ANALYSIS OF A MULTIJUNCTION SOLAR CELL OPERATING UNDER NATURAL CONDITIONS

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ABSTRACT: It is evaluated the performance of a CPV multijunction (MJ) cell (InGaP/InGaAs/Ge) of 1.0 cm^2 area, for concentration rates varying from 1 up to 122X. The parameters which characterize the cell are extracted from experimental characteristic curves using the one diode model. Special attention is given to the series resistance, which affects significantly the cell performance. Results obtained show that the procedure adopted is considerably consistent, enabling to obtain a general picture of solar cell behavior in spite of large temperature and irradiance experimental variations. A large value of series resistance (3.8 Ω) is observed for low concentration values. This resistance decays rapidly, attaining a stable value for high concentrations (0.024 Ω). Average conversion efficiencies of 35% have been measured when converted to temperatures of 47 °C. Series resistance obtained for high concentrations (0.024 Ω) limit the concentration rate corresponding to maximum efficiency to values between 243 and 278. Higher efficiencies with higher concentrations, probably, require further reduction of series resistance.

***Key words**:* MJ solar cells, efficiency analysis, characteristic parameters.

1. INTRODUCTION

Since 1980, multijunction (MJ) solar cells, associated with solar radiation concentrator systems for terrestrial applications or without concentration for space applications, have been able to improve considerably the efficiency of photovoltaic converters. The finding that high efficiency values are tangible in practice has encouraged the development of both research and commercial interest for such devices (King, 2007). To ensure the conditions necessary to control the tests and repeat the results, the experiments are usually held in laboratories equipped with artificial sources of radiation. That is so, e.g., for the determination of the cell efficiency from the characteristic curve (current versus voltage (I-V)) obtained under certain conditions of irradiance (absolute value and spectral distribution) and temperature (Dominguez, 2010).

In 2005, a cell formed by $In_{0.495}Ga_{0.505}P/In_{0.01}Ga_{0.99}As/Ge$ developed by Spectrolab, a leading manufacturer of high performance cells, reached an efficiency of 39.0%, employing an AM1.5G spectrum and concentration rate of 236 suns (King, 2005). Later, in 2007, the same cell with different percentage components $In_{0.56}Ga_{0.44}P/In_{0.08}Ga_{0.92}As/Ge$, reached 40.7%, with AM1.5D spectrum and under concentration of 240 suns (King, 2007). In 2009, the Fraunhofer Institute in Germany increased the concentration of indium to form the structure $In_{0.65}Ga_{0.35}P/In_{0.17}Ga_{0.83}As/Ge$, obtaining an efficiency of 41.1% under 454 Suns and AM1.5D spectrum (Guter, 2009). Currently, the maximum conversion efficiency was established in 2010 by Spire Semiconductor, a Spire Corporation subsidiary, which, with a cell of 0.97 cm^2 under AM1.5D spectrum and concentration of 406 suns, reached 42.4% (NREL, 2010).

Several methods, analytic or algebraic, have been developed and applied in the analysis of the operational characteristics of PV solar cells. Algebraic methods employ simple equations to correct the characteristic curve (I-V) for temperature and irradiance (Shockley, 1961 & Campbell, 1986), while the physics of semiconductors admits analytical methods to describe the effects of moderate variations in those parameters (Emery, 2003). Considering the phenomena of diffusion and recombination of charge carriers in the neutral and load regions of the cell, responsible for the diode current (I_D), the two diodes model yields the most detailed evaluation of the parameters describing (I-V) curve (Veissid, 1991). However, since recombination dominates at low voltages, where photovoltaic devices do not work often, one diode model can be satisfactory (Garcia, 1995).

In this paper we evaluate the performance of a CPV multijunction (MJ) cell (InGaP/InGaAs/Ge) of 1.0cm^2 area, for concentration rates varying from 1 up to 122X. The efficiency of concentrating PV cells is usually expressed as a function of incident radiation trough the concentration rate (C) and, according to the model adopted, its greatness depends on the following parameters: photo generated current (I_L), saturation diode current (I_0), ideality factor (m), parallel resistance (R_p) and series resistance (R_s). Different procedures are available to extract these parameters from the characteristic curve (CC) of the cell and, as commented before, they are usually obtained indoor, under controlled conditions of irradiance and temperature. However, outdoor tests provide relevant information that can be used to determine the real operational behavior of the cell (Tanabe, 2009). In this work the model parameters are extracted from the experimental curves and special attention is given to the series resistance, which affects significantly the cell performance, as will be shown.

