PN Junction

Most semiconductor devices contain at least one junction between p-type and n-type material. These p-n junctions are fundamental to the performance of functions such as rectification, amplification, switching, and other operations in electronic circuits.

Contact Potential:

Let us consider separate regions of p- and n-type semiconductor material, brought together to form a junction (this is not a practical way of forming a device, but this "thought experiment" is to discover the requirements of equilibrium at a junction). Before they are joined, the n material has a large concentration of electrons and few holes, whereas the converse is true for the p material.

Upon joining the two regions, we expect diffusion of carriers to take place because of the large carrier concentration gradients at the junction. Thus holes diffuse from the p side into the n side, and electrons diffuse from n to p. The resulting diffusion current cannot build up indefinitely, however, because an opposing electric field is created at the junction.

If we consider that electrons are diffusing from n to p leave behind uncompensated donor ions (N_d^+) in the n material, and holes leaving the p region leave behind uncompensated acceptors (N_a^-), it is easy to visualize the development of a region of positive space charge towards the n side of the junction and negative charge towards the p side. The resulting electric field is directed from the positive charge toward the negative charge.

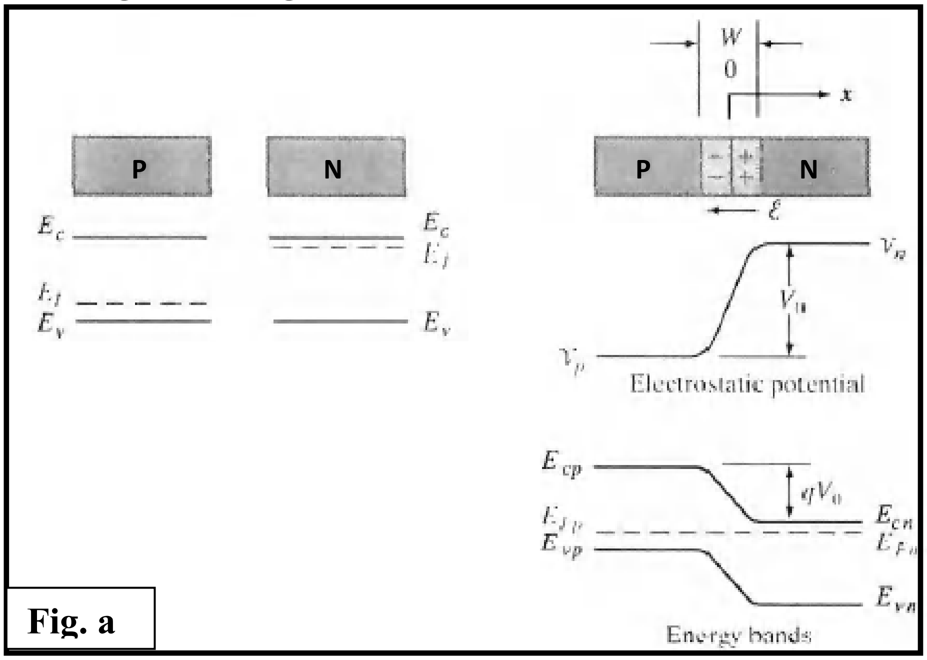


Fig. a

Thus electric field E is in the direction opposite to that of diffusion current for each type of carrier. Therefore, the field creates a drift component of current from n to p, opposing the diffusion current.

Since we know that no *net* current can flow across the junction at equilibrium (i.e., no external voltage applied), **the current due to the drift of carriers in the E field must exactly cancel the diffusion current**. Furthermore, since there can be no net buildup of electrons or holes on either side as a function of time, **the drift and diffusion currents must cancel for *each* type of carrier**.

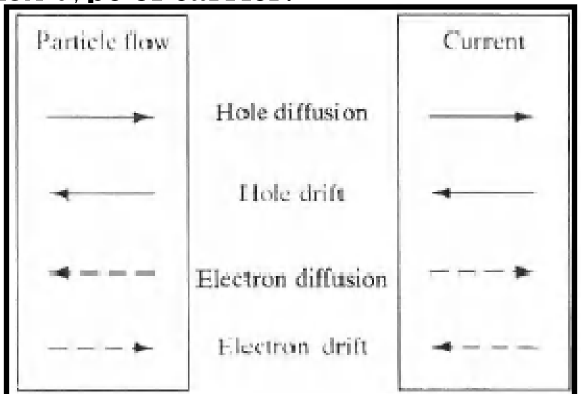


Fig. b

J_p(drift)+J_p(diffusion)=0
J_n(drift)+J_n(diffusion)=0
Therefore, the electric field E is built up to the point where the net current is zero at equilibrium. The electric field appears in some region W about the junction, and there is an equilibrium potential difference V_0 across W.
There is a gradient in potential (Fig.a) in the direction opposite to electric field E where, $E=-dV/dx$.

