Course title: **Electronic circuit I**

Course code: **EEE 215**

Lecture 2

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Semester: Summer 2020

Classification of Semiconductor

1. **Direct Bandgap** Semiconductor
2. **Indirect Bandgap** Semiconductor

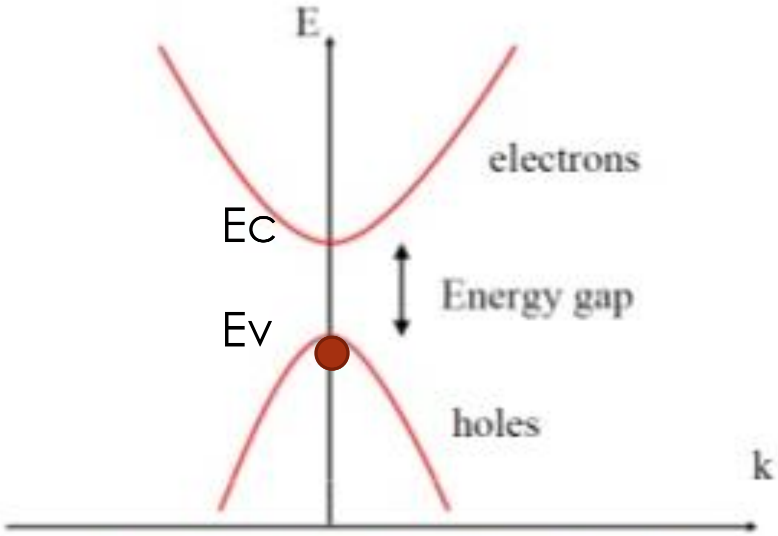
1. Intrinsic Semiconductor (pure)
2. Extrinsic Semiconductor →

1. Non-degenerate Semiconductor
2. Degenerate Semiconductor

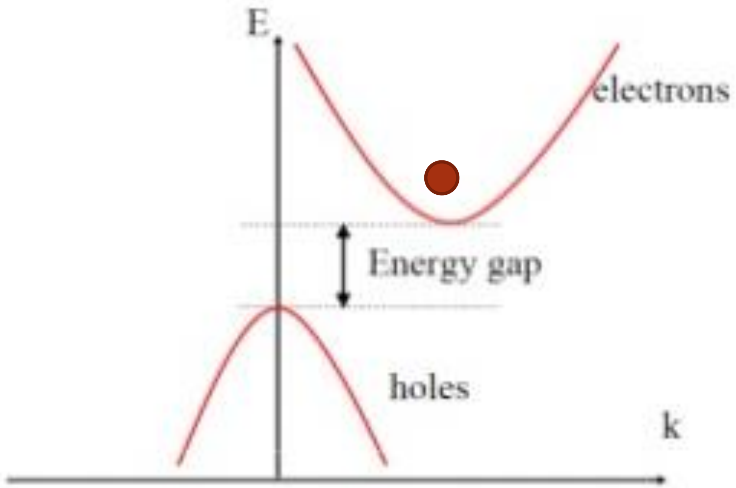
N-type Semiconductor
P-type Semiconductor

Direct Band-gap & Indirect Band-gap Semiconductor

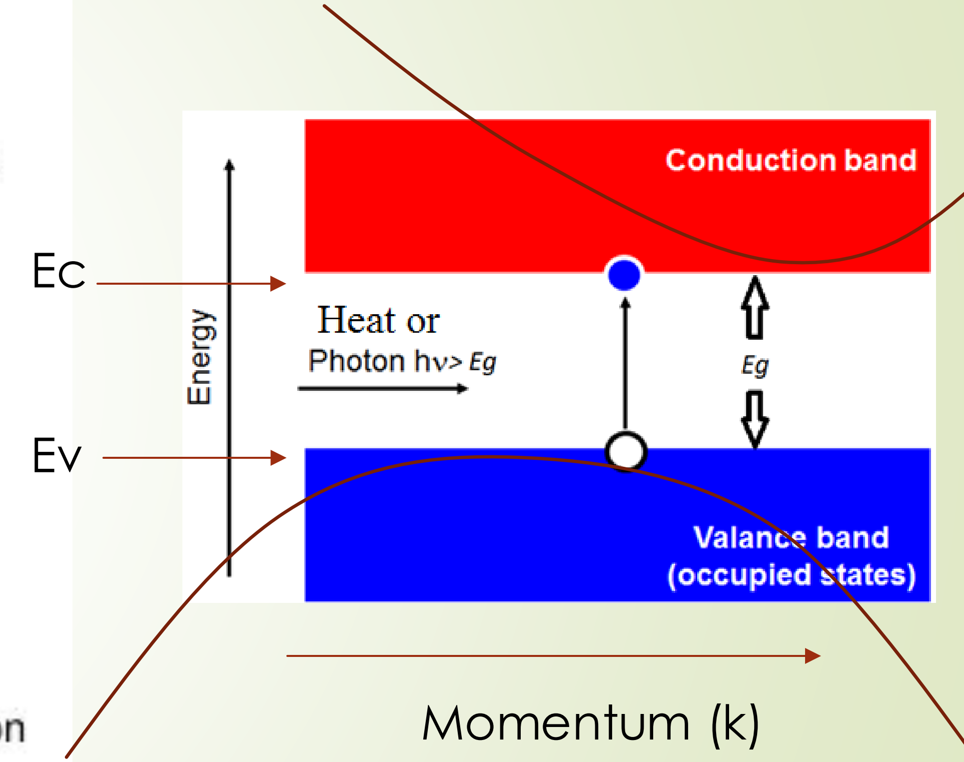
Direct and Indirect bandgap semiconductors:



Direct bandgap semiconductors



Indirect bandgap semiconductors



- Those materials for which maximum of valence band and minimum of conduction band lie for same value of k, called direct bandgap materials (i.e. satisfies the condition of energy and momentum conservation). For example: GaAs, InP, CdS..etc

- Those materials for which maximum of valence band and minimum of conduction band do not occur at same value of k, called indirect bandgap materials. For example: Si and Ge

Classification of Semiconductor

in terms of adding impurity or doping

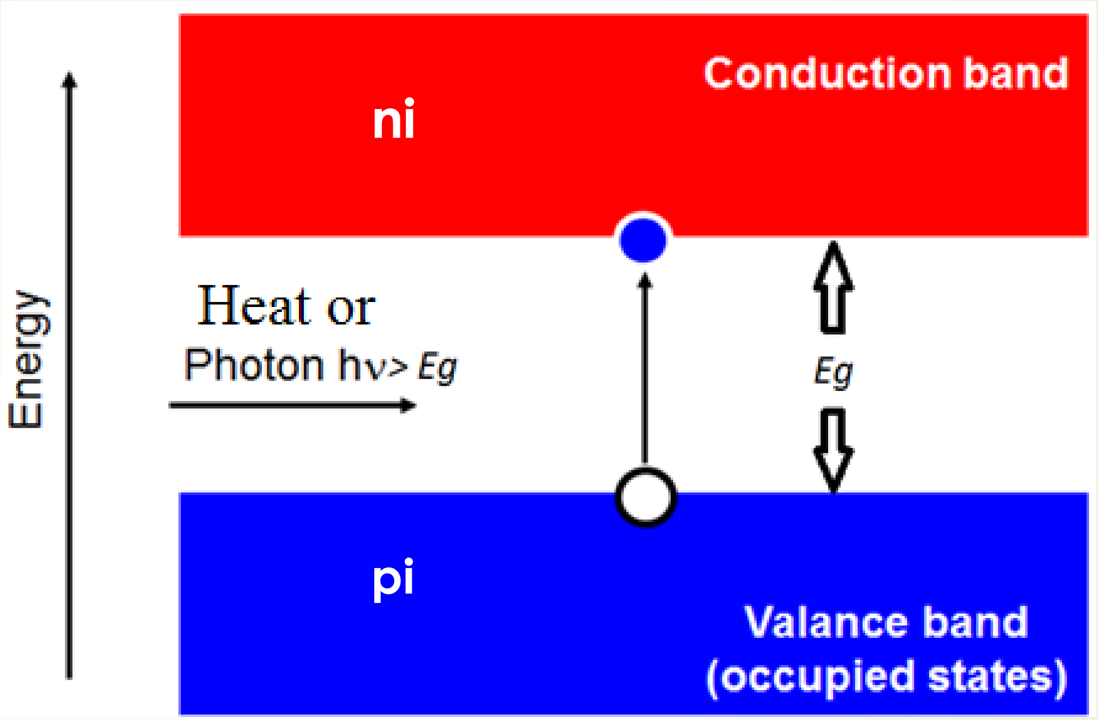
1. Minority
2. Majority

Intrinsic Semiconductor
(pure form/no dopant)
Temperature/photon source (minority)

Extrinsic Semiconductor
(impurity are added)
Majority

N-type semiconductor
Majority are electrons

p-type semiconductor
Majority are holes



empty

Filled by electrons

When T is 0 kelvin

When T is increased to 300 Kelvin

EHP= electron-hole pair, **ni=pi** **Minority**

Thermalization process.

Extrinsic Semiconductors: 1. n-type & 2. p-type

Extrinsic semiconductors are made from intrinsic semiconductors by a process called doping, and the impurity atoms are called dopants

The impurity atom can be penta-valent (n-type doping, donor) or tri-valent (p-type doping, acceptor)

Atoms on the right column are donors and on the left column are acceptors

Example: For Si, P, As are donors while B, Ga are acceptors

Table 1.2 Abbreviated Periodic Chart of the Elements.

II	III	IV	V	VI
4 Be	5 B	6 C	7 N	8 O
12 Mg	13 Al	14 Si	15 P	16 S
30 Zn	31 Ga	32 Ge	33 As	34 Se
48 Cd	49 In	50 Sn	51 Sb	52 Te
80 Hg	81 Tl	82 Pb	83 Bi	84 Po

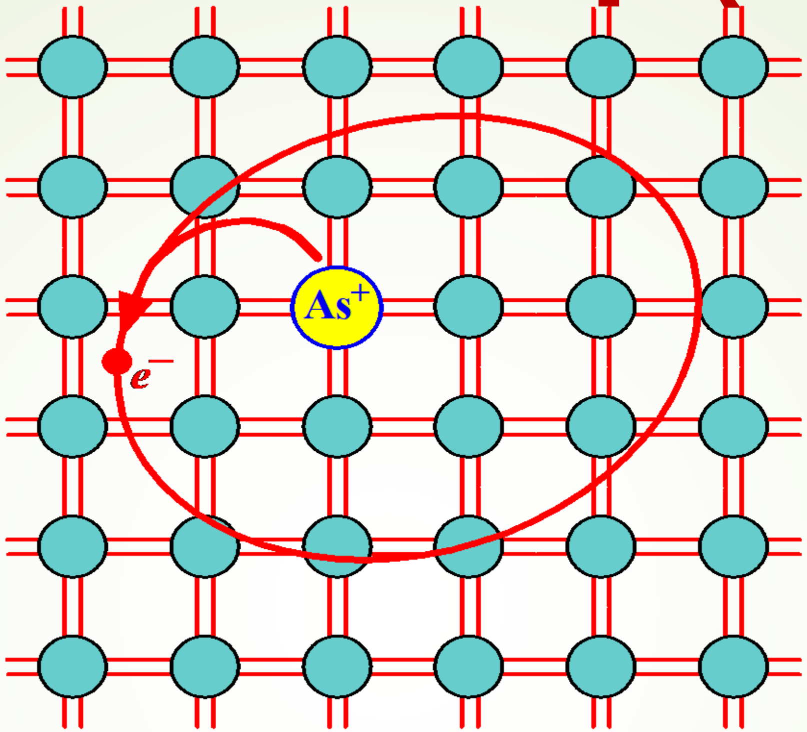
Extrinsic Semiconductors [n (electron)-type]

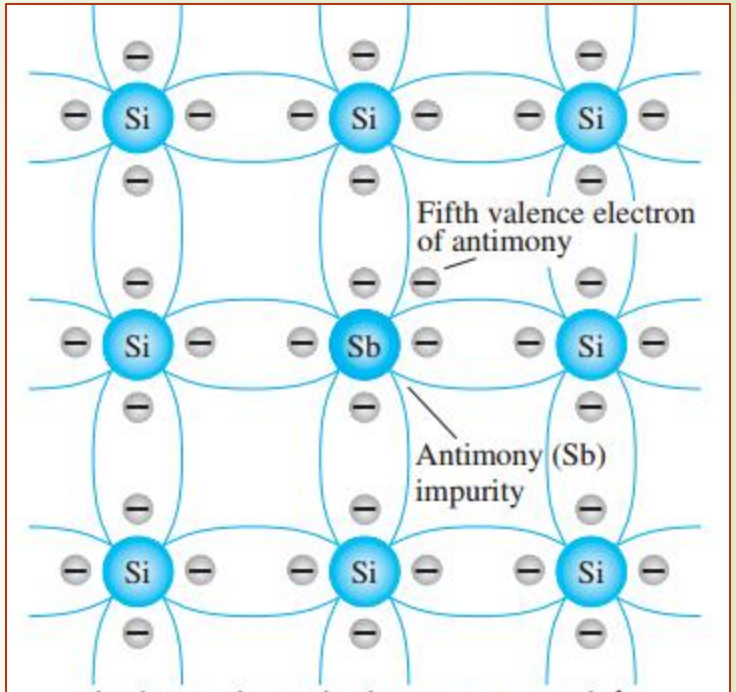
1 electron
1 As

4 As/Sb/P
4 electron
As/Sb/P= Donor impurity

Donor impurity=N_D= n_n

n_n= majority carrier





Antimony impurity in n-type material.

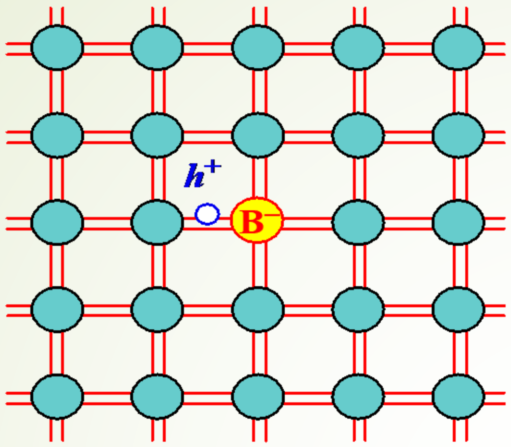
Si (4)+ pentavalent-Sb-impurity (4+1) = n-type

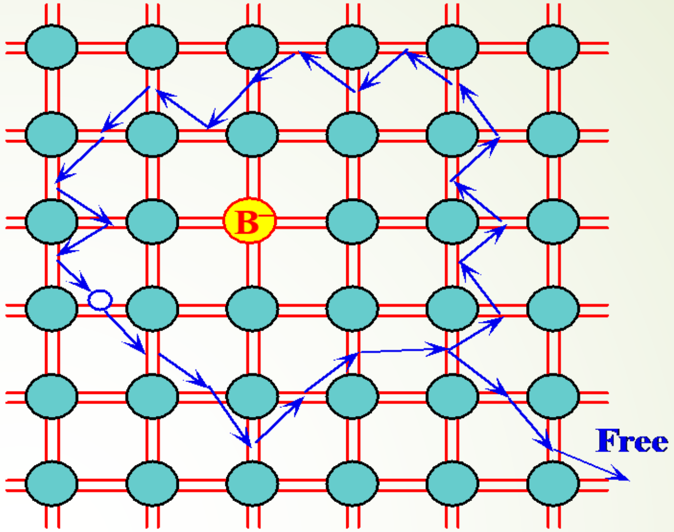
Fig. 5.9: Arsenic doped Si crystal. The four valence electrons of As allow it to bond just like Si but the fifth electron is left orbiting the As site. The energy required to release to free fifth-electron into the CB is very small.

