Effects of Temperature and Concentration Mono and Polycrystalline Silicon Solar Cells: Extraction Parameters

M Khalis1, R Masrour2, G Khrypunov3, M Kirichenko3, D Kudiy3 and M Zazoui1

1Laboratory of Condensed Matter, F.S.T., University of Hassan II Mohammedia, Casablanca, Avenue Hassan II, BP 146, 28800 Mohammedia, Morocco.
2Laboratory of Materials, Processes, Environment and Quality, Cady Ayyed University, National School of Applied Sciences, 63 46000, Safi, Morocco.
3National Technical University, 61002 Kharkov, Ukraine.

E-mail: rachidmasrour@hotmail.com

Abstract. The simple and efficient method for the extraction of all the parameters of a solar cell from a single current-voltage curve under one constant illumination level based on the Lambert $W$ function. On calculating the lsqcurvefit function with constraints, between the experimental current-voltage characteristic and a theoretical arbitrary characteristic based on Lambert $W$-function. It is significant to understand the effect of the light intensity and temperature on output performance of the crystalline solar cells. The effect of light intensity and temperature on performance parameters of mc-si and pc-si solar cells is discussed. The experiments have been carried out under a solar simulator for various intensity levels in the range 1-2.5 sun and 25–60°C, respectively. The experiment was carried out employing solar cell simulator with varying cell temperature at constant light intensity. The results show that cell temperature has a significant effect on the photovoltaic parameters and it controls the quality and performance of the solar cell. The maximum power and efficiency are found to be decreased with cell temperature and the temperature coefficient of the efficiency and maximum output power is found to be negative.

1. Introduction

Photovoltaic solar paradoxically harm the particularity to withstand the heat. This operation itself produces heat that isn't evacuated if it isn't converted into electrical energy. The electrical performances of a silicon solar cell are very sensitive to temperature [1] Polycrystalline silicon is made through a simpler method and less expensive. Instead of going through the slow and more expensive process of creating a single crystal; mc-si solar cells cost more than pc-si for the same size. Mc-si cells have a higher efficiency 25% in laboratory, standard industrial cells; however, remain limited to 14–18% than pc-si cells 20% in laboratory, commercial limited to 11-15 % [2, 3] These values found in the market are all described in the operating conditions of a solar cell, the spectral distribution of the irradiance and the temperature [4, 5] standard reporting conditions (SRC: illumination =1000 W/m², temperature=25°C and AM1. 5 reference spectrum). However, these conditions practically never occur during normal outdoor operation as they do not take into consideration the actual geographical and meteorological conditions at the installation site. The knowledge of solar cell model parameters from measured current-voltage $I-V$ characteristics are of vital importance for the quality control and evaluation of the performance of the solar cells. Several authors [6–23] proposed methods to devise ways for extracting the parameters that describe the non-linear electrical model of solar cells. These parameters are usually the saturation current, the series
resistance, the ideality factor, the shunt resistance and the photocurrent. Some of the suggested methods involve both illuminated and dark I-V characteristics \[24, 25\], while others use dynamic measurements \[26, 27\] or integration procedures \[28\] based on the computation of the area under the current-voltage curves. Here, we propose a simple fitting method \[29\] to estimate all the parameters of a solar cell just from a single I-V curve under one constant illumination level based on the Lambert \(W\) function. In this method, an accurate analytic expression for \(I\) only depends on five parameters of \(I_0\), \(I_{ph}\), \(n\), \(R_s\), and \(R_{sh}\), and is directly used to fit the experimental data. Because this analytic expression is only a function of \(V\), the fitting is only one-dimensional and, thus, a much easier method. The proposed method has been used to analyze various solar devices, including Si solar cells, GaAs solar cells \[29\], 1N4005 diode and Motorola diode \[30\]. In this paper, we have discussed the temperature and concentration variations effect on the parameters of the solar cells. This will be explained using for two crystalline silicon solar cells as an example, but the concept is also applicable to other types of solar cells. In all the examples given, to design and use solar cells correctly it is evidently necessary to understand how the two parameters, temperature and intensity of radiation, influence their behavior.

