EFFECT OF VARIOUS TEMPERATURE ON GRAPHENE BASED CONDUCTIVE INK

SITI AMIRAH BINTI ABDULLAH

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KESAN PELBAGAI SUHU TERHADAP DAKWAT KONDUKTIF BERASASKAN GRAPHENE

SITI AMIRAH BINTI ABDULLAH

**Laporan ini dikemukakan sebagai
memenuhi sebahagian daripada syarat penganugerahan
Ijazah Sarjana Muda Kejuruteraan Mekanikal**

Fakulti Kejuruteraan Mekanikal

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2020

DECLARATION

I declare that this project report entitled "Effect of Various Temperature on Graphene Based Conductive Ink" is the result of my own work except as cited in the references.

Signature :

Name : Siti Amirah binti Abdullah

Date : June 2020

PENGAKUAN

Saya akui laporan ini yang bertajuk “Kesan Pelbagai Suhu terhadap Dakwat Konduktif Berasaskan Graphene” adalah hasil kerja saya sendiri kecuali yang dipetik daripada sumber rujukan.

Tandatangan :

Nama : Siti Amirah binti Abdullah

Tarikh : June 2020

APPROVAL

I hereby declare that I have read this project report and in my opinion this report is sufficient in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering.

Signature :

Supervisor's Name : Ts. Dr. Mohd Azli bin Salim

Date :

PENGESAHAN PENYELIA

Saya akui bahawa telah membaca laporan ini dan pada pandangan saya laporan ini adalah memadai dari segi skop dan kualiti untuk tujuan penganugerahan Ijazah Sarjana Muda Kejuruteraan Mekanikal.

Tandatangan :

Nama Penyelia : Ts. Dr. Mohd Azli bin Salim

Tarikh :

ABSTRACT

The outstanding characteristics of graphene, with its good mechanical and electrical characteristics, have made it one of the best candidates to replace other conductive material when developing conductive ink. Graphene properties and the way to improve it have been researched for a decade. In this study, the development of graphene-based conductive ink and graphene properties was overview in order to understand more about the characteristics of graphene, binders and substrate. Some research was conducted to find a factor that could affect the performance of graphene conductive ink, in order to develop a new idea to improve the production of graphene conductive ink. This study shows that the performance of graphene conductive ink is mostly influenced by the conductive ink structure. While the good surface and structure of the graphene conductive ink depending on the stage of the sample preparation. This is because a lot of errors can occur at that time. For example, the formulation matrix for composition, the temperature for the curing process and patterning and printing method. Such factors may have an effect on the development of conductive ink. Therefore, this study focused more on observing the effect of various curing temperatures in order to produce a good linkage between the binders and the filler and several experiments are also being performed to determine the resistance, voltage and microscopy image of the graphene conductive ink. The study was conduct on three size of sample which is 1 mm, 2 mm and 3 mm and with four difference patterns and was cure under temperature of 90 °C, 100 °C and 110 °C. The outcome show sheet resistivity was lower at 3 mm width and at

temperature of 110 ℃. Thus the finding from this study are, sheet resistivity was decrease by increasing the width and the curing temperature for graphene based conductive ink.

ABSTRAK

Ciri luar biasa graphene, dengan terdapat ciri mekanikal dan elektrikal yang baik, menjadikan ia salah satu calon terbaik untuk menggantikan bahan konduktif lain bagi menghasilkan dakwat konduktif. Sifat-sifat Graphene dan cara memperbaikinya telah diteliti selama satu dekad. Dalam kajian ini, penghasilan dakwat konduktif berasaskan graphene dan sifat graphene adalah gambaran keseluruhan untuk memahami lebih lanjut mengenai ciri-ciri graphene, pengikat dan substrat. Beberapa kajian dilakukan untuk mencari faktor yang dapat mempengaruhi prestasi dakwat konduktif berasaskan graphene, untuk mengembangkan idea baru bagi meningkatkan fungsinya. Kajian ini menunjukkan bahawa prestasi dakwat konduktif graphene kebanyakannya dipengaruhi oleh struktur dakwat konduktif. Manakala permukaan dan struktur dakwat konduktif berasaskan graphene yang baik bergantung pada tahap penyediaan dakwat konduktif. Ini kerana banyak kesalahan boleh berlaku pada masa itu. Antaranya ialah, matriks formulasi untuk komposisi, suhu untuk proses pemanasan dan kaedah percetakan. Faktor-faktor tersebut boleh memberi kesan kepada penghasilan dakwat konduktif. Oleh itu, kajian ini lebih memfokuskan kepada pemerhatian kesan pelbagai suhu pemanasan dakwat konduktif untuk menghasilkan hubungan yang baik antara pengikat dan pengisi dan beberapa eksperimen juga dilakukan untuk menentukan rintangan, voltan dan gambar mikroskopi dakwat konduktif graphene. Kajian dilakukan pada tiga ukuran sampel iaitu 1 mm, 2 mm dan 3 mm dan dengan empat corak perbezaan dan dipanaskan pada suhu 90 ℃, 100 ℃ dan 110 ℃. Hasilnya menunjukkan rintangan lebih rendah pada lebar 3 mm dan pada suhu 110 ℃. Oleh itu,

penemuan dari kajian ini adalah, rintangan akan berkurang dengan meningkatkan lebar dan suhu pengawetan untuk dakwat konduktif berasaskan graphene.

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°C	-	Temperature in degree of Celsius
R_s	-	Sheet Resistivity
R	-	Resistance
L	-	Length
W	-	Width
V	-	Voltage
I	-	Current (Ampere)

CHAPTER 1

INTRODUCTION

1.1 Introduction

The population of electronics application increase the demand of wireless electronic application. Thus, this was lead to the development of graphene conductive ink. The background of conductive ink, graphene, and its function in mechanical and electrical field was explained in this chapter. Objective of this study and the problem statement occurs on current studies also provided.

1.2 Background

The world of consumer electronics has seen huge improvements in manufacturing techniques to the production of smaller, faster and more efficient devices for everyday use. However, the use of traditional solid-state technology is limited to the flexibility of the device, environmental concerns and processing costs. As a result, conductive ink has been promising in recent years as a new electronic device that is lighter, more compact and wearable compared to traditional manufacturing.

Most of the research study focuses on conductive nanomaterials and conductive polymer ink for the production of printed electronic application. Conductive nanomaterials and conductive polymer have excellent characteristics that can give a huge impact on future technology. According to its excellent electronic properties and compatibility with liquid phase processing, conductive nanomaterials are required for the development of flexible printed electronic device (Secor et al., 2017). Flexibility was add to conductive nanomaterials to extends their application in the area of mobile devices, electromagnetic interference (EMI) protection and wearable antennas, as well as in the field of textile-integrated application such as health monitoring sensors (Naghdi, Rhee, Hui, & Park, 2018).

Nowadays, printed electronic has successfully growing in material science and technology field and gain interest of most technologies in the world. Printed electronic is an application of printing technology for electronic device. The significant increase in the number of flexible electronic publications over the last 10–15 years has clearly shown that the functionality, foldability and mechanical strength of flexible 2D and 3D devices for future print electronics will increase.

Flexible printed electronics have bloomed in recent times and are emerging technologies with a potentially large influence on everyday life. This technology would allow the production of high-performance, low-cost electronic devices, high throughput and scalable manufacturing platforms. However, the development of ink based on electronic device is therefore crucial to progress in this field.

The formation of conductive ink for new technology applications was subject to printing on a number of substrates, such as paper, textile, glass and polymer substrates, depending on their application purpose. The printed ink on the flexible substrate offering a high flexibility and stretch ability electronic devices. A transparent conductive film or flexible film can be used for the printed ink depends on the quality and the type of the device used and the application of conductive nanomaterials. As example, optical transparency is beneficial for some applications, while it is crucial for others. In addition, flexibility and good mechanical properties are essential for thin film electrodes on plastic substrates, whereas they are not necessary for rigid substrates electrodes (Naghdi et al., 2018).

There is a lot of study has been done on conductive nanomaterials and conductive polymer inks for the production of printed electronic applications. Conductive metal nanomaterials have an important role to play in the forming of stretchable nanoparticles and polymers, because the mechanical properties provide greater flexibility and stretch ability than in traditional conductive materials (Naghdi et al., 2018).

The results show that, metal based ink containing silver nanoparticles (AgNPS), copper nanoparticles (CuNPS) and gold nanoparticles (AuNPS) has outstanding electrical conductivity. However, AuNPS and AgNPS required high sintering temperature and the cost for the material is quite high and expensive. Those two materials will be having a problem using flexible substrate due to high sintering temperature (Saidina, Eawwiboonthanakit, Mariatti, Fontana, & Hérold, 2019)

Further research on conductive polymer inks has been conducted and found that CuNPs are a good alternative rather than using AuNPS and AgNPS due to lower costs but lack in the electrical conductivity rather than those two materials. Besides that, CuNPs have problems with oxidation under thermal and humid conditions that limit their application. Due to the problems occur on AuNPS, AgNPS and CuNPS, graphene was considered as an option to replace other traditional materials based on its advantages over other conductive polymers and conductive nanoparticles (Saidina et al., 2019).

Two dimensional carbon lattice is called as graphene, received good recognition because of its outstanding mechanical, thermal and electrical properties. Graphene is a thin single layer of graphite which have almost same element with carbon but slightly different properties because the atoms were arrange in different way. Graphene is one of the greatest thermal conductive material aside to diamond and carbon nanotubes (Li, Lei, Lai, Chen, & Li, 2019). It is also having other properties which are light weight, transparent, good mechanical strength and impermeable to most gases and liquids. Graphene is labelled as ' the thinnest, most flexible and strongest known material, which conducts very good heat and electricity. There were variety of graphene-like materials, from monolayer to multilayer graphene, turbostratic carbon, graphite nanoplatelets (GNPs), nanosheets, nanoflakes and graphene oxides (GOs) (Saidina et al., 2019).

In this arena, there is constant increase of demand for highly thermal conductive material. Thus, the use of graphene nanomaterials has increased due to its numerous and unique properties. Composites based on graphene have recently been considered the most successful choice for heat dissipation product in both market and academy due to extremely high thermal conductivity (~5300 Wm-1K-1) and good mechanical properties. In addition, graphene quality can be determined by several variables, like roughness and size of the grain of the substrate, the lattice interaction between substrate and graphene and the growth state, including temperature and pressure (Fang, Bai, & Wong, 2018).

Graphene nanoplatelets (GNPs) has a great arrangement of crystal structure due to its thermal conduction go ballistic between carbon x and y plane. However, the crystal structure of the graphene will generate large boundary holes as well as defects when creating a microscopic device structure. Interfacial thermal resistance can occur at the boundary gaps. Thus, binder was used to reduce interfacial area (Fang et al., 2018).

Ink formulation and properties mainly influence the printing quality and flexibility. Therefore, graphene was mixed with binder such as epoxy and hardener based on formulation to increase the mechanical strength and electrical conductivity of sample. Selection for binder’s material also depends on the application and the product requirements. Epoxy and hardener are the type of binder used in this study because of its properties, which can transform the material to make the surface of the sample more flexible and quickly harder.

Epoxy resins is an epoxy that appears after process of curing. Curing is a chemical process in which the material hardens after being exposed to air, heat or chemical additives. Epoxy cure happens with the aid of a catalyst, a chemical additive that increases the speed of chemical reactions. This results in an oxidizing agent that induces a cross-linking of the polymer. This cross-linking is responsible for the rigidity and durability of the epoxy products.

Curing process is one of the important process in order to maintain a good performance of graphene conductive ink. Usually curing method used for develop conductive ink is by heating the conductive ink in certain temperature. Heating a conductive ink can stronger the crosslink between graphene and binders, thus a good composition material can be produced. The stronger the crosslink, the lower the resistivity occur and the greater the mechanical reliability.

Graphene electrical conductivity and its high current density encourages researchers to study more about graphene-based conductive ink. As a response, several experiments were performed in this analysis to explore the properties of the mechanical and electrical of conductive ink after graphene was mixed with epoxy and hardener under the chosen formulation and temperature based on previous research.

1.3 Objective

i. To identify the electrical properties of graphene based conductive ink for different sizes and patterns.

ii. To design and analysis the effect of various temperature on graphene based conductive ink.

1.4 Problem Statement

Based on observations and analysis from previous studies, there are no actual data on the various temperature of graphene-based conductive ink. Previous studies have their observation only depends on experiments conducted at specified temperatures. In addition, no detailed data are available on the comparison of the electrical properties of graphene-based conductive ink utilizing different temperatures for the curing process.

1.5 Scope of Project

The scope of this study are to investigate the electrical properties of graphene based conductive ink for straight line, zigzag, square and sinusoidal patterns of 1 mm, 2 mm and 3 mm width of each pattern. In addition, this scope also aims to ensure that the temperature is well distributed along the conductive ink. The other scope is to cure the conductive ink at three different temperatures, such as 90 °C, 100 °C and 110 °C.

CHAPTER 2

LITERATURE REVIEW

2.1 Conductive Ink

Conductive ink is a liquid that can be applied to conduct electricity. The typical purpose of conductive ink is to construct conductive structures for use as connectors (Saidina et al., 2019). Conductive ink consists three types of material which is filler, binder and hardener. There are two types of filler usually use in developing conductive ink which is metal-based filler and carbon-based filler. While epoxy and hardener is type of binder that usually use in developing the conductive ink. Conductive ink with metal based filler has the best conductivity. Besides that, the amount of conductive filler can affect the conductivity of the circuit.

Carbon based ink is one of conductive ink that were particularly used in the produce of conductive components in printed circuits and sensor electrodes. Such as screens, backplanes, radio frequency identification (RFID), photovoltaics, lighting disposable electronics and memory detectors, as well as traditional thick film applications in which screen printing is used for the development of PCBs, automotive heaters, EMI shielding and membrane switches.

Big retailers and organizations required to do track inventory Extra precise and more effective and FRID and print electronics have been known as the perfect solution. As a result, printed electronics and RFID gain more interest among these conductive components. Printed electronics is a revolution in the perception of information technology through everyday life. The possibility of printing electronic circuits will further facilitate the development of applications to the Internet of Things.

2.2 Graphene

2.2.1 Introduction

Graphene is a two-dimensional material with a single atom size that consists of sheets of carbon atoms bound together in a hexagonal pattern. The word graphene was invented as a mixture of graphite and suffix-ene by Hans Peter Boehm, who defined single-layer foils in 1962 (Ji, Xu, Zhang, Cui, & Liu, 2016). The strongest material ever investigated is the most stretchable crystal imaginable and highly transparent. It has a historical with 10 times thermal conductivity is higher than copper and the greatest electron mobility rather than silicon by almost 100 times (Ren & Cheng, 2014).

2.2.2 Formulation and Preparation of Graphene

Many techniques for the development of graphene have been studied and these methods are divide into two groups which is bottom-up approach (from carbon precursors) and top-down approach (from graphite). The example method of development of graphene from bottom-up approach are, silicon carbide synthesis, chemical vapour deposition and solvent-thermal reaction. While the example method of development of graphene from top-down approach are, micromechanical cleavage, liquid phase exfoliation, chemical reduction of GO, and exfoliation of graphite intercalation compounds (Saidina et al., 2019).

Graphene was formed using some method such as liquid exfoliation, mechanical exfoliation, oxidation-reduction methods or chemical vapour deposition (Li et al., 2019). Mechanical exfoliate method was used in the previous days for splitting the graphene from graphite to become single platelet. However, new method of development of graphene was identified. The new method is liquid-phase exfoliation with the help of sonication, which results in the graphene being separated from graphite into a single particle. Usually used organic solvent, but can also use aqueous solutions containing surfactants (Kamyshny & Magdassi, 2019).

Chemical vapour deposition, CVD is a method which deposit graphene material from carbon sources. This method capable of producing large scale, defect free graphene sheet on metal substrates. In example, a large area of graphene monolayer was obtained from Cu films. Plasma enhanced CVD is capable of growing high throughput lower reaction times for single-layer graphene and smaller deposition temperature conditions than the CVD process (Yang & Wang, 2016).

In addition, synthesis of graphene using silicon carbide substrates, SiC is also one of the technique to produce graphene. Formation of graphene layer occur when the SiC substrate was decomposed. The benefits of this technique are there is no transportation and transition of the resulting substance from the metal substrate to the dielectric form substrate, the resulting graphene film is free of impurities, and the regulated initiation and development of the product can be adjusted to the correct choice of substrate (Yang & Wang, 2016).

Even though less defect graphene can be produced from those methods, but those methods are not commonly used due to their difficulty, limited scaling capability and high cost of metal substrates (Yang & Wang, 2016).

Thus, another approach was found in giving more advantages in producing graphene. Graphene was produced by assure the intercalation, chemical functionalization and bulk graphite sonication. There are several methods for producing graphene has been identified, such as chemical reagent reduction, photochemical reduction, thermal reduction, photothermal reduction, sonolysis, microwave-assisted reduction and electrochemical reduction. Those method, generate graphene using the current bulk material type, which is beneficial in terms of high yield, solution based process ability and ease of operation (Yang & Wang, 2016). Among these approaches, GO's chemical reduction is the most flexible solution and provides the most flexibility and potential for large-scale graphene processing. Figure 2.1 show the flow of formulation of graphene from graphite to chemical converted graphene, CCG.

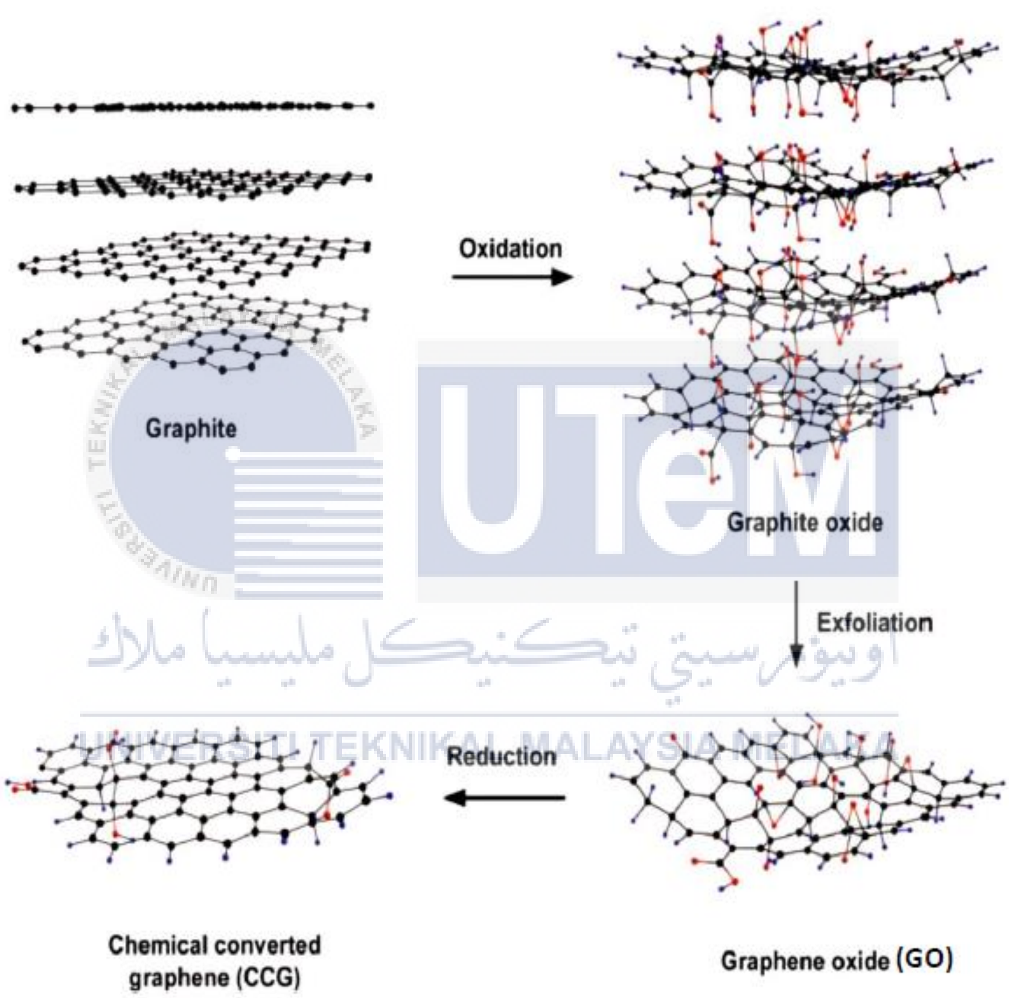


Figure 2. 1: Preparation of Chemical Converted Graphene (CCG) by Reduction of Graphene Oxide

2.2.3 Properties of Graphene

Graphene has revolutionized scientific expression due to its extraordinary physical, electrical, and chemical properties such as impervious to all gasses, transparent at one atom thick, highest surface area, most thermal conductive, completely hydrophobic and most electrically conductive. The special plane structure and geometry of the monolayer graphene arise to its super-properties, including high Young's modulus (1100 GPa), high fracture strength (125 GPa), excellent electrical (106 S/cm) and thermal conductivity (5000 W/mK), fast charge carrier mobility (200,000 cm^2/Vs) and large specific surface (Ji et al., 2016).

The properties of graphene such as high carrier mobility at room temperature, large surface area, high Young's modulus and excellent thermal conductivity make it unique. Versatile synthetic route has been developed to prepare graphene and its derivatives for the development of various applications by exploiting those properties. However, the low dispersibility of common organic and inorganic solvents is a major problem that needs to be considered for graphene before its application.

i. Mechanical properties of graphene

Graphene has been commonly used today due to its unique natural characteristics. Characteristics provided from graphene include its mechanical properties. There are several mechanical properties of graphene that have been identified, such as stiffness, strength and toughness.

Stiffness is one of the outstanding mechanical properties of graphene and also one of the factors why graphene stands out both as a single material and as a strengthening agent in composites. Graphene has most stretchable ability and can stretch to 20% of its initial size without break the structure (Mertens, 2019). Explanations for the outstanding mechanical properties of the graphene lies in the stability of the sp2 bonds which form the hexagonal lattice and are opposed in variety of in-plane deformation.

The mechanical properties of free-standing monolayer graphene were first tested by Hans and co-workers using nano-indentation machine and the graphene was established as “the strongest material ever measured” in their words. Reaction of force displacement from the graphene membrane is used by the researcher to achieved both the elastic properties and the breaking stress of graphene. The breaking force of 55 Nm^{-1} estimated from this formula unable to be considered correct, since this method lacks nonlinear elasticity, breaking force relationship with the third order elastic has been identified constantly by set of numeric calculations. From the experimental result, the force was almost equal to the simulation value and the second order elastic stiffness for the experimental value was equivalent to $E^{2D} = 340 \pm 50\ Nm^{-1}$. This value refers to the Young's modulus E = 1.0 ± 0.1 TPa, considering an active thickness of 0.335 nm (Papageorgiou, Kinloch, & Young, 2017).

Tensile strength of graphene is over 1 TPa. Tensile strength means the maximum stress a material can withstand before failing or breaking when being pulled or stretched (Mertens, 2019). Defect-free, monolayer graphene is believed to be the strongest material ever studied, as Hone and co-workers measured the inner strength of the monolayer membrane at 42 N m^{-1}, equal to an inner strength of 130 GPa (Papageorgiou et al., 2017).

ii. Electrical properties of graphene

The graphene's electrical current density is million times higher than copper and the electron's mobility is stronger than silicon. It means that graphene has the highest density of electrical current and the highest intrinsic mobility. With the presence of new methods in the production of graphene superconductive material, graphene has become the most efficient conductor material.

iii. Thermal Properties of graphene

Previous study prove that graphene has the highest thermal conductivity than diamond, graphite and carbon nanotubes which is over 5000 w/m/K. Graphene is an isotropic conductor because it can conduct heat in all directions (Mertens, 2019).

2.2.4 Modification of graphene

The isolation of graphene from graphite and the measurement of its electrical, mechanical and thermal properties have led to a great deal of interest among the scientific community in exploiting its unique properties for various applications. Even though the mechanical, thermal and electrical properties of polymer and graphene nanocomposites are improved, the increase is far below the theoretically expected properties. It is due to the aggregation of graphene nanosheet due to high van der Waals attraction forces between them. Modification of graphene using covalent and non-covalent method are used to overcome the high van der Waals forces.

Covalent method is considered to be a suitable method of modifying GNPs for strong chemical bonding between the graphene and the modifier. However, pure GNPs are difficult to operate because their surfaces are smooth and rigid with few functional groups. Thus, covalent method was used to active graphene surface with functional group like hydroxyl or amino group. In result, the natural honeycombs of graphene structure were destroyed due to heteroatoms on the graphene lattice and also increase the phonon leaking. Nevertheless, the advantages of improved interfacial interaction from covalent modification can outweigh the weakness of functional graphene from the reported results (Fang et al., 2018).

Non-covalent methods include π - π stacking interactions, electrostatic interactions, hydrogen bonding, coordination bonds, and van der Waals force (Ji et al., 2016). The natural graphene structure can be sufficiently protected by this modification, but the interactions between the functionality and the graphene surface are relatively weak. Therefore, it is not suitable for some applications where strong interactions are required. Composites with a strong graphene-modifier interaction can be developed using a covalent method but the original graphene structure will typically be destroyed, leading to weakened electrical conductivity and mechanical properties.

It was assumed that the actual existence of stand-alone single layer graphene will not be possible due to the thermal fluctuation, since the stability of the long-range crystalline order contained in graphene was considered impossible at finite (room) temperatures. This assumption was turned into a belief through experiments when the stability of thin films was found to be directly related to the thickness of the film (Atif, Shyha, & Inam, 2016).

Nowadays, graphene composite was prepared by mixing other components in obtaining isotropic materials. Thus, most graphene composites are prepared by mixing different components directly to obtain isotropic materials, it is difficult to form periodic morphological structures and to regulate the distribution of graphene.

2.3 Binder

Binder are used to link conductive filler elements to each other and offer good formability during printing, they also produce in inadequate electrical conductivity due to their non-conductivity. Conductive filler is difficult to form a continuous track without binder linkage thus will lead to crack on the printed structure, wide interface resistance and less mechanical performance. There are several type of polymer binder that usually used for conductive ink, such as acrylics, alkyds, cellulose, epoxy resins and rubber resins (Wang et al., 2018).

Polymeric composites are one of the best options for filling gaps between solid interfacial surfaces to reduce systemic thermal resistance. For example, epoxy-based composites are widely used as an agent to fill a blanket between chips and a PCB for heat transfer. Besides that, another popular alternative is silicon-based composites that was used for interfacial thermal material (TIM). Highly thermal conductive thermoplastics such as polypropylene (PP), polyamide (PA) and polystyrene (PS) are commonly used as electronic encapsulation and lamp cover (Fang et al., 2018).

2.3.1 Epoxy

Nowadays, epoxy matrix composites are widely used in the manufacture of various products for automotive, aerospace, marine, sports and electronic device. This is mainly due to its characteristic which is it can combine dissimilar material and produce a high strength to low weight ratio, low shrinkage during curing, better stress distribution and low creep capability, huge modulus, tensile strength and easy of processing (Khan, Halder, & Goyat, 2016).

Epoxy is a compound of organic matter. It is made from carbon chains linked to other elements such as oxygen, hydrogen or nitrogen. This relation is made through a covalent bond when the atoms share a pair of electrons in order to stay together. Molecules containing a functional epoxy group can react chemically to produce a rigid but highly flexible material.

The function of epoxy it to produce a rigid yet highly flexible material. Besides that, epoxy chemically suitable with most substrates and are well adapted to composite applications due to their ability to wet surfaces easily.

Composite materials with epoxy resin-based matrices are commonly used in the automobile, airspace and marine industries (Svendsen, 2014). The mechanical property profile can be strengthened by changing the molecular architecture and the composition of the epoxy matrices. Besides that, stiffness and strength of epoxy material can be improving by increasing the crosslink density. Moreover, highly crosslink may lead to spontaneous failure because of highly crosslink can cause abnormally brittle.

Several limitations were found in epoxy composition, but graphene is therefore one of the filler materials that can be used for the epoxy matrix due to its various properties. High strength, small shrinkage, strong adherence to different substrates, efficient electrical insulation, chemical and liquid resistance, low cost and minimal toxicity are all great properties of epoxy. The number of repeated chains (n) in the epoxy resin ranges from 0 to 25 and the final application of the resin relies on the number of chains. (Svendsen, 2014).

In fact, the curing method for the formulation containing epoxy must also be considered. It is best to use a moderate heat cure with an epoxy system to achieve maximum strength. The proper curing process can increase the strength of the composition (A.May, 2018).

By combining graphene with epoxy with a good formulation, a flexible conductive ink can be obtaining. For the condensation of the composite, various hardeners can be combined with the epoxy resin and provide the strongest polymer properties. Epoxy resin and hardener curing processes can be adjusted to achieve the required mechanical strength and characteristics in the material. Epoxy materials that are resistance to heat, electricity or chemical can be obtain by choosing the perfect temperature or humidity setting for the curing process (Svendsen, 2014).

2.4 Formulation of Graphene and Binder

Binder material, which is epoxy and hardener are used to improve the characteristic of conductive ink by adding it into the formulation with graphene nano particles. The function of epoxy and hardener were added in this formulation is because epoxy can stick the particles together and hardener was use to harder the mixture. The composition of formulation was studied by (Maizura Mokhlis, 2019) and shown as the Table 2.1 below.

Table 2. 1: Composition of Graphene Loading

Sample	**Filler**		**Binder**		**Hardener**	**Total (g)**
	(%)	**(g)**	**(%)**	**(g)**		
1	10	0.2	90	1.8	0.54	2.54
2	20	0.4	80	1.6	0.48	2.48
3	30	0.6	70	1.4	0.42	2.42
4	40	0.8	60	1.2	0.36	2.36
5	50	1.0	50	1.0	0.30	2.30
6	60	1.2	40	0.8	0.24	2.24
7	70	1.4	30	0.6	0.18	2.18
8	80	1.6	20	0.4	0.12	2.12
9	90	1.8	10	0.2	0.06	2.06

The study was conducted by preparing filler loading in amount of 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80% and 90% while the hardener amount was 30% from binder amount in gram.

The experimental result show that, resistance occurs only in a sample of 30% and 40% of filler loading while resistance does not occur at 10% and 20 % of filler loading. Existence of resistivity indicate that there is conductivity of that sample produced. While if there is no resistance on the sample, no electrical conductivity is produce due to agglomeration effect because of small amount of filler loading. For the 50%, 60%, 70%, 80% and 90% filler loading, the sample cannot form an ink mixture because the combination of the materials is not well bonded during the stirring and mixing process because the powder is still produced (Maizura Mokhlis, 2019). Thus, this research show that combination of graphene with binder for 30% and 40% of filler loading is the best formulation obtained.

2.5 Substrates

Conductive ink technology application was subject in printing the conductive ink onto substrate to performing electrical circuit. Several types of substrate are usually used for this technology, such as paper, textile, glass and polymer substrate. Polymer substrate is typically used because of its elastic properties. The properties of the substrate can also affect the characteristics of the conductive ink due to previous study mention that flexible substrate cannot withstand high sintering temperatures (Saidina et al., 2019). The selection of substrates must be addressed, based on the application purpose.

2.6 Patterning or Printing

Several types of printing were used in patterning the conductive ink onto the substrate's surface. The example of the equipment that commonly used for printing conductive ink is inkjet printing, screen printing and microcontact printing. Printing is one of the main cause that can affect the mechanical and electrical properties on conductive ink. This is due to the way of the printing techniques.

Previous study noticed that by increasing the size of graphene materials in conductive ink can be the key to improve the performance of conductive ink. Thus in obtaining a good size of graphene, a continuous and uniform printing need to be taken into account. Besides that, the viscosity of the ink also one of the reason that can affect the performance of the ink. The viscosity need to be low in order to maintain a continuous form of printable ink. In addition, the wettability of the ink also can influence the ink quality (Huang, Huang, Liang, Wan, & Chen, 2011). Applying multiple passes when printing can produce conductive material with lower resistance compare to single passes. Thus, the greater the size of conductive ink, the lower the resistance occurs (Nguyen Bich & Nguyen Van, 2016)

Inkjet printing is widely used for patterning the ink on substrate. This is because it has several advantages to be compared with another printing device. The advantages of using inkjet printing is also due to the low cost, flexibility and can ease the mass production. The production of ink using inkjet printing is easier because this process doesn't need a contact with a substrate, no mask patterning, low temperature processing and low vacuum processing (Huang et al., 2011).

2.7 Application of Graphene Based Ink

Graphene has received significant attention recently due to its excellent electrical, mechanical and thermal properties. On the basis of these unique properties, graphene is predicted to have a wide range of applications in various fields, such as electronics, chemical and biological sensors and energy storage materials. The most popular and widely used application by graphene based ink are electronic device and energy device. There are a lot of previous study that resulting fabrication of electrical device application using graphene based ink such as rugged and flexible sensor using inkjet-printed film, printed microcircuits, fabricate transparent conductive electrode and micro pattern of electrode. While a battery-powered device has been built for energy storage purposes. The rechargeable lithium battery was developed and produces a good performance when the output is measured at room temperature (Yang & Wang, 2016).

2.8 Temperature Effect

Formulation of conductive ink is one of the important things to improve the ink properties. By adding the binder into the formulation, graphene nanoplatelets will attach to each other and offer good formability during printing. However, the formulation will lack of electrical conductivity due to their non-conductivity. In addition, the presence of such binders complicates the process of curing and sintering, because longer or higher temperatures are needed to remove or decompose these binders. However, if binders are removed, the graphene particles have difficulty forming a continuous path without binder linkages and it will lead to crack the printed structure, interface resistance become large and less mechanical reliability (Wang et al., 2018).

Epoxy resins are usually in a viscous form, but they harden with treatment by adding hardener, and through curing. But if the curing temperature is too high, the thermal stress is likely to occur, the hot-cure of the polymers must be undergoing volume shrinkage after cooling from high temperature (curing temperature) to ambient temperature. The polymer shrinkage is depending on the material chemical structure. Epoxy resin was shrinkage was intendedly measure in previous study and found out the shrinkage volume is 5%. Thus, the study found out reducing curing temperature may also reduce shrinkage. Epoxy can undergo a curing temperature below 150 ℃ but a research was suggested maximum curing temperature is on average 40% lower than 150 ℃ (Marques, Da Silva, Banea, & Carbas, 2014). In addition, curing process also the main important for composition, because it can lead to strengthen the composition of filler and binder (A.May, 2018).

The required temperature for sintering and curing process also depends on the boiling points of the organic solvents used and the degree of conductive network formulation. Sintering temperature sometimes goes up more than 300 ℃ for 3 hours long, which is not practical to perform on a flexible substrate because can cause deformation on substrate (Yang & Wang, 2016). However, different types of paper have an important influence on the conductivity of printed films. The paper substrates used in flexible electronics are usually heat-sensitive. The observation find the photo papers become crisp when the curing temperature exceeds 120 ℃, which seriously affects their usage for flexible electronics. Therefore, the curing temperature was set to 100 ℃ (Xu, Yang, Jing, Wei, & Han, 2014).

Graphene need higher temperature in order to improving its mechanical and electrical characteristics. By increasing the sintering temperature, it can improve the grain size of graphene, get a better alignment, present of spacious and continuous structure and lessen the interlayer binding energy. Past study have found that thermal conductivity of graphene will increase by increasing the grain size. This is because large grain size can reduce the phonon inside of graphene. Phonon interfacial scattering will surround graphene layer thus will block thermal conductivity. (Fu et al., 2020)

CHAPTER 3

METHODOLOGY

3.1 Introduction

There are several steps in conducting the methodology of this study. The stages involve gathering the related data from the previous study, analysing data, preparing sample based on information gathered, conducting the experiments, observing the results, making a comparison and concluding the whole process. Figure 3.1 show the flow chart for the development of graphene-based conductive ink.

