EC 201 Electronics Devices and circuits I: PCC 4-0-0 4 credit

Introduction to Semiconductor

Band Theory of solids (Metal, semiconductors, Dielectrics), Energy bands in intrinsic and extrinsic semiconductors, Fermi function, equilibrium carrier concentrations and mas Action law, direct and indirect band-gap semiconductors. Carrier transport: diffusion current, drift current, mobility and resistivity, generation and recombination of carriers, Poisson and continuity equations, Hall Effect and its applications, **Determine the Energy gap using tauc method.**

Junction Formation: Metals-Semiconductor junctions, PN junctions.

Semiconductor Diodes: Band structure of pn junction, current components, Quantitative theory of pn diode, Volt-ampere characteristics and its temperature dependence, Narrow-base diode, Transition and diffusion capacitance of p-n junction diodes, Breakdown of junctions on Reverse Bias, Zener and Avalanche Breakdowns, **Zener Diode**, Tunnel Diode and Its V-I characteristics. The principles of photo diode, photo transistor, LED & LCD,

Application of Diodes: Diode as a rectifier, Half wave and Full wave, Half wave and Full wave with filters, Bridge rectifiers with and without filters, Ripple factor and regulation characteristics, photo diode, photo transistor, LED & LCD, **Photo voltaic cell (solar cell)**.

Junction Transistor: PNP and NPN junction transistors, Characteristics of the current flow across the base regions, Minority and majority carrier profiles, Transistor as a device in CB, CE and CC configurations, and their characteristics, Ebers-Moll Model of BJT.

Transistor Biasing: The Operating Point, DC & AC Load Lines, Fixed Bias and Problems, Collector Feedback Bias, Emitter Feed Back Bias, Self-Bias and Problems, Stabilization, Various Stabilization Circuits, Thermal Runaway and Thermal Stability.

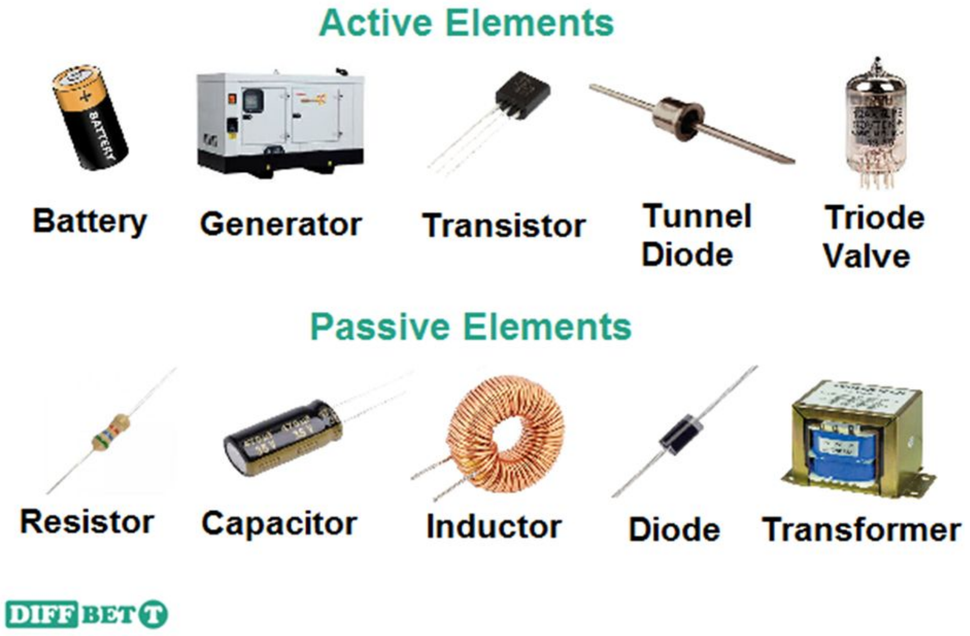
Field Effect Transistors: JFET and its characteristics, Pinch off voltage and drain saturation current, **MOS Capacitor**, MOSFET: enhancement, depletion modes, Biasing of FETs, **CV characteristics, Thin Film Transistors (TFTS), FINFET, vacuum transistors (latest technology currently used in semiconductor industry).**

Small Signal Low Frequency Transistor Amplifier Circuits: Transistor hybrid model, Analysis of transistor amplifier circuits using ‘h’ parameters, Conversion formulae for the parameters of the three configurations, Analysis of single stage transistor amplifier circuits, RC coupled amplifier. Effect of bypass and coupling capacitors on the low frequency response of the amplifier, Emitter follower amplifier, FET amplifiers - low frequency and high frequency models, Amplifier configurations, Low and high frequency response of amplifier circuits, Analysis of single stage FET amplifier circuits.

Active and Passive components

Active components are parts of a circuit that rely on an external power source to control or modify electrical signals. Active components such as transistors and silicon-controlled rectifiers (SCRs) use electricity to control electricity.

Passive components like resistors, transformers, and diodes don’t need an external power source to function. These components use some other property to control the electrical signal.



ACTIVE AND PASSIVE COMPONENTS

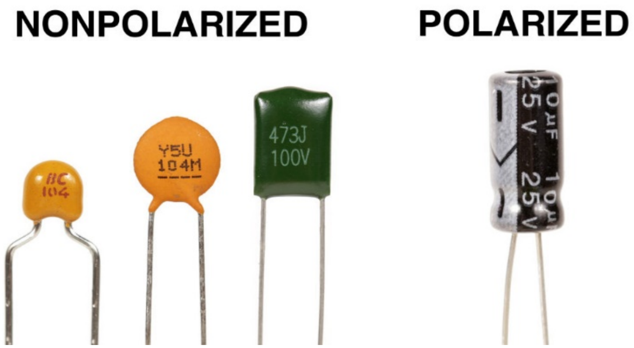
Electronic systems are built around analog and digital components. They comprise resistors, capacitors, diodes, inductor, operational amplifiers and transistors.

ACTIVE			PASSIVE		
Transistor			Resistor		
Diode			LDR		
LED			Thermistor		
Photodiode			Capacitor		
Integrated Circuit		-	Inductor		
Operational Amplifier			Switch		
Seven Segment Display			Variable Resistor		
Battery			Transformer		

Active and Passive components are present almost in every electronic circuit. They are required to build efficient electronic products that meet the real time and user friendly applications.

Passive components

Passive components are electronic components that do not require a source of energy to perform their functions.

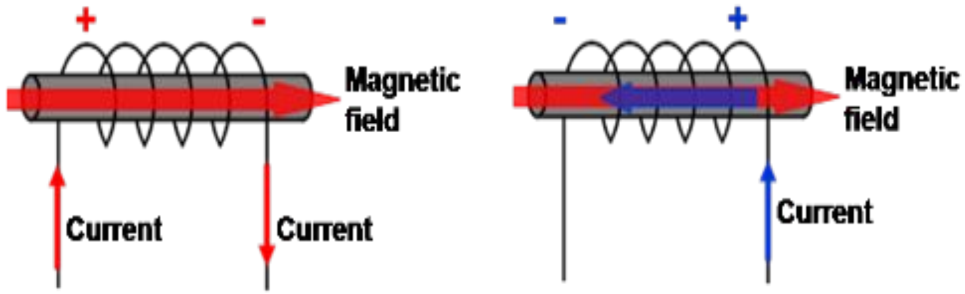
Resistors	Capacitors	Inductors
• They resist the flow of electric current. • The resistance is measured in **Ohms(Ω)**. • $\mathbf{R} = \rho \frac{l}{A}$	• Capacitors can store energy in its electric field when connected to a voltage source. • The capacitance is measured in **Farads(F)**. • $\mathbf{C} = \frac{Q}{V}$ • $\mathbf{C} = \varepsilon \frac{A}{d}$	• Inductors store energy in its magnetic field when electric current flows through it. • They are measured in **Henrys(H)**. • $\mathbf{L} = \mu_{\circ} \mathbf{N}^2 \frac{A}{l}$
		

Principle of Working

Inductor

- Working Principle behind inductor is Lenz's law

- Lenz's law states that the current induced in a circuit due to a change or a motion in a magnetic field **is** so directed as to oppose the change in flux and to exert a mechanical force opposing the motion.



Faraday's Law

$$\text{Emf} = -N\frac{\Delta\Phi}{\Delta t}$$

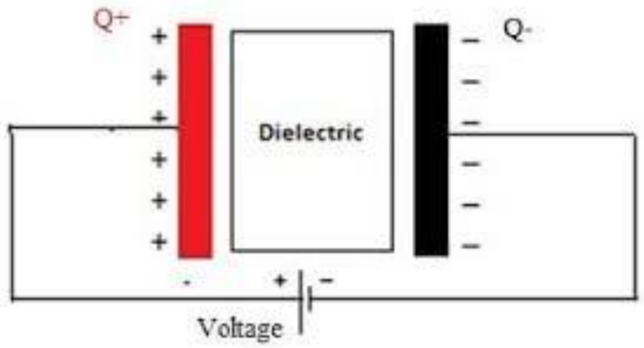
Lenz's Law

where N = number of turns
Φ = BA = magnetic flux
B = external magnetic field
A = area of coil

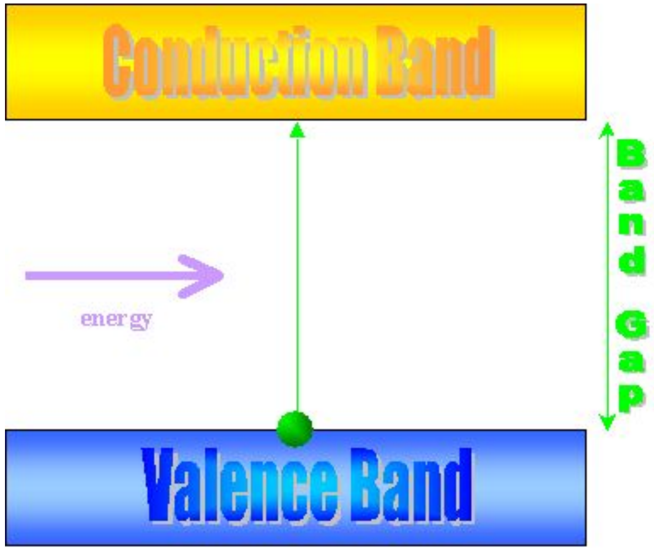
The minus sign denotes Lenz's Law.
Emf is the term for generated or induced voltage.

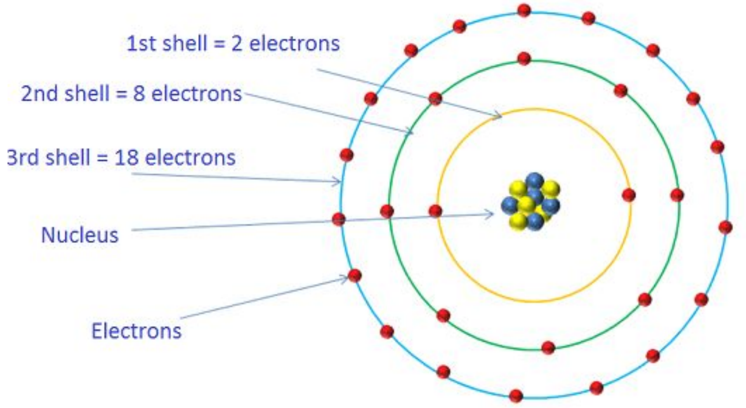
Capacitor

- When a potential difference is applied across the plates of capacitor the dielectric material get polarised and one plate will get positively charged and the other will get negatively charged.



Scientific Principle of Conduction

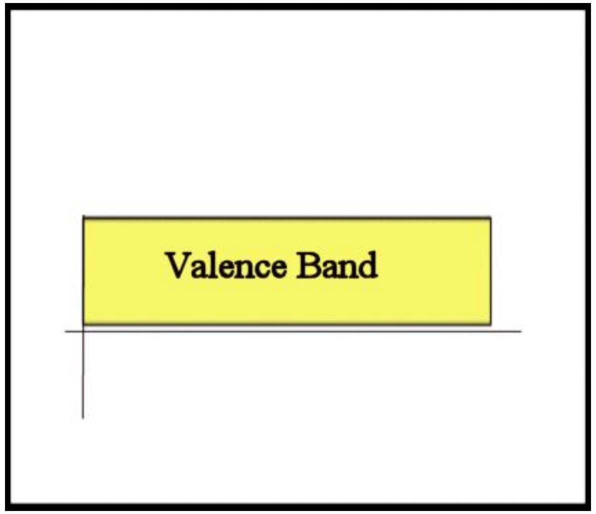




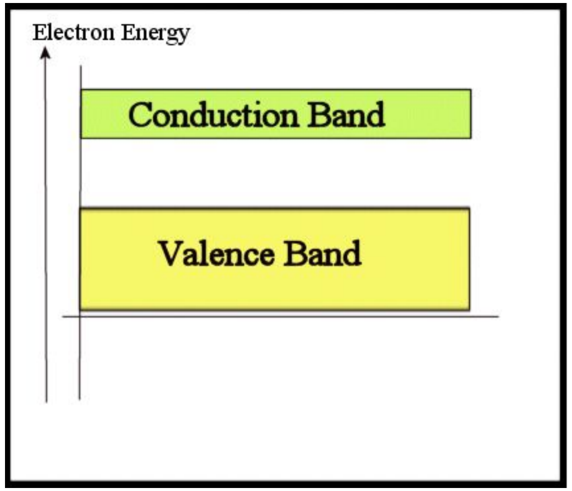
Solids, which are composed of a large number of atoms (about 1023), thus have a large number of orbitals occupying a large number of newly separated energy levels called **energy bands.**

The energy levels are quantized and there are certain energies that the electrons can never possess called the forbidden energy levels (**energy band gap**).

