

Inexpensive Current-Voltage System with Electronically-Controlled Resistance under Xenon Arc Light for Solar Cell Efficiency Measurements

(Sistem Arus-Votan yang Murah dengan Rintangan Terkawal-Elektronik di bawah Lampu Xenon Arka untuk Pengukuran Kecekapan Sel Suria)

Mukhlis Mokhtar, Samir Ahmad, Suhaila Sepeai*, Norizam M. Daud & Saleem H. Zaidi
Solar Energy Research Institute, Universiti Kebangsaan Malaysia, Bangi, Malaysia
*Corresponding author: suhailas@ukm.edu.my

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ABSTRACT

Crystalline silicon solar cell efficiency is required in order to accurately determine its performance and evaluate the fabrication process. Extensive automation has led to development of expensive instrumentation. In this study, simple, inexpensive method for measuring solar cell efficiency is reported. A controllable direct current (dc) illumination intensity method based on low power xenon arc lamps was designed and constructed. Low resistance electrical contacts were formed with conventional front surface probes and back surface Au-plated metal plate with vacuum attachment. In order to measure current-voltage (I-V) response, variable resistance approach was chosen. Commercially available, low cost electronic loads power supply is used to precisely vary resistance while measuring cell voltage and current. The resistance is controllably varied from a short circuit to an open circuit position on the I-V curve while measuring cell voltage and current. Plotting current as a function of voltage generates the characteristic solar cell I-V response. Solar cell efficiency measurements were recorded and plotted using LabVIEW program. The light intensity was varied by increasing number of high intensity discharge (HID) 50 W from 1 to four in order to vary respective illumination intensities from 330 to 1200 W/m² range. The variation in light intensity was aimed at investigation of the electronic loads power supply at low and high currents. This I-V tester has been applied to different types of solar cell to validate its performance. Solar cells measured as part of this study included commercial silicon solar cell and laboratory solar cells with phosphorus oxytrichloride (POCl₃) and phosphoric acid (H₃PO₄) emitter formation. This I-V measurement system for commercial cell exhibited an efficiency of 15.83% and efficiency of 16.2% and 13.3% for solar cells with POCl₃ and H₃PO₄ emitters.

Keywords: Current-Voltage; DC Light; Electronic Load; Solar Cell; Testing

ABSTRAK

Kecekapan sel suria silikon kristal diperlukan untuk menentukan prestasi peranti secara tepat dan mengesahkan proses fabrikasinya. Dalam pembuatan industri, automasi telah membawa kepada pembangunan peralatan yang mahal. Dalam kajian ini, satu kaedah yang mudah dan murah untuk mengukur kecekapan sel suria telah dilaporkan. Kaedah intensiti pencahayaan arus terus (dc) yang terkawal berdasarkan lampu arka xenon berkuasa rendah telah direka dan dibina. Sentuhan elektrik berkerintangan rendah dibentuk dengan prob permukaan hadapan yang konvensional dan permukaan belakang dengan plat logam bersalut Au yang bervakum. Untuk mengukur tindak balas arus-voltan (I-V), pendekatan pada pengubahsuaian rintangan telah dibangunkan. Rintangan telah divariasikan dari litar pintas ke kedudukan litar terbuka pada lengkung I-V semasa mengukur voltan sel, dan ciri I-V yang terhasil adalah berdasarkan hukum Ohm. Ini boleh dicapai dengan menggunakan bekalan kuasa elektronik murah yang boleh didapati secara komersial. Pengukuran kecekapan sel suria direkodkan dan diplot menggunakan program LabVIEW. Keamatan cahaya telah divariasikan dengan menambah bilangan pelepasan keamatan tinggi (HID) 50W dari satu ke empat lampu bagi mengubah keamatan pencahayaan dari 330 ke 1200 W/m². Variasi bagi keamatan cahaya telah dilakukan untuk mengkaji bekalan kuasa elektronik di arus rendah dan tinggi. Penguji I-V ini telah diaplikasikan pada jenis sel suria yang berbeza untuk mengesahkan prestasi penguji. Sel suria yang diukur sebagai sebahagian dalam kajian ini termasuklah sel suria silikon yang komersil dan sel suria makmal dengan pembentukan pemancar fosfor oksitriklorida (POCl₃) dan asid fosforik (H₃PO₄). Pengujian sistem pengukuran I-V ini ke atas sel suria komersial menunjukkan kecekapan 16% dan kecekapan 16.2% dan 13.3% bagi sel suria dengan pemancar POCl₃ dan H₃PO₄.

