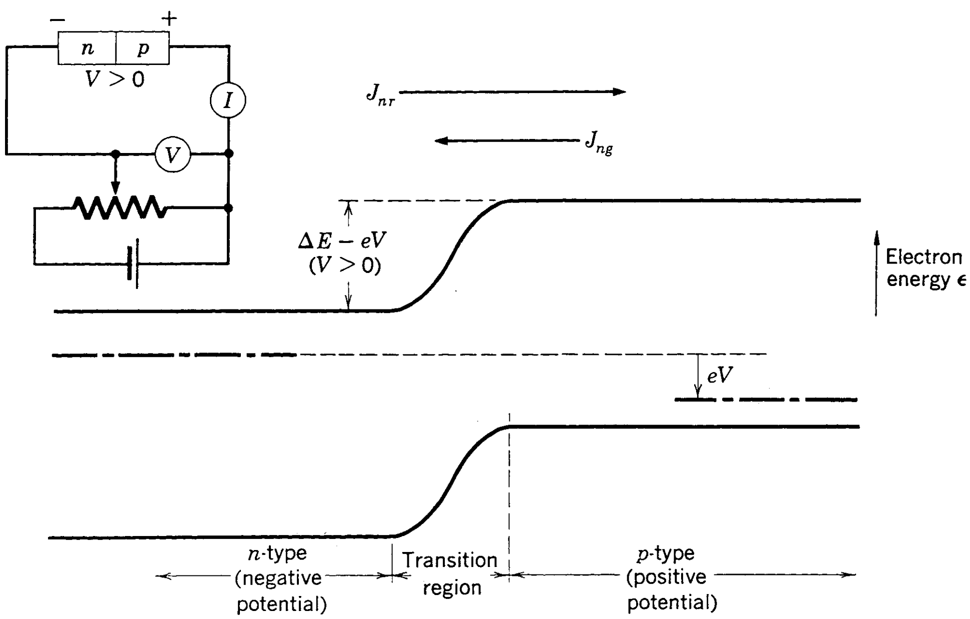
4. The Forward-Biased *p*-*n* Junction

If a positive voltage is applied to the *p*-electrode relative to the *n*-electrode, the total variation of the electric potential across the junction will decrease.



(from Kittel)

Since this reduces the electric field across the junction, the drift component of the junction current will decrease. Since the concentration gradient is unchanged, the diffusion current will exceed the drift current and a net current will flow.

This net current leads to an excess of electrons in the *p*-region and an excess of holes in the *n*-region. This "injection" condition lead to a local deviation from thermal equilibrium, i.e. $pn > n_i^2$. Equilibrium will be restored by recombination.

> Note that a depletion region exists even under forward bias, although its width is decreased. The electric field due to the space charge opposes the flow of charge, but the large concentration gradient overrides the field.

Consider holes flowing into the n-region. They will flow through the depletion region with small losses due to recombination, as the electron concentration is small compared with the bulk.

When holes reach the n-side boundary of the depletion region the concentration of electrons available for recombination increases and the concentration of holes will decrease with distance, depending on the cross-section for recombination.

Ultimately, all holes will have recombined with electrons. The required electrons are furnished through the external contact from the power supply.

On the p-side, electrons undergo a similar process. The holes required to sustain recombination are formed at the external contact to the p-region by electron flow toward the power supply, equal to the electron flow toward the n-contact.

The steady-state distribution of charge is determined by solving the diffusion equation.

$$D_n \frac{d^2 n_p}{dx^2} - \frac{n_p - n_{p0}}{\tau_n} = 0$$

Electrons flowing into the p region give rise to a local concentration n_p in excess of the equilibrium concentration n_{p0}. This excess will decay with a recombination time τ_n, corresponding to a diffusion length L_n.

The first boundary condition required for the solution of the diffusion equation is that the excess concentration of electrons vanish at large distances x,

$$n_p(\infty) = n_{p0}$$

The second boundary condition is that the carriers are injected at the origin of the space charge region $x = 0$ with a concentration $n_p(0)$.

