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PAPER

Extracting impedance spectroscopy curve of solar cells from scattered measurements under light illumination

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Abstract

Data scattering occurs in impedance spectroscopy (I-S) measurement of solar cells under light illumination, which impedes reliable data fitting for photovoltaic parameter extraction. This paper reports a method that enables reliable I-S data fitting from severely scattered I-S plots. The study shows that a valid curve fitting of I-S data is possible by using a part of the data hidden in a seemingly scattered plot. Theoretical analysis confirms the validity of this approach, which reveals that a pattern emerging from the data obtained over a high frequency range represents the genuine part of the I-S curve. This new method was employed to investigate several commercial silicon solar cells. The results show that the photovoltaic parameters of solar cells under 1 sun illumination can be extracted with good repeatability from severely scattered measurement data, offering the capability of determining the dynamic properties of the solar cells, such as junction capacitance and charge carrier lifetime under a condition that is not possible previously.

1. Introduction

Impedance spectroscopy (I-S) has been frequently employed for characterization of all types of solar cells [1–6], which complements the current–voltage (I–V) measurements [7]. In addition to determination of series and shunt resistances directly, I-S measurements provide information on junction capacitance and operation frequency, offering the insights into the charge carrier dynamics and fabrication quality of solar cells. Although substantial literatures already exist on the topic, there is a gap in the I-S measurements of solar cells. To date, the literature on I-S data under light illumination without biasing using a small excitation signal is almost absent due to the scattering in the I-S plots, making it impossible to extract the photovoltaic parameters from those severely scattered I-S plots.

It is well-known that a smooth I-S curve of solar cells can be obtained if the tests are performed in dark [8, 9]. Under light illumination, a smooth I-S curve may also be obtained if a large excitation signal (>100 mV) is employed, but this violates a basic requirement of I-S technique, which is essentially a small signal method [10, 11]. Typically, the excitation signal should be less than 10 mV for solar cell characterisation because the open-circuit voltage of solar cells is in a range of 0.5 V to 1.2 V. A smooth I-S curve under light illumination may also be obtained by using a small excitation signal with a bias voltage [12–14]. Although biasing does not violate the measurement requirements, it introduces complication in data analysis and requires modification of the models to include specific biasing conditions. In addition, there is no standard bias voltage that can be applied to all types of solar cells for direct comparison. Clearly, it is necessary to perform I-S tests under light illumination using a small excitation signal without biasing.

This paper reports an experimental discovery that led to a simple and effective solution to the above-mentioned problem. It was observed that a clear pattern can be recovered from seemingly scattered I-S measurement data if the order of data acquisition is recorded. The efforts were made to understand the cause of the scattering. Theoretical analysis reveals that the extracted smooth pattern is a genuine part of the I-S curve, which is sufficient to reconstruct the original I-S plot, providing a novel solution for reliable I-S characterization of solar cells under light illumination using small excitation signal without biasing.

2. Experimental observation

Figures 1(a) and (b) show the I-S plots of a monocrystalline silicon solar cell (Zhejian DongShou New Energy Co., Ltd) in dark and under 1 sun illumination, respectively. The I-S measurements were performed using an impedance analyser by Metrohm (Autolab, PGSTAT302N). A small a.c. excitation signal of 5 mV with varied frequencies from 0.1 Hz to 1 MHz was applied without a bias voltage. The back electrode of the solar cell is connected to the ground and the tests were performed in a Faraday cage. The dark condition is achieved by optically blocking the light from the lamp using a shutter with the light source and all electronic systems remaining unchanged. Figure 1(a) presents a smooth curve, which enables reliable curve fitting for photovoltaic parameter extraction. However, a smooth curve can no longer be obtained when the tests were performed under light illumination (1 sun in this study). Instead, the data is vastly scattered as shown in figure 1(b), making data fitting seemingly impossible. Interestingly, it was observed during tests that a smooth curve exists among seemingly random data. Figure 1(c) shows a portion of the same dataset of figure 1(b) with the data acquisition sequence labeled. Clearly, the data points from 1 to 18 form a smooth curve, which may be used to reconstruct the original I-S plot if they represent the real data points of the I-S plot. In order to confirm this, it is crucial to ensure that these data points represent the genuine part of the I-S curve.

