AIP Advances

Non-approximated series resistance evaluation by considering high ideality factor in organic solar cell

Cite as: AIP Advances **8**, 125121 (2018); https://doi.org/10.1063/1.5053584
Submitted: 23 August 2018 . Accepted: 03 December 2018 . Published Online: 27 December 2018

Aniket Rana, Amit Kumar, Md. Wazedur Rahman, Nikita Vashistha, Kuldeep K. Garg, Sandeep Pandey, Nanda Gopal Sahoo, Suresh Chand, and Rajiv K. Singh

AIP ADVANCES **8**, 125121 (2018)

Non-approximated series resistance evaluation by considering high ideality factor in organic solar cell

Aniket Rana,[1,2,a] Amit Kumar,[1,2] Md. Wazedur Rahman,[3] Nikita Vashistha,[1,2] Kuldeep K. Garg,[1,2] Sandeep Pandey,[4] Nanda Gopal Sahoo,[4] Suresh Chand,[1,2] and Rajiv K. Singh[1,2,a]
[1]*CSIR- National Physical Laboratory, Dr. K.S Krishnan Marg, New Delhi 110012, India*
[2]*Academy of Scientific and Innovative Research (AcSIR), CSIR-NPL Campus, New Delhi 110012, India*
[3]*Centre for Green Energy Technology, Pondicherry University, Puducherry 605014, India*
[4]*Nanoscience and Nanotechnology Centre, Department of Chemistry, Kumaun University, Nainital 263001, Uttarakhand, India*

(Received 23 August 2018; accepted 3 December 2018; published online 27 December 2018)

The quality performance analysis of any solar cell can only be predicted through the parameters extracted from its current-voltage characteristics. Herein, we demonstrate an efficient analytical method to calculate the series resistance of organic solar cells without any pre approximation. It has been shown that the inaccuracy in series resistance takes place due to the high ideality factor of the organic based solar cells, usually ranging from 2-5. Using a systemic approach, we solved the single diode solar cell model to determine the series resistance expression. The dependence of series resistance on ideality factor of the device and the reverse saturation current calculation through the illuminated current-voltage characteristics has been presented here for the first time. The entire method has been programmatically realized in MATLAB. The extracted parameters values have been compared to the other methods for the proof of validation and it shows good agreement where as some outputs are better resolved. Additionally, the effectiveness of the present method is also matched with NREL certified silicon solar cell (reference cell model 60623) parameter extracted from K24XX cell software provided with PET cell tester model, CT200AAA solar simulators. The present proposed method is not restricted to the organic solar cell only but it can also be applied for the other type of solar cell as well. Therefore, the proposed method shows the relevance in the present scenario of solar cell research and development. https://doi.org/10.1063/1.5053584

INTRODUCTION

The high manufacturing cost of crystalline silicon and the latest advancements on semiconducting polymer strategy and synthesis in recent years have directed the attention of the scientist and engineer's community towards organic solar cells (OSC's).[1–4] For the estimation of organic solar cell performance and further improvement in design, fabrication, and simulation; the precise knowledge of electrical parameters from current-voltage characteristic is essential. There are numerous losses existing in the organic solar cell which affects the performance determining parameters like short circuit current density (J_{sc}), open circuit voltage (V_{oc}), fill factor (FF) and efficiency (η). The basic diode parameter, i.e. ideality factor (n), lumped parameters series resistance (R_s), shunt resistance (R_{sh}) and reverse saturation current (J_{sat}) are the factors that can control the losses. Shunt resistance in solar cell originated by the defects during the fabrication and provide an alternate conducting network for the

