Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Energy Conversion and Management 46 (2005) 1485–1494
ENERGY CONVERSION & MANAGEMENT
www.elsevier.com/locate/enconman

Dark I–U–T measurements of single crystalline silicon solar cells

Ewa Radziemska *

Department of Apparatus and Chemical Machinery, Chemical Faculty, Gdansk University of Technology, ul. G. Narutowicza 11/12, 80-952 Gdańsk, Poland

Received 23 January 2004; received in revised form 14 April 2004; accepted 21 August 2004
Available online 6 October 2004

Abstract

The effect of parasitic resistances on silicon solar cell performance was discussed. The current–voltage I–U characteristics of single crystalline silicon solar cells at different temperatures were measured in the dark. A one and two diodes equivalent model was used to describe the electronic properties of the solar cells. The diode ideality factors, the series and shunt resistance, that determine the fill factor and the efficiency of the solar cell, have been estimated. It was proved that the performance of the tested silicon solar cell can be described with enough accuracy by the one diode equivalent model with series resistance r_s equal to $0.1\,\Omega$ and an empirical ideality factor m_{id} equal to 1.4.

Keywords: Silicon solar cells; I–U curves; Series resistance; Shunt resistance

1. Introduction

The current–voltage characteristics of photocells, determined under illumination as well as in the dark, represent a very valuable tool for characterizing the electronic properties of solar cells. This technique gives a good idea about the cell's parameters and the characteristics of the real p–n

* Tel./fax: +48 583 471 874.
E-mail address: ewarad@chem.pg.gda.pl

0196-8904/$ - see front matter
doi:10.1016/j.enconman.2004.08.004

Nomenclature

D_n	electron diffusion coefficient
D_p	hole diffusion coefficient
e	elementary charge
E_g	band gap energy
I	current intensity
I_{dark}	dark current
I_s	saturation current
I_{ph}	photocurrent
I_{sc}	short circuit current
k	Boltzmann's constant
L_n	electron diffusion length
L_p	hole diffusion length
m	ideality factor
N_A	base doping concentration (acceptor concentration)
N_D	electron doping concentration (donor concentration)
n_i	intrinsic charge carriers concentration
r_s	series resistance
r_{sh}	shunt resistance
S	surface of p–n junction
T	temperature
U	voltage

junction. Particularly denominating the dark characteristics is the easy way to estimate the quality of the junction, antireflection layers, grid and contact resistances.

The usual equations (recombination and diffusion current) cannot fit some cells, and the trap-assisted tunneling current and field-assisted recombination should be added to the two-exponential model. For the recombination, the temperature dependence is greater than that for the trap-assisted tunneling. Also, the Poole-Frenkel effect requires studies versus temperature. It is very important to determine the values of the cell parameters in the exploitation temperature range. For temperature dependent experiments, the two-exponential model plus series and shunt resistances was considered. The temperature varies in the range from 295 K to 350 K. Non-linear curve fitting of the dark *I–U* curves gives the diode ideality factors *m*, the reverse saturation currents and the series and shunt resistances of the cell as well.

The series and shunt resistances of the cell influence the fill factor, the maximum power point and the efficiency of the cell. In a good silicon solar cell, the series resistance r_s will be less than 0.5 Ω, and the shunt resistance r_{sh} will be at least 500 Ω [1].

Dark current–voltage characteristics were, until now, determined for silicon solar cells without the temperature dependence being taken into account. Kaminski et al. [2] denominated the ideality factors in the two-exponential model at the near ambient temperature 288 K with $m_1 = 1.4$ and $m_2 = 4.3$. Stutenbaeumer and Masfin [3] obtained the value of m_2 equal to 2.38 and 2.6 with m_1

fixed to unity without temperature dependence. They have tested silicon solar cells made by Solarex and Siemens Solar and measured the series resistances $r_s = 0.17\,\Omega$ and $0.26\,\Omega$, respectively.

2. The equivalent models of the solar cell

We assume that the *I–U* curve under illumination can be described as a superposition of the dark *I–U* current and a voltage independent photocurrent.

The principal power losses in a solar cell are the fundamental losses associated with the light absorption and recombination processes of the charge carriers.

