International Baccalaureate

Extended essay cover

Candidates must complete this page and then give this cover and their final version of the extended essay to their supervisor.

Candidate session number			
Candidate name			
School number			
School name			
Examination session (May or November)	MAY	Year	2012

Diploma Programme subject in which this extended essay is registered: PHYSICS HL

(For an extended essay in the area of languages, state the language and whether it is group 1 or group 2.)

Title of the extended essay: WHICH STRUCTURE OF SILICON MAKES THE MOST EFFECTIVE SOLAR CELL?

Candidate's declaration

This declaration must be signed by the candidate; otherwise a grade may not be issued.

The extended essay I am submitting is my own work (apart from guidance allowed by the International Baccalaureate).

I have acknowledged each use of the words, graphics or ideas of another person, whether written, oral or visual.

I am aware that the word limit for all extended essays is 4000 words and that examiners are not required to read beyond this limit.

This is the final version of my extended essay.

Candidate's signature: ____________ Date: 15/02/12

Supervisor's report and declaration

The supervisor must complete this report, sign the declaration and then give the final version of the extended essay, with this cover attached, to the Diploma Programme coordinator.

Name of supervisor (CAPITAL letters) [redacted]

Please comment, as appropriate, on the candidate's performance, the context in which the candidate undertook the research for the extended essay, any difficulties encountered and how these were overcome (see page 13 of the extended essay guide). The concluding interview (viva voce) may provide useful information. These comments can help the examiner award a level for criterion K (holistic judgment). Do not comment on any adverse personal circumstances that may have affected the candidate. If the amount of time spent with the candidate was zero, you must explain this, in particular how it was then possible to authenticate the essay as the candidate's own work. You may attach an additional sheet if there is insufficient space here.

[redacted] is an intelligent and hardworking student.He is sound in his concepts and is highly innovative in applying those concepts.He is highly motivated towards applying his knowledge in Physics to everyday life.His research topic deals with effective use of solar cells.Its relevance in a world of dwindling fossil fuel reserves is immense.He has skilfully made the solar cells suitable for his experiment as elaborated in the procedure. His data collection technique is systematic and exhaustive ;encompassing all relevant variables.He has done in depth analysis of the data procured.His presentation of ideas is lucid,logical and coherent.He has presented a reasoned and convincing argument in relation to his research question.While analysing the data,he came up with certain unresolved questions that provides scope for further research.

This declaration must be signed by the supervisor; otherwise a grade may not be issued.

I have read the final version of the extended essay that will be submitted to the examiner.

To the best of my knowledge, the extended essay is the authentic work of the candidate.

I spent 3 hours with the candidate discussing the progress of the extended essay.

Supervisor's signature: [redacted] Date: 15.02.2012

Assessment form (for examiner use only)

Candidate session number [redacted]

Criteria	Examiner 1	maximum	Examiner 2	maximum	Examiner 3
A research question	2	2	2	2	
B introduction	2	2	2	2	
C investigation	4	4	3	4	
D knowledge and understanding	4	4	3	4	
E reasoned argument	4	4	4	4	
F analysis and evaluation	3	4	2	4	
G use of subject language	4	4	4	4	
H conclusion	2	2	2	2	
I formal presentation	3	4	3	4	
J abstract	2	2	2	2	
K holistic judgment	4	4	3	4	
Total out of 36	34		30		

e of examiner 1: [redacted] Examiner number: [redacted]
PITAL letters)

e of examiner 2: [redacted] Examiner number: [redacted]
PITAL letters)

e of examiner 3: ______ Examiner number: ______
PITAL letters)

IB Cardiff use only: B: ______

IB Cardiff use only: A: 104465 **Date:** 10/5

Candidate Name: Candidate Number:

International Baccalaureate Diploma Program

Extended Essay

Subject: Physics

in intro; title would be different from RQ

Research Question: "Which structure of silicon makes the most effective solar cell?"

Candidate Name:

Candidate Number:

School Code:

Session: May 2012

Supervisor:

Word Count: 3985

comments on p.9

Candidate Name: Candidate Number:

Abstract: **Word count: 298**

The aim of this Extended Essay is to examine which structure of silicon makes the best solar cell. Three kinds were used – amorphous, moncrystalline, and polycrystalline. The incident wavelength of light was altered by color filters of different wavelengths. The voltage and current generated by the amorphous solar cell were measured for different wavelengths of incident light. The experiment was repeated for the other solar cells.

Analysis of the data resulted in several conclusions:

1. The output of the amorphous cell varies with frequency, suggesting that it has a large bandgap.
2. The output of the polycrystalline cell varies with intensity at higher wavelengths, and with frequency at lower wavelengths, suggesting a small bandgap.
3. The output of the monocrystalline cell varies in between the other two – it has a medium-sized bandgap, varies somewhat with intensity at higher wavelengths, and somewhat with frequency at lower wavelengths.

These conclusions answered the research question, "Which structure of silicon makes the most effective solar cell?":

There is no single best solar cell, but the usage conditions determine a cell's effectiveness.

The amorphous cell is cheap and its output varies little with intensity, but does not produce much power. Thus, it suitable for low intensity environments (like indoors), for use in small devices like calculators and watches.

The output of the polycrystalline cell varies mainly with intensity, so is most useful for outdoor uses, like deserts. It also varies with frequency at low wavelengths, so is useful at dawn and dusk (bluish light), as well as midday. It produces much more power, so is suitable for large-scale production of energy.

The output of the monocrystalline cell is more than that of the amorphous cell, but not enough to offset its prohibitive cost. It is most suitable in small scales, or in processors.

RQ

concl.

def'n of effectiveness

G

ambiguity in RQ clarified...

RQ, Method, and Conclusions are clearly presented.

Abstract: 2/2

Candidate Name: Candidate Number:

Contents

Candidate Name: Candidate Number:

1. Introduction

(avoid personal pronouns)

1.1 Background of my essay:

I have always been interested in solar cells, as I think they will be very relevant in the near future. Solar power is a renewable energy source available in abundance, and with oil reserves running out, I think we need to find out which solar cell is the best, and for what application. I think that this extended essay was a very good opportunity to clear this question in a more scientific manner. My experiment is designed to explore the effectiveness of each kind of solar cell in different situations. If we find each solar cell's performance at different points along the electromagnetic spectrum, we can determine which kind would be best for different applications. This led to my research question: why quotation marks?

* RQ: 2/2

"Which structure of silicon makes the most effective solar cell?" RQ – clearly defined in the paragraph prior to the statement.

(effective for what? situations?

1.2 Theory of solar cells: [1]

Solar cells are semiconductor devices which convert solar energy to electrical energy. They are p-n junctions. The light is incident on the p-surface of the solar cell, which is made very thin to allow photons to reach the underlying p-n junction. If the energy of the incident photons is greater than or equal to that of the band gap of the material, the photons cause the breakage of covalent bonds, forming free electron-hole pairs. The electrons move across the junction to the n-side and the holes cross to the p-side, resulting in a potential difference across the ends of the cell. Metal contacts connect the cell to the external circuit.

The typical V-I characteristics of a solar cell are shown below:

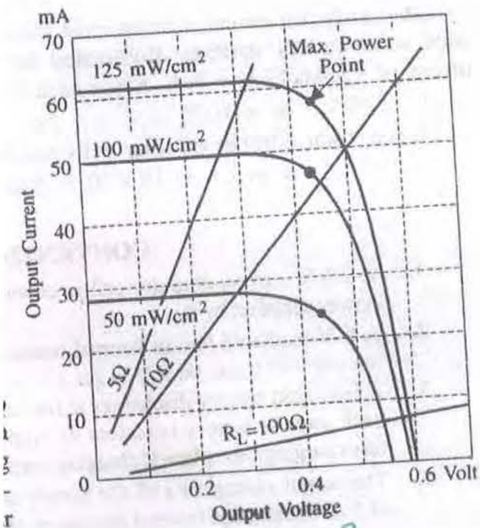


Fig. 6.9 ? ← ?

Fig 1 : label

I D C

– This graph must be explained in details .. no explanation given at all ...

– limited principles stated re production of elec. power; but nothing about determination of P_{max} in a circuit with PV cell; impact of types of cell! → principle ...

Intro: resn. worth. fine
2/2 ignores principles: "limited", marks 2

(theoretical development should be done in a "chapter" independent from the intro)

I

[1] Theraja, B.L. (2001) Basic Electronics Solid State (pp. 68 – 69). New Delhi, S. Chand & Company Ltd.

