EEE105 - Electronic Devices
Lecture 8

p-type Doping (Impurities to add Extra Holes)

Let us now consider the case where the impurity is from group III of the periodic table.

Examples of group III dopants would be:

These are know as ***acceptors*** because they ***accept*** free electrons from the Si lattice.

As there are only three outer electrons in the material, when it bonds into the Si lattice there will be one incomplete (or broken) bond. This incomplete bond is, as we described in the last lecture, a hole. This hole is able to move around in the manner described previously, leaving the fixed negatively charged acceptor atom (ion) behind.

The holes are positively charged, hence ***p***ositive charge carriers provide the conduction. Thus we have ***p-type*** material.

As was the case for donors in the n-type material, at room temperature essentially all the acceptors in p-type material are ionised and the holes are free to move around the Si crystal.

Conduction in Extrinsic Material

When we considered intrinsic material we obtained the equation: $J = q(n\mu_e + p\mu_h)E$

This equation is generally true. However, in extrinsic (doped n-type or p-type) semiconductors either n>>p or p>>n. Thus we can either write:

$J = qn\mu_e E$ (when *n*>>*p* → as is the case in n-type material) or

$J = qp\mu_h E$ (when *p*>>*n* → as is the case in p-type material)

Generation and Recombination of electron-hole pairs.

(CAL: semic(f), MPG to revise Semiconductors 1-6)

In a semiconductor bonds are broken

and remade all the time.

This effect causes the intrinsic carrier concentration and is responsible for the reverse leakage current in a p-n junction diode for example.

The rate at which e-h pairs are formed is called the generation rate, *G*. It depends (as discussed previously) on the ionisation energy, W_g (the energy required to break a bond and release an electron in the material) and on the temperature, *T*.

The rate at which the electrons and holes recombine (or get back together again) is the recombination rate, *R*.

Now let us consider what happens if we take a piece of material and arbitrarily increase its electron density. We could do this for example by .

If we increase the concentration of electrons we will increase the probability that a hole will recombine with one of them. Thus:

$$R \propto n$$

We can make a similar argument for the situation where we increase the number of holes in the material, so:

$$R \propto p$$

Where *p* and *n* are the electron and hole concentrations in the material, respectively.

Combining the above we get:

$$R \propto$$

and therefore $R =$ where

Now let us consider the relationship between *G* and *R*:

If *G*>*R* then

If *G*<*R* then

The effect of this is that the free carrier density will quickly stabilise with the relationship that $G = R$.

This situation is called a

Let us now consider the situation in intrinsic material when *G*=*R*.

$$G = R = Bn_i p_i = Bn_i^2 \qquad \text{(as } n_i = p_i\text{)}$$

(the subscript '*i*' here just means we are talking about the *intrinsic* carrier concentration.)

Now at a fixed temperature the generation rate must be *CONSTANT* (as both W_g and T are constant). This is just another way of saying that in a particular material the rate of bond breaking is fixed at a fixed temperature).

Let us now use this fact to help us understand what happens in an extrinsic semiconductor:

If the material is doped n-type then the electron concentration will be *n* rather than n_i, where $n >> n_i$.

Now we must remain in equilibrium, where *G*=*R*:

$$G = R = Bnp_n$$

where p_n is the density (or concentration) of free holes in the n-type material.

Now we can also write:

$$G = R = Bn_i^2 = Bnp_n \quad \text{and therefore: } \boxed{n_i^2 = np_n}$$

Note that as $n >> n_i$ then from the above relationship $p_n << p_i$.

By the same analysis we can show that in p-type material:

where n_p is the concentration of free electrons in the p-type semiconductor.

Minority and Majority Carriers

From the above we can see that a doped (or extrinsic) semiconductor material, both free electrons and free holes will be present. However one of the carrier types will have a higher concentration than the other.

In n-type material the electron concentration is much higher than the hole concentration.

Electrons are ***majority*** carriers — Holes are ***minority*** carriers

In p-type material the hole concentration is much higher than the electron concentration.

Holes are ***majority*** carriers — Electrons are ***minority*** carriers

We can qualitatively explain this by saying that in n-type material the thermally generated holes experience greater recombination due to the higher electron density. Although both the electron and hole concentrations will reduce due to the recombination, the holes will suffer a much greater fractional (or proportion of) loss, and the intrinsically generated electrons increase (as there are clearly less holes to recombine with.)

Example:

Consider a bar of n-type Si with a free electron concentration of 10^{22} m^{-3}.

What is fraction of the current carried in this material is due to the minority carrier holes?

(You may assume $\mu_e = 0.12\mathrm{m}^2\mathrm{V}^{-1}\mathrm{s}^{-1}$ and $\mu_h = 0.045\mathrm{m}^2\mathrm{V}^{-1}\mathrm{s}^{-1}$)

In order to address this we first need to know what the hole concentration is in the material:

We can do this using the relationship $n_i^2 = np_n$ that we derived earlier.

From last week we said that $n_i \approx 10^{16}\mathrm{m}^{-3}$ at room temperature.

Hence we can calculate $p_n = {n_i^2}/{n} = \frac{\left(10^{16}\right)^2}{10^{22}} = 10^{10}\,\mathrm{m}^{-3}$

Now let us define the conductivity due to electrons as σ_e, and the conductivity due to holes as σ_h.

We can then obtain the fraction of the conductivity due to holes from

We now need to calculate σ_e, σ_h which we can do from the relationship: $\sigma = nq\mu$

Thus $\quad \sigma_e = nq\mu_e = \left(10^{22}\right)\bullet\left(1.60\times10^{-19}\right)\bullet\left(0.12\right) = 192\Omega^{-1}\mathrm{m}^{-1}$

and $\quad \sigma_h = p_n q\mu_h = \left(10^{10}\right)\bullet\left(1.60\times10^{-19}\right)\bullet\left(0.045\right) = 7.2\times10^{-11}\Omega^{-1}\mathrm{m}^{-1}$

We can now calculate the fraction of the conductivity due to the holes to be:

Key Points to Remember:

1. Adding an impurity with three outer electrons means that there will be one broken bond left when the impurity is in the Si crystal.
    a. This broken bond, or hole, is only very weakly attracted to the impurity and at room temperature is essentially free to move around the crystal as a free hole.
    b. The group III impurity atoms are called acceptors as the accept free electrons.
    c. The material is p-type as the charge carriers are positively charged.
2. Once the positively charged hole has left the impurity, the impurity will be a fixed negatively charged atom (ion)
3. In thermal equilibrium the rate of generation of free carriers must equal the rate of recombination of the carriers.
    a. This gives the intrinsic free carrier density
4. The rate of recombination of free carriers is proportional to the density of free electrons and holes.
5. In doped material the generation rate will be the same as in intrinsic material
    a. This means the density of electrons in p-type material will be suppressed by the high concentration of holes (and vice-versa in n-type material)
6. In n-type material we say the electrons are *MAJORITY* carriers and the holes are *MINORITY* carriers, and (vice-versa in p-type material)