[a]Email: rajivsingh@nplindia.org aniket.rana@gmail.com

photogenerated carrier. The reduction in R_{sh} can adversely affect the performance of organic solar cell by decreasing the V_{oc}, FF, and η. Different layers of the organic solar cell including internal interface layers, lateral conduction through the transparent conducting oxide and aluminium contact introduces $R_{s.}$ Countless research is being carried out to develop different approaches to extract parameter from solar cell current-voltage (J-V) characteristics.[5–7] Kaminski et al. used a dark J–V curve with a single exponential model to extract series resistance.[8] M. Chegaar et al. has reported a method for extracting the electrical parameter from experimental J-V data.[9] Wolf and Rauschenbach have shown that series resistance determination from the J-V characteristics at two different illumination levels.[10] This is later analyzed by other authors and found that there is a significant increment in the series resistance with increasing terminal current. Cape and Zehr[11] found a large error in the inferred value in series resistance introduced by the temperature difference of the cell measured at two different points. Warashina and Ushirokawa[12,13] have developed a graphical method to obtain series resistance considering the constant illumination level method. All the extraction methods do not provide any information regarding the effect of ideality factor on series resistance which is crucial for the organic solar cells. Usually, for the electrical characteristic of organic solar cell single diode and double diode equivalent circuit model is used. Due to its simplicity and capability to well describe almost all types of solar cell characteristics; the single diode model has become most suitable selection for the present case of study. Whereas the majority of the parameter extraction method uses curve fitting approach by employing least square method.[13–16] In this approach, parameters are extracted by minimizing the squared error between calculated target variable and experimental data. Typically the expressions for the target variable are an implicit function which consists of dependent and independent variable at an identical time. The implicit nature of current-voltage expression increases the difficulty in the parameter extraction. To overcome this difficulty, the Jain et al. proposed the Lambert W function to obtain the explicit analytical solution to study the properties of organic solar cell.[17] It applies simulated current-voltage characteristic instead of experimental data. These types of vertical optimization method (minimizing the current quadratic error) allow the extraction of solar cell parameters simultaneously, but it requires good initial estimation of parameters such as series resistance, ideality factor and reverses saturation current for calculation. Based on Lambert W function Ortiz-Conde et al. have presented a parameter extraction method for the solar cell from the integration of illuminated current-voltage characteristics.[17] In this method, they calculated first Co-content (CC), (J-V) function from the explicit analytical solution and there after extracted the solar cell parameters. Though, CC is a function of J-V and eventually uses a bi-dimensional fitting process. The present study is free from any initial approximation for the series resistance evaluation, the derived slope (dV/dJ) at short circuit provide shunt resistance (R_{sh}) whereas at open circuit condition gives series resistance (R_s) with the added expression.

EXPERIMENTAL

Device fabrication

For the validation of present study, the organic solar cell has been fabricated with structure ITO/MoO_3/P3HT:PC_{60}BM/Al. The blending ratio of the P3HT:PC[60]BM blend was 1:0.8 by weight with 30 mg ml^{-1} solution concentration in dichlorobenzene. Indium tin oxide (ITO) coated glass substrate was patterned with a laser scriber and then ultrasonicated in a soap solution, acetone and then isopropyl alcohol stepwise each for 20 min. MoO_3 is used as a buffer layer deposited by vacuum deposition process and the active layer (P3HT:PC[60]BM) film was spin coated at 800 rpm for 60 s and annealed at 120 °C for 20 min. Aluminium (Al) used as a cathode was thermally evaporated up to 100 nm over the active layer at 10^{-6} mbar pressure with around 2 Å per second deposition rate. The final achieved cell structure was ITO/MoO_3/P3HT:PC[60]BM/Al with device area 0.04 cm^2.

Device characterization

All the device measurements were done under ambient conditions. The current-voltage characteristics were measured using a computer controlled PET solar simulator integrated with Keithley 2420 source meter. The current voltage characteristics obtained was implemented in our newly developed mathematical expression in MATLAB 2013b for the evaluation of J_o, J_{sc}, V_{oc}, R_s, R_{sh}, FF, η and Ideality Factor (n).

Mathematical modelling

The single exponential model with a lumped parameter equivalent circuit having series and parallel resistance in the simplest form has been shown in Figure 1. The mathematical expression for the output terminal current density (J_{pv}) for the equivalent circuit, shown in Figure 1, is given by the implicit equation 1.[17]

$$J_{pv} = -J_{ph} + J_{sat}\left[e^{\left\{\frac{q}{nkT}(V-J_{pv}R_s)\right\}} - 1\right] + \frac{1}{R_{sh}}(V - J_{pv}R_s) \tag{1}$$

where, J_{ph}, q, k, and T stands for photogenerated current density, electronic charge, Boltzmann's constant and operating temperature of the organic solar cell. The classic solar cell J-V characteristics in linear as well as semi-logarithmic scale indicated with important parameters have been shown in Figure 2. When short circuit condition is applied at the output of OSC (V= 0, J_{pv} = - J_{sc}), then the equation 1 is modified as per equation 3.[18]

$$-J_{sc} = -J_{ph} + J_{sat}\left[e^{\left\{\frac{q}{nkT}(J_{sc}R_s)\right\}} - 1\right] + \frac{1}{R_{sh}}(J_{sc}R_s) \tag{2}$$

$$J_{ph} = J_{sat}\left[e^{\frac{qJ_{sc}R_s}{nkT}} - 1\right] + J_{sc}\left[1 + \frac{R_s}{R_{sh}}\right] \tag{3}$$

