

Analysis of the Quantum Efficiency of Silicon Solar Cells

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1 Introduction

Solar cells convert optical energy into electrical energy by photogeneration. The efficiency of this process depends, among other things, on the wavelength of the incident light and semiconductor properties such as charge carrier recombination rates. The quantum efficiency describes the probability that an incident photon is converted into an electron-hole pair, which contributes to the electrical current generated by the solar cell. Thus, quantum efficiency measurements quantify both absorption and recombination and are therefore widely used for solar cell characterization. In this experiment, you will analyze the quantum efficiency of various silicon solar cells.

2 Remarks concerning the experiment and its evaluation

- Read this instruction manual beforehand. The understanding of the theory outlined in this manual will help you carry out and evaluate the experiment.
- At the beginning, we will talk about the basics of the experiment in order to see whether you have a basic understanding. You can also ask further questions if anything is unclear.
- Before you start with the experiment, read the entire instruction manual and think about which measurements are required in order to answer the evaluation questions. It is advisable to plan your experiments in advance.
- For carrying out the experiment, you can use our measurement setup as well as two computers with software for data evaluation. It is advisable to start evaluating the measurement results already while you are in the lab.
- If you need informations for conducting and evaluating the experiment that are not contained in this manual, please have a look at the literature, e.g., papers which are cited in this manual.
- Please indicate substantiated estimates for measurement uncertainties for **all** analyzed quantities. For this purpose, please state the uncertainties you assume for the measured quantities and the relations you use for the estimation of the uncertainty of derived quantities.
- Please ask your supervisor if anything is unclear or if you need help with the measurement setup.
- Having finished the experiment, please hand in **two** documents:
 1. A lab protocol containing all relevant parameters and settings you used during the experiment. The lab protocol should not answer the questions given in this manual but document the conducted measurements completely and comprehensible. The criterion for “completely and comprehensible” is: Using the lab protocol, it must be possible to repeat the experiment under equal conditions and to reproduce the measurement results.
 2. In addition to the lab protocol, please compose a report containing: An introduction (also summarizing the basic theory of the experiment), the results of your measurements and a discussion of the results. The report should answer the questions given in this manual; however, a simple listing of questions and answers is not appropriate. Please write a structured text and choose own headings.

3 Basics

3.1 Silicon solar cells

Figure 1a shows the structure of a typical p-type industrial *Al-BSF* (aluminum back surface field) silicon solar cell with electrical contacts on both sides. The thickness of such a solar cell is approximately 160 μm . In this example, the solar cell mainly consists of a p-doped silicon wafer. At the front surface, an emitter (n-doped) and metal fingers are added in order to realize the front contact and the pn-junction. The rear surface is fully metalized. By a high temperature step, a portion of the aluminum diffuses into the silicon and creates a highly p-doped region (BSF), which acts as rear

