Prove: $qV_0=E_{Vp}-E_{Vn}$

$$\frac{p_p}{p_n} = e^{qV_0/kT} = \frac{N_v e^{-(E_{Fp}-E_{vp})/kT}}{N_v e^{-(E_{Fn}-E_{vn})/kT}}$$

$$e^{qV_0/kT} = e^{(E_{Fn}-E_{Fp})/kT} e^{(E_{vp}-E_{vn})/kT}$$

$$qV_0 = E_{vp} - E_{vn}$$

Prove: $qV_0=\Delta E_{Fp}+\Delta E_{Fn}$

$$e^{qV_0/kT} = \frac{p_p}{p_n} = \frac{p_p}{n_i^2/n_n} = \frac{p_p.n_n}{n_i^2} = \frac{p_p.n_n}{n_i p_i} = \frac{N_V e^{-(E_{Fp}-E_V)/kT}.N_C e^{-(E_C-E_{Fn})/kT}}{N_V e^{-(E_i-E_V)/kT}.N_C e^{-(E_C-E_i)/kT}}$$

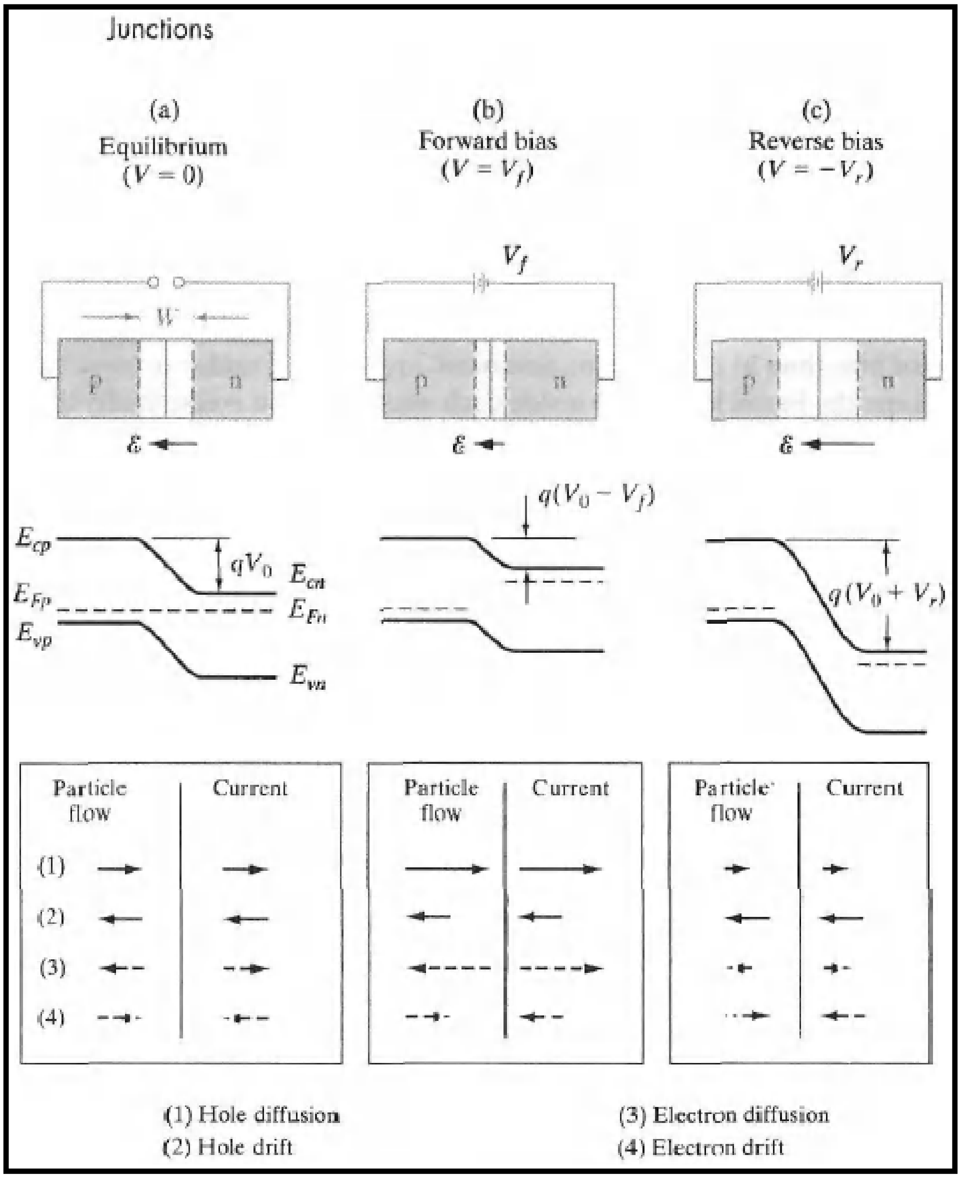
$$\begin{aligned} e^{qV_0/kT} &= \exp\left[\left(-E_{Fp}+E_V-E_C+E_{Fn}+E_i-E_V+E_C-E_i\right)/kT\right] \\ &= \exp\left[\left\{\left(E_i-E_{Fp}\right)+\left(E_{Fn}-E_i\right)\right\}/kT\right] = \exp\left[\left(\Delta E_{Fp}+\Delta E_{Fn}\right)/kT\right] \end{aligned}$$

