3.15
pn Junctions
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Reference: Pierret, chapter 5-6.

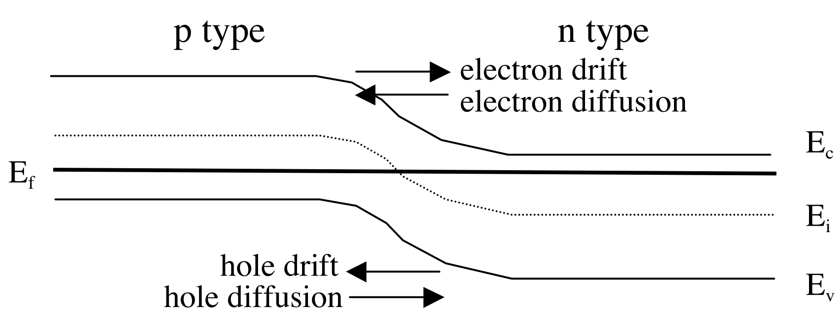
Unbiased (equilibrium) pn junction

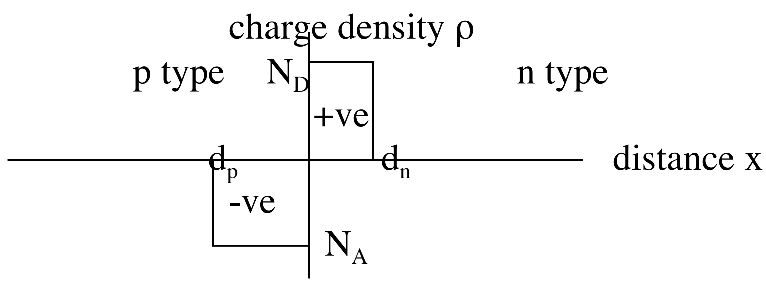
Imagine an abrupt pn junction. The p side has a high hole concentration and the n side has a high electron concentration.

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 $\mathbf{E} = 1/\varepsilon_o\varepsilon_r \int \rho(x)\, dx$ 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:

$eV_o = (E_f - E_i)_{n\text{-type}} - (E_f - E_i)_{p\text{-type}}$

$= kT/e \ln (n_n/n_p)$ or $kT/e \ln (N_A N_D/n_i^2)$

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

$E = N_A e\, d_p/\varepsilon_o\varepsilon_r = N_D e\, d_p/\varepsilon_o\varepsilon_r$ at $x = 0$

$V_o = (e /2\varepsilon_o\varepsilon_r) (N_D d_n^2 + N_A d_p^2)$

$d_n = \sqrt{\{(2\varepsilon_o\varepsilon_r V_o/e) (N_A/(N_D(N_D + N_A))\}}$

$d = d_p + d_n = \sqrt{\{(2\varepsilon_o\varepsilon_r V_o/e) (N_D + N_A)/ N_A N_D\}}$

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

$d = \sqrt{\{(2\varepsilon_o\varepsilon_r(V_o + V_A)/e) (N_D + N_A)/ N_A N_D\}}$

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 $J_o = -J_{drift} = J_{diff}$ at $V_A = 0$.
Consider an asymmetric junction with $N_A >> N_D$, 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

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

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

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

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

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

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

Include both electron and hole terms: $J_o = en_i^2 \{D_p/N_D\lambda_p + D_n/N_A\lambda_n\}$
Also, $J_{drift} = J_o$ gives an expression for J_{drift}
The ideal diode equation is then

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

What happens in reverse bias? The current reaches a reverse saturation value of J_o ($\sim 10^{-12}$ 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.