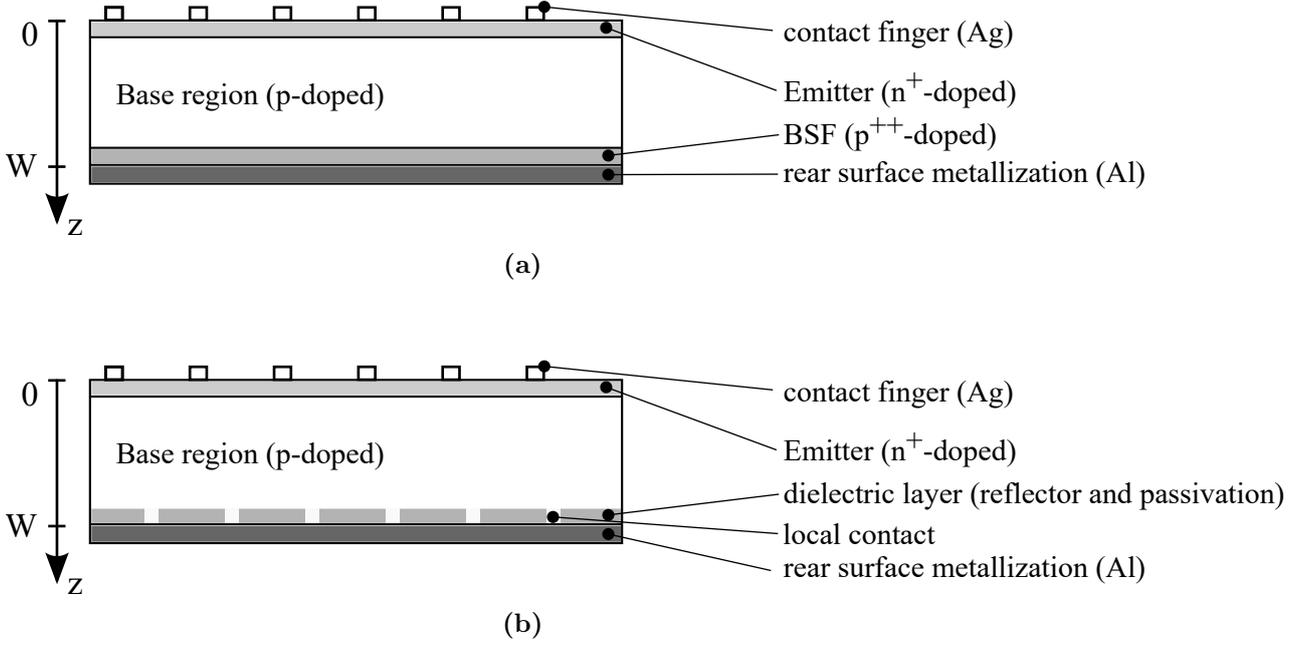


Fig. 1: Structure of a typical Al-BSF silicon solar cell (top) and a typical PERC silicon solar cell (bottom).

surface passivation. The drawing is not to scale: The emitter thickness is of the order of a few hundred nanometers, the rear surface metallization has a thickness of $10 - 20 \mu\text{m}$ and the Al-BSF has a thickness of a few microns. In the following, we will only consider the base region with a thickness of approximately W .

Figure 1b shows a typical PERC (**p**assivated **e**mitter and **r**ear **c**ell) solar cell, which is an advanced cell concept that currently enters mass production. PERC solar cells feature a dielectric rear layer, which improves the rear surface passivation and enhances the rear surface reflection. Thereby, electrical as well as optical losses are reduced. The dielectric layer is locally opened in order to realize the rear contact.

Solar cells have a huge lateral extent compared to their thickness: Typical industrial solar cells have an edge length of 15.6 mm . This structure leads to nearly vertical current flows within the solar cell. For this reason, a one-dimensional description of physical effects is sufficient in the following.

In our example, the base region is p-type doped, which means that the semiconductor is artificially contaminated with group 3 atoms, which have 3 valence electrons, whereas silicon has 4 valence electrons. Hence, these atoms are able to "accept" another electron and are therefore denoted as *acceptors*. In a band diagram as shown in Fig. 2, the acceptors add energy states slightly above the valence band edge within the forbidden band gap. At room temperature, electrons are thermally excited into these states, leaving holes in the valence band. The hole concentration is then approximately equal to the acceptor concentration N_A . Hence, in the dark, there are lots of holes, but only very few electrons in the base. The holes are therefore called *majority* charge carriers. Correspondingly, the electrons are the *minority* charge carriers. The equilibrium concentrations of electrons and holes are denoted by n_0 and p_0 , respectively. They are connected by the law of mass action,

$$np = n_i^2, \quad (1)$$

where $n_i \approx 10^{10} \text{ cm}^{-3}$ [1]. For our example, we thus have $p_0 \approx N_A$ and $n_0 \approx n_i^2/N_A$.

3.2 Absorption of light in crystalline silicon

The absorption of light in crystalline silicon is described by the common *Lambert-Beer* law

$$\Phi(\lambda, z) = \Phi_0(\lambda) \exp\left(-\alpha(\lambda)z\right) \quad (2)$$

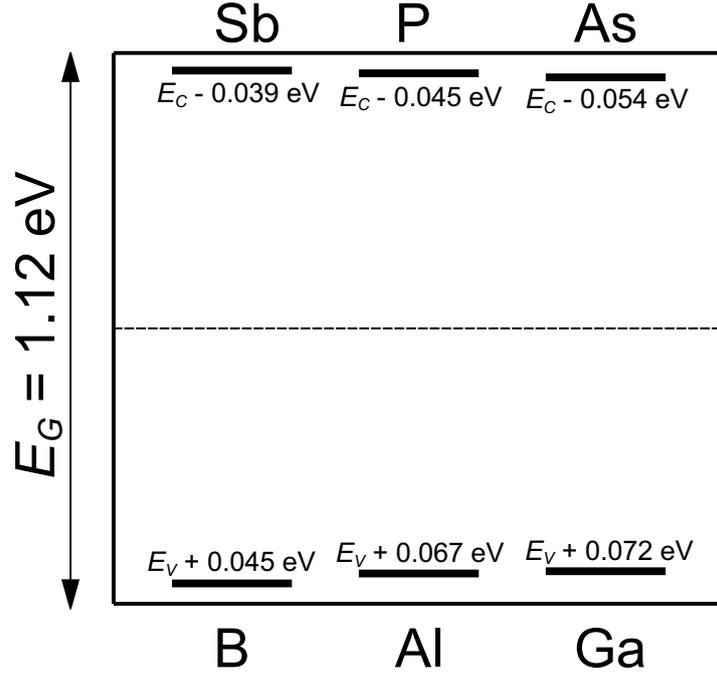


Fig. 2: Band diagram of crystalline silicon.

where Φ_0 is the initial photon flux, α is the absorption coefficient and $\Phi(z)$ the photon flux after a distance z . Figure 3 depicts the absorption coefficient of crystalline silicon as a function of wavelength. Additionally, the figure shows the spectral distribution AM1.5G [2], which is the standard solar spectrum used for measurements in photovoltaics.

