Optics Laboratory Work:

Solar cell characterization

ROOM MED 2 1117

Discovery Learning Lab

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1 Objective

The aim of this laboratory work is to acquire practical experience in spectral characterization of energy conversion devices such as solar cells. The experimental work involves characterizing the source and measuring the spectrally resolved quantum efficiency of a solar cell. The acquired data of a voltage current curve will be used to obtain parameters of an electro-optical model useful to determine optimal working conditions of a solar cell.

2 Introduction

The world-wide energy consumption has increased tremendously during the past decades. Most of this energy was produced using fossil energy sources such as oil, coal and gas. It is only recently that, for both ecological and economic reasons, one started to pay interest in the harvesting of renewable energy sources such as wind or sunlight.

Solar cells only started to be recognized as serious player on around the year 2000. The installed peak power sustained an exponential growth between 2000 and 2011 before slowing down a bit. Still it is expected that solar energy production will overcome the hydraulic energy production as well as the nuclear energy production by 2020.

Since photovoltaic devices are foreseen to become one of the main sources of electricity generation, engineering students should obtain insight into this technology during their study. This experiment is intended to provide a general background on both the operating principles of solar cells as well as their characterization.

Source : Solar Energy, edited by A. Smets, K. Jäger, O. Isabella, R. van Swaaij, M. Zeman, UIT Cambridge

Security notes

The source employed to produce the illumination light beam used in this experiment is very powerful (250W). Light bulbs delivering such power are not available in general stores. No eye protection material is required, but avoid to look directly into the opening. Even reflections from a white piece of paper will appear very intense.

Do not touch the housing as its temperature will quickly rise due to the high power consumption of the lamp. Also assure that the ventilation of the housing is on during operation to prevent from overheating.

3 Solar cells

A solar cell is a device that transforms electromagnetic radiation directly into electrical energy, i.e. current at a certain voltage. The basic effect is the photovoltaic effect.

The operation of a photovoltaic (PV) cell requires three basic attributes:

- The absorption of light
- The generation of electron-hole pairs (usually in semiconductors) or excitons (usually in organic materials).
- The separation and the extraction to external electrodes with different polarity.

The working mechanism of a solar cell can be explained as follows.

- Photons in sunlight hit the solar cell. If their energy is less than the bandgap-energy, they are not absorbed. If their energy is equal to the bandgap-energy, they can be absorbed and create an electron hole-pair. If their energy is larger, they create an electron-hole pair and the extra energy is lost to thermal excitations of the semiconductor. The bandgap energy is the maximum energetic separation between electrons and holes and thus the maximum potential that a solar cell can deliver.
- The separation of the electron-hole pair and the transport to the external electrodes can be assisted by different electron-affinities. For example, in silicon this is achieved by doping the bulk of the device with boron and with phosphorus in a region close to the front surface.

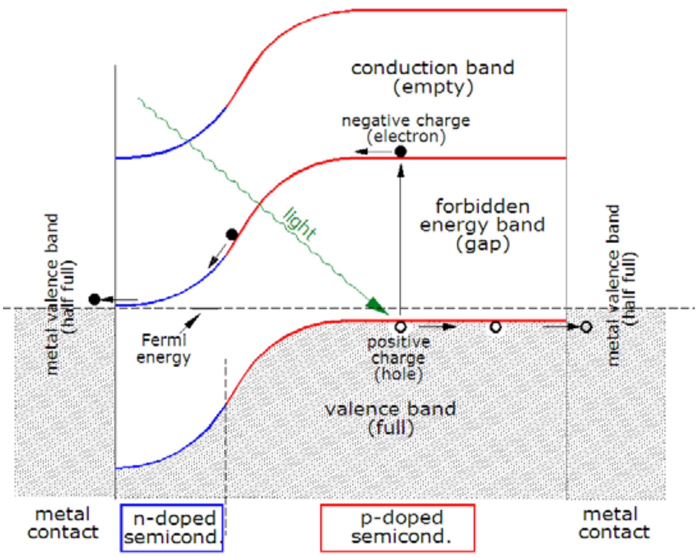

Figure 1: Band diagram of a p-n junction and the metallic contacts as it can describe the operational principle of a semiconductor solar cell. (Image: Wikipedia)

The most commonly known solar cell type is configured as a large-area p–n junction made from silicon. As a simplification, one can imagine bringing a layer of n-type silicon into direct contact with a layer of p-type silicon. In practice, p-n junctions of silicon solar cells are not made in this way, but rather by diffusing a phosphorous into one side of boron-doped wafer such that the n-type doping concentration over-compensates the p-type doping of the bulk.

If a piece of p-type silicon is placed in close contact with a piece of n-type silicon, then a diffusion of electrons occurs from the region of high electron concentration (the n-type side of the junction) into the region of low electron concentration (p-type side of the junction). When the electrons diffuse across the p-n junction, they recombine with holes on the p-type side. However (in the absence of an external circuit) this diffusion of carriers does not go on indefinitely because mobile electrons and holes leave behind ionized cores of their dopant atoms. The charge of the cores builds up an electric field that opposes and eventually balances out the diffusion of electrons and holes. The region where electrons and holes have diffused across the junction is called the depletion region because it contains practically no mobile charge carriers. It is also known as the *space charge region* because of the charge of the ionized dopants.

Ohmic metal-semiconductor contacts are made to both the n-type and p-type sides of the solar cell, and the electrodes are connected to an external load. Electrons that are "collected" by the junction to the n-type side, may travel through the wire, power the load, and continue through the wire until they reach the p-type semiconductor-metal contact. Here, they recombine with a hole that was “collected” to the p-type side of the solar cell.

A specific design of a solar cell is shown below.