From *Principles of Electronic Materials and Devices, Second Edition*, S.O. Kasap (© McGraw-Hill, 2002) http://Materials.Usask.Ca

Extrinsic Semiconductors (p(holes)-type)

Hole is absence or shortage of electron





1000000 B
1000000 Holes

Na=Acceptor impurity

$Na^- = p_p$

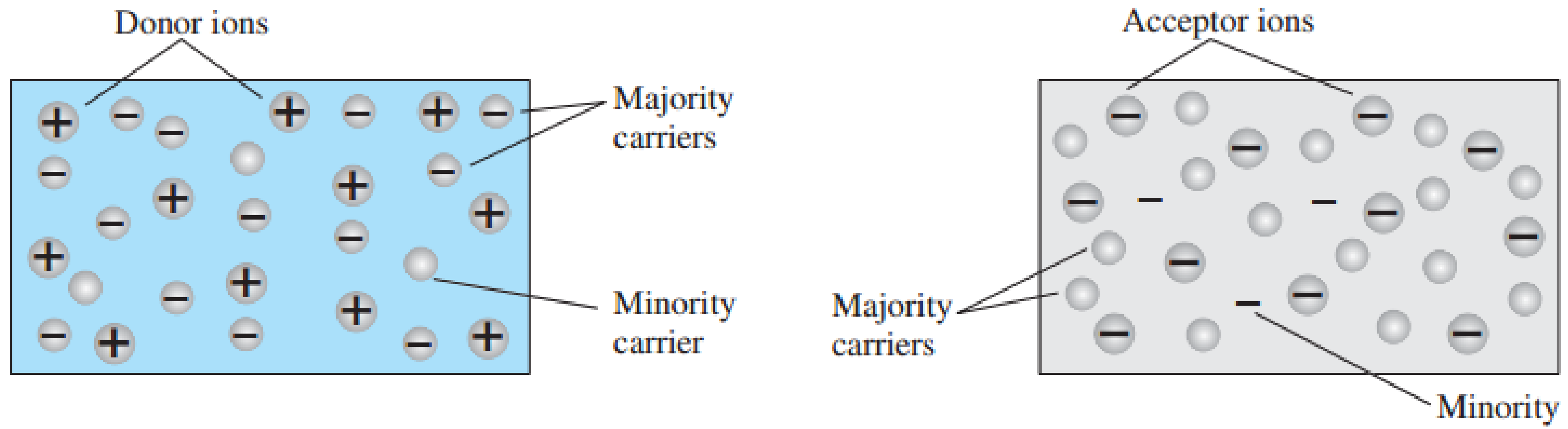
$Holes = p_p$

$1x10^{16}$

Si (4) + trivalent-B-impurity (3) = p-type

Fig. 5.11: Boron doped Si crystal. B has only three valence electrons. When it substitutes for a Si atom one of its bonds has an electron missing and therefore a hole as shown in (a). The hole orbits around the B– site by the tunneling of electrons from neighboring bonds as shown in (b). Eventually, thermally vibrating Si atoms provides enough energy to free the hole from the B– site into the VB as shown.

Majority and minority carriers:



(a) n-type material; (b) p-type material.

- *In an n-type material the electron is called the majority carrier and the hole the minority carrier. (N_D^+=donor, n_n=majority electron in 'n', p_n=minority holes in 'n')*
- *In a p-type material the hole is the majority carrier and the electron is the minority carrier. (N_a^-=Acceptor, p_p=majority holes in 'p', n_p=minority electrons in 'p')*

Extrinsic Semiconductors (Carrier Density)

ni=pi

Si

n_n p_n

N-type

p_p n_p

P-type

At equilibrium: $$p_p n_p = n_n p_n = n_i^2$$

n-type $$n_n p_n = n_i^2$$

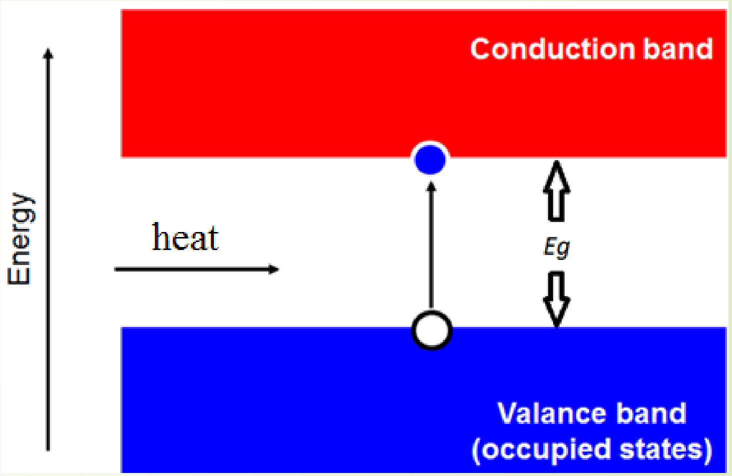
p-type $$p_p n_p = n_i^2$$

For n-type doped materials:

$$n_n = N_D \qquad p_n = \frac{n_i^2}{N_D}$$

For p-type doped materials:

$$p_p = N_A \qquad n_p = \frac{n_i^2}{N_A}$$



EHP

ni=pi it depends on Temperarure

T=300 and Si

$ni=1.5x10^{15}$ /cm3

- Thermalization process creates pair of electrons-holes that are called Minority charge carriers (**Thermally induced minority carriers, ni, pi, ni=pi**).

Table 4.2 | Commonly accepted values of n_i at $T = 300$ K

Silicon	$n_i = 1.5 \times 10^{10}$ cm^{-3}
Gallium arsenide	$n_i = 1.8 \times 10^{6}$ cm^{-3}
Germanium	$n_i = 2.4 \times 10^{13}$ cm^{-3}

Intrinsic/pure Semiconductors

CB : Free electrons reside

VB : Bound electrons & free holes reside

E_C : Conduction band edge

E_V : valence band edge

E_g : band gap

E_F : Fermi energy (probability of finding electrons)

We are interested in free electrons in CB and free holes in VB for electronic properties & desired conductivity

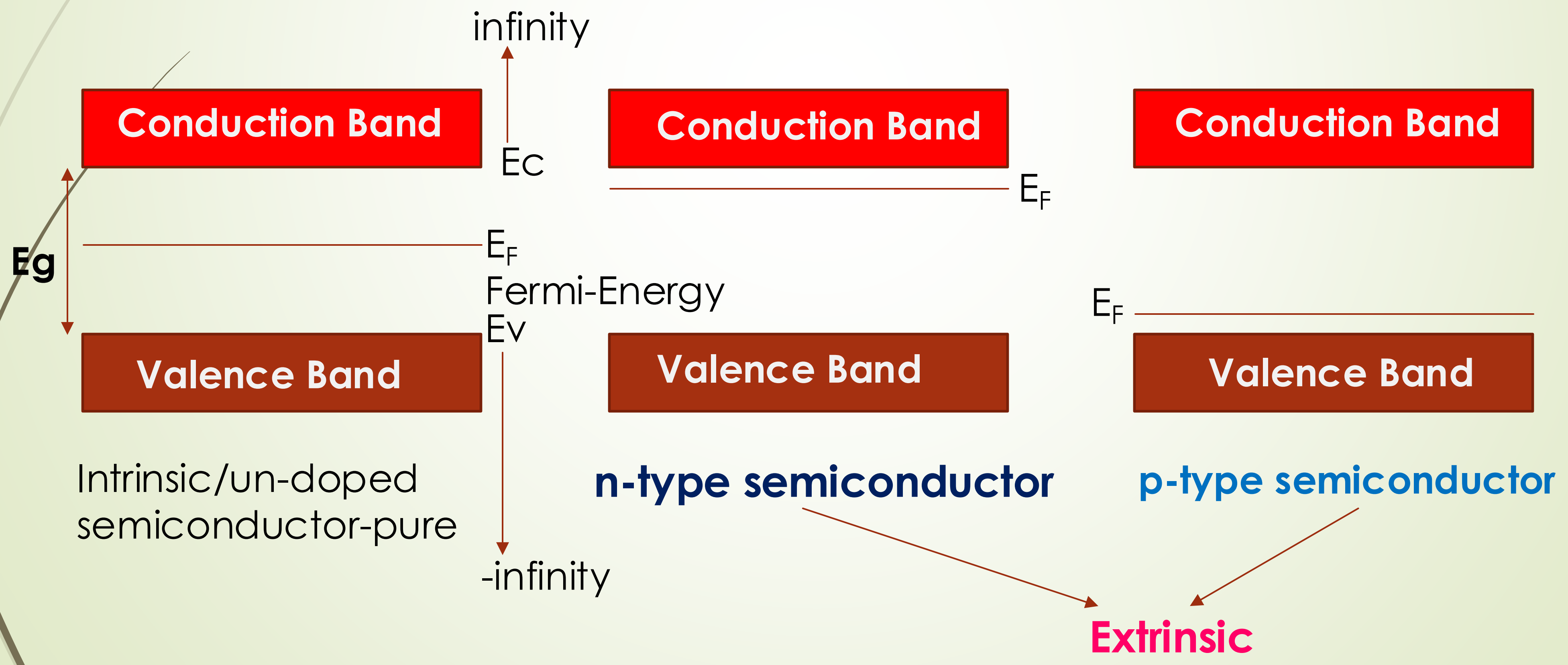
- *For intrinsic/un-doped semiconductor the Fermi energy lies at the middle of the conduction band*
- Fermi Energy (it is the energy **below** which all states are filled by electrons)

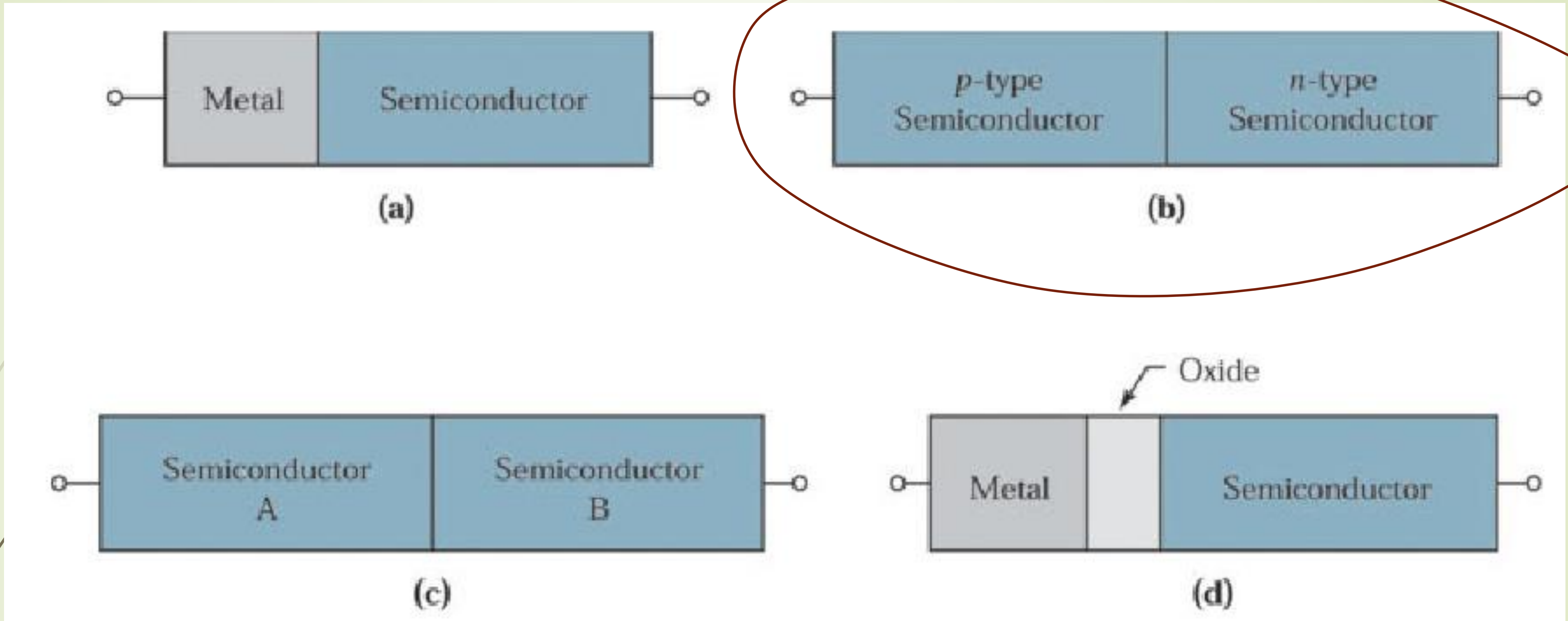
Extrinsic Semiconductors

1. n-type

2. p-type

- For intrinsic/un-doped semiconductor the Fermi energy lies at the middle of the conduction band
- For n-type semiconductor the Fermi energy, E_F is located close to the conduction band
- For p-type semiconductor the Fermi energy is located close to the valence band