Firstly, related data about graphene-based conductive ink were collected from previous research and studies. Then, data were analyse in order to get more understanding about graphene properties, material composition, binders properties and functions, ink formulation, range of temperature used and substrate characterisation.

The data was then used to prepare samples of graphene-based conductive ink. A composition of graphene nanoplatelets is mix with binders according to a formulation which is graphene (filler) 35%, epoxy (binder) 65% and hardener is 30% from binder. After that, the mixture will be print onto TPU substrate. The ink was formed in straight line, zigzag, square and sinusoidal patterns of three size for each pattern, 1 mm, 2 mm and 3 mm. Stencil printing method was used in performing patterning those four pattern. The samples were cured under three different temperatures which is 90 ℃, 100 ℃ and 110 ℃ for 30 minutes on curing oven.

Next, several experiments were conducted to determine the electrical properties and microscopy structure of the sample. Once the sample of conductive ink was taken out from the oven and the sample was completely dry, electrical test and microscopy analysis were performed to evaluate the properties of the sample. The electrical test was performed under four-point probe device while the microscopy structure of the sample was analysis under light microscope device.

The result was compared between size, patterns and temperatures to determine the conductive ink properties under different variables. Lastly, the ideal size, pattern and temperature are determined based on the experiment and previous analysis.

This chapter presents the graphene-based conductive ink preparation stage, the equipment used and the experiments to determine electrical conductivity and microscopy structure of flexible conductive ink.

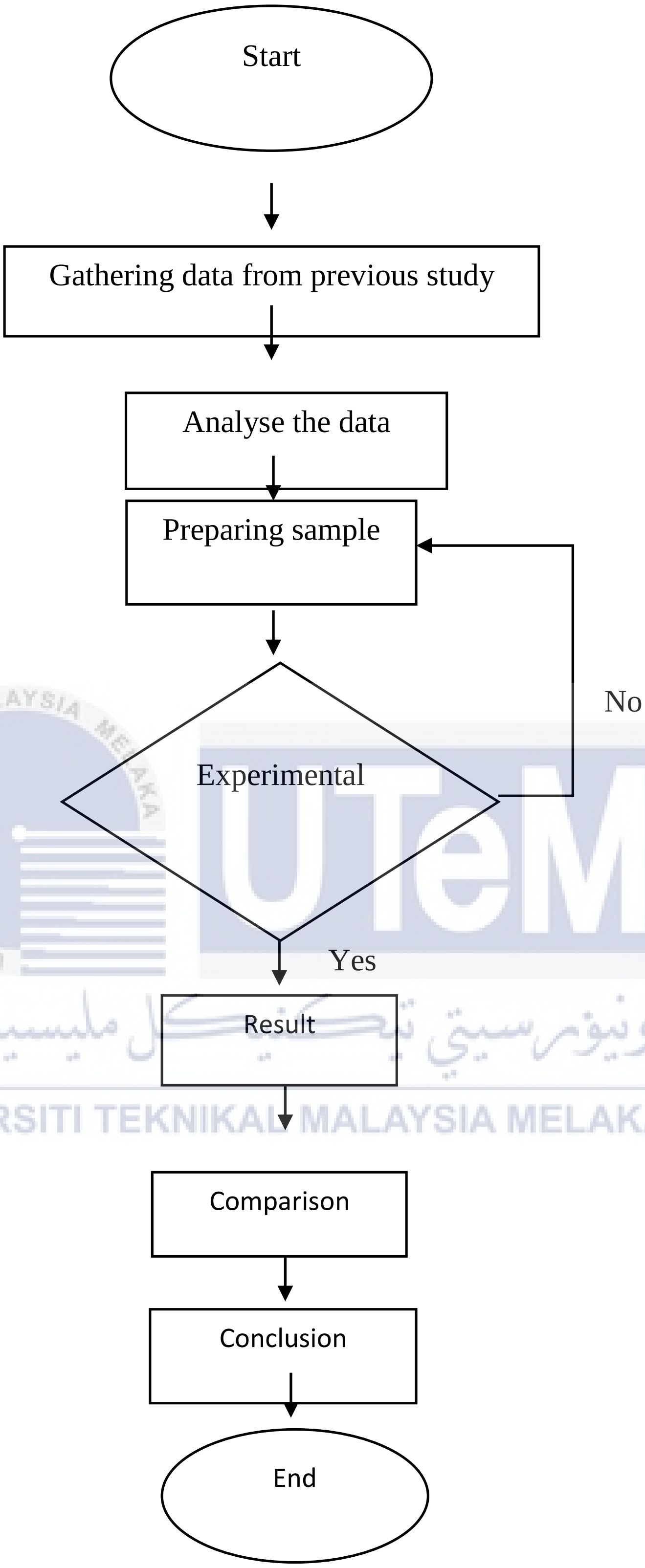


Figure 3. 1: Flow Chart

3.2 Material

The material used in preparing this sample of graphene-conductive ink are, graphene, epoxy and hardener. Figure 3.2 show the material used for the composition.

Figure 3. 2: Material Used for Process of Composition; Hardener, Graphene Nanoplatelets, Epoxy

3.2.1 Graphene

Graphene nanoplatelets (900439) were used for this study. Graphene nanoplatelets is a graphene in a form of small disk shape that consist small stack. Graphene nanoplatelets, GNP has a surface area of 500 m^2/g and a molecular mass of 12.01 g/mol. Graphene nanoplatelets have been selected as a filler due to their properties serving as a good electrical conductivity, mechanical strength and a gas barrier surface. The properties can also be affected when combining it with a different material, such as polymer Adding graphene nanoplatelets with the binder can increase the electrical, thermal and mechanical properties of the combination. Composition of graphene nanoplatelets with epoxy resin as a polymer for the mechanical stirring process can increase the hardness and elasticity of the modulus and increase the wear resistance (Aliofkhazraei, 2016).

3.2.2 Epoxy

Polymer binder that were used in this study is epoxy resin. Epoxy can produce a rigid and highly flexible material. The epoxy resin used in this study was a bisphenol-A diglycidyl (DGEBA) ethers, consisting of epichlorohydrin and bisphenol-A and having an average molecular density of ≤ 700 g/mol. The resin density is 1,168 g/ml, with a viscosity value of 500-750 mPa.s at 25 °C. The main reason for using epoxy resin as a composite material is that epoxy will build superior strength, good electrical conductor, good chemical resistance and creep resistance when the process is done under a proper curing agent (A.May, 2018).

3.2.3 Hardener

As this type of polymer is a two-component adhesive, a hardener was therefore required to complete the curing process through a cross-linking process. The HUNSTMAN polyetheramine D230 hardener, a form of curing agent class of amines, was used. The concentration of the curing agent is 0.947 g/ml with a viscosity of 9 mPa.s at 25 °C (Maizura Mokhlis, 2019).

3.2.4 Formulation

The process involves in preparing the sample is mixing, printing and curing in order to get good result in electrical conductivity and mechanical strength. Graphene nanoplatelets is mix with binder and hardener according to a formulation which is graphene (filler) 35%, epoxy (binder) 65% and hardener is 30% from binder. The formation was determined by the proposed analysis. Analysis has shown that 30% to 40% of the graphene filler will provide resistance to conductive ink (Maizura Mokhlis, 2019). The example of conductive ink formulation's ratio has shown in Table 3.1 below.

Table 3. 1: Composition of Graphene with Epoxy and Hardener

No	Total (g)	GNP (%)	GNP (g)	Epoxy (%)	Epoxy (g)	Hardener (%)	Hardener (g)
1.	5	35	1.75	65	3.25	30	0.975
2.	10	35	3.5	65	6.5	30	1.95

For the mixing process, 3.5 g of graphene nanoplatelet, 6.5 g of epoxy and 1.95 g of hardener are placed into a container to be mixed using thinky mixer in 2000 rpm for 3 minutes. The thinky mixer was used to make sure the materials are mixed properly. After that, the mixture is used to print a conductive ink onto TPU substrate using a stencil printing. The conductive ink was print into four pattern which is straight, sinusoidal, zigzag and square with three different size which is 1 mm, 2 mm and 3mm. Lastly, the printable graphene was cure in an oven with temperature 90 ℃, 100 ℃ and 110 ℃ for 30 minutes. The temperature was chosen based on previous study about suitable curing temperature for composite material and substrate.

3.3 Equipment & Procedure

The equipment and apparatus used for this study are shown and the procedure for preparing the sample has been explained in detailed in this sub-topic.

3.3.1 TPU Substrate

Thermoplastic polyurethane, TPU substrate is a flexible substrate with stretchy, has a toughness surface, and cut or tear resistance due to its stretchy property.

Measured the size of substrate to 15cm x 4 cm using ruler and marked the sized with marker pen. Cut TPU substrate based on the size that were measured. The substrate was cut much bigger than conductive ink size for easier the process of handling the conductive ink. Figure 3.3 show the TPU substrate that were already cut into the size needed.

Figure 3. 3: Thermoplastic Polyurethane, TPU Substrate

3.3.2 Digital Scale (Mettler Toledo)

Digital scale is one of the type of weighing scale is an equipment that contain beam balance to measure the weight or mass of material. There are several type of weighing scale which is, spring balance, beam balance, and electronic weighing scale. Nowadays, people was commonly used the electrical weighing scale with digital analytic balance to measure the weight of nanoparticles because this type of weighing scale capable of produce an accurate reading for small mass of material in the sub-milligram range.

The measuring beam were located in the transparent enclosure with doors to make sure no outside residual or dust were collect and affect the balance operation. Sample must be in a room temperature to prevent air inside the enclosure forming a natural convention that may affect the reading. This electronic analytic measures the weight and mass using method of mass was countered by the force. Thus a calibration adjustment is needed to compensate for gravitational differences. Only scales that have been accurately calibrated horizontally produce correct weighing tests. Force were produce by electromagnetic to counter the material being measured and the reading of the material by calculating the strength required to achieved the equilibrium state. Figure 3.4 show the digital scale used for this study.

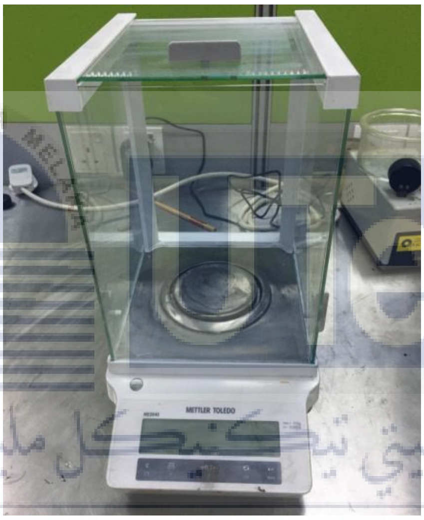


Figure 3. 4: Digital Scale (Mettler Toledo)

Aligned the scale before measure the weight of material by turn the adjustable feet of the scale until the spirit level's air bubble is inside the inner circle.

Graphene, epoxy and hardener were put in different containers to determine the weight of each material using the digital scale shown in the Figure 3.4 above. Before that, empty container was place on the weighting scale and reset the reading for zeroing the weight of container. The weight of the container was removed by reset the reading to indicates that the final reading only display the weight of the content and does not include the weight of the container. No need to remove the container from the enclose. Measured the weight of material by putting the material into container that were place in the enclosure.

After the weight of graphene, epoxy and binder were measure for 5 g of graphene, 6.5 g of epoxy and 1.95 g of hardener, those material were mixed together in another container. The gross weight of the materials with the container also be measured using digital scale.

3.3.3 Thinky Mixer

Thinky Mixer and also known as centrifugal mixer is a mixer that function to mix and de-aerate different kinds of fluid or powder materials at the one time. This mixer blends, dissolves and degasses the ingredients in seconds to minutes in a closed or non-coated container. The non-contact mixing principle enables the formulation of compounds from very small quantities such as 0.5 ml to large scales of production. Only designed container can be used on this machine. The standard size of the containers should be used is 150 ml and 300 ml. Use a container of 150 ml when the weight of the materials is less than 50 g.

Figure 3. 5: Thinky Mixture

The container was place on a thinky mixture shown at the Figure 3.5 above. Material were put into container. The adapter with container were insert into the cup holder. Revolution balance were adjusting before starting the machine by putting gross weight of the container with the materials to maintain high speed balance. The revolution speed of the mixture was set to 2000 rpm for duration of 3 minutes. This machine is used to make sure the materials was mixed properly.

3.3.4 Stencil Printing

Stencil printing is a simple method for depositing or petterning the conductive ink onto TPU substrate surface. Stencil printing is a great way to produce multiple pattern of conductive ink for saving time and energy. Stencil Printing procedure is almost same with print screen. Figure 3.6 show the stencil printing use for preparing this sample.

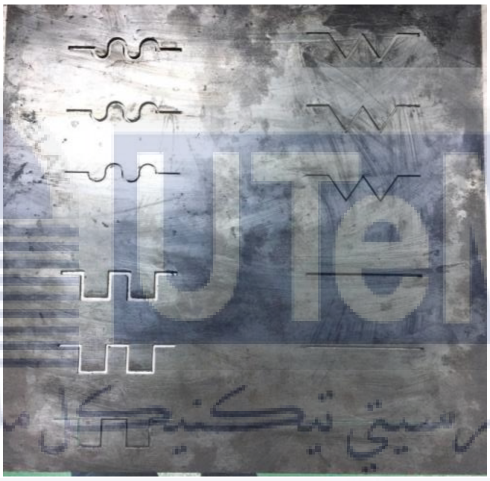


Figure 3. 6: Stencil Printing

Stencil printing is a great way to produce multiple pattern of conductive ink because it have four different pattern which is straight line, zigzag, square and sinusoidal which is each of the pattern have 1mm, 2mm and 3mm size. The sample were prepared using manual stencil printing. TPU substrate was rinse using acetone before printing process to remove residuals at the surface of the substrate. Then, TPU substrates was carefully apply at the stencil surface to avoid any air bubble forming underneath. Masking tape was used to attach TPU substrate with stencil to avoid any movement occurs during printing process. Place the conductive ink onto stencil using a spatula and use some pressure to fill the conductive ink into the pattern to ensure full coverage. Leave the conductive ink on the stencil for 5 to 10 minutes for conductive ink dry to ease remove the conductive ink without left at the stencil. Lastly, take of the TPU substrate from stencil carefully to prevent the ink from smudging.

3.3.5 Curing Oven

Curing oven is a thermal processing equipment that was designed to cure or sintering the conductive ink by heating the material with the temperature set. Curing process and also known as sintering process is a heating in an oven or on a hotplate. The purpose of this curing process are to increase the chemical reaction on the material to improve their strength and durability. Temperature requirement for this process is depending on the material solvent and substrate. Besides, physiochemical linkage also can be improved with the curing process thus it also leads to increasing the mechanical properties of material due to the high linkage. Figure 3.7 show the curing oven used for this study.

Figure 3. 7: Curing Oven

Placed the printed conductive ink onto a tray. Make sure to place a weight at the both end of the substrate to prevent the substrate crumple during curing process. Thus it will disturb the surface of conductive ink. After that, pushed the on button at the oven and set the temperature to 100 °C then push again the button to set the time for curing to 30 minutes.

Waited until the time from 30 minutes drop to 0. Then same button was pushed to stop the oven. Take out the tray using tong to prevent direct contact with the hot tray. Waited for the ink to cold down its temperature to room temperature. Conducted experiment to the sample after the temperature of ink reach room temperature. Repeat the same procedure for 90 °C and 110 °C temperature on another samples.

3.3.6 Four-Point Probe Device

The four-point probe is a simple device for measuring the resistance of semiconductor samples. The resistance of the surface can be determined by passing the current within two external probes and measuring the voltage between the inner probes. Surface resistivity can be measured using this device when the measurement of resistance across the surface of a substance in contact with an electrode. The measurement unit of surface resistivity is Ohm per square (Ω/square) based on the size of electrode. Figure 3.8 show the four-point probe device.

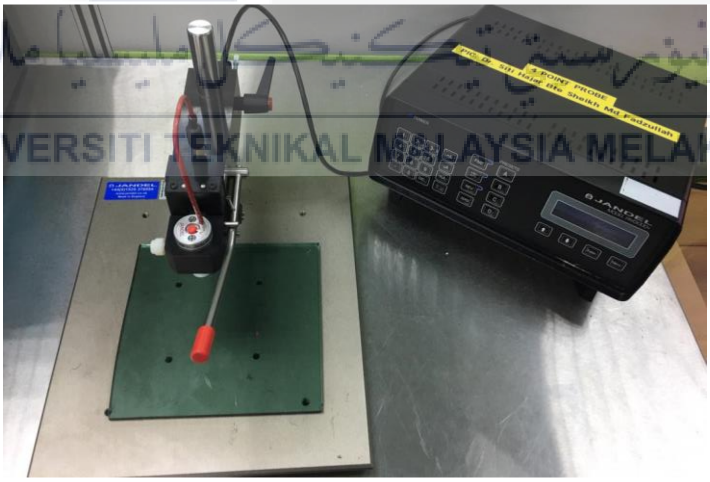


Figure 3. 8: Four-Point Probe Device

The procedure of handling this device must be practiced in order to obtain a good result. First the voltmeter was turned on and adjusted to DC mode. To remove the old display, the Enter button was pressed for 5 seconds. The value was changed to µm. The sample was then placed on the probe stage under the four pin of the probe. Then lower the probe until the surface of the sample has been touched and the probes have stabilized on the sample. Turned the current source by pressing the "SI" button. Once reading is obtained the Enter button was pressed to automatically save the reading to the machine which attaches to the computer. The probe was removed and the specimen was moved to another point in order to keep testing the diff reading. The probe was lifted and the sample was adjusted to a different point in order to continue measuring the reading at a different point. Turn off the device by pressing the "SI" button when the measurement is fully completed.

3.3.7 Light Microscope

Light microscope is a device used to visualize the small material that cannot be seen by naked eye. This device used focused light and lenses to magnify the surface of the object in finer detail. The sample's surface condition or the microstructure of the sample's surface can be visualized using this device. Figure 3.9 show the light microscope device that were used in conducting this experiment.

Figure 3. 9: Light Microscope

Several procedures need to be followed in order to get accurate result. First, turn on the power source and turn on the light source. Adjust the light setting as the comfort of the eyes. Place the sample on the centre of the stage right under the objective lens by move the stage control knobs to the right to left or forward to backward. Also make sure to clip the sample with stage clips so that the sample does not move during the experiment. Make sure the iris diaphragm is completely open and adjust it to ensure get the sufficient light. Begin to view the sample by looking through the eyepiece. Adjust the stage so the sample are not too far from objective lens and stop when the view of the sample can be seen on the eyepiece. Begin to view the sample using lowest power of objective lens and then rotate the revolving nose piece to the higher power objective lens until get the lowest level magnification of lens. Then adjust the course focus until the sample comes onto broad focus but be caution, do not contact the sample with the lens. Adjust focus using fine focus to get sharp image. The image also can be view at desktop if the light microscope were connecting to the desktop. Open Solution Lite software and click view to view the surface image of the sample. Capture the sample microstructure image using the software. Lastly, after finish using light microscope device, make sure to turn off the light and the main switch and cover the light microscope with dust cover.

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

Several experiments were conducted after the curing process to determine the electrical properties and microscopy image of this sample. Sheet Resistance and voltage on the surface of the sample were measured by a four-point probe device. While microscopy image was captured by light microscope device. Three point of reading are taken while performing this experiment. In order to ensure that the electrical properties and microscopy image of this sample are taken at the same point, this sample was marked with three points on the substrate. The reading was performed three times to minimize the error of this test. The data was then averaged and the outcome was shown in the tables to be presented in this chapter. In addition, the data was used on the graph to make the result much easier to read. Meanwhile, the error bar for monitoring data variability was also included in the graph.

The discussion was made based on result of resistivity and voltage between size, pattern and temperature. The size of sample width are 1 mm, 2 mm and 3 mm for every four patterns which is straight line, zig zag, square and sinusoidal. The temperature for curing process involved are 90 °C, 100 °C and 110 °C. Besides that, light microscope experiment was used to determine the surface structure of the sample. The image obtain from the experiment can be used to support the discussion of sample resistivity. All the results for comparison of resistivity and voltage between temperature were present in graph to easier the data reading.

4.2 Four-Point Probe (Sheet Resistivity)

An experiment was conduct on four pattern of sample which is straight line, zigzag, square and sinusoidal with three different size, 1 mm, 2 mm and 3 mm and three different temperatures, 90 ℃, 100 ℃, 110 ℃. The experiment shown the result of sheet resistivity of each sample.

Some of the result display N/A which is not applicable because the sample or experiment cannot be prepared, test, redo or retest due to the Movement Control Order (MCO) issue now.

4.2.1 Straight Line for Temperature 90 °C

Table 4.1 show the result of average resistance for pattern straight line with size of 2 mm and 3 mm for temperature 90 °C while the results for width 1 mm are shown N/A which is not applicable because the samples could not be prepared due to the Movement Control Order (MCO) for Covid-19 issue. The resistivity of this sample were measured using four-point probe device. Figure 4.1 show the graph of average resistance between sample 1, sample 2 and sample 3 for 2 mm and 3 mm straight line.

Table 4. 1: Result of Average Resistance for Pattern Straight Line, Size 2mm and 3 mm for temperature 90 °C

Pattern	Size	Point of Reading	Average Reading Resistance x 10^3 (Ω/sq)			Average Reading Resistance x 10^3 (Ω/sq)	Standard Deviation	Standard Error
			Sample 1	Sample 2	Sample 3			
Straight Line (P1)	1mm	Point 1	N/A	N/A	N/A	N/A	N/A	N/A
		Point 2	N/A	N/A	N/A	N/A	N/A	N/A
		Point 3	N/A	N/A	N/A	N/A	N/A	N/A
	2mm	Point 1	7.712	12.502	12.725	10.980	2.832	1.635
		Point 2	3.857	10.724	9.712	8.098	3.707	2.140
		Point 3	7.031	16.126	11.858	11.671	4.550	2.627
	3mm	Point 1	17.759	14.648	22.698	18.368	4.059	2.344
		Point 2	12.110	11.644	9.602	11.118	1.334	0.770
		Point 3	14.525	10.589	7.337	10.817	3.600	2.078

Figure 4.1 show the graph of average resistance for size 2 mm and 3 mm for pattern straight line. The graph show 2 mm width get lower resistivity compare to 3 mm width. The highest resistivity appears at point 1 of 3 mm width, with reading 18.368 kΩ/sq. Meanwhile, the lowest resistivity is at point 2 of 2 mm width which is the reading is 8.098 kΩ/sq The error bar is high at each reading point. It indicates, therefore, that there is a strong probability of error occurring at that point.

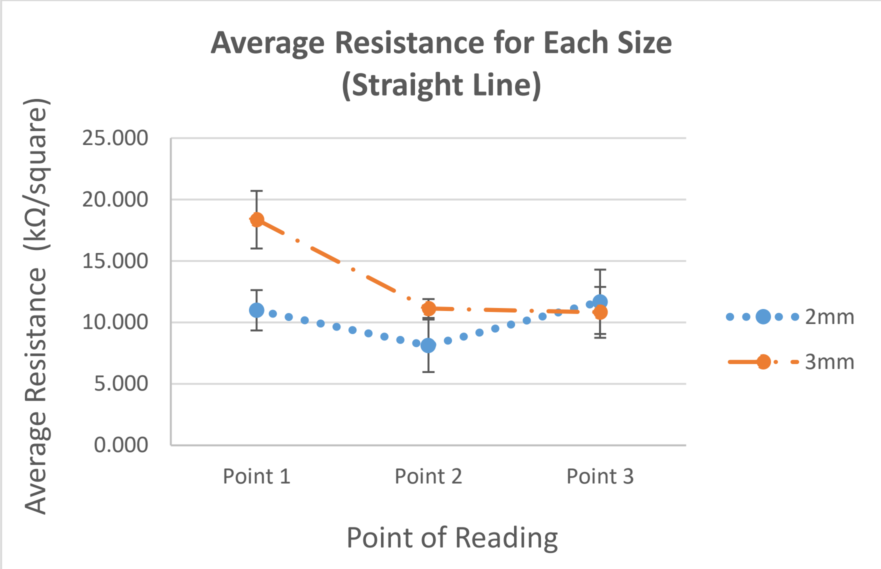


Figure 4. 1: Graph of Average Sheet Resistance between Sizes, 2mm and 3mm for Temperature 90 °C Pattern Straight Line

4.2.2 Zig Zag for Temperature 90 ℃

Result of the Zig Zag pattern of sheet resistivity between size of sample which is 1 mm, 2 mm and 3 mm for temperature 90 ℃ was shown in Table 4.2 below. A graph of the average resistance sheet for each reading point has been prepared from the data obtained. The graph can be seen below in Figure 4.2.

Table 4. 2: Result of Average Resistance for Pattern Zig Zag, Size 1 mm, 2mm and 3 mm for temperature 90 ℃

Pattern	**Size**	**Point of Reading**	**Average Reading Resistance x 10^3 (Ω/sq)**			**Average Reading Resistance x 10^3 (Ω/sq)**	**Standard Deviation**	**Standard Error**
			Sample 1	**Sample 2**	**Sample 3**			
Zig Zag (P2)	1mm	Point 1	21.426	21.743	21.642	21.604	0.162	0.094
		Point 2	20.355	20.790	21.636	20.927	0.651	0.376
		Point 3	21.549	19.549	18.216	19.772	1.678	0.969
	2mm	Point 1	8.740	9.276	9.700	9.239	0.481	0.278
		Point 2	12.304	11.036	13.880	12.407	1.425	0.823
		Point 3	10.872	11.643	11.834	11.450	0.509	0.294
	3mm	Point 1	5.441	18.589	5.430	9.820	7.595	4.385
		Point 2	4.541	22.172	7.209	11.307	9.503	5.487
		Point 3	4.873	24.166	5.717	11.585	10.904	6.295

From the graph in Figure 4.2 the average reading error bar shows a low range for each reading point. Therefore, the data obtained are almost precise. Sample for 1 mm size got the highest value of resistance while size of 2 mm and 3 mm got almost same value of resistivity for zig zag pattern. The error bar shows at sample size 3 mm was very large. Thus, the possibility of error occurs at the sample is high.

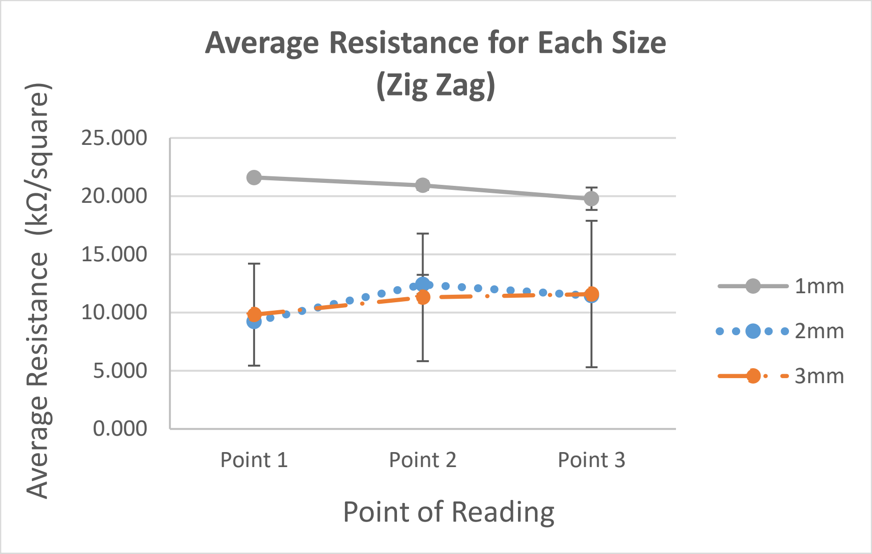


Figure 4. 2: Graph of Average Resistance between Sizes, 1mm, 2mm and 3mm for Temperature 90 ℃ Pattern Zig Zag

4.2.3 Square for Temperature 90 °C

Table 4.3 show the result for average resistance for sample square for size 1 mm, 2 mm and 3 mm for temperature 90 °C. The result was applied to the graph to make the data even easier to read. Graph of average resistance for square pattern with a width of 1 mm, 2 mm and 3 mm were shown in Figure 4.3 below.

Table 4. 3: Result of Average Resistance for Pattern Square, Size 1 mm, 2mm and 3 mm for temperature 90 °C

Pattern	**Size**	**Point of Reading**	**Average Reading Resistance x 10^3 (Ω/sq)**			**Average Reading Resistance x 10^3 (Ω/sq)**	**Standard Deviation**	**Standard Error**
			Sample 1	**Sample 2**	**Sample 3**			
Square (P3)	1mm	Point 1	14.647	17.314	16.314	16.092	1.347	0.778
		Point 2	13.389	15.156	15.122	14.556	1.011	0.583
		Point 3	12.686	14.686	15.286	14.219	1.361	0.786
	2mm	Point 1	15.300	14.790	15.160	15.084	0.263	0.152
		Point 2	8.985	10.085	12.087	10.386	1.573	0.908
		Point 3	14.606	13.956	13.058	13.873	0.777	0.449
	3mm	Point 1	7.812	11.758	12.967	10.845	2.696	1.557
		Point 2	5.925	11.646	9.298	8.957	2.876	1.660
		Point 3	8.708	7.007	12.868	9.528	3.015	1.741

Observation can be made only by looking at the graph shown on Figure 4.3. The graph show 1 mm has the highest resistivity among those size. While 3 mm has the smallest resistivity. From the graph, it shows that, the wider the size of the conductive ink, the lower the resistivity occurs at the ink, $R_s = R\,(\frac{L}{W})$. By using formula of V=IR, it can be concluded that when resistivity, R is high, the voltage, V also high. But for current, I when resistivity is high, the current flow at the ink is low due to I=V/R. Thus for square pattern, current is higher at 3 mm width while lower at 1 mm width.

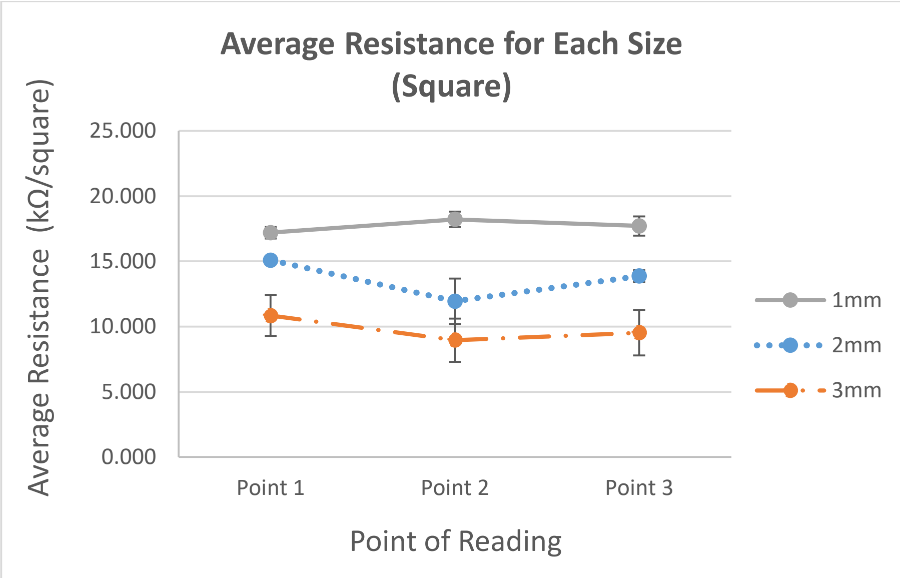


Figure 4. 3: Graph of Average Resistance between Sizes, 1mm, 2mm and 3mm for Temperature 90 ℃ Pattern Square

4.2.4 Sinusoidal for Temperature 90 ℃

Table 4.4 show the result of average resistance between three readings for sample Sinusoidal with the size 1 mm, 2 mm and 3 mm for temperature 90 ℃. The graph of the result was shown in the Figure 4.4 below.

Table 4. 4: Result of Average Resistance for Pattern Sinusoidal, Size 1 mm, 2mm and 3 mm for temperature 90 ℃

Pattern	**Size**	**Point of Reading**	**Average Reading Resistance x 10^3 (Ω/sq)**			**Average Reading Resistance x 10^3 (Ω/sq)**	**Standard Deviation**	**Standard Error**
			Sample 1	**Sample 2**	**Sample 3**			
Sinusoidal (P4)	1mm	Point 1	20.912	20.246	21.246	20.801	0.509	0.294
		Point 2	18.451	18.451	15.785	17.563	1.540	0.889
		Point 3	21.046	19.605	20.605	20.419	0.738	0.426
	2mm	Point 1	12.143	12.310	14.195	12.883	1.140	0.658
		Point 2	13.035	17.035	12.422	14.164	2.505	1.446
		Point 3	13.210	13.210	14.925	13.782	0.990	0.572
	3mm	Point 1	11.781	12.037	12.290	12.036	0.255	0.147
		Point 2	7.463	10.276	12.167	9.969	2.367	1.367
		Point 3	6.639	9.503	15.182	10.441	4.348	2.510

Figure 4.4 show the sheet resistivity for sample sinusoidal between size 1 mm, 2 mm and 3 mm. Size 1 mm show the greatest amount of resistivity while size 3 mm show the least amount of resistivity. The highest resistivity obtain from this result is 20.801 kΩ/sq while the lowest resistivity at 9.969 kΩ/sq. The graph show that, the wider the size of the conductive ink, the lower the resistivity occurs at the ink, $R_s = R\ (\frac{L}{W})$. By using formula V=IR, it can be concluded that when resistivity, R is high, the voltage, V also high. But for current, I when resistivity is high, the current flow at the ink is low due to I=V/R. Thus for sinusoidal pattern, current is higher at 3 mm width while lower at 1 mm width.

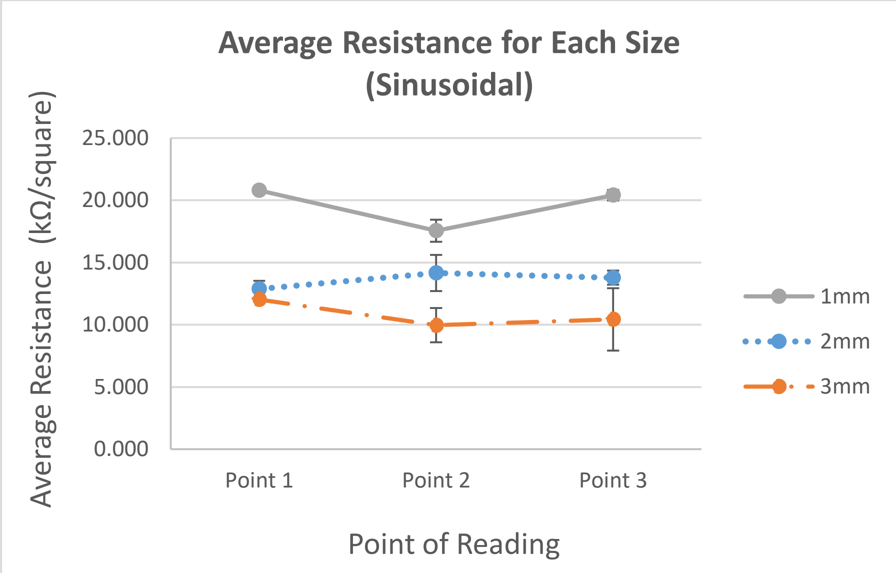


Figure 4. 4: Graph of Average Resistance between Sizes, 1mm, 2mm and 3mm for Temperature 90 °C Pattern Sinusoidal

4.2.5 Straight Line for Temperature 100 ℃

Table 4.5 show the result of average resistance for pattern straight line with size of 3 mm for temperature 100 ℃ while the results for width 1 mm and 2 mm are shown N/A which is not applicable because the samples could not be prepared due to the Movement Control Order for Covid-19 issue. The resistivity of this sample were measured using four-point probe. Figure 4.5 show the graph of average resistance between sample 1, sample 2 and sample 3 for 3 mm straight line.