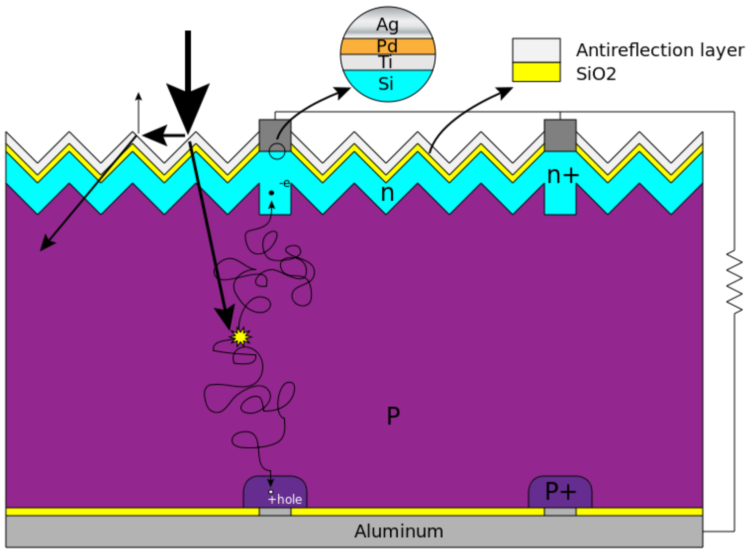

Figure 2: Typical layout of a p-n junction solar cell (Image: Wikipedia)

The cell has (from below) a back contact, a wide p doped zone, a thin n-doped zone, a front contact with antireflection layer. The front surface is often structured to increase the light capturing possibilities of the cell. The cell depicted above is the most widely used device, but other designs and semiconductors are used.

The most important parameter for solar cells is their efficiency to convert incoming energy into electrical energy. The maximum efficiency is fundamentally related to the bandgap energy via two effects. First, the maximum photocurrent is given by the flux of photons in the spectrum whose energy is higher than the bandgap energy. Second, the maximum potential cannot be higher than the bandgap-energy. A semiconductor with low bandgap can thus deliver large current with low potential whereas high bandgap-energies translate to low currents with high potential. Schockley and Queisser derived a fundamental limit of 33.7% for single-junction solar cells with an optimum bandgap-energy of 1.34 eV.

A variety of cell designs have been proposed to overcome this limit, but so far the only one demonstrated to work in real devices is the multi-junction cell. Figure 3 provides a timeline of the best certified efficiencies reported for the different technologies. It is assembled by the US National Renewable Energy Laboratory (NREL).[1]

Not all the photons hitting a solar cell provide an electron hole pair to the external circuit. There may be losses due to reflection or transmission, due to parasitic absorption by an inactive part of the cell, or due to recombination losses on the way to the electrodes. The external quantum efficiency (EQE) refers to the percentage of photons that are converted to electric current (i.e. collected carriers) when the cell is operated under **short circuit** conditions. The EQE includes the effect of optical losses such as transmission and reflection.

The quantum efficiency is most usefully expressed as a *spectral* measurement (that is, as a function of photon wavelength or energy). Since some wavelengths are absorbed more effectively than others, spectral measurements of quantum efficiency can yield valuable information about the quality of the semiconductor bulk and surfaces. Quantum efficiency alone is not the same as overall energy conversion efficiency, as it does not convey information about the fraction of power that is converted by the solar cell.

In our experiment we want to measure the external quantum efficiency EQE and measure electrical parameters of the cell.

[1] https://www.nrel.gov/pv/assets/images/efficiency-chart.png

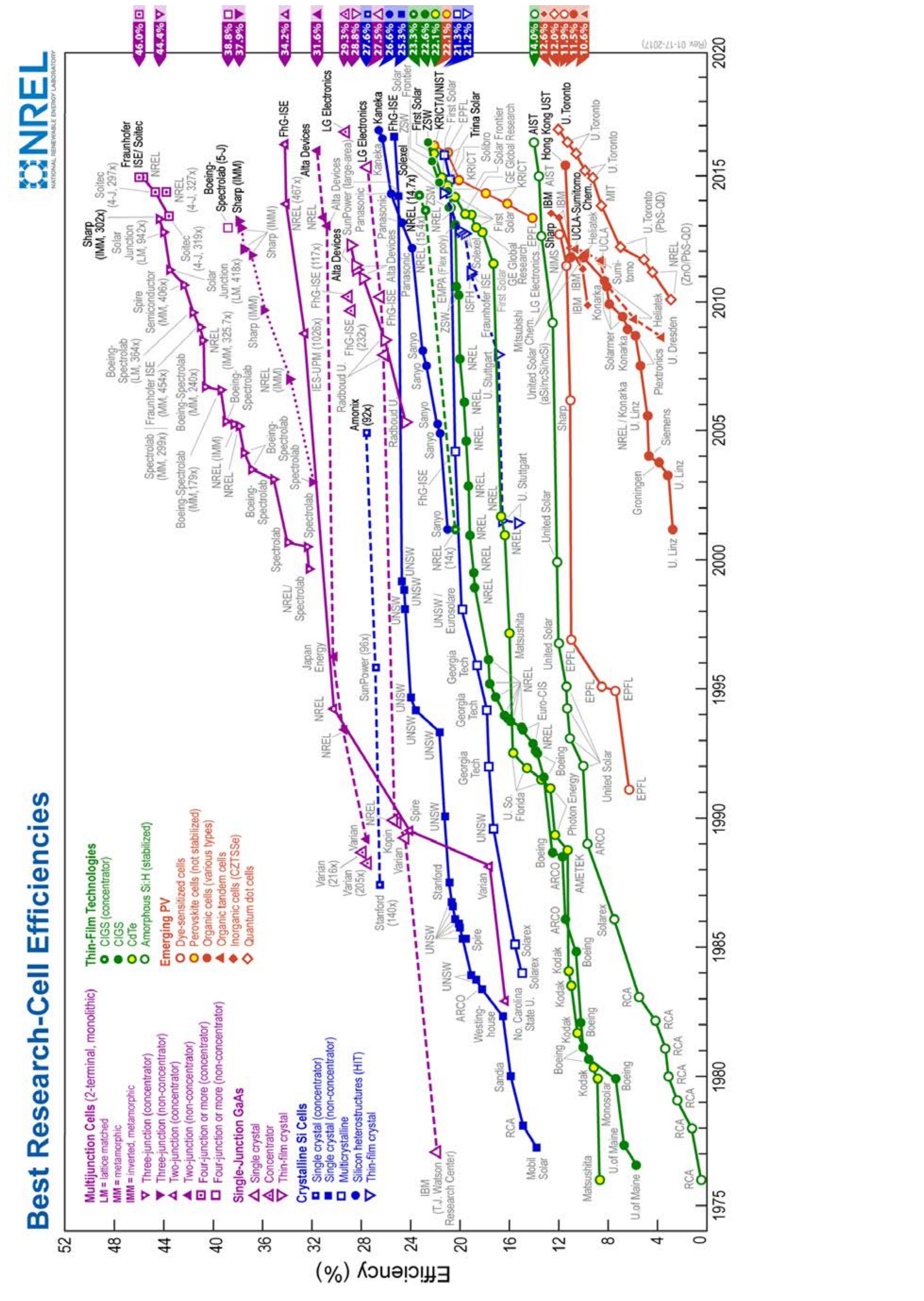

Figure 3: Reported timeline of solar cell energy conversion efficiencies since 1976 (National Renewable Energy Laboratory) (Image: Wikipedia)

4 Solar Cell Characterization

Characterization of a solar cell is achieved by measuring its fundamental parameters, thus providing a means of comparison with other photovoltaic cells. However, for the comparison to be relevant, the conditions under which these parameters were determined must concur.

