**H7. Photovoltaics: Solar Power**

I. INTRODUCTION

The sun is practically an endless source of energy. Most of the energy used in the history of mankind originated from the sun (coal, petroleum, etc.). The solar power that reaches the earth can reach 1000 W/m² and can be harvested indirectly, through wind power, water power, biomass, etc., or directly using photothermal or photovoltaic effects.

The photovoltaic effect

A photovoltaic captor is generally made up of two thin layers of doped semiconductors, forming a spread out semiconducting pn junction or diode. Photons entering this junction are absorbed, and part of their energy is used to generate free charges (electron-hole pair). Due to the electric field in the junction, the charges are separated and sent to different parts of the junction, depending on their polarity. Using conducting electrodes on both sides of the pn junction, the charges can be collected in order to generate an electric current in an external circuit.

The schematic representation of a pn junction (diode) is given in figure 1. In this diagram, the direct current $I_D$ is linked to the direct voltage $U_D$ by the following simplified equation:

$$I_D = I_{so} \left( \frac{e^{U_D / T} - 1}{e^{U_D / T} - I_\gamma} - 1 \right)$$

where: $\alpha = \text{constant}$
$T = \text{junction temperature [K]}$
$I_{so} = \text{inverse saturating current}$
$I_\gamma = \text{photovoltaic current}$

When a semiconducting junction is illuminated, an inverse photovoltaic current $I_\gamma$ is generated, proportional to the luminous intensity, which is due to the electron-hole pair formation, when absorbing incident photons. Typical $I_D(U_D)$ curves of an illuminated pn junction can be found in figure 2.
This diagram can be divided into three main sections:

- The direct conduction section, in which the junction behaves like a strongly non-linear resistor (see semiconducting diode).
- The photovoltaic section, in which the junction acts like an electric generator.
- The photoconductive section, in which the diode acts like a current regulator, controlled by the luminous intensity.

In the photovoltaic section, the junction is called photovoltaic cell or solar generator. The most basic electrical circuit is represented in figure 3, in which we connect the solar cell to a charge resistance $R_C$. The operating point of the system is given by the intersection of the characteristic diode curve $I_R = I_R(U_D)$ with the charge curve $U_D = R_C I_R$ (figure 4).

At constant illumination and temperature, the efficiency of a solar cell thus depends on the resistance of the circuit. For an open circuit ($R_C = \infty$, $I_R = 0$, $U_D = U_D\text{ max}$) or a short-circuit ($R_C = 0$, $I_R = I_R\text{ max} = I_\gamma$, $U_D = 0$), no energy is transmitted out of the system. Between both extremes, there exists an optimal resistance $R_{\text{opt}}$ for which the power $P = U_D I_R$ is maximal $P_{\text{max}}$ (figure 4).
The energetic efficiency of the solar cell is defined by $\eta = \frac{P}{P_\gamma}$, where $P_\gamma$ is the incident luminous power on the surface of the cell. For the optimal resistance $R_{\text{opt}}$ the efficiency is maximal, and $\eta_{\text{max}} = \frac{P_{\text{max}}}{P_\gamma}$. $R_{\text{opt}}$ is not a characteristic constant of the system, but depends on the radiation spectrum, and on the junction temperature. The efficiency actually decreases when temperature increases, which results in the manufacturing of hybrid cells, which consist of the combination of a solar cell and a heat captor, allowing to produce hot water and to cool down the cell simultaneously.

The power supplied by a solar cell ($P = U_D I_R$) and its efficiency ($\eta = \frac{P}{P_\gamma}$) depend of the used material, the fabrication process (amorphous, polycrystalline or monocrystalline silicon), the geometry of the junction (thickness of the layers, multiple layers, etc.) and on external parameters (temperature, spectrum and intensity of the radiation, circuit the cell is connected to, etc.).

