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Photovoltaic cell: efficiency of energy conversion

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Abstract. Two additions to student experiments with a photovoltaic cell are described. The power of the incident radiation is determined experimentally and the efficiency of the energy conversion is presented as a function of the temperature of the source of irradiation, an incandescent lamp. Two simple tools are designed for measuring the incident radiation by a comparison method.

1. Introduction

A photovoltaic cell is a good object for student experiments and well suited for investigations at different levels. The theory and features of photovoltaic cells are given in many sources (see e.g. [1, 2]).

Several student experiments with a photovoltaic cell have been reported [3–11]. Kammer and Ludington [3] determined the efficiency of a silicon solar cell, i.e. the ratio of the electrical power output to the incident solar power. The Sun's irradiance above the Earth's atmosphere (AM0 irradiation, where AM denotes the so-called 'air mass') is 1.4 kW m^{-2}. To calculate the irradiation at the Earth's surface, the distance in the atmosphere through which the radiation travels must be taken into account. For a bright, clear day the solar irradiance at sea level is 0.96 kW m^{-2} for the Sun directly overhead (AM1 irradiation). The authors claimed that the experiments can be performed with artificial sources, but sunlight is much to be preferred unless the artificial source has a similar radiation spectrum.

Chow [4] employed the solar irradiance and a halogen lamp having a spectrum similar to that of sunlight at sea level with the Sun at 30° above the horizon. In this case, the path through the atmosphere is twice that for vertical (AM2 irradiation). The author has concluded that a determination of the total irradiance is highly desirable because calibration with sunlight is not entirely reliable unless the turbidity is known or is negligible. Kissner [5] has constructed a simple instrument for measuring both the instantaneous and integrated values of solar flux. The sensor is a solar cell connected to a resistor located in an insulated water bath. The temperature of the bath is measured by a thermistor. A similar bath is used as a reference. The instrument was calibrated by means of a standard pyranometer and a digital integrator. Muoy *et al* [6] have described an auxiliary transistorized circuit for recording I–V characteristics of solar cells.

Mialhe and Charette [7] used sunlight to evaluate solar cell parameters that are dependent on the illumination and the temperature of the cell. Khoury *et al* [8] measured the open-circuit voltage of a solar cell versus its temperature, up to 100$\circ$ C. The source of irradiation was a halogen lamp. DuPuy [9] determined the solar luminosity with a silicon photodiode. The Sun was considered as a black body at 5800 K and necessary corrections were made for the spectral response of the photodiode and absorption of the sunlight in the Earth's atmosphere. Mártil and González Diaz [10] employed a halogen lamp to obtain I–V characteristics of a silicon solar cell. They pointed out that the spectrum of the lamp is different from that of sunlight. However, the authors ignored this fact when determining the incident power from the lamp. To evaluate this power, the same relation between the short-circuit current and the incident power was used as for sunlight. The incident power from the lamp was thus underestimated and the efficiency of the cell overestimated. Recently, Siemsen *et al* [11] have described how to manufacture a solar cell using spinach, toothpaste and a few other items found in any school laboratory. However, the conversion efficiency obtained appeared to be far below the expectation.

The main drawback of the experiments reported is the absence of a tool to reliably measure the power of the incident radiation. If this drawback were overcome, the use of photovoltaic cells in experiments would become more widespread.

The aim of this paper is to propose two additions to the experiments listed above. First, an experimental determination of the power of incident radiation is more appropriate than any calculation. This approach makes it possible to obtain results that are more reliable. Two simple tools are designed for this purpose. Second, the energy conversion efficiency of a photovoltaic cell is measured as a function of the temperature of the source of irradiation. This dependence is caused by the shift of the radiation spectra. This experiment leads to a better understanding of the origin of the ultimate efficiency of a photovoltaic cell. It is also of practical interest because the effect of a decrease in the temperature of the source is similar to that of an increase in the energy gap of the semiconductor used in the photovoltaic cell.

2. Ultimate energy conversion efficiency

Many authors calculated the ultimate efficiency of the energy conversion by a photovoltaic cell [12–16]. Shockley and Queisser [16] considered a photovoltaic cell in which all photons with energy $E \geqslant E_0 = h\nu_0$ produce the same effect while photons of lower energy do not contribute. Here E_0 is the energy gap of the semiconductor, ν_0 is the corresponding frequency, and h is Planck's constant. Each photon having energy $E \geqslant E_0$ produces one electronic charge at a voltage of $V = E_0/e$. Hence, the first fundamental limitation for the efficiency is caused by photons whose energy is less than E_0. The second limitation is posed by photons of higher energies, because the energy in excess of E_0 is converted into heat inside the cell.