2. EXPERIMENTAL METHODOLOGY

The MJ solar cell used on experiments is a triple junction InGaP/InGaAs/Ge structure with approximately 1.0 cm^2 area. At 500 suns and 25 ºC in indoors experiments, the efficiency is around 37%, according to manufacturer's information.

The cell has been evaluated operating under natural conditions of irradiance on two different outdoor tests. Initially, without concentration (one sun), with the cell placed on a horizontal plane inside a box with glass cover, and then, with concentration, using a Fresnel lens system mounted on a two-axis tracker. In the first case the cell is under the influence of direct and diffuse irradiance, and in the second case, only direct irradiance reaches the cell.

For the experiments it was set up an electric circuit composed of the MJ cell, responsible for current generation, a potentiometer for simulating a variable charge and a calibrated shunt to measure the current. Measurements of global and direct irradiance, were performed using three pyranometers (two photovoltaic and one thermal) and a pyreliometer. The temperature of the cell was measured using a sensor (LM35) coupled to a structure with high electric and thermal conductivity on which the cell was set up. All sensors were connected to a Campbell data acquisition system model CR10X (data logger). The voltage of the cell is directly assessed in one channel of the data logger.

Figures 1a shows the facility for the tests performed at one sun. The irradiance incident on the cell plane is evaluated using the PV pyranometer inside the box. The photovoltaic pyranometer outside the box allows evaluating the glass attenuation for the solar irradiance and the thermal pyranometer gives an appraisal of the quality of the PV measurements. Figure 1b shows the cell inside the structure used to perform the tests under concentration.

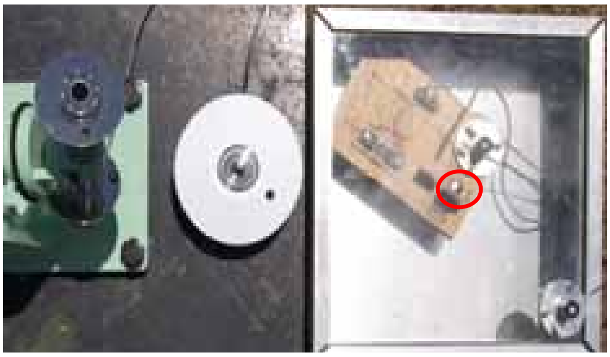

Fig. 1a: Initial assembly

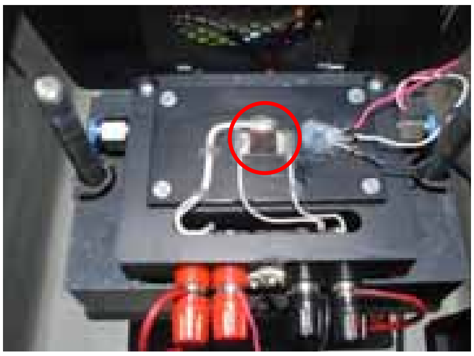

Fig. 1b: Assembly in heat sink

The experimental device for characterizing the cell with concentration uses a square Fresnel lens with side 0.30 m and focal length 0.20 m. A pair of screws fixed at the bottom of a metal box allows the adjustment of the position of the solar cell (up and down movement). The position of the cell with respect to the lens defines different concentration rates of operation. This set was placed on a high-precision (0.1°) two-axis tracker in order to collect direct irradiance. Figure 2a shows the experimental device placed on the tracker (preparation of the rig test) and Figure 2b shows the cell under concentration during experiments.

Fig. 2a: Preparation of the rig test.

