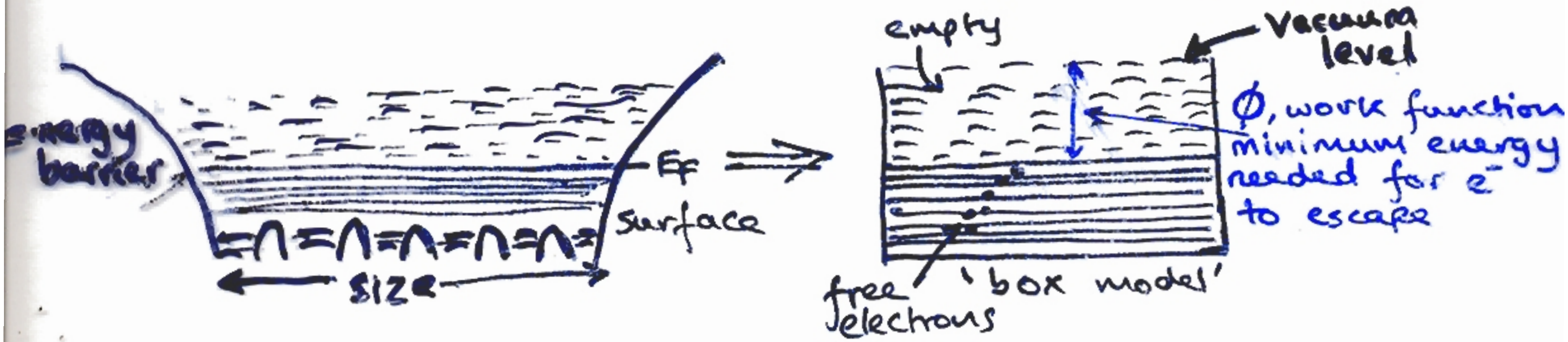
Junction Diode – band description

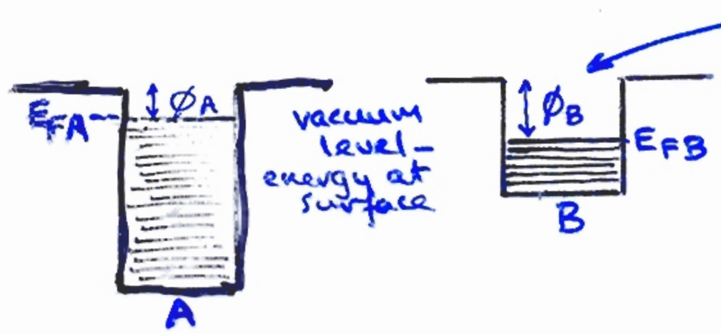
Junction in equilibrium (no bias).
In classical electrostatics, 2 bodies in equilibrium have *same* potential – **NOT** true for semiconductor junctions.

For electronic equilibrium, no net current flows – this requires a contact potential to exist between the 2 parts. e.g. p-n junction, V_o



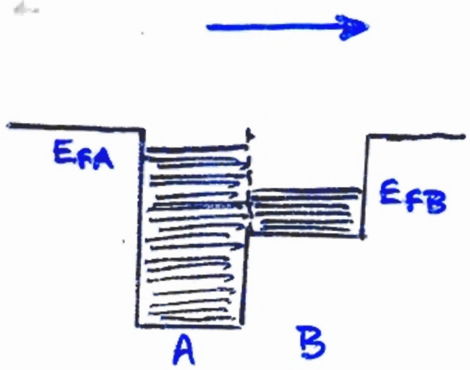
Consider joining two different pieces of material.

a)



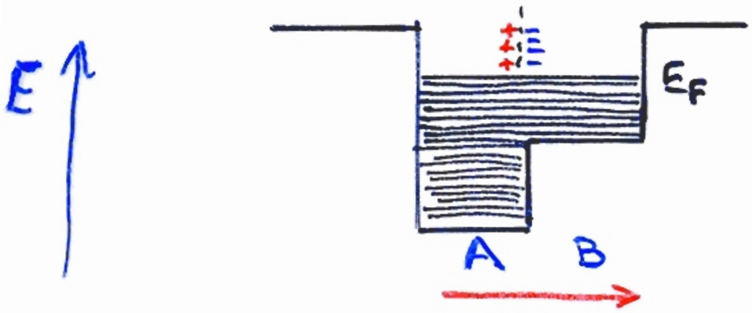
work function – minimum height of the potential energy barrier at material surface.

b) immediately after contact



electron flow from material A (higher Fermi energy level) to material B

c) In equilibrium



E-field from built-in potential.