2. Theory and Model

The electrical characteristic of a solar cell can be described by the equivalent circuit of the single-diode model, the two-diode model \[31\], or the three-diode model \[32,33\]. Among these circuit models, the single-diode model has the simplest form as shown in Figure 1. Although the single-diode mode is simple, it can well describe the characteristics of various solar cells, satisfy most of the applications, and thus becomes the most widely used circuit model \[34-51\]. In the single-diode model, the relation of the current \(I\) and the voltage \(V\) is given as:

\[
I = I_{ph} - I_0 \left( \exp \left( \frac{n(V + R_s I)}{nK_B T} \right) - 1 \right) - \frac{V + R_d I}{R_{sh}}
\]

(1)

Where, \(I\) is the output current, \(I_{ph}\) is the photocurrent, \(I_0\) is the saturation current, \(R_s\) is the series resistance, \(R_{sh}\) is the shunt resistance, \(n\) is the ideality factor, \(K_B\) is the Boltzmann constant and \(T\) is the temperature. Direct parameters extraction from Equation (1) is limited by the nonlinear I-V relation and transcendental nature of current equation for a solar cell.

To find the unknown parameters of \(I_0\), \(I_{ph}\), \(n\), \(R_s\), and \(R_{sh}\), we have used the least squares method (LMS) \[52\]. The conventional curve fitting methods, the expressions for the target variable are usually implicit functions and include the independent and dependent variables at the same time such as given in Equation (1), the expression for \(I\) includes both \(V\) and \(I\). The explicit analytic expressions of Lambert \(W\) function for \(I\) or \(V\) is given in Refs \[49-51\]:

\[
I = \frac{-V}{R_s} + \frac{V}{R_s} \left( -\text{Lambert}W \left( \frac{R_s I_0 R_{sh} \exp \left( \frac{R_{sh}(R_s I_{ph} I + R_d I) + V}{nV_t(R_s + R_{sh})} \right)}{nV_t(R_s + R_{sh})} \right) \right) + \frac{R_{sh}(R_s I_{ph} I + R_d I) + V}{nV_t(R_s + R_{sh})}
\]

(2)

where \(V_t = nK_B/q\).
One such common criterion is the minimization of the sum of the squared differences between the actual data and the predicted data due to our least squares line. The error thus is defined as:

\[ \varepsilon = \sum_{i=1}^{N} (I_i - I(V_i, p))^2 \]  

where \( N \) is the number of measured \( I(V_j) \) pairs denoted by \( (V_i, I_i) \); \( I(V, p) \) is the theoretical current for voltage \( V \) as predicted by a model containing several parameters represented by \( p \) that are the variables used to minimize the error. The photocurrent at the level of radiation defined as unity (normally 1 sun AM1.5 = 100 (mW/cm²)) is \( I_{ph1} \); the photocurrent at a level of radiation \( X \) (concentration factor: \( X \) suns) times greater is:

\[ I_{ph} = XI_{ph1} \]  

If \( V_{oc1} \) is the open-circuit voltage at 1 sun, the voltage at \( X \) suns is obtained by:

\[ V_{oc} = V_{oc1} + \frac{nK_BT}{q} \ln X \]  

The energy-conversion efficiency \( \eta \) of a solar cell is defined as the ratio between the maximum electrical power \( P_{m} \) that can be delivered to the load and the power \( P_{in} \) of the radiation incident on the cell:

\[ \eta = \frac{P_{m}}{P_{in}} = \frac{I_{mp}V_{mp}}{P_{in}} \]  

Where \( \eta \) is the efficiency, \( I_{mp} \) is the current at the maximum power point \( V_{mp} \) is the voltage at the maximum power point.

