Determination of the dark and illuminated characteristic parameters of a solar cell from *I–V* characteristics

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Abstract. We present a systematic procedure to obtain the main parameters which characterize a commercial solar cell, both in dark conditions (series and shunt resistances and recombination and diffusion saturation currents) and also under illumination (short circuit current, open circuit voltage and fill factor). All the measurements needed are made with simple and inexpensive apparatus and the calculations are straightforward.

Throughout the work the didactic aspect of the experiments was kept in mind. We have clearly shown that the common approximation of using a single exponential term with a diode factor n (different from 1 or 2) to describe the junction behaviour is not appropriate even using common laboratory multimeters if the measurements are taken carefully.

Resumen. Presentamos en este trabajo un método para obtener los principales parámetros eléctricos que caracterizan el funcionamiento de una célula solar comercial de silicio, tanto en oscuridad (resistencia series paralelo y corrientes de recombinación y difusión), como en iluminación (corriente de cortocircuito, tensión de circuito abierto y factor de curva). Todas las medidas se realizan con aparatos sencillos y los cálculos son directos.

A lo largo del trabajo, el aspecto didactico de los experimentos ha sido puesto de manifiesto. Mostramos que la aproximación usual de utilizar una única exponencial con un factor diodo n (diferente de uno o dos) para describir el comportamiento de la unión no es apropiado aunque se usen multimetros, siempre que las medidas se realicen cuidadosamente.

1. Introduction

Solar cells are very useful solid-state devices for undergraduate laboratory experiments for various reasons.

(1) They show almost all the current-limitation possibilities in a p–n junction. Series and shunt resistances and diffusion and recombination currents can be easily identified and measured by students taking courses at undergraduate level in semiconductor device physics.

(2) From a practical point of view, the large surface area of the cells leads to higher currents than in normal diodes, allowing the use of general purpose instruments.

Several papers dealing with different aspects of solar cell physics have been published [1–4]. However, a correct interpretation of the experiment measurements is not straightforward. The main reason for this misunderstanding, at least in the *I–V* characterization, is the presence of internal device resistances, i.e. series resistance (R_s) and shunt resistance (R_{sh}).

In this paper we propose a straightforward laboratory experiment to obtain the dark and illuminated *I–V* characteristics of a commercially available Si solar cell, using very simple instrumentation. We propose an analysis procedure to determine from the characteristics all the DC parameters which are representative of the conduction mechanisms.

2. Theory

2.1. Dark *I–V* characteristics

It is well known that the current–voltage relationship in a real Si solar cell device may be written as follows [5]

$$I = \frac{V - IR_s}{R_{sh}} + I_{0R}\left(\exp\left(\frac{q(V - IR_s)}{2kT}\right) - 1\right) + I_{0D}\left(\exp\left(\frac{q(V - IR_s)}{kT}\right) - 1\right) \quad (1)$$

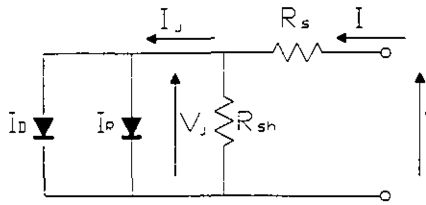


Figure 1. Equivalent circuit for a silicon solar cell.

where the I_{0R} and I_{0D} stand for recombination and diffusion saturation currents. All the other symbols have their usual meanings.

Equation (1) can be simulated by the circuit depicted in figure 1. V and I are the external voltage and current which are measured, I_J and V_J being the junction current and junction voltage drop respectively.

From equation (1) or figure 1 we can identify the four principal mechanisms which determine the I–V characteristics in a solar cell.

- The series resistance R_s limits the current I for a particular voltage V or alternatively adds an extra voltage, proportional to the current I, to the junction voltage drop. The R_s effect will become more important as the current increases.
- The shunt resistance R_{sh} adds an extra path for the current. The shunt current is added to the junction current I_J. This current increases linearly with the voltage while the junction current increases exponentially. Consequently, the shunt current should be considered only for low voltage values.
- The recombination current I_R and diffusion current I_D are the intrinsic conduction mechanisms in the junction.

In order to obtain values for all parameters involved in equation (1), we need to make some approximations, depending on the value of the voltage.