Table 4. 5: Result of Average Resistance for Pattern Straight Line Size 3 mm for temperature 100 ℃

Pattern	**Size**	**Point of Reading**	**Average Reading Resistance x 10^3 (Ω/sq)**			**Average Reading Resistance x 10^3 (Ω/sq)**	**Standard Deviation**	**Standard Error**
			Sample 1	**Sample 2**	**Sample 3**			
Straight Line (P1)	1mm	Point 1	N/A	N/A	N/A	N/A	N/A	N/A
		Point 2	N/A	N/A	N/A	N/A	N/A	N/A
		Point 3	N/A	N/A	N/A	N/A	N/A	N/A
	2mm	Point 1	N/A	N/A	N/A	N/A	N/A	N/A
		Point 2	N/A	N/A	N/A	N/A	N/A	N/A
		Point 3	N/A	N/A	N/A	N/A	N/A	N/A
	3 mm	Point 1	2.830	2.621	4.163	3.205	0.837	0.483
		Point 2	1.478	1.997	3.478	2.318	1.038	0.599
		Point 3	1.512	2.654	2.512	2.226	0.622	0.359

Figure 4.5 displays only the 3 mm graph line for the straight line sample pattern curing under 100 °C temperature. The graph of 1 mm and 2 mm cannot be plotted due to no result. As a result, the 3 mm graph indicates that the resistance of the sheet exists at three points with exactly the same reading, which is about 10 kΩ/sq. The error bar for each point shows a small number, so the readings obtained indicate the least error.

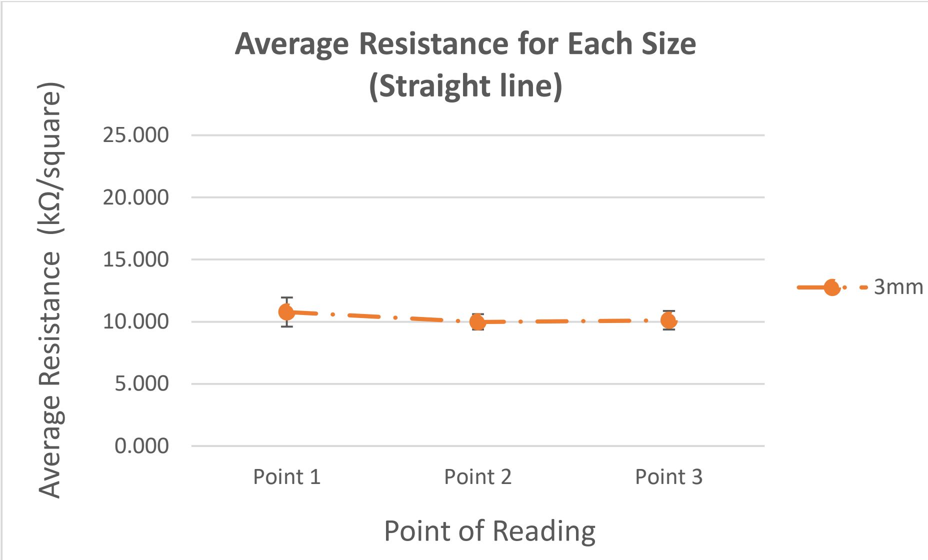


Figure 4. 5: Graph of Average Resistance for Size 3mm for Temperature 100 °C Pattern Straight Line

4.2.6 Zig Zag for Temperature 100 °C

Result of the Zig Zag pattern of sheet resistivity for sample width 1 mm, 2 mm and 3 mm was shown in Table 4.6 below. A graph of the resistance sheet for each reading point has been prepared from the data obtained. The graph can be seen below in Figure 4.6.

Table 4. 6: Result of Average Resistance for Pattern Zig Zag, Size 1 mm, 2mm and 3 mm for Temperature 100 °C

Pattern	**Size**	**Point of Reading**	**Average Reading Resistance x 10^3 (Ω/sq)**			**Average Reading Resistance x 10^3 (Ω/sq)**	**Standard Deviation**	**Standard Error**
			Sample 1	**Sample 2**	**Sample 3**			
Zig Zag (P2)	1mm	Point 1	18.529	19.306	18.529	18.788	0.449	0.259
		Point 2	19.722	21.654	19.702	20.359	1.121	0.647
		Point 3	18.417	18.571	18.635	18.541	0.112	0.065
	2mm	Point 1	16.231	17.939	16.003	16.724	1.058	0.611
		Point 2	16.808	20.591	17.237	18.212	2.071	1.196
		Point 3	14.868	16.798	17.074	16.246	1.202	0.694
	3mm	Point 1	10.493	10.295	9.158	9.982	0.720	0.416
		Point 2	13.986	13.544	13.456	13.662	0.284	0.164
		Point 3	14.857	15.508	13.623	14.662	0.957	0.553

From the graph in Figure 4.6 the average reading for 1 mm size got the highest value of resistance while average reading for size of 3 mm got the lowest value of resistivity for zig zag pattern. The graph also shows that the smaller the width of the conductive ink, the higher the resistivity occurs at the ink, $R_s = R\ (\frac{L}{W})$. By using formula V=IR, it can be concluded that when resistivity, R is high, the voltage, V also high. But for current, I when resistivity is high, the current flow at the ink is low due to I=V/R. Thus for zigzag pattern, current is lower at 1 mm width while higher at 3 mm width.

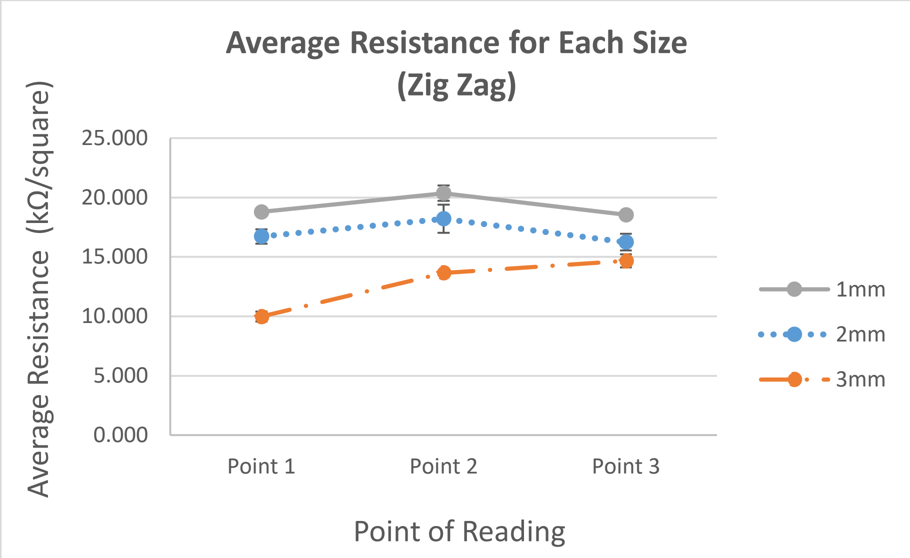


Figure 4. 6: Graph of Average Resistance between Sizes, 1mm, 2mm and 3mm for Temperature 100 °C Pattern Zig Zag

4.2.7 Square for Temperature 100 ℃

Table 4.7 show the result for average resistance for sample square for size 1 mm, 2 mm and 3 mm for temperature 100 ℃. The result was applied to the graph to make the data even easier to read. Graph of average resistance for square pattern with a width of 1 mm, 2 mm and 3 mm shown in Figure 4.7 below.

Table 4. 7: Result of Average Resistance for Pattern Square, Size 1 mm, 2mm and 3 mm for Temperature 100 ℃

Pattern	Size	Point of Reading	Average Reading Resistivity x 10^3 (Ω/sq)			Average Reading Resistivity x 10^3 (Ω/sq)	Standard Deviation	Standard Error
			Sample 1	Sample 2	Sample 3			
Square (P3)	1mm	Point 1	17.831	15.123	16.456	16.470	1.354	0.782
		Point 2	15.734	16.060	14.539	15.444	0.801	0.462
		Point 3	18.096	15.871	15.587	16.518	1.374	0.793
	2mm	Point 1	12.568	12.568	13.723	12.953	0.667	0.385
		Point 2	13.234	10.548	8.955	10.912	2.162	1.248
		Point 3	14.219	8.211	11.349	11.260	3.005	1.735
	3mm	Point 1	7.466	8.430	10.002	8.633	1.280	0.739
		Point 2	6.428	7.161	7.415	7.001	0.513	0.296
		Point 3	7.437	7.437	9.339	8.071	1.099	0.634

From the observation made for Figure 4.7 for sample width 1 mm has the highest resistivity among those size. While 3 mm has the smallest resistivity. The wider the size of the conductive ink, the lower the resistivity occurs at the ink. By using formula V=IR, it can be concluded that when resistivity, R is high, the voltage, V also high. But for current, I when resistivity is high, the current flow at the ink is low due to I=V/R. Thus for square pattern, current is higher at 3 mm width while lower at 1 mm width.

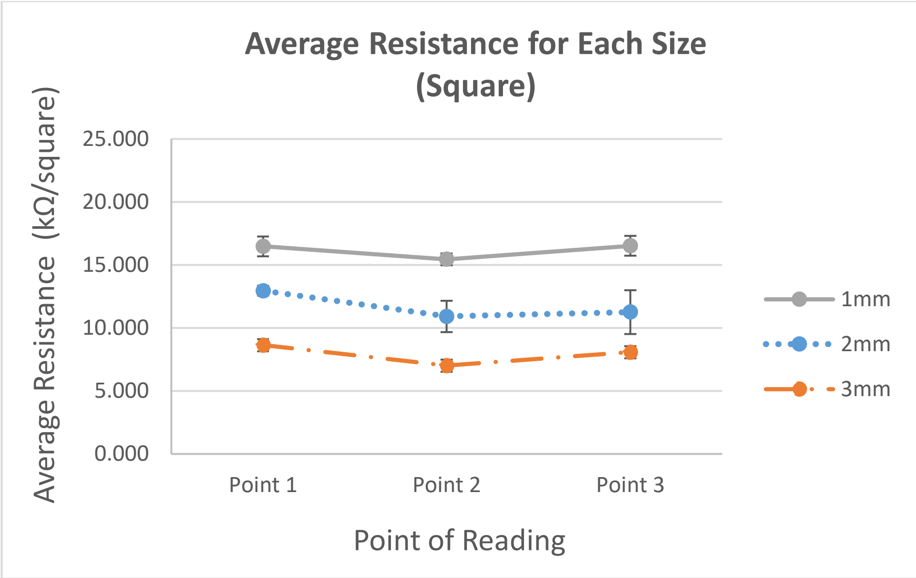


Figure 4. 7: Graph of Average Resistance between Sizes, 1mm, 2mm and 3mm for Temperature 100 ℃ Pattern Square

4.2.8 Sinusoidal for Temperature 100 °C

The result of the average resistance between three reading points was shown in Table 4.8 below and the reading was then formed in a graph style to make the data reading process easier. Figure 4.8 show the graph or average resistance between three sample of Sinusoidal pattern for 1 mm, 2 mm and 3 mm width.

Table 4. 8: Result of Average Resistance for Pattern Sinusoidal, Size 1 mm, 2mm and 3 mm for Temperature 100 °C

Pattern	Size	Point of Reading	Average Reading Resistance x 10^3 (Ω/sq)			Average Reading Resistance x 10^3 (Ω/sq)	Standard Deviation	Standard Error
			Sample 1	Sample 2	Sample 3			
Sinusoidal (P4)	1mm	Point 1	17.530	15.415	14.472	15.806	1.566	0.904
		Point 2	15.162	17.158	15.458	15.926	1.077	0.622
		Point 3	14.545	13.315	13.782	13.881	0.621	0.358
	2mm	Point 1	7.385	11.837	12.630	10.617	2.827	1.632
		Point 2	9.233	14.025	13.160	12.139	2.554	1.475
		Point 3	12.271	12.514	11.471	12.085	0.546	0.315
	3mm	Point 1	11.280	11.547	5.485	9.437	3.425	1.978
		Point 2	6.226	7.560	4.686	6.157	1.438	0.830
		Point 3	8.976	7.976	7.495	8.149	0.755	0.436

Figure 4.8 show the result of average resistance for sample size 1 mm, 2 mm and 3 mm for sinusoidal pattern that were cure under temperature 100 °C. The graph show that 3 mm width get the lowest value of resistance compare to the other size, thus it can be concluded that 3 mm had the lowest voltage also and highest current flow. It can be proved by using V=IR formula.

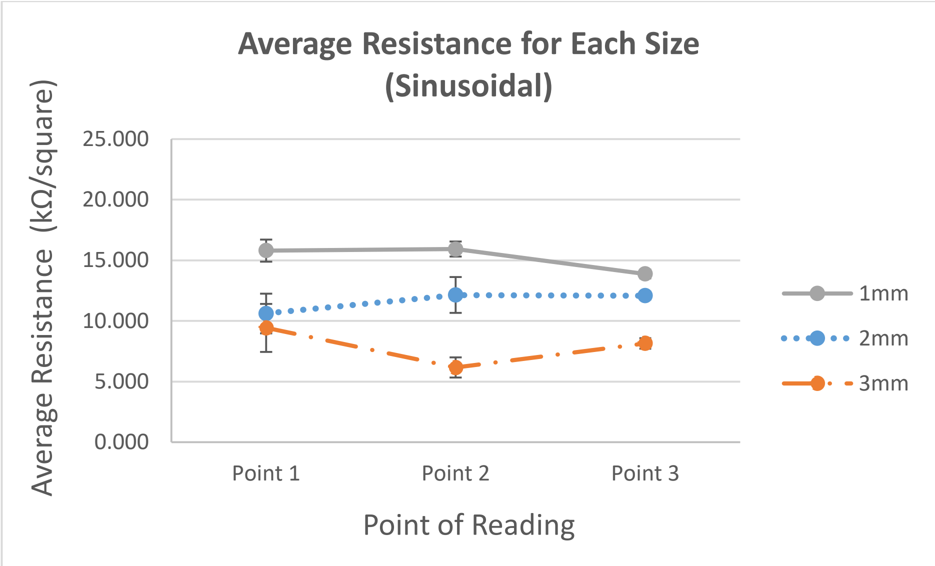


Figure 4. 8: Graph of Average Resistance between Sizes, 1mm, 2mm and 3mm for Temperature 100 °C, Pattern Sinusoidal

4.2.9 Straight Line for Temperature 110 ℃

Table 4.9 show the result of average resistance for pattern straight line with size of 2 mm and 3 mm for temperature 110 ℃ while the results for width 1 mm are shown N/A which is not applicable because the samples could not be prepared due to the Movement Control Order for covid-19 issue. The resistivity of this sample were measured using four-point probe. Figure 4.9 show the graph of average resistance between sample 1, sample 2 and sample 3 for 2 mm and 3 mm size for straight line pattern.

Table 4. 9: Result of Average Resistance for Pattern Straight Line, Size 2mm and 3 mm for Temperature 110 ℃

Pattern	Size	Point of Reading	Average Reading Resistance x 10^3 (Ω/sq)			Average Reading Resistance x 10^3 (Ω/sq)	Standard Deviation	Standard Error
			Sample 1	Sample 2	Sample 3			
Straight Line (P1)	1mm	Point 1	N/A	N/A	N/A	N/A	N/A	N/A
		Point 2	N/A	N/A	N/A	N/A	N/A	N/A
		Point 3	N/A	N/A	N/A	N/A	N/A	N/A
	2mm	Point 1	4.452	4.609	6.409	5.157	1.087	0.628
		Point 2	2.983	4.649	5.016	4.216	1.084	0.626
		Point 3	3.700	5.033	5.966	4.900	1.139	0.658
	3mm	Point 1	5.485	6.844	4.138	5.489	1.353	0.781
		Point 2	4.686	6.941	5.325	5.651	1.162	0.671
		Point 3	7.495	5.065	6.836	6.465	1.257	0.726

Result for average resistivity for sample pattern straight line with the width 2 mm and 3 mm are shown in a graph on Figure 4.9 below. The graph show 3 mm width has larger resistivity compare to 2 mm width. The error bar at each reading point is quite large. Therefore, it means that there is a high possibility of error occurring at that point.

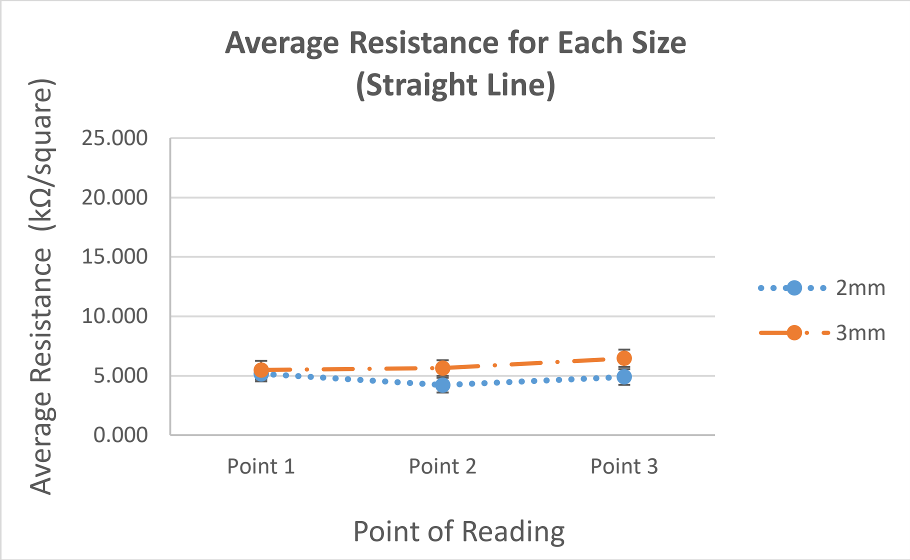


Figure 4. 9: Graph of Average Resistance between Sizes, 2mm and 3mm for Temperature 110 °C, Pattern Straight Line

4.2.10 Zig Zag for Temperature 110 ℃

Table 4.10 displays the value of the average resistance of the Zig Zag pattern with the width of 1 mm, 2 mm and 3 mm. The graph was clearly created to make it easier to understand the data. The average resistance for sample width 1 mm, 2 mm and 3 mm of the Zig Zag pattern are shown in Figure 4.10.

Table 4. 10: Result of Average Resistance for Pattern Zig Zag, Size 1 mm, 2mm and 3 mm for Temperature 110 ℃

Pattern	**Size**	**Point of Reading**	**Average Reading Resistance x 10^3 (Ω/sq)**			**Average Reading Resistance x 10^3 (Ω/sq)**	**Standard Deviation**	**Standard Error**
			Sample 1	**Sample 2**	**Sample 3**			
Zig Zag (P2)	1mm	Point 1	18.551	17.478	16.681	17.570	0.939	0.542
		Point 2	19.721	19.064	19.706	19.497	0.375	0.216
		Point 3	17.292	17.532	17.128	17.318	0.203	0.117
	2mm	Point 1	14.508	13.985	10.291	12.928	2.298	1.327
		Point 2	9.588	14.164	21.940	15.231	6.245	3.606
		Point 3	14.265	11.501	16.561	14.109	2.534	1.463
	3mm	Point 1	6.794	4.196	6.844	5.945	1.514	0.874
		Point 2	7.636	5.802	11.274	8.237	2.786	1.608
		Point 3	13.444	14.328	9.065	12.279	2.819	1.627

Figure 4.10 show the result of average resistance for size 1 mm, 2 mm and 3 mm of zig zag pattern in the form of graph. The graph show point 1 of 3 mm width get the lowest sheet resistivity which is 5.945 kΩ/sq. By general, the error bar shows that a larger amount of error is likely to occur at point 2 of 2 mm. Thus that point has the highest possibility of error occur.

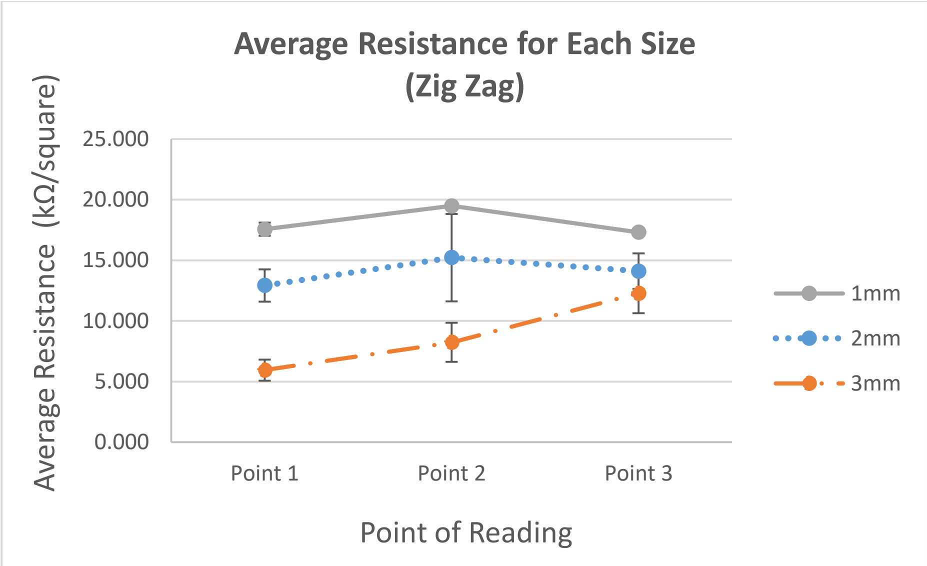


Figure 4. 10: Graph of Average Resistance between Sizes, 1mm, 2mm and 3mm for Temperature 110 ℃, Pattern Zig Zag

4.2.11 Square for Temperature 110 °C

Table 4.11 shows the result of the average resistivity of the square pattern within three size, 1 mm, 2 mm and 3 mm. The results are converted into a graph in order to ease the process of understanding the data. So, the graph was shown below in Figure 4.11.

Table 4. 11: Result of Average Resistivity for Pattern Square, Size 1 mm, 2mm and 3 mm for Temperature 110 °C

Pattern	**Size**	**Point of Reading**	**Average Reading Resistance x 10^3 (Ω/square)**			**Average Reading Resistance x 10^3 (Ω/sq)**	**Standard Deviation**	**Standard Error**
			Sample 1	**Sample 2**	**Sample 3**			
Square (P3)	1mm	Point 1	11.905	10.588	12.758	11.750	1.094	0.631
		Point 2	12.845	15.501	12.878	13.742	1.524	0.880
		Point 3	8.727	14.379	10.461	11.189	2.896	1.672
	2mm	Point 1	8.106	11.654	11.163	10.308	1.922	1.110
		Point 2	6.297	8.548	9.282	8.042	1.555	0.898
		Point 3	8.538	5.318	9.230	7.695	2.088	1.206
	3mm	Point 1	4.536	7.283	7.622	6.480	1.692	0.977
		Point 2	4.429	7.028	12.268	7.908	3.993	2.305
		Point 3	3.337	4.976	3.499	3.937	0.903	0.521

The graph of average resistance for sample square pattern for 110 °C temperature at Figure 4.11 show that point 2 of 2 mm and 3 mm have very close reading which is the resistivity for point 2 size 2 mm was 8.042 kΩ/square, while the resistivity for point 2 size 3 mm was 7.908 kΩ/square. The error bar at point 2 of 3 mm shows quite large range, so the possibility of error occur for this point is higher.

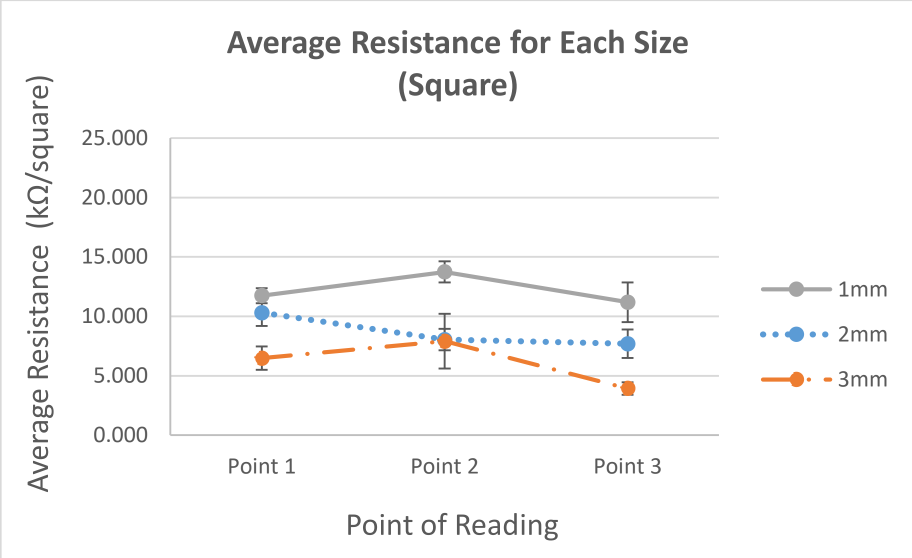


Figure 4. 11: Graph of Average Resistance between Sizes, 1mm, 2mm and 3mm for Temperature 110 ℃ for Square Pattern

4.2.12 Sinusoidal for Temperature 110 ℃

Table 4.12 show the result of resistance for sinusoidal sample with the size of 1 mm, 2 mm and 3 mm. While Figure 4.12 show the graph result from the data at Table 4.12.

Table 4. 12: Result of Average Resistance for Pattern Sinusoidal, Size 1 mm, 2mm and 3 mm for Temperature 110 ℃

Pattern	Size	Point of Reading	Average Reading Resistance x 10^3 (Ω/sq)			Average Reading Resistance x 10^3 (Ω/sq)	Standard Deviation	Standard Error
			Sample 1	Sample 2	Sample 3			
Sinusoidal (P4)	1mm	Point 1	12.522	13.822	13.568	13.304	0.689	0.398
		Point 2	13.310	12.710	12.603	12.874	0.381	0.220
		Point 3	12.207	10.407	11.773	11.462	0.939	0.542
	2mm	Point 1	5.965	6.346	8.898	7.070	1.595	0.921
		Point 2	7.066	9.215	8.224	8.168	1.075	0.621
		Point 3	11.992	10.211	10.751	10.985	0.913	0.527
	3mm	Point 1	3.610	6.580	8.495	6.229	2.461	1.421
		Point 2	3.766	3.717	4.557	4.013	0.471	0.272
		Point 3	4.986	6.220	6.237	5.814	0.717	0.414

Figure 4.12 show the result of average resistance for sample size 1 mm, 2 mm and 3 mm for sinusoidal pattern that were cure under temperature 110 ℃. The graph show that 3 mm width get the lowest value of resistance compare to the other size, thus 3 mm had the lowest voltage also and highest current flow. It can be proved by using V=IR formula. When the resistivity is high, the voltage also high but the current will reduce, I = V/R.

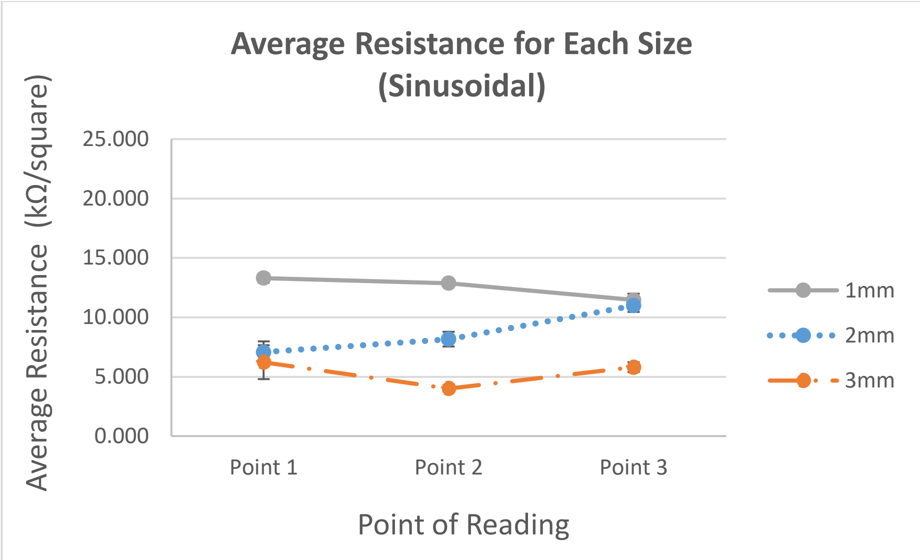


Figure 4. 12: Graph of Average Resistance between Sizes, 1mm, 2mm and 3mm for Temperature 110 ℃, Pattern Sinusoidal

4.3 Four-Point Probe (Voltage)

The sample voltage was measured using a four-point probe device and the data was read repeatedly for three times. The average resistance of the three readings was included in this sub-topic. The data was included in the form of a table and graph. Graph has been produced to make the process of understanding the data easier.

Formula for Voltage is

$$V = IR \tag{4.1}$$

Where V is Voltage (V), I is current (A), R is Resistance (Ω)

According to Eq. (4.1), voltage will increase due to the increasing of current or resistance in the sheet, while will decrease with the decreasing of the resistance.

Some of the data may display N/A which is not applicable result. This is because the sample or experiment cannot be prepared dude to the issue of Movement Control Order (MCO) for Covid -19 case.

4.3.1 Straight Line for Temperature 90 ℃

Table 4.13 show the result of average voltage for straight line pattern with 2 mm and 3 mm width for temperature 90 ℃. While the results for width 1 mm are shown N/A which is not applicable because the samples could not be prepared due to the movement control order for covid-19 issue. The graph from the result was shown in Figure 4.13 below.

Table 4. 13: Result of Average Voltage for Pattern Straight Line, Size 2mm and 3 mm for Temperature 90 ℃

Pattern	**Size**	**Point of Reading**	**Average Reading Voltage**			**Average Reading Voltage (mV)**	**Standard Deviation**	**Standard Error**
			Sample 1	**Sample 2**	**Sample 3**			
Straight Line (P1)	1mm	Point 1	N/A	N/A	N/A	N/A	N/A	N/A
		Point 2	N/A	N/A	N/A	N/A	N/A	N/A
		Point 3	N/A	N/A	N/A	N/A	N/A	N/A
	2mm	Point 1	17.02	27.58	28.08	24.23	6.25	3.61
		Point 2	8.51	23.66	21.43	17.87	8.18	4.72
		Point 3	15.51	35.58	26.16	25.75	10.04	5.80
	3mm	Point 1	39.18	32.32	50.08	40.53	8.96	5.17
		Point 2	26.72	35.69	21.18	27.86	7.32	4.23
		Point 3	32.05	33.36	16.19	27.20	9.56	5.52

Figure 4.13 show the graph of average voltage between sample for straight line pattern with the size 2 mm and 3 mm. From the graph, 3 mm width has the larger amount of voltage compare to 2 mm width. The graph also indicates a sample width of 3 mm and 2 mm has a wide range of error bars. It indicates, thus, that those readings have a high possibility of error.

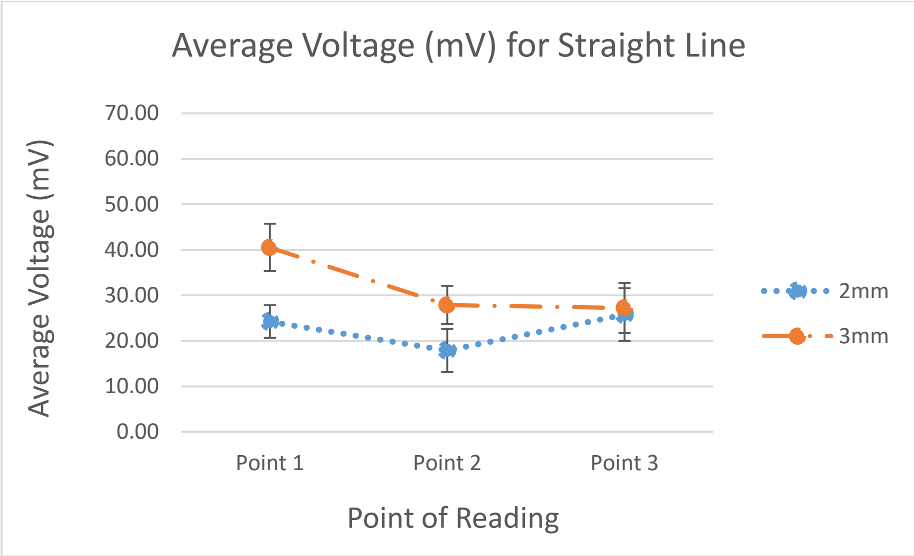


Figure 4. 13: Graph of Average Voltage between Sizes, 2mm and 3mm for Temperature 90 °C for Pattern Straight Line

4.3.2 Zig Zag for Temperature 90 ℃

Table 4.14 show the result of average voltage for zig zag pattern with 1 mm, 2 mm and 3 mm width. The graph from the result was shown in Figure 4.14 below.

Table 4. 14: Result of Average Voltage for Pattern Zig Zag, Size 1 mm, 2mm and 3 mm for Temperature 90 ℃

Pattern	**Size**	**Point of Reading**	**Average Reading Voltage (mV)**			**Average Reading Voltage (mV)**	**Standard Deviation**	**Standard Error**
			Sample 1	**Sample 2**	**Sample 3**			
Zig Zag (P2)	1mm	Point 1	61.64	59.45	65.59	62.23	3.12	1.80
		Point 2	60.89	56.23	60.56	59.22	2.60	1.50
		Point 3	62.06	62.82	66.43	63.77	2.34	1.35
	2mm	Point 1	52.00	52.05	51.98	52.01	0.03	0.02
		Point 2	50.02	53.33	55.91	53.09	2.95	1.70
		Point 3	50.75	55.53	52.61	52.96	2.41	1.39
	3mm	Point 1	44.87	40.47	50.37	45.24	4.96	2.86
		Point 2	39.70	46.41	30.62	38.91	7.92	4.57
		Point 3	46.34	46.43	54.79	49.19	4.85	2.80

From the observation for the graph in Figure 4.14, the graph shows a pattern of voltage at each point of each size are almost same. Sample for size 1 mm has the highest voltage for all three point of reading. While sample for size 3 mm has the lowest reading for all point of reading. The highest voltage for sample pattern zig zag for temperature 90 ℃ is 63.77 mV, at point 3 of 1 mm size while the lowest voltage is 38.91 mV, at point 2 of 3 mm size.

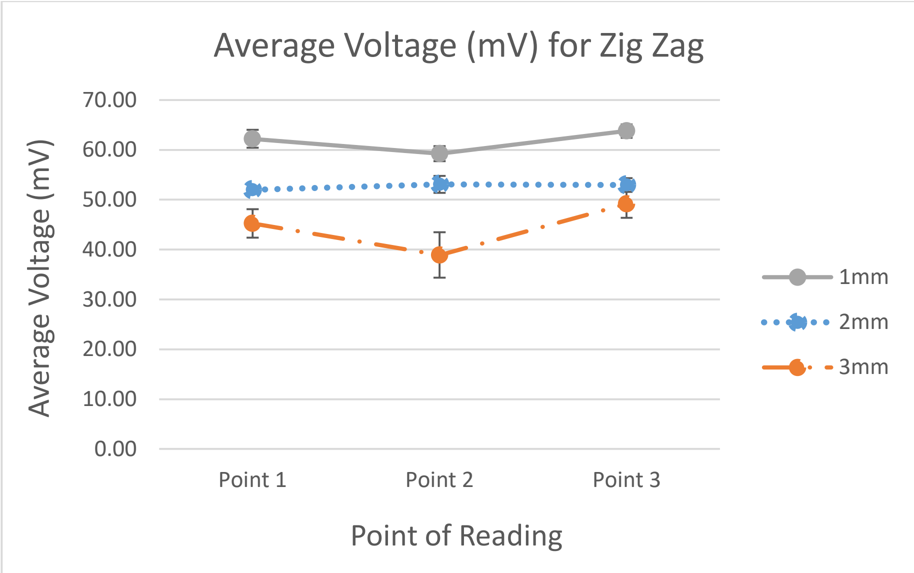


Figure 4. 14: Graph of Average Voltage between Sizes, 1mm, 2mm and 3mm for Temperature 90 °C for Pattern Zig Zag

4.3.3 Square for Temperature 90 °C

Table 4.15 show the result of average voltage for square pattern with 1 mm, 2 mm and 3 mm width. The graph for this voltage was shown below in Figure 4.15.

