An experiment to measure the *I–V* characteristics of a silicon solar cell

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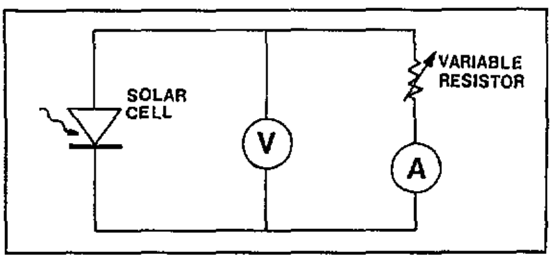
Solar cells often capture the public's attention and are a source of fascination to students (Hamakawa 1987, Zweibel 1990). We have found it profitable to tap this interest in solar cells by introducing students at an early stage of their undergraduate curriculum to the rudiments of photovoltaic devices. The purpose of this article is to describe a very simple experiment that allows college students in introductory physics courses to plot the *I–V* characteristics of a solar cell, and hence measure important photovoltaic parameters, such as the fill factor (FF) and light conversion efficiency.

A simple solar cell experiment

The following experiment was performed using a commercial polycrystalline silicon solar cell with an active area of 8.5 cm × 8.5 cm. Under illumination from an artificial light source with an intensity of 8.4 mW cm^{-2}, the short-circuit current I_{sc} of the cell is 286 mA and the open-circuit voltage V_{oc} is 0.466 V. The basic equipment needed for this experiment is an ammeter, a voltmeter and a decade box of resistors (0–100 kΩ). It is important to choose a high impedance voltmeter and low impedance ammeter to prevent loading the circuit. For these reasons we have used a digital voltmeter and a moving-coil ammeter.

Finally, a source of light is needed. Sunlight can of course be used! For example, when the Sun is directly overhead and the air is clear (turbidity free) this corresponds to AM1 (air mass one) illumination with an intensity of ~100 mW cm^{-2} (Kammer and Ludington 1977). When the Sun is at an angle θ relative to the zenith, the air mass number is increased by a factor 1/cos θ. For example, if θ = 60° the radiation is called AM2 (air mass two), which in clear air corresponds to an intensity of ~76 mW cm^{-2}. Because of the variability of natural sunlight we have utilized an artificial light source for our measurements. Our source consists of four frosted 60 W photoflood lamps located at the corners of a square of side length 30 cm. Each lamp is at a distance of 35 cm from the centre of the solar cell. The intensity of the light incident on the solar cell was measured with a calibrated radiometer consisting of a PIN silicon photodiode and a radiometric filter. In the absence of a radiometer one can conduct the experiment on a clear bright day under conditions

Figure 1. Schematic circuit diagram for determining the *I–V* characteristics of a solar cell. Here A denotes the ammeter and V the voltmeter.



of AM2 sunlight (see, for example, Kammer and Ludington 1977). However, it is important to emphasize that in practice it is unlikely to realize true AM2 illumination, except under exceptional circumstances.

Figure 1 shows the circuit for measuring the photovoltaic cell characteristics. The cell was uniformly illuminated with light from four photoflood lamps which produced an intensity of 8.4 ± 0.2 mW cm^{-2} over the active area of the cell. It is important to carry out the experiment within a short time scale ($\sim$ ¼ hour) to avoid elevating the cell temperature (above the ambient temperature), as this will result in a decrease of V_{oc}, with a relative reduction in light conversion efficiency of about 0.4% K^{-1} (Van Overstraeten and Mertens 1986). To obtain the I–V characteristics the following steps were carried out:

(1) Set the variable resistance on the decade box, R_L, to its maximum value and record both the current I and voltage V produced by the cell. If the resistance is large enough ($R_L \sim 100$ kΩ) the voltage will approximate the open-circuit value V_{oc}.

(2) Increase the current by decreasing the resistance, R_L, in steps. Record both I and V for at least 15 different settings, including the short-circuit current I_{sc} corresponding to $R_L = 0$. The light-generated component, I_L, of equation (1) (see Box 1) is found when $V = 0$.

(3) Plot the I–V curve using these data and determine the point of maximum power (V_{mp}, I_{mp}) from equations (1) and (4) in Box 1.