This yields the solution

$$n_p(x) = n_{p0} + \left(n_p(0) - n_{p0}\right) e^{-x/L_n}$$

From this we obtain the electron current entering the p-region

$$J_{np} = -q_e D_n \left.\frac{dn_p}{dx}\right|_{x=0} = q_e D_n \frac{n_p(0) - n_{p0}}{L_n}$$

This says that the electron current is limited by the concentration gradient determined by the carrier density at the depletion edge $n_p(0)$ and the equilibrium minority carrier density n_{p0} .

Determining the equilibrium minority carrier density n_{p0} is easy

$$n_{p0} = n_i^2 / N_A$$

The problem is that $n_p(0)$ is established in a non-equilibrium state, where the previously employed results do not apply.

> To analyze the regions with non-equilibrium carrier concentrations a simplifying assumption is made by postulating that the product pn is constant. In this specific quasi-equilibrium state this constant will be larger than n_i^2, the pn-product in thermal equilibrium.

In analogy to thermal equilibrium, this quasi-equilibrium state is expressed in terms of a “quasi-Fermi level”, which is the quantity used in place of E_F that gives the carrier concentration under non-equilibrium conditions.

The postulate $pn = const.$ is equivalent to stating that the non-equilibrium carrier concentrations are given by a Boltzmann distribution, so the concentration of electrons is

$$n = n_i e^{(E_{Fn}-E_i)/k_BT}$$

where E_{Fn} is the quasi-Fermi level for electrons, and

$$p = n_i e^{(E_i-E_{Fp})/k_BT}$$

where E_{Fp} is the quasi-Fermi level for holes.

The product of the two carrier concentrations in non-equilibrium is

$$pn = n_i^2 e^{(E_{Fn}-E_{Fp})/k_BT}$$

If pn is constant throughout the space-charge region, then E_{Fn}-E_{Fp} must also remain constant.

Using the quasi-Fermi level and the Einstein relationship, the electron current entering the p-region becomes

$$J_{np} = -q_e D_n \left.\frac{dn_p}{dx}\right|_{x=0} = --\, q_e D_n \frac{d}{dx}\left(n_i e^{(E_{Fn}-E_i)/k_BT}\right) = -\mu_n n \frac{dE_{Fn}}{dx}$$

These relationships describe the behavior of the quasi-Fermi level in the depletion region. How does this connect to the neutral region?

In the neutral regions the *majority* carrier motion is dominated by drift (in contrast to the injected *minority* carrier current that is determined by difusion). Consider the n-type region. Here the bulk electron current that provides the junction current

$$J_{nn} = -\mu_n n \frac{dE_i}{dx}$$

Since the two electron currents must be equal

$$J_{nn} = J_{np}$$

it follows that

$$\frac{dE_{Fn}}{dx} = \frac{dE_i}{dx}$$

i.e. the quasi-Fermi level follows the energy band variation.

$\Rightarrow$ in a neutral region, the quasi-Fermi level for the majority carriers is the same as the Fermi level in equilibrium.

At current densities small enough not to cause significant voltage drops in the neutral regions, the band diagram is flat, and hence the quasi-Fermi level is flat.

In the space charge region, *pn* is constant, so the quasi-Fermi levels for holes and electrons must be parallel, i.e. both will remain constant at their respective majority carrier equilibrium levels in the neutral regions.

If an external bias V is applied, the equilibrium Fermi levels are offset by V, so it follows that the quasi-Fermi levels are also offset by V.

