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Which silicon structure makes the most effective solar cell?

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ABSTRACT

This research paper aims at examining which silicon structure would make the best solar cell. Three different structures were used - polycrystalline, monocrystalline, and amorphous. By using different colored filters with different wavelengths, the wavelength of the incident light was altered. The current and voltage that were generated by the monocrystalline solar cell were measured for different incident light wavelengths. This was then repeated for the other 2 structures of solar cells. The analysis of the obtained data resulted in the following conclusions: 1. There is perhaps a large bandgap in the amorphous cell, as its output varies with frequency. 2. There is perhaps a small bandgap in polycrystalline cells, as at lower wavelengths, its output varies with frequency; at higher wavelengths, its output varies with intensity. 3. There is a medium-sized bandgap in monocrystalline cells. The output of the monocrystalline cell varies between the outputs of the other 2 cells. At higher wavelengths, the output varies to a certain extent with intensity; at lower wavelengths, the output varies to a certain extent with frequency. As a result, their conclusions were used in order to answer the research question that stated, "Which silicon structure makes the most effective solar cell?" There is no ideal structure for a solar cell; each structure's effectiveness is determined by its usage. The amorphous cell is not expensive, and there is little variation in its output with a change in intensity. However, it produces relatively less power. As a result, it is highly effective for smaller-scale usages such as in watches or calculators, in environments that have low intensity. The polycrystalline cell output mainly varies with intensity, which thereby makes it useful for outdoor usages such as in deserts. At low wavelengths, it shows variation with a change in frequency, which thereby makes it useful for times such as dawn and dusk when there is bluish light. Since its production of power is much greater, it is highly suitable for larger-scale productions of energy. The monocrystalline cell has an output that is greater than the amorphous cell, but not high enough to account for its expensive cost. It is applicable on a smaller scale, such as in processor chips.

Keywords: *Solar, Cells, Energy, Efficiency, Amorphous, Polycrystalline, Monocrystalline*

INTRODUCTION

Essay Background:

As the oil reserves of the planet are running out, the prevalence of renewable energy sources is going to significantly rise in the future. Solar energy is a renewable source of energy that is available in abundance. Thus, I believe that they are going to be highly prevalent in the future. This experiment is designed to evaluate the efficiencies of certain solar cells in particular situations. By finding the performance of each solar cell at various points along the electromagnetic spectrum, the best solar cell for varying applications can be determined.

Solar Cells Theory:

Solar cells are defined as "semiconductors that directly convert the energy of light into electrical energy" and are p-n junctions; p-n junctions are defined as "an interface or a boundary between two semiconductor material types, namely the p-type and the n-type, inside a semiconductor." The light is incident on the solar cell's p-surface. The p-surface is made in an extremely thin manner in order to permit the arrival of photons on the underlying p-n junction. When the incident photons possess energy that is greater (or equivalent to) than the material's band gap, free electron-hole pairs are formed as the breaking of covalent bonds are caused by the photons. The electrons travel to the n-side across the junction, while the holes cross and arrive at the p-side, which thus results in a potential difference across the cell ends. Using metal contacts, the cell is connected to the external circuit.

Shown below, are a solar cell's typical V-I characteristics:

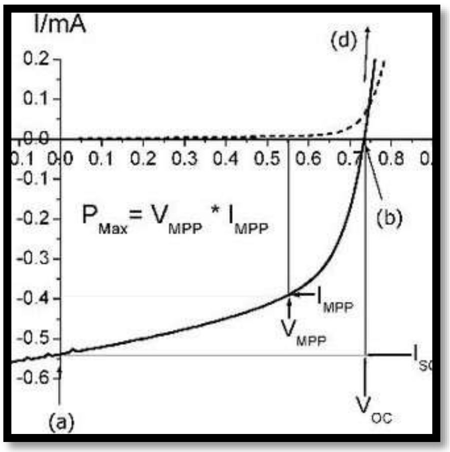


Figure 1

Variables:
Independent Variable:
The wavelength of the incident light – the readings will be taken with filters of different colors.
The structure of the silicon solar cell – the experiment will be repeated for each cell structure.
Dependent Variable:
The current that is generated by the solar cell.
The voltage that is generated by the solar cell.

The 2 quantities mentioned above will be measured with every color filter and every solar cell structure.