As an illustration of the effect of temperature, let us consider a cell described by an exponential with \( n=1 \), corresponding to behavior dominated by recombination currents in the neutral zones. This is adequate as a first approximation. The characteristic equation for the device is therefore:

\[ I = I_{ph} - I_{0}(T)\left( \exp \left( \frac{q(V+R_{s}I)}{K_BT} \right) - 1 \right) \]  

The dependence of the reverse bias saturation current on temperature can be written in the following form:

\[ I_{0} = A T^{3} \exp \left( - \frac{E_{G0}}{K_BT} \right) \]  

where \( A \) and \( E_{G0} \) (the band gap at 0 K) are both approximately constant with respect to temperature.

3. Results and discussion

Monocrystalline silicon test samples was a fragment of full format solar cells made by PSJC «Kvazar» and has area 38.44 cm². Test samples made on SHB-2 mark, p-type monocrystalline silicon wafers with thickness about 200 µm, resistance 2 Ω*cm and doping by boron up to \( 10^{16} \text{ cm}^{-3} \). Layers of n+ and p+ type made by thermal diffusion of phosphorous and aluminum up to \( 10^{19} - 10^{20} \text{ cm}^{-3} \) with thickness 0.5 and 3 µm, correspondingly. Antireflectance coating made from Si₃N₄ with thickness 80 -100 nm. Front and rear metallization made by standard «screen printed» technology from aluminum and argentum paste with thickness of layers about 40 µm.

Polycrystalline silicon test samples made by «Yingli Green Energy Holding Co» (PRC) with area 19.76 cm². Test samples made on p-type polycrystalline silicon wafers with thickness about 230 µm, resistance about 2 Ω*cm and dopant by boron up to \( 10^{16} \text{ cm}^{-3} \). Layers of n and p type made by thermal diffusion of phosphorous and aluminum up to \( 10^{19} - 10^{20} \text{ cm}^{-3} \) with thickness 0.5 and 3 µm, correspondingly. Antireflectance coating made from Si₃N₄ with thickness 80-100 nm. Front and rear metallization made by standard «screen printed» technology from aluminum and argentum paste with thickness of layers about 40 µm.

![Figure 2. Crystalline Silicon Solar Cells: mono (a) and poly (b)](image-url)
To illustrate the influence of the concentration of sunlight on \( R_s, R_{sh}, n, I_{ph}, I_0 \) and efficiency \( \eta \), a simulation was carried out. The \( I-V \) characteristics measured under a FALCON EYES SS-110B xenon flash lamp (1000 W/m\(^2\)), Digital Oscilloscope RIGOL DS 1064B and variable load resistor P33 served to extract the solar cell model parameters of Equation (1).

Figure 3. Synthetic and fitted \( I-V \) characteristic of curves of: (c) mc-si and (d) pc-si for \( T=25 \, ^\circ \text{C} \) cell temperature at 1 sun.

Figure 3(c,d) show the synthetic and fitted \( I-V \) characteristics for a mc-si solar cell and pc-si solar cell, respectively using least squares method. Table 1 show the LMS-extracted parameters for mc-si solar cell and pc-si solar cell under 1sun (1000W/m\(^2\))at 25\(^\circ\) C cell temperature, respectively.

Table 1. Parameters extracted using LMS of mc-si solar cell and pc-si solar cell with 1sun at 25\(^\circ\)C cell temperature.

| Parameters | MLS extracted values | mc-si solar cell | pc-si solar cell |
|------------|----------------------|------------------|------------------|
| \( R_{sh} (\Omega) \) | 20.5                 | 125              |
| \( R_s (\Omega) \) | 0.054 \( \times 10^8 \) | 0.164            |
| \( I_0 (A) \) | 4.78 \( \times 10^{-8} \) | 2.95 \( \times 10^{-8} \) |
| \( I_{ph} (A) \) | 1.221                | 0.517            |
| \( n \) | 1.375                | 1.339            |
| \( \eta \% \) | 13.05                | 10.48            |

Varying only of the \( I_{ph} \) parameter in Equation (1) modified \( I-V \) characteristics, because \( I_{ph} \) is proportional to the power illumination. The experimental results of the two solar cells indicated in Figure 4(e, f) shown the short circuit current \( I_{sc} \) increases with increasing the light intensity and decreases with increasing the solar cell voltage. For intensity 2.5sun, the \( I_{sc} \) is about 3.073 A and 1.299 A for the mc-si and pc-si solar cells respectively. At the same above light intensity, the \( I_{sc} \) decreases with increasing the voltage \( V_{oc} \) up to 0.62 and 0.59 Volt respectively.
We apply our method LMS to determine the five parameters for each light intensity. The results are summarized in Table 2 and in Table 3.