Hence, $qV_0=\Delta E_{Fp}+\Delta E_{Fn}$

Description of Current Flow at a Junction (external voltage applied):

It is assumed that an applied voltage bias *V* appears across the transition region of the junction rather than in the neutral n and p regions. Since an applied voltage changes the electrostatic potential barrier and thus the electric field within the transition region, we would expect changes in the various components of current at the junction. In addition, the separation of the energy bands is affected by the applied bias, along with the width of the depletion region. The *electrostatic potential barrier* at the junction is lowered by a forward bias V_f from the equilibrium contact potential V_0 to the smaller value $V_0–V_f$. For a reverse bias $(V = —V_r)$ the opposite occurs.

The *separation of the energy bands* is a direct function of the electrostatic potential barrier at the junction. The height of the electron energy barrier is simply the electronic charge *q* times the height of the electrostatic potential barrier. Thus the bands are separated less $[q(V_0-V_f)]$ under forward bias than at equilibrium, and more $[q(V_0+V_r)]$ under reverse bias. The band diagram in different bias condition is shown in the following figure.



The *diffusion current* is composed of majority carrier electrons on the n side surmounting the potential energy barrier to diffuse to the p side, and holes surmounting their barrier from p to n.

With forward bias, the barrier is lowered (to V_0-V_f), and many more electrons in the n-side conduction band have sufficient energy to diffuse from n to p over the smaller barrier. Therefore, the electron diffusion current can be quite large with forward bias. Similarly, more holes can diffuse from p to n under forward bias because of the lowered barrier.

For reverse bias the barrier becomes so large (V_0+V_r) that virtually no electrons in the n-side conduction band or holes in the p-side valence band have enough energy to surmount it. Therefore, the diffusion current is usually negligible for reverse bias.

The drift current is relatively insensitive to the height of the potential barrier. *(This sounds strange at first, since we normally think in terms of material with ample carriers, and therefore we expect drift current to be simply proportional to the applied field. The reason for this apparent anomaly is the fact that the drift current is limited not by how fast carriers are swept down the barrier, but rather how often. For example, minority carrier electrons on the p side which wander into the transition region will be swept down the barrier by the E field, giving rise to the electron component of drift current. However, this current is small not because of the size of the barrier, but because there are very few minority electrons in the p side to participate. Every electron on the p side which diffuses to the transition region will be swept down the potential energy hill, whether the hill is large or small. The electron drift current does not depend on how fast an individual electron is swept from p to n, but rather on how many electrons are swept down the barrier per second. Similar comments apply regarding the drift of minority holes from the n side to the p side of the junction. To a good approximation, therefore, the electron and hole drift currents at the junction are independent of the applied voltage.)*

The *total current* crossing the junction is composed of the sum of the diffusion and drift components.

The *net* current crossing the junction is zero at equilibrium, since the drift and diffusion components cancel for each type of carrier

Under reverse bias, both diffusion components are negligible because of the large barrier at the junction, and the only current is the relatively small (and essentially voltage-independent) generation current from n to p.

IV characteristics and derivation of current equation:

The only current flowing in this p-n junction diode for negative *V* is the small current /(gen.) due to carriers generated in the transition region or minority carriers which diffuse to the junction and are collected. The current at *V* = 0 (equilibrium) is zero since the generation and diffusion currents cancel.