Kata kunci: Arus-Voltan; Lampu DC; Beban Elektronik; Sel Suria; Pengujian

INTRODUCTION

Solar energy represents an ideal solution for alternative and sustainable energy source since it is the cleanest, ubiquitous, and climate-friendly energy resource to replace fossil fuel energy (Mat Nong et al. 2016). It is estimated that fifteen thousand ExaJoule ($1 \text{ EJ} = 10^{18} \text{ J}$) of solar energy are available in the atmosphere per year (Sakib & Ahad 2018).

Crystalline silicon solar cells convert sunlight into electricity. Absolute conversion efficiency of a solar cell is measured by characterizing its current-voltage response under standard one-sun illumination condition described either by AM1.5 G or 1000 W/m^2 (International Standard, 2006). In order to accurately measure current-voltage (I-V) response of the solar cell, light source, the electrical contacts to the solar cell and the I-V measurement system are required. A wide range of solar cell I-V measurement techniques have been developed including variable voltage, variable current, variable resistor, capacitive load, electronic load, bipolar power amplifier, fourth quadrant power supply, DC-DC converter, and more recently DAQ and Python based measurement was investigated (Duran et al. 2008; Reyes-Ramirez et al. 2018).

In this study, for electrical contact, the front contact is formed with an electronic probe and back contact with gold-plated Al plate vacuum holes for intimate contact to the backside of the solar cell. The other two systems were developed and described in some details in the following paragraph.

A solar cell is simply a large area diode. Its current voltage response under illumination is described by plotting current a function of voltage in the fourth quadrant (Figure 1). For an ideal solar cell without any resistance, maximum power will be produced in the yellow region. However, due to resistances and material imperfections, the I-V response follows a curved line shape described by the red line in Figure 1. The efficiency of the solar cell is simply determined by the ratio $P_{\text{OUT}}/P_{\text{IN}}$, where P_{OUT} is the measured solar power and P_{IN} is incident illumination power (Cojocaru et al. 2017). The maximum power is achieved at a point often referred to as the maximum power point (MPP) at which the product $P = V \cdot I = V_M \cdot I_M$ is at its maximum value (Mayer & Powell, 2011). The solar cell fill factor (FF) is defined by

$$FF = \frac{V_M \cdot I_M}{V_{OC} \cdot I_{SC}} \quad (1)$$

where V_{OC} and I_{SC} respectively represent points on the I-V curve at which no current flows through the circuit (open-circuit) and no applied voltage exists across the solar cell (short-circuit current). The response of V_{OC} and I_{SC} that fills the rectangle gives an indication of the quality of a cell's semiconductor junction and measures of how well a solar cell is able to collect the carriers generated by light (Kandil et al. 2011). Solar cell efficiency (η) is related to FF by

$$\eta = FF \cdot V_{OC} \cdot I_{SC} / P_{IN} \quad (2)$$

The incident power is related to the area of the solar cell. For example, for 100 cm^2 area solar cell at 1-sun illumination, P_{IN} would be 10000 mw or 10 W.

