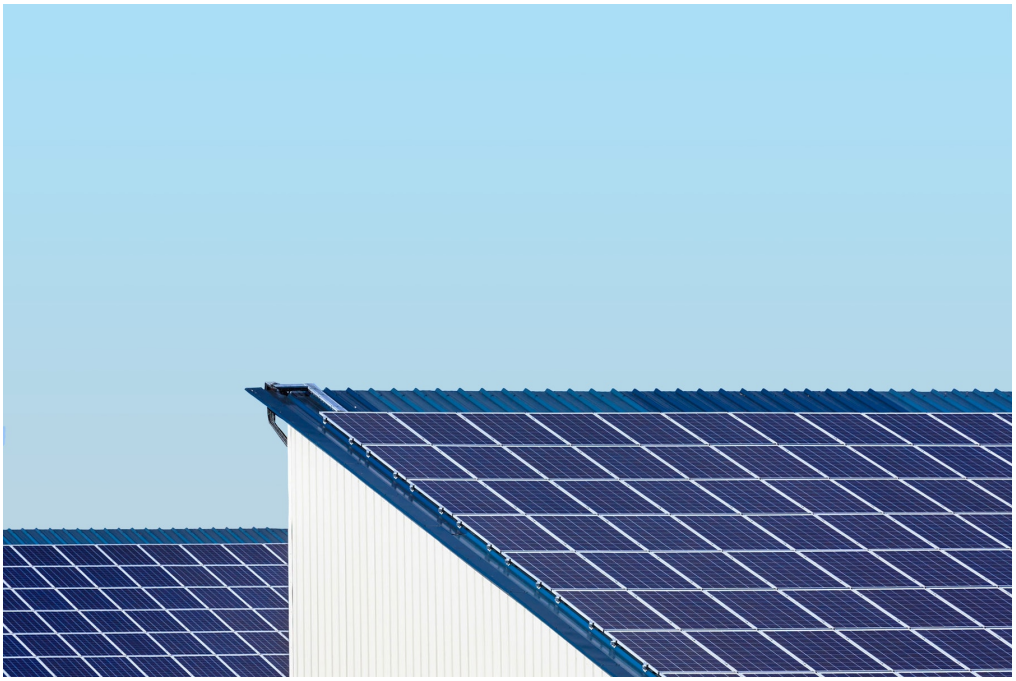
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Solar Cell Characterization



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EPFL

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***Abstract*—This report summarizes the experimental results obtained to characterize solar cells. The different experiments performed allow the determination of the reflection ratio, the external quantum efficiency (EQE) and the drawing of the $I-V$ curve of the system. Moreover, based on the data acquired, the parameters of the equivalent circuit are found. Finally, the tandem cell is studied. The EQE is more or less constant and around 70% for wavelength above $480\ nm$. For smaller wavelengths, the EQE increases a lot. The reflection ratio has the same behaviour with constant value around 4%. Based on the $V_{oc} = 534\ mV$ and $I_{sc} = 216\ mA$ computed and after doing the second experiment, the series resistance is $R_s = 0.2\ \Omega$ and the parallel resistance is $R_p = 28\ \Omega$. The fill factor at the operating point ($V_{MPP} = 0.41\ V$ and $I_{MPP} = -0.18\ A$) is 66% and the diode reality factor fitting the I-V curve is $n = 1.4$.**

I. Introduction

In the last few years, the production of electricity using photovoltaic panels has drastically increased. In less than 10 years the production has increased more than tenfold (63 TWh in 2011 and 821 TWh in 2020). This emerging energy source is the third biggest contributor to renewable energy behind hydropower (57.8%) and wind (20.8%). It went from an almost insignificant contribution (1.4% in 2011) to 11% in 2020 [1].

This report will establish the basic theory needed to understand the experiments realized. A description of the setup and the results will be provided for each tests performed followed by various explanations and calculations. A brief conclusion will sum up the major results obtained.

II. Theoretical background

The purpose of this chapter is to answer the questions asked in the assignement in order to develop the theory of solar cells. Most of the answers can be found in the assignement theory chapter [4].

- What kind of light does the sun emit?

The sun is considered as a blackbody and therefore has by definition a spectrum defined on all wavelengths. This spectrum is visible on Figure 1 where the sunlight at the atmosphere, the radiation at sea level and the behaviour of a perfect blackbody are represented [3].

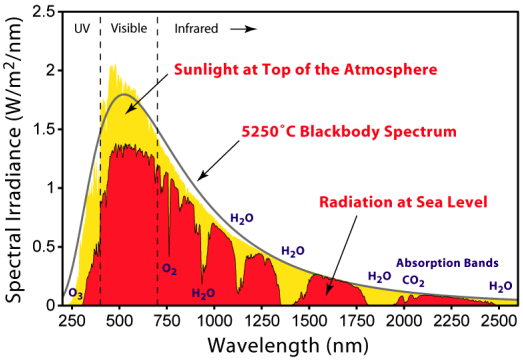

Fig. 1. Solar spectrum

- Where is the maximum of the energy emitted?

The maximum of energy is also visible on Figure 1. It corresponds to the maximum of the irradiance and is located around $\lambda = 500\ nm$. Note that there are variations between the values at the atmosphere and at sea level. It is due to absorption by water vapour, ozone, ... and by *Rayleigh* scattering [3].

- Have you heard about standardized spectra?

Standardized spectra are a reference in the world of sciences in order to allow the comparaison between different types of PV panels.

- Which latitude is Lausanne?

The exact latitude of Lausanne is 46.5196535 [2].

- Who would be interested in the $AM1.5D$ spectrum?

In the term $AMxD$, the x represent the factor between the distance PV panel - atmosphere at the zenith and PV panel - atmosphere for the path of the light as represented on Figure 2

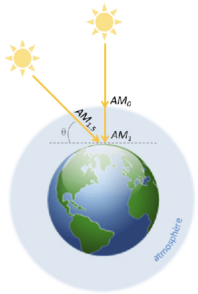

Fig. 2. Representation of the AMx situation

On the above Figure, AM1 and AM1.5 are represented with AM1.5 being the standard. Note that AM0 is the value at the limit of the atmosphere (irradiance = $1360 W/m^2$). AM1.5 implies an angle of around $48°$ between the rays of the sun and the zenith so everyone having a latitude around $48°$ could use this standard as an approximation. The D in $AM1.5D$ stands for direct meaning that it *"includes radiation coming only from small surroundings of the sun disc (5.8° aperture angle) and is projected orthogonally onto the cell"* [5]. This differs from the $AM1.5G$ (G for global) which also takes into account the various reflections (ground plane, scattering, ...) occurring along the path. PV panels are modeled based on $AM1.5G$ standards and $AM1.5D$ is used in solar concentrator power plants. [6]

- What is the maximum concentration ratio?