Valence Band and conduction band

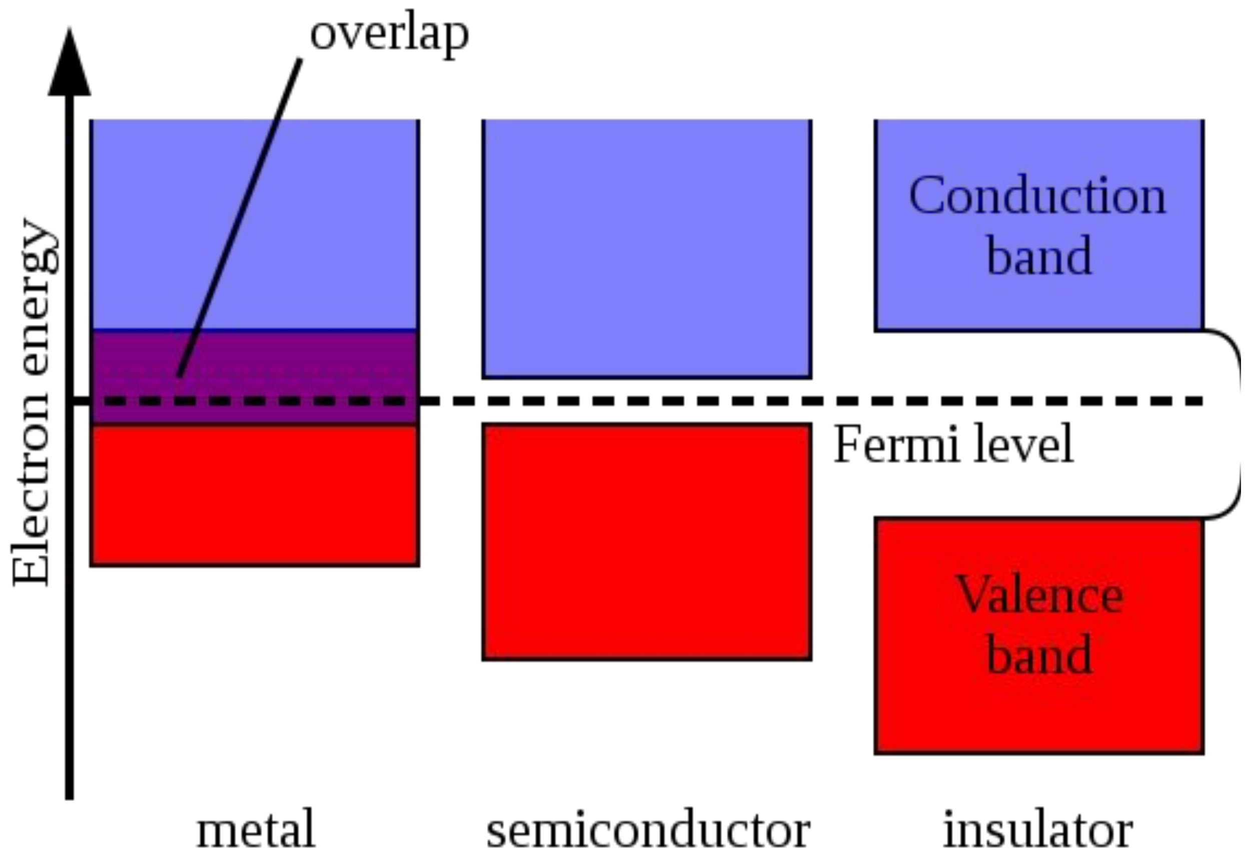


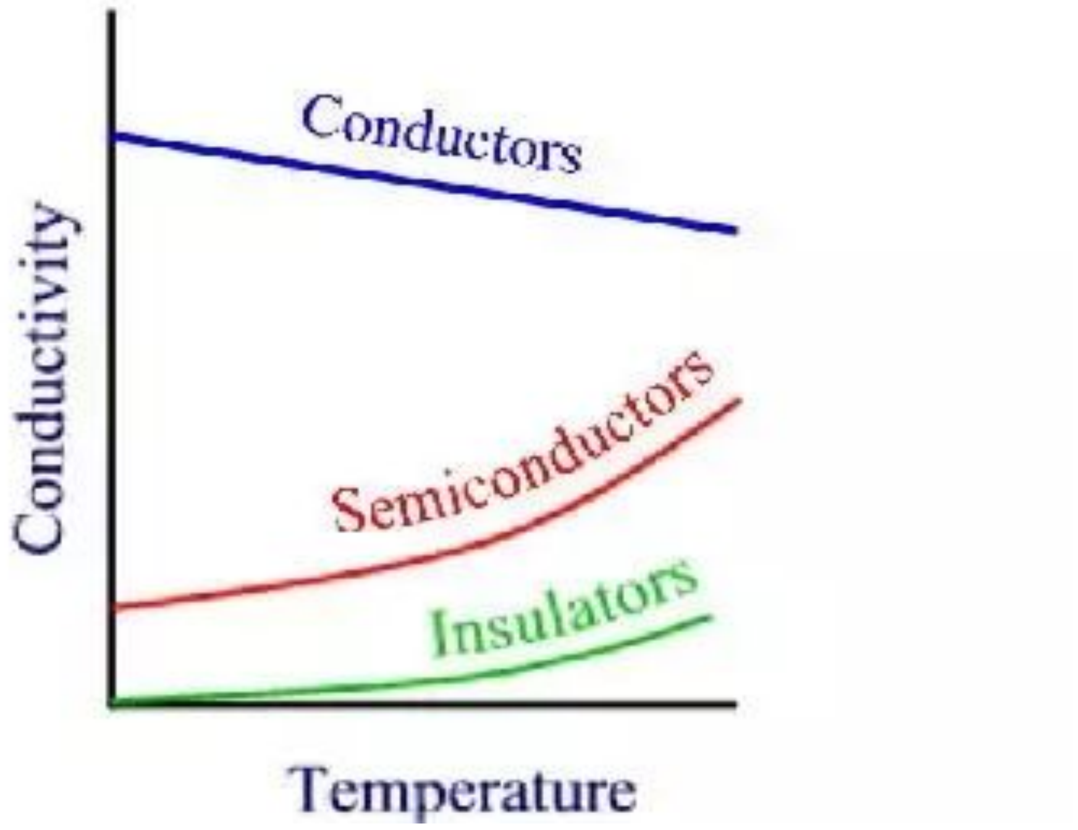
At 0K temperature, all the energy levels associated with the electrons bound to a nucleus are fully occupied. The highest band of these occupied energy levels constitutes what is called **the valence band.**



When the electrons absorb energy (at higher temperatures, due to interaction with high energy photons, etc.) and escape the nucleus of th atom, they are free to move in material. The band of energies the free electrons may occupy is defined as **the conduction band.**

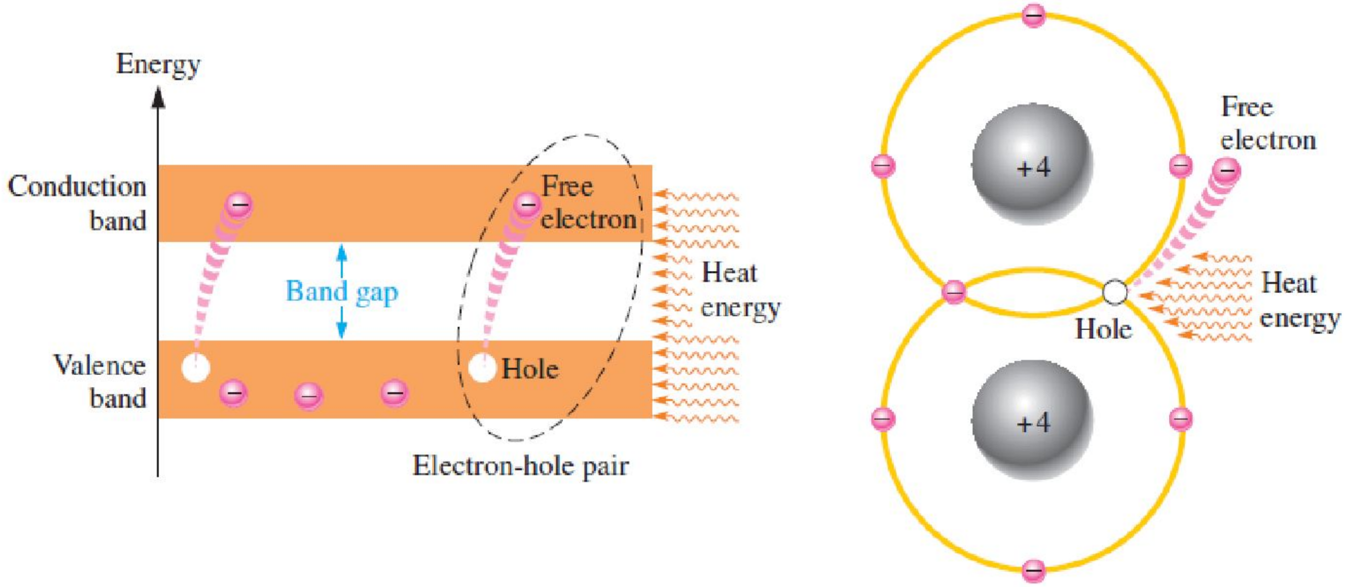
Band Diagrams





Carriers

The electrons present in the valence band correspond to the electrons involved in the bonding and are therefore not involved in charge transport.



(a) Energy diagram for the outer two bands

(b) Bonding diagram

when a bond is broken, the associated electron is free and can contribute to charge transport. These **free electrons** occupy states in the conduction band.

When the bonds of the semiconductor lattice are broken, electrons are pushed to the conduction band, and leave behind vacancies called **holes.**

Elective Mass

When an electron is placed in vacuum in a uniform electric field ξ the velocity of the electron, v, is related to the field as where m_e is the mass of the electron.

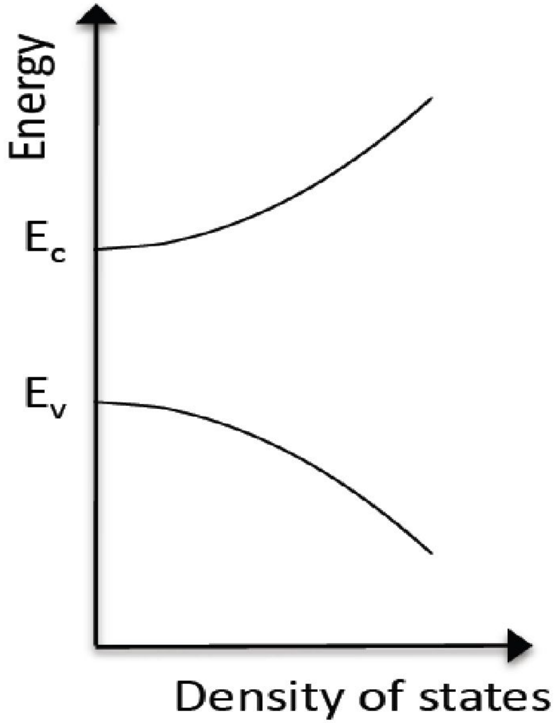
$$-q\xi = m_e dv/dt$$

when the electrons move in the semiconductor lattice under the presence of an electric field or magnetic field, then mass of the electrons varies with velocity. This means the mass of the action in the function of velocity and its terms effective mass of the electrons

Density of States

The density of states in the semiconductor defines the number of states an electron can occupy

The density of states in the conduction and valence bands are given by



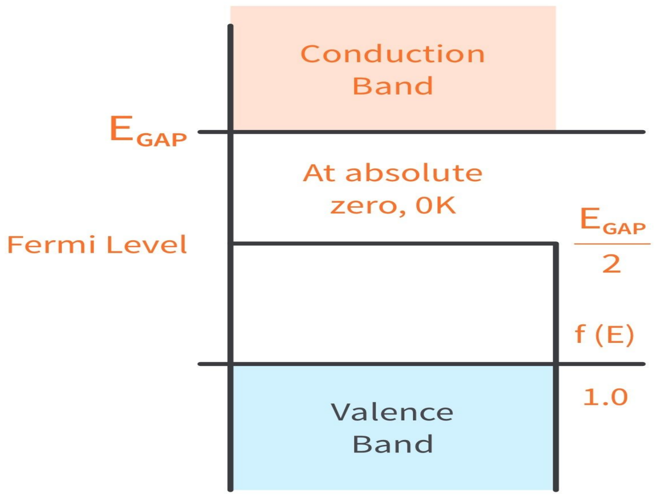
$$g_c(E) = \frac{8\pi(2(m_e^*)^3(E - E_c))^{1/2}}{h^3} \quad \text{for} \quad E \geq E_c$$

$$g_v(E) = \frac{8\pi(2(m_h^*)^3(E_v - E))^{1/2}}{h^3} \quad \text{for} \quad E \leq E_v$$

Nature of the density of states in a semiconductor assuming equal effective masses for electrons and holes.

The Fermi Level and Fermi Function

The **Fermi level** determines the probability of electron occupancy at different energy levels. The closer the Fermi level is to the conduction band energy, the easier it will be for electrons in the valence band to transition into the conduction band.