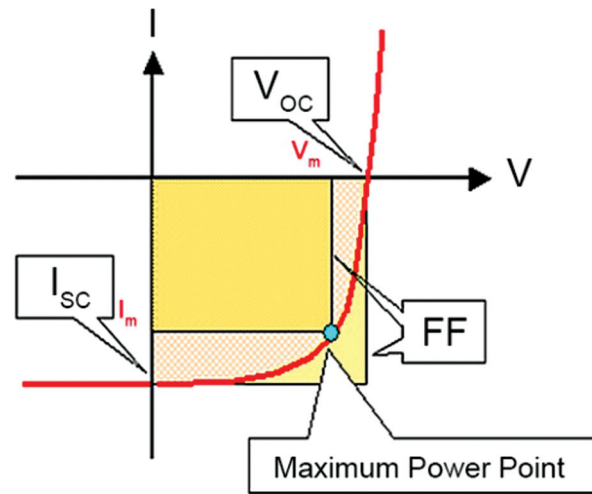


FIGURE 1. Current voltage response of a solar cell under light

METHODOLOGY

LIGHT ILLUMINATION SYSTEM

For indoor measurements, light sources with spectral content closest to the sunlight are used; xenon arc lamps are the closest and most commonly used as the illumination source (International Standard 2016). For solar cell testing system described here, xenon arc lamps operating in continuous dc mode have been investigated. In order to vary incident intensity, five identical lamps are arranged in a quasi-collimated pentagonal reflector configuration described in Figure 2(a). Figure 2(b) shows a picture of all five illuminated lamps in the reflector pointing down at the solar cell under testing; each of the five lamps is individually controllable. Figure 3 illustrates the entire solar cell testing configuration. Solar cell is placed on a conductive Au-plated metallic vacuum chuck to firmly hold the solar cell. Bottom electrical contact to the solar cell is formed through the solar cell holder, the top electrical contact is formed through the conductive probe tips; both are connected electrically to form a single contact.

Incident light intensity is controllable over a broad range ($\sim 50 \text{ mW/cm}^2$ to 150 mW/cm^2) range by simply turning lamps on and off. The solar cell response as a function of light intensity is described in Figure 4. As light intensity increases, the solar cell current (I_{SC}) increases linearly, the increase in V_{OC} is not as strong.

CURRENT VOLTAGE MEASUREMENT SYSTEM

There are three conventional methods for characterization of solar cell LIV response. In the first approach, a programmable voltage source is used to source voltage and measure current

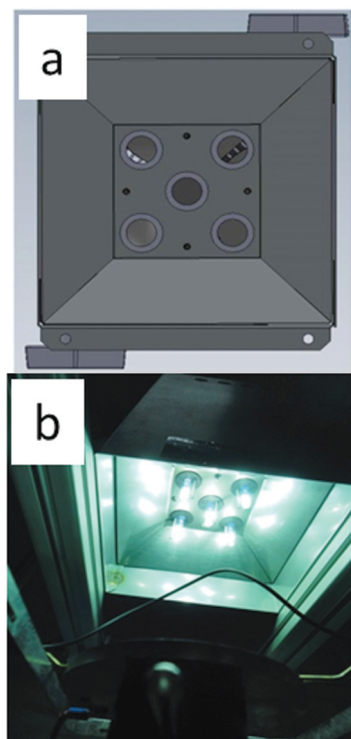


FIGURE 2. (a) Five-lamp pentagonal reflector configuration and (b) all five lamps in operation

