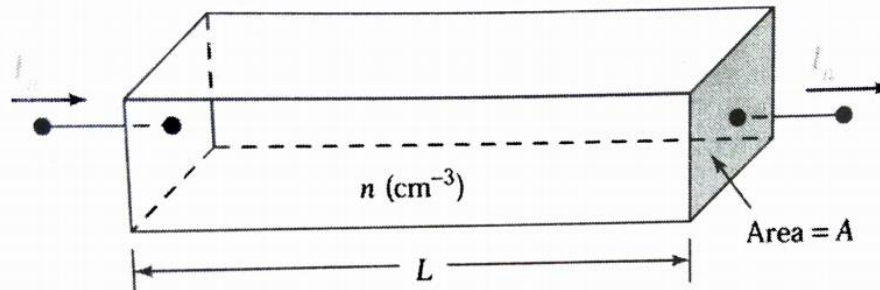
$$J_n = -nq v_{d,n} = nq \mu_n \vec{E}$$

$$J_p = nq \mu_p \vec{E}$$

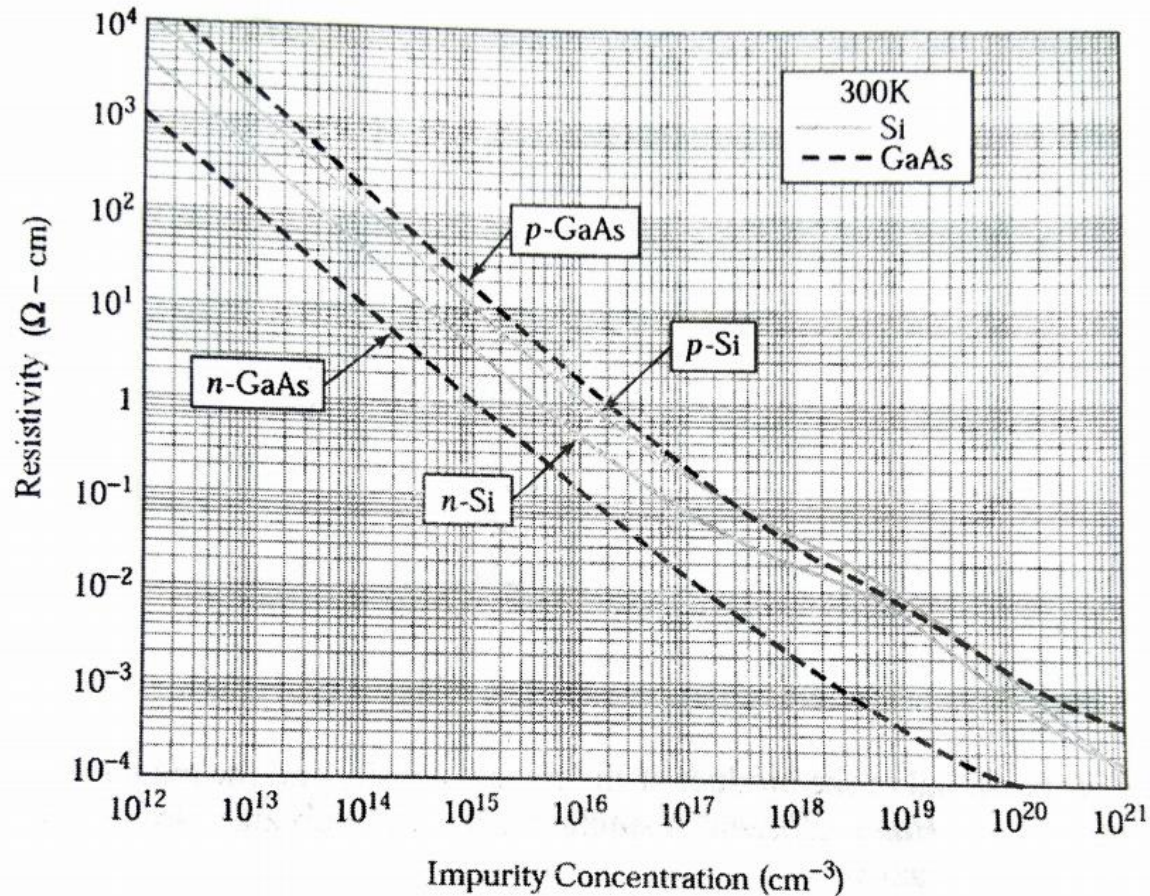
$$\therefore J = J_n + J_p = q(n\mu_n + p\mu_p) \vec{E} = \sigma \vec{E}$$