Consider, **the electric field is zero in the neutral regions outside W**. Therefore, a constant potential V_n in the neutral n material, a constant V_p in the neutral p material exist, and a potential difference $V_0 = V_n - V_p$ (as positive in n side) is developed between the two.
The region W is called the *transition region (also called depletion region or space charge region or junction region)*, and the potential difference V_0 is called the *contact potential.*
The contact potential appearing across W is a built-in potential barrier, necessary to maintain equilibrium at the junction; it does not imply any external potential.
The contact potential cannot be measured by placing a voltmeter across the devices, because new contact potentials are formed at each probe, just canceling V_0. By definition V_a is an equilibrium quantity, and no net current can be produced from it.
The contact potential separates the valence and conduction energy bands by the amount qV_0 (Fig. a).The separation of the bands at equilibrium is just that required to make the Fermi level constant throughout the device.

Relationship between V_0 and the doping concentrations:

At equilibrium, the drift and diffusion components of the hole current just cancel out each other.

$$J_p(x) = q\left[\mu_p p(x) E(x) - D_p \frac{dp(x)}{dx}\right] = 0$$

Rearranging the equation it can be obtained that

$$\frac{\mu_p}{D_p} E(x) - \frac{1}{p(x)} \frac{dp(x)}{dx} = 0 \Rightarrow \qquad \frac{\mu_p}{D_p} E(x) = \frac{1}{p(x)} \frac{dp(x)}{dx}$$

Now, using $E(x) = -\frac{dV}{dx}$ & $\frac{D_p}{\mu_p} = \frac{kT}{q}$ **(Einstein equation)**

$$-\frac{q}{kT} \frac{dV}{dx} = \frac{1}{p(x)} \frac{dp(x)}{dx}$$

In case of PN junction, we are interested in the potential on either side of the junction, V_p and V_n, and the hole concentration just at the edge of the transition region on either side, p_p and p_n.

$$-\frac{q}{kT} \int_{V_p}^{V_n} dV = \int_{p_p}^{p_n} \frac{1}{p} dp$$

$$\Rightarrow -\frac{q}{kT}\left(V_n - V_p\right) = -\frac{q}{kT} V_0 = \ln(p_n) - \ln(p_p) = \ln(p_n / p_p)$$

$$\Rightarrow V_0 = \frac{kT}{q} \ln \frac{p_p}{p_n}$$

If we consider the step junction to be made up of material with N_a acceptors/cm^3 on the p side and a concentration of N_d donors/cm^3 on the n side, we can write the above equation as

$$V_0 = \frac{kT}{q} \ln \frac{p_p}{p_n} = \frac{kT}{q} \ln \frac{N_a}{n_i^2 / N_d} = \frac{kT}{q} \ln \frac{N_d N_a}{n_i^2}$$

Also, the above relationship can be written as

$$\Rightarrow \frac{p_p}{p_n} = e^{qV_0/kT}$$

Using the equilibrium condition, $p_p n_p = n_i^2 = p_n n_n$, we can write

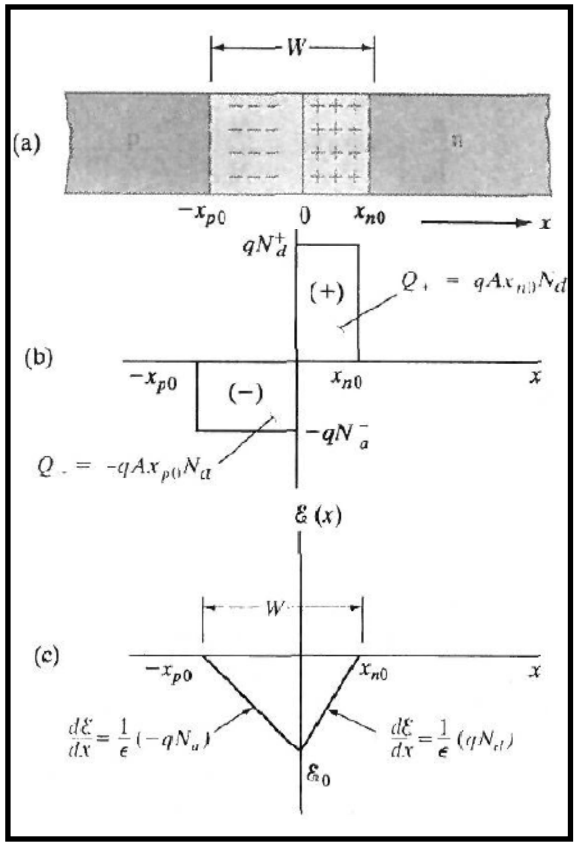
$$\frac{p_p}{p_n} = \frac{n_n}{n_p} = e^{qV_0/kT}$$

