

Photovoltaik

Group 26

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1 Introduction

Because of the worsening image of energy from nuclear sources, more precise from nuclear fission, more and more efforts focus on finding ways to find and optimise ways of using renewable energy sources.

One of these energy sources is the sun, whose energy can be harnessed via solar panels. Because of this different kinds of solar cells and their way of functioning will be introduced and discussed.

2 Basic functions of solar cells

On the most basic level a solar cell consists of both a p-doped and a n-doped semiconductor in physical contact.

As its name implies a semiconductors ability to conduct electricity lies between that of an conductor and an insulator, what can be made vivid using the following image of the conduction and valence bands of these three types of materials, depicted in figure 1. These bands occur because of the interaction between valence electrons of the atoms in

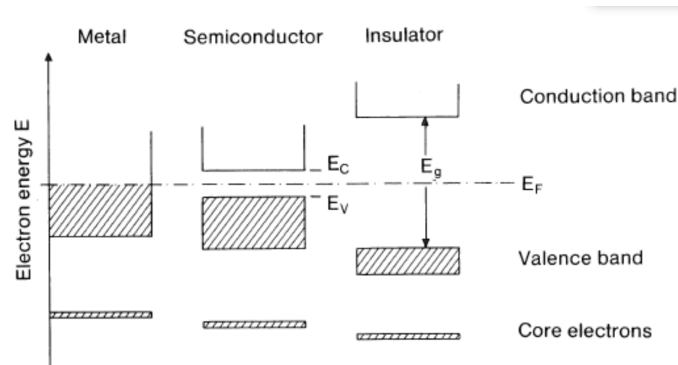


Figure 1: Depiction of the energy bands for different types of materials

a crystal and therefore forming binding and anti-binding orbitals with different energies. While only the empty or not fully filled energy bands, the conduction bands, contribute to the electrical conductivity, the full valence bands don't.

This can be seen in figure 1 where the valence bands for metals aren't completely full so the electrons can move and therefore conduct electricity, while for semiconductors and insulators there is an energy gap between the valence and conduction band. In the case of semiconductors however this gap can be overcome by exciting the electrons from the valence into the conduction band.

This process can be simplified by doping pure semiconductors, meaning the intentional injection of foreign atoms. Also there are two types of dopings, the p- and the n-doping. The first one describes the injection of foreign atoms with less valence electrons than the crystal atoms, for instance boron atoms in a silicon crystal. These atoms are called acceptors. This has the effect, that there are missing electrons, which can be de-

scribed as holes with a positive charge, which can rather freely travel through the crystal. These atoms are called donators.

n-doped semiconductors on the other side are infused with atoms, that have more electrons than the crystal atoms, like phosphorous atoms in a silicon crystal. With this you get free electrons, which can be similarly described as the free holes above.

Bringing two differently doped semiconductors in contact with each other results in a so called p-n-junction, what is exactly what a solar cell consists of. This p-n-junction has some interesting properties. For example, by bringing these two differently doped semiconductors in contact with each other the free electrons from the n-doped side diffuse to the p-doped side in order to fill the electron holes the acceptors created. This results in a so called depletion region in which there are no free charges but only the fixed ionized cores of the foreign atoms. The donators are positively charged due to losing their extra electron, while the acceptors are negatively charged because of exactly this electron filling the hole. This separation of charges then results in an electrical potential, that is hard to overcome for charged particles from outside of the depletion region, if not provided with enough energy.

If a photon now enters the p-doped part of the depletion region it separates electrons from the atomic cores in this area, producing negative and positive charges in the process. The negative electrons are then repelled by the negatively charged acceptors in the p-doped part, while the positively charged donators attract them and therefore the electrons travel through the depletion region to the n-doped side where they can be tapped by various electrical contacts. The exact same argumentation can be applied to the positive ion created by the photon, with the only difference that it is moving away from the n-doped side further into the p-doped side because of the difference of charge. This photocurrent can then be used to power various components.

3 Used materials

The materials used for the various measurements were amorphous silicon, crystalline silicon with a flat side, crystalline silicon with a rough side, silicon with a pyramidal structure on its surface, black silicon and silicon with an antireflective coating for a wavelength of 660nm. Black silicon also has a pyramidal structure on its surface, but the dimensions of these pyramids are smaller than the absorbing wavelength. This creates a smooth transition from the refractive index of air to the refractive index of silicon, sucking in the light.