Considering the open circuit condition (V=V_{oc}, J_{pv}=0) in equation 1,

$$-J_{ph} + J_{sat}\left[e^{\left\{\frac{q}{nkT}(V_{oc})\right\}} - 1\right] + \frac{1}{R_{sh}}(V_{oc}) = 0 \tag{4}$$

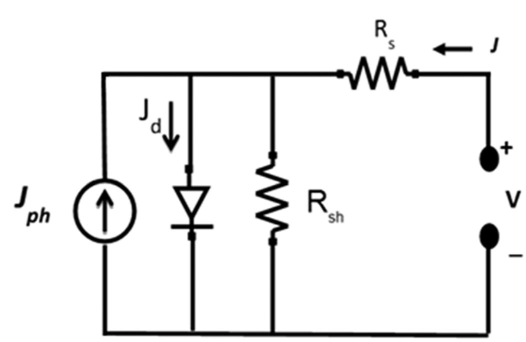

FIG. 1. The single diode equivalent circuit model for an organic solar cell with parasitic and parallel resistances.

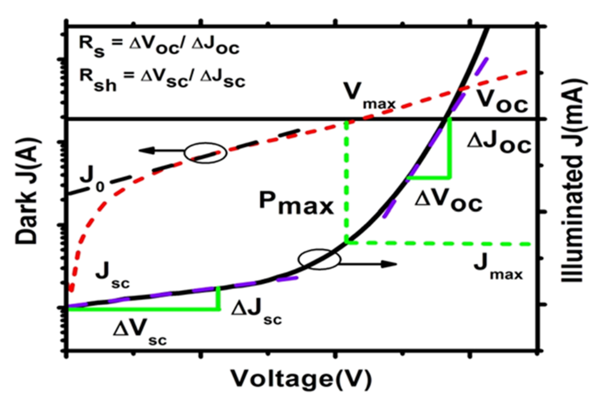

FIG. 2. Typical solar cell J-V characteristics in linear as well as a semi-logarithmic scale with the indication of different electrical parameters.

$$J_{ph} = J_{sat}\left[e^{\frac{qV_{oc}}{nkT}} - 1\right] + \frac{V_{oc}}{R_{sh}} \tag{5}$$

From equation 3 and 5 and assuming $R_s << R_{sh}$,[19]

$$J_{sat}\left[e^{\frac{qV_{oc}}{nkT}} - e^{\frac{qJ_{sc}R_s}{nkT}}\right] - J_{sc} + \frac{V_{oc}}{R_{sh}} = 0 \tag{6}$$

By differentiating the equation 1 with respect to V for the evaluation of dynamic resistance of organic solar cell

$$\frac{dV}{dJ_{pv}} = \frac{1 + R_s\left[\frac{qJ_{sat}}{nkT}e^{\frac{q(V-J_{pv}R_s)}{nkT}} + \frac{1}{R_{sh}}\right]}{\left[\frac{qJ_{sat}}{nkT}e^{\frac{q(V-J_{pv}R_s)}{nkT}} + \frac{1}{R_{sh}}\right]} \tag{7}$$

Now applying the condition of short circuit in equation 7, we obtain the resistance (R_{sc}) in device at short circuit condition, i.e.

$$R_{sc} = \left[R_s + \frac{1}{\left[\frac{qJ_{sat}}{nkT}e^{\frac{qJ_{sc}R_s}{nkT}} + \frac{1}{R_{sh}}\right]}\right] \tag{8}$$

Generally, for a good solar cell, series resistance is very small compared to shunt resistance,[20] therefore, $R_s \ll R_{sh}$ and $\frac{qJ_{sat}}{nkT}e^{\frac{qJ_{sc}R_s}{nkT}} \ll \frac{1}{R_{sh}}$.

Hence, equation 8 is reduced according to equation 9

$$R_{sh} = R_{sc} \tag{9}$$

Above expression shows that the inverse slope at short circuit condition which provide R_{sh}.