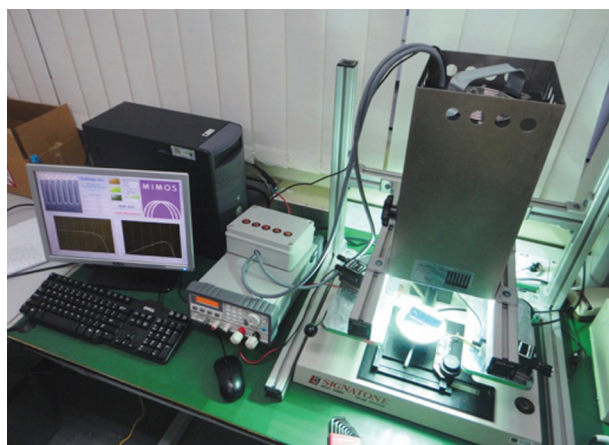


FIGURE 3. Complete DC I-V measurement system

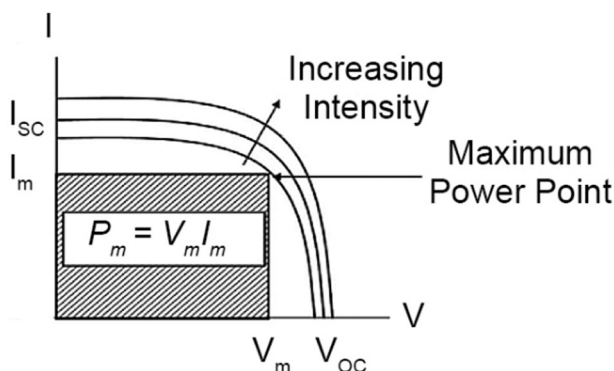


FIGURE 4. Light current-voltage (LIV) response of a solar cell as a function of increasing light intensity

across an external load. A low impedance voltage source can be used; however, it can become unstable for highly capacitive junctions (Application Note 2017). The second approach is based on a programmable current source to supply current and measure voltages (Buanossissi 2011). This method tends to increase measurement time since at low currents; it takes longer to vary cell capacitance. This approach can also lead to noisy measurements at the flat part of the I-V curve (upper left region in Figure 4). Both these approaches require expensive, high resolution power supplies with the ability to source and sink current.

Here, third approach based on a variable resistance load across has been investigated (Figure 5). At any given incident illumination, if the resistance is varied from a short circuit to an open circuit position on the I-V curve in Figures 1 & 4 while measuring cell voltage and current, the characteristic I-V is generated by plotting current as a function of voltage. This can be conveniently accomplished with inexpensive commercially available electronic load power supply (www.bkprecision.com). An electronic load is simply a programmable power supply that applies a voltage but sinks current rather than sourcing it. By changing the current direction, the electronic load electrically looks like a programmable resistor rather than a programmable voltage source. Electronic load most commonly use Field-effect transistor (FET) to act as a variable resistor. Internal circuitry in the equipment monitors the actual current through the FET, compares it to a user-programmed desired current, and through an error amplifier changes the drive voltage to the FET to dynamically change its resistance. Electronic loads are ideal solution for solar panel testing under constant light source due to their wide power range and ability to sink large amounts of current. These are not often used for solar cell testing. Electronic loads typically have four modes of operation: constant current (CC), constant voltage (CV), constant resistance (CR), and constant power (CP). The conventional practice for electronic loads is to use CC loading for devices that are by nature voltage sources and conversely use CV loading for devices that are by nature current sources. Therefore, CV mode is the preferred mode of operation for solar panel I-V curve tracing because it allows user to step through voltages incrementally and measure the current output of the solar panel under test. The electronic load sets the internal voltage equal to the V_{oc} of the solar cell in order to achieve zero current through the external circuit. Subsequently, the electronic load decreases the

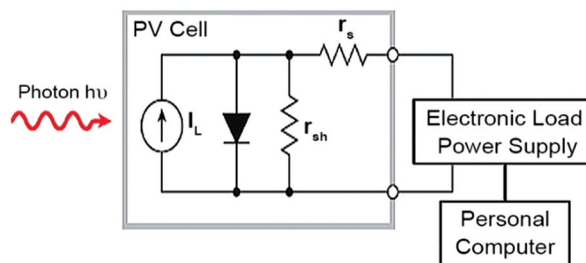


FIGURE 5. Solar cell LIV characterization system based on an electronic load power supply

internal voltage and measure the voltage (V) and current (I) from the solar cell. The measurement loop continues until maximum current flows through the circuit at which point V_{OC} becomes zero. A real-time LabVIEW programming based on serial communication are design in this project to records and plots all the acquired data from electronic load power supply. Others setup use resistive load banks and external microcontroller or DAQ LabVIEW interface as a medium to acquire data (Chokri Belhadj Ahmed et al. 2013).