$$\text{where } \sigma = q(n\mu_n + p\mu_p)$$

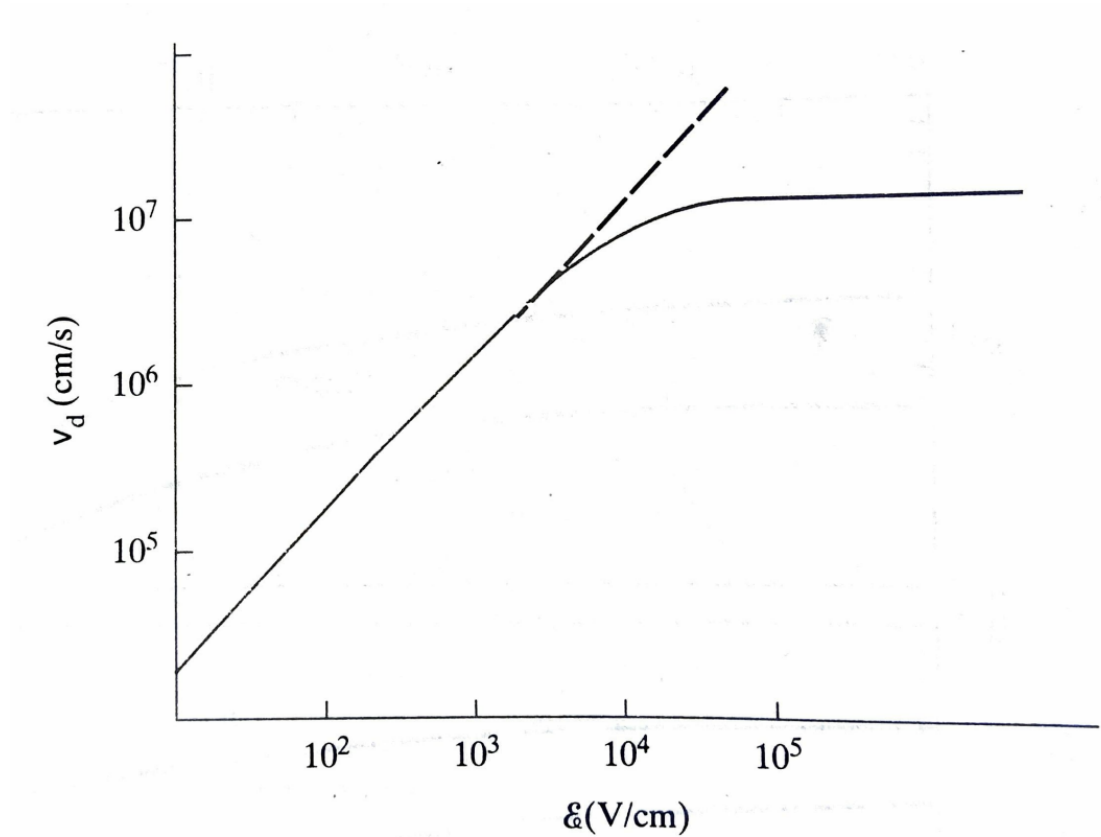
$$\therefore R = \rho \frac{l}{A} = \frac{1}{\sigma} \frac{l}{A}$$