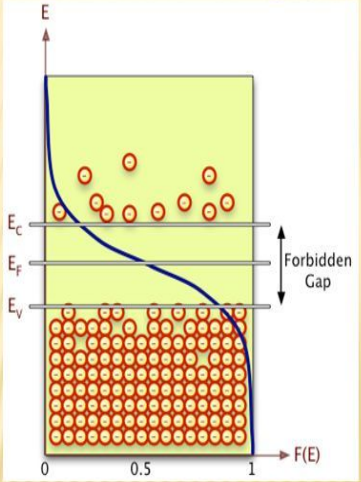


The Fermi function, f(E), defines **the probability of finding an electron at a given energy level E**.

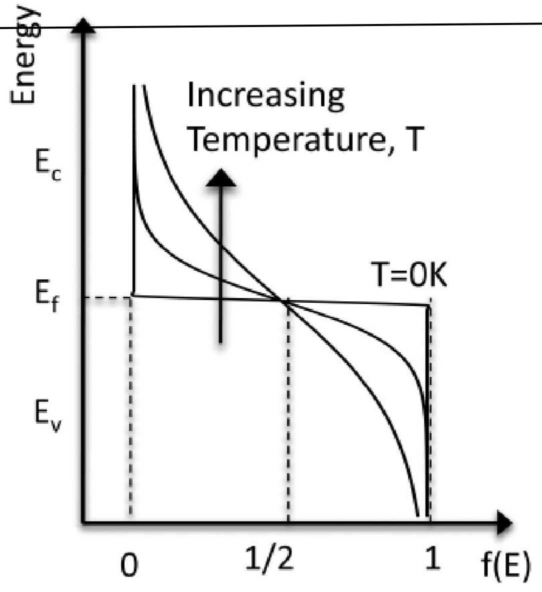
Equivalently, **the probability of finding holes at the energy level E is given by 1-f(E)**. The Fermi function is therefore a probability density function,

The Fermi Level and Fermi Function

In a semiconductor, not every energy level is allowed. For example, there are no allowed states within the forbidden gap



The density of electrons in a semiconductor, showing how the Fermi function is modulated by the density of allowed states (which is zero inside the forbidden gap).



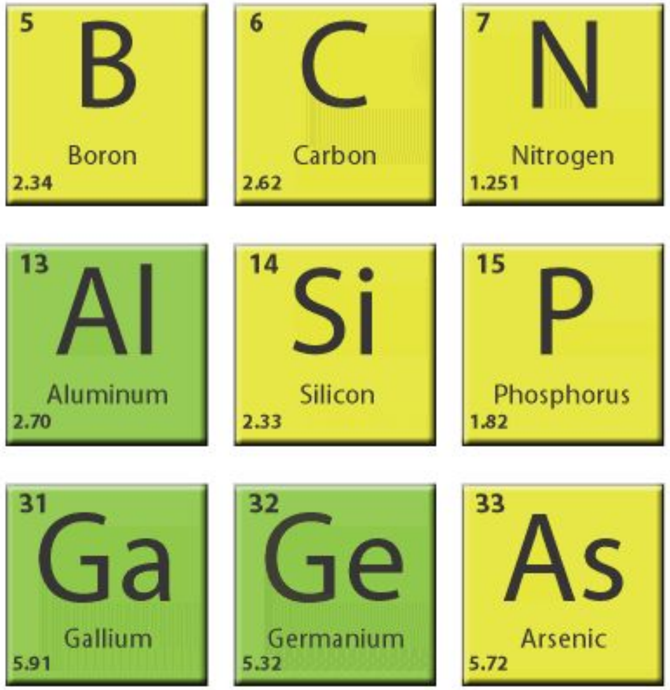
$$f(E) = \frac{1}{1 + e^{\frac{E - E_f}{kT}}}$$

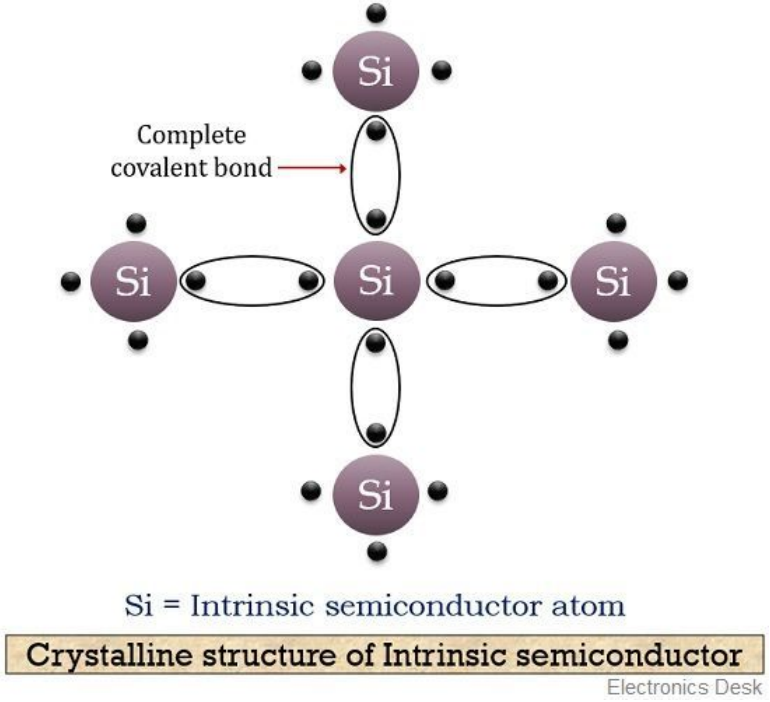
the Fermi level is the energy level at which the probability **of finding an electron is exactly 1/2 at any temperature**

The Fermi function at different temperatures. The value of the Fermi function is always 1/2 at the Fermi level.

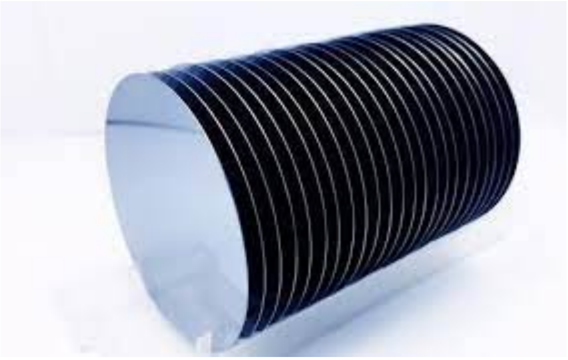
At 0K,
the probability **of finding an electron below** the Fermi level is 1 while the probability of finding an **electron above the Fermi level is 0**.

Silicon

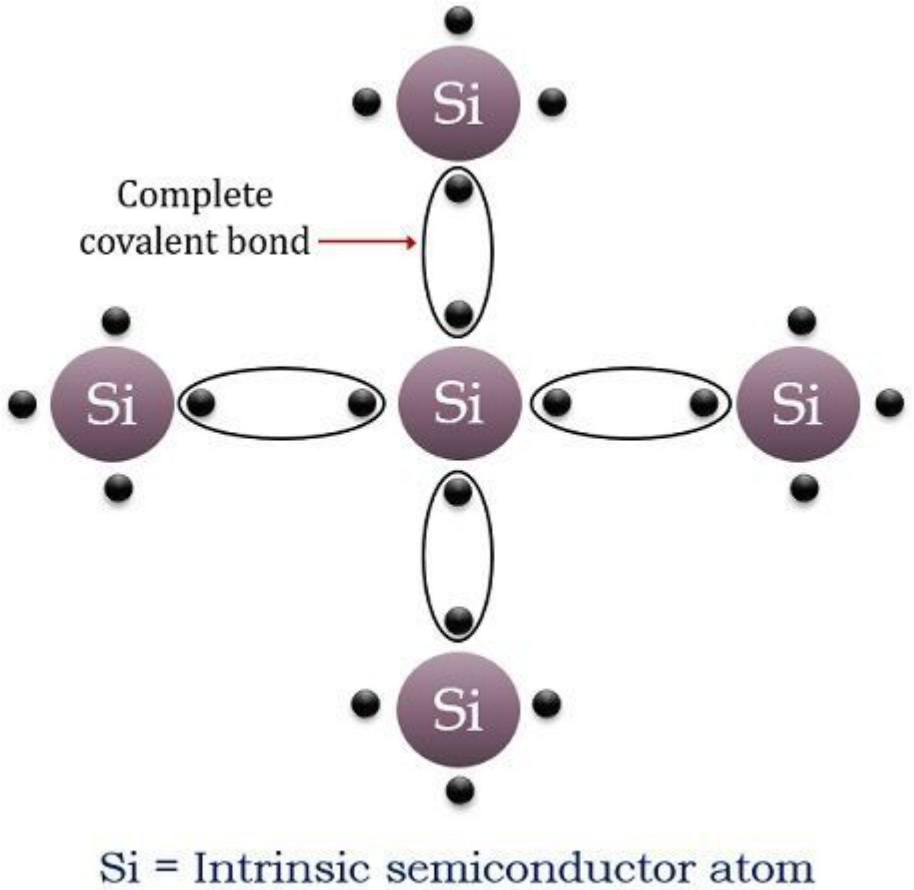




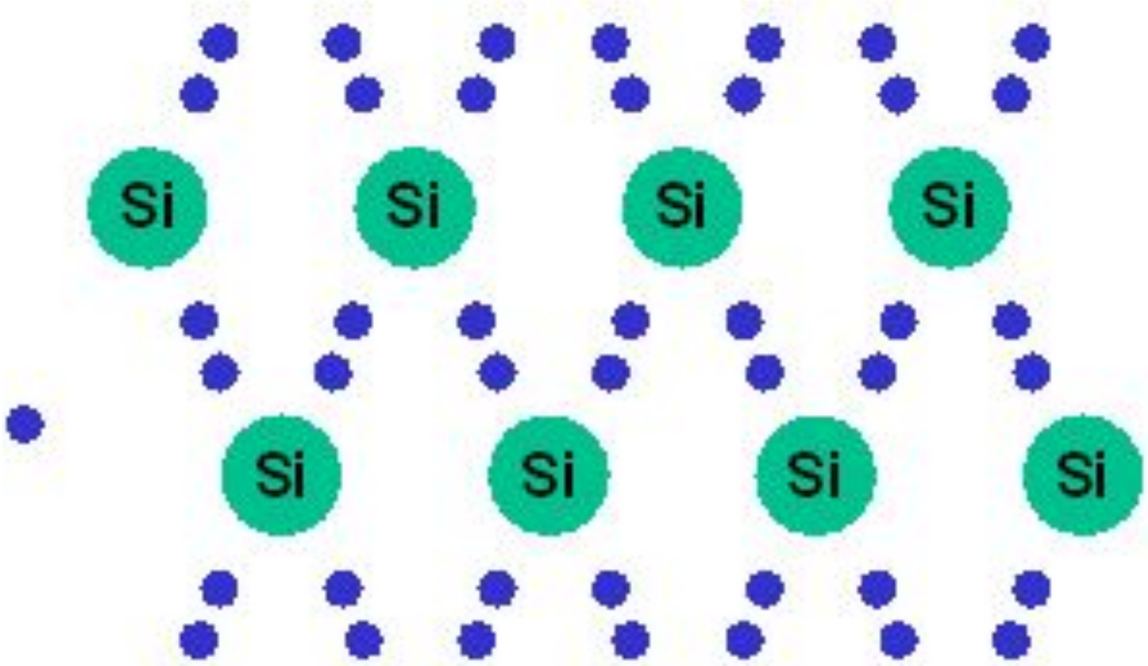
	Germanium	Silicon	Gallium Arsenide
$T = 300$ K	0.66 eV	1.12 eV	1.42 eV
$T = 400$ K	0.62 eV	1.09 eV	1.38 eV
$T = 500$ K	0.58 eV	1.06 eV	1.33 eV
$T = 600$ K	0.54 eV	1.03 eV	1.28 eV



