Photovoltaics: Direct conversion of solar radiation into electrical energy

• Excitation of electron-hole-pairs in semiconductors by absorption of a photon (inner photoelectric effect)

• Separation of electrons and holes due to the space-charge field in a p-n-diode

Experimental contents:

Part 1: Optical Characterization
Determination of the refraction index $n$ and the absorption coefficient $\alpha$ from reflection and transmission measurements;
spectrally resolved $[n(\lambda), \alpha(\lambda)]$

Part 2: Electrical Characterization
Diode characteristics with and without illumination;
Determination of the efficiency of the solar cell

Note: The symbol ‘$I$‘ denotes intensity as well as current, depending on context.

Examined materials:

1.) Crystalline silicon
2.) Amorphous silicon for thin-film solar cells
1. **Reflection** of part of the light at the air/solar cell-interface

2. **Excitation of electron-hole pairs** and separation of electrons and holes in the depletion region

3. **Transmission** of part of the light through the solar cell

4. **Current flow through external load resistor**
   - I-U characteristics of the illuminated solar cell
   - Optimal operating point
   - Fill factor (FF)
Why c-Si and a-Si?

<table>
<thead>
<tr>
<th>c-Si</th>
<th>a-Si</th>
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<tbody>
<tr>
<td>Market share</td>
<td>80%</td>
</tr>
<tr>
<td>Efficiency $\eta = \frac{\text{Electrical power}}{\text{incident optical power}}$</td>
<td>$\eta = 14%$</td>
</tr>
<tr>
<td>Price</td>
<td>high</td>
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</tbody>
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Physical differences

- Crystal
  - $\Rightarrow k$-conservation;
  - weak absorption
  - (in the visible range)
- Amorphous solid
  - $\Rightarrow$ no $k$-conservation;
  - strong absorption
  - (in the visible range)

Different principles of charge separation

- Diffusion of electrons and holes
- Drift under the influence of an electrical field
Optical absorption (inner photoelectric effect)

Fast thermalization and recombination
⇒ light energy
→ thermal energy

Electrons keep potential energy $E_g$ after thermalization, which is converted into electrical power.
rest → thermal energy

⇒ optimal adjustment of the band gap to the solar spectrum

![Graph showing theoretical efficiency vs. band gap (eV) for c-Si and a-Si]
Solar spectrum AM1.5

Indirect band gap
\( E_g = 1.1 \text{eV} \)
\( \rightarrow \lambda = 1.13 \mu\text{m} \)

Direct band gap
\( E_g = 1.7 \text{eV} \)
\( \rightarrow \lambda = 0.73 \mu\text{m} \)
Experimental determination of the optical absorption

1. $I_0(\lambda)$ without sample
2. $I_T(\lambda)$ with sample
3. $I_R(\lambda)$ with sample

Correction for reflection:

$$R = \frac{I_R}{I_0} = \left(\frac{n(\lambda) - 1}{n(\lambda) + 1}\right)^2 \Rightarrow n(\lambda)$$

4. From Lambert-Beer law:

$$I_T = (I_0 - I_R) \cdot e^{-\alpha \cdot d} \Rightarrow \alpha(\lambda) = \frac{1}{d} \cdot \ln\left(\frac{I_0(1 - R)}{I_T}\right)$$

o.k. for c-Si ($d \approx 40\,\mu m$)
a-Si \((d \approx 1\mu m \approx 2...3\lambda)\); i.e. thin films

→ Interference:

Constructive and destructive superposition of multiple reflected waves.

For more information about the analysis see description of the experiment.
Charge separation in p-n junction

- No free charge carriers
  → depletion zone
- Fixed charges of the donors and acceptors
  ↓
- Depletion zone and band bending
  ↓
- Separation of photo-generated electrons and holes

Diffusion of free charge carriers

Equilibrium potential and charge profile in the dark
I-U characteristics of a diode (dark)

\[ I_{\text{dark}}(U) = I_0 \cdot \left( \exp \left( \frac{eU}{A \cdot kT} \right) - 1 \right) \]

Detailed information see experiment.
I-U characteristics under illumination

- Under illumination, there is an additional photo current $-I_{\text{photo}}$ due to optical excited charge carriers.
- I-U curve is shifted down by $I_{\text{photo}}$.

\[ I = I_{\text{max}} \quad \text{for} \quad U = 0 \, \text{V (short-circuit current $I_{SC}$)} \]
\[ I = I_{\text{max}} \quad \text{for} \quad U = U_{\text{0}} \, \text{V (open circuit voltage)} \]

- Power of the solar cell $P = U \cdot I$ can be explained as the area of the rectangle at a certain point of the I-U curve.

- $P$ is maximal for $U = U_{\text{max}}$.

- Fill factor $FF := \frac{P_{\text{max}}}{U_{\text{0}} \cdot I_{\text{SC}}}$
Tasks

• Spectral determination of refraction index and absorption coefficient
  - crystalline silicon
  - amorphous silicon (Fabry-Perot interferences)

• Theoretical calculation of the maximal efficiency considering $\alpha(\lambda)$ and the solar spectrum

• Measurement of the dark I-U curve for a crystalline and an amorphous solar cell

• Measurement of the I-U characteristics under illumination for two different intensities ($I=2.5\text{mW/cm}^2$, $I = 25\text{mW/cm}^2$)

• Determination of the optimal operating point and the fill factor

• Measurement of short-circuit current and open circuit voltage vs. light intensity

• Experimental determination of the efficiency under laboratory illumination

• Determination of the diode factor $A$

• Field test: efficiency under sun light condition