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/m^2 and can be harvested indirectly, through wind power, water power, biomass, etc., or directly using photothermal or photovoltaic effects.

<u>The photovoltaic effect</u>

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:

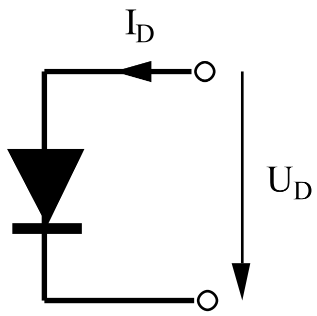

Figure 1

$$\boxed{I_D = I_{so}\left[e^{\alpha \frac{U_D}{T}} - 1\right] - I_\gamma}$$

where: α = constant
T = junction temperature [K]
I_{so} = inverse saturating current
I_γ = photovoltaic current

When a semiconducting junction is illuminated, an *inverse photovoltaic current* I_γ 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.

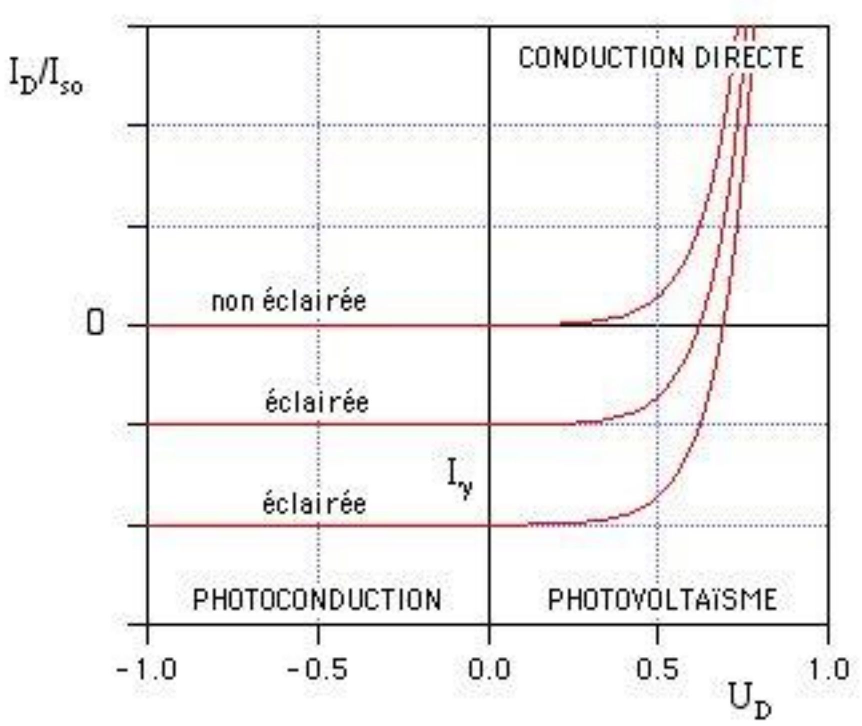

Figure 2

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.

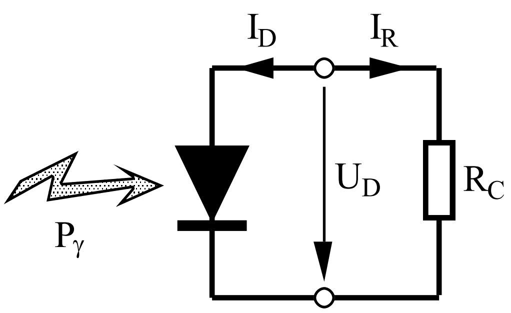

Figure 3

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 ($R_C = \infty$, $I_R = 0$, $U_D = U_{D\,max}$) or a short-circuit ($R_C = 0$, $I_R = I_{R\,max} = I_\gamma$, $U_D = 0$), no energy is transmitted out of the system. Between both extremes, there exists an optimal resistance R_{opt} for which the power $P= U_D\, I_R$ is maximal P_{max} (figure 4).