The fact that the scattering only occurs when the solar cells are subjected to light illumination implies that the scattering may be related to the photogenerated current. This is supported by inspection of the current fluctuation on the measured I–V curves. Figures 2(a) and (b) show the I–V curves measured in dark and under 1 sun illumination, respectively. The insets in the figures display the initial part of the data on a magnified scale. It can be seen clearly that the current fluctuation under 1 sun illumination is much more pronounced than that in dark. In an attempt to identify the possible causes of the fluctuation, further tests were conducted by changing the light intensity of the solar simulator and the light spectrum using optical filters. The results of these tests confirm that the observed fluctuation is not affected by the light intensity or spectral range. On the other hand, the scattering of I-S data appears to associate with the frequency of the excitation signal. The number on figure 1(c) represents data collection sequence during measurement, which corresponds to a high frequency range of the excitation signal from 1 MHz down to around 4 kHz. The fact that less scattering at high frequencies indicates that the current fluctuation exerts less impact on the I-S signals over the high frequency range. In fact, if the I-S data is presented in a Bode plot, the frequency dependence is evident. It can also be seen that the scattering occurs in both *I–V* and I-S data. However, the fluctuation occurred in the *I–V* data is very small compared to the *I–V* signals. Consequently, the noises induced by light illumination have little effect on *I–V* measurements. On the other hand, the noises induced by light illumination appear to have significant influence on the part of I-S data, leading to the problems in I-S measurements under a specific light illumination condition.

3. Model analysis

Figure 3(a) shows a simplified equivalent circuit of solar cell for I-S analysis [15]. A small a.c. signal of constant voltage, v_s, with varied frequencies is applied to the terminals A and B. By measuring both the magnitude and phase shift of its response current, i_s, the I-S curve can be determined. For a given v_s, the magnitude of the response current can be expressed as,

$$i_s = \frac{v_s}{\sqrt{\left[R_s + \frac{R_{sh}}{1+(f/f_D)^2}\right]^2 + \left[\frac{R_{sh}(f/f_D)}{1+(f/f_D)^2}\right]^2}} \quad (1)$$

with,

$$f_D = \frac{1}{R_{sh}C_D} \quad (2)$$

where, f is the frequency of the excitation signal, R_s is the series resistance, R_{sh} is the shunt resistance, and C_D is the effective junction capacitance of the solar cell. Equation (1) indicates that the response current increases with increasing frequency of the excitation voltage.

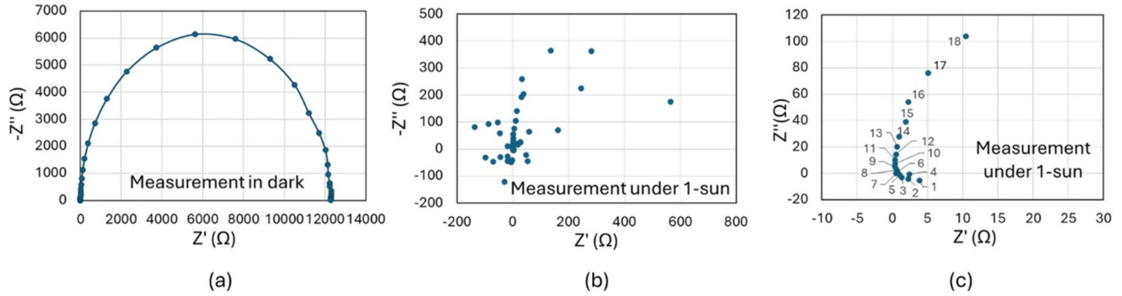

Figure 1. The I-S plots of a monocrystalline silicon solar cell. (a) The I-S data obtained in dark. (b) The I-S data obtained under 1-sun illumination. (c) A portion of the same dataset in (b) with data acquisition sequence labeled.