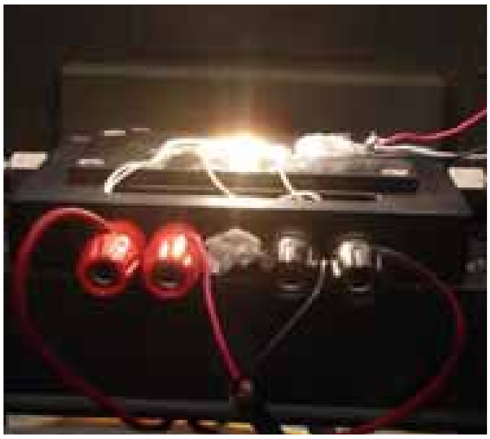

Fig. 2b: Cell under concentration.

After initial preparing the tests, the characteristic curves of the cell are obtained by varying the potentiometer resistance. In addition to the experiments for obtaining the (I-V) curves, it have been measured short-circuit current (I_{sc}) and open circuit voltage (V_{oc}) for different values of cell temperature. In order to be able to consider the influence of irradiance exclusively, an indoor experiment using an artificial light source (Hg -Xe lamp) was performed to analyze the variations of (V_{oc}) and (I_{sc}) with temperature.

The level of effective irradiance on the MJ cell during the tests with concentration was estimated considering that the relationship of short-circuit current and incident irradiance is linear. This assumption is not strictly correct; however, devices with high performance tend towards linear behavior (Sanchez and Araújo, 1984).

Thus, defining a standard (I-V) curve from the tests performed at one sun, we obtain, for the cell under concentration, the concentration rate as follows

$$C = \frac{I_{sc,conc}}{I_{sc,1sun}} \qquad \text{(eq. 1)}$$

where $I_{sc,conc}$ is the short-circuit current measured under concentration and $I_{sc,1sun}$ is the short-circuit current measured for the one-sun standard (I-V) curve.

3. MJ SOLAR CELL - CHARACTERISTIC PARAMETERS

One diode model can be described by the electrical circuit shown in Figure 3.

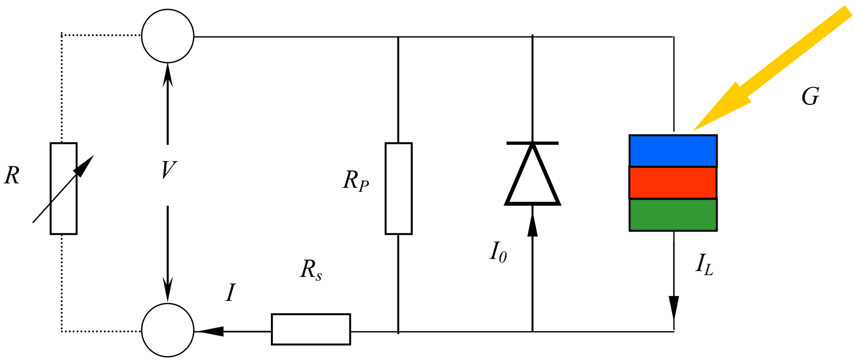

Fig. 3: Electrical circuit of one diode model

The electric current (I) established in circuit as function of voltage (V), under the effect of irradiance (G) incident on cell, operating at a given temperature value (T) is described by Eq. 2.

$$I = I_L - I_0\left\{\exp\left[\left(V + R_s I\right)/mv_t\right] - 1\right\} - \left(V + R_s I\right)/R_p \qquad \text{(eq. 2)}$$

where I_L is the light-generated current, I_0 the diode saturation current, m the ideality factor of the diode, R_s and R_p are the series and parallel resistance of the cell respectively and v_t is the thermal voltage, which relates the cell temperature T with the electronic charge q and the Boltzmann constant k ($v_t = kT/q$).

For the solar cell tested (high quality) we considered that the parallel resistance R_p is large enough such that the third term of Eq. 2 can be neglected. It is also assumed that the light-generated current can be approximated by the short-circuit current $I_L \approx I_{sc}$ (Green, 1982). Therefore, Eq. 2, with these considerations, can be written as

$$I = I_{sc} - I_0\left\{\exp\left[\left(V + R_s I\right)/mv_t\right] - 1\right\} \qquad \text{(eq. 3)}$$

The diode saturation current can be estimated, on the open circuit condition, trough Eq. 4

$$I_0 = I_{sc} \quad (\exp(V_{oc}/mV_t) - 1) \qquad \text{(eq. 4)}$$

Considering I_{sc}>>I_0 and V_{oc}>>mVt, Eq. 4 can be rewriting as the expression given in (Eq. 5). This expression allows determining the average saturation current, for a particular temperature.

$$V_{oc}/mv_t = Ln(I_{sc}) - Ln(I_0) \qquad \text{(eq. 5)}$$

Plotting the term (V_{oc}/mv_t) as a function of ($\ln(I_{sc})$), the average value of Io, for a given temperature, can be obtained as the independent term of the regression line given by Eq. 5 ($\ln(I_o)$).

