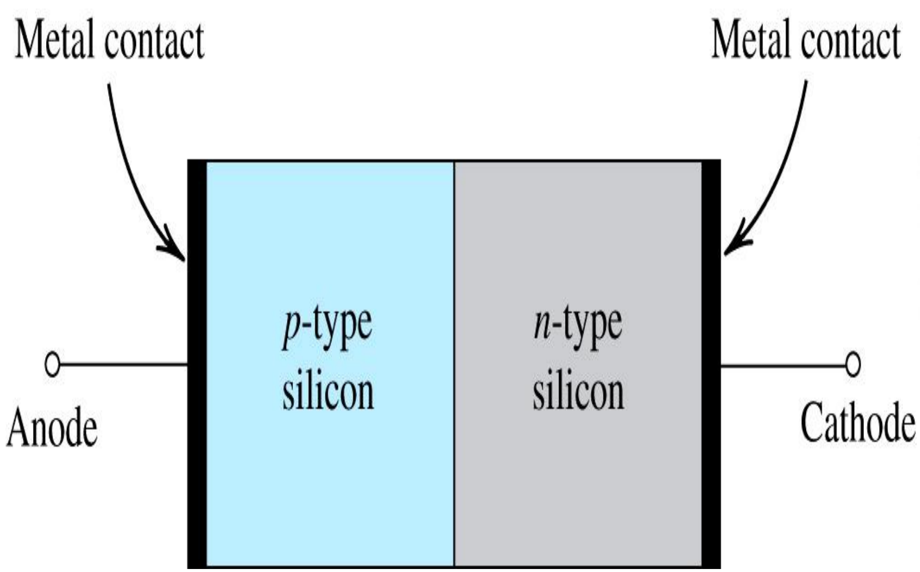
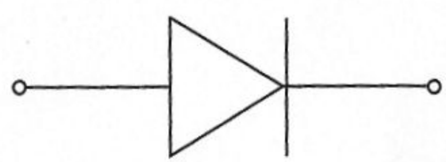
PN Junctions

- ***pn* junction (diode)** structure
  - *p*-type semiconductor
  - *n*-type semiconductor
  - metal contact for connection





PN Diodes

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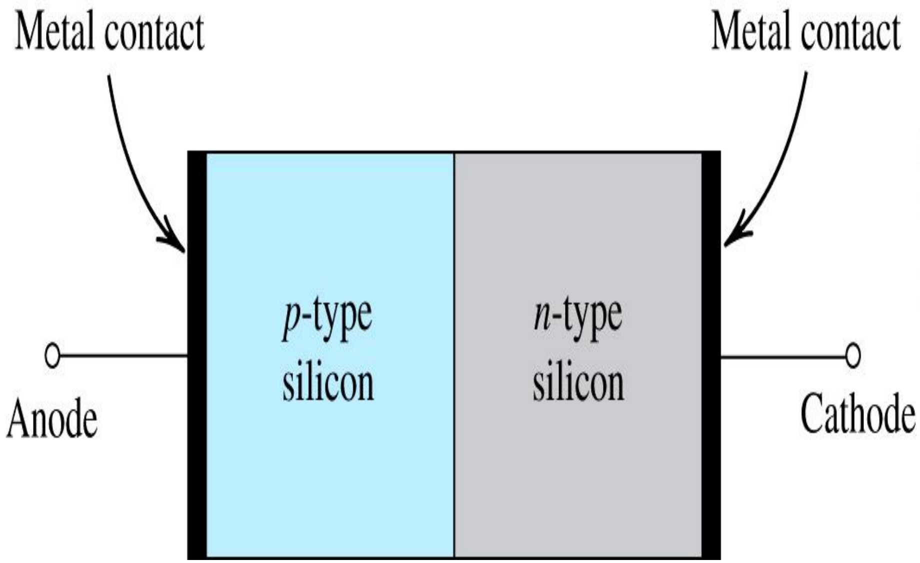
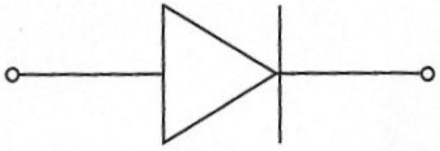
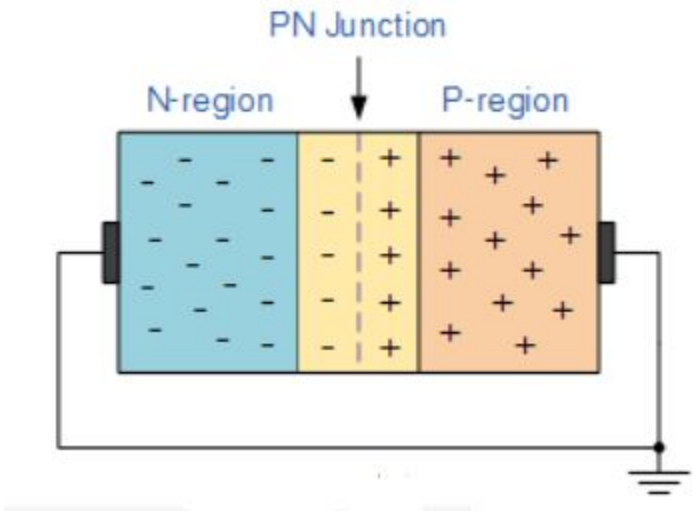


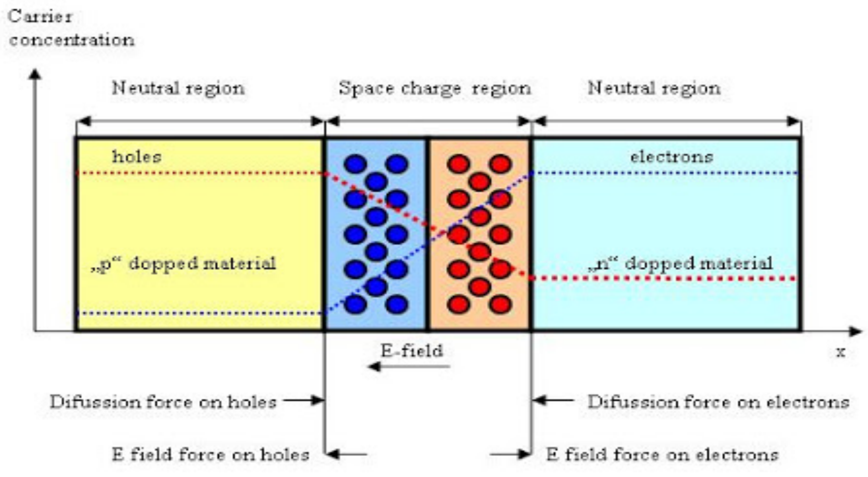


PN Junction diode in Equilibrium with no applied voltage:

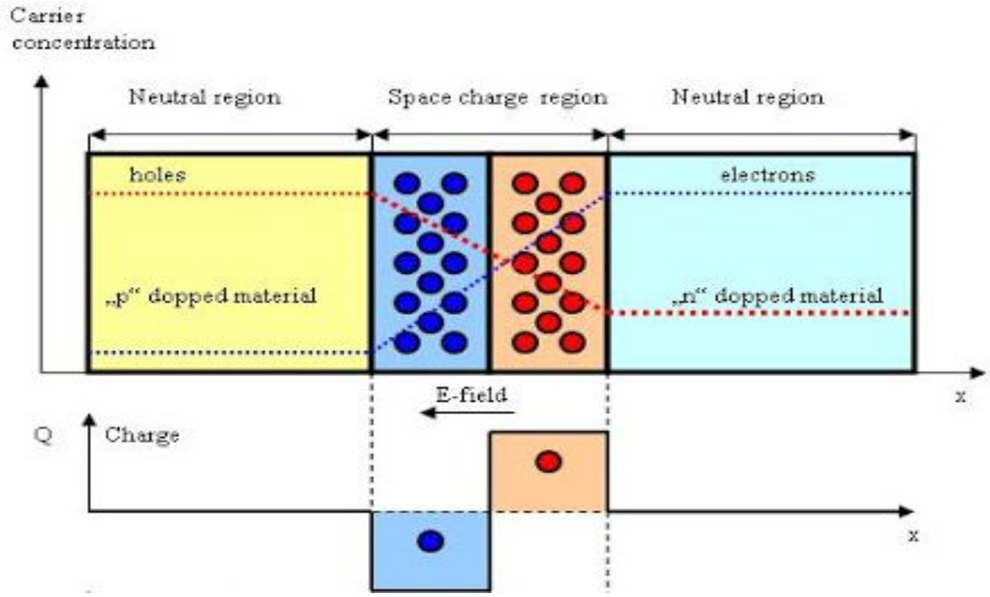
- The n type material has high concentration of free electrons, while p type material has high concentration of holes.
- Therefore at the junction there is a tendency of free electrons to diffuse over to the P side and the holes to the N side. This process is called diffusion.
- As the free electrons move across the junction from N type to P type, the donor atoms become positively charged. Hence a positive charge is built on the N-side of the junction.
- The free electrons that cross the junction uncover the negative acceptor ions by filing the holes. Therefore a negative charge is developed on the p –side of the junction.



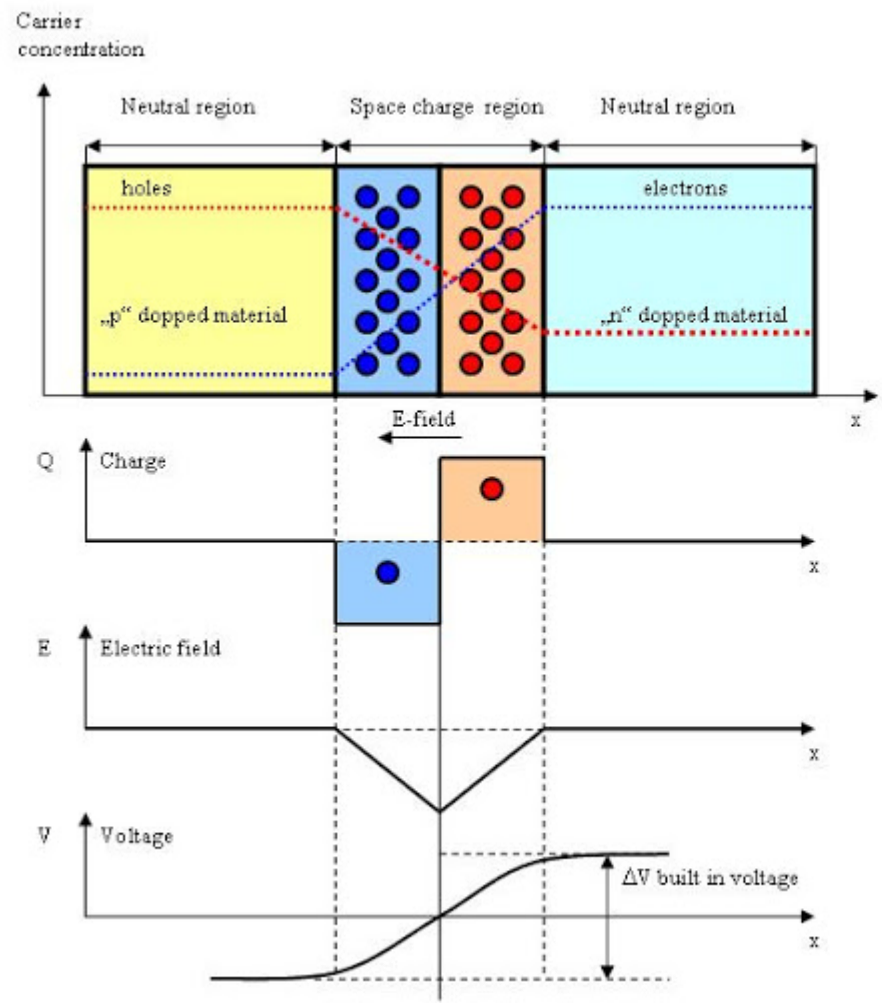
- This net negative charge on the p side prevents further diffusion of electrons into the p side.
- Similarly the net positive charge on the N side repels the hole crossing from p side to N side.
- Thus a barrier is set up near the junction which prevents the further movement of charge carriers i.e. electrons and holes.
- As a consequence of induced electric field across the depletion layer, an electrostatic potential difference is established between P and N regions, which are called the potential barrier, junction barrier, diffusion potential or contact potential, Vo.
- The magnitude of the contact potential Vo varies with doping levels and temperature. Vo is 0.3V for Ge and 0.72 V for Si.