* context suggests that effectiveness is related to power ... maximum power ...

2. Selection and Control of Variables:

light intensity is an important function of angular position of the sun (assuming PV cell fixed) 9

2.1 Independent Variable:

1. Wavelength of incident light – the readings are taken with different color filters.
2. Structure of silicon solar cell – the experiment is repeated for each of the cells.

2.2 Dependent Variable:

1. Voltage generated by solar cell
2. Current generated by solar cell

what about power? max power? 5

Each of the above quantities are measured with each of the color filters with each of the solar cells.

2.3 Controlled Variables:

do you mean solar spectrum received at the sfce of Earth .. less intensity in some λ?

color? & not a "variable" here

1. **Color of sunlight** – At sunrise and sunset, the color of sunlight changes. All of the readings are taken at midday, so the sun moves very little while the readings are taken. Assuming sufficient speed in taking the readings, the color of sunlight can be taken as constant.
2. **Angle of incidence** – For the same reason as previous, the sun moves very little. Thus, the angle can be taken to be 90° for all readings. This was carried out at a specific angle for the cell? 13° from horizontal is necessary
3. **Temperature** – Because the readings are all taken within a short time of each other at midday (on one day), there is very little temperature variation. Thus, the temperature can be taken as constant. temp.?
4. **Intensity of incident light** – The light intensity meter measures the intensity of the incident light at the time of measuring voltage and current. After collecting the intensity data, the data was adjusted to simulate constant intensity.
5. **Surface area of solar cells** – The solar cells are covered with duct tape in order to leave a specific surface area open to incident light.
6. **Structure of silicon solar cell** – While the wavelength of the incident light is being varied, the solar cells are not switched. type of...
7. **Wavelength of incident light** – The wavelengths let through by the filters remain constant, even when the structure of the solar cell changes.

(no sunlight is used, it seems)

?

Candidate Name: Candidate Number:

3. Preparing for the experiment:

I bought 1 solar cell of each structure, but their sizes were different. In order to equalize them, this procedure is required.

3.1 Apparatus required for equalising solar cells:

1. Sheet of paper cut to desired size
2. 1 amorphous silicon solar cell
3. 1 monocrystalline solar cell
4. 1 polycrystalline solar cell
5. 1 roll of black, opaque duct tape
6. Scissors
7. Ruler
8. Pencil

some details... (C)

list: not style of an EE (I)

3.2 Procedure for equalising solar cells:

1. Measure paper to a specific size (I chose 3 x 2.3cm arbitrarily) and mark with pencil
2. Cut along pencil line, take piece of paper
3. Place paper on amorphous solar cell.
4. Put duct tape along its edges in order to cover the rest of solar cell.
5. Cover the outer parts of the panel with additional duct tape, until the paper is the only part not covered.
6. Remove the paper, leaving the amorphous solar cell with only a specifically-sized area open.
7. Repeat for monocrystalline, polycrystalline solar cells.

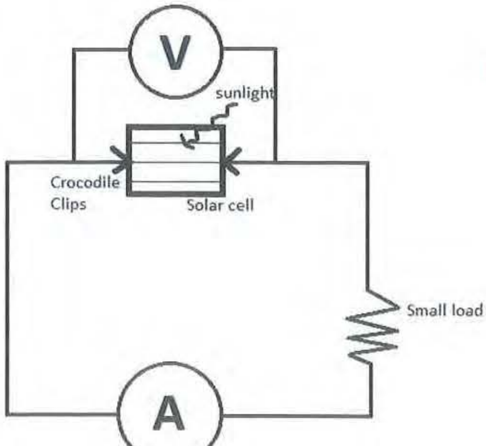
(I) - cookbook recipe style not for an EE - more net- of diagram (G)

3.3 Apparatus required to construct circuit and conduct experiment:

1. 2 multimeters details...
2. 2 crocodile clips
3. connection wires
4. amorphous, monocrystalline, and polycrystalline silicon solar cells
5. 1 lightmeter details..

(no mention of "clips" on a circuit diagram)

3.4 Circuit Diagram:



(UK circuit symbols)

Fig 2: label

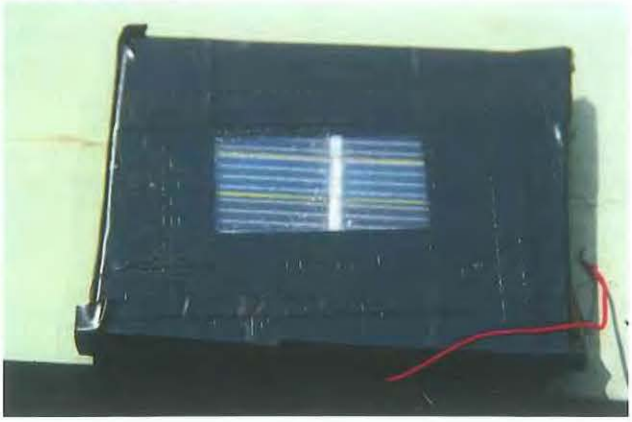
Candidate Name: Candidate Number:

3.5 Solar cells used in experiment:

For this experiment, I was only able to acquire silicon-based solar cells. However, since silicon cells are very widespread, I think that the experiment is still relevant even with only silicon cells. I have explored efficiencies of three structures of silicon: monocrystalline, polycrystalline, and amorphous silicon. ✓

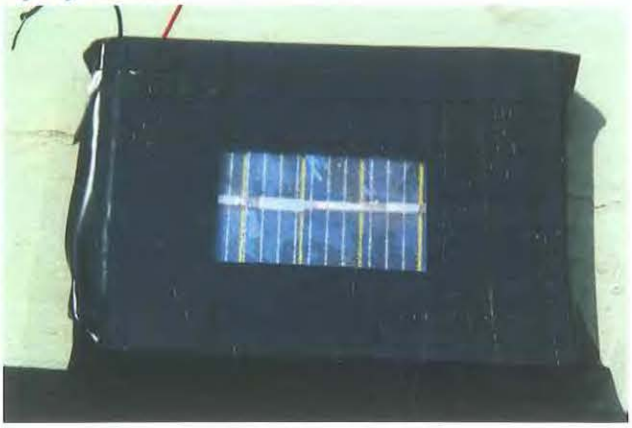
efficiency : not yet fully define operationally... G

3.5.1 Monocrystalline



(not very useful) I

3.5.2 Polycrystalline



3.5.3 Amorphous

Monocrystalline cells are made of a single crystal, and polycrystalline cells of multiple crystals. Amorphous cells do not have a crystalline structure. (limited info)

4. Data Collection Procedure:

(no exp. done with & without filters...)

1. Connect amorphous silicon solar cell as shown in circuit diagram.
2. Record voltage, current using multimeters.
3. Record light intensity displayed by light meter (displayed on computer).
4. Place colored filter on the open part of the solar cell, repeat steps 1 through 4. Do the same for the other filters.
5. Replace amorphous silicon solar cell with polycrystalline solar cell, repeat steps 1 through 5.
6. Replace polycrystalline solar cell with monocrystalline solar cell, repeat steps 1 through 5.

may be not for an EE (I)

4.1 Raw Data Tables:

4.1.1 Amorphous

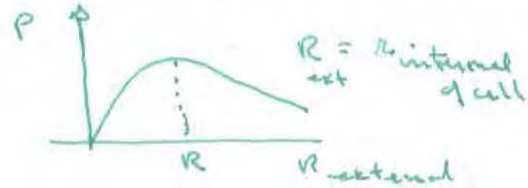
Filters	Voltage/V ± 0.01V	Current/mA ± 0.1mA	light int./lx ± 300lx
None	3.37	28.9	57700
Magenta	3.10	20.5	57300
Green	2.98	19.1	57600
peacock blue	3.21	19.4	58400
Yellow	3.32	21.9	58500
Red	3.13	18.6	63600
Blue	3.09	19.3	64200
Purple	3.16	19.9	63800

* spectral properties of the filters? (C) see later

4.1.2 Polycrystalline

Filters	Voltage/V ± 0.01V	Current/mA ± 0.1mA	light int./lx ± 300lx
None	1.09	296.0	58200
Magenta	0.65	241.6	61300
Green	0.47	179.0	63300
peacock blue	0.59	227.5	64000
Yellow	0.76	287.0	65800
Red	0.64	238.0	66100
Blue	0.51	201.8	65800
Purple	0.60	231.2	66100

