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Research Article

Shockley's Equation Fit Analyses for Solar Cell Parameters from I-V Curves

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Some of the technical problems that appear are obtaining solar cell parameters from I-V curve measurement data. One simple method is using linear graphical fit at zero current or voltage conditions. Although the accuracy of the obtained values is acceptable, other problems may arise regarding the number of parameters which could be obtained. We report a comparison between manual or graphical fit and fit using Shockley's equation. The single I-V curve under the lighting was inferred to obtain the intrinsic parameters of the solar cells' performance. The fittings were performed using the nonlinear equation of Shockley by determining some initial values of fittings such as R_s, R_{sh}, n, I_0, I_{ph}, and T. In the case of the Shockley equation fit, the iteration was performed several times to obtain the least possible inferred parameters. We have successfully obtained a better result of nonlinear Shockley fitting compared to the manual linear fit.

1. Introduction

Rapid growth in science, technology, and industry has increased electric energy needs. About 87% of the world's energy consumption comes from fossils (oil, natural gas, and coal) which are a natural resource that cannot be renewed and lead to negative impact on the environment [1]. Therefore, developing electric energy from other natural resources which is eco-friendly is urgently required, such as the development of electric energy from solar energy [2]. Technically, solar energy can be converted into electric energy with a solar cell [3]. The solar cell is a device for green and clean electric power generation from solar energy. Solar cells have continued to evolve from single crystal silicon, thin film, organic solar cell, dye-sensitized solar cell (DSSC), and perovskite solar cell (PSC). Solar cell performance is continuously studied to raise conversion efficiency and capacity.

So far, the developing solar cell efficiency has been performed by improving the materials [4], construction [5, 6], contact systems [7], and characterizations [8, 9]. The solar cell optimization could also be optimized for analysis and modeling. One model for solar cell analysis is proposed based on the Shockley diode model. The analysis model of the solar cell from I-V characterization is with or without illumination.

One model for analyzing solar cell work is the single-diode model shown in Figure 1. At a given illumination, the

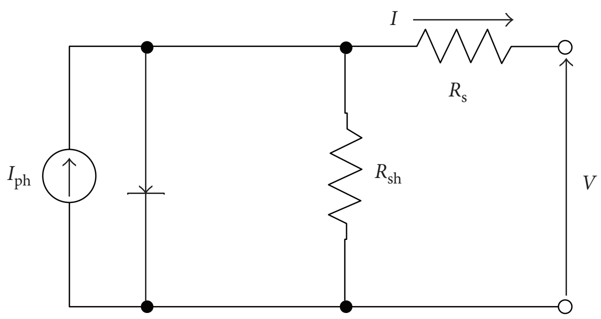


FIGURE 1: Single-diode model for a solar cell.

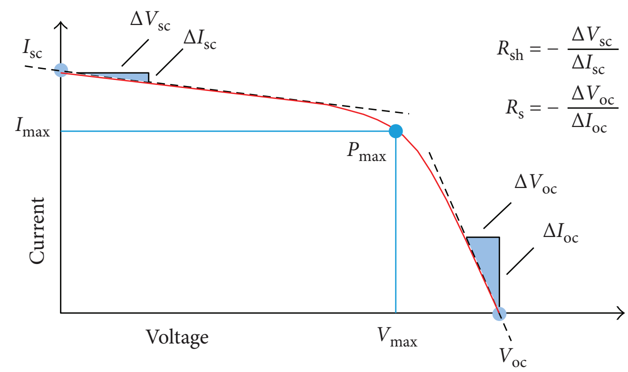


FIGURE 2: Series and shunt resistance extraction from a single I-V curve under illumination.

current/voltage relationship is given by (1) from the Shockley equation.

$$I = I_{ph} - I_0 \left[\exp\left\{ \frac{q(V + R_s I)}{nk_B T} \right\} - 1 \right] - \frac{V + R_s I}{R_{sh}}, \quad (1)$$

where I_{ph}, I_0, R_s, R_{sh}, q, n, k_B, and T are the photocurrent, the saturation current of the diode, the series resistance, the shunt resistance, the electron charge, the ideality factor, the Boltzmann constant, and the temperature, respectively.

