

According to the assumption that the solar cell behaves as an ideal diode, the Shockley equation describing the J-V characteristic is applicable. Using Eq. (8.25) we determine the saturation-current density,

$$\begin{aligned} J_0 &= q n_i^2 \left(\frac{D_N}{L_N N_A} + \frac{D_P}{L_P N_D} \right) = 1.602 \times 10^{-19} \text{ C } (1.5 \times 10^{16})^2 \text{ m}^{-6} \\ &\times \left(\frac{2.58 \times 10^{-3} \text{ m}^2 \text{ s}^{-1}}{500 \times 10^{-6} \text{ m } 10^{23} \text{ m}^{-3}} + \frac{2.58 \times 10^{-4} \text{ m}^2 \text{ s}^{-1}}{100 \times 10^{-6} \text{ m } 10^{25} \text{ m}^{-3}} \right) \\ &= 1.95 \cdot 10^{-9} \frac{\text{C}}{\text{m}^2 \text{ s}} = 1.95 \times 10^{-9} \frac{\text{A}}{\text{m}^2}. \end{aligned}$$

Using Eq. (9.1) we determine the open-circuit voltage,

$$V_{oc} = \frac{k_B T}{q} \ln \left(\frac{J_{ph}}{J_0} + 1 \right) = 0.0258 \text{ V} \ln \left(\frac{350 \text{ Am}^{-2}}{1.95 \cdot 10^{-9} \text{ Am}^{-2}} + 1 \right) = 0.67 \text{ V}.$$

The fill factor of the cell can be calculated from Eq. (9.3). First, we normalise V_{oc} ,

$$v_{oc} = V_{oc} / \frac{k_B T}{q} = \frac{0.67 \text{ V}}{0.0258 \text{ V}} = 26.8.$$

Hence,

$$FF = \frac{v_{oc} - \ln(v_{oc} + 0.72)}{v_{oc} + 1} = 0.84.$$

Finally, the conversion efficiency is determined using Eq. (9.5),

$$\eta = \frac{J_{sc} V_{oc} FF}{P_{in}} = \frac{350 \text{ Am}^{-2} 0.67 \text{ V} 0.84}{1000 \text{ Wm}^{-2}} = 0.197 = 19.7\%.$$

9.2 The external quantum efficiency

The external quantum efficiency $\text{EQE}(\lambda)$ is the fraction of photons incident on the solar cell that create electron-hole pairs in the absorber, which are successfully collected. It is wavelength dependent and is usually measured by illuminating the solar cell with monochromatic light of wavelength λ and measuring the photocurrent I_{ph} through the solar cell. The external quantum efficiency is then determined as

$$\text{EQE}(\lambda) = \frac{I_{ph}(\lambda)}{q \Psi_{ph,\lambda}}, \quad (9.6)$$

where q is the elementary charge and $\Psi_{ph,\lambda}$ is the spectral photon flow incident on the solar cell. Since I_{ph} is dependent on the bias voltage, the bias voltage must be fixed during measurement. The photon flow is usually determined by measuring the EQE of a calibrated photo diode under the same light source.

The shape of this EQE curve is determined by optical and electrical losses, like parasitic absorption and recombination losses, respectively, which can make the analysis complex.

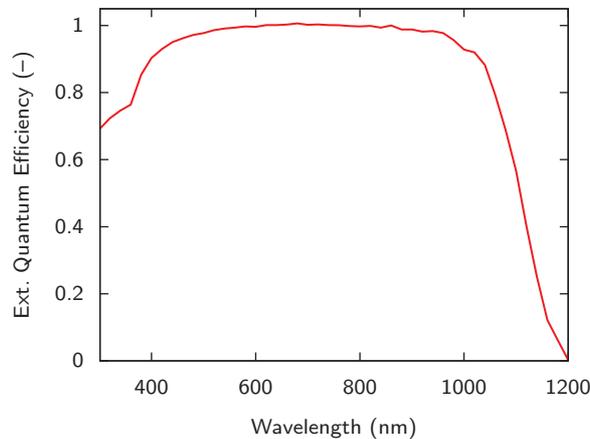


Figure 9.2: The external quantum efficiency of a high-quality crystalline silicon based solar cell.

Figure 9.2 illustrates a typical EQE for a high quality crystalline silicon based solar cell. In such a solar cell the minority-carrier diffusion length in the crystalline silicon substrate is very long and surface recombination is virtually suppressed. In that case we can identify the major optical loss mechanisms in the EQE for such a solar cell: For short wavelengths only a small fraction of the light is converted into electron-hole pairs. Most photons are already absorbed in the layers that the light traverses prior to the absorber layer; this is called parasitic absorption .