Crystalline silicon has a bandgap energy of 1.12 eV, which corresponds to a wavelength of approximately 1150 nm. This wavelength is also denoted as *absorption edge*. Above this wavelength, i.e., at photon energies below the bandgap energy, we observe a steep decrease of the absorption coefficient. The shoulders which are visible in the wavelength range above 1150 nm are due to absorption processes assisted by one or more phonons [3].

From Fig. 3, it is obvious that the relevant wavelength range for the operation of crystalline silicon solar cells is between approximately 300 nm and 1200 nm. In this wavelength range, the absorption coefficient varies by over six orders of magnitude. The absorption length

$$L_\alpha(\lambda) = \frac{1}{\alpha(\lambda)} \quad (3)$$

is a measure for the penetration depth of light within the solar cell. At 300 nm, the absorption length is about 6 nm, which means that after a penetration depth of 6 nm, the initial intensity is decreased by a factor of $1/e \approx 0.37$ and all light is absorbed close to the front surface. At 1100 nm, however, the absorption length is about 3 mm. Compared to a typical thickness of silicon solar cells of 160 μm , it is obvious that the incident light is not only able to reach the rear surface, but it can also be reflected internally several times before being absorbed.

3.3 Generation and collection of excess charge carriers

Under illumination, *excess charge carriers* are generated by optical excitation of electrons from the valence band to the conduction band. The concentration of excess electrons and holes are denoted by Δn and Δp , respectively. Since each excited electron leaves a hole in the valence band, $\Delta n = \Delta p$

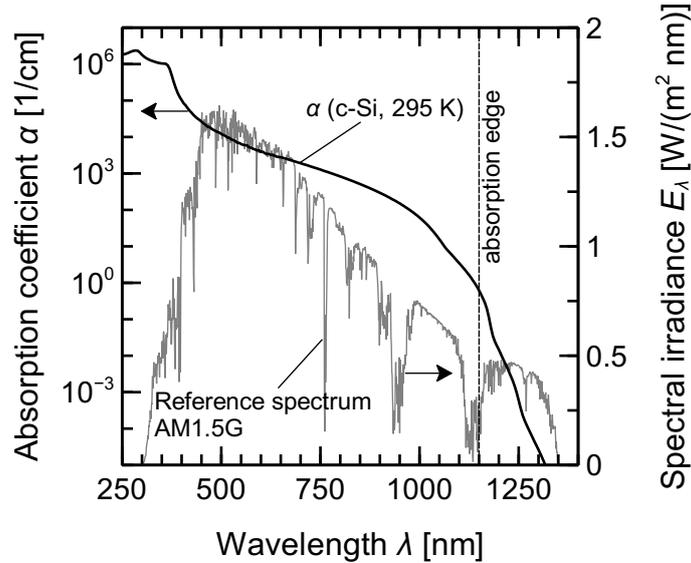


Fig. 3: Absorption coefficient of crystalline silicon (from [4]).

holds. The excess charge carrier concentrations add to the equilibrium concentrations. The overall charge carrier concentrations are therefore

$$n = n_0 + \Delta n, \quad (4)$$

$$p = p_0 + \Delta p. \quad (5)$$

If the concentration of excess majority charge carriers is small compared to their equilibrium concentration, one speaks of *low level injection*. For a p-type semiconductor as considered above, this means

$$n \approx \Delta n \text{ (because } n_0 \approx 0), \quad (6)$$

$$p \approx p_0 \text{ (because } \Delta p \ll p_0). \quad (7)$$

The rate of charge carrier generation $g_0(z)$ is given by the negative change of the photon flux:

$$g_0(\lambda, z) = -\frac{d\Phi(\lambda, z)}{dz}. \quad (8)$$

For instance, at short wavelengths where internal reflections can be neglected, the charge carrier generation rate is $g_0(z) = (1 - R) \Phi_0 \alpha \exp(-\alpha z)$, where R is the reflectance of the solar cell.

