TED ANKARA COLLEGE FOUNDATION HIGH SCHOOL

International Baccalaureate

Physics High Level

Extended Essay

Effect of Frequency on Solar Cell Power

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Word Count: 3655

Abstract

In this study, it was aimed to show the effect of frequency of light on current and potential values in a solar cell. According to the research question: 'How does current and potential values read on a standard solar cell change when the light intensity changes due to the change in frequency?', an experiment was done by using a standard solar cell, a powerful light source, transparent glass films and Vernier data logger measurement devices.

In the experiment, the solar cell is placed in front of the light source and light probe, and ampermeter and voltmeter are connected to it. By covering the surface of the light source with red, orange, yellow, green, blue and purple transparent glass films respectively, the frequency of light is changed. Increase in frequency means increase in energy of photons of light. When the energy of photons increases, their ability to excite electrons from solar cell surface rises as well. As a result, number of electrons passing through the circuit in unit time, which means current, improves. As the internal resistance of the system is constant, potential increases due to the increase in current. Not only current and potential, but also illuminance changes when the frequency changes as the total energy of photons increases light intensity.

In the result of the experiment, it is concluded that the current and potential values read on a solar cell is directly proportional with the frequency of light. As the frequency of light is increased from red to purple, the power in the solar cells will increase due to the increase in current and potential values.

(Word count: 268)

Contents

Background Information

Solar cell is a device which converts light energy into electrical energy. While doing this, it mainly uses the principals of photovoltaics. Photovoltaics is a method of generating electrical power by converting solar radiation into direct current electricity using semiconductors that exhibit the inner photoelectric effect.[1]

The photovoltaic effect was first discovered by French physicist A. E. Becquerel in 1839. However, not until 1883 the first solar cell was built. The efficiency of that cell was about 1%. After the discovery of photoelectric effect in 1887, the first photoelectric cell was built in 1888. Albert Einstein was the one who explained the principles of photoelectric effect and received a Nobel Prize for his studies in 1921. The highly efficient solar cell was first developed in 1954 using a diffused silicon semiconductor p-n junction. In the past four decades, remarkable progress has been made, with Megawatt solar power generating plants having now been built.[2]

Solar cells are used in many areas in today's world as they are using the main alternative energy source which is sunlight. Solar cells are covered with mainly glass in order to both let the sunshine pass and protect the cell material from outer harmful effects. By connecting more than one cells together in series both from inside and outside, solar cell modules are obtained which is suitable to use in daily life. The cost of solar cells produced today is mainly sourced from their production process, which involves the materials used and the sizes of the cell. When compared with its efficiency, it would be seen hard to make a profit in short term by using solar cell modules as energy sources, as today's solar cell devices are reached the limiting efficiency of 30%. But, when the terms like global energy insufficiency are considered, usage of this kind of energy sources seems very beneficial in long term.

Materials used in solar cells depend on efficiency and cost. Semiconductors are the most suitable materials for observing photoelectric effect and absorbing light in all wavelengths, and silicon and its derivatives are highly used.

[1] <http://www.scienzagiovane.unibo.it/english/solar-energy/3-photovoltaic-effect.html>
[2] A textbook of Engineering Physics by Navneet Gupta & S. K. Tiwari

Semiconductors are used in p-n junctions where p-type semiconductor and n-type semiconductor are joined together in very close contact.

P-N junctions are elementary "building blocks" of almost all semiconductor electronic devices such as diodes, transistors, solar cells, LEDs, and integrated circuits; they are the active sites where the electronic action of the device takes place.[3]

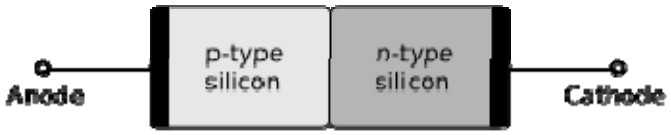


Figure 1[4]: Usage of silicon in a typical p-n junction

Solar cells produce voltage difference and as a result, current with the help of the p-n junction. However, there are some basic steps for a solar cell to work.

First of all, the photons coming from sunlight are hit the cell panel and absorbed by the semiconductor material which is generally silicon. Photovoltaic principles are set in here. Energy of a photon package is transferred to an atom in p-type silicon and forces one of its valance electrons move from valance band to conduction band. Those electrons build up in n-type silicon as they are free to move now. Although this process has same principles with photoelectric effect, as the free electrons can not go out of the system, it is considered under the name of photovoltaics.

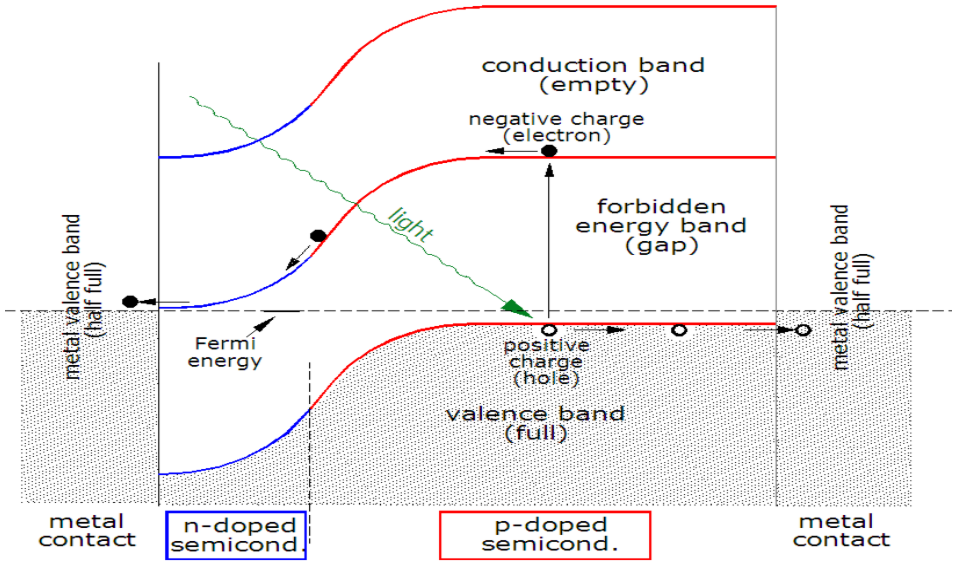


Figure 2[5]: Illustration of photovoltaic effect and p-n junction

[3] <http://cleanroom.byu.edu/pn_junction.phtml>
[4] <http://en.wiki/File:PN_Junction_Open_Circuited.svg>
[5] <http://en.wiki/File:BandDiagramSolarCell-en.gif>

Then, a voltage difference is formed between the different sides of the junction when too many electrons are collected in one type of silicon, leaving the atoms in the other type of silicon ready to take electrons. These ready sites are called ‘holes’ of ‘photovoltaic’ cell. When the two sides are connected with conducter metals and an external circuit, named as a load, electrons move towards the holes and a direct current is formed.

Lastly, by combining photovoltaic cells in parallel and series, a solar cell is made giving desired current for ready to use.

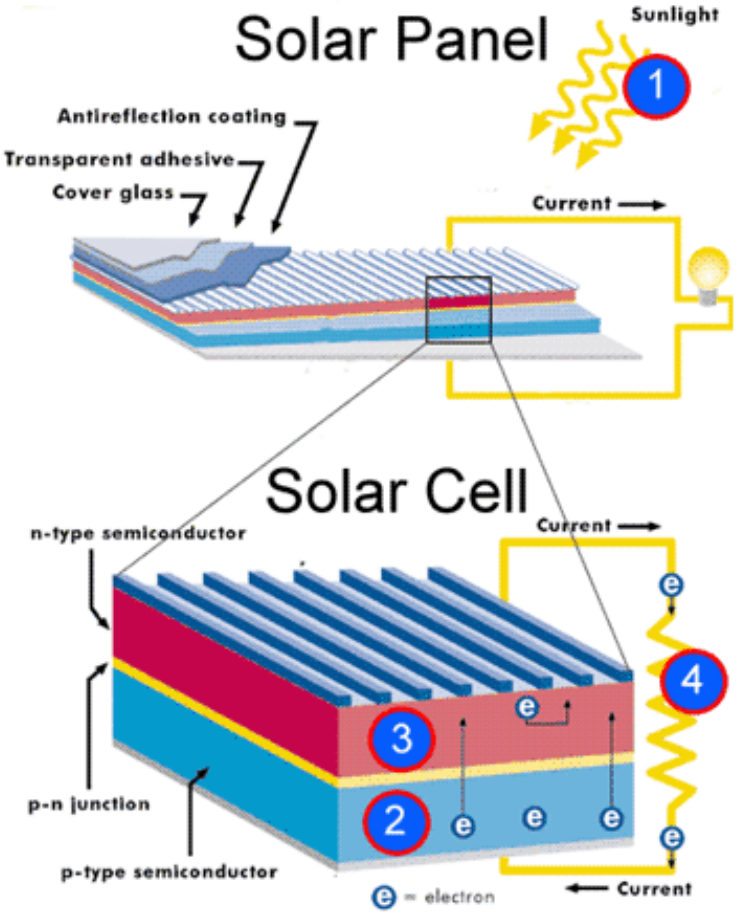


Figure 3[6]: Illustration of how solar cell works

It doesn’t mean that every single photon of light has enough energy to excite an electron. There is threshold energy for every semiconductor material, for silicon as well, which is called band gap value. Band gap can be defined as the energy required to free a valance shell electron from its orbital to become a mobile charge, able to move in the semiconductor freely.

[6] <http://www.energymasters.com/faq_questions.php#two>

For sunlight, much of the photons reaching to Earth have greater solar radiation than band gap of silicon requires. High energy photons absorbed by the solar cell generate electron-hole pairs but most of their energy turns into heat. This is the reason of low efficiency values of solar cells.

For artificial light sources which are different than sunlight, energy of the photons is important in order to take a good yield from solar cell. Energy of light is directly proportional with its frequency. The relation comes from the equation;

$$E = h \cdot f$$

where h=6.62606896(33)·10^{-34}Js is Planck's constant.[7]

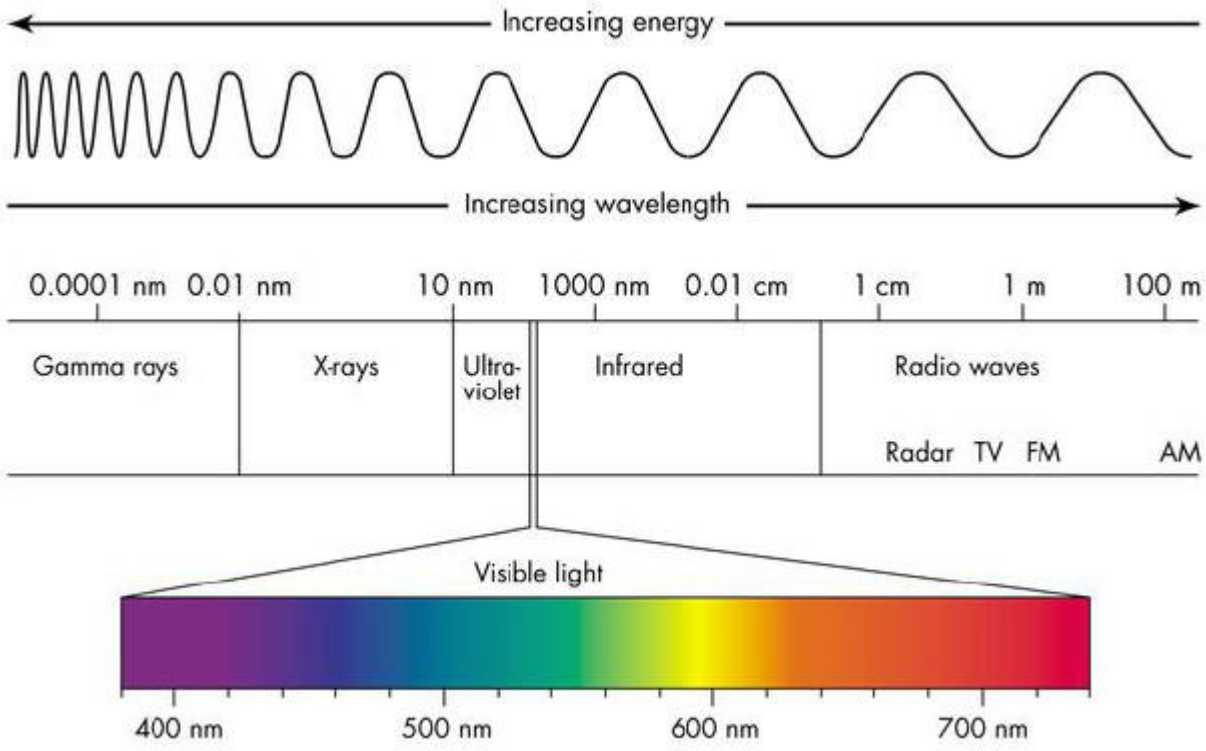


Figure 4[8]: Inverse relationship between wavelength and energy of light

Photons have different energies due to their frequencies which is inversely proportional with their wavelengths. The colours which human eye can see is known as the visible spectrum and visible light's frequency is also ranges from purple to red. So, the colour of the light also affects the efficiency of a solar cell.

[7] <http://physics.nist.gov/cgi-bin/cuu/Value?h>
[8] <http://www.antonine-education.co.uk/physics_gcse/Unit_1/Topic_5>

Like frequency is directly related with energy of light, energy of all photons in that light is directly related with illuminance. Energy of the whole photons means light intensity or in other words luminous intensity. Illuminance is inversely proportional with the square of the distance from the light source and directly proportional with the light intensity which means when the light intensity increases, illuminance increases as well. As a result, frequency becomes directly proportional to the illuminance. It can be summarized as when frequency increases, energy of the photons increases, light intensity increases and illuminance increases.

Introduction

Solar cells are started to be used in many fields. Besides the trials of engineers for building up a car which totally works with solar power, calculators, traffic lights, optical wires, satellites and many other devices which is used frequently in daily life takes their energy from solar cells. It is now possible to supply the needs of a summer house like electricity and hot water just with solar cells. Their usefulness is surprising.

Although today's energy sources are mainly composed of fossil fuels, solar cells are the main branch of alternative energy sources. Petroleum is highly consumed as it is the most efficient fuel for all vehicles. But, its harm to nature due to the release of highly concentrated CO_2 and risk to run out in future are major problems for human under the consideration of global warming and greenhouse effect. Cost of petroleum is not the cheapest thing in the world as well. On the contrary, it gets more and more expensive every other day due to the distress of energy.
On the other hand, solar power is totally costless. It is free to use the energy of sun radiation. Only thing to pay for is to construct the solar cell system in a way to obtain sufficient and suitable energy.

However, the biggest obstacle for solar cells to become dominant in energy market is their low efficiency. Of course, nothing gives more yield than fossil fuels. But, it is obvious that hybrid technologies are developing as well. Hybrid cars for example, are both using gasoline and electricity as energy sources to make profit by reducing the usage of petroleum. So it is

logical to use alternative energy sources as much as we can in order to decrease the usage of fossil fuels which are also harmful to the environment.
So, as it is mentioned before, photons coming from the sun has more than enough energy to exceed band gap energy and excite electrons in semiconductor material. Moreover, most of their energy is used to increase the kinetic energy of electrons and turn into heat which is useless. That is the reason of low efficiency rates in solar cells.

In indoors, on the other hand, artificial light photons may not have enough energy to excite every single electron as they can't pass the band gap value. That's why energy of photons is important for internal light sources. Although it is not frequently seen, indoor energy supplies are started to turn into hybrid as well. In places completely closed to sunlight such as offices, shopping malls and night clubs, solar cells are started to be furnished as a part of interior decoration. By this way, some part of the energy needs of that place can be supplied. This shortly means obtaining electricity by using electricity.
But of course it is not logical to light up and consume a lot in order to make more profit from cells. Energy of light gains consequence here. In places like malls and clubs, colour of the light differs in general sense. Yellowish tones are preferred for creating a day-like perception in shopping malls or red and green lights are used for composing some themes in night clubs. It is important to arrange those colours perfectly, if the owner of the place wants to spend less for all that electricity.

Colour means frequency for the lights in visible spectrum. Frequency increases from red to purple which means increase in energy. So, my experiment depends on all of this knowledge. The behaviour of a solar cell under the light with different colours, which means different frequencies, is wondered. By using a standard solar cell and a light source with coloured films, the light intensity, current and potential values are measured. It was all in order to understand the relationship between frequency, illuminance, current and potential.

Experimentation

Design

Research Question

How does the light frequency of red, orange, yellow, green, blue, purple colours of a 500W light source affects the illumination, and current and potential values read on a polycrystalline solar cell with 12 Wp nominal power efficiency under 20cm constant distance?

Purpose

To find the relationship between the frequency as the colour of the light of a 500W light source and illuminance, and current and potential values read on the polycrystalline solar cell with 12Wp nominal power efficiency

Hypothesis

Illuminance, and current and potential values read on the polycrystalline solar cell with 12Wp nominal power efficiency will increase as the frequency of light of 500W light source increases from red to purple.

Increase in frequency from red to purple in visible spectrum means increase in energy of light photons.

