Electrical Characterization of Solar Cell using Arduino and Polarization Film

Mark Lancaster,[1,2] Ahana Jhamb,[1,3] Xilai Song,[1,4] Marissa Youderian,[1,5] Gabriel Unger,[1] and Gyuseok L. Kim[1,a)]
[1)] *Singh Center for Nanotechnology, University of Pennsylvania 3205 Walnut St. Philadelphia, PA 19104*[b)]
[2)] *Lower Merion High School, 315 E Montgomery Ave, Ardmore, PA 19003*
[3)] *Singapore American School, 40 Woodlands Street 41, Singapore 738547*
[4)] *Basis Independent Mclean, 8000 Jones Branch Dr, McLean, VA 22102*
[5)] *North Shore Country Day School, 310 Green Bay Rd, Winnetka, IL 60093*

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A solar cell laboratory course for high school and college undergraduate students is proposed. The electrical characterization of the solar cell is performed to confirm the functionality of the device as both a diode and a power source. The efficiency of the solar cell in the illuminated condition is found to be 13.1 %. We find the efficiency of the solar cell slightly decreases as the intensity of light decreases. However, there is no significant difference in efficiency except for in the opaque condition. A calibrated solar cell, multimeter, current sensor, Arduino, coding and polarization are used to perform the experiment.

Key words: Solar cell, efficiency, electrical characterization, Arduino, coding and polarization

I. Introduction

Energy harvesting is a process by which energy from natural resources is captured, stored and converted into electrical energy. Energy can be harvested from a vast array of naturally occurring processes, including light, sound, wind, thermal gradients and pressure. Solar energy harvesting has many advantages over fossil fuel energy sources. The amount of solar energy that reaches the earth each hour can power the world for a year[1]. Solar energy is not only abundant but also economically and environmentally friendly. Covering only 0.4% of the area of the United States with photoelectric cells (often called solar cells) would be sufficient to fulfill all of the country's electric requirements. 30% of new electricity produced in the United States in 2019 was produced by photoelectric cells, making solar energy a significant contributor to the energy industry[2]. The rise in prominence of solar cells can be attributed to their declining cost and increasing efficiency.

Many solar cells are made from extrinsic semiconductors, often pn junctions in silicon wafers[34]. The pn junctions can be made either by diffusion or implantation of n-type dopant (e.g. phosphorous) into silicon wafers doped by p-type dopant (e.g. boron). In the depletion region, excess electrons in the n-type silicon diffuse into the p-type silicon, leading to a combination of electrons and holes (spaces unoccupied by electrons). This causes the n-type silicon in the depletion region to become positively charged as the n-type dopants lose their electrons. In the same manner, the p-type silicon in the depletion region becomes negatively charged as the p-type dopants accept the lost electrons. The positively charged n-type silicon and negatively charged p-type silicon constitute an electric potential in the depletion region. When a solar cell absorbs solar energy greater than the band gap energy of the silicon, the electrons and holes are separated from their atoms. The charges (electrons and holes) then drift through the semiconductor due to the electric potential. The generated charge can be collected by connecting electric cables to the ends of the p-type and n-type silicon. For example, the band gap energy of silicon is 1.12 eV. Since the energy range of visible light is from 400 nm to 700 nm in wavelength, which corresponds to 1.8 to 3.1 eV, silicon-based solar cells absorb the photon energy from the sunlight and can generate electricity.

The solar cell is also an excellent subject for education since various topics such as economics, environmental science, and engineering can be discussed. In terms of engineering, for example, semiconductors, band gap, nanofabrication, diffusion, lithography, etch, deposition, thermal annealing, resistance, diodes, electrical characterization and efficiency can be discussed. In particular, the theory of fabrication and characterization of solar cells has been taught to graduate students at the University of Pennsylvania and the Massachusetts Institute of Technology. However, this fabrication process is impractical at the K-12 educational level because manufacturing a Si-based solar cell usually requires nanofabrication processes involving expensive instruments. An alternative method of solar cell fabrication using printed circuit boards (PCB) has been proposed for a do-it-yourself (DIY) project[5]. However, most DIY experiments confirm the function of a solar cell by simply connecting multi-

[a)] Electronic mail: kimgyu@seas.upenn.edu
[b)] These authors equally contributed to this work.