Charge carriers move in the solar cell mainly by diffusion and will recombine after a certain period of time, which is denoted as *charge carrier lifetime* τ . In order to obtain an electrical current, electrons and holes must be separated from each other. This is achieved by charge carrier selective contacts, which have a high conductivity for one charge carrier species and a low conductivity for the other species. Hence, in order to be separated, charge carriers need to diffuse to the respective contact before recombining. The lifetime defines the *diffusion length*

$$L = \sqrt{D\tau} \quad (9)$$

which a charge carrier is able to travel before recombining. In the latter equation, D is the diffusion constant, which is a material property.

The probability that a minority charge carrier diffuses to the minority contact before recombining is denoted as *collection probability* η_c . It depends on the position of charge carrier generation z and on the recombination properties of the device. Under low level injection conditions, recombination is

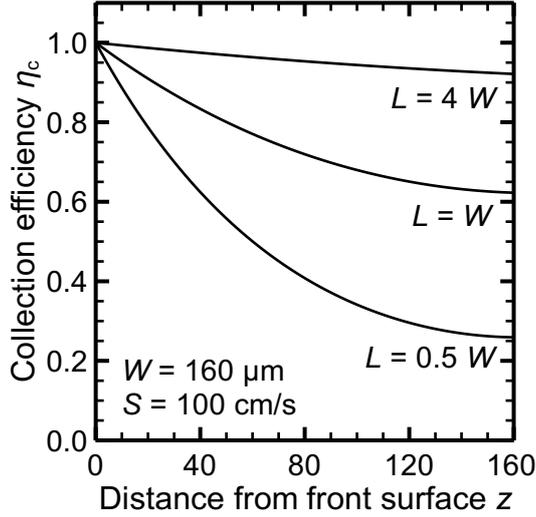


Fig. 4: Collection efficiency η_c according to Eq. (10) for different diffusion lengths L .

always limited by the minority charge carrier concentration. In the p-type semiconductor considered above, holes are plenty, but each recombination process also requires an electron and there are only few. The collection probability in the base region of a solar cell can then be expressed as [5–7]

$$\eta_c(z) = \cosh\left(\frac{z}{L}\right) - \frac{L}{L_{\text{eff}}} \sinh\left(\frac{z}{L}\right), \quad (10)$$

where

$$L_{\text{eff}} = L \frac{LS \sinh(W/L) + D \cosh(W/L)}{LS \cosh(W/L) + D \sinh(W/L)} \quad (11)$$

is the *effective diffusion length* which depends on the thickness W of the solar cell and the rear surface recombination velocity S . Figure 4 depicts the collection efficiency according to Eq. (10) for different diffusion lengths L .

3.4 Short circuit current and external quantum efficiency

The short circuit current density j_{sc} (short circuit current per area A of the solar cell) follows from the charge carrier generation rate and the collection probability for generated charge carriers by integrating over the thickness of the solar cell :

$$j_{\text{sc}} = q \int_0^{\infty} d\lambda \int_0^W dz g_0(\lambda, z) \eta_c(z). \quad (12)$$

Equation (12) can be rewritten as

$$j_{\text{sc}} = q \int_{300 \text{ nm}}^{1200 \text{ nm}} d\lambda \Phi_0(\lambda) \int_0^W dz g(\lambda, z) \eta_c(z) \quad (13)$$

with the normalized generation rate

$$g(\lambda, z) = \frac{g_0(\lambda, z)}{\Phi_0(\lambda)} \quad (14)$$

according to Eq. (8) and by restricting the integration to the relevant wavelength range, where the integrand is significantly larger than zero. The last terms in the latter equation represent the *external quantum efficiency*

$$EQE(\lambda) = \int_0^W dz g(\lambda, z) \eta_c(z) \quad (15)$$

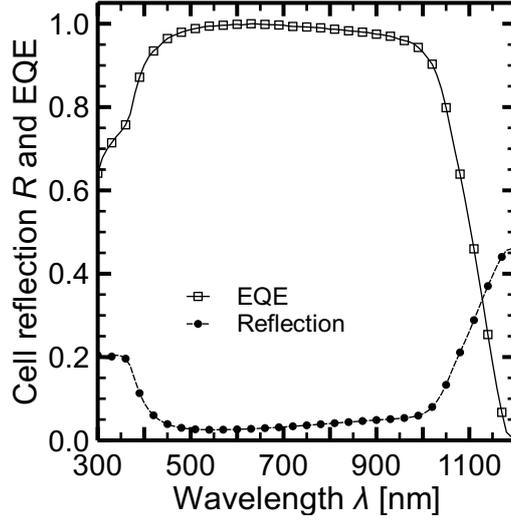


Fig. 5: Typical external quantum efficiency and reflection of a silicon solar cell featuring an anti-reflection coating.

of the solar cell. Hence, the short circuit current density can finally be expressed as

$$j_{sc} = \int_{300 \text{ nm}}^{1200 \text{ nm}} d\lambda j_{gen}(\lambda), \quad (16)$$

where

$$j_{gen}(\lambda) = q \Phi_0(\lambda) EQE(\lambda) \quad (17)$$

is the short circuit current density contribution by light of wavelength λ . Under standard testing conditions (STC), which require the use of the AM1.5G spectral distribution, Φ_0 is given by Φ_{STC} . Note that the EQE is a dimensionless quantity.

