

3.15

pn Junctions

C.A. Ross, Department of Materials Science and Engineering

Reference: Pierret, chapter 5-6.

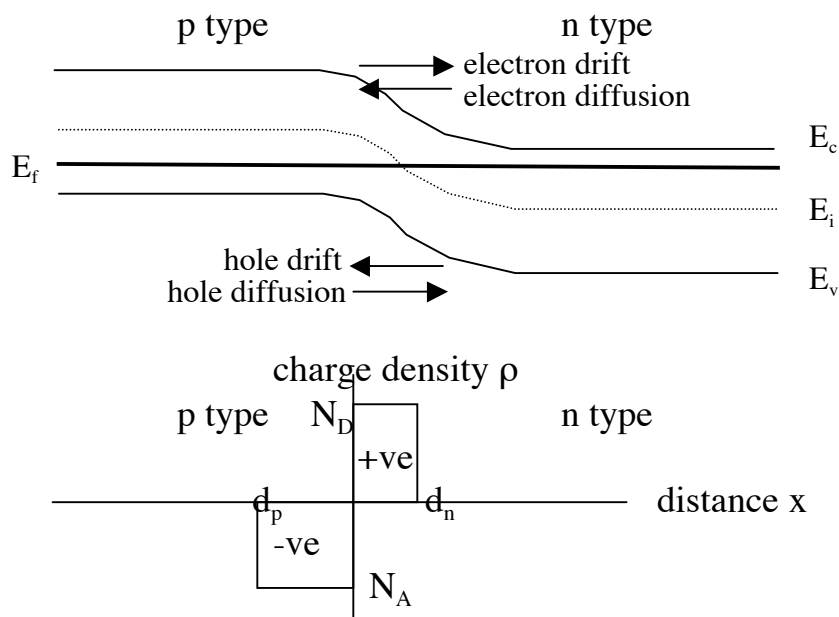
Unbiased (equilibrium) pn junction

Imagine an abrupt pn junction. The p side has a high hole concentration and the n side has a high electron concentration.

There is immediate **diffusion** of the carriers down the concentration gradient.

This leaves a space charge due to the ionized dopants. The resulting electric field leads to **drift** of carriers *in the opposite direction* compared to the diffusion flux.

At equilibrium the drift and diffusion currents are balanced.



Gauss' law $\mathbf{E} = 1/\epsilon_0 \epsilon_r \int \rho(x) dx$ where $\rho = e(p - n + N_D - N_A)$

Energy (i.e. position of energy bands) = eV ; can be found from voltage vs distance; calculate from $\mathbf{E} = -dV/dx$

Depletion region width $d = d_p + d_n$ (some books use $d = x_p + x_n$)

Built-in voltage V_o : from earlier,

$$n = n_i \exp (E_f - E_i)/kT$$

$$p = n_i \exp (E_i - E_f)/kT$$

The Fermi level is flat across the junction:

$$eV_o = (E_f - E_i)_{n\text{-type}} - (E_f - E_i)_{p\text{-type}} \\ = kT \ln (n_n/n_p) \text{ or } kT \ln (N_A N_D/n_i^2)$$

Using the depletion approximation $\rho = -N_A e$ in the p-type and $N_D e$ in the n-type:

$$E = N_A e d_p / \epsilon_o \epsilon_r = N_D e d_n / \epsilon_o \epsilon_r \quad \text{at } x = 0 \\ V_o = (e / 2 \epsilon_o \epsilon_r) (N_D d_n^2 + N_A d_p^2) \\ d_n = \sqrt{\{(2 \epsilon_o \epsilon_r V_o / e) (N_A / (N_D (N_D + N_A)))\}} \\ d = d_p + d_n = \sqrt{\{(2 \epsilon_o \epsilon_r V_o / e) (N_D + N_A) / N_A N_D\}}$$

Biased pn junction (apply voltage V_A)

Forward bias raises the n-side energy levels (or lowers the p-side)

by applying -ve to the n-side (or +ve to p-side)

This **reduces** the voltage barrier. The quasi-Fermi level is higher on the n-side.

The diffusion term changes because the number of carriers eligible to diffuse increases exponentially.

The drift term does not change.

Outside the depletion region there is a net diffusion current.

Reverse bias lowers the n-side energy levels.

Diffusion is reduced; drift is unchanged. Only a small reverse current flows.

Reverse bias increases the depletion width (V_A is -ve)

$$d = \sqrt{\{(2 \epsilon_o \epsilon_r (V_o - V_A) / e) (N_D + N_A) / N_A N_D\}}$$

The ideal diode equation

In forward bias the diffusion flux increases because more carriers are able to diffuse. This comes from the Fermi function. When E_f is away from the band edge,

$$f(E) = 1 / \{1 + \exp (E - E_f) / kT\} \sim \exp -(E - E_f) / kT$$

If we shift the energy levels by V_A , we change the available number of carriers by a factor

$$\{\exp -(e(V_o - V_A) - E_f) / kT\} / \{\exp -(eV_o - E_f) / kT\} \\ = \exp eV_A / kT$$

Therefore diffusion flux $J_{diff} = J_o \exp eV_A / kT$

To evaluate J_o , we know that $J_o = -J_{\text{drift}} = J_{\text{diff}}$ at $V_A = 0$.

Consider an asymmetric junction with $N_A \gg N_D$, then the current is mainly holes, and their concentration decays in the n-type material (outside the depletion region) over a distance $\lambda_p = \sqrt{\tau_p D_p}$. The diffusion current

$$J_{\text{diff}} = eD_p \nabla p = eD_p (p_{n(x=0)} - p_{no}) / \lambda_p \quad (\text{where } p_{no} = n_i^2 / N_D)$$

$$\sim eD_p (p_{n(x=0)}) / \lambda_p$$

$$p_n = p_p \exp -eV_o/kT \text{ (unbiased)}$$

$$\text{and } p_n = p_p \exp -e(V_o - V_A)/kT \text{ (forward biased)}$$

$$\text{so } p_n = p_{no} \exp -eV_A/kT$$

$$\text{Hence } J_{\text{diff}} = \{eD_p n_i^2 / N_D \lambda_p\} \exp -eV_A/kT = J_o \exp eV_A/kT$$

Include both electron and hole terms: $J_o = en_i^2 \{D_p/N_D \lambda_p + D_n/N_A \lambda_n\}$

Also, $J_{\text{drift}} = J_o$ gives an expression for J_{drift}

The ideal diode equation is then

$$J = J_{\text{diff}} + J_{\text{drift}} = J_o \{ \exp eV_A/kT - 1 \}$$

What happens in reverse bias? The current reaches a reverse saturation value of J_o ($\sim 10^{-12} \text{ A cm}^{-2}$ in Si)

All minority carriers reaching the depletion region are sucked across (i.e. the junction 'collects' minority carriers). There is no diffusion flux across the depletion region. There is a diffusion flux outside the depletion region that supplies minority carriers to the junction: its value is just $-en_i^2 \{ p_{no} D_p / \lambda_p + n_{po} D_n / \lambda_n \} = -J_o$.

Reverse bias pn junction collects minority carriers

Forward bias pn junction injects minority carriers

Non-idealities:

a) Reverse bias Zener breakdown, where carriers tunnel through a narrow depletion width

b) Avalanche diode, where impact ionization generates more carriers in the depletion region.