ASSESSMENT OF SOLAR CELL PARAMETERS EXTRACTION METHODS THROUGH TEMPERATURE DEPENDENT CURRENT-VOLTAGE MEASUREMENTS

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ABSTRACT: The cell parameters corresponding to the classical DC single diode model with series and shunt resistances are extracted thanks to current versus voltage characteristics analysis. We have implemented with Matlab two different methods recently proposed in the literature. The first method, which is exact, is based on the use of the Lambert function to solve analytically the non-explicit equation describing the electrical equivalent circuit . The second method, which is an approximate one, consists in separating the I-V characteristics into two parts, a linear and an exponential one to derive the parameters which are the most significant for each zone. A third method has also been used with a variational least squares minimisation over all data points. We have applied these extraction methods to I (V, T) measurements performed at different temperatures and we have analyzed the temperature evolution of the 4 extracted parameters of a crystalline silicon solar cell under dark conditions (series and parallel resistance, saturation current density and ideality factor of the diode). This gives us insight on the electronic transport in the solar cell. We discuss the validity range of a single diode model and we establish the complementarity of these methods over a range of temperatures.
Keywords: Silicon Solar Cell, Parameter Extraction, Characterisation

1 INTRODUCTION

For a long time, the problem of parameters extraction of a solar cell has been the object of a great deal of work as knowledge of them is important as a diagnostic test of the technological process and as a tool to investigate the physical mechanisms controlling the photovoltaic performance. However this task is not straigthforward even with the simplest DC classical electrical equivalent circuit because this circuit is described by an implicit transcendental equation which cannot be solved analytically using elementary functions. This problem has been adressed by recent works presenting two new methods [1, 2] where relevant references on the subject can also be found. The purpose of the present work is to use these two new methods along with a third one [3] to investigate the temperature dependence of the extracted parameters in order to test their usefulness as a tool to gain some insight into the transport mechanisms controlling the electrical behaviour of the device. Indeed, it is very interesting to vary the sample temperature in order to have a better knowledge of the physical processes involved whereas usually extraction methods on solar cells are performed mainly at room temperature. Here we adress the case of a crystalline silicon cell and in a companion paper, we apply these methods to two thin films technologies, investigating amorphous silicon and CIGSe based solar cells [4].

2 EXPERIMENTAL DETAILS AND METHODS

2.1 Experiment

The I–V measurements were performed with a Keithley 2400 Source Meter. The samples were mounted into a vacuum chamber with the possibility to cool down to liquid nitrogen temperature and to heat up to 500 K. Measurements were performed in the range 100K–400K with a 3 K step.

The solar cell under test was a commercial crystalline Si photodiode (Silonex SLCD-61N5) with a 1 x 1 cm^2 total area.

2.2 Parameters extraction methods

The equivalent circuit expresses the dark current I_D in terms of a single diode described by saturation current Io, ideality factor n, and, series and parallel resistances Rs and Rp, and where q, K_B and T have their usual meaning, as follows:

$$I_D = I_0\left[\exp\left(\frac{q(V - I_D R_S)}{nK_B T}\right)\right] + \frac{(V - I_D R_S)}{R_P} \quad (1)$$

This work compares and contrasts the relative advantages of three methods of parameter extraction, with a view to establishing the validity of each of them. It also investigates, as a result, the validity of this common single diode equivalent circuit to a real situation.

The first method we call "Analytical Lambert Method" (ALM) here uses the method of Ortiz-Conde et al. [1]. It uses a mathematical function called the Lambert function which enables to write explicitly the equation I=f(V). Then the integration of the current I minus the short-circuit current over the tension V gives a five-parameter linear relation. The five parameters are linked with four parameters of the cell. The last parameter is finally obtained taking a specific point of the I=f(V) curve. In practice, Matlab is used. It integrates the current minus the short-circuit current, and then computes an optimisation in term of minimizing the quadratic error, thanks to the "fmincon" function. Indeed a linear fit does not work because over the five parameters, only four are free. That generates bad fitting in practice. Nevertheless these results from the linear fit are used as starting points for the optimisation methods. Once the four parameters

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are obtained, the last one is calculated for every point of the curve; the one minimising the quadratic error is chosen. Note that in the present work, the short-circuit current was taken equal to zero as the fitted experimental results were obtained under dark conditions.