The diffusion effects in the junction region and electron–holes recombination [4] are limiting the fill factor FF, so the FF value determines the maximum power point position. The fill factor decrease, observed in silicon with temperature increase, is created by the series resistance r_s and the shunt resistance r_{sh} of the cell, which can be deduced from the *I–U* dark characteristic.

The effect of the series resistance r_s on the fill factor can be described by

$$\mathrm{FF} = \mathrm{FF}_0\left(1 - \frac{r_s I_{sc}}{U_{oc}}\right) \tag{1}$$

where FF_0 is the fill factor for the ideal solar cell characteristic [5]. There is also a strong relationship between the shunt resistance r_{sh} and the fill factor for a single silicon solar cell type, namely the larger r_{sh} the larger is the fill factor. For one solar cell type, the larger shunt resistance and smaller series resistance go together with a higher efficiency of the solar cells [3].

The photovoltaic solar cell *I–U* characteristics under darkness conditions ($I_{ph} = 0$) at different temperatures was estimated with the use of an experimental set up for examination of the temperature influence on the electric parameters of silicon diodes and photocells (Fig. 1).

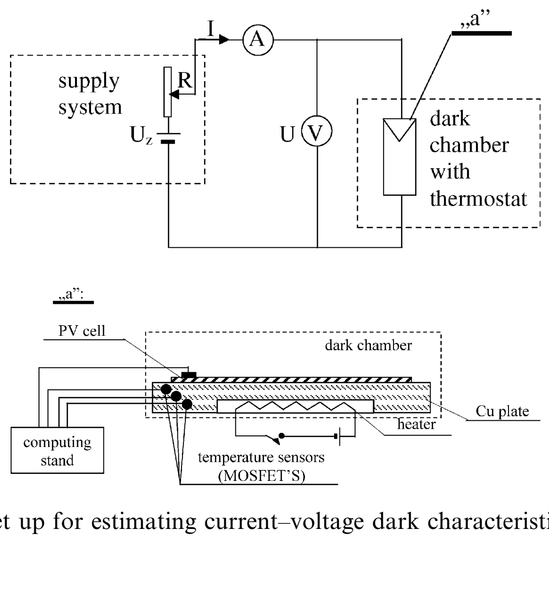

Fig. 1. The experimental set up for estimating current–voltage dark characteristics in the forward direction.

Supposing an infinite value of the shunt resistance r_{sh} of the cell, with the use of one diode equivalent model, one can estimate the value of the series resistance r_s from the semi-logarithmic plot $\ln I$–U from the equation:

$$I = I_s \exp\left[\frac{e(U - Ir_s)}{mkT}\right] \tag{2}$$

The effect of recombination in the depletion region can be deduced from the dark I–U characteristic (Fig. 2) for low currents (region A). The value of the recombination currents is dependent on the concentration of generation–recombination centers. These centers could be constituted from the various impurities and defects of the grid. For high currents (region B in Fig. 2) the series resistance r_s should be taken into account. It could be estimated from the slope of ray B on the semi-logarithmic plot on the basis of Eq. (2).

This result indicates that the series resistance influences the characteristic only in the region B at the current I' and voltage $\Delta U = I'r_s$ for high currents and leads to the deviation from the ideal characteristic in the region C.

For estimating r_s, it is enough to present Eq. (2) in the form:

$$\ln I = \ln I_s + \frac{e}{mkT}(U - Ir_s) \tag{3}$$

The series resistance r_s can be determined directly from the measured I–U characteristic with the use of the two diode equivalent model.

The two diode equivalent model is presented in Fig. 3, where I_{D1} is the diffusion current, I_{D2} is the recombination current, I is the current through an applied load and U is the voltage drop across this load. The current generator on the left side of the circuit represents the photocurrent I_{ph} generated by the solar cell.

