Introductory Chapter: Introduction to Photovoltaic Effect

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Additional information is available at the end of the chapter

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1. Spectral characteristics of solar radiation

Solar radiation is a radiant energy emitted by the Sun as a result of its nuclear fusion reactions. Spectral characteristics of solar radiation, both external to the Earth's atmosphere and at the ground, can be seen in **Figure 1**. Over 99% of the energy flux from the Sun is in the spectral region of 0.15–4 μm, with approximately 50% in the visible light region of 0.4–0.7 μm. The total amount of energy emitted by the Sun and received at the extremity of the Earth's atmosphere is constant, that is, 1370 W/m²/s. The amount of energy received per unit area of the

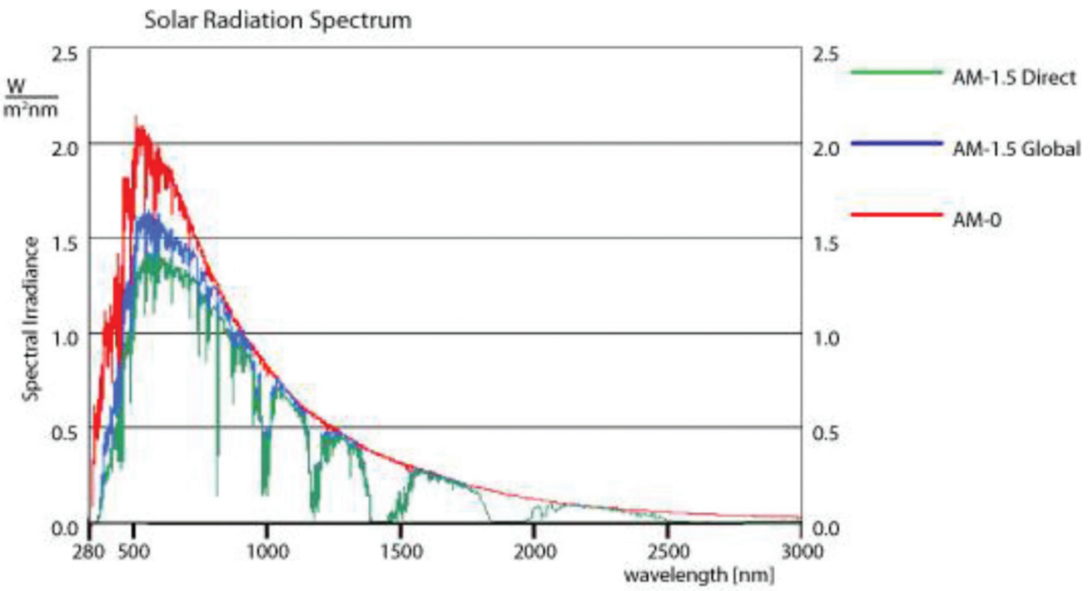

Figure 1. Spectral distribution of radiation intensity [1].

Earth's surface is 343 $W/m^2/s$. The standard spectrum for space applications is referred to as AM_0. It has an integrated power of 1366.1 W/m^2. Two standards are defined for terrestrial use: (1) the $AM_{1.5}$ global spectrum is designed for flat plate modules and has an integrated power of 1000 W/m^2 and (2) the $AM_{1.5}$ direct spectrum is defined for solar concentrator work. It includes the direct beam from the Sun and the circumsolar component in a disk of 2.5° around the sun. The direct and circumsolar spectra have an integrated power density of 900 W/m^2 (**Figure 1**).

2. History of photovoltaic effect

The photovoltaic effect was discovered in 1839 by the French physicist, Alexandre Edmond Becquerel. While experimenting with metal electrodes and electrolyte, he discovered that conductance increases with illumination. Willoughby Smith discovered the photovoltaic effect in selenium in 1873. Albert Einstein described the phenomenon in 1904. The first silicon monocrystalline solar cell was constructed in 1941. In 1951, the first germanium solar cells were made. Bell's Laboratories published the results of the solar cell operation with 4.5% efficiency. The efficiency was increased to 6% within a few months. In 1957, Hoffman Electronics introduced a solar cell with 8% efficiency. A year later, in 1958, the same company introduced a solar cell with 9% efficiency. The first radiation-proof silicon solar cell was produced for the purposes of space technology in the same year. In 1960, Hoffman Electronics introduced another solar cell with 14% efficiency. In 1977, the world production of photovoltaic modules exceeded 500 kW. In 1984, ARCO Solar introduced the first amorphous modules. In 1985, researchers at the University of New South Wales in Australia constructed a solar cell with more than 20% efficiency. In 1996, BP Solar purchased APS announced a commercial CIS solar cells production. During 2000 and 2001, the production by Japanese manufacturers increased significantly.

