FoP3B Part II Lecture 6: pn junction (part II)

In this lecture we will calculate the **built-in potential** ϕ_{bi} and **space charge widths** to complete our discussion on the *equilibrium* pn junction. We will then move onto *non-equilibrium* pn junctions, specifically the application of an external voltage, i.e. **electrical biasing**. It will be shown that current flows for only one voltage polarity, a process known as **rectification**. Finally we will briefly describe the working principles of two pn junction devices, i.e. **solar cells** and **light emitting diodes**.

Calculation of Built-in potential (equilibrium case)

The semiconductor band diagram before and after forming the pn junction is shown in Figure 1. Initially the chemical potentials are at different energy levels (i.e. μ_p for *p*-type and μ_n for *n*-type). For the equilibrium pn junction the chemical potential μ must be uniform everywhere, which gives rise to the built-in potential ϕ_{bi} and band bending. It therefore follows that the energy $e\phi_{bi}$ must be equal to the difference in chemical potential (μ_n-μ_p).

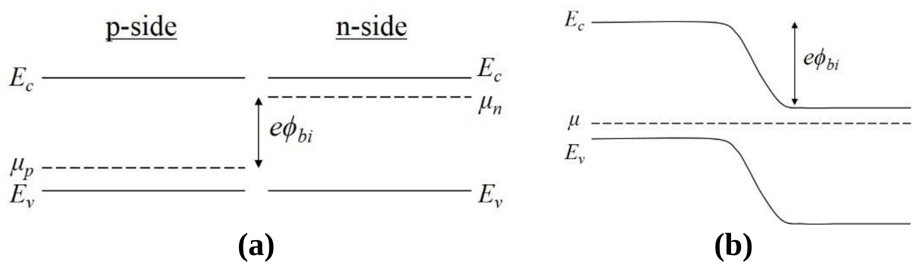


Fig 1: Chemical potential μ and band edges (a) before and (b) after the *p*- and *n*-sides come together to form a pn junction.

From Lecture 4:

$$\mu_p = E_v + kT\ln\left(\frac{N_v}{N_A}\right) \quad \ldots (1)$$

$$\mu_n = E_c - kT\ln\left(\frac{N_c}{N_D}\right) \quad \ldots (2)$$

Therefore:

$$\phi_{bi} = \frac{(\mu_n - \mu_p)}{e} = \frac{E_g}{e} - \frac{kT}{e}\ln\left(\frac{N_v N_c}{N_A N_D}\right) \quad \ldots (3)$$

where E_g = (E_c-E_v) is the **band gap**. From the **law of mass action**:

$$np = n_i^2 = N_c N_v \exp\left(-\frac{E_g}{kT}\right) \quad \ldots (4)$$

Substituting the expression for E_g derived from (4) in (3) gives:

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

… (5)

Calculation of Space Charge widths (equilibrium case)

From Lecture 5 the potential $\phi(x)$ for the p-side was shown to be:

$$\phi(x) = \frac{eN_A}{2\epsilon_r\epsilon_0}\left(x + w_p\right)^2$$

… (6)

And for the n-side:

$$\phi(x) = \phi_{bi} - \frac{eN_D}{2\epsilon_r\epsilon_0}(x - w_n)^2$$

… (7)

The potential must be continuous at the pn junction $x = 0$ (Figure 2), so that from (6) and (7):

$$\frac{eN_A}{2\epsilon_r\epsilon_0} w_p^2 = \phi_{bi} - \frac{eN_D}{2\epsilon_r\epsilon_0} w_n^2$$

… (8)

Equation (8) can be solved for either w_n or w_p using the **charge conservation** condition $N_A w_p = N_D w_n$. The final result is:

$$w_p = \left[\frac{2\epsilon_r\epsilon_0\phi_{bi}}{e}\left(\frac{N_D}{N_A}\right)\left(\frac{1}{N_A + N_D}\right)\right]^{1/2}$$
$$w_n = \left[\frac{2\epsilon_r\epsilon_0\phi_{bi}}{e}\left(\frac{N_A}{N_D}\right)\left(\frac{1}{N_A + N_D}\right)\right]^{1/2}$$

… (9)

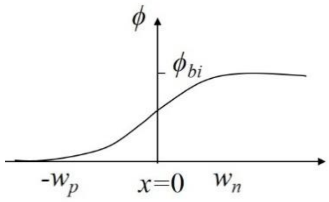


Fig 2: Potential variation across the pn junction. The space charge edges are at $x = -w_p$ (p-side) and $x = w_n$ (n-side)

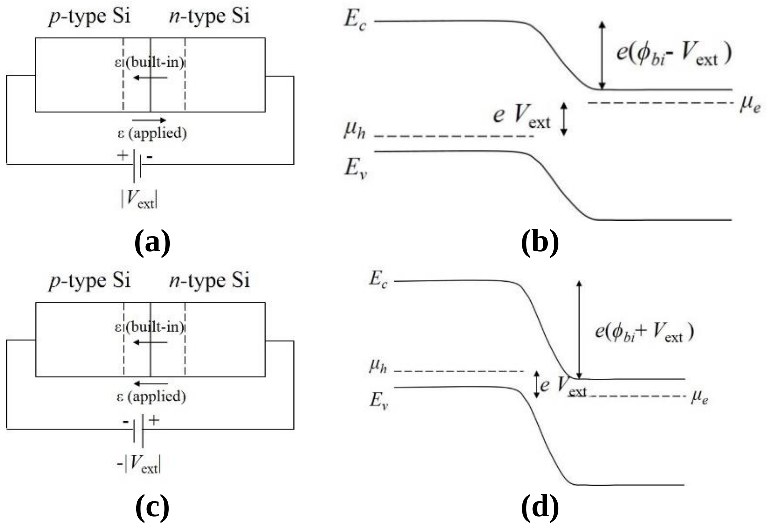
Non-equilibrium pn junction: electrical biasing