Table 4. 15: Result of Average Voltage for Pattern Square, Size 1 mm, 2mm and 3 mm for Temperature 90 °C

Pattern	**Size**	**Point of Reading**	**Average Reading Voltage (mV)**			**Average Reading Voltage (mV)**	**Standard Deviation**	**Standard Error**
			Sample 1	**Sample 2**	**Sample 3**			
Square (P3)	1mm	Point 1	41.03	51.03	45.43	45.83	5.01	2.89
		Point 2	51.08	47.22	48.15	48.82	2.02	1.16
		Point 3	45.06	44.94	44.28	44.76	0.42	0.24
	2mm	Point 1	37.07	37.05	48.89	41.00	6.83	3.95
		Point 2	19.82	22.25	33.29	25.12	7.18	4.14
		Point 3	30.16	38.73	36.27	35.05	4.41	2.55
	3mm	Point 1	22.82	25.94	28.61	25.79	2.90	1.67
		Point 2	27.74	25.70	29.34	27.59	1.83	1.05
		Point 3	18.18	15.46	31.68	21.77	8.69	5.01

Figure 4.15 displays the voltage graph between average three samples for a square pattern with a width of 1 mm, 2 mm and 3 mm. This graph shows that sample with width 1 mm has the highest voltage amongst the 3 width. Reading of average voltage at point 2 of sample size 2 mm show that it has lower voltage compare to point 2 at 3 mm. The maximum voltage for the sample square for temperature 90 °C is 48.82 mV at point 2 of the sample size 1 mm while the lowest voltage value is 21.77 mV at point 3 of the sample size 3 mm.

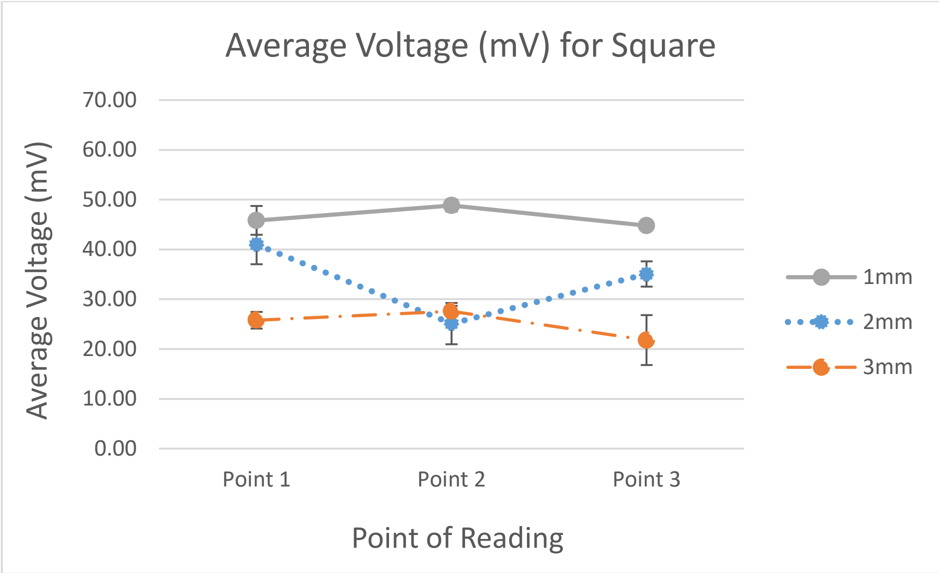


Figure 4. 15: Graph of Average Voltage between Sizes, 1mm, 2mm and 3mm for Temperature 90 °C for Pattern Square

4.3.4 Sinusoidal for Temperature 90 ℃

Table 4.16 show the average voltage for sinusoidal pattern with size 1 mm, 2 mm and 3 mm width. The graph obtain from this result was shown in Figure 4.16.

Table 4. 16: Result of Average Voltage for Pattern Sinusoidal, Size 1 mm, 2mm and 3 mm for Temperature 90 ℃

Pattern	**Size**	**Point of Reading**	**Average Reading Voltage (mV)**			**Average Reading Voltage (mV)**	**Standard Deviation**	**Standard Error**
			Sample 1	**Sample 2**	**Sample 3**			
Sinusoidal (P4)	1mm	Point 1	46.82	36.82	42.82	42.15	5.03	2.91
		Point 2	41.86	31.86	45.20	39.64	6.94	4.01
		Point 3	47.19	30.53	40.53	39.42	8.39	4.84
	2mm	Point 1	31.16	27.16	31.32	29.88	2.36	1.36
		Point 2	32.92	37.58	33.93	34.81	2.45	1.42
		Point 3	36.75	37.08	34.20	36.01	1.58	0.91
	3mm	Point 1	10.55	26.56	18.29	18.47	8.01	4.62
		Point 2	16.47	24.73	18.54	19.91	4.30	2.48
		Point 3	14.65	20.97	18.23	17.95	3.17	1.83

Figure 4.16 shows the average voltage between samples with a sinusoidal pattern of 1 mm, 2 mm and 3 mm size. The graph shows a close range of values between the 1 mm and 2 mm size, wide range of value between 2 mm and 3 mm size. The reading of 3 mm size indicates the lowest voltage between those three sample size. Most of the error bar indicating a low value due to the small gap between the voltage test. Therefore, those samples have lower error occurs.

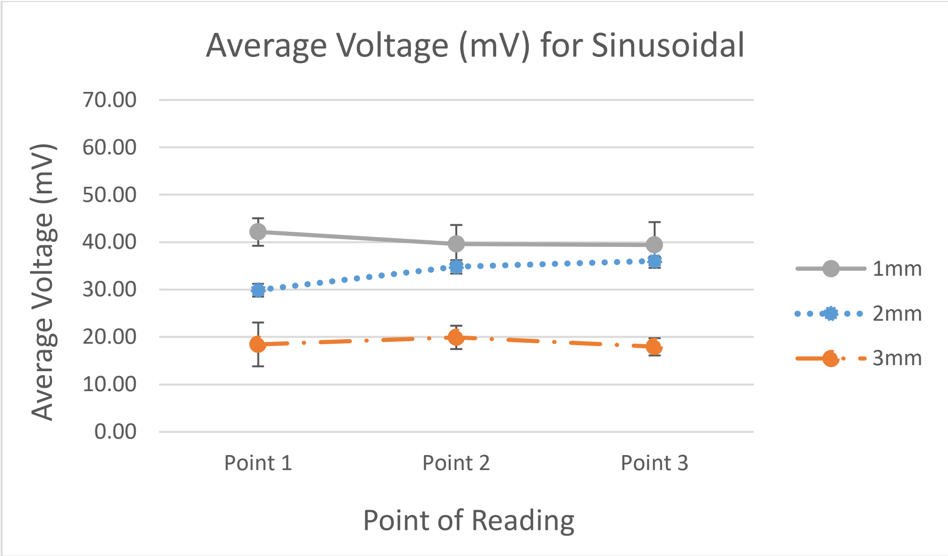


Figure 4. 16: Graph of Average Voltage between Sizes, 1mm, 2mm and 3mm for Temperature 90 °C for Pattern Sinusoidal

4.3.5 Straight Line for Temperature 100 ℃

The average voltage of pattern of straight line for curing temperature 100 ℃ was shown in Table 4.17 below. There is only result for 3 mm size, meanwhile the result for 1 mm and 2 mm size cannot be prepared due to the current situation now with Movement Control Order (MCO). The result was shown in graph on Figure 4.17 below.

Table 4. 17: Result of Average Voltage for Pattern Straight Line, Size 3 mm for Temperature 100 ℃

Pattern	Size	Point of Reading	Average Reading Voltage			Average Reading Voltage (mV)	Standard Deviation	Standard Error
			Sample 1	Sample 2	Sample 3			
Straight Line (P1)	1mm	Point 1	N/A	N/A	N/A	N/A	N/A	N/A
		Point 2	N/A	N/A	N/A	N/A	N/A	N/A
		Point 3	N/A	N/A	N/A	N/A	N/A	N/A
	2mm	Point 1	N/A	N/A	N/A	N/A	N/A	N/A
		Point 2	N/A	N/A	N/A	N/A	N/A	N/A
		Point 3	N/A	N/A	N/A	N/A	N/A	N/A
	3mm	Point 1	27.36	25.18	18.81	23.78	4.45	18.81
		Point 2	23.73	23.12	19.28	22.04	2.41	19.28
		Point 3	24.08	23.84	19.06	22.32	2.83	19.06

Figure 4.17 show the graph of average voltage for size 3 mm width for pattern straight line that was cure under temperature 100 ℃. Graph line for 1 mm and 2 mm width cannot be plotted due to no result obtained. The result show point 1 has the highest voltage which is 23.78 mV while the average voltage for point 2 and 3 are almost same lies on the 22 mV.

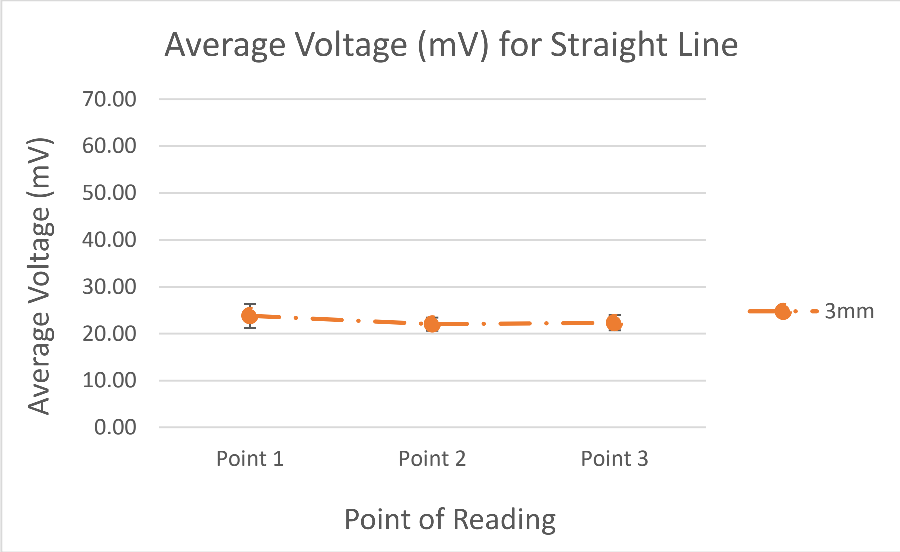


Figure 4. 17: Graph of Average Voltage for Size 3mm for Temperature 100 °C for Pattern Straight Line

4.3.6 Zig Zag for Temperature 100 °C

Table 4.18 show the result of average voltage for zig zag pattern with 1 mm, 2 mm and 3 mm width for temperature 100 °C. The graph from the result was shown in Figure 4.18 below.

Table 4. 18: Result of Average Voltage for Pattern Zig Zag, Size 1 mm, 2mm and 3 mm for Temperature 100 °C

Pattern	Size	Point of Reading	Average Reading Voltage (mV)			Average Reading Voltage (mV)	Standard Deviation	Standard Error
			Sample 1	Sample 2	Sample 3			
Zig Zag (P2)	1mm	Point 1	40.12	46.81	44.82	43.92	3.44	1.99
		Point 2	45.31	41.32	48.41	45.01	3.55	2.05
		Point 3	50.58	45.13	49.62	48.44	2.91	1.68
	2mm	Point 1	35.81	39.58	35.31	36.90	2.33	1.35
		Point 2	37.09	47.16	38.03	40.76	5.57	3.21
		Point 3	32.80	37.06	37.67	35.85	2.65	1.53
	3mm	Point 1	25.49	27.71	28.21	27.14	1.45	0.84
		Point 2	30.86	29.88	29.69	30.14	0.63	0.36
		Point 3	34.48	33.22	35.45	34.38	1.12	0.65

Figure 4.18 show the graph of average voltage between sample for zigzag pattern with the size 1 mm, 2 mm and 3 mm. The graph show sample size 3 mm has smallest range of error bar between those three sample size. Therefore, it shows that 3 mm size has the precisely result compare to 1 mm and 2 mm.

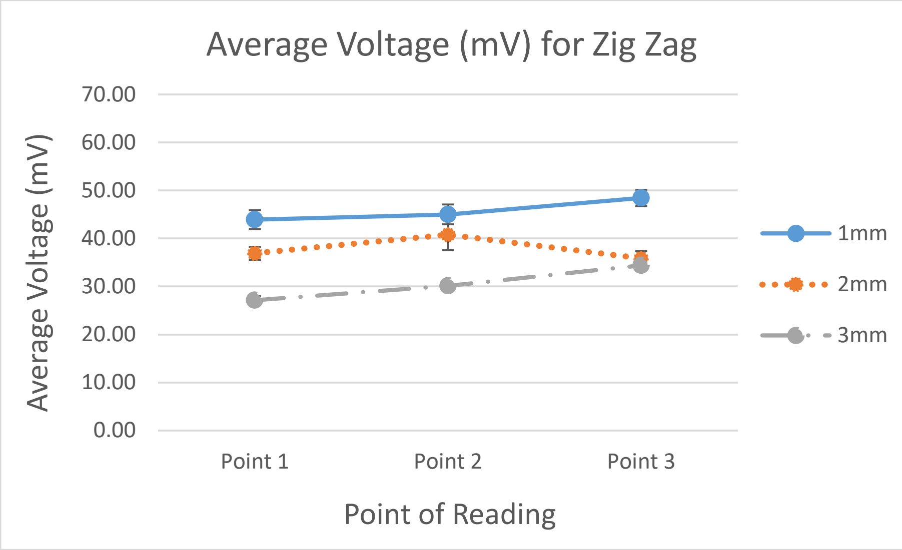


Figure 4. 18: Graph of Average Voltage between Sizes, 1mm, 2mm and 3mm for Temperature 100 °C for Pattern Zig Zag

4.3.7 Square for Temperature 100 ℃

Table 4.19 show the result of average voltage for square pattern with 1 mm, 2 mm and 3 mm width for temperature 100 ℃. The graph from the result was shown in Figure 4.19 below.

Table 4. 19: Result of Average Voltage for Pattern Square Size 1 mm, 2mm and 3 mm for Temperature 100 ℃

Pattern	Size	Point of Reading	Average Reading Voltage (mV)			Average Reading Voltage (mV)	Standard Deviation	Standard Error
			Sample 1	Sample 2	Sample 3			
Square (P3)	1mm	Point 1	30.04	31.13	34.74	31.97	2.46	1.42
		Point 2	30.35	30.12	38.75	33.07	4.92	2.84
		Point 3	31.79	30.13	36.70	32.87	3.42	1.97
	2mm	Point 1	18.62	29.39	27.57	25.19	5.76	3.33
		Point 2	19.48	24.74	24.89	23.04	3.08	1.78
		Point 3	22.07	19.65	24.60	22.11	2.47	1.43
	3mm	Point 1	10.01	16.07	16.82	14.30	3.73	2.16
		Point 2	9.77	15.51	27.07	17.45	8.81	5.09
		Point 3	17.36	20.98	17.72	18.69	1.99	1.15

Figure 4.19 show the graph of average voltage between size for zigzag pattern. The graph show 1 mm has the highest voltage while 3 mm has the lowest voltage reading. Besides, the graph also shows that the smaller the width of conductive ink, the higher the voltage can occur at the ink. From the graph, the error bar for point 2 of sample size 3 mm width show the biggest gap compare to the other error bar. Therefore, point 2 at 3 mm size show the reading have highest potential of error.

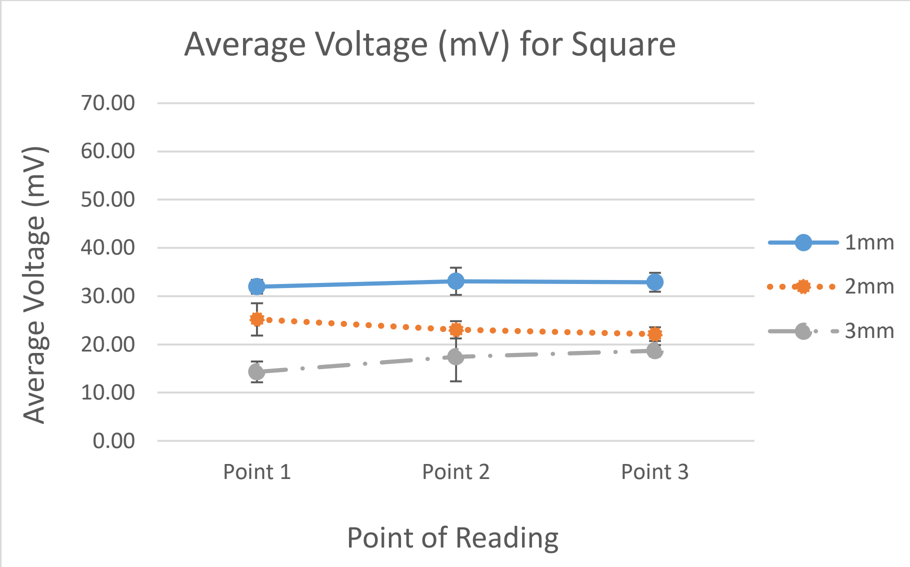


Figure 4. 19: Graph of Average Voltage between Sizes, 1mm, 2mm and 3mm for Temperature 100 °C for Square Pattern

4.3.8 Sinusoidal for Temperature 100 °C

Table 4.20 show the result of average voltage for sinusoidal pattern with 1 mm, 2 mm and 3 mm width for temperature 100 °C. The graph from the result was shown in Figure 4.20 below.

Table 4. 20: Result of Average Voltage for Pattern Sinusoidal Size 1 mm, 2mm and 3 mm for Temperature 100 °C

Pattern	**Size**	**Point of Reading**	**Average Reading Voltage (mV)**			**Average Reading Voltage (mV)**	**Standard Deviation**	**Standard Error**
			Sample 1	**Sample 2**	**Sample 3**			
Sinusoidal (P4)	1mm	Point 1	31.66	34.39	30.33	32.12	2.07	1.19
		Point 2	30.26	32.10	31.30	31.22	0.92	0.53
		Point 3	30.32	34.86	29.10	31.43	3.03	1.75
	2mm	Point 1	16.29	26.12	32.28	24.90	8.06	4.65
		Point 2	11.55	30.94	29.04	23.84	10.69	6.17
		Point 3	11.63	27.61	25.31	21.52	8.64	4.99
	3mm	Point 1	7.97	14.52	18.74	13.74	5.43	3.14
		Point 2	8.31	8.20	10.05	8.85	1.04	0.60
		Point 3	11.00	13.72	13.76	12.83	1.58	0.91

Graph of average voltage between three size for square pattern was shown in Figure 4.20 below. The graph show sample for 2 mm width has the biggest gap of error bar for every point of reading. Thus, it shows that sample 2 mm has the most potential of error occur.

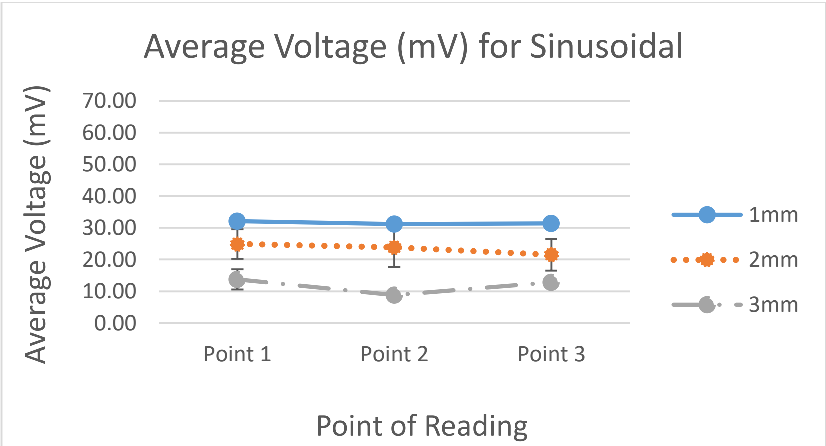


Figure 4. 20: Graph of Average Voltage between Sizes, 1mm, 2mm and 3mm for Temperature 100 °C for Sinusoidal Pattern

4.3.9 Straight Line for Temperature 110 ℃

Table 4.21 show the result of average voltage for sinusoidal pattern with 2 mm and 3 mm width for temperature 110 ℃. While the results for width 1 mm are shown N/A which is not applicable because the samples could not be prepared due to the movement control order for covid-19 issue. The graph from the result was shown in Figure 4.21 below.

Table 4. 21: Result of Average Voltage for Pattern Straight Line Size 2mm and 3 mm for Temperature 110 ℃

Pattern	**Size**	**Point of Reading**	**Average Reading Voltage (mV)**			**Average Reading Voltage (mV)**	**Standard Deviation**	**Standard Error**
			Sample 1	**Sample 2**	**Sample 3**			
Straight Line (P1)	1mm	Point 1	N/A	N/A	N/A	N/A	N/A	N/A
		Point 2	N/A	N/A	N/A	N/A	N/A	N/A
		Point 3	N/A	N/A	N/A	N/A	N/A	N/A
	2mm	Point 1	9.82	21.02	19.17	16.67	6.00	3.47
		Point 2	6.58	11.49	21.22	13.10	7.45	4.30
		Point 3	8.16	13.38	16.42	12.66	4.18	2.41
	3mm	Point 1	3.52	6.47	6.92	5.64	1.85	1.07
		Point 2	6.66	10.19	7.34	8.06	1.88	1.08
		Point 3	2.27	9.50	10.67	7.48	4.55	2.63

The graph of average voltage between sizes, 2 mm and 3 mm of straight line pattern for curing temperature 110 ℃ are shown in graph on Figure 4.21 below. From the graph, it shows that the error bar range at the 2 mm size is very wide. Therefore, the error occurs between the reading of the three samples is bigger and the result can even be inaccurate due to the chance of error occurring during the reading.

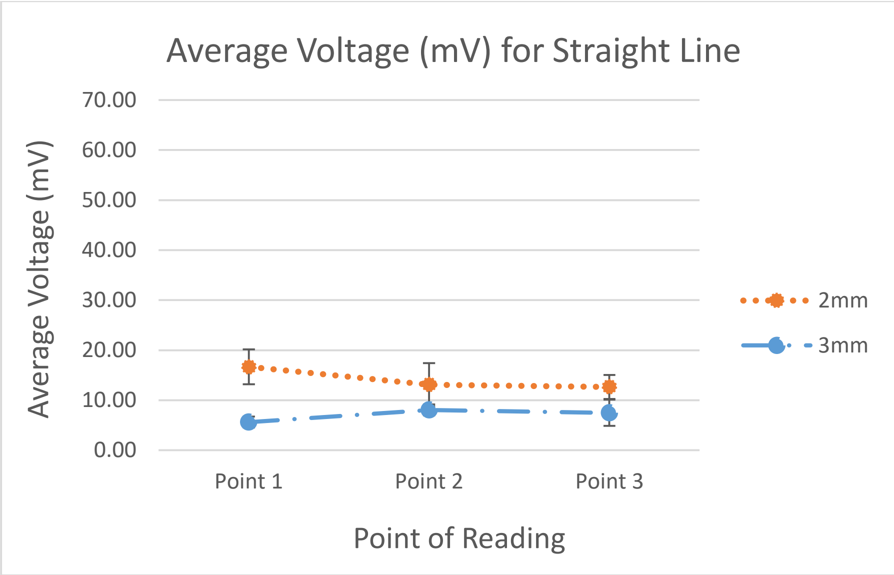


Figure 4. 21: Graph of Average Voltage between Sizes, 2mm and 3mm for Temperature 110 °C for Straight Line Pattern

4.3.10 Zig Zag for Temperature 110 ℃

Table 4.22 show the result of average voltage for zig zag pattern with 1 mm, 2 mm and 3 mm width for temperature 110 ℃. The graph from the result was shown in Figure 4.22 below.

Table 4. 22: Result of Average Voltage for Pattern Zig Zag Size 1 mm, 2mm and 3 mm for Temperature 110 ℃

Pattern	**Size**	**Point of Reading**	**Average Reading Voltage (mV)**			**Average Reading Voltage (mV)**	**Standard Deviation**	**Standard Error**
			Sample 1	**Sample 2**	**Sample 3**			
Zig Zag (P2)	1mm	Point 1	35.43	32.25	37.70	35.13	2.74	1.58
		Point 2	31.30	34.44	32.36	32.70	1.60	0.92
		Point 3	37.35	34.18	35.43	35.65	1.60	0.92
	2mm	Point 1	29.95	18.79	27.96	25.57	5.95	3.44
		Point 2	25.77	29.19	26.06	27.01	1.89	1.09
		Point 3	19.41	22.80	24.48	22.23	2.58	1.49
	3mm	Point 1	28.23	19.26	15.10	20.86	6.71	3.87
		Point 2	20.45	12.80	24.88	19.37	6.11	3.53
		Point 3	16.78	9.55	11.17	12.50	3.79	2.19

Figure 4.22 show the graph of the average voltage between sample sizes 1 mm, 2 mm and 3 mm for curing temperature 110 ℃. The observation can be made from this graph is 1 mm size has the smallest gap of error bar, thus the result from the 3 samples reading of 1 mm sizes has the least error compare to the 2 mm and 3 mm sizes. Meanwhile, the 3 mm sizes have the biggest gap of error bar, therefore reading between 3 samples of size 3 mm have the highest error among those three sizes.

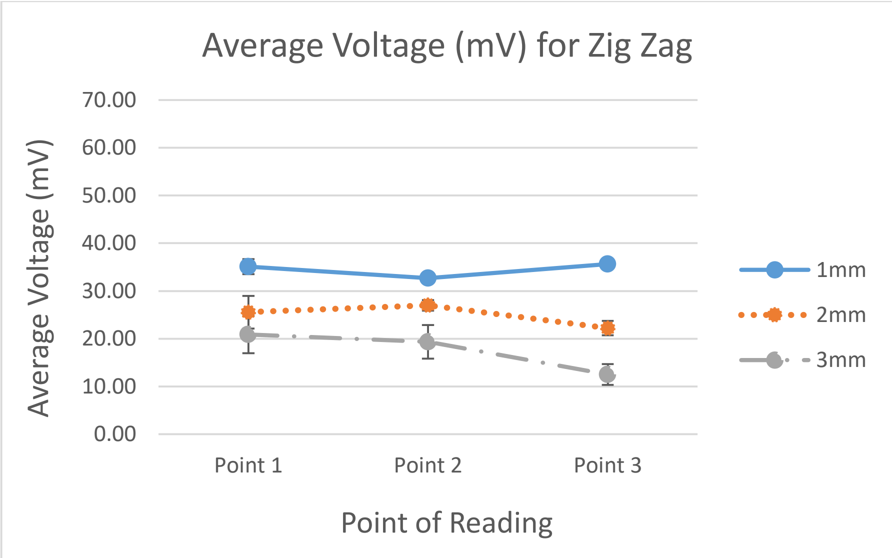


Figure 4. 22: Graph of Average Voltage between Sizes, 1mm, 2mm and 3mm for Temperature 110 ℃ for Zig Zag Pattern

4.3.11 Square for Temperature 110 ℃

Table 4.23 show the result of average voltage for square pattern with 1 mm, 2 mm and 3 mm width for temperature 110 ℃. The graph from the result was shown in Figure 4.23 below.

Table 4. 23: Result of Average Voltage for Pattern Square Size 1 mm, 2mm and 3 mm for Temperature 110 ℃

Pattern	Size	Point of Reading	Average Reading Voltage (mV)			Average Reading Voltage (mV)	Standard Deviation	Standard Error
			Sample 1	Sample 2	Sample 3			
Square (P3)	1mm	Point 1	20.38	22.34	25.25	22.66	2.45	1.41
		Point 2	29.80	25.11	27.76	27.56	2.35	1.36
		Point 3	28.12	28.98	23.75	26.95	2.80	1.62
	2mm	Point 1	15.70	14.16	14.83	14.90	0.77	0.45
		Point 2	19.59	11.51	19.76	16.95	4.72	2.72
		Point 3	14.50	13.70	25.04	17.75	6.33	3.65
	3mm	Point 1	11.81	13.07	10.71	11.86	1.18	0.68
		Point 2	11.39	11.21	11.59	11.40	0.19	0.11
		Point 3	16.41	15.61	16.19	16.07	0.41	0.24

Figure 4.23 show the graph of average voltage between three sizes of width, they are 1 mm, 2 mm and 3 mm. The result shown on the graph show that error bar at point 3 of 2 mm sizes have the biggest gap which is 3.65. Therefore, the possibility of error occurring is highest at that point. While the error bar at all point of sample 3 mm size have the smallest gap between those three sample sizes. Therefore, the sample for 3 mm has the least possibility of mistakes that occur.

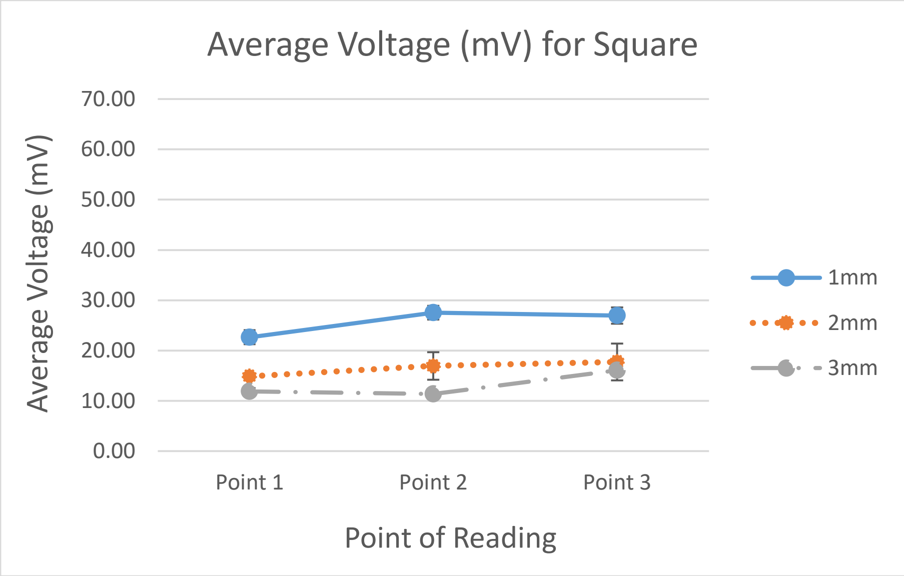


Figure 4. 23: Graph of Average Voltage between Sizes, 1mm, 2mm and 3mm for Temperature 110 °C for Square Pattern

4.3.12 Sinusoidal for Temperature 110 °C

Table 4.24 show the result of average voltage for sinusoidal pattern with 1 mm, 2 mm and 3 mm width for temperature 110 °C. The graph from the result was shown in Figure 4.24 below.

Table 4. 24: Result of Average Voltage for Pattern Sinusoidal Size 1 mm, 2mm and 3 mm for Temperature 110 °C

Pattern	**Size**	**Point of Reading**	**Average Reading Voltage (mV)**			**Average Reading Voltage (mV)**	**Standard Deviation**	**Standard Error**
			Sample 1	**Sample 2**	**Sample 3**			
Sinusoidal (P4)	1mm	Point 1	25.11	26.48	24.46	25.35	1.03	0.60
		Point 2	28.18	21.25	26.20	25.21	3.57	2.06
		Point 3	23.71	20.56	25.05	23.11	2.30	1.33
	2mm	Point 1	13.16	12.56	22.87	16.20	5.79	3.34
		Point 2	15.59	9.77	26.97	17.44	8.75	5.05
		Point 3	11.01	13.70	23.72	16.15	6.70	3.87
	3mm	Point 1	11.22	10.44	12.10	11.25	0.83	0.48
		Point 2	13.74	16.34	10.34	13.47	3.01	1.74
		Point 3	9.80	13.54	9.20	10.85	2.35	1.36

Figure 4.24 show the graph of average voltage between sizes, 1 mm, 2 mm and 3 mm of sinusoidal pattern for curing temperature 110 °C. From the graph, it shows that gap of error bar occur at 2 mm size is very large. Thus, the error occurs between reading of the three samples are bigger and the result may also inaccurate due to the possibility of error occurring at those reading.

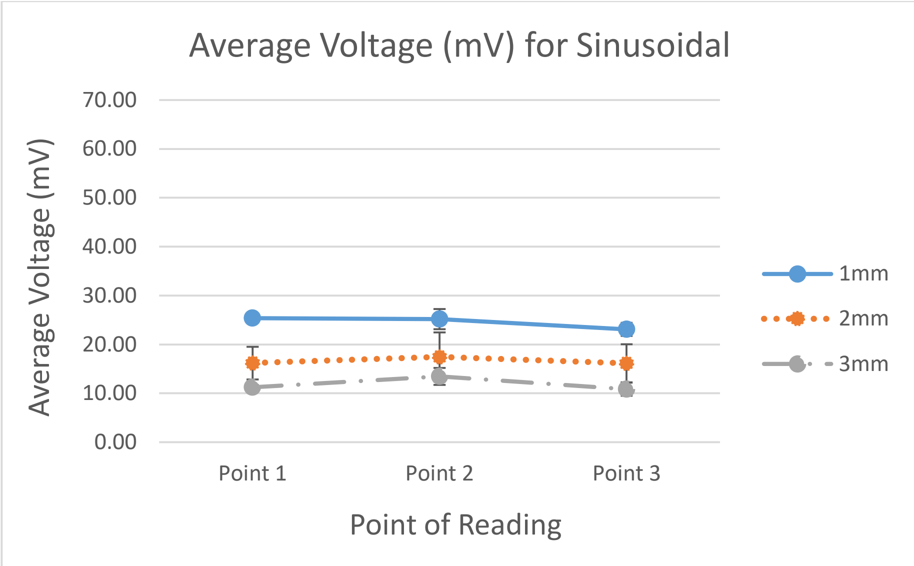


Figure 4. 24: Graph of Average Voltage between Sizes, 1mm, 2mm and 3mm for Temperature 110 °C for Sinusoidal Pattern

4.4 Relationship between Sheet Resistivity and Microscopy Image

This section presents the relationship between the microscopy image capture on the surface of the samples with the sheet resistivity occurs on the samples. of A comparison was made between the resistivity of each sample and the microscopy image. However, owing to the movement control order (MCO) due to the COVID-19 case, the microscopy image experiment could not be prepared for all three samples. Only sample 2 with a width of 2 mm and 3 mm has been done. Therefore, this section shows the correlation between the image of the microscopy and the resistivity of the sample 2. The graph of sheet resistivity sample 2 was also shown in this section. Each of the samples was labelled at three reading points on the substrate. This is because to ensure that every experiment was performed at the same place. The resistivity of the sample was taken at the three point and the microscopy image was also taken at the same point. Therefore, the correlation and relation between the image of the microscopy and the resistivity may be obtained.

In the microscopy image, the dark spot indicates the existence of the filler while the bright spot shows the binder. The amount of graphene on the sheet represented by the volume of the dark area. Epoxy is the binder for this conductive ink, meaning that the epoxy has a bright spot on the surface.

4.4.1 Straight Line Width 2 mm for Temperature 90 °C

Figure 4.25 show the graph of average resistivity for sample 2 for pattern straight line width 2 mm. The graph show point 2 has the lowest resistivity while point 3 has highest resistivity among those three points of reading.