$$E_{Fn} - E_{Fp} = q_e V$$

Consequently, the *pn*-product in non-equilibrium

$$pn = n_i^2 e^{(E_{Fn} - E_{Fp})/k_B T} = n_i^2 e^{q_e V / k_B T}$$

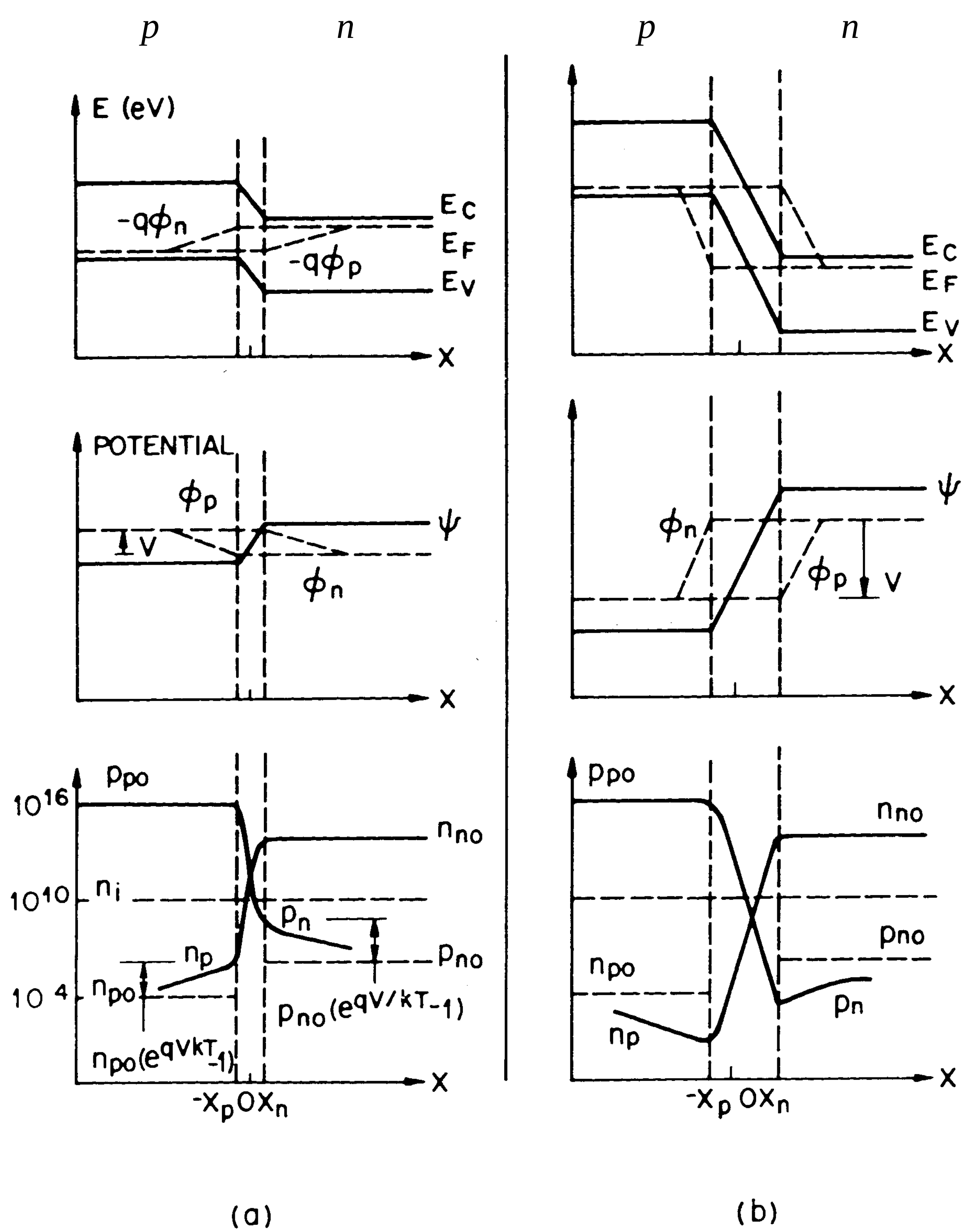
If the majority carrier concentration is much greater than the concentration due to minority injection (“low-level injection”), the hole concentration at the edge of the *p*-region remains essentially at the equilibrium value. Consequently, the enhanced *pn*-product increases the electron concentration.

$$n_p(0) = n_{p0} e^{q_e V / k_B T}$$

Correspondingly, the hole concentration in the *n*-region at the edge of the depletion zone becomes

$$p_n(0) = p_{n0} e^{q_e V / k_B T}$$

Energy band diagrams showing the intrinsic Fermi level Ψ, the quasi-Fermi levels for electrons Φ_n and holes Φ_p, and the carrier distributions for forward (a) and reverse bias conditions (b).

