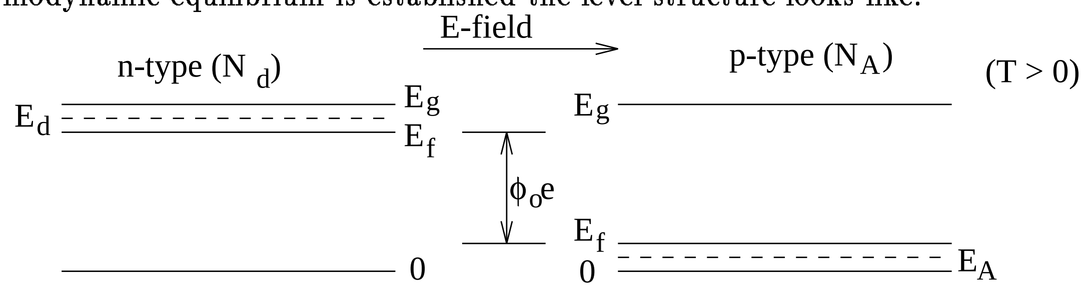
Title: The p-n junction

Since we have a basic understanding of the workings of a doped homogeneous semiconductor, the simplest non-ohmic device that can be fabricated in a *p*-*n* junction.

For this a single crystal of Si is doped so that part has *p*-type doping and part has *n*-type doping. Assume that a sharp concentration boundary exists. Before thermodynamic equilibrium is established the level structure looks like:



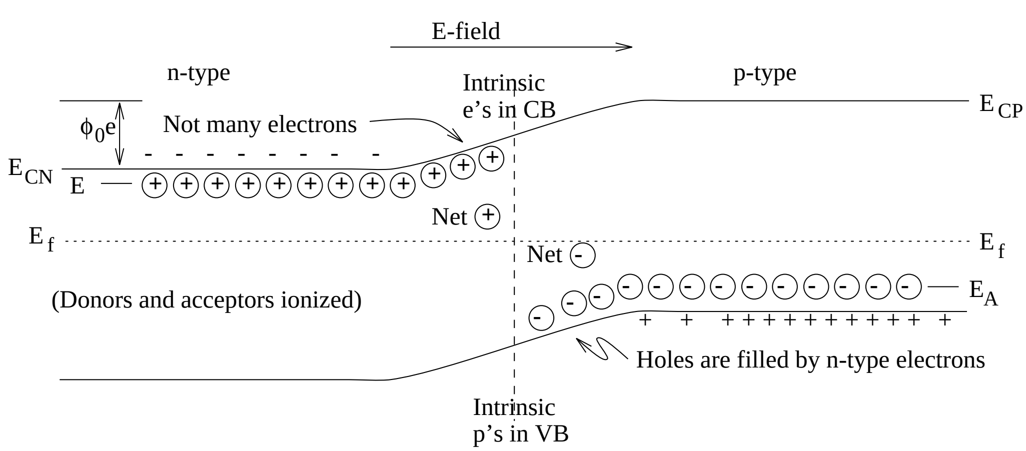
Since there exists a difference in the respective Fermi levels, a "contact potential" exists (ϕ_0). The response is as follows:

(1) In order to equilibrate the Fermi levels, electrons diffuse to the right and holes diffuse to the left. This produces a concentration gradient in the charge.

(2) This produces a net NEGATIVE charge in the p-type fraction of the interface and a positive charge in the n-type fraction.

(3) In effect, there is an $\vec{E}$-field which opposes the diffusion.

(4) Since there is an $\vec{E}$-field in the interfacial region, the energy levels of the p-type side are raised while the energy levels of the n-type side are lowered.



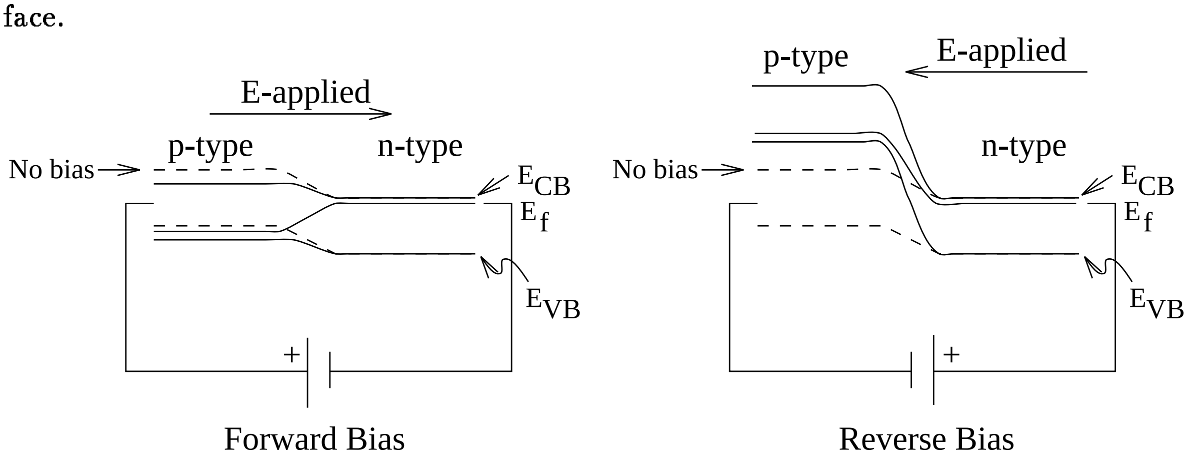
(5) When μ(T) (or ϵ_F(T)) is the same throughout, equilibrium is established.