Now applying the open circuit condition in equation 7 and equating resistance (R_{oc})

$$R_{oc} = \left[R_s + \frac{1}{\left[\frac{qJ_{sat}}{nkT}e^{\frac{qV_{oc}}{nkT}} + \frac{1}{R_{sh}}\right]}\right] \tag{10}$$

In equation 6 $\frac{qJ_{sat}}{nkT}e^{\frac{qJ_{sc}R_s}{nkT}} \ll J_{sc}$ and it is also a smallest term compared to the remaining terms, therefore, this particular term can be neglected. If we calculate each term in equation 6 separately according to the parameter values obtained for the fabricated device given in Table I. Then the calculated values separately equate to $J_{sat}\left[e^{\frac{qV_{oc}}{nkT}}\right] = 0.081$ A/cm^2, $J_{sat}\left[e^{\frac{qJ_{sc}R_s}{nkT}}\right] = 1.4080 \times 10^{-5}$ A/cm^2, $J_{sc} = 0.0085$ A/cm^2 and $\frac{V_{oc}}{R_{sh}} = 0.038$ A/cm^2, respectively. It is clearly evident from the equated numbers that the value for $J_{sat}\left[e^{\frac{qJ_{sc}R_s}{nkT}}\right]$ is smallest and negligible compared to the other terms in equations 6. Moreover, in addition operation, it does not affect the final value significantly. Therefore, this term can be omitted, hence we can get a more simplified expression for the series resistance and reverse saturation current.

TABLE I. Comparison of proposed methods with the other methods for the organic solar cell.

Parameters	Present Study	Chegaar et.al[26]	N. Nehaoua et.al[27]	Amit Jain et.al[23]
Jsat (A/cm^2)	1.1482x10^{-5}	1.2021	--	--
Jsc (mA/cm^2)	8.465	8.465	8.465	8.465
Voc (V)	0.46308	0.46308	0.469	0.4631
Rs (ohm-cm^2)	1.7	4.7	2.06	1.8
Rsh (ohm-cm^2)	122	48.0493	92.72	92.41
FF (%)	41.479	41.4789	41.39	41.48
Efficiency (%)	1.626	1.626	1.62	1.62
Ideality Factor (n)	3.20	3.39	1.92	2.0

After neglecting and equating $\frac{qJ_{sat}}{nkT}e^{\frac{qV_{oc}}{nkT}}$ from equation 6 and putting in equation 10. The series resistance can be approximated as follows:

$$R_s = \left[R_{oc} - \frac{\frac{nkT}{q}}{J_{sc} - \left[\frac{V_{oc} - \frac{nkT}{q}}{R_{sh}}\right]}\right] \tag{11}$$

The above approximation is quite suitable for single diode model and it is valid for any type of solar cells with varying device area. Moreover, the above approximation is not easily implementable in double diode model for which the detail has been given in supplementary material. From equation 6 and 11 we can calculate the reverse saturation current, i.e,

$$J_{sat} = n\frac{kT}{q}\left[\frac{1}{R_{oc} - R_s} - \frac{1}{R_{sh}}\right]e^{\frac{qV_{oc}}{nkT}} \tag{12}$$

Now, Equation 9, 11, and 12 can be used for evaluating R_{sh}, $R_{s,}$ and J_{sat} respectively. For the calculation of ideality factor for organic solar cell, the dark J-V characteristics (Figure 2) have been used. The ideality factor has been derived from the slope of the semi-logarithmic dark J-V curve and represented by equation 13 given below.

$$n = \frac{q}{kT}\frac{dV}{d\ln(J)} \tag{13}$$

At very low voltages, the current from the diode is dominated by the trap-assisted recombination and shunt resistance. However, current at higher voltages is dependent upon series resistance. In the intermediate voltage range, the recombination current exists and controlled by the J_{sat} and n. Therefore, for the calculation of ideality factor, the slope of thesemi-logarithmic dark J-V curve should be selected in the intermediate recombination region.

RESULT AND DISCUSSION

The developed method has been implemented in MATLAB[21] to determine the various solar cell parameters such as R_s, R_{sh}, n, and J_{sat}. Figure 3(a, b) shows a semi-log plot of dark current-voltage characteristics and illuminated current-voltage characteristic under 100 mW/cm^{-2} constant illumination, generated as the output of the program. The parameters extracted in this work are quite good in predicting the organic solar cell behavior as well as the device physical constitution. These parameters could be helpful in the selection of materials for the fabrication of organic solar cells.

