ET3034TUx - 3.3.2 - Spectral utilization 1 - External quantum efficiency

We discuss the second design rule: spectral utilization.

How is spectral utilization determined?

We will discuss this in the coming two blocks.

Let's consider a single junction solar cell in which the absorber layer is a material with a certain band gap energy.

We know that when the energy of a photon is smaller than the band gap, it is lacking the energy to excite an electron to the conduction band.

When the energy is larger than the band gap, absorption of the photon results in a mobile electron and hole.

Let's see how the band gap affects the open-circuit voltage and short-circuit current density.

In this illustration the conduction, valence band and band gap of the absorber material are shown.

In addition I represent the solar spectrum by arrows with various length and colors.

The blue arrows correspond to energetic photons: their photon energy is much higher than the band gap.

The green and red arrows correspond to photons with lower photon energy.

The red photons have a low energy.

It is even smaller than the band gap energy.

Note that in this illustration the band gap is relatively large.

Only the blue and partly the green photons are able to excite charge carriers.

If we look at the J-V curve, this is indicated by a relatively low short-circuit current density, while due to the large band gap, a higher open-circuit voltage can be obtained.

If we now consider an absorber material with a lower band gap, we see that more photons in the spectrum can excite charge carriers.

This material will result in larger short-circuit current densities.

However, due to the smaller band gap, the splitting of the quasi-Fermi levels and the resulting open-circuit voltage will become small.

This is reflected in the blue J-V curve.

The J-V curve of the solar cell with the low band gap material, has a larger short-circuit current density, whereas the open-circuit voltage is smaller.

An important conclusion of this simple exercise is that the choice of semiconductor material determines the open-circuit voltage and the short-circuit density through its band gap.

Now we are going to look in more detail how spectral utilization of a solar cell can be determined and measured.

For that we introduce the external quantum efficiency.

Here we see a solar cell.

Let's consider a certain amount of photons at a certain wavelength which are incident on the solar cell.

These photons will generate electrons collected at the terminals.

The external quantum efficiency is the number of electrons collected at the terminals per incoming photon at a certain wavelength.

Not every photon incident on a solar cell will result in electrons collected at the contacts.

Lower EQE can be attributed to several optical and electrical loss mechanisms for charge carriers.

For example, photons can be reflected back from the solar cell, photons are not absorbed as they have an energy smaller than the band gap, the absorber layer is too thin and does not absorb all photons, parasitic absorption losses in the inactive PV layers of the cell and recombination of the light excited charge carriers before they are collected at the contacts.

Let's say we have a material with band gap E_gap.

The ideal external quantum efficiency would look like this graph.

Note that the horizontal axis is plotted in wavelength.

Smaller wavelengths correspond to higher energetic photons, the blue spectral part.

Longer wavelengths correspond to lower energetic photons, the red spectral part.

Above the band gap all photons result in a collected electron, or in other words the EQE is 1 or 100%.

In reality the EQE is always smaller than 100% and its value varies with wavelength.

EQE spectra are measured using an EQE setup also called spectral response measurement.

I won't go in detail, but such setup needs a wavelength selective light source, a calibrated light detector and a current meter.

A xenon lamp is a standard light source used in EQE setups as it emits photons in the same spectral range of interest of the solar spectrum.

Using filters and a monochromator only light within a narrow band of photon energies is incident on the solar cell.

First, using a calibrated detector, the number of photons per narrow wavelength band can be determined.

Secondly, the current density generated by the solar cell is measured with the same photons incident on the cell.

In this procedure the number of collected electrons and the number of photons per wavelength are measured and the EQE can be determined.

If we perform this measurement under short-circuit conditions, the short-circuit current density can be determined out of the spectral EQE.

The advantage of measuring the short-circuit current density using an EQE setup above that of the earlier discussed J-V measurements is that the current density measured by the EQE setup is independent of the spectral shape of the light source used.

Secondly, on lab-scale the real contact area of solar cells is not accurately determined.

The EQE measurement setup, when using shading masks, is independent on the contact area.

Let's go to the PV lab to see a typical measurement of an EQE setup.

This is an example of a homebuilt EQE setup, which is used to measure the spectral response of small, lab-scale solar cells.