The parameters in (1) correspond to the intrinsic characteristic of solar cell construction. The series resistance R_s represents the total resistance of the cell and is a composite of (1) the interfacial and active layer resistances, (2) the electrode resistances, and (3) the various contact and interconnect resistances [10]. The shunt resistance R_{sh} represents the p-n junction solar cell [11]. Parameters R_s and R_{sh} correspond to the fill factor (FF) of energy conversion in the solar cell.

$$\text{FF} = \frac{I_{max} V_{max}}{I_{sc} V_{oc}} \quad (2)$$

Decreasing R_s makes I_{sc} and V_{max} increase, and increasing R_{sh} makes V_{oc} and I_{max} increase [11, 12]. Many researchers develop solar cell trough variation R_s [10] and R_{sh} [13, 14]. The ideality factor n is related to the diode and its recombination [15]. In the case of $n = 1$, it represents a perfect crystalline structure with no structural defects [16]. The value of $n > 2$ is associated with the tunneling effect or the reduction of mobility due to the defects or less crystalline material [15].

The intrinsic solar cell parameters have been extracted from any method, such as a manual method with ideality factor approximation [17]. So, R_s and R_{sh} values correspond to the slope near V_{oc} and I_{sc}, respectively. By using this technique, many other parameters have not been found, such as I_{ph}, I_0, and n. Many researchers have done extraction of the solar cell parameter from the I-V curve. The parameters from (1) were extracted using the nonlinear fitting technique on a single I-V curve [18, 19]. However, the stability of the extraction results is difficult to achieve. Therefore, to extract the solar cell parameters like I_{ph}, I_0, R_s, R_{sh}, and n, the orthogonal distance regression with implicit equation model of the Shockley equation using origin lab was implemented.

2. Materials and Method

Data analysis technique on the I-V curve solar cell was needed to prove solar cell performance. Analysis of the I-V characteristic curve was done using the single-diode model equivalent circuit as shown in Figure 1 and (1). The intrinsic parameters of the solar cell were extracted using manual linear and nonlinear fitting methods using orthogonal distance regression.

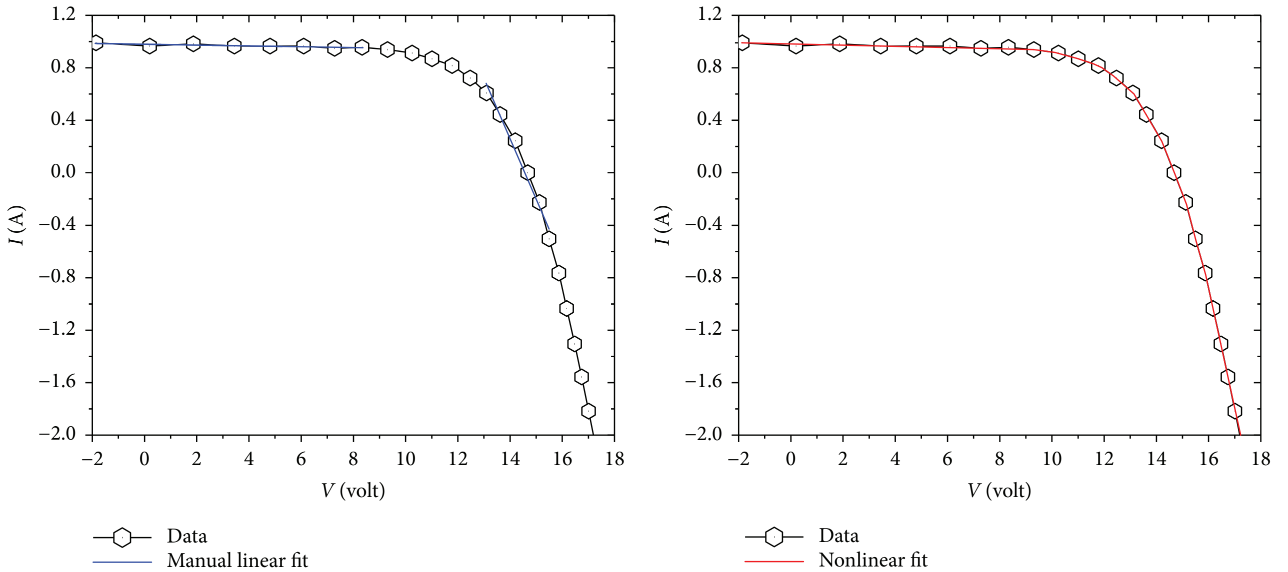
The essential parameters of the solar cell based on the single-diode model was analyzed using the manual method with ideality factor value approximation [17]. Figure 2 shows how to determine the series resistance (R_s) and shunt resistance (R_{sh}) from an inverse slope near the V_{oc} and I_{sc}, respectively [17, 20].