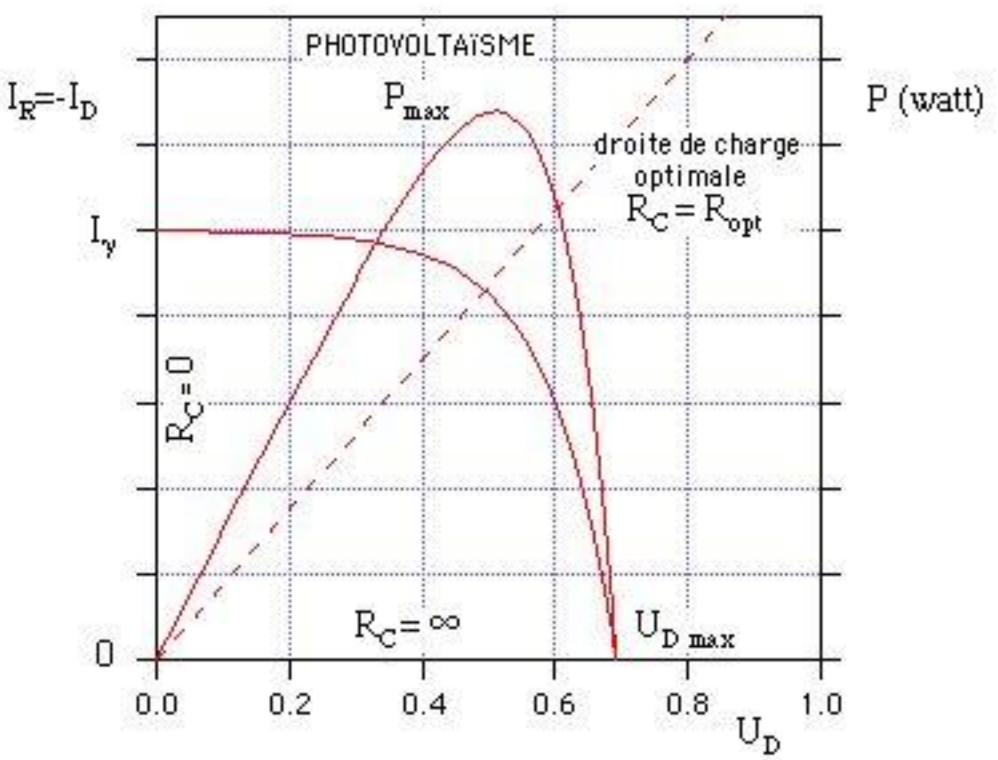

Figure 4

The *energetic efficiency* of the solar cell is defined by $\eta = P/P_\gamma$, where P_γ is the *incident luminous power* on the surface of the cell. For the optimal resistance R_{opt} the efficiency is maximal, and $\eta_{max} = P_{max}/P_\gamma$. R_{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 ($\eta = P/P_\gamma$) 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).

4) Two multimeters for measuring U_{D}, I_R et P.
5) A thermocouple for measuring the junction's temperature.
6) A luminous intensity captor allowing to determine P_{γ}.
7) A variable resistance used as R_C.
8) A set of photographic filters used to modify the incident light spectrum.

III. SUGGESTED EXPERIMENTS

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

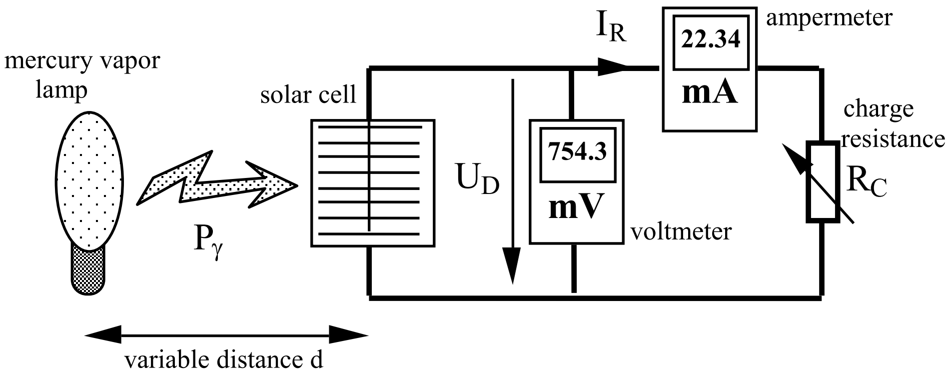

Figure 5

1) Measure the incident luminous power P_γ 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_{max} and, using the luminous intensity captor, η_{max} for both lighting conditions. Compare the efficiencies of the different cells.

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

5) For a fixed distance d, measure the short-circuit current $I_R = I_{R\ max} = I_\gamma$ ($R_C = 0$, $U_D = 0$) 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_γ/P_γ (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/m^2. Compare this efficiency with the one measured in the lab.

