ET3034TUx - 3.1 - Solar cell operation

How can we determine the performance of a solar cell?

Or in other words, how much of the energy in the solar spectrum can be converted into electrical energy?

This is the first important question, which will be addressed this week.

First, in this block I will present a simple electrical circuit and corresponding current-voltage curves, which are able to describe the behavior and the performance of solar cells under illumination and under voltage bias, as we have discussed in detail last week.

Before I do that, I will quickly summarize last week's important highlights concerning the physical working principle of a solar cell.

Last week we have shown that we can dope semiconductor materials n-type and p-type.

In p-type the holes are the majority charge carriers and in n-type the electrons are the majority charge carriers.

If we have semiconductors in which one part is doped p-type and another part is doped n-type, we have created a so-called p-n junction.

We have also seen that two different mechanisms control the transport of charge carriers in semiconductors: diffusion and drift.

Diffusion is controlled by a density gradient, whereas drift is controlled by electric fields, which you can build in the p-n junction or apply externally.

In a p-n junction the diffusion of majority charge carriers through the p-n interface, followed by recombination creates a space charge region or depletion zone at the p-n interface.

In the dark and in thermal equilibrium drift of minority charge carriers and diffusion of majority charge carriers are in balance.

If we apply a reverse bias on such p-n junction in the dark, the depletion zone gets wider, the diffusion of majority charge carriers is suppressed and only an extreme small current related to drift of minority charge carriers is generated.

If we apply a forward bias on such p-n junction in the dark, the width of the depletion zone is getting smaller, the diffusion of the majority charge carriers is significantly enhanced and overrules the drift of minority charge carriers.

The p-n junction becomes conductive and is able to generate a current.

If we illuminate the p-n junction, the density of the minority charge carriers is increased many orders of magnitude and as a result the drift becomes dominant and the p-n junction generates a large current.

Now, we are going to construct first an equivalent circuit in which we can describe the behavior of a p-n junction solar cell.

We have discussed that in the dark a p-n junction behaves like a diode.

A diode is an electrical element that if you apply a forward bias on it, it becomes conductive in one direction, whereas if you apply a reverse bias on it, a diode is hardly conductive and basically blocks the current in the opposite direction.

P-n diodes are electrical elements used in many electrical circuits and their main function is to allow an electrical current in one direction and block an electrical current in the other direction.

A p-n junction is represented by the electrical symbol shown here.

It's a triangle with on top of its vertex a line.

The triangle points in the direction in which the diode allows an electrical current to flow under forward bias conditions.

In the opposite direction the diode blocks the current.

So now we put the p-n junction in the dark and apply a reverse bias.

The p-n junction generates an extreme small current in the block direction of the diode.

The current direction in electrical circuits in general points in the direction in which the positive charges flow.

It means that the electrons, which are negatively charged, flow in the opposite direction of the current direction.

This implies that under reverse bias, the extreme small current in the block direction can be represented by electrons moving in the direction of the triangle.

Now, we consider a p-n junction in the dark under forward bias.

The p-n junction generates a significant current in the forward direction of the diode.

As current direction is defined in the direction of the flow of positive charge, it means that under forward bias the electrons responsible for the current flow in the block direction of the diode.

Note that the current under forward bias is opposite and much higher than under reverse bias.

The relation between the current and voltage of a p-n junction can be illustrated in an so-called I-V curve.

The vertical axis corresponds to the current of the p-n diode and the horizontal axis represents the voltage applied over the p-n diode.

A negative voltage, reflected by the grey area in the I-V plot, corresponds to reverse bias voltages.

As we can see the current is close to zero.

Applying a positive voltage, reflected by the light yellow area, corresponds to the forward bias.

Above a certain voltage the current starts to significantly increase with increasing the voltage.

This is a characteristic I-V curve of an ideal silicon p-n junction in the dark.

This I-V curve can be described by a relatively simple expression which shows that the relation between current and voltage is an exponential function.

The I stands for the current at a given voltage V, q is the elementary charge of the electron, k_B is the Boltzmann constant and T is the temperature of the p-n diode.

I_0 is the extreme small current in the block direction under reverse bias conditions.

This current is very often referred to as the leakage current of a p-n junction.

We won't derive why the current and voltage are related by this exponential expression, you only have to know for the moment that the I-V curve of a p-n junction in the dark can be described by this expression.

If we put a very large negative voltage into this equation you can easily see that the exponential term becomes zero and the current is equal to the small leakage current I_0, close to zero .

If we apply a large positive voltage, we see that we get a large positive current and the exponential term dominates over the -1 term in the equation.

Note that the current on the vertical axis is positive, if the current flows in the forward direction of the diode, whereas it is negative if it flows in the block direction of the diode.

Now we will illuminate the p-n junction using light.

It means that we are going to generate a large current, dominated by the drift of the minority charge carriers, which is opposite to the forward direction of the p-n diode.

This is represented in the equivalent circuit by a current source, which is connected in parallel with the diode.

The electrical symbol of a current source is a circle with an arrow.

The arrow points in the direction of the positive current.

It means that the far majority of electrons in this equivalent circuit travel through the current source in the opposite direction of the arrow.

The current generated by the light absorption is I_ph, where ph stands for photo.

Note that the photocurrent is in the opposite direction of the forward current of the diode.

Now we look at the I-V curve again.

The red line corresponds to the I-V curve of the diode in the dark.

Adding the photocurrent, the typical I-V curve of the diode shifts down the vertical axis in the direction of negative currents in reference to the forward bias direction of the diode.

This circuit is the circuit for an ideal solar cell, this means that we have not included all types of electrical and optical losses.

We will come back to that later this week.

The IV- curve of an ideal solar cell can be described by a simple equation.

The total current generated by an illuminated p-n junction is the photocurrent minus the current of the p-n diode in the dark.

In the equations so far we have used current I which has the unit ampere.

This is sometimes not the most convenient unit to express the electrical response of a solar cell to light.

If we would increase the area of a solar cell, it means that the total current of the solar cell is increasing as well.

So the current depends on the area.

In the lab, researchers like to use the unit current density J, this is the current generated per area.

The advantage of this unit is that you can compare different solar cell technologies, as not every technology generates the same amount of current per square meter.

If we assume that A is the area of a solar cell, the current density J is equal to the current I divided by the area A.

So, the current density is expressed in milliamperes per square centimeter or amperes per square meter.

As you see, the vertical axis of the current-voltage plots are already expressed in current density.

From this point on, we won't talk about I-V curves, but we will talk about J-V curves.

So from now on we will use current density.

Summarized, I have introduced an electrical circuit and simple expression which describes the behavior of a p-n junction solar cell under voltage biasing and illumination.

This behavior can be represented in a so-called J-V curve.

How does this J-V curve relate to the performance of a solar cell?

Or in other words: the conversion efficiency of light energy into electrical power.

I will answer this question in the next block.