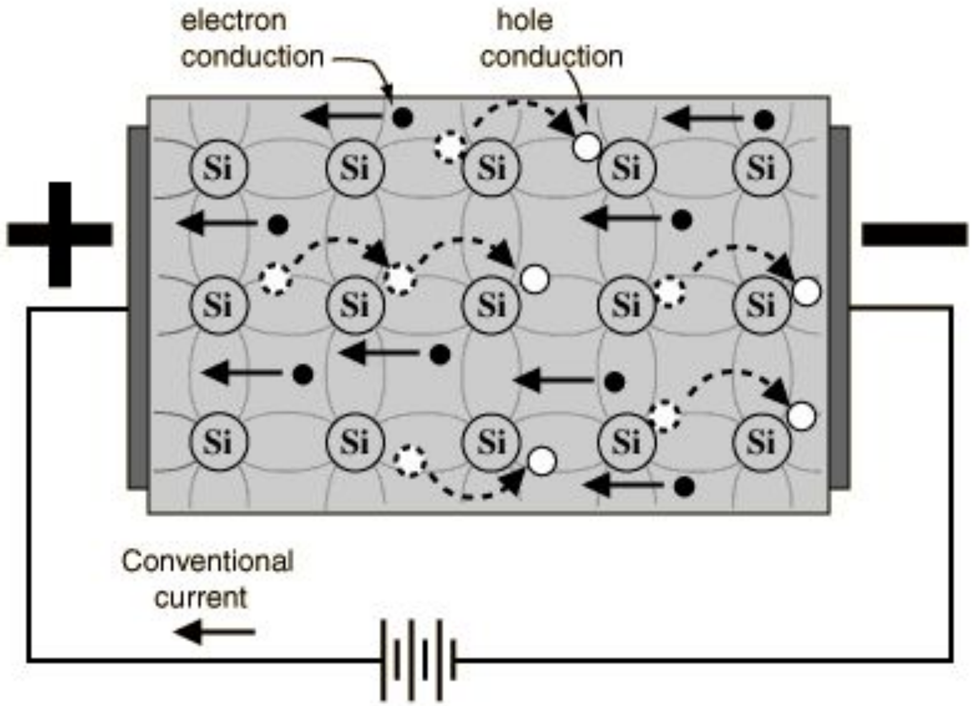
Intrinsic Silicon



Crystalline structure of Intrinsic semiconductor

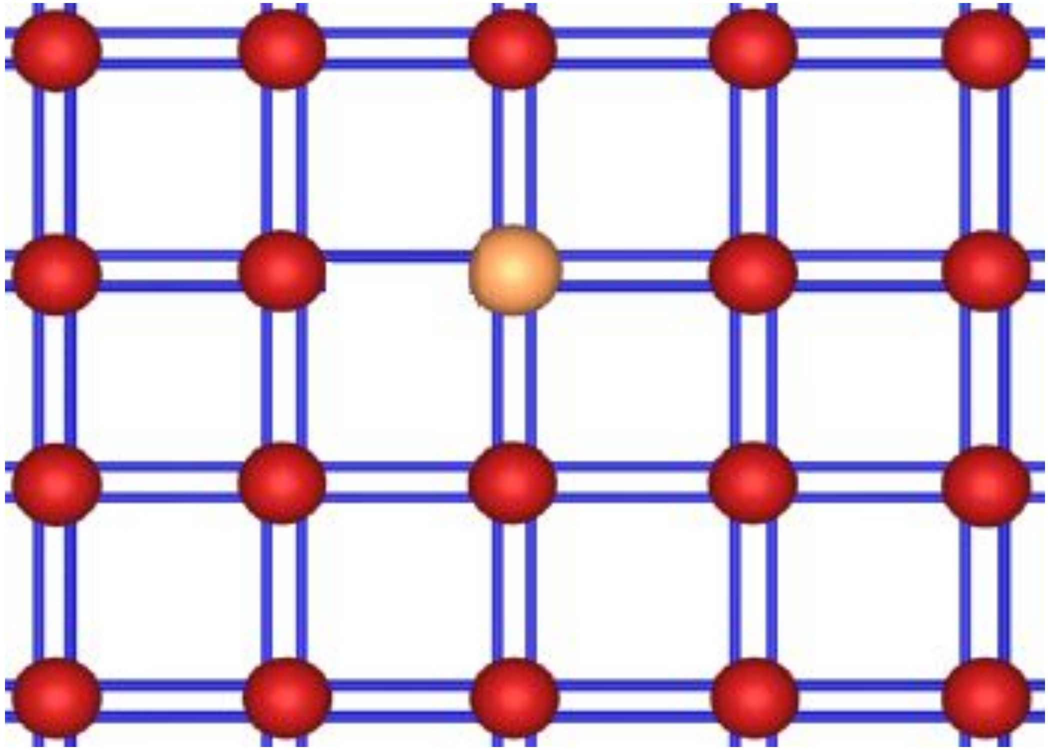


Current Flow



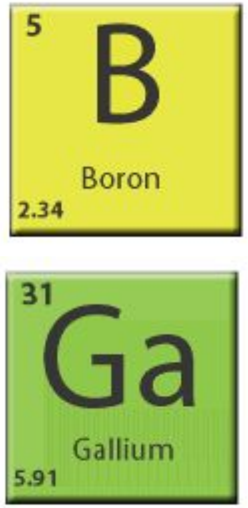
If a voltage is applied, then both the electron and the hole can contribute to a small current flow.

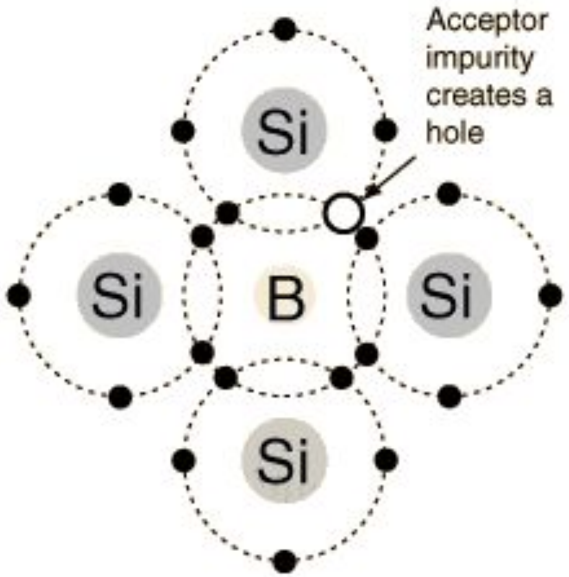
Extrinsic semiconductor (Doping)

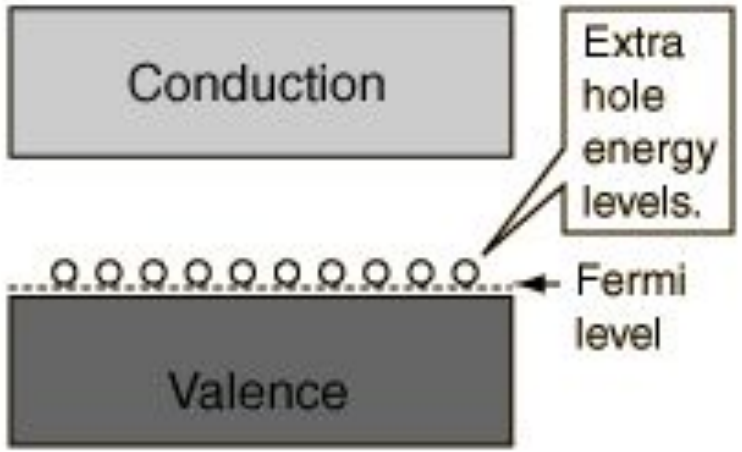


Doping (adding an impurity) can produce 2 types of semi-conductors depending upon the element added.

P-Type Doping



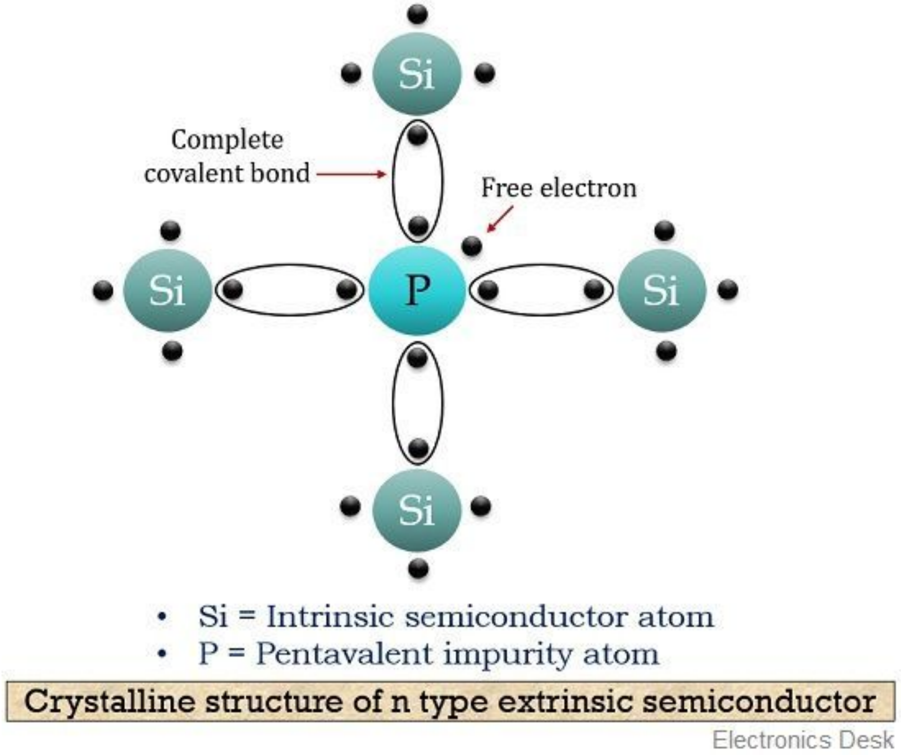


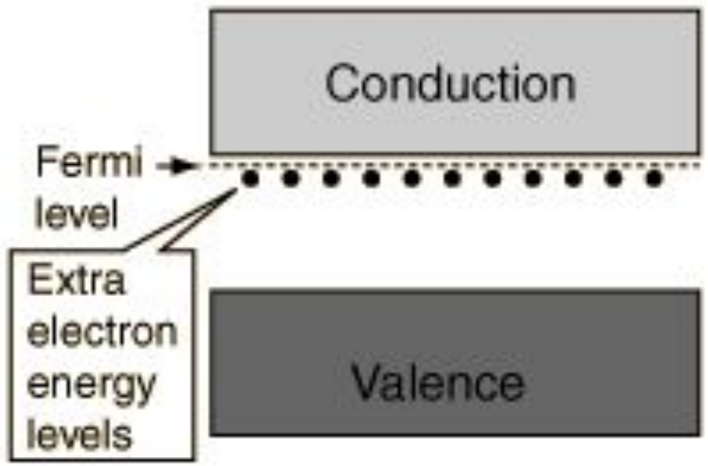


In P-type doping, boron or gallium is the dopant.

Holes can conduct current Holes accept electron from a neighbor, moving the hole over a space

N-Type doping





Electrons have a negative charge

Phosphorus and arsenic each have five outer electrons, so they're out of place when they get into the silicon lattice.

Number of Carriers

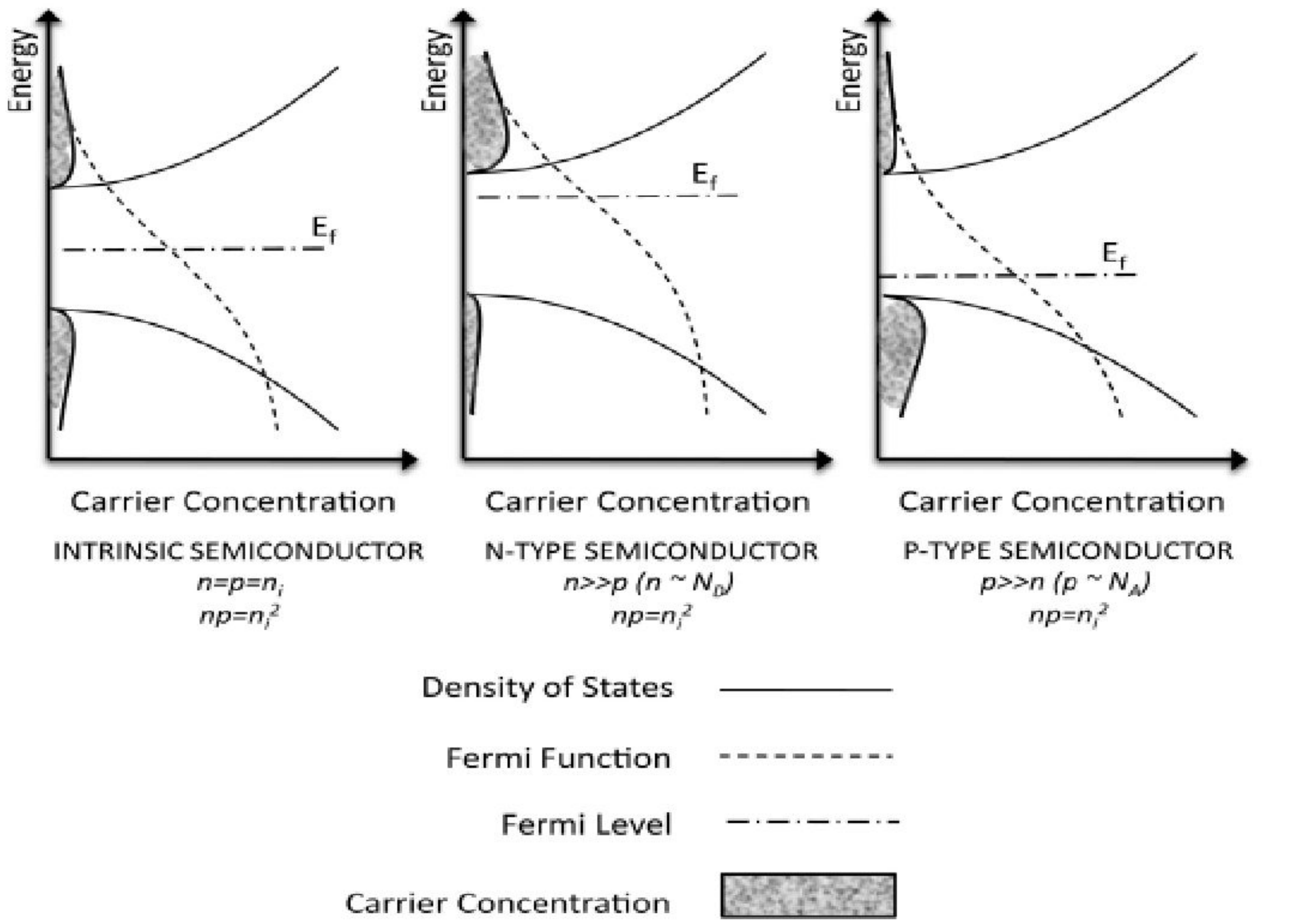
Therefore, the number of electrons and holes found between the energy levels E and E + dE in the **conduction band** is given by

$$n(E) = f(E)g_c(E)dE$$
$$p(E) = (1 - f(E))g_c(E)dE$$

Therefore, the number of electrons and holes found between the energy levels E and E + dE in the **valence band** is given by

