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Effect of Mechanical stress on Organic Photovoltaics due to bending.

Metropolia University of Applied Sciences

Bachelor of Engineering

Degree Programme

Thesis

19 May 2019

Author Title Number of Pages Date	Hemanta Bhattarai Effect of Mechanical stress on organic photovoltaics due to bending 33 pages + 3appendices (40 pages) 13 May 2019
Degree	Bachelor of Engineering
Degree Program	Environmental engineering
Specialization option	Renewable energy
Instructors	Antti Tohka, Project manager Kari Salmi, Principal lecturer Minna Paananen-Porka, Language Supervisor

This thesis discusses about the effect of bending on open circuit voltage of organic photovoltaics (OPVs). The OPVs were provided by VTT technical research center of Finland which has been involved in manufacturing of lightweight, ultra-thin OPVs.

The OPVs provided were bent in three different angles: 30°, 60° and 90°. The differences of bending the OPVs in these different angles was studied. For each bending angle three OPVs were used and bending were done differently. Two additional tests were also performed to check the effect of heat and orientation of OPV making a total of 11 OPVs to be experimented. The thesis is does not concern on improving the efficiency, rather analyses degradation of OPVs by bending.

Keywords	OPVs, Mechanical degradation, Photovoltaic technology, Open circuit voltage

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Contents

List of Abbreviations

Al	Aluminium
a-Si	Amorphous Silicon
Ca	Calcium
Ca-Te	Cadmium Telluride
CIGS	Copper Indium Gallium Selenide
CZTSSe	Copper Zinc Tin Sulphide Selenide
ETL	Electron Transport Layer
eV	Electron Volt
GaAs	Gallium Arsenide
HOMO	Highest Occupied Molecular Orbit
HTL	Hole transport Layer
IDE	Integrated Development Environment
ITO	Indium Tin Oxide
LUMO	Lowest Occupied Molecular Orbit
OPV	Organic Photovoltaic
PCBM	Methanofullerene [6,6]-phenyl C61-butyric acid methyl ester
PEDOT: PSS	Poly(3,4-ethylenedioxythiophene)-poly(styrenesulphonate)
PSCs	Polymer based Solar Cells

PTB7	Poly[[4,8-bis[(2-ethylhexyl)oxy]benzo[1,2-b:4,5-bǫ]dithiophene-2,6-diyl][3-fluoro-2-[(2-ethylhexyl)carbonyl]thieno[3,4–b]thiophenediyl]]
P3HT	Poly(3-hexylthiophene-2,5-diyl)
R2R	Roll to roll
TIO_2	Titanium Dioxide
Voc	Open Circuit Voltage

1 Introduction

Human needs are unlimited. Such is the demand of energy in this growing and developing world that we are living today. Every year we see a rise in the energy consumption as new technologies and innovations get introduced. With growing population and infrastructure, the resource available is declining. For a long time, humans have been dependent on fossil fuels as a major source of energy, but these are limited sources of energy which might get used up with time. Hence, there is an urge for an alternative and reliable source to meet the demand hat is on rise.

Sun is a perpetual source of energy. The amount of solar energy reaching the Earth is immensely in excess to the world's current production and potential of energy requirements. The energy from the sun reaches the earth in the form of sunlight and heat and is the largest source of energy received by the earth. Photosynthesis is a process that notifies the importance of solar energy. Plants utilize solar energy through photosynthesis for their growth, which serves as major food resource to all the living creatures on the earth. Additionally, most of natural processes happening on earth like nitrogen cycle, wind force and water cycle driven by solar radiation. These forces are responsible for harvested energy in different forms like wind energy, hydro power, biomass and even fossil fuels which formed due to heat from the sun.

Solar energy can be directly gained as heat or photovoltaics. Although, utilizing solar energy requires lot of effort for its collection, conversion and storage various technologies have evolved over time to harness the energy that we receive from the sun. Solar heating, solar thermal power, molten salt power plants and photovoltaics are some examples that are in practice to harness as much solar energy as possible. The fact that it is also a renewable source of energy and cost effective increases its importance for now and the future as a major segment in energy production. It has become one of the dominant growing sources of energy and most of the countries have driven their focus towards the development and enhancement of solar energy.

The development of solar energy has grown over time from less efficient solar cells to efficient solar cells with efficiency up to 30 percent. By integrating these efficient solar

cells, countries have been able to construct large solar farms, which are able to generate huge amount of energy. Nevertheless, the development is still lacking considering the cost of the solar panels which are far too expensive and the materials to build these being rare. Therefore, companies around the world are looking for better options which they have found in polymer based solar cells or organic photovoltaics (OPVs). (Rajput, 2017) (Fraas, 2014)

VTT Technical Research of Finland is one of the major organisations in Finland, which strives towards the process and development of organic photovoltaics (OPVs). They have been involved in technological innovation of manufacturing ultra-thin, light and flexible OPVs, which can be designed in any shape or size depending on the electrical output required. They have been able to engineer a feasible method to manufacture these from commercially available material. Their vision is to focus towards the development of OPVs which can replace silicon based solar panels through intelligent manufacturing systems. The focus is also to establish a better emission free environment in the future and encourage sustainable growth (VTT Technical Research Center Finland).

The next chapter, Theoretical Background discusses the photovoltaic technology and its development, concept of OPVs and its mechanics.

2 Theoretical background

This thesis is based on using the OPVs provided by VTT Technical Research of Finland to analyze the effect mechanical stress on the open circuit voltage of given OPVs. VTT provided 12 different OPVs which were to be tested under stress applied by bending the OPVs in three different angles (30, 60 and 90 degrees). For each angle three OPVs were used and the rest OPVs were used for miscellaneous tests explained in the result section.

2.1 VTT Organic Solar Cells

The development of mass production of organic solar cells using printing technologies in VTT began back in 2016 with their involvement in LIWE façades project. The main idea of the project was to integrate these solar modules into building façades to enhance energy production and sustainability. These modules are designed to harvest optimum energy from interior lighting as well as sunlight by placing them on windows or on powering electrical devices.

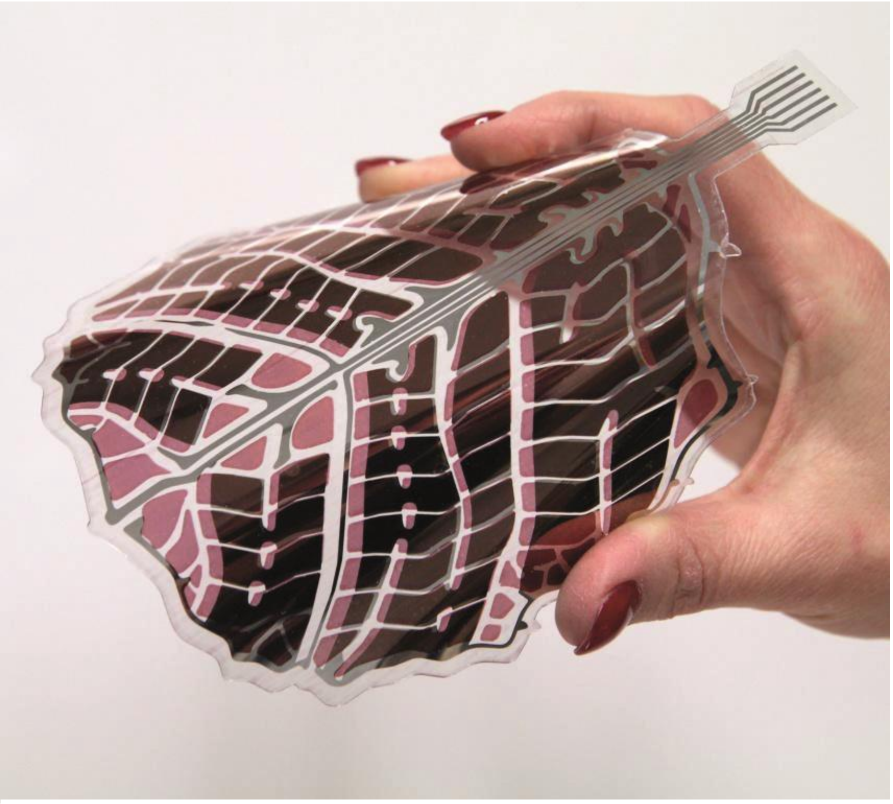

Figure 1. VTT's printed organic solar module design (VTT Technical Research Finalnd, 2015)

VTT has been manufacturing thin film OPVs using roll to roll printing technology or coating technique (VTT Technical Research Finalnd, 2015). This technique will make production and installation of solar cells much cheaper than traditional silicon based solar cells. Manufacturing using printing technique also provides freedom to design the OPV. The OPV can be manufactured in different shapes as shown in Figure 1 in a shape of a leaf. An example according to VTT is about using these photovoltaic leaves as an energy harvesting tree. Additionally, the visual appearance can be improved with innovation in graphics design. VTT aims to commercialize these flexible solar modules in the near

future and replace costlier traditional silicon-based PVs. The next chapter goes deeply into the technology of photovoltaics.

2.2 Photovoltaics

Solar energy can be harnessed and converted into electricity, which has become one of the basic requirements to the humans. The mechanism of converting energy from sunlight to electricity using semiconductors that exhibit a photovoltaic effect is called photovoltaics.

