A

TRANSITION AND DIFFUSION CAPACITANCE

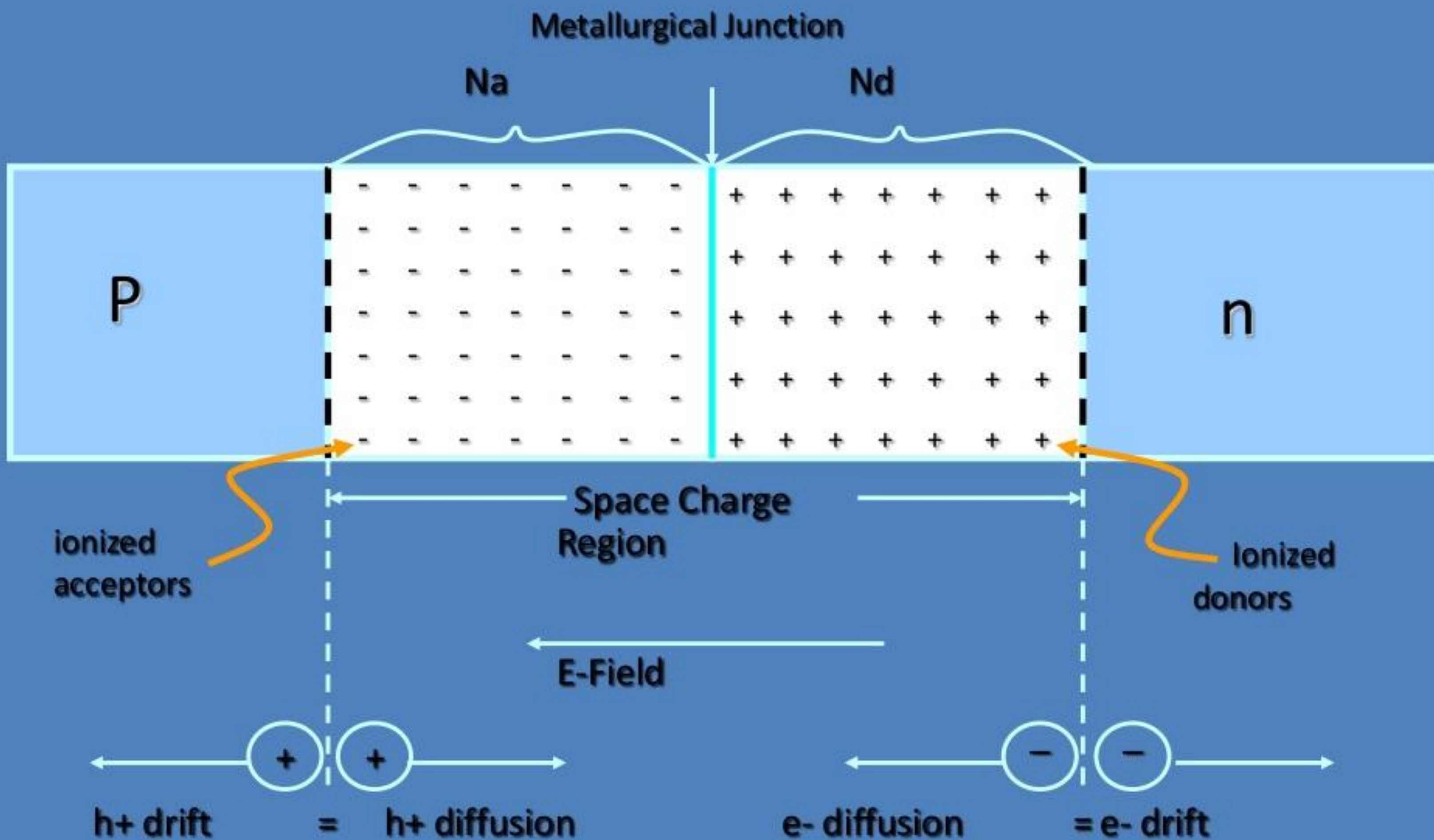
STEP GRADED JUNCTION

A junction is said to be step graded if there is an abrupt change from acceptor ion concentration on the P-side to donor ion concentration on the N-side.Such a junction is get formed in alloyed or fused junction. Usually the acceptor density N_a and the donor density N_d are kept unequal.

LINEARLY GRADED JUNCTION

A junction is said to be linearly graded if the charge density varies gradually with the distance in transition region. Such a junction gets formed in a growth junction diode.