Resistivity vs. Impurity Concentration



High-field Effects



Diffusion of Carriers

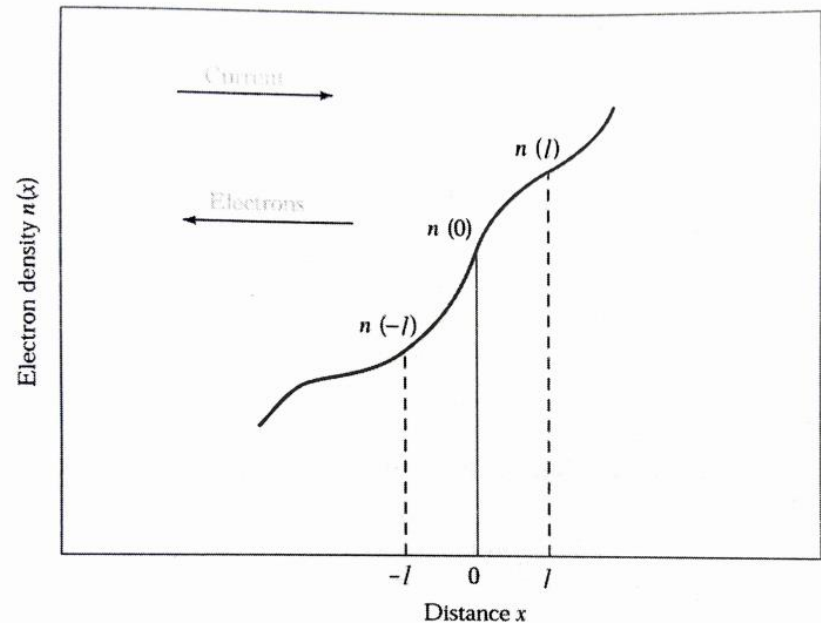
$\frac{1}{2}$ of the electrons at $x = -l$ will move from left to right across the plane $x = 0$ in a free time τ_c . Hence, the average rate of electron flow per unit area across the plane $x = 0$ is then

$$F_1 = \frac{\frac{1}{2} n(-l) \cdot l \cdot l}{\tau_c} = \frac{1}{2} n(-l) \cdot v_{th}$$

$$\left(\text{as } \frac{l}{v_{th}} = \tau_c \Rightarrow v_{th} = \frac{l}{\tau_c} \right)$$

Similarly, av. rate of electron flow per unit area of electrons at $x = l$ crossing the plane $x = 0$ is

$$F_2 = \frac{1}{2} n(l) \cdot v_{th}$$



Diffusion of Carriers (Contd.)

∴ Net rate of electron flow from left to right is

$$F = F_1 - F_2 = \frac{1}{2} v_{th} [n(-l) - n(l)]$$

Approximating the densities at $x = \pm l$ by the 1st two terms of Taylor series expansion, one obtains

$$F = \frac{1}{2} v_{th} \left\{ \left[n(0) - l \frac{dn}{dx} \right] - \left[n(0) + l \frac{dn}{dx} \right] \right\}$$
$$= -v_{th} l \frac{dn}{dx} = -D_n \frac{dn}{dx}$$

where $D_n \equiv v_{th} \cdot l$ is called the diffusion coefficient or diffusivity.

$$\text{Hence, } J_{n, \text{diffusion}} = -qF = qD_n \frac{dn}{dx}$$

$$\text{Similarly, } J_{p, \text{diffusion}} = -qD_p \frac{dp}{dx}$$

Current Equations

$$J_n = q\mu_n n \vec{E} + qD_n \frac{dn}{dx}$$

$$J_p = q\mu_p p \vec{E} - qD_p \frac{dp}{dx}$$

$$\text{and } J = J_p + J_n$$

Einstein Relation

$$v_{th} = \sqrt{\frac{3kT}{m^*}} \quad , \quad \mu = \frac{q\tau_c}{m^*} \quad , \quad D = \frac{1}{3} v_{th} l$$

$$\text{Also } l = v_{th} \cdot \tau_c \Rightarrow v_{th} = \frac{l}{\tau_c}$$

$$\therefore \frac{D}{\mu} = \frac{\frac{1}{3} v_{th} l}{\frac{q\tau_c}{m^*}} = \frac{1}{3} v_{th} l \times \frac{m^*}{q\tau_c} = \frac{1}{3} v_{th}^2 \cdot \frac{m^*}{q}$$