2.1.1. High voltage values. In the high voltage range, taking into account typical values for the parameters quoted in equation (1), we can write the I–V relationship as follows:

$$I = I_{0D} \exp\left(\frac{q(V - IR_s)}{KT}\right). \tag{2}$$

Because of the R_s influence, V and V_J have different values. On the other hand, $I = I_J$ in this range, provided that the shunt value is negligibly small. We can determine the R_s value following the procedure described in [6]: for two consecutive pairs of experimental data (I_N, V_N), (I_{N+1}, V_{N+1}); we can rearrange equation (2) to obtain:

$$Y = \frac{I_{N+1} + I_N}{\ln(I_{N+1}/I_N)} = -\frac{kT}{qR_s} + \frac{1}{R_s}\frac{V_{N+1} - V_N}{\ln(I_{N+1}/I_N)}$$

$$= -\frac{kT}{qR_s} + \frac{1}{R_s}X. \tag{3}$$

A least squares fit of the Y variable versus the X variable should be done using all the experimental points measured at higher voltages in order to obtain the R_s value. Once R_s is determined, we can obtain the junction voltage drop V_J by means of the equation

$$V_J = V - IR_s \tag{4}$$

If we substitute equatiuon (4) into equation (1), the R_s influence is removed, giving us an equation with separate variables:

$$I = \frac{V_J}{R_{sh}} + I_{0R}\left(\exp\left(\frac{qV_J}{2kT}\right) - 1\right)$$

$$+ I_{0D}\left(\exp\left(\frac{qV_J}{kT}\right) - 1\right). \tag{5}$$

2.1.2. Low voltage values. For this voltage range, equation (1) may be simplified to:

$$I \simeq V_J/R_{sh} \tag{6}$$

i.e. the shape of the I–V characteristic is mainly due to the influence of R_{sh}. The slope of a linear plot of I against V data allows us to obtain the R_{sh} value.

After the determination of R_{sh}, its influence on the I–V characteristics can be eliminated by means of the equation:

$$I_J = I - V_J/R_{sh}. \tag{7}$$

The substitution of both equations (4) and (7) into equation (1) allows us to write the equation for the characteristic curve for the junction values I_J and V_J:

$$I_J = I_{0R}\left(\exp\left(\frac{qV_J}{2kT}\right) - \right) + I_{0D}\left(\exp\left(\frac{qV_J}{kT}\right) - 1\right) \tag{8}$$

Now, a plot of I_J against V_J data can be used to determine I_{0R} and I_{0D}, as we will show in the results section.

2.2. Illuminated I–V characteristics

Under illumination, the solar cell characteristic becomes (7):

$$I = \frac{V - IR_s}{R_{sh}} + I_{0R}\left(\exp\left(\frac{q(V - IR_s)}{2kT}\right) - 1\right)$$

$$+ I_{0D}\left(\exp\left(\frac{q(V - IR_s)}{kT}\right) - 1\right) - I_L \tag{9}$$

where I_L is the light generated current, voltage independent. In this way, solar cell characteristics are the same as in dark conditions but translated to the fourth quadrant. The main parameters that determine the illuminated behaviour of the solar cell are the following:

V_{oc}: open circuit voltage
I_{sc}: short circuit light generated current
FF: fill factor, defined in the results section.
η: power conversion efficiency.

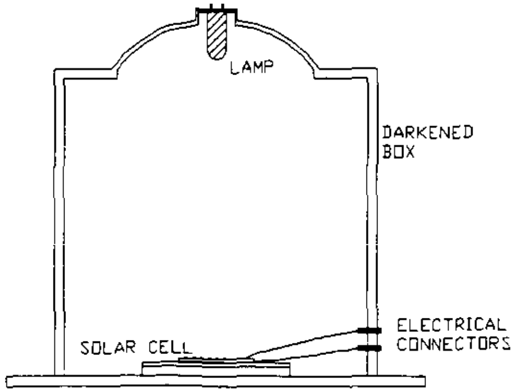


Figure 2. Experimental arrangement used for measurements on the silicon solar cell.

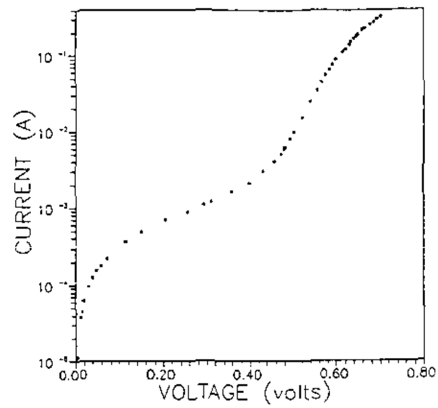


Figure 4. Experimentally obtained current and voltage values of the measured silicon solar cell (log *I* against *V*).