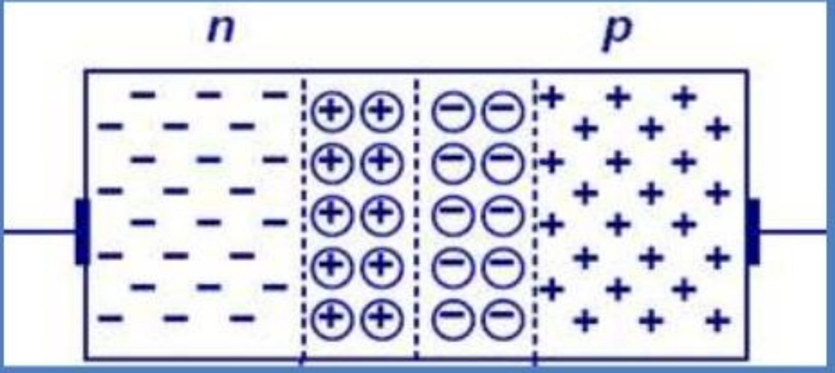
DEPLETION LAYER

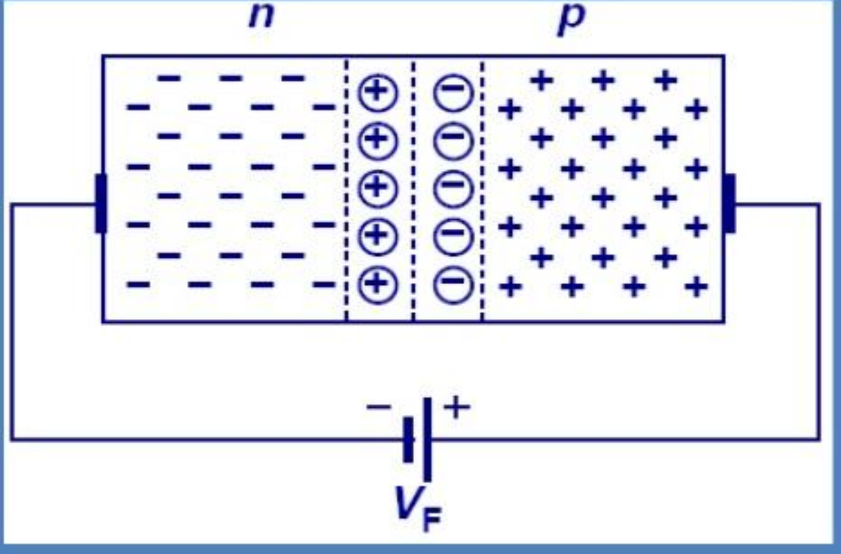


DEPLETION LAYER

Figure represents the net positively and negatively charged regions for a semiconductor P-N junction where there are no external connection, no applied voltage , no field etc. The net positive and negative regions induce an electric field near the junction in the direction from the n-region to the P-region. Since the electrons and the holes both pushed out of the space charge region of the electric field, the region is depleted of any mobile charge is called the depletion region.

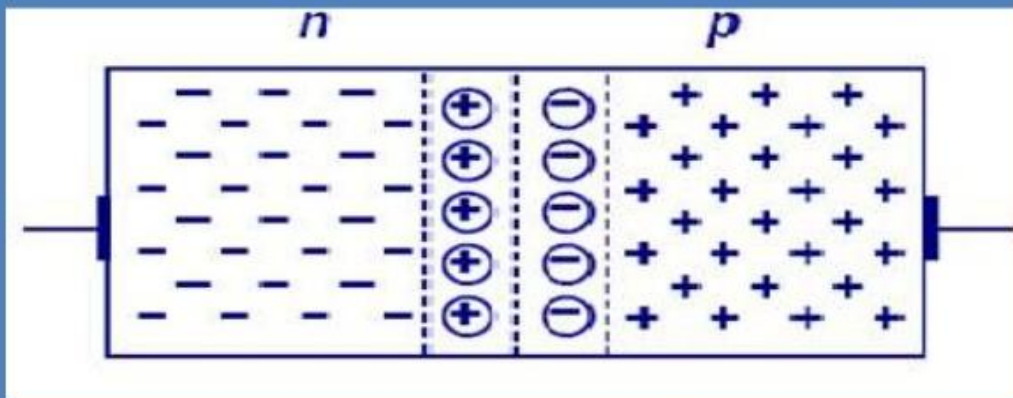
WIDTH OF DEPLETION LAYER IN FORWARD BIAS

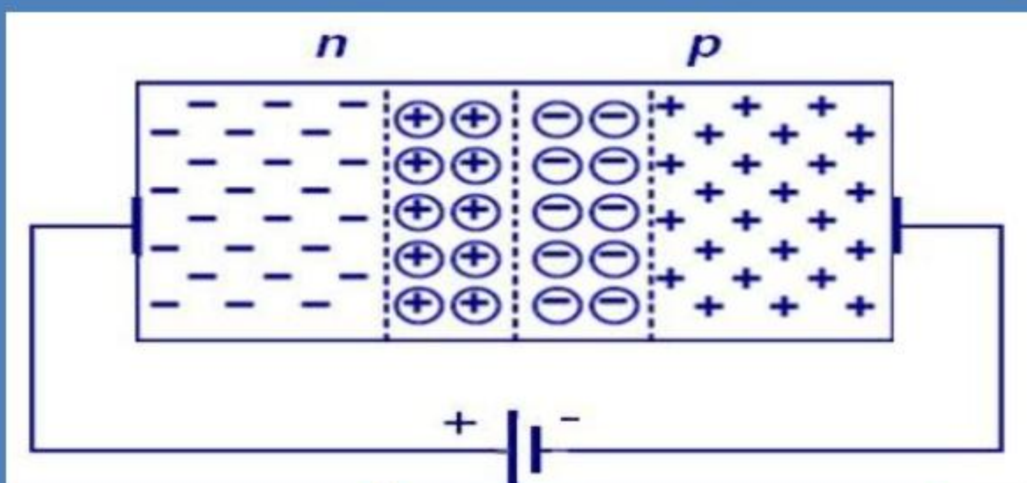




when the P-N junction is Forward Biased ,the width of depletion region is reduced and the barrier potential is also reduced .