Table 2. Parameters extracted of mc-si solar for $T=25^\circ C$ cell temperature at different light intensities.

| $X \times 1000W/m^2$ | 1     | 1.5   | 2     | 2.5    |
|----------------------|-------|-------|-------|--------|
| $R_{sh}(\Omega)$     | 20.44 | 5000  | 87.7  | 769.30 |
| $R_s(\Omega)$        | 0.054 | 0.037 | 0.0349| 0.0351 |
| $n$                  | 1.375 | 1.563 | 1.462 | 1.561  |
| $I_0(x10^{-7}A)$     | 0.478 | 4.532 | 1.677 | 5.41   |
| $I_{ph}(A)$          | 1.221 | 1.823 | 2.495 | 3.073  |
| $V_{oc}(V)$          | 0.604 | 0.614 | 0.624 | 0.632  |
| $\eta(\%)$           | 13.05 | 13.5  | 13.17 | 12.2   |

Table 3. Parameters extracted of pc-si solar cell for $T=25^\circ C$ cell temperature at different light intensities.

| $X \times 1000W/m^2$ | 1     | 1.5   | 2     | 2.5    |
|----------------------|-------|-------|-------|--------|
| $R_{sh}(\Omega)$     | 1250  | 135.13| 34129 | 52630  |
| $R_s(\Omega)$        | 0.164 | 0.154 | 0.132 | 0.133  |
| $n$                  | 1.339 | 1.395 | 1.536 | 1.320  |
| $I_0(x10^{-8}A)$     | 2.9   | 7.3   | 4.0   | 3.13   |
| $I_{ph}(A)$          | 0.517 | 0.791 | 1.040 | 1.299  |
| $V_{oc}(V)$          | 0.568 | 0.572 | 0.580 | 0.592  |
| $\eta(\%)$           | 10.48 | 9.344 | 9.60  | 8.816  |

The form of the characteristic efficiency-concentration curve of Figure 4(g) makes evident the great importance of the series resistance in the design of solar cells. The design is influenced considerably in this respect by the levels of concentration at which the device operates.
Figure 5. Variation of the efficiency and series resistance with the concentration of the light.

Figure 4(e, f) shows a large concentration, increases the short-circuit current, without affecting the open-circuit voltage. Even when the cell is in short circuit, with zero external voltage, the junction is biased by a voltage of value $I_{sc}R_s$, produced by the passage of current through $R_s$. This bias produces a current through the diode in the opposite direction to $I_{sc}$. This can be degraded significantly, resulting in poor efficiency, especially if the current is high as in cells working under optical concentrators. The dependence of efficiency on light intensity, for the two solar cells, is shown in Figure 5(g). It has been found that the efficiency of each cell demonstrated a small decrease with light intensity. So, the efficiency of the mc-is and pc-is solar cells decreased from 10.48 and 13.5 % to 8.816 and 12.2% for light intensity 1 and 2.5 Sun respectively. Figure 5(h) shows the dependence of series resistance with light intensity for the two cells. It has been found that the series resistance, of each solar, decreases with increasing light intensity due to the increase in conductivity of the active layer with the increase in the light intensity $[53]$ So, the series resistance of the mc-is and pc-is solar cells decreased from 0.054 and 0.164 to 0.0351 and 0.133 Ω for light intensity 1 and 2.5 suns respectively. The product $I_{sh}R_s$ of the mc-si and pc-si solar cells increased from 0.065934 and 0.084788 (V) to 0.1078623 and 0.172767 V for light intensity 1 and 2.5 Sun respectively. In all cases these values are larger than the thermal voltage $V_t = 0.025(V)$. So the effects of series resistance are not negligible and dominate, consequently efficiency decrease as shown in Figure 5(g).

