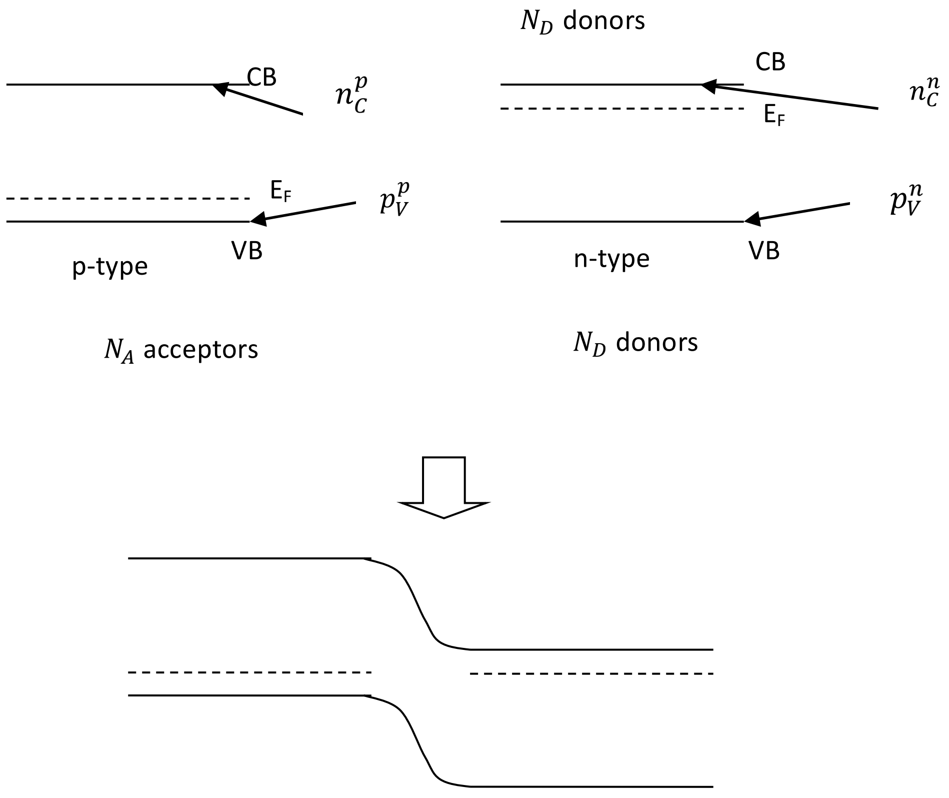
Semiconductors. PN junction

We have previously looked at the electronic properties of intrinsic, n-type and p-time semiconductors. Now we will look at what happens to the electronic structure and macroscopic characteristics (e.g. current-volatge, etc.) as we bring p- and n-type semiconductors together. Thus, we shall consider the P-N junction. First, we shall look at how the electronic structure is affected across the P-N junction. In the following we assume for simplicity that both n- and p-type semiconductors have identical atomic structures and band gaps and only differ in the position of the Fermi level. We will address questions related to surface conditions as well as to the band gap variations later in this module.

Consider a pn-junction with N_D donors and N_A acceptors on the n- and p-type sides respectively. If these are fully ionised at room temperature then the electron and hole concentrations are:
$n_C^n = N_D$ and $p_V^p = N_A$. These are the *majority carrier* densities. The superscript indicates the side of the junction. There will also be small but important concentrations of the opposite, *minority carriers*, in each region, which can be calculated from the *law of mass action:*

$$p_V^n = \frac{n_i^2}{N_D} \text{ and } n_C^p = \frac{n_i^2}{N_A}$$

related to surface conditions as well as to the band gap variations later in this module.