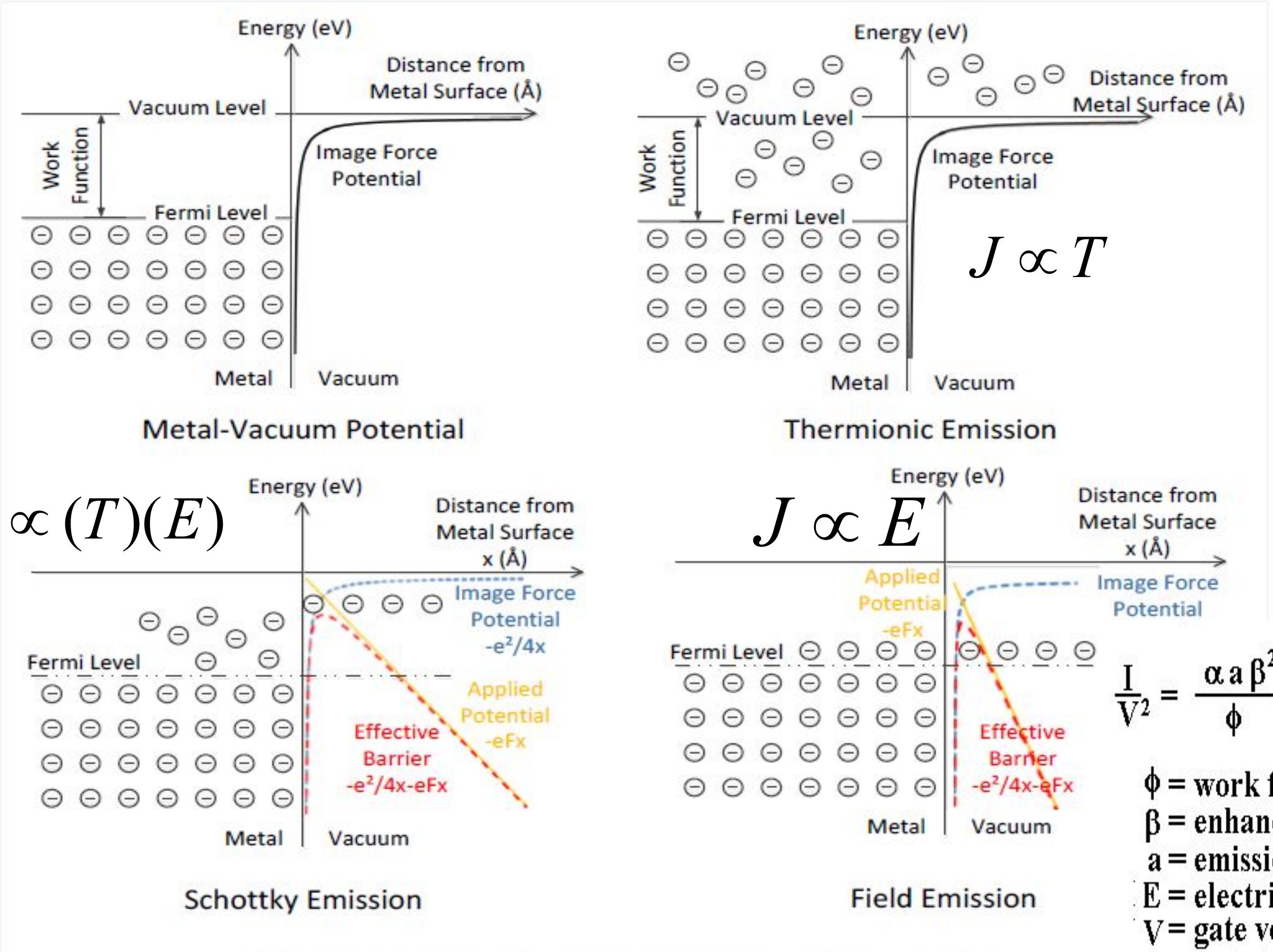
$$n(E) = f(E)g_v(E)dE$$
$$p(E) = (1 - f(E))g_v(E)dE$$

The free carrier density for an Intrinsic and Extrinsic semiconductor



The free carrier density for an intrinsic, n-type doped and p-type doped semi-conductor.

EMISSION OF ELECTRON FROM METALS



$J \propto T$

$J \propto (T)(E)$

$J \propto E$

Figure 2-6: Schematic diagram of thermionic emission, Schottky emission and field emission

$$\frac{I}{V^2} = \frac{\alpha\, a\, \beta^2}{\phi} \exp\left(\frac{-b\,\phi^{3/2}}{\beta V}\right)$$

ϕ = work function
β = enhancement factor
a = emission area
E = electric field strength
V = gate voltage
I = emission current
α, b = constants

Nanotube field electron emission: principle ,development, and applications. Yunhan Li1,et al Nanotechnology 26 (2015) 242001 (23pp)

Junction formation

1) Metal –Metal formation
2) Semiconductor- Metal formation
3) Semiconductor- semiconductor formation

Metal -Semiconductor Junction

Depending on the semiconductor and metal used, the contact may be **rectifying or ohmic**.

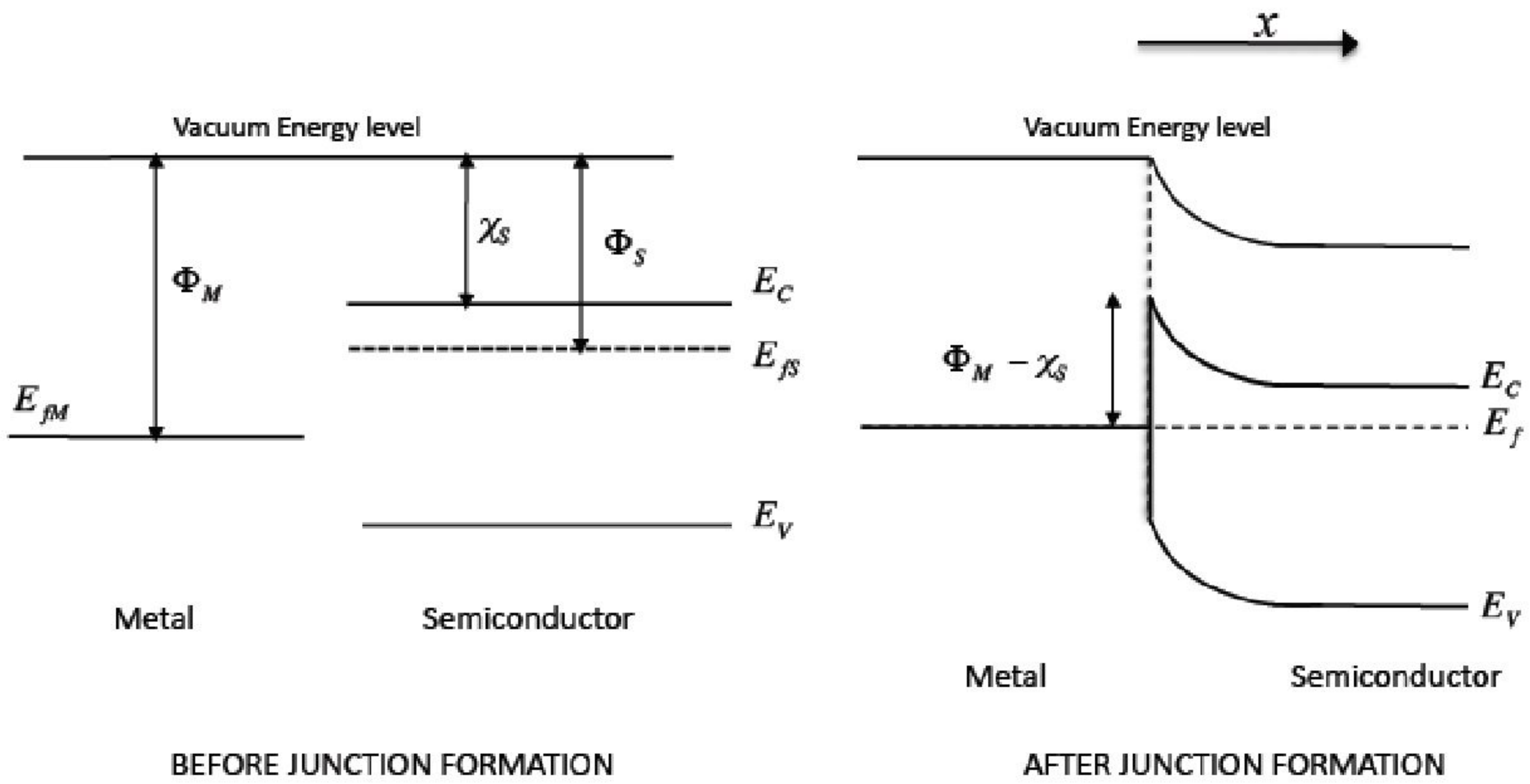
A **rectifying contact** allows current to pass in one direction only while it blocks the movement of carriers in the opposite direction.

An ohmic contact allows current to pass in either direction.

If the semiconductor is **n-type with $\Phi_S < \Phi_M$** or if it is **p-type with $\Phi_S > \Phi_M$** the contact formed is **rectifying or blocking**.

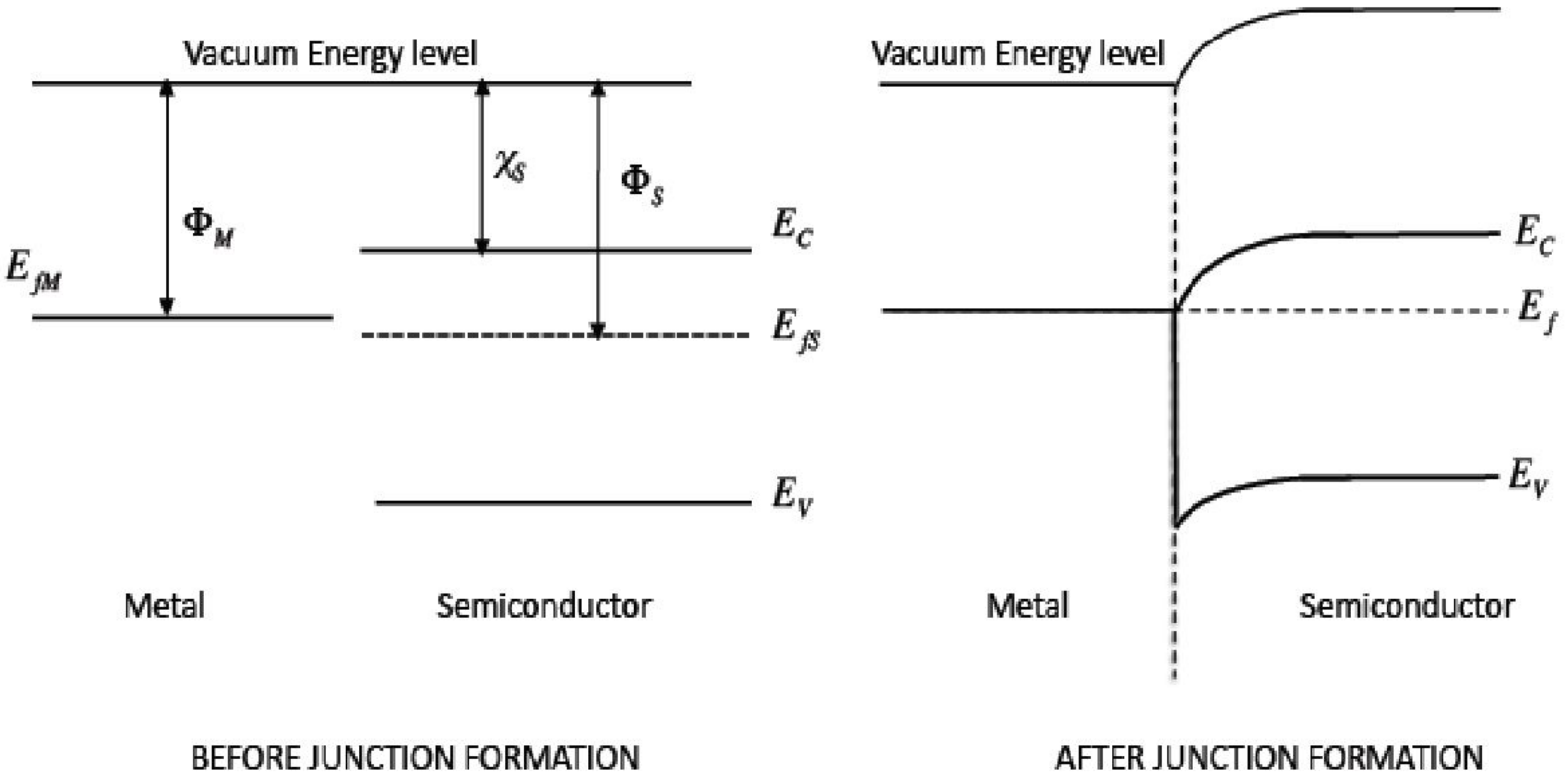
If the semiconductor is **n-type with $\Phi_S > \Phi_M$** or if it is **p-type with $\Phi_S < \Phi_M$** the contact formed is ohmic .