The nonlinear fit was done using orthogonal distance regression using implicit model function (1) with origin lab. The initial value of the parameters was determined from the manual method for R_s and R_{sh}. The regression was done using about 500 iterations on the I-V curve until the best fit between the model and experimental data is obtained. By using this procedure, we found the intrinsic solar cell parameters of I_{ph}, I_0, R_s, R_{sh}, and n.

3. Results and Discussion

The comparison manual and nonlinear fittings of the I-V curve solar cell were applied to any solar cell generation. The comparison of two different equations was performed to know the effectivity for obtaining solar cell parameters based on the single-diode model. The intrinsic solar cell parameters were used to optimize the solar cell conversion efficiency.

3.1. Application to Silicon Solar Cell. The first result of the solar cell parameters of a silicon solar cell (R.T.C France) [21] using two different equation is presented. Figure 3 shows a comparison between the manual and nonlinear methods. It is observed that the linear method only fits in a particular area. Both the linear (solid blue line) and the nonlinear (solid red line) agree with experimental data



(a) (b)

Figure 3: Curve fit on a silicon solar cell (R.T.C France) using the manual method (a) and the nonlinear curve fit using the Shockley equation (b).

Table 1: Comparison of manual and Shockley nonlinear fit on any solar cell. The Δ is from reference while χ^2 is from this work.

Number	Solar cell	V_{oc} (V)	I_{sc} (A)	I_{ph} (A)	I_0 (μA)	R_s (Ω)	R_{sh} (kΩ)	n	T (°C)	Δ/χ^2
	Cell Si (R.T.C France) [21]	0.5728	0.7608	0.7608	0.3223	0.0364	0.0538	1.484		8.9×10^{-7}
1	Manual	0.567	0.758	—	—	0.11	0.0324	—	33	—
	Previous work [18]	0.57	0.76	0.77	0.2	0.037	0.032	1.4		5.6×10^{-7}
	Nonlinear fit	0.568	0.758	0.7595	0.186	0.047	0.0355	1.418		2.9×10^{-6}
	Module Si (Photowatt-PWP-201) [21]	16.778	1.03	1.0318	3.2876	1.2057	0.549	48.45		8.3×10^{-6}
2	Manual	14.57	0.979	—	—	2.196	0.312	—	45	—
	Previous work [18]	17	1	1	2.3	1.3	0.83	47		6.3×10^{-6}
	Nonlinear fit	14.69	0.979	0.98	10	0.518	0.404	46.83		7×10^{-5}
	Organic solar cell: ITO/CuPc/PTCBI/Ag [22]	—	—	—	—	—	—	—		—
3	Manual	1.203	0.00449	—	—	78.59	1.222	—	20	—
	Previous work [18]	1.2	0.0046	0.0047	0.92	48	1.4	5.8		1.1×10^{-3}
	Nonlinear fit	1.204	0.00449	0.00468	0.918	48.34	1.232	5.74		3.13×10^{-10}
	Organic solar cell-based p-type NiO: glass/ITO/NiO/P3HT:PCBM/LiF/Al [23]	—	—	—	—	—	—	—		
4	Manual	0.638	0.0113	—	—	6.468	1.757	—	27	—
	Previous work [10]			0.0117	0.365	1.4	3.96	2.38		—
	Nonlinear fit	0.6406	0.0113	0.0113	0.0747	2.196	2.438	2.08		3.2×10^{-9}
	Perovskite solar cell: mp-TiO_2/CH_3NH_3PbI [9]	—	—	—	—	—	—	—		—
5	Manual	0.944	0.018	—	—	8.687	0.503	—	27	—
	Nonlinear fit	0.938	0.018	0.0182	0.0558	1.115	0.513	2.87		6.36×10^{-8}
	DSSC [8]	0.704	0.00206	—	0.035	43.8	3.736	2.5		—
6	Manual	0.708	0.002	—	—	93.27	3.532	—	20	—
	Nonlinear fit	0.702	0.00206	0.0021	0.0345	38.55	3.402	2.55		1.4×10^{-10}

