P1 Solar Cell Research Exercise Report

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Abstract: The objective of this exercise was to explore the electrical characteristic of a silicon solar cell. The variation of illumination conditions explored during this exercise were light intensity and angle of incidence. By using current and voltage data collected under various light intensities, characteristics and performance of the solar cell were evaluated.

1. Introduction

Solar cells were commonly used as clean energy source. It is a photoelectric device that can convert the energy of light (photon) into electricity, without any pollutions.

The solar cell can be modelled as a diode with a current source, with parasitic shunt and series resistors as shown by Figure 1.

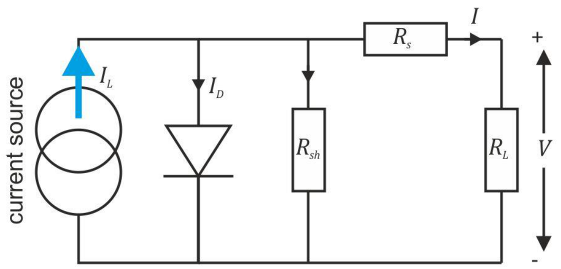

Figure 1: Solar cell modelling (adapted from [1])

The equipment used in this exercise was a $1\,\mathrm{cm}^2$ crystalline silicon solar cell with Peltier system for temperature control, a halogen bulb as light source with power density of approximately $0.3\,\mathrm{kW\,m^{-2}}$ at a distance of 15 cm, mounted on a mounting rail that can adjust the distance between light source and solar cell, and angle of incidence to the solar cell.

2. Baseline data acquisition and analysis

The Current-Voltage characteristics of the solar cell in baseline measurement conditions was measured firstly, as a reference for various illumination conditions.

The baseline measurement conditions was defined to be the lowest temperature, normal incidence and with the distance between light source and the solar cell approximately 10 cm apart.

2.1 Measurement

The *I-V* measurements were done by connecting a resistance box across output terminals of the solar cell, than measure voltages across the resistance box by using a digital multimeter. Voltage across the output terminals can be easily read directly from the multimeter, while current could be calculated by $I = \frac{V}{R}$ and power $P = VI$.

By taking measurements at various resistance, output current and power vs. output voltage curves was plotted from collected data as shown by Figure 2.

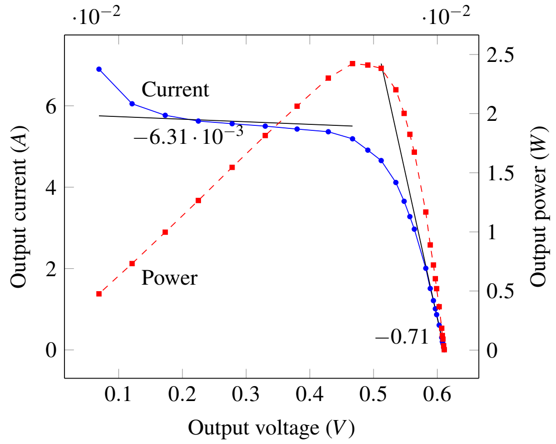

Figure 2: Output current, power vs. output voltage, in baseline measurement condition

2.2 Extract parameters

A few parameters extracted for analysis the characteristic of the solar cell, relative to Figure 2, which were:

Open circuit voltage V_{oc}, the voltage when load resistance connected across the output terminals became very large, shown by x-intercept on *I-V* curve, was 6.11 V.

Short circuit current I_{sc}, the current flow through shorted output terminals, shown by y-intercept on *I-V* curve. The peak on *I-V* curve near x-axis was caused by imprecise resistance of the resistance box at low resistance, a measurement shows when setting the resistance box to $1\,\Omega$, it was actually about $2.5\,\Omega$ measured by a digital multimeter. Therefore, ignoring first few measurements near x-axis, and following the trend of the curve, I_{sc} was approximately 5.5 mA.

Voltage and current when output power was at maximum, V_{mp} and I_{mp}. To extract them, the maximum power point need to be found firstly by plotting a Power-Voltage curve. As shown in Figure 2, $V_{mp} \approx 0.467\,\mathrm{V}$ and $I_{mp} \approx 51.9\,\mathrm{mA}$.