PC1D SIMULATION

PC1D simulation software was used to simulate performance of solar cell in order to compare with the efficiency of measured solar cells. The simulation was carried out for p-type silicon solar cell with fixed series resistance, shunt conductance, and 200- μm wafer thickness. Pyramidal texture was assumed with fixed 10 % front surface reflectance. Base contact and internal conductor were respectively set at 0.0015 Ω and 0.3 S. Bulk conductivity concentration was $1.513 \times 10^{16}/\text{cm}^3$. The front surface emitter doping concentration was set at $1.27 \times 10^{17}/\text{cm}^3$. The minority carrier lifetime was set at 100 μs . Finally, the front surface recombination velocity was set at 1×10^6 cm/s (Sepeai et al. 2013).

RESULTS AND DISCUSSION

Figures 6 (a) to 6 (c) plot solar cell I-V data as a function of increasing intensity for a commercially manufactured 16% efficiency for 18- cm^2 area solar cell. The plotted data in Figures 6 record all the measured solar cell parameters including series and shunt resistances from which solar cell efficiency parameters can be deduced. Table 1 summarized the commercial cell performances at three different light intensities, which were 330, 660 and 1200 W/m^2 . The current response is linear as the incident illumination intensity increases from 0.199 to 0.783 A; the V_{OC} increases from 0.577 to 0.617 V. The response of the 16 % commercial solar cell to one, three, and four lamps corresponds to respective illumination intensities of 330, 660 and 1200 W/m^2 were produced the efficiency of 13.8 %, 17.17 % and 15.83%. This result indicates that this system works best at three lamps since the efficiency produced was near to the benchmark of standard cell.

Figure 7 describes application of this solar cell tester with three lamps (1200 W/m^2) to fabricated solar cells. Figure 7 plots the I-V response of solar cells fabricated with POCl_3 (Figure 7(a)) and phosphoric acid (H_3PO_4) doped solar cells (Figure 7(b)). The red line in these measurements represents simulation of the LIV data using commercially available PC1D software; black line is experimental measurement. Excellent agreement is observed between theory and experiment; the POCl_3 -doped efficiency at 16.2 % is significantly higher than phosphoric acid at 13.8 %; the