No current will flow since the probability of electrons having a particular energy E is the same on each side .

$$P(E) = \frac{1}{1 + \exp\left(\frac{E - E_F}{kT}\right)}$$

(E_F and T same on each side)

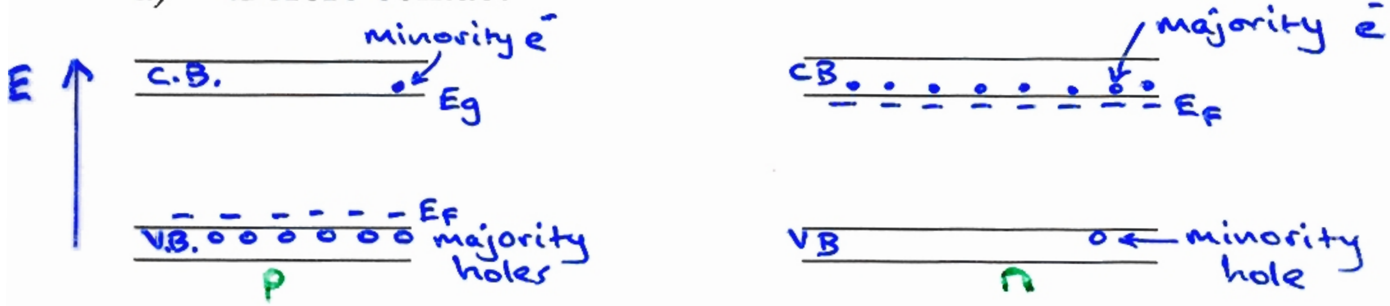
E_F is continuous and aligned across the junction. But a <u>contact</u> or <u>built-in</u> potential, V_o, exists to ensure no net flow of electrons.

i.e. **E_F rather than Vo remains in equilibrium – applies to all junctions in equilibrium.** (No applied voltage and no current flow).

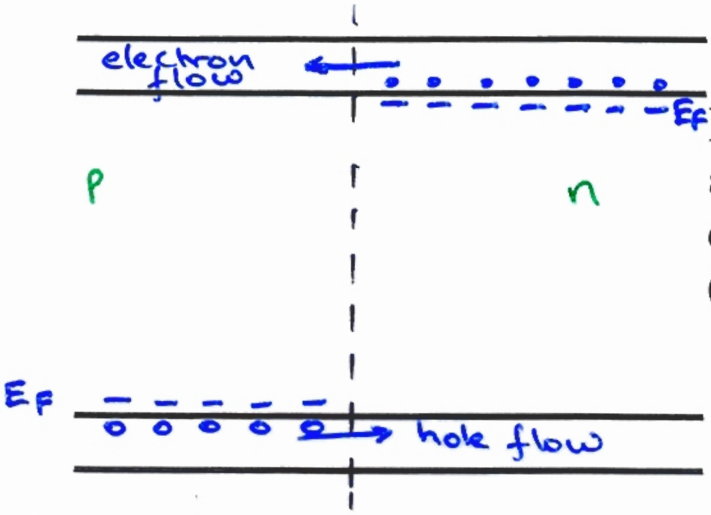
P-N Junction in Equilibrium

Bring ‘p’ and ‘n’ semiconductors together to form a junction .*(N.B. not possible to do this in reality)*

a) Before contact

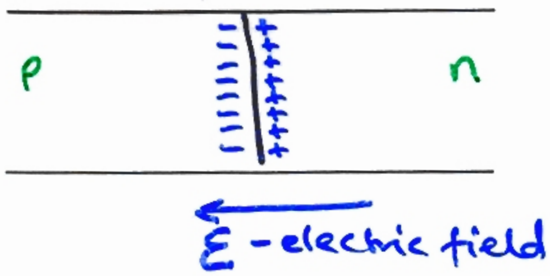


b) On contact



Majority carriers flow across the junction into empty states opposite (diffusion).