Controlled Variables:
Sunlight color – the sunlight color changes depending on the time of the day (sunrise and sunset). Thus, all the readings were taken around noon, to ensure that there is minimal movement of the sun whilst the readings are taken. Assuming that there is sufficient speed during the data collection, the sunlight color can be considered to be constant.
Angle of incidence – As mentioned in the previous point, the movement of the sun is minimal. Thus, the angle of incidence for all readings can be considered to be 90°.
Ambient temperature – The temperature can be considered to be constant, as all the readings were taken within a short span of time (around noon) on the same day. Thus, there was very little variation in the temperature.
Wavelength of the incident light – Even when there is a change in the structure of the solar cell, the wavelength that is let through by a certain filter remains constant.
Solar cell surface area – Using duct tape, the solar cells are covered in such a manner that the same surface area is exposed to the incident light.
Intensity of incident light – Whilst measuring the current and voltage, the light intensity meter simultaneously measured the incident light intensity. Post the collection of intensity data, it was adjusted in order to simulate a constant intensity.
Silicon solar cell structure – The structures of the solar cells are kept constant whilst the incident light wavelengths are varied.

Experiment Preparation:
For each structure, I bought 1 solar cell. However, they were of different sizes. Thus, in order to equalize them, the following procedure was required.

Required Apparatus (for equalizing solar cells):
A sheet of paper to cut to the desirable size
1 silicon solar cell with a monocrystalline shape
1 silicon solar cell with a polycrystalline shape
1 silicon solar cell with an amorphous shape
1 roll of duct tape (black)
Pencil
Scissors
Ruler
Procedure (for equalizing solar cells):
Measure a certain size of the paper and mark it using a pencil (I arbitrarily chose 3 by 2.3 cm).
Take the piece of paper obtained post cutting along the line drawn by pencil.
Place the cut piece of paper on the monocrystalline solar cell.
Using the black duct tape, cover the rest of the solar cell.
Using additional duct tape, cover the other external parts of the solar cell, until only the paper remains uncovered.
Remove the paper, only leaving a specifically sized area exposed on the monocrystalline solar cell.
Repeat steps 1-6 for the polycrystalline and amorphous solar cells.

Required Apparatus (constructing circuit and conducting experiment):

2 multimeters
Monocrystalline, polycrystalline, and amorphous solar cells
1 light meter
Connection wires
2 crocodile clips

Diagram of the circuit:

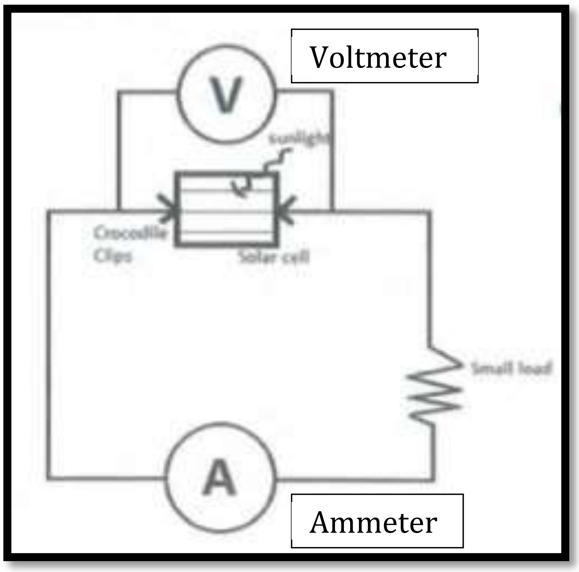


Figure 2

Solar Cells Utilized in the Experiment:
In this experiment, only silicon based solar cells were utilized. However, considering the fact that silicon solar cells are highly widespread, it is sufficient to make the experiment relevant. I have investigated the efficiency of 3 different structures of silicon that are monocrystalline, polycrystalline, and amorphous.
Monocrystalline:

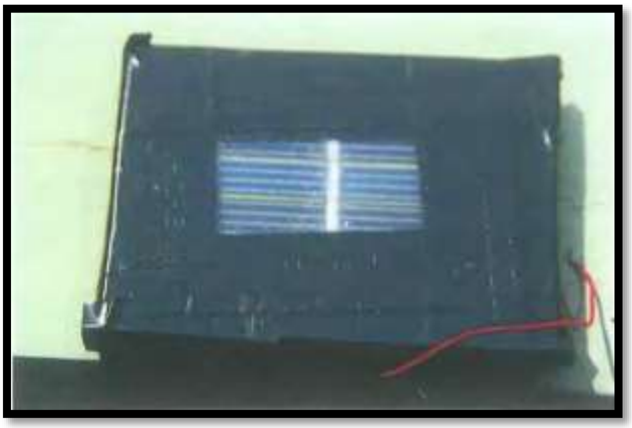


Figure 3

Polycrystalline:

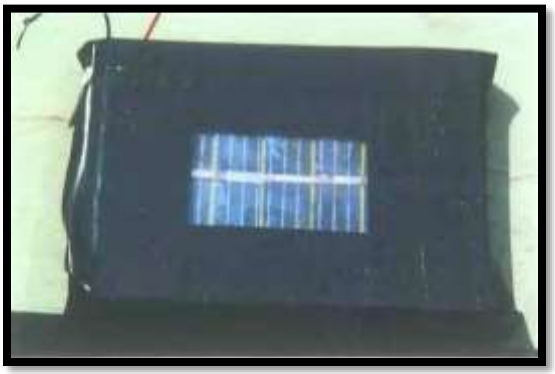


Figure 4

Amorphous:

Figure 5

Monocrystalline cells consist of a single crystal, polycrystalline cells consist of multiple crystals, and amorphous cells are absent of a crystalline structure.

Procedure of Data Collection:
Connect the monocrystalline silicon structured solar cell, as depicted in the circuit diagram (figure 2).

Using a multimeter, measure the current and the voltage.

Note down the light intensity that is displayed by the light meter.

On the exposed part of the cell, place a colored filter.

Repeat steps 1-4 for the other filters.

Replace the monocrystalline silicon solar cell with a polycrystalline and amorphous solar cell and repeat steps 1-5.

Raw Data Table:

Monocrystalline:

Table 1

Filters	Voltage/V ($\pm\mathbf{0.01V}$)	Current /mA ($\pm\mathbf{0.1mA}$)	Light intensity/lx ($\pm\mathbf{300lx}$)
None	2.18	108.1	67000
Magenta	1.70	75.0	66900
Green	1.48	60.4	69100
Peacock blue	1.56	67.7	69200
Yellow	1.76	80.3	69500
Red	1.64	74.3	69600
Blue	1.53	65.7	69100
Purple	1.61	72.2	68800

Polycrystalline:

Table 2

Filters	Voltage/V ($\pm\mathbf{0.01V}$)	Current /mA ($\pm\mathbf{0.1mA}$)	Light intensity/lx ($\pm\mathbf{300lx}$)
None	1.10	296.1	58300
Magenta	0.66	241.7	61400
Green	0.48	179.1	63400
Peacock blue	0.60	227.6	64100
Yellow	0.77	287.1	65900

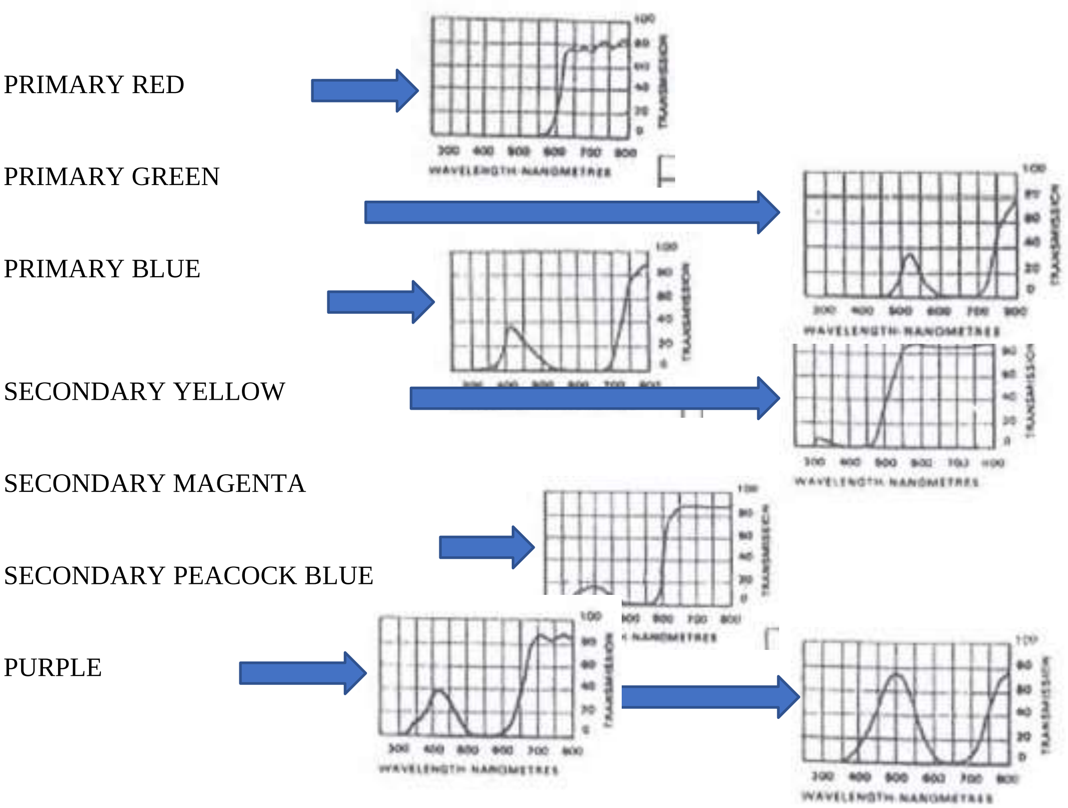
Red	0.65	238.1	66200
Blue	0.52	201.9	65900
Purple	0.61	231.3	66200