4.1 Standard Test Conditions (STC)

Standard test conditions (STC) were defined for the sole purpose of solar cell characterization by the International Electrotechnical Commission (IEC). Similar standards were established by the American Society for Testing and Materials (ASTM). The following conditions are defined within the standard IEC 60904-3.

1. Irradiance: 1000 W/m^2
2. Illumination spectrum: AM1.5g
3. Cell temperature: 25°C

Conditions 1) and 2) are typical values for sunlight shining in Central Europe and parts of North America. Compared to the illumination in space, the propagation through the Earth's atmosphere attenuates the solar radiation by reflection, scattering and absorption. For radiation reaching the Earth's surface, minimum attenuation occurs when the Sun is at zenith. Any departure from this position results in higher loss due to longer propagation in the atmosphere. Air mass (AM) is defined as the ratio between the optical path when the Sun is at an angle θ with respect to the zenith and the optical path at zenith itself namely

$$AM := \frac{1}{\cos(\theta)} \tag{1}$$

The spectrum just outside of the atmosphere is referred to as AM0 and resembles the one of a black body at about 5500°C. The AM1.5 spectrum corresponds to the situation where the Sun makes an angle of approximatively 48° with respect to the zenith and shines on a plate tilted at 37° with respect to the Earth's surface as illustrated in Figure 4.

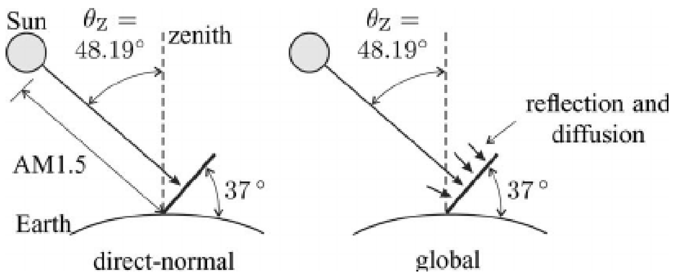

Figure 4: Illumination conditions leading to an AM1.5 spectrum measured on the Earth's surface

Besides direct radiation several phenomena including earth's albedo contribute to the measured spectrum. The reference spectra AM0, AM1.5 direct and AM1.5 global can be readily found and downloaded from the internet. They are depicted in Figure 5.

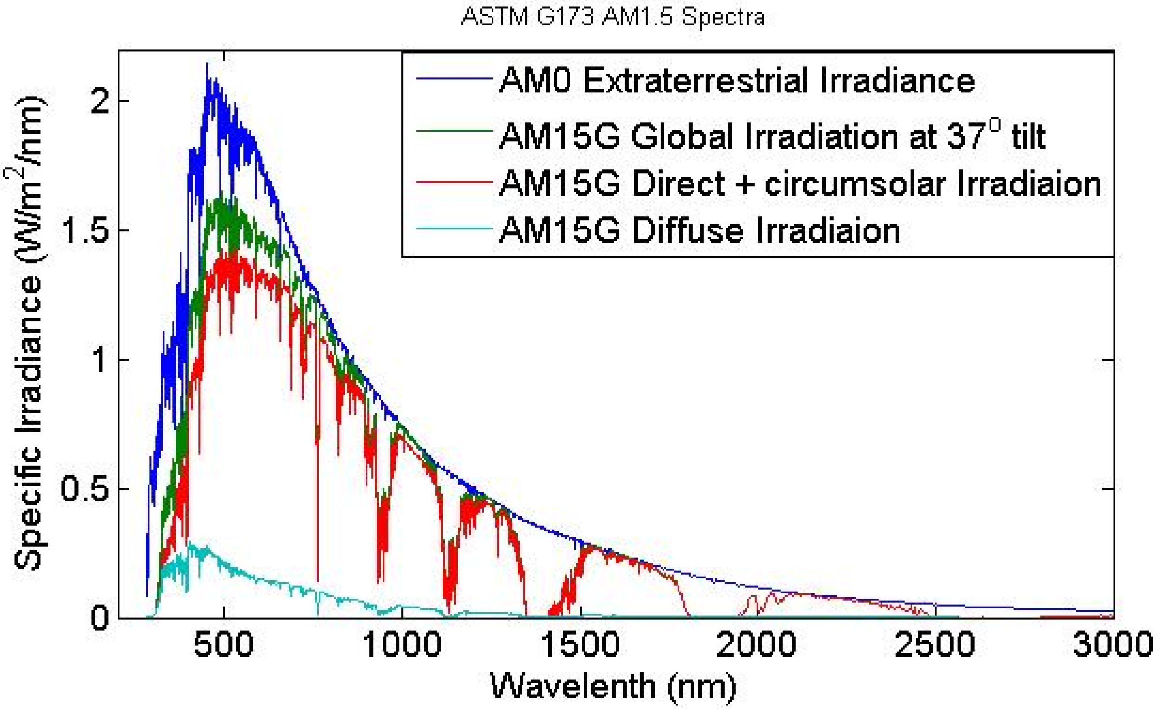

Figure 5: Reference AM0, AM1.5 direct and AM1.5 global spectra

4.2 Light sources

Characterizing solar cells as if they were illuminated by sunlight requires to create a light source with similar characteristics. A light source designed to produce a sun-like illumination is called a solar simulator. Solar simulators are classified according to their spectral composition, spatial uniformity and temporal stability. Common architectures for solar simulators include halogen lamps, xenon lamps as well as LEDs.

In our experiment we do not have a lamp at hand that shows a close match to the solar spectra. We will use a halogen lamp whose spectrum can be modeled by black body radiation.