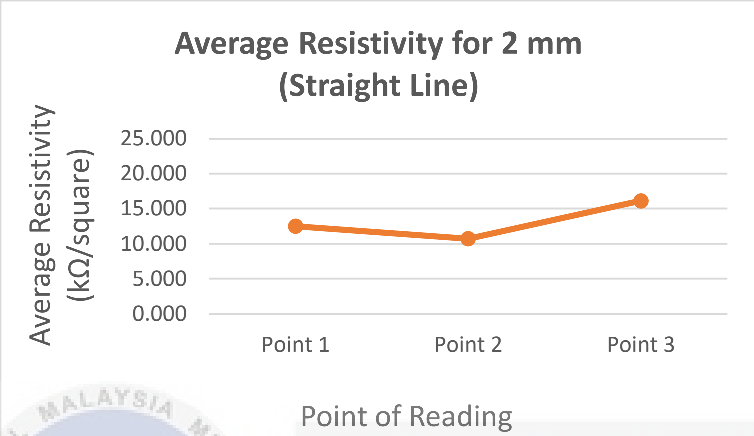
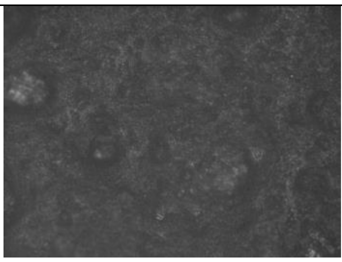
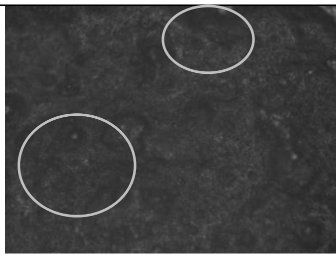
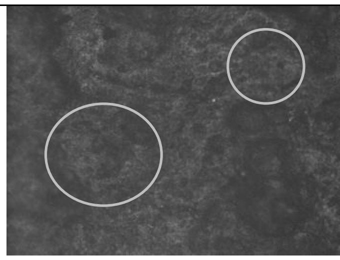


Figure 4. 25: Graph of Average Resistivity for Sample 2 Width 2 mm Pattern Straight Line

Table 4.25 show the microscopy image at three point of reading for sample 2 that was captured by light microscope device. The grey circle on point 2 show there is a large volume of dark area on the sample while at point 3 show the presence of more bright spot. Thus, point 2 has the greater amount of graphene while image at point 3 show there is a lot of epoxy on the sample. The relationship of the sheet resistivity with the surface of the sample can be seen through the graph and microscopy image. Sheet resistivity is higher at the point which have more epoxy and lower at point contains more graphene.

Table 4. 25: Microscopy Image for Sample 2 Width 2 mm Pattern Straight Line

Point 1	Point 2	Point 3
		

4.4.2 Straight Line Width 3 mm for Temperature 90 °C

Graph of average sheet resistivity for sample 2 pattern straight line with the width 3 mm was shown in Figure 4.26 below. The resistivity at point 1 is quite higher compared to point 2 and point 3. Meanwhile, at points 2 and 3, the result for the resistance of the sheet is quite similar.

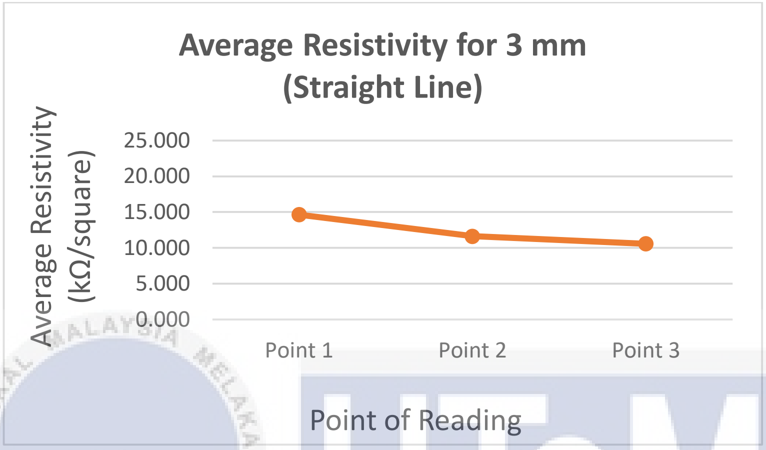
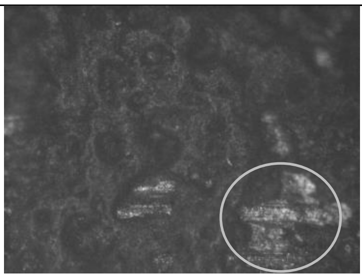
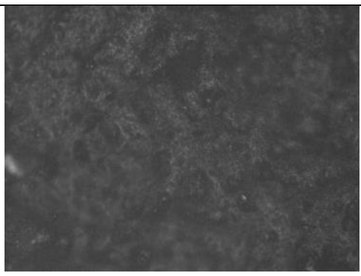
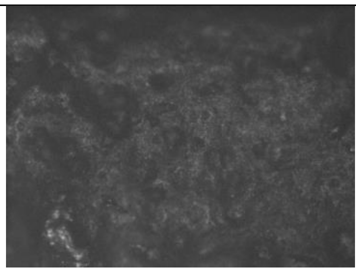


Figure 4. 26: Graph of Average Resistivity for Sample 2 Width 3 mm Pattern Straight Line

Table 4.26 show the microscopy image of each point for sample 2. The grey circle at point 1 show defect occurs at the sample. Meanwhile the microscopy image for point 2 and point 3 shows almost the same image with almost the same amount of graphene and epoxy in that area.

Table 4. 26: Microscopy Image for Sample 2 Width 3 mm Pattern Straight Line

Point 1	Point 2	Point 3
		

4.4.3 Zig Zag Width 2 mm for Temperature 90 °C

Figure 4.27 show the graph of average resistivity of sample 2 for pattern zig zag size 2 mm. From the graph, point 1 has the least amount of sheet resistivity while point 3 has the most amount of sheet resistivity.

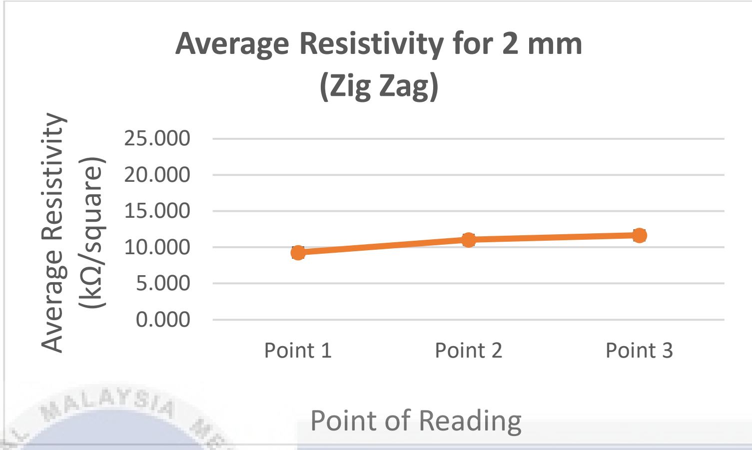
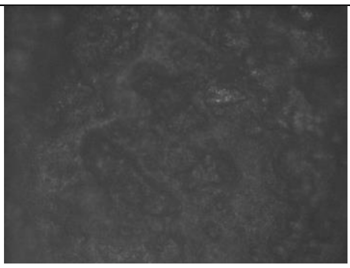
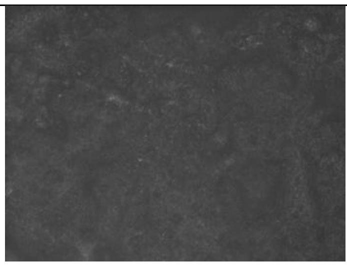
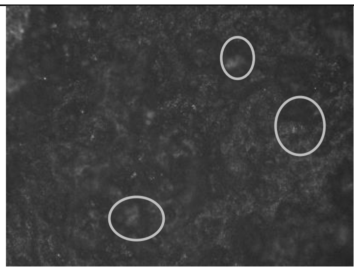


Figure 4. 27: Graph of Average Resistivity for Sample 2 Width 2 mm Pattern Zig Zag

The microscopy image for each point of reading was display on Table 4.27 below. The image for point 1 and point 2 indicates that the volume of graphene is greater as both images show large quantity of dark region. While for point 3 of the sample, there is some amount of binder present at that point because the image shows some area of bright region.

Table 4. 27: Microscopy Image for Sample 2 Width 2 mm Pattern Zig Zag

Point 1	Point 2	Point 3
		

4.4.4 Zig Zag Width 3 mm for Temperature 90 °C

The graph of average resistivity for pattern zig zag with 3 mm width was shown in Figure 4.28 below. The graph indicates that result at point 1 has the smallest sheet resistivity while point 3 has the largest sheet resistivity.

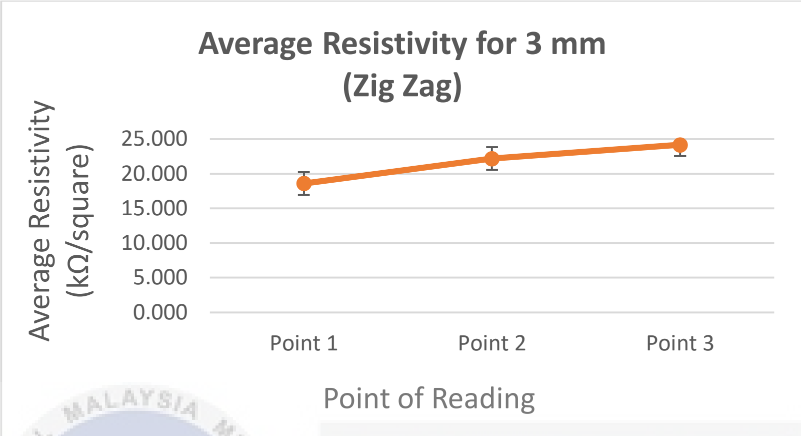
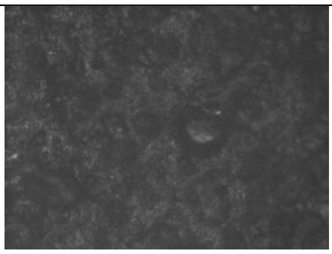
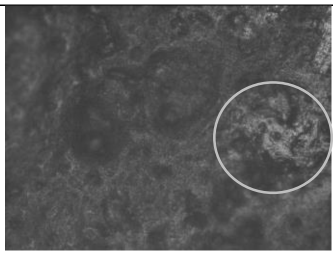
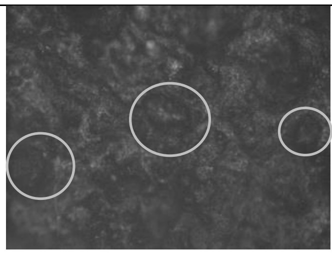


Figure 4. 28: Graph of Average Resistivity for Sample 2 Width 3 mm Pattern Zig Zag

Microscopy images of this sample were shown in Table 4.28 below, which is point 1 show the large area of dark spot also mean huge amount of graphene. Meanwhile point 2 show the least area of graphene and larger area of binder can see at the grey circle. Furthermore, at point 3, there are some roughest surface area due to the present of bump and porous.

Table 4. 28: Microscopy Image for Sample 2 Width 3 mm Pattern Zig Zag

Point 1	Point 2	Point 3
		

4.4.5 Square Width 2 mm for Temperature 90 °C

Figure 4.29 show the graph of average resistivity for pattern square size 2 mm width. The graph show point 2 has the smallest value of resistivity while point 1 and point 3 has quite same value.

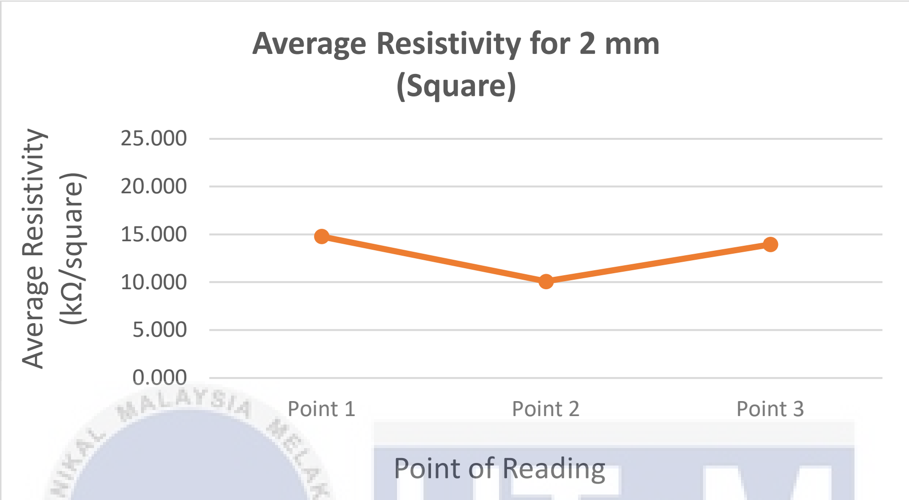
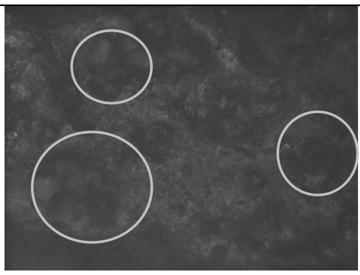
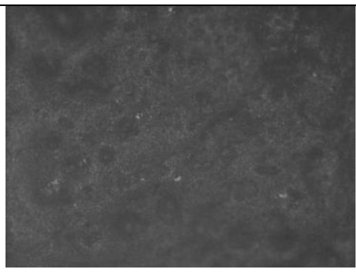
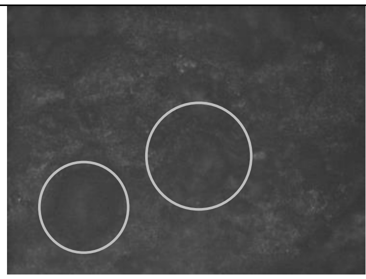


Figure 4. 29: Graph of Average Resistivity for Sample 2 Width 2 mm Pattern Square

The image of microscopy for every point was shown in Table 4.29 below. The existence of filler and binder for those three point almost same but at point 1 and point 3 show the surface of sample at that points were rough due to the present of large bump and porosity.

Table 4. 29: Microscopy Image for Sample 2 Width 2 mm Pattern Square

Point 1	Point 2	Point 3
		

4.4.6 Square Width 3 mm for Temperature 90 °C

Average resistivity for pattern square with 3 mm width was shown in Figure 4.30 below. From the graph, there is not much different on resistivity appear at point 1 and point 2 but the resistivity is lowest at point 3.

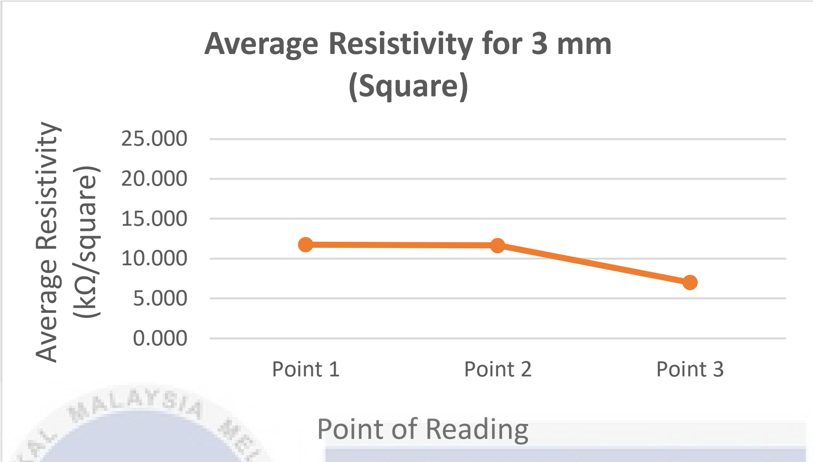
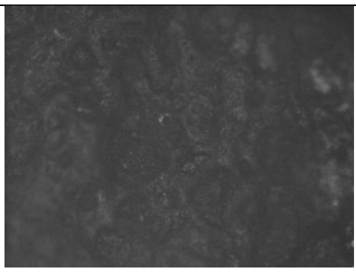
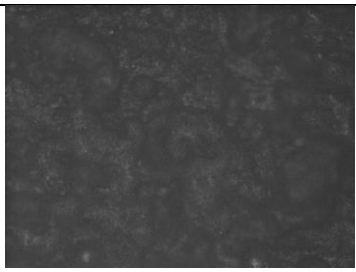
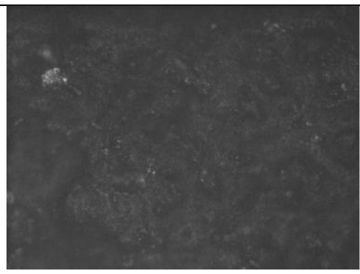


Figure 4. 30: Graph of Average Resistivity for Sample 2 Width 3 mm Pattern Square

The microscopy images show on Table 4.30 below are the image capture for each point of reading. The images show large amount of filler at all of the sample's surface. There is no large difference between the three images. The surface roughness of the images is poor owing to the appearance of bumps and porosity. Moreover, the surfaces were full of graphene, so the resistance in this sample was not too high.

Table 4. 30: Microscopy Image for Sample 2 Width 3 mm Pattern Square

Point 1	Point 2	Point 3
		

4.4.7 Sinusoidal Width 2 mm for Temperature 90 °C

The graph of average resistivity for pattern sinusoidal with 2 mm width was shown in Figure 4.31 below. From the graph, point 1 has the lowest average resistivity, then followed by point 3. Meanwhile point 2 has the highest resistivity.

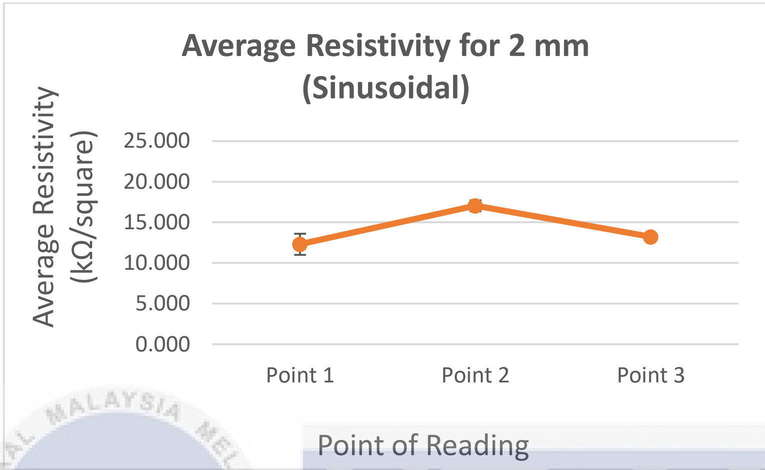
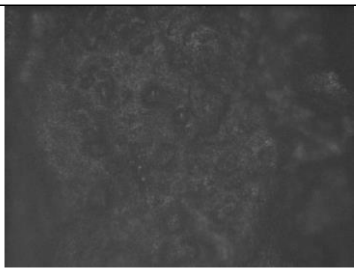
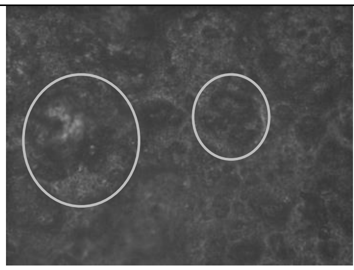


Figure 4. 31: Graph of Average Resistivity for Sample 2 Width 2 mm Pattern Sinusoidal

The microscopy image of the sample show on Table 4.31 below. Image at point 1 has large area of dark spot which is large amount of graphene compare to point 2 and point 3. Point 2 and point 3 show brighter surface area. Thus, the area is full with filler. Besides that, point 2 and point 3 also show the bumpy surface shown on the grey circle.

Table 4. 31: Microscopy Image for Sample 2 Width 2 mm Pattern Sinusoidal

Point 1	Point 2	Point 3
		

4.4.8 Sinusoidal Width 3 mm for Temperature 90 °C

Graph of average resistivity for pattern sinusoidal with 3 mm width was shown in Figure 4.32 below. From the graph, it shows that point 1 has the highest average resistivity while point 3 has the lowest resistivity.

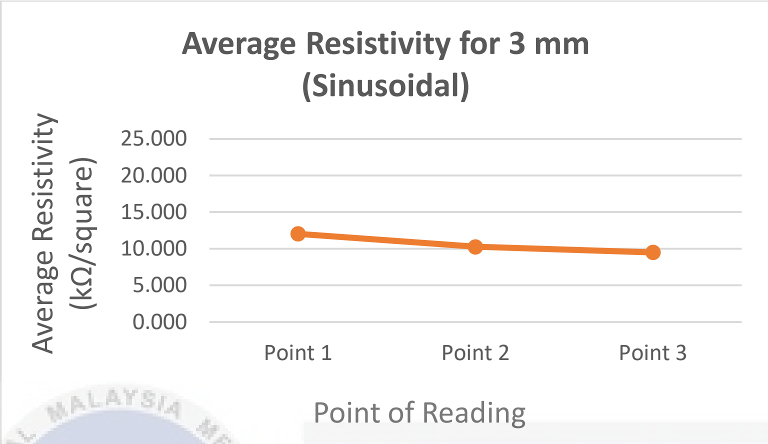
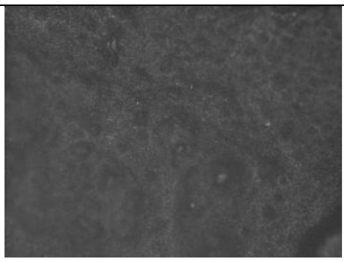
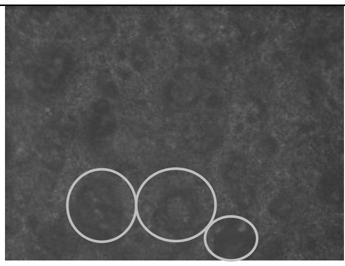
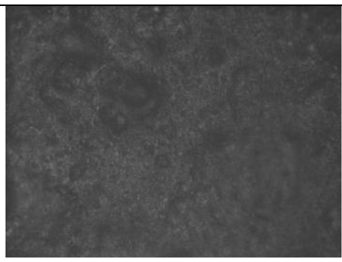


Figure 4. 32: Graph of Average Resistivity for Sample 2 Width 3 mm Pattern Sinusoidal

From the microscopy images on Table 4.32 below, the images on point 1, point 2 and point 3 show there is not much different for amount of filler and binder. However, the surface of point 2 is rougher due to the existing of large porous.

Table 4. 32: Microscopy Image for Sample 2 Width 3 mm Pattern Sinusoidal

Point 1	Point 2	Point 3
		

4.4.9 Straight Line Width 3 mm for Temperature 100 °C

The average resistivity graph for the straight line sample with a width of 3 mm was seen in Figure 4.33 below. The results show, reading of sheet resistivity for the three points are very similar. The readings of sheet resistivity for this sample are closely to 10 kΩ/sq.

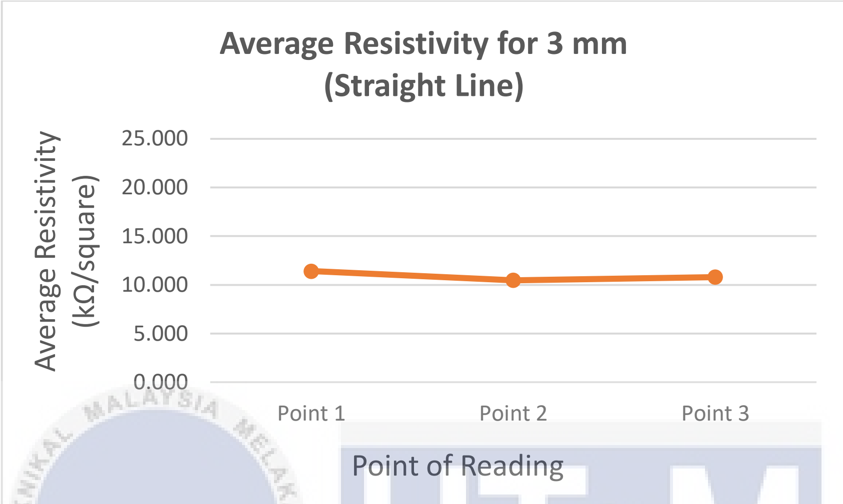
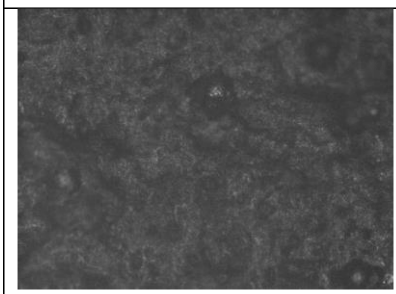
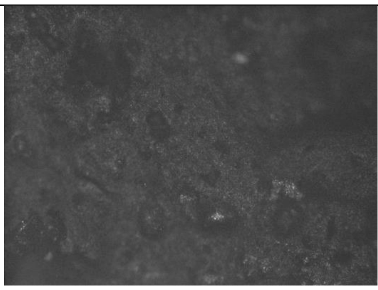
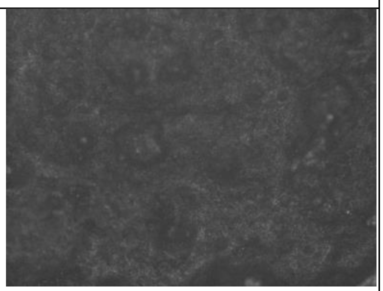


Figure 4. 33: Graph of Average Resistivity for Sample 2 Width 3 mm Pattern Straight Line

Microscopy image for this sample were present on Table 4.33 below. The images also displayed quite the same surface with a number of dark spots on the reading area. However, for point 1 there is an existence of a binder throughout the area, which can be seen where the bright surface is more than the dark spot.

Table 4. 33: Microscopy Image for Sample 2 Width 3 mm Pattern Straight Line

Point 1	Point 2	Point 3
		

4.4.10 Zig Zag Width 2 mm for Temperature 100 °C

Figure 4.34 below show the graph of sheet resistivity for zig zag with a width of 2 mm. The graph shows the sheet resistivity range for this sample is between 15 kΩ/sq to 20 kΩ/sq. Point 2 has the higher reading of sheet resistivity while point 3 has the least sheet resistivity.

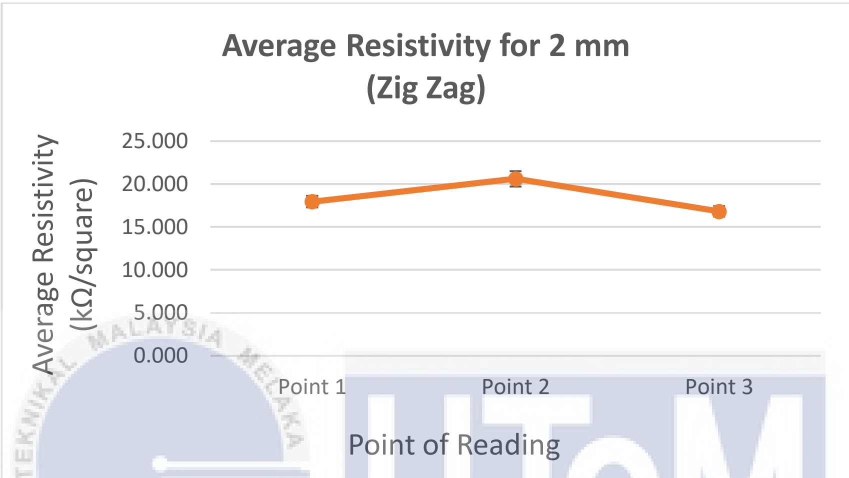
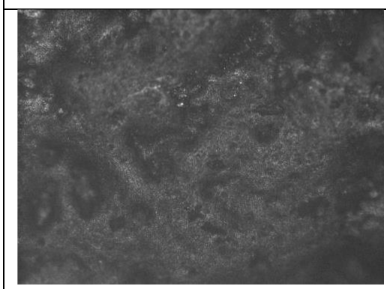
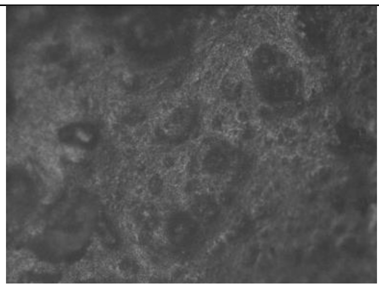
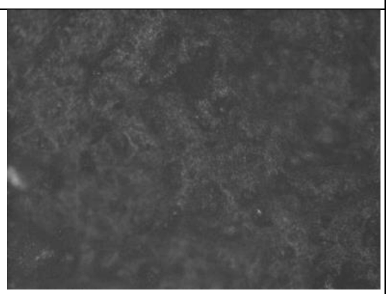


Figure 4. 34: Graph of Average Resistivity for Sample 2 Width 2 mm Pattern Zig Zag

Table 4.34 below show the microscopy image of each point of reading. Image at point 2 show more bright area compare to the dark spot. Thus, it indicates that point 2 was filled with binder. Meanwhile the image at point 3, the area was full with dark spot, thus the area was covered with graphene.

Table 4. 34: Microscopy Image for Sample 2 Width 2 mm Pattern Zig Zag

Point 1	Point 2	Point 3
		

4.4.11 Zig Zag Width 3 mm for Temperature 100 °C

Figure 4.35 show the graph of sheet resistivity for zig zag with a width of 3 mm. The graph show readings of sheet resistivity from point 1 to point 3 are increasing from 10 kΩ/sq to 15 kΩ/sq.

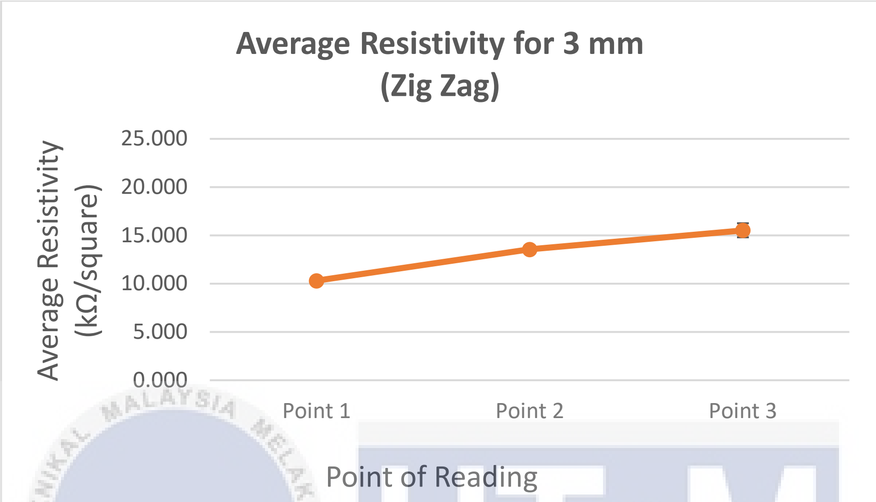
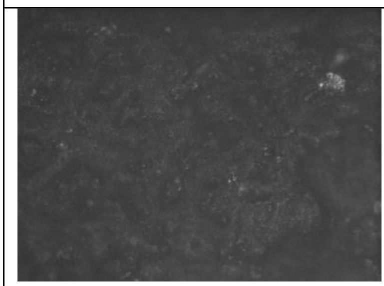
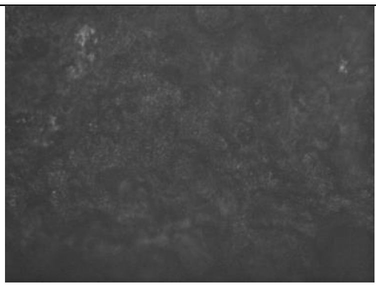
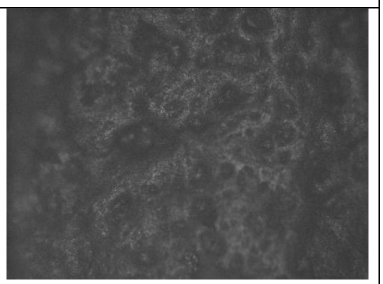


Figure 4. 35: Graph of Average Resistivity for Sample 2 Width 3 mm Pattern Zig Zag

Table 4.35 below show the images of the sample for each point of reading that were capture by the light microscope device. The images show point 1 and point 2 have been covered with dark spot for the entire area. Meanwhile, point 3 show the area is not fully covered by dark spot because there is bright area more. Thus it means point 1 and point 2 has more volume of graphene compare to point 3.

Table 4. 35: Microscopy Image for Sample 2 Width 3 mm Pattern Zig Zag

Point 1	Point 2	Point 3
		

4.4.12 Square Width 2 mm for Temperature 100 °C

The graph of sheet resistivity for sample square with a width of 2 mm was shown in Figure 4.36 below. The graph shows the results for sheet resistivity from point 1 to point 3 has a decreasing value.

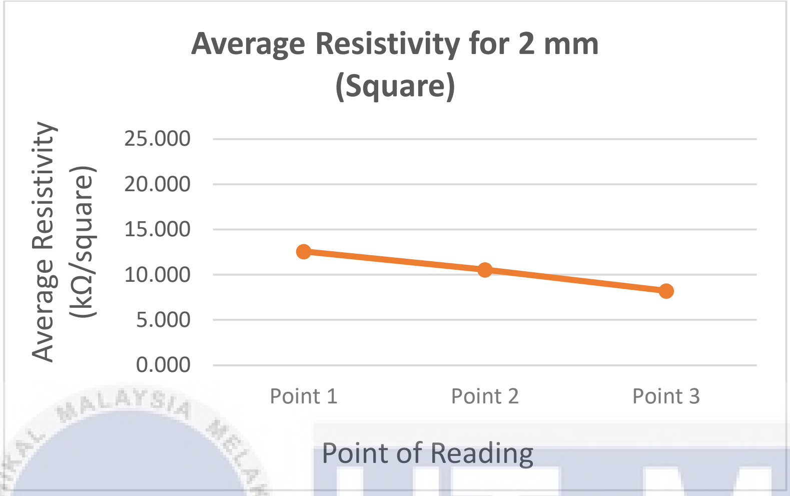
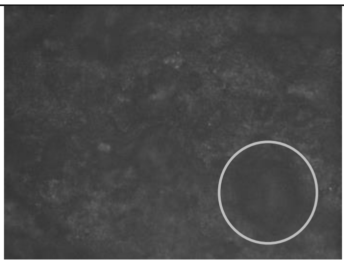
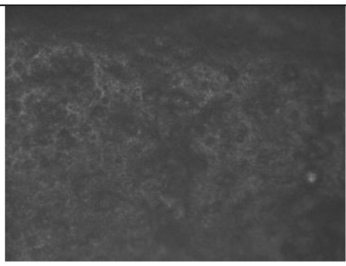
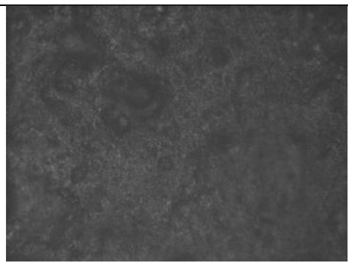


Figure 4. 36: Graph of Average Resistivity for Sample 2 Width 2 mm Pattern Square

Microscopy images of each point of reading for this sample were shown in Table 4.36 below. From the images, point 1 has the higher volume of dark spot surrounding the area while point 2 and point 3 have more bright area. However, the surface of point 1 is rougher with the presence of porosity and bump.

Table 4. 36: Microscopy Image for Sample 2 Width 2 mm Pattern Square

Point 1	Point 2	Point 3
		

4.4.13 Square Width 3 mm for Temperature 100 °C

The results of sheet resistivity for sample square size 3 mm width were shown in a graph on Figure 4.37 below. The graph show point 1 has the highest resistivity while point 2 and point 3 closely value of resistivity.