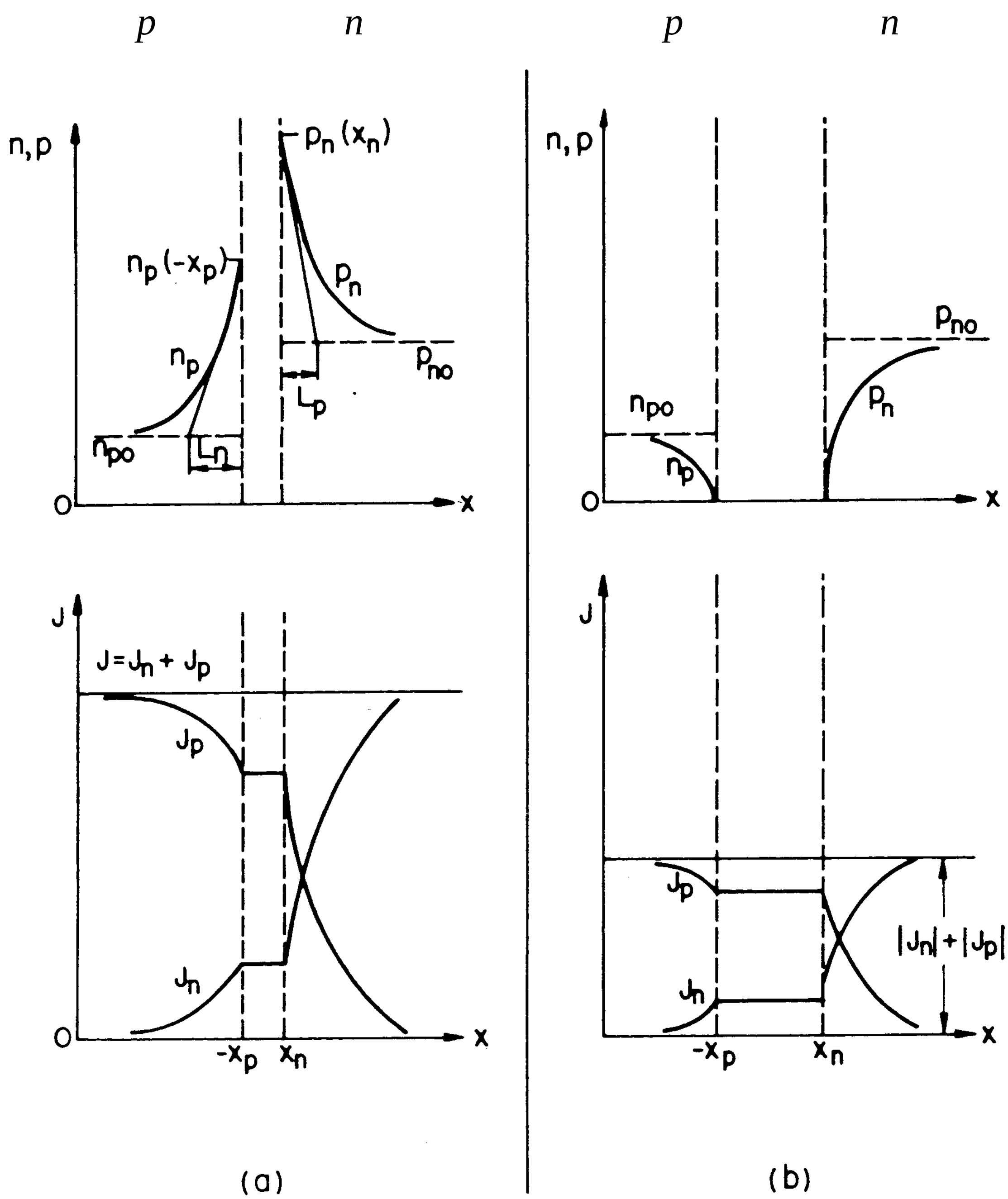


forward bias

reverse bias

(from Sze)

Carrier distributions and current densities for forward (a) and reverse bias conditions (b)



forward bias | reverse bias

(from Sze)