Even though the spectrum of the lamp does not match the solar spectrum, its power can be chosen to generate the same density of electron-hole pairs and thus the same photocurrent. In the experiment, this is achieved by using a 250W (24V nominal driving voltage) halogen lamp which is powerful enough to generate an illumination intensity equivalent to 1 sun on the cell after its propagation through the different elements of the characterization setup. The spectral composition of light emitted by a halogen bulb differs quite significantly from the one of the sun as illustrated in Figure 6. A first task is therefore to measure the spectral composition of the lamp. To do so the spectrum is filtered into bands and for each spectral band the power is measured with a calibrated power meter.

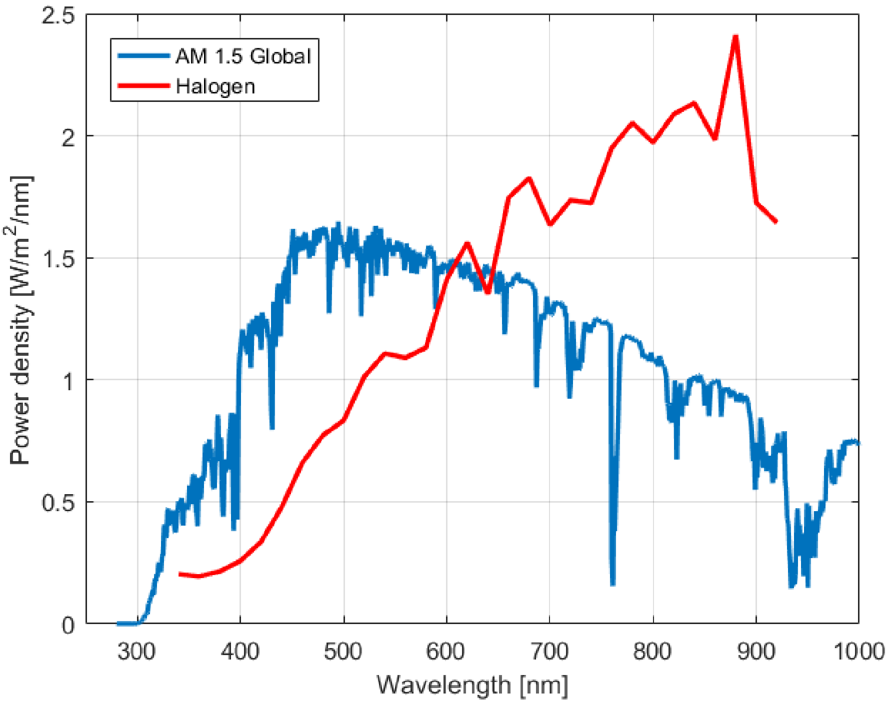

Figure 6: Reference AM1.5 global spectrum together with the spectrum measured from a halogen lamp.

4.3 Sampling the spectrum

When sampling light from a broadband source one can generally either make use of selective filters or of a monochromator. The latter operates by spatially separating the spectral components of a signal by refraction through a prism or diffraction by a grating. The desired wavelength is then extracted by collecting the light through a narrow slit. This allows for a much finer sampling than the one achievable with filters. However, it requires a precise alignment and results in very little output power implying the use of an optical chopper together with a lock-in amplifier to measure the current delivered by the cell.

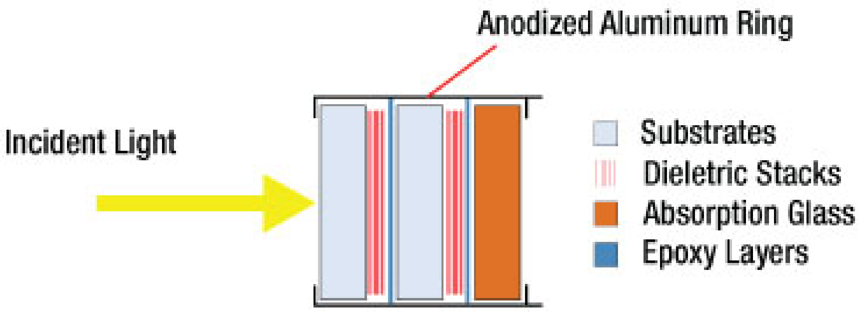

Figure 7: Schematic representation of a bandpass filte. An n order half wavelength cavity is sandwiched between two highly reflective mirrors. Additional filtering is ensured by the presence of an absorption glass plate. The filter is then sealed in an aluminum ring. This image was downloaded from Thorlabs' website.

Bandpass filters are a simple and effective way to sample light at different wavelengths. Their design relies on the use of a Fabry-Pérot cavity built by surrounding a dielectric spacer by two highly reflective Bragg mirrors as illustrated in

Figure 7. The latter are built by stacking dielectric layers with two different refractive indexes. The width of the cavity (n*λ/2) as well as the width of the dielectric layers (λ/4) are design parameters that allow to aim at a specific bandwidth. Additional filtering is ensured by addition of a broadband absorption glass. We use spectral interference filters such us FB520-10 from Thorlabs, a filter with its central wavelengths at 520 nm and with a spectral width of 10 nm (Full width half maximum FWHF) that blocks from 200 to 3000 nm. More technical information can be found on Thorlabs' website (www.Thorlabs.com).

The spectrum delivered to the sample is determined by turning one filter after another in the light path and measuring the transmitted optical power density with a power meter.

4.4 Solar Cell Equivalent Circuit

A basic solar cell is simply a p-n junction exposed to external illumination and behaves very much like a diode. The photocurrent I_{ph} generated by the light adds to the current produced by the diode. An ideal solar cell can thus be modelled by a current source in parallel with a diode. To account for several loss mechanisms including Ohmic loss due to electric contacts, a slightly more complicated yet more accurate model can be obtained by adding a series resistance R_s and a parallel resistance R_p to the previous scheme as illustrated in Figure 8. The model in Figure 8 can be used to determine internal parameters of the cell after measuring voltage current characteristics. The aim of one part of the experiment is exactly this, measure the U-I curve and try to find the values for different resistances. A Matlab code is available that allows you to fit the parameters.