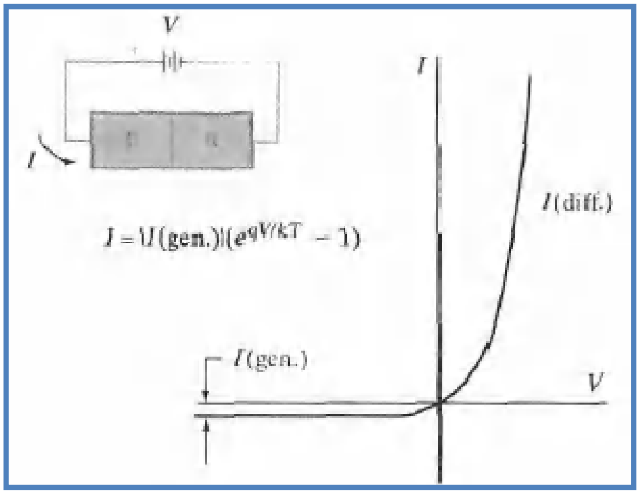
$$\mathbf{I = I_{diff} - |I(gen)| = 0 \;\; for \;\; V = 0}$$

An applied forward bias $V = V_f$ increases the probability that a carrier can diffuse across the junction, by the factor $\exp(qV_f/kT)$. Thus the diffusion current under forward bias is given by its equilibrium value multiplied by $exp(qV/kT)$; similarly, for reverse bias the diffusion current is the equilibrium value reduced by the same factor, with $V=-V_r$. Since the equilibrium diffusion current is equal in magnitude to |/(gen.)|, the diffusion current with applied bias is simply |/(gen.)| $exp(qV/kT)$. The total current *I* is then the diffusion current minus the absolute value of the generation current, which we will now refer to as I_0:

$I=I_0(e^{qV/kT}-1)$

The applied voltage *V* can be positive or negative, $V=V_f$ or $V=-Vr$. When *V* is positive and greater than a few *kT/q (kTlq* = 0.0259 V at room temperature) at V at room temperature), the exponential term is much greater than unity. The current thus increases exponentially with forward bias.

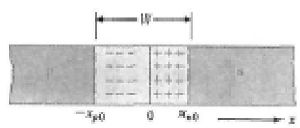
When *V is* negative (reverse bias), the exponential term approaches zero and the current is $-I_0$, which is in the n to p (negative) direction. This negative generation current is also called the *reverse saturation current.*



Career injection:

The relationship of equilibrium hole concentrations on each side is

$$\frac{p_p}{p_n} = \exp(qV_0 / kT)$$



Now with bias (career would be injected)

$$\frac{p(-x_{p0})}{p(x_{n0})} = \exp[q(V_0 - V)/kT]$$

Injected career concentration is negligible compared to majority career concentration: $p(-x_{p0})=p_p$.

$$\therefore \frac{p(-x_{p0})}{p(x_{n0})} = \frac{p_p}{p(x_{n0})} = \exp[q(V_0 - V)/kT]$$

$$\therefore \frac{p(x_{n0})}{p_p} = \exp[q(V - V_0)/kT] = \exp[-qV_0/kT]\exp[qV/kT] = \frac{p_n}{p_p}\exp[qV/kT]$$

$$\therefore p(x_{n0}) = p_n \exp[qV/kT]$$

$$\therefore \Delta p_n = p(x_{n0}) - p_n = p_n\left(e^{qV/kT} - 1\right)$$

Similarly for excess electron: $\Delta n_p = n_p\left(e^{qV/kT} - 1\right)$

If the n region is long compared to the hole diffusion length L_p, the injected holes in the n material diffuse and recombine, giving an exponential distribution of excess holes.
Similarly, If the p region is long compared to the electron diffusion length L_n, the injected holes in the p material diffuse and recombine, giving an exponential distribution of excess electrons.
So, expression of excess careers (e & h) at any length can be expressed as

$$\delta n(x_p) = \Delta n_p e^{-x_p/L_n} = n_p\left(e^{qV/kT} - 1\right)e^{-x_p/L_n}$$

$$\delta p(x_n) = \Delta p_n e^{-x_n/L_p} = p_n\left(e^{qV/kT} - 1\right)e^{-x_p/L_n}$$

The hole diffusion current at any point xn in the n material can be calculated from

$$I_p(x_n) = -qAD_p \frac{d\delta p(x_n)}{dx_n} = qA\frac{D_p}{L_p}\Delta p_n e^{-x_n/L_p} = qA\frac{D_p}{L_p}\delta p(x_n)$$