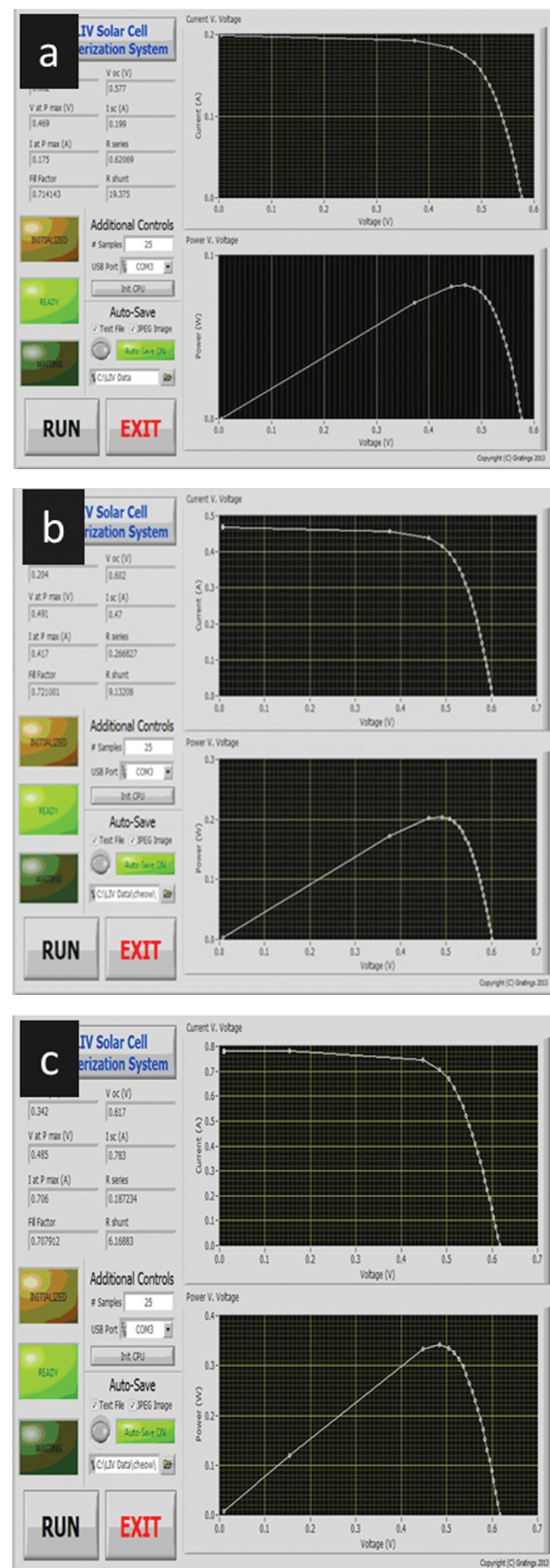
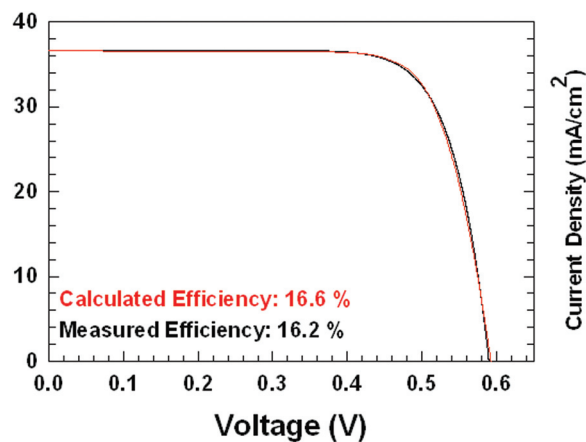


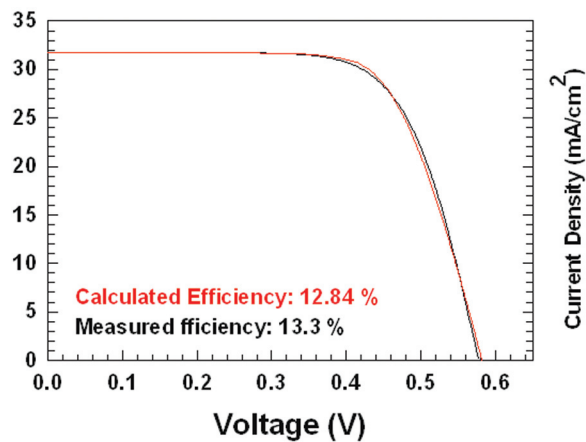
FIGURE 6. Current-voltage response of 16 % efficiency commercial cell 1 (a) one lamp, (b) 3 lamps and (c) 4 lamps

TABLE 1. Performance of commercial cell at three different light intensity

Xenon Arc Lamp Quantity	1	3	4
Intensity (W/m ²)	330	660	1200
P _{max} (Watt)	0.082	0.204	0.342
V _{oc} (V)	0.577	0.607	0.617
I _{sc} (A)	0.199	0.47	0.783
Fill Factor	0.71	0.72	0.70
Efficiency (%)	13.8	17.17	15.83



(a)



(b)

FIGURE 7. Light current voltage measurements of (a) POCl₃-doped and (b) phosphoric acid-doped solar cells

performance reduction is attributed to reduced passivation, poor minority carrier lifetime, and high reflection losses (Sepeai et al. 2013).