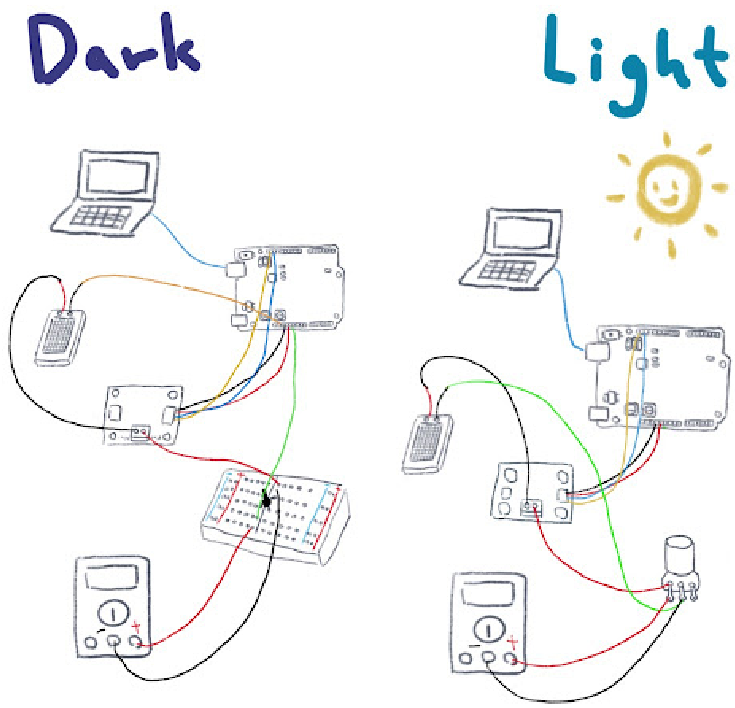

FIG. 1. Experimental configurations for dark and illuminated conditions. The wiring information is described in Appendix A.

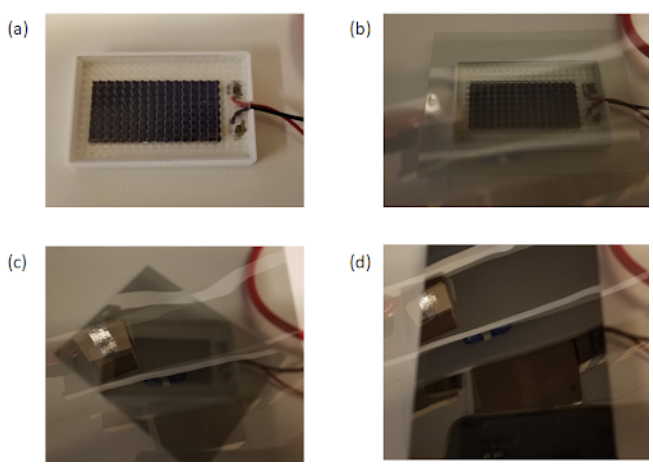

FIG. 2. Solar cell at various opacities: (a) no polarization film (fully illuminated), (b) 0° between films (translucent), (c) 45° between films (50% translucent), (d) 90° between films (opaque).

meters, rather than characterizing current-voltage (IV) characteristics and efficiency.

In this paper, we report on the characterization of a solar cell using polarization films, potentiometers, Arduino, and coding. The IV characteristics were obtained under dark and illuminated conditions. The polarization films were used to control the intensity of light whereas the potentiometers were used to change the load (resistance) on the circuit. This provided a protocol to characterize the solar cell and measure its efficiency in a safe manner and at a relatively low cost.