Variables

Independent variable

- Colour of transparent film covered on the light source (frequency of light)

Dependent variables

- Illuminance read by Vernier light sensor
- Current in solar cell read by Vernier current probe
- Voltage in solar cell read by Vernier voltage probe

Controlled variables

- Nominal power efficiency of the solar cell (Pmpp: 12Wp)
- Power of the light source (500W)
- Distance between the solar cell and the light source (20.0±0.5cm)

Materials

- Solar cell (brand: Centrosolar, model: SM50S, Pmpp (nominal efficiency as power): 12Wp, weight: 1.3kg, dimensions: 468×250cm)
- Light source (500W halogen projector)
- Transparent glass films (red, orange, yellow, green, blue, purple)
- Vernier light sensor
- Vernier current probe
- Vernier voltage probe
- Cables with alligator clips
- Portable computer (Logger pro graphical analysis program installed)
- Ruler (±0.5cm)

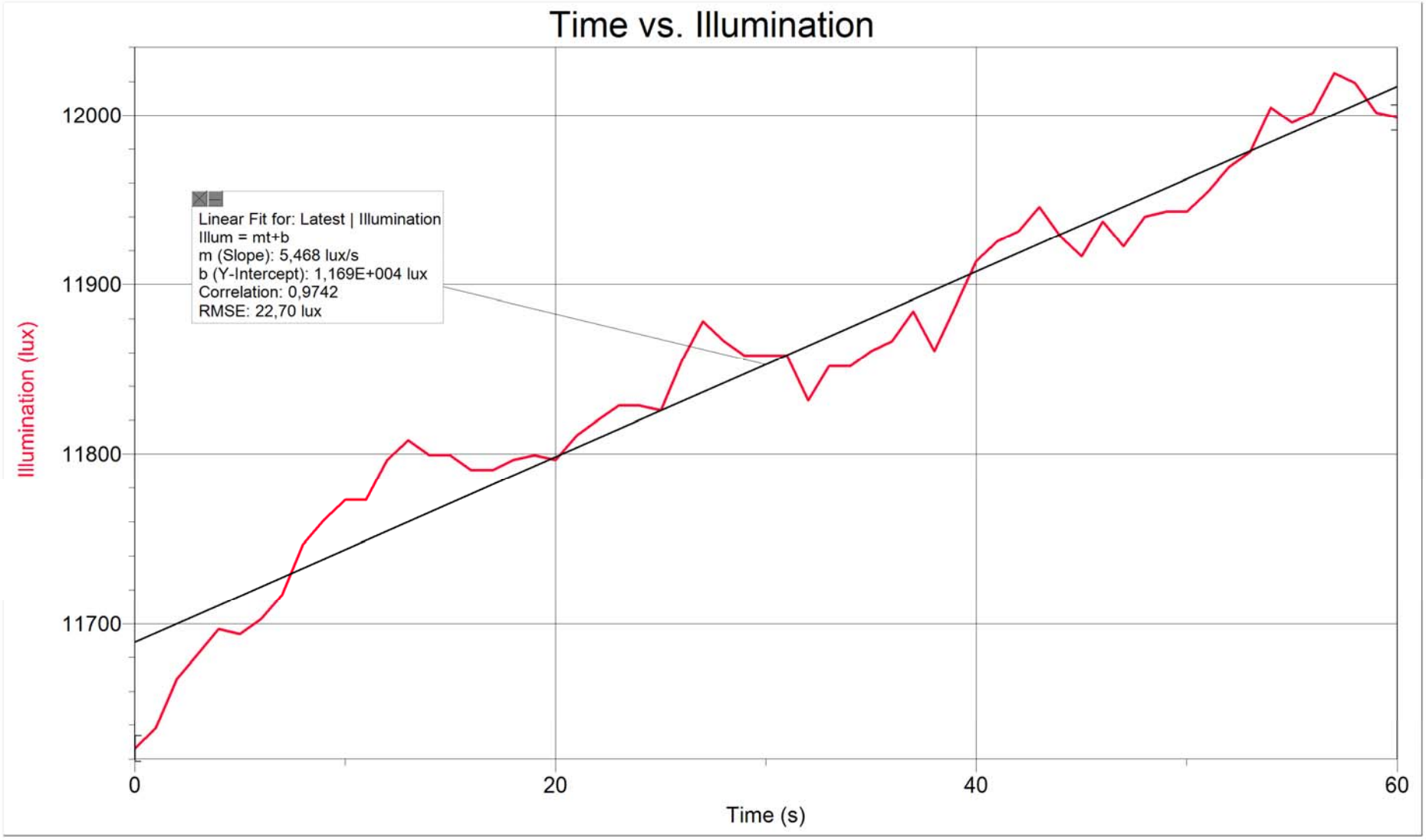
Procedure

1. Solar cell is put vertically on its long side on the ground.
2. Light source is placed in front of the solar cell by leaving 20cm distance between them in order to focus maximum light on the cell.
3. The front surface of the light source is covered with red transparent glass film.
4. Vernier light sensor is connected to the computer and placed to the top of the cell.
5. Vernier current probe and voltage probe are connected to the computer and solar cell.
6. It is made sure that every other light source is turned off or blocked and the experiment room is darkened in order to warranty that the solar cell only absorbs the light of the single light source used in experiment.
7. The light source is turned on and left a minute to reach its maximum brightness.
8. Logger pro program installed in computer is opened.
9. Data collection is arranged with the period of 1 second.
10. The data collection is started.
11. The data is recorded for 1 minute time.
12. The data collection is stopped.
13. Red transparent glass film is uncovered from the surface of the light source.
14. The light source is covered with another transparent glass film.
15. Steps from 4 to 14 are redone for each other colour of transparent glass film.
16. A last trial is done without covering the light source with any glass films.

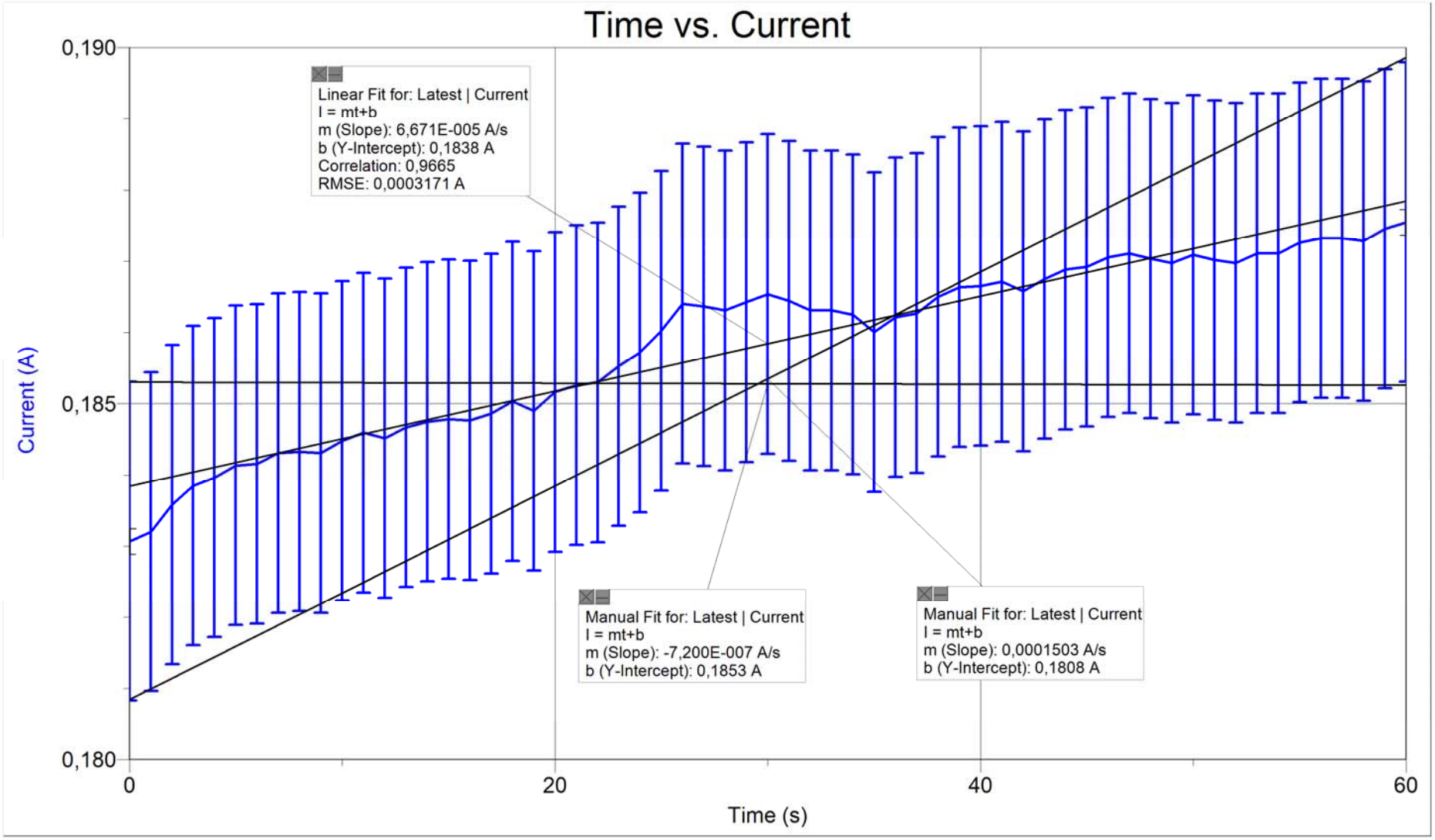
Data Collection and Processing

Red Light			
Time (s)	Illumination (lux)	Current (A)	Potential (V)
0	11626.4025879	0.183067322	0.015830994
1	11638.1286621	0.183200836	0.015830994
2	11667.4438477	0.183582306	0.016021729
3	11682.1014404	0.183849335	0.016021729
4	11696.7590332	0.183963776	0.015830994
5	11693.8275146	0.184135437	0.015830994
6	11702.6220703	0.184154510	0.015830994
7	11717.2796631	0.184307098	0.015830994
8	11746.5948486	0.184326172	0.015830994
9	11761.2524414	0.184307098	0.016021729
10	11772.9785156	0.184478760	0.015830994
11	11772.9785156	0.184593201	0.016021729
12	11796.4306641	0.184516907	0.015830994
13	11808.1567383	0.184669495	0.015830994
14	11799.3621826	0.184745789	0.015830994
15	11799.3621826	0.184783936	0.016021729
16	11790.5676270	0.184764862	0.015640259
17	11790.5676270	0.184860229	0.016212463
18	11796.4306641	0.185031891	0.016021729
19	11799.3621826	0.184898376	0.015830994
20	11796.4306641	0.185165405	0.016212463
21	11811.0882568	0.185260773	0.016021729
22	11819.8828125	0.185298920	0.016212463
23	11828.6773682	0.185527802	0.016021729
24	11828.6773682	0.185718536	0.016212463
25	11825.7458496	0.186023712	0.016212463
26	11855.0610352	0.186405182	0.016021729
27	11878.5131836	0.186367035	0.016593933
28	11866.7871094	0.186309814	0.016021729
29	11857.9925537	0.186424255	0.016212463
30	11857.9925537	0.186538696	0.016403198
31	11857.9925537	0.186443329	0.016212463
32	11831.6088867	0.186309814	0.016212463
33	11852.1295166	0.186309814	0.016021729
34	11852.1295166	0.186252594	0.016212463
35	11860.9240723	0.186004639	0.016212463
36	11866.7871094	0.186214447	0.016021729
37	11884.3762207	0.186271667	0.016212463
38	11860.9240723	0.186500549	0.016212463
39	11887.3077393	0.186634064	0.016403198
40	11913.6914063	0.186653137	0.016021729
41	11925.4174805	0.186710358	0.016403198
42	11931.2805176	0.186576843	0.016212463
43	11945.9381104	0.186748505	0.016212463
44	11928.3489990	0.186882019	0.016212463
45	11916.6229248	0.186920166	0.016403198
46	11937.1435547	0.187053680	0.016403198
47	11922.4859619	0.187110901	0.016212463
48	11940.0750732	0.187034607	0.016021729
49	11943.0065918	0.186977386	0.016784668
50	11943.0065918	0.187091827	0.016021729
51	11954.7326660	0.187015533	0.016021729
52	11969.3902588	0.186977386	0.015830994
53	11978.1848145	0.187110901	0.016403198
54	12004.5684814	0.187110901	0.016403198
55	11995.7739258	0.187263489	0.016212463
56	12001.6369629	0.187320709	0.016403198
57	12025.0891113	0.187320709	0.016403198
58	12019.2260742	0.187282562	0.016212463
59	12001.6369629	0.187454224	0.016403198
60	11998.7054443	0.187549591	0.016593933

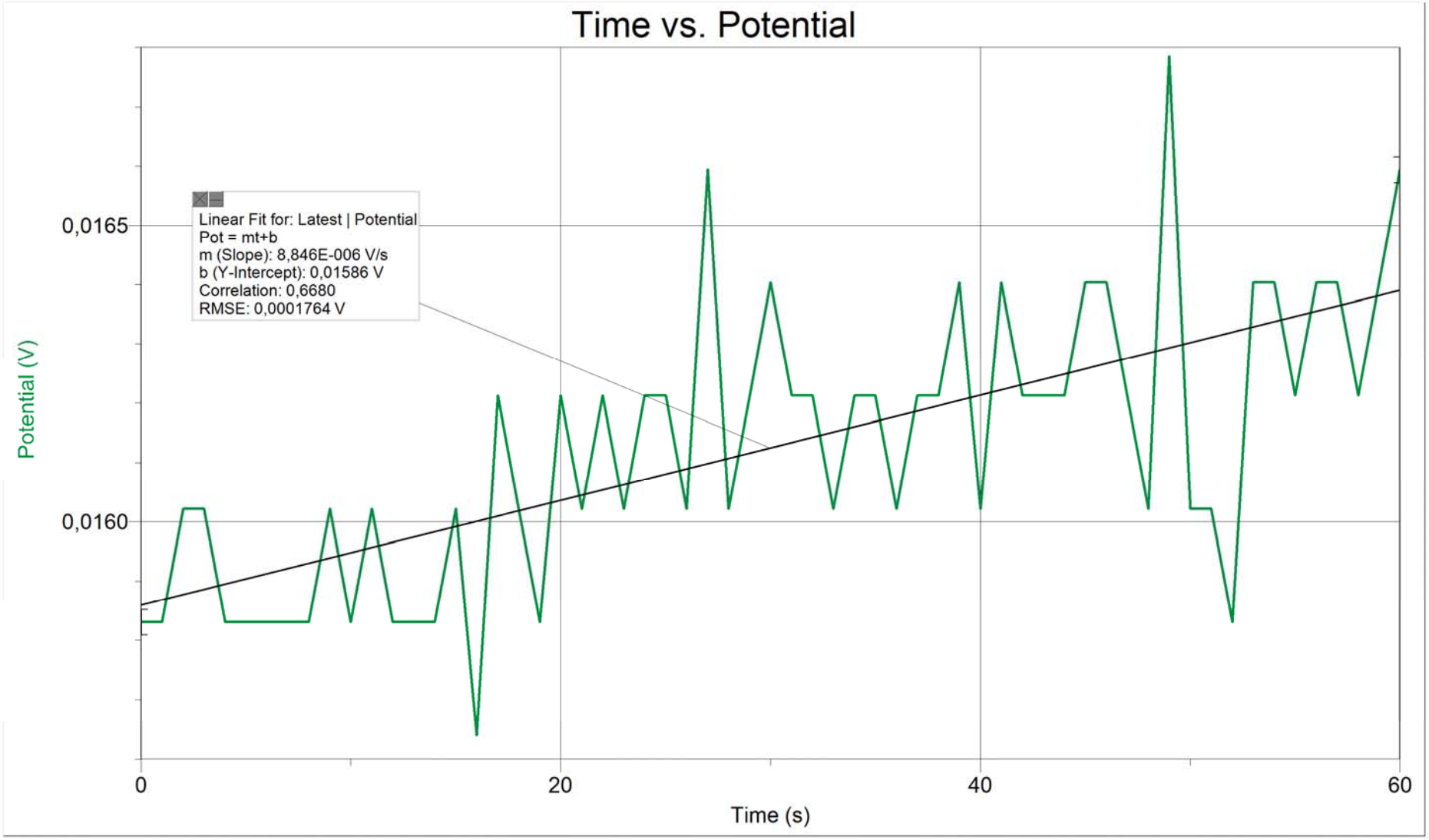
Table 1: Raw data of illumination, current and potential for red light



Graph 1: Graph of illumination versus time for red light



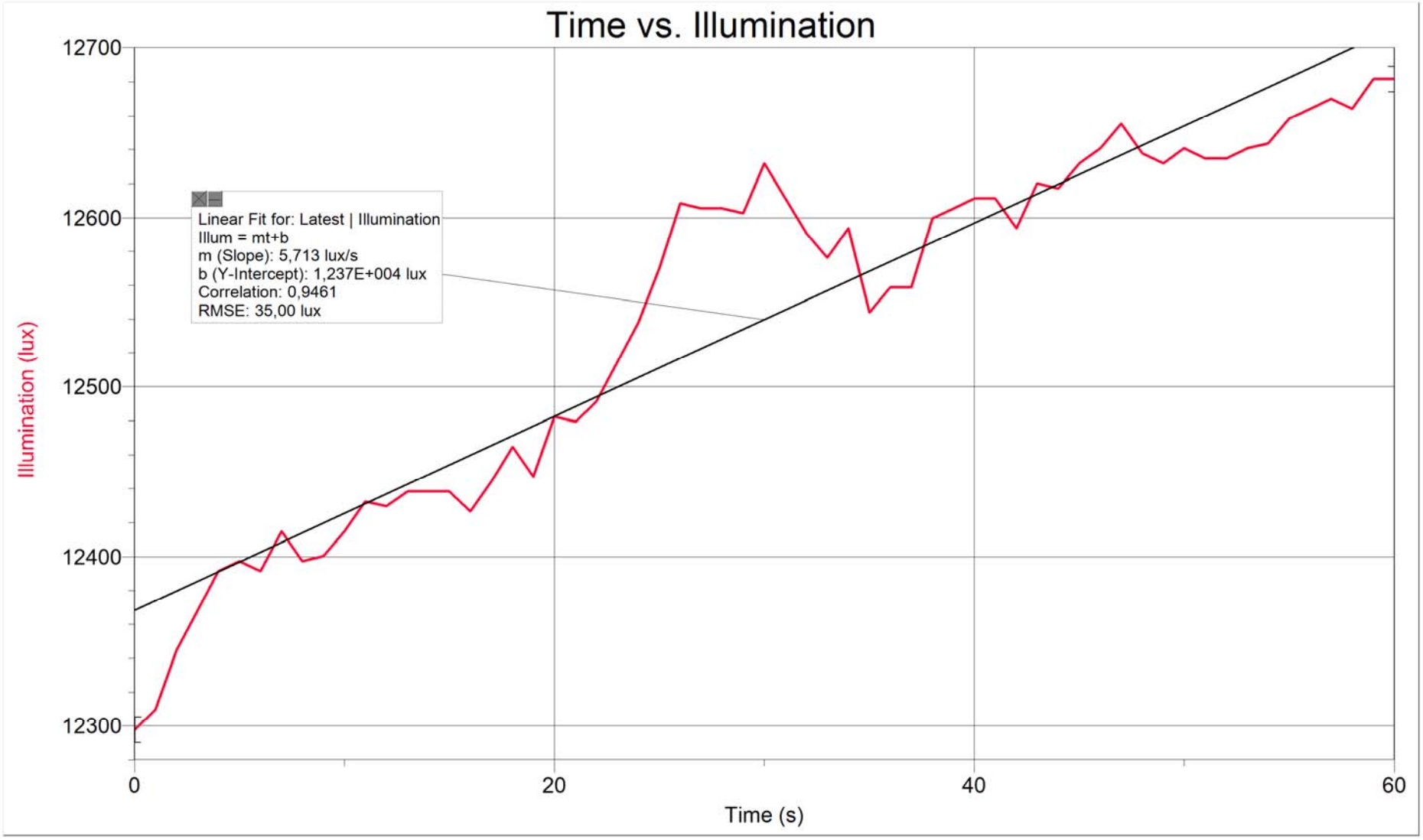
Graph 2: Graph of current versus time for red light