3. Experimental

We have made measurements on a $2\,cm^2$ Si solar cell (Solarex, 2T 205). The cell was placed in a darkened box, and electrical connections were made by means of simple plugs fixed in the box wall. In the top of the box we placed a commercial lamp (Osram Halo Star KLR51) to obtain the illuminated *I–V* characteristics. A cross section of the experimental arrangement is shown in figure 2.

The electrical circuits to measure both dark and illuminated *I–V* characteristics are shown in figure 3. We use a general purpose power supply and multimeters, because for the usual voltage range (up to 0.7 V), the solar cell current was in the range $10^{-5}-10^{-1}$ A. It should be pointed out that the spectral irradiance of the commercial lamp is different from sunlight irradiance, and so the illuminated parameters that we obtain are different from those that could be obtained under sunlight illumination. However, we think that this is not a problem.

4. Results and interpretation

4.1. Dark *I–V* characteristics

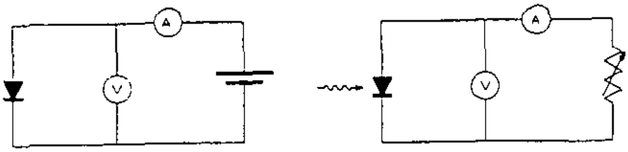
In figure 4 we show the experimentally obtained *I–V* characteristic of the Si solar cell. From this figure the influence of both resistances, R_s and R_{sh}, is clearly seen. Following the analysis procedure previously described, we have determined the R_s value for voltages higher than 0.55 V, and the R_{sh} value for voltages lower than 0.3 V. These are $R_s = 0.23\,\Omega$ and $R_{sh} = 316\,\Omega$.

Using these values of R_s and R_{sh} in equations (4) and (7), we found the values of corresponding data pairs V_J, I_J. To these data we have fitted the curve specified by equation (8). In our case there is a strong overlap between recombination and diffusion regions, removing the possibility of fitting both zones separately. The fitting was made using a commercial algorithm for arbitrary function fitting (ASYST). At the optimum fitting the saturation recombination current was $(3.1 \pm 0.2) \times 10^{-7}$ A and the saturation diffusion current was $(4.2 \pm 0.4) \times 10^{-12}$ A, which are in very good agreement with theoretical values for these saturation currents [5, 7] in Si devices.

Validation of the method is given in figure 5, which shows the experimental current *I* versus V_J (dots), the three current components (broken lines) and the final simulation current (full line). The fitting between the experimental points and the modelled results is almost perfect.

For similar problems, some papers and textbooks use a simpler expression for the junction current, simulating the *I–V* characteristic with a single

Figure 3. Electrical circuits used to measure both dark and illuminated *I–V* characteristics of the Si solar cell: (a) dark characteristics, (b) illuminated characteristics.



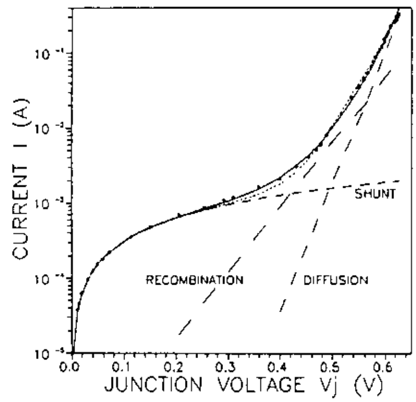


Figure 5. Comparison between experimental points and the theoretical curve fitted using two exponential terms (full line) or a single exponential current term (dotted line). Also shown: shunt, recombination and diffusion current terms. See text for explanation.

