APPLICATION TO DIFFERENT THIN FILM SOLAR CELL TECHNOLOGIES OF EXPLICIT ANALYTIC SOLUTIONS FOR THEIR PARAMETERS EXTRACTION FROM CURRENT VERSUS VOLTAGE CHARACTERISTICS AT DIFFERENT TEMPERATURE

A. Darga[1], J-C. Denis[1,*], F. Lmai[1], J.P. Connolly[2] and D. Mencaraglia[1]
1. Laboratoire de Génie Électrique de Paris (LGEP), UMR 8507 CNRS-SUPELEC, Université Pierre et Marie Curie, Université Paris-Sud 11, 11 rue Joliot-Curie, Plateau de Moulon, 91192 Gif-sur-Yvette Cedex, France
2. Nanophotonic Technology Centre, Universidad Politécnica de Valencia, Camino de Vera s/n, 46022 Valencia, Spain

ABSTRACT: In this work, we have compared three different methods for thin film solar cell electronic transport parameters extraction from dark current versus voltage at different temperatures (I (V,T)) measurements. These parameters correspond to the classical dc single diode model with series and shunt resistances. 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. These methods have been applied to two different thin film solar cell technologies, amorphous silicon base p-i-n cell and CIGSe/CdS (or ZnS) hetero-junctions. We have analyzed the temperature evolution of the 4 extracted parameters of amorphous silicon base p-i-n cell and CIGSe/CdS (or ZnS) hetero-junctions solar cells 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: Thin Film Solar Cells, Parameter Extraction, Characterization

1 INTRODUCTION

In the search for low cost and efficient solar cells, semiconductor thin films play a key a role, as their efficiency continue to improve [1]. However, due to their polycrystalline or amorphous structure, recombination mechanisms via electronic deep states play an important role on the device photovoltaic performance [2]. Current versus voltage measurement at different temperatures (I(V,T)) is a powerful electronic transport characterization technique. If the set-up of this technique is relatively simple, the interpretation of data is not straightforward. The difficulties have two sources: first, the simple DC equivalent circuit of a solar cell consisting of a series resistance (Rs), a parallel resistance (Rp) and one or two diode is described by an implicit transcendental equation which cannot be solved analytically using elementary functions. Second, for non ideal, non crystalline solar cells such as thin film cells, this circuit may not be sufficient to describe the I(V) characteristics.

Significant efforts have been devoted to refining the analysis of I(V,T) characteristics [2]. Recently, this problem has been adressed by works presenting two new methods [3, 4] 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 [5] 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 behavior of the device. Of great interest in the work presented here is the variation of 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. These methods have been applied to two different thin film solar cell technologies, amorphous silicon base p-i-n cell and CIGSe/CdS (or ZnS) hetero-junctions. In a companion paper, these methods are also applied to a crystalline silicon cell [6].

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 10 K step.

The devices under test were CIGSe/CdS, CIGSe/ZnS and amorphous silicon p-i-n solar cells.

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:

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

[*] Present: PhD position at School of Engineering and Physical Sciences, Heriot-Watt University, Edinburgh, Scotland

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. [3]. 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 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. [4]. 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 analytical ALM method is expected to be numerically more exact for data which better approximates 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. This could be the case of an homjunction (e.g.crystalline or amorphous silicon solar cells) as opposed to heterogeneous solar cell design (e.g. CIGS based solar cells). However, as soon as the data depart 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

We will start this section with a qualitative description of I(V,T) curves. Figures 1a, 1b, 1c shows respectively the I(V,T) data curves at different temperatures, for CIGSe/CdS solar cell, CIGSe/ZnS solar cell and a-Si p-i-n solar cell.

From the classical DC electrical equivalent circuit (Rs, Rp and one Diode) of a thin film solar cell under dark condition, forward I(V) curve can be described by three regions: Reg. 1 (Low Voltage) : 0 - 0.4 V : Parallel resistance influence zone; Reg. 2 (Medium Voltage) : 0.4 - 0.8 V: diode like behaviour and Reg. 3 (High Voltage) : 0.8 - 2 V: series resistance. The contribution of each region to the I(V) curve is strongly dependent on the temperature. Also the behavior of each region is dependent on the cell technology.

For CIGSe/CdS solar cell, we note that, at low temperature (100 K– 190 K) the parallel resistance (Rp) dominates the I(V) curve, the diode behavior is not well marked and the series resistance (Rs) is not visible. It is therefore anticipated that it will be relatively difficult to extract Rs and diode parameters n and Io here.

