Photovoltaic devices: Optical properties of amorphous and crystalline Silicon as a base material for solar cells (M33)

1. Introduction

On the one hand, the aim of this experiment is to provide the basic concepts of optical spectroscopy and characteristic experimental methods with a simple example, namely the determination of optical constants from transmission and reflection measurements.

On the other hand, the students should learn about the relationship between fundamental physical properties of materials (here the refractive index and the absorption coefficient) and the resulting design features for technical use of the materials (here as a solar cell).

2. Literature

- Practical Handbook of Photovoltaics, McEvoy

3. Preparation

a) Derive from the Fresnel coefficient for normal incidence of light the transmittance and reflectance of a thin free-standing layer (both surfaces adjoin vacuum) with the complex refractive index \( \tilde{n} = n + ik \). For this calculate the superposition of all reflected partial waves with correct phase relationships. How can you check your calculated results with the help of energy conservation?

b) Transmission and reflection spectra possess local extreme points. At which wavelengths are they located (approximately)? How can one determine the refractive index \( n \) and the absorption constant \( \alpha \) with the help of these extreme points?

c) What’s the difference, in nanometers, between the expected spectral extrema from the previous question? What’s the minimal sampling resolution (in nanometers) that you’d need to get out of the experimental measuring system in order to resolve these peaks?

d) Derive the transmittance and reflectance of an optically thick layer, where no interference structures can be resolved. Execute a summation of the light intensities of the individual partial beams instead of doing an in-phase addition of the complex wave amplitudes. Compare your findings with the results in reference 2 where the calculation was done for thin layers.

e) In the case of optically thick layers, how is it possible to get the optical constants \( n \) and \( k \) and the absorption constant \( \alpha \) from the measured transmission and reflection?

f) In the experiment, you’ll be using a lock-in amplifier and a chopper. Explain the general usage of such a device, how it works, what is a chopper and what’s its role.
4. Experiment

4.1 Using the lab equipment

Preparing the monochromator

(a) Make sure that the motor power supply circuit is complete (blue banana cable).
(b) Set the top switch on the motor switching box to “MAN”.
(c) Set the bottom switch to the right for longer wavelengths, or left for shorter ones.
(d) At rotation speed setting “10”, reach 500nm or 2500nm (your decision) on the monochromator.

Acquiring data

(a) Make sure that the bottom switch is set to the appropriate direction for this scan.
(b) Make sure that the rotation speed is appropriate for your intended measurement. For the background scan – you can use a speed setting of “10”. For the actual measurements, you must deduce the correct setting yourself: what’s the resolution (in nm) for a given velocity? How much do you need to resolve your expected data?
(c) Set the top switch to “PC”.
(d) Open the “measure_spectrum” data acquisition program.
(e) Read and write down the starting wavelength from the monochromator.
(f) Click “Start Measurement”, then choose a destination and filename for the recorded data.
(g) Once the monochrometer reaches the target wavelength, click “Stop Measurement”. The data is then saved to the selected file and the measurement is finished.

NOTES:

“Sampling rate” - the number in this box is the sampling rate (how many data points per second are taken). It can be changed by changing the value in the box before starting the measurement. The maximum sampling rate is limited by the program to 200.

Graph: the graph shows the recorded spectrum in (close to) real-time. The y-axis is the output from the lock-in amplifier, the x-axis is the number of points recorded.

Shutting off the monochromator

(a) Once you’re done with the measurements, make sure you disconnect the motor power supply (blue banana cable).

4.2 Optical setup

Build an optical setup with which you are able to measure the transmission and reflection spectrum of the crystalline and the amorphous silicon sample. To do this, use the lock-in amplifier and PbS cell as a detector. Make sure that only transmitted / reflected light is measured through / off the sample. (Why is this important? How can you be sure? How can you verify this?) In the beginning of the experiment switch on the lamp since it needs approximately 30 minutes until it is stabilized.
4.3 Measuring spectra of the amorphous sample

There are three different spectra which should be measured: The spectrum of the incident light on the sample, the transmission spectrum behind the sample, and the spectrum of the reflected light off the sample. For these measurements the amorphous sample is used. Correct carefully for any background signals. (Why does a background signal appear? How can the background distort your interpretation?).

4.4 Measuring spectra of the crystalline samples

Measure the three types of spectra described above for the two crystalline samples in the spectral range 550 nm to 1000 nm. Be sure to correct for background signals as well!

Note: When doing the measurements described in 4.3 and 4.4 make sure that you measure with good resolution also in the region of the lowest wavelengths. There it is possible to get fairly high absorption coefficients. How could the signal-to-noise ratio be improved? What is the reason for a limit of the spectral range while determining the optical constants?

5. Data analysis

5.1 Determine from the spectral position of the interference extreme points in the transmission spectrum the amorphous sample the refractive index of amorphous Silicon for the corresponding wavelengths. (Thickness of a-Si: H Layer: 0.80 μm). Use the enclosed calibration curve of the monochromator.

5.2 Determine the values of the absorption coefficients by using the transmittance and the values for the refractive index you got in exercise 5.1 at the same wavelengths. Also try to continue this analysis in the region of strong absorption (where no Interference extreme points can be distinguished) as far as it seems useful. How do you determine the refractive index in that region?

5.3 Determine the refractive index and absorption constant for the measured wavelength for the crystalline sample. From the two measured variables the transmittance and reflectance are to be determined. Although the corresponding system of equations is not explicitly solvable, it is possible to find its solution by an iterative method. Which initial values should be chosen to ensure the fastest possible convergence?

5.4 Show for both silicon modifications the dispersion (n(hv)) and the absorption (log(α(hv))/cm⁻¹) curves. Discuss the results in terms of systematic errors.

5.5 Sketch the solar spectrum, that is, the spectral power density dP/d(hν) of sunlight with the help of the Planck radiation formula for a black body (T = 5900K). Show both the spectrum and the curves (1 – exp(–α(hν)d)) for a 300 nm thick amorphous silicon layer and a 300 nm thick crystalline silicon sample in a diagram. Is it possible to determine an upper limit for the efficiency of the given solar panels just by using this diagram? How will the efficiency change if one would take into account that only the fraction of the photon energy that matches the bandgap could be used for the photovoltaic process? (Crystalline silicon: 1.2 eV, amorphous silicon: 1.8 eV). What is the physics behind this? What happens to the rest of the energy?