*** what about the load? P_{max} is obtained when $R_{load} \sim r_{cell}$ => Load must be varied to get max product VI. (C) (D) (F)



Candidate Name: Candidate Number:

4.1.3 Monocrystalline

Filters	Voltage/V ± 0.01V	Current/mA ± 0.1mA	light int./lx ± 300lx
None	2.17	108.0	66900
Magenta	1.69	74.9	66800
Green	1.47	60.3	69000
peacock blue	1.55	67.6	69100
Yellow	1.75	80.2	69400
Red	1.63	74.2	69500
Blue	1.52	65.6	69000
Purple	1.60	72.1	68700

A: some ambiguity re defn of "most effective" in the RQ presented in the introduction .. which applications/situations ? b.o.d. near mark 2;

C: sources limited; many good data but some question regarding procedure followed to obtain what should be maximum power; limitations & uncertainties appreciated; approach to filter spectra too simple;

D: knowledge: lack of info re atomic structure/energy bands of different types of cells; also re circuitry: role of external resistance + internal resistance of cell in circuit

E: generally good argument, with parts of essay related coherently; some exception but overall near mark 4;

F: the V-I characteristics of solar cell ignored + its implications; characteristics of filters (spectral) not well taken care off; some adjustment of Data not well supported; the interpretation of graphs in context in the context of energy bands as a function of frequencies not supported in an academic context; impact of recognized limitations not clearly recognized;

G: no set up diagram + a few terms imprecise but generally fine;

H: good overview of conclusion & implications;

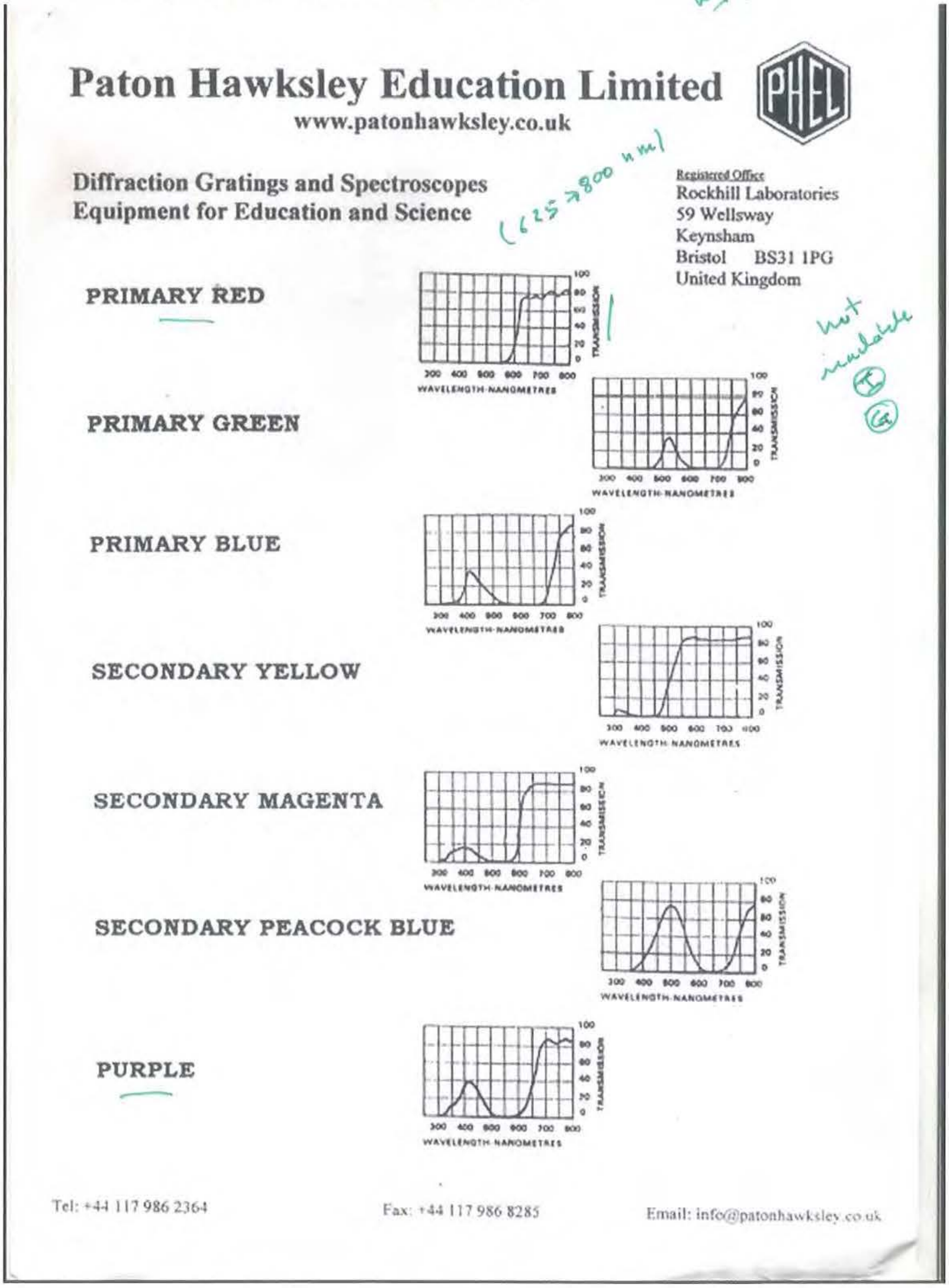
I: in parts IA style followed rather than an EE style; figures not numbered + labelled; poor spectral graphs of filters; graphs chosen to represent Data are not actually illustrating formally a function between two variables;

K: challenging initiative; info re solar & filter spectra gathered but info re energy band lacking; some procedural weaknesses but clear determination in making sure all relevant parameters are taken care of and adjusted if needed; overall clear evidence of acquired qualities, some qualities being not as strong as others; a very ambitious investigation, possibly explaining why some "corners" have been cut;

5. Data Analysis:

ref. link not visible

5.1 Data Comparison (adjusted for intensity):



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SECONDARY MAGENTA

SECONDARY PEACOCK BLUE

PURPLE

not readable

(T) (G)

Extract relevant info + present results in a data tables

(F) (C)

Tel: +44 117 986 2364 Fax: +44 117 986 8285 Email: info@patonhawksley.co.uk

The wavelengths of the filters are described by this paper from their manufacturer. This data is used to order the filters in terms of increasing wavelength (except for magenta and yellow, as they allow multiple

Candidate Name: Candidate Number:

wavelengths, and cannot be sorted).

The values of voltage and current cannot be compared when the incident intensities they relate to are different. To correct this, I have taken an arbitrary value (60000lx) and adjusted all the values to account for the change:

** what do you assume when adjustment made?

Adjusted Amorphous Voltage$_{none}$ = 3.37 * (60000/57700) = 3.50V ±

Adjusted Amorphous Current$_{none}$ = 28.9 * (60000/57700) = 30.1mA ±

From these adjusted values, I have calculated the power generated by the cells, through the formula P = VI:

Adjusted Amorphous Power$_{none}$ = 3.50 * 30.1 = 0.11W ±

(3 sig-fig allowed)

I repeated these actions for all values of voltage, current and power, for all three solar cells.

5.1.1 Data Tables (adjusted for intensity)

5.1.1.1 Amorphous (wrt 60000lx)

Filters (wavelength, % transmitted)	Voltage/V ± 0.01V	Current/mA ± 0.1mA	light int./lx ± 300lx	Power/W ± 0.001W
None	3.50	30.1	60000	0.105
magenta (400, 17% + 670, 90%)	3.25	21.5	60000	0.070
yellow (320, 7% + 600, 90%)	3.40	22.5	60000	0.076
purple (410, 40%)	2.97	18.7	60000	0.056
blue (420, 37%)	2.89	18.0	60000	0.052
peacock blue (500, 75%)	3.29	19.9	60000	0.066
green (525, 37%)	3.10	19.9	60000	0.062
red (650, 75%)	2.95	17.5	60000	0.052

5.1.1.2 Polycrystalline (wrt 60000lx)

Filters (wavelength, % transmitted)	Voltage/V ± 0.01V	Current/mA ± 0.1mA	light int./lx ± 300lx	Power/W ± 0.001W
None	1.12	305.2	60000	0.341
magenta (400, 17% + 670, 90%)	0.64	236.5	60000	0.151
yellow (320, 7% + 600, 90%)	0.69	261.7	60000	0.182
purple (410, 40%)	0.55	209.9	60000	0.115
blue (420, 37%)	0.47	184.0	60000	0.086
peacock blue (500, 75%)	0.55	213.3	60000	0.118
green (525, 37%)	0.44	169.7	60000	0.075
red (650, 75%)	0.58	216.0	60000	0.125

actually not a narrow band filter; also what about IR region?