The structure of device presented here is ITO/MoO_3/P3HT:PC[60]BM/Al. Each of the layers has its own effect on the device performance, therefore, the device parameters will be also affected. To determine the connection between the parameters and the materials physical constitution as well as device mechanism, we need to understand the origin of such extracted parameters and the factors affecting them. Ideality factor is one of the important parameters which measure how the diode follows

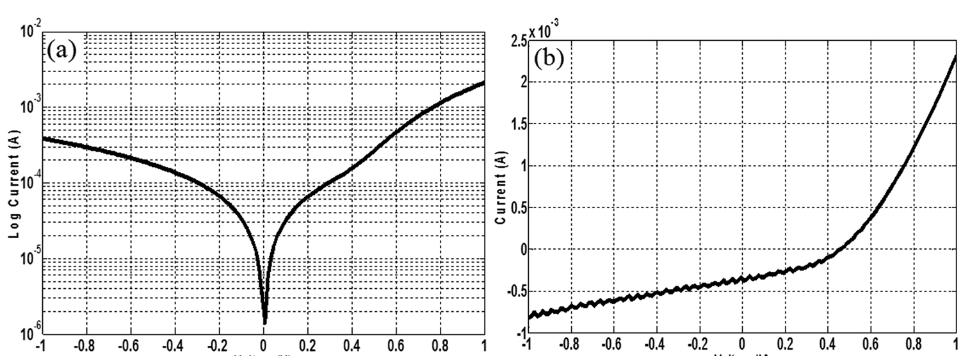

FIG. 3. Simulated output of experimental (a) dark semi-log current vs. voltage and (b) light current vs. voltage for device stricture- ITO/MoO_3/P3HT:PC[60]BM/Al.

the ideal diode characteristics. For the ideal p-n junction, there is only diffusion current flow through the junction, therefore, the ideality factor (n) is unity.[22] The recombination takes place in the organic solar cell during exciton diffusion or even after the exciton dissociation. The possibility of charge carrier recombination is higher in the organic solar cell compared to inorganic solar cells. There is two important processes, which affects the ideality factor in organic solar cells. First is exciton diffusion which takes place during the geminate recombination and second takes place during the charge collection which is dominated by bimolecular recombination and space charge effects. Both types of recombination processes cause the charge carrier loss in the device. Due to these losses, ideality factor of the device increases beyond unity, sometimes greater than 3. Usually, series resistance in these devices originates from the bulk resistance of the active layer and electrodes which means it depends on the physical constitution of the material and the contact resistance between the active layer and the electrodes. Whereas, the shunt resistance originates from the pinholes created during device fabrication as well as the purity of materials used. These pinholes induce leakage current in the device. Besides this, the leakage current in the device can also originate from the edges of the device. J_{sc} is affected by various factors such as the area of the cell, the number of photons incident on the cell, the spectrum of light, optical properties (absorption and reflection of material) and the charge carrier collection properties on the electrodes. All the above electrical solar cell parameters control the device working mechanism. The method which has been presented for extraction of these parameters, in this manuscript, is very much practical and can also be applied to the other device structures such as inverted, tandem, etc. In this method, none of the parameter value has been taken by assumption which is normally taken in other evaluation methods.[23] Further, the reverse saturation current calculation through the illuminated current-voltage characteristics has been presented here for the first time. This parameter also predicts about the device quality and recombination effect. The single diode model for the parameter extraction was selected due to it is wide acceptability to the different kind of structures in organic solar cells. Therefore, this model does not have any risk for being applicable to some certain cases. Commonly series resistance is calculated as the inverse slope at V_{oc}. In the present finding, it has been clearly shown that series resistance also depends on ideality factor, open circuit voltage, short circuit current and shunt resistance of the device. In the case of the organic solar cell, ideality factor has a higher value compared to the inorganic counterpart. The higher value of ideality factor than unity can be attributedto recombination of hole and electrons at the donor-acceptor interface and Fermi level pinning or a largeamount of voltage drop at the interface.[24] It also depends on the spacial inhomogeneous distribution of charge within the device. Therefore, $\frac{\frac{nkT}{q}}{J_{sc}-\left[\frac{V_{oc}-\frac{nkT}{q}}{R_{sh}}\right]}$ cannot be neglected. The plot the $R_{oc} - R_s$ vs. rest term in equation 10 gives better understanding about dependence of R_s the on other quantities like ideality factor and short circuit current as shown in Figure 4(a, b). As the ideality factor increases the device series resistance also increases. From equation 12, the reverse saturation current from illuminated J-V curve is evaluated, which are quite similar with the conventionally calculated from dark J-V characteristics.