In order to evaluate the diode ideality factor (m) of the cell, we consider the logarithmic dependence of the open circuit voltage (V_{oc}) with the solar irradiance, or with concentration rate (C), written as

$$V_{oc}(C) = V_{oc,1sun} + mv_t \ln(C) \qquad \text{(eq. 6)}$$

where $V_{oc,1sun}$ is the open circuit voltage at one sun condition and $V_{oc}(C)$ is the open circuit voltage for a given concentration rate.

A plot of experimental values of V_{oc} as a function of $\ln(C)$ results in a straight line with slope equal to the product mv_t.

The parameter R_s, can be obtained by different methods (Ortiz-Conde, 2006). In this paper we use the optimization method where theoretical values of the current, calculated with Eq. 3, are compared with experimental values. For each experimental characteristic curve the series resistance is found when the minimum root mean square deviation between these values is attained.

4. RESULTS AND ANALYSIS

4.1 One sun experiment

According to present proposal, first experiments were devoted to characterize the MJ cell functioning without concentration. Thus, short circuit current, open circuit voltage and operating temperature behaviors were observed for several values of irradiance incident on the cell aperture. Figure 4 shows these behaviors for irradiance range between 200 W/m^2 and 1200 W/m^2, approximately.

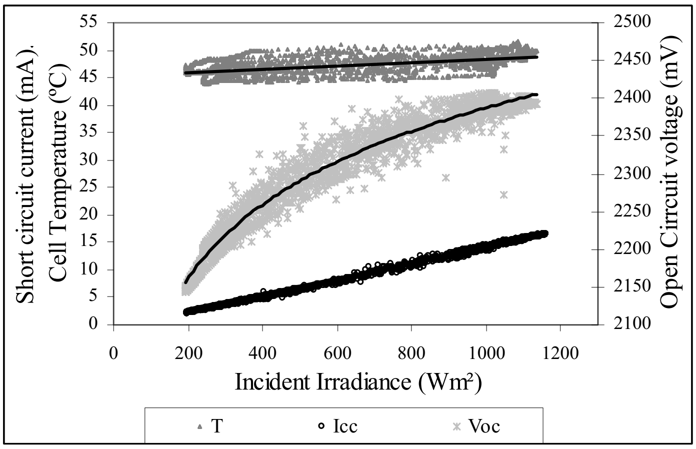

Fig. 4: Temperature, short circuit current and open circuit voltage behavior versus incident irradiance.

Temperature of the cell observed in this experiment varies in the range of 43.8 ºC to 51.5 ºC for irradiance going from 192 W/m² to 1135 W/m². The gradient of temperature is around 0.003 ºC/Wm^{-2}. At one sun condition (1kW/m^2) cell temperature is 47.0 ±1.3 ºC. For the same range of temperature it is shown in Figure 4 the logarithmic trend of open circuit voltage with irradiance, with minimum value of 2.15 V and maximum around 2.4 V. As expected, in this range, the short circuit current presents a clear linear behavior with solar irradiance, with small root mean square deviation of the order of 2.8%. For the standard condition of one sun we found values of short-current density around 14.1 ± 0.3 mA/cm^2 and open circuit voltage of 2.41 ±0.02 V.

The coefficients of variation of short circuit current and open circuit voltage with temperature have been determined, as mentioned before, with indoor experiment using an artificial light source. Keeping the incident irradiance at a constant value around 1000 W/m², the cell is heated and the values of V_{oc} and temperature are measured. The same procedure is applied for I_{cc}. Short-circuit current and open circuit voltage as temperature functions are shown in Figure 5. The experiments were implemented with temperature range for current (55 ºC up to 100 ºC) and for voltage (47 ºC up to 75 ºC).