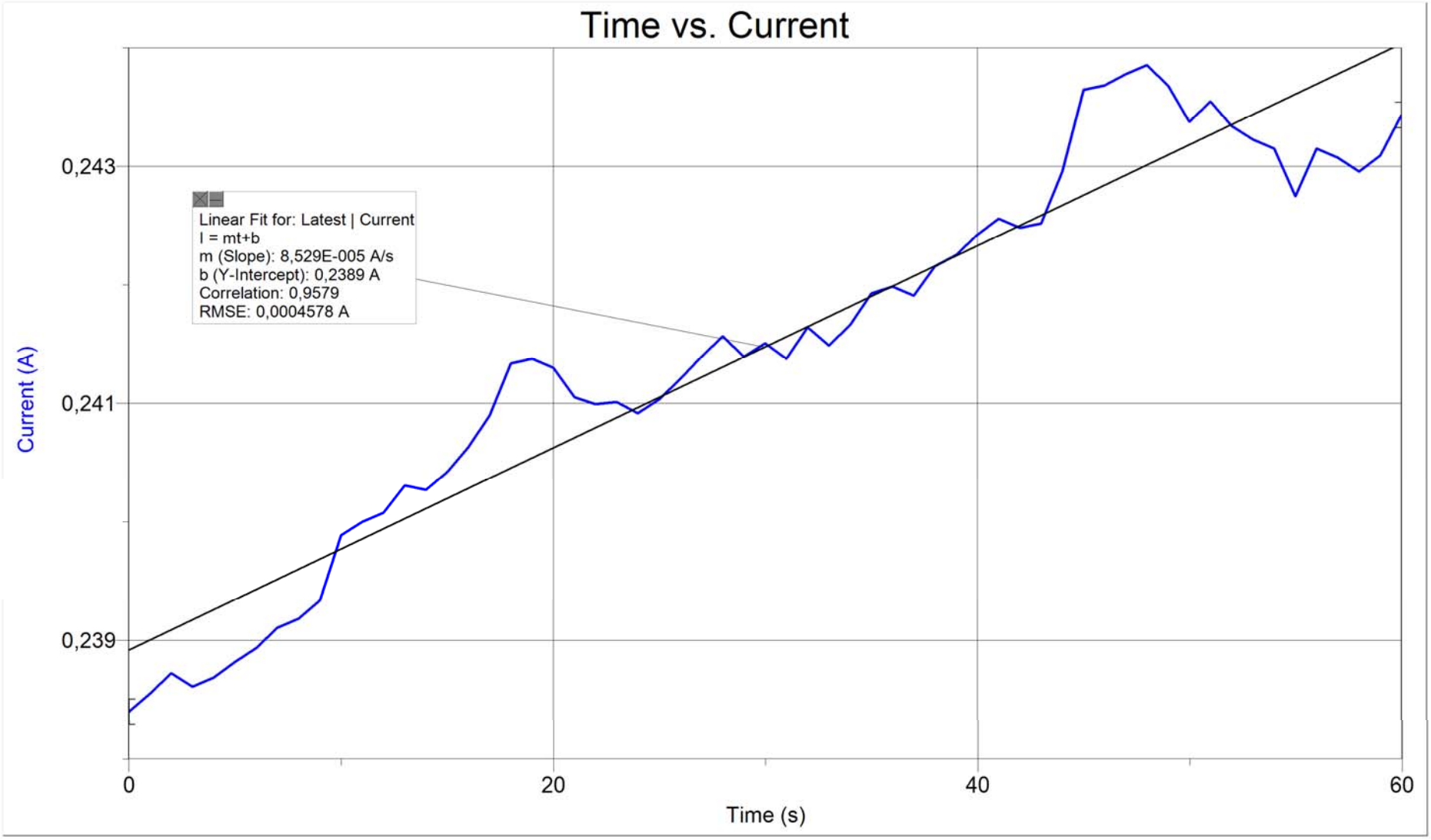
Graph 3: Graph of potential versus time for red light

Orange Light			
Time (s)	Illumination (lux)	Current (A)	Potential (V)
0	12297.7203369	0.238399506	0.025367737
1	12309.4464111	0.238552094	0.025177002
2	12344.6246338	0.238723755	0.024795532
3	12368.0767822	0.238609314	0.025177002
4	12391.5289307	0.238685608	0.025367737
5	12397.3919678	0.238819122	0.025367737
6	12391.5289307	0.238933563	0.025177002
7	12414.9810791	0.239105225	0.025558472
8	12397.3919678	0.239181519	0.024986267
9	12400.3234863	0.239334106	0.025177002
10	12414.9810791	0.239887238	0.025177002
11	12432.5701904	0.240001678	0.025939941
12	12429.6386719	0.240077972	0.025939941
13	12438.4332275	0.240306854	0.025558472
14	12438.4332275	0.240268707	0.025177002
15	12438.4332275	0.240421295	0.025558472
16	12426.7071533	0.240631104	0.025558472
17	12444.2962646	0.240898132	0.025367737
18	12464.8168945	0.241336823	0.025367737
19	12447.2277832	0.241374969	0.025367737
20	12482.4060059	0.241298676	0.025749207
21	12479.4744873	0.241050720	0.025558472
22	12491.2005615	0.240993500	0.025177002
23	12514.6527100	0.241012573	0.024795532
24	12538.1048584	0.240917206	0.025749207
25	12570.3515625	0.241031647	0.024986267
26	12608.4613037	0.241203308	0.025749207
27	12605.5297852	0.241394043	0.025558472
28	12605.5297852	0.241565704	0.025558472
29	12602.5982666	0.241394043	0.025177002
30	12631.9134521	0.241508484	0.025749207
31	12611.3928223	0.241374969	0.025558472
32	12590.8721924	0.241641998	0.025367737
33	12576.2145996	0.241489410	0.025939941
34	12593.8037109	0.241661072	0.025749207
35	12543.9678955	0.241928101	0.025558472
36	12558.6254883	0.241985321	0.025939941
37	12558.6254883	0.241909027	0.025749207
38	12599.6667480	0.242156982	0.026130676
39	12605.5297852	0.242252350	0.025749207
40	12611.3928223	0.242424011	0.025367737
41	12611.3928223	0.242557526	0.025939941
42	12593.8037109	0.242481232	0.026130676
43	12620.1873779	0.242519379	0.025939941
44	12617.2558594	0.242958069	0.026130676
45	12631.9134521	0.243644714	0.025367737
46	12640.7080078	0.243682861	0.026130676
47	12655.3656006	0.243778229	0.025939941
48	12637.7764893	0.243854523	0.025367737
49	12631.9134521	0.243682861	0.026130676
50	12640.7080078	0.243377686	0.026130676
51	12634.8449707	0.243549347	0.025558472
52	12634.8449707	0.243339539	0.025939941
53	12640.7080078	0.243225098	0.025558472
54	12643.6395264	0.243148804	0.025367737
55	12658.2971191	0.242748260	0.025367737
56	12664.1601563	0.243148804	0.025367737
57	12670.0231934	0.243072510	0.025558472
58	12664.1601563	0.242958069	0.025749207
59	12681.7492676	0.243091583	0.025558472
60	12681.7492676	0.243434906	0.025558472

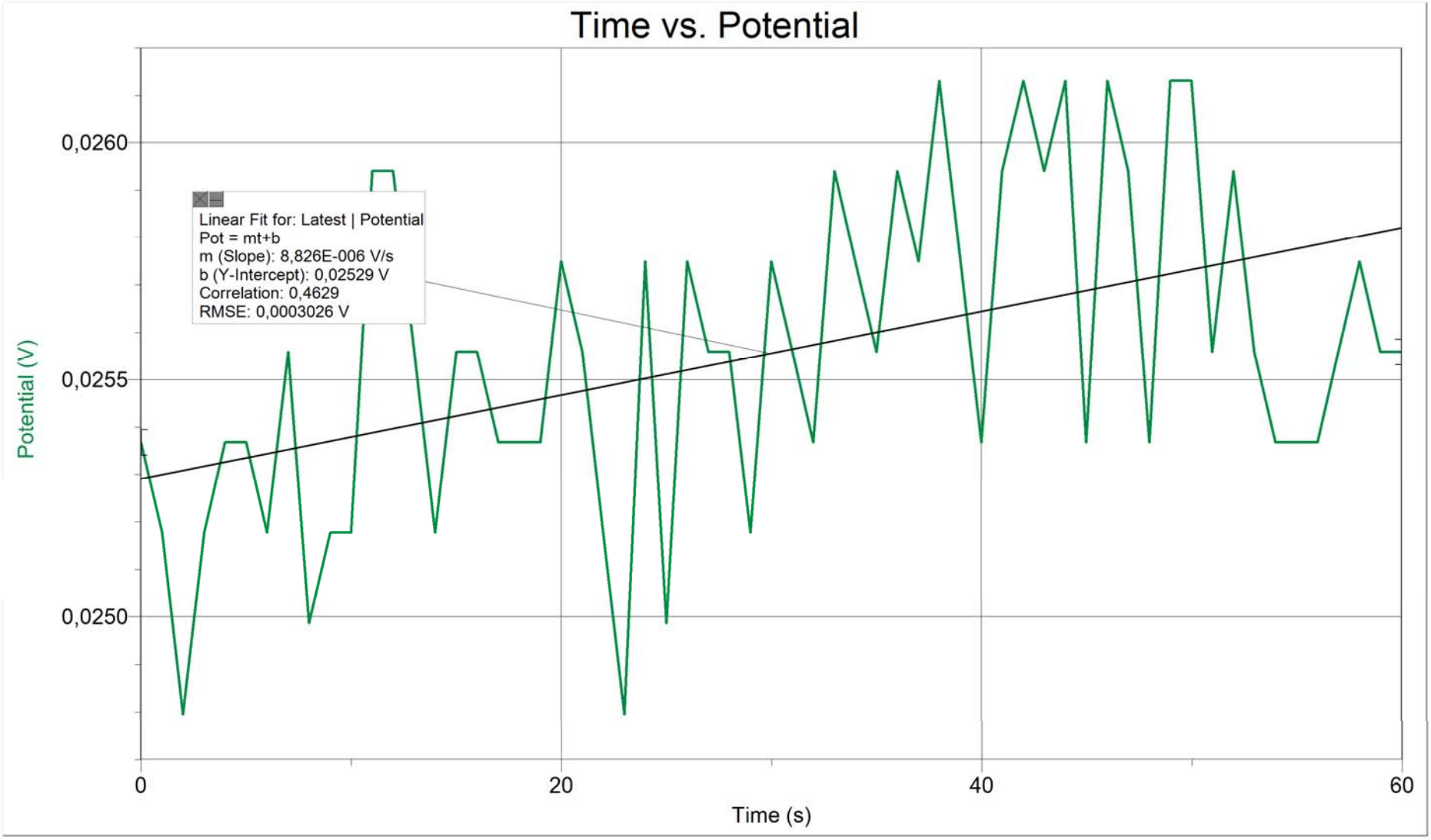
Table 2: Raw data of illumination, current and potential for orange light



Graph 4: Graph of illumination versus time for orange light



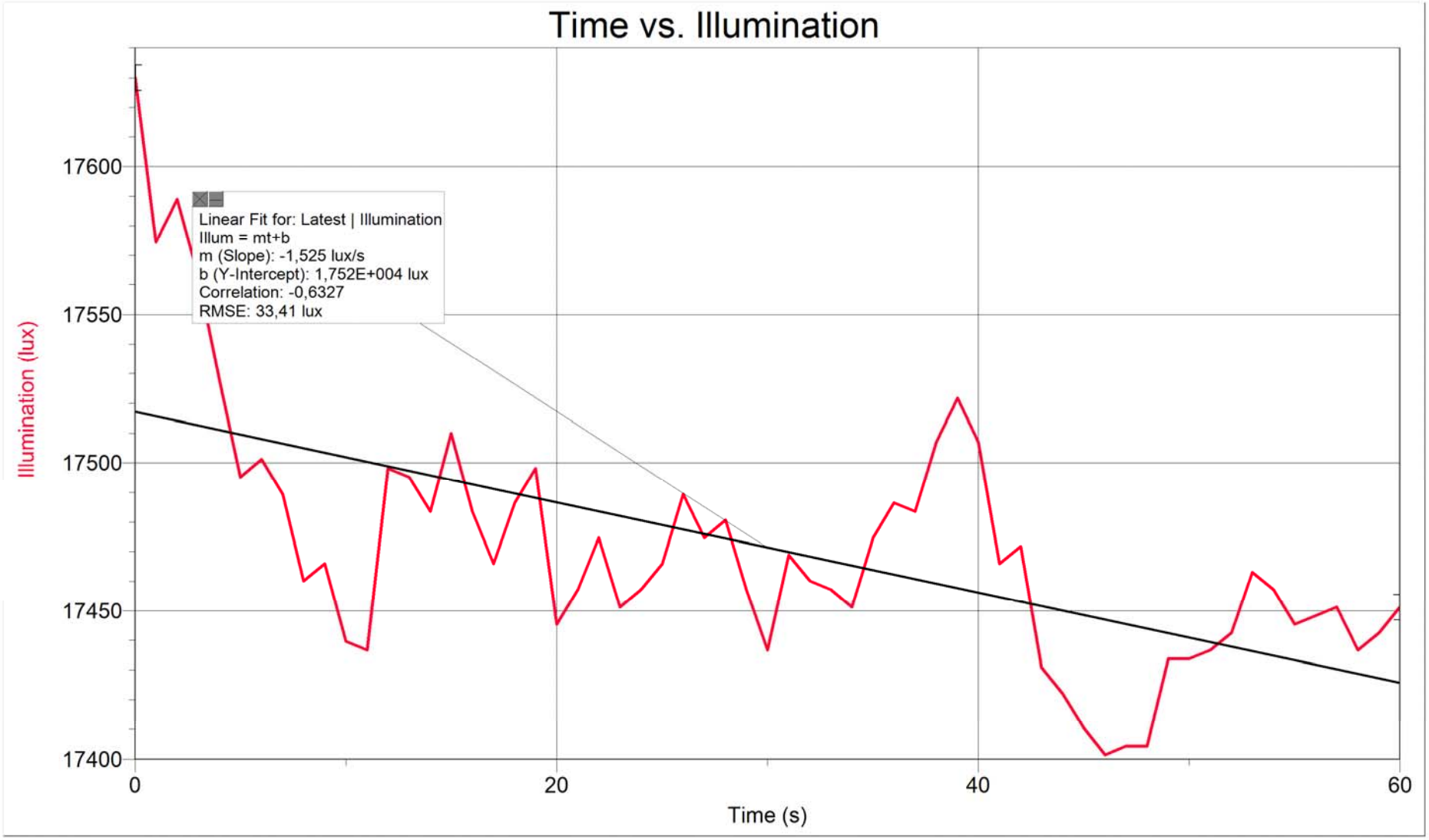
Graph 5: Graph of current versus time for orange light



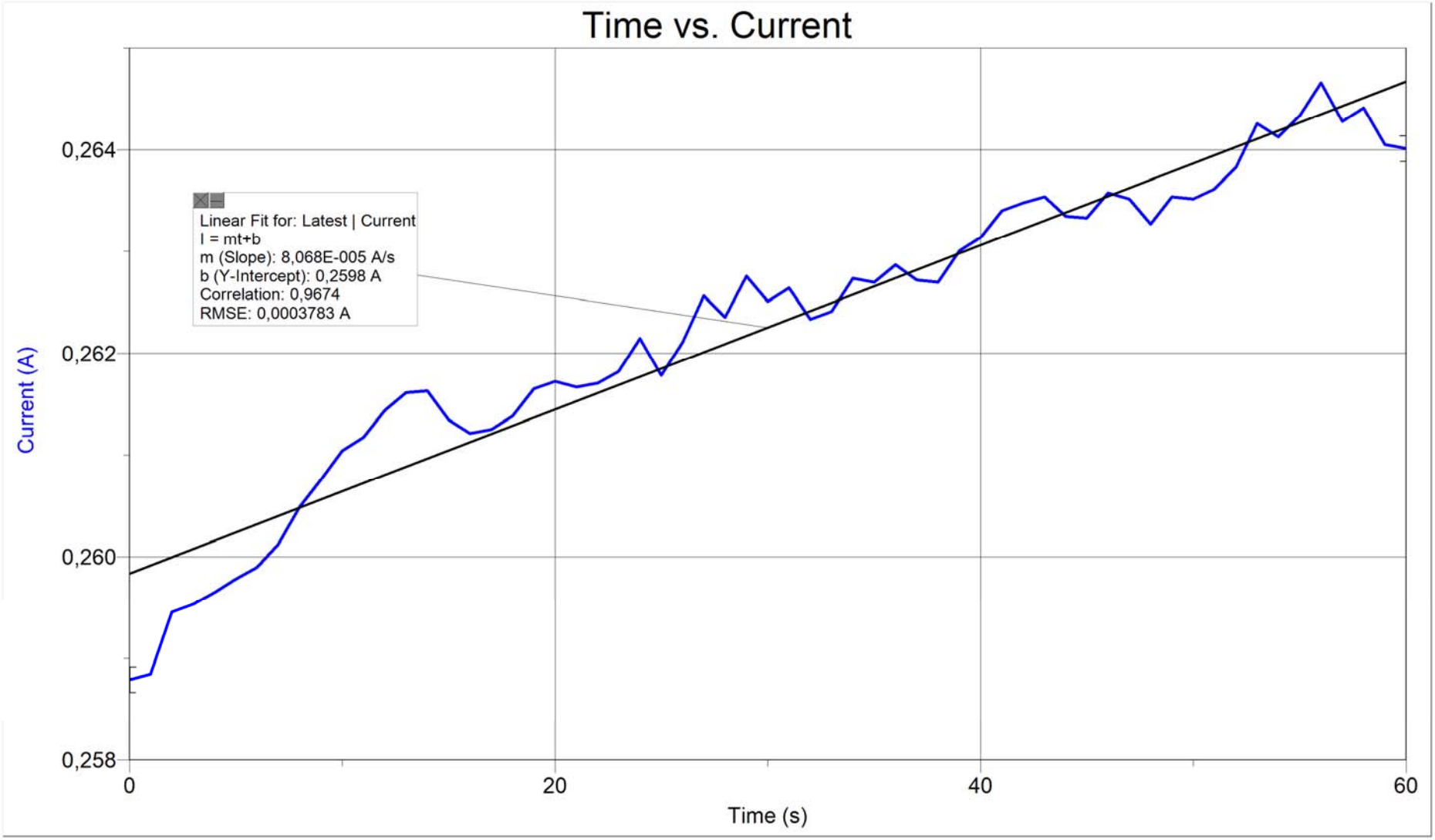
Graph 6: Graph of potential versus time for orange light