The solar system contains one sun but by using panels to focus the light on a given point, it is possible to increase the number of theoretical suns up to 45900. The concentration of the sun rays allow an improvement of the efficiency by

10% (considering one panel) [3]. The increase of the voltage in open circuit (V_{oc}) when focusing the light is found using Equation (1), the equation of the current in a diode.

$$I_L = I_0[e^{\frac{qV}{k_B T}} - 1] - I_{ph} \longrightarrow V_{oc} \approx \frac{k_B T}{q} ln(\frac{I_L}{I_0}) \quad (1)$$

If a concentration of 1000 suns is considered, then the ratio $\frac{I_L}{I_0} = 1000$ and the gain V_{oc} is only $174\ mV$ (for $k_B = 1.38\ 10^{-23}\ J/K$, $q = 1.6\ 10^{-19}\ C$ and $T = 293.15\ K$).

- Which part of the spectrum is absorbed in a semiconductor?

Every semiconductor is characterized by a bandgap. A hole-electron pair is generated only if the energy of the photon reaching the solar panel is equal or greater than the band gap energy (E_{gap}). Recalling that the formula for the energy of a photon is given by Equation (2), the smaller the wavelength will be the greater the energy.

$$E_{ph} = h\nu = \frac{hc}{\lambda} \quad (2)$$

Typical values of bandgaps for semiconductors are between $0.8\ eV$ and $2\ eV$ so to have such bandgap energies, λ must be smaller than $155\ nm$ ($0.8\ eV$ being the strong constraint). As a reminder, h is Planck's constant ($= 6.63\ 10^{-34}\ Js$) and c is the speed of light ($3\ 10^8\ m/s$).

- How does the absorption coefficient of typical semiconductors vary with energy?

The absorption coefficient α (cm^{-1}) of a semiconductor determines the depth at which a photon can penetrate a bulk before being absorbed. In other words, the depth before it interacts with an electron in the valence band and makes it cross through the bandgap to reach the conduction band. The absorption coefficient can be linked to extinction coefficient of the semiconductor k and the wavelength λ by $\alpha = \frac{4\pi k}{\lambda} \cdot 10^7$.

- What happens to the light with energy less than the bandgap energy?

Because the condition $E_{ph} \geq E_{gap}$ is not matched the photon is not absorbed and the electron-hole pair is not generated. No current will be created in the conduction/valence band. The behaviour of the semiconductor can be associated to an insulator.

- What happens to the light with energy higher than the bandgap?

Because $E_{ph} \geq E_{gap}$ the electron-hole pair will be created and current will circulated in the semiconductor. The excess energy will be converted into thermal losses so to avoid to much losses, the bandgap energy and the photon energy have to be close (with photon energy always being higher). The problem is the variation of the energy with the wavelength. To solve this problem, multi layers semiconductor are manufactured and try to optimize the absorption using different materials with different bandgap energies.

- So, to get as much current as possible, I should use a very low bandgap energy?

A low bandgap is useful if the user wants large current values but in terms of generating large powers, it won't efficient. Indeed, because of the low bandgap, there is almost no resistance to the creation of a electron-hole pair and thus the voltage is small.

- Then, should I use a semiconductor with a very high bandgap?

This time the problem is reversed. The voltage will be high enough but the generation of pair will be almost nonexistent because the photon energy required is too high.

- What is the optimum bandgap energy for a solar cell?

Schockley and Queisser derived a fundamental limit of 33.7% *for single-junction solar cells with an optimum bandgap-energy of* $1.34\ eV$ [4]. This affirmation is right without taking into account the possibility of concentration [3]. On Figure 3, one of the best material is *GaAs*.

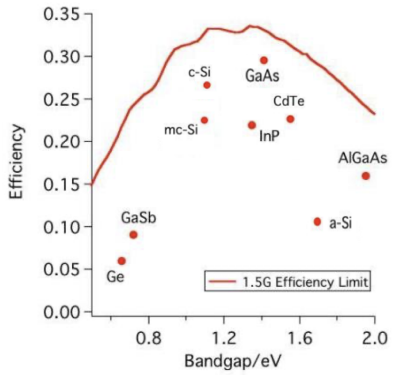

Fig. 3. Evolution of the efficiency with the bandgap

- How does a solar cell work after the light is absorbed?

Once the light has been absorbed, if the energy is high enough an electron-hole pair is formed. If a PN type of semiconductor is considered, a diffusion of electrons takes place to establish an equilibrium between the highly doped electron area and the poor electron area. The electrons go from the N-type to the P-type inducing a current from flowing from the P-type to the N-type. Due to the diffusion, positive and negative charges appear and an electric field is created. This field becomes stronger and stronger as the diffusion continues. This phenomena is happening until the electrical field compensate the diffusion. Then an equilibrium is created and three regions appear: two doped regions and a depletion region. This depletion area is located between the two doped regions and contains almost no charges.

- What is the external quantum efficiency (EQE)?

The external quantum efficiency is a measurement of the ratio between the number of photons absorbed and converted into electric current with respect to the total number of photons hitting the solar cell. This measurement is done under short circuit conditions.

- How does an ideal EQE look like?

An ideal EQE would be equal to 100% for any wavelengths from the gamma-rays (1×10^{-24} m) to the long radio waves (1×10^{5} m). It would allow the use of semi-conductors with many different bandgaps.

- Which effects may reduce the EQE?

The EQE is affected by several parameters. First of all, there may be losses due to reflection or transmission on the solar panel, parasitic absorption by an inactive part of the cell is also one of the negative effect. Recombination losses on the way to the electrodes is the last parameter affecting the performances.

- How much reflection would you expect for bare silicon?

A bare silicon has a surface reflection of over 30%. [10]

- How can you reduce the reflection losses?