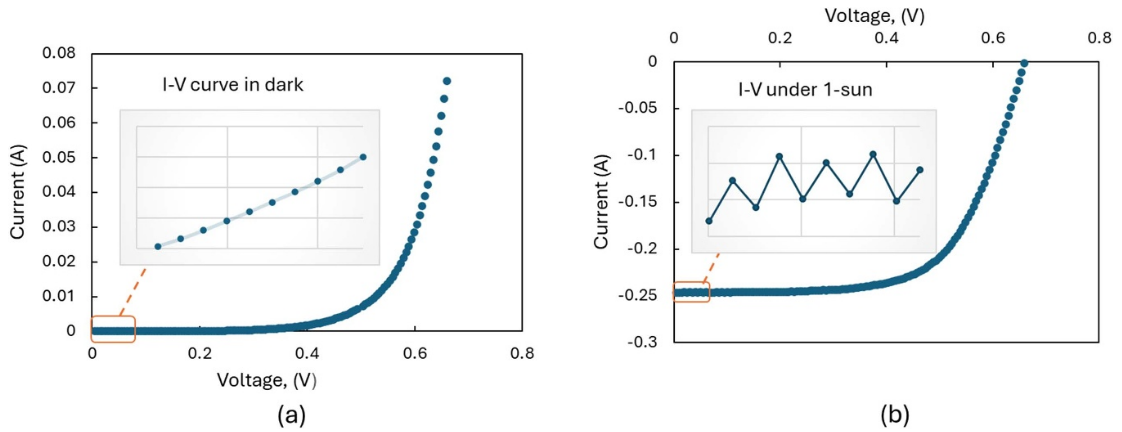

Figure 2. *I–V* curves of a monocrystalline silicon solar cell. The insets in the figures display the initial part of the data inside the red box on a magnified scale. (a) *I–V* data obtained in dark. (b) *I–V* data obtained under 1 sun, showing significant fluctuation compared with the data obtained in dark.

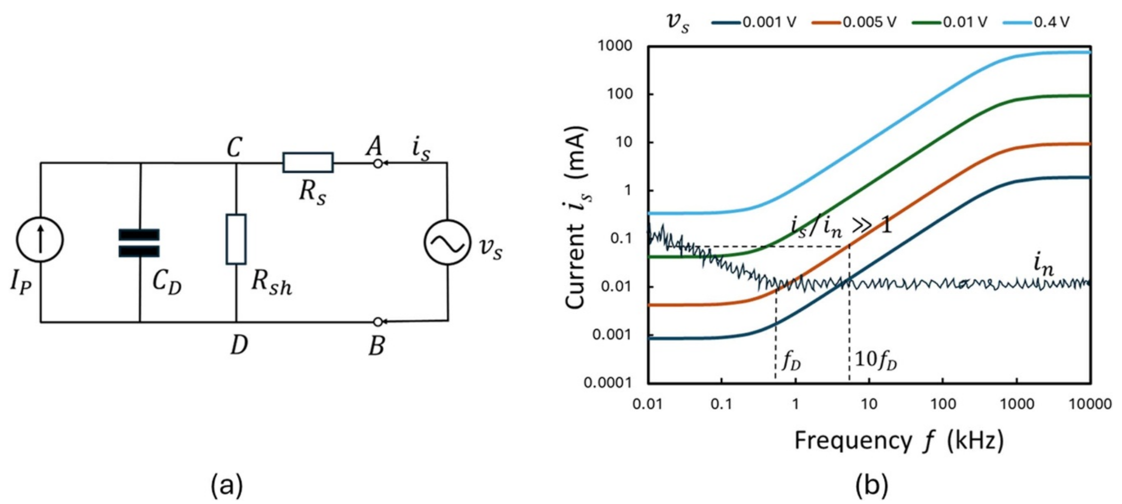

Figure 3. (a) Simplified equivalent circuit of the solar cells for impedance spectroscopy (I-S) analysis. (b) The response current, i_s, as a function of the frequency of the excitation voltage for different voltage levels. The noise level of the solar cells is also shown schematically for illustration purposes.