Yellow Light			
Time (s)	Illumination (lux)	Current (A)	Potential (V)
0	17630.1525879	0.258789063	0.029754639
1	17574.4537354	0.258846283	0.029754639
2	17589.1113281	0.259456635	0.029373169
3	17562.7276611	0.259532928	0.029945374
4	17527.5494385	0.259647369	0.029563904
5	17495.3027344	0.259780884	0.029754639
6	17501.1657715	0.259895325	0.029754639
7	17489.4396973	0.260124207	0.029945374
8	17460.1245117	0.260486603	0.029563904
9	17465.9875488	0.260753632	0.029754639
10	17439.6038818	0.261039734	0.029754639
11	17436.6723633	0.261173248	0.030136108
12	17498.2342529	0.261440277	0.029754639
13	17495.3027344	0.261611938	0.030136108
14	17483.5766602	0.261631012	0.030326843
15	17509.9603271	0.261344910	0.030136108
16	17483.5766602	0.261211395	0.029945374
17	17465.9875488	0.261249542	0.029945374
18	17486.5081787	0.261383057	0.030708313
19	17498.2342529	0.261650085	0.029754639
20	17445.4669189	0.261726379	0.030326843
21	17457.1929932	0.261669159	0.029945374
22	17474.7821045	0.261707306	0.030326843
23	17451.3299561	0.261821747	0.029945374
24	17457.1929932	0.262145996	0.029754639
25	17465.9875488	0.261783600	0.029945374
26	17489.4396973	0.262107849	0.029945374
27	17474.7821045	0.262565613	0.029945374
28	17480.6451416	0.262355804	0.030136108
29	17457.1929932	0.262756348	0.029945374
30	17436.6723633	0.262508392	0.030517578
31	17468.9190674	0.262641907	0.030136108
32	17460.1245117	0.262336731	0.029754639
33	17457.1929932	0.262413025	0.030326843
34	17451.3299561	0.262737274	0.029945374
35	17474.7821045	0.262699127	0.030326843
36	17486.5081787	0.262870789	0.029563904
37	17483.5766602	0.262718201	0.030326843
38	17507.0288086	0.262699127	0.029945374
39	17521.6864014	0.263004303	0.029754639
40	17507.0288086	0.263137817	0.030517578
41	17465.9875488	0.263404846	0.030136108
42	17471.8505859	0.263481140	0.030899048
43	17430.8093262	0.263538361	0.030136108
44	17422.0147705	0.263347626	0.030517578
45	17410.2886963	0.263328552	0.031661987
46	17401.4941406	0.263576508	0.030326843
47	17404.4256592	0.263519287	0.029945374
48	17404.4256592	0.263271332	0.030326843
49	17433.7408447	0.263538361	0.030136108
50	17433.7408447	0.263519287	0.030326843
51	17436.6723633	0.263614655	0.029945374
52	17442.5354004	0.263824463	0.030899048
53	17463.0560303	0.264263153	0.029945374
54	17457.1929932	0.264129639	0.030326843
55	17445.4669189	0.264339447	0.030708313
56	17448.3984375	0.264663696	0.030517578
57	17451.3299561	0.264282227	0.030708313
58	17436.6723633	0.264415741	0.029945374
59	17442.5354004	0.264053345	0.030899048
60	17451.3299561	0.264015198	0.030708313

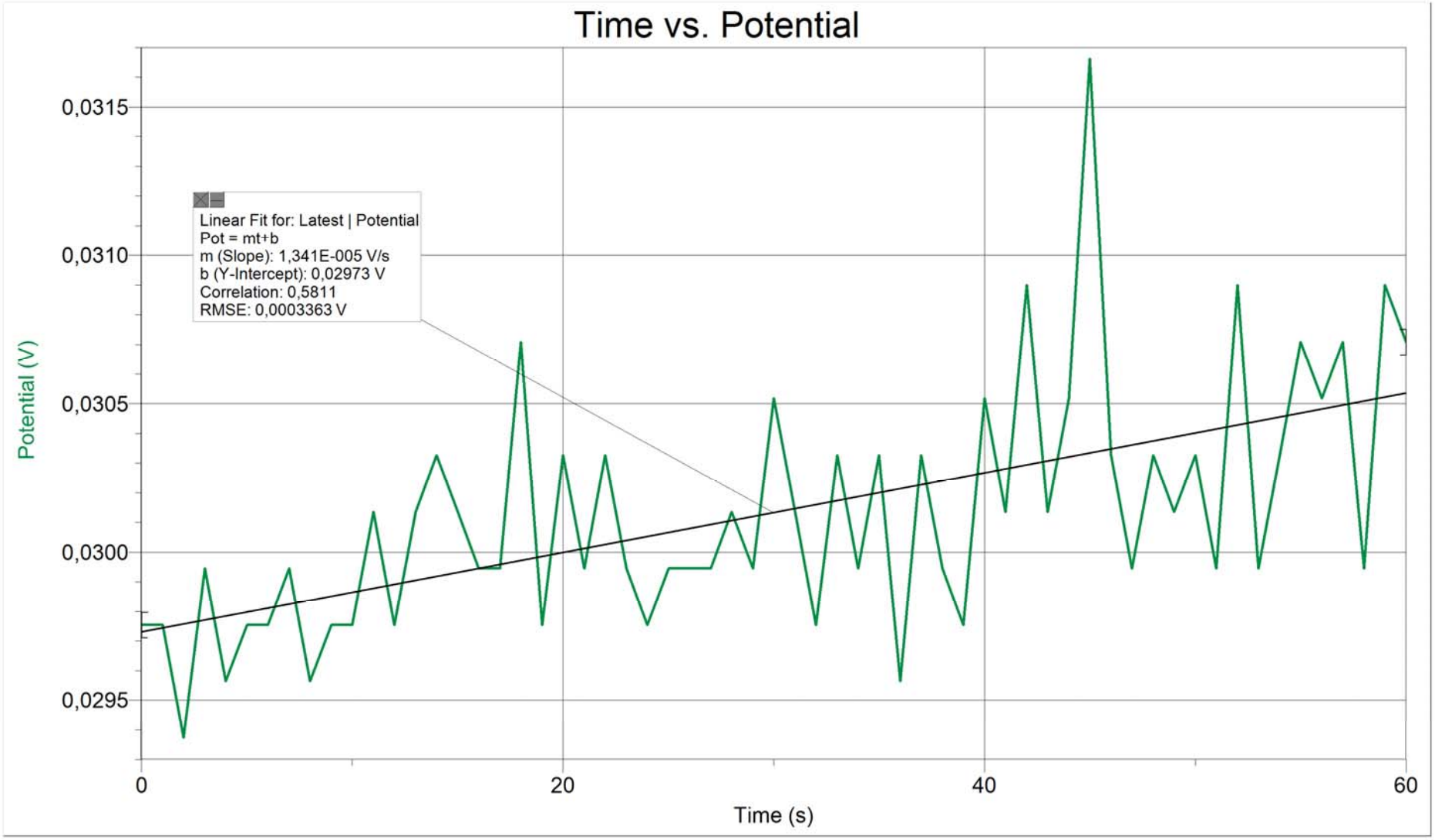
Table 3: Raw data of illumination, current and potential for yellow light



Graph 7: Graph of illumination versus time for yellow light



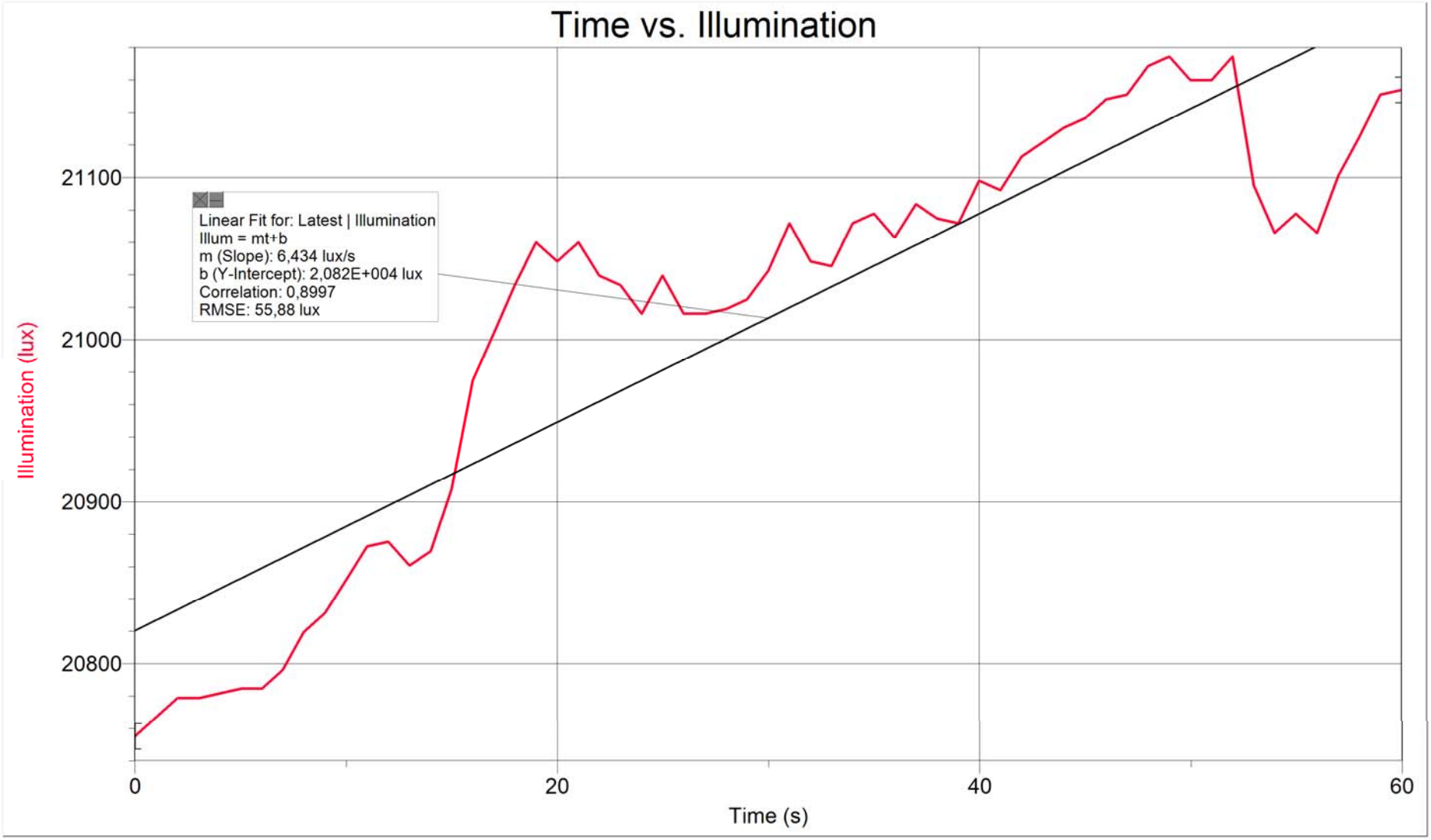
Graph 8: Graph of current versus time for yellow light



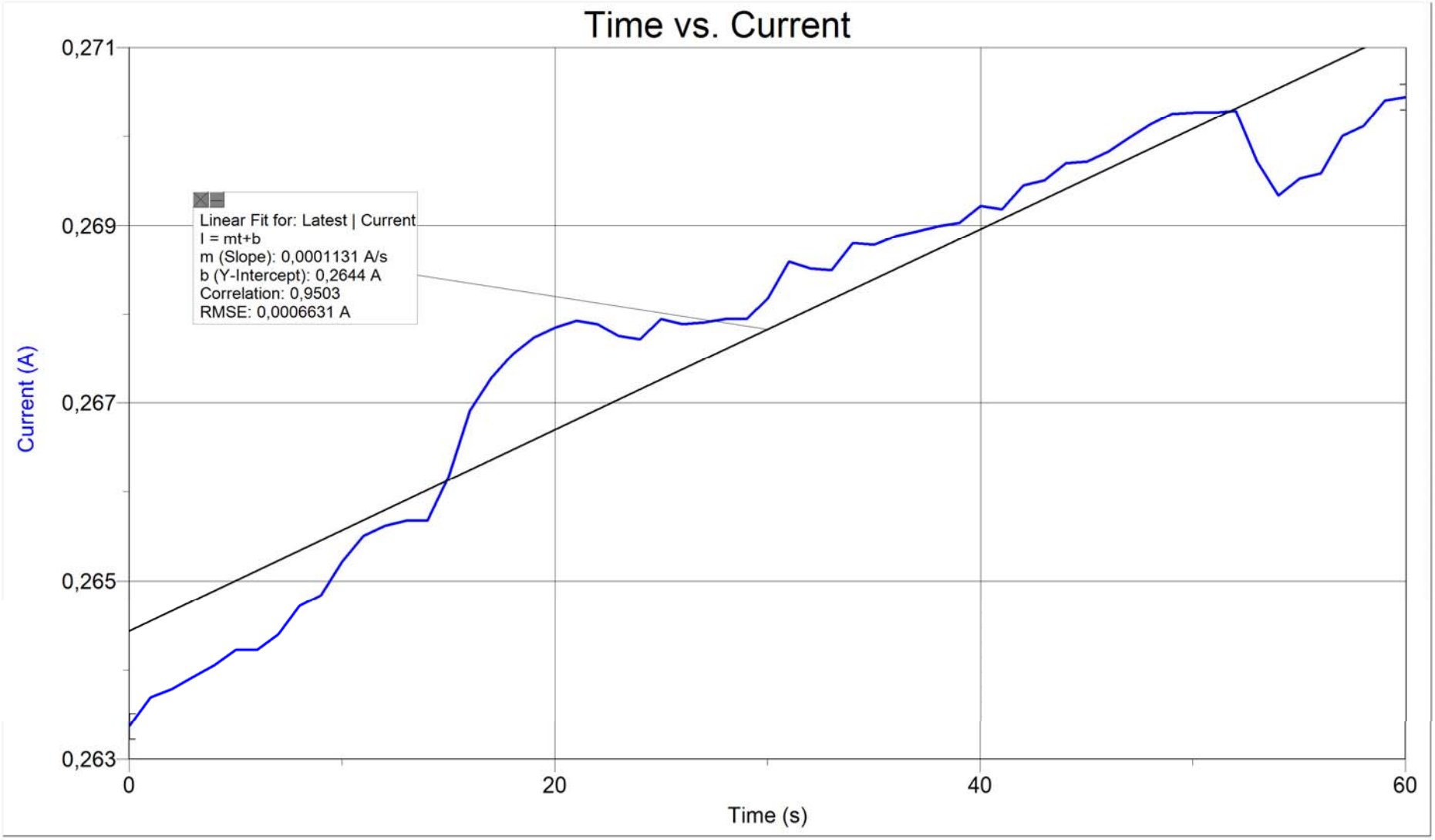
Graph 9: Graph of potential versus time for yellow light

Green Light			
Time (s)	Illumination (lux)	Current (A)	Potential (V)
0	20755.1513672	0.263366699	0.029754639
1	20766.8774414	0.263690948	0.029182434
2	20778.6035156	0.263786316	0.029373169
3	20778.6035156	0.263919830	0.029373169
4	20781.5350342	0.264053345	0.029373169
5	20784.4665527	0.264225006	0.029182434
6	20784.4665527	0.264225006	0.028991699
7	20796.1926270	0.264396667	0.029373169
8	20819.6447754	0.264720917	0.029754639
9	20831.3708496	0.264835358	0.029945374
10	20851.8914795	0.265216827	0.029373169
11	20872.4121094	0.265502930	0.029754639
12	20875.3436279	0.265617371	0.029754639
13	20860.6860352	0.265674591	0.029373169
14	20869.4805908	0.265674591	0.029754639
15	20907.5903320	0.266170502	0.029945374
16	20975.0152588	0.266914368	0.029754639
17	21004.3304443	0.267276764	0.030326843
18	21033.6456299	0.267543793	0.029754639
19	21060.0292969	0.267734528	0.030136108
20	21048.3032227	0.267848969	0.029945374
21	21060.0292969	0.267925262	0.030326843
22	21039.5086670	0.267887115	0.029945374
23	21033.6456299	0.267753601	0.029945374
24	21016.0565186	0.267715454	0.029945374
25	21039.5086670	0.267944336	0.029945374
26	21016.0565186	0.267887115	0.030136108
27	21016.0565186	0.267906189	0.029945374
28	21018.9880371	0.267944336	0.030326843
29	21024.8510742	0.267944336	0.029754639
30	21042.4401855	0.268173218	0.030517578
31	21071.7553711	0.268592834	0.029945374
32	21048.3032227	0.268516541	0.030136108
33	21045.3717041	0.268497467	0.030326843
34	21071.7553711	0.268802643	0.030136108
35	21077.6184082	0.268783569	0.030326843
36	21062.9608154	0.268878937	0.029945374
37	21083.4814453	0.268936157	0.030708313
38	21074.6868896	0.268993378	0.030517578
39	21071.7553711	0.269031525	0.030517578
40	21098.1390381	0.269222260	0.030326843
41	21092.2760010	0.269184113	0.030326843
42	21112.7966309	0.269451141	0.030708313
43	21121.5911865	0.269508362	0.030517578
44	21130.3857422	0.269699097	0.030326843
45	21136.2487793	0.269718170	0.030326843
46	21147.9748535	0.269832611	0.030326843
47	21150.9063721	0.269985199	0.030517578
48	21168.4954834	0.270137787	0.030517578
49	21174.3585205	0.270252228	0.030517578
50	21159.7009277	0.270271301	0.030899048
51	21159.7009277	0.270271301	0.030708313
52	21174.3585205	0.270290375	0.030517578
53	21095.2075195	0.269718170	0.029945374
54	21065.8923340	0.269336700	0.030326843
55	21077.6184082	0.269527435	0.030326843
56	21065.8923340	0.269584656	0.030136108
57	21101.0705566	0.270004272	0.030136108
58	21124.5227051	0.270118713	0.029945374
59	21150.9063721	0.270404816	0.030708313
60	21153.8378906	0.270442963	0.030517578

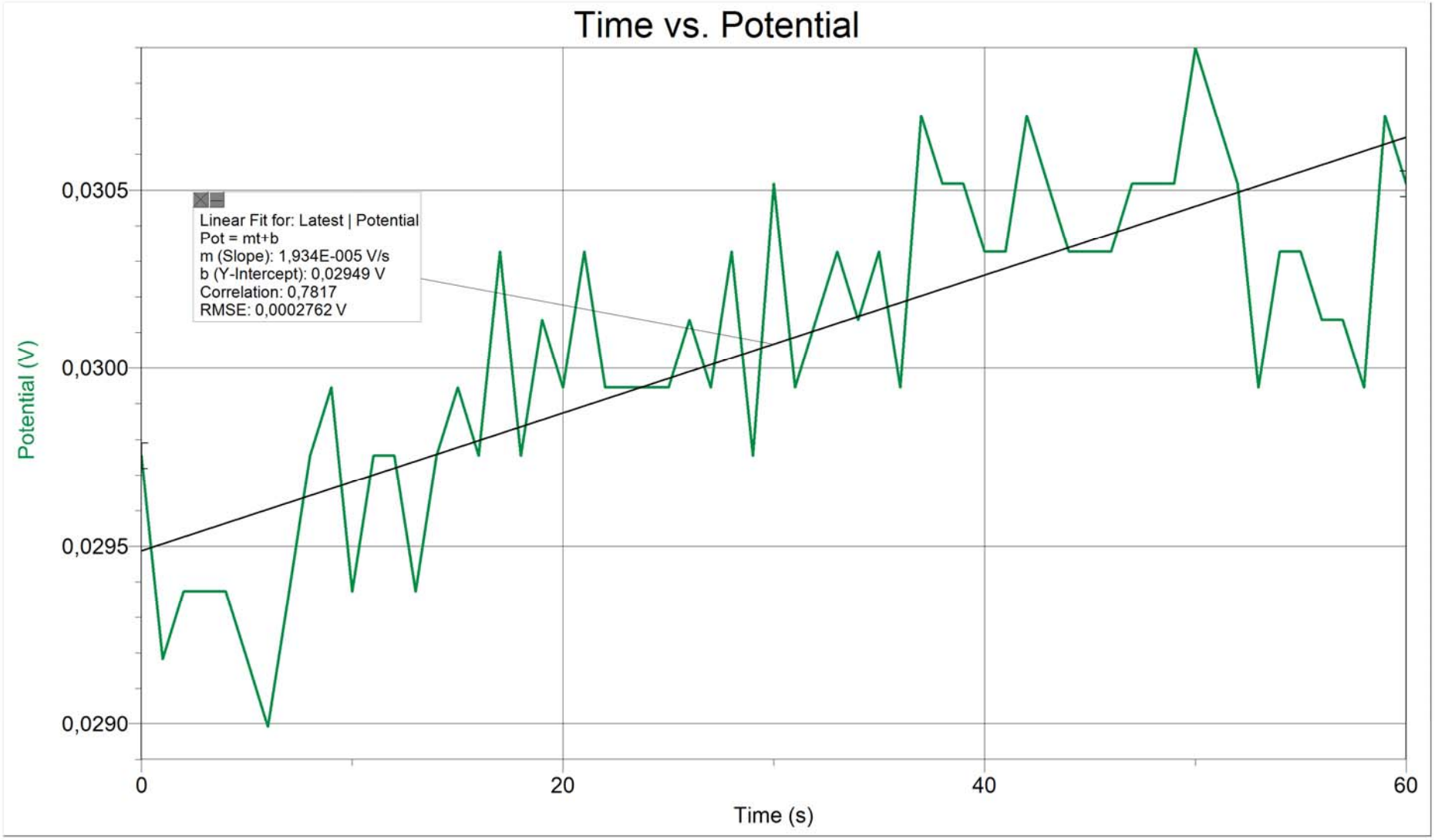
Table 4: Raw data of illumination, current and potential for green light