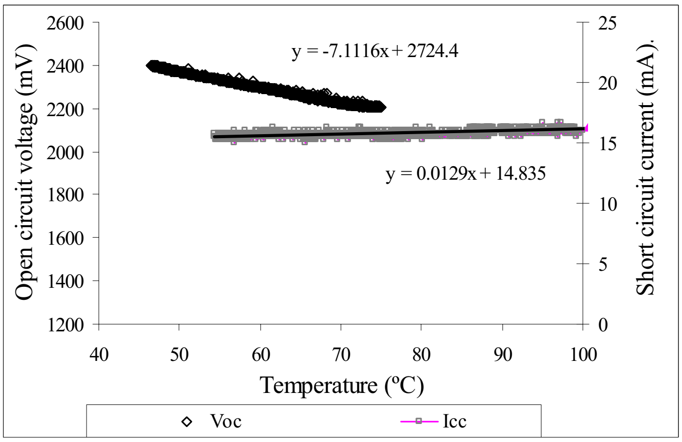

Fig. 5: Short-circuit current and open circuit voltage versus temperature.

Short-circuit current under the effect of temperature shows a very small gradient, (0.013. ±0.001 mA/ºC) and can be considered negligible. On open circuit voltage, temperature variation effects show a constant gradient with mean value of (-7.11 ± 0.03 mV/ºC).

The characteristic curve measured at one sun condition is shown in Figure 6. The power is also plotted as a function of voltage.

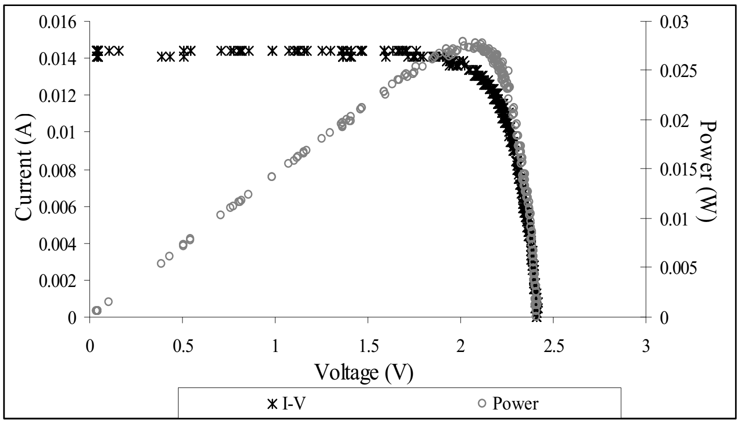

Fig. 6: Characteristic curve obtained for one sun condition at 1000 W/m² - Standard curve

The curve shown in Fig. 6 has been taken as the standard one sun curve and its short circuit current used afterwards in order to estimate the concentration rate in the tests of the cell under concentration. Average temperature of the cell during the experiment was 47 ºC. This temperature is also taken as a reference temperature in this work. Values obtained for the fill factor, short circuit current and open circuit voltage are 0.805, 14.1 mA and 2.41 V respectively. The maximum power obtained was 27.9 mW, resulting in an experimental efficiency of the order of 28%, rather high for one sun experiment.

4.2 Solar cell tests under concentration

Several experimental characteristics curves were obtained for different solar radiation concentration values. Figure 7 shows a sample of the characteristic curves obtained experimentally under concentration and the fits with the one diode model. Three curves are presented, the highest, for 121 suns, the average for 63 suns and the lowest for 15.6 suns.