Figure 5 shows the external quantum efficiency and reflection of a typical crystalline silicon solar cell featuring an anti-reflection coating (ARC). At wavelengths around 300 nm, all light is absorbed within the ARC and the emitter. The high recombination rates in these regions of the solar cell lead to a small collection efficiency and thus to a small EQE . The EQE increases towards unity for larger wavelengths, where the reflection of the solar cell is approximately zero due to the ARC and all light is absorbed within the solar cell, mainly within the base region, where the collection efficiency is around unity. (Note that the remaining reflection of a few percent, which is visible in Fig. 5, is due to the reflection of the front surface metallization.) Above 600 nm, we observe a slight decrease of the EQE due to a slight increase of R . Above 1000 nm, the absorption decreases strongly, which leads to a decreasing EQE . The steep increase of the reflection is a consequence of the weak absorption at these wavelengths, which leads to a contribution to the overall reflection from the rear surface.

3.5 Experimental assessment of the external quantum efficiency

From Eq. (17), we see that the EQE , which is the ratio of the numbers of generated charge carriers N_{ph} and incident photons N_{ph} , can in principle be assessed experimentally by using the relation

$$EQE(\lambda) = \frac{N_{el}}{N_{ph}} = \frac{j_{sc}(\lambda)}{q \Phi_0(\lambda)}, \quad (18)$$

i.e., by measuring the incident photon flux (photons per area and time, in units of $1/(s \text{ m}^2)$) and the short circuit current density (current per area, in units of A/m^2) of the solar cell when the solar cell is illuminated by monochromatic light. In order to determine the EQE under standard testing

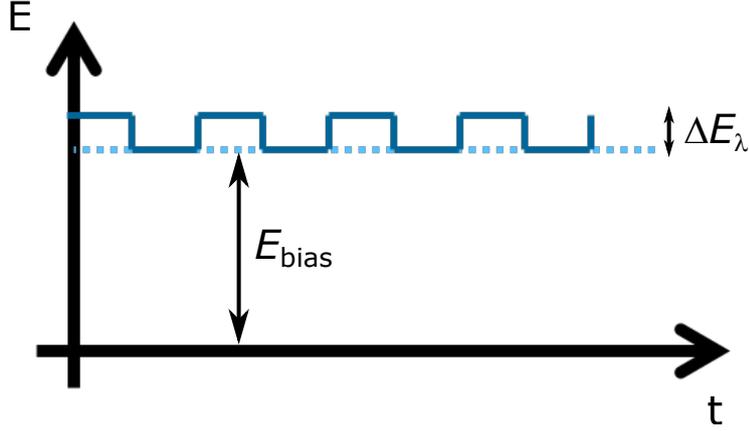


Fig. 6: Bias illumination and additional monochromatic illumination.

conditions, EQE_{STC} , the use of the AM1.5G spectral distribution is required for defining the injection conditions of the solar cell. Hence, the determination of the EQE under STC actually requires an illumination with white light and the determination of $j_{gen}(\lambda)$ at the same time.

In order to realize this condition experimentally, a *differential* measurement is carried out as depicted in Fig. 6. The solar cell is illuminated with white light featuring a spectral distribution similar to the AM1.5G distribution. This white light is also denoted as *bias light*, as it determines the injection conditions of the solar cell. Additionally, the solar cell is illuminated by modulated monochromatic light of low intensity and wavelength λ and the resulting change $\Delta j_{sc}(\lambda)$ is measured. This yields the *differential* EQE, from which the EQE under STC is calculated as described in the next section.

4 Measuring the external quantum efficiency

The (differential) external quantum efficiency cannot be measured directly. Instead, the (differential) *spectral responsivity* is determined, from which the external quantum efficiency is calculated in a second step. This procedure and its experimental realization is explained in the following.