To see the effect of temperature on the behavior of solar cells, we set the value of the load resistance to the value which gives the maximum electric power and we vary the temperature. Table 4 shows the output parameters of solar cells under different temperature.
Table 4. Output parameters of solar cells under different temperature and 1sun.

| Sample | Temperature(°C) | V_{mp}(V) | I_{mp}(A) | P_{m}(W/m²) | η(%) |
|--------|----------------|-----------|-----------|-------------|------|
| pc-si  | 25             | 0.428     | 0.475556  | 1.03E+02    | 10.30|
|        | 30             | 0.42      | 0.466667  | 9.92E+01    | 9.92 |
|        | 35             | 0.416     | 0.462222  | 9.73E+01    | 9.73 |
|        | 40             | 0.412     | 0.457778  | 9.54E+01    | 9.54 |
|        | 45             | 0.404     | 0.448889  | 9.18E+01    | 9.18 |
|        | 50             | 0.4       | 0.444444  | 9.00E+01    | 9.00 |
|        | 55             | 0.39      | 0.433333  | 8.55E+01    | 8.55 |
|        | 60             | 0.384     | 0.426667  | 8.29E+01    | 8.29 |
| mc-si  | 25             | 0.452     | 1.13      | 1.33E+02    | 13.29|
|        | 30             | 0.448     | 1.12      | 1.31E+02    | 13.05|
|        | 35             | 0.445     | 1.1125    | 1.29E+02    | 12.88|
|        | 40             | 0.44      | 1.1       | 1.26E+02    | 12.59|
|        | 45             | 0.432     | 1.08      | 1.21E+02    | 12.14|
|        | 50             | 0.428     | 1.07      | 1.19E+02    | 11.91|
|        | 55             | 0.424     | 1.06      | 1.17E+02    | 11.69|
|        | 60             | 0.42      | 1.05      | 1.15E+02    | 11.47|

Figure 6. shows the variation of the maximum power and efficiency with temperature, in addition to that temperature coefficients are calculated by means of a fit linear and we find dP_{m}/dT = -0.55 W/m²/°C for both cells, dη/dT = -0.55(%/°C) for mc-si and dη/dT = -0.558(%/°C) for pc-si. It has been found that the maximum power of the two solar cells decreases with increasing temperature as shown by the results of the experiment (see Figure 6 (k)), where the maximum power solar cells of the mc-si and the pc-si for temperature=25°C was 133 W/m² and 103 W/m², respectively. The increasing the temperature to 60°C causes the decrease of the power by 13.53% and 19.51% to reach values 115 W/m² and 82.9 W/m² respectively.

![Figure 6](image)

Figure 6. Variation of the maximum power and efficiency with the temperature under 1 sun.

This decrease in maximum power is due to the increase in I_{0}(see Equation 8) and to the rounding of the elbow of the characteristic I-V curve, evident from the effect of increasing T in the exponential term of Equation 7, which explains the decrease of the maximum power and consequently the degradation of the cell i.e. decrease efficiency, this is in agreement with the experimental as shows in curve of Figure 6(λ). The photocurrent I_{ph} increases slightly with temperature, in part because of greater diffusion lengths of the minority carriers and in part because of the narrowing of the band gap that displaces the absorption threshold towards photons of lower energy. This improvement of the photocurrent with temperature is more appreciable in Si cells [32]. It is always quite small, however, and can be ignored as a first approximation. Therefore, the change in the characteristic equation of the cell with temperature rises through the exponential term and through I_{0}(T). We concluded that in the
non-concentrated cells the effect of the temperature appears too, but at different values. The results of the two solar cells indicated that light intensity has a dominant effect on current parameters. It is found that photocurrent; short circuit current and maximum current have been increased linearly with increasing light intensity. The conversion efficiency $\eta$ of solar system decreases. The effect of cell temperature on the photovoltaic parameters of mc-si and pc-si solar cells is undertaken.

