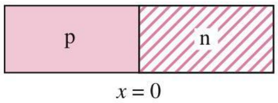
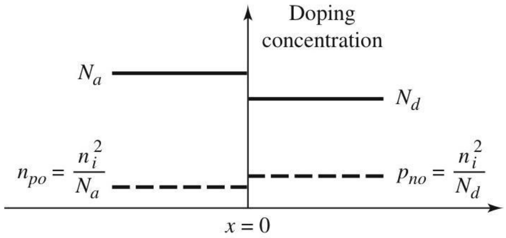
## The pn Junction




(a)

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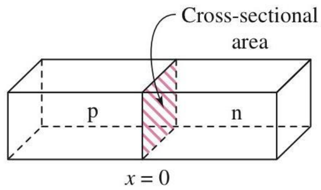



(c)

Most semiconductor devices contain at least one junction between p-type and n- type semiconductor regions. The pn junction diode itself provides characteristics that are used in rectifiers and switching circuits. Figure shows the pn junction. It is important to realize that the entire semiconductor is a single crystal material in which one region is doped with acceptor impurity atom to form p region and the adjacent region is doped with donor atoms to form the n region. The interface separation the n and p regions is referred to as the junction.

Majority carrier electrons in the n region will begin to diffuse into the p region and majority carrier holes in the p region will begin to diffuse into the n region. As electrons diffuse from n region, positively charged donor atoms left behind. Similarly, as holes diffuse from p region, negatively charged acceptor atoms left behind. The net positively and negatively charged regions induce an electric field in the region near junction. This region referred to as the ***depletion region*** or ***space charge region***. Since it is depleted of any mobile.

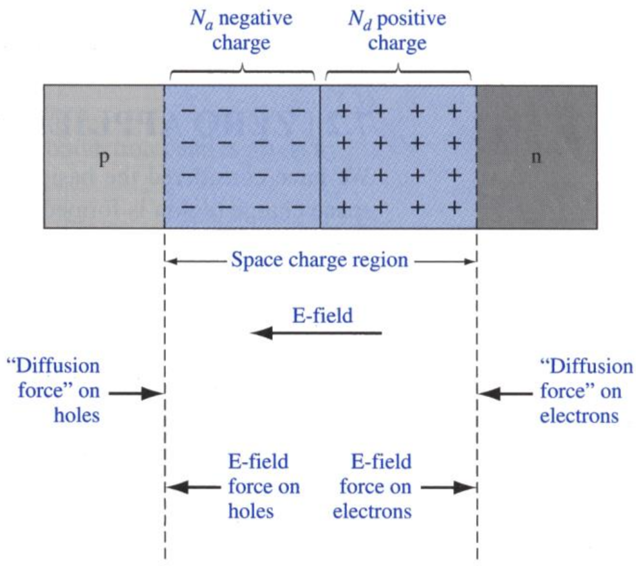



*Figure 1 The space charge region, the electric field, and the forces acting on the charged carriers.*

The diffusion forces acting on electrons and holes at the edge of depletion region are shown in the figure. The electric field in the depletion region produce another force on the electrons and holes which is in opposite direction to the diffusion force. In thermal equilibrium the diffusion forces and E-field force exactly balance each other.

## Zero applied bias

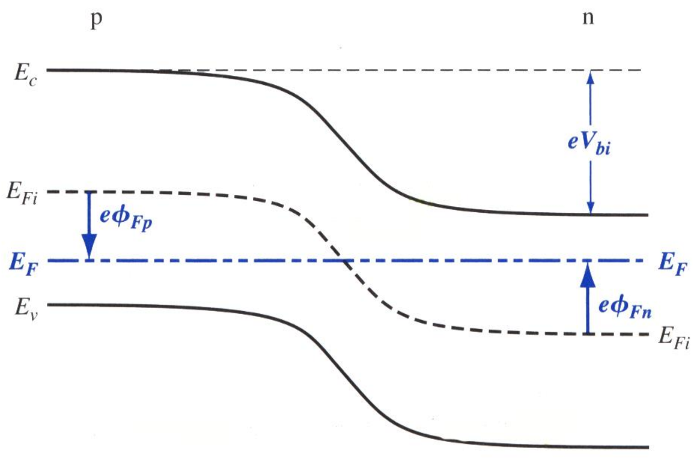



*Figure 2 Energy*-band diagram of a pn junction *in thermal equilibrium.*

If we assume that no voltage is applied across pn junction, then the junction is in thermal equilibrium, the Fermi level is constant throughout the entire system. The conduction and valence band energies must bend as we go through the depletion region.