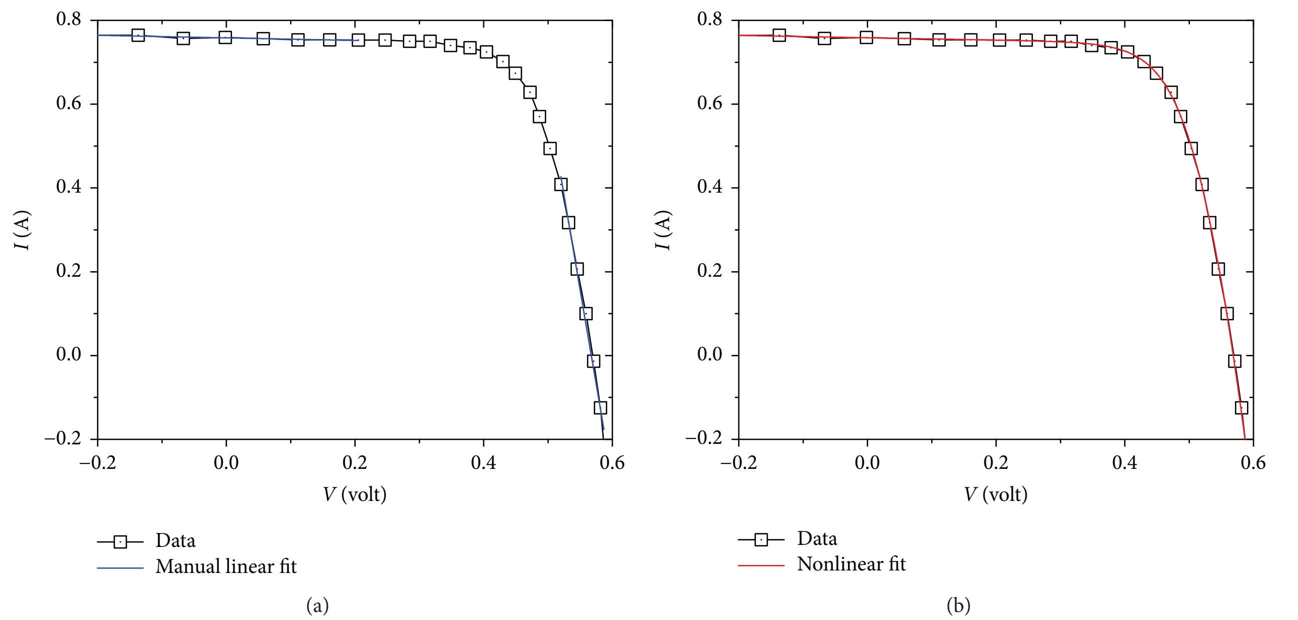


Figure 4: I-V curve fit on a silicon solar cell module (Photowatt-PWP-201) using the manual method (a) and nonlinear curve fit using the Shockley equation (b).