It turned out that the efficiency of a photovoltaic cell depends only upon the quantity $X = E_0/k_B T$, where k_B is Boltzmann's constant, and T is the temperature of the source of irradiation. This means that the energy gap of the semiconductor and the temperature of the source of radiation influence the efficiency in a similar manner. The authors have presented their results as a graph of the ultimate efficiency versus X. The maximum efficiency is achieved at $X = 2.2$. A silicon photovoltaic cell is thus very suitable for converting solar radiation into electrical power. The ultimate efficiency has been evaluated to be 44%. However, several other factors reduce this figure. One important factor is internal resistance of the cell. Nowadays, the maximum efficiency achieved for silicon solar cells is about 20% [2]. Attempts to enhance the efficiency of solar cells are still being made (see e.g. [17]).

On the other hand, one may consider the efficiency of a photovoltaic cell as a function of the temperature of the source of irradiation. For black-body radiation, the total power of the incident radiation can be written as

$$P_{\text{in}} \propto \int_0^\infty \nu^3 \, d\nu/[\exp(h\nu/k_B T) - 1].$$

To evaluate the ultimate output power from a photovoltaic cell, one has to multiply the number of photons having energy $E \geqslant E_0$ by $E_0 = h\nu_0$. Hence,

$$P_{\text{out}} \propto \int_{\nu_0}^\infty \nu_0 \nu^2 \, d\nu/[\exp(h\nu/k_B T) - 1].$$

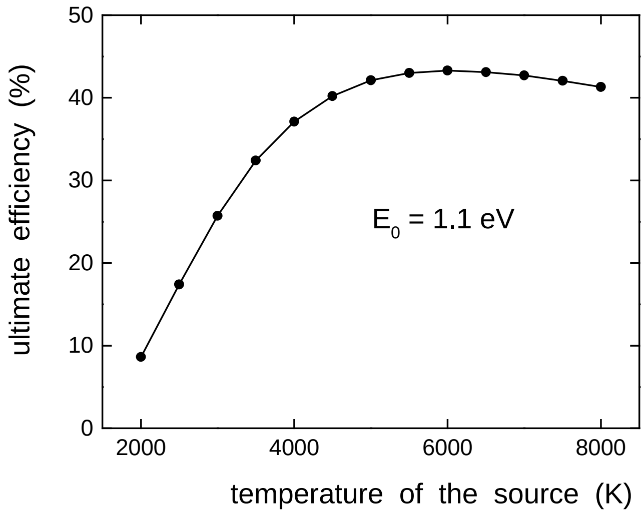

Figure 1. Calculated ultimate conversion efficiency for $E_0 = 1.1$ eV as a function of the temperature of the source of irradiation.

The ultimate energy conversion efficiency η^* thus equals

$$\eta^* = \int_{\nu_0}^{\infty} \nu_0 \nu^2 \, \mathrm{d}\nu / [\exp(h\nu/k_\mathrm{B}T) - 1] \bigg/ \int_0^{\infty} \nu^3 \, \mathrm{d}\nu / [\exp(h\nu/k_\mathrm{B}T) - 1].$$

Necessary calculations were made for $E_0 = 1.1$ eV and various temperatures of the source of irradiation (figure 1).

3. Simple tools to measure incident radiation

In determinations of the efficiency of a photovoltaic cell, the best approach would be a measurement of the power of the incident radiation. Two simple tools have been designed for this purpose. The first sensor is made of thin copper foil, painted black and provided with current and potential leads. Its absorptivity is supposed to be 100%. The sensitive area of the sensor is 2.6 cm^2, and its resistance, between the potential leads, is 0.012 Ω. The sensor is fed from a DC supply operating in the constant-current mode and from a variable AC source (figure 2). The AC source consists of a variac and an insulating low-voltage transformer. The DC and AC currents are measured by multimeters. The DC current serves to determine the resistance of the sensor that is a measure of the increment in its temperature and thus of the incident power. This current, 1 A, heats the sensor above the ambient temperature by about 1.5 K. The AC current serves to change the electrical power dissipated in the sensor. Employment of AC heating makes the calibration much simpler.