Amorphous:

Table 3

Filters	Voltage/V ($\pm\mathbf{0.01V}$)	Current /mA ($\pm\mathbf{0.1mA}$)	Light intensity/lx ($\pm\mathbf{300lx}$)
None	3.38	29.0	57800
Magenta	3.11	20.6	57400
Green	2.99	19.2	57700
Peacock blue	3.22	19.5	58500
Yellow	3.33	22.0	58600
Red	3.14	18.7	63700
Blue	3.10	19.4	64300
Purple	3.17	20.0	63900

Data Analysis:
Data Comparison: (adjusted for intensity)
The wavelengths of the filters are described as follows:



There cannot be a comparison between the current and voltage, when there are different incident intensities that they relate to. Thus, in order to rectify this, I have arbitrarily chosen a value (60000 lx) and accordingly made adjustments to the values in order to account for the same.

Adjusted Amorphous Voltagenon#
= 3.37 × 60000 = 3.50V
57700

Adjusted Amorphous Current

non#
= 28.9 × 60000 = 30.1mA
57700
By utilizing these adjusted values, the power generated by the cells has been calculated by using the formula P = VI.

Adjusted Amorphous Powernon# = 3.50 × 30.1 = 0.11W These calculations were repeated for all 3 solar cells.
Processed Data Tables: (adjusted for intensity)

Amorphous (with respect to 60000 lx)

Table 4

Filter	Wavelength	% Transmitted	Voltage/V ($\pm 0.001V$)	Current/ mA ($\pm 0.1mA$)	Light Intensity/ lx (± 300 lx)	Power/ W ($\pm 0.001W$)
None	-	-	3.51	30.2	60000	0.106
Magenta	400	17%+670, 90%	3.26	21.6	60000	0.070
Yellow	320	7%+600, 90%	3.41	22.6	60000	0.077
Purple	410	40%	2.98	18.8	60000	0.056
Blue	420	37%	2.90	18.1	60000	0.052
Peacock blue	500	75%	3.30	20.0	60000	0.066
Green	525	37%	3.11	20.0	60000	0.062
Red	650	75%	2.96	17.6	60000	0.052

Polycrystalline (with respect to 60000 lx)