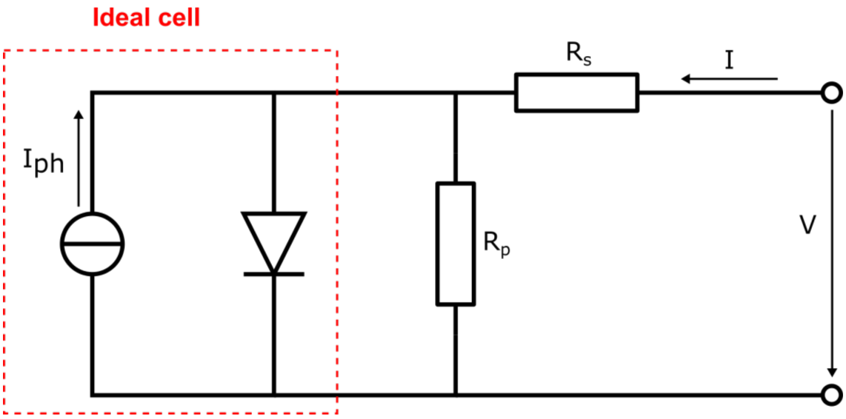

Figure 8: Modelling of an ideal solar cell making use of a current source in parallel with a diode (red-dashed rectangle). A more realistic model is obtained by adding a series and a parallel resistance.

4.5 Main Parameters

The I-V response of the system described in Figure 8 is given by the following implicit expression

(2)

$$I = I_0\left[exp\left(e\frac{V - IR_s}{nk_BT}\right) - 1\right] + \frac{V - IR_s}{R_p} - I_{ph}$$

where I_0 is the saturation current or dark current and k_B is Boltzmann constant. The parameter n is called the ideality factor. It equals 1 for an ideal diode but takes higher values to take into account manufacturing imperfections. The I-V curve of a solar cell departs from the one of an ideal diode due to the parasitic resistances R_s and R_p. This typical response is depicted in Figure 9.

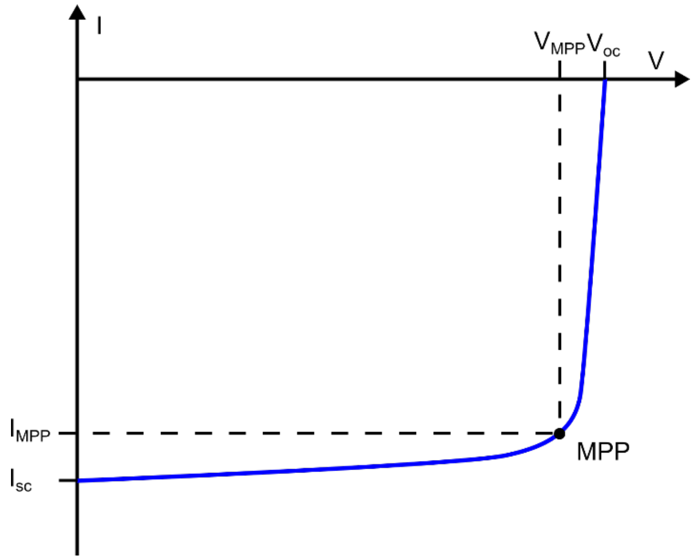

Figure 9: I-V curve of a solar cell. V_{MPP} and I_{MPP} correspond to values of voltage and current procucing the maximum output power.

The main parameters of a solar cell are the open circuit voltage V_{oc}, the short circuit current I_{sc}, the peak power P_{max} or maximum power point (MPP) as well as the fill factor *FF*. This last quantity expresses the ratio of achievable maximum power over the product of I_{sc} and V_{oc}. It can be expressed like

$$FF = \frac{I_{MPP}V_{MPP}}{I_{sc}V_{oc}} \tag{3}$$

The different values (current at maximum power point I_{MPP}, voltage at maximum power point V_{MPP}, short circuit current I_{SC}, open circuit voltage V_{OC}) can be read from Figure 9.

4.6 Modeling

The procedure described here below follows with some simplifications an article published in 2009 [2] in IEEE Transactions on Power electronics. It aims at finding the

[2] M. G. Villalva, J. R. Gazoli and E. R. Filho, "Comprehensive Approach to Modeling and Simulation of Photovoltaic Arrays," in *IEEE Transactions on Power Electronics*, vol. 24, no. 5, pp. 1198-1208, May 2009.
URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4806084&isnumber=4815917

parameters *n*, R_s and R_p, such that Eq. (3) fits as accurately as possible the I-V curve obtained. The algorithm is built in a way that the fitting curve obtained will always pass by the three remarkable points that are the open voltage, the short circuit and the MPP.

4.6.1 Initialization

I_0 is unknown while initial values must be set to both R_s and R_p. The diode ideality factor *n* is to be chosen arbitrarily. Since R_s is small, it can be initialized at 0. R_p is first set at a minimum value, corresponding to the slope of the line segment between the MPP and the short circuit point that is

$$R_{p,min} = \frac{V_{MPP}}{I_{MPP} - I_{sc}} \tag{4}$$

I_0 is obtained by evaluating (3) at the open-voltage condition and neglecting the current induced in the parallel resistance R_p while assuming that $I_{sc} \approx -I_{ph}$

$$I_0 = -\frac{I_{sc}}{exp\left(\frac{eV_{oc}}{nk_BT}\right) - 1} \tag{5}$$

4.6.2 Iteration

The iterative procedure comprises the following steps:

1. I_{ph} is given a better approximation by including the effect of the parasitic resistances that is

$$I_{sc} = -I_{sc}\frac{R_s + R_p}{R_s} \tag{6}$$

2. R_p is obtained by multiplying (3) at MPP by V_{MPP} and assuming it to be equal to the measured maximum power *Pmax*

$$R_p = V_{MPP}\left\{\frac{V_{MPP} - R_s I_{MPP}}{P_{max} + I_{ph} - I_0\left[exp\left(e\frac{V_{MPP} - I_{MPP}R_s}{nk_BT}\right) - 1\right]}\right\} \tag{7}$$

3. Since (3) is a transcendental equation it must be solved numerically. Once *I* is known, the calculation of the electric power is straightforward.
4. The maximum value found is then to be compared with the measured value. If the difference lies below a certain threshold the algorithm stops. If not, R_s is incremented and steps 1 to 3 are to be repeated.

4.7 External Quantum Efficiency (EQE)

Solar cells do not generate electric current uniformly over the electromagnetic spectrum. Multiple phenomena that are either optical or electrical ones intervene and shape what is referred to as the external quantum efficiency (EQE). It is defined as the ratio between the rate of produced electrons over the rate of incoming photons at a certain wavelength and provides information on the device spectral response. The EQE is retrieved in practice from the incoming optical power P_λ and the output electric current I_λ at a given wavelength using

$$EQE = \frac{I_\lambda}{P_\lambda}\frac{hc}{e\lambda} \qquad (8)$$

where h is the Planck constant, c is the speed of light in vacuum and e is the elementary charge. In practice the cell is measured in short circuit configuration.