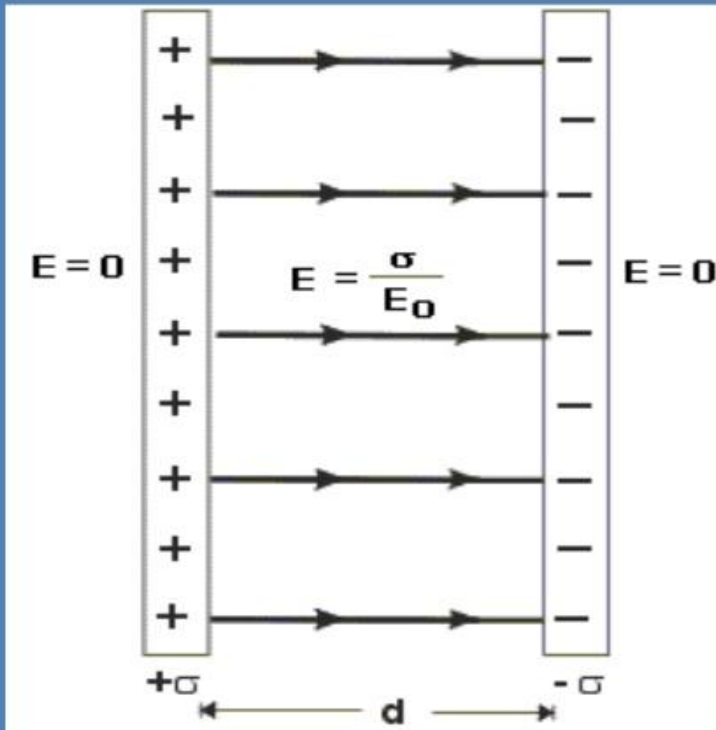
DEPLETION LAYER IN REVERSE BIAS

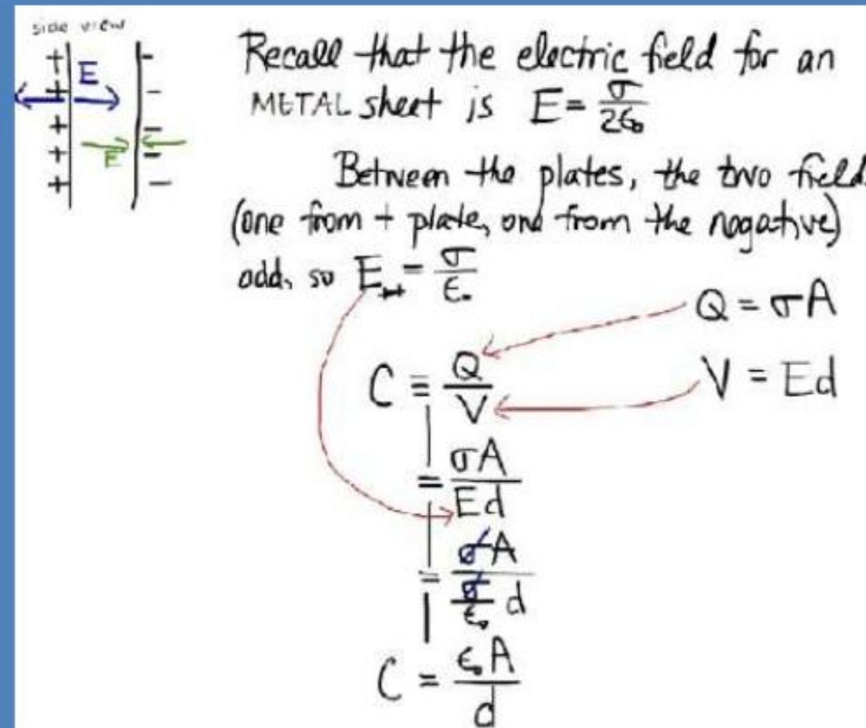




When the P-n junction is reverse biased , the depletion region is widened and the barrier potential is also increased.

CAPACITANCE



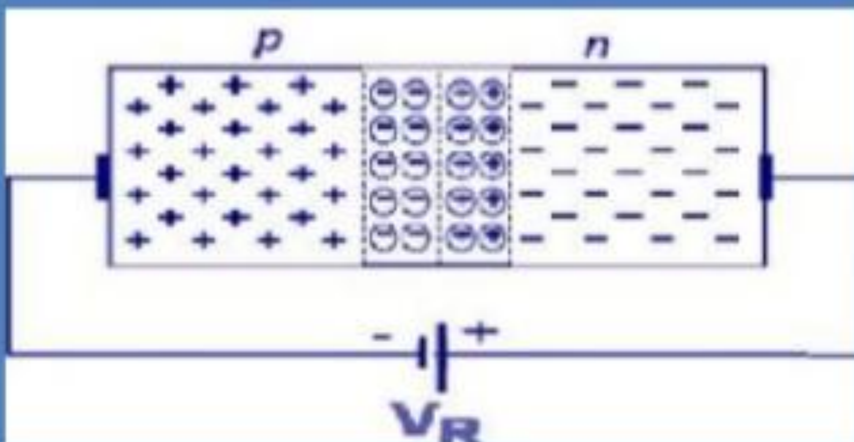


Capacitance is the property to hold charge by a capacitor. In case of a parrallel plate capacitor the formula for the capacitance is given by

$$C=\varepsilon A/D=Q/V$$

A = cross section area of capacitor plates,D=separation b/w capacitor plates, **ε**=absolute permittivity of the medium b/w the capacitor plates, Q=charge stored on capacitor plates,V=potential applied