The formation of a rectifying Metal-Semiconductor junction



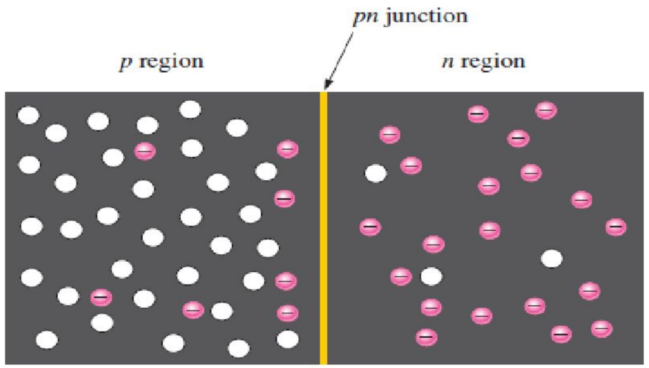
The formation of a rectifying Metal-Semiconductor junction

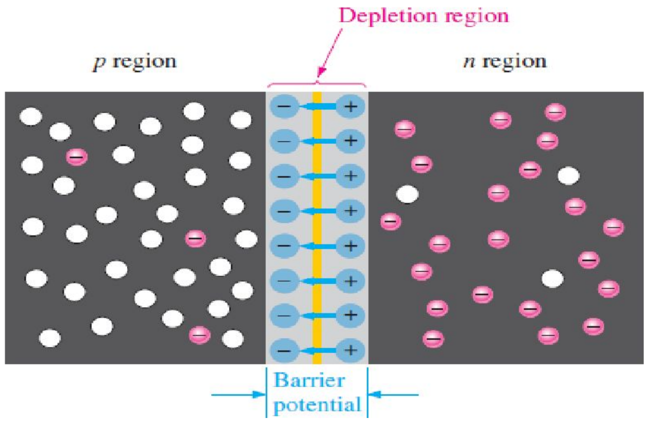
The formation of a ohmic Metal-Semiconductor junction



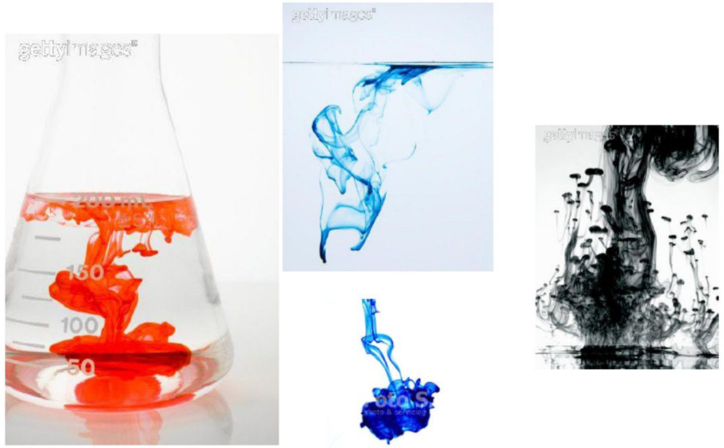
The formation of a ohmic Metal-Semiconductor junction. The semi conductor is N type

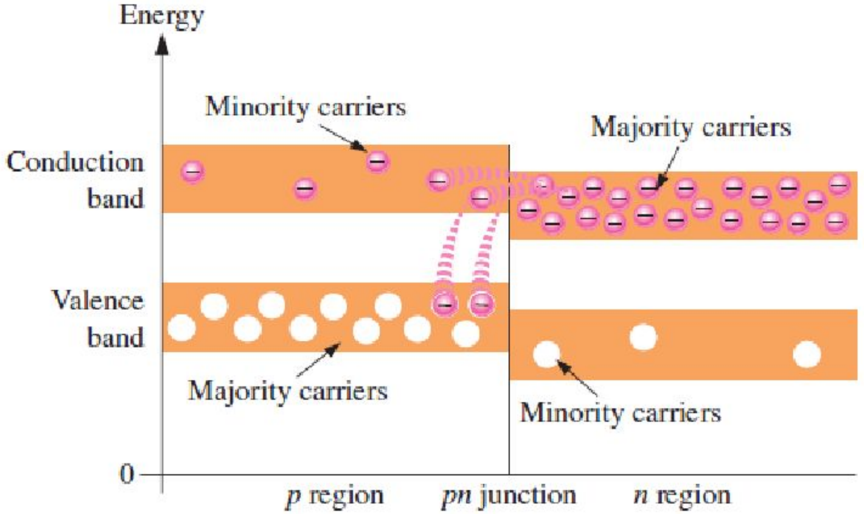
P-N Junction



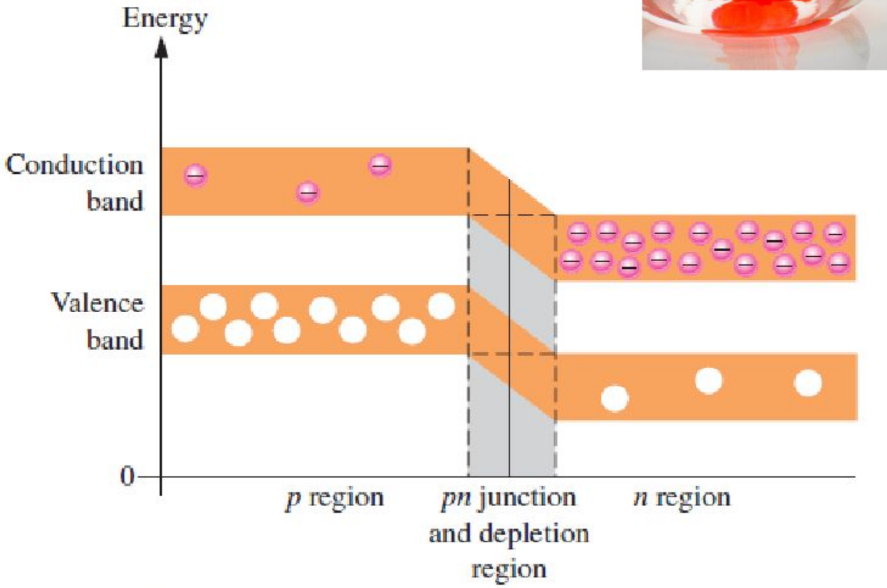


Gradients drive diffusion





(a) At the instant of junction formation



(b) At equilibrium

Mass-Action Law

If we consider a semiconductor in thermal equilibrium, free charge carriers are continuously created due to the presence of thermal energy. The generation rate of free charge carriers is G = g(T), and is purely a function of the temperature and the properties of the semiconductor crystal lattice.

The generation of electron and holes in the semiconductor is balanced by their recombination and this balance of generation and recombination maintains thermal equilibrium in the semiconductor.

Mass-Action Law

The recombination is proportional to R = npr(T), where r(T) is again purely a function of temperature and crystal property. Equating the generation and recombination rates, np = g(T)/r(T)

- n_0 : thermal-equilibrium concentration of electrons
- p_0 : thermal-equilibrium concentration of holes
- $n_0p_0 = n_i^2 = f(T)$ (function of temperature)
- The product of n0 and po is always a constant for a given semiconductor material at a given temperature.

Equilibrium Electron and Hole Concentrations

- n_0 : thermal-equilibrium concentration of electrons
- p_0 : thermal-equilibrium concentration of holes
- n_d : concentration of electrons in the donor energy state
- p_a : concentration of holes in the acceptor energy state
- N_d : concentration of donor atoms
- N_a : concentration of acceptor atoms
- N_d^+ : concentration of positively charged donors (ionized donors)
- N_a^- : concentration of negatively charged acceptors (ionized acceptors)

Built-in Potential

N-region $$n = N_d = N_c e^{-qA/kT} \Rightarrow A = \frac{kT}{q} \ln \frac{N_c}{N_d}$$

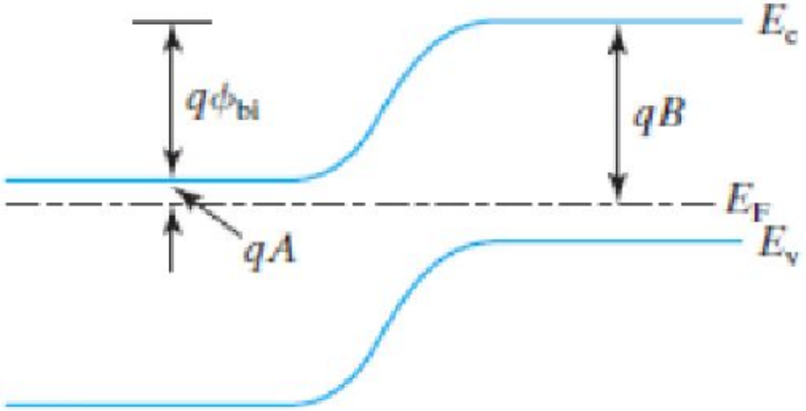
donor density

P-region $$n = \frac{n_i^2}{N_a} = N_c e^{-qB/kT} \Rightarrow B = \frac{kT}{q} \ln \frac{N_c N_a}{n_i^2}$$

acceptor density

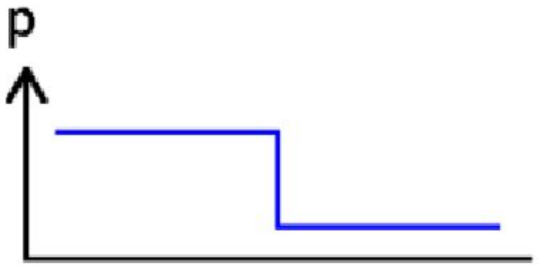
$$\phi_{bi} = B - A = \frac{kT}{q}\left(\ln \frac{N_c N_a}{n_i^2} - \ln \frac{N_c}{N_d} \right)$$