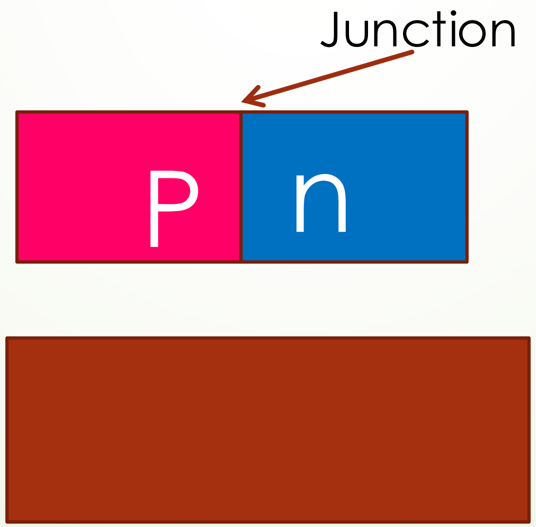


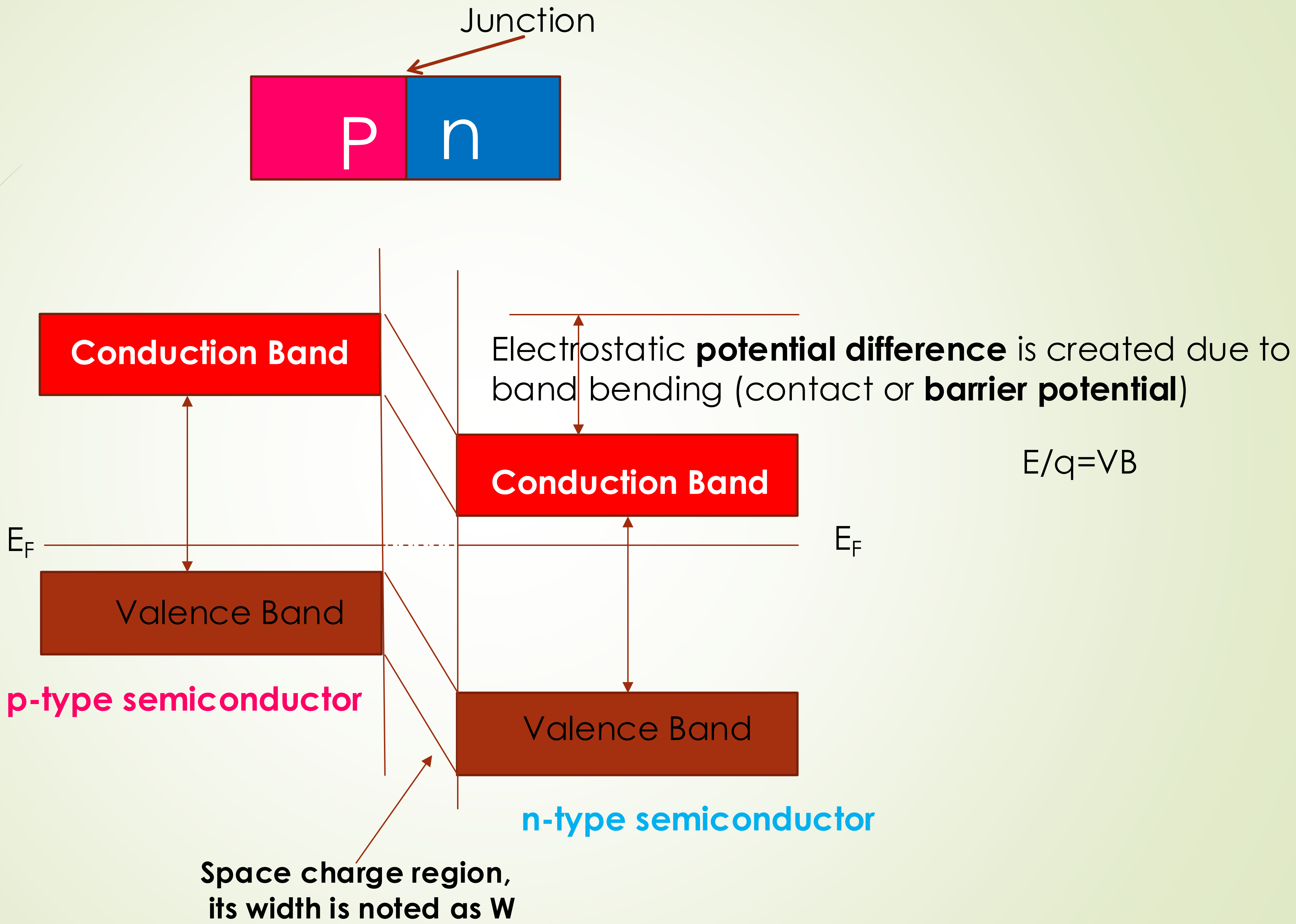


Basic device building blocks: (a) Metal-semiconductor interface; (b) p-n homo-junction; (c) p-n n-n or p-p heterojunction interface; and (d) metal-oxide-semiconductor structure

p-n Junction is the most fundamental device building block

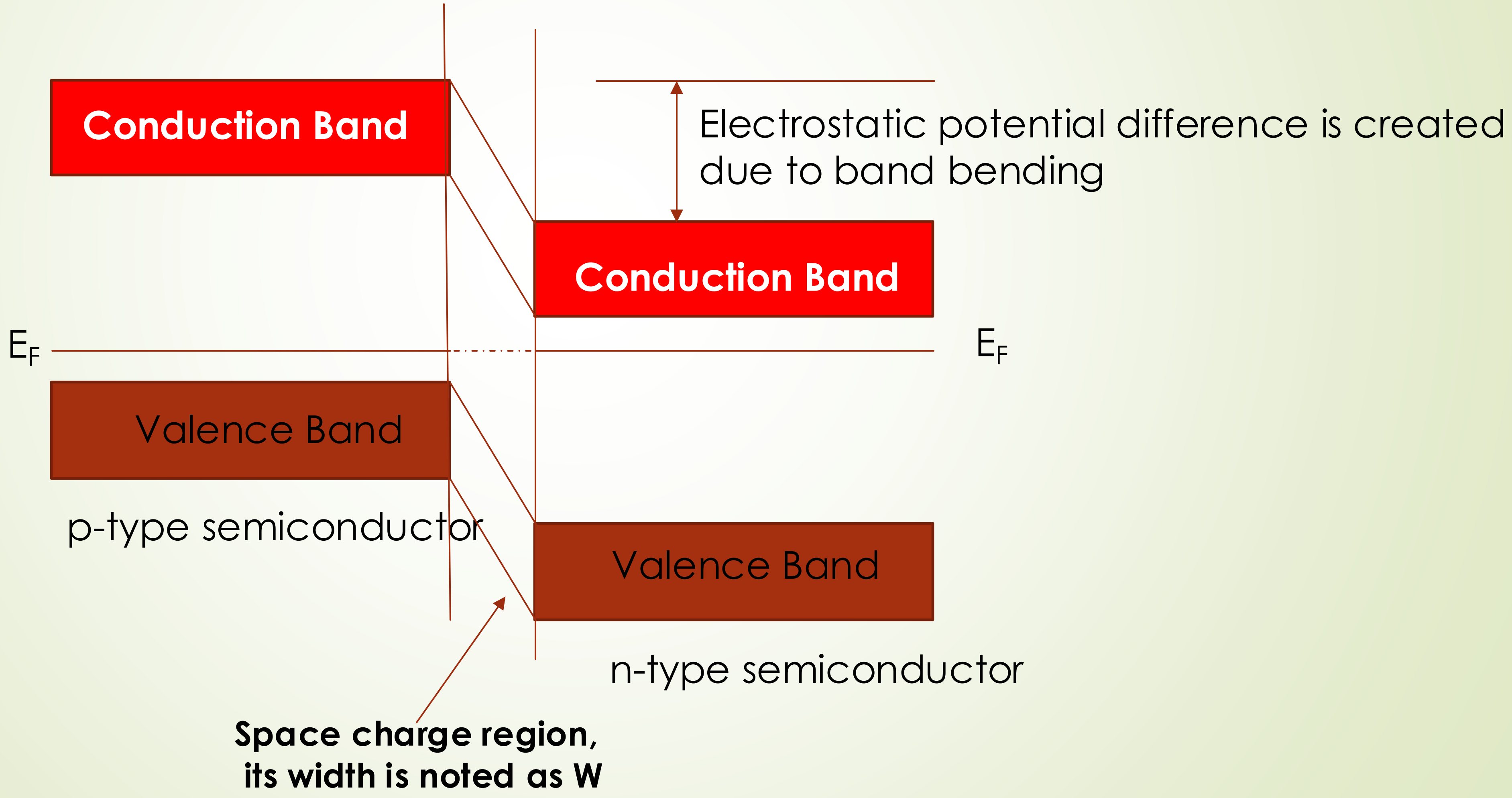
- When p-type Semiconductor is suitably in contact with n-type semiconductor, the p-n junction is formed.




Junction
p
n
Conduction Band
Electrostatic **potential difference** is created due to band bending (contact or **barrier potential**)
E/q=VB
Conduction Band
E_F
E_F
Valence Band
p-type semiconductor
Valence Band
n-type semiconductor
Space charge region,
its width is noted as W

p-n junction: when p type is suitably in contact with n type how does the energy diagram look?

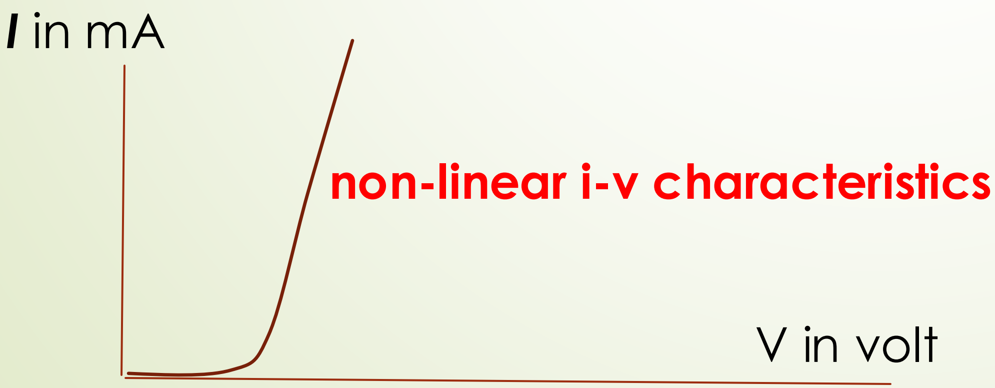
1. Fermi level should be continuous throughout the junction
2. and therefore there will be band bending at the junction



Semiconductor diode:

Diodes are the most simplest and fundamental non-linear circuit elements.

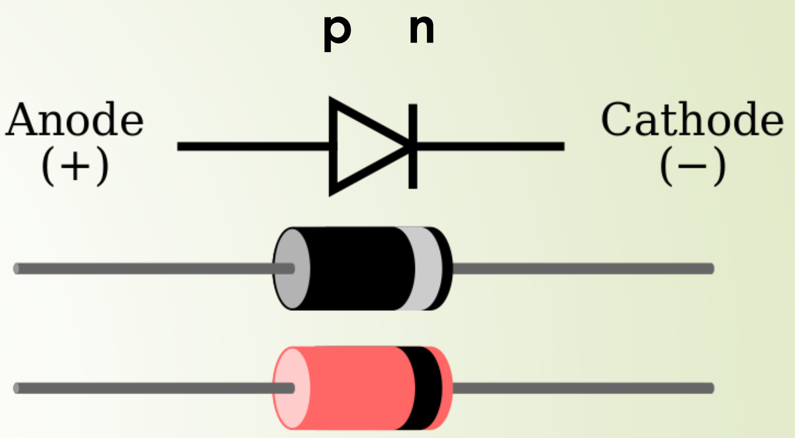
- A **diode** is a **two-terminal electronic component**, Just like resistors, but unlike the resistor which has linear relationship between the current flowing through it and the voltage appearing across it, **the diode has non-linear i-v characteristics.**

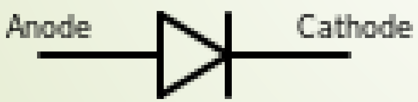


Semiconductor diode:

A **diode** shows

- low (ideally zero) resistance to current flow in forward direction,
- and high (ideally infinite) resistance in the reverse.
- The discovery of crystals' rectifying abilities was made by German physicist Ferdinand Braun in 1874. Today most diodes are made of silicon (Si), but other semiconductors such as selenium or germanium (Ge) are sometimes used.
- **A semiconductor diode, the most common type today, is a crystalline piece of semiconductor material with a [p–n junction] connected to two electrical terminals.**





Conventional Diode

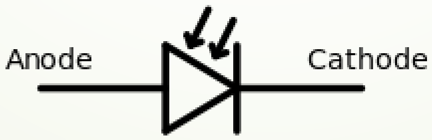
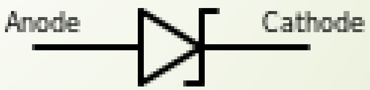
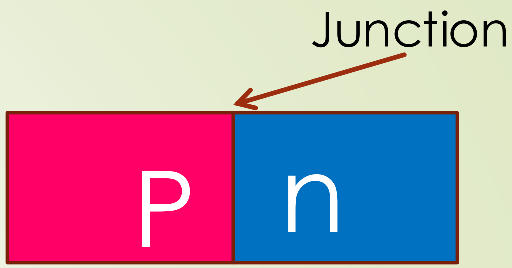


Photo diode symbol



Zener diode symbol

A diode is formed by the formation of p-n junction:



When a p-type semiconductor is suitably in contact with a n-type semiconductor, the contact surface is called p-n junction.

It is important to note that simply butting an n-type semiconductor against a p-type semiconductor does not form a junction. The irregular surface atomic forces at such a physical discontinuity at the interface simply prevent junction formation. It is essential that the crystalline background forces are uniform across the junction, i.e., the basic internal crystal regularity is maintained across the junction.

A semiconductor junction is commonly formed by doping a semiconductor so that the impurity concentration varies from n-type to p-type. The electrical junction forms about the 'metallurgical' junction where the transition from one doping type to the other occurs.

The p-n junction may be produced by any one of the following

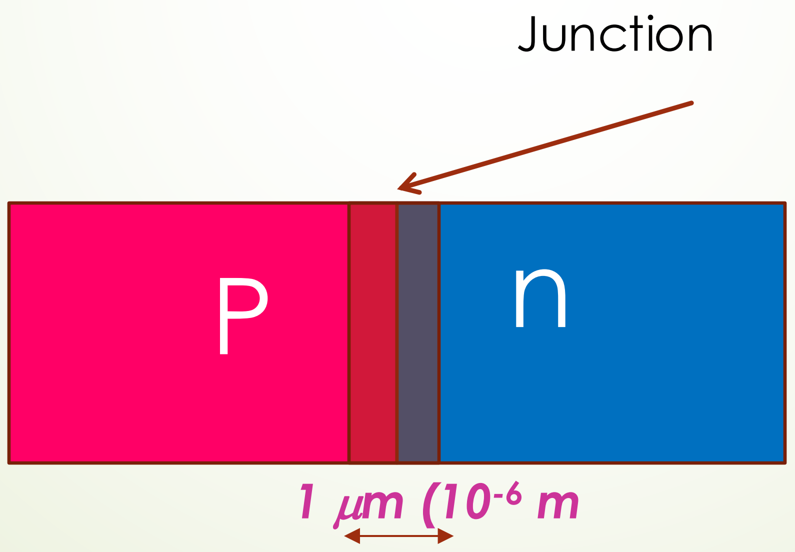
i. Grown junction
ii. Alloy junction
iii. Diffused junction
iv. Epitaxial growth, v. point contact junction

Physical properties of p-n junction:

During the formation of p-n junction, following two phenomena take place:

i. ***A thin depletion layer (or region) is set up on both sides of the junction** and is so called because it is depleted or devoid of free charge carriers. Its typical width is about 1 μm (10^{-6} m).*

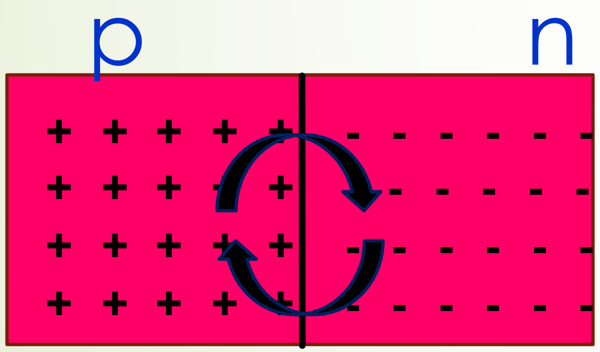
ii. ***A junction or barrier potential V_B** is developed across the junction whose value is about **0.3 V for Ge** and **0.7 V for Si**.*



