ET3034TUx - 3.2.1 - External parameters of an ideal solar cell

How can we determine the performance of a solar cell?

In the previous block we have introduced the J-V curve of an ideal solar cell and its corresponding electrical circuit.

In this block we are going to discuss the external parameters that determine the light-to-electricity conversion efficiency of an ideal solar cell.

Let's consider that the terminals of an illuminated solar cell are not connected.

This situation is called an open circuit.

In open-circuit the solar cell does not produce any current and solely produces a voltage.

This voltage is called the open-circuit voltage.

The voltage is easily recognized in the J-V plot by the intersection of the J-V curve with the horizontal axis corresponding to a current density equal to zero.

We can derive a simple equation for the open-circuit voltage of an ideal solar cell.

In the previous block we have derived a simple equation for the current density which had two components, the photocurrent generated by light excited charge carriers and the typical J-V characteristic of a diode in the dark.

Under open-circuit conditions the current density J is equal to zero.

If we solve this equation we arrive at a simple expression for the open-circuit voltage.

It is linear with the Boltzmann constant times the temperature, divided by the charge of an electron.

And it is linear with the natural logarithm of the ratio between photocurrent and the leakage current of a diode plus 1.

Note that in text books the first term also contains a diode ideality factor n.

This factor reflects to which extent the J-V curve can be described by the behavior of an ideal diode.

For the moment we have assumed that the recombination occurs in the bulk through defect traps in the band gap, the so-called Shockley-Read-Hall (SRH) recombination and that the recombination is limited by the minority charge carriers.

In that case the ideality factor is equal to 1.

However, if the recombination occurs for instance at interfaces, or is limited by both charge carriers, or is determined by Auger recombination, this factor differs from 1.

However, during this course we will consider the situation that the ideality factor is equal to 1.

The equation shows that the open-circuit voltage depends on several parameters.

First the equation shows that if the photocurrent density is increased the open-circuit voltage is increased as well.

This means that by increasing the irradiance, or in other words, by shining more light on the solar cell, the open-circuit voltage can be increased.

Secondly, the open-circuit voltage depends on the temperature.

Although this equation on first eye suggests that the open-circuit voltage increases with temperature, this is not the case.

The leakage current J_0 of the diode strongly depends on the temperature.

The higher the temperature, the larger the leakage current and the smaller the open-circuit voltage will be.

The open-circuit voltage depends on other factors as well, such as the band gap of the absorber material, the amount of doping of the doped layers and the quality of the material or in other words the defect density.

We will come back to these relations later during the course.

If we short-circuit both terminals of the solar cell, the illuminated solar cell will solely produce a current and will produce no voltage.

This current density is called the short-circuit current density.

The short-circuit current density can easily be recognized in the J-V curve as well.

It is the intersection between the vertical line corresponding to zero voltage and the J-V curve.

We can derive a simple equation for the short-circuit current density of an ideal solar cell using again the expression of the J-V relation.

If we take a voltage equal to zero, the short-circuit current density is equal to the photocurrent density.

The short-circuit current density depends on several factors like the incident light intensity, the spectrum of the incident light, the optical properties and the collection probability.

Now we like to know how much power a solar cell can deliver and how power is related to the J-V curve.

As you might know from your physics class, the power is equal to the current times the voltage.

The unit for power is watt and therefore is equal to ampere-voltage.

However, since we use current density in the J-V curves, we will talk about power density, which is power per area.

So, current density is expressed in A/m^2 or mA/cm^2.

which means that the power density is expressed in W/m^2 or mW/cm^2 We have added the power density in the J-V curve as a function of the voltage using the green curve.

The vertical axis on the right shows the scale of the power density.

Note, that if the power density on this scale is negative, it means that the solar cell is generating power, whereas if the power density is positive, it means that the solar cell is consuming or dissipating power.

The green curve shows that the power density is varying with the voltage and it shows that the power density has a maximum.

On the J-V curve this point is called the maximum power point and the power density generated at this point on the green line is P_max.

