EEE105 - Electronic Devices
Lecture 13

The p-n junction and current continuity.

(CAL: pn(j), pn(k))

In the last lecture we derived the diode equation:

Where the I_0 term has two parts and is given by . $I_0 = I_{e0} + I_{h0} = qAn_i^2\left[\frac{D_e}{L_e N_a} + \frac{D_h}{L_h N_d}\right]$

Now when we talk about the current flowing through a diode we can discuss it in terms of the ***"electron current"*** and the ***"hole current"*** in the device. So let us define these terms.

Electron Current:

Hole Current:

Let us consider the value of the hole current density at a particular distance, *x*, into the n-type material:

$$J_h = -qD_h \frac{d[\delta p(x)]}{dx}$$

Note this is a diffusion current.

Now we can use the equation for minority carrier diffusion length:

to give us the equation:

$$J_h = \frac{qD_h}{L_h}\delta p_0 \exp\left(-\frac{x}{L_h}\right)$$

This means that the value of the hole current density, J_h, decreases exponentially with distance away from the junction edge. However we know that under steady state conditions the total current density must be constant (assuming that the cross-sectional area, *A*, of the p-n junction is constant).

To achieve this we need to say that the extra current comes from electrons flowing towards the junction through the n-type material and that these replace the electrons lost by recombination. Therefore the current comes from the negative terminal and exactly compensates the reducing hole current near the p-n junction.

Note that this means that depending on the situation not all the electrons injected at the n-contact will get to the junction, diffuse across and become part of the "electron current". Many electrons will be lost in the n-type material, recombining with the minority carrier holes.

The relative magnitudes of the electron and hole current.

The electron current depends on how many of the electrons actually diffuse into the p-type material and become minority carriers there (becoming part of the electron current) and how many of the holes actually diffuse into the n-type material and become minority carriers there (becoming part of the hole current).

The values of the electron and hole currents may be very different. A key question is what controls the ratio of electron versus hole current in a p-n junction. This is not just a semantic question. It will be seen later that this is a critical issue in the design of a bipolar junction transistor.

We know from the last lecture that $J_0 = J_{e0} + J_{h0}$ where J_{e0} is the electron current pre-exponential term and J_{h0} is the hole current pre-exponential term. These pre-exponential terms (or electron and hole saturation currents) relate to the thermal generation of carriers in the depletion region.

Now: $J_0 = J_{e0} + J_{h0} = qn_i^2\left[\frac{D_h}{L_h N_d} + \frac{D_e}{L_e N_a}\right]$

To calculate the relative magnitude of the electron and hole currents let us take the ratio J_h / J_e :

$$\frac{J_h}{J_e} = \frac{J_{h0}}{J_{e0}} \frac{\exp\left(\frac{qV}{kT}\right) - 1}{\exp\left(\frac{qV}{kT}\right) - 1} = \frac{D_h}{L_h N_d} \frac{L_e N_a}{D_e}$$

We can now use the Einstein Relation: giving: $\frac{D_h}{D_e} = \frac{\mu_h}{\mu_e}$

And also use the conductivity equation: giving $\frac{\sigma_p}{\sigma_n} = \frac{N_a \mu_h}{N_d \mu_e}$

To give $\frac{J_h}{J_e} = \frac{L_e}{L_h}\frac{\sigma_p}{\sigma_n}$

Now let us assume for simplicity that $L_e \approx L_h$

We therefore can say that $\frac{J_h}{J_e} \approx \frac{\sigma_p}{\sigma_n}$

The key point about this is that if we dope one side of a p-n junction much more heavily than the other then the diode current will be dominated by carriers from that side. For example if the acceptor concentration in the p-type material is much larger than the donor concentration in the n-type, then $\sigma_p >> \sigma_n$ and hence $J_h >> J_e$.

This means that only a many holes will diffuse into the n-type material, but only a few electrons will be diffuse into the p-type material. Most of the electrons injected from the n-contact will be used up recombining with holes in the n-material.

Remember this is concept will be critical to our understanding of how a bipolar junction transistor is designed.

Light Emitting Diodes.

(CAL: LED)

When a p-n junction is forward biased then the electrons and holes are being injected across the junction where they become minority carriers and recombine.

The process of recombination has been described before and consists of the electron falling in energy from an excited state back into a bonding state. (Alternatively we can say that the electron falls from the conduction band back down in energy to the valence band.) As the electron loses energy, the energy lost must be emitted in some manner. This energy can appear in the form of heat, or in many materials, in the form of a photon being emitted, giving light.

If a photon is emitted the energy of a photon will be equal to the energy lost by the electron in falling back into the bonding state. This is given by the ionisation energy (or forbidden gap energy), W_g .

If we know the energy of the photons being emitted we can calculate the wavelength of the light from:

Where *h* is Planck’s Constant.

Some semiconductors are very poor at emitting light, such as Si and Ge, while others, notably the so-called III-V semiconductors such as gallium arsenide (GaAs) and gallium nitride (GaN) are very good. Through the choice of material we can get light emission at any wavelength from the near infrared to near ultra-violet. Such diodes that emit light are called Light Emitting Diodes (LEDs).

In designing LEDs we usually aim to make the surface of the device through which the photons are emitted large.

Furthermore if we design the material carefully then we can also make a laser, called a Laser Diode.

