

ET3034Tux - 2.3.2 – Excitation of charge carriers 2

Secondly, we are going to intentionally put boron impurities in the silicon network.

Since the boron atom has only three valence electrons, it is missing one electron to make a molecular bond with its four neighboring silicon atoms.

As a consequence one molecular bond is filled with only one electron.

This entity is the same as the hole.

This extra hole is easily excited to a free mobile state as well.

The boron atom left behind is not neutral anymore, but becomes negatively charged.

This negative charge is fixed to the position where the boron atom is residing in the lattice.

The result is that by adding a boron impurity we have one extra free mobile hole available and one fixed negative charge.

This is called p-doping.

These states are called acceptors as it accepts one electron from the valence band.

For p-doped semiconductors, the electrons are called the minority charge carriers as the density of electrons is much smaller than the density of the holes.

The holes are the majority charge carriers in p-doped materials.

p-doping of silicon can be illustrated by an electronic band diagram as well.

The boron atoms result in acceptor states.

These acceptor states have an energy level within the forbidden band gap of the silicon matrix and the acceptor states can be occupied by electrons.

The energy level of the acceptor states is closer to the valence band than to the conduction band.

This means that it requires much less energy for an electron to jump from the valence band to the acceptor state than to the conduction band.

For silicon at room temperature many electrons of the valence band can be excited to the acceptor states.

As a result we have more free mobile holes than mobile electrons in a p-type semiconductor.

The electrons are the minority charge carriers, the holes are the majority charge carriers.

As the holes are the majority charge carriers the Fermi level will be closer to the valence band than to the conduction band.

Let's get a feeling for the typical concentrations for majority and minority charge carriers in doped silicon networks in the dark.

Typical densities for majority charge carriers in silicon are 10^{16} cm^{-3} , whereas the density of minority charge carriers in that case would be 10^4 cm^{-3} .

This shows that the density of the majority charge carriers can be many orders of magnitude higher than that of the minority charge carrier.

Note that the silicon density in crystalline silicon is $5 \cdot 10^{22} \text{ cm}^{-3}$.

This means that the total number of charge carriers is much lower than the typical density of silicon atoms, the ratio majority charge carriers to silicon atoms in this example is 1 to 5 million.

The densities of charge carriers can be described by the law of mass action.

What does this law mean for charge carriers in semiconductor materials?

This law tells us that at a given temperature the product of the electron density and the hole density is constant, independent of the doping concentration.

If n corresponds to the electron density and p corresponds to the hole density, this law tells us that the product $n \cdot p$ is constant if we would manipulate either n or p .

So let's consider intrinsic silicon.

This is silicon without any impurities.

At room temperature the electron density N and hole density P are equal.

For silicon the electron and hole density is in the order of $1.1 \cdot 10^{10} \text{ cm}^{-3}$.

This means the product, $n \cdot p$, is equal to $1.21 \cdot 10^{20} \text{ cm}^{-3}$ squared.

Now we consider a n-doped silicon material.

We incorporate a density of phosphorous atoms in the lattice, which we call N_D .

We assume that all donors give a free electron to the lattice.

So it means the electron density n_0 is equal to N_D .

Now we can calculate the hole density p_0 .

The law of mass action tells us at a given temperature the product of the electron density and hole density is constant, independent of doping.

So p_0 is equal to the square of the intrinsic charge carrier density divided by the electron density n_0 .

The same is valid for p-doped silicon material.

We incorporate boron atoms with a density of N_A in the silicon network.

We assume that all acceptors take one electron and therefore create hole density p_0 equal to the acceptor density N_A .

This means that the electron density n_0 is equal to the square of the intrinsic charge carrier density divided by the hole density p_0 .

Let's take an example.

We incorporate 10^{16} cm^{-3} phosphorous atoms in the lattice, or in other words: we have a donor density N_D of 10^{16} cm^{-3} .

As we assume that all donors give a free electron to the lattice the electron density n_0 is equal to the donor density N_D .

Now we can calculate the hole density p_0 .

So p_0 is equal to the square of the intrinsic charge carrier density divided by the electron density n_0 .

So the hole density is given by $1.21 \cdot 10^{20}$ divided by the number 10^{16} and then we get the hole density of $1.21 \cdot 10^4 \text{ cm}^{-3}$.

Now we consider a third approach to excite charge carriers, which is by light absorption.

Let's consider the electronic band diagram again and photon with an energy equal to the band gap, indicated by the green arrow.

This photon can be absorbed in a semiconductor material and can be used to excite an electron from the valence band to the conduction band.

So, light can make a semiconductor material more conductive.

However, if we have a photon with an energy smaller than the band gap, this photon is lacking the energy to excite an electron from the valence band to the conduction band.

This photon cannot be absorbed by the semiconductor material.

Another situation is when the photon has an energy much larger than the band gap.

This photon can excite an electron at an energy level deeper in the valence band into the conduction band.

Or an electron to a higher energy level into the conduction band.

In these situations the hot electrons or holes very fast relax back to the lower energy positions.

For the electron this is the bottom of the conduction band and for the hole this would mean the top of the valence band.

This extra energy is released as heat and will heat up the semiconductor material.

So the rest energy, which is the photon energy minus the band gap energy, ends up as heat.

Finally in this block I would like to discuss how light absorption affects the charge carrier density in doped materials.

Let's consider again the situation with a density of majority charge carriers of 10^{16} cm^{-3} and density of minority charge carrier of 10^4 cm^{-3} .

Now let's assume we generate electron-hole pairs by light absorption.

We generate 10^{11} cm^{-3} electron-hole pairs.

What will happen to the density of the majority and minority charge carriers?

So we will simply add up the numbers.

What you can see is that the majority charge carrier density is not affected by the light absorption.

10^{11} is much smaller than 10^{16} .

On the other hand the density of minority charge carriers is drastically affected.

10^{11} is much larger than 10^4 . Its density is increased with 7 orders of magnitude.

This is an important conclusion, which we will need later to understand the working principle of solar cells.

In doped semiconductor materials, light absorption has only effect on the density of minority charge carriers.

Summarized, in this block we have discussed how to excite charge carriers in a semiconductor material, by temperature, doping and light absorption.

The next question is: how do those charge carriers move around and what makes them move around in a semiconductor material?

I will talk about that in the next block, where we are going to discuss transport of charge carriers.