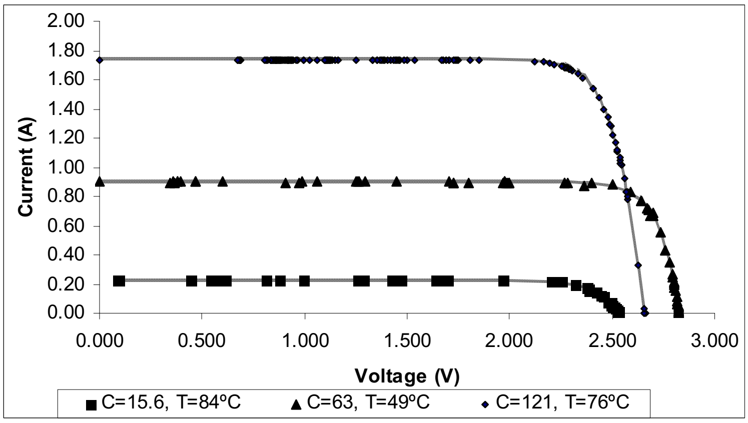

Fig. 7: Characteristics curves obtained different concentration rate

The cell temperature for each curve is also given. Two effects are present in the V_{oc} variation shown in Fig. 8: irradiance and temperature. It can be seen that temperature prevails in the case of 121 suns as compared with 63 suns. Results of experiments and parameters estimative with concentration are summarized in Table 1.

Tab. 1: Characteristic parameters according to concentration rate.

C	V_{mp} (V)	I_{mp} (A)	V_{oc} (V)	I_{sc} (A)	*T* (ºC)	*DI* (%)	*FF*
1.0	2.08	0.01	2.41	0.01	47.1	4.2	0.80
2.7	2.03	0.04	2.38	0.04	72.3	2.1	0.81
3.9	1.91	0.05	2.40	0.06	76.2	1.7	0.78
5.9	2.10	0.08	2.44	0.08	81.9	2.0	0.83
13.0	2.28	0.18	2.65	0.19	67.3	1.4	0.82
14.4	2.31	0.20	2.68	0.21	60.1	3.0	0.83
15.6	2.26	0.21	2.53	0.22	83.9	1.8	0.84
28.6	2.35	0.40	2.78	0.41	42.8	2.0	0.84
38.3	2.38	0.52	2.72	0.54	77.4	2.7	0.84
40.3	2.49	0.56	2.76	0.58	56.0	2.4	0.88
42.1	2.34	0.63	2.69	0.65	68.1	3.5	0.84
54.2	2.26	0.75	2.61	0.78	80.4	0.8	0.83
60.0	2.53	0.82	2.82	0.86	50.1	7.6	0.86
63.1	2.50	0.88	2.83	0.90	49.0	1.9	0.86
69.4	2.39	0.94	2.79	0.99	56.3	2.8	0.82
72.7	2.30	1.01	2.64	1.05	80.9	1.5	0.84
99.0	2.37	1.42	2.79	1.44	61.2	2.2	0.83
107.5	2.35	1.42	2.66	1.55	80.0	1.9	0.81
110.6	2.45	1.56	2.80	1.59	55.3	1.8	0.86
114.9	2.27	1.56	2.66	1.65	82.1	2.6	0.81
121.3	2.31	1.61	2.66	1.75	76.2	0.6	0.80
122.3	2.49	1.55	2.75	1.75	67.1	4.4	0.80

The fill factors shown in Table 1 were obtained from the values of V_{oc}, I_{sc}, V_{mp} and I_{mp}. The root mean square deviations (DI) were calculated between the values of current, measured and estimated with one diode model for all points in each curve. Although the temperature of the cell during experiments presents large variations (20% deviation, average temperature of 67º C), it can be observed some important characteristics of the MJ cell when concentration rate varies. The open circuit voltage increases rapidly for low concentrations, reducing its increase rate for high values of C (logarithmic behavior). For the whole range of concentration, high and relatively uniform values of fill factor are observed (above 0.8). The average value is around 0.83 ± 0.02.

4.3 Determination of characteristic parameters

Results of open circuit voltage of the cell with concentration were corrected to the same temperature (47ºC), using the temperature coefficient obtained in Fig. 5 (- 0.0071 V/ºC). Figure 8 shows (V_{oc}) plotted vs. ln (C).

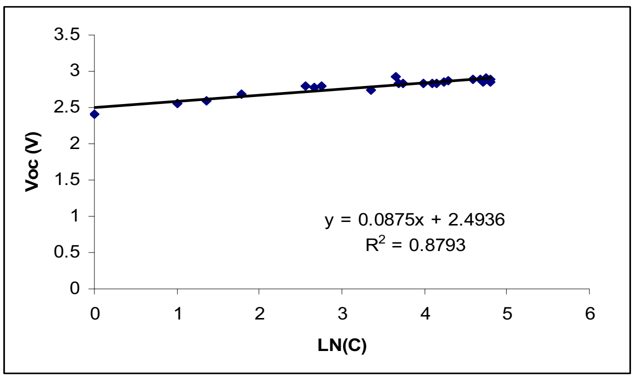

Fig. 8: Open circuit voltage as a function of natural logarithmic of concentration rate.