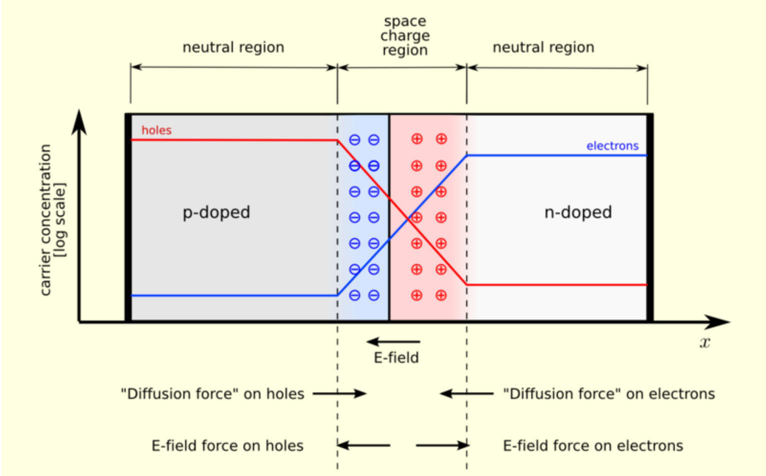
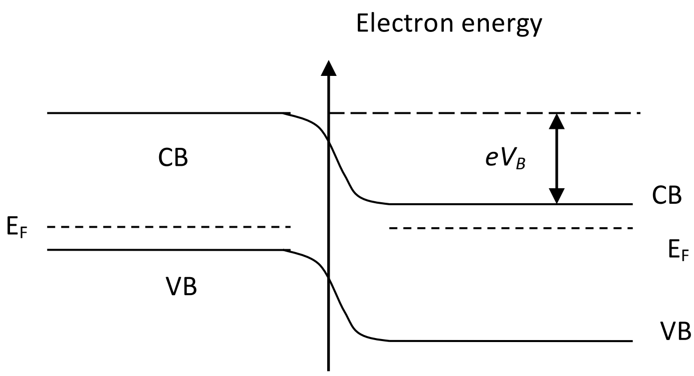
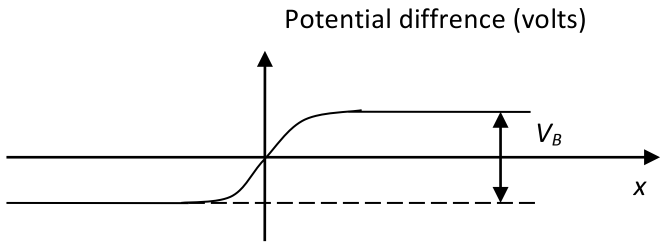
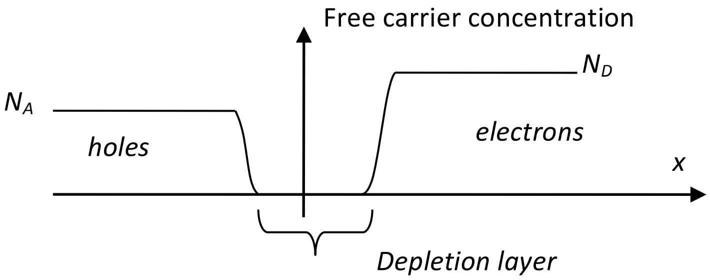


Figure A. A p–n junction in thermal equilibrium with zero bias voltage applied. Electrons and holes concentration are reported respectively with blue and red lines. Grey regions are charge neutral.

Eventually, the state of equilibrium is reached once electrostatic interaction and diffusion balance each other. This equilibrium is achieved with the aid of the diffusion of the majority of carriers on each side into direction of carrier minority: holes diffuse into n-type material and electrons diffuse into p-type. The equilibrium situation is then as follows:







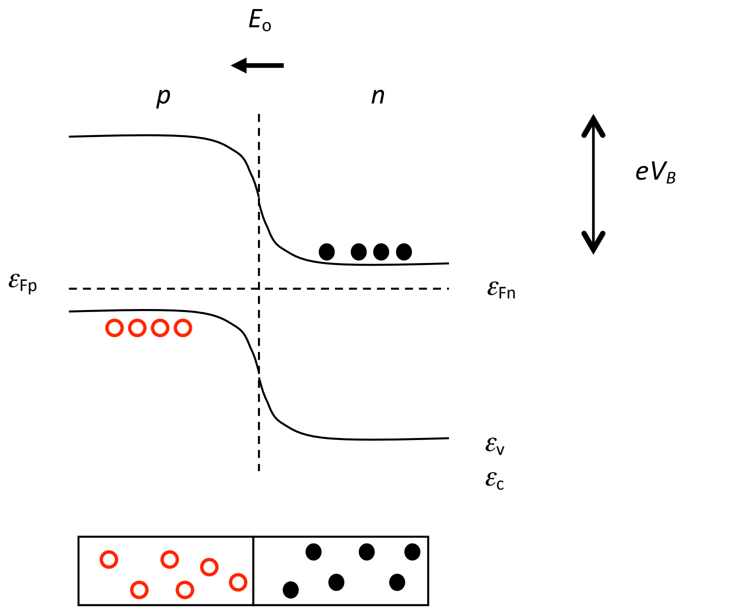
Once the equilibrium is reached the Fermi energy is constant across the device and there is a built-in potential difference V_B. The absence of free carriers means that the potential difference is dropped across the depletion layer giving a high electric field there and the energy bands are bent in the depletion layer to form a step. The height of the step in energy is eV_B. Let's follow the conduction band edge from the n- to the p- side. The CB line corresponds to the energy of an electron at rest – *potential energy* (as kinetic energy is zero). We can see that along CB line the *potential energy* of the electron is increased by $|eV_B|$. Similarly, the potential energy of a hole would increase as it moves from the p- to n-region *down* the step in the valence band.

The p–n junction possesses properties which have useful applications in modern electronics. Both p-doped and n-doped semiconductors are relatively good conductors, but the junction between them can become depleted of charge carriers, and hence nonconductive, depending on the relative voltages of the two semiconductor regions. By manipulating this non-conductive layer, p–n junctions are commonly used as diodes: circuit elements that allow a flow of electricity in one direction but not in the other (opposite) direction. This property is explained in terms of *forward bias* and *reverse bias*, where the term *bias* refers to an application of electric voltage to the p–n junction.

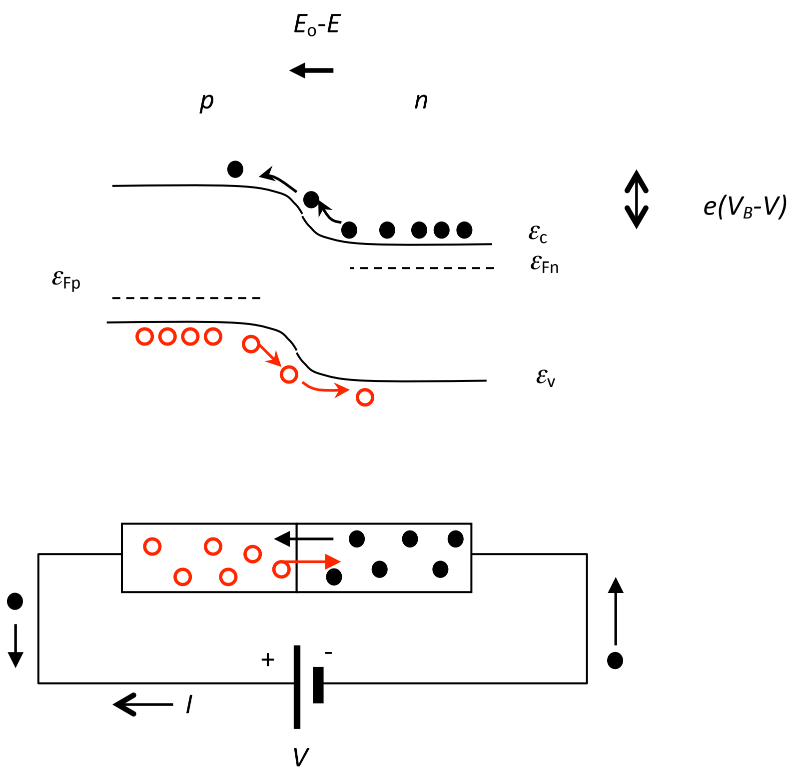
Normally, p–n junctions are manufactured from a single crystal with different dopant concentrations diffused across it. Creating a semiconductor from two separate pieces of material would introduce a grain boundary between the semiconductors which severely limits its usage by scattering the electrons and holes.