These cells are made of semi conductive materials, which have the ability to loose electrons from their atoms when light strikes on their surface. When these electrons leave their original atoms, it creates a hole, which is occupied by excited electron from other atoms. This results in flow of electrons in a direction that produces electricity. Several solar cells can be interconnected to each other to generate large amount of electricity. This produced electricity can power households, industrial buildings or connected to the grid. (Aggarwal & Aggarwal, 2014)

Photovoltaic clearly shows the connection between photons and volt. Photons are elementary particles that transmit light over space and volt is the unit for electric potential. Hence, the production of electric current when exposed to light in a material is photovoltaic effect. Photovoltaic effect is seen widely in semiconductor materials such as crystalline silicon, whose conductance is relatively low where the atoms are not able to move freely within the crystal. The photovoltaic effect is provided in Figure 2. The conductivity of the material is dependent on the amount of external energy acquired by the valence electron in its last orbit of the atom. The external energy in the form of photon is absorbed by the crystal to activate the electron from its original state to excited state making the electron to move in one direction through the crystal. A free space or hole is left behind due to the movement of electron, which is occupied by an electron from another atom. This movement of the electrons create a negative charge in one side junction with respect to the other. The material is now conductive producing voltage and current proportionally to the amount of light absorbed. The amount of energy required to excite an electron is also called band gap energy. (Solar Energy, 2017)

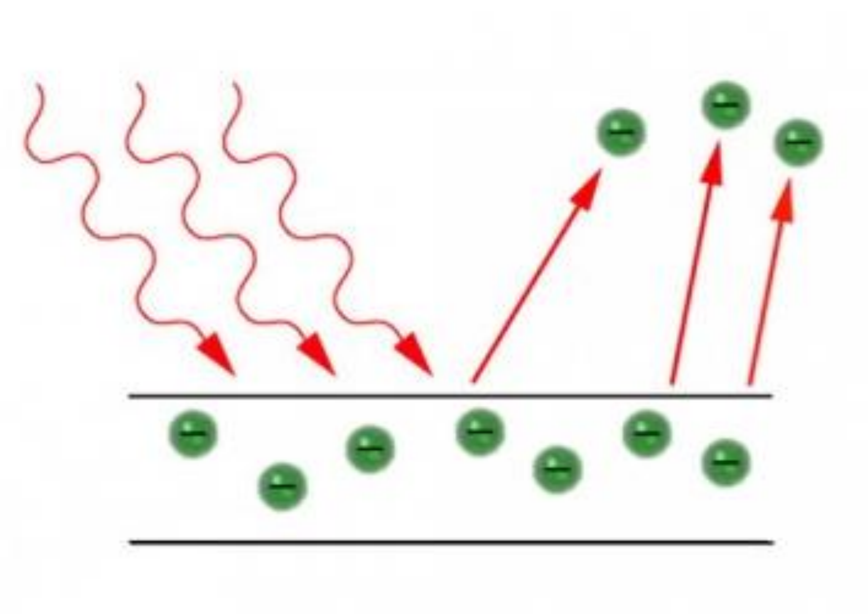

Figure 2. Excitation on electrons after hitting the photovoltaic surface (Solar Energy, 2017)

Photovoltaic effect depends on the type of semiconductor material and the amount of energy will allows the electrons to be released. This energy resembles to the frequency of photons that strike the surface of the material. Similarly, different materials require different amount of energy to allow the flow of electrons. When a material has appropriate band gap energy, then it is possible to absorb effective amount of energy. Photovoltaic effect will not be induced when the band gap is very high and when a material has low band gap energy, there will be more than required energy to excite electron which goes wasted. Silicon has a special property having efficient bandgap (1.1 eV) that corresponds to the energy to free electrons. During photovoltaic effect, certain amount of energy is also lost in the form of heat. This implies that when a photon of 2 eV hits a silicon material then, the energy utilized to excite the electron is 1.1eV, and the rest of the energy is lost in the form of heat energy (Brownson, 2014).

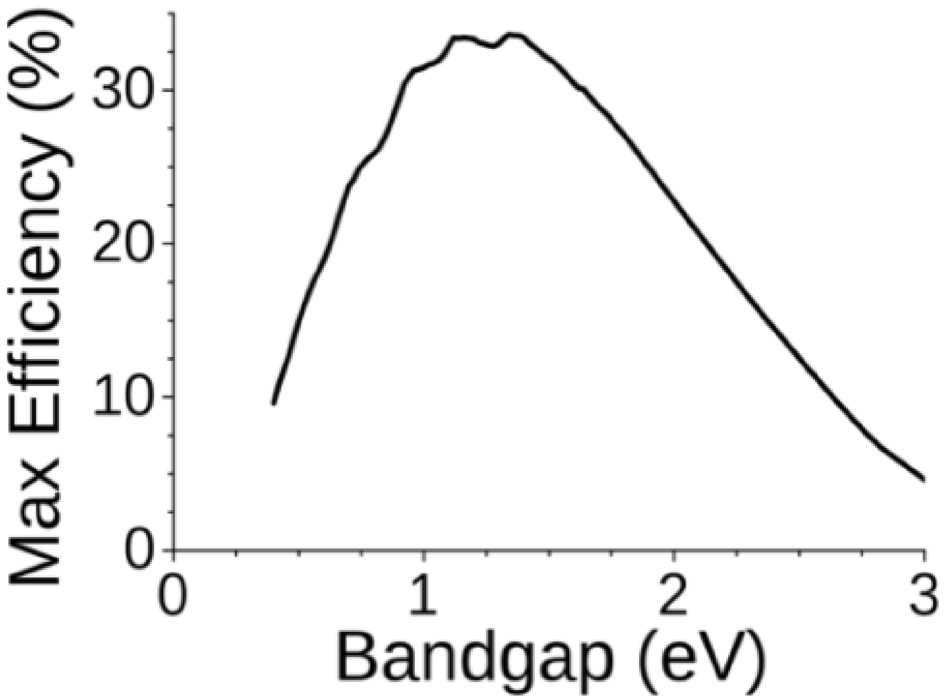

Figure 3. Maximum efficiency of solar cell as a function material band gap (Brownson, 2014).

Overall photovoltaic effect can be summarized in three main steps:

- Absorption of energy (photons)
- Induction of charge carriers (electrons)
- Movement of electrons between electrodes.

The discovery of photovoltaic technology dates to 19th century, noticed by French physicist A.E. Becquerel. However due to the abundance of coal and fossil fuels experimentation on solar technology ceased in the early 20th century. In 1918, a method to construct monocrystalline silicon solar cell was discovered by a polish scientist, Jan Czochralski. This discovery enabled the first monocrystalline silicon solar cell to be constructed in 1941. Since then development and research of solar technologies have accelerated throughout the late 20th century. The importance of PV cells concerning global warming and supply of oil and natural gases led countries focusing on the development of PV cells commercially as well as residentially. Since 2000, the growth of PV technology has averaged above 40 percent per year. Currently advanced development in the field of PV technology in an attempt to reduce manufacturing costs and increase efficiency. (Fraas, 2014)

Different types of photovoltaics have been developed overtime. Brief overview of the types PV materials is described below.

2.3 First-generation solar modules

These solar modules were developed in 1950s. These modules used boron and phosphorous as semi-conductive material doped in mono or poly crystalline silicon. These solar cells showed high efficiency when tested in laboratories with efficiency reaching 25%. However, commercial modules showed efficiency or nearly 16% and lifetime of about 20 years. Its major disappointment was that it required high grade silicon which was expensive to process. This made the module to be costly and payback time to be longer depending upon the location and availability. (Schneider, 2015)

2.4 Second-generation solar modules

To overcome the high manufacturing cost of first-generation solar modules, thin film solar cells, also second-generation solar cells were introduced. The objective was to reduce the use of costly silicon and use thin film photovoltaic material as substrate. The substrates used in these cells maybe amorphous silicon (a-Si), copper indium gallium selenide (CIGS), cadmium telluride (Cd-Te) or gallium arsenide (GaAs). These cells are flexible, light and offer better lifetime. Although cheap to manufacture, these films have not been able to achieve high efficiency compared to the first-generation solar cells. (Schneider, 2015)

2.5 Third-generation Solar modules

Third generation solar cells include modules which are in development phase and not properly commercialized. These modules are introduced by several manufacturers in search of better efficiency with lower cost (Schneider, 2015). Some of third generation modules are listed below.

Copper zinc tin sulfide selenide (CZTSSe) solar cells

CZTSSe is used as absorbing material in these solar cells. The material used in these solar cells have similar attributes as the material used in the second-generation solar cells. It is advantageous in a sense that the material used is abundant and non-toxic.

Dye-sensitized solar cells

These cells use an organic dye which is mixed with titanium dioxide (TiO_2) dipped in an electrolyte. The dye absorbs photons and the excited electrons penetrate TiO_2 and are then reduced by the ion from the electrolyte. Low stability and toxicity are the disadvantages of these cells.

Polymer based/organic solar cells (PSCs)

PSCs are the latest solar cell technologies which are not yet commercialized and are still in the research phase. These cells are composed of a thin inorganic film on the outer layer but uses organic material to induce flow of electrons. They are flexible, lightweight and easy to manufacture using solution processed technologies like roll to roll (R2R) technology. They are cheap to manufacture, although some component materials are still quite expensive (Schneider, 2015).

This thesis focuses on analyzing polymer based organic PVs and the effects of mechanical stress on the voltage yield of organic PVs.

3 Organic Photovoltaics

A huge amount of research is being carried out towards the development of new photovoltaics and enhancing the performance of the existing cells. Although silicon-based first-generation solar cells have proven to be able to achieve 20 percent efficiency, they are costly and difficult to handle. In order to get rid of economic complication due to inorganic PVs, the focus has now shifted towards organic PVs. Organic PVs are manufactured using thin films of material making them light and wasting less material. This makes organic PVs elastic, flexible and easy to handle. Organic PVs are manufactured using solution processing technologies like roll to roll printing(R2R), which eases and reduces the cost of manufacture. Despite having advantages, organic PVs lack some useful properties. In terms of efficiency, organic PVs have not been able to

reach the same level as their inorganic traditional counterpart. Organic PVs have shown to yield energy conversion efficiency of about (1-10) percent. Additionally, to manufacture the components materials involves toxic reactions. As well as Long-term reliability is also a challenge that organic PVs are yet to overcome. (Suren Gevorgyan, 2018)

3.1 Charge generation in organic photovoltaics

A normal organic PVs is comprised of one or more photoactive layer placed between two electrodes. These active layers possess semi-conductive properties and are composed of organic materials in the form of conjugated polymers. Conjugated polymers contain overlapped p-orbitals which leads to the delocalization of π electrons of aligned p-orbitals. This results in the formation of electron-hole pair is also known as excitons. The binding energy of an exciton is between 0.3 eV-1 eV which is large enough to prevent its dissociation by an electrical field. The first photoactive material was designed by Dr. Ching W. Tang in 1979 by overlapping two n and p type semiconductors. The bilayer planar heterojunctions that were used had a power conversion efficiency of 1 percent. As a result, when light was absorbed, the energy difference between the highest occupied molecular orbital (HOMO) of acceptor and lowest unoccupied molecular orbital (LUMO) of donor led to the dissociation of excitons. However, such planar junction restricted the area between the donor and the acceptor material and the electrons and holes would recombine before reaching the electrodes, which led towards further development of OPVs. (Kaur, et al., 2014)

Development of OPVs came in 1995 with the introduction of bulk heterojunction with polymer-fullerene, where instead of having distinct donor and acceptor layer, donor and acceptor material is mixed together forming a polymer blend. In these types of OPVs, exciton formed by the absorption of photons can diffuse within the bulk blend of polymer before being separated as electron-hole pair. These cells mostly comprise of five layers. The first layer is a transparent material, indium tin oxide (ITO) which acts as anode. The second layer, the hole transporting layer is made up of hole transporting material (HTL) poly(3,4-ethylenedioxythiophene)-poly(styrenesulphonate) (PEDOT: PSS), which disallows unwanted negative charge to reach the anode. The third layer is an active layer which consists blend of donor poly[[4,8-bis[(2-ethylhexyl)oxy]benzo[1,2-b:4,5-bǫ]dithiophene-2,6-diyl][3-fluoro-2-[(2-ethylhexyl)carbonyl]thieno[3,4–b]thiophenediyl]] (PTB7) or poly(3-hexylthiophene-2,5-diyl) (P3HT) and an acceptor methanofullerene

[6,6]-phenyl C61-butyric acid methyl ester (PC71BM), where photon is absorbed, and charge is transferred, separated and transported. It is followed by electron-transporting layer (ETL) Calcium (Ca) and then finally by cathode Aluminum (Al) (Pelzer & Darling, 2016). Visual representation of charge generation in OPVs can be seen in Figure 4.