Table 5

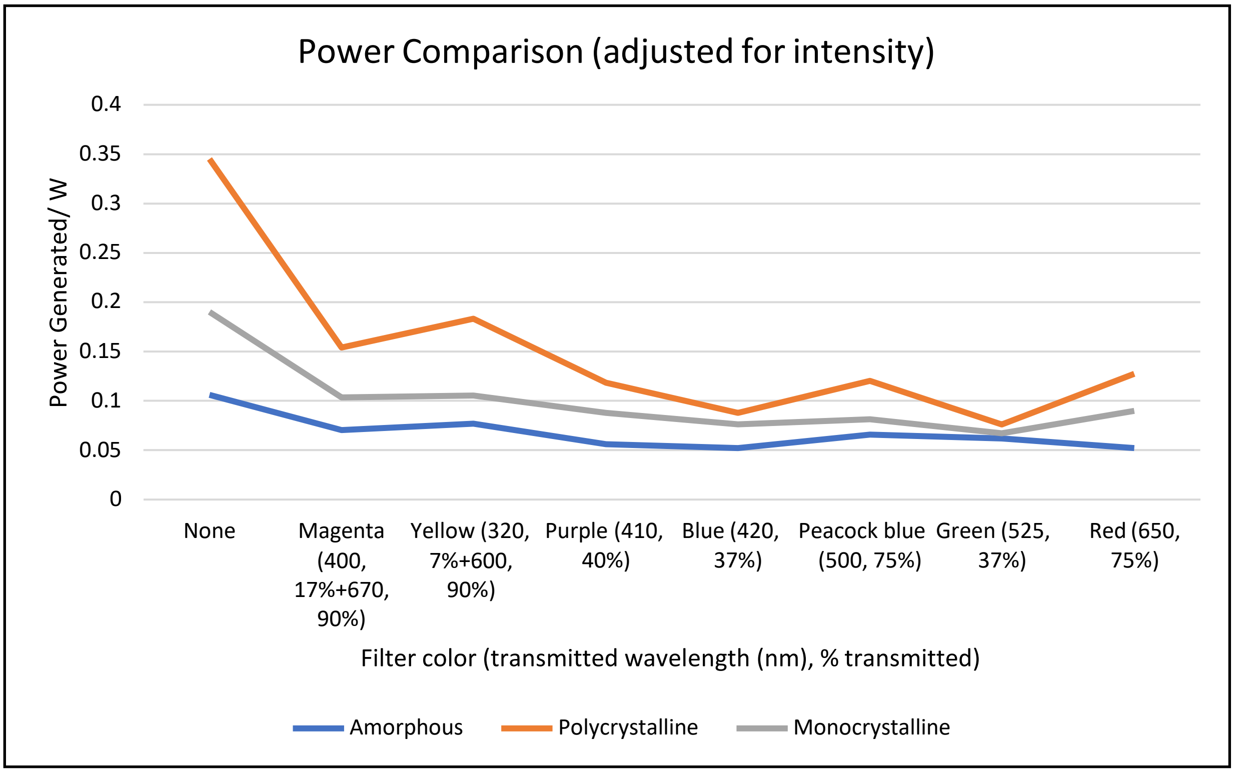
Filter	Wavelength	% Transmitted	Voltage/V ($\pm 0.001V$)	Current/ mA ($\pm 0.1mA$)	Light Intensity/ lx (± 300 lx)	Power/ W ($\pm 0.001W$)
None	-	-	1.13	305.3	60000	0.345
Magenta	400	17%+670, 90%	0.65	236.6	60000	0.154
Yellow	320	7%+600, 90%	0.70	261.8	60000	0.183
Purple	410	40%	0.56	210.0	60000	0.118
Blue	420	37%	0.48	184.1	60000	0.088
Peacock blue	500	75%	0.56	213.4	60000	0.120
Green	525	37%	0.45	169.8	60000	0.076
Red	650	75%	0.59	216.1	60000	0.127

Monocrystalline (with respect to 60000 lx)

Table 6

Filter	Wavelength	% Transmitted	Voltage/V ($\pm 0.001V$)	Current/ mA ($\pm 0.1mA$)	Light Intensity/ lx (± 300 lx)	Power/ W ($\pm 0.001W$)
None	-	-	1.96	97.0	60000	0.190
Magenta	400	17%+670, 90%	1.53	67.4	60000	0.103

Yellow	320	7%+600, 90%	1.52	69.2	60000	0.105
Purple	410	40%	1.39	63.1	60000	0.088
Blue	420	37%	1.33	56.9	60000	0.076
Peacock blue	500	75%	1.37	58.8	60000	0.081
Green	525	37%	1.28	52.5	60000	0.067
Red	650	75%	1.40	64.0	60000	0.090