- The electrostatic field across the junction caused by the positively charged N-Type region tends to drive the holes away from the junction and negatively charged p type regions tend to drive the electrons away from the junction.
- The majority holes diffusing out of the P region leave behind negatively charged acceptor atoms bound to the lattice, thus exposing a negatives pace charge in a previously neutral region.
- Similarly electrons diffusing from the N region expose positively ionized donor atoms and a double space charge builds up at the junction as shown in the fig

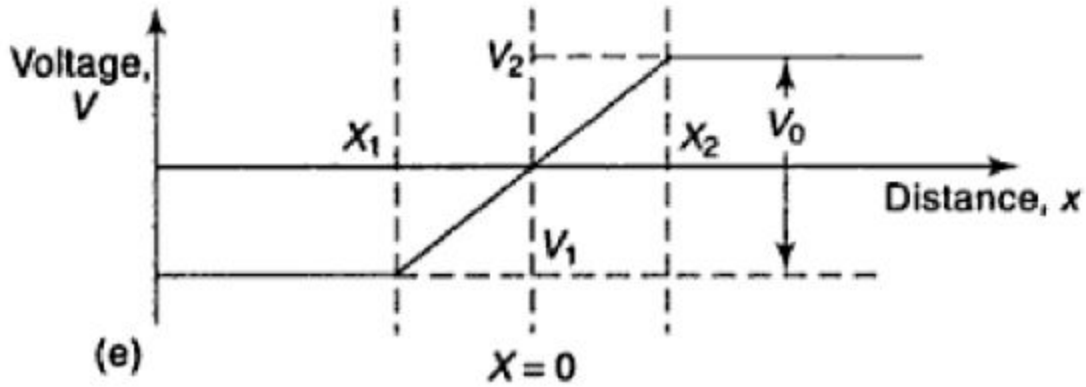


- The space charge layers are of opposite sign to the majority carriers diffusing into them, which tends to reduce the diffusion rate.
- The shape of the charge density, ρ, depends upon how diode is doped.
- The depletion region is of the order of 0.5μm thick.
- There are no mobile carriers in this narrow depletion region. Hence no current flows across the junction and the system is in equilibrium.
- To the left of this depletion layer, the carrier concentration is $p = N_A$ and to its right it is $n = N_D$



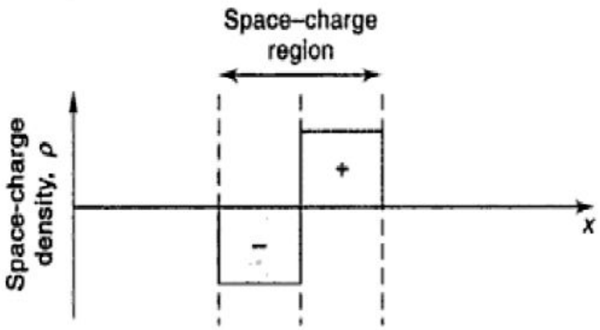
Depletion width

- Consider the variation in potential built up across the junction



- P-side of the junction is at the lower potential than the N-side which means that the electrons on the P-side have a great potential energy.

- Let us consider an alloy junction in which there is an Abrupt change from acceptor ions on P- side to donor ions on N-side



(i) For abrupt or alloy junction

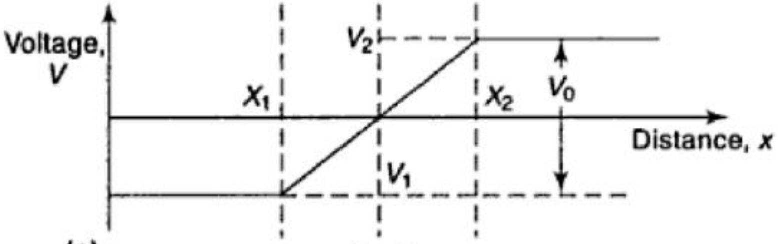
- The region of space charge is described as

  $\rho = -qN_A$, $X_1 < x < 0$

  $\rho = qN_D$, $0 < x < X_2$

  $\rho = 0$, elsewhere

- ρ is the space charge density



(e)

- The potential variation in the space charge region can be calculated by using Poisson's equation

$$\nabla^2 V = -\frac{\rho(x,y,z)}{\varepsilon_0 \varepsilon_r}$$

ε_r is the relative permittivity.

$$\frac{d^2V}{dx^2} = -\frac{\rho}{\varepsilon_0 \varepsilon_r}$$

- At P-side of the junction, $\rho = -qN_A$, $X_1 < x < 0$

$$\frac{d^2V}{dx^2} = \frac{qN_A}{\varepsilon_0 \varepsilon_r}$$

- Integrating,

$$\frac{dv}{dx} = \frac{qN_A x}{\varepsilon_0 \varepsilon_r} + C$$

- Integrating twice,

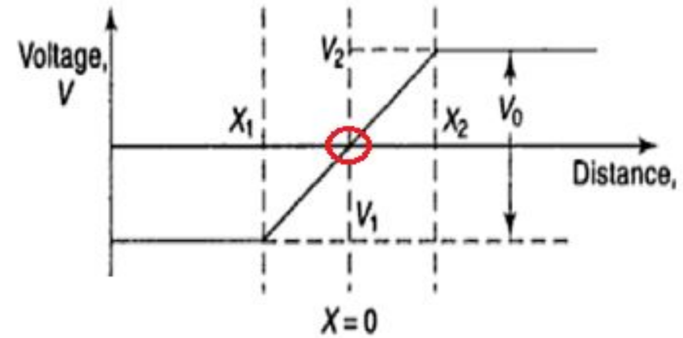
$$V = \frac{qN_A x^2}{2\varepsilon_0 \varepsilon_r} + Cx + D$$

C and D are the constants of integration.

From fig, V=0 at x=0,

D= ?

D= 0



When $x<X_1$ on the P-side,

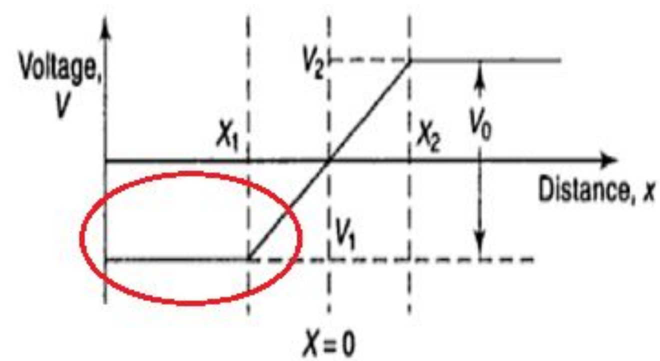
the potential is constant,

(ie) $\frac{dv}{dx} = 0 \ at \ x = x_1$

Sub

$$\frac{dv}{dx} = \frac{qN_A x}{\varepsilon_0 \varepsilon_r} + C = 0;\ C=?$$

$$C = -\frac{qN_A}{\varepsilon_0 \varepsilon_r} X_1$$



- Therefore, $V = \frac{qN_A x^2}{2\varepsilon_0\varepsilon_r} - \frac{qN_A}{\varepsilon_0\varepsilon_r} X_1 x$

$$V = \frac{qN_A}{\varepsilon_0\varepsilon_r}\left(\frac{x^2}{2} - X_1 x\right)$$

- At x= X_1, let V= V_1

$$V_1 = - \frac{qN_A}{2\varepsilon_0\varepsilon_r} X_1^2$$

- Applying same procedure to N-side

$$V_2 = \frac{qN_D}{2\varepsilon_0\varepsilon_r} X_2^2$$

- The total built- in potential or the contact potential V_0 *is*

$$V_0 = V_2 - V_1 = \frac{q}{2\varepsilon_0\varepsilon_r}(N_A X_1^2 + N_D X_2^2)$$

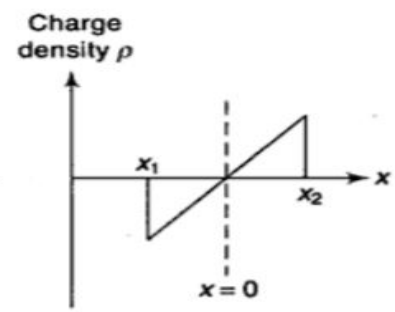
- In neutral condition, Positive charge on the N-side must be equal in magnitude to the negative charge on the P-side. Hence,

$$N_A X_1 = -\, N_D X_2$$

- Sub in exp. for V_0

$$V_0 = \frac{q}{2\varepsilon_0\varepsilon_r}\left(N_A X_1^2 + N_D X_2^2\right);$$

$$V_0 = \frac{q}{2\varepsilon_0\varepsilon_r}\left(N_A X_1^2 + \cancel{N_D}\,\frac{N_A^2 X_1^2}{N_D^{\cancel{2}}}\right)$$



(c) (ii) For graded or grown junction

$$X_1 = -\left[\frac{2\varepsilon_0\varepsilon_r V_0}{qN_A\left(1+\frac{N_A}{N_D}\right)}\right]^{1/2}$$

$$X_2 = \left[\frac{2\varepsilon_0\varepsilon_r V_0}{qN_D\left(1+\frac{N_A}{N_D}\right)}\right]^{1/2}$$