4.1 Experimental setup

Figure 7 shows a schematic drawing of the measurement setup. The solar cell is placed on a temperature controlled chuck, where it is fixed by applying a vacuum. The halogen lamp above the solar cell provides the bias light. Its intensity can be regulated by adjusting the lamp current. The monochromatic light is provided by either a xenon lamp ($\lambda < 430$ nm) or a halogen lamp ($\lambda \geq 430$ nm) in combination with a grating monochromator. A chopper wheel is used to modulate the monochromatic light, which is then guided onto the solar cell by a mirror. A transimpedance amplifier (TIA) keeps the solar cell at short circuit conditions and provides a voltage signal which is proportional to the cell's current. A lock-in amplifier (LIA) extracts the modulated part of the signal and provides an output signal which is proportional to the change of the short circuit current ΔI_{sc} of the solar cell. A second LIA is connected to a monitor photodiode, which is used to take variations of the irradiance over time into account.

4.2 Determination of the differential spectral responsivity

The *differential spectral responsivity* (DSR) $\tilde{s}(\lambda)$ is the ratio of the short circuit current density variation Δj_{sc} of the solar cell when illuminated with bias light of irradiance E_{bias} and additional monochro-

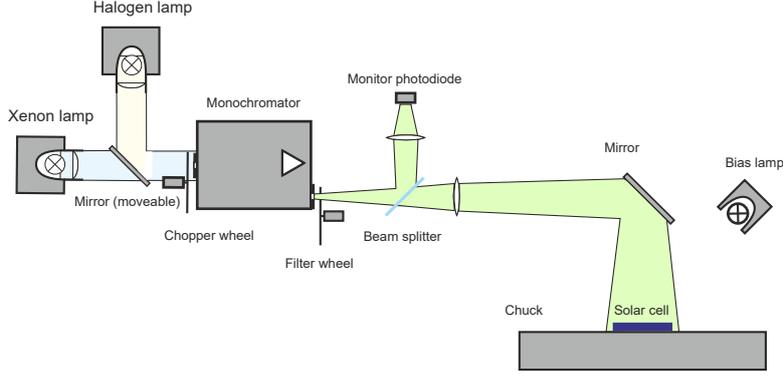


Fig. 7: Schematic drawing of the measurement setup.

matic light of wavelength λ :

$$\tilde{s}(\lambda, E_{\text{bias}}) = \frac{\Delta j_{\text{sc}}}{\Delta E_{\lambda}(\lambda)}. \quad (19)$$

In Eq. (19), ΔE_{λ} is the irradiance variation of the monochromatic light (in units of W/m^2). The DSR thus has units of $\text{A m}^2/\text{W}$ and can be measured directly by illuminating the solar cell while it is kept under short circuit conditions.

In order to determine the DSR curve of the test cell, $\tilde{s}_{\text{test}}(\lambda, E_{\text{bias}})$, the setup needs to be calibrated with respect to ΔE_{λ} and E_{bias} . This is done by using a reference solar cell, whose DSR $\tilde{s}_{\text{ref}}(\lambda, E_{\text{bias}})$ is known from a primary calibration. Before analyzing the test cell, the reference cell is mounted and the output signal of the LIA

$$S_{\text{ref}}(\lambda) = C_{\text{ref}} \Delta j_{\text{sc,ref}}(\lambda) \quad (20)$$

is acquired. The factor C_{ref} in the latter equation is a proportionality factor, which takes the conversion of Δj_{sc} into a voltage signal by the TIA and the subsequent measurement by the LIA into account. This factor is of the order of unity, but its exact value depends on the TIA and is generally unknown. Note that $\Delta j_{\text{sc,ref}}$ is therefore unknown as well, as only S_{ref} can be acquired. Afterwards, the test cell is mounted and

$$S_{\text{test}}(\lambda) = C_{\text{test}} \Delta j_{\text{sc,test}}(\lambda) \quad (21)$$

is acquired. Again, C_{test} and $\Delta j_{\text{sc,test}}$ are unknown. Moreover, since the amplification factor of the TIA depends on the specific solar cell which is connected, C_{ref} and C_{test} have different values in general. Finally, the ratio of S_{test} and S_{ref} is multiplied with \tilde{s}_{ref} , giving

$$\frac{S_{\text{test}}(\lambda)}{S_{\text{ref}}(\lambda)} \tilde{s}_{\text{ref}}(\lambda) = \frac{C_{\text{test}} \Delta j_{\text{sc,test}}(\lambda)}{C_{\text{ref}} \Delta j_{\text{sc,ref}}(\lambda)} \frac{\Delta j_{\text{sc,ref}}(\lambda)}{\Delta E_{\lambda}(\lambda)} = \frac{C_{\text{test}}}{C_{\text{ref}}} \tilde{s}_{\text{test}}(\lambda) \quad (22)$$

according to Eqs. (19) through (21). In order to compensate for variations of the irradiance E_{λ} over time, which would affect Δj_{sc} and thereby S , the irradiance is monitored by a photodiode, which is also connected to a LIA and yields the signal S_{mon} . The signals S_{ref} and S_{test} are then divided by the monitor signal, giving

$$R_{\text{ref}}(\lambda) = \frac{S_{\text{ref}}(\lambda)}{S_{\text{mon}}(\lambda)}, \quad (23)$$

$$R_{\text{test}}(\lambda) = \frac{S_{\text{test}}(\lambda)}{S_{\text{mon}}(\lambda)}. \quad (24)$$