The ideality factor (m) is then be determined according to Eq. 6 by dividing the slope of the curve obtained in Fig.7 by the value of the thermal voltage (v_t) (reference temperature of 47 ºC). The value of m is of the order of 3.2, corresponding to what is expected for a three junction solar cell (above 3).

The average diode saturation current is determined according to Eq. (5), by plotting ln(Isc) vs Voc/mVt (Fig.9). The independent term of the regression line yields the average (I_o).

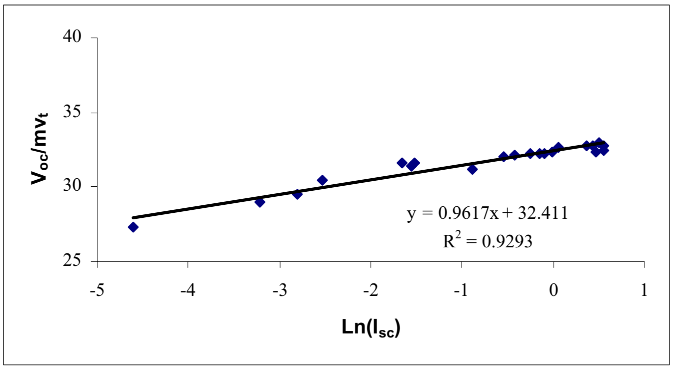

Fig. 9: Saturation diode current determination for T=47ºC.

In Fig. 9 the open circuit and thermal voltage are also corrected for the reference temperature (47 ºC). Within the range of concentration rates evaluated ($1 \leq C \leq 122$), and for the reference temperature, the average diode saturation current is around 8.40E-15 A.

Using the optimization method the series resistance is obtained for each characteristic curve. With the values of I_{sc}, V_{oc}, m and I_o (the last one calculated using Eq. 4), it is found the series resistance (R_s) that minimizes the root mean square deviation of all points of the characteristic curves. For the one sun curve presented in (Fig. 6), the value obtained for R_s was very high, around 3.8Ω with a root mean square deviation in the values of current (DI) of 4.2%. Sánches and Araújo (1984), analyzing the efficiency of CPV cells, provide a relation between the concentration rate which corresponds to the maximum efficiency (C_M) and series resistance of the cell, assumed as a constant Eq. 7.

$$C_M = mv_t / R_s I_{1sun} \qquad \text{(eq. 7)}$$

where I_{1sun} is the current generated by the cell at one sun condition. From Equation 7, it can be verified that the value of R_s calculated for one sun would not allow the cell to reach high efficiency at more than two suns. This result disagrees with the expected behavior of the cell, designed to reach maximum efficiency at high concentration rates. In fact, results of R_s obtained from tests under concentration show a considerably variation in series resistance, with strong decrease when concentration varies from one (R_s=3.8 Ω) up to thirty (R_s=0.029 Ω). For concentrations greater than 30 up to 122, the average series resistance found is around 0.024 ± 0.008 Ω. The average root mean square deviation observed for all the curves is around 2.05%. The behavior of series resistance as a function of concentration rate is plotted in Figure 10.

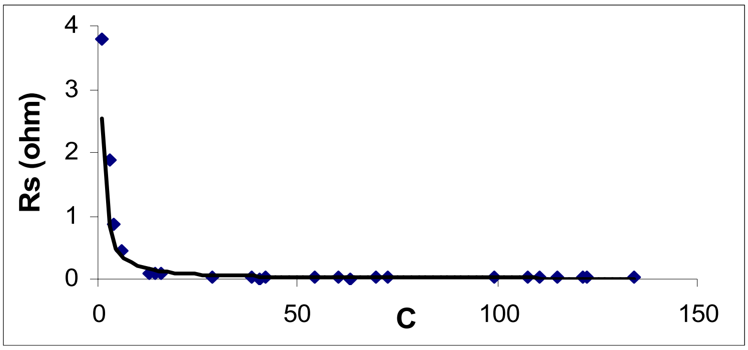

Fig. 10: Series resistance vs. Concentration Rate.