- Total depletion width,

$$W = X_2 - X_1 \;\; ; W_2 = (X_2 - X_1)^2$$

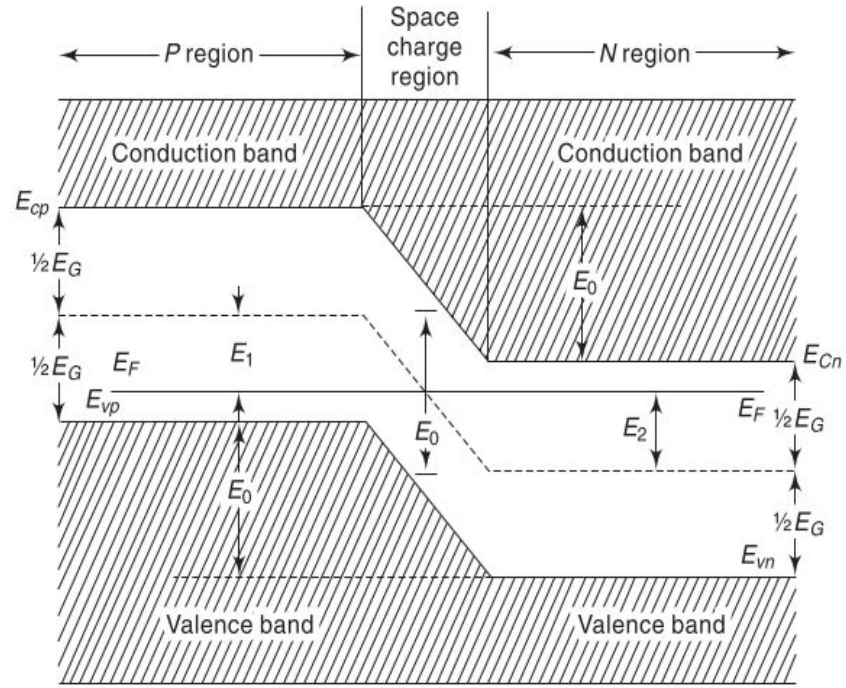
$$W_2 = X_2{}^2 + X_1{}^2 - 2X_1X_2$$

$$W = \left[\frac{2\varepsilon_0\varepsilon_r V_0}{q}\left(\frac{N_A+N_D}{N_AN_D}\right)\right]^{1/2}$$

- In an alloy junction,
  - depletion width W is proportional to $(V_0)^{1/2}$
- In a Graded junction,
  - the charge density varies linearly with distance x
  - W varies $(V_0)^{1/3}$

Energy band structure of Open Circuited PN junction

- When a P-type and N-type materials comes in close physical contact
- at the junction the energy band of these two regions undergo relative shift to equalize the Fermi level.
- At equilibrium, the Fermi level E_f should be constant throughout the specimen.
- The distribution of electrons or holes in allowed energy states is dependent on the position of the Fermi level.
- electrons on one side of the junction would have an average energy higher than those on the other side, and this causes transfer of electrons and energy until the Fermi levels on the two sides get equalized.



Energy band structure

- However, such a shift does not disturb the relative position of the conduction band, valence band and Fermi level in any region.

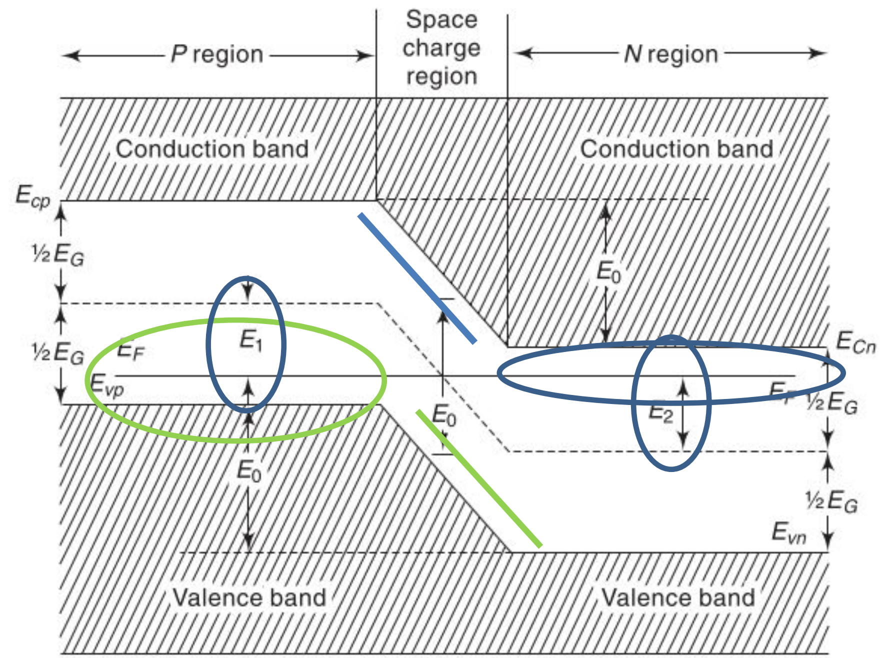
Energy Band Diagram for PN junction (Open Circuited)

- The Fermi level E_f is closer to the conduction band edge E_{cn} in the N-type material while it is closer to the valence band edge E_{vp} in the P-type material.

- The conduction band edge E_{cp} in the P-type material is higher than the conduction band edge E_{cn} in the N-type material.

- Similarly, the valence band edge E_{vp} in the P-type material is higher than the valence band edge E_{vn} in the N-type material.

- E_1, and E_2, indicate the shifts in the Fermi level from the intrinsic conditions in the P and N materials respectively.



Energy band structure

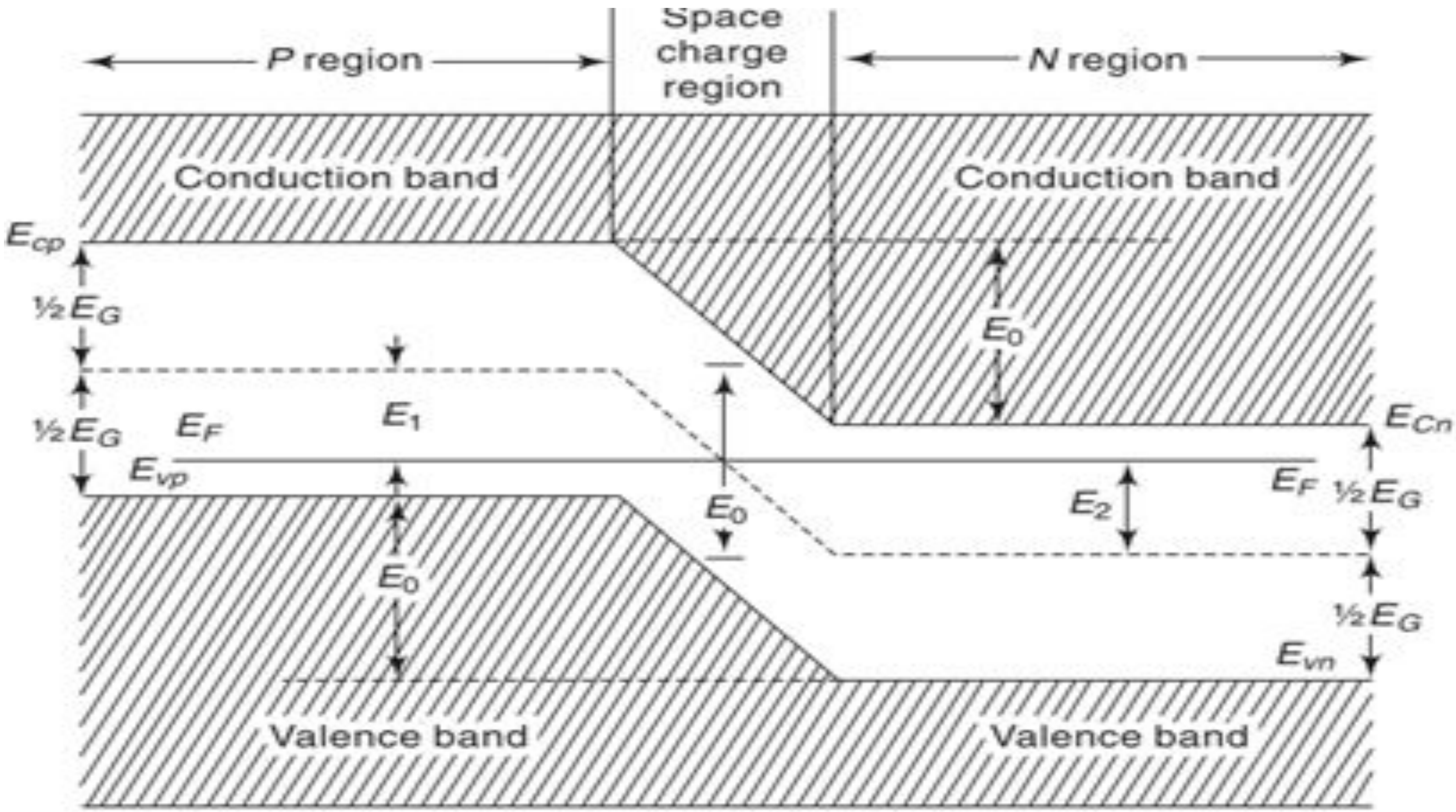
- The total shift in the energy level E_o, is given by

$$\boxed{E_0 = E_1 + E_2 = E_{cp} - E_{cn} = E_{vp} - E_{vn}}$$

Contact difference of Potential

The contact between a PN junction creates a potential difference

- $E_F - E_{vp} = \frac{1}{2}E_G - E_1; \;\; E_{cn} - E_F = \frac{1}{2}E_G - E_2$



Energy band structure

- Combining the above equation,

$$E_0 = E_1 + E_2$$
$$= E_G - (E_{cn} - E_F) - \left(E_F - E_{vp}\right)$$

- We know that,

$$n = N_C\ e^{-(E_c - E_F)/kT}$$
$$p = N_V\ e^{(E_F - E_v)/kT}$$
$$np = N_C N_V e^{-E_G/_{kT}}$$
$$= n_i^2 \text{ (Mass action law)}$$
$$E_G = kT \ln \frac{N_C N_V}{n_i^2}$$

- for N type material, $E_F = E_c - kT \ln \frac{N_C}{N_D}$

$$E_{cn} \text{-} E_F = kT \ln \frac{N_C}{n_n} = kT \ln \frac{N_C}{N_D}$$

- Similarly, for P type material, $E_F = E_V + kT \ln \frac{N_V}{N_A}$

$$E_F - E_{vp} = kT \ln \frac{N_V}{P_p} = kT \ln \frac{N_V}{N_A}$$

•

$$E_0 = kT\left[\ln\frac{N_C N_V}{n_i^2} - \ln\frac{N_C}{N_D} - \ln\frac{N_V}{N_A}\right]$$
$$= kT\ln\left[\frac{N_C N_V}{n_i^2} x \frac{N_D}{N_C} x \frac{N_A}{N_V}\right]$$
$$= kT\ln\left[\frac{N_D N_A}{n_i^2}\right]$$

As $E_0 = \mathrm{q}V_o$

$$V_o = \frac{kT}{q}\ln\left[\frac{N_D N_A}{n_i^2}\right]$$

- E_0 depends upon the equilibrium concentrations and not on the charge density in the transition region.
- Also E_0 may be obtained by substituting the equations of $n_n = N_D$, $P_p = \frac{n_i^2}{N_D}$,

$n_n P_p = n_i^2$, $P_p = N_A$, $n_p = \frac{n_i^2}{N_A}$ then

$$E_0 = kT\ln\left[\frac{P_{po}}{P_{no}}\right] = kT\ln\left[\frac{n_{no}}{n_{po}}\right]$$

- Where subscript "o" represents the thermal equilibrium condition

Problem

P1 The resistivities of the P-region and N-region of a germanium diode are 6 Ω-cm and 4Ω-cm, respectively. Calculate the contact potential V_o and potential energy barrier E_o. (b) If the doping densities of both P and N-regions are doubled, determine V_o and E_o. Given that $q = 1.6 \times 10^{-19}$ C, $n_i = 2.5 \times 10^{13}/\text{cm}^3$, $\mu_p = 1800\ \text{cm}^2/\text{V-s}$, $\mu n = 3800\ \text{cm}^2/\text{V-s}$ and $V_T = 0.026$ V at 300 °K.