Graph 10: Graph of illumination versus time for green light



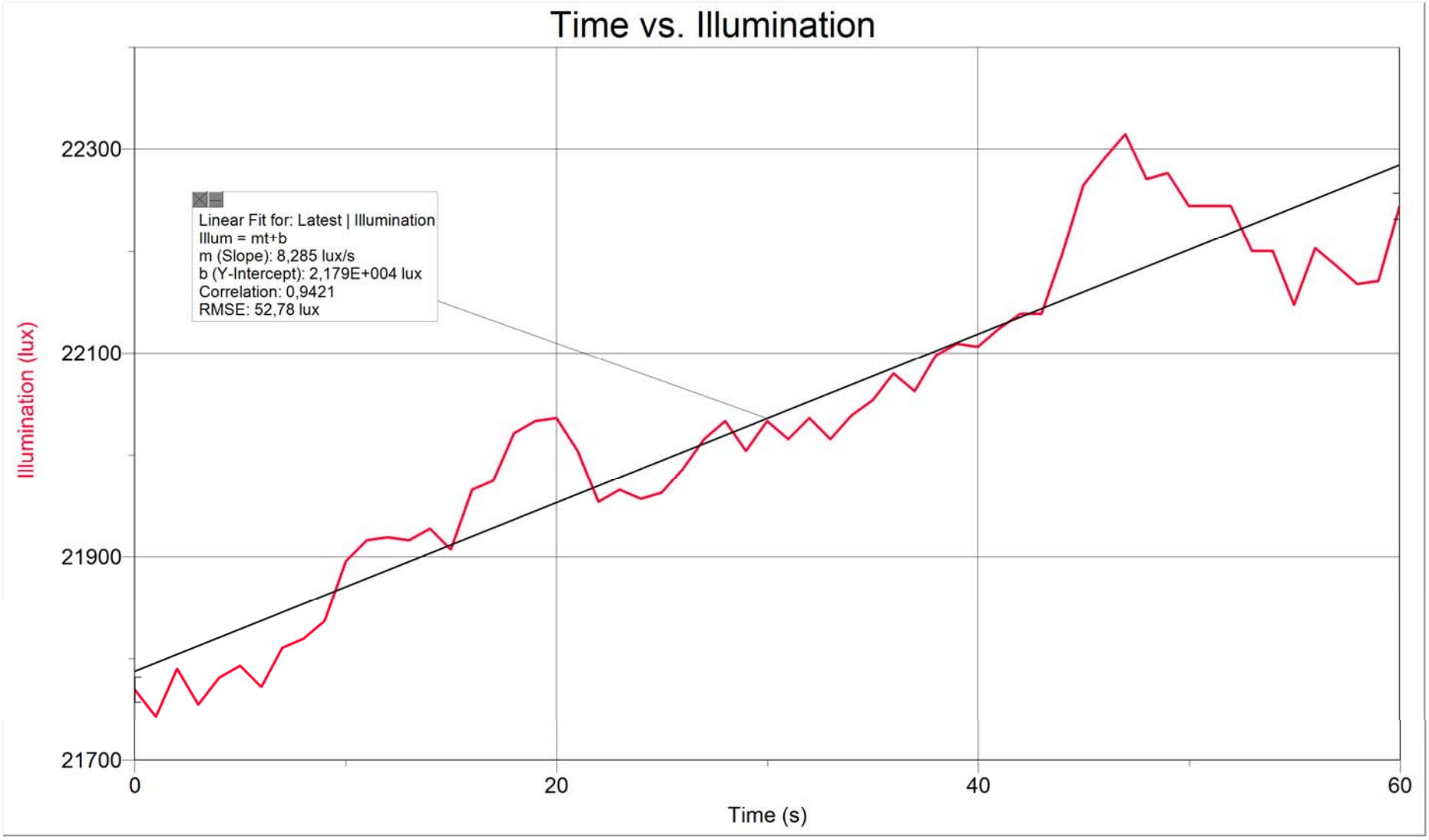
Graph 11: Graph of current versus time for green light



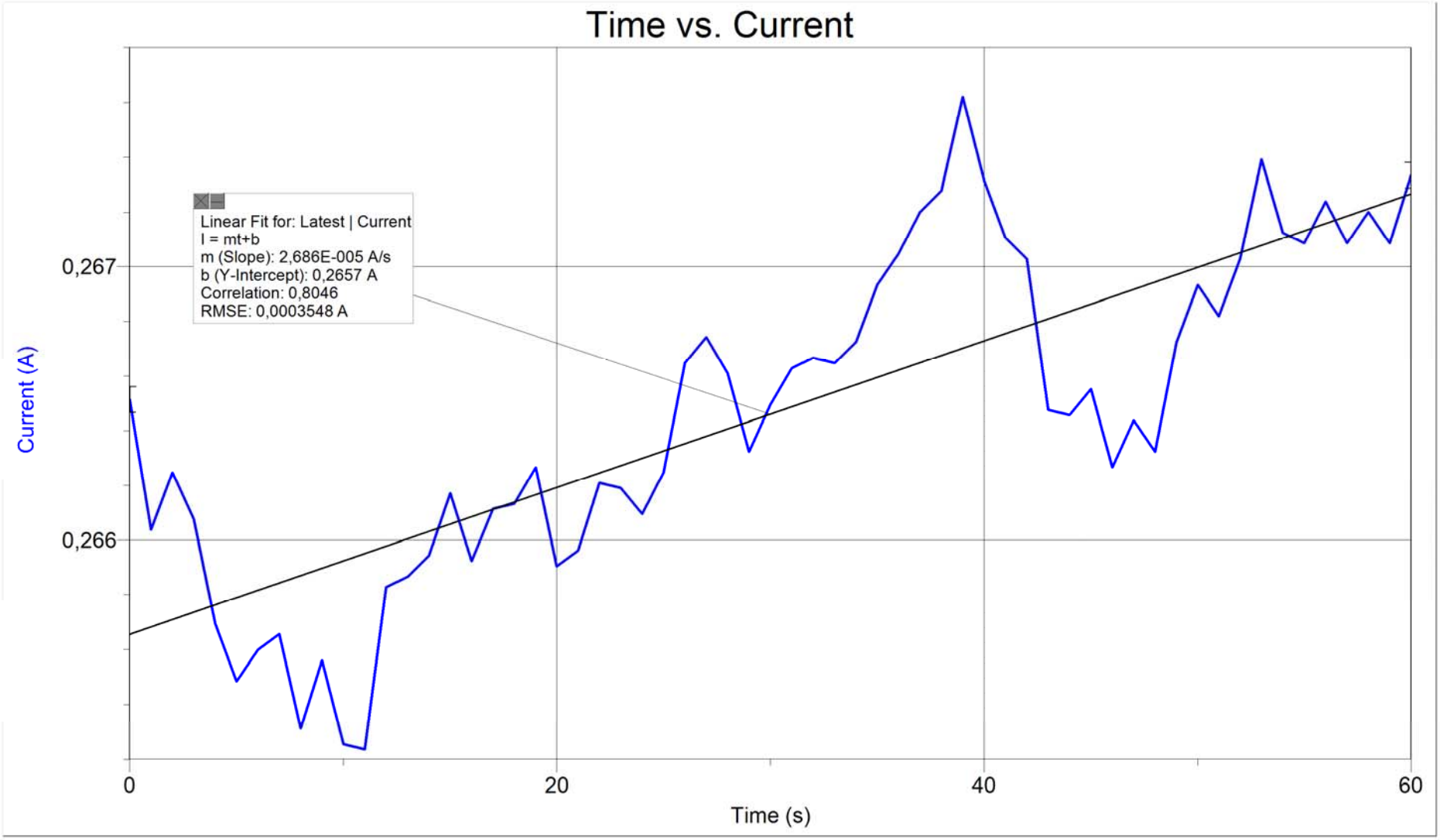
Graph 12: Graph of potential versus time for green light

Blue Light			
Time (s)	Illumination (lux)	Current (A)	Potential (V)
0	21769.4567871	0.266513824	0.029945374
1	21743.0731201	0.266036987	0.029182434
2	21789.9774170	0.266246796	0.029754639
3	21754.7991943	0.266075134	0.029945374
4	21781.1828613	0.265693665	0.030136108
5	21792.9089355	0.265483856	0.029754639
6	21772.3883057	0.265598297	0.029754639
7	21810.4980469	0.265655518	0.029945374
8	21819.2926025	0.265312195	0.029754639
9	21836.8817139	0.265560150	0.030136108
10	21895.5120850	0.265254974	0.029563904
11	21916.0327148	0.265235901	0.029754639
12	21918.9642334	0.265827179	0.029373169
13	21916.0327148	0.265865326	0.030136108
14	21927.7587891	0.265941620	0.030136108
15	21907.2381592	0.266170502	0.029754639
16	21965.8685303	0.265922546	0.029945374
17	21974.6630859	0.266113281	0.029754639
18	22021.5673828	0.266132355	0.030136108
19	22033.2934570	0.266265869	0.029754639
20	22036.2249756	0.265903473	0.029945374
21	22003.9782715	0.265960693	0.029945374
22	21954.1424561	0.266208649	0.029945374
23	21965.8685303	0.266189575	0.030136108
24	21957.0739746	0.266094208	0.029563904
25	21962.9370117	0.266246796	0.029754639
26	21986.3891602	0.266647339	0.029945374
27	22015.7043457	0.266742706	0.029945374
28	22033.2934570	0.266609192	0.029182434
29	22003.9782715	0.266323090	0.029563904
30	22033.2934570	0.266494751	0.029754639
31	22015.7043457	0.266628265	0.030136108
32	22036.2249756	0.266666412	0.030136108
33	22015.7043457	0.266647339	0.029945374
34	22039.1564941	0.266723633	0.030136108
35	22053.8140869	0.266933441	0.030136108
36	22080.1977539	0.267047882	0.030136108
37	22062.6086426	0.267200470	0.029945374
38	22097.7868652	0.267276764	0.030136108
39	22109.5129395	0.267620087	0.030136108
40	22106.5814209	0.267314911	0.029563904
41	22124.1705322	0.267105103	0.029754639
42	22138.8281250	0.267028809	0.030136108
43	22138.8281250	0.266475677	0.029754639
44	22197.4584961	0.266456604	0.030326843
45	22264.8834229	0.266551971	0.029754639
46	22291.2670898	0.266265869	0.030326843
47	22314.7192383	0.266437531	0.029945374
48	22270.7464600	0.266323090	0.029945374
49	22276.6094971	0.266723633	0.029945374
50	22244.3627930	0.266933441	0.029754639
51	22244.3627930	0.266819000	0.029754639
52	22244.3627930	0.267028809	0.030136108
53	22200.3900146	0.267391205	0.030326843
54	22200.3900146	0.267124176	0.030136108
55	22147.6226807	0.267086029	0.030326843
56	22203.3215332	0.267238617	0.029945374
57	22185.7324219	0.267086029	0.029945374
58	22168.1433105	0.267200470	0.029754639
59	22171.0748291	0.267086029	0.029945374
60	22244.3627930	0.267333984	0.029945374

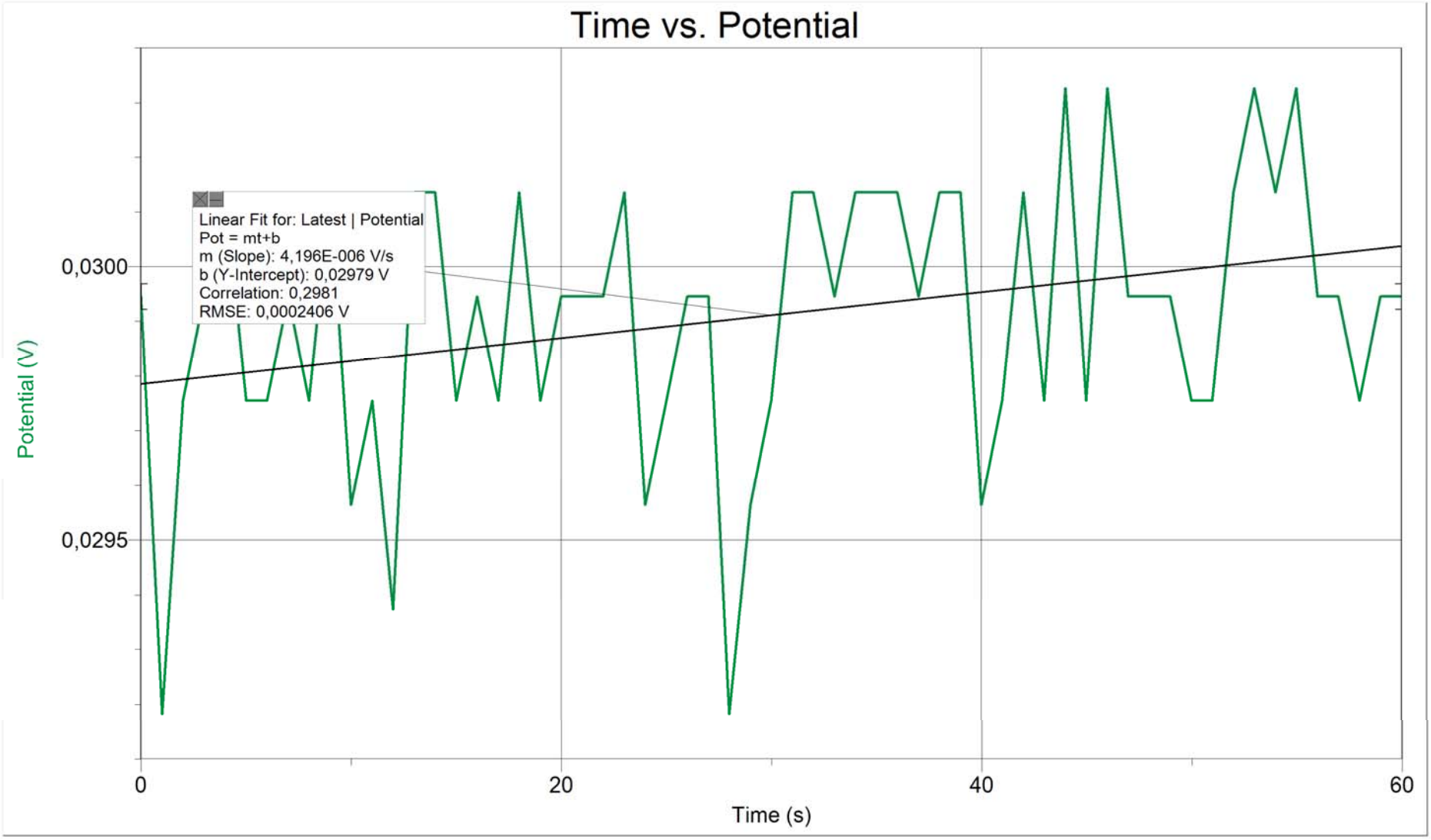
Table 5: Raw data of illumination, current and potential for blue light



Graph 13: Graph of illumination versus time for blue colour



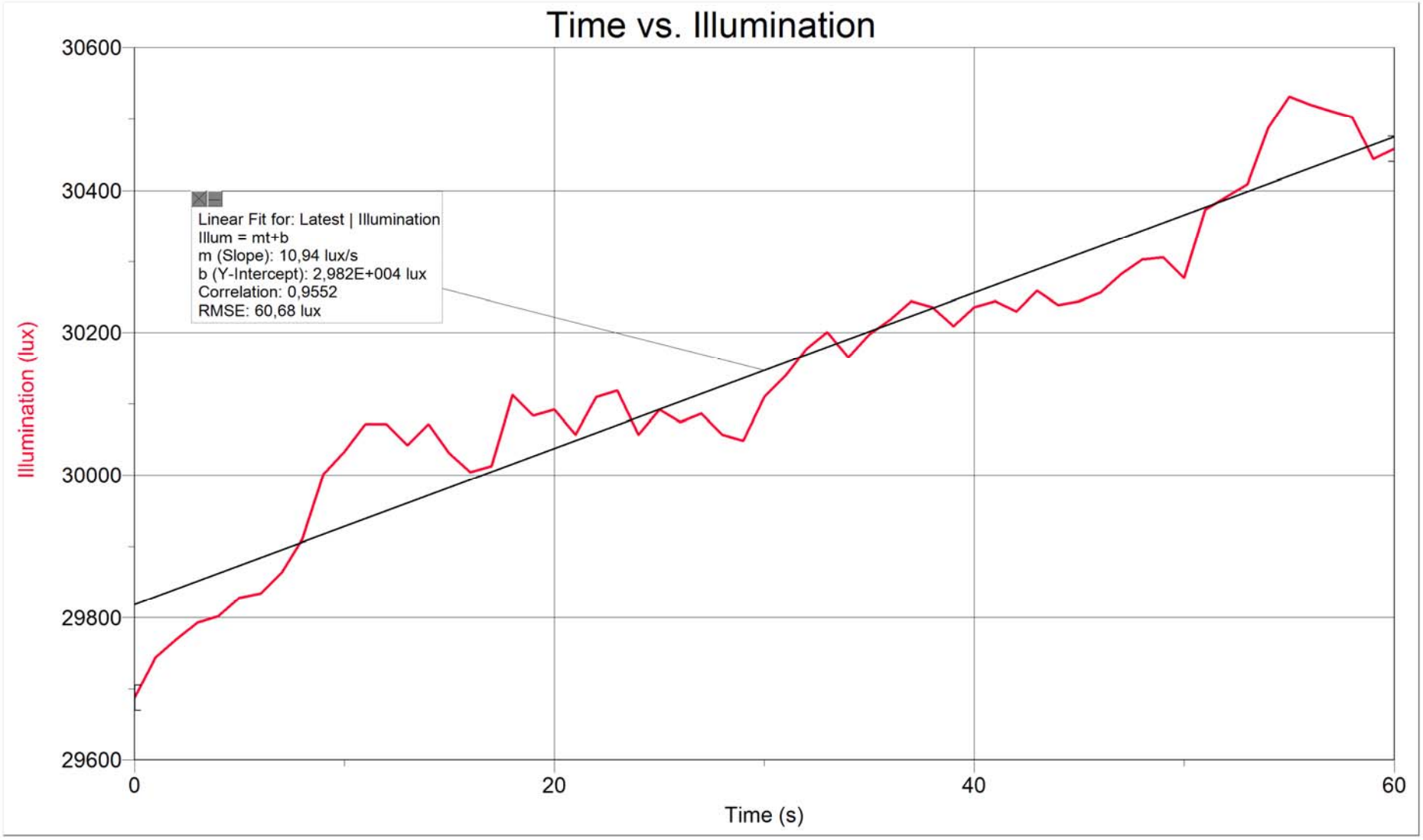
Graph 14: Graph of current versus time for blue colour