The value obtained for the average series resistance at high concentration rates (C>30) (R_s=0.024 ± 0.008 Ω) agrees with information found in literature. A detailed evaluation of series resistance (R_s) of a cell with similar characteristics was performed by Nishioka (2006). Considering contributions of ohmic contacts, tunneling junctions and electrodes resistance the R_s found was in the order of 0.025Ω. Smaller R_s value was found by Dominguez (2010), on the order of 0.017 Ω.

Maximum conversion efficiency presented by cell during operation was determined by maximum generated power and incident power (incident irradiance multiplied by cell the area). Figure 11 presents experimental efficiency as a function of concentration rate. Also, values of efficiency translated to the temperature of 25 ºC (usual reference temperature in photovoltaics) and for the reference temperature used in this work (47 ºC) are shown.

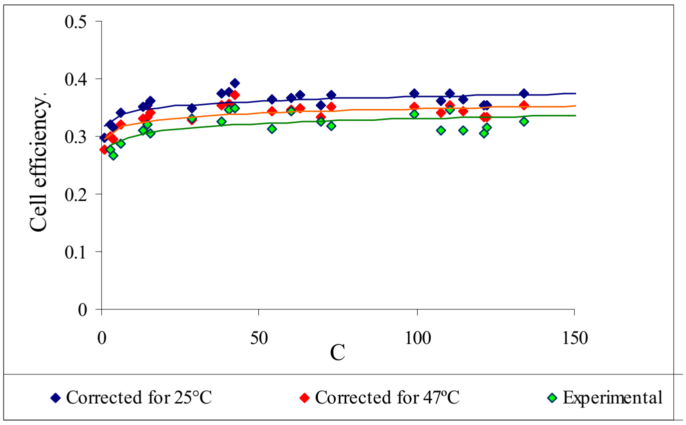

Fig. 11: Efficiency vs. Concentration Rate.

It is observed in Figure 10 an increase of efficiency for very low values of concentration. The lowest efficiency was 27% for (C=4) and cell temperature of (71 ºC). For concentrations grater than 30, the efficiency increases slowly, almost stabilizing, with an average value of 0.33±0.02. It is expected that for some high value of concentration the efficiency will start to fall down. This behavior can not be observed in the restricted range of C used in the experiments. The average values of efficiencies corrected for temperatures of 47 ºC and 25 ºC, obtained for concentration rates greater than 30 are respectively 0.35±0.01 and 0.37±0.01.

Smalls values of series resistance obtained for high levels of concentration rate (C>*30*) allow reaching high efficiency at this region. Using the average R_s of 0.024 Ω we estimate the concentration rate which provides the maximum efficiency for the three cases: experimental, cell temperature translated to 47 ºC and to 25 ºC (Eq.6). Results obtained are 278, 261 and 243, much higher than that obtained from the one sun experiment (R_s=3.8 Ω, T=47ºC and concentration for maximum efficiency C=1.6).

5. CONCLUSIONS

The procedure adopted to obtain characteristic parameters, based on the one diode model, of 1.0 cm^2 MJ cell, working under real operating conditions and subject to concentration rates varying between (1) and (122X), yields a consistent general picture of solar cell behavior in spite of large temperature and irradiance experimental variations. Furthermore, the determination of the ideality factor, saturation current and series resistance allowed characterizing the MJ solar cell within the concentration interval analyzed.

A large series resistance (3.8 Ω) is observed for low concentration values. This resistance is rapidly decaying, attaining a stable value two orders of magnitudes lower (0.029 Ω) at a concentration rate of 30. For concentrations rate above 30, average conversion efficiencies of 35% have been measured when converted to temperatures of 47 ^oC. Series resistance obtained for high concentrations (0.024 Ω) limit the concentration rate corresponding to maximum efficiency to values between 243 and 278. Higher concentration rates and probably higher efficiencies require further reduction of series resistance.

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