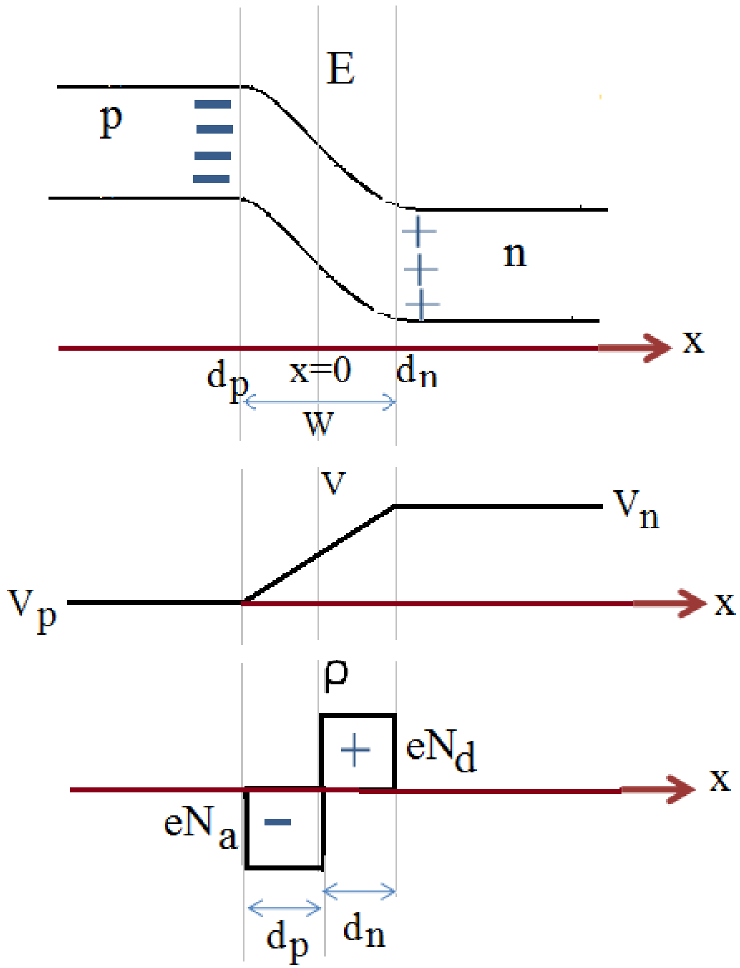
TRANSITION CAPACITANCE



When a p-N junction is reverse biased the depletion region acts like an insulator or dielectric material while the P and N type regions on either side have a low resistance and act as the plates. Thus P-N junction may be considerd as a parrallel plate capacitor.The jumction capacitance is termed as space charge capacitance or transition capacitance and is denoted by C_T.

As mentioned earlier, a reverse bias causes majority carriers to move away from the junction, thereby uncovering more immobile charges. So the thickness W of the depletion layer increases with the increase in reverse bias voltage . This increase in uncovered charge with applied voltage may be considered a capacitative effect . The incremental capacitance may be defined as- C_T = **dQ/dV** where dQ is increase in charge with increase in voltage, dV.

Transition capacitance for abrupt/step junction

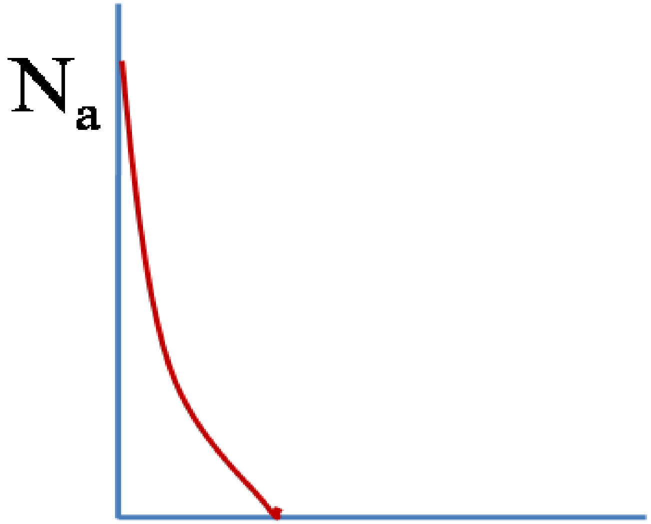


To a good approximation we can consider the space charge within the transition regions only due to uncompensated donar and acceptor ion separated by some distance constitute a capacitor. These immobile ions some distance constitute a capacitor.

For a sample of cross sectional area A the total uncompensated charge on the either side of the junction

$$eN_dAd_n = eN_aAd_p$$

$N_ad_p=N_dd_n$. Neutrality condition



For an abrupt or step junction impurity profile is very step , the abrupt approximation is usually acceptable. Abrupt junction is usually formed in alloyed junction

Now considering the Poisson equation on the n side

$$\frac{d^2V}{dx^2} = -\frac{\rho}{\varepsilon} = -\frac{eN_d^+}{\varepsilon} = -\frac{eN_d}{\varepsilon} \qquad 1$$

$$\frac{dV}{dx} = -\frac{eN_d}{\varepsilon}x + const \qquad 2$$

At $x=d_n$, $\frac{dV}{dx} = 0$

$$const = \frac{eN_d}{\varepsilon}d_n \qquad 3$$

From equation 2 using equation 3 we get

$$V = -\frac{eN_d}{2\varepsilon}x^2 + \frac{eN_d}{\varepsilon}d_n x + const$$

At $x=d_n$ $V=V_n$

$$V = -\frac{eN_d}{2\varepsilon}x^2 + \frac{eN_d}{\varepsilon}d_n x + \left(V_n - \frac{eN_d}{2\varepsilon}d_n^2\right)$$

Now considering the Poisson equation on the other side of the junction

$$\frac{d^2V}{dx^2} = -\frac{\rho}{\varepsilon} = +\frac{eN_d^-}{\varepsilon} = \frac{eN_a}{\varepsilon}$$

$$V = \frac{eN_a}{2\varepsilon}x^2 - \frac{eN_a}{\varepsilon}d_p x + \left(V_p + \frac{eN_a}{2\varepsilon}d_p^2\right)$$

Since the potential has unique value the potential is must be equal at any value of x including 0.