Fill factor, defined by (1), is a key parameter in evaluating solar cell performance. A higher fill factor means less power dissipated in internal losses. All values required to calculate were already known, the fill factor could be therefore calculated as $FF \approx 0.721$.

$$FF = \frac{I_{mp}V_{mp}}{I_{sc}V_{oc}} \tag{1}$$

2.3 Power efficiency

Power density of light from lamp related to distance as shown in (2).

$$P_l \propto \frac{1}{d^2} \tag{2}$$

From laboratory notes, the surface area of the crystalline silicon solar cell was $1\,\mathrm{cm}^2$, and assuming the halogen bulb has a power density of $0.3\,\mathrm{kW\,m^{-2}}$ at a distance of 15 cm apart.

Therefore, power density of light received by the solar cell was about $P_{in} = 0.3 \times 10^3 \cdot \frac{15^2}{10^2} \cdot (1 \times 10^{-2})^2 = 0.0675\,\mathrm{W}$.

Power efficiency was calculated as shown in (3).

$$\eta = \frac{P_{max}}{P_{in}} = \frac{V_{mp}I_{mp}}{P_{in}} = \frac{0.467 \times 0.0519}{0.0675} = 35.9\% \tag{3}$$

2.4 Conclusion

From National Renewable Energy Laboratory, the efficiency of best crystalline Si research-cells was $\sim 25\%$ [3], which means the value obtained above was not correct or very inaccurate.

Some possible source of inaccuracy could be the environmental light exist in the laboratory, higher power density of the halogen bulb than the assumed value, which led to a higher power density of light received by the solar cell than the value used in calculation.

3. Variation in intensity

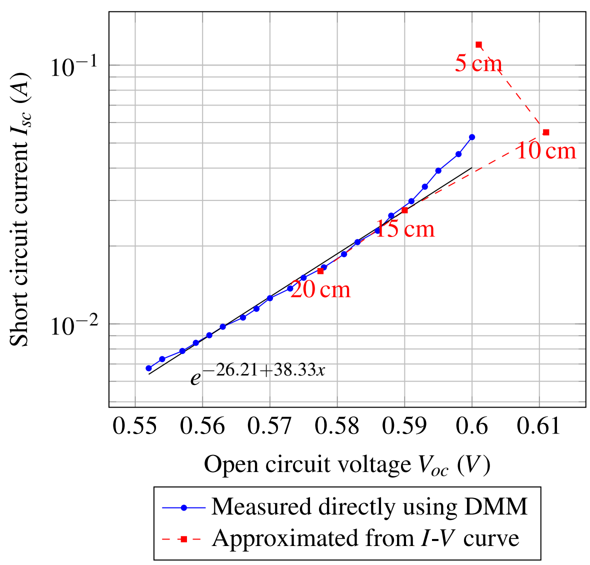

Figure 3: Short circuit current vs. open circuit voltage, on various distances

Several *I-V* curves were measured at different intensities of incident light, by changing the distance between the lamp and the solar cell, as shown in Appendix A Figure 7, 8 and 9. V_{oc} and I_{sc} were therefore estimated and plotted on Figure 3.

The estimated point of 5 cm distance was far away from the trend line from other points, possibly because the solar cell was heated by the bulb at that distance, therefore the data obtained were not at the same condition as others, should be ignored.

V_{oc} and I_{sc} for more distances were also measured using a digital multimeter directly, as shown in the Figure 3. Ignoring first few points taken at a short distance so that the solar cell might be heated by the bulb, since the trend line was similar to the data estimated from *I-V* curve, the trend line obtained here was used in later calculations.