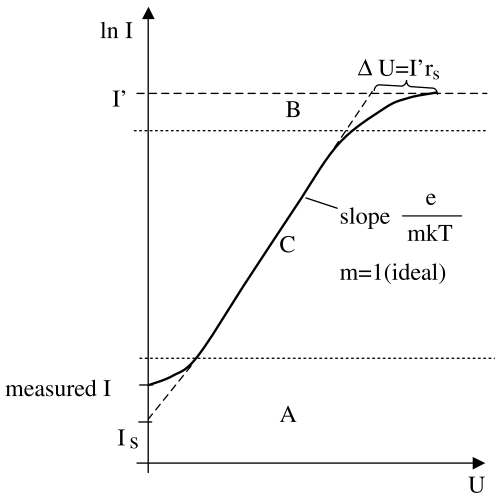

Fig. 2. Semi-logarithmic plot of the dark I–U characteristic in the forward direction on the basis of the equivalent one diode model in the range of low currents (A), high currents (B) and average (diffusion) currents (C).

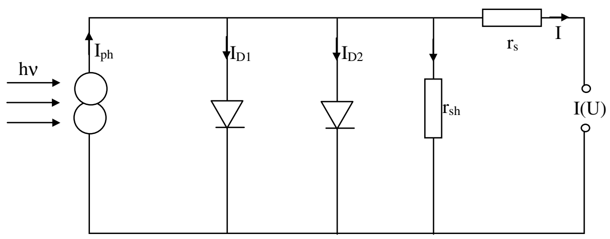

Fig. 3. Two diode equivalent model [6].

The equivalent circuit has two resistors: the resistor r_s represents the series resistance in the top surface of the semiconductor and the metal contact-to-semiconductor interface and r_{sh} represents any high conductivity path through the solar cell or on the edge caused by crystal damage in the junction or a metallization spike through the p–n junction.

Therefore, in this model, the generated current can be expressed as a function of the voltage U [6]:

$$I = I_{ph} - I_{s1}\left(\exp\frac{e(U - Ir_s)}{m_1 kT} - 1\right) - I_{s2}\left(\exp\frac{e(U - Ir_s)}{m_2 kT} - 1\right) - \frac{U - Ir_s}{r_{sh}} \tag{4}$$

where I_{ph} is the photogenerated current, I_{s1} and I_{s2} are the diode saturation currents, m_1 and m_2 are the ideality factors and r_s and r_{sh} are the series and shunt resistances, respectively. These parameters are determined so that Eq. (4) gives a good description of the experimental characteristic.

The effects of the second diode and the series and parallel resistances on the *I–U* characteristic are presented in Fig. 4.

The diffusion current is influenced by the properties of the quasi-neutral regions of the p–n junction, while the recombination mechanisms are influenced by the density of defects states in the energy band gap. These second defects are formed by the energy released from recombination of electron–hole pairs.

According to diffusion theory, based on minority carrier diffusion, the value of $m_2 = 1$ is associated with a next-to-ideal junction. Taking into account generation- recombination in the space

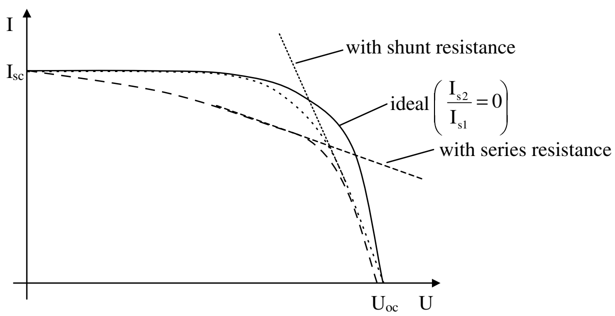

Fig. 4. The effect of the second diode and the series and parallel resistances on *I–U* characteristic.

charge region of the p–n junction and assuming that the energy level recombination traps are located at the intrinsic Fermi level, this ideality factor should equal 2 rather than 1.

The results of experimental studies [7] give values of m_2 in the range $1 \leqslant m_2 \leqslant 2$. Values of the ideality factor $m_2 > 1$ indicate low quality of the junction and are considered as a signature of recombination losses [8].

Instead of the two diode equation, an empirical ideality factor m_{id} can be introduced in the single diode equation:

$$I(U) = I_{ph} - I_s\left(\exp\frac{e(U - Ir_s)}{m_{id}kT} - 1\right) \tag{5}$$

The seven two diode model parameters can be determined also with the use of the special program PARADI [9] based on the Newton–Raphson numerical method. This program finds the parameter physical value and yields a physical description of the operating device.