3. Solar cell structure

When a solar cell is illuminated by sunlight, photon energy of the incident light is converted to direct current electricity through the process of photovoltaic effect of the solar cell. Incident light causes electron–hole pairs to be generated in the semiconductor, and there is an increase in the concentration of minority carriers (electrons in the p-type region and holes in the n-type region) in the depletion region. This increase in the concentration of minority carriers results in the flow of the minority carriers across the depletion region into the quasineutral regions. These photo-generated carriers cause the flow of photo-generated current. When the junction is in the open-circuit condition, no net current can flow inside the p-n junction; thus, the current resulting from the flux of photo-generated and thermally generated carriers is balanced by the opposite recombination current (**Figure 2**).

If a load is connected between the electrodes of the illuminated p-n junction, some fraction of the photo-generated current will flow through the external circuit. The potential difference between the n-type and p-type regions will be lowered by a voltage drop over the load. Also, the electrostatic potential difference over the depletion region will be decreased, which results in an increase in the recombination current [2].

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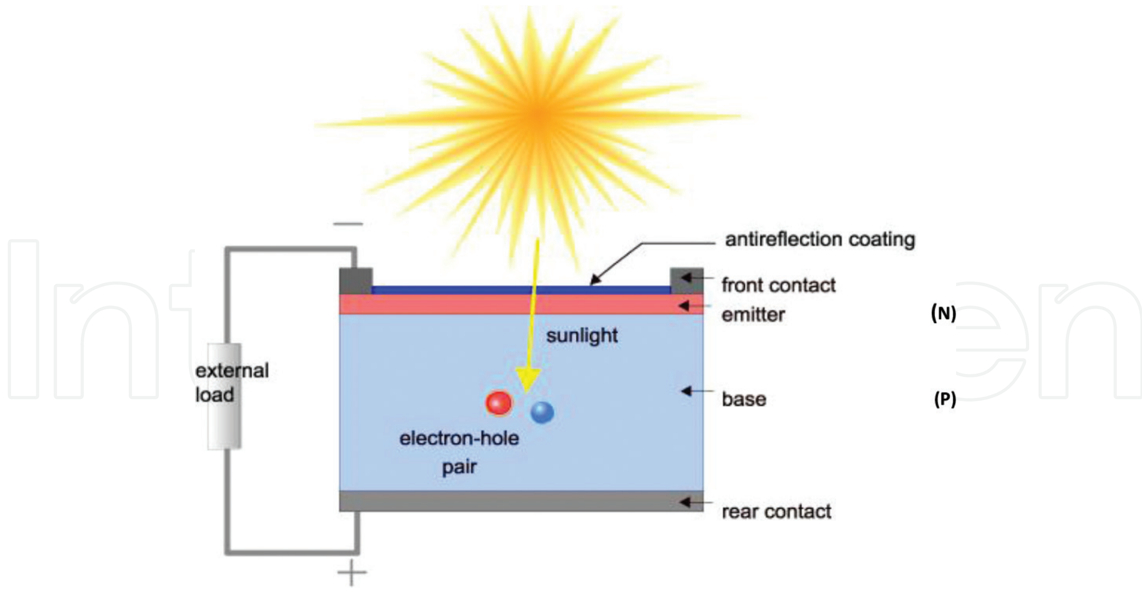

Figure 2. Incident light on a typical PN solar cell.

4. Basic structure of a solar cell

Most solar cell technologies [3] have:

- Anti-reflecting coating (ARC), which is a very important part in solar cell fabrication. It is usually sprayed over bare silicon cell because silicon has a high surface reflection.
- Front contacts that are necessary to collect the current generated by a solar cell. They are usually made of metals.
- An emitter that absorbs the incoming photons and transports their energies to the excited state of charge carries. Pentavalent-doped silicon (n-type) has a higher surface quality than trivalent doped silicon (p-type), so it is placed at the front of the cell, where majority of the light is absorbed.
- In p-n junction, in its simplest form, the base (p-type) region is joined at a junction with emitter (n-type) region leading to majority electrons in the n-type side close to the junction to diffuse of to the p-type side and majority hole from the p-type to diffuse n-type side.
- Rear contact is a less important than the front contact because it is much way from the junction and does not need to be transparent.

5. Equivalent circuit of a solar cell

To understand the electronic behavior of a solar cell, it is useful to create a model, which is electrically equivalent and is based on discrete electrical components whose behavior is well known. An ideal solar cell may be modeled by a current source in parallel with a diode;

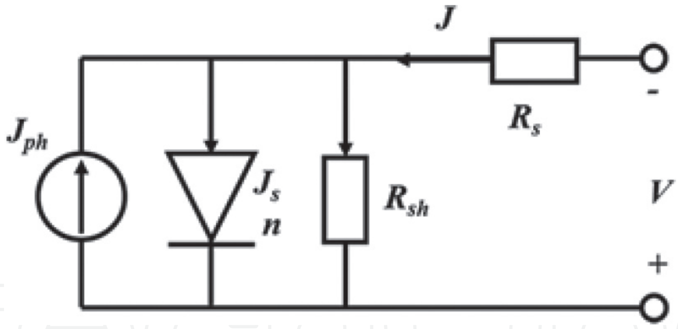

Figure 3. The equivalent circuit of a solar cell.

in practice, no solar cell is ideal, so a shunt resistance and a series resistance component are added to the model (**Figure 3**) [4, 5].