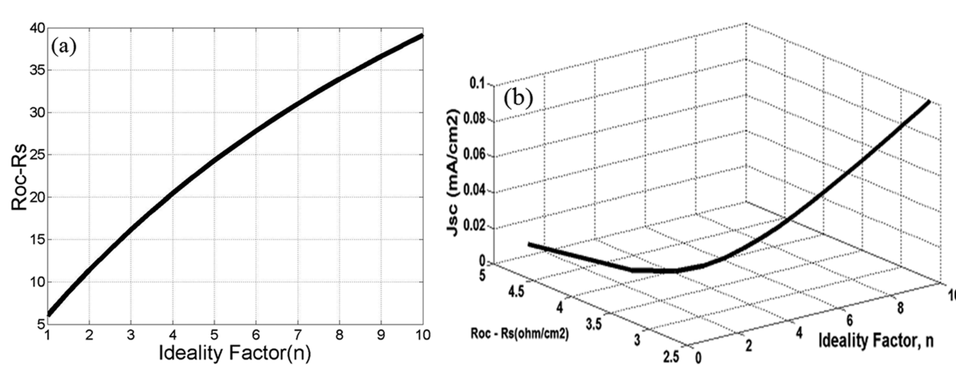

FIG. 4. (a) dependence of R_{oc}–R_s on ideality factor (b) dependence of R_{oc}–R_s simultaneously on ideality factor and short circuit current.

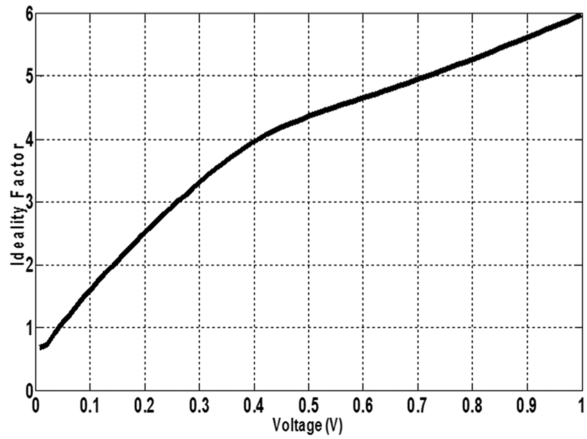

FIG. 5. Program output for ideality factor vs. applied voltage.

The versatility of the present program the important parameter has also been discussed, and the output has been presented. The ideality factor can either be given as a single value or plotted as a function of voltage. Figure 5 shows the variation in ideality factor of a diode according to the applied bias. Ideality factor is a powerful tool to investigate the recombination mechanisms in a device. The measurement of J_D (diode current) is only valid when the ideality factor is stable.[25] For the calculation of ideality factor equation 13 has been used. For the validation of the parameters evaluated based on present method, we have also calculated these parameters using the different methods and both the values are given in Table I for the sake of comparison. It is observed from the Table I that the parameters calculated by present proposed method are in good agreement with the other methods and even better resolved in some cases such as series resistance and reverse saturation current.

It means we present here an explicit analytical solution for short-circuit current, open-circuit voltage and ideality factor as well as power consuming parameters like series and shunt resistances. M Chegaar et al.[26] and N. Nehaoua et al.[27] both developed their methods for solar cell parameter extraction using J-V curve and the conductance (G), a derivative of the J-V curve. These methods followed up with some approximation for fitting with the experimental data, and then they extract parameters from J-V curve. The Newton method is used to get the approximation for the nonlinear equation although the Newton method converges very rapidly it needs some starting point, while in present case we approach towards the simple analytical approach by getting same value of J_{sc}, V_{oc}, FF, and efficiency are 8.465mA/cm^2, 0.46308 V, 41.479 % and 1.626 respectively, i.e it represents the almost zero percent error in analysis while comparing the reported and presented one. Further, the value of ideality factor in this case was found to be exhibiting nearly close relation to reported one. To validate this equation more accurerly we further correlate the present one with the other method proposed by N. Nehaoua et al. where J-V characteristics are corrected after the evaluation of shunt conductance. The shunt conductance was calculated from the linear fit. Again we are getting the almost similar value of J_{sc}, V_{oc}, FF, and efficiency (Table I). It all shows that in terms of accuracy our method uses no approximations for solving the equations. Futher, we apporach our method for the analysis of quality performance of organic solar cells with the work reported by Amit Jain et al. in which they introduce a new solution based on Lambert W-function to express the transcendental current-voltage characteristic containing parasitic power consuming parameters like series and shunt resistances. W-function-type solutions can be an alternative to study parameter extraction but not as a first choice due to the complexity of mathematical expression especially for the organic solar cell, where some other parameters play a vital role in device performance. Again, we are getting the almost same value of Jsc, Voc, FF, and efficiency (Table I). Further, the utility of the present method was also compared with NREL certified silicon solar cell (reference cell model 60623 with area 4 cm^2) parameter extracted from K2420 cell Tester 3.3 software provided with PET cell tester model # CT200AAA Solar Simulators. Our finding reveals that the present method fits well with some of the parameters while few parameters like to be fitted with the border line of result extracted through

TABLE II. Comparison of proposed methods with the PET solar simulator fitting software.