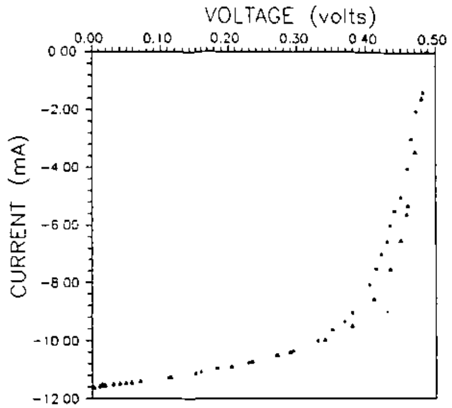


Figure 6. Experimentally obtained current and voltage values of the Si solar cell under illumination at an equivalent input luminous power of 24.2 mW cm^{-2} ($*$). Also shown are the data for the dark I–V characteristic translated to the fourth quadrant in accordance with equation (9) (Δ).

exponential term, thus introducing an empirical diode factor n, i.e. one used only for fitting purposes. We have fitted our experimental data to an I–V_J characteristic given by:

$$I = \frac{V_J}{R_{sh}} + I_0[\exp(qV_J/nkT) - 1]. \qquad (10)$$

The result of the fitting is also plotted in figure 5. Poorer agreement was obtained compared with the result of using equation (5). Also the fitting parameters have no physical meaning. In fact, values of $I_0 = 5.7 \times 10^{-9}$ A and $n = 1.4$ were obtained. No such values have been reported in the literature for the usual conduction processes present in Si junction devices [5, 6].

4.2. *I–V* characteristics under illumination

Figure 6 shows the solar cell I–V characteristic under illumination in the fourth quadrant. The determination of the characteristic parameters under illumination is straightforward, and the results are shown in table 1. From the figure, by extrapolation to the $V = 0$ axis we have obtained a value for the short circuit current of 1.16×10^{-2} A. At open circuit conditions, $I = 0$, an open circuit voltage of 0.488 V was measured.

The fill factor can be determined by means of the definition [7]:

$$\text{FF} = \frac{V_m I_m}{V_{oc} I_{sc}}$$

where $V_m I_m$ is the upper value of the VI product. A value of 64% was obtained for this parameter, as we have quoted in table 1.

The power conversion efficiency η is defined as [7]:

$$\eta = \frac{P_{GEN}}{P_{IN}}$$

where $P_{GEN} = V_m I_m$. P_{IN} can be determined once the input power radiation is known. In fact, the Si solar cell used in this experiment is calibrated to supply 4.8×10^{-2} A if the input power radiation is 100 mW cm^{-2}. Other values of the input power radiation can be related to the solar cell current by means of a simple linear relation. From these calibration data and the short circuit current value of 1.16×10^{-2} A, we obtain an input power radiation of 24.2 mW cm^{-2}. We have not attempted to measure this parameter directly. Once the input power radiation is known, it is possible to determine the power conversion efficiency. As quoted in table 1, a 7.5% conversion efficiency was deduced.

As a final comment, a comparison between dark and illuminated I–V characteristics could be made, because the illuminated characteristics should be obtained by a simple subtraction of the short circuit current ($I_{sc} \cong I_L$) from the dark I–V characteristic at all the voltage values analysed, in agreement with the theoretical prediction of equations (5) and (9).

In figure 6, we have plotted the result of such a subtraction from the dark I–V characteristic shown in figure 4. There is no perfect fitting between both characteristics, due probably to the device heating

Table 1. Experimentally obtained characteristic parameters of the Si solar cell under illumination.

I_{sc} (mA)	V_{oc} (V)	FF	η
(11.6 ± 0.2)	0.488 ± 0.02	(64 ± 5)%	(7.5 ± 1)%

produced by the lamp. Heating effects have as a direct consequence a lowering in the cell voltage for a fixed current value (4). This effect could be avoided with a properly cooled cell holder. However, this experimental modification is far beyond the aim of the experiment described in this paper.

5. Conclusions

A method to obtain dark and illuminated characteristic parameters of Si solar cells has been described. The experiment can be done with very simple and inexpensive apparatus. An analysis procedure to obtain the values of all the electrical parameters that are responsible for the electrical behaviour of the Si solar cell is given. These, for the Solarex type 2T 205 solar cell used, have been found to be $R_s = 0.23\,\Omega$, $R_{sh} = 316\,\Omega$, $I_{0R} = (3.1 \pm 0.2) \times 10^{-7}$ A and $I_{0D} = (4.2 \pm 0.4) \times 10^{-7}$ A. From the data for the illuminated characteristic, and the calibration data for the cell, the values for the photovoltaic parameters can also be found in a straightforward way. They are listed in table 1.

The importance of using a model (for the junction) which contains two exponential terms has also been shown.

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