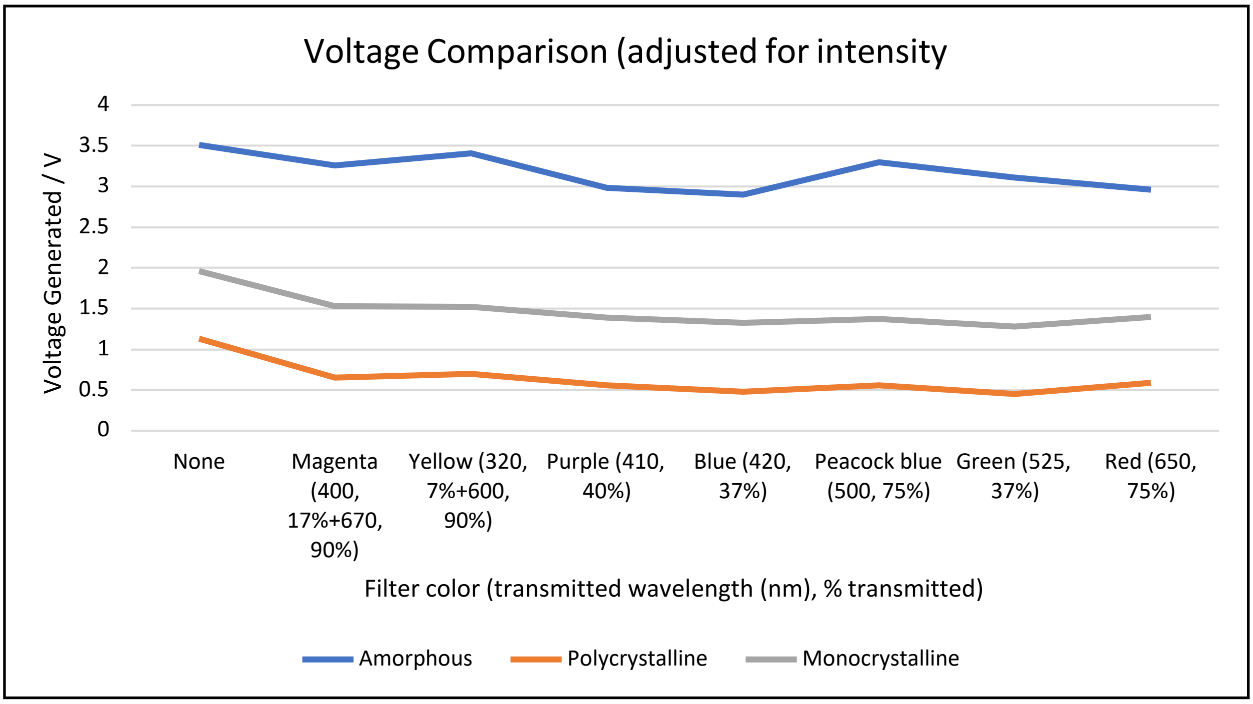
Graph 1

With reference to graph 1, it can be observed that the much more power was generated by the polycrystalline solar cell (approximately three times more than the amorphous solar cell without a filter). However, the high output comes along with the power output varying as the incident light color changes. To a certain extent, this is also applicable to the monocrystalline solar cell, wherein there is a lesser output, which has lesser variation as well. For example, yellow and magenta filters have a nearly identical output, which is opposed by the output of the polycrystalline solar cell which has a variation of 0.03W. In this data, it is always the amorphous solar cell that is the weakest. However, it has greater stability as it has relatively lesser variation in its output as compared to the other cells.

With reference to the graph, the polycrystalline cell has an output that is majorly dependent on the incident light's intensity. For example, the output in the last 4 data points fluctuates a lot. The peaks are coincided with the filters that have a high % transmission like red and peacock blue, while the troughs are coincided with the filters that have a low % transmission like green and blue. The intensity is the number of emitted photons; each photon interacts with an electron (one electron). As a result, since more electrons have the ability to jump to the conduction band (across the bandgap), the polycrystalline solar cell is more powerful. This thus implies that the bandgap in the polycrystalline solar cell will be the lowest out of the 3 different structures. Given this is true, there would be a low voltage (as each electron only has a little energy), and the current would be high due to the presence of more electrons. This will be verified in the following graphs (graphs 2 and 3).

Since the other cells had power outputs that showed lower variance with intensity, this suggests that they possess a relatively larger bandgap (especially in the amorphous solar cell). The electrons are able to be excited only by a few high-energy photons, which thereby makes the effect of adding more photons (for a higher intensity) minimal. This perhaps explains the utilization of amorphous solar cells in calculators. Its output does not fall as much as a polycrystalline solar cell in low light conditions. Thus, the amorphous solar cell must possess the lowest current (fewer current-carrying electrons) and the highest voltage (many energetic electrons). This will be verified in the following graphs (graphs 2 and 3)

It is observed that the solar cell's power outputs vary (upwards and downwards) at the same spots, with the exception of red light (anomaly). In the case of red light, while there is a decrease in output for the amorphous solar cell, there is an increase in the output of the other 2 cells. This suggests that the efficiency at certain wavelengths is prominently determined by the material that is used, rather than the structure.