Two ways can be used for reducing reflection losses: texturing and using Lambertian back reflectors. The principle of texturing is to increase the chances of reflected light to bounce back onto the surface, by making this latter more textured. The use of a Lambertian back reflector randomizes the direction of the reflected light which incomes to the cell, making this light internally reflected and trapped.

- Other methods?

Another way is to apply anti-reflection coatings (ARC) to the surface. The ARC consists of a thin layer of dielectric material deposited on the semiconductor, so that the light reflected by the surface of the semi-conductor and the one reflected by the coating result in a destructive interference.

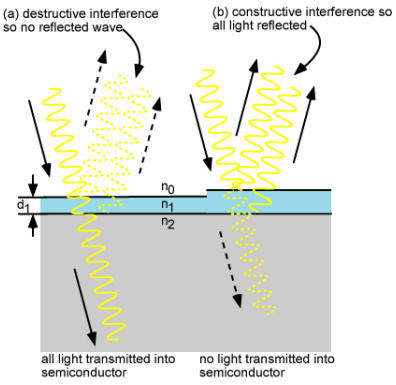

Fig. 4. Use of a quarter wavelength anti-reflection coating to counter surface reflection [10]

- In a tandem cell, typically two cells are in series. Can you imagine limitations of that approach?

For solar cells in series, the overall current produced is equal to the lowest current of each cell. We can imagine that one of the cells does not receive any light because of some dust or object from the environment placed between the source and the cell, then the current produced by the cell is zero and so is the one produced by all the series. More generally, any issue faced by one of the cells is fatal to the entire system.

- How do you stack the two cells?

Two cells are stacked monolithically with a thin tunnel junction between as shown in Figure 5. One electrode is placed at each edge of the stack to collect the electric current produced. The electrode on top has to be transparent to visible light and is often made of glass, contrarily to the rear electrode, which is black to stop the visible light. A global overview of such tandem cells in shown in Figure 16.

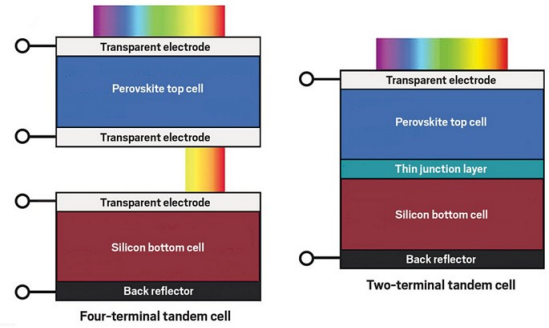

Fig. 5. Stack of solar cells [12]

- How would the EQEs of the single cells look like, how the one of the tandem cell?

Each of the cells absorbs some light with a certain energy so the EQE of a single cell is a curve centered at a certain wavelength which is approximately the mean of both relative wavelengths. The EQE of a tandem solar cell is the result of the sum of both of the two curves (see Figure 6).

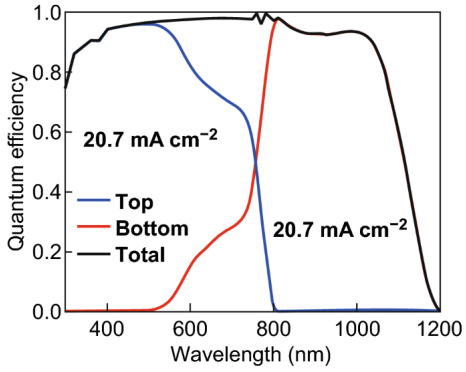

Fig. 6. EQE of single and tandem cells [11]

- So, what is the advantage of having a tandem when the bottom cell alone absorbs exactly the same spectral range?

The layer on top of the tandem cell (with the higher bandgap) will already absorb the high energy photons with less thermal losses than if those photons where absorbed by the second layer. Indeed, the difference between the bandgap energy and the photon energy has to be the smallest as explained before.

III. Measurement the external quantum efficiency of a solar cell

The purpose of the first experiment is to analyze the behaviour of the external quantum efficiency of a solar cell when the wavelength varies. The procedure done during the laboratory is essential due to the non-uniform profile of the electric current generated. Indeed, the wavelength influences the EQE through optical and/or electrical phenomena as shown in Equation (3).

$$EQE = \frac{I_\lambda}{P_\lambda}\frac{hc}{q\lambda} \tag{3}$$

The formula to find the EQE can be interpreted as *"the ratio between the rate of produced electrons over the rate of incoming photons at a certain wavelength."* [4].

The experiment was conducted in two steps: the calibration of the power reflected by the beam and the measurement of the optical power of the reference beam and the electric current of the cell when it is exposed to the light of a halogen lamp.

The glass plate in the optical path is used as a beam divider so the amount of power reflected has to be measured in order to use it as a reference. To do this, one will measure the incident power P_{cell} at all wavelengths between $350\,\mathrm{nm}$ and $920\,\mathrm{nm}$ by the use of filter wheels as shown in Figure 7. It was important not to move the power meter head before placing the solar cell and perform the second measurement.

This second measurement consists in the qualification of the solar cell by the electric current it produces I_{EQE} and the power P_{refl} it provides when exposed to light.

A. Setup

To perform this experiment, a $250\,\mathrm{W}$ halogen bulb producing collimated light through a lens system was used. The light goes through some filter wheels that let pass a specific wavelength. Then the filtered light is splitted into two beams: one going to the power meter and the other one reaching the solar cell by reflection on a mirror. Afterwards, the current produced by the solar cell is measured by plugging the cell to the multimeter with "crocodile clips" and "banana connectors". An enclosure is also used to prevent light from the room to interfere with the measurement. It covers the setup from the end of the filter wheels to the solar cell. The overall setup is shown in Figure 7.

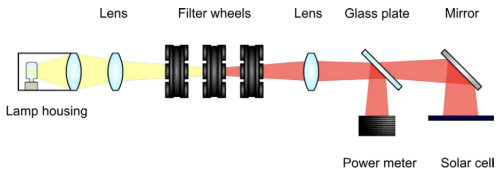

Fig. 7. Setup for EQE measurement

The instruments used are a Newport Power and Wavelenth Meter ($OMM-6810B$ and $OMH6742B$) with Silicon Optical Power/Wavelength Measurement Head, $1\,\mathrm{W}$, $350-1100\,\mathrm{nm}$ like in Figure 8 and a digital multimeter $HMC8012$ from Rohde&Schwartz.

