

Bachelor Thesis
Comparison of amorphous silicon cells with
transparent ZnO back contact and standard contact

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thesis number: 2012.02

July 30, 2012

Abstract

To make it possible to apply an upconversion layer at the back of a thin film hydrogenated amorphous silicon (a-Si:H) solar cell, the standard a-Si:H cell must be adjusted. Instead of a layer of ZnO:Al/Ag as back contact, a layer of transparent ZnO:Al (thickness 1500 nm) functions as back contact. On these adjusted cells a diffuse white layer (Oerlikon white foil) is attached as back reflector. To compare these two kind of cells, measurements are performed with the solar simulator and the spectral response measurement system. Cells with i-layer thickness of 230 nm, 350 nm and 500 nm are used for both types of cells. Results show no big differences between cell with ZnO:Al/Ag and ZnO:Al (thickness 1500 nm) back contact with white diffuse back reflector for i-layer thicknesses 230 nm and 350 nm. Unexpectedly, cells with ZnO:Al (thickness 1500 nm) back contact, white diffuse back reflector and i-layer thickness of 500 nm have a higher ECE for wavelengths in the range 350 - 550 nm than cells with the same i-layer thickness and ZnO:Al/Ag back contact. Overall cells with i-layer thickness 350 nm (cells with ZnO:Al/Ag and cells with ZnO:Al (thickness 1500 nm) back contact with white diffuse back contact) have the highest ECE and the best parameters when measured with the spectral response and the solar simulator.

Contents

1	Introduction	3
2	Theory	4
2.1	Solar spectrum	4
2.2	Amorphous silicon	4
2.3	Standard a-Si solar cell	5
2.4	Important solar cell parameters	7
2.5	Upconversion	11
3	Experimental Methods	13
3.1	Solar simulator	13
3.2	Spectral Response	15
4	Results	17
4.1	Results measurements solar simulator	17
4.1.1	Characteristic features of reference cells with ZnO:Al/Ag back contact	17
4.1.2	Characteristic features of cells with thick ZnO:Al back contact	18
4.1.3	Degradation	18
4.2	Results measurements spectral response	21
4.2.1	Comparison with and without white diffuse back re- flector	21
4.2.2	Comparison cells ZnO:Al/Ag back contact and ZnO:Al back contact	22
5	Discussion	27
6	Conclusion	29

1 Introduction

Utilizing solar energy as renewable energy source is promising. The light of the sun is for free and it has more than enough energy to fulfill the need of energy in the world. Problem is how to convert solar energy to electric energy. The most common way to do this, is by solar cells made of semi-conduction materials. At the moment it is possible to do this conversion with an efficiency of 25.0 ± 0.5 % for single junction crystalline silicon solar cells and an efficiency of 34.1 ± 1.2 % for multi-junction cells for unconcentrated light[1]. The capacity of worldwide photovoltaic manufacturing is approximately 40 gigawatt per year and is steadily growing [2].

A lot of research is done on how to make the efficiency of solar cells higher, but also on how to make these cells profitable. Most common material now used is crystalline silicon. Cells made of this material have a lot of advantages, but also some disadvantages. A lot of silicon is needed to make crystalline silicon solar cells, which makes the solar panels expensive. Also, high temperatures are needed for the manufacturing of crystalline cells. A good alternative are thin film solar cells, especially amorphous silicon cells. Amorphous silicon solar cells have a lot of benefits, for example: high optical absorption, thus less silicon is needed, the cells can be deposited at low temperatures, on large surfaces and on different materials (glass, steal, plastics), et cetera. These advantages make the cells cheaper than cell of crystalline silicon and though they have a lower efficiency ($\sim 10\%$), it makes them profitable [3].

That is why a lot of research is done on amorphous silicon cells. High efficiency solar cells require absorption of photons of the full solar spectrum followed by effective generation, separation and collection of charge carriers. A lot of methods are invented to meet those demands for high efficiency solar cells, one of these is upconversion. Upconversion is a process whereby two or more low energy photons are converted to one photon with a high energy. This process is interesting for amorphous silicons cells, because a large part of the spectrum in the infra red is lost due to the high bandgap of amorphous silicon (~ 1.8 eV) [4].

To be able to use upconversion in amorphous silicon solar cells, the standard amorphous cell with ZnO:Al/Ag back contact needs to be adjusted. In this thesis the adjusted amorphous silicon cell with transparent ZnO:Al (thickness 1500 nm) back contact and with diffuse white back reflector is compared with the standard amorphous silicon cell with ZnO:Al/Ag back contact.

2 Theory

2.1 Solar spectrum

The spectrum of the sun, measured outside the Earth's atmosphere, closely matches a black body radiator of about 5800 K. When the light of the sun passes through the atmosphere, the light is scattered and absorbed. Especially in the infrared part of the spectrum it is absorbed by water vapor and CO_2 . But also, the ultraviolet light of the spectrum is absorbed by the ozone in the upper atmosphere. The amount of the light that is scattered and absorbed is dependent on the path length through the atmosphere. For a path length L through the atmosphere the *Air Mass coefficient* is:

$$AM = \frac{L_0}{L} \approx \frac{1}{\cos z} \quad (1)$$

Where z is the angle of incident relative to the normal of the Earth's surface and L_0 is the zenith path length (i.e. the path length normal to the Earth's surface) at sea level. The spectrum outside the atmosphere is AM-0, because the path L through the atmosphere is 0. The standard spectrum used for measurements with solar cells is AM-1.5, corresponding to a solar zenith angle of $z = 48.2^\circ$. AM-1.5 is a good representation of the solar spectrum at mid-latitudes[3]. The AM-1.5 spectrum, the AM-0 spectrum and the spectrum of the black body radiator are shown in figure 1.

2.2 Amorphous silicon

Amorphous silicon is the non-crystalline form of silicon. Silicon is a fourfold coordinated atom and normally makes tetrahedrally bonds to four neighboring silicon atoms. In crystalline silicon this tetrahedral structure has a large range, it forms a well-ordered crystal lattice. For the amorphous form of silicon this is different, instead of a large range structure only a short range structure is present. The atoms form a continuous random network, where not all the atoms are fourfold coordinated, some atoms have a *dangling bond*. These dangling bonds present defects in the continuous random network. In the cells used for this research, the material of the active layer is hydrogenated amorphous silicon (a-Si:H). This is amorphous silicon passivated by hydrogen. This reduces the dangling bond density by several orders of magnitude[3].

Because of the continuous random network, amorphous silicon has an electronic band structure, shown in figure 2. The energy levels of the outer shell electrons of the silicon atoms will split in the valence band and the

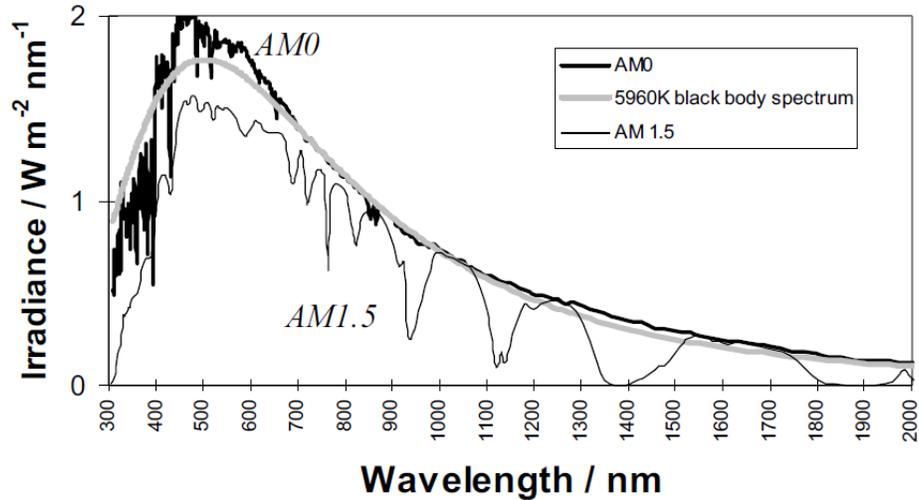


Figure 1: The AM-1.5 spectrum, the AM-0 spectrum and the spectrum of the black body radiator. [5]

conduction band. Like with all semiconductors, between the top of the valence band and the bottom of the conduction band there is a band gap. This is equivalent to the energy required to free an outer shell electron from its orbit around the nucleus and to become a mobile charge carrier. Electrons can gain enough energy to jump from the valence band to the conduction band by absorbing a photon[6].

