ET3034TUx - 2.3.3 – Transport of charge carriers

What are the charge carrier transport principles?

In this block the two transport mechanisms will be discussed: diffusion and drift.

We will discuss that for net movement of charge carriers either a concentration gradient is required or an electrical field is required.

Let's consider a free gas of particles at a temperature larger than the absolute zero.

In case of a free electron gas these particles are electrons.

The particles have kinetic energy and can move around freely.

All particles move around in a so-called random walk.

They move in random directions until they collide with another particle.

After the collision both particles will move in a different direction and the velocity of the particles is changed.

In a free electron-gas the interaction of the particles is ruled by Coulomb-Coulomb interactions, the particles not really collide into each other but they bend each other's trajectories.

Let's consider the situation that the density of the particles is uniformly distributed, i.e.

no density gradient exist.

On average the particles with a random walk will have no net movement.

Just as many particles will move to the right as will move to the left.

Just as many particles will be moving up as will be moving down.

Now we consider a nonuniform particle distribution.

At the right you see that the particle density is higher than at the left.

In other words: a density gradient is present going from right to left.

If these particles all move randomly around, the flux of particles to the volume with lower density on the left will be higher.

The flux of particles to the volume with higher density on the right will be smaller.

There will be a net movement of particles until the density is uniformly distributed.

In the current situation the density is uniform, no gradient exist, so there is no net movement of particles due to diffusion.

The net movement of particles induced by density gradients is called diffusion.

It can be described by Flick's law of diffusion, J_e in this case is the electron current density, expressed in current per area.

q is the elementary charge, D is the diffusion coefficient of the electrons and dn/dx represents the density gradient in direction x.

Diffusion of electrons results in a net movement of electrons to the location with lower electron densities.

Diffusion will be present as long as there is a density gradient.

The same equation is valid for holes.

Diffusion of holes results in a net movement of holes to the location with lower holes densities.

Now we move to the second transport mechanism, which is called drift.

Charged particles like electrons and holes can also be moved under influence of an electric field.

Let's consider an electric field, which points to the left.

If a positively charged hole is positioned in this electric field it will experience an electric force in the direction of the electric field, so in this case: to the left.

Consequently, it will start moving in that direction.

A negatively charged electron will experience a force in the opposite direction of the electric field.

The electron will start moving to the right.

The current density induced by an electric field is given by the product of the density of electrons (n), the electron charge q, the mobility constant mu and the electric field E.

Similar, the hole current density induced by an electric field is given by the product of the density of holes (p), the electron charge q, the mobility constant mu and the electric field E.

The presence of an electric field can also be represented in an electronic band diagram.

Let's consider again an electric field, pointing to the left.

In the figure you can see a conduction and valence band.

The electric field induces a slope over the valence band and conduction band.

The slope of the electronic band is positive in the direction of the electric field.

It is important to remember that the excited electrons in the conduction band will on average always move down the slope of the conduction band when a slope is present, the holes will on average always move up the slope of the valence band.

These are the two mechanisms which are responsible for charge transport in solar cells.

Holes and electrons have net movements due to either a density gradient, which we call diffusion, or an electric field.

In the previous block we discussed that we can excite electrons and holes by absorption of light.

However, holes and electrons also suffer from loss mechanisms.

If an excited electron and hole meet each other they are able to recombine.

They join each other and lose their mobile state or in other words the electron is glued again to the background in a molecular orbital.

We can distinguish three types of recombination mechanisms.

The first one is radiative recombination.

An electron and hole recombine together.

The energy released is sent out in the form of a photon.

As it costs at least the energy of the band gap to excite an electron and hole pair, radiative recombination sends out a photon with at least the energy of the band gap as well.

The second recombination mechanism is Auger recombination.

The energy released by the recombination of an electron-hole pair is transferred to a neighboring free electron in the conduction band.

This electron is excited to a higher energy level in the conduction band.

This hot electron will lose its energy again as heat to the lattice of the semiconductor.

The third recombination mechanism is Shockley-Read-Hall recombination.

Semiconductor materials can have various types of defects in the lattice.

These defects can have energy states in the forbidden band gap, like we have seen for donor and acceptor states in the case of doping.

An electron can be trapped in such defect state.

If then freely moving around holes can find these trapped electrons, they can recombine as well.

The loss mechanism like recombination determines the lifetime of the charge carriers.

If the recombination rate is high, the lifetime of charge carriers is low.

The diffusion length L is the average distance the excited charge carriers can move around and is determined by the lifetime of the charge carriers.

If the recombination rate is high, the diffusion length will be shorter.

When the recombination rate is low, the diffusion length will be longer.

The diffusion length and the lifetime are related with the relatively simple equation L is the square root of the product of D and tau, where D is the diffusion coefficient and tau is the lifetime.

Now let's consider a p-doped semiconductor material.

The holes (the blue dots) are the majority charge carriers and the electrons (the red dots) are the minority charge carriers.

The holes have a small probability that they will meet an electron and therefore the recombination rate for holes is small.

On the other hand, the electrons have a high probability to meet one of the holes as the hole density is many orders of magnitude higher.

This means that the recombination rate for the electrons is high, or in other words: the diffusion length of the electrons L_e is shorter than that of the holes L_h.

Let's consider now n-doped semiconductor materials.

The electrons (the red dots) are the majority charge carriers, and the holes (the blue dots) are the minority charge carriers.

The electrons have a small probability that they will meet a hole and therefore the recombination rate is small.

On the other hand, the holes have a high probability to meet one of the electrons as the electron density is many orders of magnitude higher.

This means that the recombination rate for the holes is high, or in other words: the diffusion length of the holes, L_h, is shorter than that of the electrons, L_e.

Important to remember is that in a doped material the minority charge carriers have a short diffusion length in reference to the majority charge carriers.

So, now we know how to excite charge carriers, we know how to manipulate the semiconductor material to create majority and minority charge carriers and we understand the transport mechanisms of charge carriers.

It is time to build a solar cell, using these tools.

We will do that in the next block.