(filter characteristics and solar spectrum characteristics to be compared see later)

** any test done to show that both V and I varies proportionally to the light intensity variations ?

Candidate Name: Candidate Number:

5.1.1.3 Monocrystalline (wrt 60000lx)

Filters (wavelength, % transmitted)	Voltage/V ± 0.01V	Current/mA ± 0.1mA	light int./lx ± 300lx	Power/W ± 0.001W
None	1.95	96.9	60000	0.189
magenta (400, 17% + 670, 90%)	1.52	67.3	60000	0.102
yellow (320, 7% + 600, 90%)	1.51	69.3	60000	0.105
purple (410, 40%)	1.40	63.0	60000	0.088
blue (420, 37%)	1.32	57.0	60000	0.075
peacock blue (500, 75%)	1.35	58.7	60000	0.079
green (525, 37%)	1.28	52.4	60000	0.067
red (650, 75%)	1.41	64.1	60000	0.090

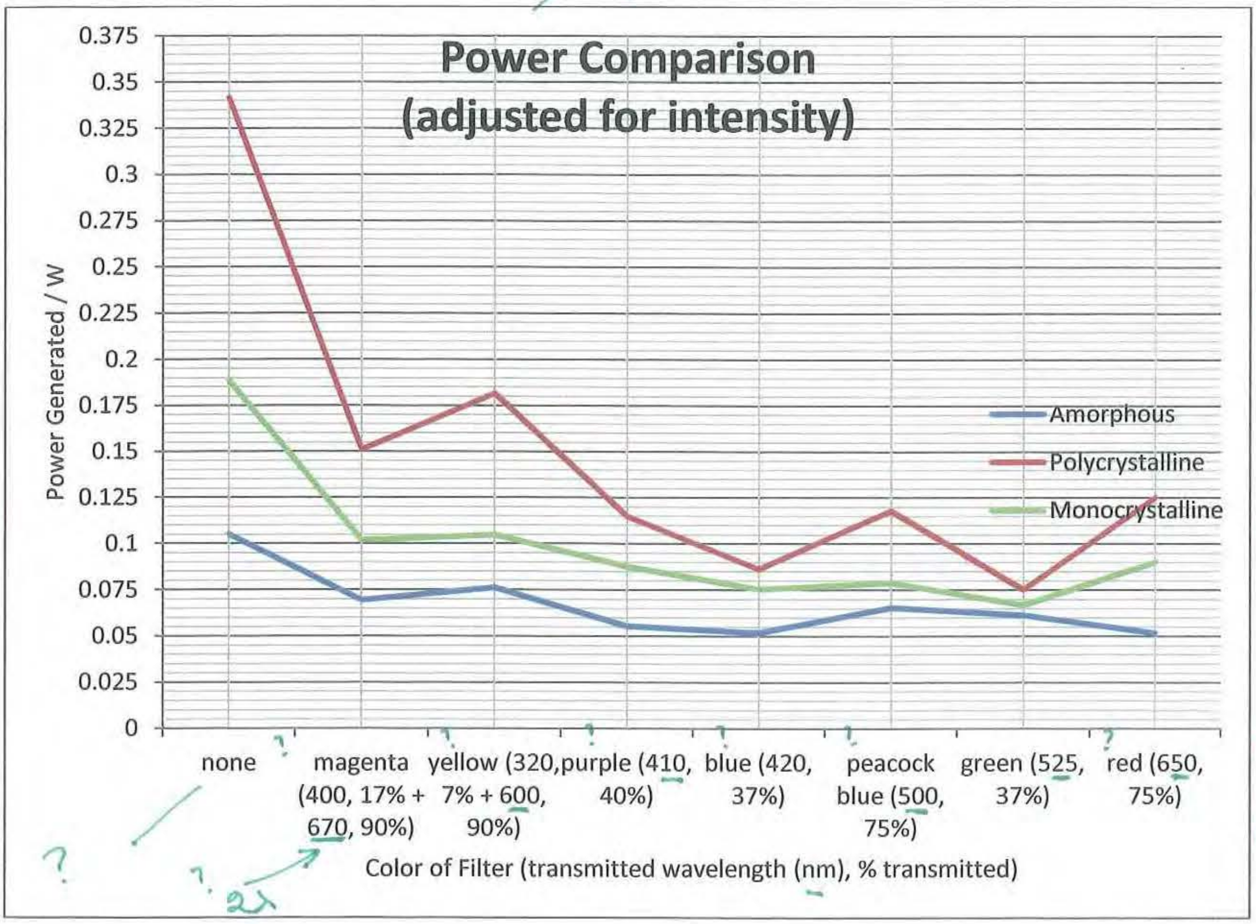
C
F

- .. some questions mainly about the choice of λ & transmittance of filters .. "situation" very simplified;
- .. careful consideration should be given to this important aspect ..
  .. if not, problems raised as seen on graph #( ) on p. 13 (abscissa);

|| what is the load used? .. same for all cells it seems; see VI graph on p4 (C)

see comment on p8

Candidate Name: Candidate Number:



max power ? (G)

how can we read label graph (I)

why line segments?

abscissa: very confusing (I)

how are λ values actually handled ...

From this graph, it can be seen that the polycrystalline solar cell generates much more power (thrice that of amorphous without a filter). However, with this high output also comes a very large variance in power output with the color of the incident light. This also applies somewhat to the monocrystalline solar cell, in that it has less output, but also varies much less. For example, the output with magenta and yellow filters is almost identical, as opposed to those of the polycrystalline solar cell, which varies by .03W. The amorphous solar cell is always the weakest in this data. However, it also possesses greater stability. Its output varies little compared to the other cells.

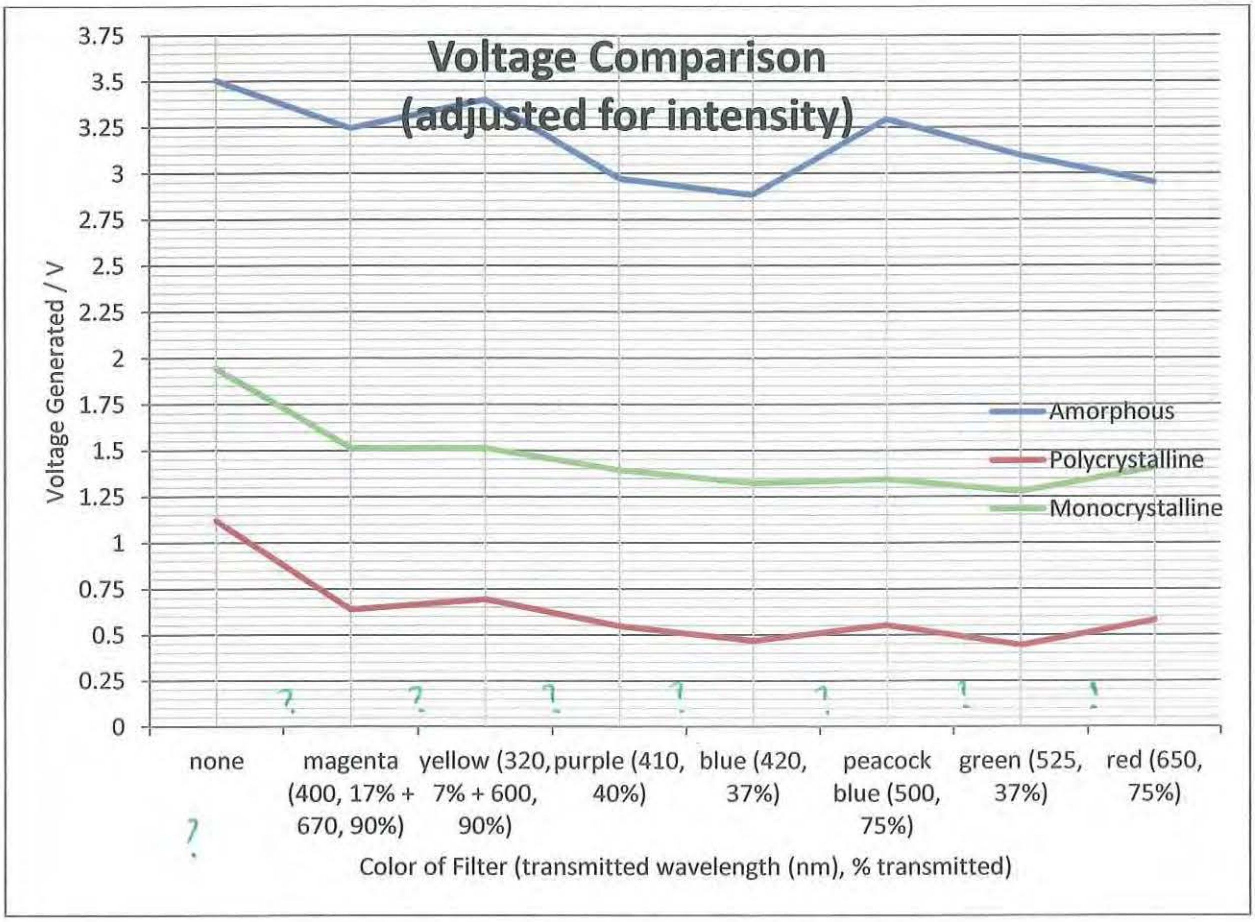
From the graph, the output of the polycrystalline cell is heavily dependent on the intensity of the incident light. For example, its output vacillates in the last four data points. The troughs coincide with low % transmitted filters (blue, green), and the peaks coincide with high % transmitted filters (peacock blue, red). Intensity is the number of photons emitted, and each photon can only interact with one electron. Thus, the polycrystalline cell is more powerful because more electrons are able to jump across the bandgap to the conduction band. This indicates that the polycrystalline silicon bandgap will be the lowest of the three. If this is true, then the voltage should be low (each electron has little energy), but the current should be high (many electrons). We can verify this in the next graphs.