Resistivity, $$\rho = \frac{1}{\sigma} = \frac{1}{N_A q \mu_p} 6\,\Omega - \text{cm}$$

$$N_A = \frac{1}{6q\mu_p} = \frac{1}{6 \times 1.6 \times 10^{-19} \times 1800} = 0.579 \times 10^{15}/\text{cm}^3$$

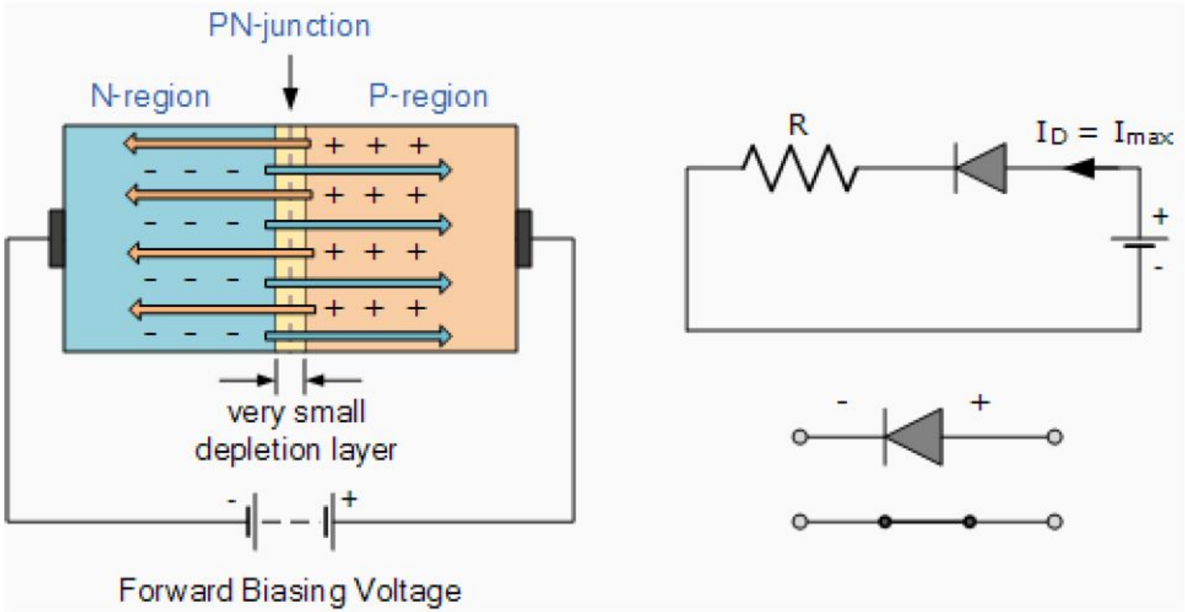
$$N_D = \frac{1}{4q\mu_n} = \frac{1}{4 \times 1.6 \times 10^{-19} \times 3800} = 0.579 \times 10^{15}/\text{cm}^3$$

$$V_o = V_T \ln \frac{N_D N_A}{n_i^2} = 0.026 \ln \frac{0.579 \times 0.411 \times 10^{30}}{(2.5 \times 10^{13})^2} = 0.1545\ \text{V}$$

$$V_o = 0.026 \ln \frac{2 \times 0.579 \times 10^{15} \times 2 \times 0.411 \times 10^{15}}{(2.5 \times 10^{13})^2} = 0.1906\ \text{V}$$

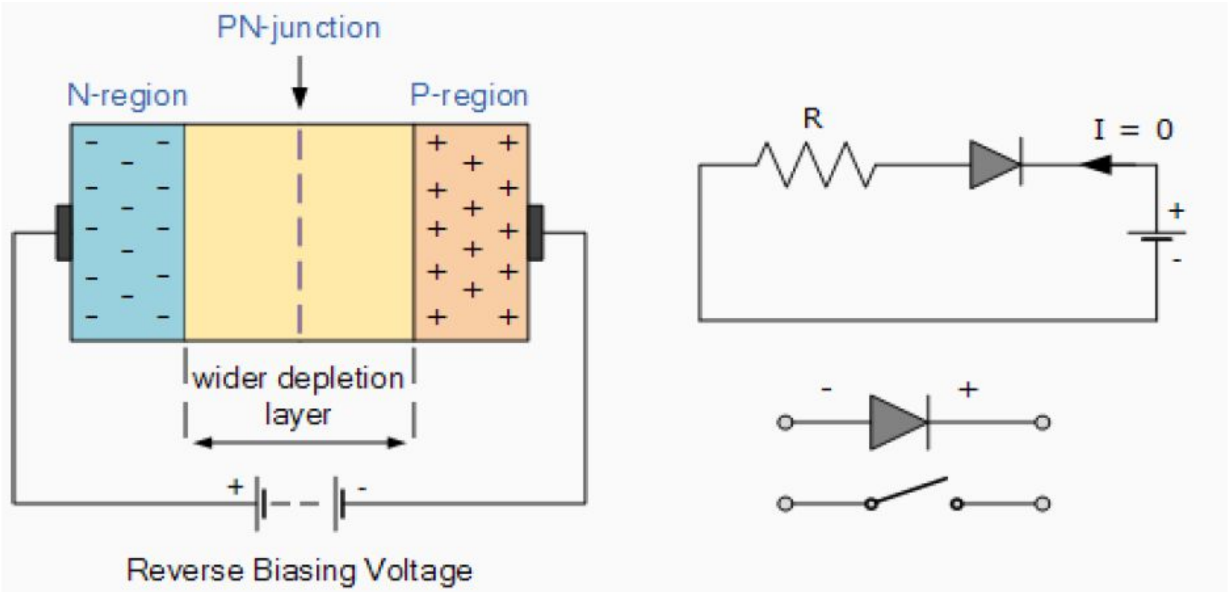
FORWARD BIASED PN DIODE

- Negative voltage is applied to the N-type material and
- Positive voltage is applied to the P-type material.
- If this external voltage becomes greater than the value of the potential barrier, approx. 0.7 volts for silicon and 0.3 volts for germanium, the potential barriers opposition will be overcome and current will start to flow.
- Depletion layer becoming very thin and narrow

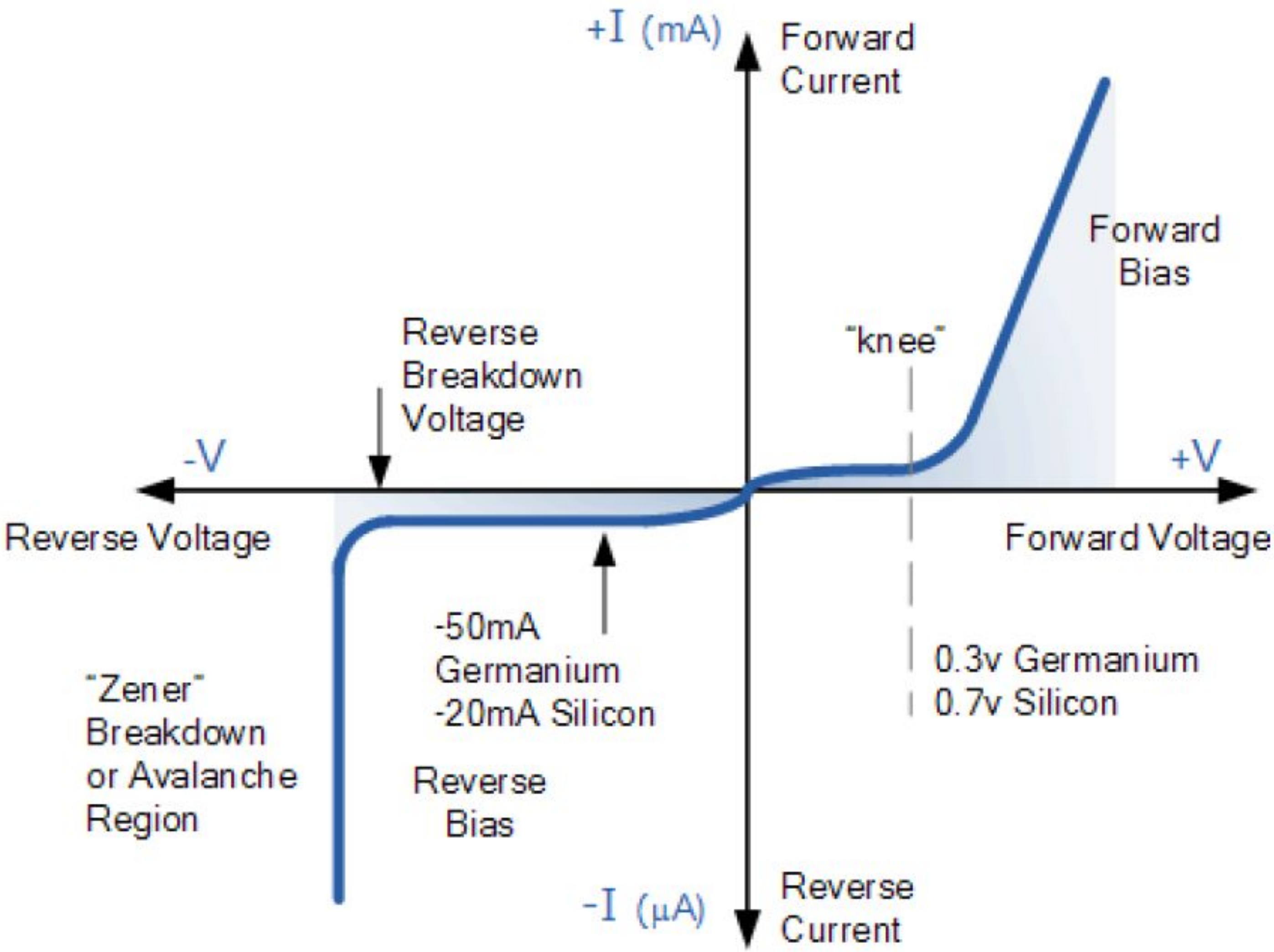


REVERSE BIASED PN DIODE

- Positive voltage is applied to the N-type material and
- Negative voltage is applied to the P-type material.
- The positive voltage applied to the N-type material attracts electrons towards the positive electrode and away from the junction, while the holes in the P-type end are also attracted away from the junction towards the negative electrode.
- Depletion layer grows wider