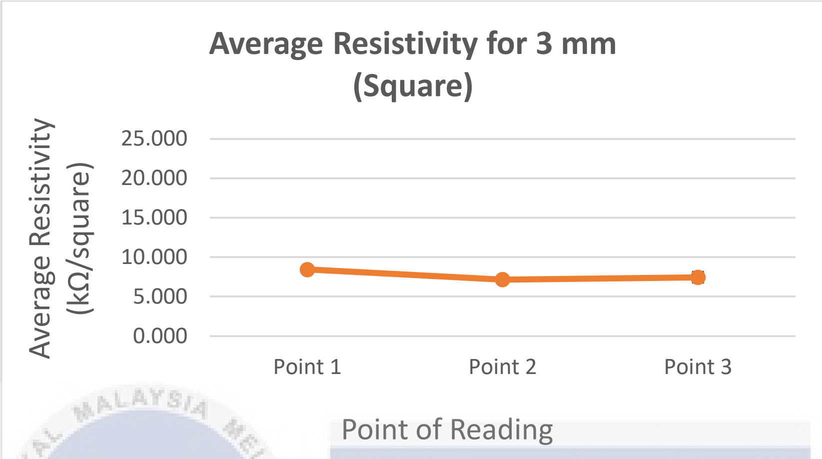
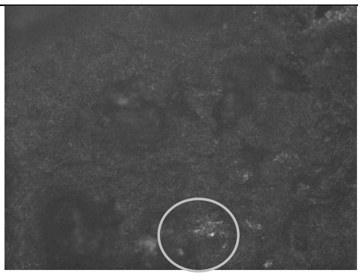
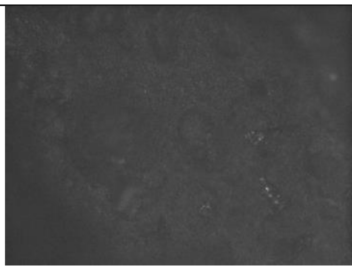
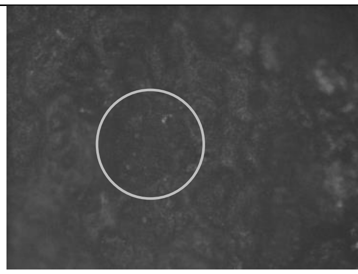


Figure 4. 37: Graph of Average Resistivity for Sample 2 Width 3 mm Pattern Square

Table 4.37 below show the images captured on sample's surface. The images show large presence of dark spot on every image. However, image on point 2 has the smoothest surface without much porosity and bump.

Table 4. 37: Microscopy Image for Sample 2 Width 3 mm Pattern Square

Point 1	Point 2	Point 3
		

4.4.14 Sinusoidal Width 2 mm for Temperature 100 °C

Figure 4.38 show the graph of sheet resistivity for sinusoidal with a width of 2 mm. The graph show point 2 has the highest sheet resistivity while point 1 and point 3 has almost similar value of reading.

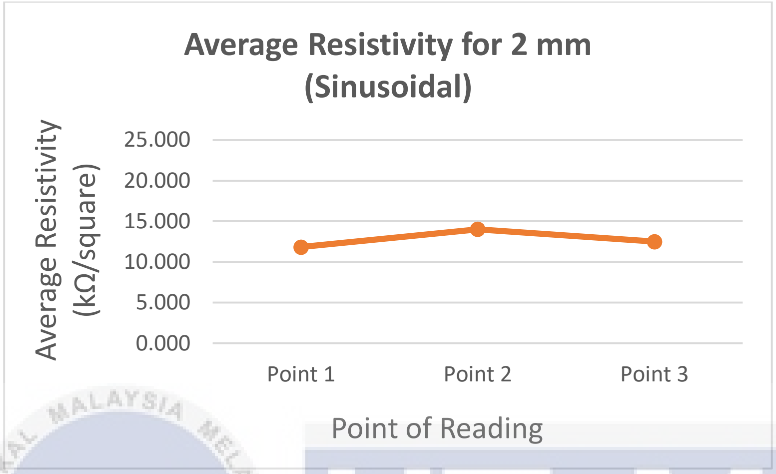
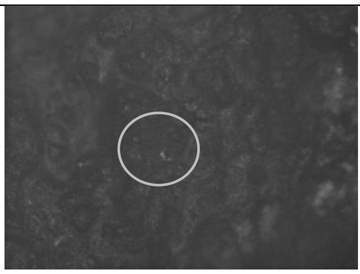
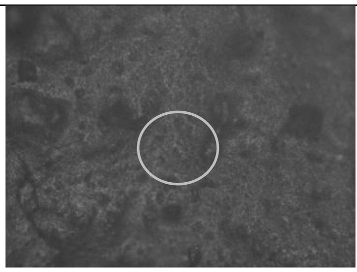
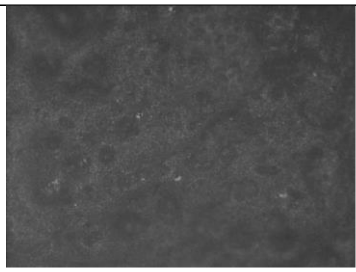


Figure 4. 38: Graph of Average Resistivity for Sample 2 Width for 2 mm Pattern Sinusoidal

Table 4.38 show the image of sample's surface. Image on point 1 show dark spot covered the surface of the area. Thus, it means graphene appeared a lot at that location. Meanwhile, point 2 show brighter surface compare to point 1 and point 3. It means surface of point 2 has binder more than filler on that area.

Table 4. 38: Microscopy Image for Sample 2 Width for 2 mm Pattern Sinusoidal

Point 1	Point 2	Point 3
		

4.4.15 Sinusoidal Width 3 mm for Temperature 100 °C

Graph of sheet resistivity for sample sinusoidal with a width of 3 mm was shown in Figure 4.39 below. From the graph, point 1 has the highest sheet resistivity while point 2 and point 3 has nearly same value of sheet resistivity.

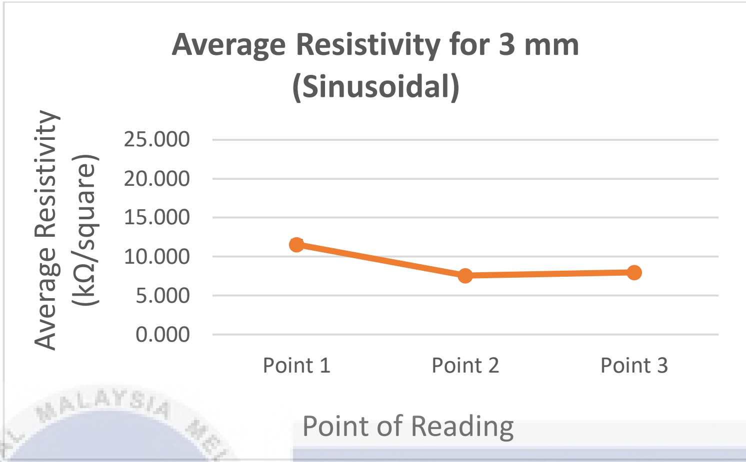
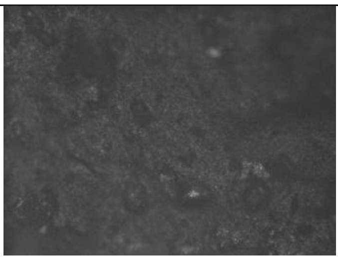
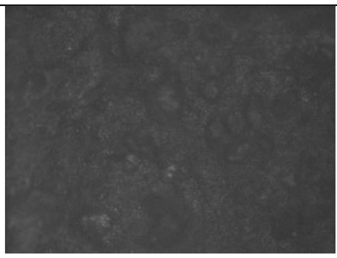
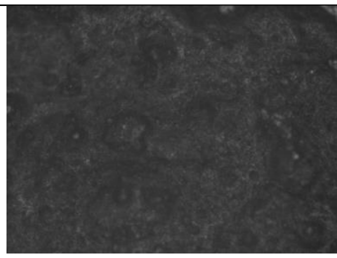


Figure 4. 39: Graph of Average Resistivity for Sample 2 Width 3 mm Pattern Sinusoidal

From Table 4.39 below, the microscopy image of the sample on every point have all covered with dark spot. Thus it means, volume of graphene is high on every point.

Table 4. 39: Microscopy Image for Sample 2 Width for 2 mm Pattern Sinusoidal

Point 1	Point 2	Point 3
		

4.4.16 Straight Line Width 2 mm for Temperature 110 °C

The graph of average resistivity for pattern straight line with 2 mm width that was cure under 110 °C temperature was shown in Figure 4.40 below. The results indicate that the readings of sheet resistivity for point 1, point 2 and point 3 are not much different. All of the points get sheet resistivity close to 5 kΩ/sq.

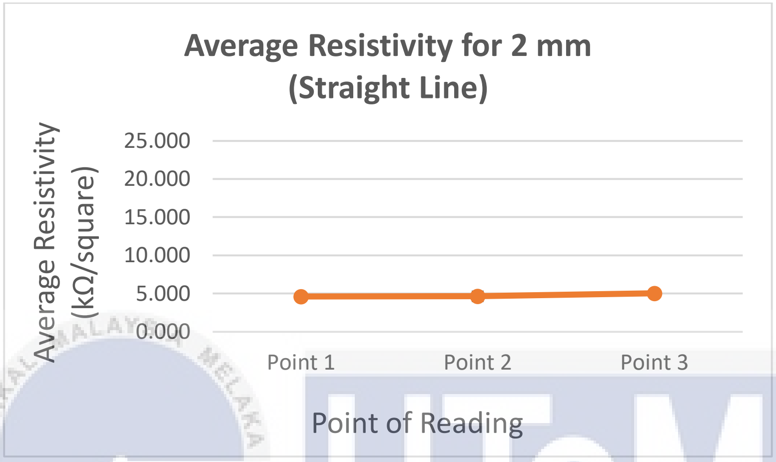
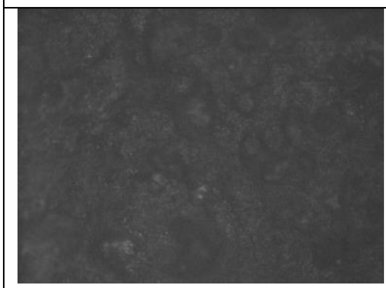
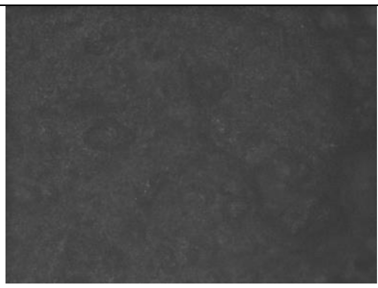
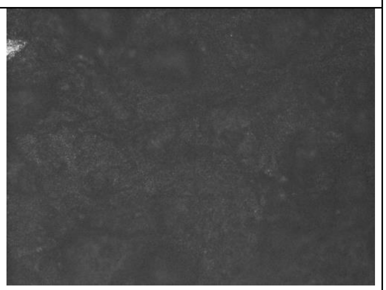


Figure 4. 40: Graph of Average Resistivity for Sample 2 Width 2 mm Pattern Straight Line

The microscopy images in Table 4.40 for point 1, point 2 and point 3 of the sample also present not much differentiation in their surface structure. The three points have a huge amount of graphene that can be seen in the images, there is a complete region of dark spot.

Table 4. 40: Microscopy Image for Sample 2 Width 2 mm Pattern Straight Line

Point 1	Point 2	Point 3
		

4.4.17 Straight Line Width 3 mm for Temperature 110 °C

The graph for results of average resistivity for pattern straight line with 3 mm width that was cure under temperature 110 °C was shown in Figure 4.41 below. From the graph, the sheet resistivity for point 3 is the lowest among those three points while point 1 and point 2 have almost same value of sheet resistivity.

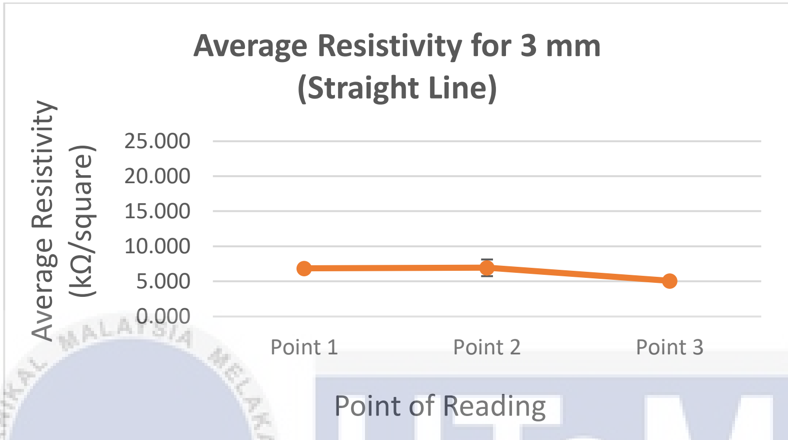
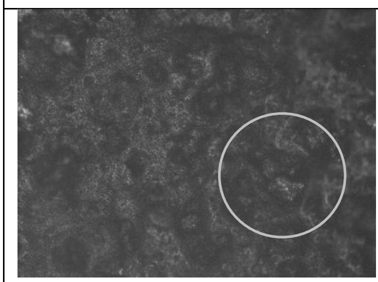
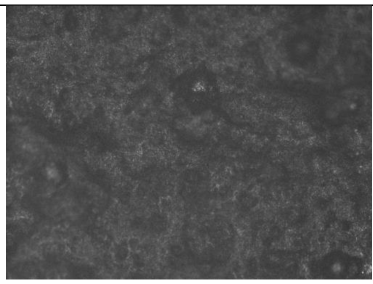
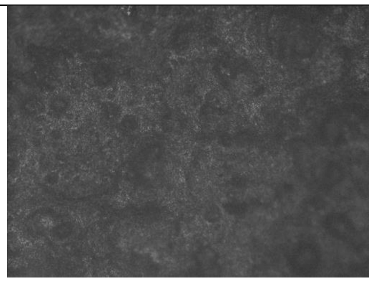


Figure 4. 41: Graph of Average Resistivity for Sample 2 Width 3 mm Pattern Straight Line

The images for microscope shown in Table 4.41 show not much different for binder and filler volume but the surface on point 1, show a lot of bump and porosity appear. Meanwhile the image at point 3 show the smoothest surface compare to the surface at point 1 and point 2.

Table 4. 41: Microscopy Image for Sample 2 Width 3 mm Pattern Straight Line

Point 1	Point 2	Point 3
		

4.4.18 Zig Zag Width 2 mm for Temperature 110 °C

Figure 4.42 show the graph of average resistivity of zigzag pattern with 2mm width that was cure under temperature 110 °C. From the graph, the sheet resistivity was smallest at point 3 and larger at point 1 and point 2.

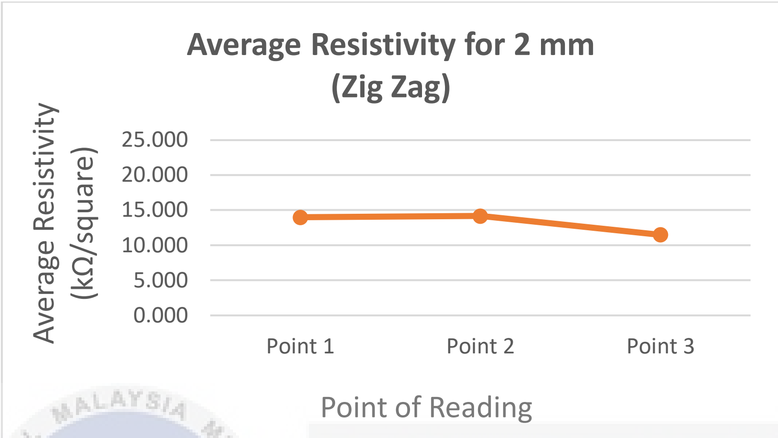
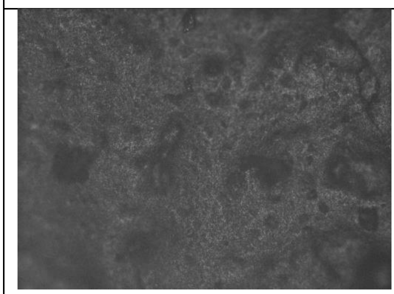
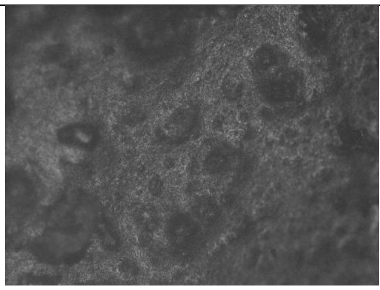
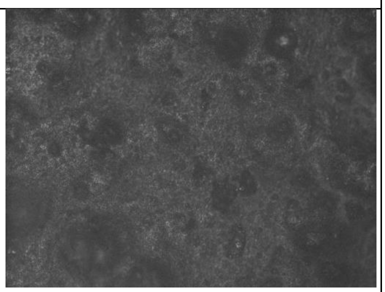


Figure 4. 42: Graph of Average Resistivity for Sample 2 Width 2 mm Pattern Zig Zag

For microscopy images on Table 4.42, the image seen at point 2 have a rough surface compared to point 1 and point 3 due to the present of bump and porosity. Meanwhile, the graphene is not entirely covered those three points, relate to the brighter area compare to dark spot.

Table 4. 42: Microscopy Image for Sample 2 Sample 2 Width 2 mm Pattern Zig Zag

Point 1	Point 2	Point 3
		

4.4.19 Zig Zag Width 3 mm for Temperature 110 °C

The graph of average resistivity for pattern zig zag with 3 mm width was shown in Figure 4.43 below. From the graph, the results show that average sheet resistivity for point 3 is highest which is near to 15 kΩ/sq while point 1 and point 2 only have sheet resistivity close to 5 kΩ/sq.

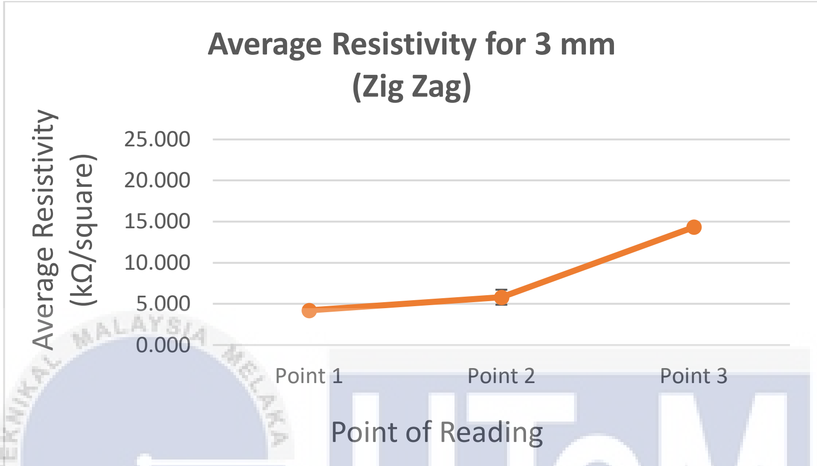
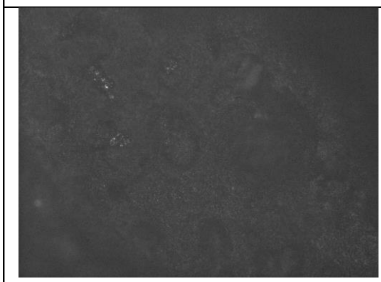
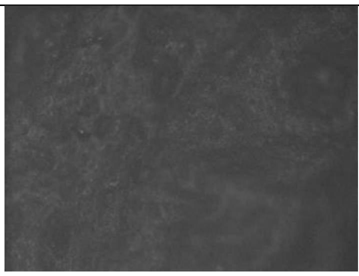
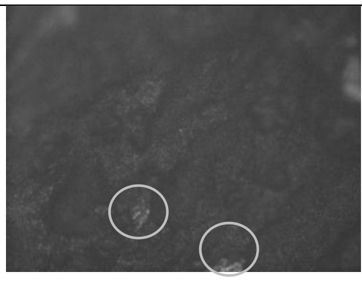


Figure 4. 43: Graph of Average Resistivity for Sample 2 Width 3 mm Pattern Zig Zag

The microscopy image of the sample on Table 4.43 show that the sample is fully covered by graphene at every point of reading due to the present of dark spot fully on the images. Moreover, at point 3, there are some brighter area occur at the surface as shown in the red circle.

Table 4. 43: Microscopy Image for Sample 2 Width 3 mm Pattern Zig Zag

Point 1	Point 2	Point 3
		

4.4.20 Square Width 2 mm for Temperature 110 °C

Figure 4.44 show the graph of average resistivity for pattern square with 2 mm width. The graph shows the average sheet resistivity for this sample decrease from point 1 to point 3. The highest resistivity is 11 kΩ/sq while the lowest sheet resistivity is 5 kΩ/sq.

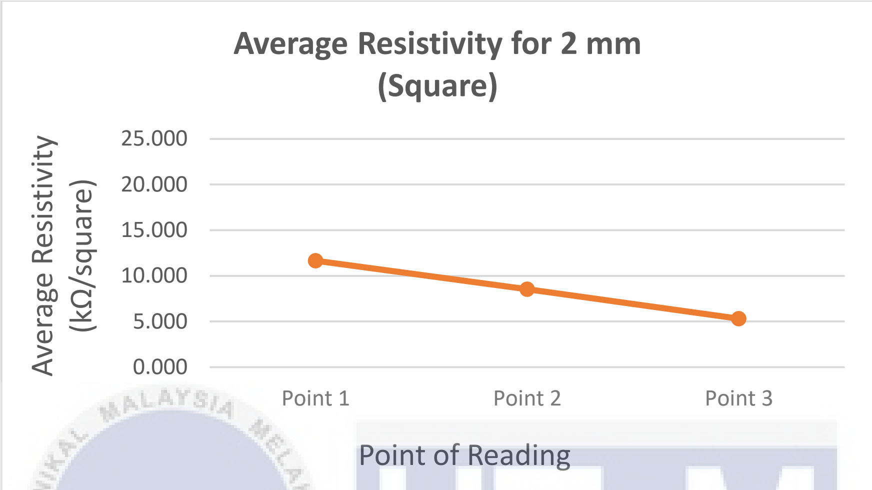
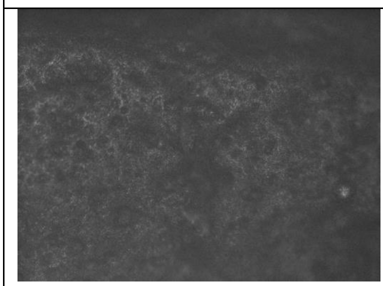
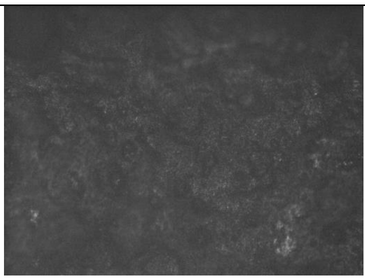
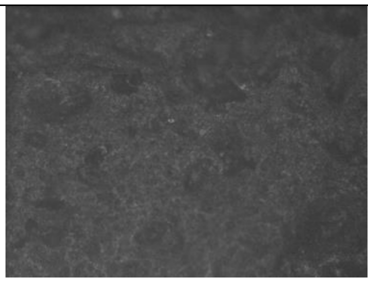


Figure 4. 44: Graph of Average Resistivity for Sample 2 Width 2 mm Pattern Square

From the microscopy images that was capture on every point of reading, point 3 which shown in Table 4.44 below has the smooth surface compare to point 1 and point 2. The present of graphene on every images are almost fully covered the area of readings.

Table 4. 44: Microscopy Image for Sample 2 Width 2 mm Pattern Square

Point 1	Point 2	Point 3
		

4.4.21 Square Width 3 mm for Temperature 110 °C

Figure 4.45 show the graph of average resistivity for pattern square with 3 mm width. The graph show reading for average resistivity at point 3 is the lowest while point 1 and point 2 have closely results.

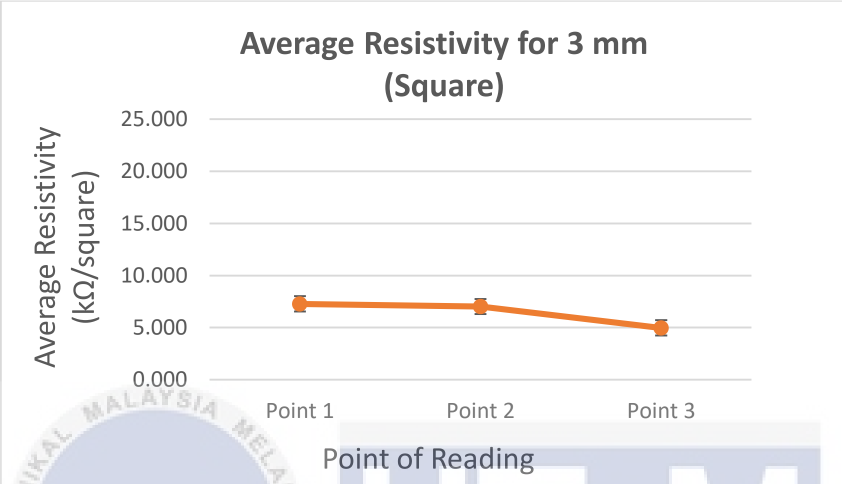
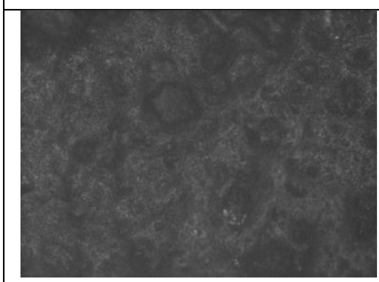
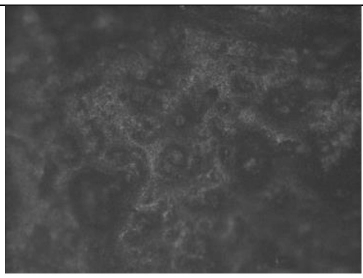
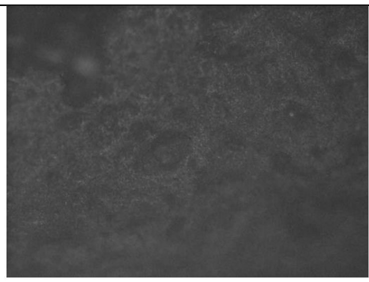


Figure 4. 45: Graph of Average Resistivity for Sample 2 Width 3 mm Pattern Square

From the microscopy images shown in Table 4.45 below, the images show the amount of filler and binder covered the sample surface. Image on point 3 show the biggest amount of graphene because the image fully covered by dark spot. Meanwhile, image on point 2 show the least amount of graphene but more amount of filler due to the bright area seen more than dark area. Besides that, point 1 and point 2 also has a lot of porosity and bump occur at the surface.

Table 4. 45: Microscopy Image for Sample 2 Width 3 mm Pattern Square

Point 1	Point 2	Point 3
		

4.4.22 Sinusoidal Width 2 mm for Temperature 110 °C

Average resistivity for sample sinusoidal with 2 mm width that was cure under 110 °C temperature was shown in graph on Figure 4.46 below. The graph indicate point 1 has the smallest sheet resistivity while point 3 has the largest sheet resistivity.

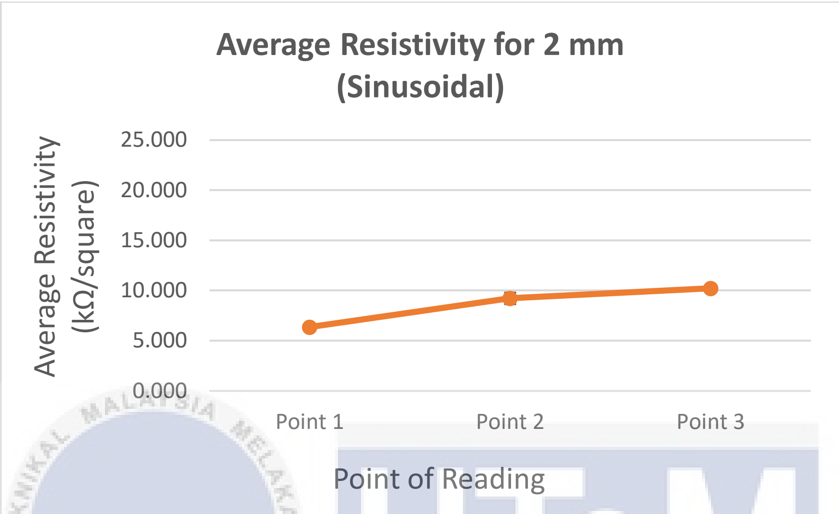
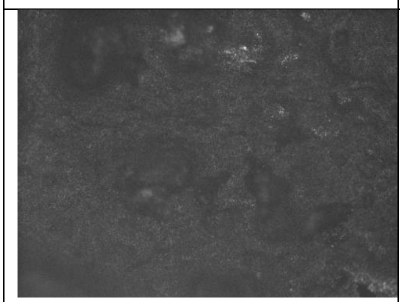
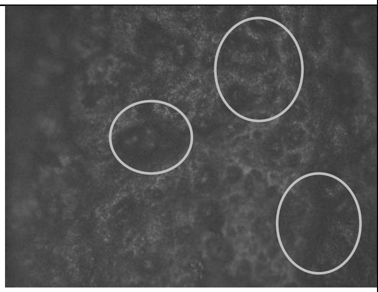
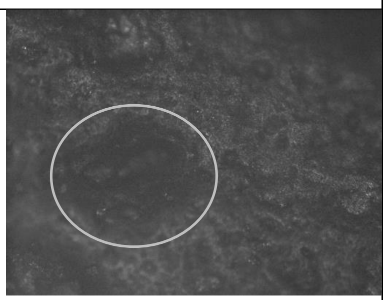


Figure 4. 46: Graph of Average Resistivity for Sample 2 Width 2 mm Pattern Sinusoidal

Microscopy images for every point of reading were shown in Table 4.46 below. The image at point 1 show graphene was fully covered the surface area due to the dark spot fully appear at the surface. Meanwhile, image at point 2 and point 3 show the area was not fully covered by graphene because there is more bright area, thus that area is cover by binder. Besides that, point 2 and point 3 has a lot of porosity and bump appears on the surface. Thus, the resistivity occur must be higher than point 1.

Table 4. 46: Microscopy Image for Sample 2 Width 2 mm Pattern Sinusoidal

Point 1	Point 2	Point 3
		

4.4.23 Sinusoidal Width 3 mm for Temperature 110 °C

Figure 4.47 show the graph of average resistivity for sample sinusoidal with 3 mm width. From the graph, point 2 has the lowest resistivity while point 1 and point 3 have closely result.

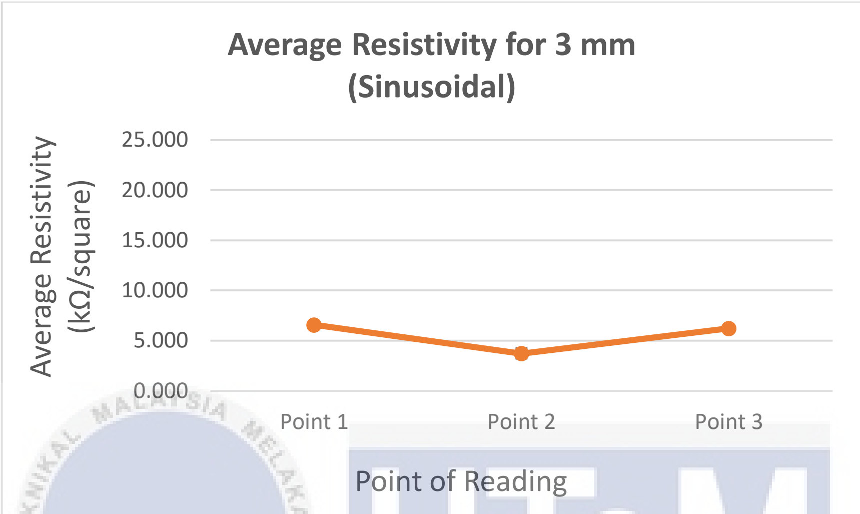
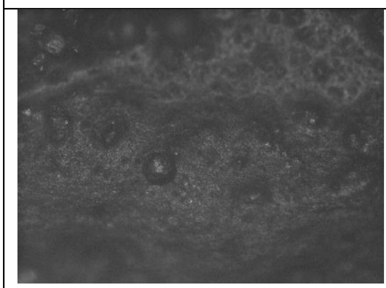
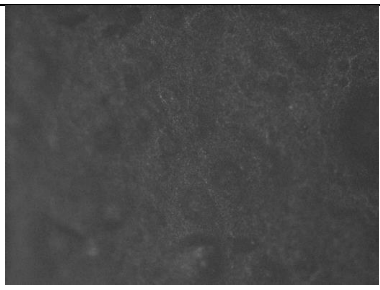
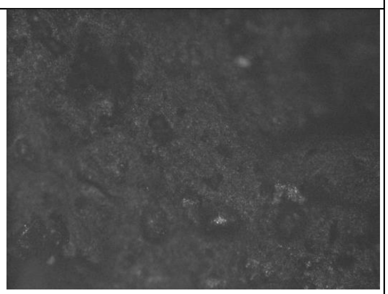


Figure 4. 47: Graph of Average Resistivity for Sample 2 Width 3 mm Pattern Sinusoidal

The microscopy image was shown on Table 4.47 below. The image at point 2 show that the dark spot was fully covered the area, means the present of graphene was higher at that region. Meanwhile, point 1 and point 3 have some bright area due to the present of binder.

Table 4. 47: Microscopy Image for Sample 2 Width 3 mm Pattern Sinusoidal

Point 1	Point 2	Point 3
		

4.5 Resistivity Between Temperature

The resistivity of every pattern and size of width sample between temperature were shown in figures below. The data were collect from the previous result and were present in the form of graph line between temperature 90 ℃, 100 ℃ and 110 ℃.

4.5.1 Average Resistivity for Straight Line Width 2 mm

The graph of average resistivity between temperature for pattern straight line with 2 mm width was shown in Figure 4.48 below. There is only result for temperature 90 °C and 110 °C were shown in figure below. This is because the result for 100 °C for 2 mm size cannot be read and need to redo the sample. However, due to the Covid-19, the experimental cannot be done. From the graph, it shows that 90 °C get higher resistivity compare to 110 °C. Thus, the lower the curing temperature the higher the resistivity occurs on the sample. This is because the higher the curing temperature, the higher the size of grain size of the graphene. When the graphene size become larger, it can easily connect to each other and form a continuous flow through the conductive ink. The presence of resistivity will decrease due to the larger size of grain size. Thus the electrical conductivity will increase due to the decreasing of resistivity.

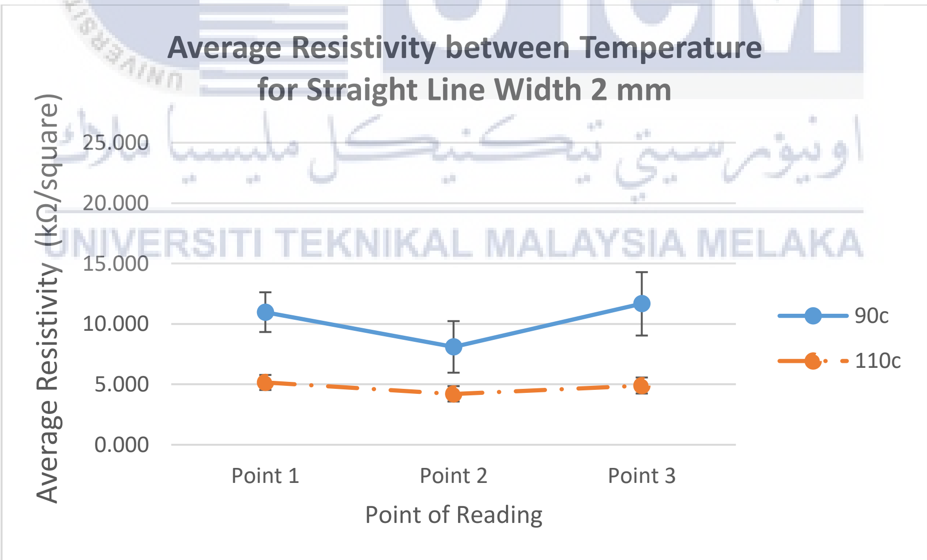


Figure 4. 48: Graph of Average Resistivity between Temperature 90 °C and 110 °C for Pattern Straight Line Width 2 mm

4.5.2 Average Resistivity for Straight Line Width 3 mm

Figure 4.49 show the graph of average resistivity between three temperatures for pattern straight line size of width 3 mm. The figure shows that 90 °C temperature lead those three graph line and followed by 100 °C temperature and lastly 110 °C. The observation can be made from this graph are, the lower the temperature of curing, the higher the resistivity occurs and the resistivity reduces when the curing temperature increase. Based on the theory, resistivity will occur at the presence of phonon crosslink. In order to reduce the presence of phonon, the temperature has been raised. Thus, the higher the temperature, the lower the resistivity occur.