Space charge at a junction

Within the transition region, electrons and holes are in transit from one side of the junction to the other. Some electrons diffuse from n to p, and some are swept by the electric field from p to n (and conversely for holes). To a good approximation, we can consider the space charge within the transition region is due to the uncompensated donor and acceptor ions only. The charge density within *W* is plotted in following Fig.

Neglecting carriers within the space charge region, the charge density on the n side is just *q* times the concentration of donor ions N_d, and the negative charge density on the p side is -*q* times the concentration of acceptors *Na.* The assumption of carrier depletion within *W* and neutrality outside W is known as the *depletion approximation.*

Since the dipole about the junction must have an equal number of charges on either side, the transition region may extend into the p and n regions unequally, if doping concentrations are different in P and N side. For example, if the p side is more lightly doped than the n side $(N_a<N_d)$, the space charge region must extend farther into the p material than into the n,



$$\mathbf{qAx_{p0}N_a = qAx_{n0}N_p}$$

Total width of the transition region

$W=X_{n0}+X_{p0}$

According to the Poisson's equation

$$\vec{\nabla}.\vec{E} = \frac{\rho}{\varepsilon}, \Rightarrow \frac{dE}{dx} = \frac{q}{\varepsilon}\left(p - n + N_d^+ - N_a^-\right)$$

For depletion region , p-n=0

$$\Rightarrow \frac{dE}{dx} = \frac{q}{\varepsilon}N_d \quad \text{for } 0 < x < x_{n0};$$

$$\Rightarrow \frac{dE}{dx} = -\frac{q}{\varepsilon}N_a \quad \text{for } -x_{p0} < x < 0$$

(For complete ionization: $N_d^+=N_d$, $N_a^-=N_a$)

$$\int_{E_0}^{0} dE = \frac{q}{\varepsilon}N_d\int_0^{x_{n0}} dx, \quad \text{for } 0 < x < x_{n0}$$

$$\int_0^{E_0} dE = -\frac{q}{\varepsilon}N_d\int_{-x_{p0}}^{0} dx, \quad \text{for } -x_{p0} < x < 0$$

Therefore, the maximum value of the electric field is

$$E_0 = -\frac{q}{\varepsilon}N_d x_{no} = -\frac{q}{\varepsilon}N_a x_{p0}$$

It is simple to relate the electric field to the contact potential V_0, since the E field at any x is the negative of the potential gradient at that point:

$$\mathbf{E(x) = -\frac{dV}{dX} \quad \Rightarrow -V_0 = \int_{-x_{p0}}^{x_{n0}} E(x)dx}$$

Thus the negative of the contact potential is simply the area under the E(x) vs. x triangle.

$$\mathbf{V_0 = -\frac{1}{2}E_0\left(x_{n0} + x_{p0}\right) = -\frac{1}{2}E_0 W = \frac{1}{2}\frac{q}{\varepsilon}N_d x_{n0} W}$$

$$\mathbf{Now,\ x_{n0}N_d = x_{p0}N_a, \quad and \quad W = x_{n0} + x_{p0}}$$

$$\mathbf{Then,\ x_{n0}N_d = x_{p0}N_a = (W - x_{n0})N_a \Rightarrow x_{n0} = \frac{WN_a}{N_a + N_d}}$$

$$\mathbf{\therefore V_0 == \frac{1}{2}\frac{q}{\varepsilon}N_d x_{n0} W = \frac{1}{2}\frac{q}{\varepsilon}N_d \frac{WN_a}{N_a + N_d}.W = \frac{1}{2}\frac{q}{\varepsilon}\frac{N_d N_a}{N_a + N_d}.W^2}$$

$$\boxed{\mathbf{\therefore W = \left[\frac{2\varepsilon V_0}{q}\left(\frac{N_d + N_a}{N_d N_a}\right)\right]^{1/2} = \left[\frac{2\varepsilon V_0}{q}\left(\frac{1}{N_d} + \frac{1}{N_a}\right)\right]^{1/2}}}$$