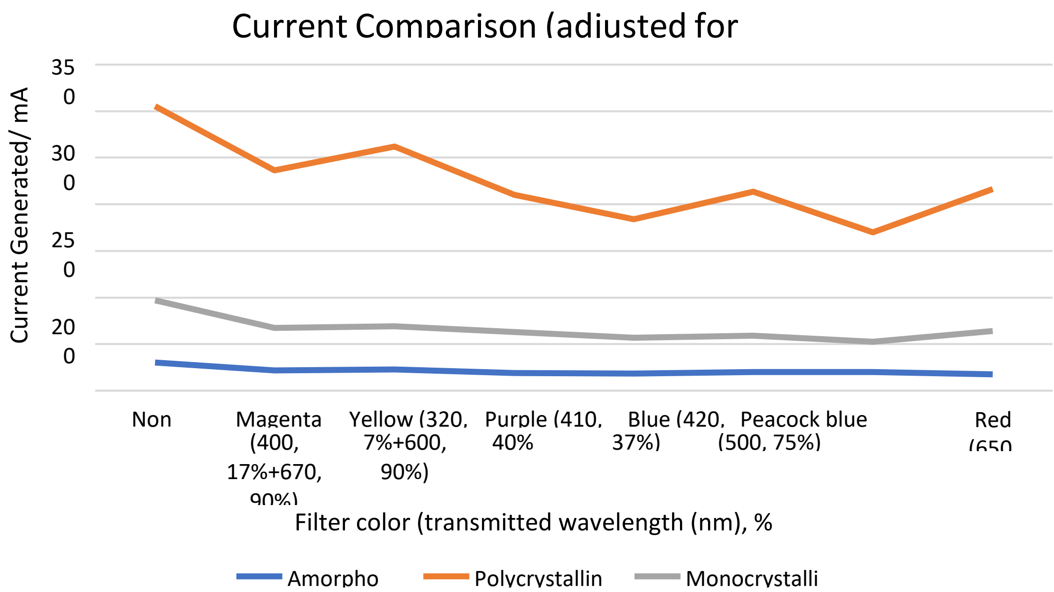


Graph 2

The comparison depicted in the graph above is in accordance with the idea aforementioned – there is a high voltage in the amorphous solar cell, which indicates that the electrons have a high average energy. The idea of having a high bandgap is supported by this, as the photons that have relatively lower energies are unable to sufficiently excite the electrons to cross the bandgap.

Once again, despite having a lower output, the polycrystalline solar cells show a lot of variation in comparison to the monocrystalline solar cell. The previous conclusion that since the polycrystalline solar cell has a lower bandgap, more electrons can jump under the sunlight and have lower average energies is validated. Based on this, the polycrystalline cell should have the highest current. Moreover, since the voltage peaks where the % transmitted is the highest, it can be deemed that the voltage is dependent on the intensity to a great extent. Furthermore, a low voltage corroborates to the fact that the polycrystalline solar cell's power output is high due to the presence of low energy electrons (a large amount of low energy electrons). This explains the usage of amorphous cells in calculators; less variation is shown with light intensity, which thus makes it effective at low intensities as well. Besides, in a location that has low lighting (classroom/ study hall), the polycrystalline cells would be largely ineffective.

Additionally, the relatively higher voltages possessed by the amorphous and monocrystalline cells indicates that they would have a lower current. As a result, using the equation $Ploss = I2R$, there would be a reduction in the power loss over a large distance.



Graph 3

However, this difference would only be noticeable when the power is being transmitted over distances that are large enough to nullify the power difference between the polycrystalline and other cells.

As implied by the voltage comparison, the highest current is possessed by the polycrystalline cell, which is heavily dependent on the incident light's intensity (% transmission). In order to permit this, there must be a lower bandgap. As a result, this is in accordance with the previous graph (graph 2), wherein the number of photons was the determining factor.

The 2 other cells had substantially lower current outputs relative to the polycrystalline cell. There was a mild downward curve as the wavelength increased for the output of the amorphous cell. Once again, this is in accordance with the idea of a high bandgap since the energy that is transmitted is dependent on the high average energy of the photons. Based on this, one would expect the voltage comparison to have large variations, and to show greater variance with a change in wavelength (rather than intensity). Indeed, there are huge variations. However, they have a minimal correlation with the incoming light intensity. For example, the output for red light (75%) is lower than the output for green light (37%) in the amorphous cell. Thus, there is no intensity cap to the amorphous cell and to a certain extent, the monocrystalline cell as well. Rather, they have a frequency cap, as the cells' determining factor is each photon's energy. Thus, it can be deduced that there is a frequency cap for the amorphous and monocrystalline silicon solar cell, while there is an intensity cap for the polycrystalline silicon solar cell.

Hence the best application for each structure can be shown:
Polycrystalline solar cells would be a preferred structure for the large-scale generation of electricity. For instance, in a desert, wherein irrespective of the wavelength, there is a very high intensity. Amorphous cells (and monocrystalline cells to a certain extent) would be highly useful in an unstable and low lighting environment such as a classroom.

Monocrystalline cells seem to be in the middle of polycrystalline and amorphous cells. They would be satisfactory in large-scale productions, but far more efficient than amorphous cells in terms of small-scale productions. However, its main weakness is its cost. A small cell could be highly expensive, which makes it unpractical to be used in a calculator. Thus, since amorphous solar cells are relatively cheaper, they are perhaps used in calculators.

Evaluation:
Errors:
Measurement delay – Since the readings of the current and the voltage are taken separately, this affects their readings. Alongside this, the time required to look at the data-logging computer that was connected to the multimeter introduced a lag; the light intensity would often change during this time. As a result, the light intensity had a greater uncertainty. This error could have been rectified through the utilization of computerized data-loggers. Using this would permit a near- instantaneous light intensity value for the measurement of each current and voltage. This would lessen the impact of random errors on the light intensity by decreasing its uncertainty.