Fig. 8. Picture of the power meter

B. Results

The reflection ratio of the glass plate is given by the formula of Equation (4).

$$R = \frac{P_{refl}\cdot A_{refl}}{P_{cell}\cdot A_{cell}}\cdot 100\ [\%] \tag{4}$$

where A_{refl} is the cross section of the incident beam on the powermeter head and A_{cell} is the cross section of the incident beam on the solar cell. Since we measured $d_{refl} = 40\,\mathrm{mm}$ and $d_{cell} = 95\,\mathrm{mm}$, we have $A_{refl} = \pi\cdot(\frac{d_{refl}}{2})^2 = 1.26\times 10^3\,\mathrm{mm}^2$ and $A_{cell} = 7.09\times 10^3\,\mathrm{mm}^2$. The reflection ratio depends on the wavelength and as it is shown in Figure 9. We can approximate it is 4% for the range of light we are interested in.

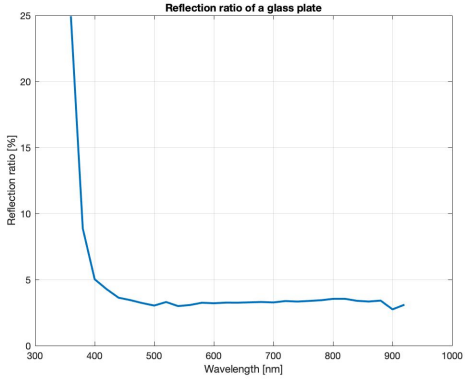

Fig. 9. Reflection ratio of a glass plate

Reproducing the light coming from the sun is not currently possible. Even if the power density with respect to the wavelength cannot be simulated, its behaviour can be approximated for small wavelength using a halogen bulb. Note that using other tools such as LED or xenon light, the behaviour can be approximated for other wavelength ranges. The distribution of the power density follows Wien's displacement law [8] which states that the smaller the temperature of a black body is, the wider the distribution will be (see Figure 10). The temperature of the sun is $5778\ K$ and the temperature of a halogen light bulb is around $3000\ K$. By looking at the green and brown curves (closest to the temperatures analyzed), it appears that for the analyzed range of wavelengths ($340 - 920\ nm$), the power density of the halogen bulb should always increase ($\lambda_{peak} \approx 950\ nm$) and the power density of the sun should increase and then decrease ($\lambda_{peak} \approx 500\ nm$) [7]. The distance between the two different sources (sun and halogen bulb) and the solar cell influences the amount of power arriving to the target as demonstrated later.

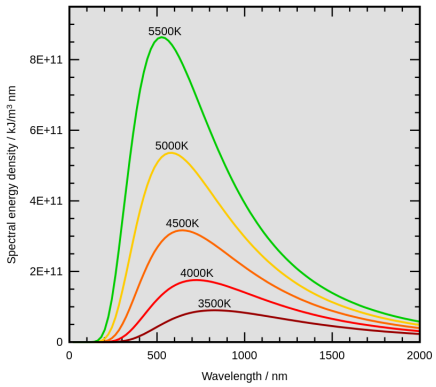

Fig. 10. Wien's displacement law

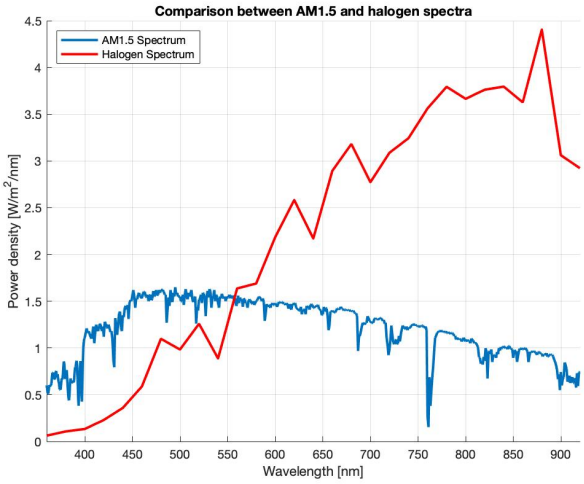

Fig. 11. Reference AM1.5 global spectrum together with the spectrum measured from halogen lamp

After performing the experiment, Figure 11 shows the spectral composition of light emitted by a halogen bulb and the one emitted by the Sun. This graph is important in this study since the solar cell is normally used when exposed to the Sun. For testing the solar cell, the environment, and especially the light source it is exposed to, shall thus be as close as possible to the Sun light.

For the wavelengths before $\lambda = 550\,\mathrm{nm}$, the shapes of both curves are similar. The power density increases with the wavelength and is between 0 and $1.5\,\mathrm{W/m^2/nm}$. Above $\lambda = 550\,\mathrm{nm}$, the power density of the halogen light and the power density of the sun diverge but the maximum difference in the visible light spectrum is about a factor 3. The behaviour of the curves in Figure 11 follows the theory of black body explained in Figure 10 and the amplitude of the Sun is smaller due to the distance travelled. Note that this graph is very sensitive to the power used by the halogen bulb. For the rest of this report, the halogen bulb will be considered as a good solar simulator while keeping in mind the difference for higher λ in the case of incoherent results.

The graph of the EQE is obtained from the data of Table I measured during the lab and is given in Figure 12.

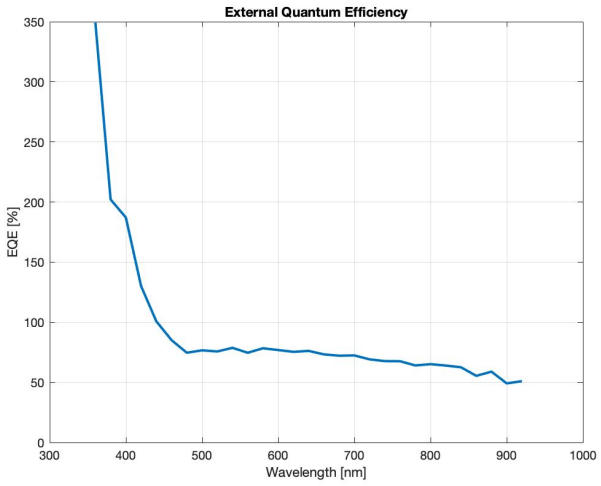

Fig. 12. EQE of the solar cell

It seems that the EQE is at a stable level of 70% for almost all the visible light wavelengths. However it is a little lower than the expected value. This difference can be explained by looking at Equation (3). All components are either constant (h, c and e) or easily measurable quantities (I_λ and λ) except for the incoming optical power P_λ. The latter is not a precise measurement as it depends a lot on the alignment of the head power meter and the measured size of the solar cell.