The saturation currents values I_{s1} and I_{s2} depend significantly on the temperature because of the dependence:

$$I_s = eSn_i^2\left(\frac{D_n}{L_nN_A} + \frac{D_p}{L_pN_D}\right) \tag{6}$$

where S is the surface of the p–n junction and n_i is the intrinsic charge carriers concentration:

$$n_i = CT^{3/2}\exp\left(\frac{-E_g}{2kT}\right), \quad C = \text{const.}, \; E_g = \text{energy gap}$$

Standard values of the saturation current for silicon junctions at room temperature are situated in the range from 10^{-15} A to 10^{-12} A.

Making the assumption that for the first diode $m_1 = 1$ while for the second one $m_2 = 2$ [10], the diffusion current is characterized by

$$I_{D1} = I_{s1}\left(\exp\frac{e(U - Ir_s)}{kT} - 1\right) \qquad I_{s1} \propto T^3\exp\left(-\frac{E_g}{kT}\right)$$

while the recombination current is

$$I_{D2} = I_{s2}\left(\exp\frac{e(U - Ir_s)}{2kT} - 1\right) \qquad I_{s2} \propto T^{3/2}\exp\left(-\frac{E_g}{2kT}\right) \qquad [3]$$

The total dark current is, accordingly to Eq. (4), described by

$$I_{dark} = I_{s1}\left(\exp\frac{e(U - Ir_s)}{m_1kT} - 1\right) + I_{s2}\left(\exp\frac{e(U - Ir_s)}{m_2kT} - 1\right) + \frac{U - Ir_s}{r_{sh}} \tag{7}$$

In the case of silicon solar cells, the recombination mechanism dominates over the diffusion one for low currents, while for high currents, the diffusion mechanism is significant (Fig. 5).

For small values of r_s, the product Ir_s is small in comparison to U, and for low currents, the following approximation could be assumed:

$$I_{dark} = I_{s1}\left(\exp\frac{eU}{m_1kT} - 1\right) + I_{s2}\left(\exp\frac{eU}{m_2kT} - 1\right) + \frac{U}{r_{sh}} \tag{8}$$

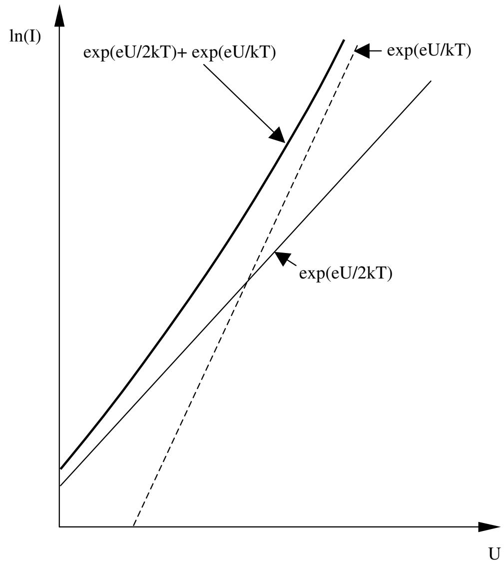

Fig. 5. Slope of the semi-logarithmic dark I–U characteristic with recombination effects included [3].

From the I–U curve, one can recognize four different voltage regions (Fig. 6), according to Eq. (8). In the first region (between 0 and 0.15 V), the dark current is mainly determined by the shunt resistance; in the second one (from 0.2 to 0.4 V), the dark current is determined by the recombination mechanism; and in the third region (up to 0.6 V), diffusion dominates. From 0.6 V upwards, the series resistance controls the dark current.

The determination of the parameters is done with the following sequences [3]:

- calculation of I_{s1}, r_s, m_1 for high voltages from the linear regression $\ln I$ as the function of $(U - Ir_s)$;
- calculation of I_{s2} and m_2 from the linear regression $\ln I(U)$;
- determination of r_{sh} according to the equation:

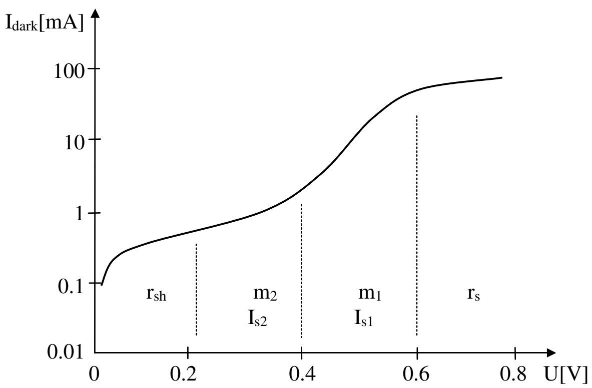

Fig. 6. Semi-logarithmic plot of dark I–U characteristics of silicon solar cell in the dark with the different two diode equivalent model parameters that influence the curve in the various regions.

$$r_{\mathrm{sh}} = \left[\left(\frac{\mathrm{d}I}{\mathrm{d}U}\right)_{U\to 0} - I_{\mathrm{s1}}\frac{e}{m_1 kT} - I_{\mathrm{s2}}\frac{e}{m_2 kT}\right]^{-1} \tag{9}$$

on the condition that ($\mathrm{d}I/\mathrm{d}U$) is high in comparison with r_{sh}^{-1} in the whole range of voltages, otherwise the least squares fit at the low voltage range to find I_{s2}, m_2 and r_{sh} simultaneously should be used.

The series resistance r_{s} could be estimated more exactly when, in addition to the dark current measurements, the illuminated I–U characteristics for different illuminations are also obtained [3]. To obtain the same dark current in the dark compared to the illuminated curve, a larger voltage U_{A}, as the open circuit voltage U_{oc}, is needed because the additional voltage drop across r_{s} has to be overcome. The difference between U_{A} and U_{oc} determines r_{s} as

$$r_{\mathrm{s}} = \frac{U_{\mathrm{A}} - U_{\mathrm{oc}}}{I_{\mathrm{sc}}} \tag{10}$$

where I_{sc} is the short circuit current.

The knowledge of the parasitic resistances r_{s} and r_{sh} is important in the further improvement of the solar cells to higher efficiencies. It was proved that when r_{s} increased five times, both P_{m} and FF are reduced by about 25%. An increase of 10 times in r_{s} results in losses of P_{m} and FF of approximately 50% [6].

3. Experimental

In order to determine the temperature dependence of the parameters, the dark I–U characteristics have been measured by forward biasing at various temperatures. In the heating stand of the silicon photocell shown in Fig. 1, the electric heater heated the copper plate with the tested solar cell. Four temperature sensors (MOSFET'S) were used to measure the upper and lower surface temperatures of the cell. They were calibrated at four different temperatures. The temperature of the plates was held uniform to within ±0.1 K, so the uncertainty of determination of temperature was 0.2%. The tested solar cell was the commercial Siemens Solar cell of the surface $10 \cdot 10\,\mathrm{cm}^2$.

For measurements of the short circuit current I_{sc}, an ammeter with a small internal resistance and a measuring error of 0.2% was used. In the case of the voltage U measurements, the error was only 0.06%.

Measurements were performed in the range of 295–350 K with a step of 5 K. Fig. 7 shows the example measurement curves.

In Table 1, the resulting values of the series resistance r_{s} and the empirical ideality factor m_{id} are displayed. The corresponding saturation current I_{s} at room temperature, estimated from the results shown in Fig. 7, is equal to $7.3 \cdot 10^{-11}\,\mathrm{A}$.

The variation of the series resistance r_{s} versus temperature (Fig. 8) could be explained by variation of the resistivities of the different layers. It is the sum of the grid, contact, sheet, base and back contact resistances. Some of these components vary exponentially with temperature, whereas some of them vary linearly.

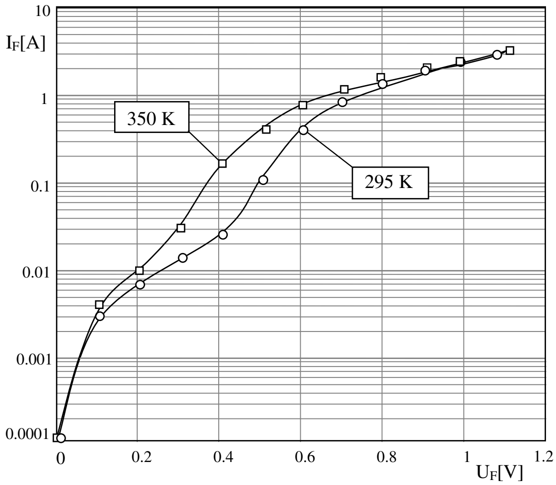

Fig. 7. The forward dark *I–U* characteristics versus temperature.

