ET3034TUx - 2.4.1 – Semiconductor Junction I: Basic Principles

Finally, we are going to build a solar cell.

Most solar cells are based on a p-n junction.

The question is: What is a p-n junction?

Again we take as an example the case for silicon.

We have introduced the fact that semiconductors can be doped: n-type and p-type.

In the n-type material the majority charge carriers are electrons and the doping atoms that donated an electron are fixed, positive charges in the network.

In a p-type material the majority charge carriers are holes and the doping atoms that accepted an electron are fixed, negative charges in the network.

On the left we see a p-type semiconductor material.

The electronic band diagram of the p-layer is illustrated on the left, as well.

I would like to address again that for the p-type silicon, the Fermi level, indicated by the dashed black line is closer to the valence band than to the conduction band.

On the right we see the n-type semiconductor material.

Its corresponding electronic band diagram is illustrated on the right.

The Fermi level is closer to the conduction band for the n-type material.

Now, we glue the n-type and p-type semiconductor materials together, and this is what we call a p-n junction.

In reality, we take one piece of silicon material, in which we intentionally dope one part p-type and the other part n-type.

Now we first consider the situation that this p-n junction is in the dark and is in thermal equilibrium.

What will happen?

How will the charge carriers be distributed over the p-region and the n-region?

On the left we have a majority of holes, on the right we have a majority of electrons.

As we obviously can see, the p-n junction has an enormous density gradient close to the interface between the p- and n-region.

The hole density is much lower in the n-region than in the p-region, whereas the electron density is much lower in the p-region than the n-region.

As we discussed earlier this week, diffusion is driven by density gradients.

So, let's assume that the charge carriers diffuse until the point that the electron and hole densities are equally distributed over the p-region and the n-region.

The question to you is, will this really happen in nature?

Let's take a moment to think about it. Will this happen?

The answer is no.

But why not?

Because we have not considered the second transport mechanism, which is based on the electric field: drift.

Let's consider the homogeneously distributed charge carriers as shown here.

Are the p-region and the n-region neutrally charged?

The answer is no.

The p-region is negatively charged, although there are just as many holes as electrons, there are still many fixed negatively charged acceptor atoms in the background.

The other way around, the n-region is heavily positively charged, although there are just as many holes as electrons, there are still many fixed positively charged donor atoms in the background.

So this charge will create a strong electric field from the n-region to the p-region.

This internal field over the depletion zone pushes holes back to the p-region and the electrons back to the n-region.

So what happens in reality?

At the interface region, some holes will diffuse to the n-region and some electrons will diffuse to the p-region.

As the diffusion length of holes in n-type is short,

they will soon recombine with one of the majority electrons.

The same is valid for the electrons, as the diffusion length of electrons in p-type is short as well, they will soon recombine with one of the majority holes.

As a result there is a small region around the p-n interface in which all charge carriers

are wiped out.

In this region the only charges present are the charges related to the background donor and acceptor atoms.

This region is called the space charge region.

We also use for this region the term depletion zone.

The space charge region is depleted from mobile charge carriers.

In this example the left side of the space charge region, facing the p-type side, is negatively charged, whereas the right side of the space charge region, facing the n-type side, is positively charged.

This results in an electric field across the space charge region,

which is directed from the n-type region to the p-type region.

This will induce an opposite movement of charge carriers in reference to the diffusion.

The electric field at the space charge region will force the minority charge carriers in the p-region, the electrons, to move to the n-region, whereas the electric field will force the minority charge carrier in the n-region, the holes, to move to the p-region.

So, we are considering at the moment a p-n junction that is in the dark and is in thermal equilibrium.

The two transport mechanisms over the space charge region are in balance.

We have introduced two simple equations for the drift and the diffusion earlier this week.

The diffusion current density for electrons is ruled by the density gradient, which is the electron density at the n-region minus the electron density in the p-region.

The electrons are the minority charge carriers in the p-region, which means that the density gradient is fully determined by the majority electron density in the n-region.

The same is true for the holes.

The diffusion current density for holes is ruled by the density gradient, which is the hole density at the p-region minus the hole density in the n-region.

The holes are the minority charge carriers in the n-region, which means that the density gradient is fully determined by the electron density in the n-region.

With other words, the diffusion is controlled by the majority charge carriers in the p- and n-region.

It is important to realize that you can vary the diffusion current density in two different ways.

As the diffusion scales with the gradient dp/dx or dn/dx,

you have either to increase the density of the majority charge carriers, in this case dp, or you have to change the width of the depletion zone dx.

In the following final block of this week, I will show that you can manipulate the width by putting a voltage bias over the solar cell.

Diffusion is controlled by the density of the majority charge carriers.

To the contrary, the drift works on the minority charge carriers.

The electric field will force the electrons in the p-region, where the electrons are the minority charge carriers, to move back to the n-region.

Similar, the electric field will force the holes in the n-region, where the holes are the minority charge carriers, to move back to the p-region.

So the drift is controlled by the minority charge carrier density.

Increasing the drift current density can be accomplished by either increasing

the density of the minority charge carriers, in this case p, or by increasing the electric field E over the depletion zone.

In this example, the p-n junction is in thermal equilibrium, the current densities at the depletion zone are in equilibrium.

If we would connect the left side of the p-region and the right side of the n-region with an electrical circuit, we would have no current flowing through the circuit.

The electric field will create a built-in voltage over the space charge region.

The origin of the built-in voltage can be demonstrated by looking at the electronic band diagram of a p-n junction.

In a p-n junction in thermal equilibrium, the Fermi level is constant across the entire junction.

I will try to visualize this using a simple explanation.

You can compare the Fermi level in a junction under thermal equilibrium with that of water level in a water tank, consisting of two reservoirs.

The two water reservoirs are separated with a barrier.

The left one has a low water level and the right reservoir has a high water level.

Let's say the left side is the p-region with a Fermi level close to the valence band, and the right side is the n-region with a Fermi level further away from the valence band.

If we remove the barrier between the both reservoirs the water levels will equalize over the two reservoirs.

The same is applicable for the Fermi Level.

Important to know is that the relative position of the electronic bands like the conduction and valence band to the Fermi level remains the same.

This means that the mechanism of equalizing the Fermi level, will move and bend the conduction and valence band.

This is demonstrated in this animation.

If we equalize the Fermi levels, the conduction and valence band are bended in the depletion zone.

We see that in thermal equilibrium the valence and conduction band have a steep slope across the depletion zone.

As discussed earlier a slope in an electronic band diagram represents an electric field.

The electric field across the depletion zone is equal to q*V_bi, q is the charge of the hole or electron, V_bi is the built-in voltage over the depletion zone.

This slope will make the minority electrons move from the p-region to the n-region, whereas, the minority holes in the n-region will go up the slope of the valence band, to the p-region.

Now we have discussed a p-n junction in thermal equilibrium in the dark, in which diffusion and drift are in balance.

However, we can manipulate this equilibrium by first applying a bias voltage over the p-n junction.

Secondly, we can manipulate this equilibrium by illuminating the p-n junction to increase the minority charge carrier densities.

In that case we have created a solar cell.

The working principle of the solar cell will be revealed in detail in the next, final block of this week!