TABLE I
RESULTS EQE MEASUREMENTS

$\lambda\ [nm]$	$P_{cell}\ [mW]$	$P_{ref}\ [mW]$	$I_{EQE}\ [mA]$
340-350	2.15	2.95	0.122
360	1.77	2.49	0.122
380	3.04	1.52	0.128
400	3.777	1.07	0.155
420	6.511	1.57	0.195
440	10.16	2.08	0.247
460	16.63	3.23	0.357
480	31.05	5.64	0.61
500	27.8	4.76	0.584
520	35.59	6.63	0.768
540	25.1	4.24	0.585
560	46.27	8.03	1.06
580	47.7	8.75	1.19
600	61.77	11.18	1.562
620	73.01	13.41	1.871
640	61.36	11.26	1.64
660	81.84	15.13	2.17
680	89.94	16.76	2.42
700	78.41	14.47	2.179
720	87.3	16.62	2.382
740	91.7	17.26	2.518
760	100.71	19.22	2.836
780	107.25	20.79	2.939
800	103.61	20.7	2.96
820	106.36	21.28	3.06
840	107.31	20.54	3.091
860	102.55	19.32	2.68
880	124.58	23.96	3.54
900	86.56	13.41	2.1
920	82.64	14.44	2.125

IV. MEASUREMENT OF THE I-V RESPONSE OF A SOLAR CELL AND DETERMINATION OF THE PARAMETERS FOR THE EQUIVALENT CIRCUIT

In this section, the variation of current and voltage is analyzed when a decade resistance is placed in parallel to the solar cell. The decade resistance (R_D) will vary from short circuit situation ($R_D = 0$) to open circuit situation ($R_D = \infty$). This variation in the resistance will be performed in three sections.

To define these sections, the first step is to measure the short circuit current (I_{sc}) and the open circuit voltage (V_{oc}). Based on the two values, the resistances R_1, R_2 and R_3 are defined as followed : R_1 is the resistance for which the voltage is $\frac{V_{oc}}{2}$, R_2 is the resistance for which the current is $\frac{I_{sc}}{2}$ and R_3 is the short circuit resistance. The preliminary results needed for the experiment are taken in Table II.

TABLE II
PRELIMINARY RESULTS

$V_{oc}\ [mV]$	$I_{sc}\ [mA]$	$R_1\ [\Omega]$	$R_2\ [\Omega]$	$R_3\ [\Omega]$
534	216	1	4.5	600

The resistance R_3 is not ∞ because after 600 Ω the current doesn't significantly decreases. The division into the three sections is now possible. It is simply done following Formula (5).

$$[0, R_1] \quad [R_1, R_2] \quad [R_2, R_3] \tag{5}$$

For the two first sections ($[0, 1]$ and $[1, 4.5]$), the measurements are taken for constant steps of resistance but for the last section ($[4.5, 600]$) the step are constant for current values. This is due to the exponential behaviour of the resistance. By looking at the results in Table V it is clear that this method is a good choice.

A. Setup

For this experiment, the multimeter of Rohde & Schwarz($HMC8012$) is used again to measure the current and the voltage at the same time. The voltage is measured at the connections of the solar panel and the current measured is flowing through the decade resistance. The setup is represented on Figure 13.

It is possible for the multimeter to measure the current and the voltage at the same time using the automatic mode for voltage measurement and by setting the 2 A range for current measurement. The configuration used has by convention a negative power because of the direction of the current but the current appearing on the multimeter will be positive. In order to respect the convention, a minus sign will be added.

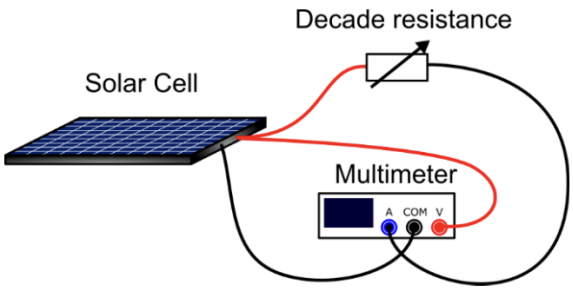

Fig. 13. Setup for measurement of the I-V curve

B. Results

TABLE III
RESULTS OF FIRST SECTION

R_d $[\Omega]$	U $[V]$	I $[A]$
0	0.072	-0.2159
0.1	0.081	-0.2157
0.2	0.103	-0.2156
0.3	0.1232	-0.2153
0.4	0.144	-0.215
0.5	0.1648	-0.2147
0.6	0.1863	-0.2142
0.7	0.205	-0.2135
0.8	0.2245	-0.213
0.9	0.2447	-0.2122
1	0.2632	-0.2111

TABLE IV
RESULTS OF SECOND SECTION

R_d $[\Omega]$	U $[V]$	I $[A]$
1.4	0.3357	-0.2044
1.7	0.377	-0.196
2.1	0.4167	-0.181
2.4	0.4373	-0.1685
2.7	0.4512	-0.1575
3.1	0.4648	-0.1436
3.4	0.4724	-0.1344
3.7	0.4784	-0.1263
4.1	0.4848	-0.1168
4.5	0.4899	-0.1086

TABLE V
RESULTS OF THIRD SECTION

R_d $[\Omega]$	U $[V]$	I $[A]$
5.2	0.4958	-0.09681
6	0.5017	-0.0855
7.2	0.5072	-0.074
8.7	0.512	-0.063
11	0.5167	-0.052
14.7	0.521	-0.041
22	0.525	-0.0299
44	0.529	-0.0183
600	0.5329	-0.00723

C. Determination of the parameters

Based on the result and the I-V curve obtained, the parameters of the equivalent circuit can be found and the solar cell can be characterized. The equivalent circuit is composed of a parallel (R_P) resistance and a serie resistance (R_S). It also has a diode and a current source.