Consider connecting a pn junction device to a battery. In the **forward bias** configuration the positive terminal of the battery is connected to the p-side (Figure 3a). *The external electric field due to the battery is confined to the space charge region and opposes the built-in electric field*[1]. This results in a smaller net electric field and consequently less band bending within the space charge region (Figure 3b). *Furthermore, the pn junction is no longer in equilibrium and consequently the chemical potential is not constant*. For forward bias the chemical potential on

[1] Note that the quasi-neutral region cannot contain the external electric field, since otherwise any electrons in the conduction band or holes can drift out of this region creating a new space charge region.

the p-side is lower than the n-side. This simply means that electrons in the p-side have lower energy due to the positive potential of the battery.

The situation is reversed when the positive terminal of the battery is connected to the n-side, which is the **reverse bias** condition (Figure 3c). *Here the external electric field is in the same direction as the built-in electric field and consequently the net electric field is larger, leading to more prominent band bending in the space charge region* (Figure 3d). Furthermore, the chemical potential on the n-side is now lower than the p-side due to the change in voltage polarity.



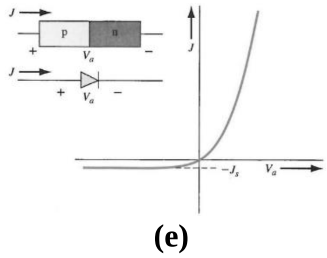


Fig 3: (a) pn junction under forward bias and (b) the corresponding band diagram. V_{ext} is the magnitude of the external applied voltage. (c) shows the pn junction under reverse bias and (d) the corresponding band diagram. (e) is the current density (J)-voltage (V) graph for a pn junction.

In an equilibrium semiconductor the diffusion current for electrons or holes at the space charge edge is equal and opposite to the drift current due to the built-in electric field. In other words the electric field creates an energy barrier for electrons to flow from n- to p-side (Figure 1b). *For forward bias however the energy barrier decreases due to a smaller net electric field, so that electrons and holes can be* <u>*injected*</u> *across the space charge region*. Clearly the larger the applied voltage the greater the current generated. *For reverse bias however the net electric field and energy barrier increases, so that current flow is effectively blocked*. This phenomenon of current flow for only one bias polarity is called *rectification* (Figure 3e).

Examples of semiconductor devices: solar cells and light emitting diodes (LED)

In solar cells light is converted to electricity. When photons with energy greater than the semiconductor band gap are absorbed electron-hole pairs are generated by promoting valence band electrons into the conduction band. *The electrons and holes diffuse randomly through the material and therefore there is no net electric current. The built-in electric field of the pn-junction is required in order to generate an electric current*. Provided the photon-generated electrons from the p-layer diffuse to the space charge region they can be injected into the n-layer via the electric field; similarly holes from the n-layer can be injected into the p-layer (Figure 4a). The electrons and holes extracted by the electric field flow through the external circuit as an electric current.

In LEDs electricity is passed through the device to generate light (reverse process of a solar cell). <u>The pn junction is operated under forward bias</u>. *Since the built-in potential barrier is* *lowered electrons and holes are injected across the space charge region to produce excess minority carriers in the quasi-neutral regions* (Figure 4b). For example, holes injected from the *p*-side across the space charge region become minority carriers when they enter the *n*-side, where electrons are the majority carriers. *When these excess minority carriers recombine with majority carriers energy is released as light*. The photon energy and wavelength is determined by the band gap of the semiconductor.

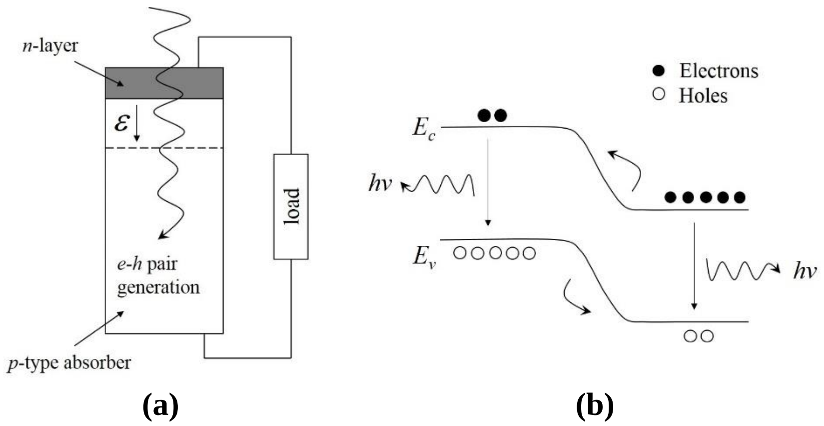


Fig 4: (a) schematic of a solar cell device. (b) shows injection of electrons and holes across the space charge region under forward bias. The excess minority carriers in the quasi-neutral region recombine with the majority carriers to emit light.