Amorphous silicon (a-Si:H) has a band gap of ~ 1.8 eV [4], but there is a significant density of states in the band gap. The presence of defects in a-Si:H is caused by two mechanisms: the lack of order in the material causes a broadening of the valence and conduction bands, leading to band tails where localized energy states exist and unpassivated dangling bonds cause defect states near the center of the band gap (shown in figure 2). The absence of long range order results in a much larger absorption in the visible part of the solar spectrum, in comparison with crystalline silicon[6].

2.3 Standard a-Si solar cell

A standard optimized amorphous silicon solar cell has a structure as shown in figure 3. The glass is where the cell is deposited on, it needs to be as transparent as possible. TCO stands for *Transparent Conductive Oxides*, it

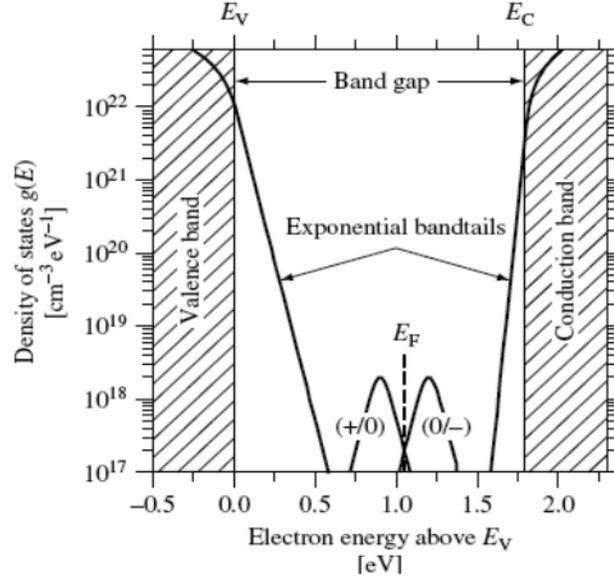


Figure 2: Bandgap of amorphous silicon, the top of the valence band and the bottom of the conduction band are not well defined[6]

acts as a window for light to pass through to active material beneath (where carrier generation occurs) and it acts as an ohmic contact for carrier transport out of the solar cell. The ZnO:Al layer is a TCO. The ZnO:Al/Ag layer on the back of the cell has the function of back contact and back reflector. The back reflector reflects the light that is not absorbed by the cell back into the cell. Crystalline solar cells mostly have a pn-junction. Amorphous pn-junctions however do not have rectification features, the p-layer and the n-layer have too many defect levels. Carriers generated in the doped layers will recombine before they can be separated at the contacts. By sandwiching an intrinsic or undoped layer between the doped layer, recombination is eliminated between the p- and n-layers. This makes the i-layer the active layer and the p- and n-layer contact layers. When the cell is illuminated, it is in the i-layer where the free carriers are created. Charge separation takes place due to the p-i and the i-n junctions and after that the charge carriers are collected in the n- and p-layers. The n- and p-layer have a thickness of 10 - 20 nm, the i-layer has a thickness of maximum 500 nm.

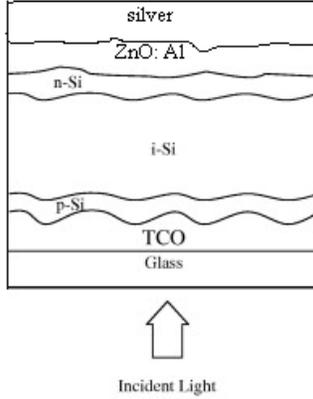


Figure 3: A standard optimized amorphous silicon solar cell with ZnO:Al/Ag back contact: glass, TCO layer, a-Si pin-junction, ZnO:Al layer and Ag back contact.

The characteristic features of a solar cell can change due to degradation. Long term illumination can decrease the fill factor and the short circuit current, especially in cell with thick i-layer. The short circuit voltage stays more or less the same. The short circuit current depends on the free path length. And the free path length of charge carriers depends on the lifetime of the carriers, i.e. the collection length, the electric field in the solar cell and the mobility of the charge carriers. The electrical field in the cell is fixed, the mobility of the carriers depends mostly on temperature, so the decrease in J_{sc} is caused by a decrease in lifetime. Which means that the density of defect in the intrinsic layer, where recombination of charge carriers takes place, has increased [3].

2.4 Important solar cell parameters

A solar cell is a photovoltaic device, it converses in a one-step process light energy to electrical energy. It makes use of the photovoltaic effect. Normally excited electrons relax back into their ground state, but in a photovoltaic device a build-in asymmetry separates the electron-hole pair and feeds them to an external circuit. How efficient the photovoltaic device is, depends on the choice of materials and the way they are connected to the external circuit.

A solar cell can be considered as a two terminal device, like a diode, which generates a voltage when charged by the sun. The voltage the cell develops when the terminals are isolated (infinite load resistance) is called the *open circuit voltage* V_{oc} . When the terminals are connected together, a current is drawn. This current is called the *short circuit current* I_{sc} . For any intermediate load resistance R_L , a voltage V between 0 and V_{oc} is developed and the cell delivers a current such that $V = IR_L$. Thus both I and V are dependent of the load and the illumination of the cell. The current is approximately proportional to the illuminated area of the cell, which makes the *short circuit current density* J_{sc} is a useful quantity for comparison [5].

The short circuit current density is dependent on the incident light, to relate those two quantities the *External Collection Efficiency* (ECE) is needed. ECE is the probability that an incident photon of wavelength λ will deliver one electron to the external circuit. So:

$$J_{sc} = q \int b_s(\lambda) ECE(\lambda) d\lambda \quad (2)$$

where b_s the number of photons of wavelength in the range λ to $\lambda + d\lambda$ which are incident on unit area in unit time, i.e. the incident spectral photon flux density and q is the charge of one electron. ECE depends on how well the material absorbs light, on the efficiency of charge separation and the efficiency of charge collection in the device [5].