An electric field is created across the junction to exactly cancel the diffusion flow of electrons and holes.



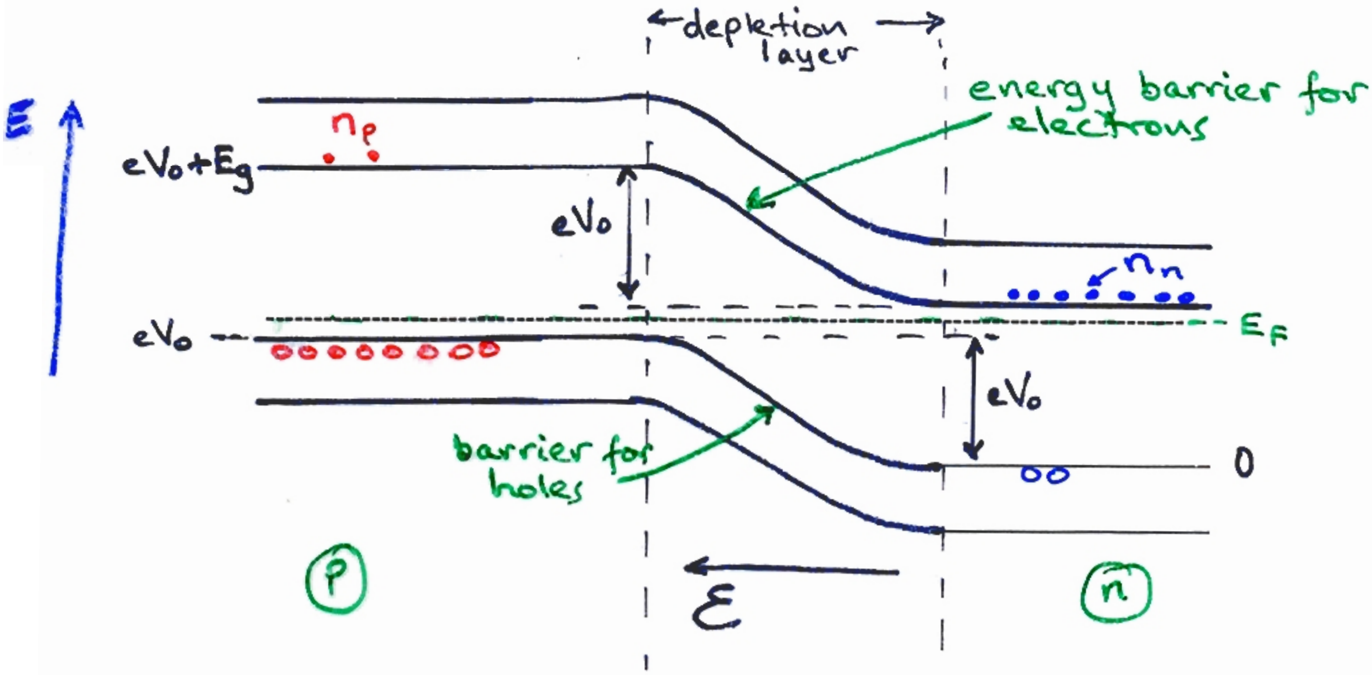
V_o across junction

c) In equilibrium

At equilibrium net current = 0. Hence drift current flow due to the electric field opposes diffusion current flow.
i.e. diffusion current = drift current.

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

E builds up until net current is zero at equilibrium.



Holes have left the p-region leaving behind fixed negative acceptor charge – all energy levels rise.
Electrons have left n-region leaving behind fixed positive donor charge – all levels fall.
But C.B., V.B.& E_F are fixed, so alignment only possible if all levels in p-type move relative to those in n-type. Each side of junction takes up a different potential, V_o.
This so called space charge (fixed charge) produces the electric field.

A barrier of height eV_o forms due to this electric field which brings the junction into equilibrium and prevents further current flow.