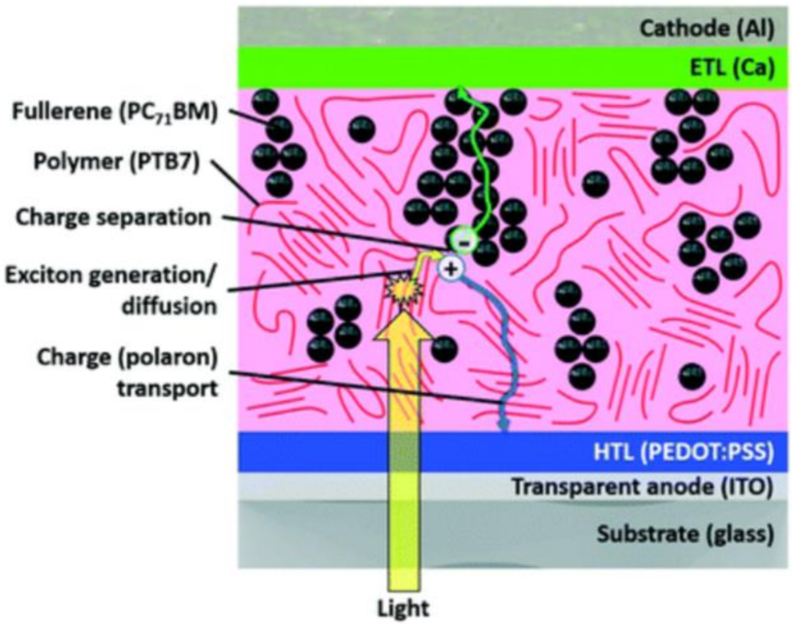

Figure 4. Charge generation in polymer based OPV (Pelzer & Darling, 2016).

3.2 Mechanical stability of OPVs

Stability is a huge concern regarding OPVs. As mentioned earlier, an OPV comprises of different layers of materials. These layers have different chemical composition, properties and molecular structure which portray how stable the OPV is. Stability is an important factor to determine the lifetime of an OPV. Therefore, stability of active materials is essential to achieve overall stability of an OPV. The organic semi-conductors lose their color during photo oxidation which is also called photo bleaching which is a critical subject to improve. As a result, mechanical degradation of OPVs occur due to the external forces acting upon the OPV (Savagatrup, et al., 2014).

3.3 Degradation of OPVs

Degradation is a natural phenomenon occurring to any material after it continues to be used or handled improperly. The materials used and the technique to manufacture the OPV is one of the major reasons to determine how the OPV degrades. Degradation occurs due to three attributes of the OPV which are, mechanical properties of the materials used, interfacial adhesion between the layers and thermal expansion. The focus is on the mechanical degradation due to bending as proposed by this thesis. For organic photovoltaics that we have used, the mechanical properties of the semi-conductors and the shape of the organic photovoltaics play important role in determining the effect of stress on the photovoltaic used. Several determining mechanical factors like polymorphism, molecular structure of the semiconductor, and micro structure reveal the influence of bending on the OPVs (Grossiord, et al., 2011).

3.4 Mechanical stress

Mechanical stress in thin films based OPVs maybe compressive or tensile. As mentioned earlier organic photovoltaics are manufactured by using a mix of organic semiconductors which possess several mechanical properties. Applying stress to the OPVs may alter the chain alignment of the molecules present in the semiconductor which are responsible for the movement of the electron to create a potential difference. Similarly, other effects that can occur to the semi-conductor due to the stress applied are, reorientation of the molecules of the semi-conductor, increased crystallinity, cracking and decohesion. Additionally, applying stress may also cause the OPVs in the form of thin films to delaminate and crack. In this thesis normal bending stress has been applied to the film by bending the structure to different level of angles as asked by the instructor. The motive is to observe the effects of bending on the photovoltaic output of the OPVs. (Savagatrup, et al., 2014)

4 Experiment

The theme of the thesis was to determine and analyze the change in the open circuit output voltage of OPVs. The experiment was carried out by bending the organic photovoltaics provided by the instructor in three different angles: 30 degrees, 60 degrees

and 90 degrees. Also, an additional horizontal bending was done to see the effect of horizontal bending. The experiment was performed inside a laboratory, using an artificial solar lamp as an energy source to induce voltage in the OPVs.

4.1 Open circuit Voltage (V_{oc})

Open circuit voltage is the maximum voltage that an OPV can produce. It is calculated when external load is not connected to the circuit. As there is no connection of external load in the circuit, zero current flows in this condition. Open circuit voltage is usually measured in standard conditions. Particularly, Voc is dependent on four important factors which are temperature, light intensity, work function of the electrode and material microstructure (Qi & Wang, 2012). In this thesis Voc is taken as a variable to determine the changes and degradation within the OPVs. The dependency of Voc with respect to time is addressed in this thesis. Simple example of Voc is presented in Figure 5.

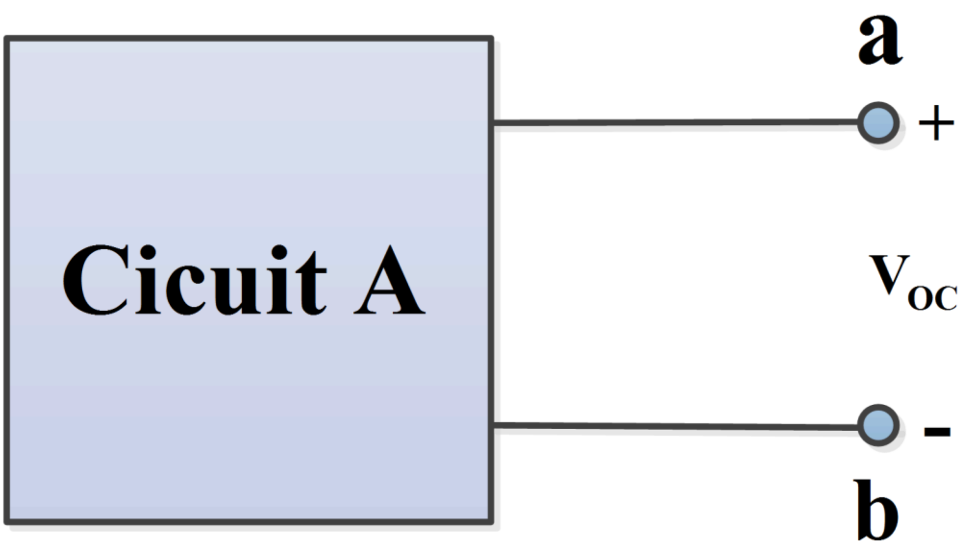

Figure 5. Open circuit Voltage (Ahmad Faizan, 2017)

4.2 Equipments and programs

4.2.1 Piston mover

The piston mover is a physical device which follows the command instructed in the program integrated to it. It consists of two pistons and an actuator which controls the piston. The actuator is responsible for the movement of one piston and the other can be moved and adjusted voluntarily as required.

4.2.2 Raspberry pi

Raspberry pi is a handy, low cost programmable computer having numerous functional capabilities. It is easy to use and even children can play with it while learning. It has components for input, output and storage (Johnson, 2012). Simple model of a raspberry pi and its components can be seen in Figure 6.

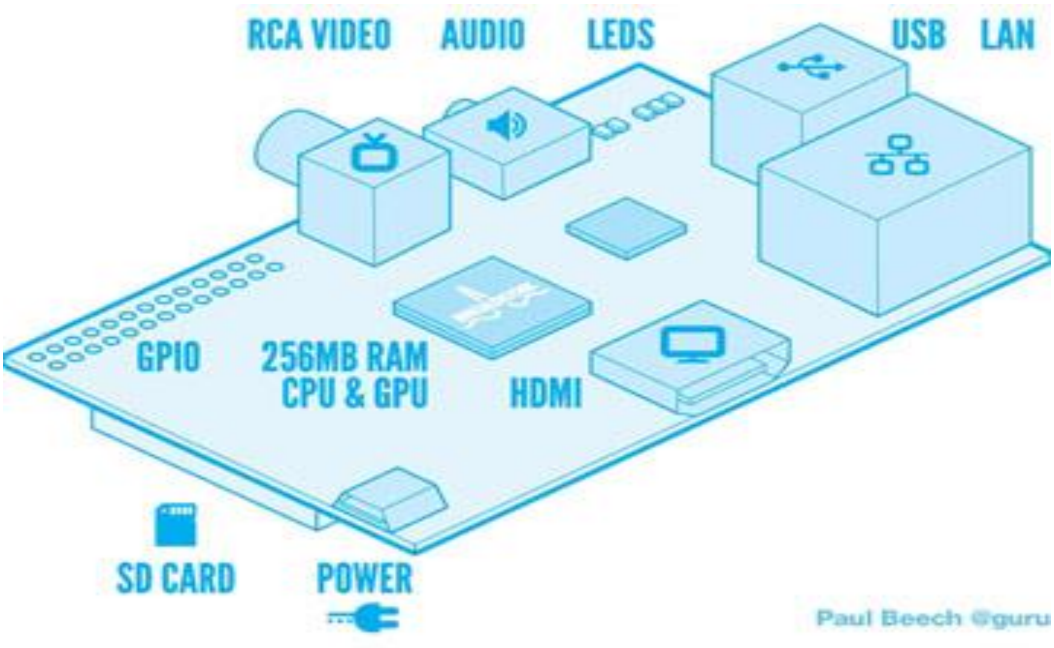

Figure 6. Diagram of Raspberry Pi (Johnson, 2012).