The second method named the "Two Regions Method" (TRM) is inspired by Bouzidia et al. [2]. The idea is to approximate one branch of the I=f(V) curve as a linear curve, and another one as an exponential one. A fit of the exponential curve enables to determine the three parameters playing a role in this part, and a fit of the linear part enables to obtain the two remaining parameters. Here, this method has been implemented under Matlab as well. The linear fit is proceeded thanks the "lsqnonneg" method, with constraints on the coefficient for them to be positive (for a physical sense, otherwise in case of a bad quality I=f(V) curve, they can appear negative). The exponential fit is made through the linear least square method (indeed it is linear in case of a logarithmic scale) using a reduced QR matrix decomposition. The difficult bit with this method is to be able to separate the two parts of the curve. It is automatically done, as the implemented algorithm leads these calculations for all the possibility of separation and of transition region length. It selects the best result in terms of quadratic error.

The third method [3] called the "Least Squares Variational" (LVM) is a variational least squares minimisation over all data points in terms of an equivalent circuit comprising parallel and series resistances and one to three diodes in parallel. The single diode mode used in this work leads to fits in terms of four parameters which are diode ideality n, saturation current Io, and series and parallel resistances Rs and Rp. A complex procedure provides initial guesses by separately examining different regimes in the data by automating the tasks a human operator would typically complete in order to estimate the different parameters. The dark current is then fitted by running through all parameters in an optimised order, subject to constraining individual tolerances for each parameter. The cyclical fitting procedure repeats the loop over all parameters until an overall fit quality tolerance is obtained. This quality tolerance is the misfit Chi. This is defined as the sum of least squares between the logarithm of data and numerical result for the diode equation representing the chosen equivalent circuit.

3 RESULTS AND DISCUSSION

3.1 Preliminary assessment

The three methods are first validated by fitting synthetic or exactly calculated dark current-voltage I(V) curves. They give satisfactory results in cases where the fit parameter has a relatively important impact on the I(V) curve.

Further applicability and complementarity of the methods is investigated by fitting experimentlal dark current-voltage data as a function of temperature are as follows. First, as for the synthetic data, all three are reliable for parameters that dominate the data.

The analytical ALM method is expected to be numerically more exact for data with better approximated the equivalent circuit that it represents, partly because it avoids numerical approximations inherent in the two other methods, but mainly because it uses a simpler, analytical solution where the other methods use numerical approximations. However, as soon as the data departs from this equivalent circuit, it is expected to rapidly become less reliable as usual for analytical models.

The two regions TRM method is expected to be more flexible in the sense that the analytical expession is separated into different regimes. The requirement that the analytical expression used for different regimes being less stringent than the requirement of overall accuracy makes this TRM method less susceptible to overall failure. This is however at the expense of accuracy due to a more approximate expression for the system in different regimes.

The least squares multi-parameter variational method LVM is a further progression down this methodological route and represents the most general approach. Involving no approximations as to operating regime, is it in principle the most robust. Involving however a numerical solution to the implicit diode equation, it is prone to numerical error, Finally, the variational method used in addition to the implicit solver is susceptible to instability if the data is such that the initial guess is poor. In this study, however, the latter case does not arise.

To conclude, the three methods present a progression from more accurate but less general methods, to more general methods with less accuracy. This three-fold approach allows us to extract greater meaning from the approximation of a semiconductor diode by a simple single diode equivalent circuit, by showing the regimes where different approximations are better suited.

3.2 Analysis

Figures 1 shows the I(V,T) data curves at different temperatures, and a significant change in behaviour between the two extremes, with a significantly increased slope at lower temperatures indicating a change in dominant recombination mechanism, and variations in resistive properties that require quantitative analyses to discuss.

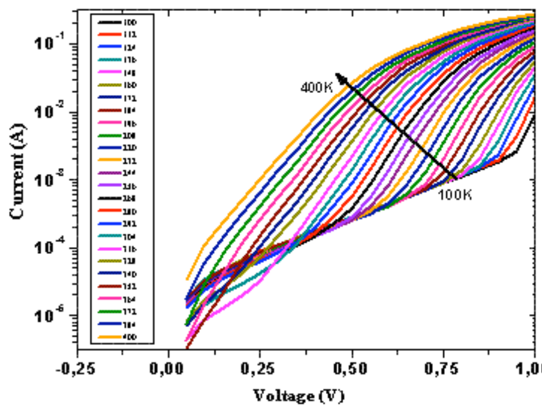

Figure 1: Dark current data as a function of bias and temperature I(V,T)

Figures 2 to 5 show the parameter extraction by methods ALM, TRM and LVM progressively.