At x=0

$$V_n - \frac{eN_d}{2\varepsilon} d_n^2 = V_p + \frac{eN_a}{2\varepsilon} d_p^2$$

$$V_n - V_p = \frac{eN_d}{2\varepsilon} d_n^2 + \frac{eN_a}{2\varepsilon} d_p^2$$

$$\Delta\Phi = \frac{e}{2\varepsilon}\left(N_d d_n^2 + N_a d_p^2\right)$$

$$= \frac{e}{2\varepsilon} N_d^2 d_n^2 \left(\frac{N_a + N_d}{N_a N_d}\right)$$

$$d_n = \frac{1}{N_d}\left\{\frac{2\varepsilon}{e}\Delta\Phi\,\frac{N_a N_d}{N_a + N_d}\right\}^{1/2}$$

$$d_p = \frac{1}{N_a}\left\{\frac{2\varepsilon}{e}\Delta\Phi\,\frac{N_a N_d}{N_a + N_d}\right\}^{1/2}$$

$$W = d_n + d_p = \left\{\frac{2\varepsilon}{e}\Delta\Phi\,\frac{N_a N_d}{N_a + N_d}\right\}^{1/2}\left[\frac{1}{N_a} + \frac{1}{N_d}\right]$$

$$= \left\{\frac{2\varepsilon\Delta\Phi}{e}\,\frac{N_a + N_d}{N_a N_d}\right\}^{1/2}$$

When the junction is biased the width of the junction varies

Forward bias

$$W(V) = \left\{ \frac{2\varepsilon(\Delta\Phi - V)}{e} \frac{N_a + N_d}{N_a N_d} \right\}^{1/2}$$

Reverse bias

$$W(V) = \left\{ \frac{2\varepsilon(\Delta\Phi + V)}{e} \frac{N_a + N_d}{N_a N_d} \right\}^{1/2}$$

Now the capacitance of the parallel plate capacitor is given by

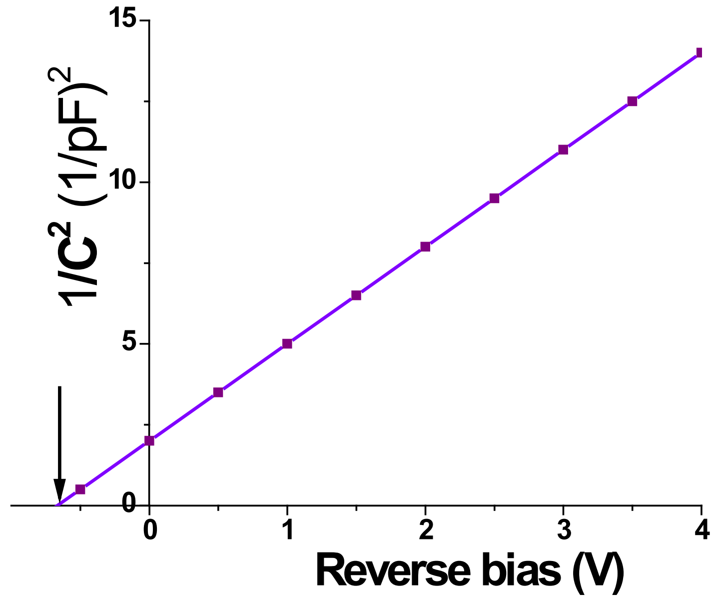
$$C = \frac{\varepsilon A}{W(V)}$$

$$C = \frac{\varepsilon A}{\left\{ \frac{2\varepsilon(\Delta\Phi + V)}{e} \frac{N_a + N_d}{N_a N_d} \right\}^{1/2}}$$

$$= \frac{1}{B^{1/2}(\Delta\Phi + V)^{1/2}}$$

where $$B = \left\{ \frac{2\varepsilon(\Delta\Phi + V)}{\varepsilon^2 A^2 e} \frac{N_a + N_d}{N_a N_d} \right\}$$

Hence $$\frac{1}{C^2} = B(\Delta\Phi + V)$$



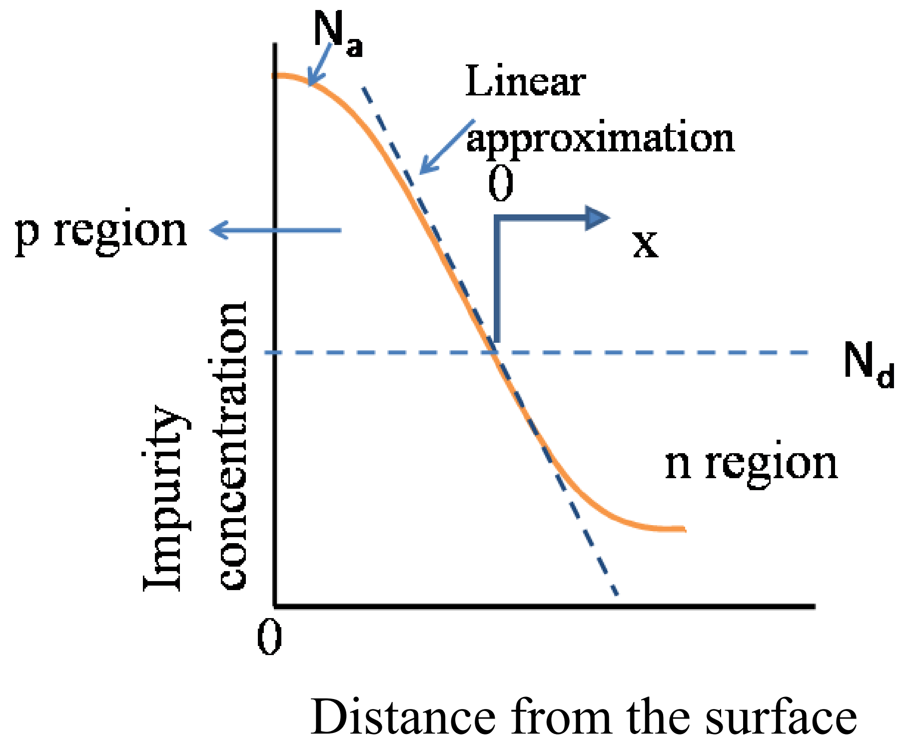
If we plot $1/C^2$ *vs* V for reverse bias in an abrupt junction we get the barrier potential $\Delta\varphi$ from the intercept on the V axis.