4.2.3 Arduino

Arduino is an open-source electronics platform based on easy-to-use hardware and software. Arduino board uses microprocessors and controllers equipped with sets of digital and analog pins to read inputs and turn into an output (arduino2go, 2016). By sending a set of instruction to the microcontroller board, several tasks can be performed. Arduinos can be used to control physical machines such as motors or piston mover in this our case in conjunction with Raspberry pi. The analog inputs in Arduino can be used to measure voltage up to 5 volts. The OPVs provided by VTT can generate open circuit voltage over 5 volts. By establishing voltage divider circuit, it can be made possible for the Arduino to measure voltage over 5 volts which is explained in the setup section. Sample of common Arduino board is shown below in Figure 7.

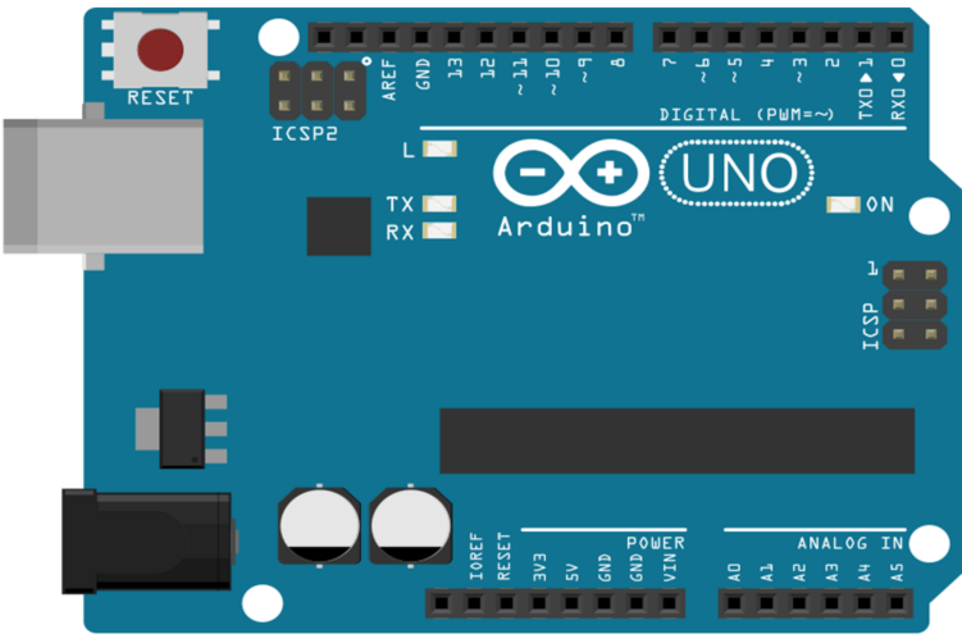

Figure 7. Simple Arduino board (arduino2go, 2016)

4.3 Setup

The OPV was placed between the pistons as shown in Figure 8 and the movement of the piston forced the OPV to bend. The movement of the piston is controlled by the command written in python mentioned in Appendix 2.

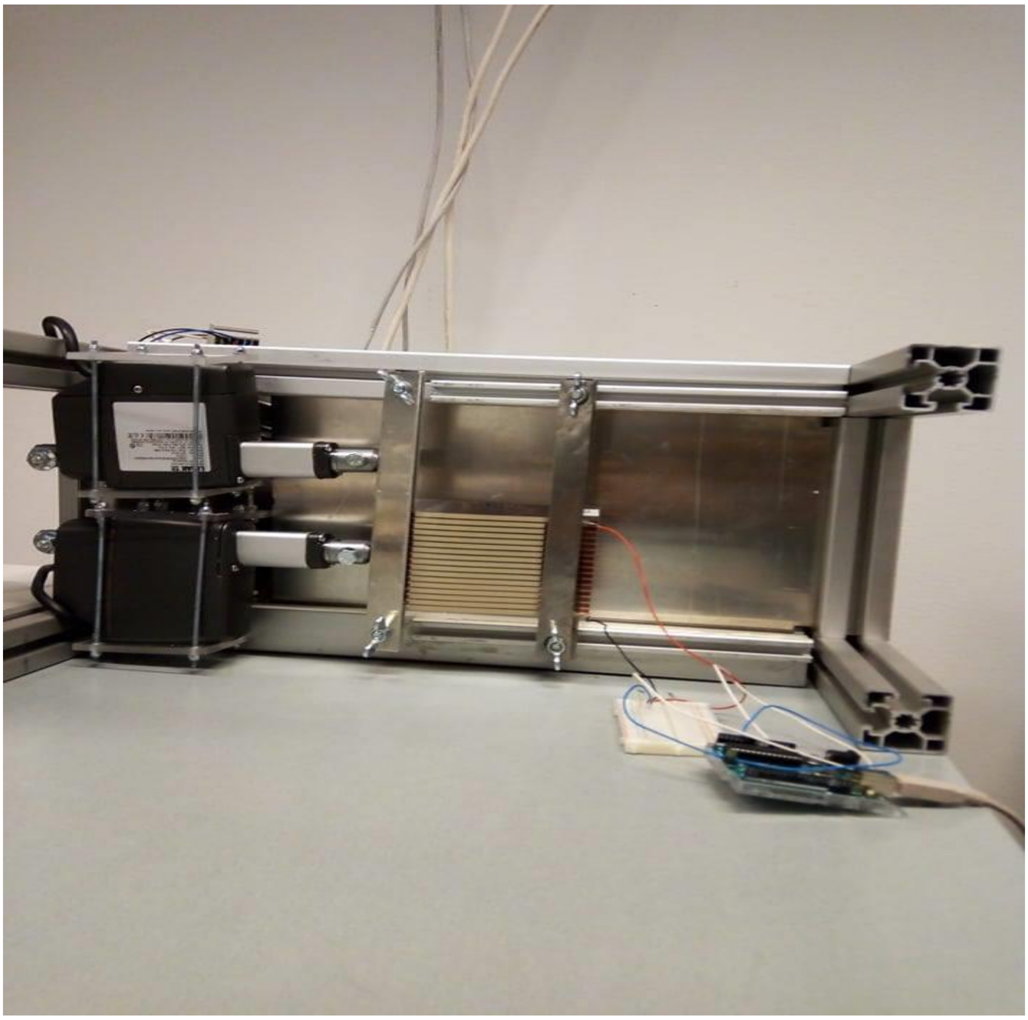

Figure 8. OPV placed between piston mover connected with breadboard and Arduino.

4.3.1 Digital voltmeter using Arduino

Voltage divider technique was used for the Arduino to be able to measure voltage over 5 volts. Two resistors were connected to the circuit so that the voltage could be decreased within the range of Arduino's Analog input shown in Figure 9. The circuit was made within a breadboard using wires and resistors connecting with both OPV and Arduino. The connections must be made to the correct pins in the Arduino board so that it resembles the code written in the Arduino IDE. Any connection made which does not match the codes written in the IDE will provide misleading data in the monitor. The codes in IDE allows the Arduino to act as a digital voltmeter which calculates the voltage drop in a loop continuously. The codes written in Arduino IDE can be found in Appendix 2 and the circuit made in the laboratory which resembles to Figure 9 can be seen in Appendix 3.

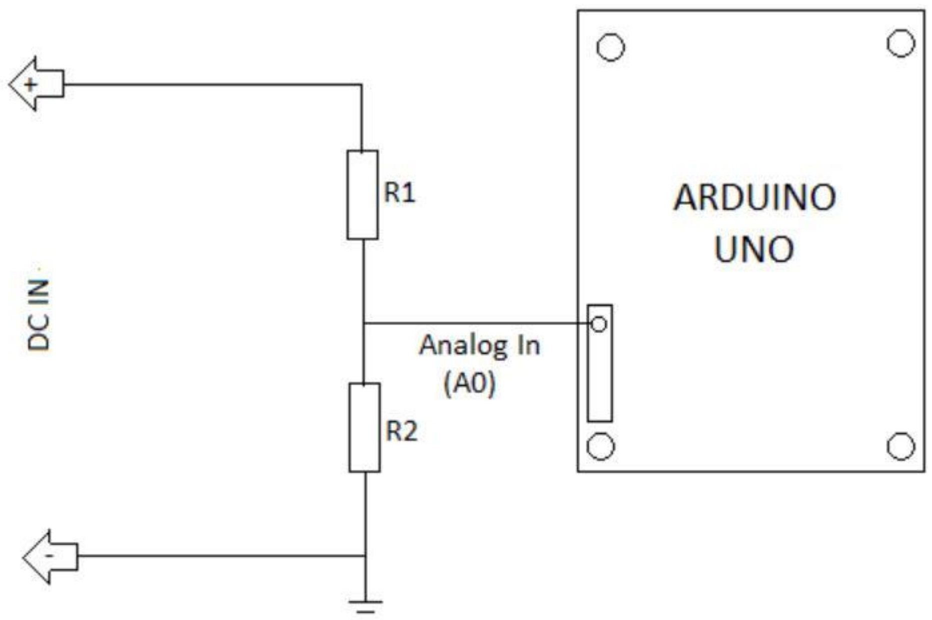

Figure 9. Voltage divider circuit connected to Arduino. (Hareendran, 2014)

4.4 Data collection methodology

The bending was done in three different angles: 30 degrees, 60 degrees and 90 degrees for which 12 samples of OPVs were provided by the instructor. The photoactive surface area of all the samples were measured to be 7224mm^2. Each sample of OPV possessed a different proportion of the active material in the OPV making the OPVs different by their mechanical properties and differed from each other regarding the performance in their output open circuit voltage (Voc). For each angle three samples of OPVs were bent differently considering the number of bends in a single run.

The voltage reading of the OPVs was calculated for time frame every second and an average voltage reading with time frame of 6 seconds, 10 seconds and 14 seconds depending on the bending angle. Data for every second voltage output and average voltage output was obtained in different folder in the monitor. The data obtained was used to create a graph for the proper analysis of the changes in voltage caused by bending the OPVs. The analysis of the change in voltage reading of every second was complex and irrelevant thus only the average voltage reading was used to analyze the effect of bending for this thesis.