A potential difference develops between the terminals of a solar cell and a current is caused by the potential difference. This current acts in the opposite direction to the photo current and the net current is reduced from its short circuit value. This reverse current is, in analogy with the current I_{dark} which flows across the device under a bias voltage V in the dark, called the *dark current*. Most solar cells behave like a diode in the dark, which means that they admit a much larger current under forward bias than under reverse bias. Since an asymmetric junction is needed to achieve charge separation, this is a feature of all photovoltaic devices. The *dark current density* J_{dark} for an ideal diode varies like:

$$J_{dark}(V) = J_0(e^{qV/k_B T} - 1) \quad (3)$$

where J_0 is a constant, k_B is Boltzmann's constant and T is the temperature in Kelvin. The current-voltage characteristic (IV-curve), the overall current voltage responds of the cell, can be approximated as the sum of the short circuit photo current and the dark current. The current that flows in an illuminated cell is not exactly the same as the current that flows in a

dark photovoltaic device, but the approximation is good enough. The sign convention for current and voltage in photovoltaics is such that the photo current is positive (although in the results of the measurements of the solar simulator the opposite is the case)[5]. So for the net current density in the cell (with the approximation of the ideal diode and assumed that the photo current does not depend on the voltage) is:

$$J = J_{sc} - J_0(e^{qV/k_B T} - 1) \quad (4)$$

The potential difference has a maximum value when the contacts are isolated, this is the open circuit voltage V_{oc} . This is the same as when the dark current and the photo current exactly cancel out. Again for an ideal diode:

$$V_{oc} = \frac{k_B T}{q} \ln\left(\frac{J_{sc}}{J_0} + 1\right) \quad (5)$$

The current-voltage product is positive when the voltage is between 0 and V_{oc} , this is when the cell generates power. The power density of the cell is given by $P = JV$. P reaches a maximum at the cell's *maximum power point*. The voltage at this maximum power point is V_m , the current is J_m . The *fill factor* is defined as the ratio:

$$FF = \frac{J_m V_m}{J_{sc} V_{oc}} \quad (6)$$

The fill factor describes the 'squareness' of the IV-curve. An IV-curve with J_{sc} , V_{oc} , FF en maximum power point is shown in figure 4.

In real cells the power is less than ideal because of resistance of the contacts and through leakage currents around the sides of the device. This makes that the IV- curve is less square and the FF lower, this can be seen in figure5.

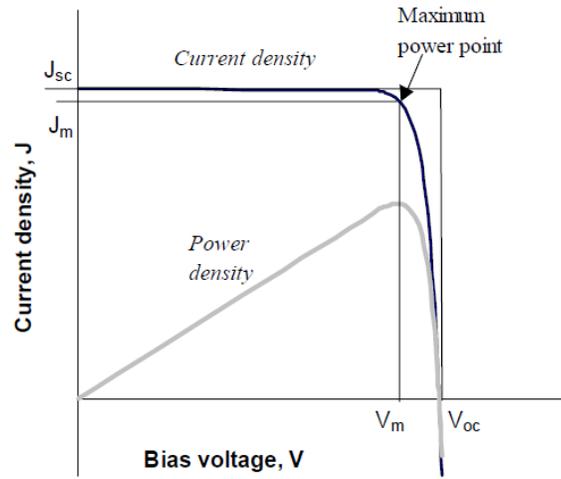


Figure 4: IV-curve with J_{sc} , V_{oc} , FF en maximum power point[5].

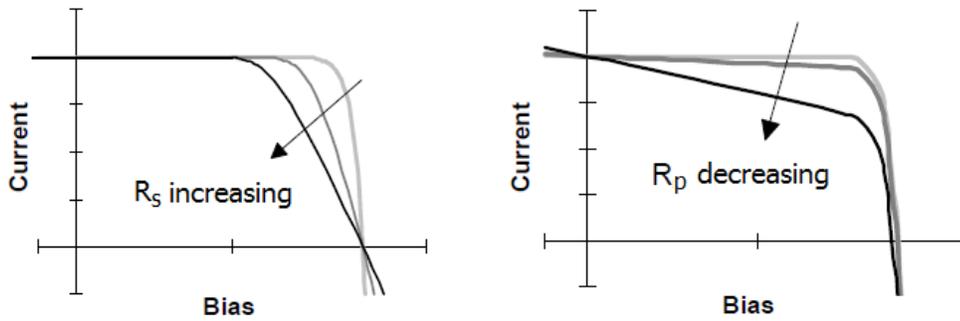


Figure 5: Here is shown what happens to the IV- curve when R_s decreases (left) and when R_p increases (right)[5].

These effects are equivalent to an ideal solar cell in a circuit with two parasitic resistances, one in series with the solar cell (R_s) and one parallel to the solar cell (R_p). The R_s is caused by the resistance of the material of the cell to the current flow, especially through the front surface to the contacts and the contacts itself. R_s is a problem for cells with high current densities. The parallel resistance prevents leakage of current through the cell, around the edges of the device and between the contacts of different polarity. In poorly rectifying cells the parallel resistance is low. For an efficient cell R_s is as small as possible and R_p is as large as possible (figure 5). When the resistances are included the diode equation looks like this:

$$J = J_{sc} - J_0(e^{q(V+JAR_s)/k_B T} - 1) - \frac{V + JAR_s}{R_p} \quad (7)$$

A solar cells behaves seldom as an ideal diode. The dark current depends commonly less on the bias voltage. The actual dependence on V is qualified by an ideality factor, N and the current-voltage characteristic given by the non-ideal diode equation:

$$J = J_{sc} - J_0(e^{qV/nk_B T} - 1) \quad (8)$$

with n typically lies between one and two, for a good solar cell n is close to one[5].

2.5 Upconversion

Amorphous silicon has a band gap of ~ 1.8 eV, which means that it is transparent for sub band gap near infrared light. These photons just go through the cell and are lost. To enhance the response of the cell in the infrared *upconversion* can be useful. Upconversion is a process whereby two or more photons with a low energy are combined to one photon with a high energy. When a layer of upconversion material is attached to the back of a amorphous solar cell, the sub band gap photons that pass through the cell, are absorbed by the upconverter material. After this, photons with high energy are emitted and send back into the solar cell by a back reflector [4]. For this to work, some changes most be made in the design of the solar cell. The standard a-Si solar cell, shown in figure 3, has a ZnO:Al/Ag back contact which has also the function of back reflector. The upconverter layer needs to be placed behind the back contact, so the back contact must be transparent. On the rear of the cell a back reflector must be attached, this will be a white back reflector. This could be a silver back reflector, but the electric conductivity is not needed here, a diffuse white back reflector

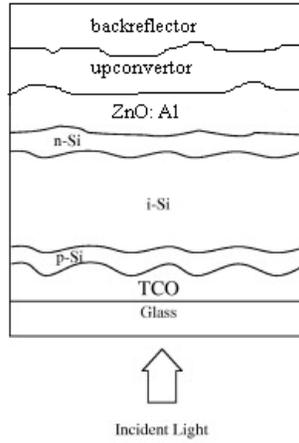


Figure 6: Adjusted amorphous silicon solar cell with ZnO:Al backcontact: glass, TCO layer, a-Si pin junction, ZnO:Al layer of thickness 1500 nm, up-conversion layer and white back contact.

is preferred. The design for the cell with the ZnO:Al back contact with upconverter layer and white back reflector is shown in figure 6.

3 Experimental Methods

Measurements are performed on p-i-n cells. p-i-n cells are described in the section ‘Theory’. Of these cells two types of cell are compared. The first type is standard a-Si cell with ZnO:Al/Ag back contact and i-layer thicknesses of 230 nm, 350 nm and 500 nm. The second type is a-Si cell with ZnO:Al layer of thickness 1500 nm as back contact and a diffuse white back reflector and with i-layer thicknesses of 230 nm, 350 nm and 500 nm. The diffuse white back reflector is made of Oerlion white foil. For the characterization of these solar cells two methods are used: the solar simulator and the spectral response measurement system. Both are further explained in the following subsections.