Linearly graded junction

While the abrupt junction approximately describes the properties of the alloyed junction, many epitaxial structures, it is often inadequate in analyzing the diffused junction devices. For diffused junction impurity profile is spread out into the sample. This result in a graded junction.

Thus graded junction problem can be solved analytically if we make a linear approximation of the net impurity distribution near the junction. We assume that the graded region can be described approximately by $N_D - N_A = \alpha x$

where α is the grade constant giving the slope of the net impurity distribution.



Originally surface was n type. But as we diffuse impurity (i.e. p type) into the n region near the surface becomes p type but away from the surface impurity concentration decreases to n region

Now considering the n region

$$\frac{d^2V}{dx^2} = -\frac{\rho}{\varepsilon} = -\frac{e(N_d - N_a)}{\varepsilon} = -\frac{e\alpha x}{\varepsilon}$$

$$\frac{dV}{dx} = -\frac{e\alpha}{2\varepsilon}x^2 + const$$

Putting Boundary condition at x=d_n, $\frac{dV}{dx} = 0$

$$const = \frac{e\alpha d_n^2}{2\varepsilon}$$

$$V = -\frac{e\alpha}{2\varepsilon 3}x^3 + \frac{e\alpha d_n^2}{2\varepsilon}x + const$$

At x=d_n V=V_n

$$V_n = -\frac{e\alpha}{2\varepsilon 3}{d_n}^3 + \frac{e\alpha d_n^3}{2\varepsilon} + const$$

We get

$$V = -\frac{e\alpha}{2\varepsilon 3}x^3 + \frac{e\alpha}{2\varepsilon}d_n^2 x + \left(V_n - \frac{e\alpha}{3\varepsilon}d_n^3\right)$$

Now considering the p region

$$\frac{d^2V}{dx^2} = -\frac{\rho}{\varepsilon} = -\frac{e(N_a - N_d)}{\varepsilon} = \frac{e\alpha x}{\varepsilon}$$

From this we get

$$V = \frac{e\alpha}{2\varepsilon 3}x^3 - \frac{e\alpha}{2\varepsilon}d_p^2 x + \left(V_p + \frac{e\alpha}{3\varepsilon}d_p^3\right)$$

Since the potential is unique we get both potentials must be same at any value of x including 0.

At x=0

$$V_n - V_p = \frac{e\alpha}{3\varepsilon}\left(d_n^3 + d_p^3\right)$$

$$\Delta\Phi = \frac{e\alpha}{3\varepsilon}(d_n^3 + d_p^3)$$

$$= \frac{e\alpha}{12\varepsilon} W^3$$

$$W^3 = \frac{12\varepsilon}{e\alpha}\Delta\Phi$$

$$W = \left(\frac{12\varepsilon}{e\alpha}\Delta\Phi\right)^{1/3}$$

When the bias is applied

$$W(V) = \left(\frac{12\varepsilon}{e\alpha}(\Delta\Phi \pm V)\right)^{1/3}$$

For Reverse bias

$$W(V) = \left(\frac{12\varepsilon}{e\alpha} (\Delta\Phi + V) \right)^{1/3}$$

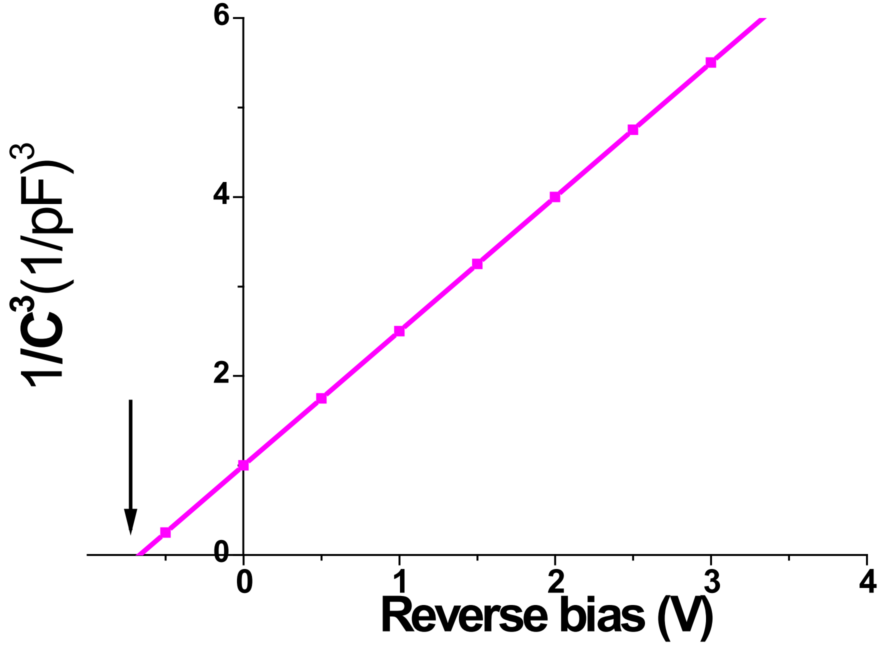
$$C_j(rev) = \frac{\varepsilon A}{W(V)}$$