The power output of the other cells varies less with intensity, which suggests they have a large bandgap (especially in the case of the amorphous cell). Only some high-energy photons are able to excite the electrons, so the addition of more photons (higher intensity) has little effect. This might be why an

(*) is Power generated max power as suggested by RQ .. some ambiguity no numerical values of λ on the abscissa ⇒ this is not a graph of power as a function of λ .. an histogram should be used;

amorphous solar cell is used in my calculator – in low light conditions, its output will not fall by as much as a polycrystalline cell. According to this, the amorphous cell should have the highest voltage (energetic electrons) but the lowest current (not many current-carrying electrons). We can also verify this in the next graphs.

The power output of solar cells appears to vary upwards and downwards at the same places, except for in the case of red light. For red light, the amorphous solar cell decreases its output, while the other two increase output. This suggests that for the most part, efficiencies at specific wavelengths are determined mainly by the material used, rather than its structure.



use a histogram

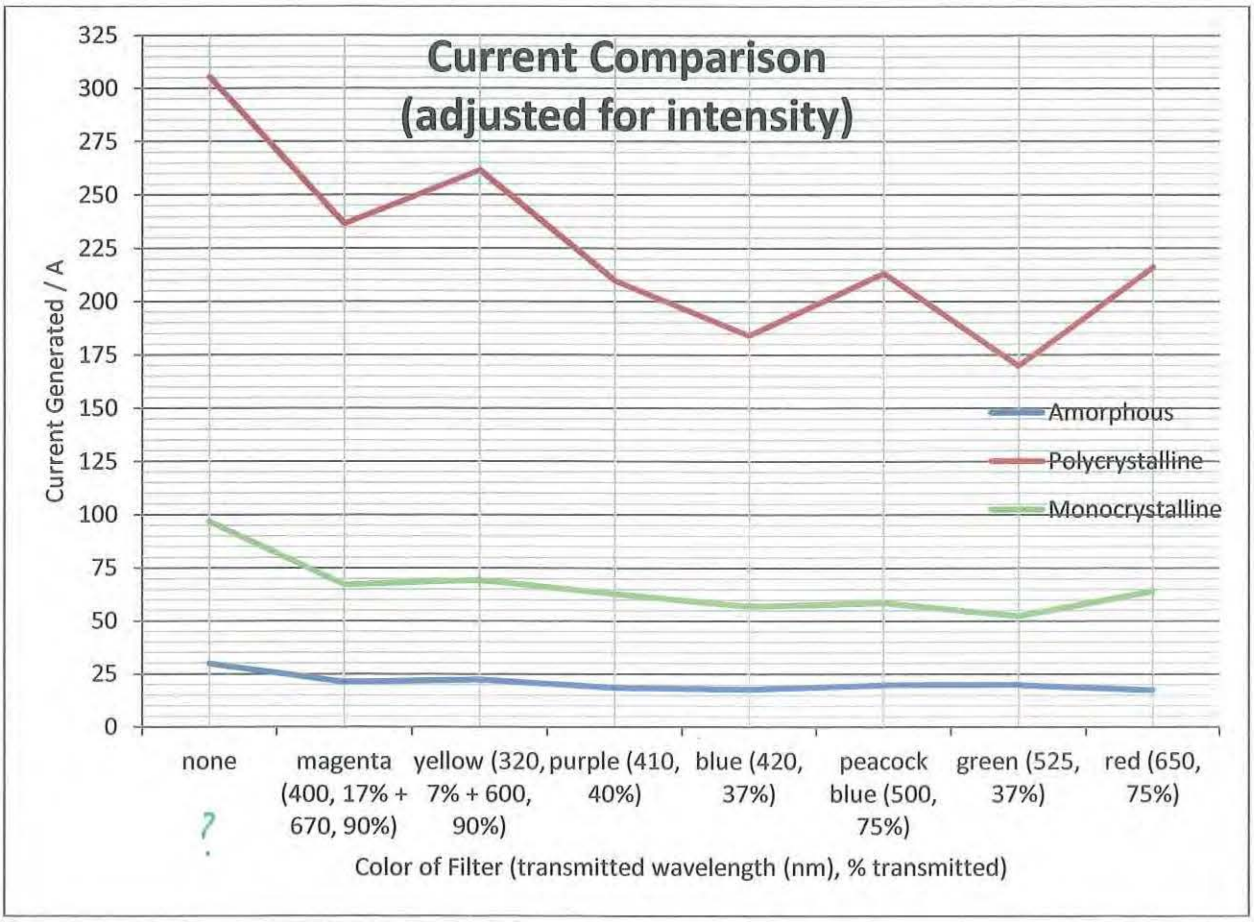
any complication from filter mixture?

This comparison confirms the idea held before – the amorphous silicon has very high voltage, indicating that the average energy of its electrons is high. This supports the idea of a very high bandgap; lower energy photons cannot excite the electrons enough to cross the bandgap.

However, the polycrystalline cell still varies a lot compared to monocrystalline, despite its lower output. This validates the previous conclusion: the bandgap in polycrystalline silicon is lower, so more electrons jump across under sunlight and their average energy is lower. Following this, the current should be maximum for the polycrystalline cell. The voltage is highly dependent on the intensity, as its peaks are where the % transmitted is highest. As the voltage is low, this confirms that the polycrystalline cell's high power output is due to having low energy electrons, but a large amount of them.

This can explain why the amorphous cell is used in calculators – it shows less variation with light intensity, so remains somewhat effective at low intensities. On the other hand, polycrystalline cells would be rendered ineffective by a low-light situation like a study hall, classroom, etc. is it the case?

In addition, the relatively high voltages of the monocrystalline and amorphous silicon solar cells would mean that their current would be lower – reducing power loss when transmitted over large distances (by the equation $P_{loss} = I^2R$). This, however, would probably only make a difference when transmitting power over very large distances – large enough to nullify the difference in power between the polycrystalline cells and the others.



any literature info?

As suggested by the voltage comparison, the polycrystalline cell has the highest current, and it is heavily dependent upon the intensity (% transmitted) of the incident light. The bandgap must be lower to allow for this. Thus, this agrees with the previous graph, in that the determining factor is the number of photons.

The other two have much lower current outputs. The amorphous cell's output has a slight downward curve with increasing wavelength. This confirms the idea of the high bandgap again; the energy transmitted depends on the average energy of the photons being high. According to this, we would expect to see large variations in the voltage comparison, varying more with regards to wavelength than with intensity. Sure enough, there are large variations, but they have little correlation with the intensities of the incoming light. For example, the amorphous panel's output for green light (37%) is higher than that of red light (75%).