3.1 Solar simulator

The *solar simulator* is one of the most important characterization setups in the group Physics of Devices. The group actually has two solar simulators, but only one is used for calibrated efficiency measurements. Like the name says, the solar simulator simulates the light of the sun with respect to spectral distribution and total intensity. The spectrum that is matched is called the AM-1.5 Global spectrum. The spectrum is built with two types of lamps: a 1000 Watt xenon lamp for the UV and visible part of the spectrum (below 700 nm) and a 300 Watt halogen lamp for the infrared part. The Xenon lamp current is adjusted in order to get sufficient light output in the range of 350-700 nm. The halogen lamp current is set to 20 Ampere all the time. The light output in the range of 700-1100 nm is regulated by adjusting the position of the lamp in the Z-direction. With help of a computer and a Keithley 238 source meter, an IV-curve can be obtained for a photovoltaic device. Important parameters can be derived from the IV-curve, like J_{sc} , V_{oc} , FF, R_s and R_p . Also diode characteristics, like N, can be obtained by measuring the IV-curve in the dark [7].

The solar simulator setup has two main parts. First the solar simulator itself and secondly the IV-measurement setup. A schematic drawing of the solar simulator is shown in figure 7. The solar simulator is a commercial system which projects light of AM-1.5 spectrum and one sun intensity on a 14x14 cm area, at a temperature of 25°C, i.e. the standard conditions. The cells are placed in this area[7]. The light of the Halogen lamp and the Xenon lamp are mixed by a mirror(indicated with 1, 15 and 5 in figure 7).

There are two way to measure solar cells with the solar simulator. One way is by hand, the cells are connected by hand and only one cell at the time

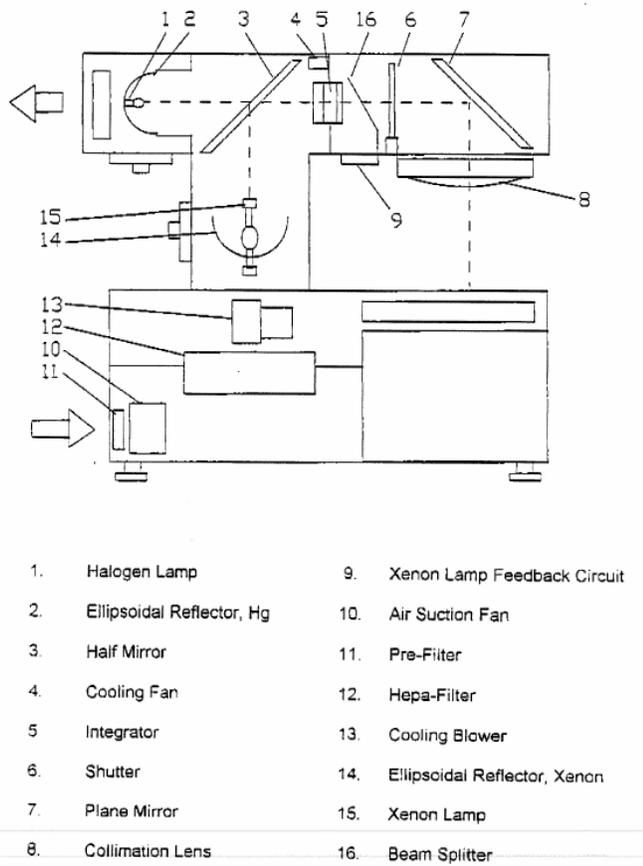


Figure 7: A schematic drawing of the solar simulator [8].

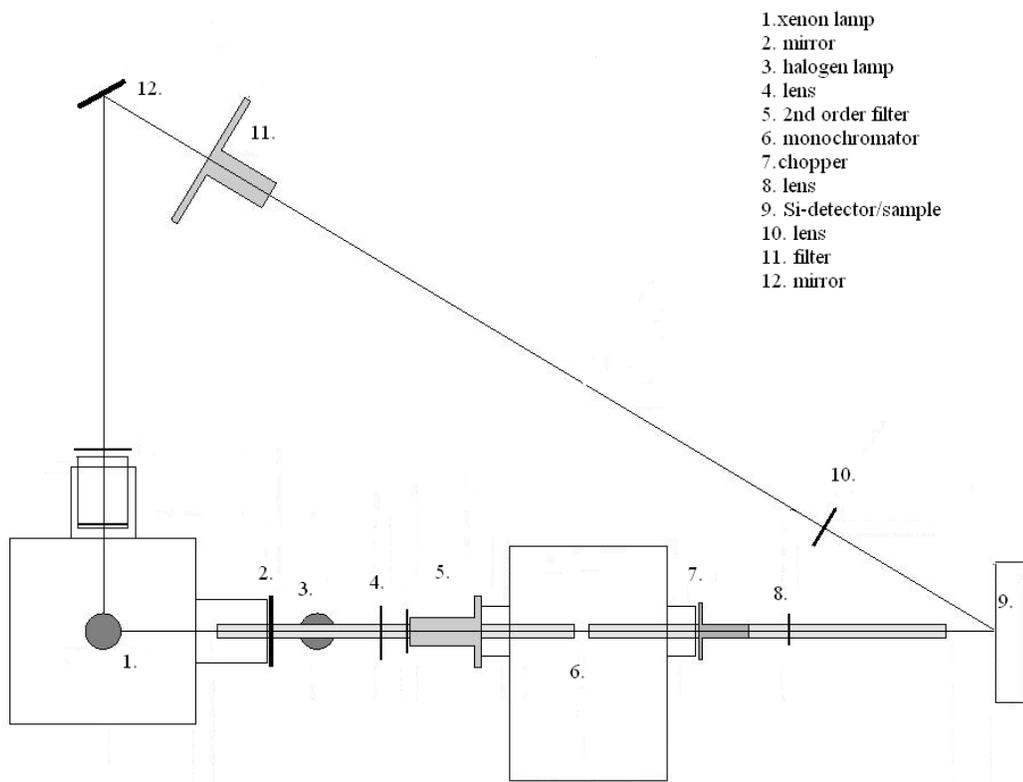
can be measured. The other way is with the ‘Automatic IV-measurement setup’. The setup has two main purposes. First to automate the measurement of samples with many cells. Secondly to make the measurement more accurate and repeatable. It turned out that the contacts of the cells need to be of a very good quality for this to work, that is why a lot of the measurements with the solar simulator are performed by hand.

3.2 Spectral Response

A lot of information of solar cells can be obtained by analyzing the spectral response of these solar cells. The purpose of the *spectral response measurement system* is to obtain the External Collection Efficiency (ECE) for amorphous silicon solar cells for different wavelengths under certain boundary conditions.

A schematic drawing of the spectral response measurement system is shown in figure 8. The light source is a 1000 W High Pressure Xenon lamp (indicated with 1. in figure 8), a xenon lamp is used because it has a spectral distribution resembling the sun and because a xenon lamp is an arc lamp, which means it is a bright radiating source, close to a point source. The xenon lamp is mounted in a lamp housing with two exit beams; the monochromator beam and the bias beam. The monochromator beam leaves the lamp housing and passes a monochromator (indicated with 6 in figure 8), the chopper (indicated with 7 in figure 8) and illuminates the sample. The bias beam leaves the lamp housing on the other side and via a mirror and a filter (indicated with 12 and 11 in figure 8) it shines on the sample if the measurement is performed with bias light. A lock-in amplifier picks up the signal at the chopper frequency and suppresses any background illumination. In this way it is possible to superimpose the chopped monochromatic light beam with a intense full spectrum bias light. A measurement can be performed with and without bias light and also with and without bias voltage. The bias voltage is regulated by the computer [9].

The solar cell is placed between two sliding bars (indicated with 9 in figure 8). The solar cell is translated in a plane perpendicular to the monochromator beam. The longer probe must make contact with the back contact of the solar cell. Before every series of measurements, a reference measurement must be done, the reference measurement is performed on a calibrated photodetector without bias light and without bias voltage. The reference measurement is used to determine the number of photons entering the cell. The solar cell measurement is used to determine the number of electrons collected at the solar cell electrodes[9].