$$\Rightarrow \frac{D}{\mu} = \frac{1}{3} \cdot \frac{3kT}{m^*} \cdot \frac{m^*}{q} = \frac{kT}{q}$$

$$\boxed{\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = \frac{kT}{q}}$$

Generation and Recombination of Carriers

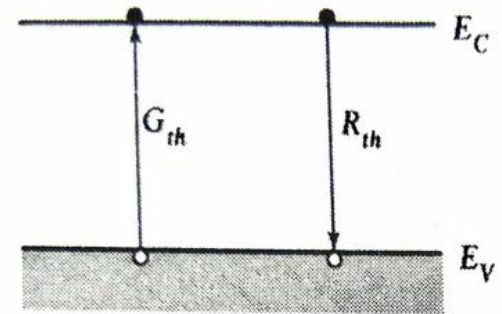
In a semiconductor in thermal equilibrium, $p_0 n_0 = n_i^2$. When excess carriers are introduced (called carrier injection), equilibrium condition is disturbed i.e., $pn \neq n_i^2$. Mechanism that restores the system to equilibrium ($pn = n_i^2$) is recombination of excess minority carriers with majority carriers. In a direct band gap semiconductor, direct band to band recombination dominates and the energy released from the recombination process can be emitted as a photon. The process is called radiative recombination. Indirect recombination via band gap recombination centers dominates in an indirect band gap semiconductor and the energy released is dissipated as heat to the lattice. This process is called non-radiative recombination.

Direct Recombination

Thermal energy enables a valence band electron to make an upward transition, called generation process. Similarly, when an electron makes a transition from downward, the process is called recombination.

In thermal equilibrium, recombination rate, $R_{th} \propto n_0 p_0 \Rightarrow R_{th} = C n_i^2$, C is proportionality const.

Also, in equilibrium, generation rate $G_{th} = R_{th}$
i.e., $G_{th} = C n_i^2$.



Minority Carrier Lifetime

Let us assume that at $t=0$, EHP's are created by a short pulse of light and initial excess electron and hole concentrations are equal, i.e., $\Delta n = \Delta p$. Consider that $\delta n(t)$ and $\delta p(t)$ are excess e^- & h^+ concentrations at $t = t > 0$.

$$\begin{aligned}\therefore \frac{dn(t)}{dt} &= G - R = C n_i^2 - C [(n_0 + \delta n(t))(p_0 + \delta p(t))] \\ &= \cancel{C n_i^2} = C n_i^2 - C [n_0 \delta p(t) + p_0 \delta n(t) + \delta n(t) \delta p(t)]\end{aligned}$$

For low level injection, $\delta n(t) \delta p(t)$ can be neglected.

Minority Carrier Lifetime (Contd.)

$$\therefore \frac{dn(t)}{dt} = \frac{d\delta n(t)}{dt} = -c n_0 \delta p(t) - c p_0 \delta n(t)$$