4 Experimental Results

4.1 Optical properties of crystalline silicon

First the wavelength - dependent reflectivity of six different surfaces was measured, what can be achieved in the following way.

With two materials of two different refractive indices n_1 and n_2 , the reflectivity is given

by equation 1.

$$R = \left(\frac{n_2 - n_1}{n_1 + n_2} \right)^2 \quad (1)$$

With an approximated refractive Index of air of 1.0, the equation formulates to 2. After applying the equation to each datapoint in figure 2a one gets the wavelength-dependent reflections of crystalline silicon, seen in figure 2b.

$$n(\lambda) = \frac{\sqrt{R(\lambda)} + 1}{\sqrt{R(\lambda)} - 1} \quad (2)$$

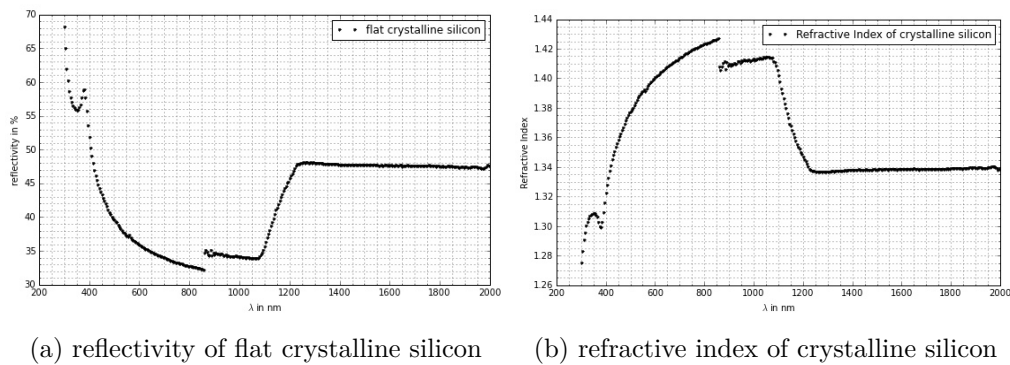


Figure 2: properties of flat crystalline silicon

Silicon with nonflat surfaces Another form to reduce the reflections on the silicon is to increase its effective surface. There are two variations of the preparation. One is to make the silicon rough and create irregular shapes on the surface, increasing the size of the surface. Another way is to put a strong acid on the surface of the flat silicon. Due to the crystalline structure of the silicon the acid etches small square pyramids into the surface. This increases the surface for the incoming light, and increases the way for the light through the silicon, making the absorption of a photon more probable. As described above, the black silicon has small needles with a thickness of a few hundreds nanometers and a length of about $5\mu\text{m}$ on the surface, which create a smooth transition of the refractive index from air to silicon.

4.2 Amorphous silicon

The Amorphous silicon in our experiment was partly transparent. This creates interference Effects, which lead to either very high or very low reflectivity of the silicon depending on the Wavelength. The reflectivity of amorphous silicon is seen in figure 5. The condition for destructive interference is following: The thickness of the material d needs to be just right in order to cause a phase shift between the first-reflection wave