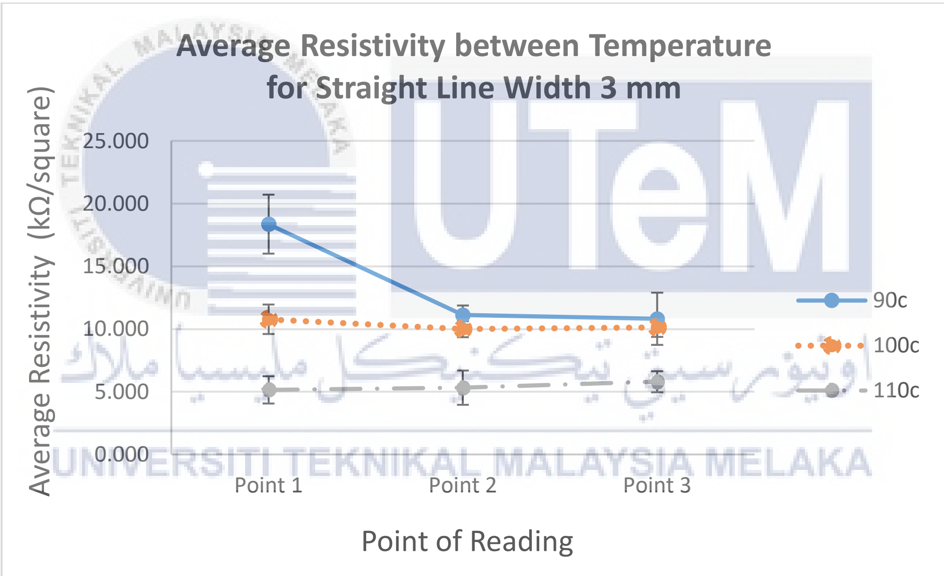


Figure 4. 49: Graph of Average Resistivity between Temperature 90 °C, 100 °C and 110 °C for Pattern Straight Line Width 3 mm

4.5.3 Average Resistivity for Zig Zag Width 1 mm

The average resistance for pattern zig zag width 1 mm was shown in the form of graph on Figure 4.50 below. The result was compared between three temperatures which is 90 °C, 100 °C and 110 °C. From the graph, it shows that graph line for pattern zigzag width 1 mm are closely to each other. But their arrangement still 90 °C temperature get the highest value and 110 °C get the lowest value of resistivity. The higher the temperature, the better electrical conductivity of the sample due to the decreasing of resistivity.

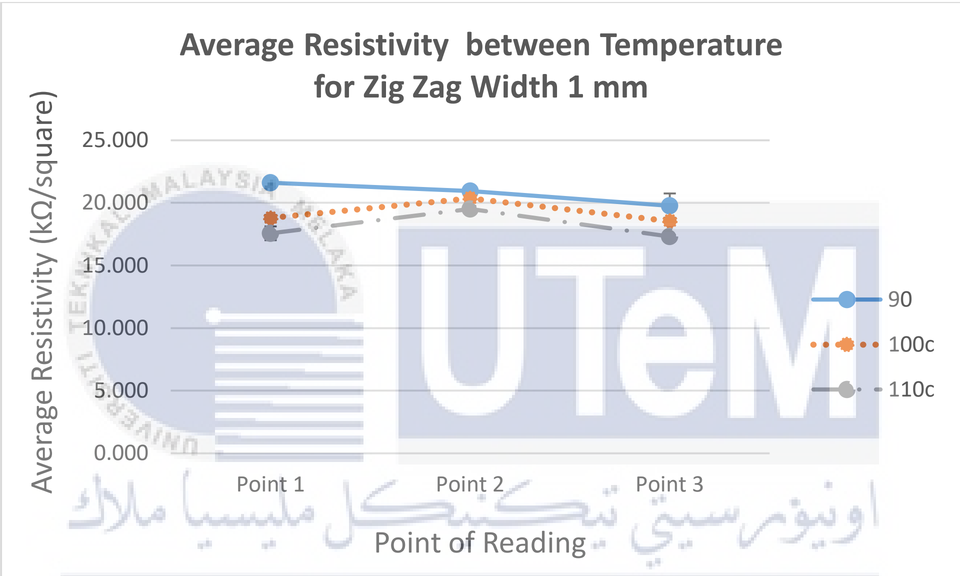


Figure 4. 50: Graph of Average Resistivity between Temperature 90 °C, 100 °C and 110 °C for Pattern Zig Zag Width 1 mm

4.5.4 Average Resistivity for Zig Zag Width 2 mm

Figure 4.51 show the average resistivity of sample pattern zig zag with width 2 mm. The average resistivity between three temperatures from the graph below show that 100 ℃ and 110 ℃ get higher result compare to 90 ℃. While 90 ℃ temperature get the lowest value of resistivity. Result for temperature 100 ℃ and 110 ℃ supposed to be must less than 90 ℃. This is because based on the theory, the higher the curing temperature, the bigger the size of grain size. Thus it will decrease the area of phonon scattering inside the graphene. The error occurs on the data results are probably because of the incorrect resistivity reading due to the condition of the sample's surface which have several bumps and porous.

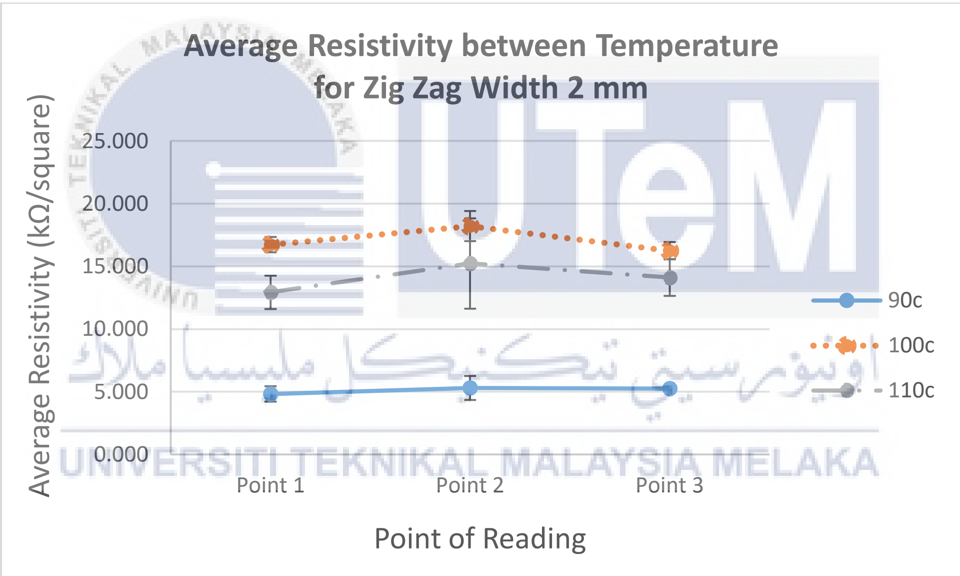


Figure 4. 51: Graph of Average Resistivity between Temperature 90 ℃, 100 ℃ and 110 ℃ for Pattern Zig Zag Width 2 mm

4.5.5 Average Resistivity for Zig Zag Width 3 mm

Graph of average resistivity between three temperatures was obtain and shown in Figure 4.52 below. The graph show that temperature of 90 °C is at the middle of temperature 100 °C and 110 °C. The 90 °C is supposedly at the top of those two temperature because the resistivity will increase due to the decreasing of temperature. The error bar also biggest at line 90 °C, thus the possibility of error is high. The error may happen due to the mishandling the sample preparation or experimental.

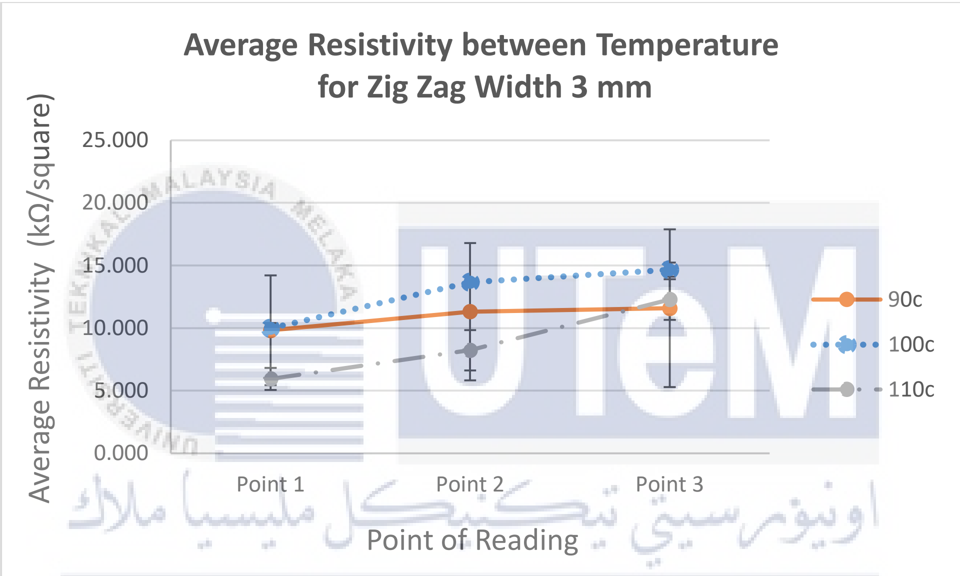


Figure 4. 52: Graph of Average Resistivity between Temperature 90 °C, 100 °C and 110 °C for Pattern Zig Zag Width 3 mm

4.5.6 Average Resistivity for Square Width 1 mm

Figure 4.53 show the graph of average resistivity between three temperatures for pattern square with 1 mm width. The graph show that 90 ℃ temperature get the highest resistivity while 110 ℃ get the lowest resistivity reading. Based on the theory, the resistivity will higher if the phonon occurs on graphene is bigger. Thus, by increasing the temperature, the grain size will increase and reduce the phonon in graphene. Therefore, the resistivity will higher if the curing temperature is lower. Besides, the lower the resistivity, the higher the electricity can be conduct along the sample of conductive ink.

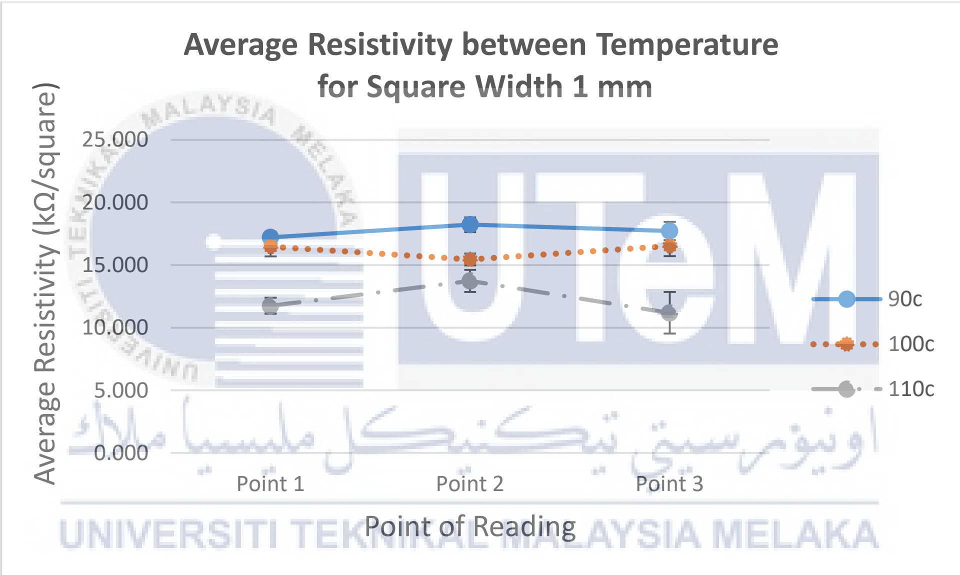


Figure 4. 53: Graph of Average Resistivity between Temperature 90 ℃, 100 ℃ and 110 ℃ for Pattern Square Width 1 mm

4.5.7 Average Resistivity for Square Width 2 mm

Figure 4.54 show the graph of average resistivity for square pattern for 2 mm width. The observation made for the graph is about change of resistivity due to the change of temperature. From the graph, curing the sample at 110 °C get the least amount of resistivity while 90 °C get the largest resistivity among those three temperature. Thus, it shows that the experimental result gets the same observation as theoretical related to the reducing of resistivity if the temperature increase.

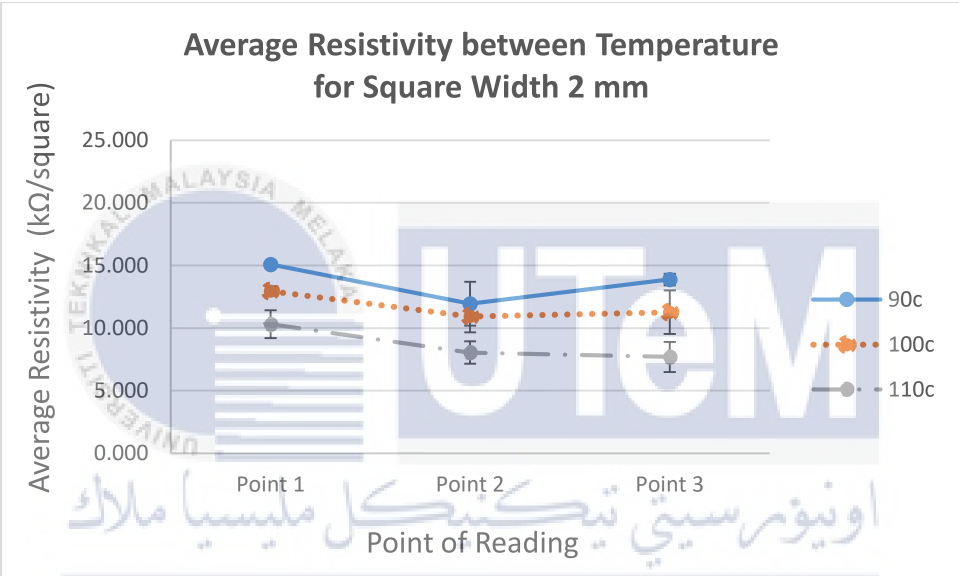


Figure 4. 54: Graph of Average Resistivity between Temperature 90 °C, 100 °C and 110 °C for Pattern Square Width 2 mm

4.5.8 Average Resistivity for Square Width 3 mm

Figure 4.55 show the graph of average resistivity between three temperatures for pattern square with 3 mm width. The graph show that point 2 of 110 °C temperature is higher than the 100 °C temperature. Anyways, the error bar at point 2 of 110 °C temperature also has a big gap. Thus it shows that point 2 of 110 °C has the possibility of error. For general observation, the graph show that 90 °C temperature get the highest resistivity, and 110 °C get the lowest resistivity. Thus the electrical conductivity is highest at 110 °C of curing temperature.

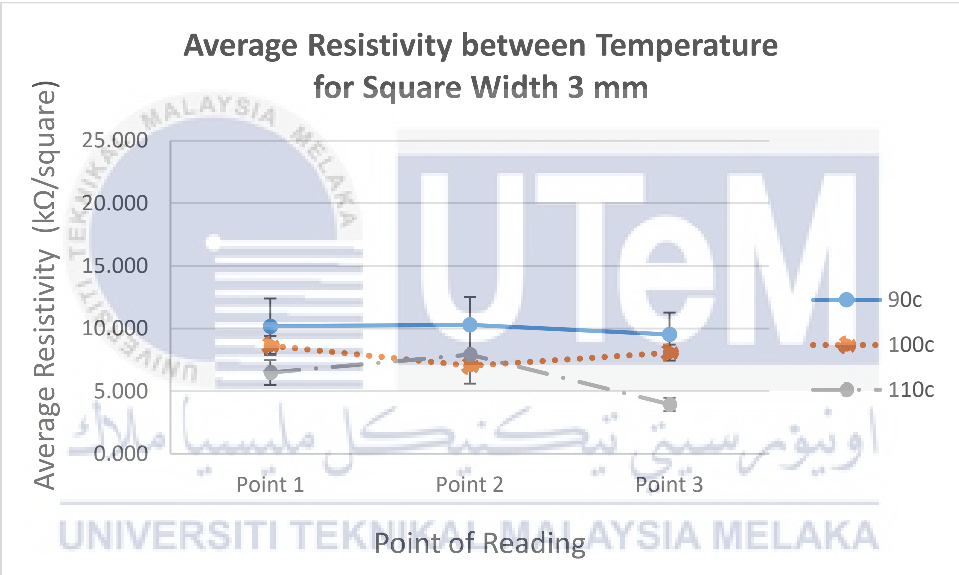


Figure 4. 55: Graph of Average Resistivity between Temperature 90 °C, 100 °C and 110 °C for Pattern Square Width 3 mm

4.5.9 Average Resistivity for Sinusoidal Width 1 mm

Average resistivity between temperature for sinusoidal pattern with 1 mm width is shown in the form of graph on Figure 4.56 below. The graph show that 100 °C result line lie at the middle of 90 °C and 110 °C. With the 90 °C at the top of those three result. The observation that can be made from the graph result is, the higher the curing temperature, the lower the resistivity occur at the sample of conductive ink. This is because, the temperature can increase the size of grain in the graphene thus will reduce the amount of phonon.

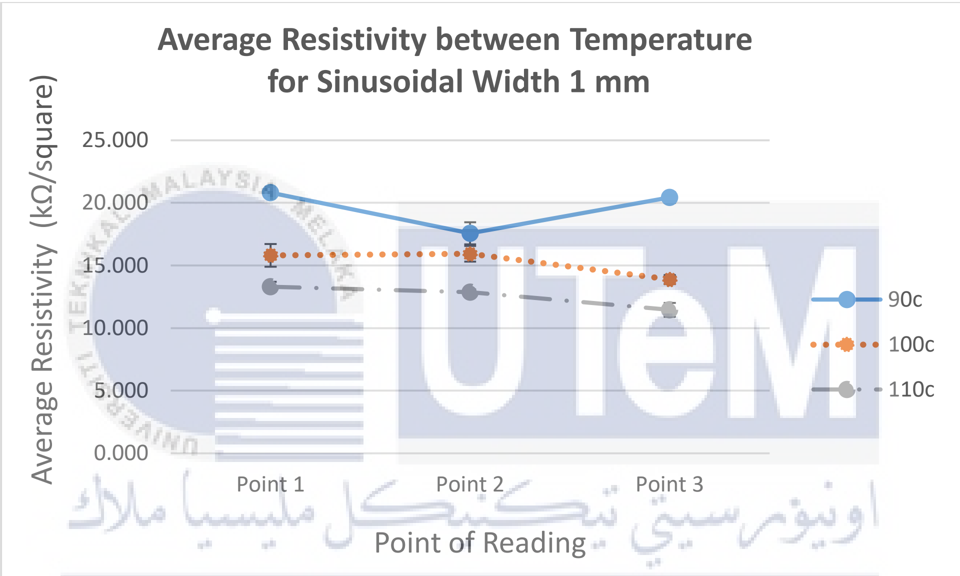


Figure 4. 56: Graph of Average Resistivity between Temperature 90 °C, 100 °C and 110 °C for Pattern Sinusoidal Width 1 mm

4.5.10 Average Resistivity for Sinusoidal Width 2 mm

Figure 4.57 show the average resistivity between temperature for pattern sinusoidal with 2 mm width. The graph shows 90 ℃ get highest resistivity while 110 ℃ temperature get the lowest. This is because the higher of curing temperature, the bigger the size of grain, thus it will reduce the size of phonon in graphene. When the size of phonon decrease, the resistivity also decreases because it cannot pass the path with the presence of larger amount of grain size.

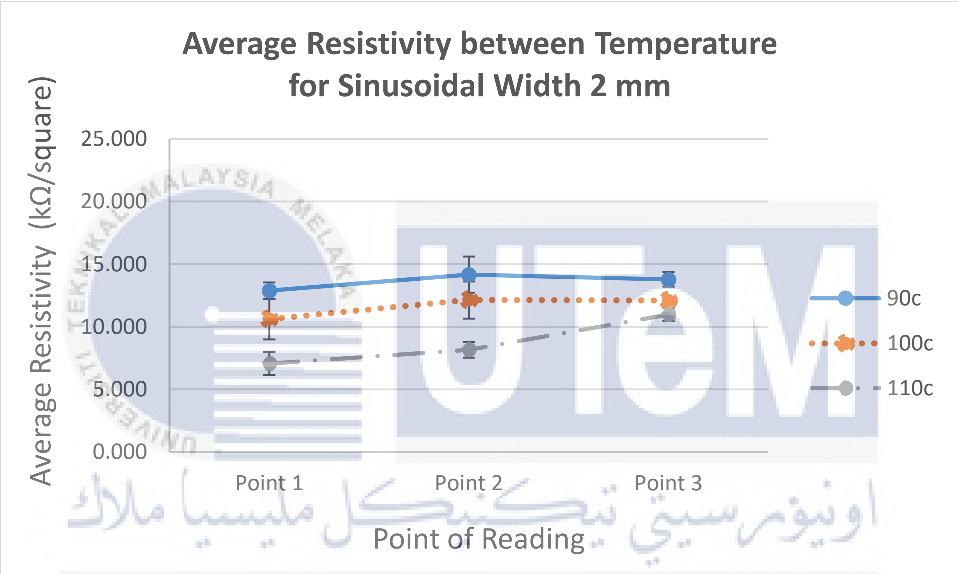


Figure 4. 57: Graph of Average Resistivity between Temperature 90 ℃, 100 ℃ and 110 ℃ for Pattern Sinusoidal Width 2 mm

4.5.11 Average Resistivity for Sinusoidal Width 3 mm

Figure 4.58 show the graph of average resistivity between temperature for sinusoidal with 3 mm width. The graph shows curing at 90 °C temperature has the highest resistivity while curing at 110 °C has the lowest resistivity. The lower the curing temperature, the higher resistivity occurs at the sample. This is because due to the bigger size of phonon leakage and large boundary gap between graphene particles.

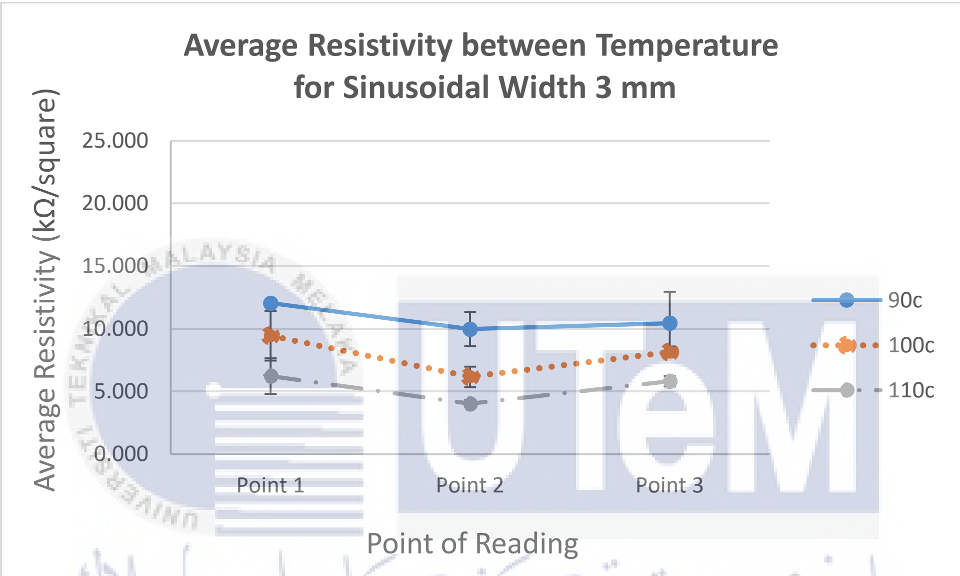


Figure 4. 58: Graph of Average Resistivity between Temperature 90 °C, 100 °C and 110 °C for Pattern Sinusoidal Width 3 mm

4.6 Voltage Between Temperature

The discussion of the results for voltage between temperature of 90 °C, 100 °C and 110 °C for four pattern, straight line, zig zag, square and sinusoidal with the width of 1 mm, 2 mm and 3 mm are shown in this section. The results were shown in the graph and the discussion were well explained above the graph.

4.6.1 Average Voltage for Straight Line Width 2 mm

Figure 4.59 show the graph of average voltage between temperature for pattern straight line with 2 mm width. There is only result for temperature 90 °C and 110 °C were shown in figure below. This is because the result for 100 °C for 2 mm size cannot be read and need to redo the sample. The graph show that the voltage increase by the decreasing the curing temperature. This is due to the increasing of the resistivity and it can be prove using formula V=IR. From the formula, voltage will increase by increasing the resistivity.

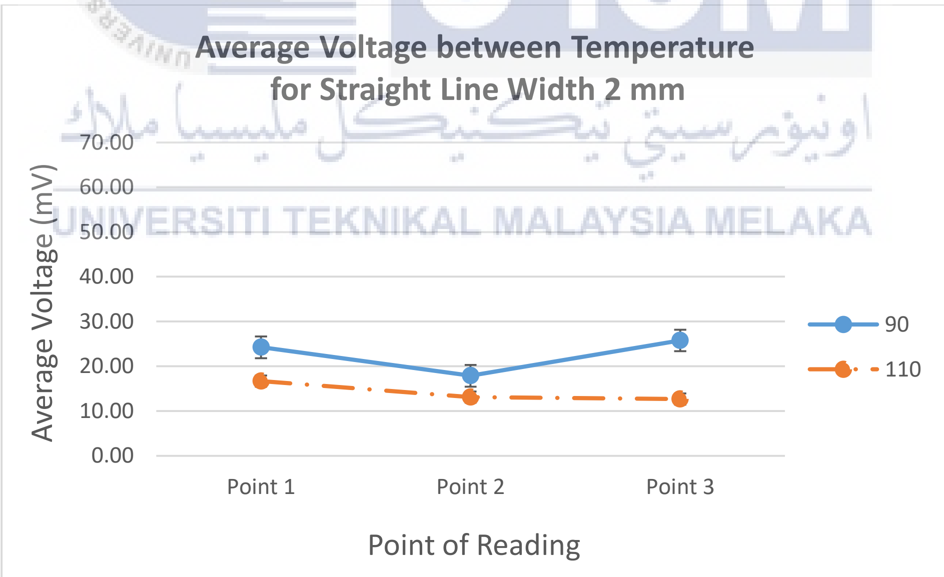


Figure 4. 59: Graph of Average Voltage between Temperature 90 °C, 100 °C and 110 °C for Pattern Straight Line Width 2 mm

4.6.2 Average Voltage for Straight Line Width 3 mm

The average voltage for sintering temperature 90 °C, 100 °C and 110 °C are shown in graph at Figure 4.60 below. From the graph, the voltage shown highest value on 90 °C while lowest at 110 °C. Higher curing temperature can reduce the phonon size on graphene thus it will also block the resistivity from passing the grain boundary. When resistivity decrease, the voltage also decreases, V=IR.

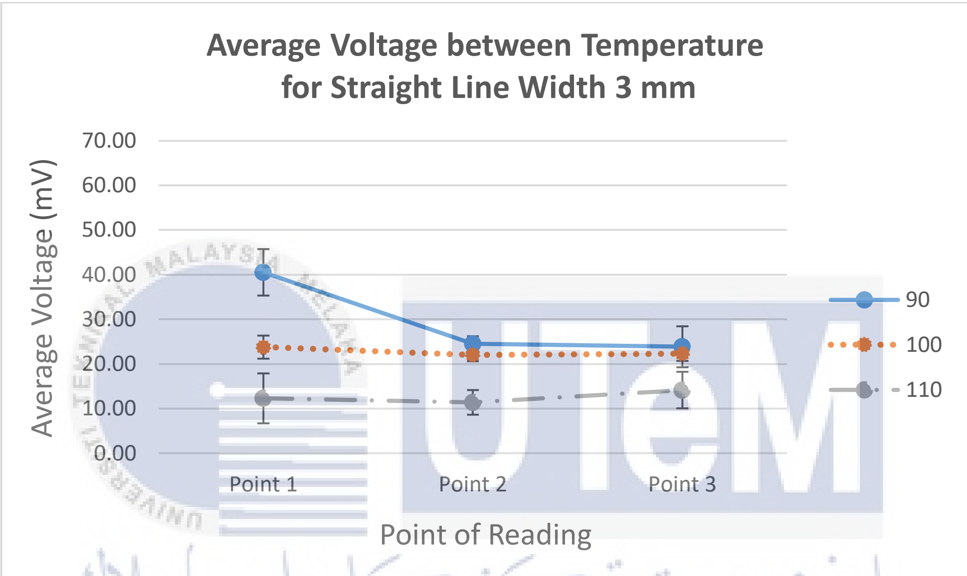


Figure 4. 60: Graph of Average Voltage between Temperature 90 °C, 100 °C and 110 °C for Pattern Straight Line Width 3 mm

4.6.3 Average Voltage for Zig Zag Width 1 mm

Graph from Figure 4.61 below show the result of average voltage between three different curing temperature for sample zig zag with width 1 mm. The result obtain show that 90 ℃ temperature get the highest average voltage followed by 100 ℃. From the observation obtain by reading the graph is voltage higher at lower curing temperature. This is due to the presence of phonon between the graphene layer. Thus the resistivity can pass the layer through the phonon. Means, the lower the curing temperature will cause more resistivity occurs and increasing the voltage.

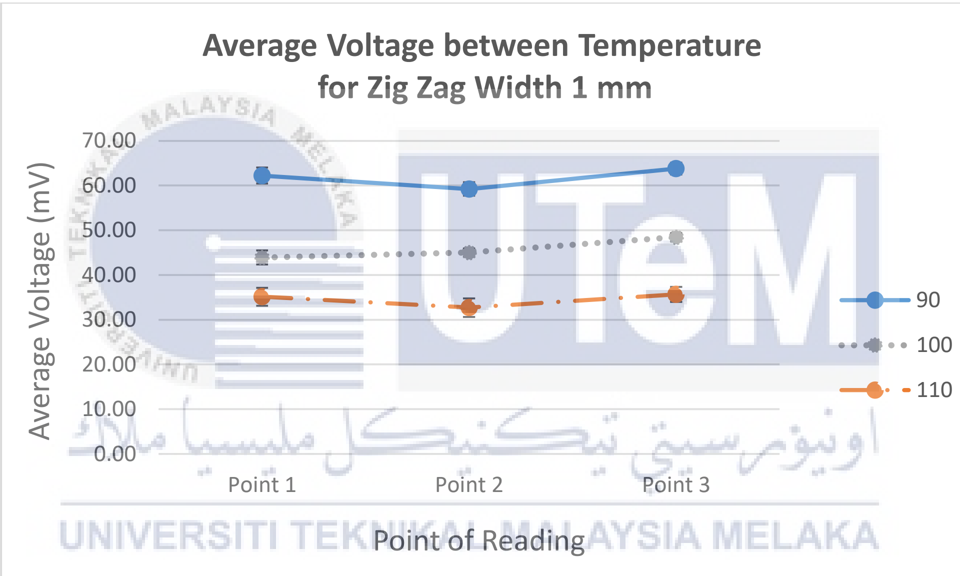


Figure 4. 61: Graph of Average Voltage between Temperature 90 ℃, 100 ℃ and 110 ℃ for Pattern Zig Zag Width 1 mm

4.4.4 Average Voltage for Zig Zag Width 2 mm

Average voltage for temperature 90 ℃, 100 ℃ and 110 ℃ for pattern zig zag with the width of 2 mm are shown in Figure 4.62 below. The graph show temperature for 90 ℃ get the lowest voltage compared to 100 ℃ and 110 ℃. Theoretically, when the temperature becomes high, the resistivity may reduce due to an improvement in grain size. Therefore, as the resistance drops, the voltage also drops on the basis of equation V=IR. In the case of a sample which was cured at a temperature of 90 ° C, the voltage would be the highest among the three temperatures. The mistake could be related to mishandling of the sample during the preparation of the sample or to a mistake during conducting the four-point probe experiment.

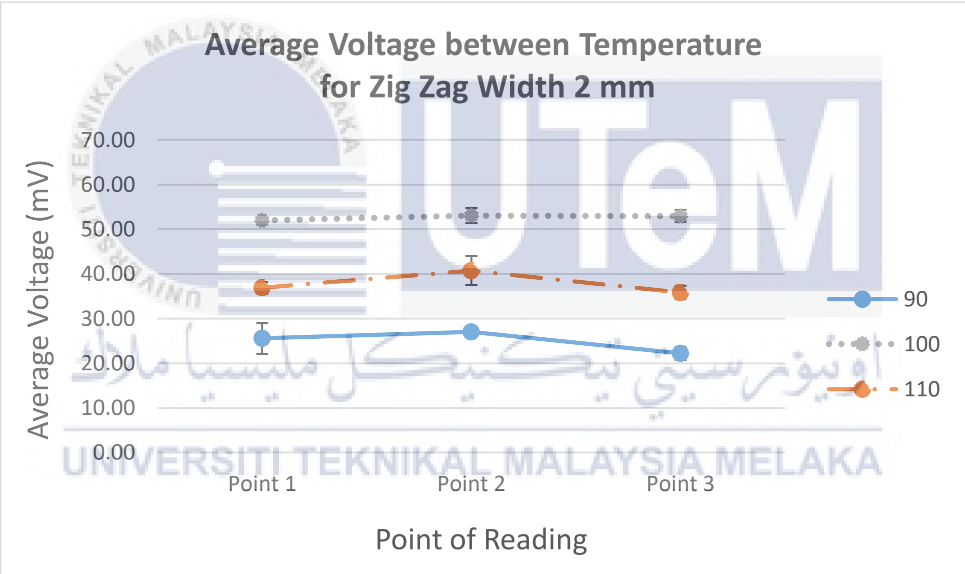


Figure 4. 62: Graph of Average Voltage between Temperature 90 ℃, 100 ℃ and 110 ℃ for Pattern Zig Zag Width 2 mm

4.6.5 Average Voltage for Zig Zag Width 3 mm

Figure 4.63 show the graph of average voltage between temperature for zig zag pattern with width 3 mm. The result obtains from the graph show that 90 ℃ temperature get the highest voltage while 110 ℃ get the lowest voltage. The voltage decrease due to the increasing of temperature. This is because resistance tends to be smaller at higher temperatures owing to the greater grain size of the graphene when the material was heated to higher temperatures.