II. OBJECTIVE OF THE EXPERIMENT

The objective of this experiment is to get comfortable with the fundamental properties of different silicon solar cells, and to compare the fabrication processes (amorphous, polycrystalline or monocrystalline), and study the behavior of the cell as a function of the external parameters (spectrum and intensity of the light, temperature, incident angle of light, etc.)

The setup is made up of the following items:

1) An optical bench.
2) A light source that whose spectrum ranges over then ultraviolet, visible and infrared spectra. Since the sun isn’t always available for doing measurements, is replaced by a lamp with a similar spectrum for the sake of the experiment. An incandescent lamp isn’t fitted for this task, which is why we use a mercury vapor lamp, with metal halides and additional dysprosium iodide (OSRAM HQI, HQL) instead.
3) Three solar cells with different fabrication processes (amorphous, polycrystalline or monocrystalline silicon).
III. SUGGESTED EXPERIMENTS

Recreate the setup shown in figure 5. An image of the setup can be found in figure 6.

1) Measure the incident luminous power \( P_\gamma \) for different distances \( d \). Plot \( P_\gamma(1/d^2) \), and explain the reason for this dependency.

2) For two different lighting conditions (two different distances \( d \)), plot the characteristic curves \( I_R(U_D) \) of the three different solar cells by modifying the charge resistance \( R_C \).

3) Plot the power curves \( P(U_D) \) of the three cells for the two different lighting conditions used in 2). Determine \( P_{\text{max}} \) and, using the luminous intensity captor, \( \eta_{\text{max}} \) for both lighting conditions. Compare the efficiencies of the different cells.

4) For different distances \( d \), measure the short-circuit current \( I_R = I_{R \text{ max}} = I_\gamma (R_C = 0, U_D = 0) \) of the different cells. Plot \( I_\gamma(P_\gamma) \), using the luminous intensity captor. Measure the average characteristic value \( i = I_\gamma/P_\gamma \) (mA/W) of each of the available cells. Discuss.

5) For a fixed distance \( d \), measure the short-circuit current \( I_R = I_{R \text{ max}} = I_\gamma (R_C = 0, U_D = 0) \) of the three different cells and alter the spectrum using a filter. By measuring the luminous intensity through those same filters, determine the characteristic value \( i = I_\gamma/P_\gamma \) (mA/W) for the different spectra of the incident light. Discuss the spectral sensitivity of the different solar cells.

6) The manufacturer guarantees an efficiency of 10% for the monocrystalline silicon, for lighting conditions of 1000W/m². Compare this efficiency with the one measured in the lab.

Other suggestions:

7) Determine the variation of \( I_\gamma \) as a function of the incident angle of the light.

8) Determine the variation of \( I_\gamma \) as a function of the distance \( d \).

9) Determine the variation of \( I_\gamma \) as a function of the junction temperature.
Fig. 6: Experimental setup

IV. APPENDIX: characteristics of the available filters

<table>
<thead>
<tr>
<th>Filter number</th>
<th>Filter color</th>
<th>Wavelength of the bandwidth</th>
<th>Transmissivity in the bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>2B</td>
<td>light yellow</td>
<td>$\lambda &gt; 400$ nm</td>
<td>90 %</td>
</tr>
<tr>
<td>8</td>
<td>yellow</td>
<td>$\lambda &gt; 500$ nm</td>
<td>90 %</td>
</tr>
<tr>
<td>16</td>
<td>yellow-orange</td>
<td>$\lambda &gt; 550$ nm</td>
<td>90 %</td>
</tr>
<tr>
<td>25</td>
<td>red</td>
<td>$\lambda &gt; 600$ nm</td>
<td>90 %</td>
</tr>
<tr>
<td>87C</td>
<td>infrared</td>
<td>$\lambda &gt; 850$ nm</td>
<td>90 %</td>
</tr>
</tbody>
</table>
| 47            | blue           | $500$ nm $>\lambda > 400$ nm  

et $\lambda > 700$ nm | 50 % | 90 % |
| 58            | green          | $600$ nm $>\lambda > 500$ nm  

et $\lambda > 700$ nm | 50 % | 90 % |