VI Characteristics



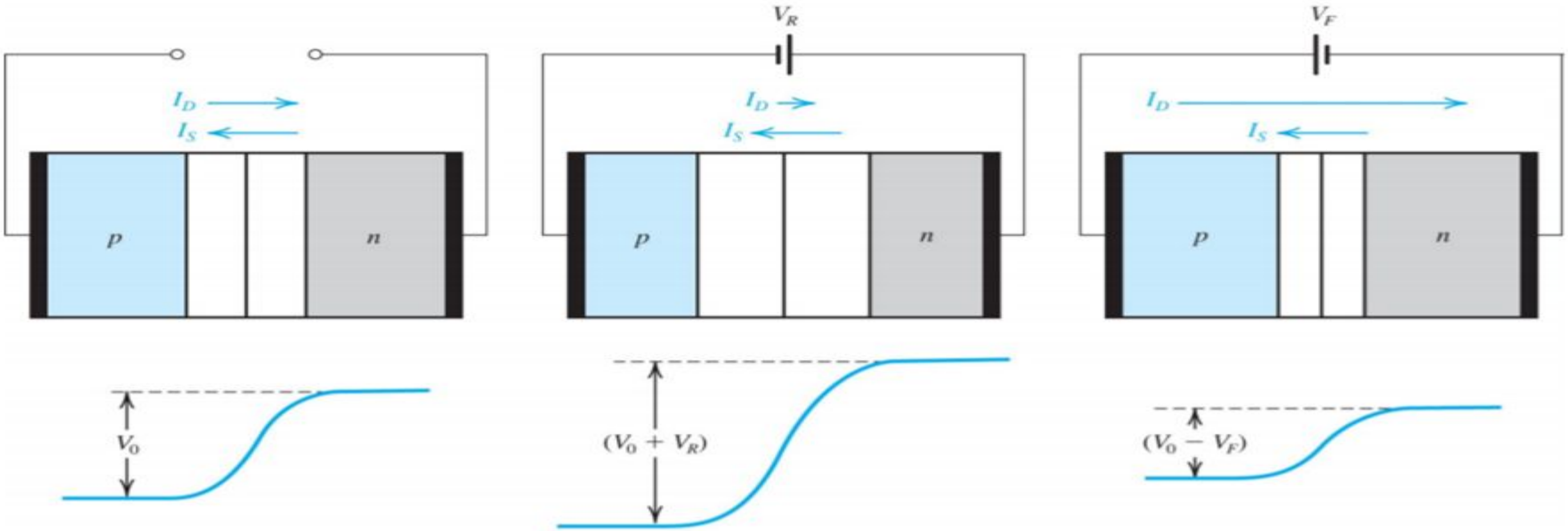
Diode Characteristics

Characteristics of Ideal Diode

- Diode always conducts in one direction.
- Diodes always conduct current when “Forward Biased” (Zero resistance)
- Diodes do not conduct when Reverse Biased

  (Infinite resistance)

Depletion Width under Biasing



(a) Open-circuit (equilibrium)

(b) Reverse bias

(c) Forward bias

$$W = \left[\frac{2\varepsilon_0\varepsilon_r(V_0 - V)}{q}\left(\frac{N_A + N_D}{N_A N_D}\right)\right]^{1/2}$$

V is the applied voltage to the pn junction,

it's positive for forward bias and negative for reverse bias.

Depletion width is widened in reverse bias

PN Diode currents

- Expression for the total current as a function of the applied voltage (the volt –ampere characteristics),
  - let us assume that the depletion width is zero.
  - When the forward bias is applied to a diode, holes are injected from the p-side into the n-side.
  - Thus the concentration of holes in the n-side (p_n) is increased above its thermal equilibrium value (p_{n0})
  - injected hole concentration [$p'_n(x)$] *decreases exponentially with respect to distance (x).*

Increase in hole concentration

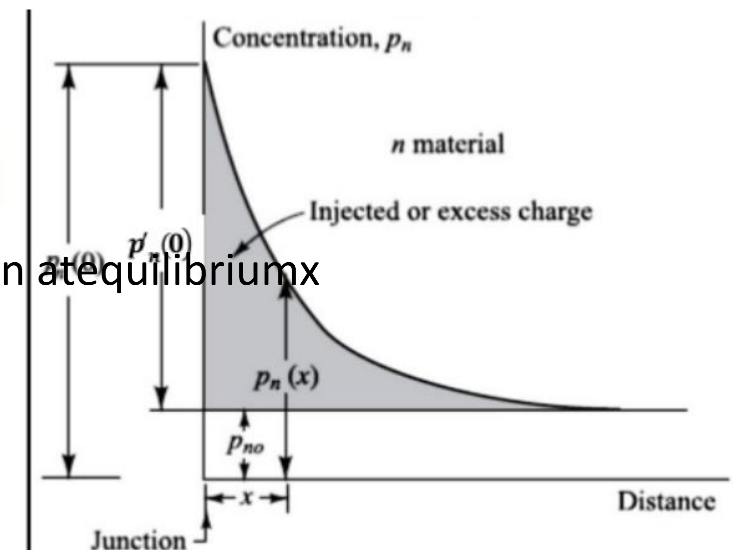
$$p'_n(x) = p_n(x) - p_{no} = p'_n(o)e^{-x/L_p}$$

hole concentration at x

hole concentration at equilibrium

$$\therefore \quad p_n(x) = p_{no} + p'_n(0)e^{-x/L_p}$$

Where, L_p is the diffusion length for holes in n-type semiconductor



- Injected hole concentration at *x=0* is

$$\therefore \; p'_n(0) = p_n(0) - p_{no}$$

From the Boltzmann relationship of kinetic gas theory:

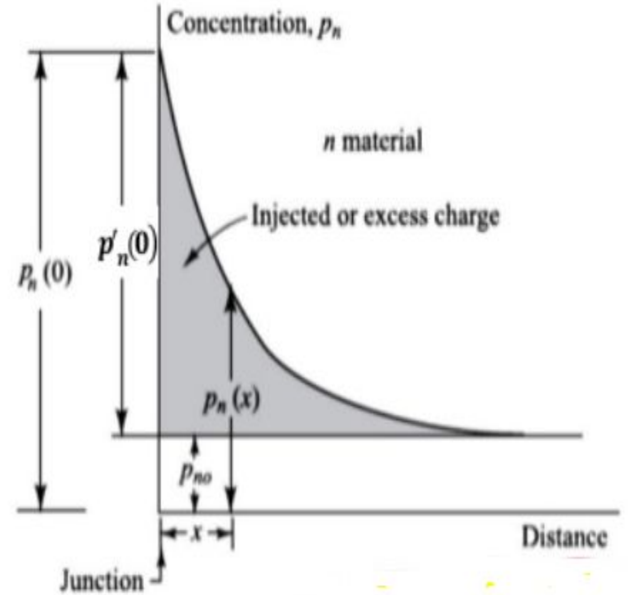
$$p_p = p_n e^{V_B/V_T}$$

where

- p_p and p_n are hole concentrations at the edges of the space charge region in p and n material respectively.
- V_B is the barrier potential across the depletion layer

$$V_B = V_o - V.$$

- The hole concentration throughout the p region is constant and equal to the thermal equilibrium value $p_p = p_{po}$
- The hole concentration varies with distance into the n-side as shown in figure below



- At the edge of depletion layer
- i.e. at x=0 $p_n = p_n(0)$
- Therefore, the Boltzmann relationship

for this case is

$$p_p(0) = p_n(0)\left[\exp\left((V_o - V)/V_T\right)\right]$$

- We know that, in an unbiased pn junction diode, under equilibrium condition

$$p_{po} = p_{no} \exp\left[\frac{V_0}{V_T}\right]$$

- Therefore by combining the equation obtained in previous slide with the above equation, we obtain

$$p_n(0) \exp\left[\frac{V_0 - V}{V_T}\right] = p_{no} \exp\left[\frac{V_0}{V_T}\right]$$

$$p_n(0) \cancel{\exp\left[\frac{V_0}{V_T}\right]} \exp\left[-\frac{V}{V_T}\right] = p_{no} \cancel{\exp\left[\frac{V_0}{V_T}\right]}$$

$$p_n(0) \exp\left[-\frac{V}{V_T}\right] = p_{no}$$

$$p_n(0) = p_{no} \exp\left[\frac{V}{V_T}\right]$$

This condition is called the law of junction.

- Thus, the hole concentration $p'_n(0)$ injected into the n-side at the junction is obtained as given below:

$$p'_n(0) = p_{no}[\exp(V/V_T) - 1]$$

- The diffusion hole current in the N- side

$$I_{pn} = -AqD_p \frac{dp_n}{dx}$$

$$I_{pn}(x) = \frac{AqD_p p'_n(0)}{L_p} e^{-x/L_p} \qquad \text{since} \quad \frac{dp_n}{dx} = \frac{p'_n(0)}{L_p} e^{-x/L_p}$$

- From the above equation it is evident that the injected hole current decreases exponentially with distance.
- The hole current crossing the junction in to n side, with x=0, is given by

$$I_{pn}(0) = \frac{AqD_p p_{no}}{L_p} [\exp(V/V_T) - 1]$$

- Since the injected concentration is a function of voltage applied across the pn-diode, thus we can say that I_{pn} depends upon the applied voltage V.
- Similarly

$$I_{np}(x) = \frac{AqD_n n'_p(0)}{L_n} e^{x/L_n}$$

- similarly, the electron current crossing the junction into the p-side, with x=0, is given by

$$I_{np}(0) = \frac{AqD_n n_{po}}{L_n} [\exp(V/V_T) - 1]$$

- Finally, the total current I is the sum of $I_{pn}(0)$ and $I_{np}(0)$.
- Therefore

$$I = I_{pn}(0) + I_{np}(0)$$

$$I = \left[\frac{AqD_p p_{no}}{L_p} + \frac{AqD_n n_{po}}{L_n}\right][\exp(V/V_T) - 1]$$

$$I = I_0[\exp(V/V_T) - 1]$$

- Where, $I_0 = \left[\frac{AqD_p p_{no}}{L_p} + \frac{AqD_n n_{po}}{L_n}\right]$
- I_o is the reverse saturation current.

- The carrier generation and recombination in the space-charge region is neglected
- Such an assumption is valid for a germanium diode, but not for a silicon device.
- If we consider the carrier generation and recombination in the space-charge region, the general equation of the diode current is approximately given by

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

Where, For silicon $\eta = 2$ and for Germanium $\eta=1$.

$V_T=kT/q=T/11600$, volt-equivalent of temperature, i.e., thermal voltage

K=Boltzmann's constant (1.38×10^{-3} J/K)

q=charge of the electron (1.602×10^{-19} C)

T=temperature of the diode junction (k) =(degree C +273)

At room temperature, (T=300k), V_T=26mv

Problems

P2 When a reverse bias is applied to a germanium PN junction diode, the reverse saturation current at room temperature is 0.3 μA. Determine the current flowing in the diode when 0.15 V forward bias is applied at room temperature.