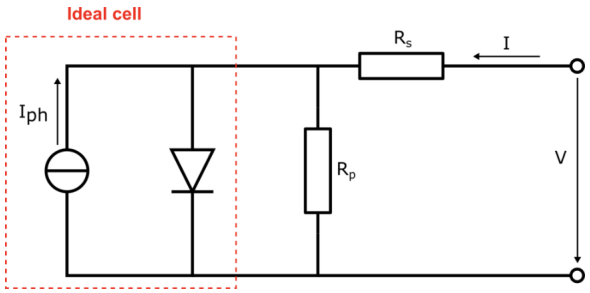

Fig. 14. Equivalent circuit of a solar cell

By using the *Matlab* code written on Figure 21 with a $n = 1.4$ diode reality factor, the plot on Figure 15 is drawn.

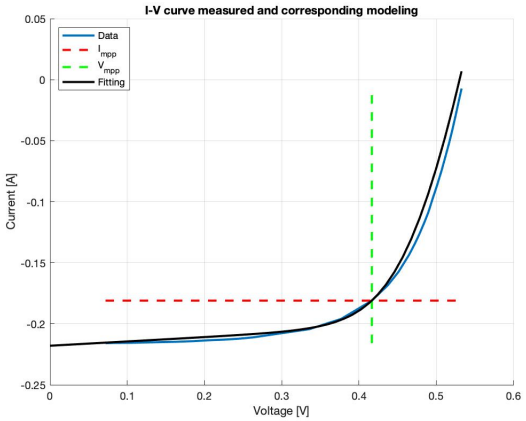

Fig. 15. Comparison of measured and theoretical I-V curve of the solar cell

The code allows to fit the curve using the data measured. To get the two curves almost overlapping, the resistance in serie is set to $R_s = 0.2\,\Omega$ (obtained by trial for best fitting). The resulting parameters are $R_p = 28\,\Omega$ and $FF = 66\%$ (the fill factor). These parameters are interesting to know for building simulations including solar cells. It seems logical to have $R_p \geq R_s$ because otherwise most of the current generated would not go to the consumer. R_p can't be too low because it is at the origin of the voltage drop V visible on Figure 14. The fill factor is a measurement of the performance of the solar cell. The ideal case is a fill factor of 100% meaning that the operating point developing the most power (MPP = maximum power point) has a voltage $V = V_{oc}$ and a current $I = I_{sc}$. This scenario is not possible because by definition a circuit cannot be open and shorted at the same time. However, it is possible to get close to this point using for example $GaAs$ (FF up to 89%) [9]. In our case the fill factor is obtained using formula (6) where $I_{MPP} = -0.18\,\text{A}$ and $V_{MPP} = 0.41\,\text{V}$ are found by the program.

$$FF = \frac{I_{MPP} V_{MPP}}{I_{sc} V_{oc}} \times 100\ [\%] \tag{6}$$

V. The tandem cell

A good way to increase the efficiency of a solar cell is to use a tandem solar cell, composed by a pair of cells, one on another (see Figure 16). Since we obtain a stack of semiconductors with different band gaps, the range of wavelenghts the system can absorb without losses is larger. In fact, the cell with the highest band gap energy (or top-cell) on top gets first the incoming sun light. Then the cell with lower band gap energy (or bottom-cell) receives the rest of photons that did not have enough energy to excite electron-hole pairs in the first cell. Electrically, the equivalent circuit is a connection in series of two cells, this is why the current cannot exceed the current generated by the weakest component.

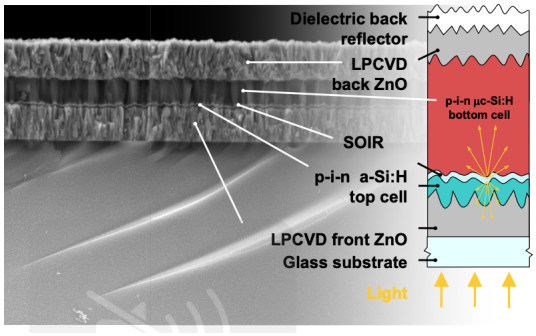

Fig. 16. Cross section through a thin film silicon tandem solar cell. Illumination is from the bottom. [4]

A. Setup

Let us measure the EQE of a tandem cell that combines an amorphous silicon solar cell with band gap energy of $1.7\,\mathrm{eV}$ and a micro-crystalline solar cell with band gap energy of $1.1\,\mathrm{eV}$ [4]. The setup for this experiment is the same as the one for the first experiment with a tandem solar cell, it is shown in Figure 7.

B. Results

The results obtained for this experiments are stored in Table VI. In fact we only took note of the current produced by the top and bottom cells $I_{top} = I_{btm}$ for different wavelengths, because the setup did not change so P_{cell} and P_{ref} should have not been modified. These latter do not depend on the type of cell, they characterize the incoming light and the powermeter.

TABLE VI
Results EQE Measurements

$\lambda\ [nm]$	$P_{cell}\ [mW]$	$P_{ref}\ [mW]$	$I_{top} = I_{btm}\ [mA]$
340-350	2.15	2.95	0.1280
360	1.77	2.49	0.1280
380	3.04	1.52	0.1280
400	3.777	1.07	0.1310
420	6.511	1.57	0.1330
440	10.16	2.08	0.1340
460	16.63	3.23	0.1360
480	31.05	5.64	0.1390
500	27.8	4.76	0.1410
520	35.59	6.63	0.1440
540	25.1	4.24	0.1440
560	46.27	8.03	0.1570
580	47.7	8.75	0.1660
600	61.77	11.18	0.1850
620	73.01	13.41	0.2010
640	61.36	11.26	0.1880
660	81.84	15.13	0.1940
680	89.94	16.76	0.1850
700	78.41	14.47	0.1600
720	87.3	16.62	0.1490
740	91.7	17.26	0.1380
760	100.71	19.22	0.1350
780	107.25	20.79	0.1310
800	103.61	20.7	0.1300
820	106.36	21.28	0.1280
840	107.31	20.54	0.1290
860	102.55	19.32	0.1290
880	124.58	23.96	0.1290
900	86.56	13.41	0.1300
920	82.64	14.44	0.1280

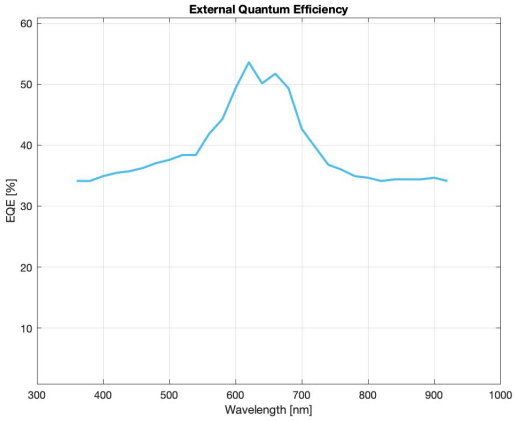

Fig. 17. EQE of a tandem solar cell

With the *Matlab* code of Figure 20, the Figure 17 is plotted.