Thus, the amorphous and (to a lesser extent) monocrystalline cells are not intensity capped, but rather frequency capped – the energy of each photon is the determining factor for these cells. Now we can see that monocrystalline and amorphous silicon solar cells are frequency capped, while polycrystalline silicon solar cells are intensity capped. Thus, we can show the best applications for each. Polycrystalline cells would likely be very good for large-scale electricity generation (for example, in a desert, where the intensity is very high regardless of the wavelength). Amorphous (and to a lesser extent, monocrystalline) cells are useful in unstable, low-light environments like classrooms and such. Monocrystalline cells seem to be a kind of middleman, merely all right for large scale operation, but more powerful than amorphous cells in small-scale operation. Their weakness, however, is their cost[2] – a single 300mm wafer can be $200, much too expensive for use in calculators, etc. This may be the reason that calculators seem to generally have amorphous silicon solar cells – they are relatively cheap.

the RQ is about solar cell: at the end, should we not use the full spectrum of sun light and see which type of PV cells yields the maximum power (including role played by the load resistance)? ⇒ "no filter" values of power:

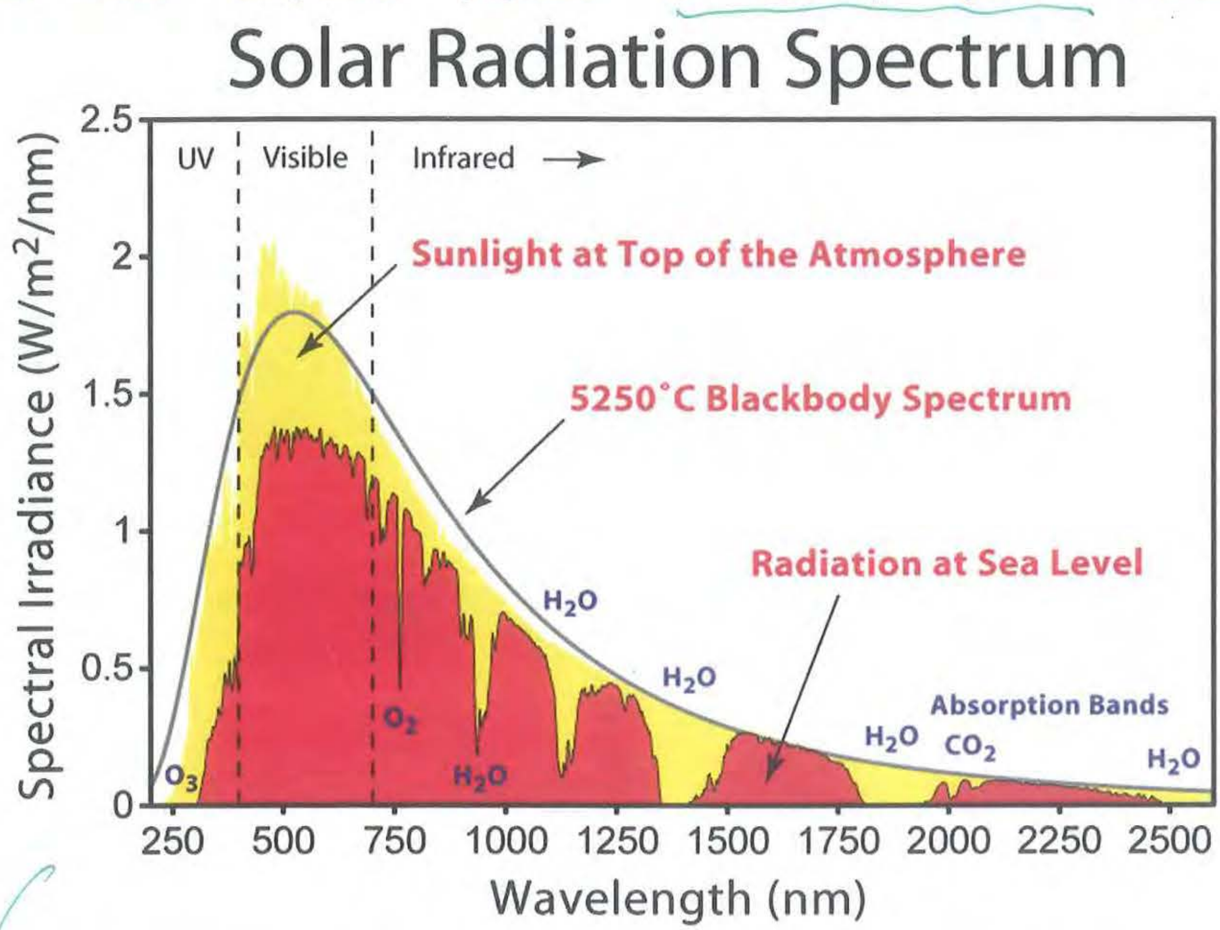
0.105 W → amorphous 3
0.541 W → poly. cryst. 1
0.189 W → mono. cryst. 2

((adjusted power values)

[2] http://en.wikipedia.org/wiki/Polycrystalline_silicon_photovoltaics

Candidate Name: Candidate Number:

5.2 Data Comparison (adjusted for intensity, spectral irradiance)



All of the previous graphs show the efficiency of the solar cells at different wavelengths from the sun, but this does not take into account the fact that the sun is not a purely white source. What would the graphs be like if it was? To find out, we can take the solar radiation spectrum[3] and adjust the values to correct for the differences in spectral irradiance. This will result in values depicting the cells' efficiencies at each wavelength. For these adjustments, I have only taken the single-wavelength colors: Purple, Blue, Peacock Blue, Green, and Red.

(realistic ? ...)

Spectral Irradiance / W m^{-2} nm^{-1}
Purple - 0.875
Blue - 0.95
Peacock Blue - 1.375
Green - 1.375
Red - 1.325

320 nm

650 nm

show how this is done: values + calculation

see p19

[3] http://en.wikipedia.org/wiki/Solar_radiation

Candidate Name: Candidate Number:

I have taken the average of the spectral irradiance for the visible spectrum as 1.1 W m^{-2} nm^{-1} (estimated from the above graph). I then adjusted the voltage and current values as follows:

using purple filter

White-light Amorphous $Voltage_{purple}$ = 2.97 * (1.1/0.875) = 3.74V

why exactly do this?
justification (physics)

White-light Amorphous $Current_{purple}$ = 18.7 * (1.1/0.875) = 23.5mA

F

White-light Amorphous $Power_{purple}$ = .056 * (1.1/0.875) = 0.070W

This was repeated for all five colors, and for all three solar cells.

5.2.1 Data Tables (adjusted for intensity, spectral irradiance)

5.2.1.1 Amorphous (wrt 60000lx, 1.1Wm^{-2}nm^{-1})

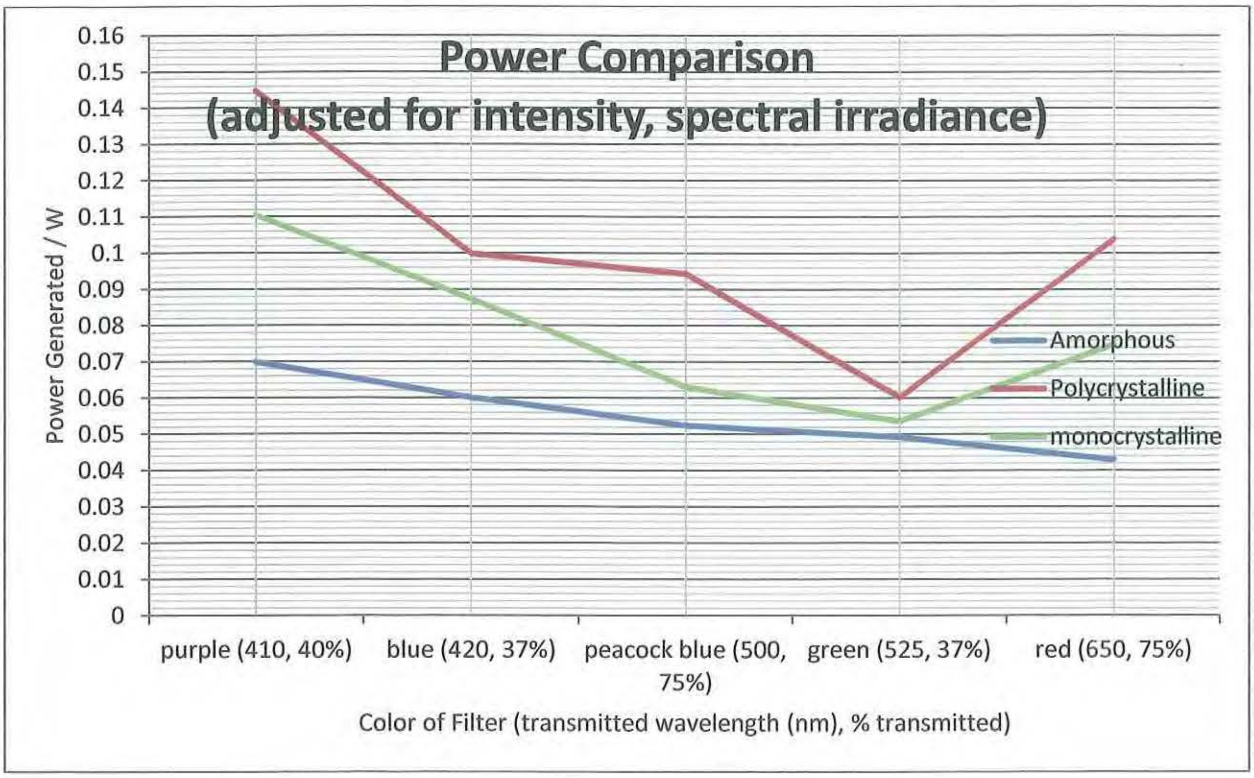
Filters	Voltage/V ± 0.01V	Current/mA ± 0.1mA	Power/W ± 0.001W
Purple	3.74	23.5	0.070
Blue	3.34	20.9	0.060
Peacock Blue	2.64	15.9	0.053
Green	2.48	15.9	0.049
Red	2.45	14.6	0.043