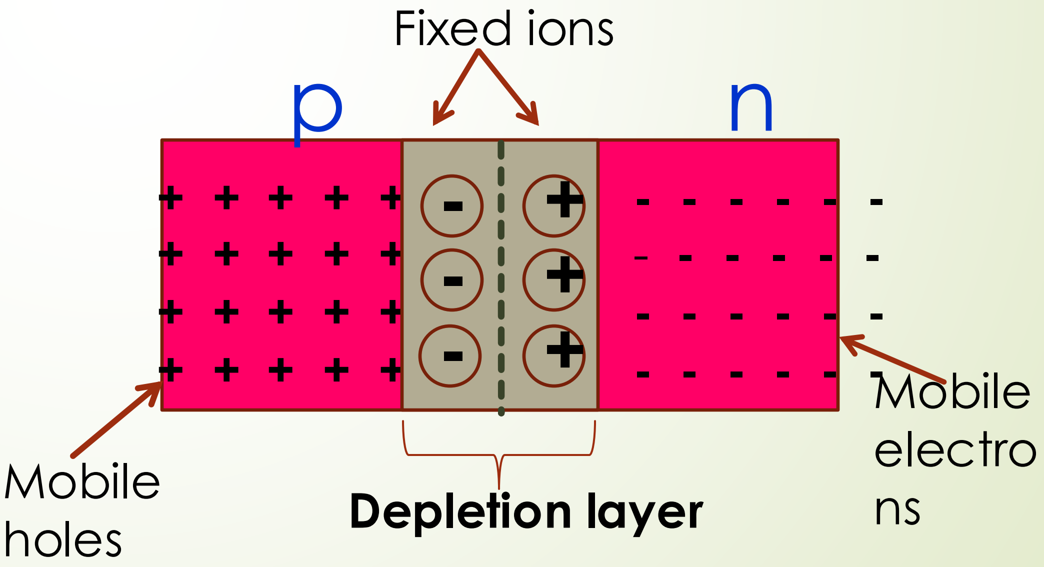
Formation of depletion region:

After a p-n junction is formed, a difference in concentration of carriers creates a density gradient of carriers across junction which will result is majority carrier diffusion .

- *i.* ***The holes diffuse from p to n region while electrons from n to p. This recombination of carrier will cause a lack of free carrier at the junction leaving behind the fixed/immobile ions .***
- *ii.* ***This region of uncovered positive and negative ion is called depletion region/layer.***
- *iii.* ***Since this layer contain no free charge it behaves like insulator.***



Diffusion



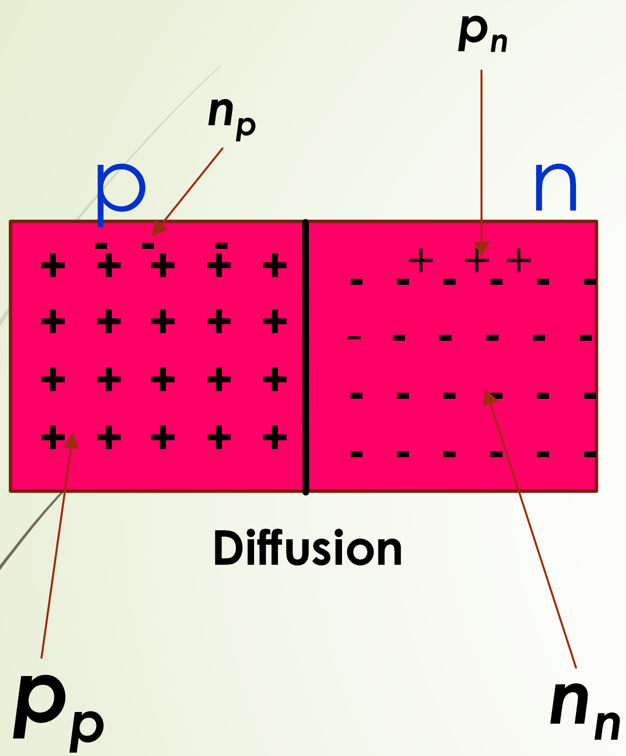
ni=pi

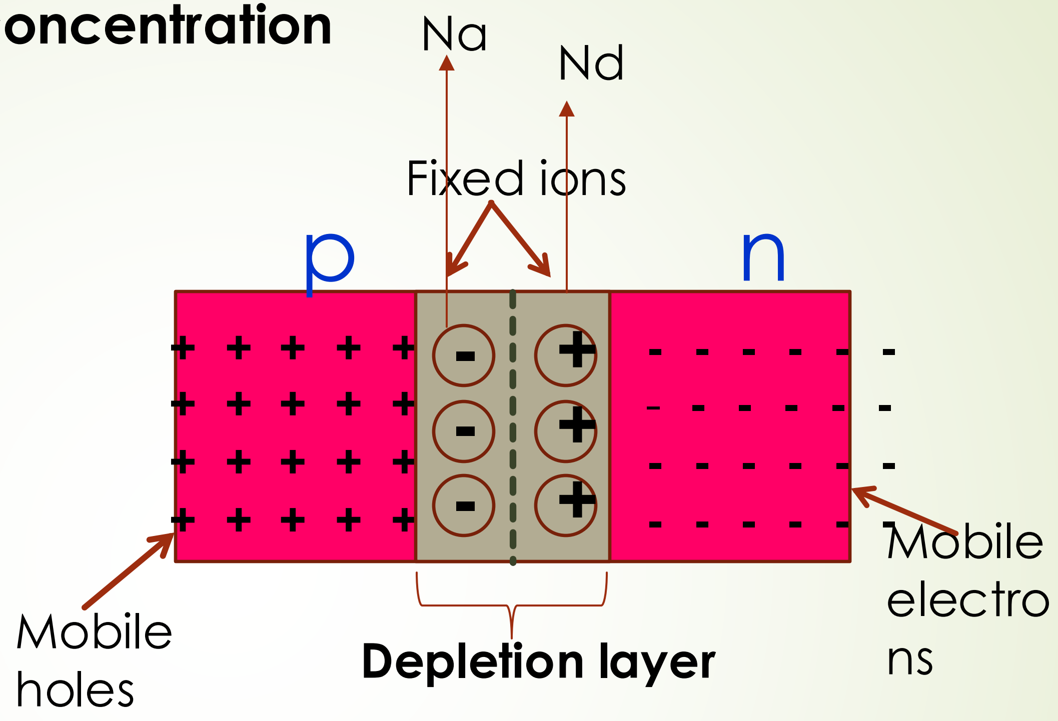
Si

N-type

P-type

High concentration to low concentration





Hole will diffuse from p to n

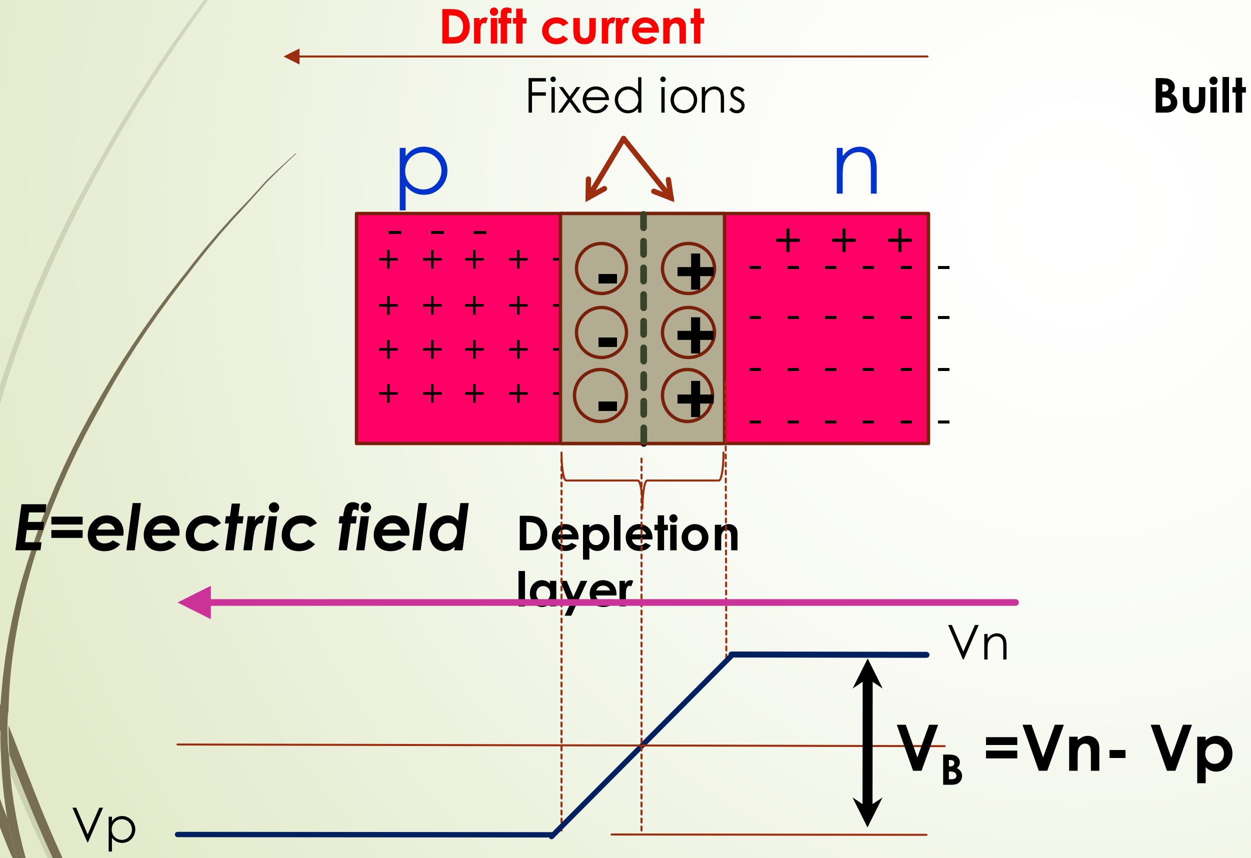
Electron will diffuse from n to p

There is diffusion current from p to n

Formation of junction or barrier voltage:

Since the depletion layer contain only fixed rows of oppositely charged carriers,

i. ***due to this charge separation an electric potential V_B is established across the junction***
ii. ***This potential difference further opposes the diffusion of majority carriers across the junction***
iii. ***The width of depletion region/layer depends on doping level. For heavy doping, depletion layer is physically thin.***



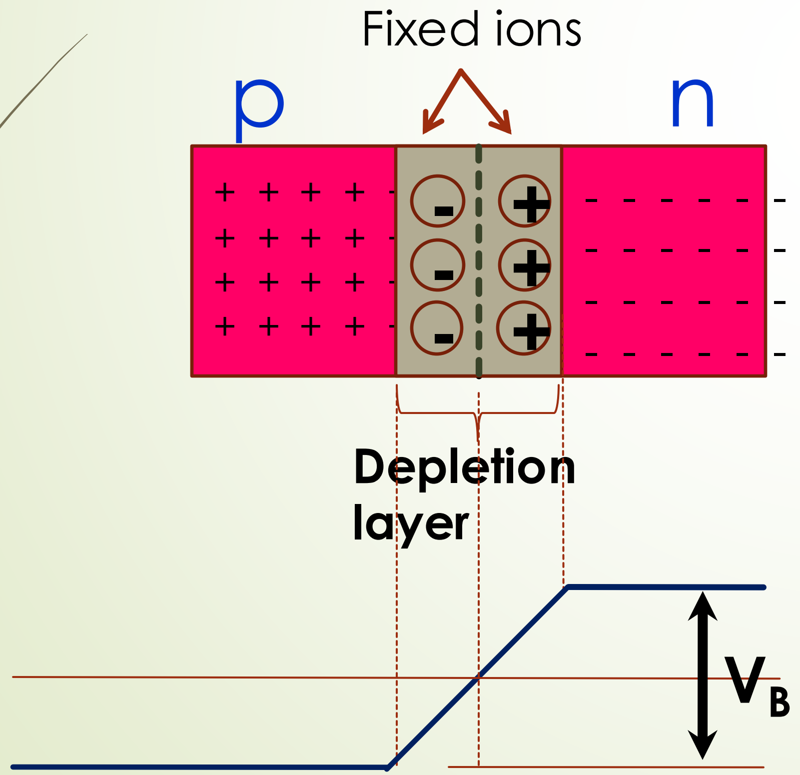
Built in Electric Field $= \dfrac{change - in - potential}{change - in - dis\tan ce}$

$$E = -\frac{dV}{dx}$$

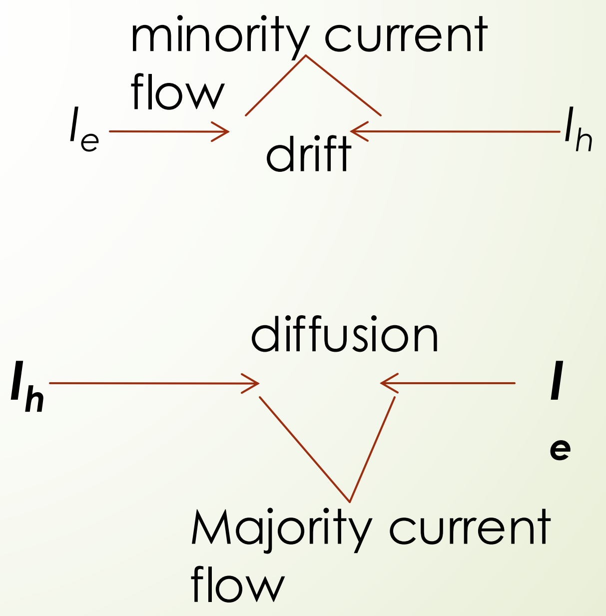
Formation of junction or barrier voltage:

Since the depletion layer contain only fixed rows of oppositely charged carriers,

i. ***due to this charge separation an electric potential V_B is established across the junction***
ii. ***This potential difference further opposes the diffusion of majority carriers across the junction***
iii. ***The width of depletion region/layer depends on doping level. For heavy doping, depletion layer is physically thin.***



Under no bias net current flow across the junction = zero



$J = I/A$ current density

Drift and diffusion:

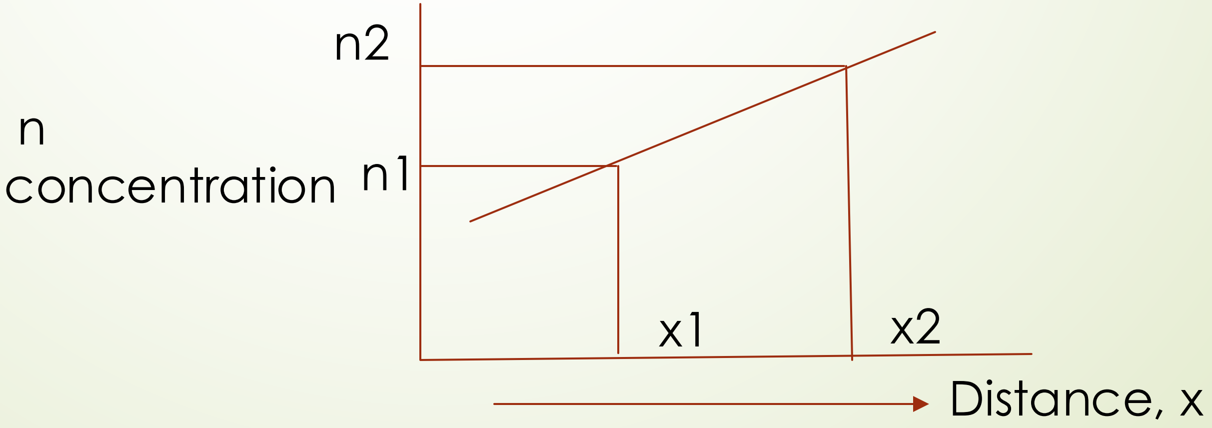
There are two mechanisms by which holes and electrons move through the silicon crystal-**drift** and **diffusion**.