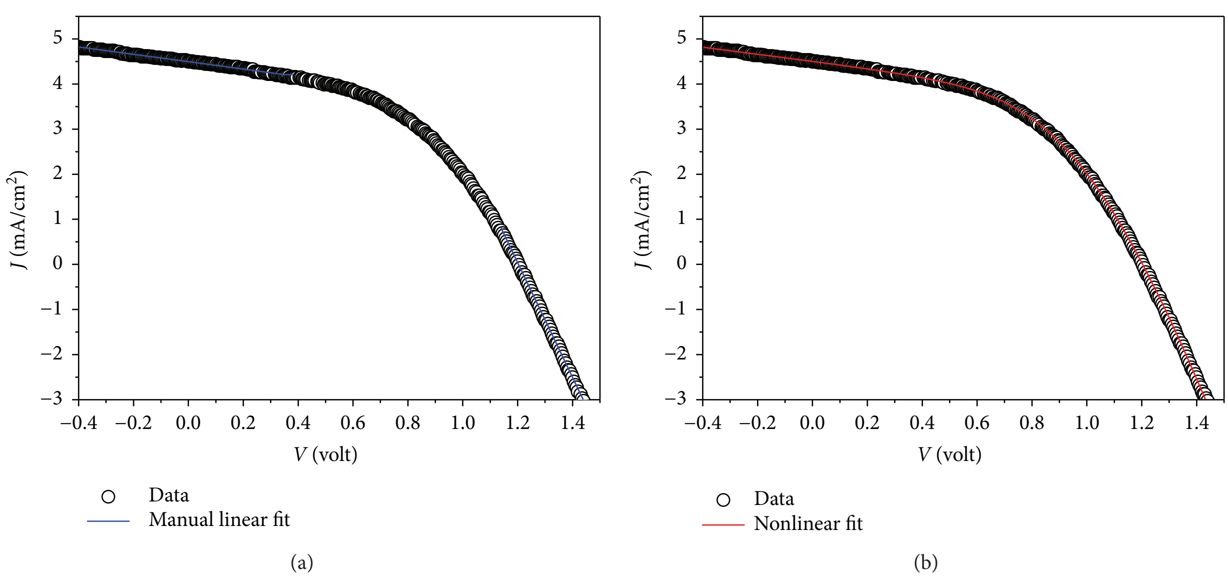


Figure 5: I-V curve fit on an organic solar cell based on ITO/CuPc/PTCBI/Ag: (a) manual method and (b) nonlinear curve fit.

of the I-V curve. Table 1 shows the result of the comparison of any extraction method.

Figure 4 shows the result of the I-V curve fit on a silicon solar cell module (Photowatt-PWP-201) [21]. It shows that the nonlinear fit method agrees with experimental data of the I-V curve and previous work.

3.2. Application to Organic Solar Cell. Comparison manual and nonlinear fit method on the I-V curve of an organic solar cell, ITO/CuPc/PTCBI/Ag [22], is shown in Figure 5. Not only silicon solar cell but also organic solar cell parameters can be extracted using nonlinear fit using orthogonal distance regression. Table 1 shows the result of comparison of any extracted method and the previous work.

The comparison manual and nonlinear curve fit applied to other organic solar cell-based p-type NiO, glass/ITO/NiO/P3HT: PCBM/LiF/Al [23], is shown in Figure 6. It shows suitability between the experimental data and nonlinear fit.

3.3. Application to Perovskite Solar Cell. Not only silicon and organic solar cells but also a perovskite solar cell I-V curve can be used to compare the manual and nonlinear curve fit based on the Shockley equation. Figure 7 shows the