5.2.1.2 Polycrystalline (wrt 60000lx, 1.1Wm^{-2}nm^{-1})

Filters	Voltage/V ± 0.01V	Current/mA ± 0.1mA	Power/W ± 0.001W
Purple	0.69	263.8	0.145
Blue	0.54	213.1	0.100
Peacock Blue	0.44	170.6	0.094
Green	0.35	135.7	0.060
Red	0.48	179.4	0.104

5.2.1.3 Monocrystalline (wrt 60000lx, 1.1Wm^{-2}nm^{-1})

Filters	Voltage/V ± 0.01V	Current/mA ± 0.1mA	Power/W ± 0.001W
Purple	1.75	79.2	0.110
Blue	1.53	66.1	0.087
Peacock Blue	1.08	47.0	0.063
Green	1.02	41.9	0.054
Red	1.17	53.2	0.075



✓

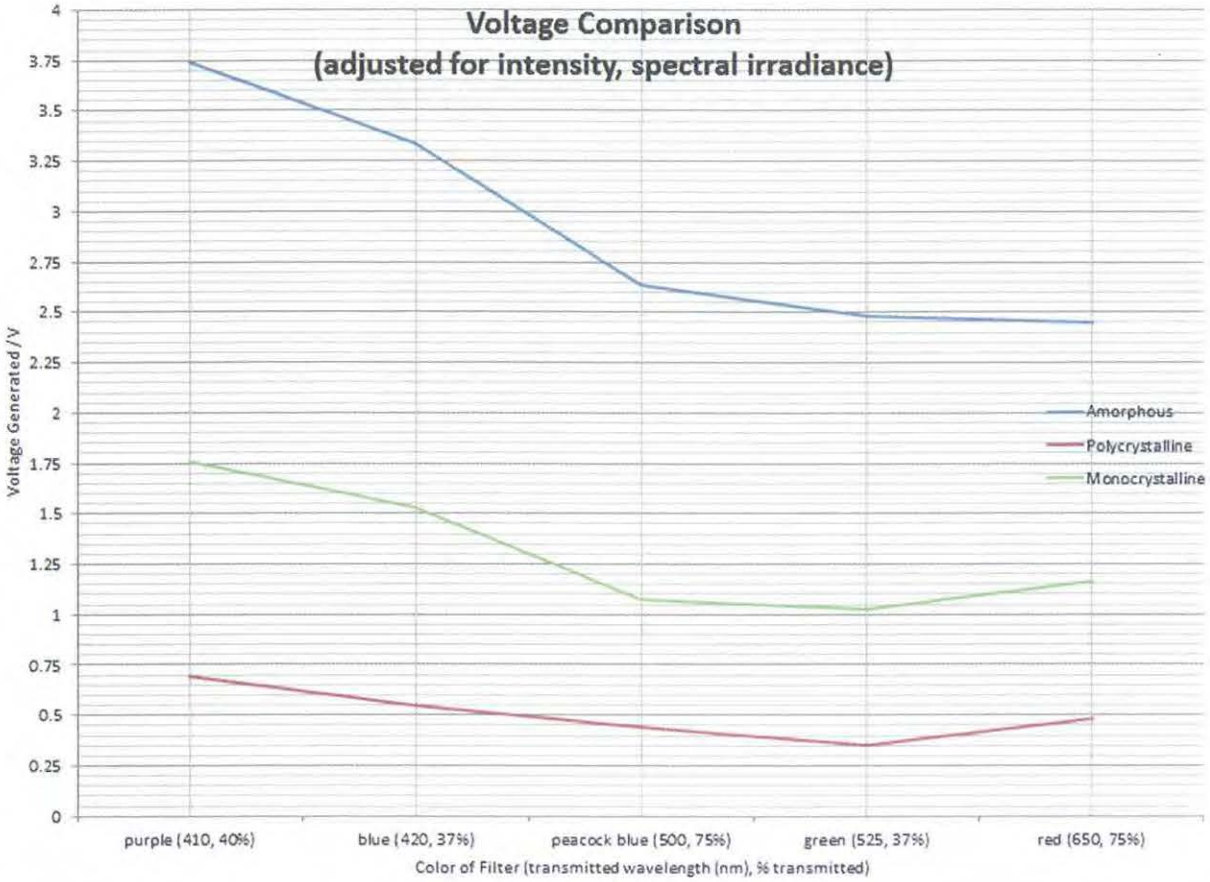
Now that the differences in the irradiation of the sun are accounted for, we can see the variation solely with respect to incident wavelength.

Here, in the case of the polycrystalline cell, we see a slightly different picture. Before, we saw that the power output was heavily dependent on the intensity of the incident light – the bandgap is small. However, here, its effect only extends until the green wavelength. The three values with the higher wavelengths (peacock blue, green, and red) appear to vary with intensity, as before. However, the lower wavelengths do not. Despite their low intensities, they still allow high power output. Thus, my previous statement should be modified somewhat – the polycrystalline cell is intensity limited for higher wavelengths of light, but frequency limited at lower wavelengths. In other words, the bandgap isn't as small as I thought. Radiation with a very high frequency (energy) can still increase the number of electrons crossing the bandgap. Looking back, this agrees with the previous power comparison graph. ✓

Again, the monocrystalline and amorphous solar cells appear to be affected little by incident intensity. Especially in the case of the amorphous cell, the only meaningful variation seems to be a downward slope with increasing wavelength (again confirming a large bandgap).