- 1. xenon lamp
- 2. mirror
- 3. halogen lamp
- 4. lens
- 5. 2nd order filter
- 6. monochromator
- 7. chopper
- 8. lens
- 9. Si-detector/sample
- 10. lens
- 11. filter
- 12. mirror

Figure 8: A schematic drawing of the spectral response [9].

4 Results

4.1 Results measurements solar simulator

Cells with thick ZnO:Al back contact and white diffuse back reflector and cells with ZnO:Al/Ag back contact are hard to compare, because the area of cells with ZnO:Al/Ag back contact is exactly 16 mm^2 , while the area of cells with ZnO:Al back contact is only approximately 16 mm^2 . The area of the cell is especially relevant for the current, that is why it is not possible to compare the current of two different types of cells with measurements of solar simulator. The results are the average of measurements on three to five solar cells.

4.1.1 Characteristic features of reference cells with ZnO:Al/Ag back contact

In table 1 the characteristic features of the reference cells with ZnO:Al/Ag back contact are listed. Measurements have been done on three types of cells, cells with an i-layer with a thickness of 230 nm, with an i-layer with a thickness of 350 nm and with an i-layer with a thickness of 500 nm. The measurements are performed with the solar simulator. These measurements are performed when the cells were just made, so degradation has not influenced these measurements. Overall the cells with i-layer thickness of 350 nm give the best results. Except for the V_{oc} , this parameter is better for cells with i-layer thickness of 230 nm. Unlike expected, cells with i-layer thickness of 500 nm do not have the highest J_{sc} , this can also be seen in the results of the spectral response measurements.

	i=230 nm	i=350 nm	i=500 nm
$J_{sc}[mA/cm^2]$	15.1 ± 0.2	16.1 ± 0.1	15.36 ± 0.06
$V_{oc} [V]$	0.832 ± 0.001	0.802 ± 0.001	0.800 ± 0.002
FF	0.708 ± 0.002	0.720 ± 0.001	0.714 ± 0.003
$R_s [\Omega/cm]$	5.3 ± 0.1	4.3 ± 0.1	4.6 ± 0.1
$R_p [\Omega/cm]$	1663 ± 270	1762 ± 194	872 ± 39
$I_o[A/cm^2]$	$(1.8 \pm 0.6) * 10^{-11}$	$(1.1 \pm 0.2) * 10^{-11}$	$(1.9 \pm 0.1) * 10^{-11}$
N	1.60 ± 0.03	1.50 ± 0.01	1.59 ± 0.02

Table 1: Results of measurements with the solar simulator of cells with silver backcontact.

4.1.2 Characteristic features of cells with thick ZnO:Al back contact

In table 2 the characteristic features of cells with ZnO:Al (thickness 1500 nm) back contact and without back reflector are listed. These measurements are performed when the cells were just made, so degradation has not influenced these measurements.

	i=230nm	i=500nm
Jsc [mA/cm^2]	13.2 ± 0.2	16.9 ± 0.1
Voc [V]	0.832 ± 0.001	0.833 ± 0.002
FF	0.680 ± 0.003	0.693 ± 0.002
Rs [Ω/cm]	7.0 ± 0.2	5.5 ± 0.1
Rp [Ω/cm]	957 ± 18	1677 ± 139
Io [A/cm^2]	$(1.4 \pm 0.8) * 10^{-12}$	$(6.4 \pm 0.4) * 10^{-12}$
N	1.66 ± 0.09	1.48 ± 0.03

Table 2: Results of measurements with the solar simulator of cells with ZnO:Al back contact and without back reflector.

4.1.3 Degradation

It is hard to compare the cells with ZnO:Al/Ag back contact with the cells with ZnO:Al back contact in measurements with the solar simulator. In table 3 and in figure 9 two measurements with the solar simulator are compared, both of the same solar cells, ZnO:Al back contact without back reflector and i=230 nm. One measurement is performed when the cells were just made, on June 15 2010, called the first measurement. The other measurement is performed on February 8 2012, called the second measurement. In table 3 as well as in figure 9 can be seen that R_s increases and the current decreases. But the FF does not degrade, which suggests loss of reflection. The same kind of comparison is done for cells with a silver back contact. The first measurement is performed on February 28 2012 and the second measurements on April 14 2012. The results of these measurements are shown in table 4 and in figure 10. The characteristic features of the cell are in both measurements more or less the same, so that for these types of cells the reflection does not degrade.

	first measurement	second measurement	difference
$J_{sc}[mA/cm^2]$	16.9 ± 0.1	13.7 ± 0.3	-0.19 ± 0.04
$V_{oc} [V]$	0.833 ± 0.002	0.817 ± 0.002	-0.019 ± 0.004
FF	0.693 ± 0.002	0.694 ± 0.004	0.001 ± 0.001
$R_s [\Omega/cm]$	5.5 ± 0.1	7.1 ± 0.3	0.29 ± 0.05
$R_p [\Omega/cm]$	1677 ± 139	3697 ± 1881	1.2 ± 0.4
$I_o[A/cm^2]$	$(6.4 \pm 0.4) * 10^{-12}$	$(6.9 \pm 0.5) * 10^{-12}$	0.01 ± 0.14
N	1.48 ± 0.03	1.52 ± 0.01	0.027 ± 0.006

Table 3: Results of measurements with the solar simulator of cells with ZnO:Al back contact without back reflector and i-layer thickness of 230 nm, comparing two measurements of the same cells to check for degradation.

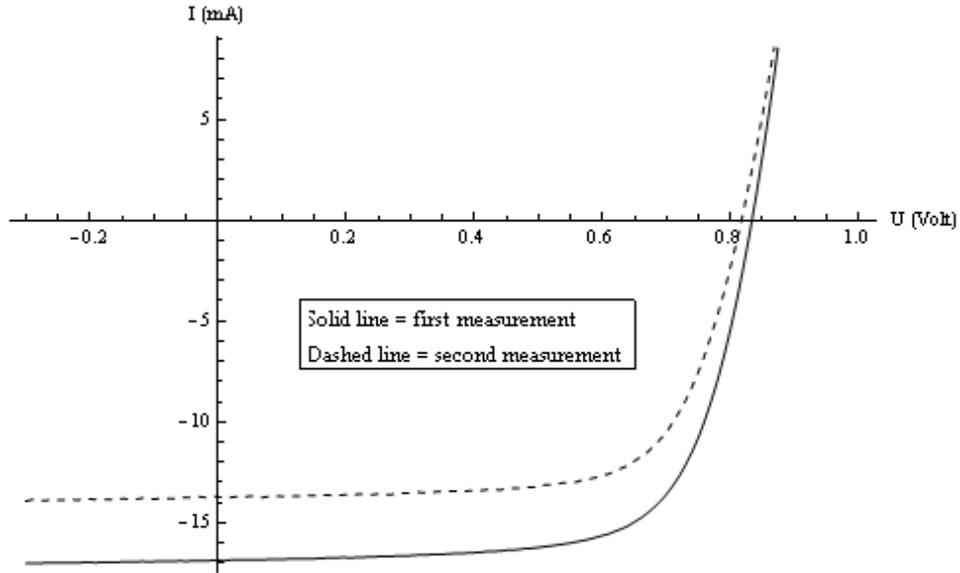


Figure 9: IV-curve of the first and second measurement of cells with ZnO:Al back contact without back reflector and i-layer thickness of 230 nm.

	first measurement	second measurement	difference
$J_{sc}[mA/cm^2]$	15.2 ± 0.224	15.8 ± 0.156	0.04 ± 0.02
$V_{oc} [V]$	0.832 ± 0.001	0.828 ± 0.001	-0.005 ± 0.003
FF	0.711 ± 0.001	0.706 ± 0.002	-0.006 ± 0.004
$R_s [\Omega/cm]$	4.98 ± 0.09	4.71 ± 0.08	-0.01 ± 0.03
$R_p [\Omega/cm]$	2147 ± 306	1446 ± 263	-0.3 ± 0.5
$I_0[A/cm^2]$	$(7.4 \pm 0.3) * 10^{-12}$	$(1.5 \pm 0.1) * 10^{-11}$	1.0 ± 0.1
N	1.55 ± 0.01	1.60 ± 0.01	0.03 ± 0.01

Table 4: Results of measurements with the solar simulator of cells with ZnO:Al/Ag back contact and i-layer thickness of 230 nm, comparing two measurements of the same cells to check for degradation.