With this sensor, a simple method can be used to compensate for changes in the ambient temperature during the measurements. A thin copper wire (not shown in the figure) with potential leads is fed by a DC current from an additional source. The voltage between the potential leads is added to the voltage from the sensor. The DC current through the compensation wire is adjusted to balance the voltage from the sensor. In the absence of the irradiation and of the AC heating, the output voltage is zero. Since the sensor and the compensation wire have the same temperature coefficient of resistance, this balance does not depend on the ambient temperature. The compensation wire is placed near the sensor but it is shielded from the irradiation. The output voltage is measured by a Keithley 197A multimeter of 1 μV resolution. An integrating circuit ($R = 50$ kΩ, $C = 10$ μF) is included at the input

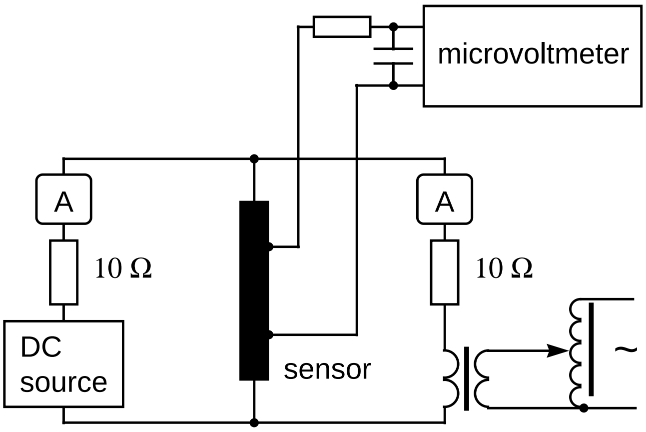

Figure 2. Electric circuit for measuring the power of incident radiation.

to the meter to suppress the AC component of the voltage that appears when the AC current passes through the sensor.

When the sensor is exposed to radiation, its temperature becomes higher. The resistance of the sensor therefore increases, by about 0.4% per kelvin. This increase is seen from the increase in the voltage from the sensor. For small temperature increments, this increase is proportional to the absorbed power. Only the coefficient of proportionality has to be known. It is available from measurements of the resistance of the sensor versus the AC electrical power dissipated in it. The calibration should be made with the same position of the sensor as under the measurements. Otherwise, changes in the heat loss from the sensor may cause significant errors. The increase in the resistance of the sensor is proportional to the dissipated electrical power (figure 3). In our case, the sensitivity of the sensor expressed as the increment in its resistance per unit dissipated power is 5.96 mΩ W^{-1}. The scatter of the data does not exceed 5%.

The incident power is measurable if it heats up the sensor by 1 K or more. When measuring

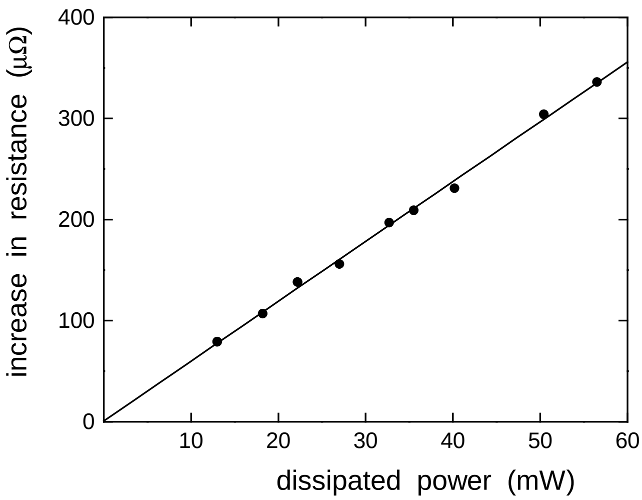

Figure 3. Increase of the resistance of the sensor versus electrical power dissipated in it.