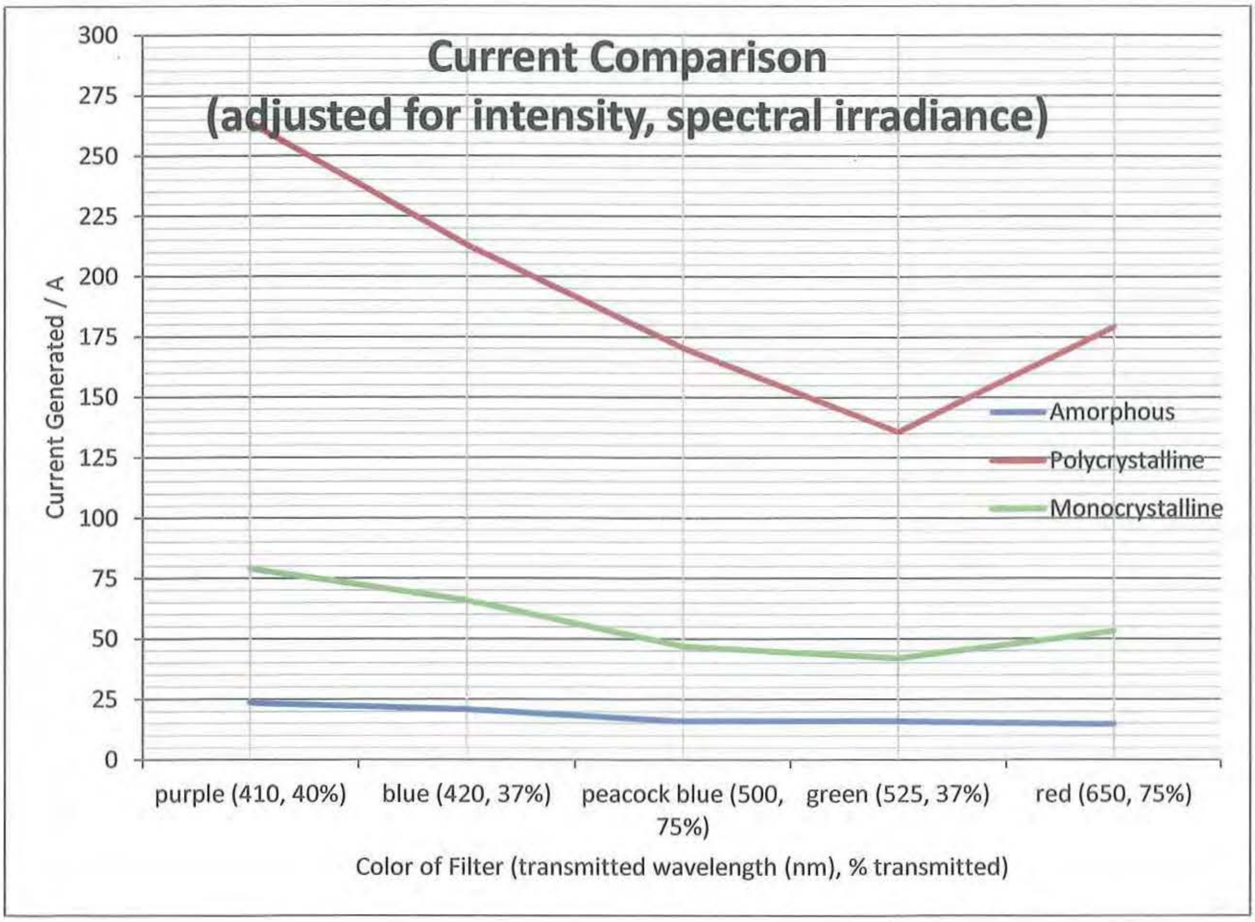
** any info re bandgaps of cells from literature? ...
E

Candidate Name: Candidate Number:



This data agrees with the other comparisons. Again, the amorphous cell is purely wavelength limited – the line slopes downward with increasing wavelength. The polycrystalline cell varies with intensity at higher wavelengths, and with frequency at lower wavelengths.

The monocrystalline cell varies like the amorphous cell at lower wavelengths, and like the polycrystalline cell at higher wavelengths. It varies less than either, however, so the size of its bandgap must be between the other two.



Again, the amorphous cell hardly varies at all with intensity, and has a slight downward slope with increasing wavelength. The polycrystalline cell displays the same properties we have seen before – it is intensity limited at high wavelengths and frequency limited at low wavelengths. The monocrystalline cell seems to be a hybrid of the two others – it varies with intensity and with frequency, rather than one or the other.

what is the ultimate criterion re most effective PV cell in sunlight ?

Candidate Name: Candidate Number:

6. Evaluation

6.1 Errors:

limitations ..

1. **Delay in measurement:** the voltage and current readings have to be taken separately from each other – doing those together affects both their readings. This, as well as the time taken to look to the data-logging computer from the multimeter, introduces a lag, during which the light intensity often changed. This increased the uncertainty on light intensity. I think this could have been removed with the use of computerized data-loggers. Each measurement of voltage or current could also have a near-instantaneous value for light intensity. This would decrease the uncertainty in light intensity, through random errors.
2. **Color filter precision:** the filters used in the experiment did not only let through one wavelength of light – rather, they let through a range, which peaked at the values that I have described. More precise filters would allow more detailed analysis of the effects of the wavelength on the power generated. Also, apparently, they only filter out light in the visible spectrum. They allow all the light from the ultraviolet and infrared spectra. Since they all do this, it does not affect the outcome, but it does mean that the results cannot be extrapolated easily to those spectra.
3. **Color filter intensity:** In addition, the intensities of the light they let through varied from filter to filter. Ideally, they would all let through the same intensity, to allow the variable to be controlled by other factors. Unfortunately, the only way to do that is to buy other filters, which I could not do.
4. **Filter placement:** It was quite difficult to place the filter exactly upon the open part of the solar cell. This would result in a systematic error, where the power measured is less than it would be with the filter placed perfectly. Guiding vanes placed atop the cell would help remove this uncertainty.
5. **Light intensity meter placement:** The meter only took in light from one direction, while the solar panel can take in light from any direction. This would produce a small systematic error, which could be solved by an open light sensor (mine was opaque on the sides).
6. **Solar panel temperature:** The solar panels would get very hot under the sun, which could affect their efficiency. This systematic error could be solved by getting reflective tape, or by covering the tape in reflective material, like aluminum foil.

? still, how air temperature affects the internal resistance of the cell & its maximum power ? ..

(impact of most important limitations on the results ?)

7. Conclusion

7.1 Which structure of silicon makes the most effective solar cell?

There is no single best solar cell, but the usage conditions determine a cell's effectiveness.

An amorphous cell is very effective in darker environments with low power requirements, due to its cheapness and the fact that it is frequency limited (its bandgap is very large). Thus, only the high energy photons excite electrons, and enough of these exist even at low intensities. This means that its power output is not determined by the intensity of the incident light until very low intensities are reached (less than 37% of normal light, according to my data). Thus, it can be used in devices like calculators, where the light may be from inside a dark classroom.

A polycrystalline cell has relatively high output. However, it is intensity limited at higher wavelengths, due to its small bandgap. Thus, it depends on many electrons being excited to generate power, as each electron has little energy. It would be best for large-scale power generation, as the intensity somewhere like a desert does not vary much through a day (especially in long-wavelength radiation). It is also frequency-limited at lower wavelengths, so it would be especially suitable for power generation at sunrise and sunset; it can take advantage of relatively low-intensity but high-frequency (bluish) scattered radiation.

The monocrystalline cell acts as a middle ground. Its power generation is not as much as the polycrystalline cell, but more than the amorphous cell. The variance in its power generation is in the middle too. It behaves like the polycrystalline cell, in that it is intensity limited at higher wavelengths and frequency limited at lower wavelengths, but the intensity plays a much larger part than in the polycrystalline cell. Thus, it varies like a in between the other two. It would be a decent all-round performer, if not for its extremely high cost.

Thus, to answer the question, amorphous cells are most suitable for small-scale operation, while polycrystalline cells are best for large scale operation.

7.2 Scope of research:

Initially I intended to take every kind of solar cell available, and test them at wavelengths between 250-2500nm. However, due to difficulties in availability, I was only able to find silicon-based solar cells, and filters for the visible spectrum. This limits the scope of the experiment to the visible spectrum. The scope of the experiment can be expanded as follows:

1. Using filters for a larger range of wavelengths
2. Using other kinds of solar cells, like gallium arsenide, etc.
3. Testing the output at different temperatures (by heating/cooling the cells) to simulate different environments
4. Taking readings from multiple units of each solar cell type.

Candidate Name: Candidate Number:

8. Bibliography

Description of working of solar cells

[1]Theraja, B.L. (2001) Basic Electronics Solid State (pp. 68 – 69). New Delhi, S. Chand & Company Ltd.

Wikipedia article on polycrystalline silicon photovoltaics

[2]http://en.wikipedia.org/wiki/Polycrystalline_silicon_photovoltaics (referenced by: Green, M. A. (2004), "Recent Developments in Photovoltaics", *Solar Energy* **76** (1–3): 3–8, doi:10.1016/S0038-092X(03)00065-3)

→ access date?

Wikipedia article on solar radiation

[3]http://en.wikipedia.org/wiki/Solar_radiation (Image created by Robert A. Rohde / Global Warming Art, http://www.globalwarmingart.com/wiki/File:Solar_Spectrum_png)

→ one source missing in biblio

An interesting and well presented investigation. Primary research and the student's own work explain how a silicon solar cell generates electricity. The approach then successfully compares outputs at different frequencies of incident light and accounts well for variation in intensity, both due to environmental variations and the variations caused by the radiation curve for the light source - the sun. Impressive conclusion and analysis.