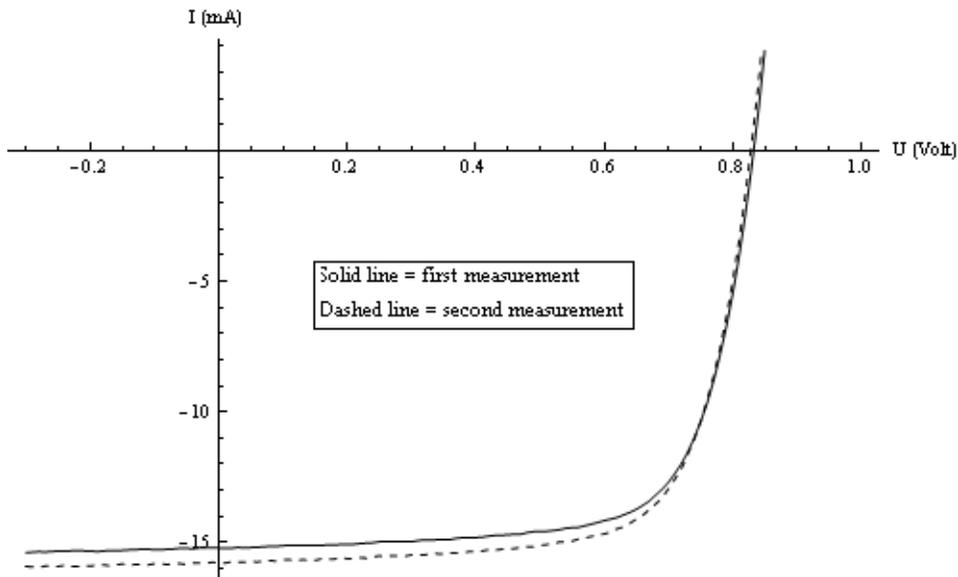


Figure 10: IV-curve of the first and second measurement of cells with ZnO:Al/Ag back contact and i-layer thickness of 230 nm.

4.2 Results measurements spectral response

All measurements presented in this subsection are performed without bias light and without a bias voltage. Some measurements were done with bias light, but turned out that it did not make a difference. Also by a bias voltage of -1 Volt some measurements were performed, this made a little difference. The current for measurements by bias voltage of -1 Volt is a little higher. This is to be expected, because R_p is not infinite, but around 1 k Ω /cm. Because the difference is not big and it can be explained, all the following measurements are performed by a bias voltage of 0 Volt and without bias light.

The benefits of spectral response measurements above measurements with the solar simulator are that the current of the cells with ZnO:Al back contact and with ZnO:Al/Ag back contact can be compared and the R_s does not play a role. When measuring with the spectral response, light is concentrated on the cell and does not illuminate the whole area. This is always done in the same way, so the current generated by the different types of cells can be compared. The R_s does not play a role, because measurements with the spectral response are done at only one bias voltage, in this case just at 0 Volt. The results are the average of measurements on three to five solar cells.

4.2.1 Comparison with and without white diffuse back reflector

Table 5 shows the results of measurements with the spectral response on p-i-n cells with a ZnO:Al back contact, with and without white diffuse back reflector. The enhancement made by the back reflector is especially in the range of 550 nm to 800 nm. An example is given in figure 11, this is the result of a measurement with the spectral response of the cells with and without back reflector with $i=350$ nm. For all thicknesses of the i-layer the graph looks more or less the same, though the enhancement of the cells with $i=230$ nm is larger than the enhancement of the other cells. This is because the i-layer is very thin, so a large part of the light passes through the cell, a bigger part of the total incoming light is reflected, which results in a larger enhancement.

	Curr [mA/cm ²] without	Curr [mA/cm ²] with	Difference
i=230nm	11.8 ± 0.1	13.84 ± 0.04	0.17 ± 0.02
i=350nm	13.0 ± 0.1	14.3 ± 0.1	0.10 ± 0.02
i=500nm	13.42 ± 0.03	14.8 ± 0.4	0.10 ± 0.01

Table 5: Results of measurements with the spectral response of p-i-n cells with ZnO:Al back contact, comparing with and without white diffuse back reflector.

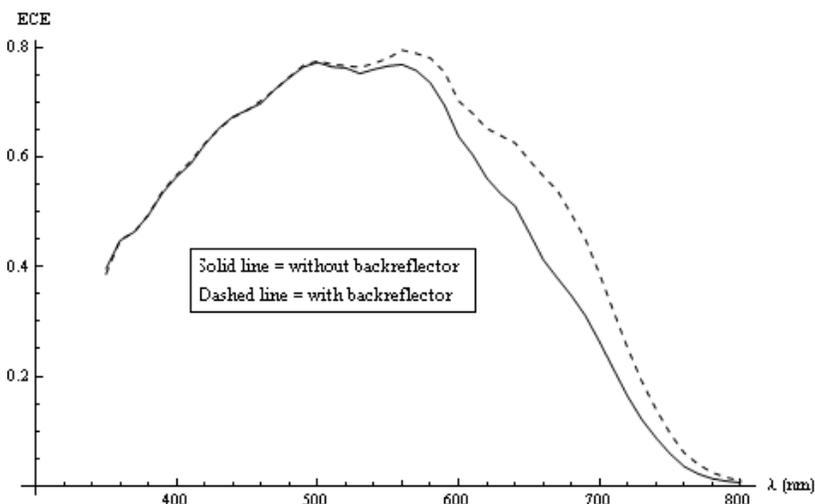


Figure 11: Spectral response measurement of cells with i=350 nm with and without white diffuse back reflector.

4.2.2 Comparison cells ZnO:Al/Ag back contact and ZnO:Al back contact

The results of measurements with the spectral response on cell with a ZnO:Al back contact with diffuse white back reflector and on cell with ZnO:Al/Ag back contact are shown in table 6. The figures 12,13 and 14 show the difference in spectral response measurements of cells with ZnO:Al back contact and cells with ZnO:Al/Ag back contact, for different thicknesses of the i-layer. For the i-layer thickness of 230 nm and 350 nm the cells with ZnO:Al/Ag back contact are slightly better, especially in the range of 300 nm to 600 nm. This is also shown in table 6, these type of cells have a slightly higher total current per area of the cell. For the thickness of the i-layer of 500 nm the cells with ZnO:Al back contact are better in the range of 300

nm to 600 nm, this makes that the total current per area larger for this type of cell.

