



**EXERCISE
104**

PHOTOVOLTAIC EFFECT – SOLAR CELL

Exercise Objective: Determination of the current-voltage characteristic $I(V)$ of a solar cell before and after illumination by light; short-circuit current, open-circuit voltage and fill factor.

Topics: p-n junction, photovoltaic effect, solar cell.

1. Introduction

Photovoltaics is a technology that involves generating electrical energy by converting solar radiation energy directly into electric current. This conversion takes place in semiconductors, where the photovoltaic effect occurs. The basic photovoltaic element is the cell, from which panels (a set of multiple cells) and panel arrays are constructed.

Solar radiation

To describe lighting conditions outside the atmosphere and after passing through it, the concept of the amount of air mass (AM) was introduced, meaning the amount of air mass through which the light passes. At noon on the equator, light reaches the atmospheric surface with an intensity of $H = 1.37 \text{ kW/m}^2$ (the so-called solar constant). This corresponds to an air mass of zero, so these are AM0 lighting conditions. Approximately 73% of H reaches the Earth's surface — these are AM1 conditions. Solar cell efficiencies are given for an irradiance of AM1.5 = 1000 W/m^2 . Besides illuminance, the most important characteristic of solar radiation that must be considered when designing a solar cell is its spectral distribution (Fig. 1). Ideally, the cell's spectral sensitivity should match this spectral distribution.

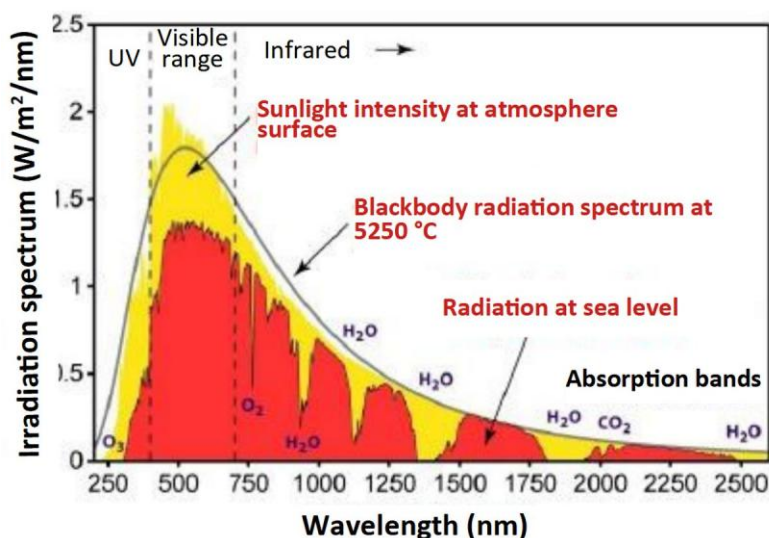


Fig. 1. Spectral distribution of the solar radiation spectrum outside the atmosphere, after passing through the atmosphere, and the spectrum of a perfectly black body at a temperature of 5520 K.

Semiconductors

Silicon is a semiconductor that dominates the photovoltaic market. A silicon atom has four electrons in its valence shell. Neighboring atoms in a Si crystal form a covalent bond (Fig. 2a) — two electrons are shared. A semiconductor in which all atoms are of the same type is called an **intrinsic semiconductor**. A Si crystal in which some atoms are replaced by atoms from Group V of the periodic table (e.g., phosphorus) is called an **n-type semiconductor**. One of the five valence electrons lacks a covalent bonding partner (Fig. 2b) – it becomes a free electron, while the phosphorus atom becomes a positive ion (donor). If some Si atoms are replaced with

atoms from Group III of the periodic table (e.g., boron), one bond will remain vacant – a surplus unoccupied state – a hole – will appear (Fig. 2c). This empty state can accept an electron. This creates a negative ion – the acceptor – and a free positive charge – a hole. This creates a **p-type semiconductor**.