4.8 QUESTIONS

- **What kind of light does the sun emit?**
- **Where is the maximum of the energy emitted?**
- **Have you heard about standardized spectra?**
- **Which latitude is Lausanne?**
- **Who would be interested in the AM1.5d spectrum?**
- **What is the maximum concentration ratio?**
- **Which part of the spectrum is absorbed in a semiconductor?**
- **How does the absorption coefficient of typical semiconductors vary with energy?**
- **What happens to the light with energy less than the bandgap energy?**
- **What happens to the light with energy higher than the bandgap?**
- **So, to get as much current as possible, I should use a very low bandgap energy?**
- **Then, should I use a semiconductor with a very high bandgap?**
- **What is the optimum bandgap energy for a solar cell?**
- **How does a solar cell work after the light is absorbed?**
- **What is the external quantum efficiency (EQE)?**
- **How does an ideal EQE look like?**
- **Which effects may reduce the EQE?**
- **How much reflection would you expect for bare silicon?**
- **How can you reduce the reflection losses?**
- **Other methods?**
- **In a tandem cell, typically two cells are in series. Can you imagine limitations of that approach?**
- **How do you stack the two cells?**
- **How would the EQEs of the single cells look like, how the one of the tandem cell?**
- **So, what is the advantage of having a tandem when the bottom cell alone absorbs exactly the same spectral range?**

5 Experiment

We use light from a 250W halogen bulb that is collimated and reflected on the sample. A glass plate serves as simple beam splitter to assess the power incident on the solar cell.

Spectral measurements are obtained with 10 nm bandpass filters mounted on three rotating wheels allowing to sample up to 30 spectral components.

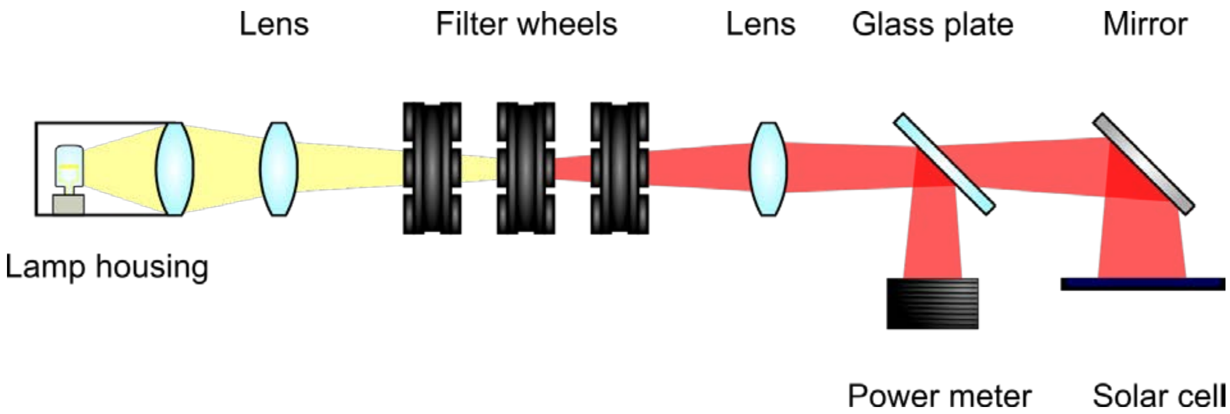

Figure 10 Full setup comprising a 250W halogen bulb encapsulated in a housing, a first collimating lens, filter wheels, a second collimating lens, a glass plate as well as an elliptical mirror. Power incident on the solar cell is being indirectly measured from light reflected on the glass plate.

The lamp is a halogen lamp that operates at 24 V. We use a power supply Peaktech (connectors on the back side) that delivers max 32 V and 20 A. **Please be careful when setting the lamp parameters (<24V, <10 A) to not burn the lamp**.

Since solar cells absorb light at most wavelengths including visible light and as the power levels involved after sampling are quite low, the cell is enclosed within a box preventing ambient illumination to bias the results. Figure 11 shows photographs of the actual setups.