	Curr [mA/cm ²] ZnO	Curr [mA/cm ²] silver	Difference
i=230nm	13.84 ± 0.04	14.54 ± 0.02	0.05 ± 0.01
i=350nm	14.3 ± 0.1	14.85 ± 0.02	0.04 ± 0.01
i=500nm	14.8 ± 0.4	13.63 ± 0.05	-0.08 ± 0.01

Table 6: Results of measurements of the spectral response to compare cells with ZnO:Al/Ag back contact and cells with ZnO:Al back contact and white diffuse back reflector.

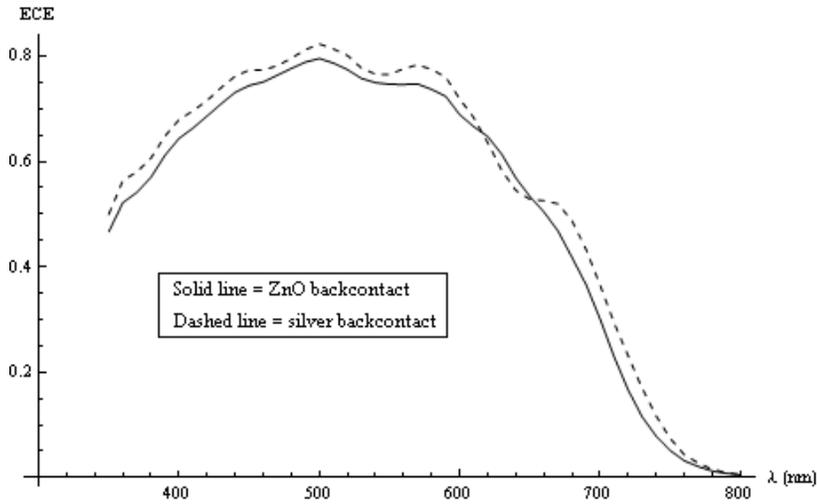


Figure 12: Spectral response measurement of cells with i=230 nm with ZnO:Al back contact and with ZnO:Al/Ag back contact.

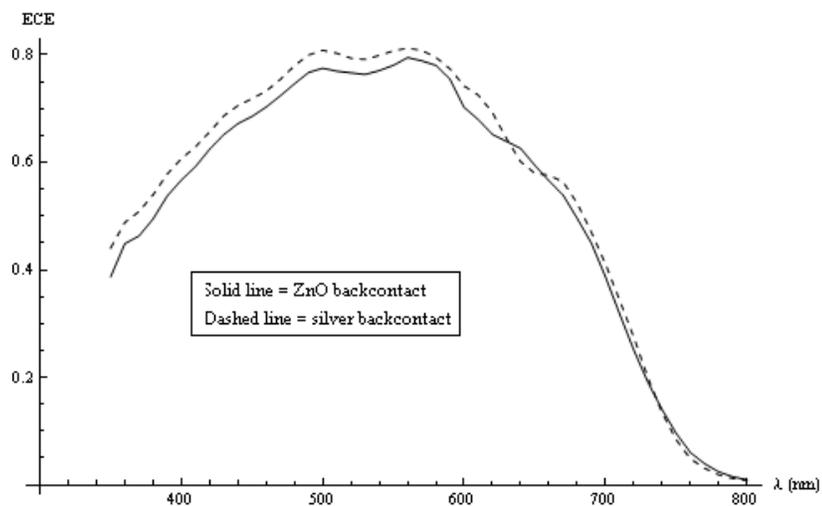


Figure 13: Spectral response measurement of cells with $i=350$ nm with ZnO:Al back contact en with ZnO:Al/Ag back contact.

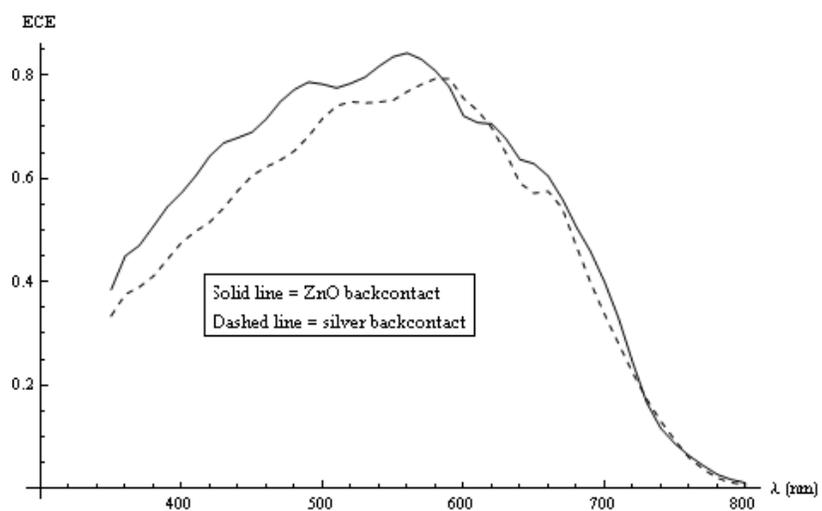


Figure 14: Spectral response measurement of cells with $i=500$ nm with ZnO:Al back contact en with ZnO:Al/Ag back contact.

Figure 15 compares the results of measurements with the spectral response for cells with ZnO:Al back contact with i-layer thicknesses of 230 nm, 350 nm and 500 nm. Figure 16 does the same for cells with ZnO:Al/Ag back contact. There are remarkable differences, the cells with ZnO:Al/Ag back contact and i-layer thicknesses of 230 nm and 350 nm perform as expected, cells with i-layer thickness of 500 nm do not. That while for cells with ZnO:Al back contact of all layer thicknesses perform more or less as expected.

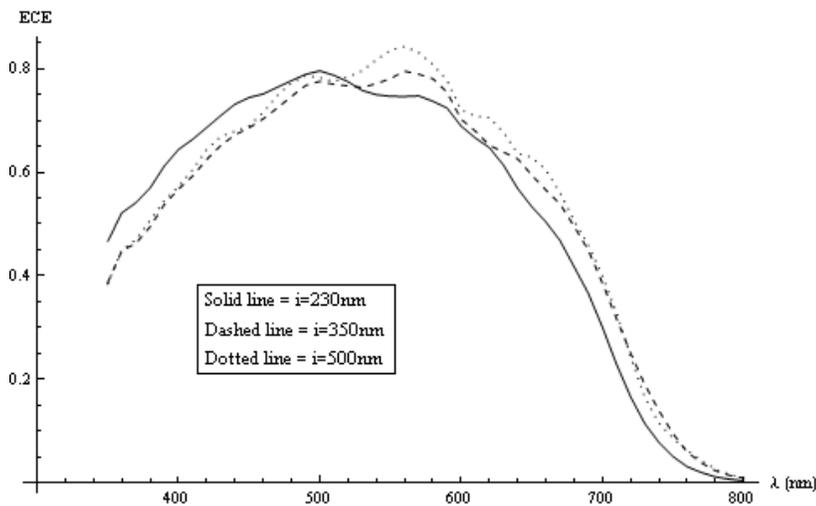


Figure 15: Spectral response measurement of cells with ZnO:Al back contact and diffuse white back reflector.

In the range of 600 nm to 800 nm, for the cells with ZnO:Al back contact there is a clear difference between the cells with an i-layer of 230 nm and the cells with an i-layer of 350 nm and 500 nm, the latter perform better. While for cells with ZnO:Al/Ag back contact all three kinds of cells have the same ECE in between those wavelengths.