Table 2 summarizes the performance of commercial and fabricated cell measured by this inexpensive I-V measurement system. The comparison used the measurement by three lamps with light intensity of 1200 W/m². The comparison shows the good agreement with efficiency of ~16 % in commercial and fabricated cell with POCl₃ emitter. The fabricated cell

with phosphoric acid is typically lower than commercial as it used less-toxic and lower temperature process compared to the industrial process that used POCl₃ emitter. It is worth noting that phosphoric acid is often used in foods and soft drinks (Samir et al. 2017).

TABLE 2. Comparative evaluation of solar cell tested by

Solar Cell	Emitter	Efficiency (%)
Commercial	POCl ₃	15.83
Fabricated	POCl ₃	16.2
Fabricated	H ₃ PO ₄	13.3

In order to validate the results, the commercial solar cell has been tested on both commercial I-V tester (brand IVT-Solar) and these in-expensive electronic load I-V measurements. The comparison results were shown in Figure 8 and Table 3. At 16% efficient solar cell, V_{oc} should be above 0.6 V and J_{sc} value is above 34 mA/cm², therefore, comparing these two values, it appears that electronic loads able to produce comparable results with the commercial tester. Comparison of fill factor, shunt, and series resistances suggests that wafer testing in the electronics loads leads to higher shunts, which may be due to sample heating. Higher performance is also due to the lamps that been used and the resistance can be varied to obtain identical performance with commercial tester.

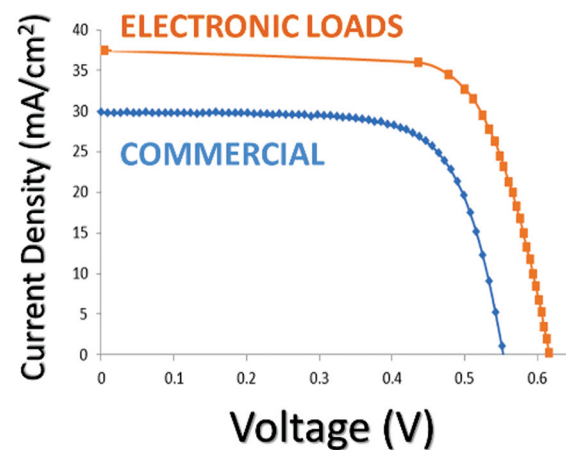


FIGURE 8. Comparison of commercial cell between commercial I-V tester and electronic loads I-V tester

TABLE 3. Comparison of commercial cell between commercial I-V tester and electronic load I-V Tester

Value	I-V Tester	
	Commercial	Electronic Load
JSC (mA/cm ²)	~ 30	~ 37
VOC (V)	~ 0.56	~ 0.58
Efficiency	~ 12.8 %	~ 16.7 %
Fill Factor	~ 73 %	~ 70 %
Shunt Resistance (Ohm)	~ 3581	~ 26
Series Resistance (Ohm)	~ 6	~ 1

CONCLUSION

A simple and inexpensive I-V characterization system based on resistance variation has been successfully demonstrated. In this low-cost system, incident intensity variation was achieved through individually controllable low power xenon arc lamps. This system has the inherent advantage of application to small as well as large area solar cells. In terms of cost, system only requires a low cost, easily available electronic loads power supply with a built-in LABVIEW interface. Xenon lamps are also easily available as they are used in automobile headline lamps. Application of this I-V tester to commercial and fabricated solar cells was successfully demonstrated. Further more, experimentally-measured I-V data was matched with PC1D simulations. Future work will focus on incorporation of a calibrated Si photodetector for absolute measurements and geometrical distribution of lamps to ensure intensity distribution over $156 \times 156 \text{ cm}^2$ areas. Additionally, the uniformity of the illumination system needs to be improved in further research.

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