In Figure 2 all methods show phenomenological agreement for Rp within less than an order of magnitude at temperatures above 300K. Inspection of Figure 1 shows however that Rp does not dominate at low bias leading to the slightly different values from the three methods. The analytical and two-regions methods are in closer agreement here because they explicitly approximate the low bias region as dominated by Rp whereas the variational multi-parameter method avoids this approximation. As a result of this greater generality, the variational method shows more sensitivity below 300K with a gradual linearly decreasing series resistance pointing to a Rp dominated by vibrational effects or phonons, rather than effects such as dopant activation, as expected at these temperatures.

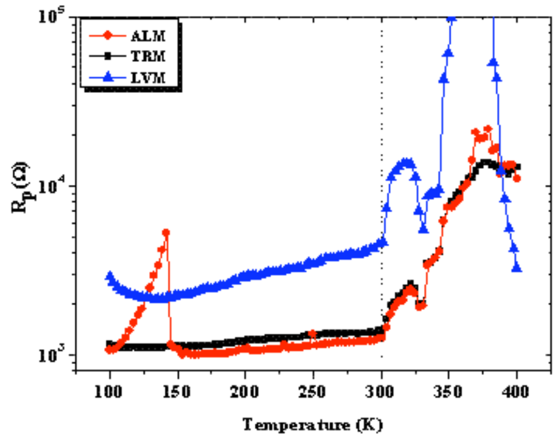

Figure 2: Parallel resistance *Rp* as a function of temperature for three fit methods

Figure 3 shows extracted series resistance Rs values. In this case, we see significant agreement between the all three methods down to 200K. The analytical ALM diverges below 200K. Examination of Fig. 1 shows this is clearly attributable to a departure from the single diode equation behaviour: A transition between two different diode idealities is observable starting at approximately 200K. The inconsistency of the data with the single diode equivalent circuit together with the analytical nature of this method make the results diverge, confirming preliminary comments above.

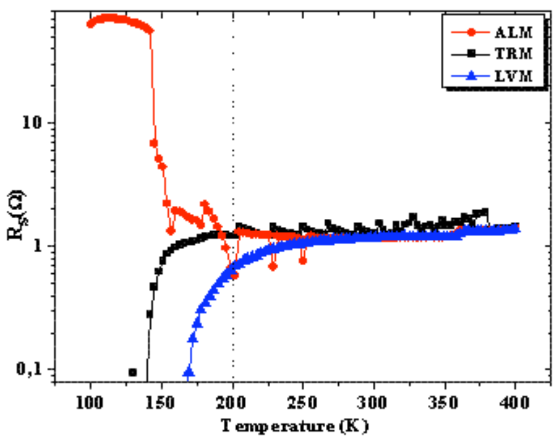

Figure 3: Series resistance *Rs* as a function of temperature for three fit methods

The two-regions TRM shows greatest noise at high temperatures but otherwise agrees qualitatively with the variational LVM. Since the agreement is qualitative only, the low temperature reduction in resistance is numerically unreliable. It does, however, coincide with the reduction in Rp at low temperatures mentioned above, suggesting a common origin for these two phenomena, which we suggest may be lattice vibrational.

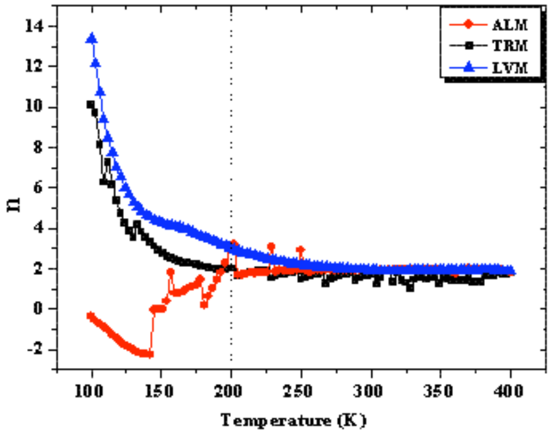

Figure 4: Ideality *n* as a function of temperature for three fit methods

The ideality factor is the clearest indicator of physical regime. Figure 4 shows good agreement for all methods down to the limit, as in previous effects, of approximately 200K. The ideality of 2 corresponds to activation energies reported in previous work [3] of roughly mid-gap traps according to Shockley-Read-Hall recombination statistics [5]. Furthermore, the transition from a constant n=2 ideality to idealities increasing with decreasing temperature is a clear indicator of increased recombination assisted by tunneling through mid-gap traps [3, 6] in the space-charge region of the diode. The failure of the analytical ALM is clearest here and confirms our observations regarding Rs above: The inconsistency of the single diode equivalent circuit with data showing contributions from two parallel diodes dominating at different biases is the reason for the physically meaningless idealities extracted by the ALM method.