Since the equilibrium concentrations

$$n_{p0} = \frac{n_i^2}{N_A} \quad \text{and} \quad p_{n0} = \frac{n_i^2}{N_D}$$

the components of the diffusion current due to holes and electrons are

$$J_n = q_e D_n \frac{n_i^2}{N_A L_n}\left(e^{q_e V / k_B T} - 1\right)$$

$$J_p = q_e D_p \frac{n_i^2}{N_D L_p}\left(e^{q_e V / k_B T} - 1\right)$$

The total current is the sum of the electron and hole components

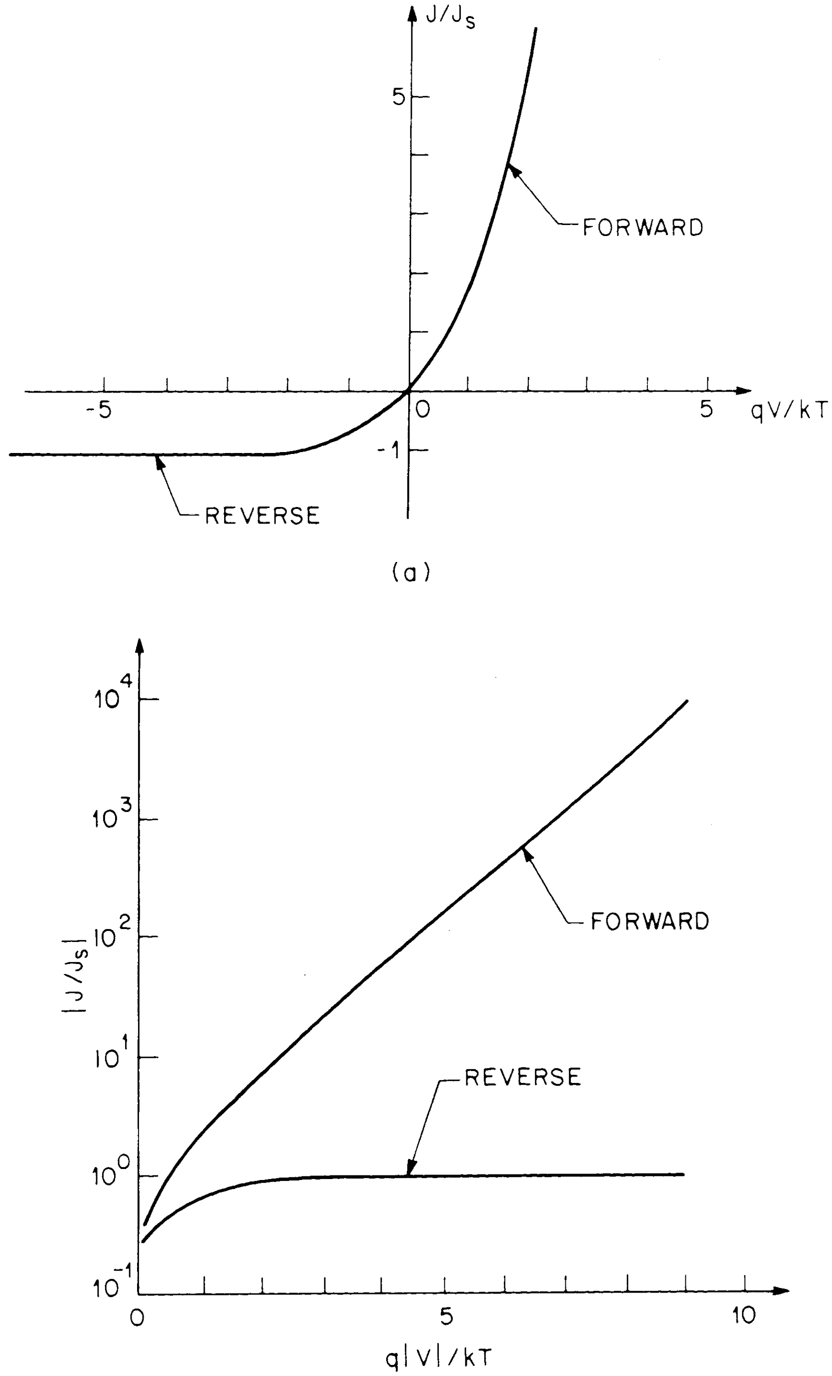
$$J = J_n + J_p = J_0 (e^{q_e V / k_B T} - 1)$$

where

$$J_0 = q_e n_i^2 \left(\frac{D_n}{N_A L_n} + \frac{D_p}{N_D L_p} \right)$$

is the reverse saturation current, i.e. the current that flows under reverse bias conditions when $V >> k_B T / q_e$.