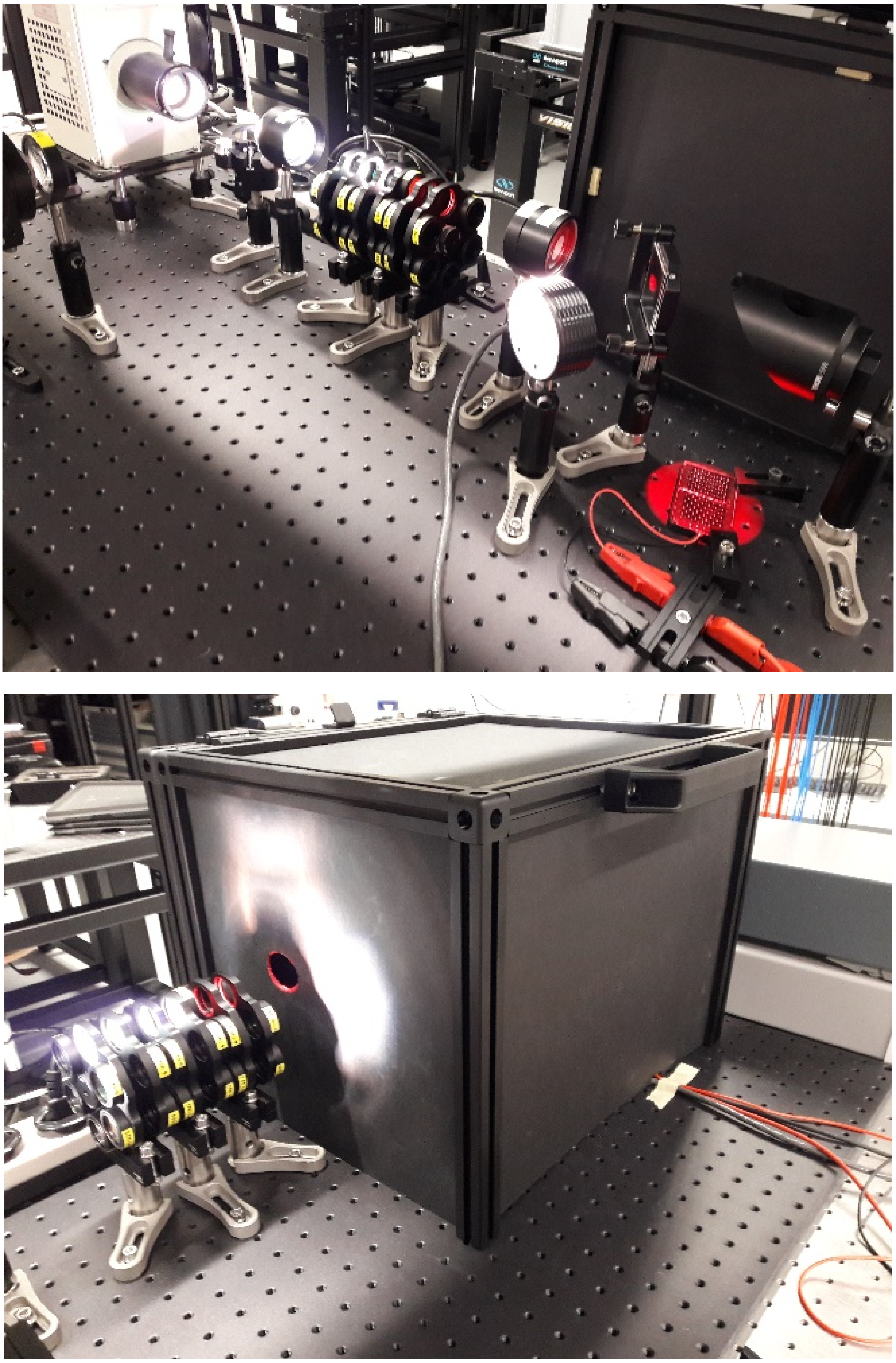

Figure 11 : Picture of the full setup (top) and enclosure used to prevent ambient light to interfere with the measurements (blow). One easily recognizes the lamp, some collimation optics and the filter wheels. The solar cell is visible in the red illuminated circle and connected with banana clamps.

5.1 Optical test equipment

The experiment uses a Newport Optical Power and Wavelength Meter OMM-6810B with OMH6742B with Silicon Optical Power/Wavelength Measurement Head, 1W, 350-1100nm.

The OMM-6810B is a power meter capable of measuring the optical power and wavelength of light. It was originally designed for laser measurements. We have a measurement head sensitive between a wavelength ranges from 350 to 1100 nm. .

The power meter needs to be calibrated on the wavelength that is to be measured. The OMM-6810 is has an automatic mode that works well if the power is not too small. **For each measurement the settings have to be verified at the display.**

Please refer to the manual for further instructions of use.

5.2 Power meter

We use a digital multimeter from Rohde&Schwarz (HMC8012).

The HMC8012 can measure voltage current characterizes in a single instrument. That will be very useful when measuring the U-I curve.

Please refer to the manual for further instructions of use.

6 Tasks

During this lab you will be asked to:

1) Measure the external quantum efficiency of a solar cell
2) Measure the I-V response of a solar cell
3) Determine the parameters of the equivalent circuits based on the data acquired

6.1 External Quantum Efficiency (EQE)

The glass plate in the optical path serves as a low ratio optical coupler. It is used to perform indirect power measurements or referencing. Since the power reflected by the plate is unknown, it must be characterized first in order to be used as reference.

1) Place the powermeter head in place of the solar cell and rotate the filter wheels to obtain a measurement of the incident power at all wavelengths. Note these measurements in the first column of appendix A.
   Remark: The powermeter will have trouble finding the appropriate wavelength below 500 nm at such little powers. Set the wavelength manually in this case. In any case, correct the detected wavelength if it diverges from more than 1nm with respect to the filter center wavelength.
2) Place the powermeter head in the path of the beam reflected by the glass for the reference measurement of the next step.
   Remark: Once this step has been achieved, you should not move the powermeter head or the glass plate anymore as your system has been characterized for this particular configuration.
3) Using clamps, fix the solar cell onto the breadboard making sure that the whole surface is being illuminated. Connect the bare wires of the solar cell to the crocodile clips, then connect these to the ammeter.
4) Rotate the filter-wheels to select the desired wavelength, measure simultaneously optical power of the reference beam and the electric current of the cell. Enter the results in column 2 and 3 of appendix A.
   Remark: The multimeter employed to measure the current delivered by the cell uses different resistances at different measurement ranges. **Set the multimeter to a fixed measurement range of 2A**.
5) Measure or find and write down here below the following complementary information :
   - Diameter of the powermeter head aperture
   - Diameter of the beam incident on the solar cell
   - Diameter of the beam reflected on the powermeter head
   - Dimensions of the solar cell
4) Enter your data under the “data entry” of the matlab script “SolarCell_1.m” and run the code.

All measurements should be done with the cover closed!

6.2 I-V Measurement

1) Connect the solar cell, the decade resistance R_d and the multimeter as depicted in Figure 12 and proceed to illuminate the solar cell. In principle, the multimeter can be used to measure simultaneously voltage and current. Set the multimeter in automatic for voltage measurement and set the 2 A range for current measurement.
   In reality it may be more accurate to work with two different meters, one for voltage and a second one for current.

   Remark 1: Since the cell acts as a source, the current it delivered as well as the power calculated are by convention negative.

   Remark 2: The electrical connection is set in order to avoid including the aperemeter resistance in the voltage measurement. However and with such a configuration you will measure a positive value current. Still write the result as negative in order to stick with the convention.

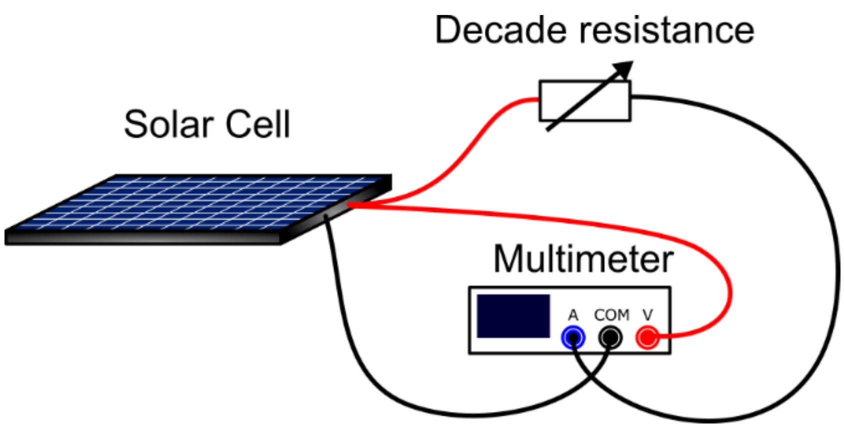

Figure 12 : Electrical connection for U-I measurements.