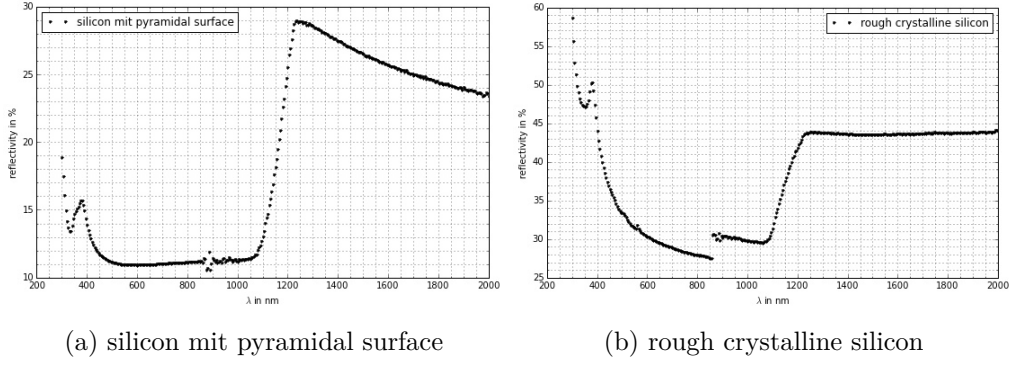


Figure 3: reflectivities for rough and pyramidal silicon

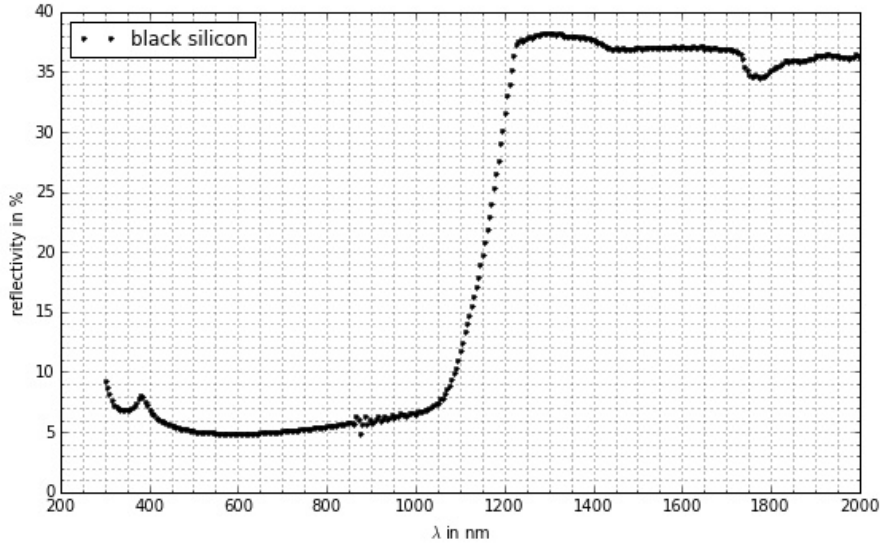


Figure 4: black silicon

and the second-reflection wave of $\lambda/2$. This is condition is described in equation 3. The number m is the number waves within the material.

$$2d = \frac{(2m + 1)}{2} \cdot \lambda_n \quad (3)$$

The figure 5 shows a whole interference pattern. Each minimum is given by the condition above. From the difference of those interference minima it's possible to calculate the number of waves within the material⁴, and thus the thickness of the amorphous silicon. It's important to calculate these wavelengths with the respect to the correct refractive indizes for the given wavelength, as the travelling time though the material causes the phase-shift.

$$m = \frac{1}{2} \left(\frac{\lambda_2}{\lambda_1 - \lambda_2} - 1 \right) \quad (4)$$

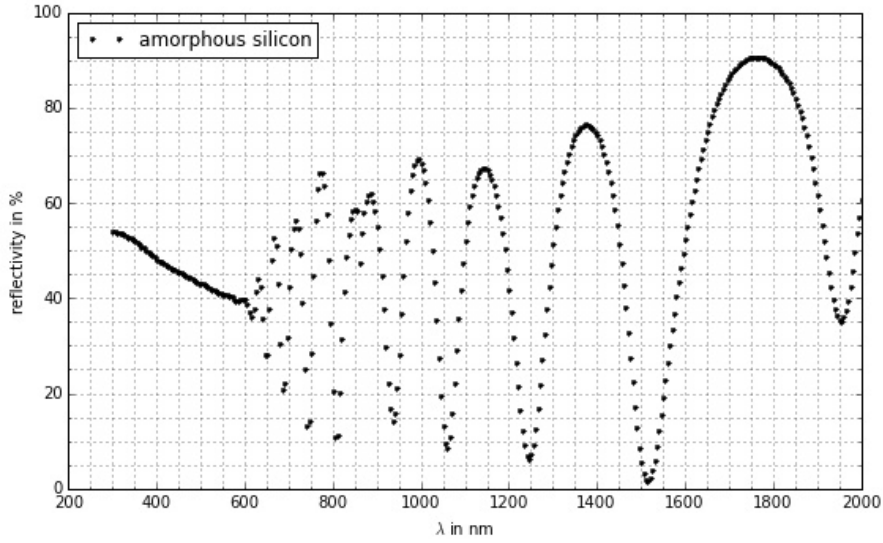


Figure 5: interference pattern in amorphous silicon

with $\lambda_1 > \lambda_2$

The wavelengths of minimal reflection [1955.0nm, 1515.0nm, 1245.0nm] and the refractive indices of crystalline silicon at those give wavelengths [1.34, 1.33, 1.33] were used. The resulting thickness for the amorphous silicon is 1286 ± 24 nm.