5 Result

5.1 30 degrees bending

The first set of OPVs was bent to a 30-degree angle. As the test was done by bending the OPV in several runs and not by bending the OPV continuously, the series number in each graph represents the run. For example, the first run which is represented by series 1, the second run by series two, the third run by series three and accordingly. Voltage reading with respect to time is an average reading of 6 seconds.

Module I-332

The number of bends in each run and the total number of bends can be seen in Appendix 1. The series number in the graph represents the run while bending.

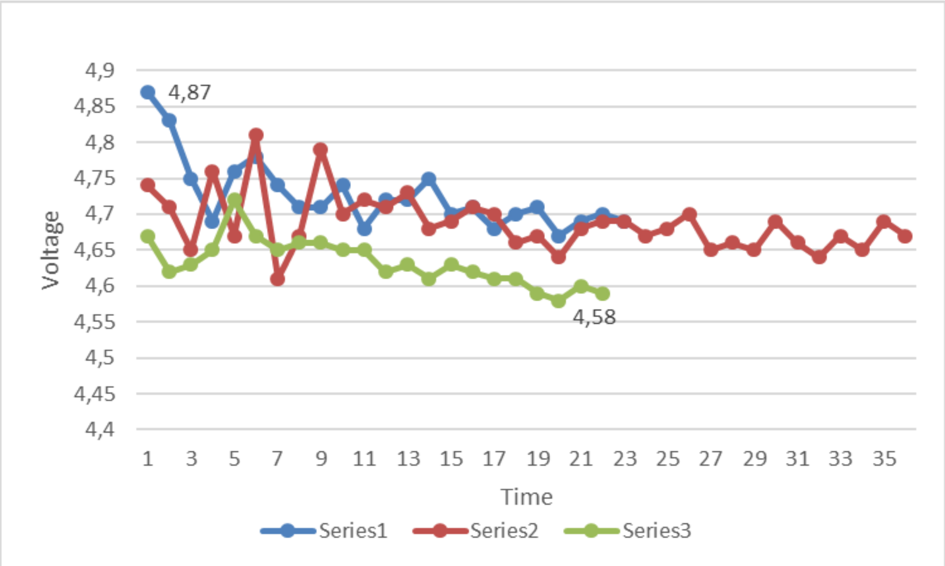

Figure 10. Time Vs Voltage graph for module I-332

Module I-550

The number of bends in each run and the total number of bends can be seen in Appendix 1. The series number in the graph represents the run while bending.

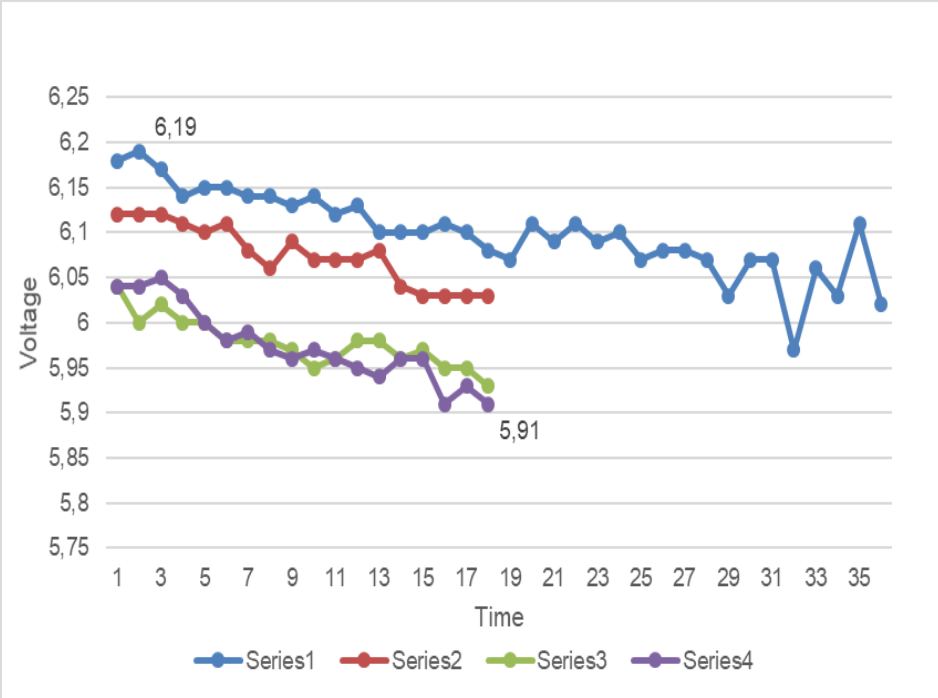

Figure 11. Time vs Voltage graph for module I-550.

Module I-558

The number of bends in each run and the total number of bends can be seen in Appendix 1. The series number in the graph represents the run while bending.

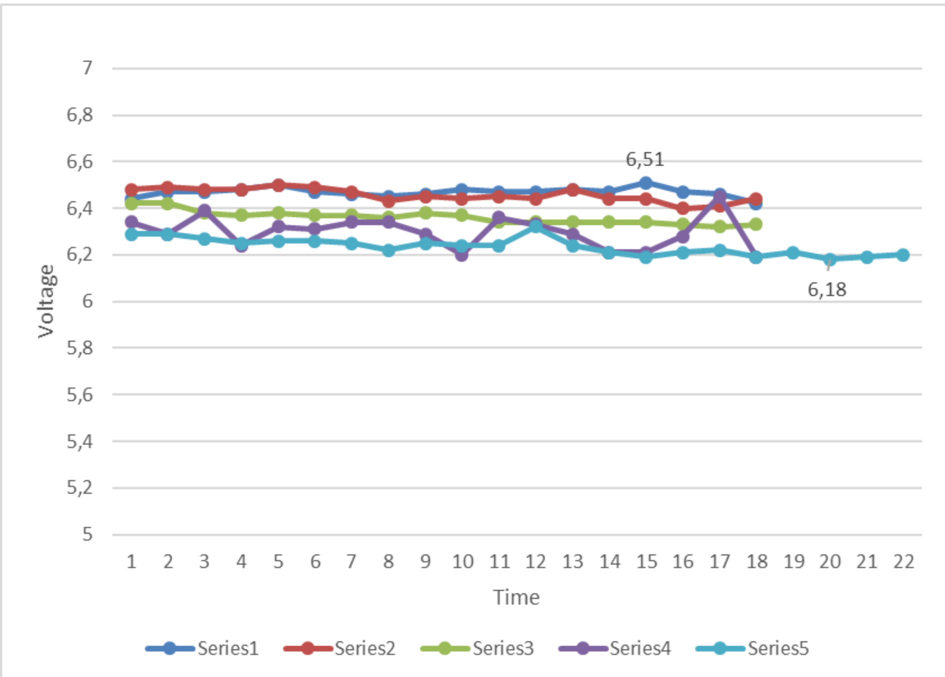

Figure 12. Time vs Voltage graph for panel I-558.

5.2 60 degrees bending

The procedure of bending OPVs was done the same way as the 30-degree tests. Similarly, the graphical representations of the runs are labelled with series number shown in the graph heading. The change made was increasing the bending angle from 30 degrees to 60 degrees. Also, voltage reading with respect to time is an average reading of 10 seconds.

Module I-330

The number of bends in each run and the total number of bends can be seen in Appendix 1. The series number in the graph represents the run while bending.

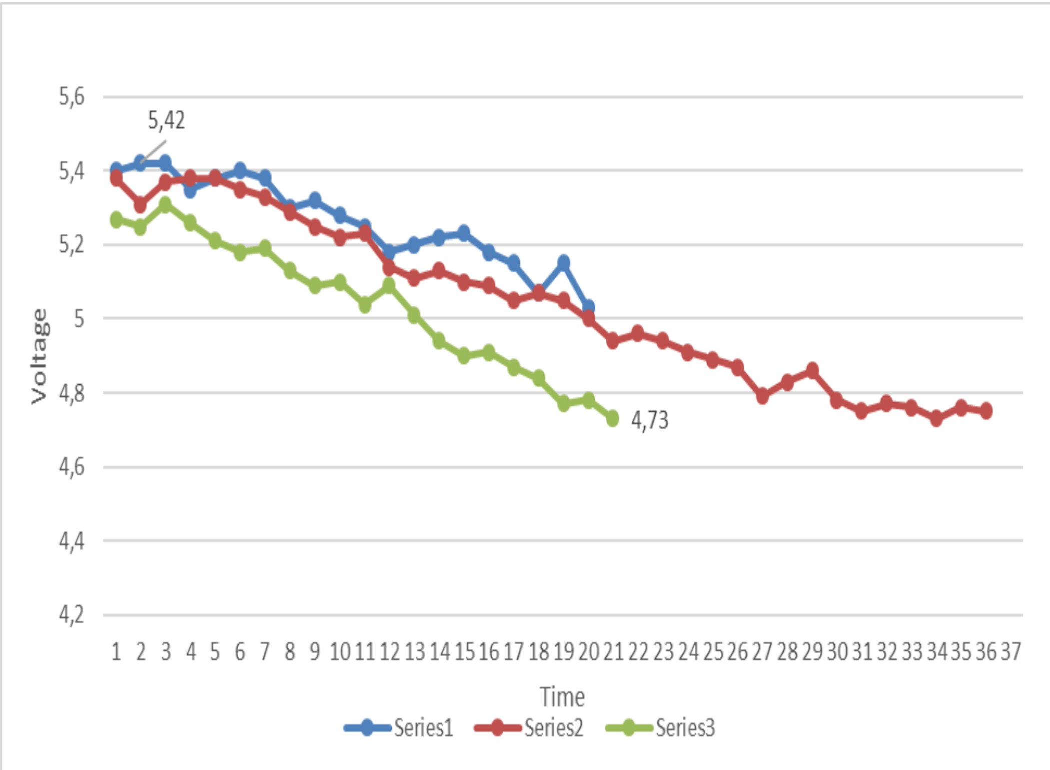

Figure 13. Time Vs Voltage graph for panel I-330

Module I-553

The number of bends in each run and the total number of bends can be seen in Appendix 1. The series number in the graph represents the run while bending.