Forward and reverse characteristics of a *pn*-junction diode



(from Sze)

Note that in the diode equation

$$J = J_n + J_p = J_0 (e^{q_e V / k_B T} - 1)$$

a) The band gap does not appear explicitly
(only implicitly in the reverse saturation current via n_i)

$$J_0 = q_e n_i^2 \left(\frac{D_n}{N_A L_n} + \frac{D_p}{N_D L_p} \right)$$

b) The total current has two distinct components, due to electrons and holes.

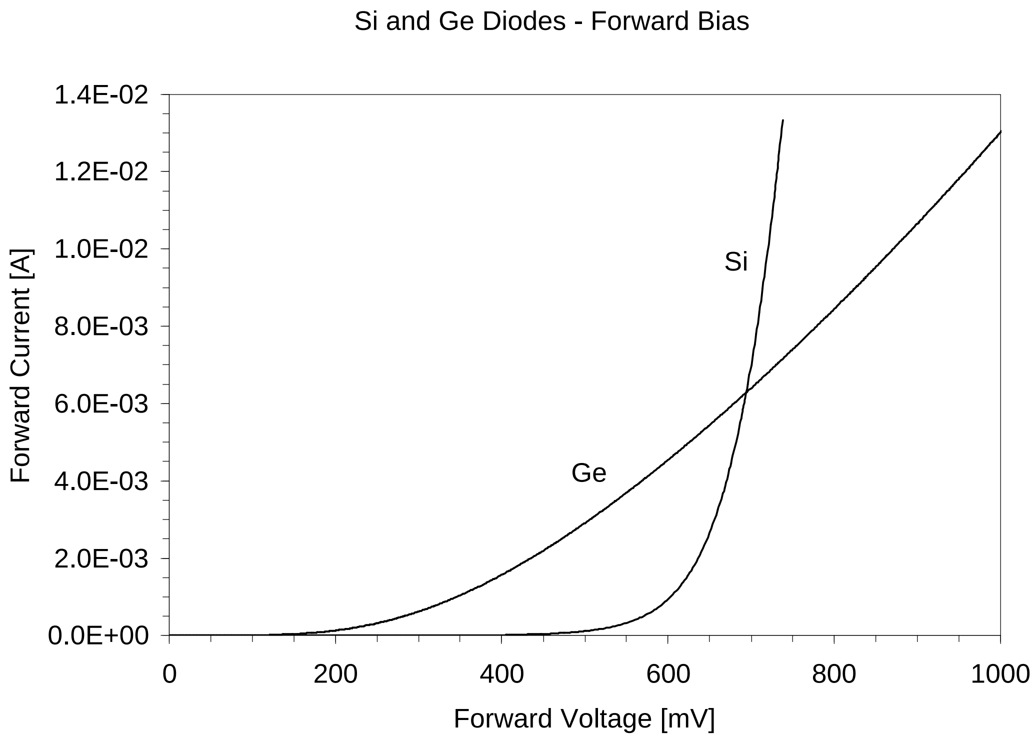
c) The electron and hole currents generally are not equal

$$\frac{I_n}{I_p} = \frac{N_D}{N_A} \quad \text{if} \quad \frac{D_n}{L_n} = \frac{D_p}{L_p}$$

d) Current flows for all values of V. However, when plotted on a linear scale, the exponential appears to have a knee, often referred to as the “turn-on” voltage