Electrons in the conduction band of the n region see a potential barrier in trying to move into the conduction band of the p region. The potential barrier referred to as the ***built-in potential barrier***

(***$V_{bi}$***) and is given as

$$V_i = \frac{kT}{e} \ln\left(\frac{N_a N_d}{n_i^2}\right)$$

From this point $N_d$ and $N_a$ will denote the net donor and acceptor concentrations in the individual n and p regions.

**Example**

Calculate the built-in potential barrier in a silicon pn junction at T=300K, $N_a=10^{18}/cm^3$ and $N_d=10^{15}/cm^3$, $n_i=1.5\times10^{10}$/cm3

**<u>Solution</u>**

$$V_{bi} = \frac{kT}{e}\ln\left(\frac{N_a N_d}{n_i^2}\right)$$

$$V_{bi} = 0.0259\ln\left(\frac{(10^{18})(10^{15})}{(1.5\times10^{10})^2}\right) = 0.754V$$

If we change the acceptor doping from $N_a=10^{18}/cm^3$ to $N_a=10^{16}/cm^3$ then the built-in potential barrier becomes $V_{bi}$ =0.635V.

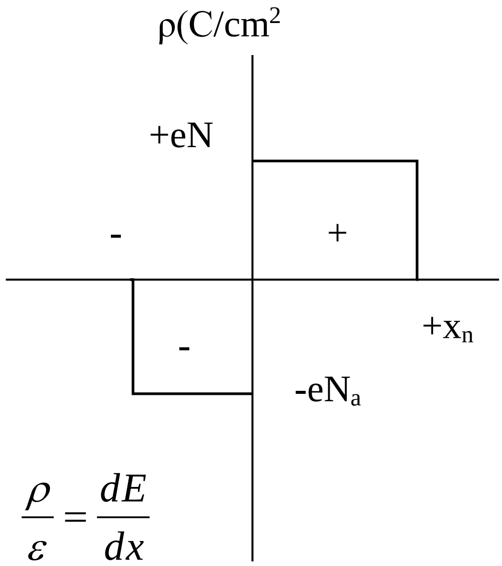
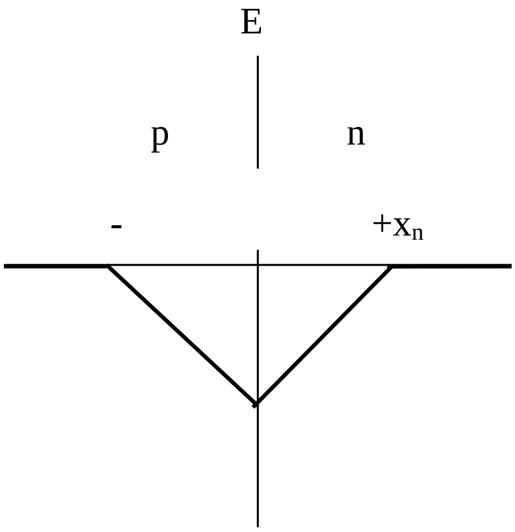



*Fig.4. The space charge density in a uniformly doped pn junction assuming the abrupt junction approximation.*

## Electric Field

An electric field is created in the depletion region by the separation of positive and negative charge densities. The figure shows the volume charge density distribution in the pn junction. We will assume that the space charge region abruptly ends in the n region at $x=+x_n$ and abruptly ends in the p region at $x=-x_p$.

The electric field in the p region is then given by




$$E = \frac{dV}{dx}$$

*Fig.5.Electric field in the **space** charge region of a uniformly doped pn junction.*

$$E = \frac{-eN_a}{\varepsilon_s}\left(x + x_p\right) \qquad -x_p \le x \le 0$$

The electric field in the n region is then given by

$$E = \frac{-eN_d}{\varepsilon_s}\left(x_n + x\right) \qquad 0 \le x \le x_n$$

The maximum electric field at the junction is

$$E_{\max} = \frac{-eN_d x_n}{\varepsilon_s} = \frac{-eN_a x_p}{\varepsilon_s}$$

## Space charge width

We can determine the distance that the space charge region extends into the p and n regions from the junction

$$x_p = \frac{N_d x_n}{N_a}$$

$$x_n = \left\{ \frac{2\varepsilon_s V_{\text{bi}}}{e} \left[ \frac{N_a}{N_d} \right] \left[ \frac{1}{N_a + N_d} \right] \right\}^{1/2}$$

$$x_p = \left\{ \frac{2\varepsilon_s V_{\text{bi}}}{e} \left[ \frac{N_d}{N_a} \right] \left[ \frac{1}{N_a + N_d} \right] \right\}^{1/2}$$