The same interference effect is used to optimize the efficiency of solar cells for the solar spectrum. The sun emits the most light in the range of 500 - 700 nm. To reduce the reflections for these wavelengths, one can apply a coating with an optical thickness of 150nm and use the interference effect to increase the absorption of light in the solar cells. The reflection spectrum of silicon with an anti-reflective coating is shown in figure 6.

4.3 Electric properties of solar cells

Optimal point of operation Solar cells have an optimum point of operation where their efficiency is maximal. This point can be measured by lighting the solar cell, connecting a reverse voltage to it, and gradually changing it, while looking at the current. The optimal point of operation is when the $P = U \cdot I$ is maximal. In figures 7a and 7b the voltage-current graphs for amorphous and crystalline silicon are shown. The lightly marked area describes the Product of the short-circuit-current I_{sc} and the maximum voltage with no current U_{oc} . The stronger marked area describes power, which can be taken from the solar cell at its optimal point of operation $P_{opt} = U_{opt} \cdot I_{opt}$. The ratio between these two powers is called specific filling factor $FF = (U_{opt} \cdot I_{opt}) / (I_{sc} \cdot U_{oc})$. This factor gives an information about the quality of the solar cell, especially with respect to the internal serial R_s and parallel R_p resistances within the solar cell. The power of the incoming light was tuned to be 100 mW/cm^2 , and the diameter of the whole, into which the

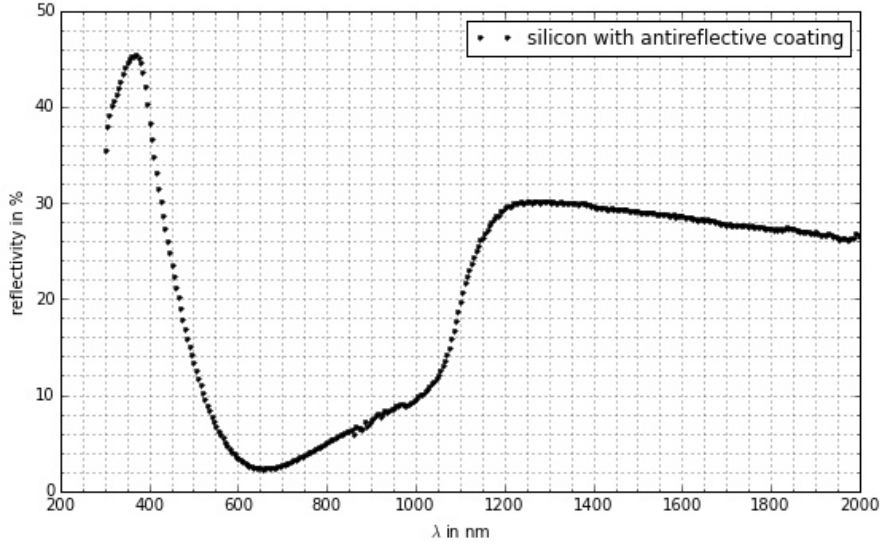
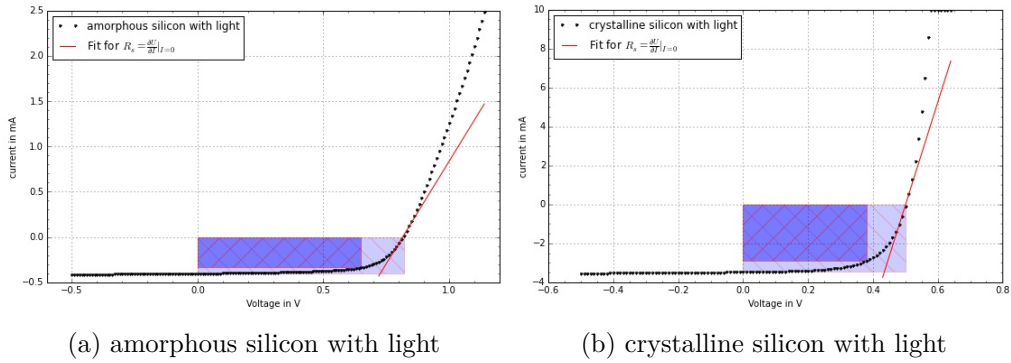