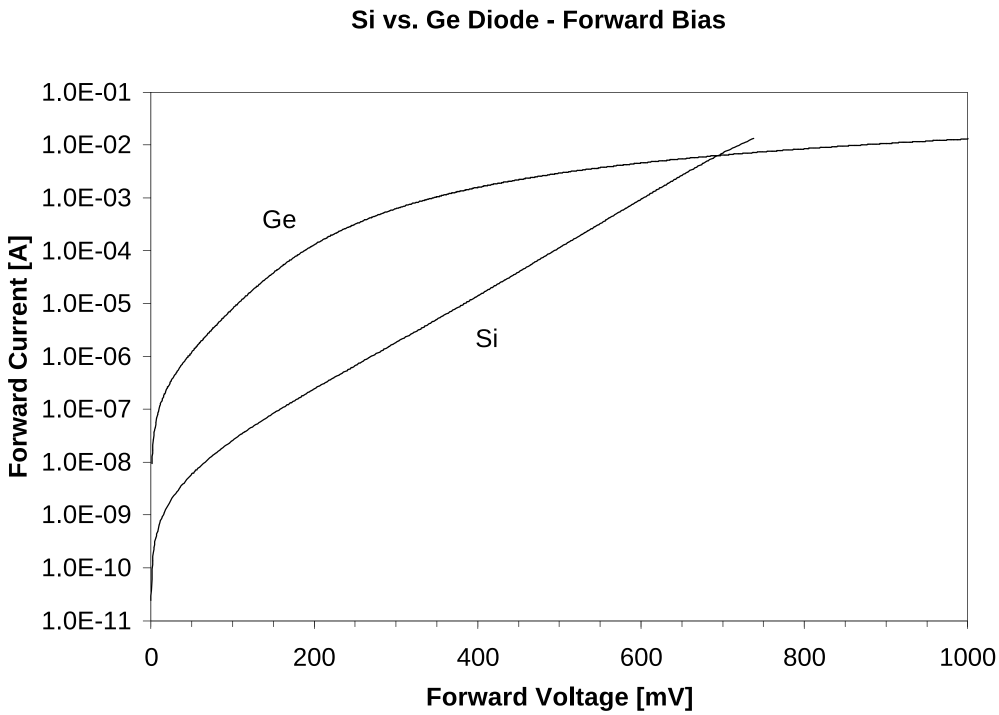
e) The magnitude of the turn-on voltage is determined by I_0. Diodes with different band-gaps will show the same behavior if I_0 is the same.

Comparision between commercial Si and Ge junction diodes (1N4148 and 1N34A)

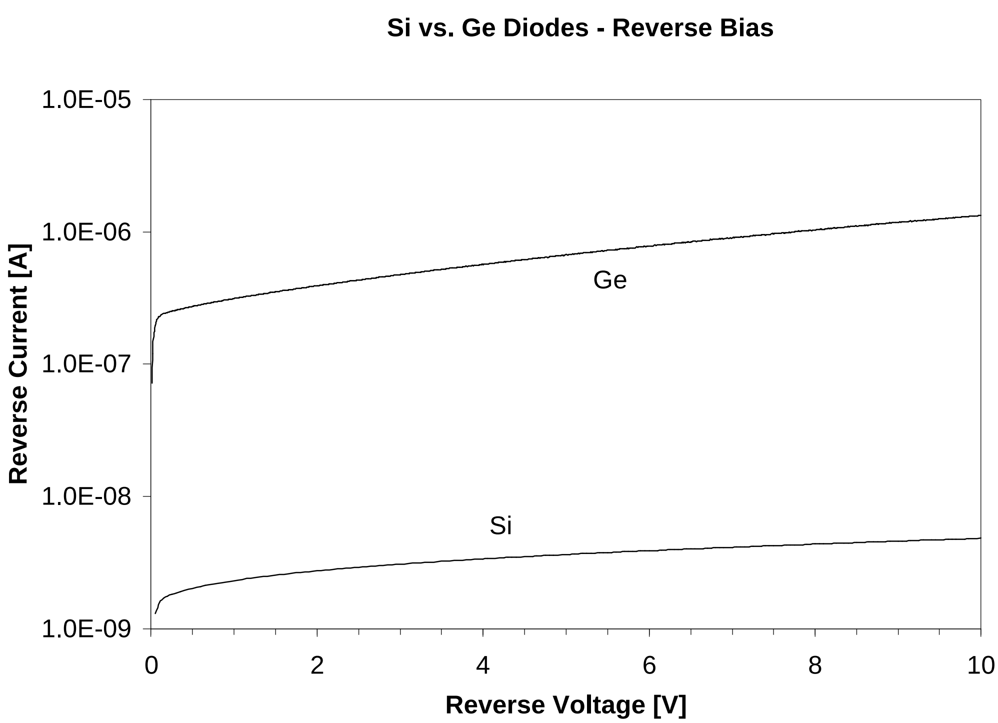


On a linear scale the Ge diode “turns on” at 200 – 300 mV, whereas the Si diode has a threshold of 500 – 600 mV.