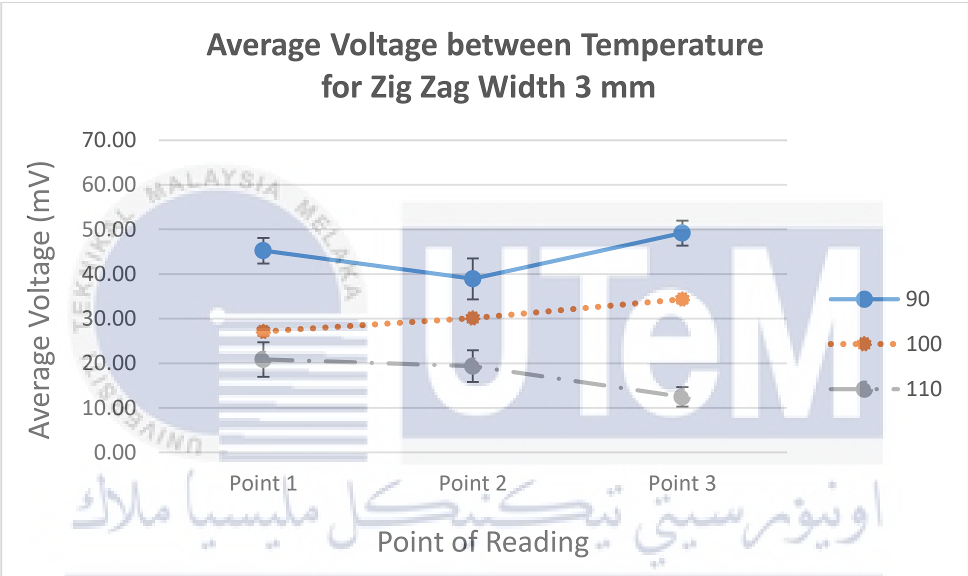


Figure 4. 63: Graph of Average Voltage between Temperature 90 ℃, 100 ℃ and 110 ℃ for Pattern Zig Zag Width 3 mm

4.6.6 Average Voltage for Square Width 1 mm

Average voltage between three different temperatures for square pattern with 1 mm width were shown in Figure 4.64 below. The graph show sample that were curing under temperature 90 °C get the highest average voltage. Besides, from the graph the observation can be made is, the lower the curing temperature, the higher the voltage of the sample. By applying V=IR at here, we can conclude that the higher the voltage, the higher the resistivity occur at the sample.

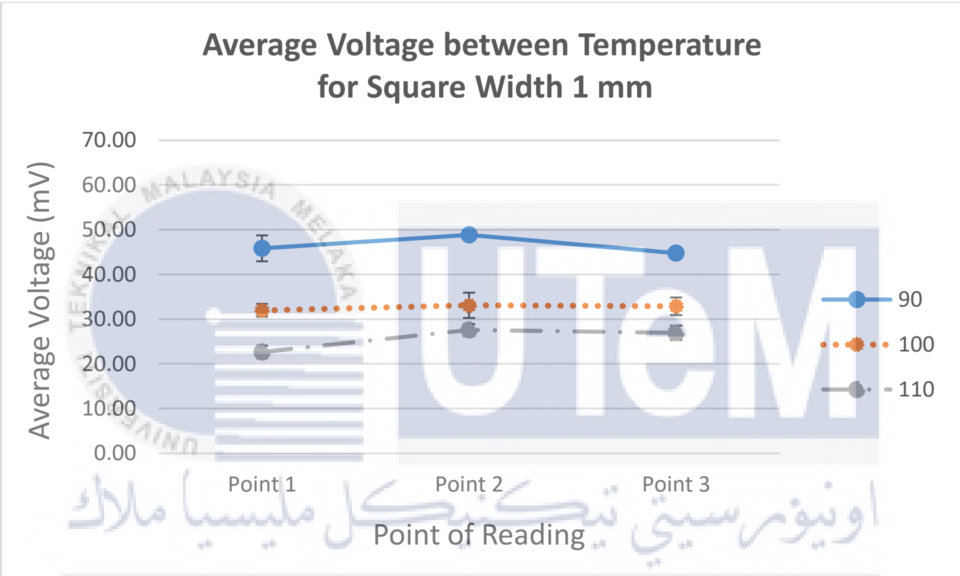


Figure 4. 64: Graph of Average Voltage between Temperature 90 °C, 100 °C and 110 °C for Pattern Square Width 1 mm

4.6.7 Average Voltage for Square Width 2 mm

Figure 4.65 show the graph of average voltage for sample that were cure under three different temperatures to identify which temperature get the highest or lowest voltage. From the graph, it shows that the lower the curing temperature, the higher the voltage occur at the sample. Higher temperature can reduce the phonon area thus will also reduce the present of resistivity between graphene particles. By applying formula V=IR, the voltage also reduces when the resistivity is reducing.

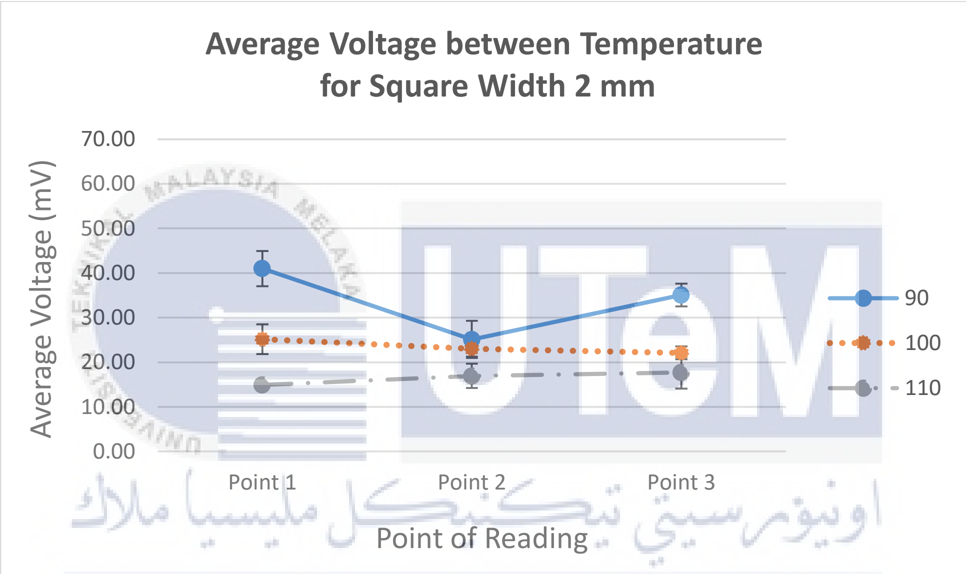


Figure 4. 65: Graph of Average Voltage between Temperature 90 °C, 100 °C and 110 °C for Pattern Square Width 2 mm

4.6.8 Average Voltage for Square Width 3 mm

Graph on Figure 4.66 below show the result of average voltage for sample square with width 3 mm between three different temperatures. The samples were cure under 90 °C, 100 °C and 110 °C temperature to identify the different of the voltage occur at the sample. From the result obtain, 110 °C get the lowest average voltage. From formula V=IR, voltage, V will decrease when resistivity, R decrease. From this experiment, resistivity become lower when the sample was heated under high temperature.

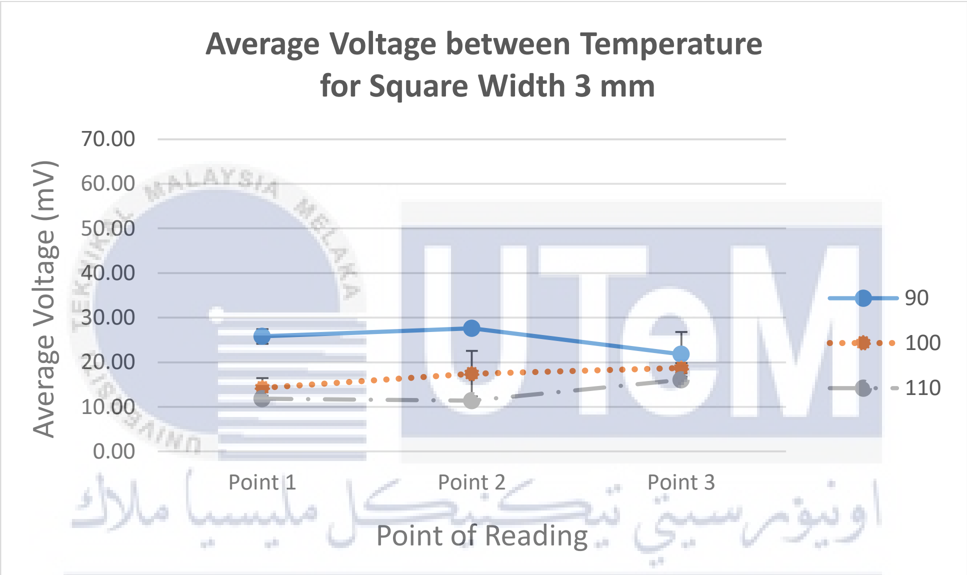


Figure 4. 66: Graph of Average Voltage between Temperature 90 °C, 100 °C and 110 °C for Pattern Square Width 3 mm

4.6.9 Average Voltage for Sinusoidal Width 1 mm

Average voltage between temperature 90 ℃, 100 ℃ and 110 ℃ for sample pattern sinusoidal with width 1 mm were shown in Figure 4.67 below. The graph show that voltage of sample depends on the curing temperature. When the temperature increase, the voltage will decrease. This is because the resistivity decrease when the temperature increase. Based on V=IR formula, voltage will decrease if the resistivity decrease.

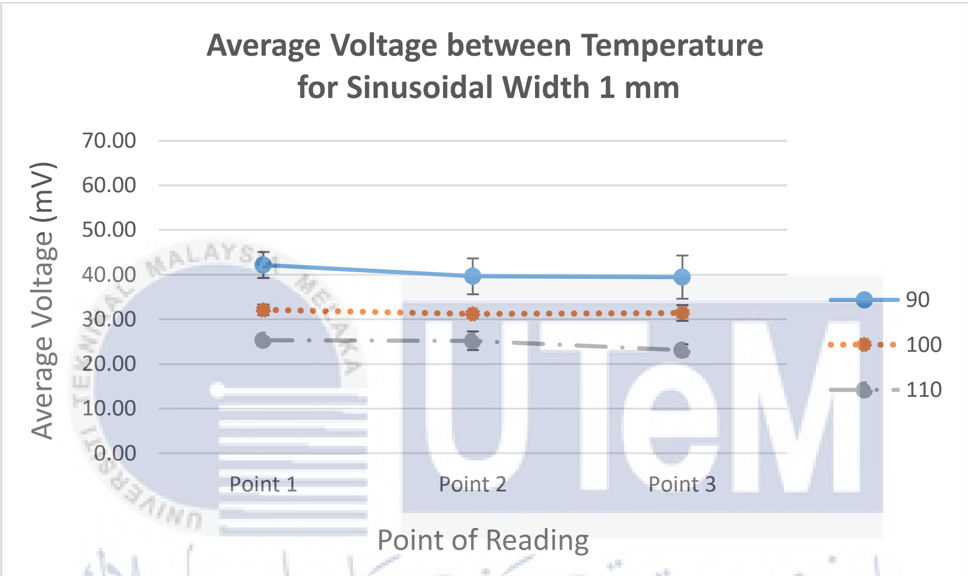


Figure 4. 67: Graph of Average Voltage between Temperature 90 ℃, 100 ℃ and 110 ℃ for Pattern Sinusoidal Width 1 mm

4.6.10 Average Voltage for Sinusoidal Width 2 mm

Figure 4.68 show the graph of average voltage between three temperatures for pattern sinusoidal with width 2 mm. From the graph, it shows that voltage occurs higher at temperature 90 ℃ and lower at temperature 110 ℃. The lower the curing temperature the higher the voltage occur at the sample. This is because the presence of resistance at low temperature is higher than high temperature.

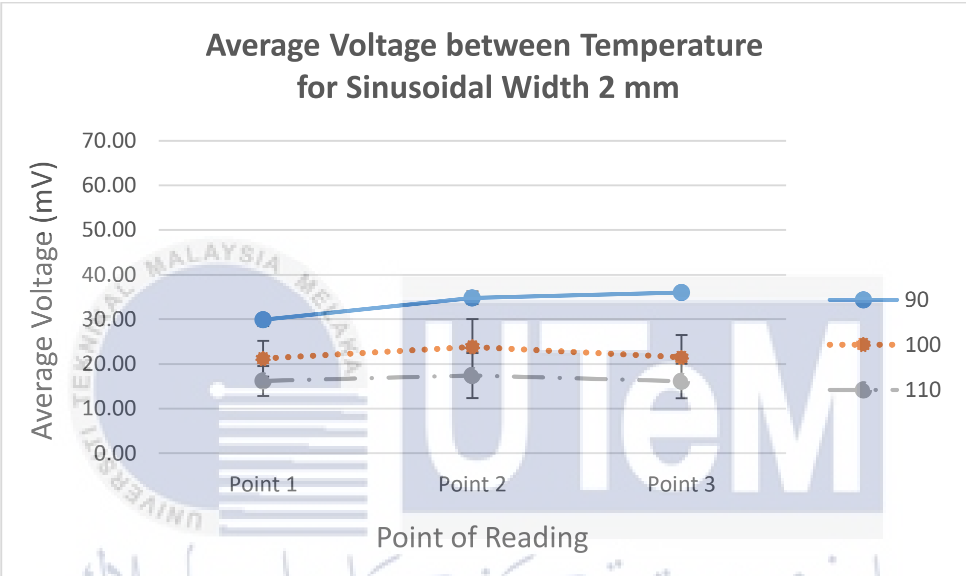


Figure 4. 68: Graph of Average Voltage between Temperature 90 ℃, 100 ℃ and 110 ℃ for Pattern Sinusoidal Width 2 mm

4.6.11 Average Voltage for Sinusoidal Width 3 mm

Average voltage for three temperatures for pattern sinusoidal with width 3 mm were shown on Figure 4.69 below. For temperature 100 ℃ and 110 ℃, the average voltage is unbalance at point 2. Supposed to be point 2 of temperature 110 ℃ is lower than 100 ℃. This may be due to the incorrect handling of the experiment on the sample. However, the graph still indicate lowest curing temperature show the highest voltage while highest curing temperature show the lowest voltage.

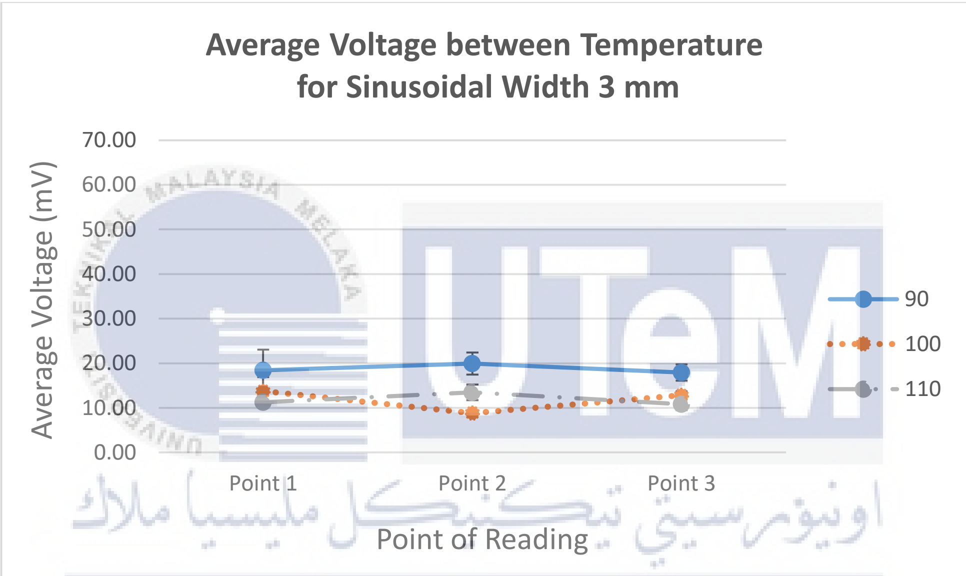


Figure 4. 69: Graph of Average Voltage between Temperature 90 ℃, 100 ℃ and 110 ℃ for Pattern Sinusoidal Width 3 mm

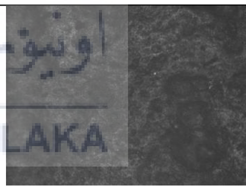
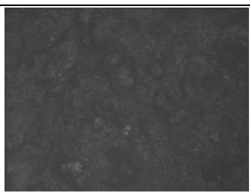
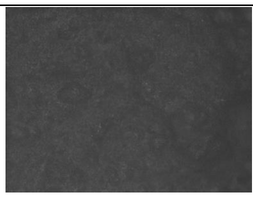
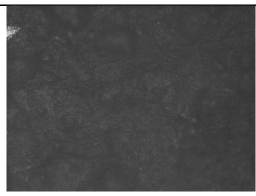
4.7 Microscopy Image of Sample between Temperature

The microscopy image of the sample surface was viewed using a light microscope device. The microscopy image was captured at three point of the sample where it is the same point of resistivity and voltage reading using four-point probe device. Each of the microscopy image of every point was shown in Table below to compare between temperatures in this section.

4.7.1 Microscopy Image for Straight Line Width 2 mm

Table 4.48 show the microscopy image of sample for temperature 90 °C and 110 °C for pattern straight line for 2 mm width. Point 1 and point 3 for temperature 90 °C show a very rough surface and lots of porosity appear in the surface. While point 2 show the least surface roughness, so point 2 has large amount of electrical conductivity because the electricity can easily pass through the sample without much obstacle. For temperature 110 °C, point 1 show surface that have more porosity that surface at point 2 and point 3. Thus point 1 at 110 °C has the largest resistivity occurs. The observation made from the images in Table 4.48 below, it shows that 110 °C has the better surface compare to 90 °C due to more dark area in every point of reading. The dark area is a presence of graphene in the sample.

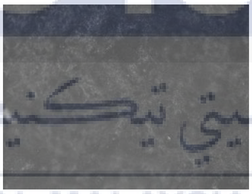
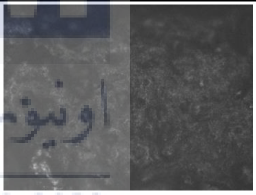
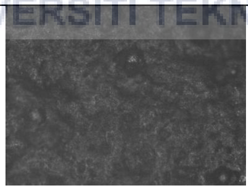
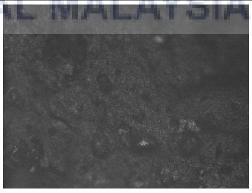
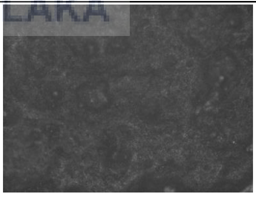
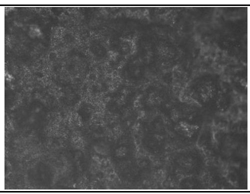
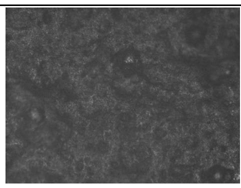
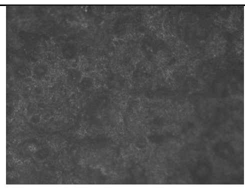
Table 4. 48: Microscopy Image of Sample for Straight Line Width 2 mm

Temperature (°C)	**Point of Reading**		
	1	**2**	**3**
90			
110			

4.7.2 Microscopy Image for Straight Line Width 3 mm

The image of microscope for sample straight line with width 3 mm were shown in Table 4.49 below. Images captured on sample for 90 °C temperature show that point 1, has rough surface compare to point 3. While for 100 °C temperature, point 1 surface is rougher than point 3. Meanwhile the image for temperature 110 °C show that point 3 is better than point 1. For the overall observation, point 1 for temperature 90 °C show the very rough surface among those image while point 3 for temperature 110 °C show the least amount of porosity and roughness. The current flow less at sample temperature 90 °C compare to 110 °C because the current is difficult to flow through the rougher surface due to the present of high resistivity.

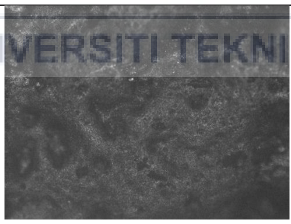
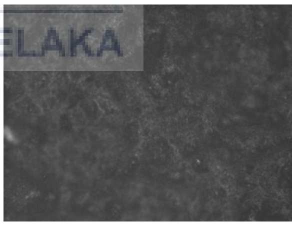
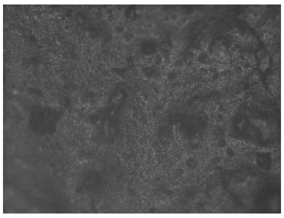
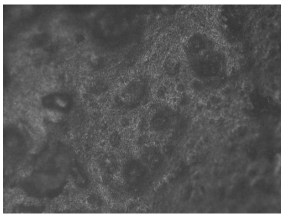
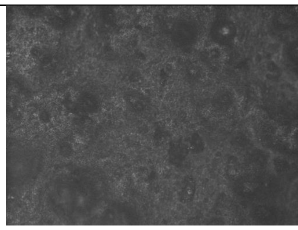
Table 4. 49: Microscopy Image of Sample for Straight Line Width 3 mm

Temperature (°C)	**Point of Reading**		
	1	**2**	**3**
90			
100			
110			

4.7.3 Microscopy Image Zig Zag Width 2 mm

Table 4.50 show the microscopy image of sample zig zag for width 2 mm between three temperatures. Image at point 1 for temperature 90 ℃ show the large number of porosity occurs at the sheet. While image at point 3 show the high amount of bumps appear at the sheet. For temperature 100 ℃, the image at point 1 show large number of bumps and porous. Images at temperature 110 ℃ show point 2 has much porosity among those three images. Generally, the samples at a temperature of 90 ° C display the greatest amount of dark spot on the surface area and sheet resistivity could be found in minimum number on the sheet due to the existence of significant quantities of graphene.

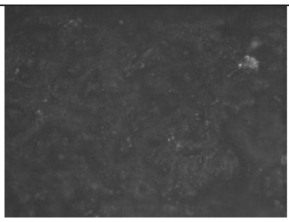
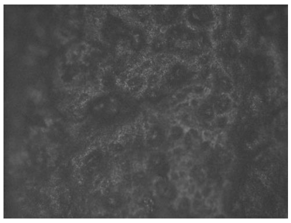
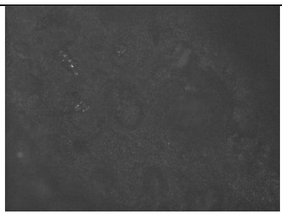
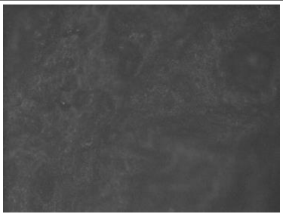
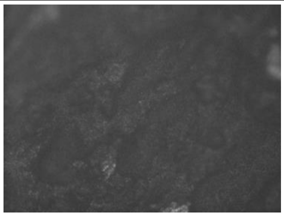
Table 4. 50: Microscopy Image of Sample for Zig Zag Width 2 mm

Temperature (℃)	**Point of Reading**		
	1	**2**	**3**
90			
100			
110			

4.7.4 Microscopy Image for Zig Zag Width 3 mm

Microscopy image for pattern zig zag for width 3 mm are shown in Table 4.51 below. For temperature 90 °C, all the images show the large amount of bump and porosity appeared on the sheet surface. At the temperature of 100 °C, the images seen in point 1 and point 2 indicates a better condition than the surface at temperature of 90 °C. Meanwhile, microscopy images at a temperature of 110 °C are the best of the three temperatures, since the surface has a smaller number of bump and porosity. Based on the Table 4.51, the sample at the temperature with 90 °C can show a high degree of resistance whereas a sample at the temperature of 110 °C will show the least resistance. Current will have the highest flow at the sample temperature of 110 ° C due to the lowest resistance.

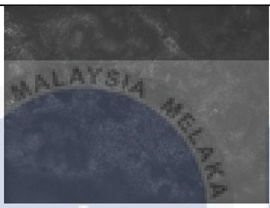
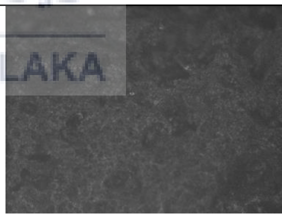
Table 4. 51: Microscopy Image of Sample for Zig Zag Width 3 mm

Temperature (°C)	**Point of Reading**		
	1	**2**	**3**
90			
100			
110			

4.7.5 Microscopy Image for Square Width 2 mm

Images on Table 4.52 below show the surface structure for the sample square with width 2 mm. From the images at temperature 90 ℃, point 1 and point 3 has the rougher surface compare to point 2. For temperature 100 ℃, there are not much different for the surface roughness between this two sample but there is a present of large porosity at point 1. While for temperature 110 ℃, the images seem less porous and bump.

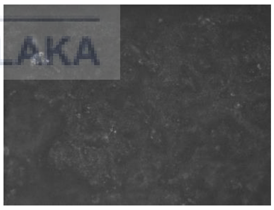
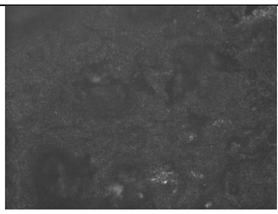
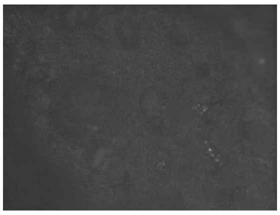
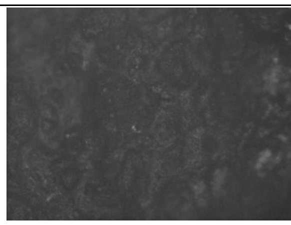
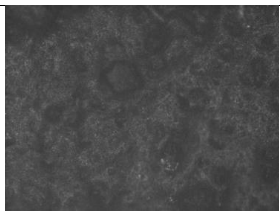
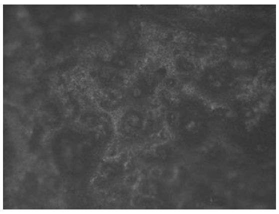
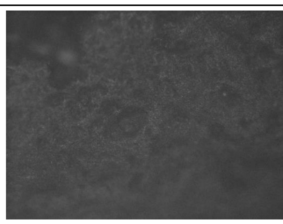
Table 4. 52: Microscopy Image of Sample for Square Width 2 mm

Temperature (℃)	**Point of Reading**		
	1	**2**	**3**
90			
100			
110			

4.7.6 Microscopy Image for Square Width 3 mm

Microscopy image for sample pattern square with width 3 mm are shown in Table 4.53 below. From temperature 90 °C reveals a bumpy surface on the whole sheet, whereas figure (b), point 3 indicates a decent surface roughness. Resistivity can be greater at point 2 as there are more barriers to the rough surface. For temperature 100 ° C, the image at point 2 has a smooth surface opposed to the images at point 1 and point 3. Resistivity are larger at point 1 compare to point 2. Temperature 110 ℃ show image at point 2 indicates a significant quantity of porosity happening on the surface. For complete review, point 2 for temperature 100 ℃ and point 3 for temperature 110 ℃ will have least resistivity due to the greater amount of graphene and least amount of bump and porous on the surface. Current will also move passively across the area that has bump and porous owing to the existence of the blocker.

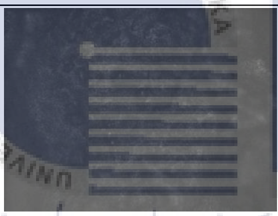
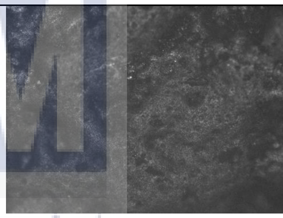
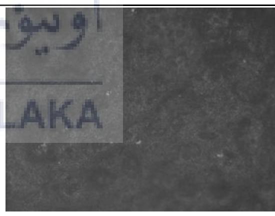
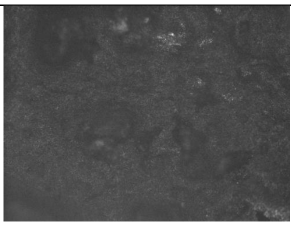
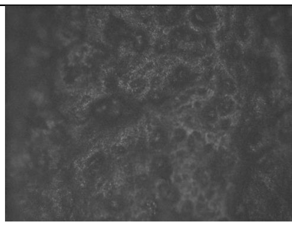
Table 4. 53: Microscopy Image of Sample for Square Width 3 mm

Temperature (℃)	**Point of Reading**		
	1	**2**	**3**
90			
100			
110			

4.7.7 Microscopy Image for Sinusoidal Width 2 mm

Table 4.54 show the microscopy image for sample pattern sinusoidal with width 2 mm. Sample for temperature 90 ℃ show point 1 has higher amount of graphene and less amount of porous and bump on the surface. Meanwhile for point 2 and 3 there are numbers of porous and bump on the surface. For temperature 100 ℃ image at point 1 of the sample show better image rather than image at point 2. The microscopy image at point 3 for temperature 110 °C indicates a wide porosity at the centre of the sheet and the resistance that appear are stronger at that point.

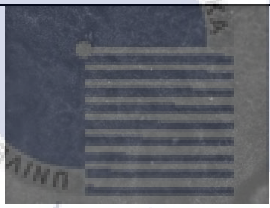
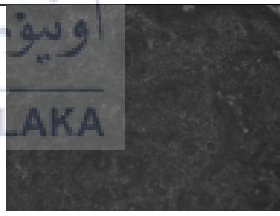
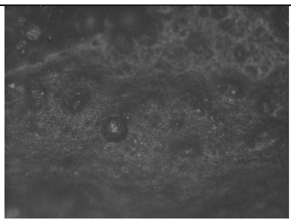
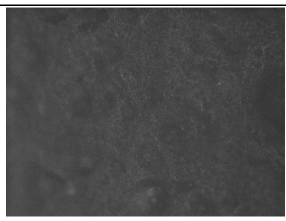
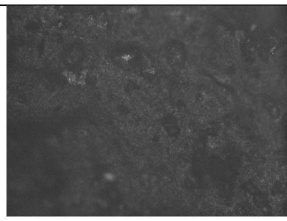
Table 4. 54: Microscopy Image of Sample for Sinusoidal Width 2 mm

Temperature (℃)	**Point of Reading**		
	1	**2**	**3**
90			
100			
110			

4.7.8 Microscopy Image for Sinusoidal Width 3 mm

Microscopy image for sample pattern sinusoidal for width 3 mm show on Table 4.55 below. For temperature 90 ℃ there is no significant difference between the image for this sample. For temperature 100 ℃ image at point 2 is better than point 1 and point 3 because less porosity on the surface. Temperature 110 ° C indicates the point 2 is less bumpy and porosity relative to point 1 and point 3. Generally, image at point 2 for temperature 110 ℃ show the best surface and the resistivity may less occur at that point. Thus, the current flow is greater at that point due to smaller blockage.

Table 4. 55: Microscopy Image of Sample for Sinusoidal Width 3 mm

Temperature (℃)	**Point of Reading**		
	1	**2**	**3**
90			
100			
110			

4.8 Summarization of the Effect of the Width of the Sample towards Resistivity of the Graphene Based Conductive Ink

The experimental results show that the majority of the 3 mm wide sample has a lower sheet resistivity compared to 2 mm and 1 mm. Opposite to the width of 1 mm which has the highest sheet resistivity between the three widths. Therefore, it can be concluded that the wider width results in the lower sheet resistivity. Thus it is the same with the result of the theoretical formulation for the sheet resistivity.

Refer to the sheet resistivity formula from Patil (2015)

$$R_s = R\left(\frac{L}{W}\right) \tag{4.2}$$

Where Rs is Sheet Resistivity (Ω/sq), R is Resistance (Ω), L is Length (mm) and W is Width (mm)

While formula for Resistance is,

$$R = \frac{V}{I} \tag{4.3}$$

Where V is Voltage (V) and I is Current (A)

Thus by insert equation (4.3) into equation (4.2) the formula of sheet resistivity will be

$$Rs = \frac{VL}{IW} \tag{4.4}$$

According to the Eq. (4.4) the sheet resistivity is inversely proportional to the width of the sample. Thus, width of the sample would affect the sheet resistivity. Increasing the width of the sample may reduce the resistivity of the sheet.

4.9 Summarization of the Effect of Curing Temperature towards Graphene Based Conductive Ink

Graphene based conductive ink contains filler and binder whereas both of it are important to form a good conductive ink. A good conductive ink usually contains more filler than binder. In addition, a quality conductive ink also was determined by several factors which are surface roughness, the grain size of graphene, the boundary gaps between graphene atoms and the substrate condition. All of this factors were affect by the curing temperature.

The results show that sheet resistivity decrease when the curing temperature was increase. This is because, high curing temperature can increase the grain size of graphene thus will reduce the phonon leakage and boundary gaps between graphene particles. Thus, when the boundary gap was reducing, the atoms were contact to each other and electrical conductivity will easy to be carry along the atoms with least presence of resistivity.

Besides that, increasing curing temperature also can reduce the viscosity of binder which is epoxy. Epoxy will become more creep in higher temperature and the mechanical properties of epoxy will change to brittle and leading to cracking the material. Therefore, the cracking conductive ink can lead to the increasing of resistivity due to the boundary gap present. Furthermore, too high temperature also not suitable for curing an epoxy as was mention in above literature review. The volume of epoxy will shrink when the sample was cooling in room temperature after it was take out from the oven.

4.10 Possibility of Errors during Preparation of Samples and Experimental

Certain errors can occur during the preparation of the samples and the experimental. This include errors in printing process. Unequal pressure during printing can trigger some places to lose graphene and more epoxy. Besides that, not enough pressure during printing can also cause porous on the sample’s surface. In addition, the speed of printing also can cause an uneven amount of filler and binder at the sample thus will lead to different amount of graphene, epoxy and hardener at every point of reading. Error also can occur during mixing the combination of materials and make the combination is inconsistent. Which will lead to some area will mix more graphene and some contains more binders. In addition, during the curing process, the oven may also be unstable and cause the temperature not to drop, even after the time set has reduced. Other than that, error also can happen while taking the reading for the experimental four-point probe test. This is due to the uneven surface of the sample which does not make the reading so accurate.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

Graphene is famous nowadays due to its unique characteristics in mechanical, electrical and thermal applications. As a response, many researchers and technologies conducted a number of studies and experiments under different variables to identify the best performance of graphene. This study shows, aside to the composition of graphene with binder, temperature also is the high reason for maintaining a good structure to conductive ink. A good conductive ink structure can improve the electrical and mechanical performance of the conductive ink.

Temperature is also the primary factor in the combination of the filler and the binders for good material composition. This is because, curing temperature can affect the linkage between binder and filler thus it will lead to smooth electrical and thermal conductivity. However, too high of curing temperature can also be harmful to the conductive ink because can cause cracking or deformation on conductive ink surface. Besides, curing temperature also can affect the shape of the substrate. TPU substrate will go under deformation in high curing temperature.

Therefore, several experiments were conducted to justify the analysis from previous study. Samples with different width and patterns have been tested under curing temperature of 90 ℃, 100℃ and 110 ℃ in order to determine the electrical properties and microscopy image of the sample using four-point probe and light microscope device.

From the experiment and studies, it can be conclude that width of the conductive ink plays an importance role in order to achieve good electrical properties. The result show that bigger width can flow more current due less resistivity. Besides that, result from the experiment also show that high curing temperature can obtain good result of low resistivity thus will lead to high current flow, using formula I=V/R, current, I will increase with decreasing of resistivity, R. From the research and experimental result, it can be conclude that analysis the effect of various temperature on graphene based conductive ink is important in order to improve the performance of graphene based conductive ink by manage the temperature or thermal related properties. Lastly, the objective of this research were achieved.

The recommendation for future works is, conduct an experiment to determine the mechanical properties of graphene conductive ink after curing using nano-indentation device. Therefore, it is possible to decide which temperature is better in order to producing flexible conductive ink.

In addition, use bigger range or of curing temperature in order to see significant difference for resistivity and also microscopy image. That is because the temperature range at 10 °C is so low and the gap in the sheet resistivity reading is therefore minimal and also the difference in the microscopy image is not too noticeable. Other than that, future studies should also begin from the minimum temperature to the maximum temperature at which the filler and binder can endure. It would then be easier to define the temperature where a good graphene based conductive ink will achieve. Besides that, the maximum temperature for graphene based conductive ink can also be determined.

Finally, the printing method has to be enhanced with the usage of the printing machine. That if the printing machine is used, the force, speed and pressure for printing the ink will always be consistent. This helps to reduce the errors that happens during the printing process.

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