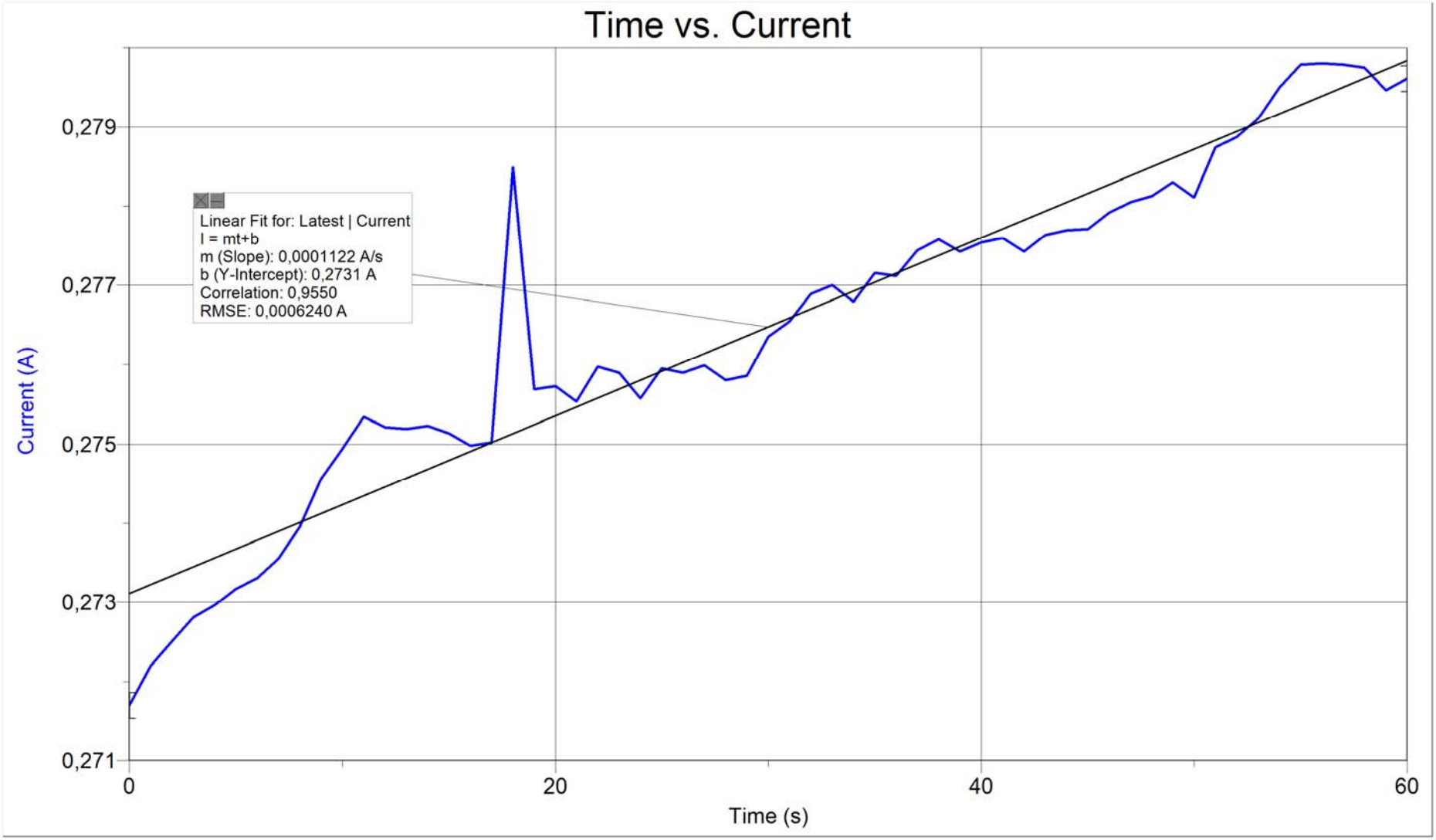
Graph 15: Graph of potential versus time for blue colour

Purple Light			
Time (s)	Illumination (lux)	Current (A)	Potential (V)
0	29687.4884033	0.271701813	0.031089783
1	29743.1872559	0.272197723	0.031661987
2	29769.5709229	0.272502899	0.031089783
3	29793.0230713	0.272808075	0.031280518
4	29801.8176270	0.272960663	0.031089783
5	29828.2012939	0.273170471	0.031471252
6	29834.0643311	0.273303986	0.030899048
7	29863.3795166	0.273551941	0.031471252
8	29910.2838135	0.273952484	0.031280518
9	30001.1608887	0.274562836	0.031661987
10	30033.4075928	0.274944305	0.031471252
11	30071.5173340	0.275344849	0.032043457
12	30071.5173340	0.275211334	0.031661987
13	30042.2021484	0.275192261	0.031471252
14	30071.5173340	0.275230408	0.031661987
15	30030.4760742	0.275135040	0.031280518
16	30004.0924072	0.274982452	0.032424927
17	30012.8869629	0.275020599	0.031471252
18	30112.5585938	0.278491974	0.031852722
19	30083.2434082	0.275688171	0.031852722
20	30092.0379639	0.275726318	0.031661987
21	30056.8597412	0.275535583	0.031852722
22	30109.6270752	0.275974274	0.032234192
23	30118.4216309	0.275897980	0.032234192
24	30056.8597412	0.275573730	0.031661987
25	30092.0379639	0.275955200	0.031661987
26	30074.4488525	0.275897980	0.031471252
27	30086.1749268	0.275993347	0.031471252
28	30056.8597412	0.275802612	0.031471252
29	30048.0651855	0.275859833	0.031471252
30	30109.6270752	0.276355743	0.031852722
31	30138.9422607	0.276546478	0.031661987
32	30177.0520020	0.276889801	0.031852722
33	30200.5041504	0.277004242	0.031661987
34	30165.3259277	0.276794434	0.031471252
35	30197.5726318	0.277156830	0.032234192
36	30218.0932617	0.277118683	0.032234192
37	30244.4769287	0.277442932	0.031471252
38	30235.6823730	0.277576447	0.032424927
39	30209.2987061	0.277423859	0.032043457
40	30235.6823730	0.277538300	0.031661987
41	30244.4769287	0.277595520	0.031471252
42	30229.8193359	0.277423859	0.032424927
43	30259.1345215	0.277633667	0.032043457
44	30238.6138916	0.277690887	0.032424927
45	30244.4769287	0.277709961	0.032043457
46	30256.2030029	0.277919769	0.031661987
47	30282.5866699	0.278053284	0.032043457
48	30303.1072998	0.278129578	0.032615662
49	30306.0388184	0.278301239	0.031852722
50	30276.7236328	0.278110504	0.032234192
51	30373.4637451	0.278739929	0.032234192
52	30391.0528564	0.278873444	0.032424927
53	30408.6419678	0.279102325	0.032424927
54	30487.7929688	0.279502869	0.032424927
55	30531.7657471	0.279788971	0.032997131
56	30520.0396729	0.279808044	0.032997131
57	30511.2451172	0.279788971	0.032806396
58	30502.4505615	0.279750824	0.032806396
59	30443.8201904	0.279464722	0.032424927
60	30458.4777832	0.279617310	0.032424927

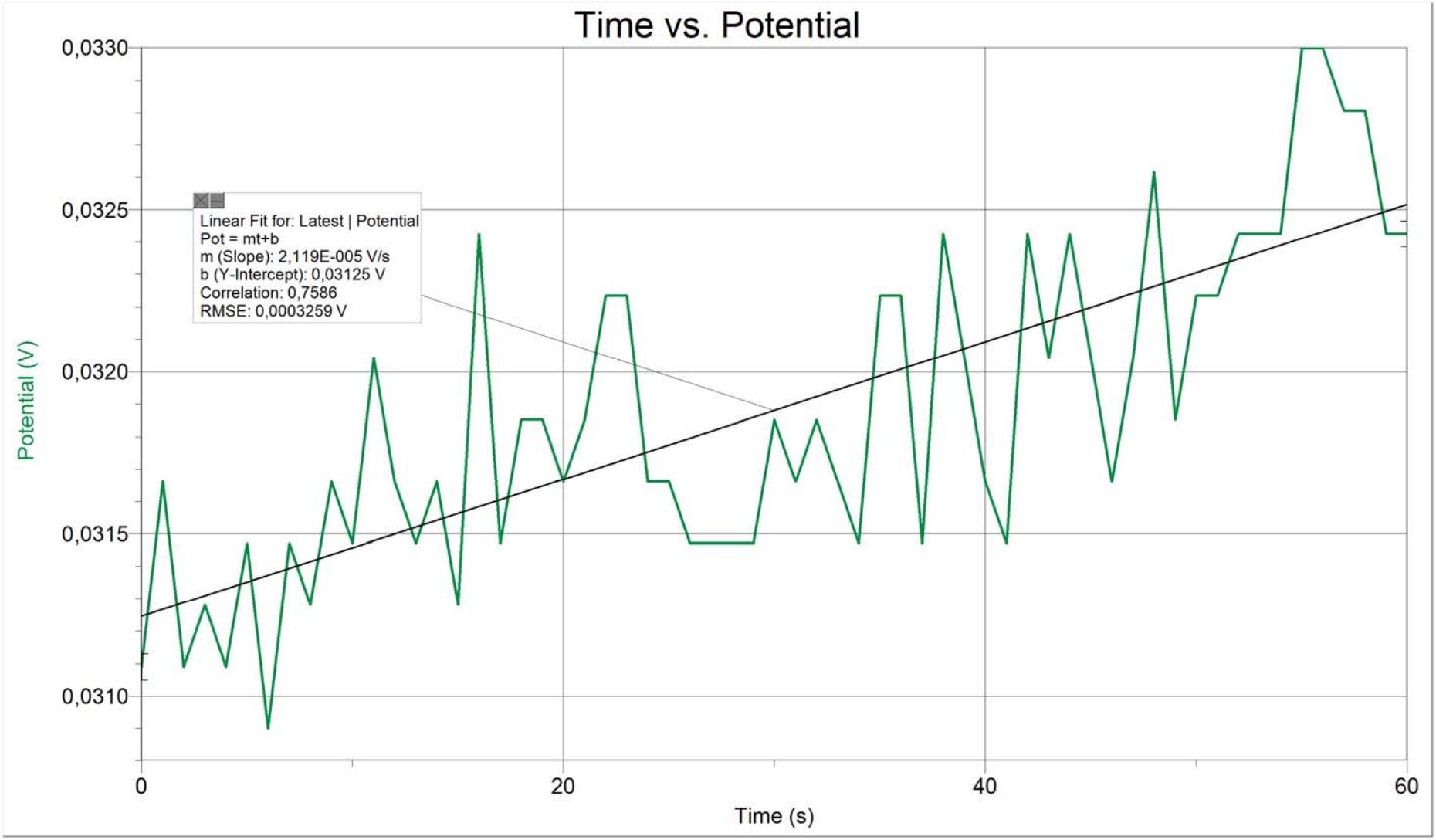
Table 6: Raw data of illumination, current and potential for purple light



Graph 16: Graph of illumination versus time for purple colour



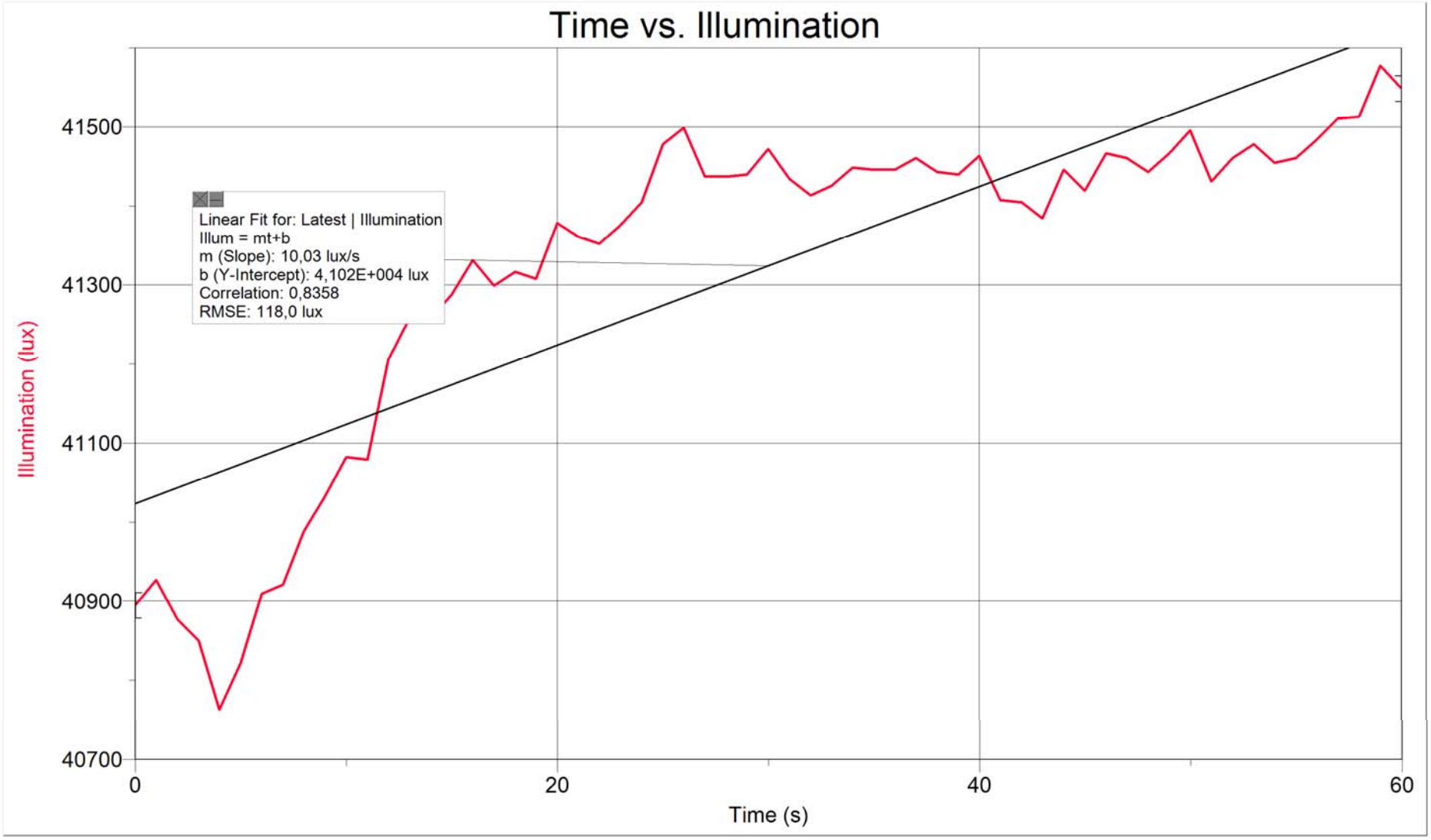
Graph 17: Graph of current versus time for purple colour



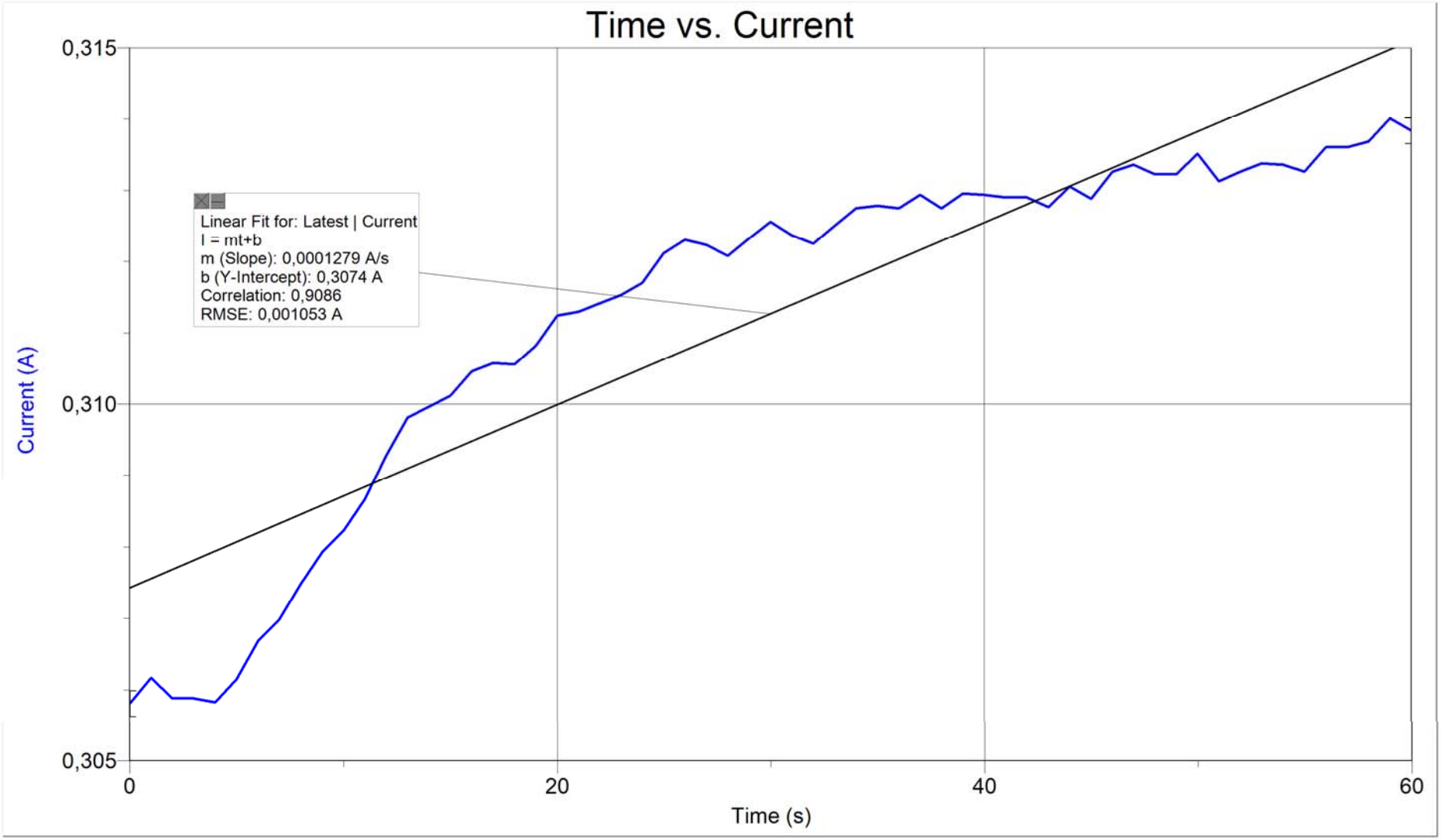
Graph 18: Graph of potential versus time for purple light