$$\mathbf{\therefore x_{p0} = \frac{WN_d}{N_a + N_d} = \frac{N_d}{N_a + N_d}\left[\frac{2\varepsilon V_0}{q}\left(\frac{N_d + N_a}{N_d N_a}\right)\right]^{1/2} = \left[\frac{2\varepsilon V_0}{q}\left(\frac{N_d}{N_a\left(N_d + N_a\right)}\right)\right]^{1/2}}$$

$$\mathbf{\therefore x_{n0} = \frac{WN_a}{N_a + N_d} = \frac{N_a}{N_a + N_d}\left[\frac{2\varepsilon V_0}{q}\left(\frac{N_d + N_a}{N_d N_a}\right)\right]^{1/2} = \left[\frac{2\varepsilon V_0}{q}\left(\frac{N_a}{N_d\left(N_d + N_a\right)}\right)\right]^{1/2}}$$

An abrupt Si p-n junction has Na = 10^{18}cm^{-3} on one side and Nd=$5x$ 1015cm-3 on the other.

(a) Calculate the Fermi level positions at 300 K in the p and n regions.

(b) Draw an equilibrium band diagram for the junction and determine the contacpotential V_0 from the diagram.

(c) Consider the semiconductor piece has a circular cross section with a diameter of 10 µm. Calculate x_{n0}, x_{p0}, $Q+$, E_0 (300 K).

(d) Sketch E(x) and charge density to the scale.

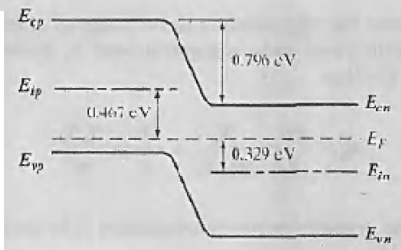
(a)

$$E_{ip} - E_F = kT \ln \frac{p_p}{n_i} = 0.0259 \ln \frac{10^{18}}{(1.5 \times 10^{10})} = \mathbf{0.467\ eV}$$

$$E_F - E_{in} = kT \ln \frac{n_n}{n_i} = 0.0259 \ln \frac{5 \times 10^{15}}{(1.5 \times 10^{10})} = \mathbf{0.329\ eV}$$

$$qV_0 = 0.467 + 0.329 = \mathbf{0.796\ eV}$$

(b)



(c) $A = \pi(5 \times 10^{-4})^2 = 7.85 \times 10^{-7}\mathrm{cm}^2$

$$W = \left[\frac{2\epsilon V_0}{q}\left(\frac{1}{N_a} + \frac{1}{N_d}\right)\right]^{1/2}$$

$$= \left[\frac{2(11.8)(8.85 \times 10^{-14})(0.796)}{1.6 \times 10^{-19}}(10^{-18} + 2 \times 10^{-16})\right]^{1/2} = \mathbf{0.457\ \mu m}$$

$$x_{n_0} = \frac{W}{1 + N_d/N_a} = \frac{0.457}{1 + 5 \times 10^{-3}} = \mathbf{0.455\ \mu m} \quad x_{p_0} = \frac{0.457}{1 + 200} = \mathbf{2.27 \times 10^{-3}\ \mu m}$$

$$Q_+ = qAx_{n_0}N_d = qAx_{p_0}N_a = (1.6 \times 10^{-19})(7.85 \times 10^{-7})(2.27 \times 10^{11})$$

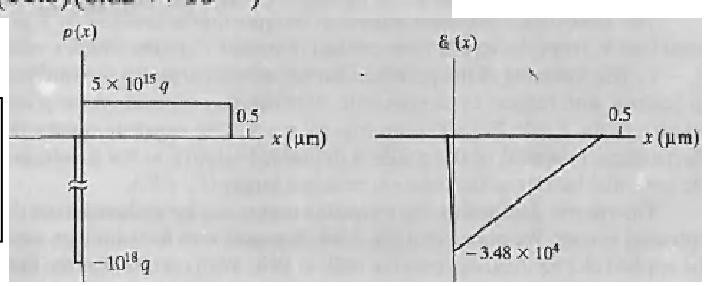
$$= \mathbf{2.85 \times 10^{-14} C}$$

$$\mathscr{E}_0 = -\frac{q}{\epsilon}x_{n_0}N_d = -\frac{q}{\epsilon}x_{p_0}N_a = \frac{1.6 \times 10^{-19}}{(11.8)(8.85 \times 10^{-14})}(2.27 \times 10^{11})$$

$$= \mathbf{-3.48 \times 10^4\ V/cm}$$

Note:

$qV_0 = \Delta E_{Fn} + \Delta E_{Fp} = E_{vp} - E_{vn} = E_{Cp} - E_{Cn}$



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