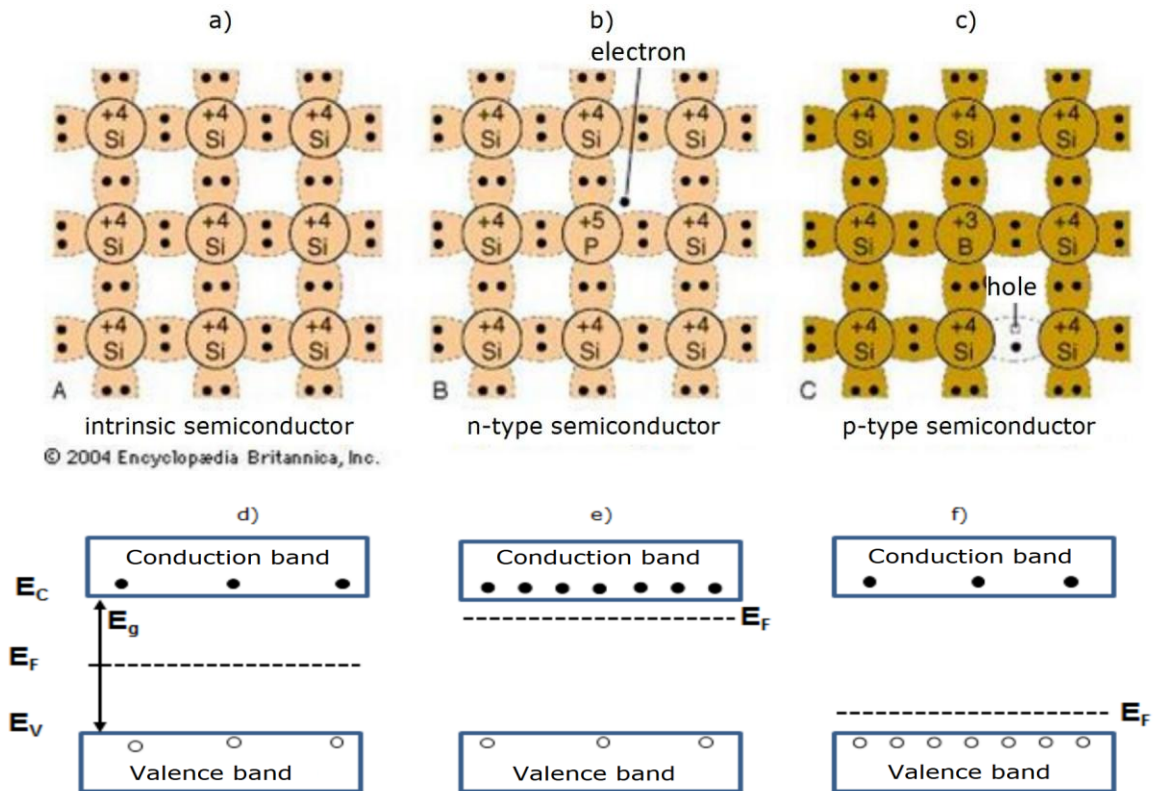


Fig. 2. Covalent bonding in Si a) intrinsic, b) n-type, c) p-type and corresponding band diagrams d), e), f).

The behavior of electrons in solids is well explained by the band theory. In isolated atoms, allowed electron energies are quantized. In a solid, when atoms are very close together (distances on the order of nanometers), discrete electron levels in the valence shells split into energy bands, separated by a range of forbidden energies. The most important from the perspective of current transport is the last band occupied by electrons, called the **valence band**, and the next bands, empty (or partially filled) by electrons, called the **conduction band**. Semiconductors are materials in which the valence band and conduction band are separated by a **band gap E_g** , of the order of several eV. In an intrinsic semiconductor, the conduction band contains the same number of electrons as holes in the valence band (Fig. 2d). In an n-type semiconductor, there are more electrons in the conduction band than holes in the valence band (Fig. 2e), and in a p-type semiconductor – the opposite (Fig. 2f). Therefore, electrons in an n-type semiconductor are majority carriers, while holes are minority carriers, and in a p-type semiconductor – the opposite. In Fig. 2d-2f, in addition to the band edges (E_c – conduction, E_v – valence), the **Fermi level**, E_F , is marked. This level separates states filled with electrons from empty states. In an n-type (p) semiconductor, the Fermi level shifts toward the conduction band edge (valence band) (Figs. 2e and 2f).