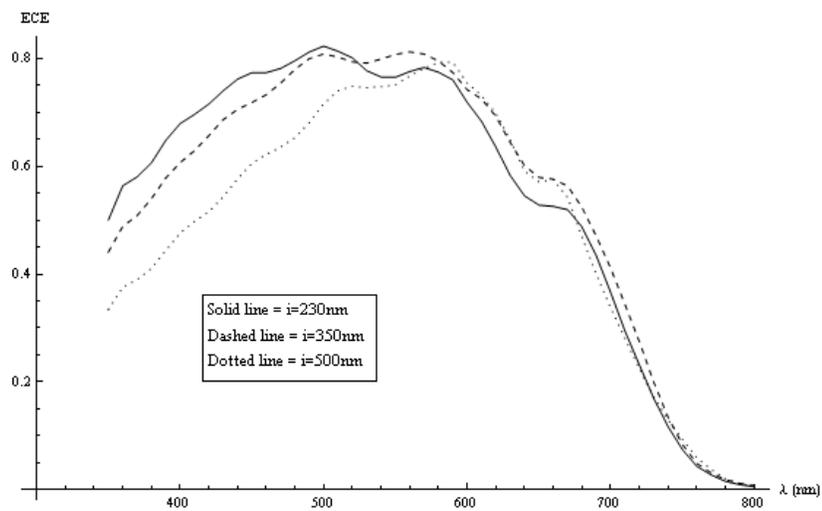


Figure 16: Spectral response measurement of cells with ZnO:Al/Ag back contact.

5 Discussion

Some of the results described in the previous section need some explanation and will be discussed in this section. First the results of the measurements with the solar simulator on cells with ZnO:Al/Ag back contact, as described in section 'Characteristic features of reference cells with ZnO:Al/Ag back contact'. It seems that the cells with $i=350$ nm performed the best, with the exception of V_{oc} , this parameter is higher for cells with i-layer of 230 nm. This is to be expected, cells with a thin i-layer have a higher V_{oc} than cells with a thicker i-layer. Cells with ZnO:Al/Ag back contact do not give the highest J_{sc} , although that is to be expected. The same effect can be seen in the results of the measurements with the spectral response.

Then the discussion of the results as shown in section 'Characteristic features of cells with thick ZnO:Al back contact'. It would have been easier to draw conclusions from the measurements with the solar simulator of the cells with ZnO:Al back contact if the cells were new and degradation had no influence (but the cells with ZnO:Al back contact that were available, were made a couple month before the measurements could be performed). Then maybe it would have been possible to make the area of the cells exactly 16 mm^2 . Now it is impossible to take the current, as measured with the solar simulator, into consideration when comparing the cells. It is to be expected that when new cells with ZnO:Al could be compared that cells with i-layer thickness of 350 nm also for cells with ZnO:Al back contact turned out to be the best.

The degradation of the cells with ZnO:Al back contact (as shown in the section 'Degradation') is likely due to an increased R_s which is caused by oxidation of the ZnO:Al layer or by water vapor uptake of the layer. That J_{sc} decreases can probably be explained by the fact that the ZnO:Al contacts of the cells are thinner on the edge than in the middle of the cell. When the contacts oxidize the resistance on the edges becomes too high to conduct and the area of the cell becomes smaller. The current is directly related to the area, so when the area decrease, the current decreases as well. Another plausible explanation is that less light in the cell is reflected.

The results of the measurement with the spectral response for cells with ZnO:Al back contact to compare the cells with and without white diffuse back reflector, as described in the section 'Comparison with and without white diffuse back reflector', are not surprising. The results for the comparison of cells with ZnO:Al back contact and cells with ZnO:Al/Ag back contact (section 'Comparison cells ZnO:Al/Ag back contact and ZnO:Al back contact') on the other hand are remarkable. Especially the results of

cells with $i=500$ nm, where the ECE of cells with ZnO:Al/Ag back contact for wavelengths of 350 nm to 600 nm is that much lower than the ECE of cells with ZnO:Al back contact, shown in 14. Also in table 1 and 2 is shown that I_0 and N were smaller for cells with $i=500$ nm and ZnO:Al back contact than for cells with $i=500$ nm and ZnO:Al/Ag back contact. This could mean that recombination is less in cells with i -layer thickness of 500 nm and ZnO:Al back contact than in cells with ZnO:Al/Ag back contact with the same i -layer thickness.

When comparing the different i -layer thicknesses, it appears again that for cells with ZnO:Al/Ag back contact and a thick i -layer recombination plays a bigger role than with cells with a ZnO back contact. For cells with ZnO:Al/Ag back contact it seems that until the wavelength of 550 nm it seems how thinner the i -layer, how higher the ECE, where for cells with ZnO:Al back contact it does not make such a difference. It is possible that something went wrong with the deposition of the cells with ZnO:Al/Ag back contact and i -layer thickness of 500 nm. The cells show bad results in the blue region of the spectrum, so there could be defects in the p -layer of in the ip -interface.

6 Conclusion

In the first instance it was the intension of this research to find out if the ZnO:Al layer of cells with ZnO:Al back contact absorbs more light than in cells with ZnO:Al/Ag back contact. This question can not be answered, but a lot of other interesting results were found.

From the ZnO:Al/Ag reference cells measured with the solar simulation it seems that the cells with i-layer of 350 nm give the best results. For all parameters these cells are better than cells with i-layer of 230 nm and 500 nm, with one exception, the V_{oc} of the cells with 230 nm is slightly better than the V_{oc} of the cells with i-layer 350 nm. It depends on which parameter is considered if the cells with 230 nm i-layer of the cells with 500 nm i-layer are better.

It is hard to compare the current of the cells with ZnO:Al back contact as measured with the solar simulator, because the area of the cells are not exactly 16mm^2 , but on bases of the other parameters can be concluded that the cells with i-layer of 500 nm perform better than cells with i-layer of 230 nm. This is also shown in the results of the measurements performed with the spectral response.

The measurements to check for degradation of cells with ZnO:Al back contact show that the J_{sc} of the cells decreases and that R_s increases. This degradation is not due to light soaking, but it is on the shelf degradation.

With the spectral response system measurements are performed to compare cells with ZnO:Al back contact, with and without white diffuse back reflector. Results of measurements with back reflector show that cells with 500 nm i-layer generate the highest current, where cells with i-layer thickness of 230 nm enhances the most.

Cells with ZnO:Al back contact and white diffuse back reflector are compared with cells with ZnO:Al/Ag back contact with the spectral response measurements. For i-layer of 230 nm and 350 nm, cells with ZnO:Al/Ag back contact generate a higher current, for i-layer of 500 nm cells with ZnO:Al back contact generate a higher current. For i=230 nm the cells with ZnO:Al/Ag back contact have a higher ECE for all wavelengths, for i=350 nm the ECE is higher for cell with ZnO:Al/Ag back contact for wavelengths from 350 to 600 nm, for i=500 nm the cells with ZnO:Al back contact and white diffuse back reflector are a lot better in the range 350 nm until 600 nm. Thought this is probably due to errors in the deposition of these type of cells.

When comparing cells with ZnO:Al back contact and white diffuse back reflector of different i-layer thicknesses it appears that for wavelengths of

500 nm, the cell with an i-layer of 230 nm performs better, after that cells with $i=350$ nm and $i=500$ nm perform better. Overall the ECE of cells with i-layer of 350 nm and 500 nm are more or less the same. The current of cells with $i=350$ and of $i=500$ nm are also almost the same and higher than the current generated by cells with $i=230$ nm.

For cells with ZnO:Al/Ag back contact the same comparison is made. To a wavelength of 550 nm it seems how thinner the i-layer, how higher the ECE, though there probably went something wrong with the cells with ZnO:Al/Ag back contact and i-layer thickness of 500 nm. In the range 550 nm until 800, cells with $i=350$ nm perform slightly better than cells with $i=230$ nm and $i=500$ nm. It turns out that 350 nm is the best i-layer thickness.

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