For silicon η = 2 and for Germanium η=1.

$V_T = kT/q = T/11600;\ T = 300K$

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

$$I = I_o\,(e^{40\,V_F} - 1)$$

$$= 0.3 \times 10^{-6}\,(e^{40 \times 0.15} - 1)$$

$$= 120.73\ \mu A$$

Problems

P3

The diode current is 0.6 mA when the applied voltage is 400 mV, and 20 mA when the applied voltage is 500 mV. Determine η. Assume $\frac{kT}{q} = 25$ mV

$$0.6 \times 10^{-3} = I_o \left(e^{\frac{qV}{\eta kT}} - 1 \right) = I_o \ e^{\frac{qV}{\eta kT}} \qquad (1)$$

$$= I_o \cdot e^{\frac{400}{25\eta}} = I_o \cdot e^{\frac{16}{\eta}}$$

$$20 \times 10^{-3} = I_o \cdot e^{\frac{500}{25\eta}} = I_o \cdot e^{\frac{20}{\eta}} \qquad (2)$$

Dividing Eq. (2) by (1), we get

$$\frac{20 \times 10^{-3}}{0.6 \times 10^{-3}} = \frac{I_o \cdot e^{\frac{20}{\eta}}}{I_o \cdot e^{\frac{16}{\eta}}}$$

$$\frac{100}{3} = e^{\frac{4}{\eta}}$$

Taking natural logarithms on both sides, we get

$$\log_e \frac{100}{3} = \frac{4}{\eta}$$

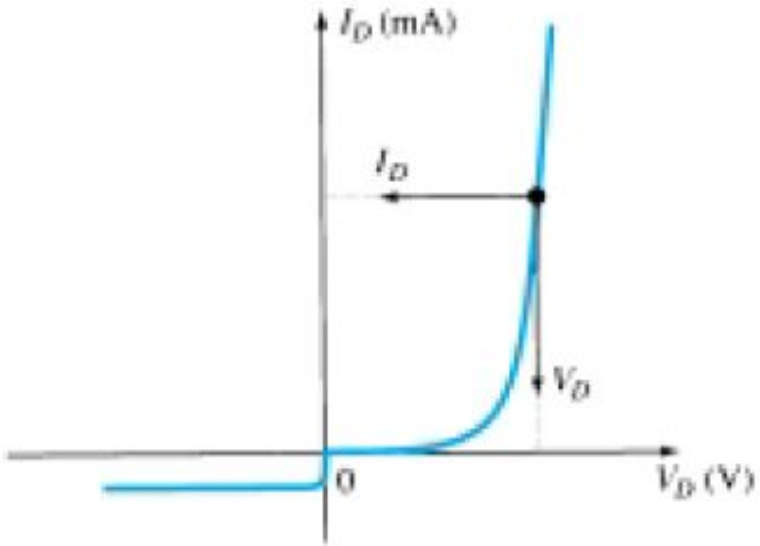
$$3.507 = \frac{4}{\eta}$$

$$\eta = \frac{4}{3.507} = 1.14$$

DC or Static Resistance

- The resistance of the diode at the operating point can be found simply by finding the corresponding levels of V_D and I_D

$$\boxed{R_D = \frac{V_D}{I_D}}$$



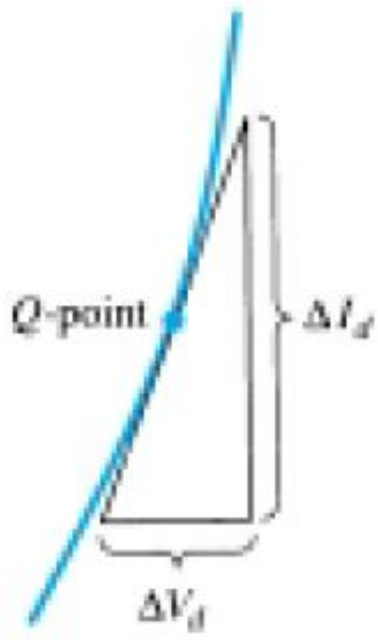
AC or Dynamic Resistance

- change in voltage and current that can be used to determine the ac or dynamic resistance

$$\boxed{r_d = \frac{\Delta V_d}{\Delta I_d}}$$

where Δ signifies a finite change in the quantity.

$$r_f = \frac{\eta V_T}{I}$$



Problems

P4

Determine the forward resistance of a PN junction diode, when the forward current is 5 mA at $T = 300^{\circ}$ K. Assume Silicon diode.

$$r_f = \frac{\eta V_T}{I}$$

$$r_f = \frac{2 \times \dfrac{T}{11,600}}{5 \times 10^{-3}} = \frac{2 \times 300}{11,600 \times 5 \times 10^{-3}} = 10.34\ \Omega$$

TRANSITION OR SPACE CHARGE (OR DEPLETION REGION) CAPACITANCE (C_T)

- Under reverse bias condition, the majority carriers move away from the junction, thereby uncovering more immobile charges.
- Hence the width of the space–charge layer at the junction increases with reverse voltage.
- This increase in uncovered charge with applied voltage may be considered a capacitive effect.
- The parallel layers of oppositely charged immobile ions on the two sides of the junction form the capacitance, C_T, which is expressed as

$$\boxed{C_T = \left|\frac{dQ}{dV}\right|}$$

where dQ is the increase in charge caused by a change in voltage dV.

$$\boxed{C_T = \frac{\varepsilon A}{W}.}$$

DIFFUSION (OR STORAGE) CAPACITANCE (C_D)

- The capacitance that exists in a forward biased junction is called a diffusion or storage capacitance (C_D), whose value is usually much larger than C_T, which exists in a reverse-biased junction.

- This is also defined as the rate of change of injected charge with applied voltage, i.e.,

$$\boxed{C_D = \frac{\mathrm{d}Q}{\mathrm{d}V}}$$

where dQ represents the change in the number of minority carriers stored outside the depletion region when a change in voltage across the diode, dV, is applied.

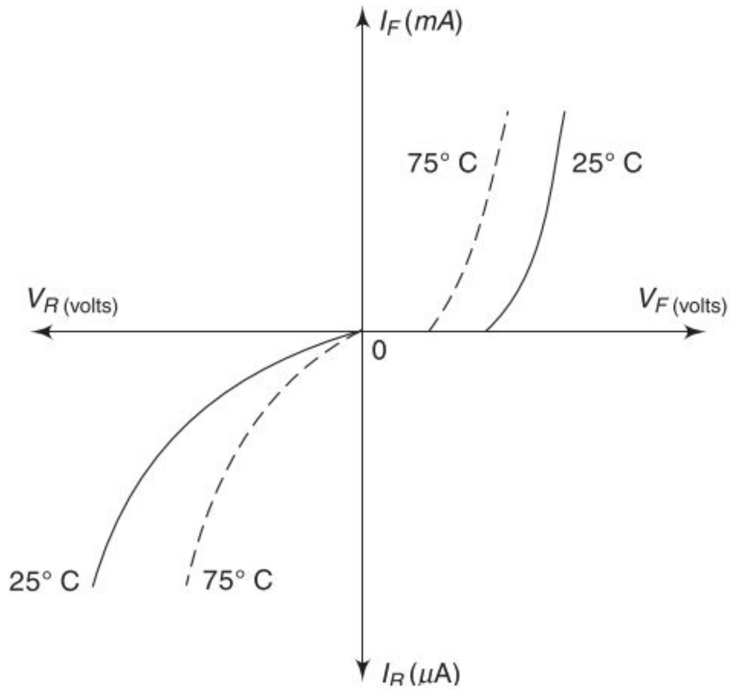
$$\boxed{C_D = \frac{\tau I}{\eta V_T}}.$$

where τ is the mean life time for holes and electrons.

$\tau = \dfrac{L_p^2}{D_p}$ is the mean life time of holes in the N-region.

Temperature Effects on Diode

- Temperature can have a marked effect on the characteristics of a silicon semiconductor diode
- reverse saturation current Io will just doubles in magnitude for every 10°C increase in temperature.



Effect of temperature on the diode characteristics

$$I_{O2} = I_{O1} \times 2^{(T_2 - T_1)/10}$$

Problem

P5

A silicon diode has a saturation current of 7.5 μA at room temperature 300 K. Calculate the saturation current at 400 K.

$$I_{O2} = I_{O1} \times 2^{(T_2 - T_1)/10}$$

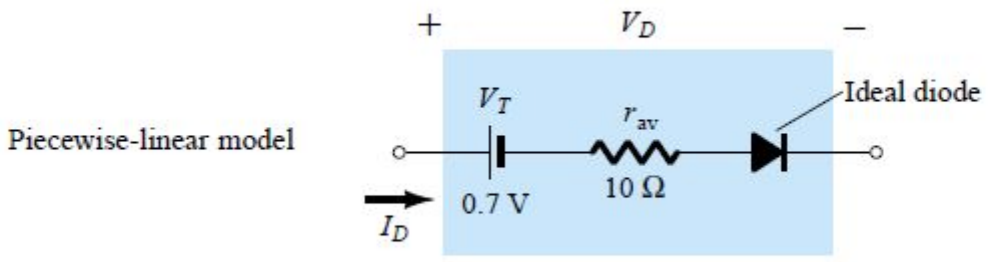
$$= 7.5 \times 10^{-6} \times 2^{(127 - 27)/10}$$
$$= 7.5 \times 10^{-6} \times 2^{10} = 7.68 \text{ mA}$$

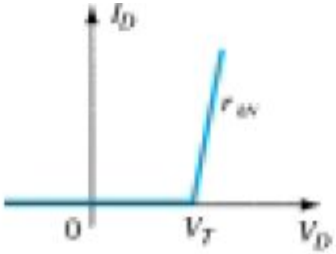
DIODE EQUIVALENT CIRCUITS

- ***An equivalent circuit is a combination of elements properly chosen to best represent the actual terminal characteristics of a device, system, or such in a particular operating region.***

Piecewise-Linear Equivalent Circuit

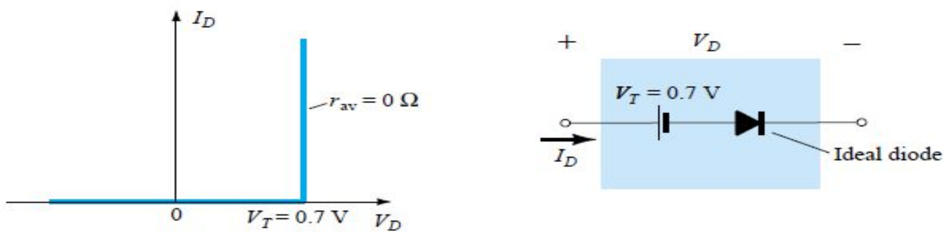
- Approximate the characteristics of the device by straight-line segments
- The resulting equivalent circuit is naturally called the piecewise-linear equivalent circuit.
- Do not result in an exact duplication of the actual characteristics, especially in the knee region.
- However, the resulting segments are sufficiently close to the actual curve to establish an equivalent circuit that will provide an excellent first approximation to the actual behavior of the device.