In I-S measurements under light illumination, the photocurrent, I_P, is generated with significant fluctuation, which induces a noise signal across R_{sh} and C_D. The current measured across the output terminals A and B is the superposition of the response current, i_s, and the noise, i_n. In such cases, reliable I-S measurements can only be achieved if the signal is sufficiently larger than the noises (i.e. the signal-to-noise ratio, $i_s/i_n > 1$). Otherwise, scattering will appear in the I-S plot. It has been reported that the flicker noise and white noise are present in solar cells [16]. This implies that i_n will initially decrease

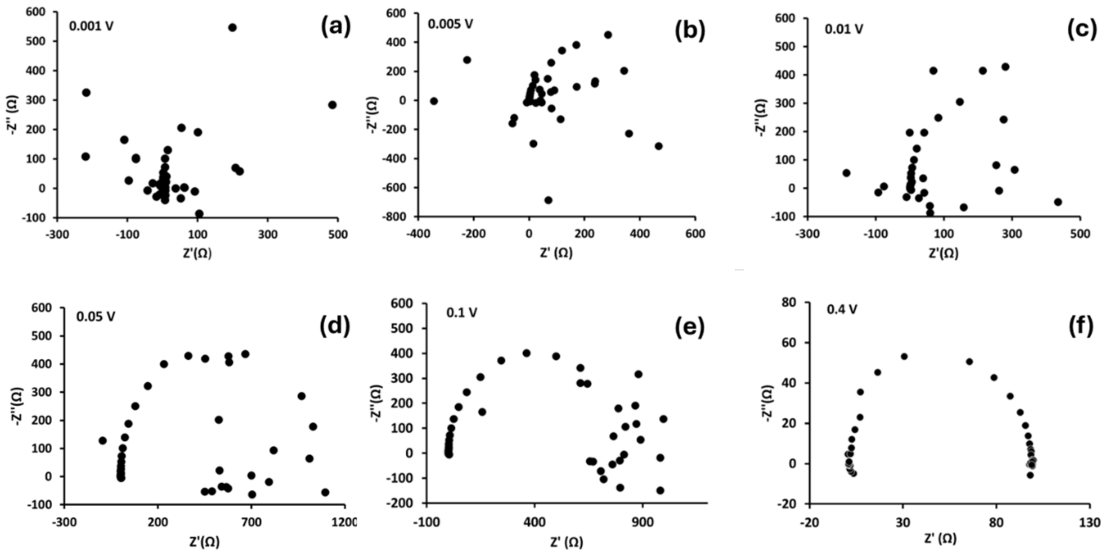

Figure 4. Impedance spectroscopy measurements under 1 sun without biasing using different excitation voltages (a) 0.001 V, (b) 0.005 V, (c) 0.01 V, (d) 0.05 V, (e) 0.1 V and (f) 0.4 V.

with increasing frequency at low frequencies (the characteristics of flicker noise) and then remains constant at high frequencies (the characteristic of white noise). On the other hand, equation (1) indicates that i_s increases with increasing frequency, resulting in a large signal-to-noise ratio, i_s/i_n, at high frequencies. Figure 3(b) shows the response current, i_s, as a function of frequency, f, for different excitation voltages, v_s. The noise level is also shown schematically. As illustrated, for an excitation voltage of 5 mV, i_s is smaller than i_n over a low frequency range (i.e. $f < f_D$), which leads to inevitable scattering in the I-S plots. When the frequency of v_s becomes higher than f_D, i_s starts to increase quickly with increasing frequency. To a certain frequency (e.g. $f = 10f_D$), i_s becomes sufficiently higher than i_n and a smooth I-S curve starts to emerge. This analysis explains the frequency dependence of the data scattering observed in figures 1(b) and (c), providing a theoretical proof that the smooth curve obtained over the high frequency range is a genuine part of the expected I-S curve. Clearly, the I-S data fitting can be performed using this part of the curve for reliable photovoltaic parameter extraction. In addition, this work offers possibility of estimating the noise levels in a solar cell.