The dimensions of the cell have been set at $Cell_L = 8\,\mathrm{mm}$ and $Cell_W = 15\,\mathrm{mm}$.

The EQE is smaller than the one expected: the main peak is at 53% whereas it was at a stable level of 70% for a single cell. It is clear that having a smaller EQE for tandem cell is a surprising result, far from the theoretical one. One main factor can explain this difference: the head of the powermeter might have change its alignment with the incoming light, resulting in a loss of sensed photons.

VI. Conclusion

This laboratory on solar cells allowed us to have an overview of the factors that qualify a cell: in particular its external efficiency and its I-V response. We also understood the equivalent representation and how it can help us to identify the parameters of the cell. In these times when scientists try to figure out how to resolve the environmental crisis, solar panels are described as a good source of carbon-free energy and are thus an important object of interest.

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VII. Appendix

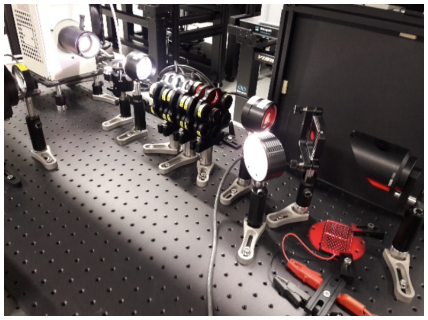

Fig. 18. Picture of the setup for the measurement of the EQE

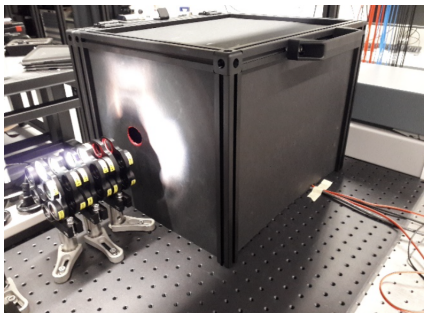

Fig. 19. Picture of the setup for the measurement of the EQE with the black box

Fig. 20. Matlab code for the first experiment

```
%% Solar Cell Experiment - First part
%
% This script is intended to display the figures corresponding to the
% measurement of a solar cell external quantum efficiency (EQE). Data is to
% be entered in the "Data Entry" section.

% Tip : Consider the use of ... to break the entry on multiple lines !

% Clearing of the work environment
clear all
close all
clc

%% Data Entry
% Wavelengths considered (in nm)
Lambda_Mes = (360:20:920);

Power incident on the solar cell. Data between the brackets is in mW
P_inc = 1e-6*[...
    1.9 , 5.4 , 8.4 , 16.0 , 26.3 , ...
    40.3 , 49.9 , 54.7 , 68.6 , 75.3, ...
    73.8 , 77.4 , 97.7 , 109.4 , 93.8, ...
    123.5 , 129 , 114.3 , 122.3 , 123.7, ...
    140.0 , 147.0 , 140.7 , 148.0 , 152.2,...
    142.6 , 173.8 , 121.4 , 115.9];

Power reflected from the glass plate. Data between the brackets is in mW
P_Refl = 1e-6*[...
    1.0 , 4.5 , 8.1 , 15.3 , 24.0 , ...
    36.0 , 43.4 , 47.0 , 58.8 , 64.3 , ...
    63.2 , 65.9 , 83.9 , 94.1 , 80.4 , ...
    106.4 , 112.2 , 99.8 , 108.7 , 109.9 , ...
    126.8 , 134.6 , 131.9 , 140.5 , 143.7 , ...
    133.5 , 161.3 , 110.6 , 102.8];

Power reflected by the LED. Data between brackets is in mW
P_LED = 1e-6*[...
    0.0 , 0.1 , 0.1 , 0.2 , 3.1 , ...
    5.8 , 2.6 , 3.7 , 5.8 , 6.7 , ...
    7.2 , 8.6 , 11.4 , 10.8 , 6.8 , ...
    5.5 , 3.4 , 1.5 , 0.9 , 0.5 , ...
    0.3 , 0.2 , 0.1 , 0.0 , 0.0 , ...
    0.0 , 0.0 , 0.0 , 0.0];

Short circuit current measured. Data between brackets is in mA
I_sc = -1e-3*[...
    0 , 3e-3 , 49e-3 , 132e-3 , 284e-3 , ...
    520e-3 , 729e-3 , 891e-3 , 1.2 , 1.44 , ...
    1.5 , 1.66 , 2.21 , 2.56 , 2.27 , ...
    3.07 , 3.31 , 3.00 , 3.25 , 3.30 , ...
    3.80 , 4.02 , 3.92 , 4.15 , 4.28 , ...
    4.00 , 4.80 , 3.35 , 3.14];
```

```
Diameter of sensor aperture. Data between brackets is in [mm]
Sensor_d = 1e-3*[6];

Diameter of the beam incident on the solar cell. Data between brackets is
in [mm]
Spot_d = 1e-3*[88];

Diameter of the beam reflected on the power meter head. Data between brackets is
in [mm]
Refl_d = 1e-3*[29];

Cells dimensions. Data between brackets is in [mm]
Cell_L = 1e-3*[62];
Cell_W = 1e-3*[31];

%% Calculation and Display of Results

Loading the reference AM specta
Ref_Spectra = csvread('ASTMG173_DATA2.csv');
Lambda_Ref = Ref_Spectra(:,1);
AM0 = Ref_Spectra(:,2);
AM_Global = Ref_Spectra(:,3);
AM_Direct = Ref_Spectra(:,4);

Some fundamental constants
h= 6.626e-34;
c = 299792458;
q = 1.602e-19;
kB = 1.3806e-23;

% Room temperature (in K)
T = 20+273.15;

% Corresponding areas
Sensor_A = pi*(Sensor_d/2)^2;
Refl_A = pi*(Refl_d/2)^2;
Spot_A = pi*(Spot_d/2)^2;
Cell_A = Cell_L*Cell_W;

% Wavelength (in m)
Lambda_m = Lambda_Mes*1e-9;

% Reflection coeffcient
k = P_Refl./P_inc;

% Reflection ratio in terms of optical power (in %)
R = k*Refl_A/Spot_A*100;

% Power density measured at the solar cell
p_Inc = P_inc/Sensor_A;
p_LED = P_LED./k/Sensor_A;

% Optical power collected by the solar cell
P_Cell = P_inc*Cell_A/Sensor_A;

% External Quantum Efficiency
```

```
EQE = I_sc/(-q)./P_Cell./Lambda_m*h*c;

Figures
figure(1)
plot(Lambda_Mes,R,'linewidth',2)
grid on
xlabel('Wavelength [nm]')
ylabel('Reflection ratio [%]')
title('Reflection ratio of a glass plate')

figure(1)
hold on
plot(Lambda_Ref,AM_Global,'linewidth',2)
% plot(Lambda_Mes,p_Inc,'r','linewidth',2)
grid on
xlabel('Wavelength [nm]')
ylabel('Power density [W/m^2/nm]')
title('Comparison between AM1.5 and halogen spectra')
legend('AM1.5 Spectrum','Halogen Spectrum','location','northwest')
xlim([Lambda_Mes(1),Lambda_Mes(end)])

figure(3)
plot(Lambda_Mes,EQE*100,'linewidth',2)
grid on
xlabel('Wavelength [nm]')
ylabel('EQE [%]')
title('External Quantum Efficiency')
```