Figure 6: silicon with antireflective coating

light fell was 3mm wide. With this information it was possible to calculate the incoming light power onto the solar cell, and the efficiency of the solar cell at it's optimal point.

silicon type	R_p	R_s	FF	U_{opt}	I_{opt}	η
amorphous	$61 \pm 1 M\Omega$	$221 \pm 5 \Omega$	0.66	$650 \pm 5 mV$	$330 \pm 5 \mu A$	$3 \pm 1 \%$
crystalline	$5,89 \pm 0,4 k\Omega$	$18 \pm 1 \Omega$	0.63	$380 \pm 5 mV$	$2880 \pm 5 \mu A$	$15 \pm 4 \%$



(a) amorphous silicon with light

(b) crystalline silicon with light

Figure 7: voltage - current graphs of lighted cells

The serial resistances was determined at a point, where the parallel resistance had the least influence on the measurement, at a zero Voltage. As $R = \frac{\Delta U}{\Delta I} \rightarrow R_s = \frac{\partial U}{\partial I} |_{U=0}$, and $R_P = \frac{\partial U}{\partial I} |_{I=0}$. These tangents were made with a linear fit with at least three points closest to $U = 0$, and $I = 0$. The tangents are shown in figures 7b, 7a, 8b and 8a.

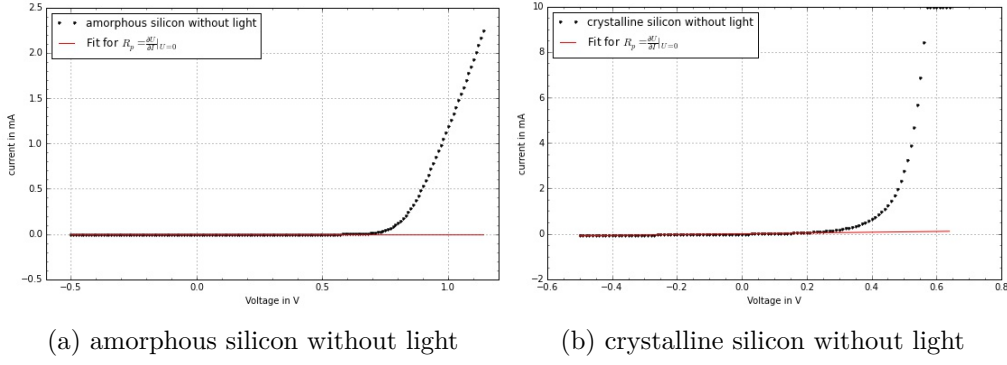


Figure 8: voltage - current graphs of unlighted cells

Quantum-efficiency of solar cells The ratio between the incoming light-current and the produced electric current from a solar cell is called quantum efficiency.

$$QEF(\lambda) = \frac{I_{el}}{I_{photo}} = \frac{U \cdot h \cdot}{P_{light} \cdot \lambda \cdot R} \quad (5)$$

A halogen lamp and an apparatus with monochromator produced light of a certain wavelength. A pyrodetector measured the intensity at different wavelengths of the light. With these intensities as a calibration, and the assumption that the quantum-efficiency at highest plateau of the crystalline silicon cell is 0.9, it was possible to calculate a calibration factor to figure out other values for quantum efficiency at other wavelengths. Using the voltages of the crystalline silicon cell U_{csi} and the calibration voltages U_{pyro} , the yet unscaled quantum efficiency was calculated as follows:

$$QEF(\lambda) = \frac{U_{csi}}{U_{pyro} \cdot \lambda} \quad (6)$$

For the calibration factor γ the average of the values between 950nm and 1030nm was taken and used as the scaling factor to be the quantumefficiency 0.9. With this scaling factor the quantum-efficiency of the amorphous solar cell was calculated. The figure 9 shows the calibration voltage of the pyrometer. After dividing by the pyrometer voltage times lambda and scaling the resultung quantum efficiency to the highest plateau, the figures 10b and 10a show the quantum efficiencies of crystalline and amorphous silicon. With the power spectrum of the sun it is possible to predict the short circuit current of the solar cells. With the given Power in figure 11 per cm^2 times 20nm P , and the area of the hole $A = \pi r^2 = 0.15cm^2\pi$ the integration became a sum:

$$I_{sc} = A \cdot \sum_{350nm}^{1150nm} \frac{P \cdot \lambda \cdot QEF(\lambda)}{hc} \quad (7)$$