For p-type material $n_0 \delta p(t) \ll p_0 \delta n(t)$

$$\therefore \frac{d\delta n(t)}{dt} = -c p_0 \delta n(t)$$

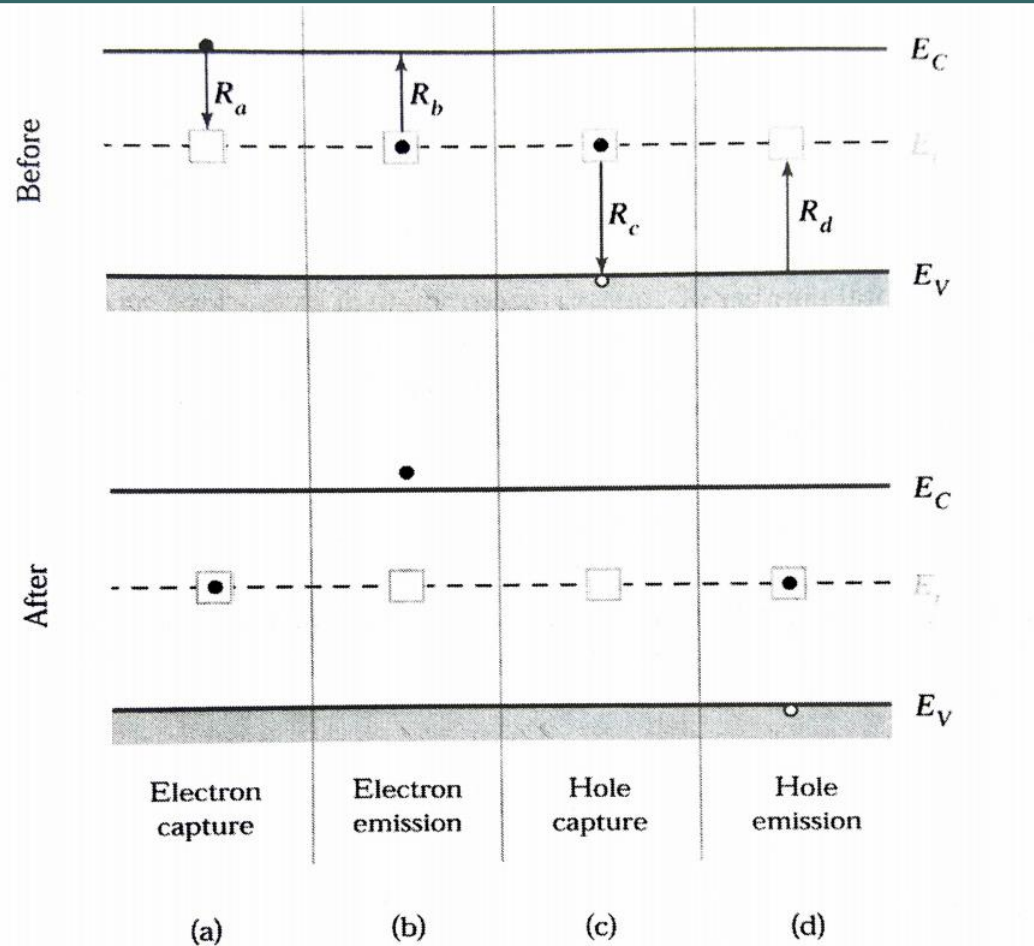
$$\Rightarrow \delta n(t) = \delta n e^{-c p_0 t} = \delta n e^{-t/\tau_n}$$

$\tau_n = \frac{1}{c p_0}$ is recombination lifetime,

Similarly, for n-type material,

$$\delta p(t) = \delta p e^{-t/\tau_p} ; \tau_p = \frac{1}{c n_0}$$

Indirect Recombination



Indirect Recombination

The net recombination rate, $R-G$ is given by

$$R-G = \frac{v_{th} \sigma_p \sigma_n N_t (pn - n_i^2)}{\sigma_p \left[p + n_i e^{\frac{E_i - E_t}{RT}} \right] + \sigma_n \left[n + n_i e^{\frac{E_t - E_i}{RT}} \right]}$$