It can be seen from equation (1), also shown in figure 3(b), that the magnitude of i_s increases with increasing the voltage level of the excitation signal. This indicates that a smooth I-S curve can also be obtained if a large excitation voltage is employed. Figure 4 shows the experimental results of I-S measurements using different excitation voltages under 1 sun illumination without biasing. The I-S plots appear to be completely random if the excitation voltage is very small (e.g. 0.001 V and 0.005 V). However, when the excitation voltage increases (e.g. from 0.01 V to 0.1 V), a smooth I-S curve starts to emerge gradually on the high frequency part of the plots. Further increasing the excitation voltage to 0.4 V, a completely smooth curve without scattering is obtained as shown in figure 4(f). This is because the signal level in this case is significantly higher than the noise level over all frequencies. The noises can no longer have significant influence on the I-S measurement as depicted by the light blue line in figure 3(b). Unfortunately, the smooth I-S curves obtained using large excitation voltages are not very useful because the models developed for extracting the solar cell parameters from the I-S curves are only valid if the excitation voltage is relatively small.

4. Photovoltaic parameters under light illumination

The above analysis confirms that the smooth curve formed over high frequencies represents the genuine part of the I-S curve of the solar cells, which enables photovoltaic parameter extraction from I-S measurements under light illumination. The method was employed to evaluate three silicon solar cells used in this study. Two of them (Mono13 and Mono24) were monocrystalline solar cells (Zhejian DongShou New Energy Co., Ltd). The third one (Poly6) was polycrystalline solar cell (Zhejian DongShou New Energy Co., Ltd). The leads for testing were soldered to the front busbar and the back contact of the solar cells using the procedures described in [17]. The *I–V* measurements were performed under the standard testing conditions to determine the power conversion efficiency (PCE) of the solar cells, which

Table 1. Photovoltaic parameters extracted from I-S measurements in dark and under 1 sun. The values are average of 10 measurements and the percentage values represent the corresponding relative standard deviation. The parameters R_s, R_{sh}, C_D, and ω_c were obtained directly from I-S data fitting. τ was calculated from ω_c.

		R_s (Ω)	R_{sh} (Ω)	C_D (nF)	ω_c (rad s^{-1})	τ (s)
Dark	Mono13	$0.37 \pm 5.2\%$	$12\,600 \pm 3.2\%$	$383 \pm 0.8\%$	$198 \pm 0.0\%$	5.05×10^{-3}
	Mono24	$0.42 \pm 21.5\%$	$7650 \pm 0.5\%$	$364 \pm 0.4\%$	$380 \pm 6.3\%$	2.58×10^{-3}
	Poly6	$0.32 \pm 7.6\%$	$3100 \pm 5.1\%$	$246 \pm 0.2\%$	$1200 \pm 7.6\%$	7.78×10^{-4}
1 Sun	Mono13	$0.53 \pm 9.7\%$	$1100 \pm 24.3\%$	$441 \pm 1.2\%$	$2000 \pm 26.9\%$	4.98×10^{-4}
	Mono24	$0.56 \pm 13.1\%$	$900 \pm 20.1\%$	$417 \pm 2.4\%$	$2600 \pm 23.1\%$	3.72×10^{-4}
	Poly6	$0.36 \pm 11.6\%$	$9460 \pm 10.6\%$	$273 \pm 1.0\%$	$8000 \pm 12.5\%$	1.23×10^{-4}

are 16.7%, 17.4% and 13.3% for Mono13, Mono24 and Poly6, respectively. These values indicate that the output terminals were prepared satisfactorily.

The I-S measurements were performed using the same equipment and testing conditions described in section 2. The solar cells were tested in dark and under 1 sun. The obtained I-S curves are similar to these presented in figures 1(a) and (b). The photovoltaic parameters of the solar cells were extracted from I-S curves using NOVA software. The curve fitting for the measurements in dark was performed using usual fitting procedure. While the curve fitting for the measurements under 1 sun involves initially identifying the high-frequency data points that forms a smooth curve, and then perform curve fitting using these points only. The test was repeated 10 times for each solar cell and the average values and the relative standard deviations are presented in table 1.