The total depletion or space charge width ($W$) is the sum of two components

$$W = x_n + x_p$$

$$W = \left\{ \frac{2\varepsilon_s V_{\text{bi}}}{e} \left[ \frac{N_a + N_d}{N_a N_d} \right] \right\}^{1/2}$$

**Example**

A silicon pn junction at T=300K with zero applied bias has doping concentration of Na=5×10$^{16}$/cm$^3$ and $N_d$=10$^{15}$/cm$^3$, $\varepsilon_r$=11.7, $n_i$=1.5×10$^{10}$/cm. Determine $x_n$, $x_p$, $W$ and $E_{max}$.

Solution

$$V_{\text{bi}} = \frac{kT}{e}\ln\left(\frac{N_a N_d}{n_i^2}\right)$$

$$V_{\text{bi}} = 0.0259\ln\left(\frac{(10^{16})(10^{15})}{(1.5\times10^{10})}\right) = 0.635V$$

$$W = \left\{\frac{2\varepsilon_s V_{\text{bi}}}{e}\left[\frac{N_a + N_d}{N_a N_d}\right]\right\}^{1/2}$$

$$W = \left\{\frac{2(11.7)(8.85\times10^{-14})(0.635)}{1.6\times10^{-19}}\left[\frac{10^{16}+10^{15}}{10^{16}\times10^{15}}\right]\right\}^{1/2}$$

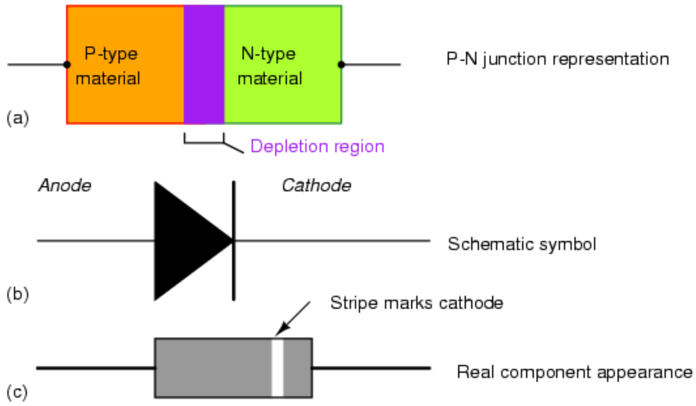
$W$=0.951×10$^{-4}$cm=0.951μm

$$x_n = \left\{\frac{2\varepsilon_s V_{\text{bi}}}{e}\left[\frac{N_a}{N_d}\right]\left[\frac{1}{N_a + N_d}\right]\right\}^{1/2} = 0.864\mu m$$

$$x_p = W - x_n = 0.086\mu m$$

$$E_{\max} = \frac{-eN_d x_n}{\varepsilon_s} = \frac{-(1.6\times10^{-19})(10^{15})(0.086\times10^{-4})}{11.7\times8.85\times10^{-14}}$$

$$E_{\max} = -1.34\times10^{4} V/cm$$




## Problems

**Q1:** Calculate the built-in potential barrier in a silicon pn junction at T=300K, $N_a=5\times10^{17}/cm^3$ and $N_d=10^{16}/cm^3$, $n_i=1.5\times10^{10}/cm$.

(Ans:0. 769V)

**Q2:** A silicon pn junction at T=300K with zero applied bias has doping concentration of $N_a=5\times10^{16}/cm^3$ and $N_d=5\times10^{15}/cm^3$, $\varepsilon_r=11.7$ , $n_i=1.5\times10^{10}/cm$. Determine $x_n$, $x_p$, $W$ and $E_{max}$.

(Ans: $x_n=4.11\times10^{-6}$cm , $x_p=4.11\times10^{-5}$cm, $W=4.52\times10^{-5}$cm and $|E_{max}|=3.18\times10^{4}$ V/cm)