Table 1
The resulting values of the series resistance r_s and the empirical ideality factor m_{id}

Temperature	295 K	310 K	318 K	343 K	350 K
r_s (Ω)	0.1115	0.1309	0.1427	0.1559	0.1584
m_{id}	1.385	1.642	1.715	2.157	2.303

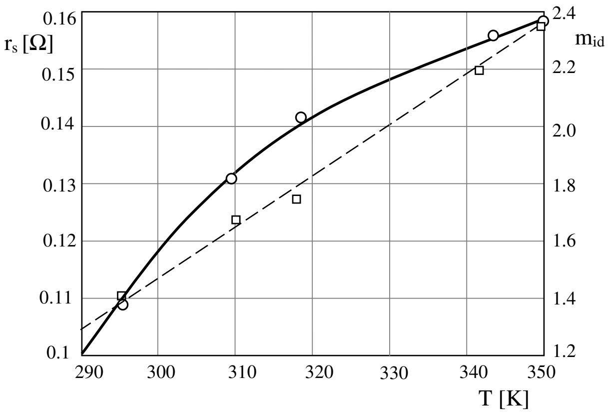

Fig. 8. The series resistance r_s (—) and the empirical ideality factor m_{id} (– – –) of the silicon solar cell in different temperatures.

The shunt resistance could be estimated with the use of Eq. (9) only approximately as greater than 800 Ω. The shunt resistance varies exponentially with temperature.

The tested cells made by Siemens Solar can be considered as good ones when the values of r_s and r_{sh} are taken into account.

4. Conclusion

The principal power losses in a solar cell are those associated with light absorption and recombination. Also, the series and shunt resistances are determinative on the fill factor, and therefore, on the maximum power point and efficiency of the solar cell.

The estimated parameters proved that the performance of the tested silicon solar cell can be described with enough accuracy by the one diode equivalent model with series resistance r_s equal to $0.1\,\Omega$ (0.2%) and an empirical ideality factor m_{id} equal to 1.4 (±0.35%) at ambient temperature. The temperature dependence of r_s and m_{id} was also pointed out.

References

[1] Mazer JA. Solar cells: an introduction to crystalline photovoltaic technology. Boston: Kluwer Academic; 1997. [quoted by [3]].
[2] Kaminski A, Marchand JJ, Laugier A. Nonideal dark *I–V* curves behaviour of silicon solar cells. Solar Energy Mater Solar Cells 1998;51:221.
[3] Stutenbaeumer U, Masfin B. Equivalent model of monocrystalline, polycrystalline and amorphous silicon solar cells. Renew Energy 1999;18:501.
[4] Radziemska E. Thermal performance of Si and GaAs based solar cells and modules: a review. Prog Energy Combust Sci 2003;29/5:407.
[5] Markvart T, Castañer L. Practical handbook of photovoltaics. Elsevier; 2003.
[6] van Dyk E, Meyer EL. Analysis of the effect of parasitic resistances on the performance of photovoltaic modules. Renew Energy 2004;29:333.
[7] El-Tahchi M, Khoury A, Mialhe P, Pelanchon F. Degradation of the ideality factor of silicon n–p solar cells. 16th European Photovoltaic Solar Energy Conference and Exhibition, United Kingdom, Glasgow; 2000, p. 1624.
[8] Das NC, Duggan WC, Nathan V. Transconductance technique for measurements of interface state density and oxide charge in LDD-MOSFET's. Phys Status Solidi 1992;133:167.
[9] El-Tahchi M, Khoury A, De Labardonnie M, Mialhe P, Pelanchon F. Degradation of the diode ideality factor of silicon n–p junction. Solar Energy Mater Solar Cells 2000;62:393.
[10] Hussein R, Borchert D, Grabosch G, Fahrner WR. Dark *I–V–T* measurements and characteristics of (n) a-Si (p) c-Si heterojunction solar cells. Solar Energy Mater Solar Cells 2001;69:123.