With the given sun spectrum, the measured quantum efficiencies and the lighted area of with radius 0.15cm the crystalline solar cell would produce approximately 32 nanoampere, and the amorphous solar cell would produce 51 microampere. The quantum efficiency of the amorphous solar cell is higher in those areas, where the sun-spectrum is

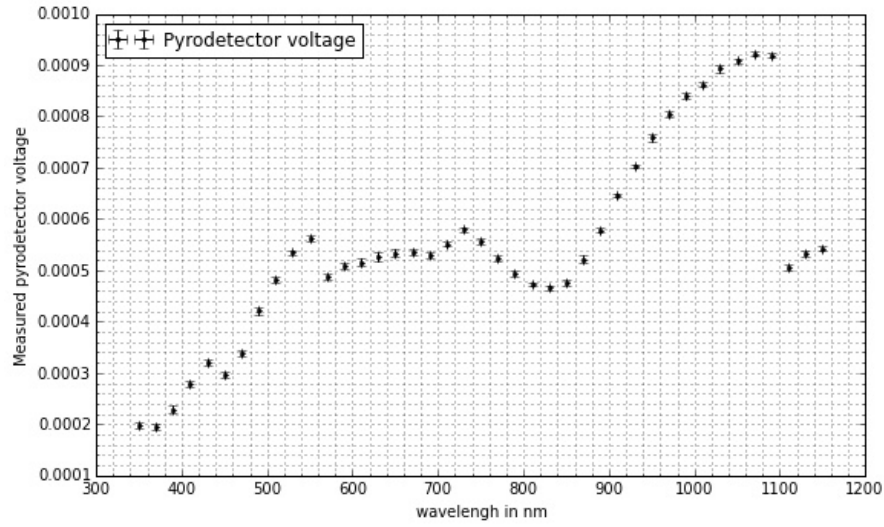
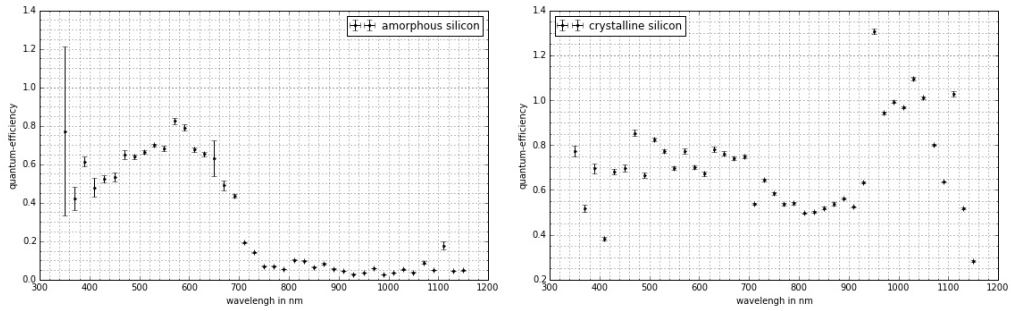


Figure 9: Pyrodetector calibration voltage



(a) quantum-efficiency of amorphous silicon (b) quantum-efficiency of crystalline silicon

Figure 10: quantum-efficiencies of crystalline and amorphous silicon

more intense. This explains the higher short circuit current of the amorphous silicon cell.

5 Questions

The question why the quantum efficiency goes down for wavelengths of around can be answered in many ways.

For the a-silicon for example one reason might be that the glass covering the silicon isn't as transparent for ultraviolet light as it is for light with higher wavelengths so there simply isn't as much light that can produce photocurrent inside of the silicon as for higher wavelengths.

On the other hand for the c-silicon one finds after looking at 2a again, that it's reflectivity for light in this range of wavelengths is particularly high, so the major part of the light