From these data the fill factor (FF) can be calculated from equation (6) in Box 1, and knowing the intensity of the light source enables the light conversion efficiency of the solar cell, η, to be calculated from equation (5) in Box 1.

A typical I–V plot is shown in figure 2. The fit to the experimental data is based on the ideal diode equation (1), in which I_0 and γ have been determined from a linear least-squares fit to equation

Box 1. The diode model of a solar cell

A solar cell can be modelled by a diode operating in 'reverse bias mode'. The characteristics of a photovoltaic cell are then described by a junction diode equation. In what follows we will assume an ideal diode. Losses arising from bulk resistance and junction leakage will not be taken into account, in which case we neglect series and shunt resistance contributions in the equivalent electrical circuit. The total current, I, under illumination from a light source is specified by (see, for example, Van Overstraeten and Mertens 1986)

$$I = I_0[1 - \exp(|e|V/\gamma k_B T)] + I_L \qquad (1)$$

where I_0 is the reverse diode saturation current, V is the terminal voltage, I_L is the light generated current, $|e|$ denotes the magnitude of the electronic charge, k_B is Boltzmann's constant, T is the absolute temperature and γ is a dimensionless constant (called the diode factor) that must be determined empirically under specified illumination. The current produced by the light, I_L, is in the same direction as the reverse diode saturation current. Setting $I = 0$ in equation (1), we obtained the open-circuit voltage:

$$V_{oc} = \frac{\gamma k_B T}{|e|} \ln\left(1 + \frac{I_L}{I_0}\right). \qquad (2)$$

The power delivered to a load resistance connected across the solar cell is given by

$$P = IV = I_o V\left[1 - \exp\left(\frac{|e|V}{\gamma k_B T}\right)\right] + I_L V. \qquad (3)$$

The voltage corresponding to the maximum power delivery, V_{mp}, is obtained from equation (3) as the condition $dP/dV = 0$; whence V_{mp} is found by solving the following implicit equation:

$$\left(1 + \frac{|e|V_{mp}}{\gamma k_B T}\right)\exp\left(\frac{|e|V_{mp}}{\gamma k_B T}\right) = 1 + \frac{I_L}{I_o}. \qquad (4)$$

The corresponding current at maximum power, I_{mp}, is conventionally determined from a load line on the I–V photovoltaic characteristic curve. The most important parameter when assessing the performance of a photovoltaic device is its light conversion efficiency η, which is defined by

$$\eta = \frac{I_{mp}V_{mp}}{P_{in}} = \frac{I_{sc}V_{oc}\mathrm{FF}}{P_{in}} \qquad (5)$$

where P_{in} is the incident radiant power, and the fill factor (FF) is defined as

$$\mathrm{FF} = \frac{I_{mp}V_{mp}}{I_{sc}V_{oc}}. \qquad (6)$$

For an ideal solar cell FF = 1, but this is never achieved in practice. In order to use the junction diode equation (1) to provide a theoretical fit to the experimental data, it is necessary to find the diode factor γ. This is readily obtained from a plot of $\ln(I_L - I)$ versus V for the region where $\exp(|e|V/\gamma k_B T) \gg 1$, i.e.

$$\ln(I_L - I) = \ln I_o + \frac{|e|V}{\gamma k_B T}. \qquad (7)$$

I_o is determined from the intercept and γ from the gradient of the graph.