Colourless Light			
Time (s)	Illumination (lux)	Current (A)	Potential (V)
0	40894.6838379	0.305805206	0.038337708
1	40926.9305420	0.306167603	0.038337708
2	40877.0947266	0.305881500	0.038909912
3	40850.7110596	0.305881500	0.038528442
4	40762.7655029	0.305824280	0.038528442
5	40821.3958740	0.306148529	0.038909912
6	40909.3414307	0.306682587	0.038146973
7	40921.0675049	0.306987762	0.038528442
8	40988.4924316	0.307483673	0.039100647
9	41032.4652100	0.307922363	0.039291382
10	41082.3010254	0.308227539	0.038909912
11	41079.3695068	0.308666229	0.038719177
12	41205.4248047	0.309276581	0.038909912
13	41258.1921387	0.309810638	0.038909912
14	41258.1921387	0.309963226	0.039100647
15	41287.5073242	0.310115814	0.038909912
16	41331.4801025	0.310459137	0.039100647
17	41299.2333984	0.310573578	0.039100647
18	41316.8225098	0.310554504	0.039100647
19	41308.0279541	0.310821533	0.038909912
20	41378.3843994	0.311241150	0.039672852
21	41360.7952881	0.311298370	0.039482117
22	41352.0007324	0.311412811	0.038909912
23	41375.4528809	0.311527252	0.039100647
24	41404.7680664	0.311698914	0.039482117
25	41478.0560303	0.312118530	0.039291382
26	41498.5766602	0.312309265	0.039100647
27	41437.0147705	0.312232971	0.038909912
28	41437.0147705	0.312080383	0.039672852
29	41439.9462891	0.312328339	0.039672852
30	41472.1929932	0.312557220	0.039291382
31	41434.0832520	0.312366486	0.039672852
32	41413.5626221	0.312252045	0.039863586
33	41425.2886963	0.312500000	0.039100647
34	41448.7408447	0.312747955	0.039672852
35	41445.8093262	0.312786102	0.039291382
36	41445.8093262	0.312747955	0.039863586
37	41460.4669189	0.312938690	0.039291382
38	41442.8778076	0.312747955	0.039672852
39	41439.9462891	0.312957764	0.039291382
40	41463.3984375	0.312938690	0.040054321
41	41407.6995850	0.312900543	0.039291382
42	41404.7680664	0.312900543	0.039482117
43	41384.2474365	0.312767029	0.039100647
44	41445.8093262	0.313053131	0.038909912
45	41419.4256592	0.312881470	0.039672852
46	41466.3299561	0.313262939	0.039863586
47	41460.4669189	0.313358307	0.039100647
48	41442.8778076	0.313224792	0.039672852
49	41466.3299561	0.313224792	0.039672852
50	41495.6451416	0.313510895	0.039482117
51	41431.1517334	0.313129425	0.039482117
52	41460.4669189	0.313262939	0.039482117
53	41478.0560303	0.313377380	0.039482117
54	41454.6038818	0.313358307	0.039482117
55	41460.4669189	0.313262939	0.039291382
56	41483.9190674	0.313606262	0.039291382
57	41510.3027344	0.313606262	0.039291382
58	41513.2342529	0.313682556	0.039863586
59	41577.7276611	0.314006805	0.039482117
60	41548.4124756	0.313835144	0.039672852

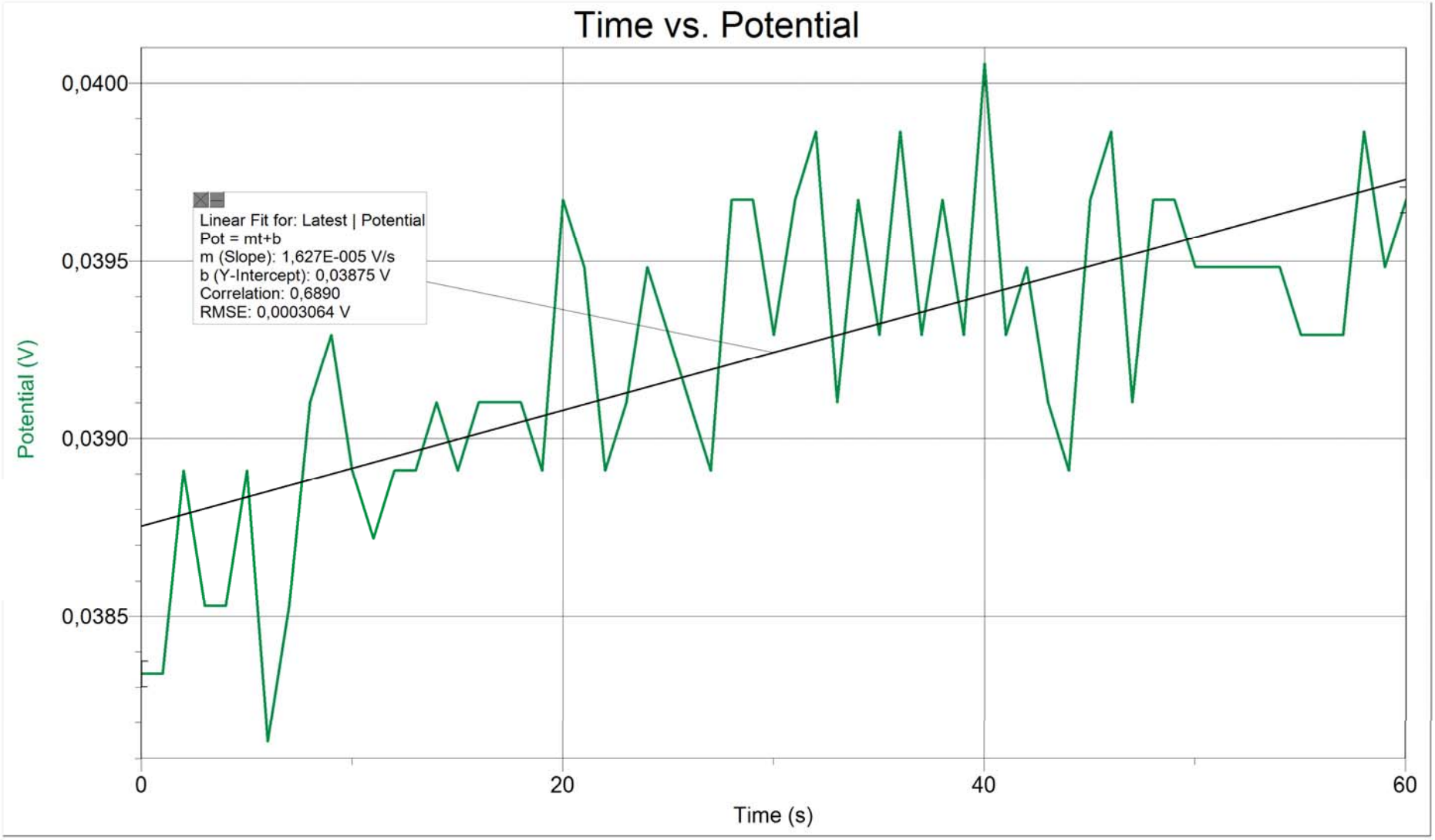
Table 7: Raw data of illumination, current and potential for colourless light



Graph 19: Graph of illumination versus time for colourless light



Graph 20: Graph of current versus time for colourless light



Graph 21: Graph of potential versus time for colourless light

Mean Values			
Colour	Mean Illumination (lux)	Mean Current (A)	Mean Potential (V)
Red	11853.0426125	0.185842358	0.016124913
Orange	12539.7388196	0.241475340	0.025555345
Yellow	17471.4180668	0.262255434	0.030132982
Green	21013.3172307	0.267827394	0.030067319
Blue	22035.8885718	0.266460356	0.029910979
Purple	30146.8717781	0.276475813	0.031880863
Colourless	41324.2233927	0.311266477	0.039241353

Table 8: Table above represents the averages of illumination, current and potential values calculated for every colour by adding all values together and dividing the sum into total number of values

Electrical power is the rate of transfer of energy in an electric circuit. While electric current is flowing in a circuit, energy can be transferred into mechanical or thermodynamic work.

Electrical power in direct current circuits is calculated by Joule's law;

$$P = I \cdot V$$

where P is the electric power, I is the electric current, V is the potential difference.

Unit of power in International System of Units is Watt abbreviated as W.

So,

Electric power for red colour,

$P=0.185842358 \cdot 0.016124913=0.002996692W$

Electric power for orange colour,

$P=0.241475340 \cdot 0.025555345=0.006170986W$

Electric power for yellow colour,

$P=0.262255434 \cdot 0.030132982=0.007902538W$

Electric power for green colour,

$P=0.267827394 \cdot 0.030067319=0.008052852W$

Electric power for blue colour,

$P=0.266460356 \cdot 0.029910979=0.007970090W$

Electric power for purple colour,

P=0.276475813·0.031880863=0.008814288W

Electric power for colourless,

P=0.311266477·0.039241353=0.012214518W

As frequency of light is directly proportional with its energy, and as the total energy of photons of light means light intensity, light intensity will increase when the frequency increases. Light intensity is directly proportional with illuminance which makes frequency related with illuminance. So, it makes sense to compare the relationship between illumination and power as they are both changing by frequency.

Power Values		
Colour	Mean Illumination (lux)	Power (W)
Red	11853.0426125	0.002996692
Orange	12539.7388196	0.006170986
Yellow	17471.4180668	0.007902538
Green	21013.3172307	0.008052852
Blue	22035.8885718	0.007970090
Purple	30146.8717781	0.008814288
Colourless	41324.2233927	0.012214518

Table 9: Table above represents the mean illumination and power of the solar cell circuit together in order to give a general sense about the relation between them

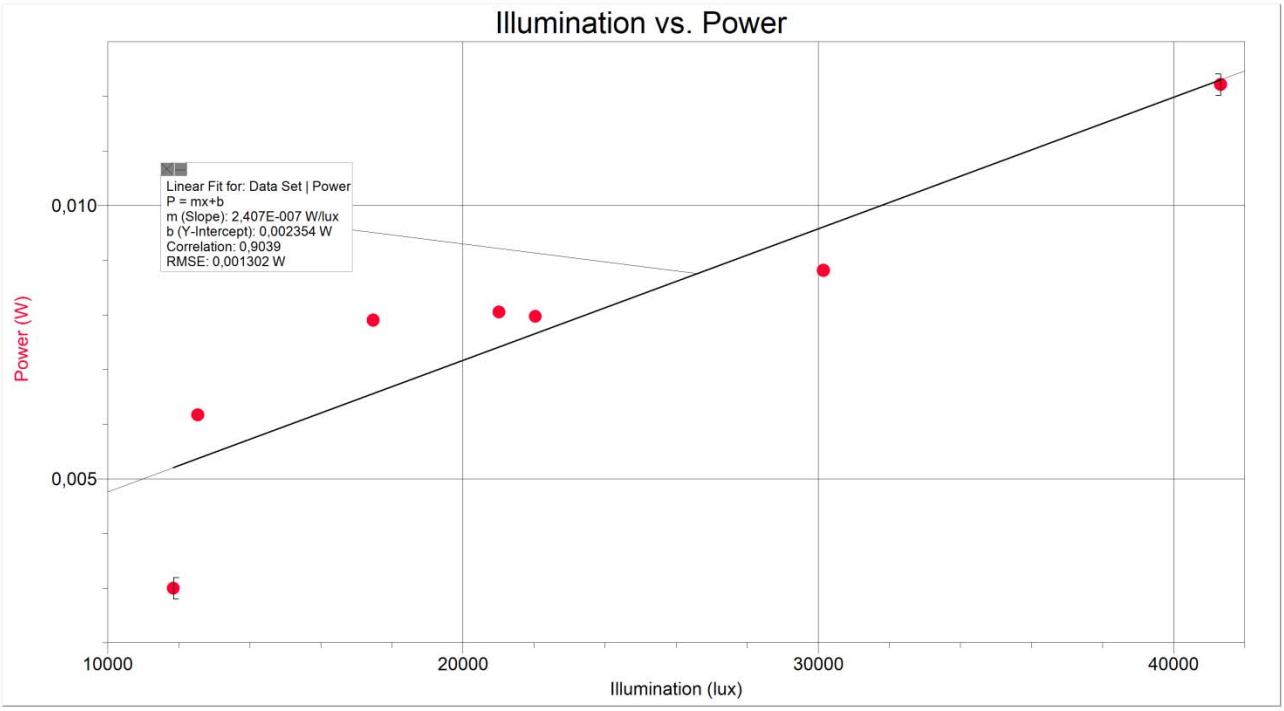
Analysis of Variance (ANOVA) provides a statistical test of whether or not the means of several groups are all equal.[9] It is used in comparison of two or more trends and a considerable meaningful relationship is looked for. P-value in ANOVA determines the significance of the relationship. If the p-value comes up as smaller than the alpha value, then it is concluded that the relationship between the groups is falling inside the confidence interval.

[9] <http://en.wiki/Analysis_of_variance>

Anova: Single Factor						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Column 1	7	156384.5005	22340.64292	108820839.6		
Column 2	7	0.054121964	0.007731709	7.71882E-06		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1746863933	1	1746863933	32.1053199	0.000104572	4.747225336
Within Groups	652925037.3	12	54410419.78			
Total	2399788970	13				

Table 10: Table above represents the ANOVA test for the relationship between different illumination values for each colour and power as the multiplication of current and potential of solar cell

As it is seen in the table above, p-value is 0.000104572 which is smaller than the alpha value of 0.05. This means there is a significant relationship between the illumination of light colour and electrical power of solar cell with 95% probability.



Graph 22: Graph above shows the relationship between illumination values for each colour measured and power as the multiplication of current and potential of solar cell calculated

As it is seen in the graph, correlation value of 0.9039 is very close to 1 which means the relationship between two samples is very strong. Also the positive slope of the graph shows that there is an increasing trend between the illumination and power of the system.

Conclusion and Evaluation

In conclusion, it is proved by statistical analysis that there is a relationship between the frequency of light which is determined by colour in visible spectrum and illumination, and current and potential values.

Moreover, power of the solar cell is calculated and benefitting from the known proportions between frequency and illumination, an increasing trend is proved between power and illumination.

Shortly, the whole experiment supports the hypothesis based on the working mechanism of solar cells. It is showed that, number of photons which have enough energy to excite electrons over the band gap value increases as the frequency of light increases from red to purple in visible spectrum due to the fact that frequency is directly proportional with the energy of photons. Increase in number of photons means increase in number of excited electrons. Electrons passing through the circuit in unit time increases which mean increase in current. As the internal resistance of the solar cell is constant, potential difference increases due to the increase in current. Another factor increasing together with frequency is light intensity, as it is the total energy of all photons in light. Illumination also increases, due to its direct proportion to light intensity. As a result, power of the solar cell system which is the multiplication of current and potential shows a significant relation with illumination changing with the colour of the light source. Furthermore, this relationship can be explained as the increase in frequency increases the power output of the solar cell.

In graph 2, an example of uncertainty calculation is showed in order to explain how it could be done. Vernier, the producer of the data loggers used in this experiment, gives no range for light sensor but gives a ±0.6A range for current probe and a ±6.0V range for voltage probe. However, as the efficiency of solar cell is too small, these values are illogical to calculate uncertainty. Then, the half of the sum of maximum and minimum values in red light current data is assumed as uncertainty. Still this fixed value of uncertainty stays too large for the measurements. When best fit line and worst lines are drawn, y-intercept of the best fit line

gives the mean of current values for the red light current data which is 0.1838A, and percent error calculation can be done by y-intercepts of worst lines as following;

$$\frac{(0.18530 - 0.18080)}{2} = 0.00225$$

$$\frac{0.00225}{0.18380} \cdot 100 = 1.22416\%$$

This kind of calculation can be done in all graphs. However, graphical analysis does not give that much accurate result due to program untrustworthiness. Also, calculating a range and then uncertainties over maximum and minimum values brings only more assumptions. So, instead of this statistical analysis is done over the data as it is more trustworthy, accurate and logical.

If the power obtained from the colourless trial is accepted as the theoretical value for the solar cell with nominal power efficiency of 12Wp lightened with a 500W halogen light source, then errors can be calculated for each colour as following;

For red colour,

$$\frac{(0.012214518 - 0.002996692)}{0.012214518} \cdot 100 = 75.466146106\%$$

For orange colour,

$$\frac{(0.012214518 - 0.006170986)}{0.012214518} \cdot 100 = 49.478268402\%$$

For yellow colour,

$$\frac{(0.012214518 - 0.007902536)}{0.012214518} \cdot 100 = 35.302088875\%$$

For green colour,

$$\frac{(0.012214518 - 0.008052852)}{0.012214518} \cdot 100 = 34.071471342\%$$

For blue colour,

$$\frac{(0.012214518 - 0.00797009)}{0.012214518} \cdot 100 = 34.749042082\%$$

For purple colour,

$$\frac{(0.012214518 - 0.008814286)}{0.012214518} \cdot 100 = 27.837610948\%$$

As it is seen from the percent errors, one of the greatest limitations of this experiment is the problem of transparency. Coloured transparent glass films are the best material to change the frequency of light with most reliable results in a limited budget. However, it can be possible to arrange the wavelength of the energy source by more developed materials which can't be afforded personally. The reason of average percent error of 42.817166% is the loss in intensity of light when it is covered with a glass film.

Another great limitation for this experiment is the lack of a frequency sensor. The relation between the power output of the solar cell and the frequency of light is discussed over the relationship between frequency and illumination. This means an indirect relationship between the investigated variables. Better hypothesis can be build up and supported by better measuring devices which is hard to obtain again.

The greatest limitation for this experiment is of course the solar cell itself. The efficiency of the solar cells is still so law that output power is so little when compared with the input energy. An average of 0.0077W power can be obtained from 500W light source which means total efficiency was

$$\frac{0.0077}{500} \cdot 100 = 0.00154\%$$

It seems thoughtful to obtain enough energy from a solar cell in an indoor place or under an artificial light in order to make a profit. However, it is again better than nothing. In greater scale, the results can be satisfying. So, it is logical to try this system in long term.

