Physics Laboratory
Vp241

Exercise 3

Solar Cells: I–V Characteristics

This lab manual is based on materials provided by the Department of Physics, Shanghai Jiaotong University.

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1 Pre-lab Reading

Chapter 3 in: *Applied Photovoltaics*, S.R. Wenham *et al.* (Earthscan, 2007)

2 Objectives

The objective of this exercise is to get familiar with the working principle of a solar cell and study its current–voltage (I–V) characteristics.

3 Theoretical Background

Solar cells are devices which are able to directly transform solar radiation into electrical energy. They have many advantages such as no consumption of energy, silent operation, no moving parts, and a long lifetime. Moreover, solar cells are easy to maintain and they do not contribute to air pollution. Therefore, solar cells are regarded as a promising energy source in the 21$^{\mathrm{st}}$ century and it is estimated that by the mid-21$^{\mathrm{st}}$ century solar cells will produce 15–20% of the total electrical energy generated in the world, and therefore become one of the leading energy sources.

3.1 Solar Cell Structure

As an example, the structure of a crystalline silicon solar cell is shown in Figure 1. It consists of n/p homo-junctions, a 10 cm $\times$ 10 cm p–type silicon plate of thickness 500 μm, covered with a heavily doped n-type layer with thickness 0.3 μm. The metallic bars on the n-type layer serve as one electrode, with a metallic film at the bottom playing the role of another one. In order to reduce the loss of energy due to reflection, an anti-reflective film is often applied to cover the surface exposed to sunlight.

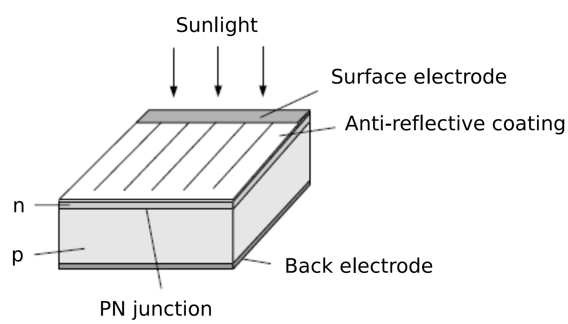

Figure 1. Structure of a crystalline silicon solar cell.

3.2 Photovoltaic Effect

When the light enters the p-n junction near the solar cell surface, and the energy of incident photons is greater than the forbidden bandwidth (energy gap) E_g, the incident photons are absorbed and excite electron-hole pairs. Minority charge carriers in the n- or p-type area diffuse due to their density gradient. Some of them are able to diffuse to the region of the p-n junction where a built-in electric field exists. This field is directed from the n-type to the p-type area. The minority carriers diffusing to the p-n junction zone between the n-type area and the p-type area are drawn by this electric field to the p-type area (in case of the holes), or to the n-type area (in case of the electrons). This results in an increase of positive charge accumulated in the p-type area and negative charge in the n-type area. Consequently, a photoelectric potential difference is generated.

The phenomenon described above is known as the *photovoltaic effect*.

3.3 Solar Cell Parameters

Relying on the photovoltaic effect, solar cells can generate an electric current I_ph from the n–type area to the p-area when there is light incident on the solar cell.

At the same time, in the device there exists a forward diode current I_D from the p-type to the n-type area, opposite to I_ph. Eventually, the net current is

$$I = I_\mathrm{ph} - I_\mathrm{D} = I_\mathrm{ph} - I_0\left[\exp\left(\frac{qV_\mathrm{D}}{nk_\mathrm{B}T}\right) - 1\right], \tag{1}$$

where V_D is the junction voltage, I_0 is the diode inverse saturation current, I_ph is the photocurrent determined by the structure and material characteristics of the solar cell. The coefficient n is a theoretical coefficient, with its values ranging from 1 to 2, that characterizes the p-n junction. Furthermore, q denotes the electron's charge, k_B is the Boltzmann's constant, and T is the temperature in the absolute (Kelvin) scale. Ignoring the internal series resistance R_s, the voltage V_D equals the terminal voltage V and Eq. (1) can be rewritten as

$$I = I_\mathrm{ph} - I_0\left[\exp\left(\frac{qV}{nk_\mathrm{B}T}\right) - 1\right].$$

When the output is short, *i.e.* $V = 0$, the short-circuit current is

$$I_\mathrm{sc} = I_\mathrm{ph},$$

whereas when the output is open, *i.e.* $I = 0$, the open-circuit voltage is

$$V_\mathrm{oc} = \frac{nk_\mathrm{B}T}{q}\ln\left(\frac{I_\mathrm{sc}}{I_0} + 1\right).$$

When there is a load resistance R (with the value of R ranging from zero to infinity), the corresponding I–V characteristics curve is shown in Figure 2. If for a certain load resistance $R = R_\mathrm{m}$ the maximum output power P_m is generated, then the value of P_m is

$$P_\mathrm{m} = I_\mathrm{m}V_\mathrm{m},$$

where I_m is the optimal operating current, and V_m is the optimal operating voltage. Then,

$$FF = \frac{P_\mathrm{m}}{V_\mathrm{oc} I_\mathrm{sc}} = \frac{V_\mathrm{m} I_\mathrm{m}}{V_\mathrm{oc} I_\mathrm{sc}}.$$

The quantity FF is an important parameter of solar cells called the *fill factor*. The greater the fill factor is, the greater the output power. The fill factor is determined by a number of parameters, such as the incident light intensity, the forbidden bandwidth, the value of the theoretical coefficient n, and the series/parallel resistance.