Here we see the xenon light source and the monochromator.

To demonstrate the operation of the monochromator, we are going to look at the light output, which is incident on a piece of paper, in the dark.

Here you see a condition in which only a narrow wavelength range in the blue light is incident on the paper.

Now we move from blue to green light and now from green to red light.

We are going to measure a solar cell.

This means we first have to calibrate our light source.

For that, we use a calibrated silicon photodiode.

This means that we can translate very accurately the light induced currents in the photodiode to the number of photons.

The photodiode signal is measured as a function of the wavelength.

After calibration of the spectral power density function of the light source, we repeat the same measurement with a solar cell.

As example, we use a c-Si wafer based lab-scale heterojunction solar cell, which will be discussed next week.

The solar cell is positioned at the same spot as the calibration photodiode.

The contacts are connected to the ampere meter to measure the generated current.

In this example, we measure the cell under short-circuit conditions.

It means that no additional voltage bias is applied to the solar cell.

The external quantum efficiency is measured as a function of the wavelength and in this movie it is going from the blue to the red.

The EQE can also be measured when additional reverse or forward bias is applied to the solar cell.

As we will discuss in a minute, the measured EQE in combination with the spectral power density of the AM1.5 solar spectrum, gives us the short-circuit current density of the solar cell.

In this case, the current density of the lab cell studied is 350 A/m^2 or in a more practical unit on lab-scale: 35 mA/cm^2.

Important to realize is that if you want to report short-circuit densities of solar cells, you cannot rely on a single J-V measurement, they have to be measured using an EQE setup.

How do we determine the short-circuit current density out of the EQE?

Under standard test conditions the solar spectrum is defined as the AM1.5 spectrum with a total power density of 1000 watts per square meter.

The total current generated at a wavelength lambda is the elementary charge multiplied by the product of the photon flux phi, at AM1.5 and the EQE.

The total short-circuit current density can be determined if we integrate over the entire wavelength range.

Or as discussed in week 1, the spectral photon flux equals the spectral power density divided by the photon energy.

In this graph the spectral power density is shown in the red.

The blue line represents the theoretical short-circuit current density at a wavelength lambda.

It shows that up to a wavelength of 2000 nm, we could theoretically generate a short-circuit current density of 62 mA per square centimeter.

Let's consider c-Si, having a band gap of 1.12 eV.

This equals a wavelength of 1107 nm, then we arrive at a theoretical current density for c-Si of 44 mA per square centimeter.

I will show you an example of an easy way to estimate the current density using a simple approximation of the solar spectrum.

Here we see the spectral power density of an AM1.5 solar spectrum.

I will make a crude simplification.

The spectral power density function of a solar spectrum can be roughly approximated with a linearly increasing line from 300 up to 500 nm, and a linearly decreasing line from 500 nm up to 1500 nm.

As discussed in week 1 the area under this triangular shaped spectrum represents the irradiance, which for this case is 900 watts per square meter.

This is in excellent agreement with the real value for the irradiance up to 1500 nm determined from the real AM1.5 spectrum.

Let's consider c-Si as absorber layer.

c-Si has a band gap of 1.12 eV which corresponds to a wavelength of 1107 nm, for simplicity we take 1100 nm.

And we assume that the EQE is 90% above the band gap.

Or in other words 10% of the photons do not result in the collection of an electron.

The short-circuit current density is the integration over the area of the product of the EQE and the simplified spectral photon flux.

If we do this exercise, we arrive at 39.4 mA/cm^2.

This is a realistic number if we consider the typical current densities of the best monocrystalline silicon based solar cells.

If we would have an EQE of 100%, we estimate a current density of 43.8 mA/cm^2.

This is again in excellent accordance with the theoretical current that c-Si can generate as we have seen earlier.

This provides you an easy tool to make realistic estimations on the possible photocurrents that various materials can generate.

In summary, we have discussed how to determine the spectral utilization of a single junction solar cell.

The band gap of the semiconductor material determines the theoretical maximum current density and open-circuit voltage that can be obtained.

In the next block we will discuss the optimum performance of single junction solar cells under standard test conditions in more detail.