The I(V,T) of the CIGSe/ZnS solar cell behaves similarly to the CdS buffered sample. The differences are: the diode behavior is less pronounced and at high forward bias voltage (reg. 3, series resistance), it shows less evidence of series resistance.

The I(V,T) of a-Si pin solar cell behave similarly as those of CIGSe/CdS sample with however less clear parallel resistance effects (reg. 1).

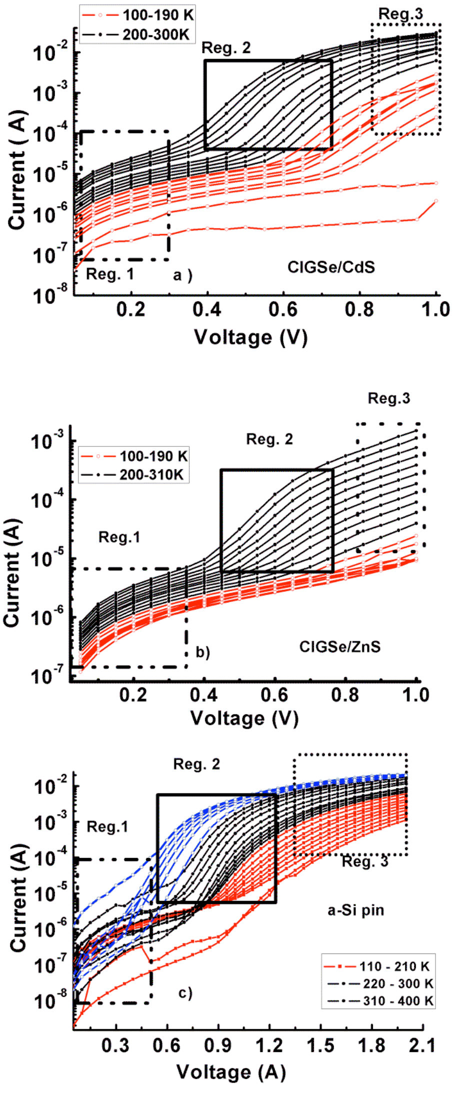

Figure 1: Dark current data as a function of bias and temperature I(V,T) for three different solar cells: a) CIGSe/CdS, b) CIGSe/ZnS and c) a-Si p-i-n

Figures 2 and 3 present a more quantitative analysis of the temperature dependence of four parameters (n, Io, Rs and Rp) based on the three parameter extraction methods described previously. We focus on the CIGSe/ZnS, which is phenomenologically similar to the CIGSe/CdS, for clarity.

In all cases we see first that the three methods are in reasonable agreement in the higher temperature range above 200K, but not at low temperatures.

In more detail, looking at the CIGSe/ZnS data we observe that the analytical ALM method is systematically the one that departs most significantly from the TRM and LVM methods, and is much noisy showing discontinuities and even failing to yield values at the lower temperatures for I_0. This is ascribed to the fundamentally greater sensitivity of the ALM method to noise in the data, which results in greater noise in extracted parameter values.