II. Experiment

A calibrated solar cell was purchased (SolarMade inc.). A calibrated solar cell provides the user with open circuit voltage and short circuit current values measured under the standard test conditions which will be discussed below. An Arduino microcontroller, a 10000 Ohm potentiometer, a 100 Ohm potentiometer, jumper wires, a breadboard, a multimeter and a current sensor (Adafruit inc., INA219) were used to obtain the current-voltage (IV) curve of the solar cell.

To confirm the functionality of the solar cell both as a diode and as an energy generator, electrical characterization with four-point probe testing was carried out under two different light conditions: dark and illuminated conditions, as shown in Figure 1. The resistance of the potentiometers was set to the maximum and decreased incrementally. Whereas the voltage was manually recorded with the multimeter, the current was automatically recorded with a computer connected to the Arduino. The wiring configuration is described in Appendix A. The full code used to gather data from the

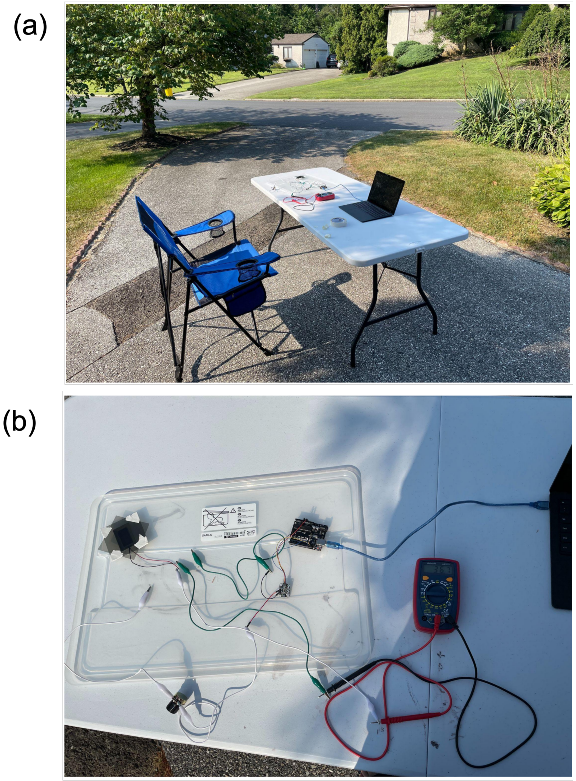

FIG. 3. Experimental setups for outdoor testing.

current sensor via the Arduino is available on Github[6].

To vary the intensity of light, two sheets of polarization film were overlapped during electrical characterization with the illuminated condition. Varied opacity was achieved without the polarized film (fully illuminated), with the polarized films at a 0-degree angle relative to one another (translucent), with the polarized films at a 45-degree angle relative to one another (semi-translucent) and with the polarized films at a 90-degree angle relative to one another (opaque) as shown in Figure 2 (a), (b), (c) and (d), respectively. The experiment was performed outdoors. The experimental setups for outdoor electrical characterization are shown in Figure 3 (a) and (b).

III. Results and discussion

A. IV characteristics in dark and illuminated conditions

Figure 4 shows the IV curve of the calibrated solar cell in dark and illuminated conditions. As mentioned above, the Si solar cell is essentially a diode with a pn junction. When the forward bias is applied to a diode (in other words, when positive and negative potentials are applied to the p-type and n-type silicon, respectively), the current increases exponentially as the voltage increases as shown by the black line in Figure 4. Note that the power source in the dark condition was the Arduino connected to a computer.

The red line in Figure 4 shows the IV curve in the illuminated condition. The current can flow when electron-hole pairs generated by light energy are collected. By introducing resistors or potentiometers, one can vary the voltage. Note that unlike in the dark condition, the power source in the illuminated condition was the solar cell itself. The reason for the negative current values in the illuminated condition is that electrons generated in the depletion region are attracted to the n-type silicon by electric potential, then flow to the resistor. Thus, the direction of electron flow in the illuminated condition was opposite that in the diode in the dark condition.