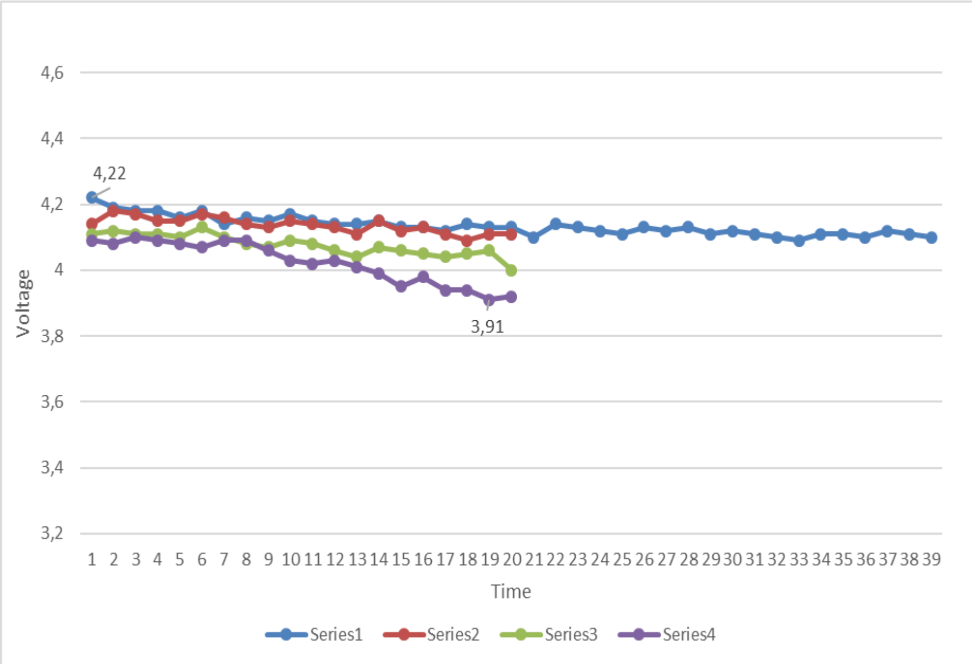

Figure 14. Time vs Voltage graph for panel I-553.

Module I-557

The number of bends in each run and the total number of bends can be seen in Appendix 1. The series number in the graph represents the run while bending.

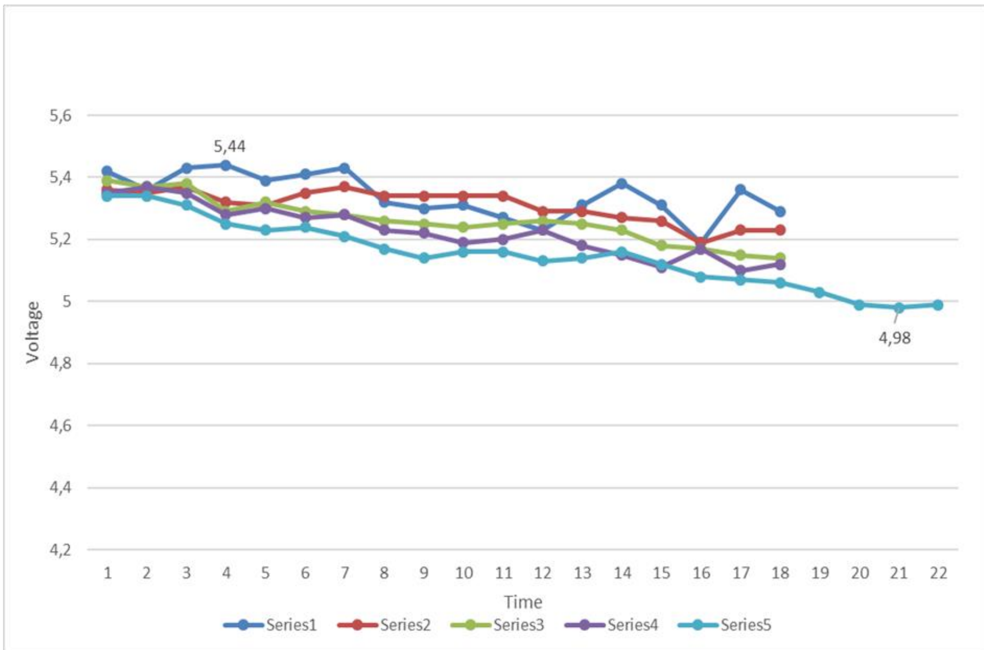

Figure 15. Time vs Voltage graph for panel I-557.

5.3 90 degrees bending

The test for 90 degrees bending is similar to the previous tests. Voltage reading with respect to time is an average reading of 14 seconds.

Module I-556

The number of bends in each run and the total number of bends can be seen in Appendix 1. The series number in the graph represents the run while bending.

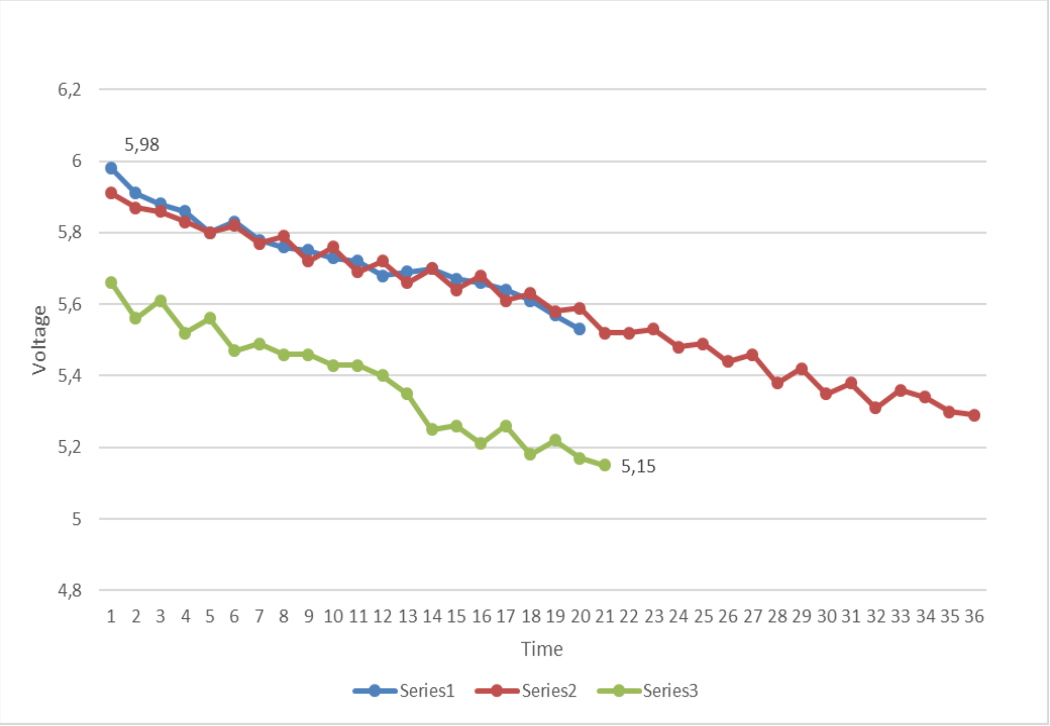

Figure 16. Time vs Voltage graph for panel I-556

Module I-552

The number of bends in each run and the total number of bends can be seen in Appendix 1. The series number in the graph represents the run while bending.

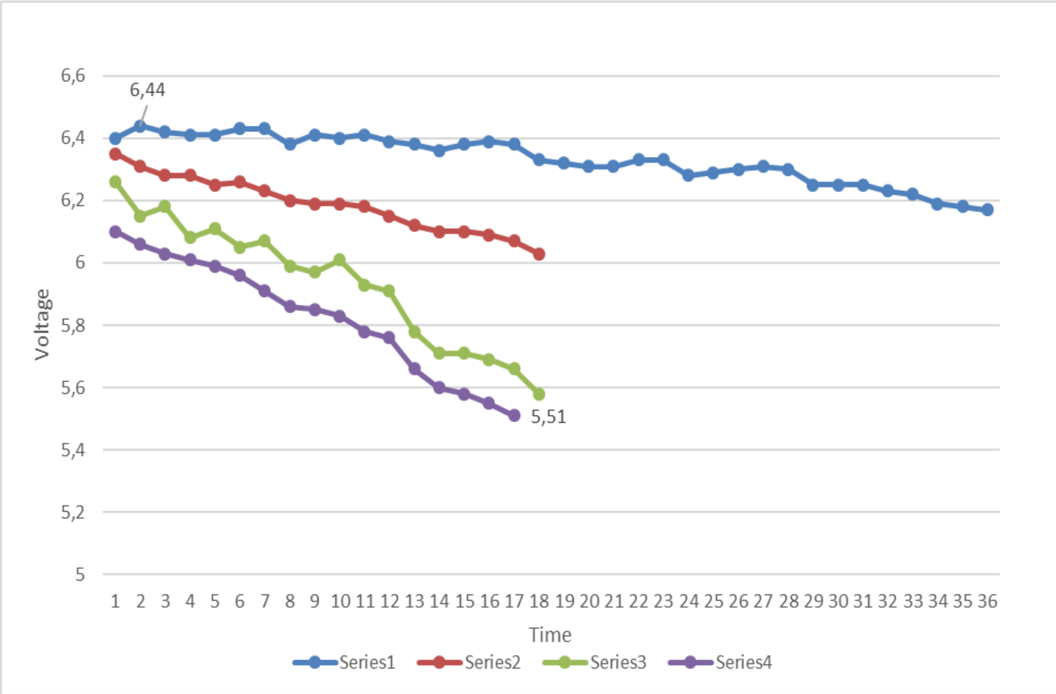

Figure 17. Time vs Voltage graph for panel I-552.

Module I-333

The number of bends in each run and the total number of bends can be seen in Appendix 1. The series number in the graph represents the run while bending.