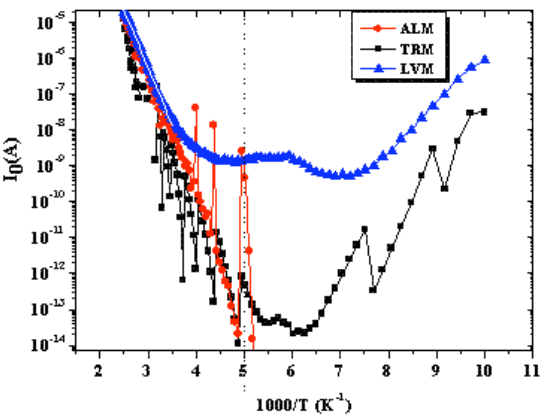

Figure 5: Diode saturation *Io* (A) as a function of temperature for three fit methods

Figure 5 shows the diode saturation current *Io* which is closely linked to ideality factor in the diode equation, leading to a degree of interference between these two parameters. In this case, the three parameters agree at high temperatures. The activation energy, here very close to half the bandgap of crystalline silicon, points to a recombination process assisted by mid-gap traps according to Shockley-Read-Hall recombination statistics [5] (and as expected, in the corresponding temperature range, the ideality factor is equal to 2 as shown in Figure 4). The good agreement between the three extraction methods is consistent in view of the fact that the saturation current level is to a first approximation the intercept of the linear section of the I(V) curve with the current axis. In the ALM model this is reliably approximated by the analytical form leading to consistent if noisy parameter extraction. At lower temperatures, however, the ALM method is not capable of extracting meaningful values for reasons as mentioned above relating to the interference between the two-diode nature of the data and the single diode analytical approximation. The two regions TRM returns similarly noisy values which however are phenomenologically consistent with the variational LVM. The sharp difference in saturation current trend at approximately 165K can be attributed to a change in behaviour between non radiative SRH and trap assisted tunnelling dominated recombination regimes. The trend remains noisy, and shows unphysical steps of an order of magnitude at low temperatures.

The variational and more general LVM shows a much less noisy parameter extraction at all temperatures but disagrees significantly with the TRM at temperatures below 200K. This confirms the differences seen in fig. 2 where the LVM shows an earlier tunnelling current onset than the TRM. However, without further work we can only conclude that the TRM and LVM methods, while not in quantitative agreement, show similar trends which suggest that trap-assisted tunnelling is dominating the recombination mechanisms.

4 CONCLUSIONS

Comparing the three methods we find that the agreement is satisfactory if not exact in cases where the parameter beign extracted is clearly dominant. A particularly clear examples is the consistent values of series resistance found for temperatures above 200K.

Agreement becomes less reliable in predictable cases. As the behaviour of the solar cell departs from single diode behaviour at lower temperatures, the conceptually more appealing analytical method begins to fail. This is reflected particularly in values for ideality and saturation current for two reasons: Firstly, because they are inter-dependent in the analytical function, and secondly because of the breakdown in applicability of the single diode model.

The two regions method retains good agreement with the analytical method where this latter is consistent. This agreement further confirms that in clearly defined cases that aproximate to an analytical solution, the analytical method is reliable, and the two-regions method is a good approximation to it.

As expected, the most general variational method is that which describes all scenarios most consistently. This method may however be subject to the least accuracy given the much greater applicability.

Finally, we have shown that the use of these three parameter extraction methods with different approaches, from analytical to numerical, complement each other. This complementarity allows greater insight into the physical processes underlying the limiting factors that control the photovoltaic perfomance of the cell.

This preliminary study strongly suggests improvements. The first is a greater range of bias particularly at low temperatures, given the increasing diode bandgap, in parallel with increased data quality and reduced noise at low temperatures.

This point should in particular address the isue of vanishing series resistance at low temperatures reported by TRM and LVM methods.

Furthermore a quantitative study of these effects in terms of fit quality quantified by a misfit parameter, together with better quality data should allow explicit estimates of trends in resistance due to effects such as vibrational contributions, dopant ionisation, and contact contributions which can identify those mechanisms specifically responsible for parallel and series resistances.

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