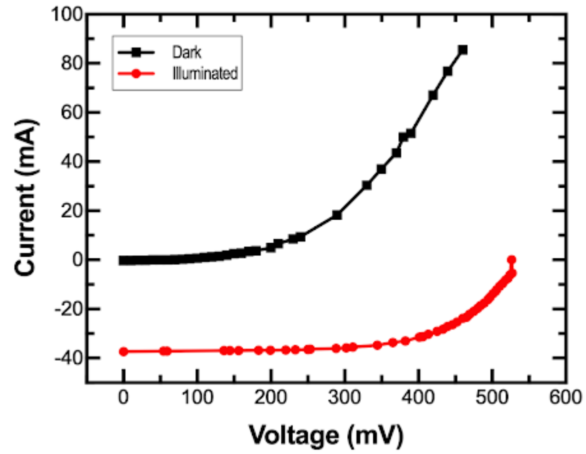

FIG. 4. IV curve for dark and illuminated conditions.

B. Efficiency of solar cell

The efficiency of a solar cell is defined by output power over input power. Figure 5 shows electrical characterization results of the solar cell in the illuminated condition. The IV curve (black) shown in Figure 5 is the reflection of the IV curve (red) in Figure 4 over the x-axis. The reflection of the IV curve is in order to facilitate data interpretation. The x-intercept and y-intercept in the IV curve are open circuit voltage and short circuit current, respectively. Whereas the open-circuit voltage is the maximum voltage that a solar cell can generate when the net current flow is zero, the short circuit current is the maximum current that a solar cell can generate when the voltage across it is zero.

$$\mathrm{P} = \mathrm{I} * \mathrm{V} \tag{1}$$

The output power can be simply calculated by multiplying current by voltage for each data point in the illuminated condition using Equation (1). The resulting values were plotted in Figure 5 (red). Note that the maximum value for power occurred neither in the short circuit current nor in the open circuit voltage. Instead, an optimum value occurred between the two extremes. It is shown that the maximum output power was 12.67 mW.

It is necessary to measure the input power in order to calculate the efficiency of the solar cell. The standard

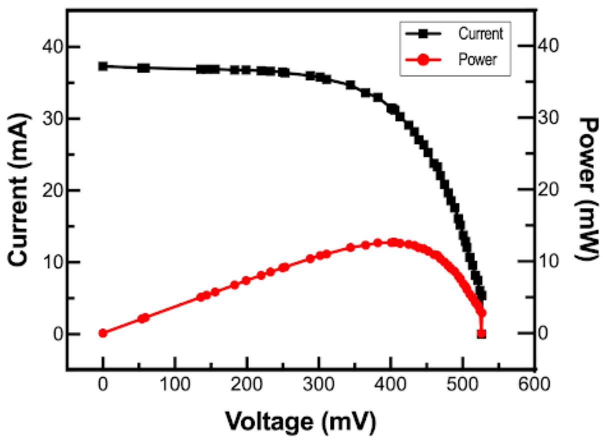

FIG. 5. IV and power-voltage curve for the illuminated condition.

test conditions (STC) to measure the efficiency of the solar cell are I) one sun of light which corresponds to 1000 W/m^2 or 100 mW/cm^2, II) 1.5 air mass, III) 25 ^oC and IV) four-point probe test[7]. However, the instrument for ensuring STC is often not available in a high school or college environment. One alternative method is to purchase a calibrated solar cell. A calibrated solar cell provides both its open circuit voltage and short circuit current measured in STC. For example, the open circuit voltage and short circuit current of the calibrated solar cell that we used were 610 mV and 308 mA, respectively.