$$= \frac{\varepsilon A}{\left(\frac{12\varepsilon(\Delta\Phi + V)}{e\alpha} \right)^{1/3}}$$

$$= \frac{1}{B^{1/3} (\Delta\Phi + V)^{1/3}}$$

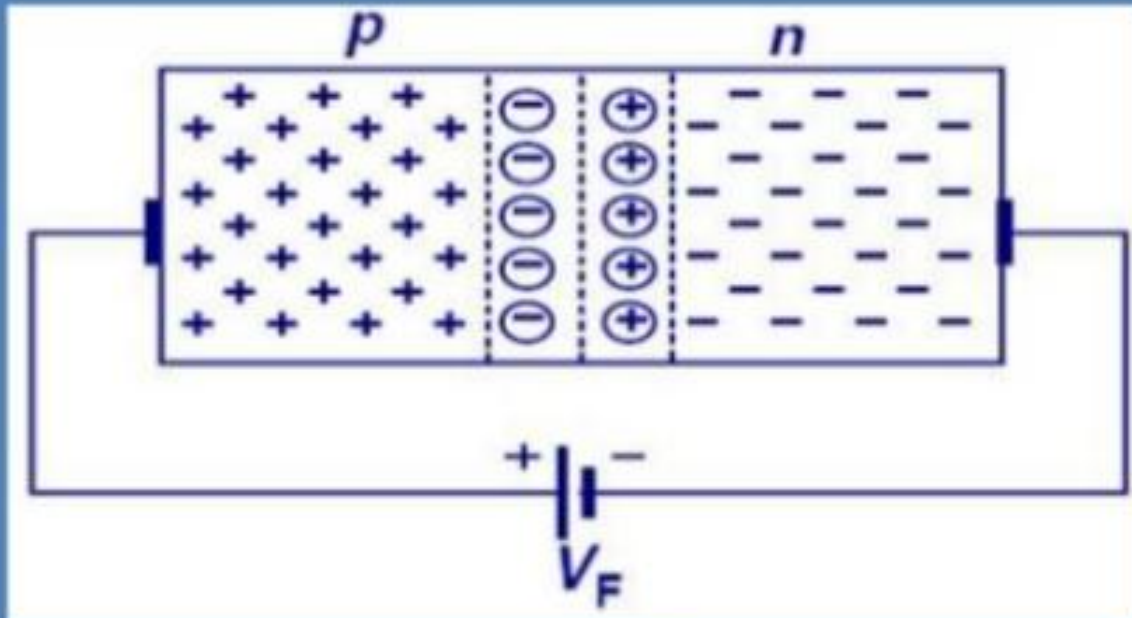
Where $$B = \frac{12(\Delta\Phi + V)}{\varepsilon^2 A^3}$$

$$\frac{1}{C_j^3} = B(\Delta\Phi + V)$$



Above fig. shows the graph where $1/C^3$ is plotted against the applied voltage. The intercept on voltage axis gives the barrier potential .

DIFFUSION CAPACITANCE



When a P-N junction is forward biased ,a capacitance which is much larger than the transition capacitance , comes into play . This type of capacitance is called the Diffusion Capacitance and is denoted by C_D.

Diffusion capacitance

The diffusion capacitance dominates under forward bias
Now we have already got

$$\frac{p_p}{p_n} = e^{e\Delta\Phi / kT}$$

$$p_p = p_n e^{e\Delta\Phi / kT}$$

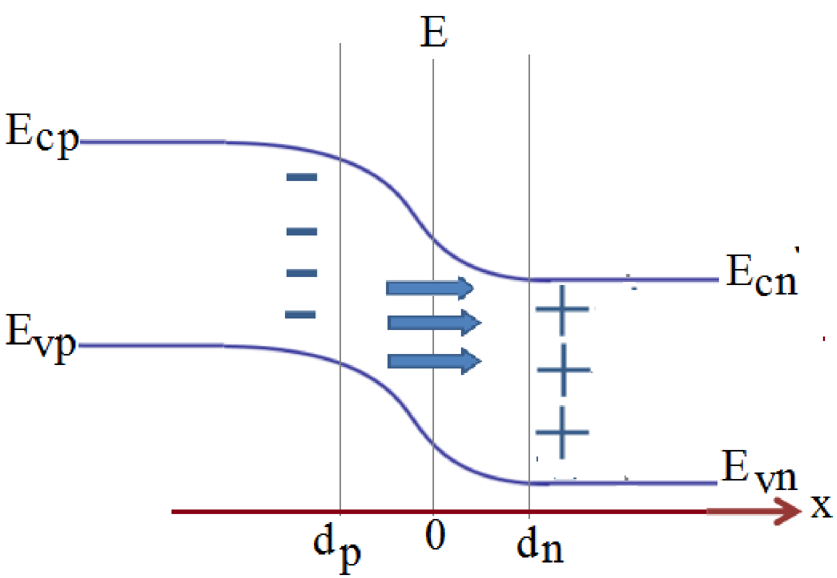
$$p_n = p_p e^{-e\Delta\Phi / kT}$$

Hence p_n denotes the thermal equilibrium hole density on n side. Thus as a result of forward bias the barrier height will be reduced

$$p'_n = p_p e^{-e(\Delta\Phi - V)/kT}$$

Injected hole

$$= p'_n - p_n$$



$$\Delta p_0 = p_p{}^{-e(\Delta\Phi - V)/kT} - p_n$$

$$= p_p{}^{\frac{-e\Delta\Phi}{kT}} e^{\frac{eV}{kT}} - p_n$$

$$= p_n e^{\frac{eV}{kT}} - p_n$$

$$= p_n\left(e^{\frac{eV}{kT}} - 1\right)$$

Consequently the injected hole at $x=d_n$ will enter into the bulk n region and start recombination.