$$\boxed{\phi_{bi} = \frac{kT}{q} \ln \frac{N_d N_a}{n_i^2}}$$



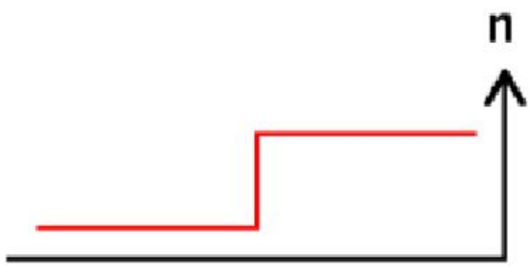
Gradients drive diffusion

Hole gradient

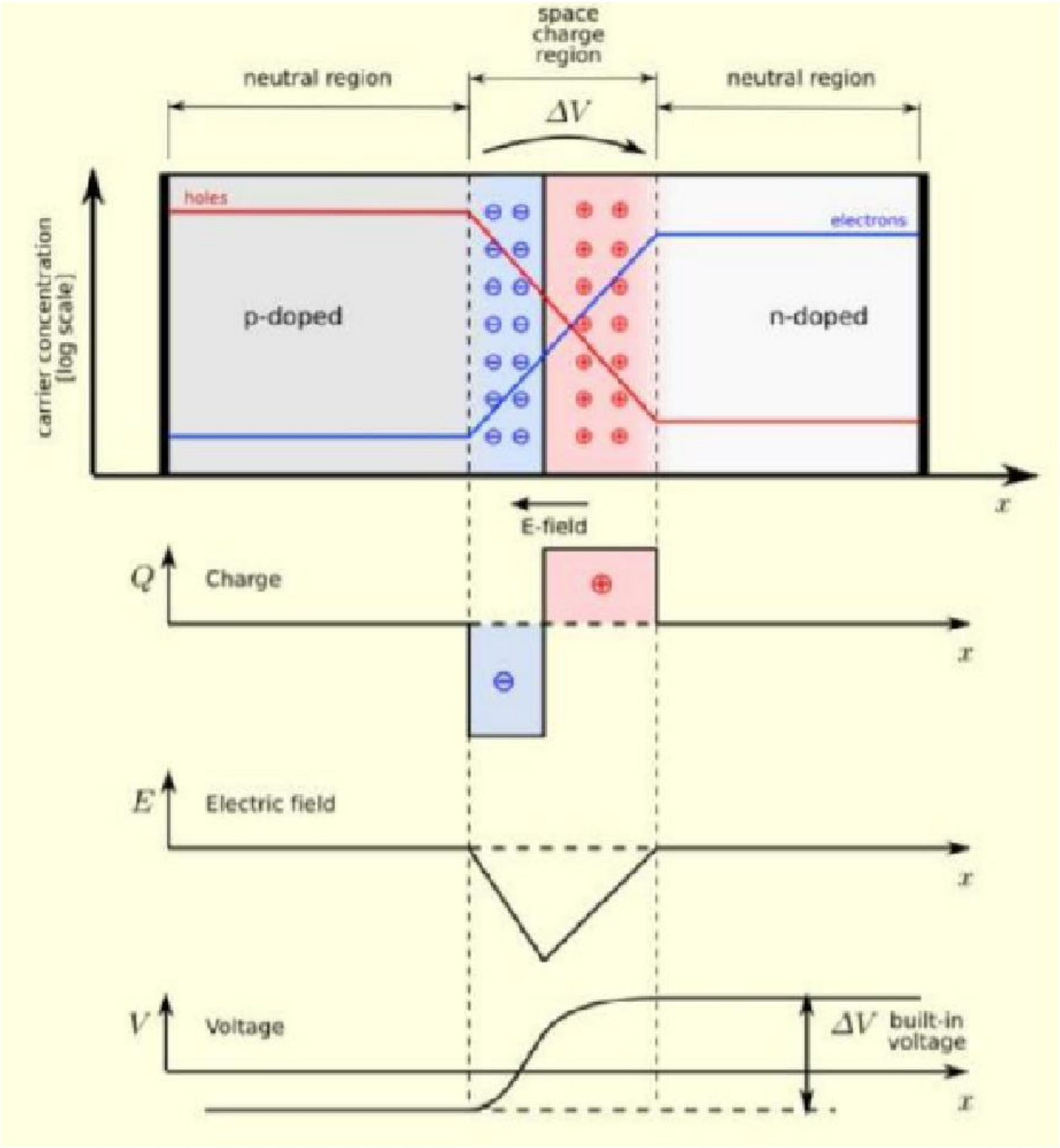


$J_{p,\ diffusion} = -qD_p\ dp/dx$ = current right, holes right

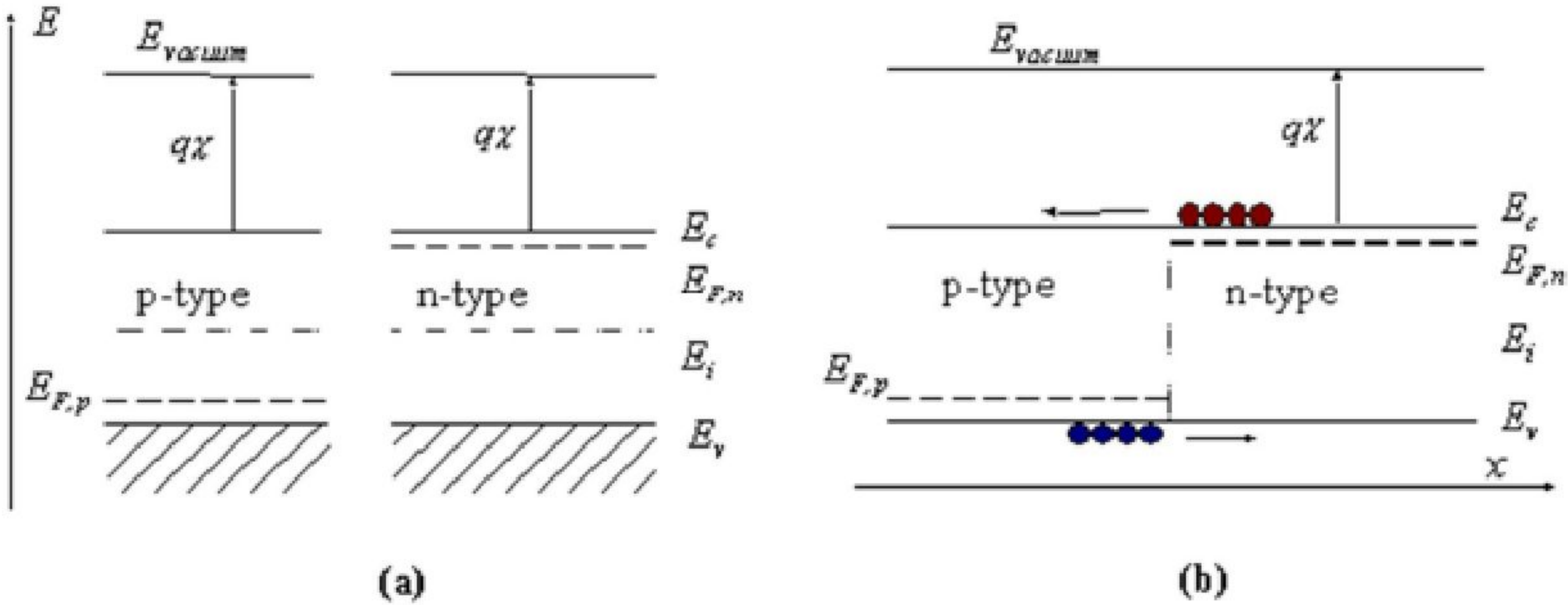
Electron gradient



$J_{n,diffusion} = -qD_n\ dn/dx$ = current right, electron left


space
charge
region
neutral region
neutral region
ΔV
holes
electrons
p-doped
n-doped
carrier concentration
[log scale]
x
E-field
Q
Charge
x
E
Electric field
x
V
Voltage
ΔV built-in
voltage
x

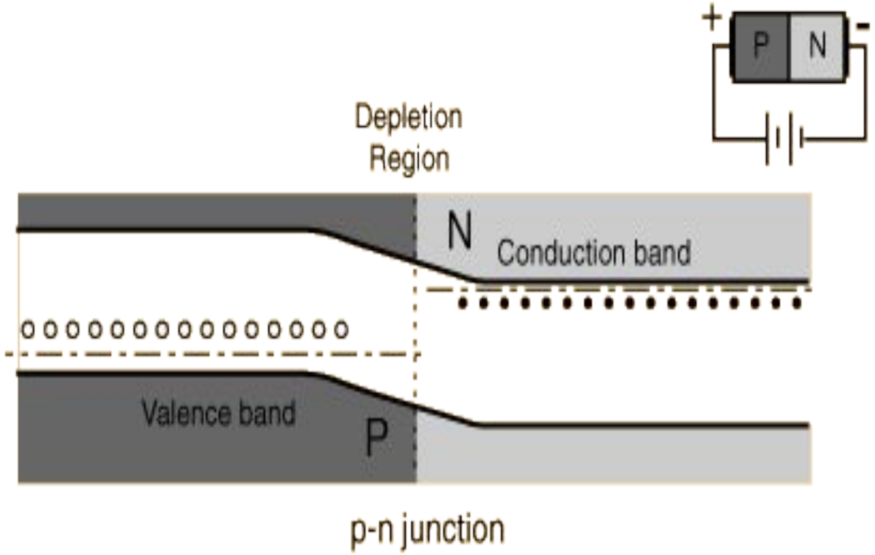
Energy band diagram of a pn junction before and after



Energy band diagram of a p-n junction (a) before and (b) after merging the n-type and p-type regions

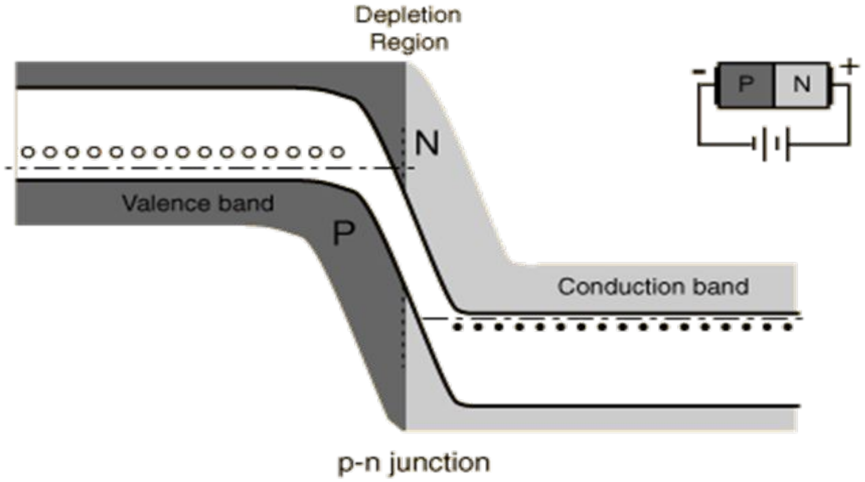
Band bending diagram for PN junction diode

Forward Biasing



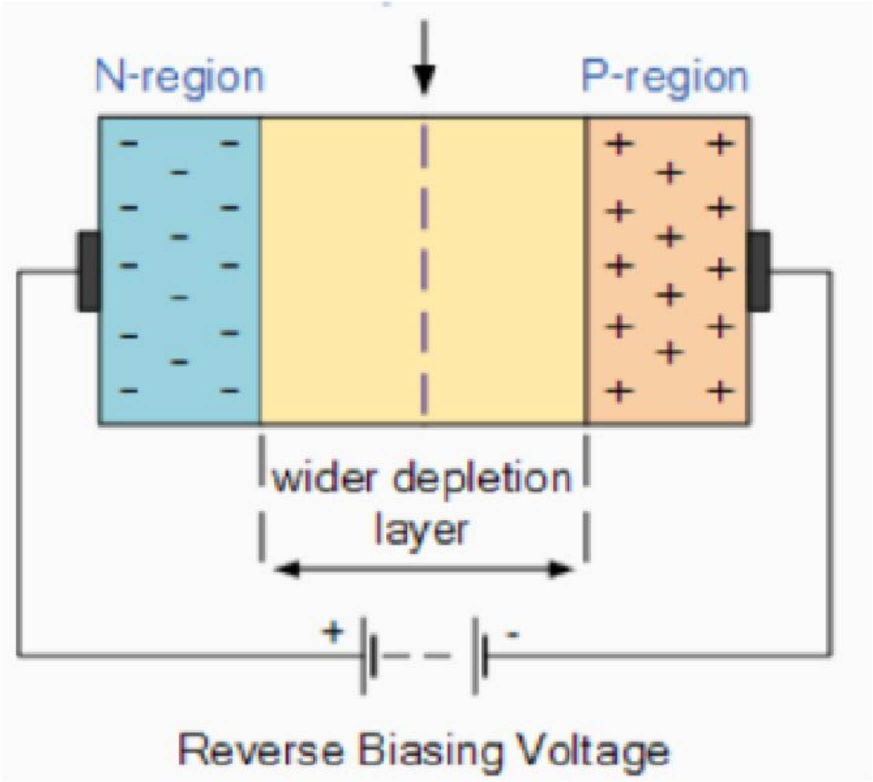
At the junction the electrons and holes combine so that a continuous current can be maintained.

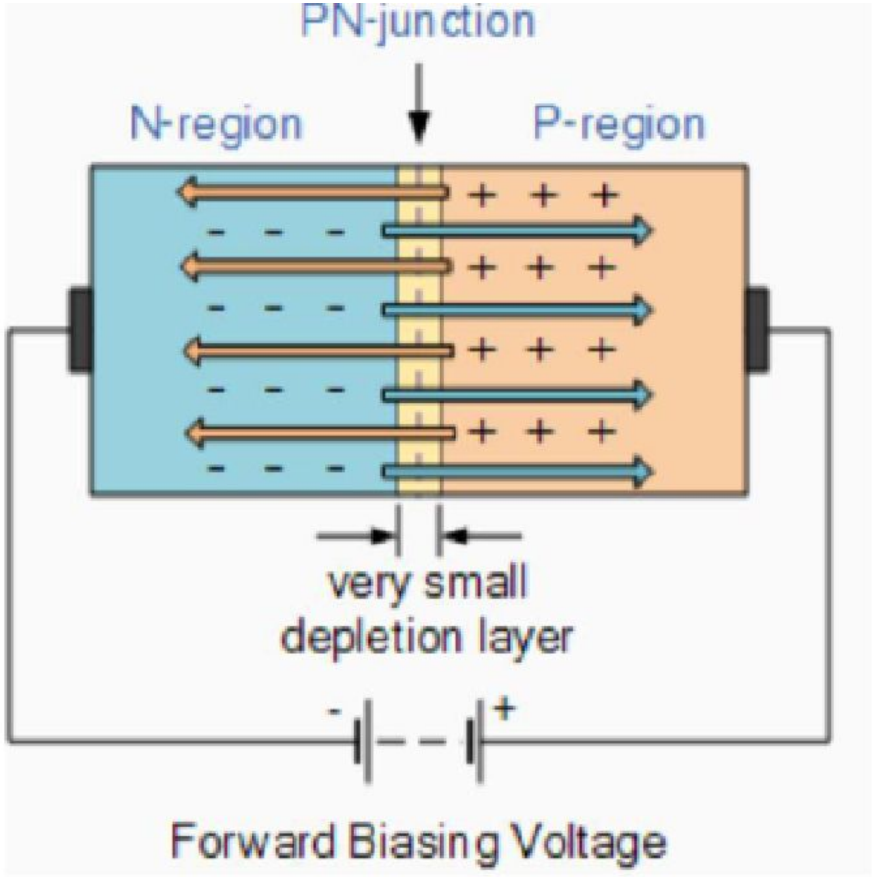
Reverse Biasing



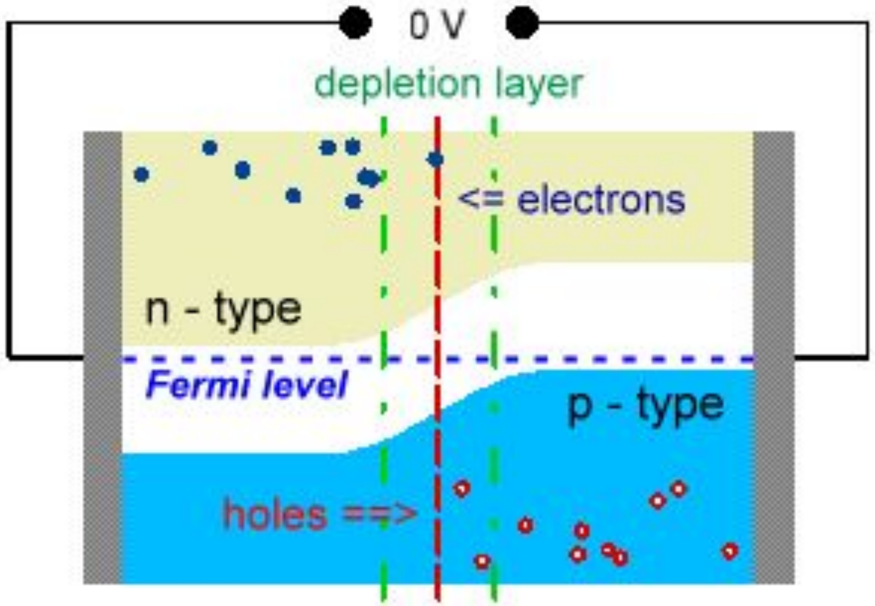
When the potential formed by the widened depletion layer equals the applied voltage, the current will cease except for the small thermal current.