The short circuit current in the specific experimental conditions can be measured by exposing the cell to light and placing multimeter terminals on the + and - wires of the cell. The short circuit current in the illuminated condition in Figure 5 was 36.5 mA. The short circuit current is almost proportional to the amount of light energy that the solar cell absorbs. The input power that the solar cell absorbed can be calculated by solving a ratio problem, 308 mA : 100 mW/cm^2 = 37.3 mA : X mW/cm^2. In order to compensate for the area of the solar cell, the cell's area can be calculated by multiplying its length (2 cm) by its width (4 cm). The input power of the solar cell was 96.9 mW in the illuminated condition. Therefore, the efficiency of the cell in the illuminated condition is calculated to be 13.1%.

The formula to calculate the efficiency of the solar cell is shown in Equation 2

$$\%\,\text{efficiency} = \frac{\text{max power}}{1\,\text{sun} * \frac{I_{sc\,\text{experimental}}}{I_{sc\,\text{under 1 sun}}} * \text{device area}} * 100\% \tag{2}$$

where P is the power generated by the cell, I is the current traveling through the circuit, and V is the voltage of the circuit.

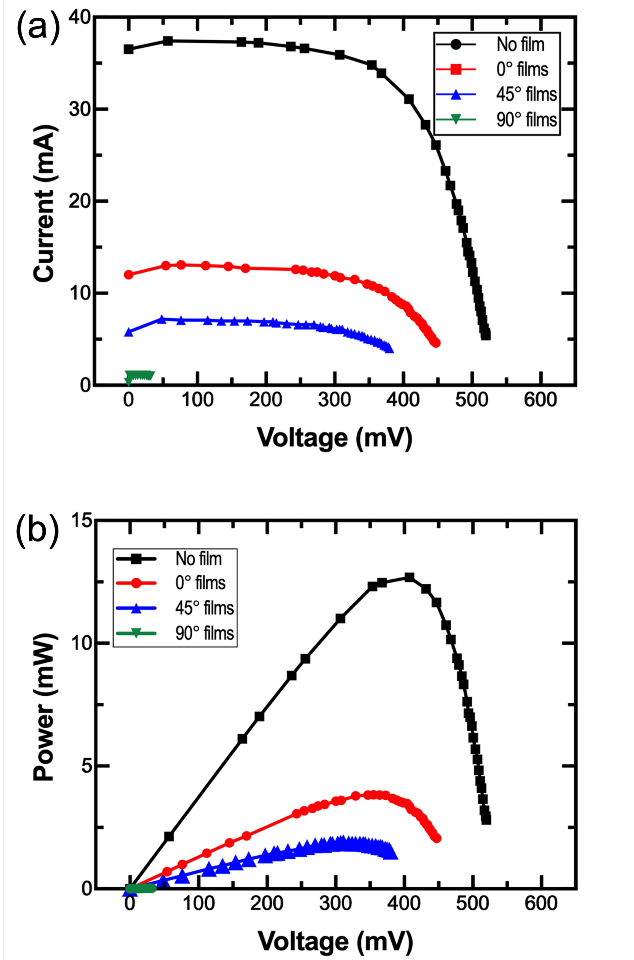

FIG. 6. (a) IV curve and (b) power-voltage curve for the varied opacity conditions.

C. Effect of light intensity of efficiency

It is known that visible light is an electro-magnetic wave that has many planes in which it can oscillate in nature. The light oscillates only in a single plane when it is polarized. Layering two polarization films further restricts the realm in which the light can oscillate. The degree to which the oscillation is restricted is dependent on the relative angle between the two films. Therefore, the intensity of light can be modulated by placing polarization film or by changing the relative angle between the two polarization films.

Figure 6 (a) and (b) shows the IV curve and output power-voltage curves for the various angles of polarization films. The IV curves were also plotted for each of the four polarized film conditions. It is observed that both short circuit current and maximum power output were largest when the polarization film was not placed on top of solar cell (fully illuminated condition), then gradually decreased as the opacity increased (in other words, as the angle between the films increased). This correlation indi-

TABLE I. Measured short circuit current and maximum output, and calculated input power and efficiency for the varied opacity conditions.