Diffusion: is associated with random motion due to thermal agitation. Carriers diffuse from the higher region of concentration to lower concentration. This diffusion process gives rise to a net flow of charge, or diffusion current.
Diffusion current density

$$J_n = qD_n \frac{dn}{dx}$$

$$J_p = -qD_p \frac{dp}{dx}$$

Where D_p = 12 cm^2/s, is the hole diffusion coefficient,
D_n = 34 cm^2/s, is the electron diffusion coefficient.



Drift:

The other mechanism in semiconductors is drift. Carrier drift when an electric field is applied across a piece of semiconductor. Free electrons and holes are accelerated by the applied electric field and acquire velocity component called drift velocity,

$\mathbf{v_{drift}=\mu_{p,n}E}$, where $\mu_{p,n}$ is the mobility of holes/electrons

The hole-drift current density is $J_{p\text{-}drift}=qp\mu_p E$

The electron-drift current density is $J_{n\text{-}drift}=qn\mu_n E$

The total drift current density is $J_{drift}=q(p\mu_p + n\mu_n)E$

The Einstien relation

$$\frac{D_n}{\mu_n}=\frac{D_p}{\mu_p}=V_T=\frac{KT}{q}=thermal\ voltage=25mV, at 300K$$

Quantitative relation between barrier potential and doping concentration on each side of the junction:

We know the drift and diffusion component **of hole** current just **cancel out each other at equilibrium**

$$q[\mu_p pE - D_p \frac{dp}{dx}] = 0 \qquad (1)$$

$$\frac{\mu_p}{D_p} E = \frac{1}{p}\frac{dp}{dx}$$

$$\boxed{V_B = \frac{kT}{q}\ln\frac{n_n}{n_p}} \qquad (2)$$

We know,

$$E = -\frac{dV}{dx} \qquad (3)$$

ing Einstein relation,

$$-\frac{q}{KT}\frac{dV}{dx} = \frac{1}{p}\frac{dp}{dx} \qquad (4)$$

$$\boxed{\frac{n_n}{n_p} = e^{qV_B/kT}}$$

After integrating,

$$-\frac{q}{KT}\int_{V_p}^{V_n} dV = \int_{P_p}^{P_n} \frac{1}{p} dp \qquad \text{or,} -\frac{q}{KT}(V_n - V_p) = \ln\frac{P_n}{P_p} \qquad (5)$$

V_n-V_p=V_B= contact potential,

$$V_B = \frac{kT}{q}\ln\frac{P_p}{P_n}, \qquad \text{or,} \frac{P_p}{P_n} = e^{qV_B/kT} \qquad (6)$$

We know, $p_p n_p = n_i^2 = p_n n_n$ We can extend equation 6 for also electron concentration

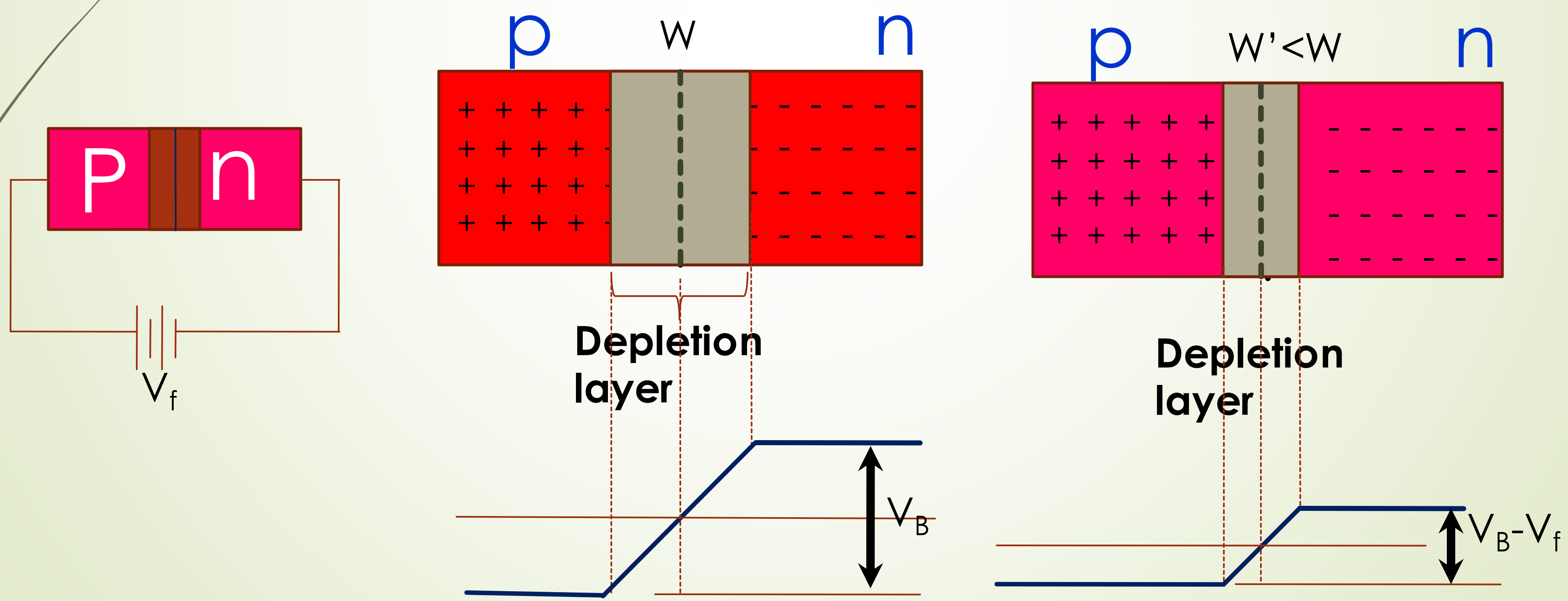
$$\frac{P_p}{P_n} = \frac{n_n}{n_p} = e^{qV_0/kT}$$

$$\boxed{V_B = \frac{kT}{q}\ln\frac{N_a}{n_i^2 / N_d} = \frac{kT}{q}\ln\frac{N_a N_d}{n_i^2}}$$

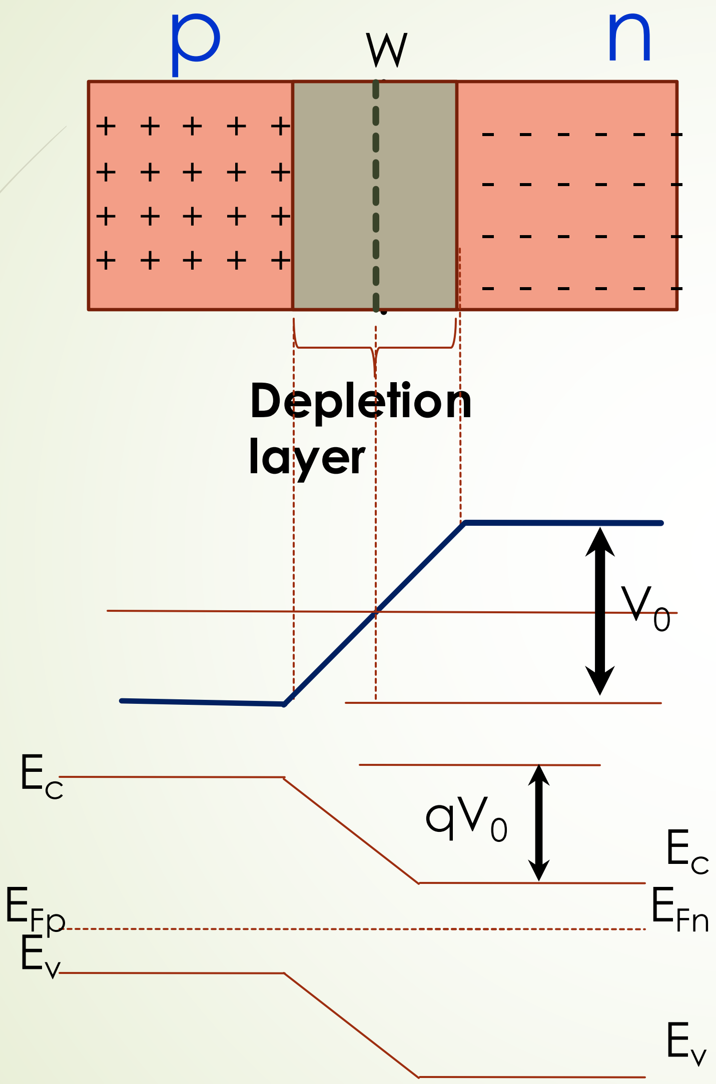
Forward biased condition of p-n junction semiconductor diode:

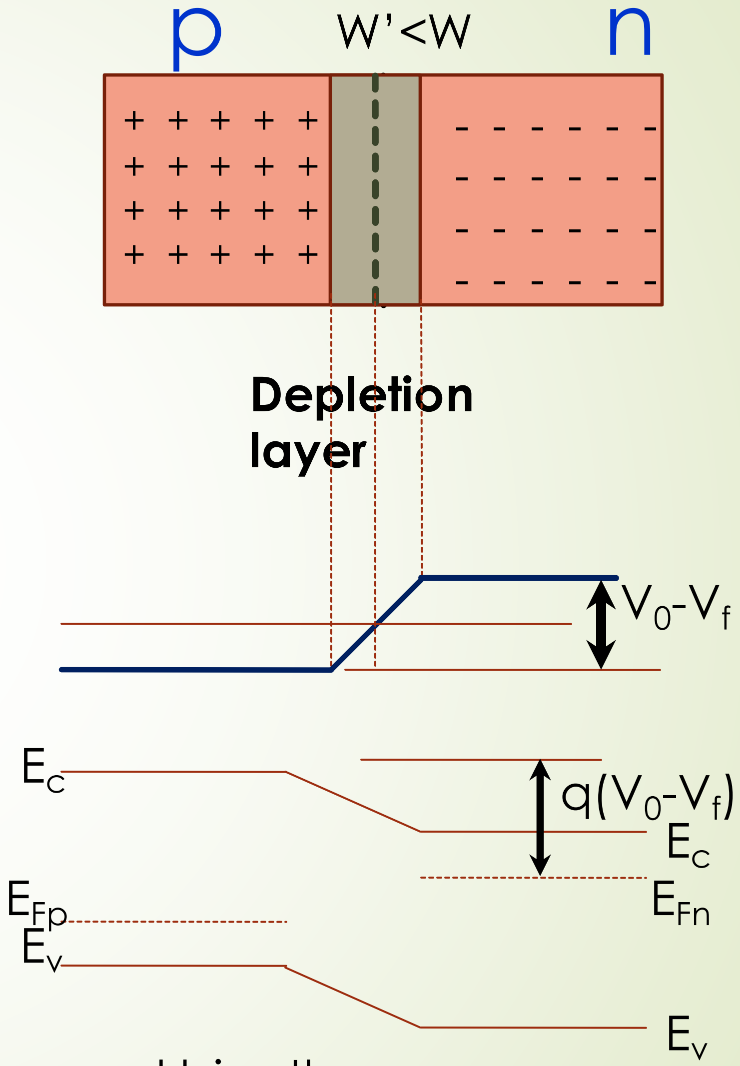
i. *A forward biased 'on' condition is obtained by applying a positive potential to the p-side of the junction and negative potential to the n-side.*

ii. *The application forward bias will cause the electrons and holes driven towards the junction where they recombine and will reduce the width of the depletion region . The resulting minority carrier flow of electrons from p to n will not change, but the reduction of depletion layer will create large amount of current flow across junction.*



Effect of forward biased on the energy band diagram of p-n junction semiconductor diode:

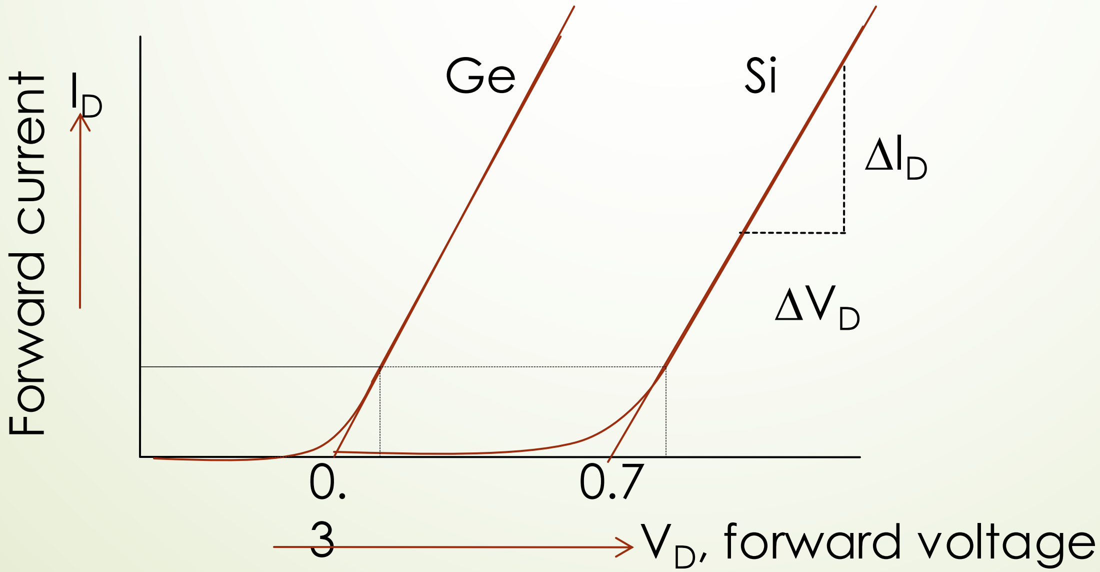




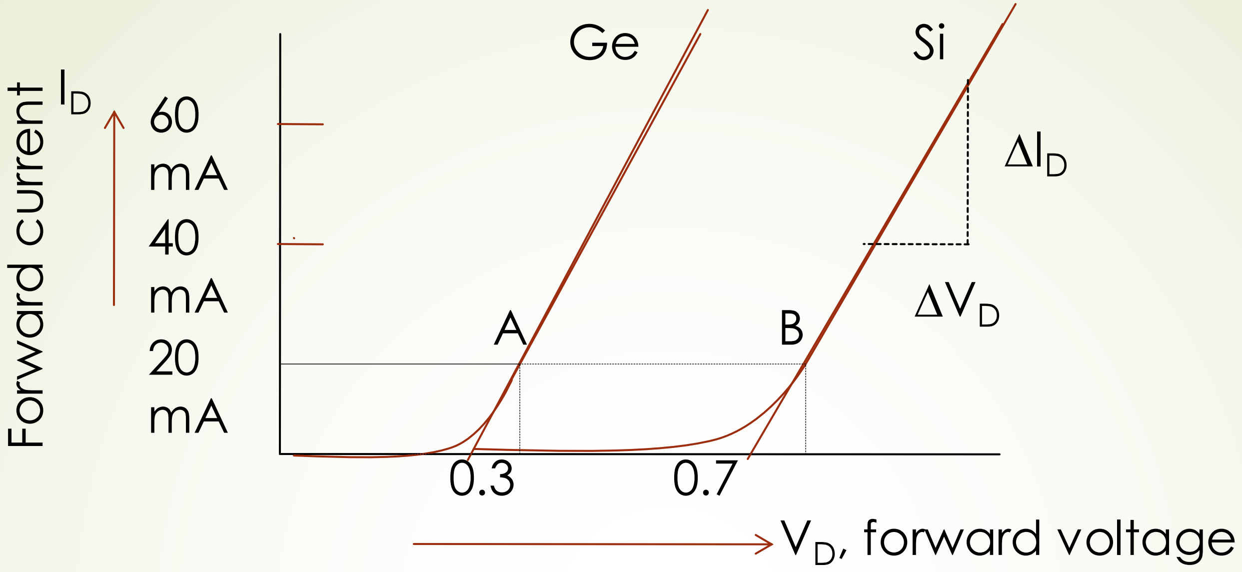
With forward bias the electrostatic potential is lowered from the equilibrium contact potential to V_0-V_f.