Color filter precision – The filters that were utilized in the experiment permitted a range of light wavelengths to pass through, rather than a single wavelength of light. A more detailed analysis on the effect of the wavelength of light on the power generated would be permitted by the utilization of more precise filters. Additionally, the filters only filter the light in the visible spectrum, thus permitting light from the infrared and ultraviolet spectra to pass. Although this means the results obtained cannot be accurately extrapolated to the singular spectra, it does not majorly affect the outcome, as the same circumstances were present in all the filters.
Filter placement – Exactly placing the filter on the solar cell's open part was difficult. As a result, there would be some systematic error, wherein the power that is measured would be lower than what it would have been if the filter had been perfectly placed. This could be rectified by placing guiding vanes on top of the cell.

Placement of light intensity meter – Solar panels can take in light from any direction. However, the meter permitted light to only enter from direction. As a result, there would be a tiny systematic error, which could potentially be solved by the inclusion of an open light sensor.

Temperature of solar panel – The efficiencies of the solar panels were hindered as they would occasionally get exceptionally hot underneath the sun. Using a reflective tape, or a reflective material (aluminum foil) would neglect this systematic error.
Sun as a source – The efficiencies of all the solar cells were evaluated at different wavelengths of the sun. However, the fact that the sun is not a pure white source wasn't taken into consideration. To tackle this, the solar radiation spectrum could have taken into consideration, and the values could have been manipulated in order to account for the spectral irradiance difference.

CONCLUSION

To answer the research question of "Which silicon structure makes the most effective solar cell?", it can simply be said that no particular structure is an ideal solar cell. Depending on the usage of the cell, its effectiveness can be determined.

Accounting to its low cost and the fact that it has a frequency cap due to its large bandgap, amorphous cells have greater efficiencies in darker environments, wherein there are lower power requirements. As a result, the electrons are only excited by the high energy photons; there are sufficient high energy photons at low intensities. Thus, unless a very low intensity has been reached (lower than 37% of normal light in this experiment), the incident light's intensity does not determine the output power. This makes the application of amorphous cells more suitable to devices such as calculators, wherein the light may be coming from inside a relatively darker room.

There is a relatively higher output in polycrystalline cells. However, since it has a small bandgap, it has an intensity cap at higher wavelengths. As a result, in order to generate power, it is dependent on many electrons being excited (since each electron does not have much energy). Thus, polycrystalline cells would be suitable for large-scale generation of power, in places such as deserts wherein there isn't much variation in long-wavelength radiation throughout the day. At lower wavelengths, there is a frequency cap, which thus makes it highly applicable for the generation of power during sunrise and sunset.

Monocrystalline cells are somewhat in the middle of polycrystalline and amorphous cells. Its generation of power is more than the amorphous cell, but less than the polycrystalline cell. The variance observed in its power generation is in between the other 2 structures as well. It behaves similar to a polycrystalline cell, as it has a frequency cap at lower wavelengths and an intensity cap at higher wavelengths. Had it not had an extremely high cost, it would have a great performance balance.

Conclusively, getting back to the research question; for small-scale operation, amorphous cells are the most suitable, while polycrystalline cells are most suitable for large scale operations.

Scope of Research:
I intended to consider multiple types of solar cells. However, due to a lack of availability, only silicon-based solar cells were taken into consideration. Future scope of the experiment is as follows:

Using filters that have a greater range of wavelengths.

Testing the power outputs at a range of temperatures (warmer/cooler cells) in order to get a simulation of different environments.
Obtaining readings from multiple units of each type of solar cell, and then finding the average value.

REFERENCES

[1] What are solar cells? TWI. (n.d.), from https://www.twi-global.com/technical- knowledge/faqs/what-are-solar-cells
[2] Admin. (2022, August 18). PN junction - definition, formation, application, VI characteristics and faqs. BYJUS, from https://byjus.com/physics/p-n-junction/
[3] Thompson, Barry C., and Jean MJ Fréchet. "Polymer–fullerene composite solar cells." Angewandte chemie international edition 47.1 (2008): 58-77.
[4] Khan, Firoz, and Jae Hyun Kim. "Emission-wavelength-dependent photoluminescence decay lifetime of N-functionalized graphene quantum dot downconverters: Impact on conversion efficiency of Cu (In, Ga) Se2 solar cells." Scientific reports 9.1 (2019): 1-9.
[5] Corcoles, Laura, et al. "Wavelength influence on the photodegradation of P3HT: PCBM organic solar cells." Solar Energy Materials and Solar Cells 141 (2015): 423- 428.