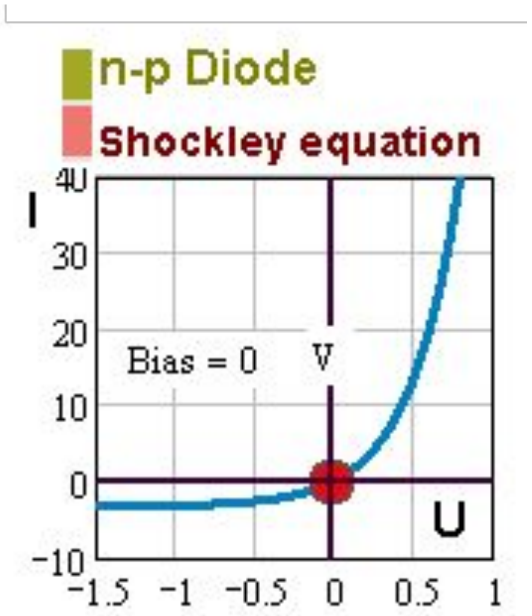
Diode


N-region
P-region
wider depletion layer
+
-
Reverse Biasing Voltage


PN-junction
N-region
P-region
very small depletion layer
-
+
Forward Biasing Voltage

P-N Junction





We create a p-n junction by joining together two pieces of semiconductor, one doped n-type, the other p-type.

Diffusion Current

- It is possible for an electric current to flow in a semiconductor even in the absence of the applied voltage provided a concentration gradient exists in the material.
- A **concentration gradient exists** if the number of either elements or holes is greater in one region of a semiconductor as compared to the rest of the Region.
- the change carriers have the **tendency to move** from the region of higher concentration to that of lower concentration of the same type of charge carriers.
- Thus the movement of charge carriers takes place resulting in a current called **diffusion current**.
- Since the hole density p(x) decreases with increasing x, dp/dx is negative and the minus sign in equation is needed in order that Jp has positive sign in the positive x direction

Diffusion Current

Diffusion current density = Charge × Carrier flux

Diffusion current density due to electron Jn and holes *Jp* is given by

$$J_n^{diff} = qD_n \frac{dn}{dx} \quad A/cm^2$$

$Dp = \lambda_2/\tau_c$ is the diffusion coefficient

$$J_p^{diff} = -qD_p \frac{dp}{dx} \quad A/cm^2$$

Average carrier velocity = Vth = 10^7 cm/s
Average interval between collisions = τc = 10-13 s = 0.1 picoseconds
mean free path = λ = $Vth\ \tau_c$ = 10^-6 cm = 10 nm

The diffusion current along the x-direction depends on the gradient of carrier concentration in this direction denoted by the first differentials dn/dx and dp/dx.

Drift Current

- When an electric field is applied across the semiconductor material, the charge carriers attain a certain drift velocity Vd , which is equal to the product of the mobility of the charge carriers and the applied Electric Field intensity E .

- Drift velocity Vd = mobility of the charge carriers X Applied Electric field intensity. ($V_d = -\mu_n E$)

- Holes move towards the negative terminal of the battery and electrons move towards the positive terminal of the battery. This combined effect of movement of the charge carriers constitutes a current known as — **the drift current.**

- Thus the drift current is defined as the flow of electric current due to the motion of the charge carriers under the influence of an external electric field.

- Drift current due to the charge carriers such as free electrons and holes are the current passing through a square centimeter perpendicular to the direction of flow.

Drift Current

Drift current density: ∝ Carrier drift velocity
∝ Carrier concentration
∝ Carrier charge

$$J_n^{drift} = -qnv_{dn} = qn\mu_n E$$

$$J_p^{drift} = qpv_{dp} = qp\mu_p E$$

n - Number of free electrons per cubic centimetre

P - Number of holes per cubic centimetre

μ(n) – Mobility of electrons in cm2 / Vs

μ(p) – Mobility of holes in cm2 / Vs

E – Applied Electric filed Intensity in V /cm

q – Charge of an electron = 1.6 x 10-19 coulomb.

The drift velocity is proportional to the applied electric eld and the constant of proportionality is called the electron mobility defined as

$\mu_e = q\tau_{me} = m_e$

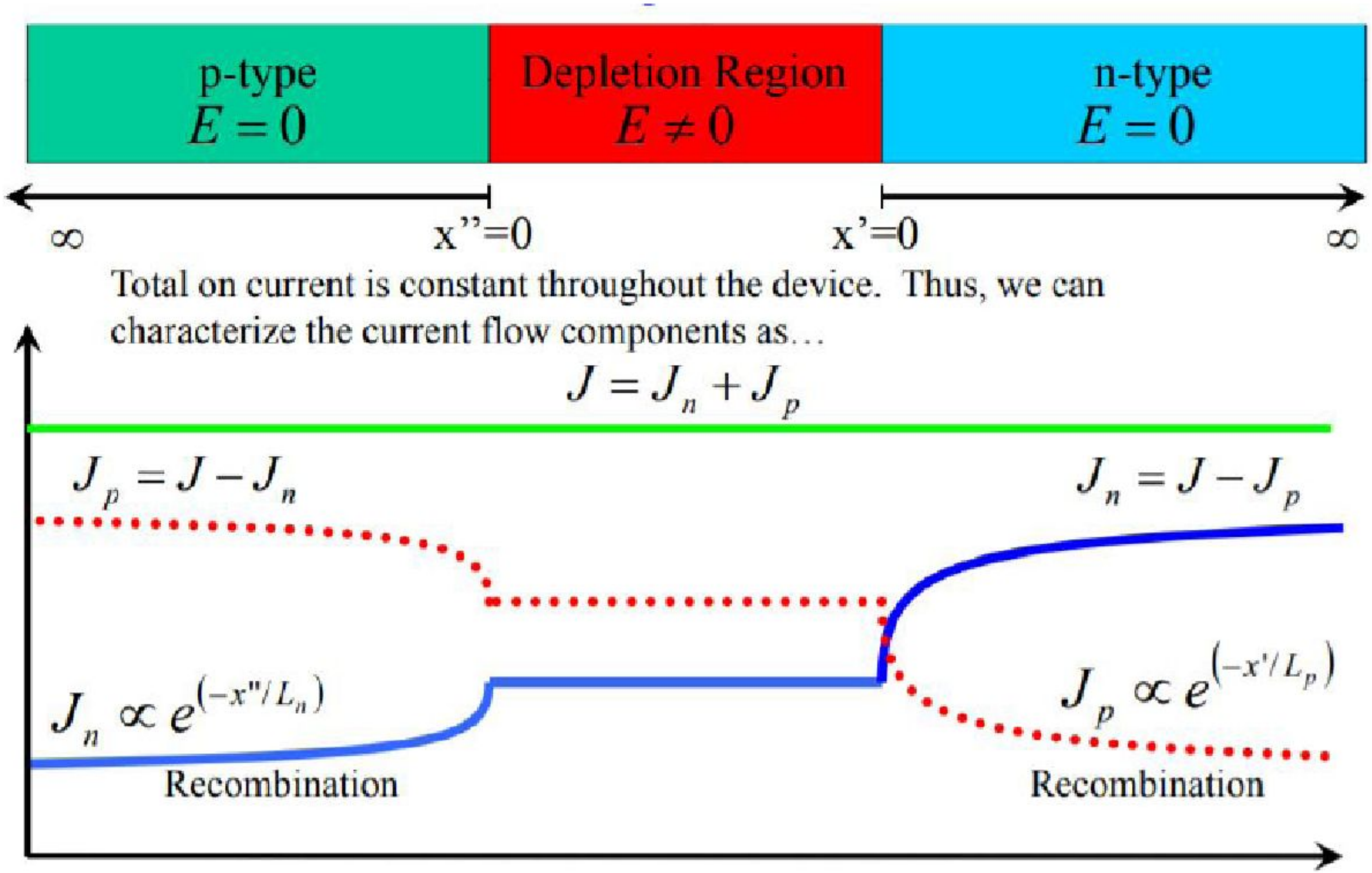
Total Current

The total current in a semiconductor (N type and P type) is the sum of both drift and diffusion currents that is given by

$$\mathbf{J_n = J_n^{drift} + J_n^{diff} = qn\mu_n E + qD_n \frac{dn}{dx}}$$

$$\mathbf{J_p = J_p^{drift} + J_p^{diff} = qp\mu_p E - qD_p \frac{dp}{dx}}$$

PN diode solution



Diode Current

Thus, evaluating the current components at the depletion region edges, we have...

$$\mathrm{J} = \mathrm{J_n}(\mathrm{x''}=0) + \mathrm{J_p}(\mathrm{x'}=0) = \mathrm{J_n}(\mathrm{x''}=0) + \mathrm{J_p}(\mathrm{x''}=0) = \mathrm{J_n}(\mathrm{x'}=0) + \mathrm{J_p}(\mathrm{x'}=0)$$

$$\mathrm{J} = q\left(\frac{D_n n_i^2}{L_n N_A} + \frac{D_p n_i^2}{L_p N_D}\right)\left(e^{qV_A/kT} - 1\right) \quad \textit{for all } x$$

or

$$\boxed{\mathrm{I} = I_o\left(e^{qV_A/kT} - 1\right) \quad \textit{where } I_o = qA\left(\frac{D_n n_i^2}{L_n N_A} + \frac{D_p n_i^2}{L_p N_D}\right)}$$

I_o *is the "reverse saturation current"*

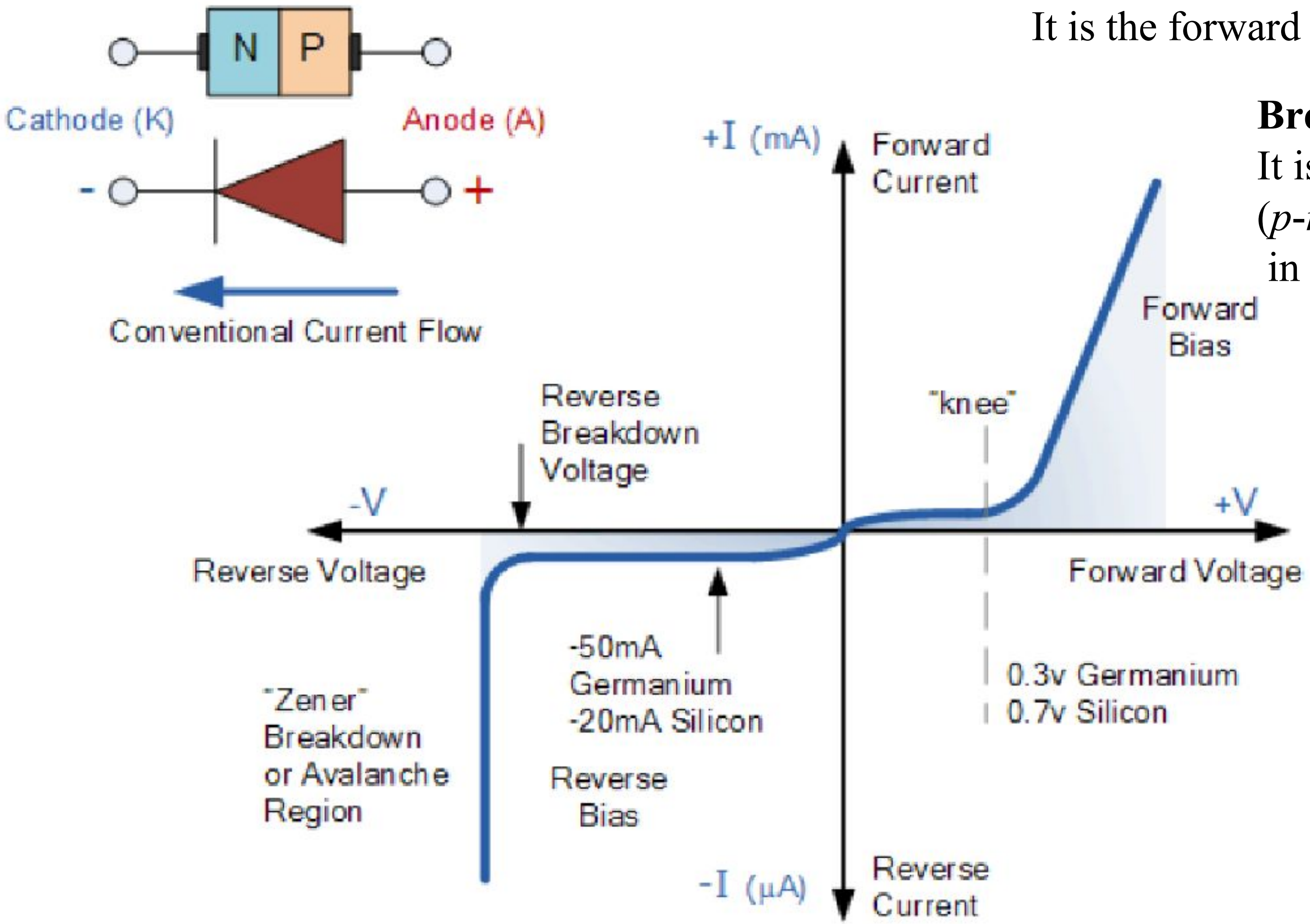
Diode Current

- Diode is **non-linear component** of an electrical circuit, which allow current in forward biasing and block current in reverse biasing.
- The behavior of a diode can be identified using VI characteristic. Current of the diode depends upon the voltage across the diode.
- The diode current can be expressed in the form of diode current equation.

$$\boldsymbol{I = I_0\, [e^{V/\eta V_T} - 1]}$$

- I – Diode Current
- Io- Diode reverse saturation current at room temperature
- V- External Voltage applied to the diode
- η – A constant, two for Silicon and one for Germanium
- $V_T - \frac{kT}{q}$ = T/11600 Volts-equivalent of temperature, thermal voltage

V-I Characteristics of PN Junction Diode



Knee Voltage or Cut-in Voltage

It is the forward voltage at which the diode starts conducting.

Breakdown Voltage

It is the reverse voltage at which the diode (*p*-*n* junction) breaks down with a suddenrise in reverse current.