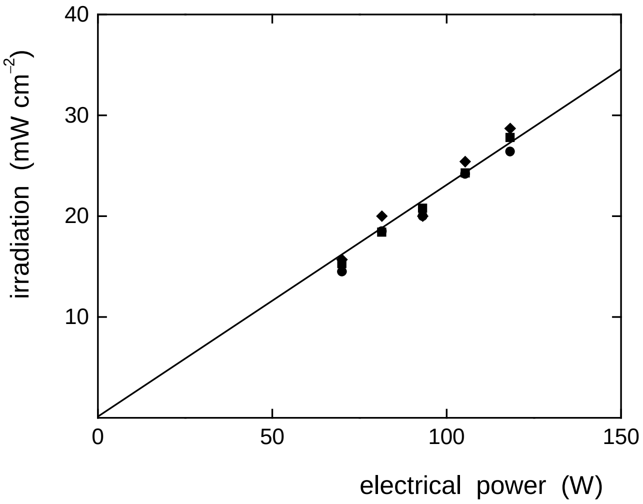

Figure 4. Results of the measurement of the incident radiation versus the power applied to the lamp. ■ – first sensor; ● – second sensor, resistance of the sensor; ♦ – second sensor, by means of the thermistor.

the incident radiation, the AC current is set at zero. With the known sensitivity of the sensor, the incident power is readily available. Another method of measurement involves replacing the radiation heating by the AC heating. In this case, one observes the increase in the sensor's resistance caused by the irradiation and one then achieves the same result with the AC heating. A comparison method is thus used to measure the incident power. This procedure is simpler and more reliable than use of a calibration graph prepared beforehand. The advantages of the sensor are quite evident: (i) it is a self-calibrated tool; (ii) it is easy and not expensive to manufacture such a sensor in any laboratory.

The second tool differs in that the temperature of a similar sensor is measured by a miniature thermistor pasted to the back of the sensor. This avoids the need for an expensive microvoltmeter. The high sensitivity of the thermistor, about 4.5% per kelvin, allows one to employ a simple multimeter to measure its resistance. The sensitive area of this sensor is 1.12 cm^2. The sensor is also provided with potential leads, so that both methods of measurement, through the resistance of the sensor and through the resistance of the thermistor, are possible. To compare the results obtained by the two sensors and using both methods of measurement, the incident power per unit area was evaluated. The irradiation from an incandescent lamp was measured by the two tools against the electrical power dissipated in the lamp. The results are in good agreement (figure 4). The scatter of the experimental points does not exceed 10%.

4. Experimental

A calibrated silicon solar cell has been purchased from Edmund Scientific, catalogue number D37346. The sensitive area of our cell is 6.8 cm^2. The short-circuit current indicated by the manufacturer equals 245 mA for a 'full Sun'. Probably this term relates to AM1 irradiation. The short-circuit current measured under experimental conditions thus shows the real intensity of the solar irradiation.

A gas-filled incandescent lamp with tungsten filament (24 V, 100 W) fed by a DC current is used as the source of irradiation. The spectral emissivity of tungsten decreases with increasing wavelength. For producing visible light, tungsten is thus more efficient than a black body of the same temperature. Here we consider tungsten as a 'grey body'. This means that its spectral emissivity is less than unity but does not depend on wavelength. The radiation spectra of a grey body are therefore similar to those of a black body of the same temperature and can be calculated from Planck's distribution. For a grey body, the efficiency of the energy conversion is the same as for the black-body radiation.

In our physics laboratory, a group of advanced first-year students performs the experiment. The aim of the experiment is an acquaintance with the problem of solar energy conversion and basic electric and temperature measurements. However, the approach described may be used in experiments of higher level. The students determine the efficiency of the photovoltaic cell at several temperatures of the tungsten filament. In the range 2500–3400 K, the temperature of a tungsten wire follows the relation $T = 261 + 166.5X - 0.76X^2$, where X is the ratio of the resistance of the wire at T to its resistance at 273 K. The above relation fits data by Roeser and Wensel [18]. Their original data were reproduced and are readily available [19]. It is difficult to determine the resistance of a low-resistance filament at room temperature accurately because of the contribution from the electric leads inside the lamp. It is therefore useful to remember that gas-filled incandescent lamps operate in the range 2700–3000 K. The temperature increases with the nominal power of the lamp. For a 100 W lamp, it is about 2850 K [20].

Before the measurements, the students make the necessary calculations and prepare a graph of the ultimate efficiency versus the temperature of the source of irradiation. The program *Origin* is used for this purpose.