4. Conclusion

In this work, we have proposed a simple method to extract all the parameters of a solar cell just from a single $I-V$ curve under one constant illumination level. With the help of the Lambert $W$ function, the explicit analytic expression for $I$ can be obtained. The expression for $I$ depends on five parameters $I_{ph}, I_0, n, R_s$ and $R_{sh}$. This analytic expression for $I$ is directly used in the numerical method to fit the experimental data and then determine the values of the parameters. The performance of solar cells is dependent on environmental conditions and their output parameters such as output voltage, current, power, and efficiency vary by light intensity and temperature. The experimental results of the two modules indicated that light intensity has a dominant effect on current parameters; the short circuit current of the mc-si and pc-si solar cells increased from 1.221 and 0.517 to 3.073 and 1.299 for light intensity 1 and 2.5 sun respectively, the efficiency of the mc-si and pc-si solar cells decreased from 10.48 and 13.5% to 8.816 and 12.2% for light intensity 1 and 2.5 sun respectively. The temperature coefficient of the efficiency and maximum output power is found to be negative. The change study of photovoltaic parameters with temperature is also undertaken. The changes are found from -0.55 W/m2/°C, -0.55%(%/°C) and -0.558(%/°C) for maximum output power mc-si and pc-si, efficiency mc-si and efficiency pc-si respectively. The results obtained are in good agreement with the available literature.

Acknowledgement:
Characterization current-voltage was performed in the laboratory of Semiconductor Physics and Applications at Kharkov Polytechnic Institute /Ukraine. We extend our gratitude to Vice-rector for Scientific-and-Pedagogical work Gennadiy Khrypunov professor, doctor of science and all staff for their availability.
References

[1] Chandera S, Purohit A, Sharma A, Arvind, Nehra SP and Dhak MS 2015 Energy. Reports. 1 104
[2] Saga T and Asia N P G 2010 Materials. 2 96
[3] Dobrzański LA, Szczesna M, Szindler M and Drygala A 2013 J. Achievements in Materials and Manufacturing Engineering. 59 67
[4] El-Shaer A, Tadros M T Y and Khalifa M A 2014 Int. J. Emerg. Tech. Adv. Eng. 4 311
[5] Tobnaghi DM, Madatov R and Naderi D, 2013 J. Achievements in Materials and Manufacturing Engineering. 59 67
[6] Laplaze D and Youm I 1985 Sol. Cells. 14 167
[7] Kaminski A, Marchand J J and Laugier A 1999 Solid. State. Electron. 43 741
[8] Aberle A G, Wenham S R and Green MA 1993 (in 23th IEEE Photovoltaic Specialist Conf, Louisville, KY, USA) p 133
[9] Van Kerschaver E, Einhaus R, Szlufcik J, Nijs J and Merten R 1997 (In Proc of 14th European Community Photovoltaic Solar Energy Conf, Barcelona, Spain) p 2438
[10] Miahle P, Khoury A and Charle J P 1984 Phys. Stat. Sol. A. 83 403
[11] Bashahu M and Habyarimana A 1995 Renew. Energy. 6 129
[12] Chan D S H, Phillips J R and Phang J C H 1986 Solid. State. Electron. 29 329
[13] Flavius-Maxim P and Leonida D T 2010 CEAI. 12 30
[14] Dib S, De la Bardonniére M, Khoury A, Pelanchon F and Mialhe P 1999 Act. Passive. Electron. Compon. 22 157
[15] Bouzidi K, Cheggar M and Nehou N 2007 4th Int Conf on Computer Integrated Manufacturing C I P, Setif, Algeria.
[16] Jain A and Kapoo A 2004 Sol. Energy. Mater. Sol. Cells. 81 269
[17] Haouari M M, Belhamel M, I Tobias and Ruiz JM 2005 Sol. Energy. Mater. Sol. Cells. 87 225
[18] Bashahu M and Habyarimana A 1995 Renew. Energy. 6 129
[19] Malaoui A and El Mansour A 2010 Revue Energies Renouvelables. 13 199
[20] Ortiz-Conde A, Francisco García Sanchez J and Muc J 2006 Sol. Energy. Mater. Sol. Cells. 90 352
[21] Chegaar M, Ouennoughi Z and Guechi F 2004 Vacuum. 75 367
[22] Chegaar M, Azzouzi G and Mialhe P 2006 Solid. State. Electron. 50 1234
[23] Wolf M and Rauschenbach H 1963 Adv. Energy. Convers. 3 455
[24] Imamura MS and Portschteller J 1970 (in Proc of 8th IEEE Photovoltaic Specialist Conf, Seattle, WA, USA) 102
[25] Charles JP, Abdelkrim M, Muoy YH, Mialhe P 1981 Sol. Cells. 4 169
[26] Khalis M, Mir Y, Hemine J and Zazou M 2011 Eur. Phys. J. Appl. Phys. 54 10102
[27] Hussein R, Borchert D, Grabosch G and Fahrner W R 2001 Sol. Energy. Mater. Sol. Cells. 91 1222
[28] Mazhari B 2006 Sol. Energy. Mater. Sol. Cells. 90 1021
[29] Wolf M and Rauschenbach H 1963 Adv. Energy. Convers. 3 455
[30] Handy R J 1967 Solid. State. Electron. 10 765
[31] Pysch D, Mette A and Glunz S W 2007 Sol. Energy. Mater. Sol. Cells. 91 1698
[32] Hussein R, Borchert D, Grabosch G and Fahrner W R 2001 Sol. Energy. Mater. Sol. Cells. 91 1222
[33] Mazhari B 2006 Sol. Energy. Mater. Sol. Cells. 90 1021
[34] Wolf M and Rauschenbach H 1963 Adv. Energy. Convers. 3 455
[35] Handy R J 1967 Solid. State. Electron. 10 765
[36] Pysch D, Mette A and Glunz S W 2007 Sol. Energy. Mater. Sol. Cells. 91 1698
[37] Hussein R, Borchert D, Grabosch G and Fahrner W R 2001 Sol. Energy. Mater. Sol. Cells. 91 1222
Cells. 69 123