Simplified Equivalent Circuit

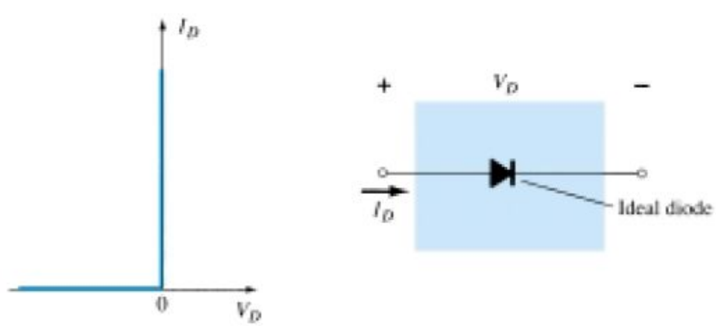
- For most applications, the resistance r_{av} is sufficiently small to be ignored in comparison to the other elements of the network.
- The removal of r_{av} from the equivalent circuit is the same as implying that the characteristics of the diode appear as shown in Fig.



Simplified equivalent circuit for the silicon semiconductor diode.

Ideal Equivalent Circuit

- r_{av} has been removed from the equivalent circuit let us establish that a 0.7V level can often be ignored in comparison to the applied voltage level.
- In this case the equivalent circuit will be reduced to that of an ideal diode as shown in Fig. with its characteristics.



DC Load Line Analysis

- In graphical analysis of nonlinear electronic circuits,
  - **DC load line** is a line drawn on the characteristic curve, (a graph of the current vs. the voltage in a nonlinear device like a diode)
  - It represents the constraint put on the voltage and current in the nonlinear device by the external circuit.
  - The load line, usually a straight line, represents the response of the linear part of the circuit, connected to the nonlinear device in question.
  - The points where the characteristic curve and the load line intersect are the possible operating point(s) (Q points) of the circuit
  - at these points the current and voltage parameters of both parts of the circuit match.

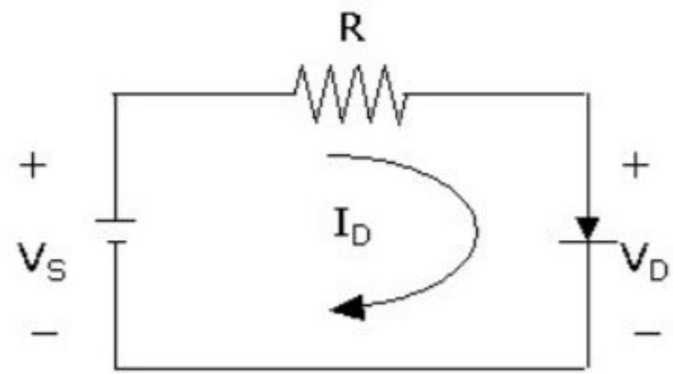
Assume that the diode is forward biased, current will flow in the circuit as shown

1. The forward biased diode equation

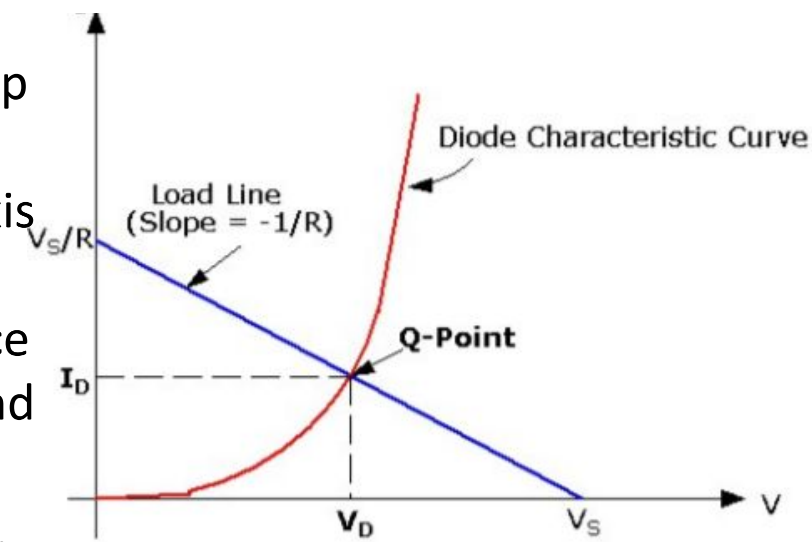
$$I_D = I_0 e^{\frac{v_D}{nV_T}}, \text{ and}$$

2. The KVL circuit equation solved for I_D:

$$I_D = \frac{V_S - V_D}{R}.$$



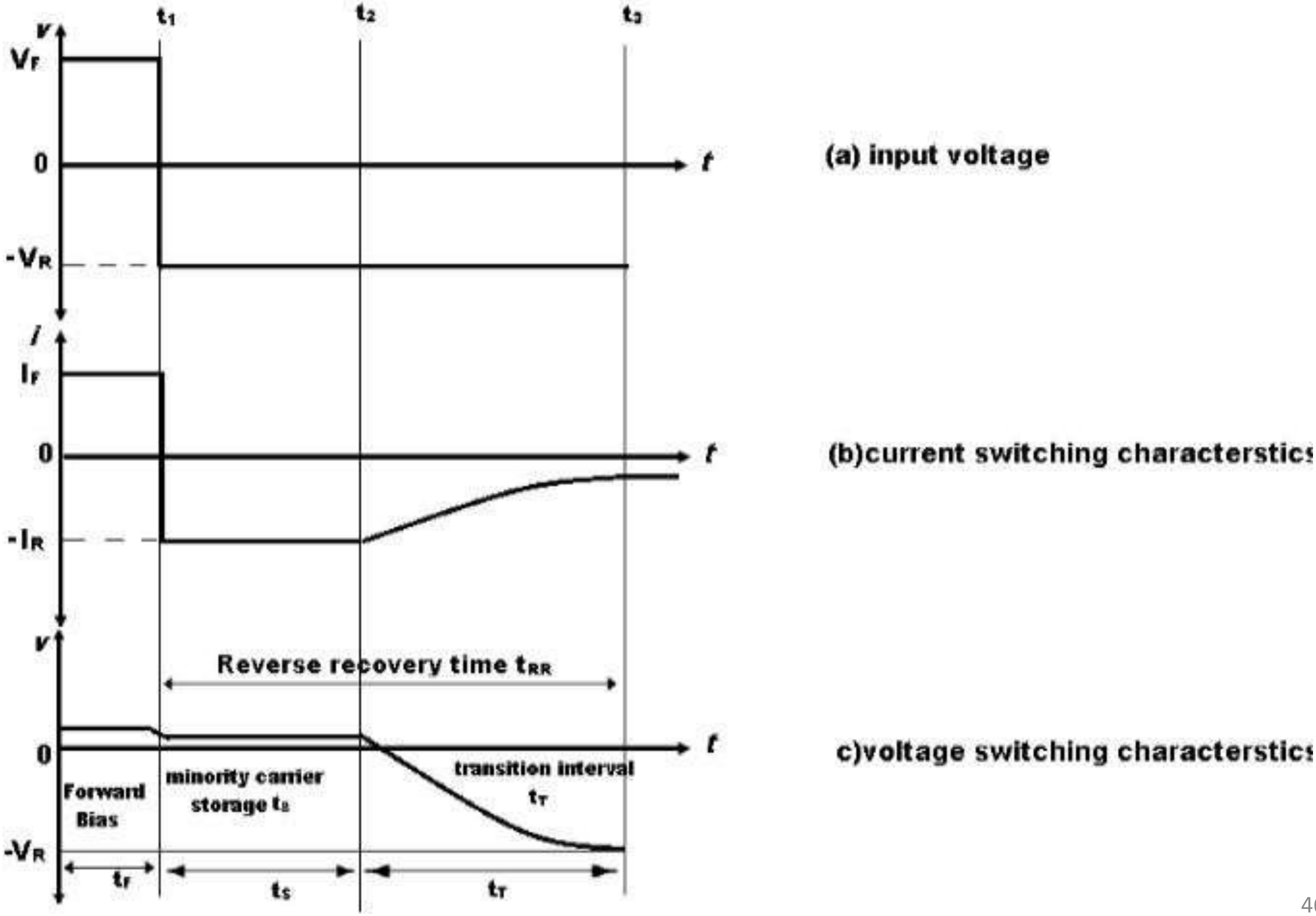
- If I_D is equal to zero, there is no drop across R and V_D=V_S.
- This will define the horizontal axis intercept.
- If V_D is equal to zero, the entire source voltage will be dropped across R and I_D=V_S/R.
- This will define the vertical axis intercept.
- The resulting load line will be a straight line with a slope of –1/R.



Switching Characteristics

- Recovery time
  - Forward Recovery Time
  - Reverse Recovery Time

Switching Characteristics



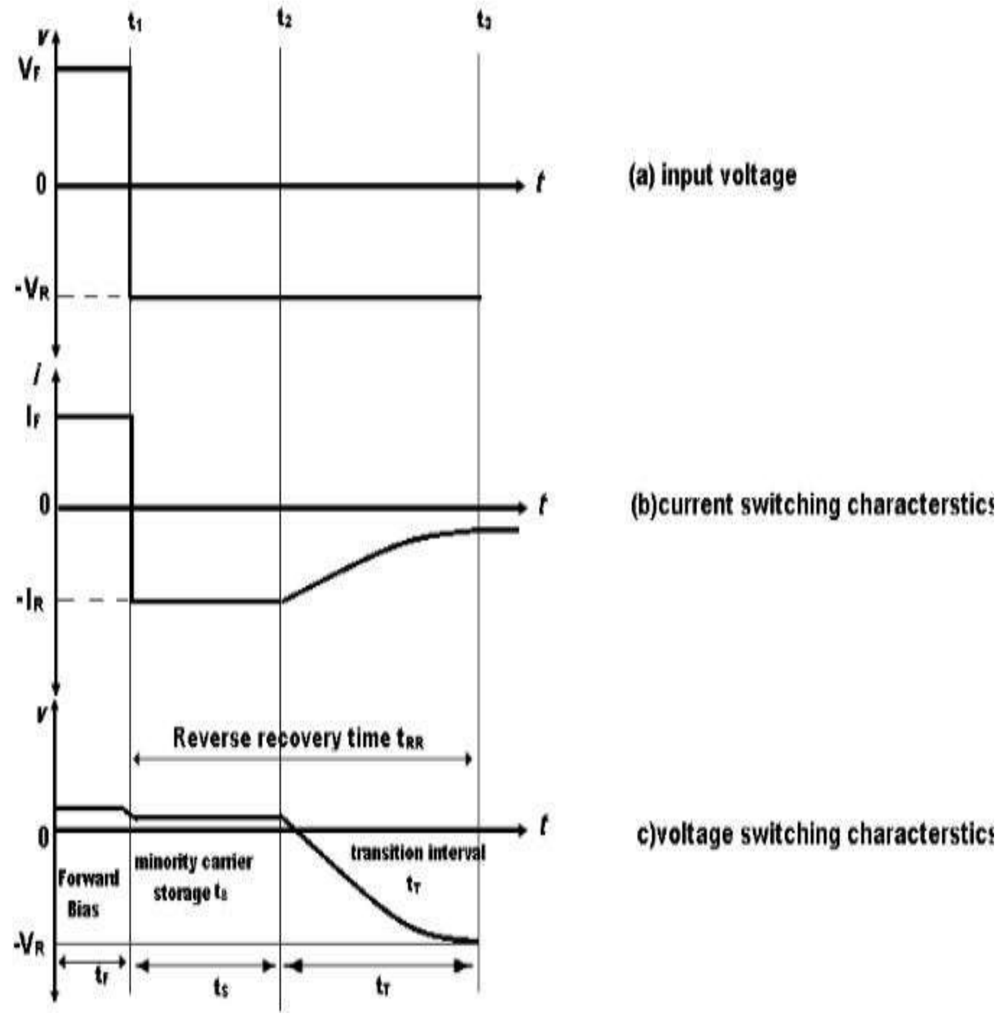
Switching Characteristics

- When the applied voltage to the PN junction diode is suddenly reversed in the opposite direction, the diode response reaches a steady state after an interval of time.