Forward V/I characteristics of p-n junction semiconductor diode:

i. *When diode is forward bias and the applied voltage is increased from zero, hardly any current flow the device in the beginning.*
ii. *It is so because the external voltage is opposed by the internal barrier voltage V_B which is 0.7 for Si and 0.3 for Ge.*
iii. *As soon as V_B is neutralized It is seen that the forward current rises exponentially with the applied forward voltage.*
iv. *This voltage is known as threshold voltage V_{th}, cut-in voltage or knee voltage.*
v. *When $V<V_{th}$, negligible current flow*
vi. *When $V>V_{th}$, current rise exponentially*



Forward biased junction resistance:



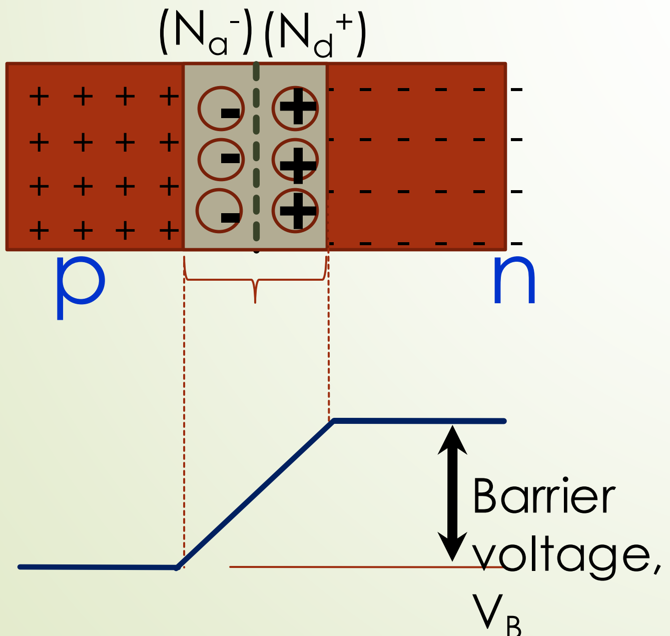
Obviously the forward-biased junction has very low resistance,
For point B in Si,
Static forward resistance is $R_F = \dfrac{0.76V}{20mA}$

In practice static resistance is not used instead ***dynamic resistance*** or ***ac resistance*** is used. It is given by the reciprocal of the slop of the forward characteristics.

$$\frac{1}{R_{ac}} = \frac{\Delta I_D}{\Delta V_D}$$

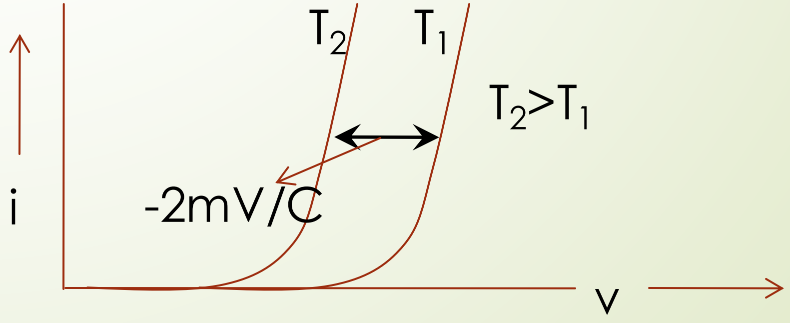
Effect of temperature on barrier voltage:

i. *Barrier voltage depends on doping density, electronic charge and temperature.*
ii. *For a given junction the first two factors are fixed, therefore V_B (barrier voltage) is mainly dependent on temperature.*
iii. *With increase in temperature results in increase of minority carriers leading to their increased drift across the junction.*
iv. *As a result equilibrium occurs at slightly reduced barrier potential.*
v. *It is found that for both Ge and Si VB is decreased about 2mV/°C*



$$\Delta V_B = -0.002.\Delta T$$

$$\Delta T = Change \text{ in } Temperature \text{ in } {}^oC$$



Reverse biased p-n junction:

i. *A reversed biased ‘off’ condition is obtained by applying a negative potential to the p-side of the junction and positive potential to the n-side.*

ii. *The application forward bias will cause the electrons and holes driven towards the junction where they recombine and will reduce the width of the depletion region . The resulting minority carrier flow of electrons from p to n will not change, but the reduction of depletion layer will create large amount of current flow across junction.*

Problem:

Q. Calculate the barrier potential of Si junction at (a) 100 ^{o}C and (b) at 0 ^{o}C if its value at 25 ^{o}C is 0.7 V.

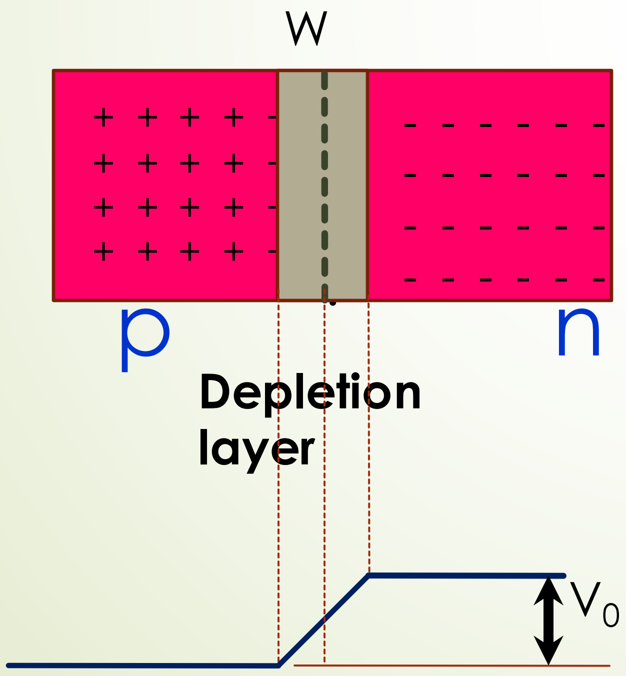
Reverse biased p-n junction:

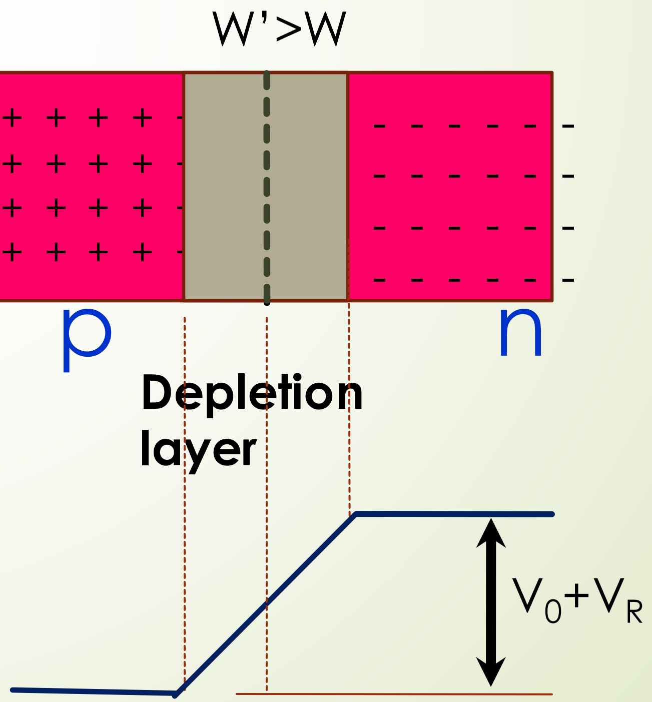
i. *A reversed biased 'off' condition is obtained by applying a negative potential to the p-side of the junction and positive potential to the n-side.*

ii. *The application forward bias will cause the electrons and holes attracted by the positive and negative battery terminals. Both electrons and holes move away from junction and away from each other*

iii. *No current flows and junction offers high resistance*

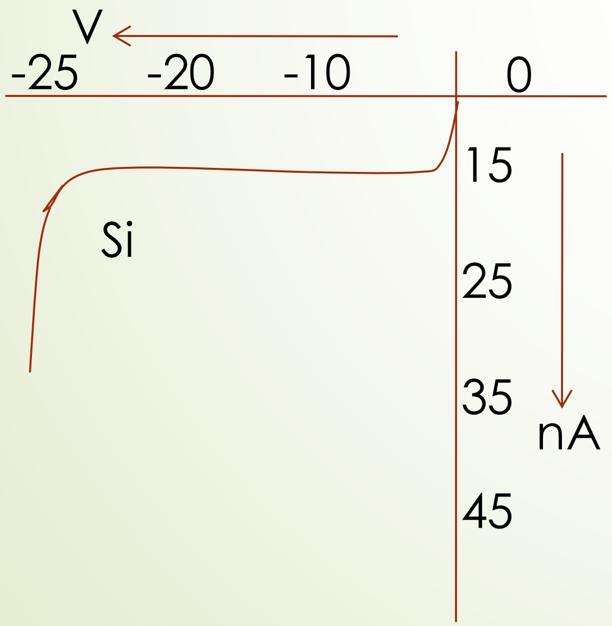
iv. *Under this condition depletion width increases and also barrier potential increases.*

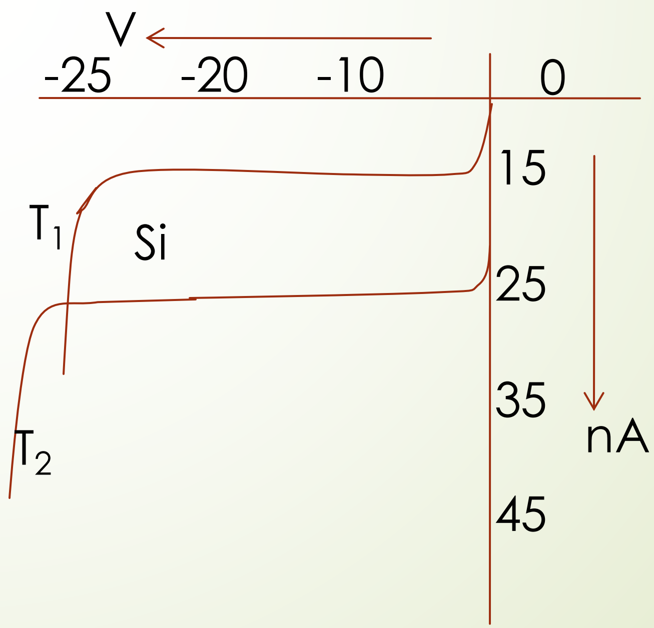




Reverse saturation current:

i. Although under reverse bias no current flows due to majority of carriers
ii. There is small amount of current (a few Pico-amp—micro-amp) flows due minority charge carriers generated by thermal agitation.
iii. This current is called reverse saturation current, I_s.
iv. Since minority carriers are thermally generated, the reverse current is extremely temperature dependent.
v. I_s is found doubled for every 10 degree C rise in temperature in Ge and for every 6 degree C rise in temperature for Si.