The graph demonstrates that if the solar cell is in open-circuit, which means it only produces an open-circuit voltage and no current density, the power density is equal to zero.

When the solar cell is in short-circuit, which means it only produces a current density and no voltage, the power density is equal to zero as well.

If the voltage is smaller than 0 V, which we call reverse bias, the illuminated solar cell does not generate power but consumes power.

Basically, an illuminated solar cell under reverse bias will heat up.

If the voltage is larger than the open-circuit voltage, the illuminated solar cell is dissipating power as well and the solar cell will heat up as well.

The solar cell will have its best performance in its maximum power point.

The voltage at the maximum power point is called V_mp and the current at the maximum power point is called J_mp.

Which means that maximum power density P_max is equal to V_mp*J_mp.

With other words, the shaded area under the maximum power point in a J-V plot represents the power density generated.

Now, we introduce the external parameter fill factor (FF).

The fill factor is the ratio between the maximum power and the product of the short-circuit current density and the open-circuit voltage.

Or the ratio between the product of maximum power point current density and the voltage and the product of the short-circuit density and the open-circuit voltage.

The FF can be easily visualized in a J-V curve.

Basically, the FF is the ratio between the area shaded red-yellow and the red area including the shaded red-yellow area.

With other words the FF is the ratio between the rectangle with sides V_mp and J_mp, and the area with the sides of the open-circuit voltage and the short-circuit current density.

This means that we can express the maximum power density as a product of the FF, the open-circuit voltage and the short-circuit current density.

It implies that it is impossible for a solar cell to have a FF equal to 1, in that case the J-V curve should have the shape of a rectangle.

In the homework of this week, we have an exercise in which you have to derive a relation between the FF and the open-circuit voltage of an ideal solar cell.

This expression will show that the larger the open-circuit voltage, the closer the FF will be to a value of 1.

Now we introduce the conversion efficiency eta of a solar cell.

This is the ratio between power density coming out of the solar cell P_out and the light power density of light incident on the solar cell, or in other words going into the solar cell, P_in.

The conversion efficiencies of solar cells are defined in its maximum power point so P_out equals P_max.

P_max, as discussed, equals the product of J_mp and V_mp.

This product equals to the product of the short-circuit current density, the open-circuit voltage and the FF.

As a result the conversion efficiency can be expressed in the external parameters of the solar cell: the open-circuit voltage, the short-circuit current density and the fill factor.

To be able to compare the efficiencies of different solar cells, the so-called standard test conditions have been introduced.

The standard test conditions describe the conditions for P_in and the temperature of the solar cell during the J-V measurements.

The temperature of solar cells under standard test conditions is determined to be 25 degrees Celsius.

The solar spectrum has the spectral shape of AM1.5 and a total irradiance of 1000 watts per square meters.

As a reminder, a typical solar spectrum with the shape of AM1.5 is shown here.

On the left vertical axis we show the spectral power density.

The irradiance under standard test conditions has to be equal to 1000 watts per square meters and is given on the right axis.

The blue line represents the irradiance and equals the area under the spectral power density up to the wavelength lambda.

As illustrated, if we integrate over the entire spectral power density the blue line, corresponding to the irradiation, equals 1000 watts per square meter.

Note, that 1000 watts per square meter equals 100 milliwatts per square centimeter.

Let's get a feeling of typical values.

Let's look at this example of a J-V curve and assume that it has been measured under standard test conditions.

The J-V curve represents a typical value for crystalline silicon based solar cells.

The maximum power density is 19 mW per square centimeter, which means under standard irradiance of 100 mW per square centimeter the conversion efficiency is 19%.

If we consider the open-circuit voltage of 0.64 V and the short-circuit current density of 35 mA/cm^2, we arrive at a FF of 84.8%.

We have introduced the external parameters of an ideal solar cell.

In the next block we will show a video clip on how a real J-V measurement of a solar cell in the Delft Solar Lab is performed.

We will see that the J-V curve of solar cells and solar panels in reality do not perfectly match the J-V curve of an ideal solar cell.

What is the origin of all these non-idealities? I will answer this question in the next block.