(Word count: 3655)

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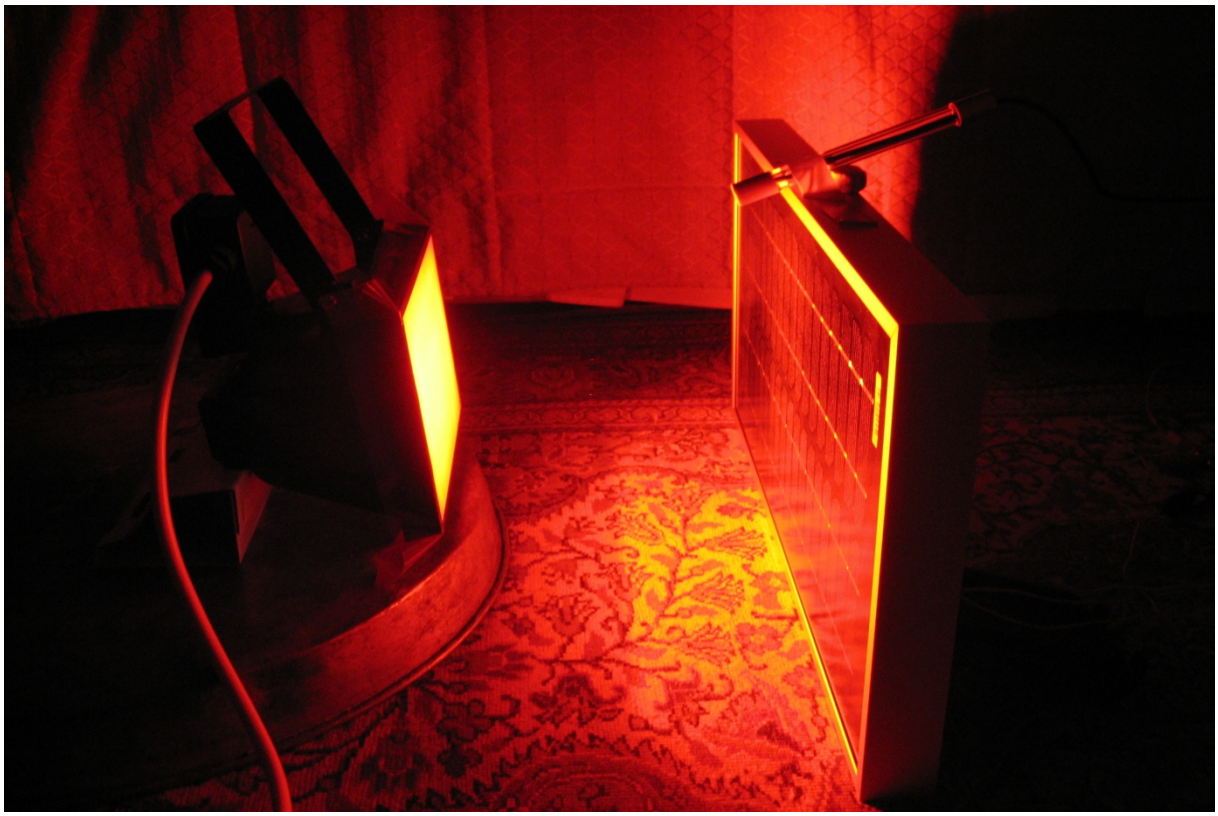
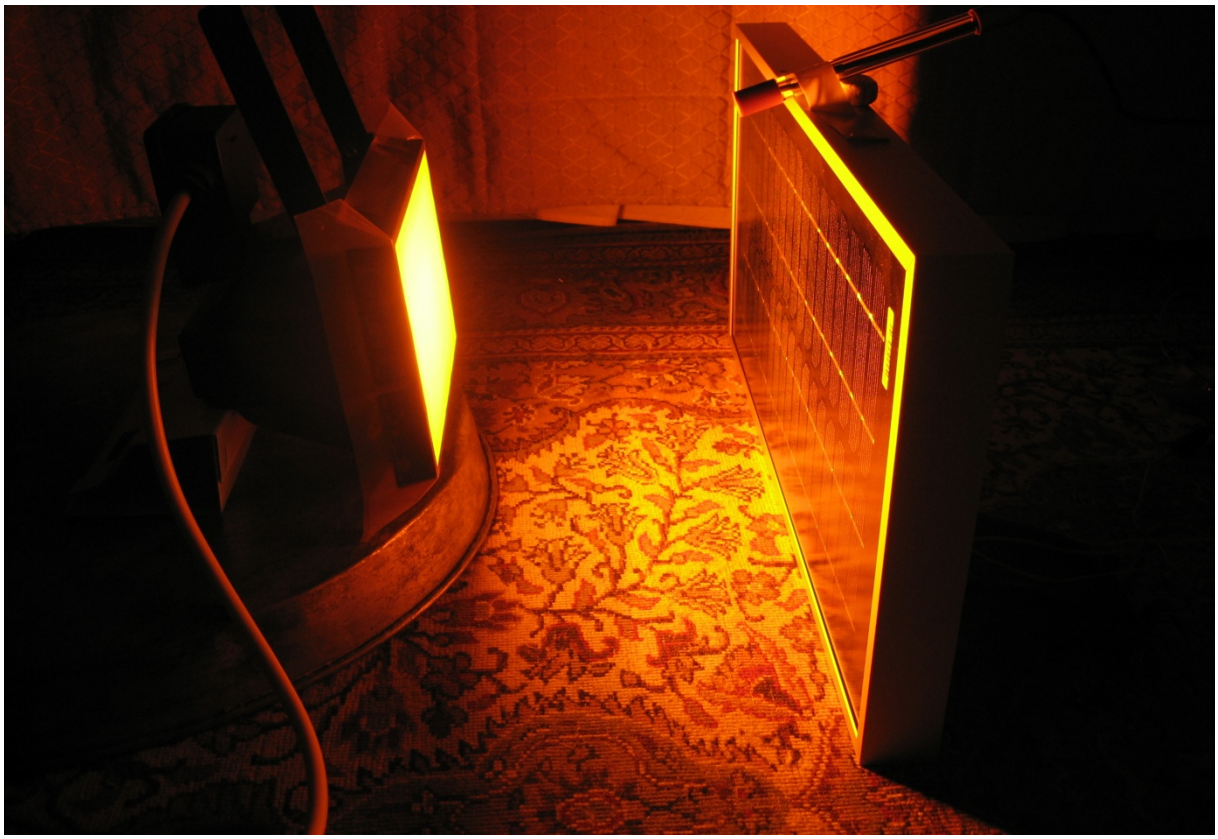
Appendix

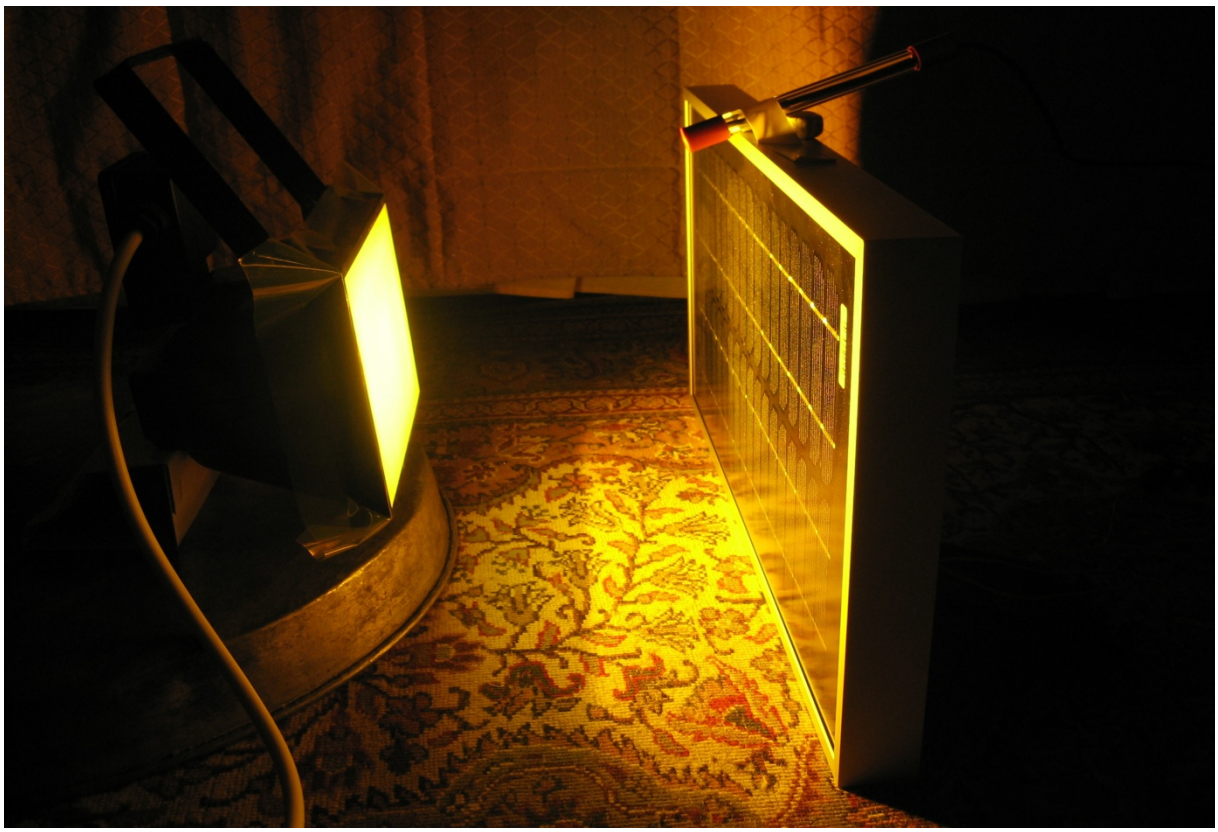
Picture 1: Transparent glass films in six colours



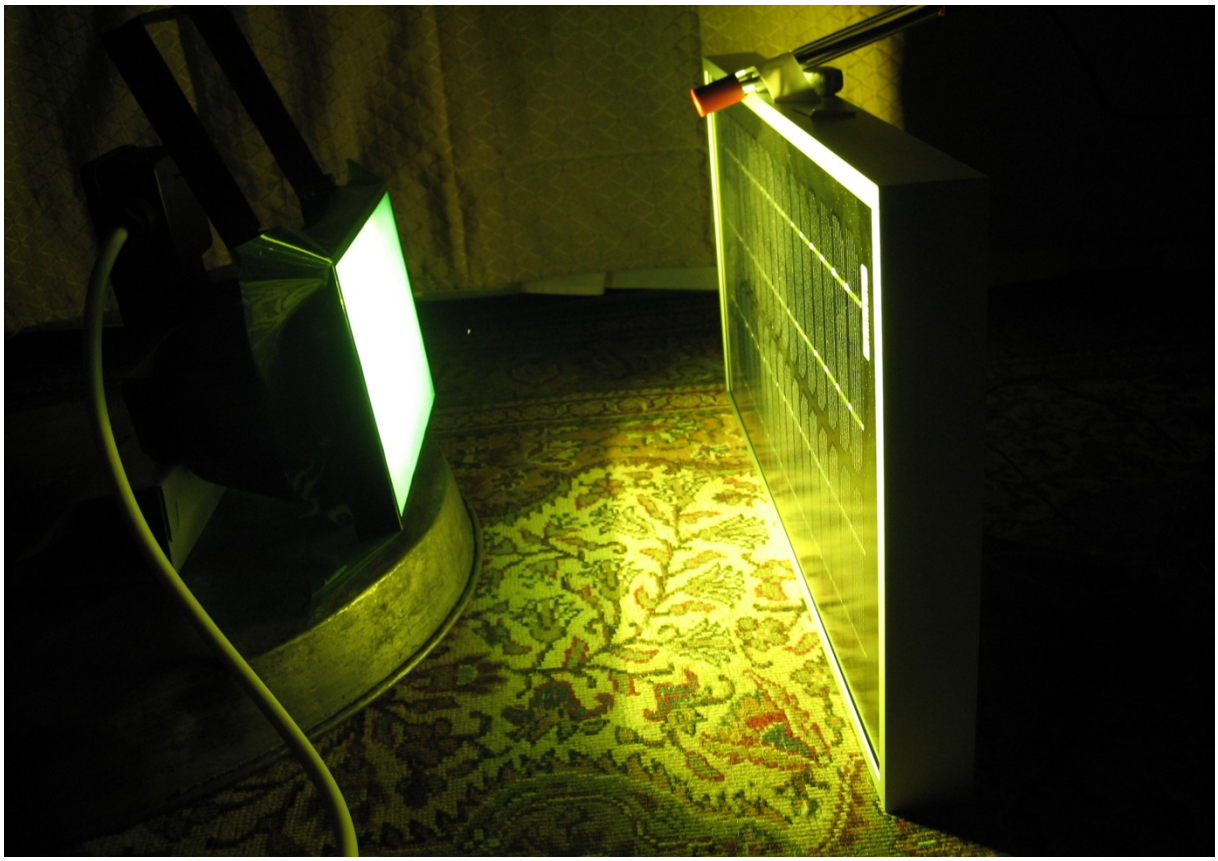
Picture 2: Experiment setup under red light



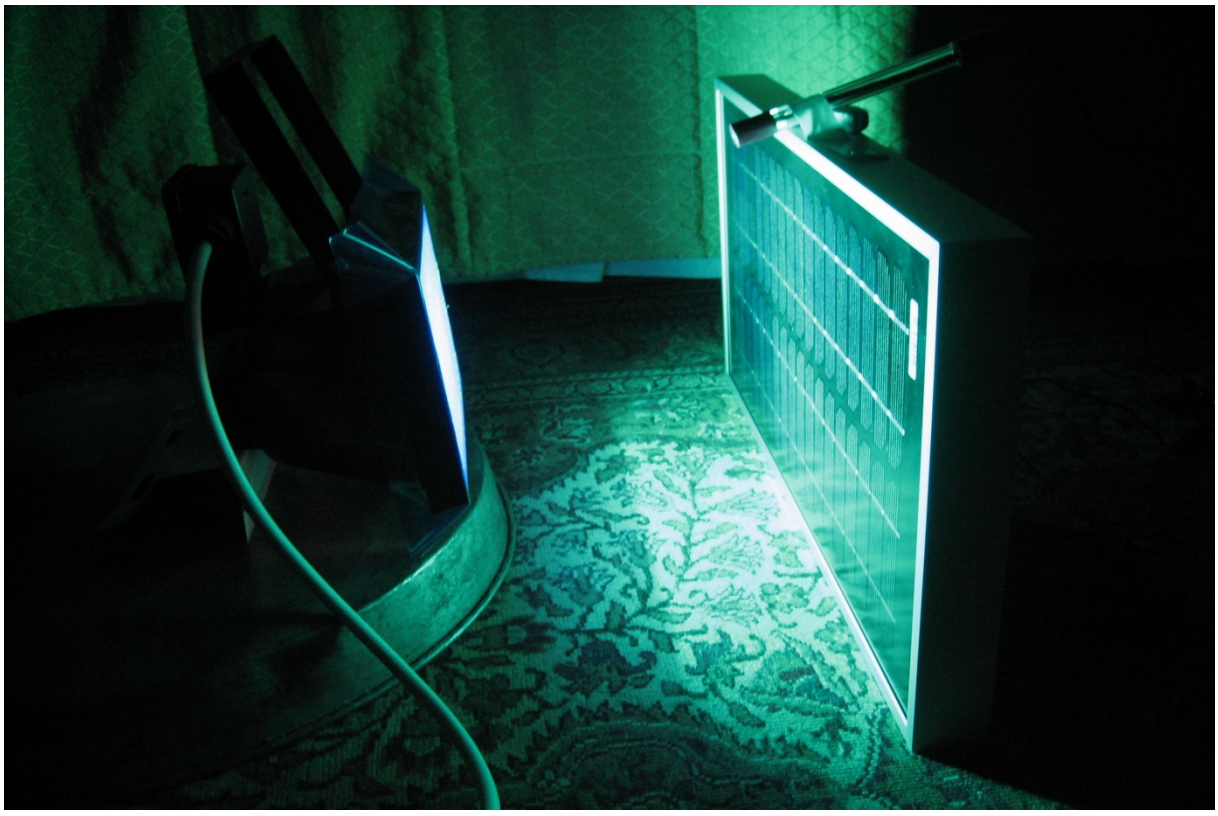
Picture 3: Experiment setup under orange light



Picture 4: Experiment setup under yellow light

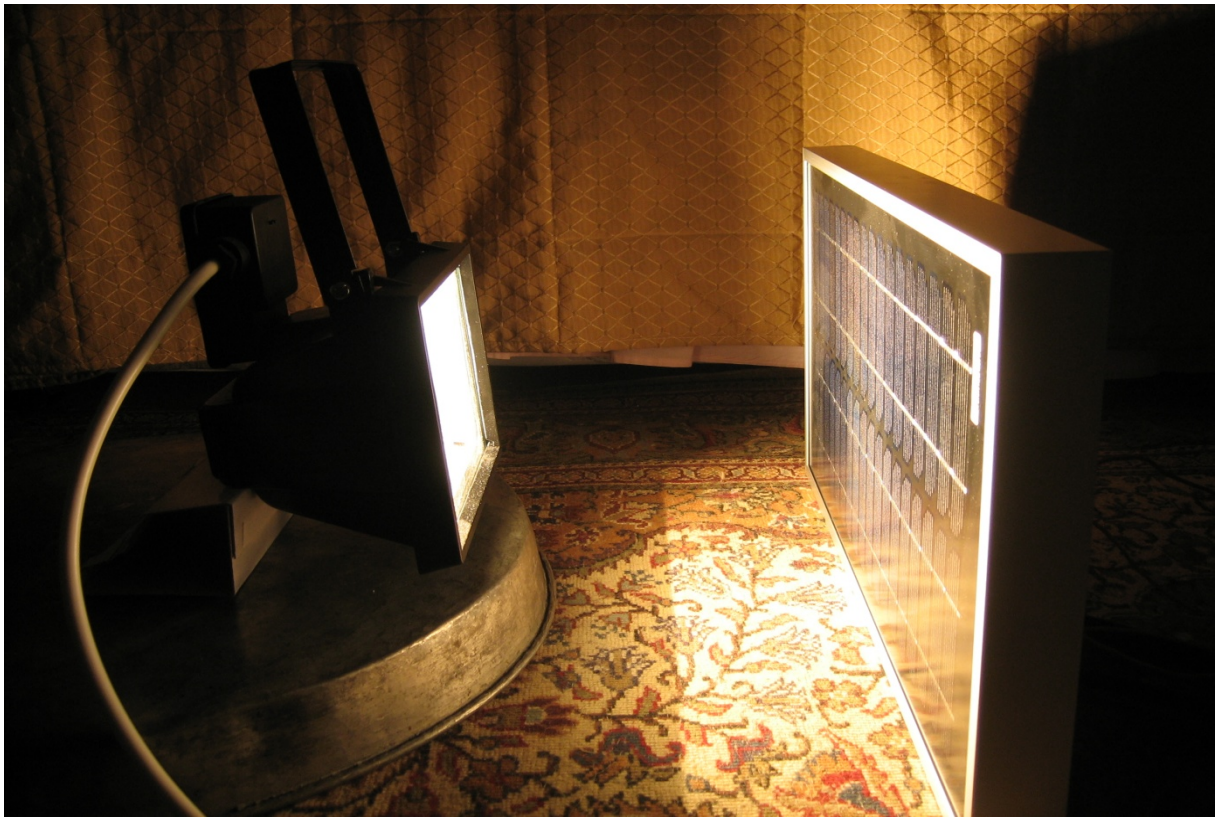


Picture 5: Experiment setup under green light



Picture 6: Experiment setup under blue light

Picture 7: Experiment setup under purple light



Picture 8: Experiment setup under colourless light