For long wavelengths, the penetration depth, which we defined in Section 4.4, exceeds the optical thickness of the absorber. Then the absorber itself becomes transparent so that most of the light leaves the solar cell before it can be absorbed. We can see that for this type of solar cells the EQE is close to 1 for a broad wavelength band. Hence, in this band almost all absorbed photons are converted into electron-hole pairs that can leave the solar cell.

For solar cells of which the minority-carrier diffusion length is shorter than the wafer thickness and/or surface recombination is not suppressed the EQE curve will be affected. In essence the EQE curve will drop to lower values reflecting recombination losses in the device.

When a bias voltage of 0 V is applied, the measured photocurrent density equals the short circuit current density. In case of *p-i-n* solar cells, when applying a sufficiently large reverse bias voltage, it can be assured that nearly all photo-generated charge carriers in the intrinsic layer are collected. Thus, this measurement can be used to study the optical effectiveness of the design, *i.e.* light management and parasitic absorption in inactive layers, such as the TCO layer, doped layers and the back reflector.

Measuring the EQE

EQE spectra are measured using an EQE-setup that is also called *spectral response setup*. For this measurement, usually a wavelength selective light source, a calibrated light detector and a current meter are required. Usually, the used light source is a *xenon gas discharge lamp* that has a very broad spectrum covering all the wavelengths important for the solar

cell performance. With the help of filters and monochromators a very narrow wavelength band of photon energies can be selected that then can be incident on the solar cell.

As already seen in Eq. (9.6), $\text{EQE}(\lambda)$ is proportional to the current divided by the photon flow. While the current can be easily determined using an Ampere meter, the photon flow must be determined indirectly. This is done by performing a measurement with a calibrated photodetector (or solar cell), of which the EQE is known. Via this measurement we find

$$\Psi_{\text{ph},\lambda} = \frac{I_{\text{ph}}^{\text{ref}}(\lambda)}{q \text{EQE}^{\text{ref}}(\lambda)}, \quad (9.7)$$

By combining Eqs. (9.6) and (9.7) we therefore obtain

$$\text{EQE}(\lambda) = \text{EQE}^{\text{ref}}(\lambda) \frac{I_{\text{ph}}(\lambda)}{I_{\text{ph}}^{\text{ref}}(\lambda)}. \quad (9.8)$$

Hence, the EQE can be determined by performing two current measurements. Of course it is very important that the light source is sufficiently stable during the whole measurement as we assume that the photon flow in the reference measurement and the actual measurement is unchanged.

If we perform the EQE measurement under short circuit conditions, the measurement can be used to determine the *short circuit current density* J_{sc} . Determining J_{sc} via the EQE has the advantage that it is independent of the spectral shape of the used light source, in contrast to determining the J_{sc} via an J - V measurement. Secondly, on lab scale the real contact area of solar cells is not accurately determined during J - V measurements. When using shading masks, the EQE measurement is independent of the contact area. Hence, for accurately measuring the short circuit current density, it is not sufficient to rely on J - V measurements only, but a spectral response setup have to be used.

For determining J_{sc} we combine the photon flow at a certain wavelength with the EQE at this wavelength, leading to the flow of electrons leaving the solar cell at this wavelength. J_{sc} then is obtained by integrating across all the relevant wavelength,

$$J_{\text{sc}} = -q \int_{\lambda_1}^{\lambda_2} \text{EQE}(\lambda) \Phi_{\text{ph},\lambda}^{\text{AM1.5}} d\lambda, \quad (9.9)$$

with the spectral photon flux $\Phi_{\text{ph},\lambda}$. For crystalline silicon, the important range would be from 300 to 1200 nm.

9.3 The equivalent circuit

The J - V characteristic of an illuminated solar cell that behaves as the ideal diode is given by Eq. (8.33),

$$\begin{aligned} J(V) &= J_{\text{rec}}(V) - J_{\text{gen}}(V) - J_{\text{ph}} \\ &= J_0 \left[\exp\left(\frac{qV}{k_B T}\right) - 1 \right] - J_{\text{ph}}. \end{aligned}$$

This behaviour can be described by a simple equivalent circuit, illustrated in Fig. 9.3 (a), in which a diode and a current source are connected in parallel. The diode is formed by a