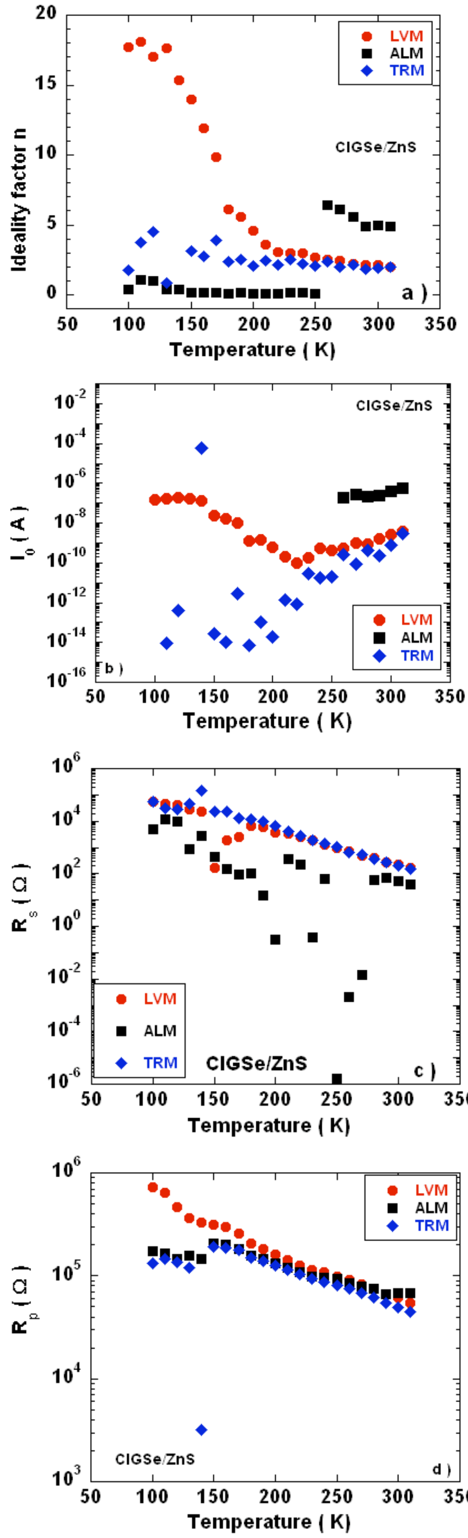

Figure 2: CIGSe/ZnS, temperature dependence of parameters for three fit methods; a) n, b) I0, c) Rs and d) Rp

We observe that the TRM and LVM methods appear highly consistent at higher temperatures giving degree of confidence in the extracted parameter values.

At lower temperatures we observe significant divergence. The clear reduction in noise for the LVM method supports earlier comments regarding the robustness and generality of this multi-parameter method using all data points. The TRM noise is partly expected to arise at least in part from the definition of linear and exponential regions with the added uncertainty that entails.

The preliminary conclusion is that the TRM and LVM agreement at room temperature gives confidence in the method, and that the greater generality of the LVM method allows it to successfully extract meaningful values at low temperatures, albeit with greater uncertainty.

Figure 3 shows similar data for the a-Si cell. In this case, the three ALM, TRM, and LVM methods yield similar parameter values and much greater agreement is achieved. In particular, the lower noise and increased confidence in ALM is a consequence of the greater material homogeneity of the amorphous silicon cell structure and manufacture compared to the more complex heterojunction structure based on the CIGSe compound.

This is emphasized when the agreement between TRM and LVM is considered: the near exact agreement over the entire temperature range for ideality and series resistance Rs, together with the good agreement for parallel resistance Rp and saturation current further underline the greater material homogeneity of the amorphous Si cell compared with the heterogeneous and polycrystalline CIGSe/ZnS cell.

These considerations lead us to assume that the parameter values extracted by the variational LVM method are verified where possible in those regimes where the ALM and TRM complementary methods apply. The triple approach to verifying these values gives us confidence in ascribing a degree of physical meaning to the parameter values extracted, concentrating on the LVM method in the following discussion.

Considering resistance values, we find that the CIGSe/ZnS cell shows much greater Rs, and roughly equivalent Rp. This points squarely at a series resistance issue in the CIGSe/ZnS layers, most probably in the thin and relatively novel ZnS window.

Moving on to the diode characteristics, we observe a much greater ideality in the CIGSe/ZnS cells at low temperature, which is classically ascribed to trap assisted tunnelling in the space charge region [5,7]. This, again, suggests high defect densities at the CIGSe/ZnS interface and the need for interface passivation. Above 300 K, LVM and TRM agree quite well, returning an ideality factor value very close to 2, which indicates recombination assisted by the more efficient mid-gap traps according to Shockley-Read-Hall recombination statistics [8].

The dark current saturation Io however does not add much information remaining comparable in the two materials which in itself is an interesting observation. It suggests that the CIGSe/ZnS loss mechanism is not fundamentally much greater than that of a good amorphous silicon solar cell.