Equation of diode/ diode Shockley's equation:

The general characteristics of a semiconductor diode can be defined by the following equations for the forward and reverse biased region

$$I_D = I_S (e^{V_D / nV_T} - 1)$$

I_D= diode current
I_s= Reverse saturation current
V_D= applied forward bias across junction
n= ideality factor; function of operating condition or physical construction, its value is generally considered 1.
V_T= thermal voltage

$$V_T = \frac{kT}{q}$$

K= is the bothzmann constant 1.38×10^{-23} J/K
q= magnitude of electronic charge 1.6×10^{-19} C
T= absolute temperature in Kelvin

Equation of diode/ diode Shockley's equation:

The general characteristics of a semiconductor diode can be defined by the following equations for the forward and reverse biased region

$$I_D = I_S (e^{V_D / nV_T} - 1) \qquad (1.1)$$

For forward bias or positive value of V_D, equation 1.1 will become

$$I_D \cong I_S e^{V_D / nV_T} \qquad (1.2)$$

For negative value of V_D, equation 1.1 will become

$$I_D \cong -I_S \qquad (1.3)$$

At zero voltage $I_D = I_S (e^0 - 1) = 0 \qquad (1.4)$

We know for forward bias or positive value of V_{D1}, diode current will become

$$I_{D1} \cong I_S e^{V_{D1}/nV_T}$$

If forward bias value is V_{D1}, diode current will become

$$I_{D1} \cong I_S e^{V_{D1}/nV_T}$$

The combination of the two equation will become

$$\frac{I_{D2}}{I_{D1}} = e^{\frac{V_{D2}-V_{D1}}{nV_T}}$$

$$V_{D2} - V_{D1} = nV_T \ln \frac{I_{D2}}{I_{D1}}$$

$$V_{D2} - V_{D1} = 2.3nV_T \log \frac{I_{D2}}{I_{D1}}$$

For a decade change in current diode voltage drop changes by $2.3nV_T$

Junction resistance/dynamic resistance:

We have found the dynamic resistance graphically. However, there is a basic definition:

The derivative of a function at a point is equal to the slop of the tangent line drawn at that point

Lets take the derivative of equation 1.1

$$\frac{d}{dV_D} I_D = \frac{d}{dV_D} I_S (e^{V_D / nV_T} - 1) \qquad (1.1)$$

$$\frac{d}{dV_D} I_D = \frac{1}{nV_T} (I_D + I_S), \qquad \text{in general } I_D >> I_S$$

$$\frac{d}{dV_D} I_D = \frac{1}{nV_T} I_D$$

$$\frac{dV_D}{dI_D} = r_d = \frac{nV_T}{I_D}$$

Substituting n=1 and V_T=26 mV

$$r_d = r_j = \frac{26mV}{I_D}$$

$$\text{Dynamic rsistance} \qquad r_{ac} = \frac{26mV}{I_D} + r_B$$

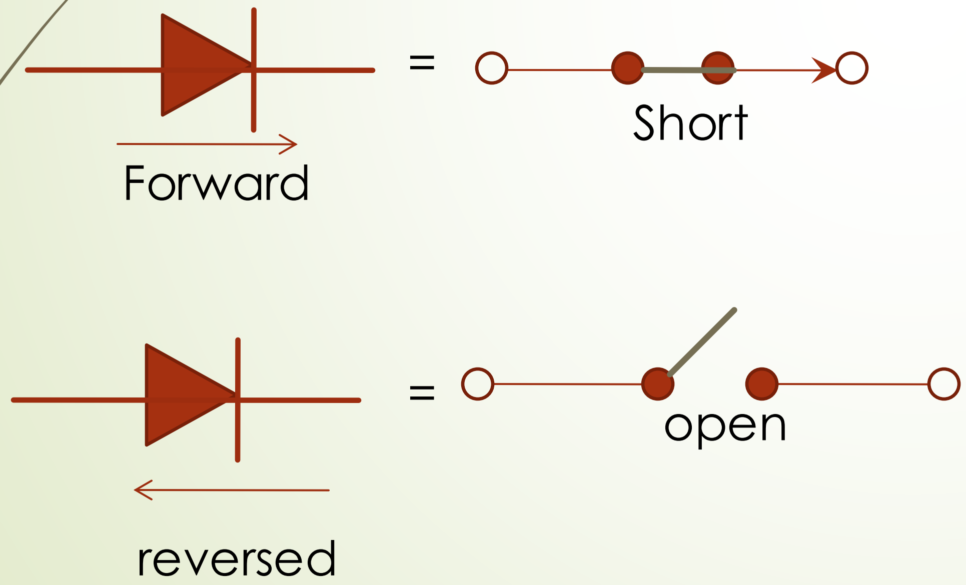
Where r_B is the body resistance

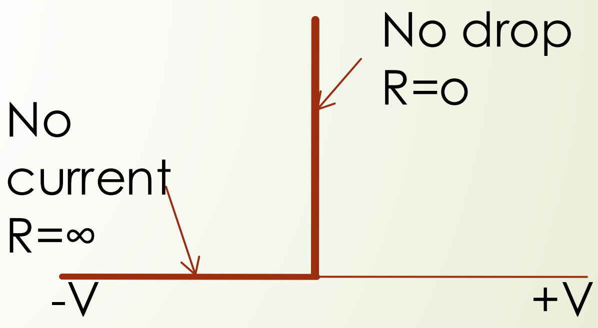
Ideal diode:

The terminal characteristics of an ideal diode can be interpreted as follows:

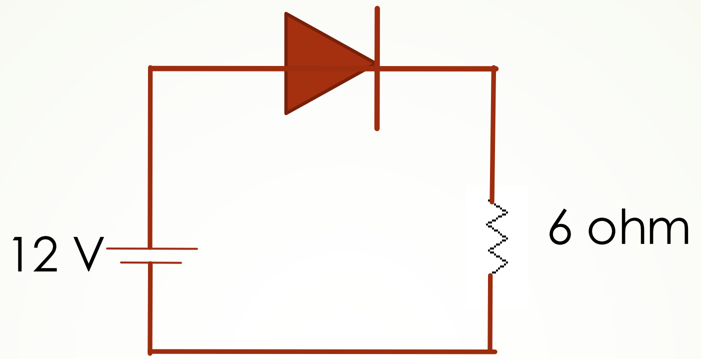
i. If a negative voltage is applied to diode, no current flows, the diode behaves as an open circuit. Diode in this mode is said to be reversed bias. It has zero current in the reverse direction and said to be **Cut-off.**

ii. If positive voltage is applied, zero voltage drop appear across diode and the diode behaves as short circuit. A forward/positive bias diode is said to be **Turned on**.

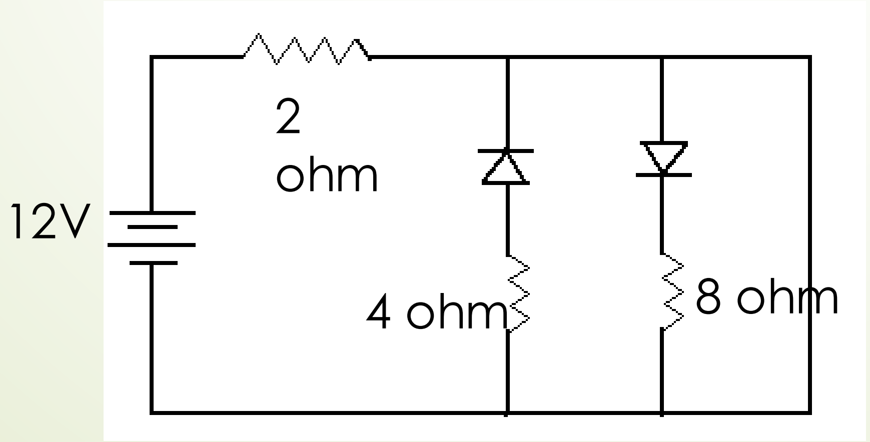




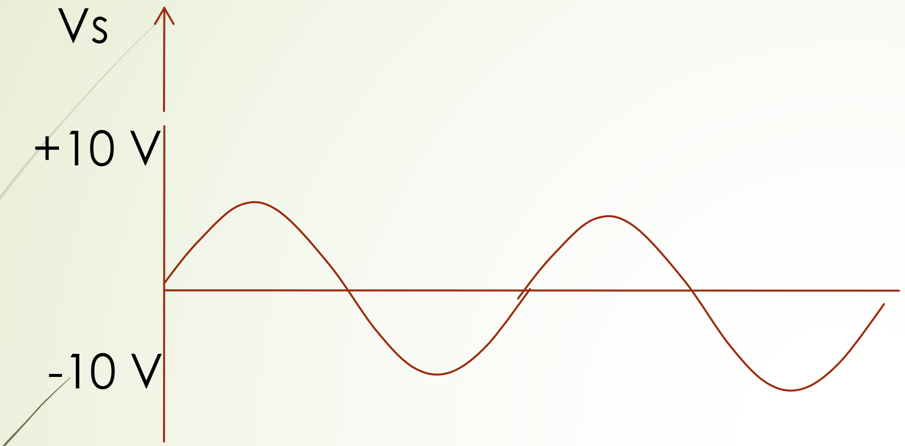
Q. Calculate the circuit current and power dissipated in the (a) ideal diode and (b) 6 ohm resistor of the circuit.

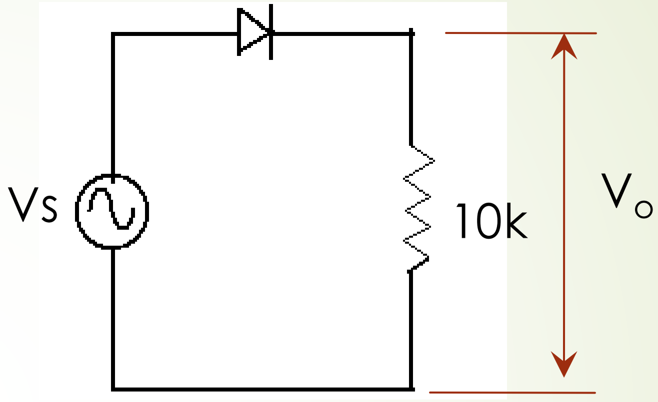


Q. Find the circuit current if any in the following circuit

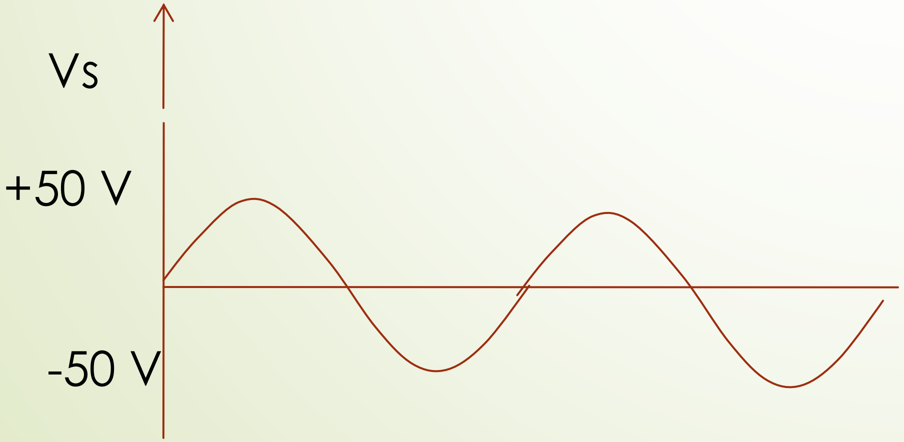


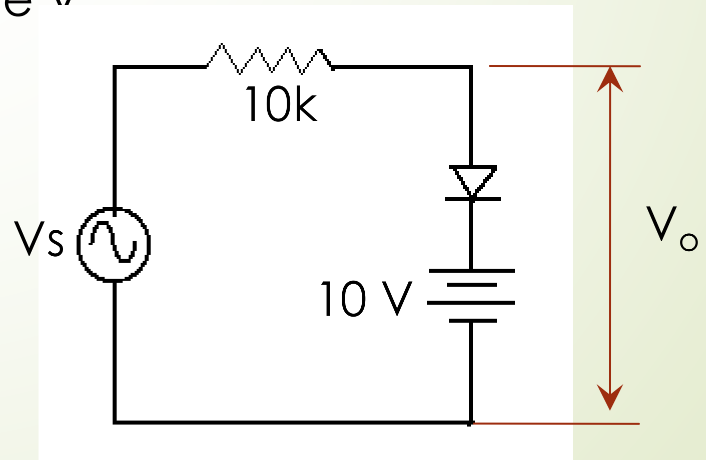
Q. Sketch the waveform of voltage V_o across 10K



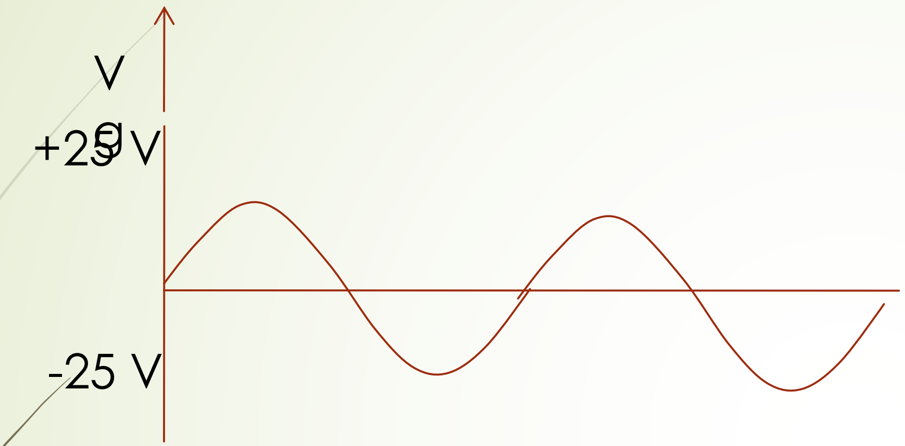


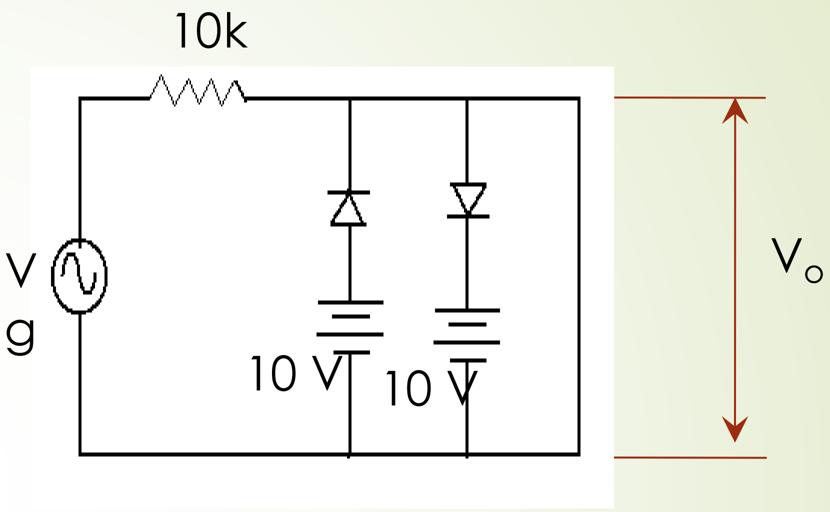
Q. Sketch the waveform of voltage V





Q. Sketch the waveform of voltage V_o across 10K

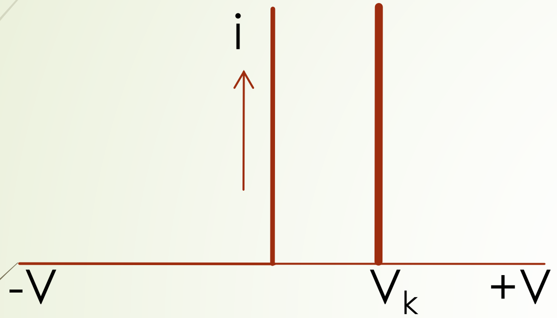


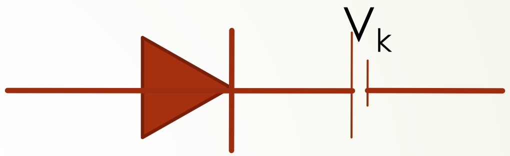


Real diode:

A real diode does not offer zero resistance in forward direction neither it offers infinite resistance in reverse direction

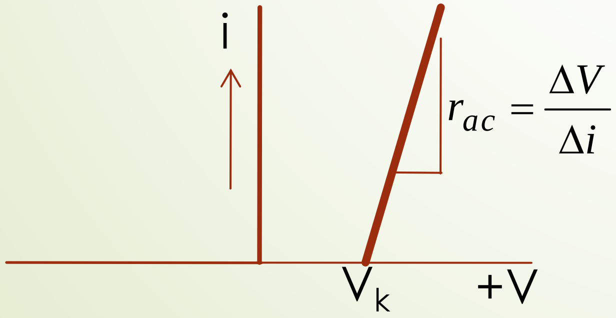
(a) First factor is that forward current does not start flowing until the voltage applied to the diode exceeds the knee voltage V_k





Simplified model

(b) Second factor is that forward dynamic or ac resistance (r_{ac}) offered by the circuit. If we take r_{ac} into account, the forward characteristics becomes



Piecewise linear model

EXAMPLE 2.9 Determine I, V_1, V_2, and V_o for the series dc configuration of Fig. 2.25.