Number of electrons in CB of n-region, $n_n \propto P(E_g)$

$$n_n \propto \frac{1}{1+\exp\left(\frac{E_g - E_F}{kT}\right)} \propto \exp-\left(\frac{E_g - E_F}{kT}\right)$$

Number of the electrons in CB of p-region, $n_p \propto P(E_g+eV_o)$

$$n_p \propto \frac{1}{1+\exp\left(\frac{E_g + eV_o - E_F}{kT}\right)} \propto \exp-\left(\frac{E_g + eV_o - E_F}{kT}\right)$$

$$\frac{n_n}{n_p} = \exp\left(\frac{eV_o}{kT}\right)$$

$$V_o = \frac{kT}{e}\log_e\left(\frac{n_n}{n_p}\right)$$

Remember that $\boxed{np = n_i^2}$, therefore
$p_p n_p = p_n n_n = n_i^2$

$$n_p = \frac{n_i^2}{p_p}$$

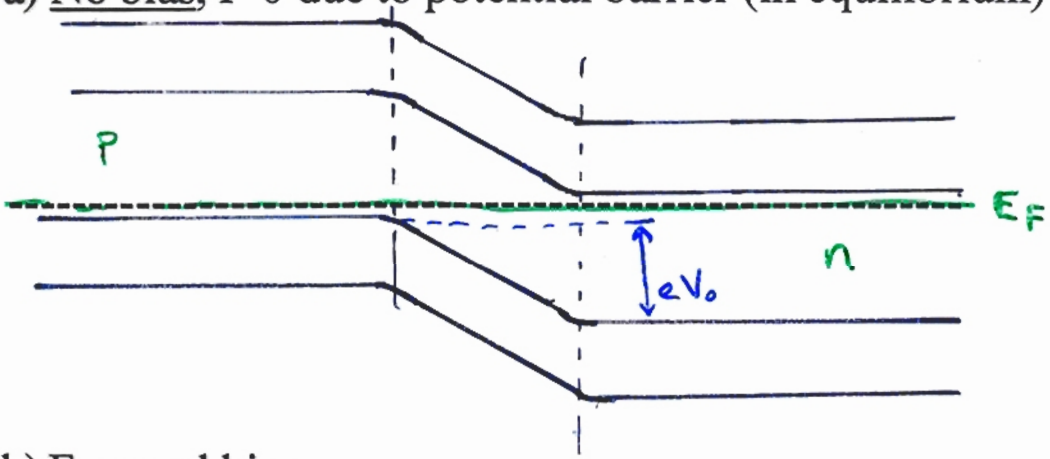
usually true at RT

If all carriers are ionized $n_n \approx N_d$ and $p_p \approx N_a$, so by substitution