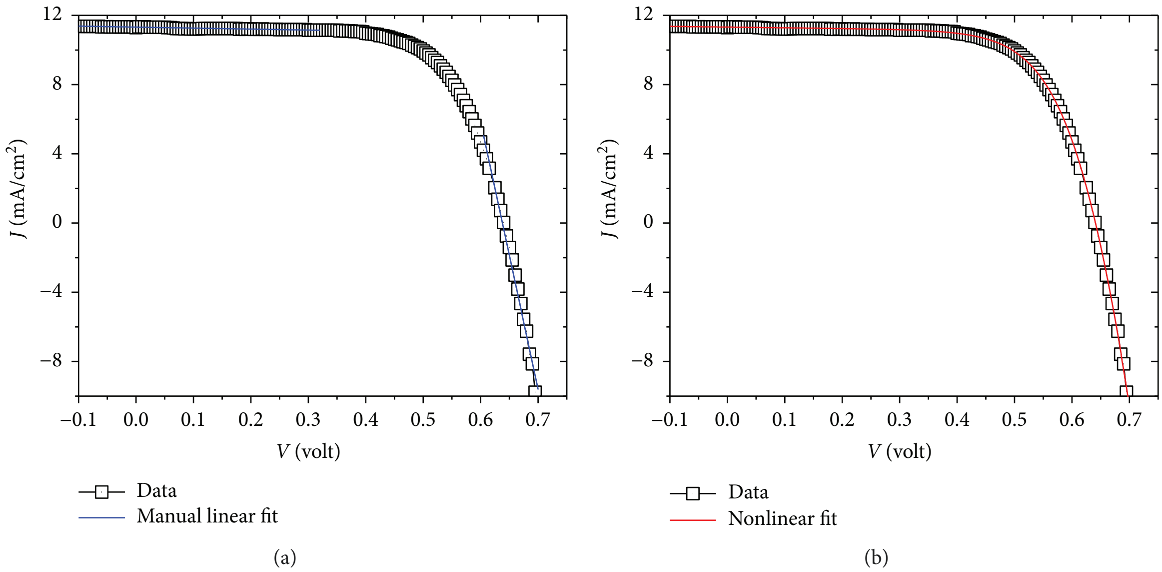


Figure 6: Organic solar cell based on p-type NiO: (a) manual method and (b) nonlinear curve fit.

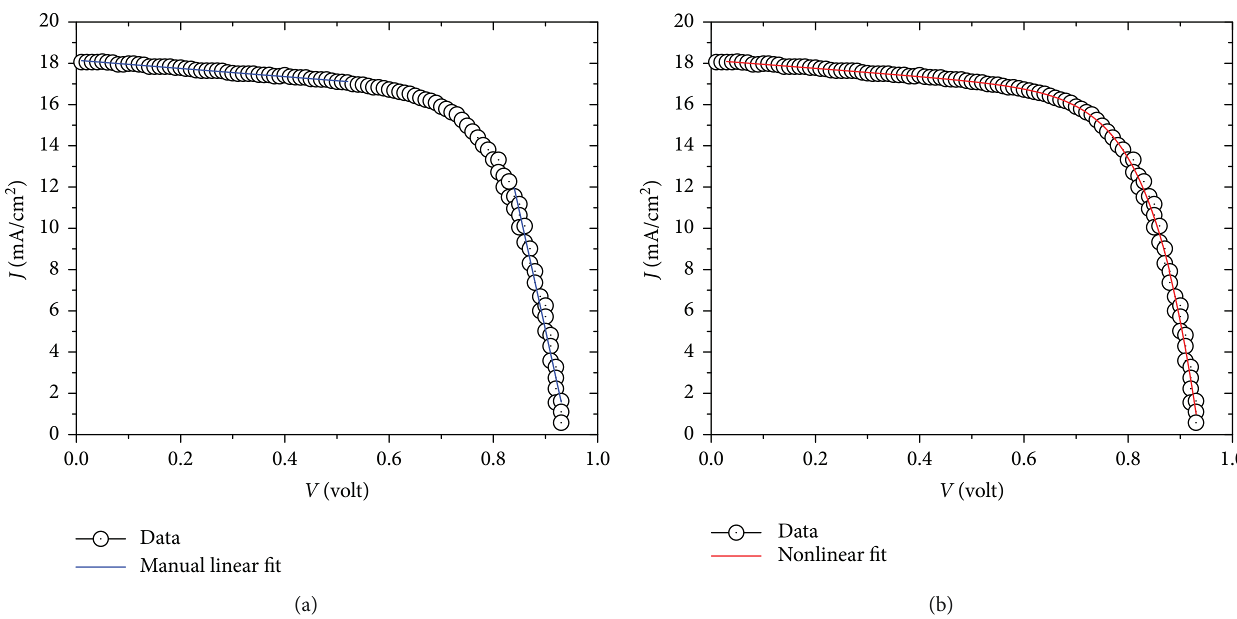


Figure 7: Fitting I-V curve perovskite solar cell based on mp-TiO_2 with CH_3NH_3PbI: (a) manual fit and (b) nonlinear curve fit.

comparison between experimental data and fitting method on a perovskite solar cell. Table 1 shows the result of the fitting method for perovskite solar cell parameters. The parameter of PSC can be used to upgrade solar cell conversion efficiency based on mesoporous TiO_2 and CH_3NH_3PbI [9].