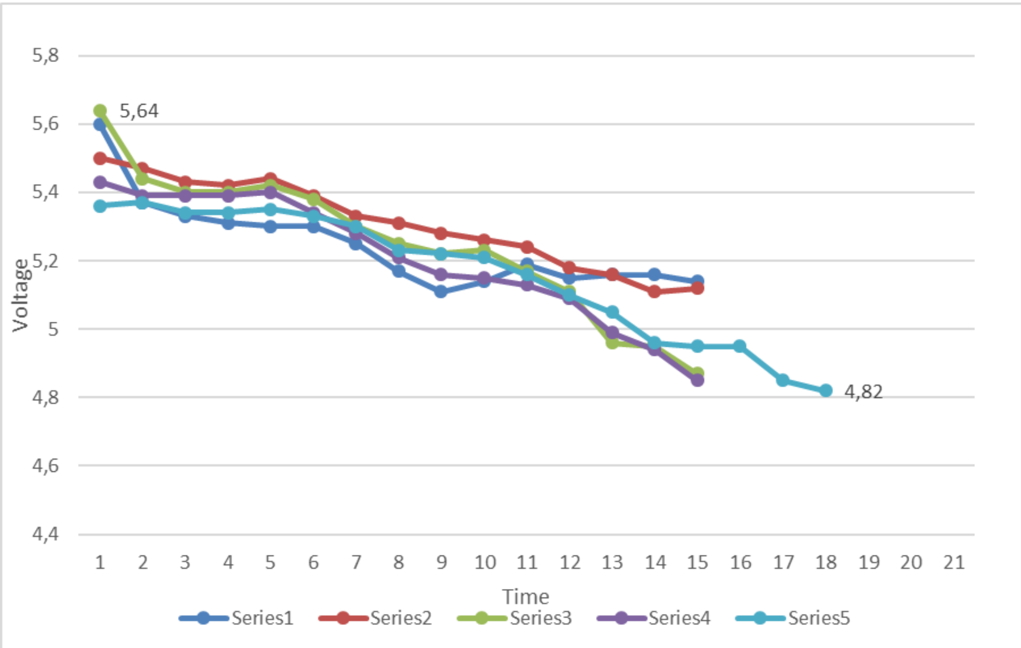

Figure 18. Time vs Voltage graph for panel I-333.

5.4 Horizontal bending

The technique used for this test resembles to those used in the vertical bending tests. However, the OPV is placed horizontally between the pistons. 60 degrees bending angle was used for the horizontal bending test. Voltage reading with respect to time is an average reading of 11 seconds.

Module I-551

The number of bends in each run and the total number of bends can be seen in Appendix 1. The series number in the graph represents the run while bending.

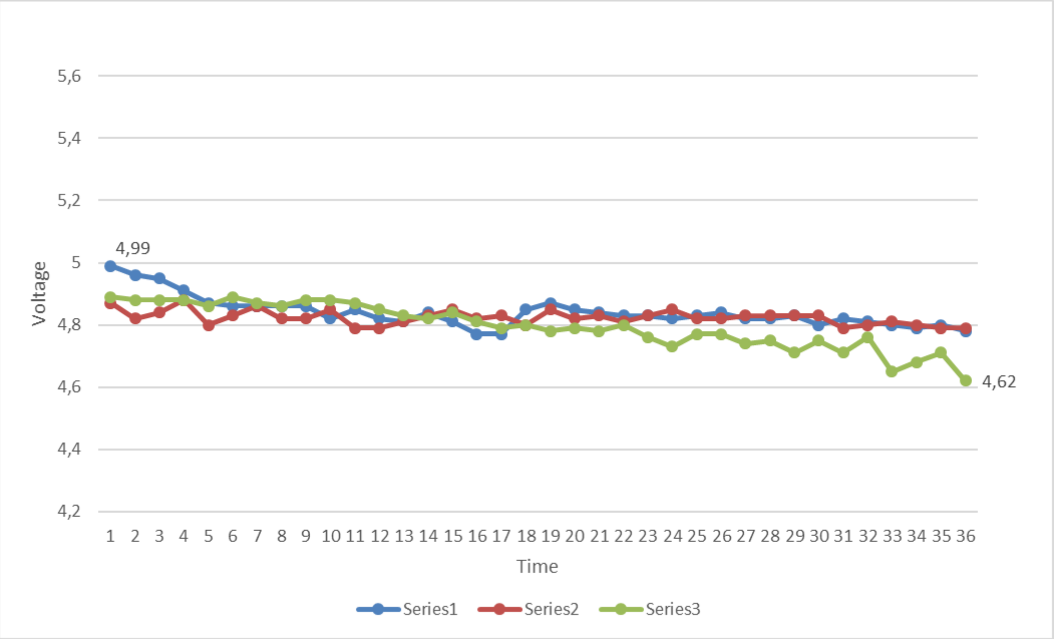

Figure 19. Time vs Voltage graph for panel I-551.

5.5 Effect of heat

This test was done by placing the solar lamp closer than the required distance, to see the change in the output voltage of the OPV due to effect of heat radiated from the source. This test was conducted without any bends. The voltage reading with respect to time is an average reading of 6 seconds.

Module I-554

The number of bends in each run and the total number of bends can be seen in Appendix 1. The series number in the graph represents the run while bending.

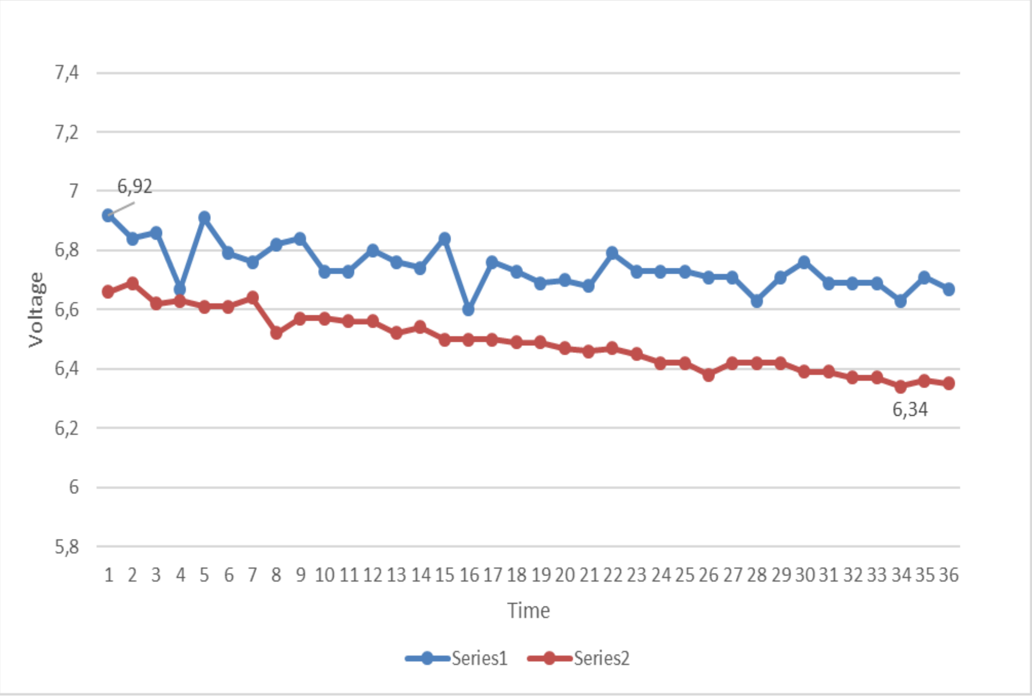

Figure 20. Time vs Voltage graph for panel I-554.

6 Discussion

The data collected from the experiments conducted by bending OPVs in different angles clearly shows that bending an OPV certainly has some effect on the output voltage of the OPV. The effect of bending is observed to be different for each angle.

When comparing the change in the output voltage among the three bending angles used, it is observed that bending the OPV with larger angle has more effect than bending it with smaller angle, which is explained by the magnitude of stress, which is different for each angle. It is obvious that bending an OPV to a 90-degree angle generates more stress within an OPV than bending it to 60-degree or 30-degree.

However, it can be noted that even with the same angle of bending that effect is seen differently for different OPVs which can be explained by the following topics.

6.1 Efficiency of OPV

When comparing two OPVs with different efficiency but with same bending angle, it was observed that bending had larger effect on the OPVs whose efficiency was high. The rate of decrease of output voltage was observed to be faster in OPVs that were more efficient. It can be assumed that efficient OPVs might have a larger proportion of organic active material or perfectly blended layers, which accounted for more stress on the active materials.

6.2 Bending Methodology

In almost all of the graphs it can be observed that the output voltage at the end of first run does match the output voltage at the start of the next run. It can be assumed that due to the fact that OPVs are thin films manufactured by R2R printing, they possess elastic properties and have the ability to retract to its original shape. The decline in output voltage was observed to be large when OPVs were bent continuously using fewer runs. It can be drawn that bending an OPV 50 times for two runs offered less effect than bending it continuously 100 times.

6.3 Limitations

The results for the experiment were based on tests done inside a closed room under unnatural condition which could be the reason for inaccurate readings if prevalent. The lamp used as light source for the thesis did not have the same effect and irradiance as sunlight which might be considered for future improvements. The heat from the radiation of the lamp also made it difficult to maintain standard temperature required during testing. Similarly, the piston mover used to bend the OPVs was not considerably reliable. The movements of the piston were mostly regular but would also infringe the command and show irregular movement. This caused the bending angle to have some inaccuracies. The programs used were also outdated and not advanced which caused program breakdowns several times, causing halts in the experiment because program to be fixed frequently.

It is recommended that in the future it would be best to use advanced, reliable and latest technologies and programs for bending the OPV. Properly automated machines and light source is also necessary. Nevertheless, it was a gratifying experience to complete the thesis with satisfying results.

7 Conclusion

This thesis studied the technology and concept of OPVs. The conclusions drawn from the experiment reviews the significance of mechanical properties and mechanical effects on OPVs in operational environments. The idea of bending OPVs in the thesis was mainly to provide a basis for the application of OPVs and not on improving its efficiency or output. A total of 11 out of 12 OPVs provided by VTT were bent by three different angles in a different pattern to observe and analyze if bending can degrade an OPV significantly.

Photovoltaics are more common these days as they are green energy. Commercialization of OPVs have been increasing and thus also the demand for better, efficient and cheap photovoltaics. However, silicon PV solar panels are seen to be more commercialized due to their higher efficiency compared to OPVs, which are still being developed and whose efficiency still needs to be improved. Nevertheless, OPVs have the advantage of being cheap and flexible. Silicon PVs possess rigid surface which makes bending impossible, but it is possible to bend OPVs, which means that they need less space when not in use. It does seem that bending does not offer any benefit for large power generation, but considering small scale users such as private homes, small stores, and parking spaces, bending OPVs as you want can offer the benefit of using less space and being easily portable.