$$\Delta p = \Delta p_o e^{\frac{-x}{L_p}}$$

$$= p_n (e^{eV/kT} - 1) e^{\frac{-x}{L_p}}$$

Thus no of holes stored per unit area of the n region just near to the junction may be obtained as

$$\frac{Q_p}{e} = \int_0^\infty \Delta p dx = \int_0^\infty p_n (e^{eV/kT} - 1) e^{\frac{-x}{L_p}} dx$$

$$= p_n (e^{eV/kT} - 1) \int_0^\infty e^{\frac{-x}{L_p}} dx = p_n (e^{eV/kT} - 1) L_p$$

$$Q_p = ep_n(e^{eV/kT} - 1)L_p$$

Now if we produce a charge dQ_p of the stored hole charge by changing potential dV, The diffusion capacitance per unit area due to hole on n side of the junction be given by

$$C_p = \frac{dQ_p}{dV} = \frac{e^2 p_n L_p}{kT} e^{\frac{eV}{kT}}$$

Similarly ,The diffusion capacitance per unit area due to electron on p side of the junction given by

$$C_n = \frac{dQ_n}{dV} = \frac{e^2 n_p L_n}{kT} e^{\frac{eV}{kT}}$$

Thus the capacitance C_p and C_n as they are connected in parallel. Hence the diffusion capacitance of the junction per unit area is given by

$$C_d = C_n + C_p$$

$$C_d = \frac{e^2}{kT}\left[p_n L_p + n_p L_n\right] e^{\frac{eV}{kT}}$$

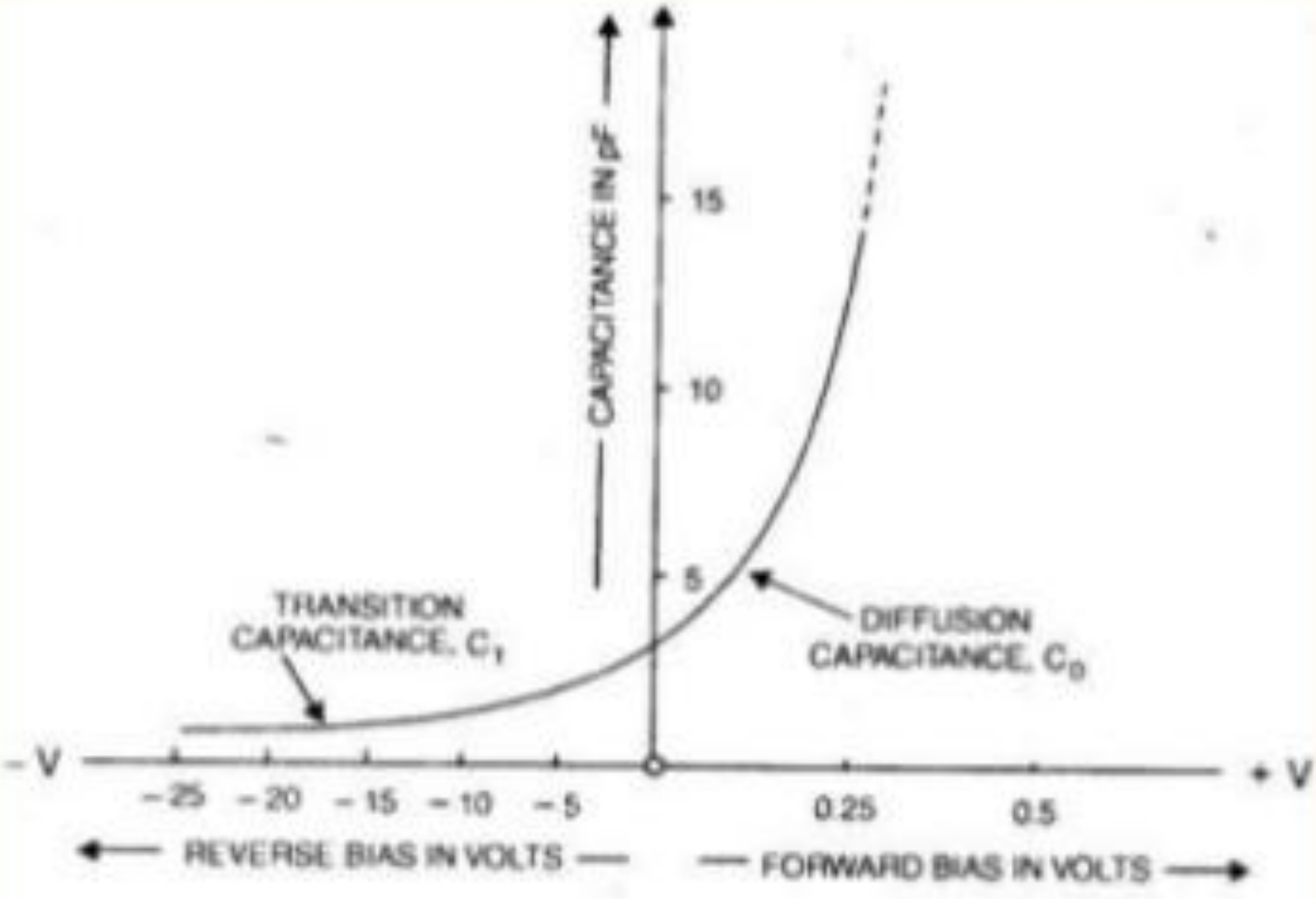


Fig. Transition and Diffusion Capacitance in a *pn* diode