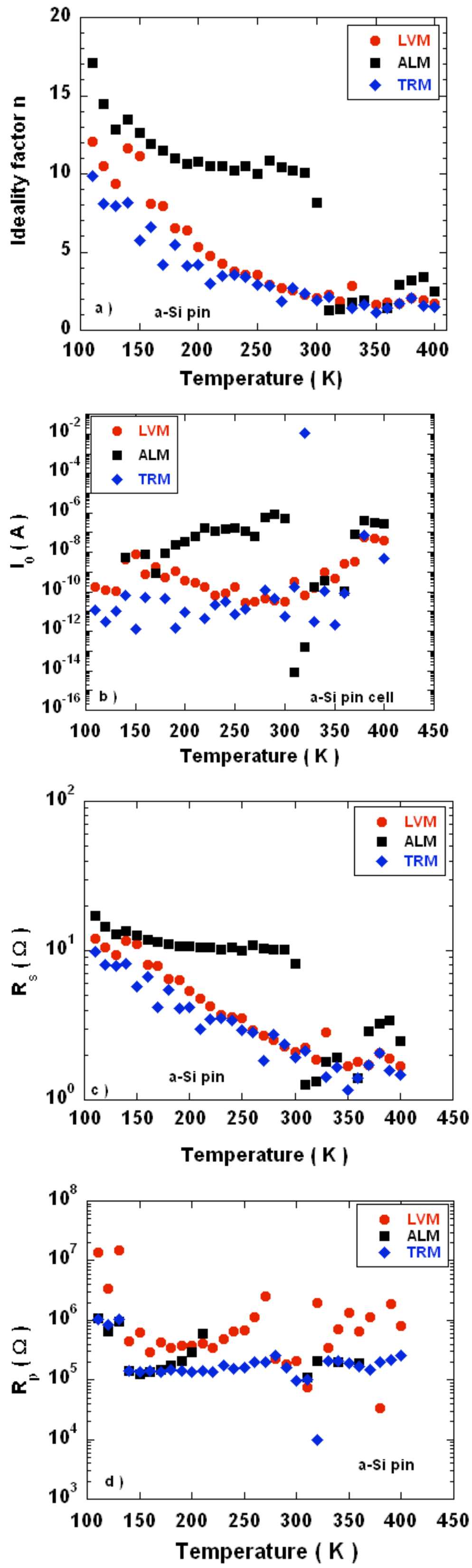

Figure 3: a-Si p-i-n, temperature dependence of parameters for three fit methods; a) n, b)I_0, c) Rs and d) Rp

4 CONCLUSIONS

Comparing the three parameter extraction methods we find that the most general LVM method yields the most useful information over the entire temperature range. The TRM method is nevertheless in good agreement over much of the parameter space, and the more delicate but fundamentally more accurate ALM method serves as a confirmation in those parameter spaces where it is applicable.

The conclusions are first that the higher homogeneity of the amorphous Si cell is clearly evident in the cleaner parameter trends, and greater zone of application of the TRM and ALM methods.

Preliminary analysis of the overall results relies mostly on the overall LVM parameter extraction and allows very interesting conclusions to be drawn.

The resistance loss comparison between the two cells suggests i/ that the window layer is a limiting factor in the CIGSe/ZnS cell, leading to higher Rs, ii/ that the CIGSe/ZnS does not suffer from significantly greater parallel resistance losses despite the technically less demanding production methods, iii/ that interfacial losses are identifiable in the CIGSe/ZnS cell again by comparison with the Si cell data.

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 cells.

Further work is intended to expand this preliminary analysis. In particular, in order to allow more accurate parameter extraction, a greater bias range is required at lower temperatures to take the increasing built in potential due to greater bandgaps into account, together with the difficult problem of obtaining lower noise at these levels.

Acknowledgments

This work is partially supported by the Agence Nationale de la Recherche (ANR) under the project ANR-06-PSPV-002-05.

References

[1] Ingrid Repins, Miguel A. Contreras, Brian Egaas, Clay DeHart, John Scharf, Craig L. Perkins, Bobby To, Rommel Noufi, Progress in Photovoltaics: Research and Applications, Volume 16, Issue 3 (2008) 235

[2] U. Rau, A. Jasenek, H.W. Schock, F. Engelhardt, Th. Meyer, Thin Solid Films 361-362 (2000) 298

[3] A. Ortiz-Conde, F.J.G. Sánchez and J. Muci, Sol. Energy Mater. Sol. Cells 90 (2006) 352

[4] K. Bouzidia, M. Chegaar and A. Bouhemadoua, Sol. Energy Mater. Sol. Cells 91, issue 18 (2007)1647

[5] J.P.Connolly, Z. Djebbour, A. Darga, C. Bazin, D. Mencaraglia, M. Benosman, N. Bodereau, J-F Guillemoles, D. Lincot, J. Kessler, N. Naghavi, J. Kurdi, O. Kerrec, Proc. 20th European Photovoltaic Solar Energy Conference, Barcelona, Spain, June 2005, p.1851.

[6] F. Lmai, J-C. Denis, A. Darga, J.P. Connolly and D. Mencaraglia, This conference (Paper 1CV.4.35)

[7] V. Nadenau, U. Rau, A. Jasenek, and H. W. Schock, JAP 87 (1) p.595 (2000)

[8] W.Shockley and W.T.Read, *Phys. Rev.* **87**, 835, (1952), R.N.Hall, *Phys. Rev.* **87**, 387, (1952)