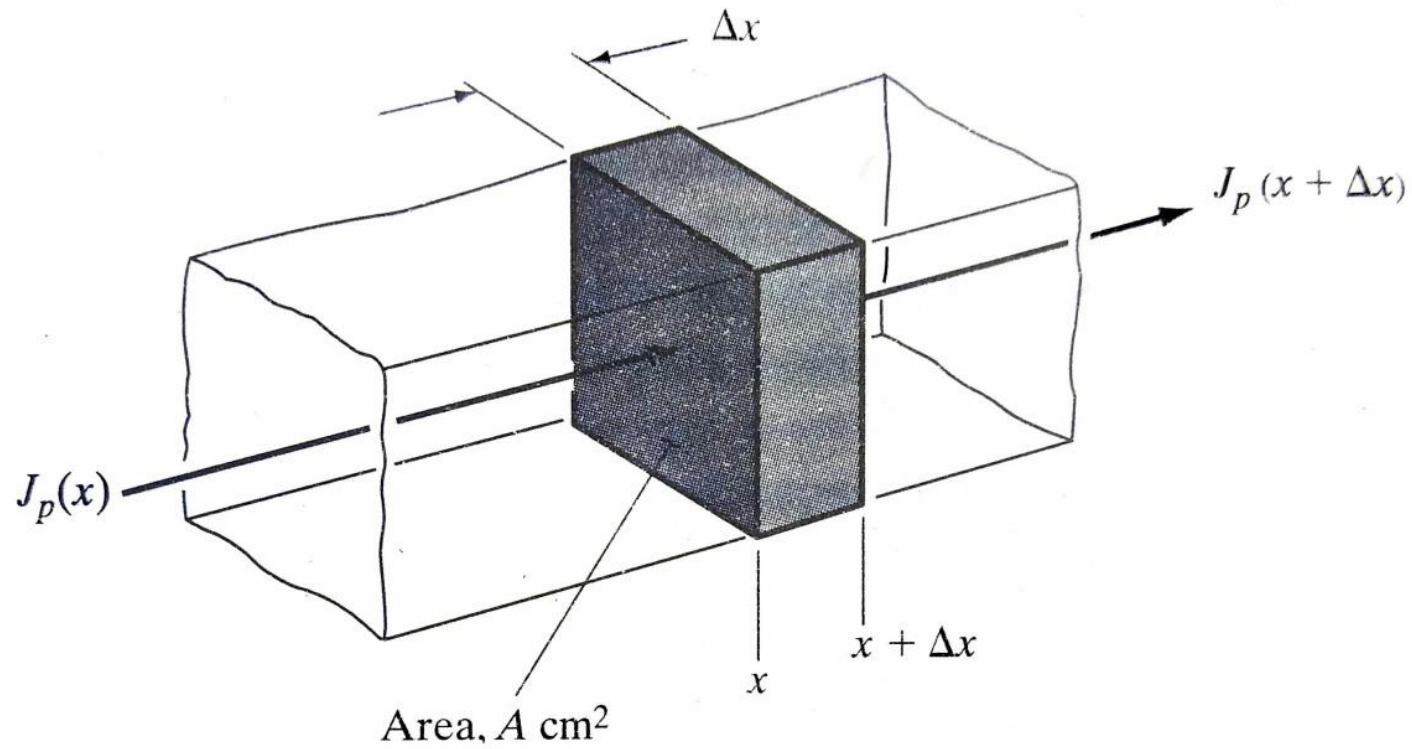
v_{th} is the thermal velocity of carriers

N_t is the concentration of recombination center

σ_n and σ_p denote electron and hole capture cross-section.

σ_n and σ_p describe the effectiveness of the center in capturing an electron and a hole and are measure of how close the electron and hole have to come to the center to be captured.

Continuity Equation



Continuity Equation for Minority Carriers

or
The rate of increase in number of hole in volume $A \Delta x$ is

$$\frac{\partial p(x,t)}{\partial t} \cdot A \Delta x = \frac{J_p(x) A}{q} - \frac{J_p(x+\Delta x) A}{q} + (G - R) A \Delta x$$

$$\text{or, } \frac{\partial p(x,t)}{\partial t} = \frac{1}{q} \frac{J_p(x) - J_p(x+\Delta x)}{\Delta x} + G - R$$

As Δx approaches zero ;

$$\frac{\partial p(x,t)}{\partial t} = -\frac{1}{q} \frac{\partial J_p}{\partial x} - \frac{\delta p}{\tau_p} \text{ in n-type material}$$

Similarly,

$$\frac{\partial n(x,t)}{\partial t} = \frac{1}{q} \frac{\partial J_n}{\partial x} - \frac{\delta n}{\tau_n} \text{ in p-type material}$$

Thank You