Parameters	Present Study	PET Solar Simulator
Jsc (mA/cm^2)	32.29	32.30
Voc (V)	620	615.60
Rs (ohm-cm^2)	0.224	0.208
Rsh (ohm-cm^2)	2655	3290
FF (%)	71.10	71.30
Efficiency (%)	14.22	14.23
Ideality Factor (n)	1.5	---

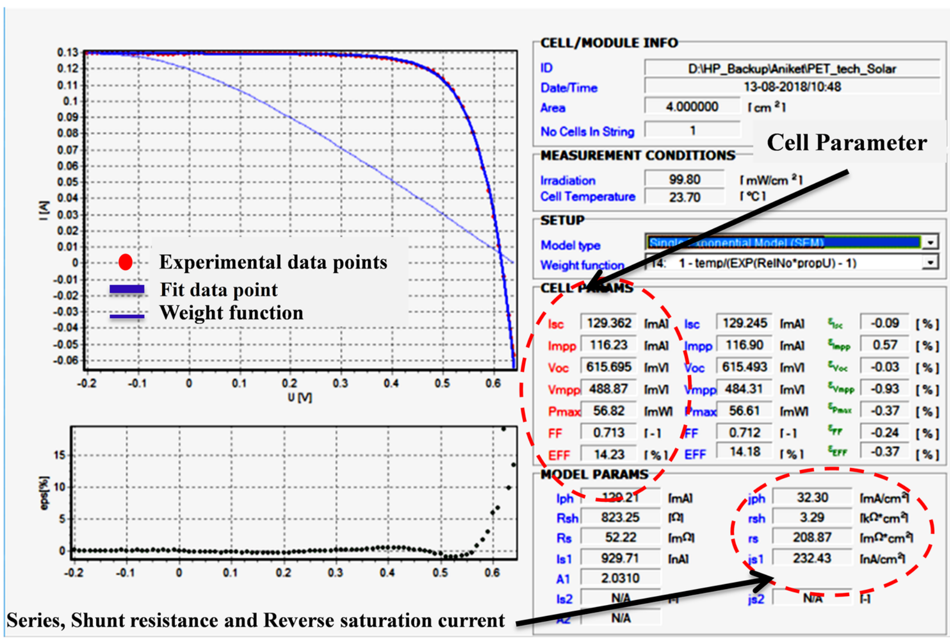

FIG. 6. NREL certified silicon solar cell (REFERANCE CELL MODEL # 60623) parameter extracted from K24XX cell Tester 3.3 software provided with PET CELL TESTER MODEL # CT200AAA Solar Simulators. For the parameter extraction single diode model is used.

K24XX cell tester (Table II). The calculated values of Jsc, Voc, Rs, Rsh, FF and efficiency in our method are 32.29 mA/cm^2, 620 V, 0.224 ohm-cm^2, 2655 ohm-cm^2, 71.1% and 14.22 % which makes a very close agreement between the values of Jsc, Voc, Rs, Rsh and FF extracted through K24XX cell tester (Figure 6). Therefore, the overall study reveals that non approximated evaluation of the series resistance by reconsidering ideality factor could become an alternative approach for the development of futuristic quick analysis of quality performance of organic solar cell. This work not only shows the validation of this kind of easy analytical approach for the quality performance of organic solar cells, but also reveals the capability of this approach for the analysis of variety of solar cells.

CONCLUSION

The present work demonstrates an effective and simple analytical method to extract the series resistance of organic solar cells from current-voltage characteristics under constant illumination condition without any pre approximation. This reduces the calculation time and error in the series resistance evaluation. It has been shown that the inaccuracy in the estimation of series resistance arises from the high ideality factor of organic solar cell as calculated by mathematical analysis. Other parameters are the ideality factors, saturation current, and shunt resistance can also be evaluated from the present program. In the calculation of series resistance we have considered the short circuit current density (J_{sc}) instead short circuit current (I_{sc}), therefore the effect of cell area has been taken care inherently. The NREL certified silicon solar cells has 4cm^2 area and gives good agreement of parameters between the present method and with the parameter extracted from K24XX cell software provided with PET cell tester model. In calculation of series resistance we have considered the short circuit current density (Jsc) instead short circuit current (Isc), therefore the effect of cell area has been taken care inherently and the study is proved to be suitable for different size of devices. As expression of series resistance (R_s) has been obtained using the single diode equation therefore it is simplest to realize programmatically and less memory as well as time consuming during the data processing. The present developed method has been compared with the other methods and shows good agreement. The present method is not restricted to the organic solar cell it can also be applied for the other type of solar cell as well. This is one of the most advantageous outcomes of the proposed method.