The experiment is performed as follows. After the sensor is irradiated by the incandescent lamp and the increase in its resistance (or the decrease in the resistance of the thermistor) is determined, the lamp is switched off and the AC heating of the sensor is adjusted to provide the same effect. The measurements can be repeated and the mean value of the AC power dissipated in the sensor should be used as the measure of the incident power.

The experimental determination of the incident power means it is permissible to concentrate the radiation by means of a lens or mirrors. On the other hand, the power of the radiation from an incandescent lamp can be kept constant for various temperatures of the lamp. For this purpose, one changes the distance between the lamp and the photovoltaic cell. With sunlight, the incident power is measured by the cell itself through the short-circuit current.

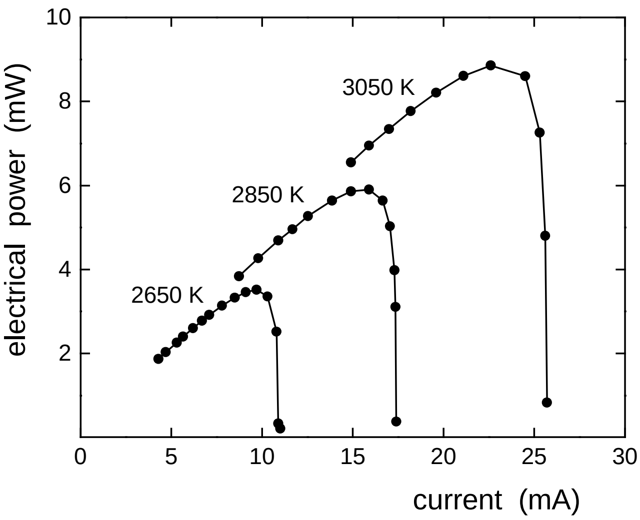

Figure 5. Electrical power generated by the photovoltaic cell versus electric current for three temperatures of the source of irradiation.

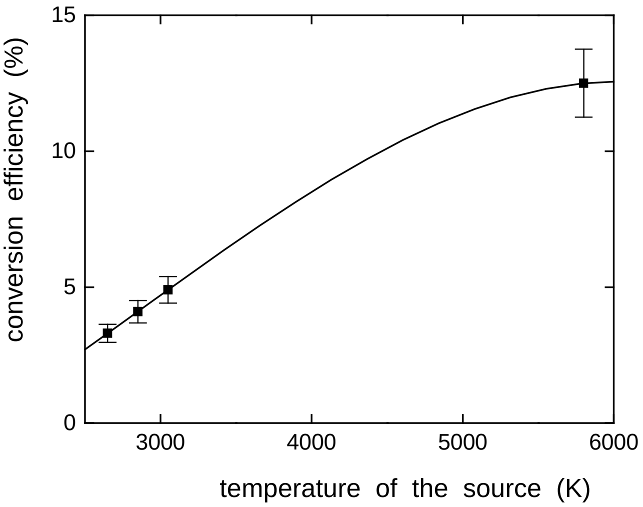

Figure 6. Energy conversion efficiency as a function of temperature of the source of irradiation.

Therefore, there is no need to calculate the absorption of the sunlight in the Earth's atmosphere. However, the calibration of the cell is valid only for irradiation with spectral distribution equal to that for AM1 irradiation. The spectrum depends on the path of the radiation through the Earth's atmosphere. For instance, the spectrum of AM2 irradiation is somewhat different from that of AM1 [15]. To characterize the incident radiation more accurately, one has to indicate its effective temperature and power.

Using a variable resistor as a load, the power generated by the photovoltaic cell is measured versus the current (figure 5). The temperatures indicated correspond to the applied voltages 20, 24 and 28 V. The irradiance of the cell at 20 cm distance from the lamp was determined to be 15.7, 21.0, and 26.5 mW cm^{-2}, respectively. The corresponding values of the conversion efficiency are 3.3%, 4.1%, and 4.9%. The solar irradiation was measured through the short-circuit current of the cell, and the conversion efficiency was determined to be 12.5%. The scatter of the data obtained does not exceed 10%.

The energy conversion efficiency can be presented as a function of the temperature of the source of irradiation (figure 6). These results can be compared with the theoretical ultimate efficiency (figure 1) only qualitatively. First, tungsten is not a grey body. Second, the difference between the ultimate efficiency and the real efficiency probably depends upon the temperature of the source of irradiation.

Acknowledgments

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