Polarlization films	Short Circuit Current (mA)	Maximum power output (mW)	Input power (mW)	Efficiency (%)
No film	36.5	12.7	94.8	13.4
0^o films	12.0	3.8	31.2	12.2
45^o films	5.8	1.90	15.1	12.6
90^o films	0.3	0.03	0.8	3.8

cates that the greater light exposure allowed by the more transparent conditions excited more electrons on the surface of the solar cell, producing a greater current. The slight drop in short circuit current in each opacity condition in Figure 6 (a) is due to the partially cloudy weather condition on the testing day. Note that this experiment was carried out outdoors.

Measured short circuit current and maximum power output, and calculated input power and efficiency using Equation 1 and 2, respectively, for the varied opacity conditions are listed in Table I. The efficiency of the solar cell was slightly decreased as the angle between the polarization films was increased except for in the 90^o polarized film angle condition, which is opaque. However, whereas the decrease in the short circuit current as opacity increased was obvious, there was no significant difference in efficiency except for in the opaque condition. This is one of the reasons that a solar cell can be applicable even in areas with limited light exposure.

A small amount of current was also measured in the opaque condition although the light was not supposed to transmit through the polarization films when they were at an angle of 90^o. The small amount of light energy reaching the solar cell was attributed to photon energy being transmitted through the white plastic side wall.

IV. Conclusion

The electrical characterization of a solar cell is an excellent academic project for high school and college undergraduate students because the subject can cover various topics including nanofabrication, nanocharacterization, circuit, diode and economics. However, instruments used to characterize solar cells in the standard testing condition are often costly and require controlled environments. As such, characterizing solar cells without costly equipment is difficult. We demonstrated the electrical characterization of the solar cell with a calibrated solar cell, Arduino and coding at relatively low cost. We also measured the efficiency of the solar cell with various light intensities by placing polarization films at various angles.

V. Acknowledgements

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A. Appendix A

1. Dark condition

First, the setup was configured to the dark condition, in which the surface of the solar cell was covered by a sheet to prevent light exposure. The electrical connections were made as follows (see Figure 1 for a visual representation):

- black (INA 219 sensor) - GND(Arduino)
- red (INA 219 sensor) - 5V (Arduino)
- blue (INA 219 sensor) - SDA (Arduino)
- yellow (INA 219 sensor) - SCL (Arduino)
- Vin+ (INA 219 sensor) - middle (potentiometer)
- Vin- (INA 219 sensor) - red (solar cell)
- 3.3V (Arduino) - left (potentiometer)
- GND (Arduino) - black (solar cell)
- black (voltmeter) - middle (potentiometer)
- red (voltmeter) - left (potentiometer)

In the Dark Configuration, the resistance of the potentiometer was set to the maximum, and was reduced incrementally. As the resistance was adjusted, the voltage and current of the circuit were measured and recorded using an Arduino microcontroller, current sensor (INA219), and voltmeter. The data points were graphed in an Excel spreadsheet, and an IV curve was generated.

2. Illuminated condition

Next, the setup was configured to the illuminated condition, in which the solar cell was exposed to either sunlight (as shown in Figure 3) or an artificial light source, such as a lamp. The electrical connections were made as follows (see Figure 1 for a visual representation):

- black (INA 219sensor) - GND(Arduino)
- red (INA 219 sensor) - 5V (Arduino)
- blue (INA 219 sensor) - SDA (Arduino)
- yellow (INA 219 sensor) - SCL (Arduino)
- Vin+ (INA 219 sensor) - left (potentiometer)
- Vin- (INA 219 sensor) - red (solar cell)
- middle (potentiometer) - black (solar cell)
- black (voltmeter) - middle (potentiometer)
- red (voltmeter) - left (potentiometer)

In the illuminated condition, the resistance of the potentiometer was this time set to the minimum, and was increased incrementally, with the decreasing values of voltage and current being recorded. An IV curve for the illuminated condition was then generated using the data points.