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

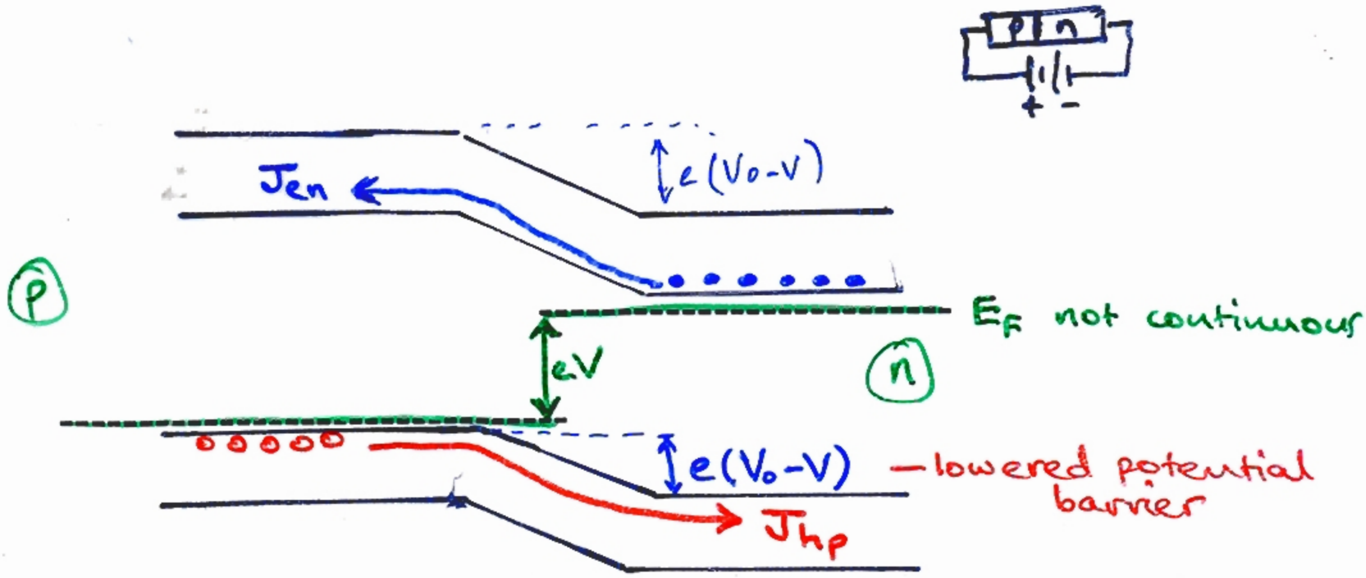
p-n with bias

a) No bias, I=0 due to potential barrier (in equilibrium)



b) Forward bias

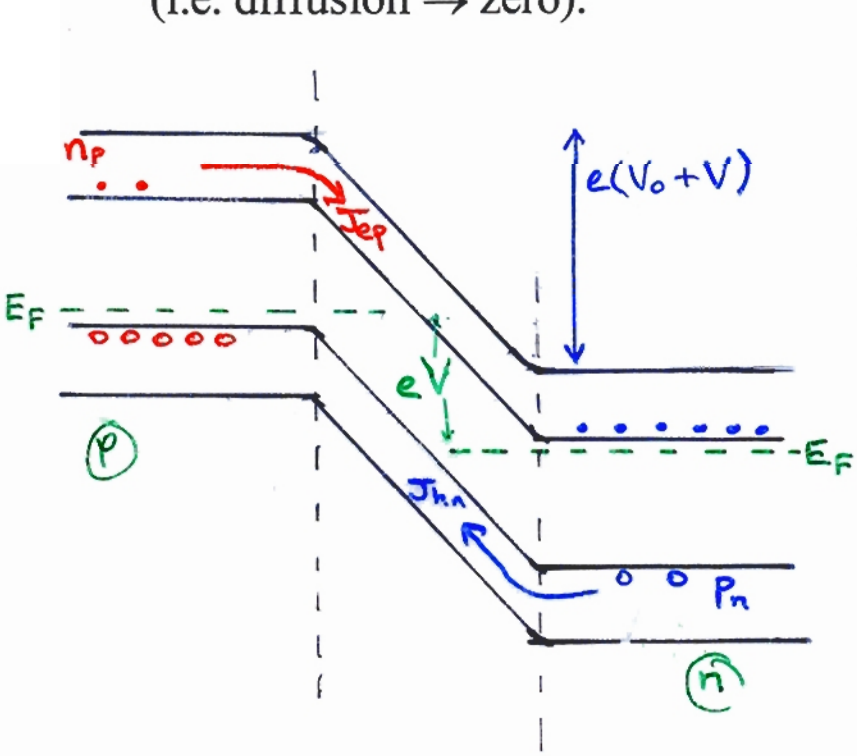
With forward bias, V, the barrier height is efficiently reduced to $e(V_o - V)$. Immediately after bias is applied, energy bands tilt – majority carriers diffuse- current flows (diffusion ≠ drift)



In steady state, carriers flow from the contacts (external circuit) to restore equilibrium away from junction. V appears across depletion layer (fewer carriers so lowers conductivity), lowering barrier height to e((V_o – V). Large majority currents flow

c) Reverse bias

In steady state, barrier height is increased, e(V_o + V). No majority carriers flow because of increased barrier height (i.e. diffusion → zero).