2) Starting from R_d = 0 (resistance of the decade), find the resistance value at which the voltage drops at one half of the open circuit voltage (V = V_{oc}/2). Report this value as R_1 in appendix B.

3) Increase R_d until the current measured drops at one half of the short circuit current (I = I_{sc}/2). Report this value as R_2 in appendix B.

4) Increase R_d until the current measured falls to 0. Report this value as R_3 in appendix B.

5) Measure 10 equally spaced points {V,I} as well as the corresponding resistance values between R_d = 0 and R_d = R_1. If that's not possible take as many measurement points as possible.

6) Measure 10 equally spaced points {V,I} as well as the corresponding resistance values between $R_d = R_1$ and $R_d = R_2$. If that's not possible take as many measurement points as possible.

7) Measure 10 points {V,I} between $R_d = R_2$ and $R_d = R_3$ as well as the corresponding resistance values. However do not take them equally spaced. Instead, adjust the decade resistance in order to decrease the current by a fixed amount until reaching 0.

   Example: If I = -150 mA at $R_d = R_2$ adjust the decade resistance in order to perform 15mA jumps each time.

6.3 Data post-processing

The Matlab scripts SolarCell_1.m and SolarCell_2.m allow you to enter your data and displays the corresponding figures and results.

6.3.1 SolarCell_1.m

This script is merely straightforward and allows you to display several results including the reflection ratio of the glass plate as well as the spectral power density of your light source.

6.3.2 SolarCell_2.m

This script comprises the algorithm described in section 3.7. You can tune several parameters that are the diode ideality factor, the incremental step of the serial resistance, the maximum number of iterations, the tolerance on the stopping criterion as well as the number of points used in the numerical solving of the transcendental equation (3). Adjusting them, try to find the best fitting curve and write down below the corresponding parameters n, R_s and R_p.

n = R_s = R_p =

7 Appendix A – EQE Measurements

λ [nm]	P_{cell} [mW]	P_{refl} [mW]	I_{EQE} [mA]
340			
360			
380			
400			
420			
440			
460			
480			
500			
520			
540			
560			
580			
600			
620			
640			
660			
680			
700			
720			
740			
760			
780			
800			
820			
840			
860			
880			
900			
920			

8 Appendix B – I-V Measurements

Resistances at particular points :

R_1 = R_2 = R_3 =

Measurement points :

R_d [Ω]	U [mV]	I [mA]
R_1		

R_d [Ω]	U [mV]	I [mA]
R_2		

R_d [Ω]	U [mV]	I [mA]
R_3		

9 Appendix C: Tandem solar cells

As mentioned in the introduction, multi-junction cells are a possibility to overcome the Schockley Queisser limit for the efficiency of single junction cells. The simplest multi-junction cell contains two cells and is called tandem solar cell. A multi-junction solar cell stacks semiconductors with different bandgap energies on top of each other. Light first enters the cell with the highest bandgap energy, such that photons that do not have enough energy to excite electron-hole pairs in this cell are transmitted to a cell with lower bandgap energy. In tandem cell, the first cell is called top-cell and second is called bottom-cell.

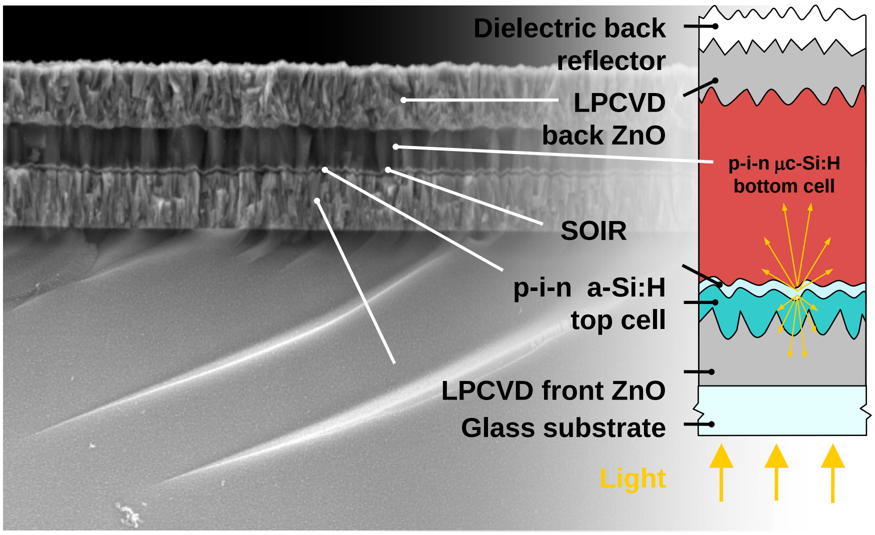

Figure 13: Cross section through a thin film silicon tandem solar cell. Illumination is from the bottom.

Multi-junction cells are often integrated monolithically, i.e. the rear of the first cell is directly connected to the front of the second and so forth. Electrically, this is a series connection and optimum performance is only achieved if all cells deliver the same current density. Obviously developers must be able to measure how much light is absorbed in the individual cells.

In this experiment, you will measure the external quantum efficiency of a tandem cell that combines an amorphous silicon solar cell with bandgap energy of 1.7 eV and a microcrystalline solar cell with bandgap energy of 1.1 eV. The measurement is based on a procedure first proposed by Glatfelter and Burdick in 1987. They made use of the fact that the current in a series-connection cannot exceed the current generated by the weakest component.

For example, shining intense red light on a tandem cell will create a large current density in the bottom cell but none in the top cell, resulting in zero total current. If one of the blue wavelengths of the EQE measurement is added, the resulting total current is exactly the one generated by the top cell under the illumination of the blue probing-wavelength, i.e. the desired EQE of the top cell. Likewise, the bottom cell is measured by using intense blue light and red probe-wavelengths.

EQE Measurements

λ [nm]	P_{cell} [mW]	P_{refl} [mW]	$I_{EQE,top}$ [mA]	$I_{EQE,btm}$ [mA]
340				
360				
380				
400				
420				
440				
460				
480				
500				
520				
540				
560				
580				
600				
620				
640				
660				
680				
700				
720				
740				
760				
780				
800				
820				
840				
860				
880				
900				
920				