The results in table 1 show clearly that the repeatable results were obtained for the I-S tests under 1 sun, even though the I-S data appeared to be vastly scattered. Compared to the results obtained in dark, the standard deviations are larger for the tests under 1 sun. This is expected because the photovoltaic parameters were extracted from curve fitting that uses only high frequency part of the curves, which are still affected by the noise to some extent. Nevertheless, it enables extraction of photovoltaic parameters with acceptable repeatability. The results also show that the photovoltaic parameters extracted from Mono13 and Mono24 are broadly similar, but they are noticeably different from these of Poly6. This is because Mono13 and Mono24 are monocrystalline solar cells while Poly6 is a polycrystalline solar cell with a lower nominal PCE compared to monocrystalline counterparts. Furthermore, some parameters such as R_{sh} and ω_c obtained in dark are significantly different from these obtained under light illumination. The results demonstrate the usefulness of the I-S measurements under light illumination.

The unique advantage of the I-S measurements is its ability to determine the junction capacitor, C_D, and the center frequency, ω_c, of solar cells, relating to their a.c. properties. Although the solar cells always operate in the d.c. mode, the a.c. parameters can provide valuable insights into the dynamics of charge carriers of the solar cells. Since the frequency response of charge carriers is governed by the same mechanisms that controls charge carrier decay in transient process, the time constant, τ, of the decay that is defined as the lifetime of the photogenerated charge carriers can be calculated from the center-frequency, ω_c, of the I-S measurements using the relation of $\tau = 1/\omega_c$. Table 1 lists the results for three silicon solar cells investigated in this work. The lifetime of photogenerated charge carriers is 372 μs to 498 μs for Mono13 and Mono24, respectively, which broadly agree with the published data [18]. The lifetime of polycrystalline solar cell (Poly6) is expected lower due to charge recombination at grain-boundaries. The value determined from this work is 123 μs, providing further evidence of the validity of this method. Although the lifetime can be derived from the I-S measurements in dark, the values are nearly an order of magnitude higher, which do not represent the true values of the solar cells in operation because there is no photocurrent generated in dark. Clearly, the charge carrier lifetime should be determined under actual operating conditions and hence, the importance of I-S measurements under light illumination.

5. Conclusions

This work demonstrates a feasibility of achieving reliable photovoltaic parameter extraction from severely scattered I-S data obtained from measurements under light illumination. It was found that a valid curve fitting of I-S data is possible using the part of the data hidden in the scattered plots. Theoretical analysis confirmed the validity of this approach, which reveals that a genuine part of I-S curve can be identified over a high frequency range because the signal-to-noise ratio of the response current in the I-S measurements increase with increasing the frequency of the excitation voltage. Upon this finding, the method was employed to evaluate the photovoltaic properties of three commercial silicon solar cells. The results show that the photovoltaic parameters can be extracted with acceptable repeatability from vastly scattered experimental data. The unique advantage of the I-S measurements is to provide useful insights on dynamic properties of the photogenerated charge carriers. This work demonstrates the importance of the I-S measurements under light illumination because their photovoltaic properties, such as the charge carrier lifetime, are significantly different from those measured in dark. In addition, the work also provides a possibility to estimate the noise level in solar cells.

The results of this work were obtained from silicon solar cells, but the technique should be applicable to other types of solar cells if the data scattering also occurs under light illumination. However, the technique should be used with caution because the data fitting is based on only the part of the I-S plots. It is valid for most solar cells that exhibit a semi-circle in the I-S plots. For a few other types of solar cells, such as dye sensitized solar cells, their I-S plots might exhibit more than one semicircle and their properties associated with the low frequency range may not be retrievable using this method because the poor signal-to-noise ratio over the low frequency range. Nevertheless, their properties corresponding to high frequency can still be reliably extracted because the pattern formed over this range represents the true characteristics of the solar cells.

Data Availability Statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Conflict of interest

The authors declare no conflict of interest.

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