EEE105 - Electronic Devices
Lecture 12

The p-n junction diode under Forward Bias.

(CAL: pn(f), pn(g), pn(h), pn(i))

Last time we showed that in a p-n junction there is a barrier formed that prevents the diffusion of electrons and holes across the junction. The barrier can be represented as a ***built-in voltage*** (or ***built-in potential***), which in equilibrium creates a drift current that exactly opposes the diffusion current in the junction, leading to the situation where there is no net current flow in the device.

We can upset this equilibrium if we apply an external bias to the device. The external bias will modify the built-in potential. Let us consider simple circuit where a battery is connected to the terminals of the p-n junction device.

We shall bias the device such that the positively charged holes in the p-type material and negatively charged free electrons in the n-type material are both pushed towards the junction region of the device.

Assuming for the moment that the resistance of the wires, and of the p- and n-type materials are able to be neglected then the applied voltage, *V*, will appear across the depletion region of the junction.

The built-in potential barrier will be reduced from V_0 to $(V_0 - V)$ and the electric field at the junction is reduced. The if the barrier is reduced the value of the drift current opposing the diffusion of the electrons from the n-type to p-type material (and holes from p-type to n-type material) is also reduced.

This means that now we will have a ***net diffusion current*** across the junction and electrons and holes will flow across the junction are recombine with the majority carriers on the other side.

Let us consider the holes. The barrier is reduced can now diffuse across the junction into the n-type material. There they become excess minority carriers. They will diffuse away from the junction further into the n-type material, with them recombining with the electrons in the n-type material.

Assuming we are continuously biasing the junction, and hence continuously injecting holes into the n-type material, we will have an exponential decay profile of the excess hole concentration in the n-type material, as we described in the discussion of minority carrier diffusion length.

At any instant in time the total charge due to the injected excess holes in the n-type material will be given by Q_p.

This will be the area under the curve given by the concentration of excess holes against distance, x, into the n-type material.

The density of excess holes that cross the depletion region into the n-type material is given by δp_0. And clearly to get the total hole concentration at this point we need to add the minority carrier density, giving: $p_{n0} = p_n + \delta p_0$.

Similarly we can say that for electrons diffusing into the p-type material we have the same processes applying and $n_{p0} = n_p + \delta n_0$

In order to estimate the current flow in our p-n junction we need to obtain values for p_{n0} and n_{p0}.

Let us go back to the equations we obtained in lecture 11 for the barrier height:

$$V_0 = \frac{kT}{q}\ln\left(\frac{p_{(p)}}{p_n}\right) \text{ which we can also write as: } p_{(p)} = p_n \exp\left(\frac{qV_0}{kT}\right)$$

Now under forward bias we must modify the built-in potential value from V_0 to $(V_0 - V)$, and the value of the hole carrier density on the n-type side on the edge of the depletion region will be p_{n0} instead of p_n giving:

$$p_{(p)} = p_{n0} \exp\left[\frac{q(V_0 - V)}{kT}\right].$$

To get the density of injected excess holes we must use the equation: $\delta p_0 = p_{n0} - p_n$, which leads to

$$\delta p_0 = \frac{p_{(p)}}{\exp\left[\frac{q(V_0 - V)}{kT}\right]} - \frac{p_{(p)}}{\exp\left[\frac{qV_0}{kT}\right]}$$

We can substitute $p_{(p)} = p_n \exp\left(\frac{qV_0}{kT}\right)$ into this equation to give us :

$$\boxed{\delta p_0 = p_n\left[\exp\left(\frac{qV}{kT}\right) - 1\right]}$$

This equation means that the excess hole concentration injected across the junction increases exponentially with bias, V .

We can similarly obtain an equation for excess electrons in the p-type material:

$$\delta n_0 = n_p\left[\exp\left(\frac{qV}{kT}\right) - 1\right]$$

Now we have values for the concentration of excess electrons and holes on either side of the depletion region in our forward biased p-n junction. We can use these equations to obtain the total amount of charge due to the holes in the n-type material (and electrons in the p-type material) by applying the equation for minority carrier diffusion length:

By integrating this equation we get:

$$Q_p = qA\int_0^\infty \delta p(x)dx \quad \text{where } A \text{ is the cross-sectional area of the junction.}$$

This gives $$Q_p = qA\delta p_0 \int_0^\infty \exp\left(-\frac{x}{L_h}\right)dx$$

$$\boxed{Q_p = qA\delta p_0 L_h}$$

And similarly for electrons in the p-type material we can obtain: $\boxed{Q_n = qA\delta n_0 L_e}$

Now the total charge due to the holes (electrons) in the n-type (p-type) material stays the same. But clearly recombination is occurring all the time (removing minority carriers) as is injection of new minority carriers. In order to get the current we need to know how quickly this "turnover" of the carriers occurs. This can be obtained from the minority carrier lifetimes, τ_h for holes in the n-type material and τ_e for electrons in the p-type material.

We can say that during the carrier lifetime on average all the charges will change.

Now current = charge/time. Applying this to our example we can say

$$I = I_e + I_h = \frac{Q_n}{\tau_e} + \frac{Q_p}{\tau_h} = \frac{qAL_e\delta n_0}{\tau_e} + \frac{qAL_h\delta p_0}{\tau_h}$$

We can now substitute for δn_0 and δp_0 using the equations $\delta p_0 = p_n\left[\exp\left(\frac{qV}{kT}\right) - 1\right]$ and $\delta n_0 = n_p\left[\exp\left(\frac{qV}{kT}\right) - 1\right]$. This will give us:

$$I = \left[\frac{qAL_e n_p}{\tau_e} + \frac{qAL_h p_n}{\tau_h}\right]\left[\exp\left(\frac{qV}{kT}\right) - 1\right]$$

This can be rewritten as

$$\boxed{I = I_0\left[\exp\left(\frac{qV}{kT}\right) - 1\right]}$$

This the diode equation

In this equation I_0 is the so-called "***SATURATION CURRENT***" where

$$\boxed{I_0 = I_{e0} + I_{h0} = \left[\frac{qAL_e n_p}{\tau_e} + \frac{qAL_h p_n}{\tau_h}\right]}$$

Note that we can write down the saturation current in another way:

$$I_0 = qA\left[\frac{L_e n_p}{\tau_e} + \frac{L_h p_n}{\tau_h}\right]$$

Now we can rewrite the diffusion length term using the relationship that

Also we can replace the minority carrier densities using the relation:

Substituting both into the equation for saturation current gives:

$$I_0 = qAn_i^2\left[\frac{D_e}{L_e N_a} + \frac{D_h}{L_h N_d}\right]$$

NOTE: The diode equation can also be written in terms of current density: $J = J_0\left[\exp\left(\frac{qV}{kT}\right) - 1\right]$ where the term for J_0 will be given by: $J_0 = {I_0}/{A}$

Finally note than in the diode equation under forward bias the exponential term will clearly increase rapidly with voltage and the "–1" term at the end will become negligible – allowing use to ignore it in certain cases.

Key Points to Remember:

1. In a p-n junction under zero bias there is a built in potential preventing carrier diffusion.
2. Under forward bias the built in potential is reduced, reducing the electric field opposing the diffusion of carriers.
    a. This allows carriers to diffuse across the junction and recombine.
3. The continuous process of carriers diffusing across the junction and recombining with the majority carriers leads to a current flow in the device.
4. The current rises essentially exponentially with voltage, according to the diode equation.