P-N Junction

The operating principle of a solar cell is based on the photovoltaic effect occurring at the junction of two semiconductors, p-type and n-type, i.e., the **p-n junction**. In a p-n junction, the concentration of holes in the p-type region is higher than in the n-type region, and similarly, the concentration of electrons is significantly higher in the n-type region compared to their concentration in the p-type region. This carrier concentration gradient creates a so-called **diffusion current**, which involves the transfer of electrons from the n-type region to the p-type

region and holes from the p-type region to the n-type region. As a result of electron diffusion from the n-type region, positively charged donor ions remain, while as a result of hole diffusion from the p-type region to the n-type region, negatively charged acceptors remain. In this way, a dipole layer of space charge and an electric field with intensity \vec{E}_0 directed from the positive potential (n-type region) to the negative potential (p-type region) are created in the transition region. This field counteracts further diffusion of majority carriers. Simultaneously, this field causes the drift of minority carriers (electrons from the p-region to the n-region and holes from the n-region to the p-region) – hence the name “**drift current**”. In thermodynamic equilibrium, these two currents balance each other, and no current flows through the junction. If an external electric field is applied, which is subtracted from the \vec{E}_0 -field, a large diffusion current, even hundreds of milliamperes, flows through the junction. This is called **forward bias** (Fig. 3a). If an external electric field is applied, which is added to the \vec{E}_0 -field, a small drift current flows through the junction (Fig. 3b). In a good diode, this current is of the order of nA. This is called **reverse bias**.

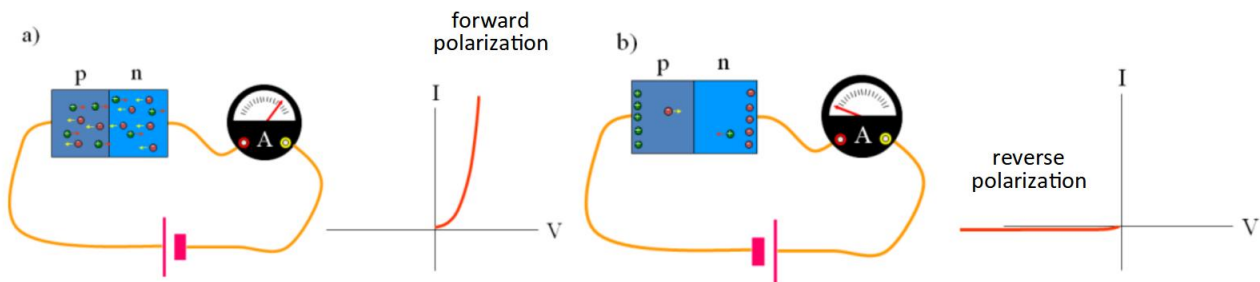


Fig. 3. P-N junction a) forward biased and b) reverse biased

Figure 4 shows a p-n junction without and after external biasing, the corresponding band diagrams, and the current-voltage characteristics, I - V . For a silicon p-n junction, the voltage at which the current increases (built-in potential V_0) is approximately 0.7 V. The I - V characteristic is described by Shockley's formula:

$$I = I_s (e^{\frac{qV}{kT}} - 1) \quad (1)$$

where q - elementary charge, T - a sample temperature (K), k - Boltzmann constant, I_s - saturation current.