The final equation for calculating the differential spectral responsivity of the test cell is thus

$$\tilde{s}_{\text{test}}(\lambda) = \frac{R_{\text{test}}(\lambda)}{R_{\text{ref}}(\lambda)} \frac{C_{\text{ref}}}{C_{\text{test}}} \tilde{s}_{\text{ref}}(\lambda). \quad (25)$$

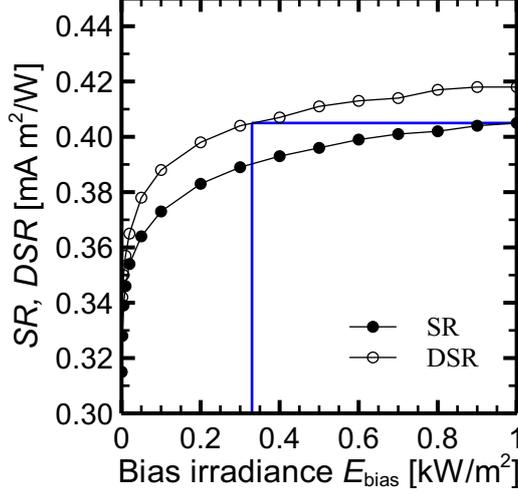


Fig. 8: Bias ramp measurement at 1050 nm for typical silicon solar cells.

In this equation, the ratio $C_{\text{ref}}/C_{\text{test}}$ is unknown and can be regarded as a scaling factor for \tilde{s}_{test} , which is therefore denoted as *relative* DSR. There are several options for the determination of the scaling factor. One option, which will be used for the evaluation of your measurements, is described in section 4.4.

4.3 Determination of the spectral responsivity

Basically, the spectral responsivity under STC, s_{STC} , is obtained by integration of the differential spectral responsivity \tilde{s} over E_{bias} up to an irradiance of 1000 W/m^2 as defined in the standard testing conditions:

$$s_{\text{STC, test}}(\lambda) = \int_0^{1000 \text{ W/m}^2} dE_{\text{bias}} \tilde{s}_{\text{test}}(\lambda, E_{\text{bias}}). \quad (26)$$

However, using this relation requires measuring the DSR for various bias irradiances E_{bias} for each wavelength λ (this is the so-called “complete DSR procedure”), which is a time-consuming task that is practicable only if the measurement setup is fully automated. The IEC 60904-8 standard [8] therefore defines four simplifications to the complete DSR procedure, which allow for an approximate determination of the SR with less effort. One simplification, which we will use in this experiment, is the measurement of the DSR using an irradiance of about 300 W/m^2 . In this case, the DSR is approximately equal to the SR under STC for typical silicon solar cells [9], i.e., $\tilde{s}(\lambda)|_{300 \text{ W/m}^2} \approx s_{\text{STC}}(\lambda)$ can be used as an approximation. Figure 8 depicts a typical bias ramp measurement for silicon solar cells and visualizes the approximation.

4.4 Calculation of the external quantum efficiency

From the SR, the EQE is obtained by multiplication with the photon energy E_{phot} , which is

$$E_{\text{phot}}(\lambda) = \frac{hc}{\lambda}, \quad (27)$$

and division by the elementary charge q and the area A of the solar cell:

$$EQE(\lambda) = s_{\text{STC}}(\lambda) \frac{hc}{qA\lambda}. \quad (28)$$

In the latter equations, c is the speed of light in vacuum and h is the Planck constant.

The EQE which is determined according to Eq. (28) will usually *not* fulfill Eq. (12) since it contains the factor $C_{\text{ref}}/C_{\text{test}}$, which is unequal to unity in general. It is thus a *relative* EQE, which needs to be scaled in order to obtain the *absolute* EQE that is to be determined. A common procedure for the determination of the required scaling factor f_{sc} is the comparison of j_{sc} calculated according to Eqs. (16) and (17) to $j_{\text{sc,exp}}$ as determined experimentally with a sun simulator:

$$f_{\text{sc}} = \frac{j_{\text{sc,exp}}}{j_{\text{sc,calc}}} = \frac{j_{\text{sc,exp}}}{q \int_{300 \text{ nm}}^{1200 \text{ nm}} d\lambda \Phi_0(\lambda) EQE(\lambda)} . \quad (29)$$

Multiplication of the relative EQE with f_{sc} then yields the absolute EQE.