3.1 Estimate dark saturation current and ideality factor

Equation 4 models simplified solar cell model, ignoring series and shunt resistance:

$$I = I_L - I_0(e^{\frac{qV}{nkT}} - 1) \tag{4}$$

When solar cell was in short circuit condition, the equation (4) now becomes:

$$I_{sc} = I_L \tag{5}$$

At open circuit condition:

$$I_L = I_{sc} = I_0(e^{\frac{qV_{oc}}{nkT}} - 1) \tag{6}$$

Since $e^{\frac{qV_{oc}}{nkT}}$ should be a lot greater than 1, therefore 1 in the equation could be ignored. By taking natural logs of both sides and rearrange, the equation (6) now becomes:

$$\ln I_{sc} = \frac{q}{nkT}V_{oc} + \ln I_0 \tag{7}$$

Looking at the trend line equation obtained in Figure 3 and equation (7), following relationships were therefore established:

$$\frac{q}{nkT} \approx 38.33 \tag{8}$$

$$\ln I_0 \approx -26.21 \tag{9}$$

Using room temperature $T = 300\,\mathrm{K}$, solve the equations: ideality factor $n \approx 1.01$, dark saturation current $I_0 \approx 4.14 \times 10^{-12}\,\mathrm{A}$.

3.2 Obtain series and shunt resistance

Since all data points plotted in Figure 3 were all on the trend line, so the method of use gradient change at high and low light intensities to estimate series and shunt resistances would not work. Therefore these resistances were estimated using the gradient near I_sc and V_oc on 10cm distance *I-V* curve, as shown in Figure 2.

Equation 10 models the solar cell including series and shunt resistance, derived from the solar cell model shown in Figure 1:

$$I = I_L - I_0(e^{\frac{q(V+IR_s)}{nkT}} - 1) - \frac{V + IR_s}{R_{sh}} \tag{10}$$

In short circuit condition, since $R_s << R_{sh}$, current flow through R_s assumed to be $I_L = I_{sc}$, while no current flow through R_{sh}. Therefore, at data points near I_{sc}, the difference between I and I_{sc} could be assumed to be the current flow through shunt resistor, and the voltage could be assumed to be the voltage across shunt resistor as well. Therefore, the gradient of *I*-*V* curve near I_{sc} should be $\frac{1}{R_{sh}}$, as indicated by Figure 4.

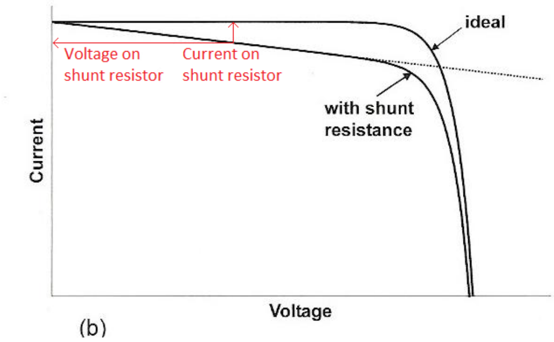

Figure 4: Estimate shunt resistance (reproduced from [2])

The series resistance can be estimated using the same method, as indicated by Figure 5.

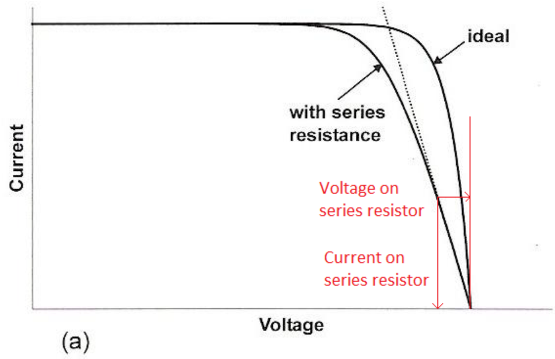

Figure 5: Estimate series resistance (reproduced from [2])

Applying the methods described above, from *I*-*V* curve at 10 cm distance shown by Figure 2, series and shunt resistance therefore estimated as:

$$R_{sh} = \frac{-1}{slope_{sc}} \approx \frac{-1}{-6.31 \cdot 10^{-3}} \approx 158.5\,\Omega \qquad (11)$$

$$R_s = \frac{-1}{slope_{oc}} \approx \frac{-1}{-0.71} \approx 1.41\,\Omega \qquad (12)$$

Series and shunt resistance determines fill factor, a power efficient solar cell should have small series resistance and large shunt resistance.

4. Variation in angle of incidence

Several *I*-*V* curves were measured at different angle of incidence to the solar cell, as shown in Appendix A Figure 10, 11 and 12. Figure 6 shows all plots on the same graph.