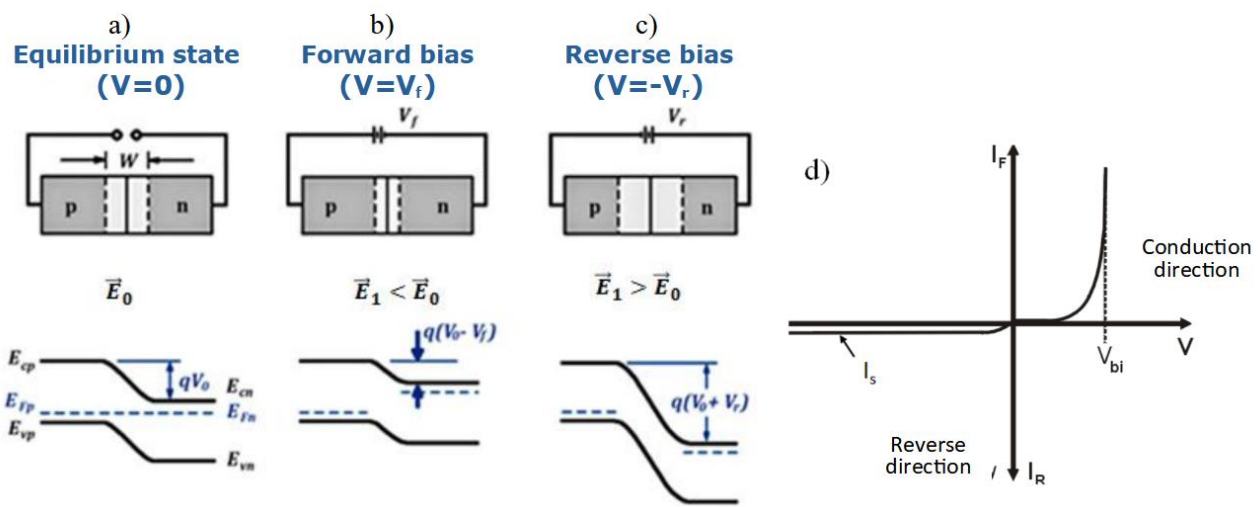


Fig. 4. P-n junction a) in equilibrium, b) forward biased by voltage V_f and c) reverse biased by voltage V_r , d) I - V characteristic.

Photovoltaic Effect at a P-N Junction

Let's assume that a semiconductor diode is illuminated by electromagnetic radiation with energy greater than the band gap E_g . When this radiation is absorbed near the junction itself, the resulting electron-hole pairs are separated by the junction's electric field. Minority carriers play a key role in the photovoltaic effect, as the concentration of majority carriers is practically unchanged by light absorption (the concentration of carriers generated by light is several orders of magnitude lower than their equilibrium concentration). Minority carriers move toward the junction, causing an increase in reverse current. If the external circuit of the junction is shorted, a short circuit current I_{sc} flows (Fig. 5a). If the junction is open, electrons flow into the n-type region, creating a negative potential at its ends. Holes flow into the p-type region, creating a positive potential at its ends. As a result, a potential difference, the so-called open-circuit voltage V_{oc} , appears at the ends of the p-n junction (Fig. 5b). This is equivalent to forward biasing the junction. The open circuit voltage of a silicon cell is $\sim 0.5V$.

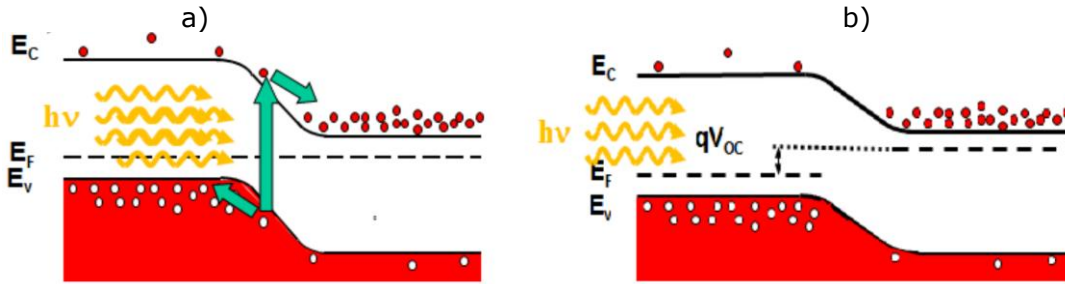


Fig. 5. Band diagram of the cell after illumination a) short-circuited, b) open

If the illuminated cell is loaded with a resistance R_L , a reverse current I_L flows through it. This current causes a voltage drop V across the resistance R_L . The voltage V forward biases the junction, which in turn causes a current I_F to flow (Fig. 6). Total current:

$$I = -(I_L - I_F) \quad (2).$$

At each point in the fourth quadrant of the I - V characteristic of the illuminated junction, the product of the current and voltage is less than zero:

$$P = I \cdot V < 0 \quad (3).$$

This means that electric power is generated. This converts electromagnetic radiation energy into electrical energy.

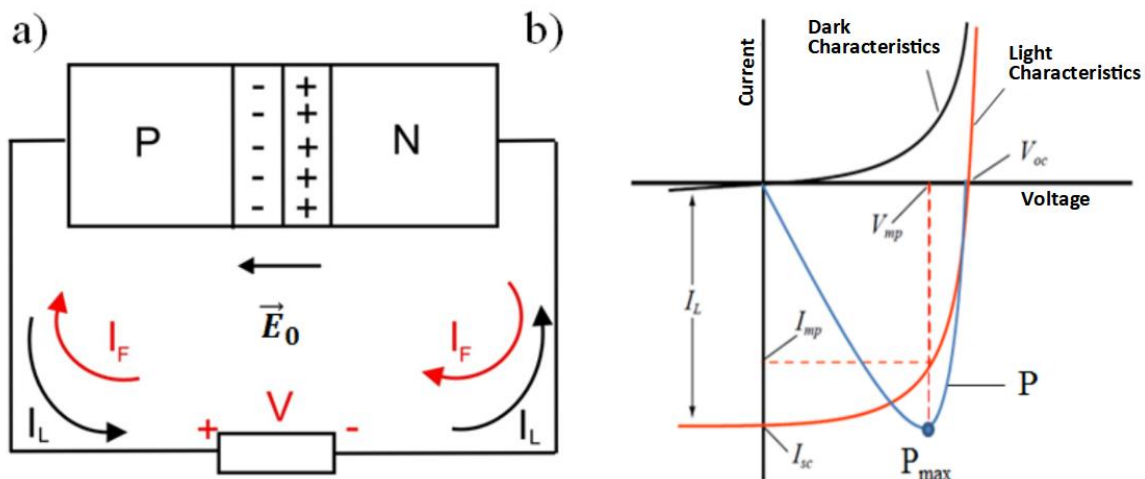


Fig. 6. a) Schematic diagram of the electrical circuit of a cell loaded with resistance R_L and b) I - V characteristics before and after illumination and the power dependence $P=f(V)$. The short-circuit current I_{sc} and open-circuit voltage V_{oc} , the point of maximum power P_{max} and the corresponding current I_{mp} and voltage V_{mp} are marked.

Solar Cell Parameters

The most important parameter determining a solar cell's usefulness is its efficiency. This is the ratio of the power generated by the cell at the point corresponding to its maximum power P_{max} (see Fig. 6b) to the power of the incident electromagnetic radiation Φ :

$$\eta = \frac{I_{mp}V_{mp}}{\Phi} \quad (4)$$

If you introduce the so-called fill factor, FF:

$$FF = \frac{I_{mp}V_{mp}}{I_{sc}V_{oc}}, \quad (5)$$

this efficiency can be expressed by the formula:

$$\eta = FF \frac{I_{sc}V_{oc}}{\Phi} \quad (6)$$

To compare the efficiency of different cells, I-V characteristics are measured under the same lighting conditions (AM1.5). The light source should have a spectral characteristic similar to that of the Sun (Fig. 1). Such sources are called solar simulators.