SUPPLEMENTARY MATERIAL

See supplementary material for analytical solution for the series resistance of solar cell based on double diode model which shows the implication of single diode model over double diode model for the present study.

ACKNOWLEDGMENTS

The authors are thankful to the Director, National Physical Laboratory, Dr. K. S. Krishnan Marg, New Delhi, for his kind support. One of us A. Rana is thankful to University Grant Commission, New Delhi, India for the award of a senior research fellowship. S. Pandey is thankful to DST INSPIRE fellowship.

[1] A. E. Becquerel, Academie Des Sciences **9**, 561 (1839).
[2] D. M. Chapin, C. S. Fuller, and G. L. Pearson, Journal of Applied Physics **25**, 676 (1954).
[3] M. A. Green, Y. Hishikawa, E. D. Dunlop, D. H. Levi, J. Hohl-Ebinger, and A. W. Y. Ho-Baillie, Progress in Photovoltaics: Research and Applications **26**, 3 (2018).
[4] C. W. Tang, Applied Physics Letters **48**, 183 (1986).
[5] Priyanka, M. Lal, and S. N. Singh, Solar Energy Materials and Solar Cells **91**, 137 (2007).
[6] A. Jain and A. Kapoor, Solar Energy Materials and Solar Cells **85**, 391 (2005).
[7] M. Bashahu and P. Nkundabakura, Solar Energy **81**, 856 (2007).
[8] A. Kaminski, J. Marchand, and A. Laugier, Solar Energy Materials and Solar Cells **51**, 221 (1998).
[9] K. Bouzidi, M. Chegaar, and A. Bouhemadou, Solar Energy Materials and Solar Cells **91**, 1647 (2007).
[10] M. Wolf and H. Rauschenbach, Advanced Energy Conversion **3**, 455 (1963).
[11] J. Marshall, J. Cohen, J. A. Cape, M. D. Paul, D. L. Miller, and J. S. Harris, Proc. SPIE **248**, 109 (1980).
[12] M. Warashina and A. Ushirokawa, Japanese Journal of Applied Physics **19**, 179 (1980).
[13] D. Pysch, A. Mette, and S. W. Glunz, Solar Energy Materials and Solar Cells **91**, 1698 (2007).
[14] R. J. Handy, Solid-State Electronics **10**, 765 (1967).
[15] E. Radziemska, Energy Conversion and Management **46**, 1485 (2005).
[16] K. Rajkanan and J. Shewchun, Solid-State Electronics **22**, 193 (1979).
[17] M. Murayama and T. Mori, Japanese Journal of Applied Physics Part 1-Regular Papers Brief Communications & Review Papers **45**, 542 (2006).
[18] J.-C. Wang, J.-C. Shieh, Y.-L. Su, K.-C. Kuo, Y.-W. Chang, Y.-T. Liang, J.-J. Chou, K.-C. Liao, and J.-A. Jiang, Energy **36**, 5968 (2011).
[19] F. Khan, S.-H. Baek, Y. Park, and J. H. Kim, Energy Conversion and Management **76**, 421 (2013).
[20] M. S. Imamura and J. I. Portscheller, in 8th IEEE Photovoltaic Specialists Conference (PVSC) (1970), pp. 102–109.
[21] F. M. González-longatt, 1 (2005).
[22] K. R. Mcintosh and C. B. Honsberg, 16th PVSEC 1651 (2000).
[23] A. Jain and A. Kapoor, Solar Energy Materials and Solar Cells **81**, 269 (2004).
[24] V. D. Mihailetchi, H. Xie, B. de Boer, L. M. Popescu, J. C. Hummelen, P. W. M. Blom, and L. J. A. Koster, Applied Physics Letters **89**, 012107 (2006).
[25] V. D. Mihailetchi, L. J. A. Koster, J. C. Hummelen, and P. W. M. Blom, 19 (2004).
[26] M. Chegaar, Z. Ouennoughi, F. Guechi, and H. Langueur, Journal of Electron Devices **2**, 17 (2003).
[27] N. Nehaoua, Y. Chergui, and D. E. Mekki, Vacuum **84**, 326 (2009).