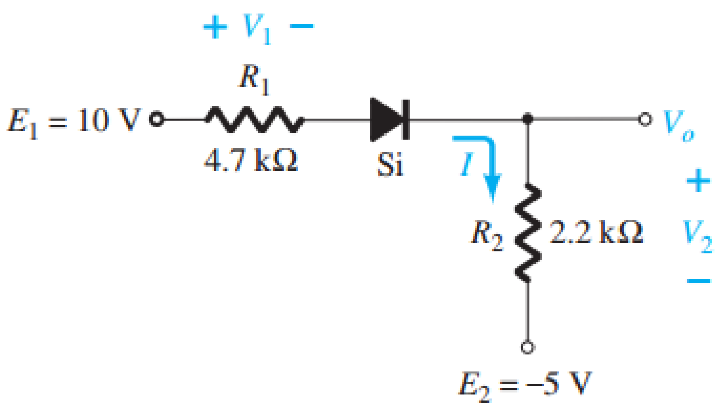


FIG. 2.25

*9. Determine V_{o_1} and V_{o_2} for the networks of Fig. 2.159.

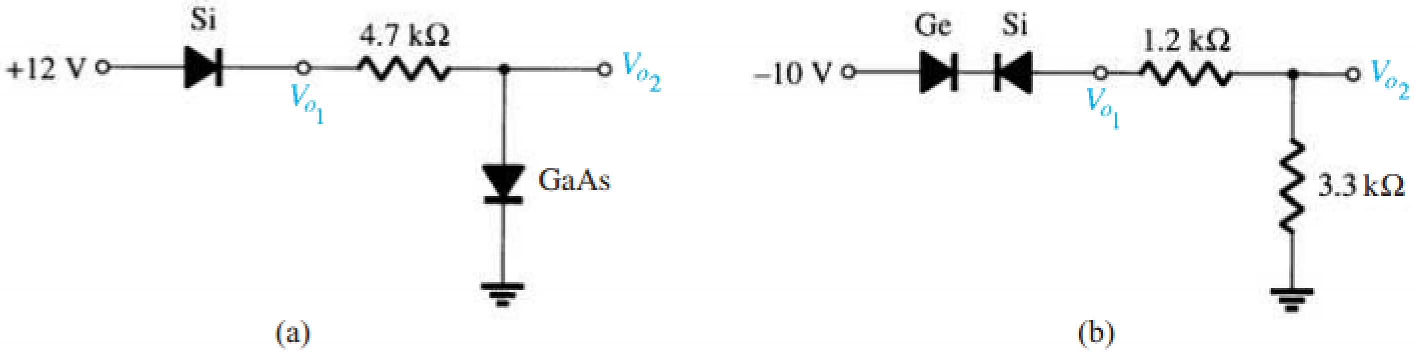


FIG. 2.159

10. Determine V_o and I_D for the networks of Fig. 2.160.

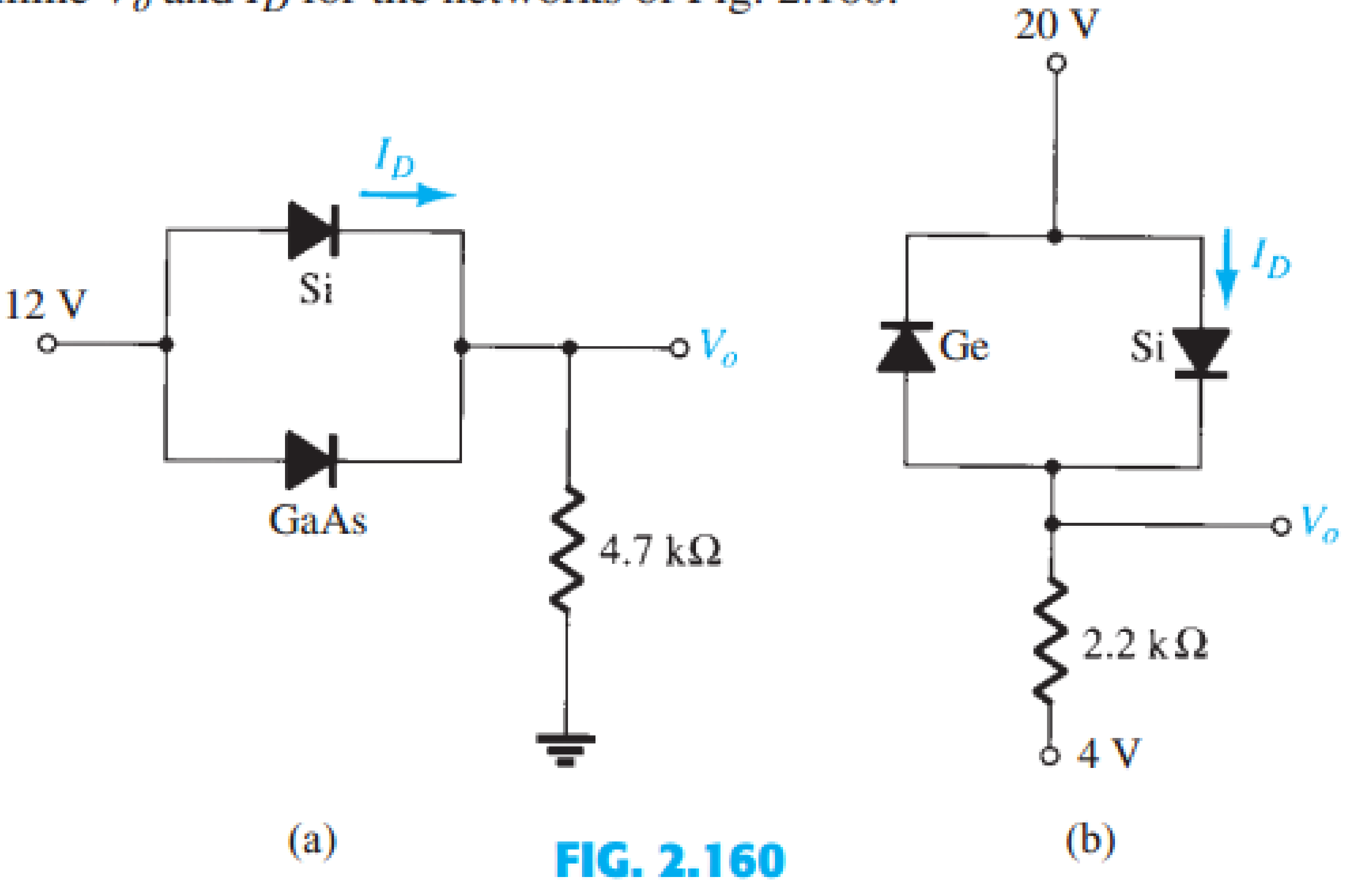


FIG. 2.160

*11. Determine V_o and I for the networks of Fig. 2.161.

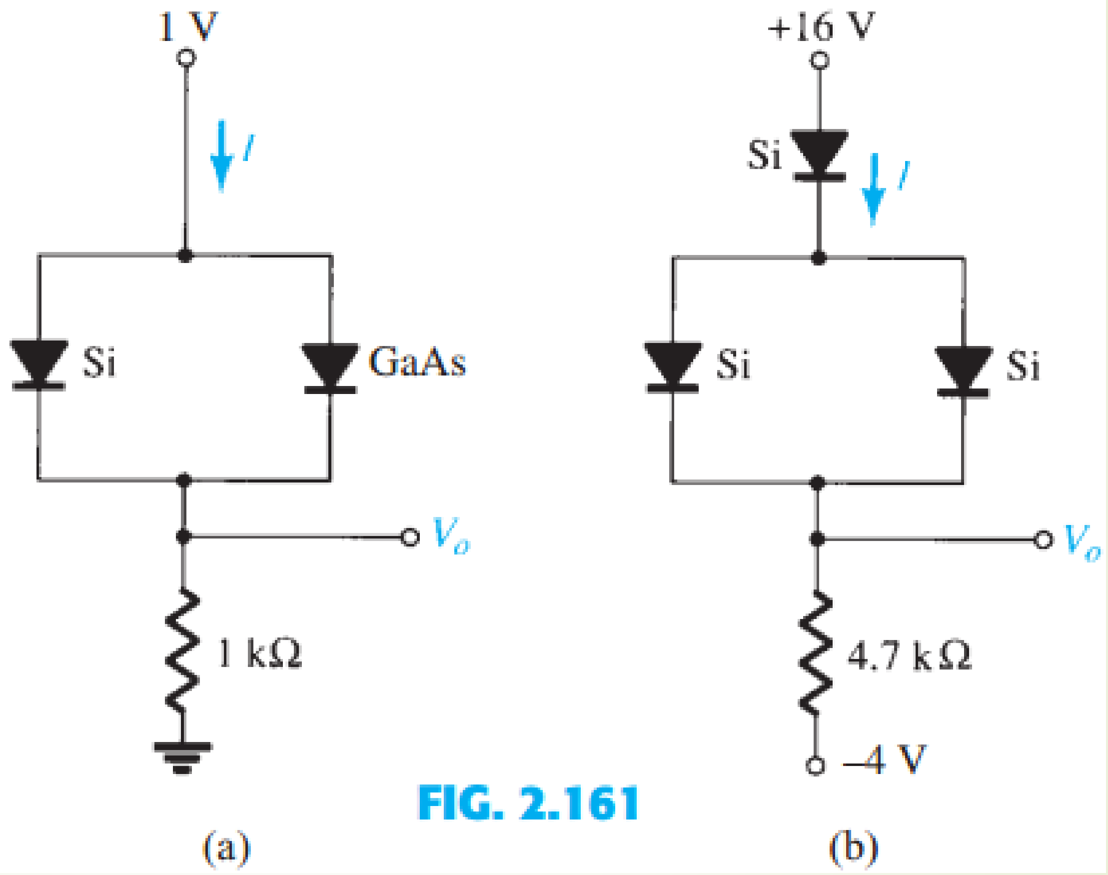


FIG. 2.161

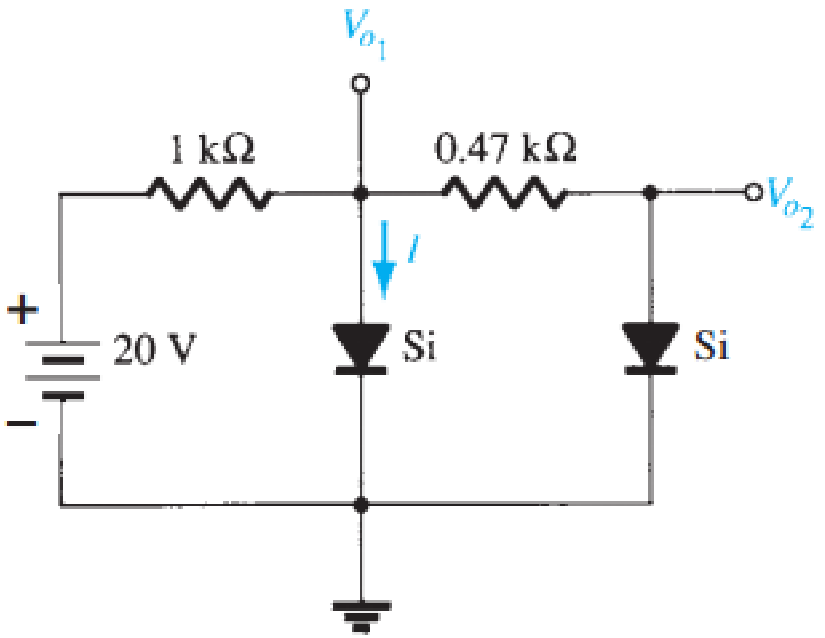


FIG. 2.162

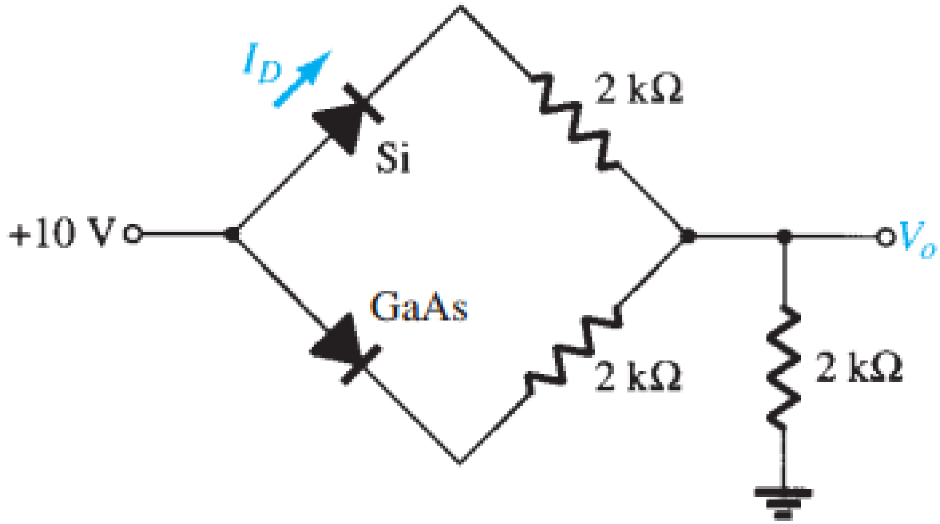


FIG. 2.163

Next class:

1. **diode circuit analysis**
2. **Diode small signal model**
3. **Diode high frequency model**
4. **Depletion layer capacitance**
5. **Diffusion capacitance**
6. **Zener break down, avalanche break down**
7. **Voltage regulation**

SIGNIFICANT EQUATIONS

1 Semiconductor Diodes $W = QV$, $1\ \text{eV} = 1.6 \times 10^{-19}\ \text{J}$, $I_D = I_s(e^{V_D/nV_T} - 1)$, $V_T = kT/q$, $T_K = T_C + 273°$, $k = 1.38 \times 10^{-23}\ \text{J/K}$, $V_K \cong 0.7\ \text{V (Si)}$, $V_K \cong 0.3\ \text{V(Ge)}$, $V_K \cong 1.2\ \text{V (GaAs)}$, $R_D = V_D/I_D$, $r_d = 26\ \text{mV}/I_D$, $r_{av} = \Delta V_d/\Delta I_d|_{\text{pt. to pt.}}$, $P_D = V_D I_D$, $T_C = (\Delta V_Z/V_Z)/(T_1 - T_0) \times 100\%/°\text{C}$

2 Diode Applications Silicon: $V_K \cong 0.7\ \text{V}$, germanium: $V_K \cong 0.3\ \text{V}$, GaAs: $V_K \cong 1.2\ \text{V}$; half-wave: $V_{dc} = 0.318V_m$; full-wave: $V_{dc} = 0.636V_m$