Other suggestions:

7) Determine the variation of I_γ as a function of the incident angle of the light.
8) Determine the variation of I_γ as a function of the distance d.
9) Determine the variation of I_γ as a function of the junction temperature.

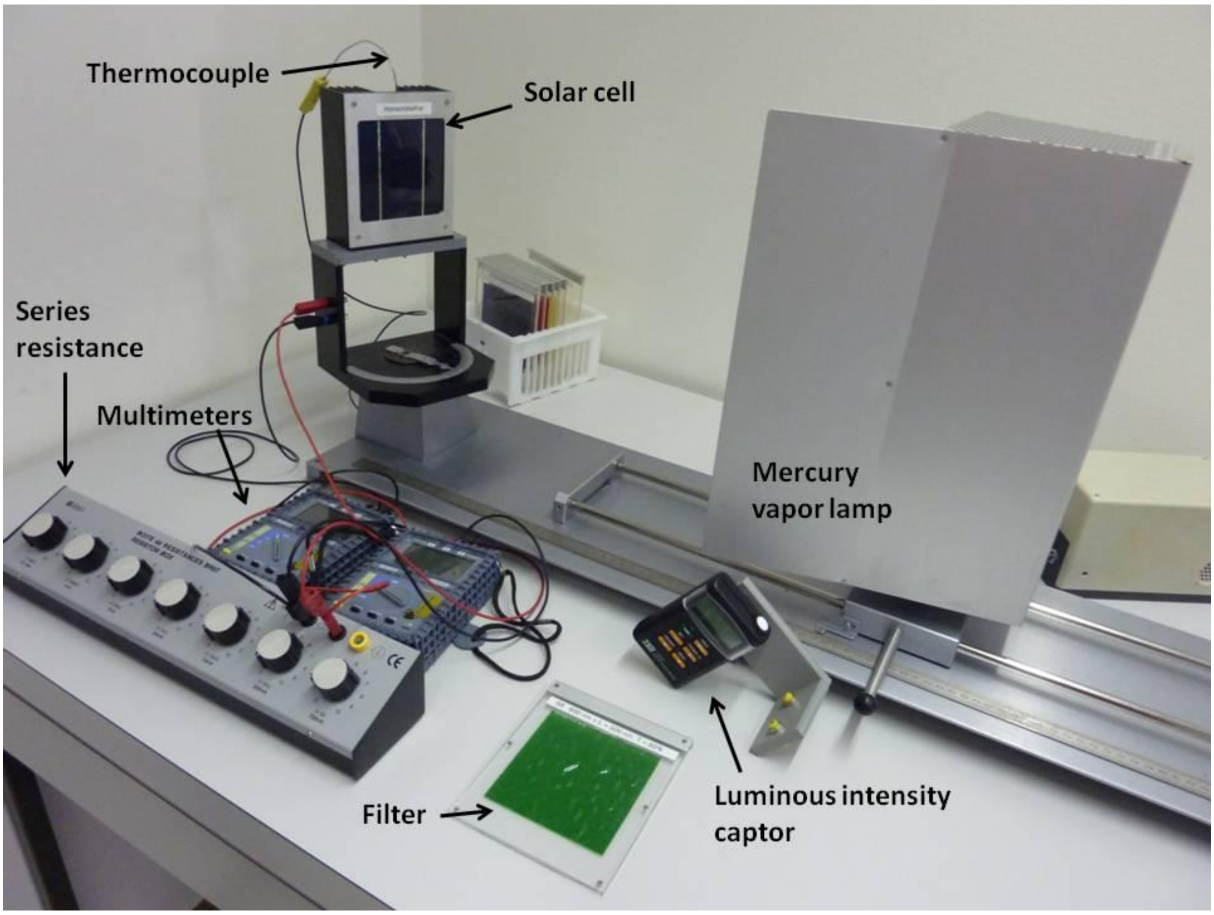

Fig. 6 : Experimental setup

IV. APPENDIX: characteristics of the available filters

Filter number	***Filter color***	***Wavelength of the bandwidth***	***Transmissivity in the bandwidth***
2B	light yellow	λ > 400 nm	90 %
8	yellow	λ > 500 nm	90 %
16	yellow-orange	λ > 550 nm	90 %
25	red	λ > 600 nm	90 %
87C	infrared	λ > 850 nm	90 %
47	blue	500 nm > λ > 400 nm **et** λ > 700 nm	50 % 90 %
58	green	600 nm > λ > 500 nm **et** λ > 700 nm	50 % 90 %