A: cross-sectional area of the junction
Thus the hole diffusion current at each position xn is proportional to the excess hole concentration at that point. The total hole current injected into the n material at the junction can be obtained as

$$I_p(x_n = 0) = \frac{qAD_p}{L_p}\Delta p_n = -\frac{qAD_p}{L_p} p_n \exp[(qV/kT) - 1]$$

Similarly,

$$I_n(x_p = 0) = -\frac{qAD_n}{L_n}\Delta n_p = -\frac{qAD_n}{L_n} n_p \exp[(qV/kT) - 1]$$

If we neglect recombination in the transition region, we can consider that each injected electron reaching $-x_{p0}$ must pass through x_{n0}. Thus the total diode current I at x_{n0} can be calculated as the sum of $I_p(x_n = 0)$ and $-I_n(x_p = 0)$.

$$I = I_p(x_n = 0) - I_n(x_p = 0) = \frac{qAD_p}{L_p}\Delta p_n + \frac{qAD_n}{L_n}\Delta n_p = qA\left(\frac{D_p}{L_p}p_n + \frac{D_n}{L_n}n_p\right)\left(e^{qV/kT} - 1\right)$$

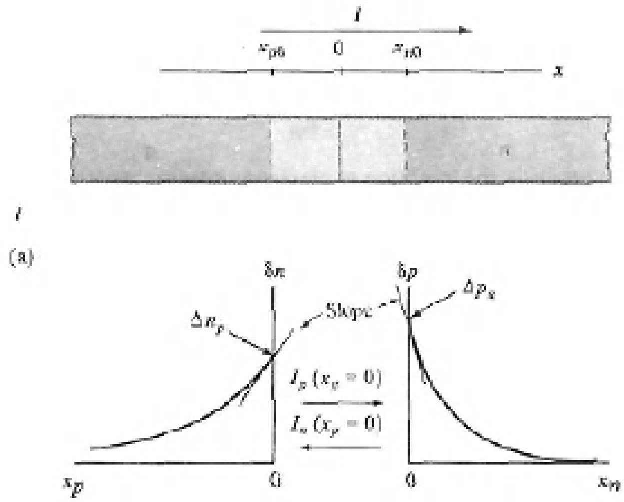
$$I = qA\left(\frac{D_p}{L_p}p_n + \frac{D_n}{L_n}n_p\right)\left(e^{qV/kT} - 1\right) = I_0\left(e^{qV/kT} - 1\right)$$

I_0 is reverse saturation current.
If reverse voltage V_r>kT/q, I=-I_0.

For forward voltage, I=$I_0e^{qV/kT}$.

Figure _

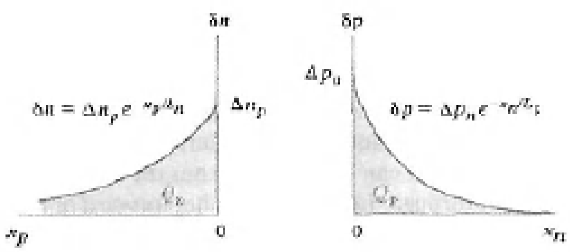
Two methods for calculating junction current from the excess minority carrier distributions: (a) diffusion currents at the edges of the transition region; (b) charge in the distributions divided by the minority carrier lifetimes; (c) the diode equation.



$$I_n(x_p=0) = qAD_n \frac{d\delta n}{dx_p}\Big|_{x_p=0} = -qA\frac{D_n}{L_n}\Delta n_p$$

$$I_p(x_n=0) = -qAD_p \frac{d\delta p}{dx_n}\Big|_{x_n=0} = qA\frac{D_p}{L_p}\Delta p_n$$

(b)



$$Q_n = -qA\int_0^\infty \delta n(x_p)\,dx_p \qquad Q_p = qA\int_0^\infty \delta p(x_n)\,dx_n$$

$$I_n(x_p=0) = \frac{Q_n}{\tau_n} = \frac{-qAL_n}{\tau_n}\Delta n_p \qquad I_p(x_n=0) = \frac{Q_p}{\tau_p} = \frac{qAL_p}{\tau_p}\Delta p_n$$

(c)

$$I = I_p(x_n=0) - I_n(x_p=0) = qA\left(\frac{D_p}{L_p}\Delta p_n + \frac{D_n}{L_n}\Delta n_p\right)$$

$$= qA\left(\frac{D_p p_n}{L_p} + \frac{D_n n_p}{L_n}\right)\left(e^{qV/kT} - 1\right)$$