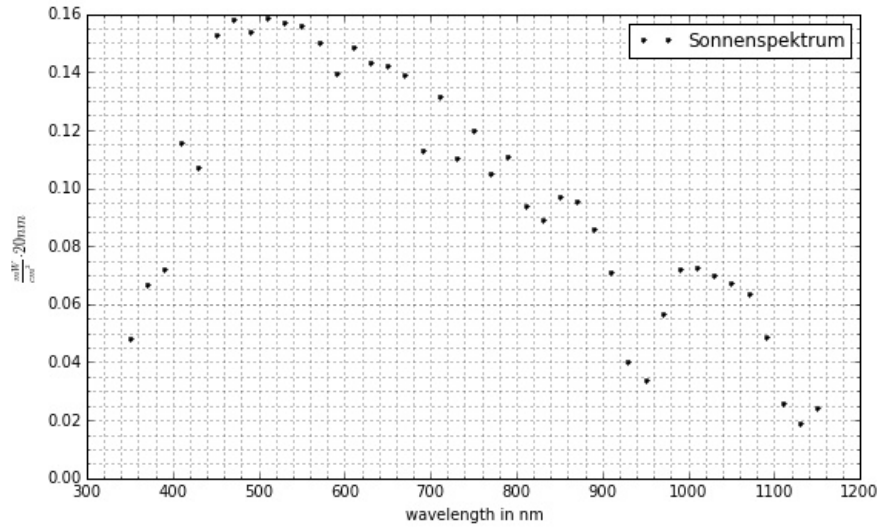


Figure 11: Powerspectrum of sunlight at different wavelengths

hitting the silicon is reflected right back and therefore there isn't that much light to produce photocurrent left as for higher wavelengths. Another reason, that applies for both cells, is that the cells simply aren't thick enough to use these rather high energy photons. This means that the energy of the photons hitting the cells is just so high that they pass right through the cell without or just barely interacting with the atoms in the solar cell hence no photocurrent is produced and the quantum efficiency falls for these wavelengths.

Also there is a connection between the way the quantum efficiency falls for wavelengths approaching the energy gap of the absorber material and the kind of energy gap. First of all the quantum efficiency falls in this range of wavelengths because now their energy is exactly the one needed to produce electron-hole pairs in the absorber material, for instance the silicon the solar cell is made of. Because these electron-hole pairs are produced outside of the depletion region there is no electric field to separate them and therefore they recombine, not contributing to the photocurrent and therefore lowering the quantum efficiency. The way the kind of energy gap and the way the quantum efficiency drops can be explained using figure 12. What you can see here is the absorption coefficient for various materials. While the absorption coefficient for materials with a direct energy gap, like GaAs, abruptly rises as soon as the photon energy reaches the energy of the gap, it rises more slowly for materials with an indirect energy gap just like crystalline silicon. This directly corresponds to the drop in the quantum efficiency, so for materials with a direct gap this drop is much more abruptly than for materials with an indirect gap.

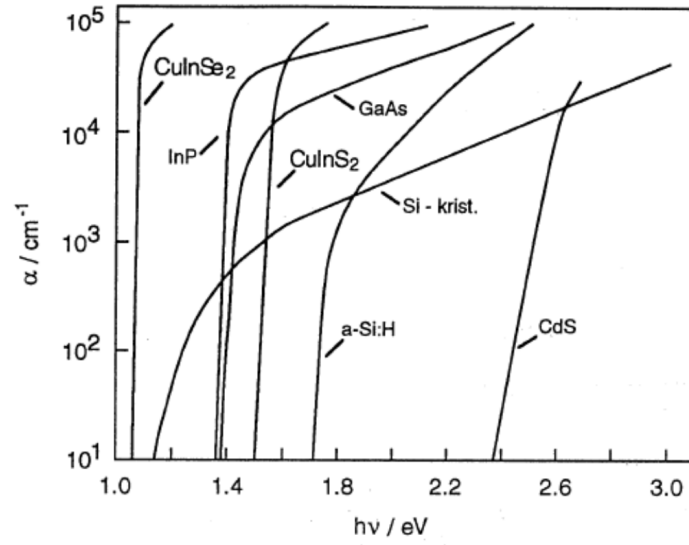


Figure 12: Wavelength dependence of the absorption coefficient for various materials

6 Calculation of uncertainties

The errors were calculated with the gaussian error propagation 9.

$$\sigma_{f(x_1, x_2, \dots)} = \sum_{i=1}^n \left| \frac{\partial f}{\partial x_i} \cdot \sigma_{x_i} \right| \quad (8)$$

$$\sigma_{f(x_1, x_2, \dots)} = \sqrt{\sum_{i=1}^n \left(\frac{\partial f}{\partial x_i} \cdot \sigma_{x_i} \right)^2} \quad (9)$$

The values were calculated using two separate script `calc.py` and `quanteneffizienz.py`. These scripts can be downloaded at <https://github.com/JackTheEngineer/photovoltaik> from the folder `calc/`.