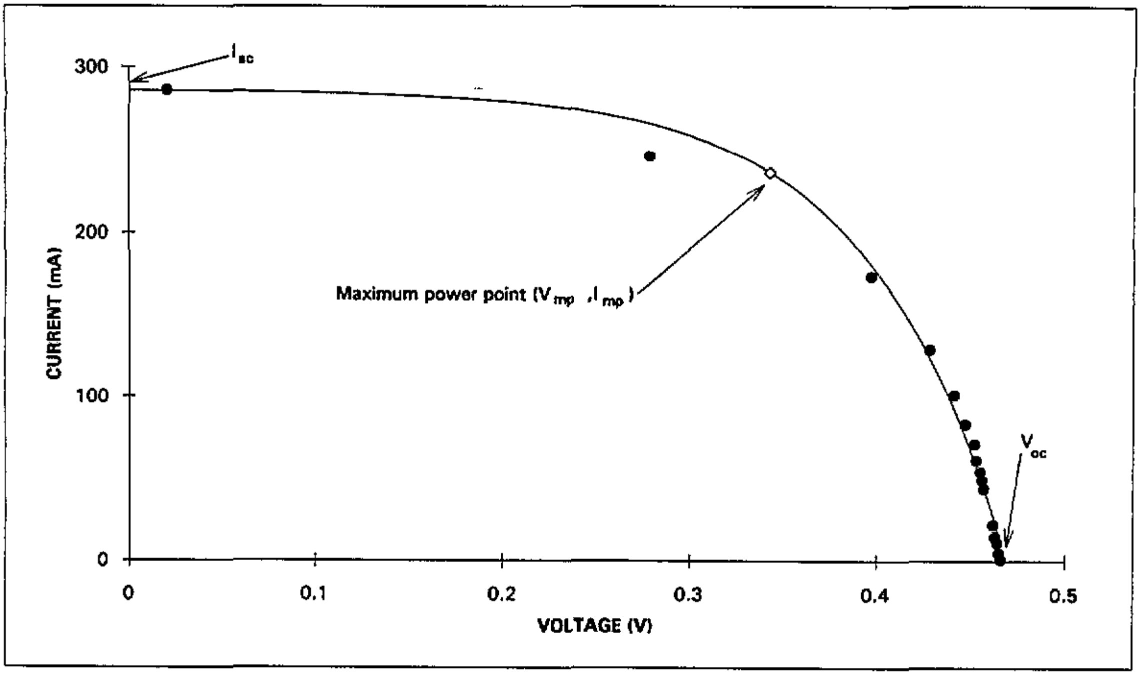


Figure 2. A typical *I–V* plot for a silicon solar cell. The open-circuit voltage and short-circuit current are labelled by V_{oc} and I_{sc} respectively. The point of maximum power is denoted by (V_{mp}, I_{mp}). The error in the voltage measurements is ± 0.002 V and the error in the current measurements is ± 2 mA. The full curve represents a fit to the experimental data based on the diode model of a solar cell as discussed in the text.

(7). We have chosen to carry out a regression analysis on the experimental data for $V > 0.4$ V, since in this region $\exp(|e|V/\gamma k_B T) \gg 1$, and a linear fit to equation (7) is obtained with a Pearson r of 0.991. From this analysis we find that $I_0 = 0.434$ mA and $\gamma = 2.88$ (at $T = 291$ K). The total diode current (in mA) under illumination is then determined from the empirical equation

$$I = 0.434[1 - \exp(13.84V)] + 286 \text{ mA}$$

where the cell voltage V is measured in volts. The voltage at the point of maximum power, V_{mp}, is found by solving equation (1), giving $V_{mp} = 0.343$ V. The corresponding current at the point of maximum power is then determined from a load line or alternatively by substituting V_{mp} into equation (8). Using the latter approach we obtain $I_{mp} = 236$ mA. From the measured values of I_{sc} and V_{oc} and the point of maximum power (V_{mp}, I_{mp}) the fill factor (FF) is calculated as $61\% \pm 2\%$. Finally the solar cell efficiency calculated from equation (5) is $13\% \pm 1\%$. This efficiency is based on a measured light intensity of 8.4 ± 0.2 mW cm^{-2} at $T = 291$ K. The intermediate efficiency of our cell ($\sim 10\%$) is typical of that obtained from commercially available polycrystalline solar cells.

Conclusion

There are many factors that dictate the performance efficiency of a solar cell. Reflection losses, the spectral characteristics of the light source and numerous other efficiency-limiting factors, such as incomplete light absorption and leakage current (see, for example, Van Overstraeten and Mertens 1986) are important considerations in the practical exploitation of solar cells. Although our model of a solar cell is naive, neglecting as it does contributions from shunt and series resistance to the equivalent electrical circuit of the cell, it nevertheless captures the essential physics and allows undergraduate students to analyse the important characteristics of a silicon solar cell.

References

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