[37] Radziemska E 2005 Energy. Convers. Manage. 46 1485
[38] Rajkanan K and Shewchun J 1979 Solid-State. Electron. 22 193
[39] Servaites J D, Yeganeh S, Marks T J and Ratner M A 2010 Adv. Funct. Mater. 20 97
[40] Mialhe P, Khoury A and Charles J P 1984 Phys. Status. Solidi. (a). 83 403
[41] Schilinsky P, Waldauf C, Hauch J and Brabec C J 2004 J. Appl. Phys. 95 16
[42] Ishibashi K, Kimura Y and Niwano M 2008 J. Appl. Phys. 103 094507
[43] Chegaar M, Ouennoughi Z and Hoffmann A 2001 Solid-State. Electron. 45 293
[44] Kaminski A, Marchand J J and Laugier A 1999 Solid-State. Electron. 43 741
[45] Murayama M and Mori T 2006 Jpn. J. Appl. Phys. 45 542
[46] Jain A and Kapoor A 2005 Sol. Energy. Mater. Sol. Cells. 86 197
[47] Ortiz C A and Garcia S F J 2005 Solid-State. Electron. 49 465
[48] Ortiz-Conde A, Garcia Sanchez F J and Muci J 2006 Sol. Energy. Mater. Sol. Cells. 90 352
[49] Kim J Y, Lee K, Coates N E, Moses D, Nguyen T, Dante M and Heeger A 2007 Science 317 , 222
[50] Yakimov A and Forrest S R 2002 Appl. Phys. Lett. 80 1667
[51] Zhang C, Zhang J, Hao Y, Lin Z and Zhu C 2011 J. Appl. Phys. 110 064504
[52] PLoS S M 1998 (Mathsoft Inc., Seattle, "Getting Started with Splus 5.0" Washington).
[53] Cuce E, Cuce P and Bali T 2013 Applied. Energy. 111 374