ET3034TUx - 2.4.2 - Semiconductor junction 2 - The solar cell

We have discussed a p-n junction in the dark in thermal equilibrium.

In this situation the diffusion and drift over the depletion zone are in balance.

Now we are going to disturb the equilibrium by applying a bias voltage or shining light on the p-n junction.

We will see that an illuminated p-n junction acts like a solar cell.

First, we consider a p-n junction in the dark and we apply a forward bias on the device.

This means we have a more positive voltage at the p-region side than at the n-region side.

The depletion zone is the area where the built-in electric field is present.

It is also the zone with the highest resistivity and the applied external bias will create an additional electric field at the depletion zone, indicated by the green arrow.

This additional field, indicated by the green arrow, is opposite to the built-in electric field, indicated by the black arrow.

The effective electric field across the depletion zone is the sum of the built-in field and the applied electric field and becomes smaller as a result of the forward bias.

As a consequence the width of the depletion zone is affected, the width becomes much narrower.

This means that the diffusion becomes more dominant than drift.

You can easily see this if we look in more detail to the equations for the current densities related to diffusion and drift.

First, since the width of the depletion zone is smaller, or in other words dx is getting smaller, the density gradients dn/dx and dp/dx become much larger As a consequence, the current density related to diffusion becomes significant larger, indicated by the larger arrows.

On the other hand, the electric field E is reduced, which means that the current density related to drift is getting slightly smaller.

Note, that the effect of the increased flux due to diffusion is much larger than the small change in drift.

This means that we generate a net current over the depletion zone.

More electrons are diffusing from the n-region to the p-region, than are drifting from the p-region to the n-region.

More holes are diffusing from the p-region to the n-region, than are drifting for the n-region to the p-region.

This means by applying a forward bias over a p-n junction in the dark we produce a net current through the electrical circuit.

The contact and wires of an electrical circuit consist of highly conductive metals.

In metals the charge carriers are free mobile electrons.

This means that the electrons move through the electrical circuit from the p-side to the n-side.

At the n-side, electrons are injected in the n-region again.

Applying a forward bias on the p-n junction can be illustrated using the electronic band diagram of a p-n junction.

The forward bias reduces the electric field over the depletion zone.

This results in a reduction of the slopes across the depletion zone in the conduction and valence band.

The p-n junction is not in equilibrium anymore and the Fermi level is not constant across the device.

This results in a splitting of the Fermi level in the depletion zone, which are called quasi Fermi levels, the upper level represents the population of electrons and the lower level represents the population of holes.

In equilibrium these distributions are mirrored and related by the Fermi-Dirac function as discussed in block 2.3.1.

However, by applying a forward bias over the p-n junction, the system is not in equilibrium anymore and the population of holes and electrons become more complex.

The energy gap between both quasi Fermi levels is q*V, in which q is the charge of electrons or holes again and V represents the forward bias applied on the junction.

Due to the reduced field or in other words the reduced slope, the drift of electrons and holes is reduced.

In addition, the reduced width of the depletion zone enhances the diffusion.

We can do the opposite of forward biasing as well.

We can apply a reverse bias over the p-n junction, which is still in the dark.

The voltage at the contact of the p-doped side is negative and the voltage at the contact of the n-doped side is positive.

The built-in electric field, indicated by the black arrow, and the applied electric field across the depletion zone, indicated by the green arrow, are now pointing in the same direction.

The total electric field over the depletion zone is increased.

As a result, the width of the depletion zone is getting much wider, or in other words dx is getting larger.

This has the opposite effect on the balance between the diffusion and drift.

The density gradient is becoming smaller, so both density gradients dn/dx and dp/dx are getting smaller, because dx is getting larger.

The current density related to diffusion of both electrons and holes is reduced.

The drift is enhanced.

Since the electric field E is larger, the drift of the electrons and holes is slightly enhanced.

In this case the drift current density is dominating the diffusion current density.

Since the drift current density is ruled by the density of the minority charge carriers in the p- and n-region, the total net current is extremely small.

In the reverse bias condition an extreme small current will move from the contact at the p-region to the n-region.

This means that on average electrons are walking from the contact of the n-region to the p-region.

Summarized, in the dark under forward bias the diffusion of charge carriers over the depletion zone is dominant, whereas under reversed bias the drift of charge carriers over the depletion zone is dominant.

Under forward bias in the dark, the p-n junction can produce relatively large currents, whereas in reverse bias, it generates very small currents.

Such a device is called a diode.

It has a high conductance in forward bias, but has a low conductance in reverse bias.

Now we are going to shine light on the device.

This means that we are looking at a solar cell.

Light is incident from the left on the p-region.

For the moment we assume the light is being absorbed in the p-region and the n-region.

The absorption of the photon will generate electron and hole pairs.

Important to realize and as discussed earlier, light absorption only affects the density of the minority charge carriers in doped semiconductor materials.

This means that the light excited charge carriers significantly increase the density of the electrons in the p-region and the density of the holes in the n-region.

Subsequently we increase the drift.

This can be easily recognized by looking at the equations for the current densities.

We see that we are significantly increasing the drift over the depletion zone, which is indicated by the larger arrows.

Many electrons drift from the p-region to the n-region and many holes drift from the n-region to the p-region.

The current density related to drift can be easily increased by many orders of magnitude under illumination in reference to the p-n junction in the dark.

By illuminating a p-n junction we can generate a current.

Finally, we're looking at the working principle of a solar cell.

Using an electrical circuit we connect the contact at the p-doped silicon with that of the n-doped silicon, or in other words we short-circuit the p-n junction.

In this condition, the illuminated p-n junction will produce only an electrical current.

We call this current the short-circuit current of a solar cell.

We can make a very simplified animation of the journey of the generated charge carriers.

On average a minority electron will drift to the n-type material and diffuses to the metal contact in which the electron is injected.

The electron moves to the contact at the p-side and is injected into the p-type silicon.

Here it quickly recombines with a hole.

The minority holes in the p-type drift across the depletion zone and diffuse to the back contact to recombine with the electrons.

However, no current is created when we open the electrical circuit.

In that case, the dominant drift current of light excited charge carriers will positively charge the p-region with holes and negatively charge the n-region with electrons.

This charging creates an electric field opposite to the built-in electric field and reduces the net drift current again.

This charging of free holes in the p-region and free electrons in the n-region will build up until both the drift currents are in equilibrium.

This means that the device does not generate a current, but builds up an electric field, or voltage.

The voltage created by an illuminated solar cell under open-circuit conditions is called the open-circuit voltage.

Summarized, by illuminating a p-n junction we can generate under closed-circuit conditions a current and under open-circuit conditions a voltage.

So, the p-n junction is a device which facilitates the photovoltaic effect.

As discussed in the first week, the photovoltaic effect has three essential steps:

1. Generation of electron-hole pairs due to light absorption.

2. Separation of electrons and holes at the depletion zone of the junction.

3. Collection of electrons and holes at the contacts.

Step 1 takes place in the semiconductor material, Step 2 occurs at the space charge region and step 3 takes place at the terminals.

We now are familiar with the working principle of a solar cell.

Under week 2, you will find a collection of exercises which helps you further in the understanding of semiconductor materials, charge carrier transport and p-n junctions.

Next week we will look how we can determine the performance of solar cells using external parameters like the short-circuit density and the open-circuit voltage.

And we will discuss some design rules how to optimize the performance of solar cells.

So see you next week!