As a result of bending OPVs in the thesis experiment, a small drop in the open circuit voltage was discovered implying that degradation had happened within the OPVs. However, the amount of degradation observed was not considerably as significant as expected depending on the angle of bending. By observing the result, it can be said that bending an OPV is not totally disadvantageous. It should also be noted that OPVs are already less efficient and have shorter lifespan. They have shown to degrade at high rate even without bending. Hence, in the present scenario, bending can be recommended if

necessary. It is also important to bend the OPVs to a proper angle and not to a large angle, which allows the OPVs to degrade even more quickly.

The current situation shows that increasing efficiency of OPVs is of greater concern than bending OPVs for good. It would be better to have degradation tests once their efficiency and output is increased to their other counterparts' level. Certainly, bending highly efficient OPVs might show a different result than the acquired result in this thesis.

OPVs possess the potential to be the future of photovoltaic industry. With proper research and advancements, it will surely prove to be a better solution for green energy in the future. Overall, the thesis was purely an act of learning about the wonderful dimension of OPVs and a source for further enthusiasm.

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Appendix 1: Results

Table 1. Result drawn from the experiment of all OPVs

Panel	Bending Angle	Bends in First run	Bends in Second run	Bends in Third run	Bends in Forth run	Bends in Fifth run	Total bends	Max. Voc	Min. Voc	Voc Drop
I-332	30°	75	100	75			250	4.87V	4.58V	0.29V
I-550		100	50	50	50		250	6.19V	5.91V	0.28V
I-558		50	50	50	50	60	260	6.51V	6.18V	0.33V
I-330	60°	75	100	75			250	5.42V	4.73V	0.69V
I-553		100	50	50	50		250	4.22V	3.91V	0.31V
I-557		50	50	50	50	60	260	5.44V	4.98V	0.46V
I-556	90°	75	100	75			250	5.98V	5.15V	0.83V
I-552		100	50	50	50		250	6.44V	5.51V	0.93V
I-333		50	50	50	50	60	260	5.64V	4.82V	0.82V
I-551	60°	100	100	100			300	4.99V	4.62V	0.37V
I-554	0°	100	100				200	6.92V	6.34V	0.58V

Appendix 2: Programs

```
unsigned long time;

int NUM_SAMPLES = 20;
char clocktime;
char time_t;
float sum1 = 0;      // sum of samples from A1
int sample_count = 0;        // current sample number
float voltage1 = 0.0;        // calculated voltage

void setup() {
  Serial.begin(9600);
}

void loop(void)
{

while (sample_count < NUM_SAMPLES)
    {
        sum1 += analogRead(A1)*11.132;
        sample_count++;
        delay(10);
    }

  voltage1 = ((float)sum1 / (float)NUM_SAMPLES) * (5.015 / 1023.0);

  Serial.println(voltage1);
  sample_count = 0;
  sum1 = 0;
  delay(1000);
}
```

Figure 21. Arduino code to create digital voltmeter

```
import os
import time
import readvoltbend
from time import sleep
timer =  2 #time in shutdown function
timeread = 0.5 #how far the piston moves
i = 1
numofruns = 10 #number of run that can be change later


voltage = []

def shutdown():
    os.system('echo in > /sys/class/gpio/gpio4/direction')
    os.system('echo out > /sys/class/gpio/gpio5/direction')
    sleep(timer)
    os.system('echo in > /sys/class/gpio/gpio5/direction')

def startup():
    os.system('echo 4 > /sys/class/gpio/export')
    os.system('echo 5 > /sys/class/gpio/export')
    main()

#def readit():
#     voltread.main()
#     c = voltread.main()
#     print(c)

def main():
    global i
    global timer
    global numofruns
    global voltage
#
#     voltread.main()
#     c = voltread.main()

    if i <= numofruns: #later need to change
        try:
            os.system('echo out > /sys/class/gpio/gpio4/direction')
            time.sleep(timeread)
            readvoltbend.main()
            os.system('echo in > /sys/class/gpio/gpio4/direction')
            time.sleep(timeread)
            readvoltbend.main()
            os.system('echo out > /sys/class/gpio/gpio5/direction')
            time.sleep(timeread)
            readvoltbend.main()
            os.system('echo in > /sys/class/gpio/gpio5/direction')
            time.sleep(timeread)
            readvoltbend.main()
            i += 1
            main()
        except:
            startup()
    else:
        shutdown()
```

Figure 22. Python code to move the piston move

```python
import volt_bending
import datetime
#from time import sleep
#later need to read about upload/download from google drive
list1 = []
i = 0
#timer = 1
def voltbending():
    vb = volt_bending.main()
    if len(vb)>1:
        try:
            x = vb.strip('')
            list1.append(float(x))
            with open('/home/pi/Desktop/M.T.E. /rawdata/voltbendraw.txt','a+') as f:
                time = '{:%y-%d-%m %H:%M:%S}'.format(datetime.datetime.now())
                f.write(str(time+','+vb))
        except:
            voltbending()
def main():
    global list1
    global i
    voltbending()
    if i>=10:
        ave = sum(list1)/len(list1)
        ave = '{:.2f}'.format(ave) #format output number with 2 decimal
        time = '{:%y-%d-%m %H:%M:%S}'.format(datetime.datetime.now())
        f = open('/home/pi/Desktop/M.T.E. /new/Data.txt','a+')
        f.write(time+','+ave+'\n')
        list1=[]
        i=0
    else:
        i=i+1

#if __name__=="__main__":
#    while True:
#        main()
#        sleep(timer)
```

Figure 23. Python code to receive the data in the monitor.

Appendix 3: Connections

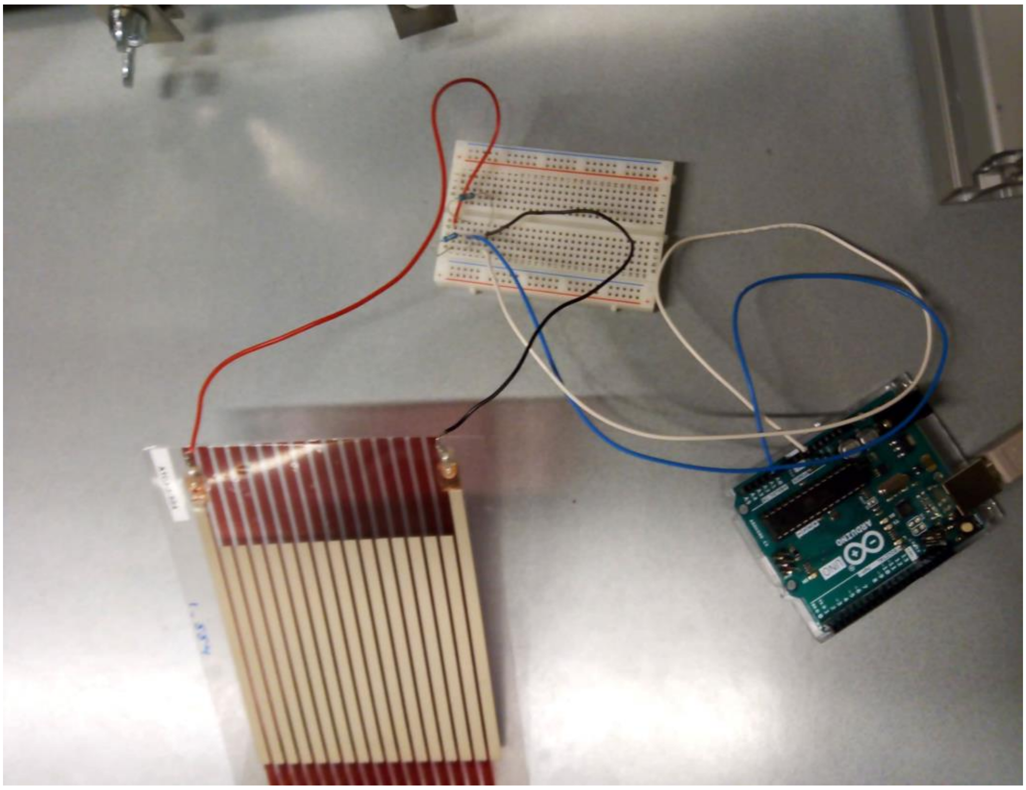

Figure 24. Connection of Arduino and OPV using breadboard.

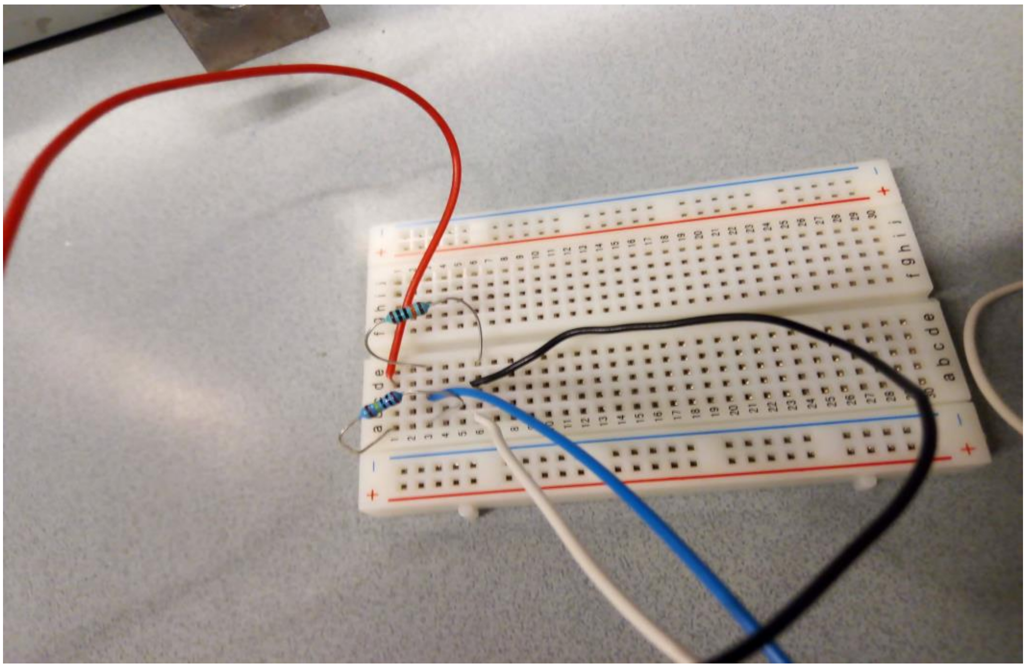

Figure 25. Circuit made in breadboard using resistors.