J_{ep} = electron flow from p-side in reverse bias

J_{hn} = hole flow from n-side in reverse bias

Very small electron current flows from p $\rightarrow$ n due to minority electrons, which are swept across by E-field (i.e. fall down potential hill). Similarly for minority holes flow. The small saturation current which does flow is I_o which is independent of V – it depends primarily on temperature. This leads to the diode (rectifier) equation:

$$I = I_o\left[\exp\left(\frac{eV}{kT}\right) - 1\right]$$

Can be proved from band model (pg.161, JA)

4 components of current flow in a p-n semiconductor junction.

i) Majority hole current from p, J_{hp}
ii) Minority hole current from n, J_{hn}
iii) Minority electron current from p, J_{ep}
iv) Majority electron current from n, J_{en}

<u>Reverse bias</u> –majority current cannot flow - get minority J_{ep} and J_{hn} as shown – they arise from thermal generation of e-h pairs in or near the depletion region. – depends on temperature.

<u>Zero bias</u> –
When V=0, $J_{hp} = J_{hn}$ and $J_{ep} = J_{en}$, **i.e. no current**

<u>Forward bias</u> with V>0, $J_{hp} = J_{hn} \exp\left(\frac{eV}{kT}\right)$ (hole flow)

$J_{en} = J_{ep} \exp\left(\frac{eV}{kT}\right)$ (electron flow)

$\therefore$ Net hole current, $J_h = J_{hp} - J_{hn} = J_{hn}\,[\exp\left(\frac{eV}{kT}\right) - 1]$

$\therefore$ Net electron current, $J_e = J_{en} - J_{ep} = J_{ep}\,[\exp\left(\frac{eV}{kT}\right) - 1]$

Total diode current $J = J_h + J_e = J_o\left[\exp\left(\frac{eV}{kT}\right) - 1\right]$,

where $J_o = J_{hn} + J_{ep}$, also called the minority or saturation current density.

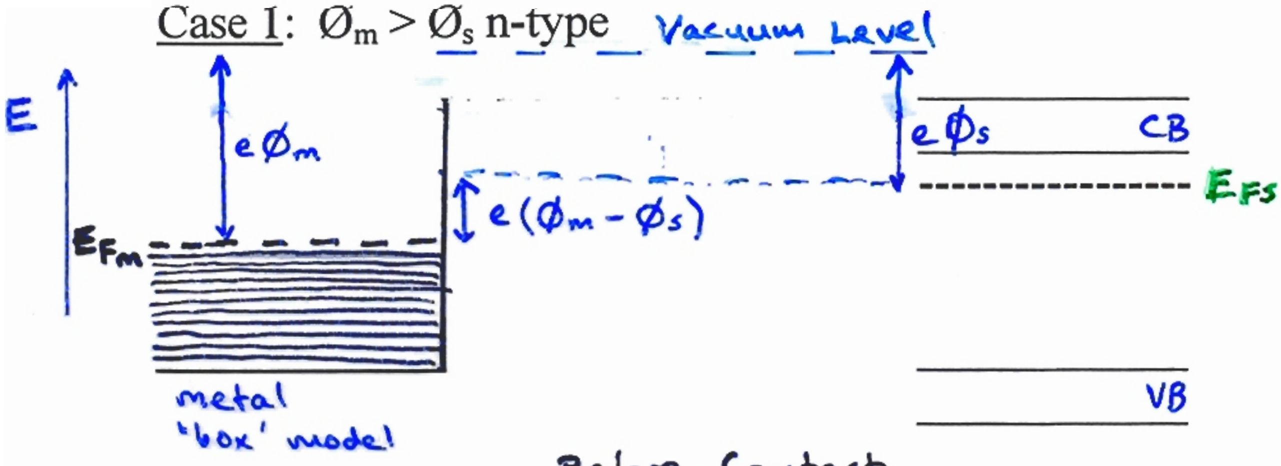
Metal / Semiconductor Junctions *(pg. 178 JA)*

Two types

- Ohmic
- Rectifying

Depends on relative work functions (Ø) of metal and semiconductor
eg metal on n-type semiconductor

Case 1: $\O_m > \O_s$ n-type



Before Contact

($\O_m$, $\O_s$ ≡ E_F to vacuum level)