2. Measurement Principle and Measuring System

2.1. List of Instruments

- | | |
|--------------------|---|
| 1. Cell Panel | 5. Stabilized Illuminator Power Supply |
| 2. Illuminator | 6. Cell Polarization Circuit |
| 3. DC Voltmeter | 7. Cell Polarization Circuit Power Supply |
| 4. DC Milliammeter | 8. Panel Cover |

2.2. Measuring System Diagram

Fig. 7 shows a setup for measuring the current-voltage characteristics of a photovoltaic panel. The photovoltaic panel (1) is placed on an optical bench. An illuminator (2) is positioned opposite the panel. The illuminator's power supply (5) allows for the selection of two lighting intensities. A voltmeter (3) and ammeter (4) are used to measure the voltage and current in the panel circuit. The circuit (6) allows for panel polarization using the potentiometers located within the circuit.

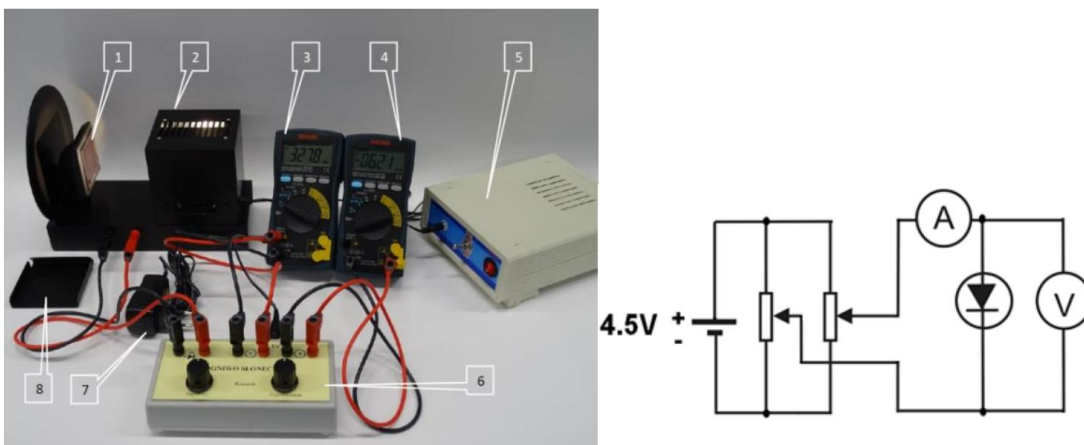


Fig. 7. Station for measuring the I-V characteristics of a solar panel and an equivalent circuit diagram for cell polarization.

3. Tasks to be Performed

3.1. Dark Characteristic Measurements:

- 1) Assemble the measuring system according to the diagram shown in Fig. 7.
- 2) Measure the current-voltage characteristic, i.e., the current-voltage relationship, for a panel covered with a shutter.

3.2. Light Characteristic Measurements:

- 1) Assemble the measuring system according to the diagram shown in Fig. 7.
- 2) Remove the shutter from the solar panel.
- 3) Turn on the illuminator's power supply. Set the switch on the power supply to the lower position. This position corresponds to lower illuminance. The upper position corresponds to higher illuminance.
- 4) Measure the current-voltage characteristic for the illuminated panel.
- 5) Repeat the I-V characteristic measurements for a higher illuminance. To do this, set the switch on the illuminator's power supply to the upper position and repeat step 4.

4. Processing the results:

- 1) Plot the solar panel's dark I-V characteristic.
- 2) Read the built-in potential V_0 from the graph.
- 3) Plot the solar panel's light I-V characteristic for two different light intensities.
- 4) Mark the short-circuit currents I_{sc} and open-circuit voltage V_{oc} on the graphs, as well as the points where the currents I_{mp} and voltage V_{mp} correspond to maximum power.
- 5) Plot the cell power $P=f(V)$ graphs.
- 6) Mark P_{max} on the graphs.
- 7) Using formula (5), determine the fill factors for both light intensities.

5. Questions:

1. What are the AM0, AM1, and AM1.5 illumination conditions?
2. Draw the spectral characteristics of the Sun.
3. What are intrinsic, p-type, and n-type semiconductors?
4. How is a p-n junction formed?
5. Explain the photovoltaic effect at a p-n junction.
7. List the parameters that characterize a solar cell.

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