LEDs and laser diodes have many applications. Clearly visible LEDs can be used as indicators in everything from a power on switch to a red or green traffic light. Huge television screens on the side of buildings are made up of millions of red, green and blue LEDs. Infrared LEDs are used in remote controls for example. The laser diode is the key component a CD or DVD player in allowing information to be read from (and written to) the disk.

Aside: Comment on Doping

Semiconductor device engineers sometimes use various terms to indicate the relative density of dopants that have been added to a particular piece of semiconductor.

The term **"heavy"** doping is used to describe the situation when the density of donors (or acceptors) is very high. The material can be described as being heavily or highly doped n-type (or p-type).

- For example, typically a heavily doped n-type semiconductor would be one where the free-electron concentration might be close to, or greater than around 10^{25} m^{-3}. It is difficult to dope above around 10^{26}-10^{27} m^{-3} as at this point the density of dopants becomes so high that the material behaves differently (at this point around one percent of the atoms in the crystal are dopant atoms).

The term **"light"** doping is used to describe the situation where the density of donors (or acceptors) is lower. The material can be described as being lightly doped n-type (or p-type).

- For example, typically a lightly doped p-type semiconductor would be one where the hole concentration might be less than around 10^{23} m^{-3}. It is difficult to dope controllably around and below 10^{21} m^{-3} in practice. In some cases the impurity density in the material when it is prepared "undoped" are at about this level. (This level of carriers represents a density of impurities of around 10 atoms per billion atoms of the material!)

When describing a p-n junction we sometime wish to make it clear that one side or the other is heavily doped, or at least more heavily doped than the other. We can represent heavily doped p-type material by using a "+" superscript. Hence a p^+-n junction is one where the concentration of acceptors on the p-type side of the junction is high and also much higher than the concentration of donors on the n-type side of the junction.

Similarly to make it clear that one side of the junction is lightly doped then we use a superscript.

In a Zener diode both the p and n sides are heavily doped so we can say this is a

Reverse Bias

(CAL: pn(l), pn(m))

Let us now consider the situation where we reverse the battery polarity.

In this case the built-in potential preventing electron and hole diffusion will be increased.

The barrier height will increase from V_0 to $V_0 + V$.

The majority carrier electrons and holes in the n- and p-type materials will now be repelled away from the junction and hence current cannot flow.

However, there will be a small current. Minority carriers are always being produced by thermal generation and can be swept through the depletion layer by the field in that region. This will give a ***small*** reverse ***leakage*** current.

Let us now revisit the diode equation:

Let us assume that the voltage is large and negative: This means that the exponential term will tend to zero.

Hence: $I = -I_0$, where I_0 is the ***reverse leakage current***.

Now from last time we obtained the equation: $I_0 = qAn_i^2\left(\frac{D_e}{L_e N_a} + \frac{D_h}{L_h N_d}\right)$

Note that in this equation $I_0 \propto n_i^2 \propto \exp\left(-\frac{W_g}{kT}\right)$

This means that the value of I_0 will increase rapidly with increasing temperature. It will also be much much smaller for a semiconductor material with a bigger ionisation energy.

The I-V characteristic for a diode can now be drawn. In forward bias the current will rise exponentially with voltage and in reverse bias the current will be equal to the saturation current value, I_0.

Clearly at some point these relationships will breakdown. In forward bias as the current gets larger then the resistance of the semiconductor material becomes important and the rise in current ceases to be exponential.

In reverse bias there comes a point as the reverse bias voltage is increased when the electric field in the depletion region becomes so large that some form of breakdown occurs and the magnitude of the current rises rapidly.

The breakdown can take one of two forms: ***Zener Breakdown*** and ***Avalanche Breakdown.***

Zener Breakdown is when we have junctions which are heavily doped then in reverse bias the electric field in the junction becomes large and eventually electrons can be "torn" out of their bonds causing the current to rise rapidly. This breakdown occurs rapidly at a particular voltage and gives the reverse bias breakdown voltage of a Zener Diode.

Avalanche Breakdown is what happens when the p- and n-type carrier concentrations are lower (the junction is more lightly doped). In this case the reverse bias field gives the thermally generated carriers larger and larger kinetic energy (KE) until the KE is so large that the electron can collide with the lattice with sufficient energy to allow another electron to jump out of its bond – creating another electron-hole pair. This electron and hole are also accelerated and can each create more free carriers and hence we have an "avalanche effect"

Key Points to Remember:

1. The electron (*hole*) current is due to electrons diffusing across the junction into the p-type (*n-type*) material and recombining there.
2. As one moves further away into the p-type side of the junction the value of the electron current decreases exponentially as the carriers recombine.
3. The current must be the same at any point in the material. Thus as the electron current decreases so the current due to holes from the p-contact must from a greater proportion of the total current.
    a. Note that the current flowing in the p-material from holes coming in from the p-contact is NOT the hole current.
4. The ratio of electron and hole current flowing in a p-n junction can be approximated by the ratio of the materials conductivities on either side of the junction.
5. In a diode electrons recombine with holes releasing energy, often in the form of light. This is the basis of a light emitting diode.
6. In reverse bias the barrier preventing diffusion becomes larger so there is no significant current flow.
    a. There is a small leakage current due to thermally generated carriers.
    b. Eventually breakdown will occur giving a rapid rise in reverse bias current.
7. We can use the term p^+ (p^-) to describe heavily (lightly) doped p-type material.