3.4. Application to DSSC. The manual and nonlinear fit methods are applied to extract solar cell parameters on DSSC with TiO_2 as the photoanode and ruthenium as the sensitizer [8], and the results are shown in Figure 8. The I-V curve fit result of the DSSC parameter is shown in Table 1. The analyses of carboxyl effects on the TiO_2 photoanode has been studied using a single-diode model. The analyses were performed by determining DSSC intrinsic parameters in terms of carboxyl effects. It was found that the use of carboxyl acid gives rise to reducing the R_s value, which indicates the increase of electrical contact among TiO_2 particles [8].

4. Conclusion

The application of manual and nonlinear fit methods on any solar cell single I-V curve has been performed. The nonlinear

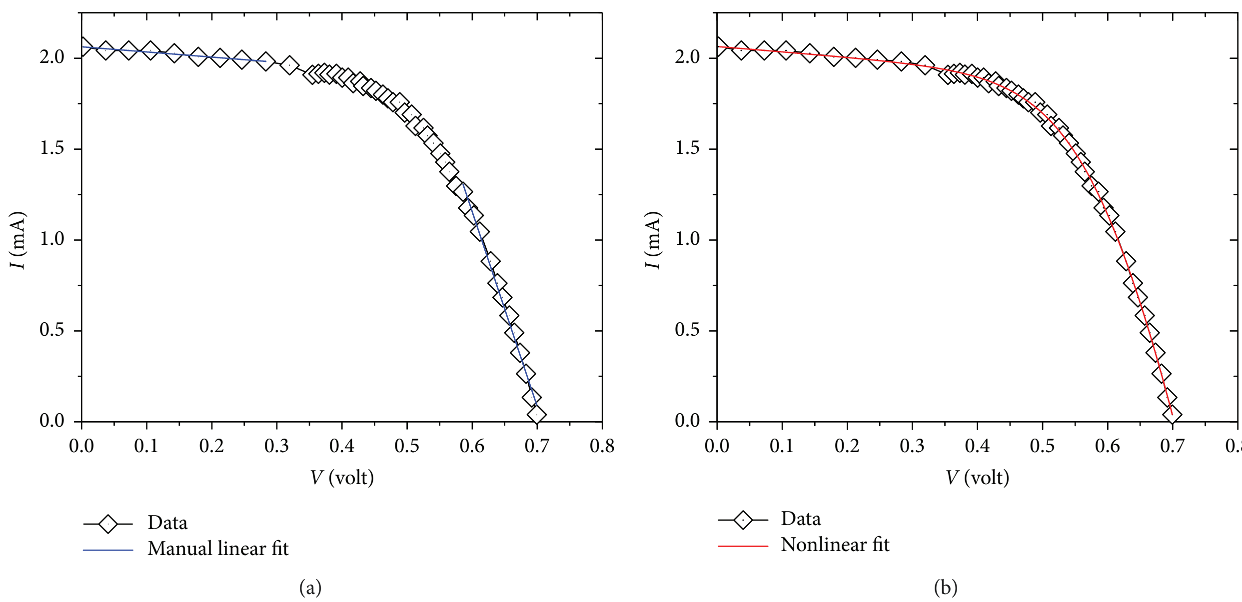


Figure 8: I-V curve fit of DSSC: (a) manual method and (b) nonlinear curve fit.

fit using Shockley's equation by employing orthogonal distance regression produces more solar cell parameters. It is also demonstrated that operating the nonlinear Shockley equation to several solar cell systems is highly agreeable with experimental data compared to the manual linear method.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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