Fig. 21. Matlab code for the second experiment

```
%% Solar Cell Experiment - Second part
%
% This script is intended to display the figures corresponding to the measurement
% of a solar cell I-V curve. Data is to be entered in the "Data Entry" section.

% Tip : Consider the use of ... to break the entry on multiple lines !

% Clearing of the work environment
clear all
close all
clc

%% Data entry

% Voltage measured. Data between brackets is in mV
V = 1e-3*[...
    0 , 34 , 64 , 94 , 125 , ...
    154 , 184 , 213 , 241 , 269 , ...
    321 , 365 , 398 , 421 , 438 , ...
    451 , 461 , 468 , 474 , 479 , ...
    481 , 488 , 497 , 503 , 509 , ...
    514 , 519 , 524 , 530 , 535];

% Current measured. Data between brackets is in mA
I = -1e-3*[...
```

```
    299 , 299 , 298 , 298 , 298 , ...
    297 , 296 , 295 , 293 , 291 , ...
    285 , 274 , 259 , 242 , 225 , ...
    209 , 195 , 182 , 170 , 160 , ...
    155 , 139 , 119 , 102 , 86 , ...
    70 , 56 , 38 , 20 , 0];

% Algorithm parameters

n = 2.5;          % Diode ideality factor
R_step = 0.01;    % Rs incremental step in Ohm
It_max = 100;     % Maximum number of iteration
tol = 1;          % Tolerance on maximum power difference (in %)
Nb_pts = 50;      % Number of points for numerical fitting

%% Initialisation

% Some fundamental constants
h= 6.626e-34;
c = 299792458;
q = 1.602e-19;
kB = 1.3806e-23;

% Room temperature (in K)
T = 20+273.15;

% Open circuit voltage and short circuit current
V_oc = max(V);
I_sc = -max(abs(I));

% Number of measurement points
Meas_Points = length(V);

% Maximum power point (MPP)
[~,Id_Max] = max(abs(V.*I));
V_mpp = V(Id_Max);
I_mpp = I(Id_Max);
P_max = V_mpp*I_mpp;

% Fill factor
FF = V(Id_Max)*abs(I(Id_Max))/max(V)/max(abs(I));

% Initial parameters
I_0 = -I_sc/(exp(V_oc*q/n/kB/T)-1);
Rp_min = V_mpp/(I_mpp-I_sc);
Rs = 0;
Rp = Rp_min;

% Vectors for numerical fitting
V_fit = linspace(0,V_oc,Nb_pts);
I_fit = zeros(1,Nb_pts);


%% Iteration

for m = 1:It_max
```

```
    % Computation of the photovoltaic current
    I_ph = -I_sc*(Rs+Rp)/Rp;

    % Computation of the parallel resistance
    Rp = V_mpp*(V_mpp-I_mpp*Rs)/(P_max+V_mpp*I_ph-V_mpp*I_0*
    exp(((V_mpp-I_mpp*Rs)*q)/(n*kB*T))+V_mpp*I_0);

    % Numerically solving the I-V equation
    for j = 1:Nb_pts

        syms x
        I_fit(j) = vpasolve(-x-I_ph+I_0*(exp((V_fit(j)-Rs*x)*
        q/n/kB/T)-1)+(V_fit(j)-Rs*x)/Rp,x);

    end

    % Maximum power of the found fitting curve
    P_max_fit = max(abs(V_fit.*I_fit));

    % Error on maximum power in %
    e = abs(P_max_fit-abs(P_max))/abs(P_max)*100;

    % Breaking condition
    if e<=tol
        break;
    end

    % Increase in Rs
    Rs = Rs+R_step;
end

%% Figures
figure(1)
hold on
plot(V,I,'linewidth',2)
plot(V,I(Id_Max).*ones(1,Meas_Points),'r--','linewidth',2)
plot(V(Id_Max).*ones(1,Meas_Points),I,'g--','linewidth',2)
plot(V_fit,I_fit,'k','linewidth',2)
grid on
xlabel('Voltage [mV]')
ylabel('Current [mA]')
legend('Data','I_{mpp}','V_{mpp}','Fitting','location','northwest')
title('I-V curve measured and corresponding modeling')

%% Display of the final results

disp(sprintf('Open circuit voltage: %d',V_oc));
disp(sprintf('Short circuit current: %d',I_sc));
disp(sprintf('Maximum power delivered: %d', P_max));
disp(sprintf('Fill factor (FF): %d', FF));
```