- This is called recover time.

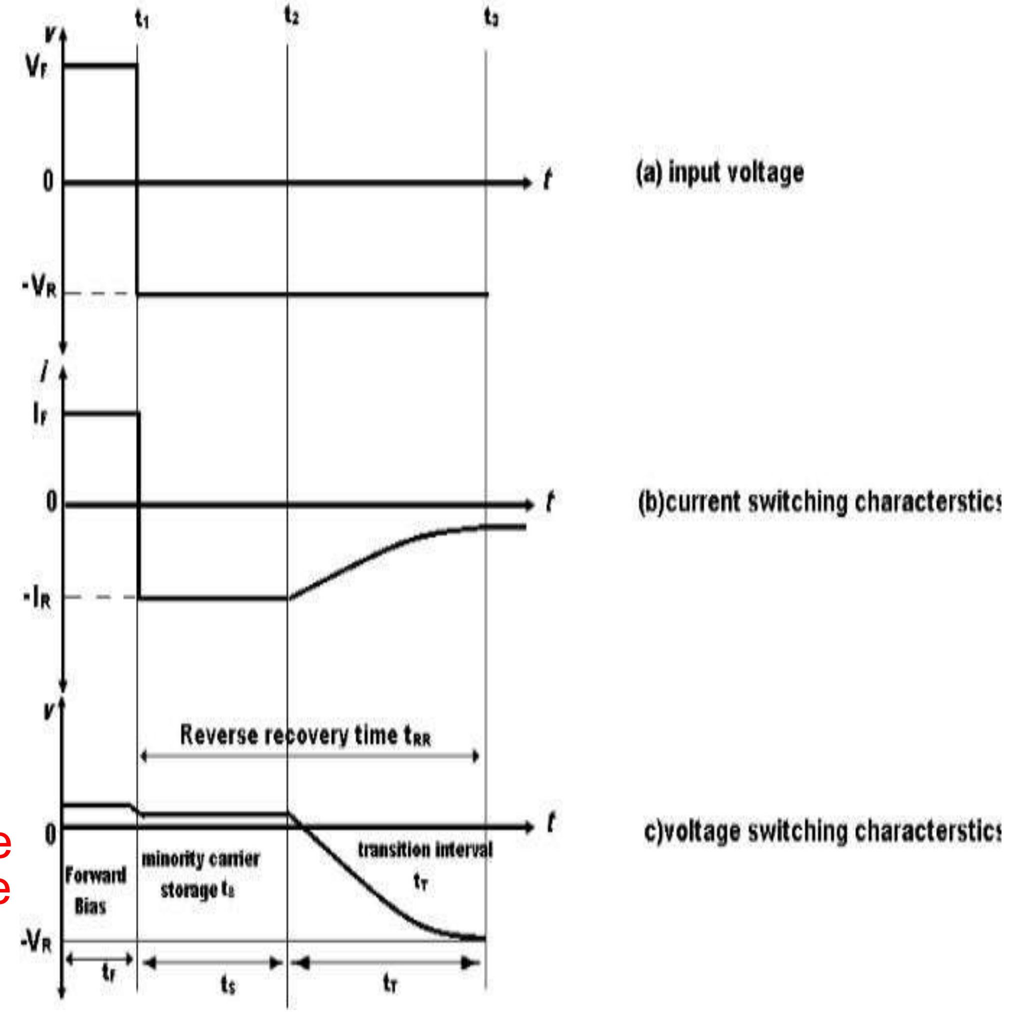
- The forward recovery time t_{fr}, is defined as the time required for forward voltage or current to reach a specified value after switching diode from its reverse to forward biased state

- Forward recovery time posses no serious problem



Switching Characteristics

- When the PN junction diode is forward biased, the minority electron concentration in the P region is approximately linear.
- If the junction is suddenly reverse biased, at t1, then because of this stored electronic charge, the reverse current I_R is initially of the same magnitude as the forward current
- The injected minority carrier have remained stored and have to reach the equilibrium state, this is called storage time (t_s)
- The time required for the diode for nominal recovery to reach its steady state is called transition time

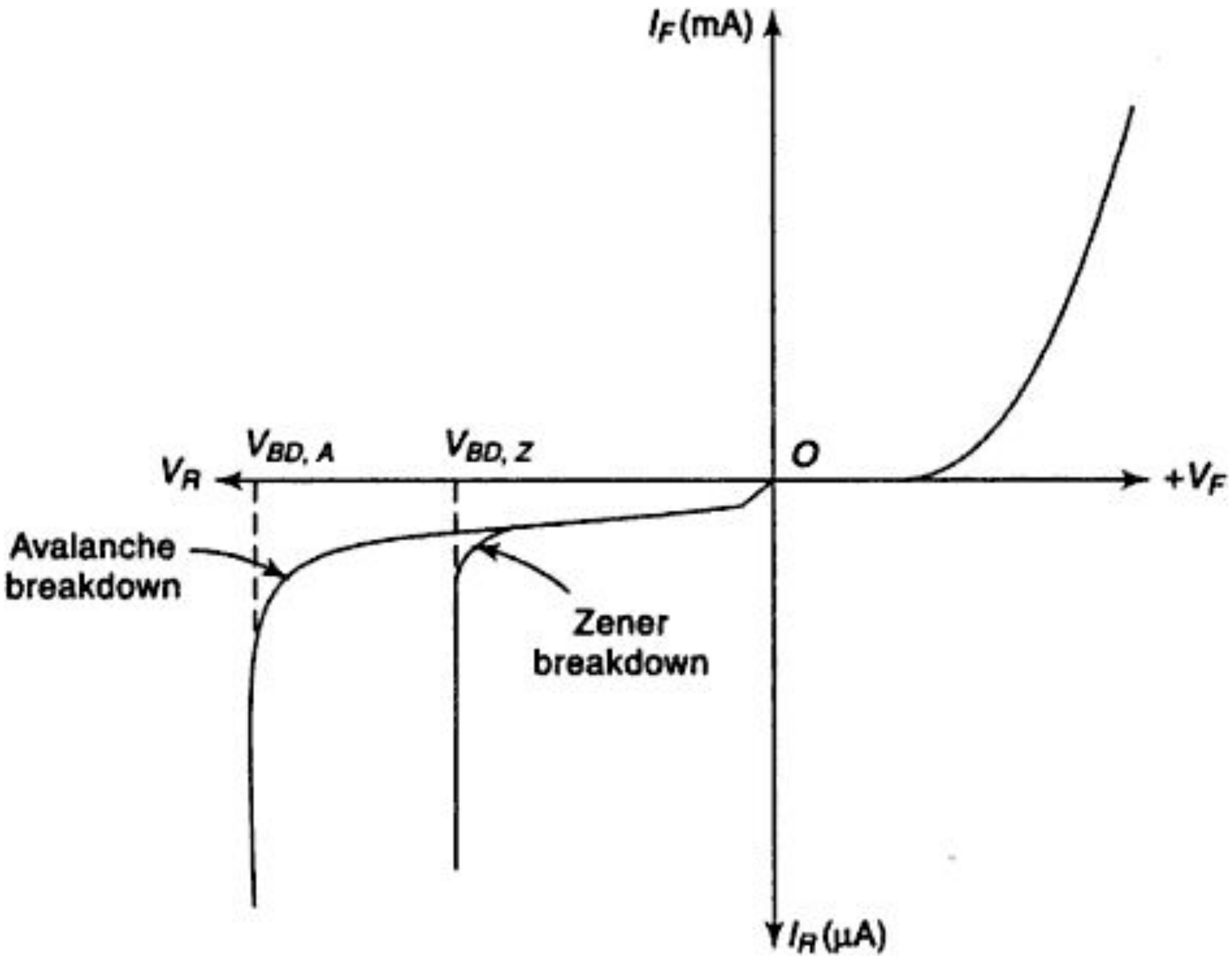


Switching Characteristics

- For commercial switching type diodes the reverse recovery time t_{rr} ranges from less than 1 ns to as high as 1 μs.
- The operating frequency should be a minimum of approximately 10 times t_{rr}.
- If a diode has trr of 2ns, the maximum operating frequency is

  $f_{max} = 1/T$ $1/(10*2*10^{-9})$ 50 MHz

Break down in PN Junction Diodes



Avalanche Break Down

- Thermally generated minority carriers cross the depletion region and acquire sufficient kinetic energy from the applied potential to produce new carrier by removing valence electrons from their bonds.

- These new carrier will in turn collide with other atoms and will increase the number of electrons and holes available for conduction.

- The multiplication e carrier may represented by

$$M = \frac{1}{1-\left(\frac{V}{V_{BD}}\right)^{n}}$$

Zener Break down

- Zener breakdown occurs in highly doped PN junction through **tunneling mechanism**

- In a highly doped junction, the conduction and valance bands on opposite sides of the junction are sufficiently close during reverse bias

- Electrons may **tunnel directly from the valence band of the P side** into the conduction band on the n side

Diode Ratings

- **Maximum Forward Current**
  - Highest instantaneous current under forward bias condition that can flow through the junction.

- **Peak Inverse Voltage (PIV)**
  - Maximum reverse voltage that can be applied to the PN junction
  - If the voltage across the junction exceeds PIV, under reverse bias condition, the junction gets damaged. (1000 V)

- **Maximum Power Rating**
  - Maximum power that can be dissipated at the junction without damaging the junction.
  - It is the product of voltage across the junction and current through the junction

Diode Ratings

- **Maximum Average Forward Current**
  - Maximum amount of average current that can be permitted to flow in the forward direction at a special temperature (25^o C)
- **Repetitive Peak Forward Current**
  - Maximum peak current that can be permitted to flow in the forward direction in the form of recurring pulses.
  - Limiting value of the current is 450 mA
- **Maximum Surge Current**
  - Maximum current permitted to flow in the forward direction in the form of nonrecurring pulses.
  - It should not be more that a few milliseconds. **(30 A for 8.3 ms)**