External Quantum Efficiency

In this video we will discuss the external quantum efficiency or E_Q_E measurement. This is a very important characterisation tool that supports and improves the accuracy of the illuminated J_V measurement and that gives insight in the spectral behaviour of the solar cell. We will start by introducing the definition of the external quantum efficiency, which can be transformed to the internal quantum efficiency, or IQE, by a simple step. Next we will show how the short-circuit current density of the solar cell can be obtained from the EQE curve. Finally, we will show a schematic overview of a typical setup, and we will go into more detail on the data acquisition method.

The external quantum efficiency of a solar cell is the ratio per time unit of the collected electron-hole pairs at the terminals of the cell to the number of photons incident on the cell. This equation thus relates to the charge carrier flux, which is the photocurrent divided by elementary charge, q, and the photon flux, phi, for every wavelength. For example, these seven yellow photons are incident on the solar cell. Three electrons and holes are collected at the terminals of the device, meaning that the EQE of this solar cell at the wavelength of the yellow photons is 3 / 7th.

This graph shows an EQE curve of a crystalline silicon solar cell, which typically extends from 300 to 1200 nanometers. The area above the curve represents the fraction of photons that does not lead to charge collected at the terminals of the cell. Possible reasons are that the charge generated by these photons is lost due to recombination in the cell, or that these photons are reflected, meaning that some of the photons are actually not absorbed in the cell. In a later video we will discuss how the reflectivity of a solar cell can be measured. If we then only look at the fraction of photons absorbed in the cell, we arrive at the internal quantum efficiency, or I_Q_E. The IQE can clearly show which wavelengths of light are lost by parasitic absorption or where charge-carrier collection problems might be present.

We previously discussed that the short-circuit current density of a solar cell is directly related to the incident photon flux. Since the spectral photon flux of a solar simulator is never exactly equal to that of the sun, but has some spectral mismatch, the value for J_sc is in most cases not quite accurate. We will now show how this spectral mismatch of the J_sc can be resolved.

This equation shows how the short-circuit current density, J_sc, is related to the external quantum efficiency and the AM 1.5 spectral photon flux. The photon flux at a certain wavelength is multiplied by the EQE of the cell, which is measured in short-circuit conditions, and is then integrated over the wavelength to obtain the total short-circuit current density. The spectral photon flux of the sun's AM 1.5 spectrum can be measured with a spectrometer. Multiplied with the EQE curve it gives the green area, representing the charge-carrier flux collected at the terminals of the solar cell. When this area is integrated over wavelength, we obtain the following curve. The total short-circuit current density of this particular cell is about 34 milliamps per square centimeter.

Now that we know the purpose of measuring an EQE curve and how it relates to the current generation of a solar cell, we will look at a schematic overview of a typical EQE measurement setup.

To start with, the setup should have a light source with a continuous spectrum, such that none of the wavelengths of interest are missing. A xenon lamp has a fairly even spectral distribution and is therefore suitable for this application. The light of the lamp will first pass through a first order filter, such that higher orders of the short wavelength light will not interfere with longer wavelengths. It will then pass through a chopper wheel that chops the light such that it has an on-off frequency of most commonly 123 Hertz. We will explain why this is necessary in a short moment. The chopped light will enter a monochromator, which is an instrument that can select a very narrow band of wavelengths from the incoming light spectrum. The low intensity chopped monochromatic light will be focussed through a lens system on the solar cell under test. As a result, the solar cell will produce an alternating current signal with a very small amplitude. This signal is converted to a voltage by leading the current through a shunt resistor and measuring the voltage drop. This signal can be retrieved by using a lock-in amplifier. You can imagine that since a solar cell is a very light-sensitive device, it is hard to block the influence of ambient light on the current produced by the cell and that this current is similar or perhaps larger than the current due to the monochromatic light. Moreover, it is a common practice to operate the solar cell under one sun equivalent illumination by means of white bias illumination while measuring the EQE curve. Hereby the quasi-Fermi level splitting is increased to the correct level, such that the recombination rate during the EQE measurement represents operating conditions better. For these reasons a lock-in amplifier is used that is capable of filtering the solar cell's response to the monochromatic light from the noise. The monochromator, chopper wheel and lock-in amplifier are usually all controlled by a computer, which programs the setup to scan through the entire light spectrum and measure the response of the solar cell. Since the spectral photon flux of the lamp should be known very accurately, a reference diode with a calibrated spectral response is measured prior to measuring the solar cell under test. We will now go into a little bit more detail on the method to retrieve the signal with a lock-in amplifier.

A lock-in amplifier can filter out the response of the solar cell to the chopped light by comparing the signal with the frequency of the chopper wheel. The chopper wheel's frequency is chosen at an arbitrary value that is not a higher order of a frequency containing noise, such as the 50 Hz frequency of artificial light.

We can visualise the signal of the chopper with a block-wave. This signal is used as a reference signal in the lock-in amplifier. The signal of the solar cell in response to the chopped monochromatic light has a certain amplitude V-sig in which we are interested. The lock-in amplifier internally forms a sinusoidal signal from the reference block wave with the same frequency and phase. The method to retrieve the measurement signal from the noise is called phase sensitive detection, or P_S_D.

The noisy measurement signal is first multiplied with the internally formed sinusoidal signal. We then arrive at the following signal, which looks rather complex. This equation is essentially a set of AC signals with cosine terms. However, we can see that in the first cosine term the frequency of the lock-in amplifier signal, omega_L, is subtracted from the measurement signal frequency, omega_sig. These frequencies are only equal for the response signal with the chopper frequency. When these frequencies are equal, the cosine term becomes 1 and we arrive at the following DC signal. Thus by passing the phase sensitive detection signal through a low-pass filter, we obtain a DC signal that is proportional to the amplitude V-sig of the measurement signal in which we are interested.

This is the reason why the probing light is chopped to obtain a measurement signal with a known frequency.

To summarise this video, we have discussed the definition of the external quantum efficiency as the ratio between the collected charge carrier flux and the incident photon flux for each wavelength. By measuring the reflectivity of the solar cell, it can be transformed into the internal quantum efficiency. The short-circuit current density of the solar cell can be determined accurately by multiplying the EQE with the solar spectrum and integrating over all wavelengths. This value can be used to correct for the spectral mismatch of the solar simulator used for the illuminated JV curve measurement. Finally we have discussed the basic EQE setup, with a lock-in amplifier as an instrument to obtain the low amplitude measurement signal from noise.