However, on a logarithmic scale it becomes apparent that both diodes pass current at all voltages >0.

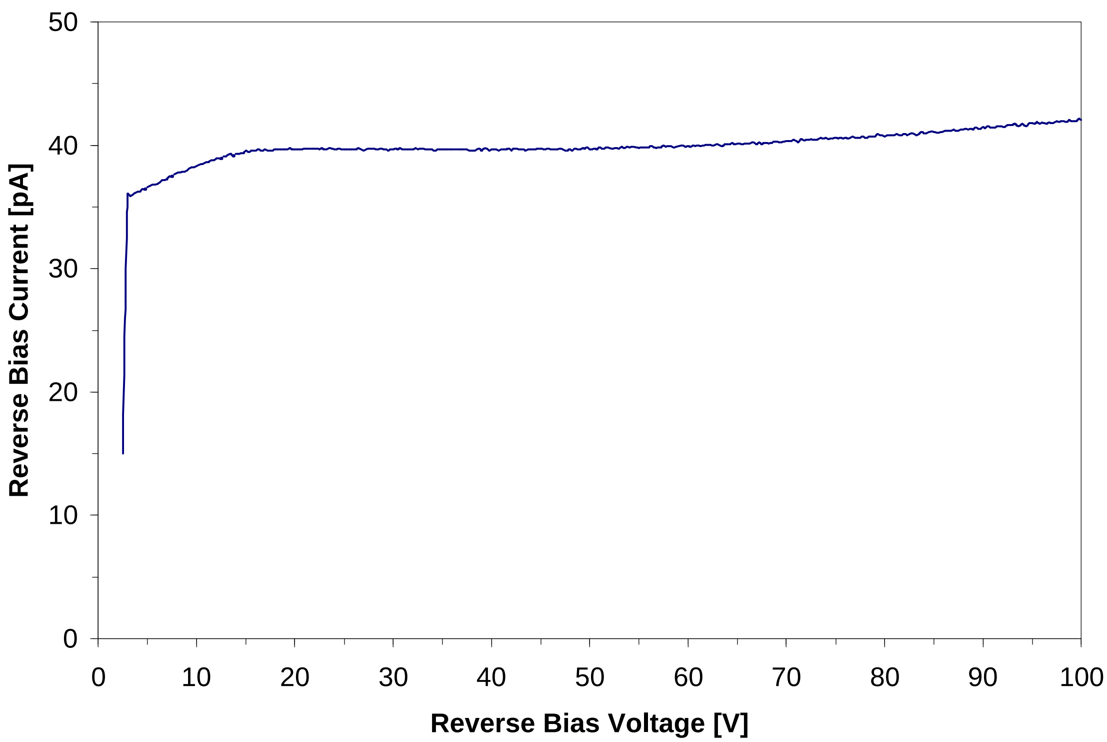


The reverse current shows why the Ge diode shows greater sensitivity at low voltages (smaller band-gap ⇒ increased n_i).



The Si diode shows a “textbook” exponential forward characteristic at currents >10 nA, whereas the Ge diode exhibits a more complex structure.

A “state-of-the-art” reverse diode characteristic (Steve Holland)



The depletion width is 300 µm, attained at about 20 V.

The area of the diode is 9 mm^2, so the reverse leakage current of 40 pA corresponds to 450 pA/cm^2, which is about 10x the theoretical value.

The discrepancies between the measured results and the simple theory require the analysis of additional processes in the depletion zone.

One can recognize four regions in the forward current:

a) generation - recombination in the depletion region
b) diffusion current (as just calculated for the ideal diode)
c) high-injection region where the injected carrier concentration affects the potentials in the neutral regions.
d) voltage drop due to bulk series resistance

The reverse current is increased due to generation currents in the depletion zone.