(6) Since at the interface, electrons in the CB were used to fill holes in the VB, there is charge which resides at the non-mobile dopant sites. Because only a small number of mobile carriers remain, this is called the depletion region. This region contains an electric double layer consisting of ionized acceptors in the p-type part and ionized donors in the n-type part.

(7) The $\vec{E}$-field counteracts the flow of charge and equilibrium is established.

Notice that while there is no NET current, charge is still flowing. Electrons which happen to be excited into the CB of the p-type region are accelerated towards the p-type region. The same is true of holes which are formed in the n-type region. Since only a fraction of the original concentration of carriers are available for conduction in the interface region, the resistance is highest at the interface.

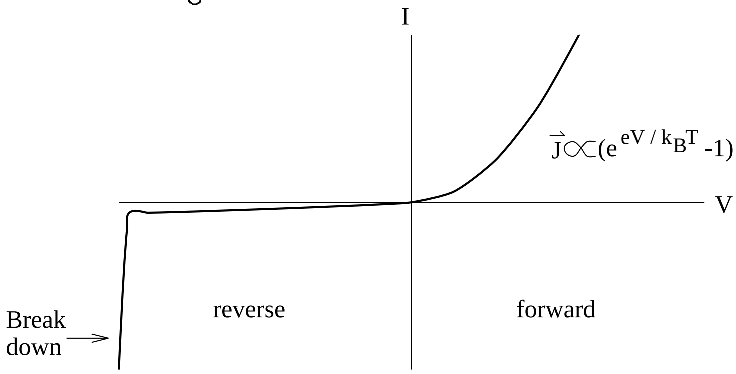
If an external electric field is applied, the voltage drop is entirely across the interface.



Forward Bias: The applied field is antiparallel to the interfacial one. The electric double layer is reduced and current flows easily. (Resistance is lowered.)

Reverse Bias: The applied field is parallel to the interfacial one. The electric double layer is increased and the resistance does also. Current flows but at only a small trickle. The resistance is a function of the depletion width.

The current-voltage characteristics are thus:



Question: What is the contact potential ϕ_0 at equilibrium?

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\begin{aligned}
e\phi_0 &= E_{cp} - E_{cn} \\
n_p &= N_c\, e^{-(E_{cp}-E_F/k_BT)} \qquad \# \text{ of } e\text{'s in CB p-type} \\
n_n &= N_c\, e^{-(E_{cn}-E_F/k_BT)} \qquad \# \text{ of } e\text{'s in CB n-type} \\
\frac{n_n}{n_p} &= e^{-(E_{cn}E_{cp})/k_BT} = e^{e\phi_0/k_BT} \\
& \text{but } n_p p_p = \text{const } \equiv n_i^2 \qquad i \rightarrow \text{intrinsic} \\
\text{so} \quad \frac{n_n}{n_p} &= \frac{n_n p_p}{n_i^2} = e^{e\phi_0/k_BT} \Longrightarrow \frac{e\phi_0}{k_BT} = \ell n(n_n p_p/n_i^2)
\end{aligned}
$$

$$\text{and} \quad n_n \approx N_d \qquad p_p \approx N_a$$

$$\text{so} \quad \phi_0 \approx \frac{k_BT}{e}\, \ell n\, \frac{N_a N_d}{n_i^2}, \text{ if } N_a \approx N_d = 10^{16}\text{cm}^{-3}$$

$$\text{then} \quad \phi_0 \sim 0.3V$$

Question: What is the width of the interface?

$$\text{From Poisson's eqn.} \quad \frac{d^2\phi(x)}{dx^2} = -\frac{4\pi}{\epsilon}\rho(x) \qquad \nabla \cdot \vec{D} = 4\pi\rho$$

$$\text{n-type} \rightarrow \frac{d^2\phi(x)}{dx^2} \approx -4\pi\, \frac{N_d}{\epsilon}\, q; \quad \text{p-type} \rightarrow \frac{d^2\phi(x)}{dx^2} \approx -4\pi\, \frac{N_A}{\epsilon}\, q$$

$$\text{If} \quad N_d = N_A = N \qquad \phi(x) = \frac{2\pi N e}{\epsilon} x^2 \text{ and } \int_0^x \vec{E} \cdot dx = \phi$$

$$\text{so} \quad x = \left(\frac{\epsilon\phi_0}{2\pi N e}\right)^{1/2} \approx .1\ \mu\text{m} \qquad |\vec{E}| = 10^5 \text{ V/cm}$$