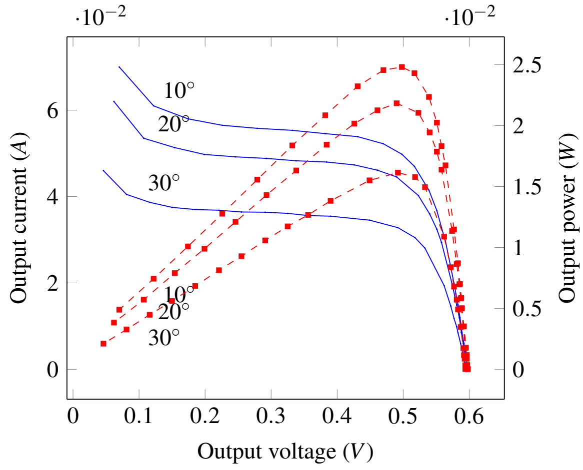

Figure 6: Short circuit current vs. open circuit voltage, on various distances

It could be seen from the figure that the maximum output power of the solar cell reduced while angle of incidence increasing, suggests the solar cell could only absorb light from a limited angle of incidence.

5. Practical deployment and operation

The best location for installation of solar cell would be place that can receive most sun light, and the weather condition need to be taken into consideration as well.

Since Earth are rotating and also orbits the Sun, angle of light coming from the Sun to the solar cell would be varying every day and seasons. Therefore, for maximum power output, the solar cell need to track the Sun, possibly installed on a controllable base and controlled by a computer system.

The solar cell could also encapsulated in a case or by another coating layer, so that enables it to absorb light from a greater angle of incidence, by changing the angle of light from outside, improves the power efficiency.

References

[1] Stuart Boden "Photovoltaics 3" [*Online*]. Available: https://secure.ecs.soton.ac.uk/notes_so/elec2201/STUART%20BODEN%20LECTURES/PV%20LECTURES/ELEC2201_SABSlides_Lecture3_Handout.pdf

[2] ELEC2201 "Complete Notes" [*Online*]. Available: https://secure.ecs.soton.ac.uk/notes_so/elec2201/SECOND%20YEAR%20ELEC2201%20COURSE%20NOTES/Complete%20Notes.pdf

[3] NREL "Best Research-Cell Efficiencies" [*Online*]. Available: http://www.nrel.gov/ncpv/images/efficiency_chart.jpg

Appendix A: Additional plots

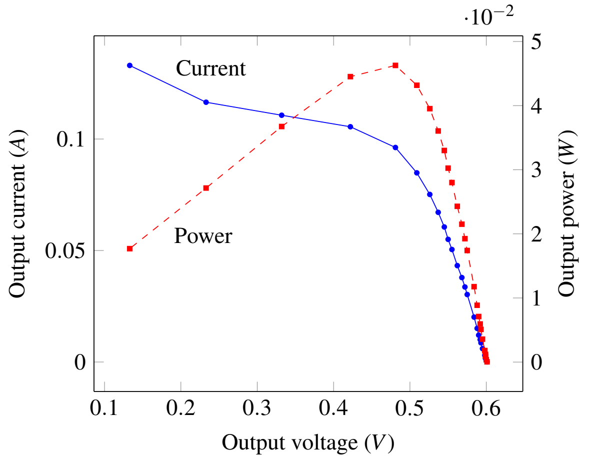

Figure 7: Output current, power vs. output voltage, light source 5 cm apart

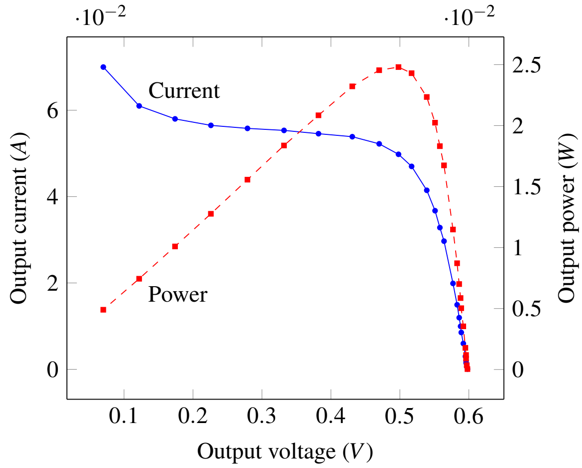

Figure 10: Output current, power vs. output voltage, light source 10 cm apart, with angle of incidence 10°