5.1. Characteristic equation

From the equivalent circuit, it is evident that the current produced by the solar cell is equal to that produced by the current source, minus that which flows through the diode, minus that which flows through the shunt resistor:

$$J = J_{ph} - J_s - J_{sh}$$

where J is the output current, J_{ph} is the photo-generated current, J_s is the diode current, and J_{sh} is the shunt current.

The current through these elements is governed by the voltage across them:

$$V_j = V + JR_S$$

where V_j is the voltage across both diode and resistor R_{sh} and V is the voltage across the output terminals.

By the Shockley diode equation, the current diverted through the diode is:

$$J_s = J_0\left[exp\left(\frac{V + J\,R_s}{n\,V_T}\right) - 1\right]$$

where J_0 is the diode reverse saturation current (A), R_S is the series resistance (Ω), R_{sh} is the shunt resistance (Ω) and n is the diode ideality factor. Here, the shunt current is:

$$J_{sh} = \frac{(V + J\,R_s)}{R_{sh}}$$

Combining this and above equations results in the complete governing equation for the single-diode model:

$$J = J_{ph} - J_0\left[exp\left(\frac{V + J\,R_s}{n\,V_T}\right) - 1\right] - \frac{(V + J\,R_s)}{R_{sh}}$$

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The output power is given by:

$$P = V\left(J_{ph} - J_0\left[exp\left(\frac{V + J\,R_s}{n\,V_T}\right) - 1\right] - \frac{(V + J\,R_s)}{R_{sh}}\right)$$

5.2. Solar cell characteristics in practice

The J-V characteristic of a solar cell in practice usually differs to some extent from the ideal characteristic. The solar cell may also contain series (R_s) and parallel (or shunt, R_p) resistances, leading to a characteristic of the form where the light-generated current J_{ph} may, in some instances, depend on the voltage, as we have already noted (**Figure 4**) [6].

5.3. Fill factor

As always in electrical engineering, optimal power output requires a suitable load resistor that corresponds to the ratio (V_m/J_m). V_m and J_m are, by definition, the voltage and current at the optimal operating point, and M_{pp} is the maximum achievable power output [7]. We now form the ratio of peak output ($V_m.\ J_m$) to the variable ($V_{oc}.J_{sc}$) and call this ratio the fill factor (FF) of a solar cell:

$$FF = \frac{V_m \cdot J_m}{V_{oc} \cdot J_{sc}}$$

5.4. Efficiency

The efficiency of a solar cell is defined as the ratio of the photovoltaic-generated electric output of the cell to the luminous power falling on it [8]:

$$\eta = \frac{V_m \cdot J_m}{P_{light}} = \frac{FF \cdot V_{oc} \cdot J_{sc}}{P_{light}}$$

The silicon solar cells have dominated the PV market for so many years. They have been produced to be used for both research and commercial purposes. They have dominated the

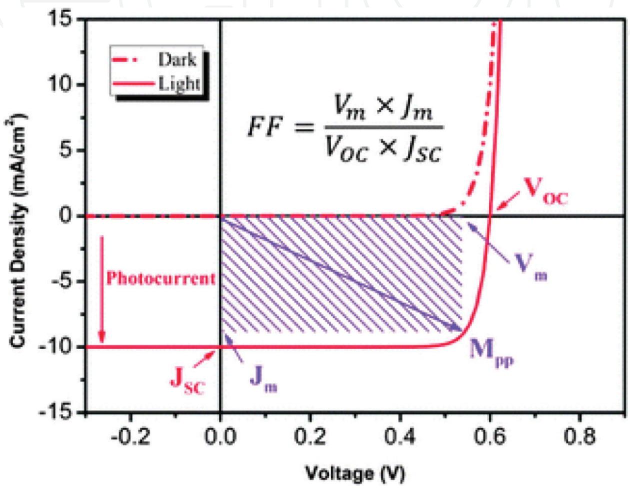

Figure 4. The superposition principle for solar cells.

Cell	Area (cm^2)	V_{oc} (v)	J_{sc} (mA/cm^2)	FF (%)	η (%)
c-Si	143.7	0.740	41.8	82.7	25.6 ± 0.5
Poly-Si	243.9	0.663	39.03	80.3	20.8 ± 0.6
a-Si:H	1.001	0.896	16.36	69.8	10.2 ± 0.3
CIGS/CdS	0.988	0.752	35.3	77.2	20.5 ± 0.6
CdTe/CIS	1.062	0.876	30.25	79.4	21.0 ± 0.4
Organic	0.993	0.793	19.40	71.4	11.0 ± 0.3

Table 1. Current operational data of compared technologies based on modules.

market because of the abundance of silicon, nontoxicity, module efficiency, and excellent cell stability. There are various levels of skills for production of the evaluated technologies (monocrystalline [9], polycrystalline [10–13], amorphous [14], and inorganic and organics cells). The current operating data of the evaluated cells in their module state are compared in **Table 1**. These data were measured under the global AM1.5 spectrum (1000 W/m^2) at 25°C.

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