IDEAL pn JUNCTION: BAND PICTURE

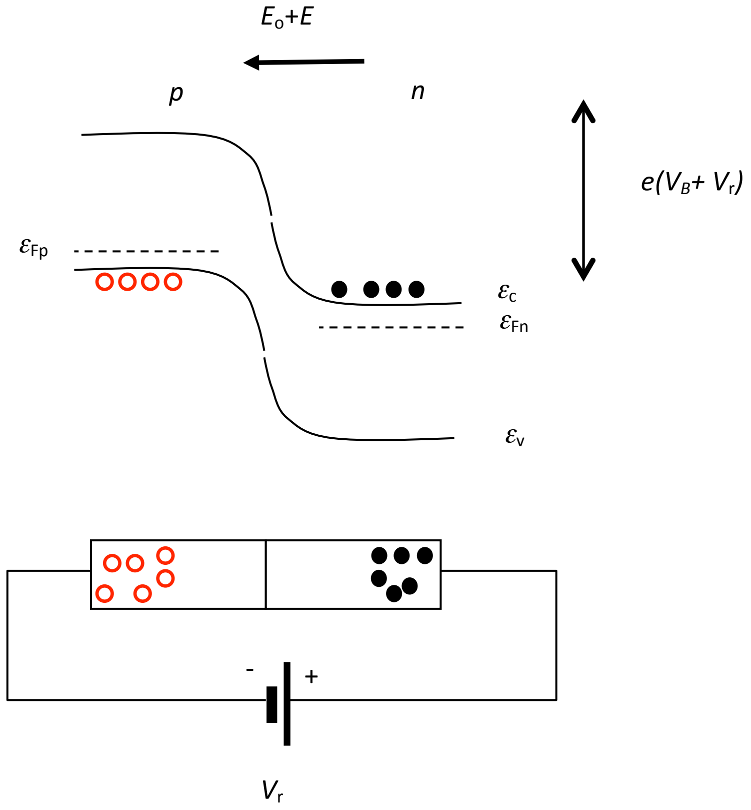
Open circuit



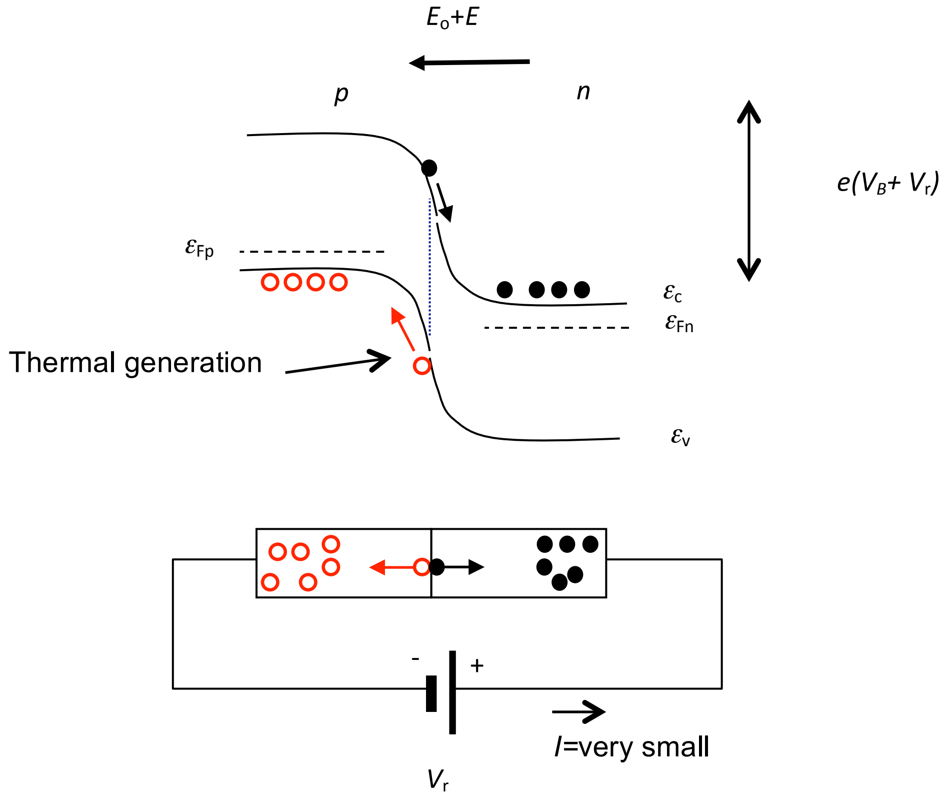
Forward bias



Reverse bias (ideal)

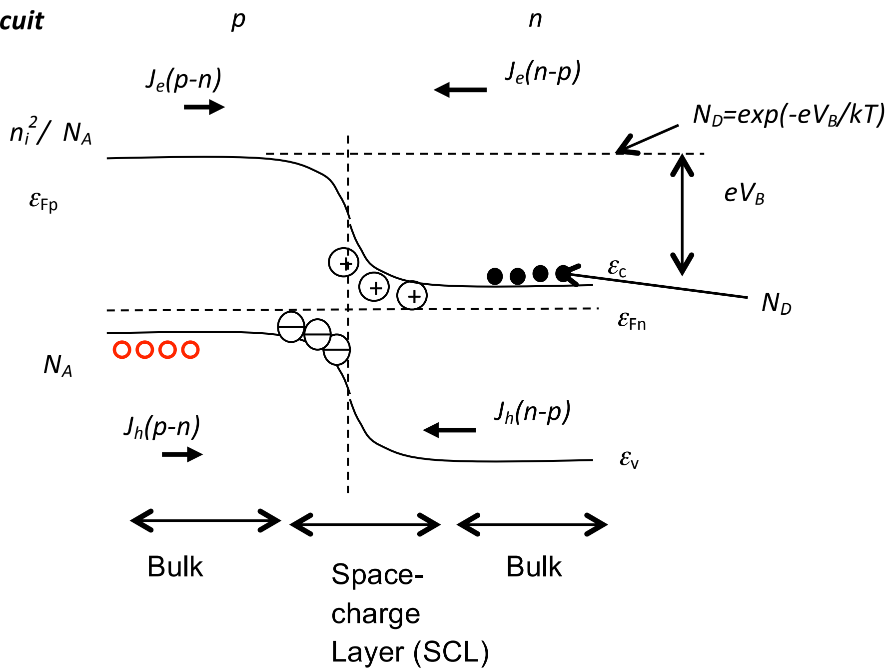


Reverse bias (real)



pn JUNCTION: CURRENT FLOWS, DIODE EQUATION

Open circuit



The electron flux from *n* to *p* side is limited by *diffusion* across the depletion layer with:

$$j_e^{diff}(n \rightarrow p) = Ae^{-eV_B/kT}$$

On the *p* side the electrons are minority carriers and their concentration is extremely low (n_i^2/N_A), but they do not require extra energy to drop down into *n* side, producing what is called the *drift* (or *generation*) flux:

$$j_e^{drift}(p \rightarrow n) \propto \frac{n_i^2}{N_A}$$

If no external voltage is applied we must have:

$$j_e^{drift}(p \rightarrow n) = j_e^{diff}(n \rightarrow p) = Ae^{-eV_B/kT}$$

An external voltage will lower or raise the potential step, so the diffusion flux will certainly change due to change in energy difference (e.g. $V_B - V$), while drift flux can be considered as unchanged (a reasonable first approximation). The total flux is then:

$$j = j^{diff}(V) + j^{drift}(V)$$

We use approximation

$$j^{drift}(V) = j^{drift}(0) = \ Ae^{-eV_B/kT} \ (see\ above)$$

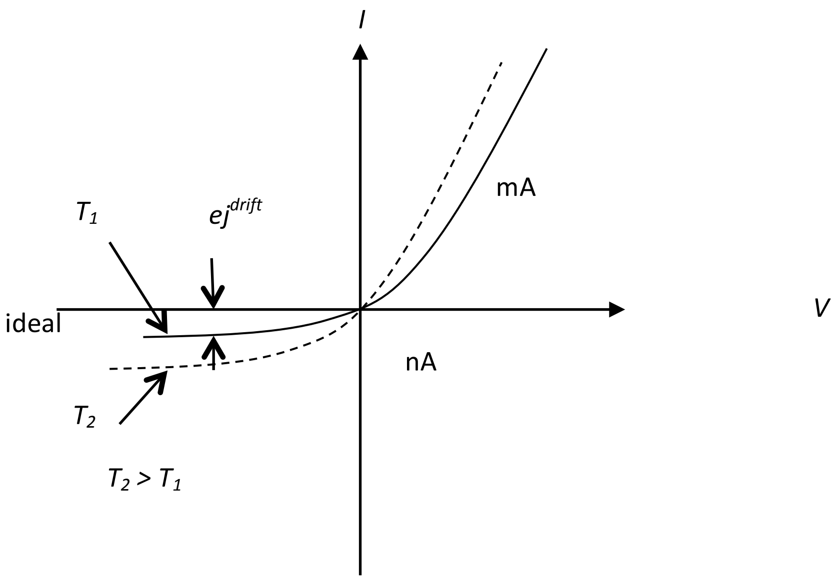
Hence

$$j \approx j^{diff}(V) + j^{drift}(0) = Ae^{-e(V_B - V)/kT)} - \; Ae^{-^{eV_B}/_{kT}} = \; Ae^{-^{eV_B}/_{kT}} \left[e^{^{eV}/_{kT}} - 1\right]$$

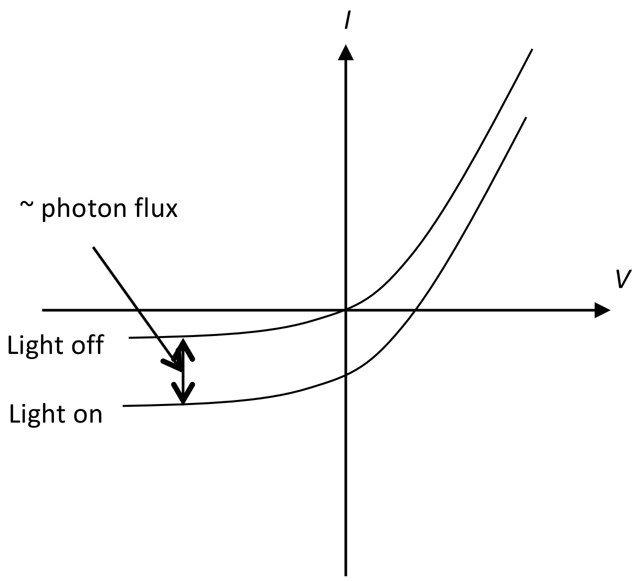
and the *diode equation* can be written as

$$j = j_0 \left[e^{^{eV}/_{kT}} - 1\right]$$

pn JUNCTION: *I-V* CHARACTERISTIC



Effect of light:



Built-in potential difference, V_B

In thermal equilibrium with $V_{ext} = 0$ the elctron density on the n side must be equal to the electron density on p side:

$$\frac{n_i^2}{N_A} = N_D e^{-eV_B/kT}$$

and finally

$$V_B = \frac{kT}{e} \ln\left(\frac{N_A N_D}{n_i^2}\right)$$