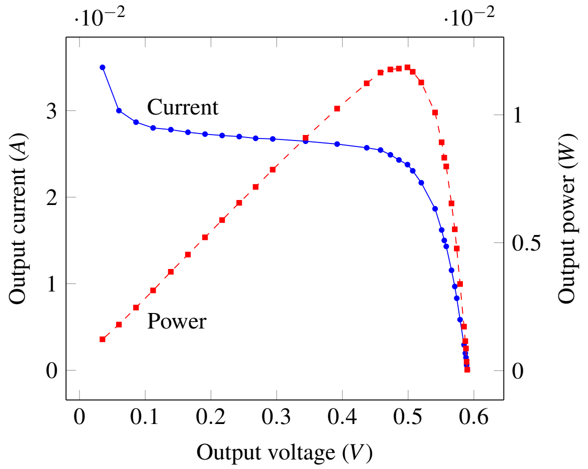

Figure 8: Output current, power vs. output voltage, light source 15 cm apart

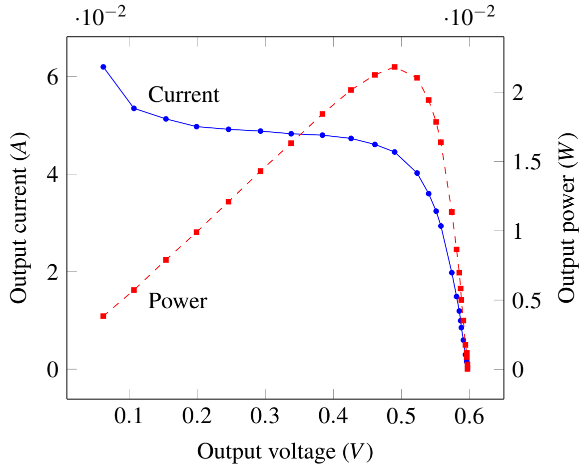

Figure 11: Output current, power vs. output voltage, light source 10 cm apart, with angle of incidence 20°

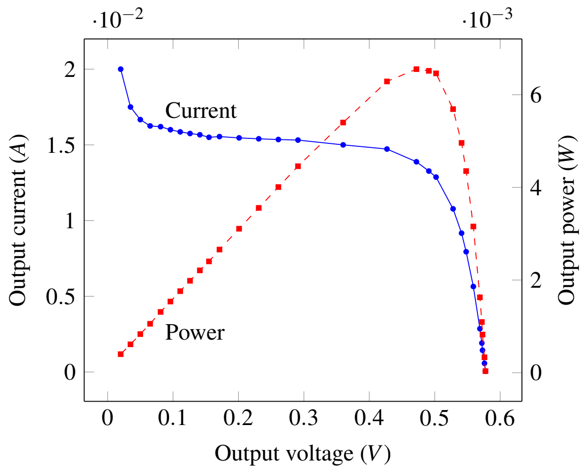

Figure 9: Output current, power vs. output voltage, light source 20 cm apart

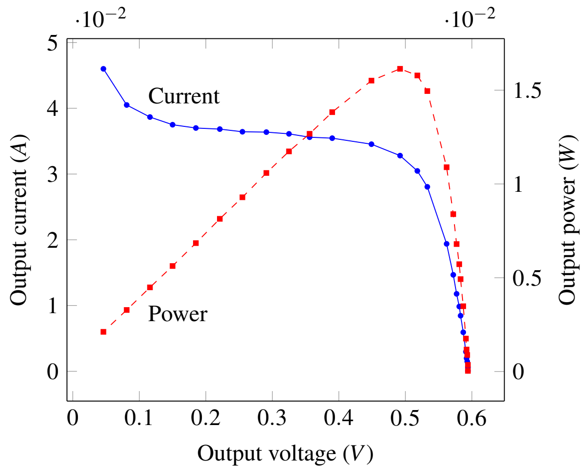

Figure 12: Output current, power vs. output voltage, light source 10 cm apart, with angle of incidence 30°