The solar cell energy conversion efficiency η is defined as

$$\eta = \frac{P_\mathrm{m}}{P_\mathrm{in}} \times 100\%,$$

where P_in denotes the total radiant power incident on the solar cell.

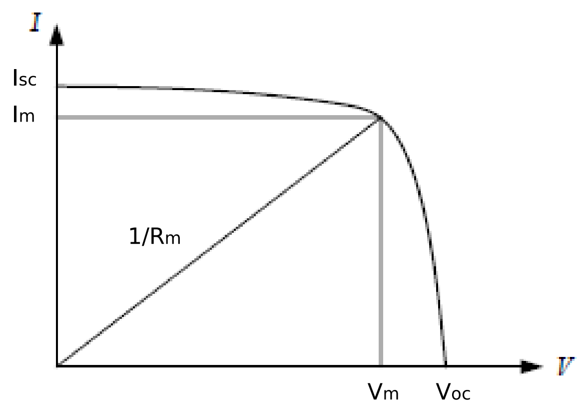

Figure 2. *T*he current-voltage characteristics of a solar cell.

3.4 Solar Cell Equivalent Circuit

As shown in Figure 3, a solar cell can be thought of as composed of a p-n junction diode D and a constant current source I_ph. Along with a series resistance R_s due to the electrodes in the solar cell and a parallel resistance R_sh, all elements form a circuit equivalent to a p-n junction leak–circuit. For the equivalent circuit one can find the following relationship between the current and the voltage

$$I = I_\mathrm{ph} - I_0 \left\{ \exp\left[\frac{q(V + R_\mathrm{s} I)}{n k_\mathrm{B} T} \right] - 1 \right\} - \frac{V + R_\mathrm{s} I}{R_\mathrm{sh}}.$$

In order to provide a greater output power, the value of R_s should be decreased, while R_sh — increased.

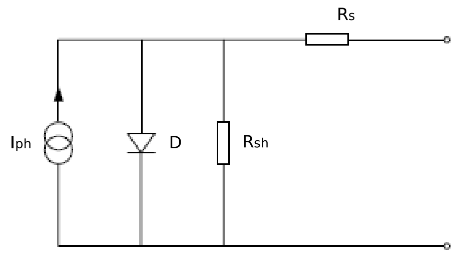

Figure 3. Solar cell equivalent circuit.

4 Measurement Setup and Procedure

4.1 Measurement Setup

The setup consists of a photovoltaic device (5 W), a 300 W tungsten–halogen lamp serving as a radiation source, two digital multimeters, two adjustable resistors, a solar power meter, a wiring board and a measuring tape.

4.2 Measurement Procedure and Data Presentation

1. Turn on both the light and the fan. Wait for at least five minutes, in order to let the light reach its working intensity.

2. Design a measuring circuit with the photovoltaic device, multimeters set in an appropriate range, and the resistance. Connect the elements into a circuit using the provided wiring board.

3. Change the resistance, measure the relevant current and voltage to draw the I–V characteristics curve. Keep the distance between the light source and the photovoltaic device and do not move around the workstation during the measurement, to ensure the same light intensity is maintained during the whole process.

4. Measure the I–V characteristics curves and the values of V_{oc} and I_{sc} under each of the following conditions:

   (a) The distance between the light source and the photovoltaic device is 100 cm; Measure the solar power by the provided solar power meter.

   (b) The distance between the light source and the photovoltaic device is 120 cm; Measure the solar power by the provided solar power meter.

   (c) The distance between the light source and the photovoltaic device is 120 cm, with two devices in series.

(d) The distance between the light source and the photovoltaic device is 120 cm, with two devices in parallel.

5. Plot (use a computer)

   (a) the I–V characteristics curves;

   (b) the graph of the output power vs. the voltage. Determine the values of $I_{\mathrm{sc}}, V_{\mathrm{oc}}, P_{\mathrm{m}}, I_{\mathrm{m}}, V_{\mathrm{m}}, R_{\mathrm{m}}$, FF, and η. Compile the data in the form of a table.

5 Safety Notice

- The temperature of the light source is **very high**, do not touch the cover.
- The power supply voltage of the light source is 220 V, beware of electric shock.

6 Preview Questions

- Describe the photovoltaic effect.
- In order to provide more power, the values of R_{s} and R_{sh} should be decreased or increased? Why?
- Discuss the I–V characteristics of a diode.
- What is the energy gap in a semiconductor?
- What is the fill factor (FF) of a solar cell? What parameters does the fill factor depend on?