5 Operation of the measurement setup

Please read this information carefully in order to ensure a safe operation of the measurement setup and a successful conduction of the experiment. If you have any questions during the experiment, please ask your supervisor!

5.1 Safety instructions

- The bias lamp becomes hot during operation. Touching the lamp can cause burns.
- The TIA is a very sensitive device. **Always switch off before contacting or decontacting a sample!** Otherwise, the TIA might be destroyed.
- Please handle all samples with care and wear gloves.
- The manipulator for contacting the samples is a sensitive device. Handle with care!
- Long hair could get into the chopper wheel, which may lead to serious injuries. Therefore, make sure that the cover is mounted before turning on the measurement setup.

5.2 Turning the setup on and off

Please follow the separate instruction manuals which are available in the lab for turning the setup on and off.

5.3 Conducting measurements

The measurement setup is controlled by a computer program, which also allows to acquire and save measurement data. Please follow the separate instruction manuals for the computer program, which are available in the lab.

6 Experiments

This experiment is divided into three parts: In the first part, you will familiarize yourself with the measurement setup and derive suitable measurement parameters. In the second part, you will measure the quantum efficiency of various solar cells. The third part focuses on the evaluation of your measurement results using physical models.

6.1 Determination of measurement parameters

In order to perform reliable measurements, it is important to know the properties of the measurement setup and to derive suitable measurement parameters. Please examine the following issues:

1. In order to be able to carry out DSR measurements with a bias irradiance of 300 W/m^2 , a calibration of the power supply for the bias lamp is required. Please determine the relation between set voltage and bias irradiance using the reference solar cell. Is a waiting time required when changing the set voltage?

2. The monochromatic light is provided by a xenon and a halogen lamp. Please analyze whether a warm-up time is required for these lamps in order to achieve a stable output signal. For this purpose, set the monochromator wavelength to 350 nm, light the xenon lamp and monitor the output signal of the lock-in amplifier. Afterwards, repeat the procedure for the halogen lamp at a wavelength of 550 nm.
3. Please analyze the impact of the positioning of reference and test cell when measuring the DSR of the test cell. For this purpose, try a few lateral and vertical positions for the test cell apart from its correct position, calculate the resulting DSR curves and compare them.
4. Please analyze the measurement noise by performing repeated measurements ($N \geq 25$) for the reference cell and one test cell of your choice at distinct wavelengths, e.g., every 100 nm.
5. Please analyze the stability of the measurement setup over time. For this purpose, please perform a measurement of the output signal for the reference solar cell several times on different days during your experiment and compare the results. Note: For analyzing the temporal stability, it is sufficient to consider the output signal of the lock-in amplifier. It is not necessary to perform complete DSR measurements for a test cell.

From these measurements, please determine suitable parameters for the measurements in the next section and discuss your results with your supervisor before continuing. Please include the discussion of these results in your report.

6.2 EQE analysis

1. Please determine the EQE of the test cells that your supervisor will give you at a temperature of 25 °C.
2. Please choose one test cell and determine the temperature dependence of the EQE in the temperature range from 15 °C to 40 °C.
3. Please choose an Al-BSF cell and a PERC cell and measure *bias ramps* at 350 nm, 550 nm, 850 nm, 1000 nm and 1100 nm, i.e., for these wavelengths, determine the DSR as a function of E_{bias} between 0 and 1000 W/m².

6.3 Evaluation of measurements

- Bundle your results concerning measurement noise, temporal stability of the measurement setup and positioning accuracy into an estimate of a typical uncertainty for your EQE measurements. Please substantiate your estimation by an appropriate analysis of your measurement data and by indicating the formulas you use for determining the uncertainty of the EQE.
- Please plot and compare the EQEs of the different test cells. Scale the EQEs according to Eq. (29) using the given j_{sc} values for the solar cells and the tabulated AM1.5G spectrum. Note: It might be necessary to perform a linear interpolation of your EQE data.
- Explain the shape of the EQE qualitatively. Please include the uncertainty you determined in the previous step in your discussion.
- Compare and discuss the EQEs of the Al-BSF and the PERC cell in the near-infrared region and explain the differences.
- Determine the temperature coefficient of the EQE and explain it. Hint: Have a look at reference 10.
- Bias ramps allow to determine the linearity of solar cells with respect to short circuit current generation: For a linear solar cell, the DSR is independent from the bias irradiance, i.e., $\tilde{s}(E_{\text{bias}})$ is constant. Please analyze the linearity of the Al-BSF and the PERC cell for the different wavelengths you investigated and consider the measurement uncertainties you determined. Are there any nonlinearities and do the EQE measurements allow to assign them to a certain region of the solar cell?

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