SCHOOL OF MATERIALS AND MINERAL RESOURCES ENGINEERING

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FABRICATION OF CONDUCTIVE INK BASED ON GRAPHENE NANOPARTICLES

By

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DECLARATION

.

I hereby declare that I have conducted, completed the research work and written the dissertation entitled **"Fabrication of conductive ink based on graphene nanoparticles"**. I also declare that it has not been previously submitted for the award of any degree or diploma or other similar tittle of this for any other examining body or university.

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LIST OF ABBREVIATION

PDMS	Polydimethylsiloxane
PDMS-OH	Polydimethylsiloxane hydro terminated
CNT	Carbon nanotube
ITO	Indium tin oxide
Ag	Silver
AgNWs	Silver nanowires
SE	Stretchable electronic
GO	Graphene oxide
RGO	Reduced graphene oxide
LED	Light emitting diode
PMMA	Polymethyl methacrylate
PI	Polyimide
PET	Polyethylene terephthalate
Si	Silicon
PEDOT	Poly(3,4-ethylenedioxythiophene)
D4	Octamethyl-cyclotetrasiloxane
VTMOS	Vinyltrimethoxysilane
SEM	Scanning electron microscopy
DSC	Differential scanning calorimetry
TGA	Thermal gravimetric analysis
ASTM	American society for testing and material
FTIR	Fourier transform infrared

FABRIKASI DAKWAT KONDUKTIF DAN BOLEH REGANG MENGGUNAKAN GRAFIN NANO

ABSTRAK

Objektif utama projek ini adalah untuk menyediakan dakwat konduktif dan boleh regang. Sampel boleh regang telah disediakan dengan menggunakan grafin nano sebagai dakwat konduktif. Sampel boleh regang terdiri daripada dua komponen iaitu substrat dan dakwat konduktif. Substrat boleh regang dihasilkan menggunakan polisiloksana. Dalam usaha untuk menghasilkan dakwat konduktif boleh regang menggunakan nanopartikel grafin, dengan kekonduksian yang baik, bahan-bahan tertentu seperti Polidimetilsiloksana hidrosida yang berat molekulnya (PDMS-OH) dan katalis-tin telah digunakan. Dalam projek ini, empat sampel boleh regang yang mengandungi kandungan grafin yang berbeza (15%, 20%, 25%, 30%) telah dicetak. Kemudian, sifat-sifat elektrik grafin pakej yang telah dicetak telah dikaji. Sifat-sifat elektrik yang telah dikaji ialah kekonduksian dan kerintangan sampel semasa dalam keadaan normal dan keadaan diregangkan. Selain itu, struktur kimia, sifat-sifat mekanikal dan sifat haba pakej yang telah dicetak juga dikaji. Hasil kajian menunjukkan sampel yang mengandungi 20% grafin mempunyai tahap regangan yang tertinggi dengan kekonduksian yang baik manakala sampel dengan kandungan tertinggi grafin iaitu 30% mempunyai kekonduksian yang paling tinggi semasa dalam keadaan normal. Namun, ia mempuyai sifat boleh regang paling lemah yang menyebabkan penurunan pada kekonduksian semasa dalam keadaan regang.

FABRICATION OF STRETCHABLE CONDUCTIVE INK BASED ON GRAPHENE NANOPARTICLES

ABSTRACT

The main objective of this project was to fabricate stretchable graphene conductive ink. The stretchable printed package was prepared by using graphene nanoparticles as conductive ink. The stretchable printed package consist of two components which is stretchable substrate and conductive ink. The stretchable substrate was prepared using polysiloxane. In order to make the graphene conductive ink stretchable with good conductivity, specific ingredients like high molecular weight polydimethylsiloxane-hydroxide (PDMS-OH) and tin catalyst was added. In this project, four samples of stretchable printed package that contain different concentration of graphene (15%, 20%, 25% and 30%) is prepared. Then, the electrical properties of the graphene printed package sample prepared was studied. The electrical properties that was studied were conductivity and resistivity of the sample during normal and stretched condition. Besides that, chemical structure, mechanical properties and thermal properties of the printed package were also studied. The results revealed that sample that contain 20% weight percentage of graphene has the highest stretchability with good conductivity while sample with the highest concentration of graphene which is 30% has the highest conductivity during unstretched condition but its stretchability is very poor that cause decreased in conductivity during stretch condition.

CHAPTER 1

INTRODUCTION

1.1 Research Background

Printable and flexible circuit are most popular techniques that start to widespread and occupy a huge market. A lot of efforts have been made in order to produce flexible, low cost, and environmental friendly printed circuit. Printed electronics are being explored for the manufacture of large scale and flexible electronics devices by the patterned application of printable materials. In addition, it is important for the electronic devices to have an ability to be stretched and also flexible. One of the challenges in developing stretchable electronics is to develop stretchable electronic materials that have the ability to offer higher electrical conductivity while enduring large repeated strains (Larmagnac et al., 2014). There are a lot of research have been done to improve the performance of the stretchable circuits.

Introducing of flexible, stretchable, electrically conductive materials on soft substrate could give unique mechanical properties allowing them to bend, fold, stretch or conform to their environment. Stretchable electronics enables a lot of new applications such as stretchable displays, flexible sensors for personalized healthcare and conformal electrode arrays to interface the heart and brain that cannot be done by using rigid electronics (Van den Brand et al., 2015). The previous flat rigid device electronics need to be transformed into a flexible or stretchable electronics device that can better follow the shape of the human body since it will give comfort and better wearability to the user.

Nowadays, due to their popularity in printed electronic and flexible electronic, conductive inks have been widely investigated (Karthik and Singh, 2015). Preparation of conductive ink plays an important role in the development of printed electronics. The ink for the stretchable printed electronics has to be specially designed. The conductive lines have to be printed on the substrate. Conductive ink is an ink that results in a printed object which has the ability to conducts electricity. There are several ink or paste and substrate combinations to choose from. Besides that, highly stretchable materials with good conductivity are highly desirable.

In recent years, expensive materials such as gold and platinum are widely used in the preparation of conductive ink (Karthik and Singh, 2015). To overcome these drawbacks, silver filler has been used to prepare conductive inks. Silver is mostly used since it has high electrical and thermal conductivities and chemical stability (Nishikawa et al., 2010). Besides silver, other conductive filler such as copper, carbon nanotubes (CNT) and indium tin oxide (ITO) also can be used to prepare conductive ink. Recent research shows that graphene is a promising next-generation conducting material with the potential to replace traditional materials such as gold, platinum, silver tin, iron and others (Jo et al., 2012).

Over the past few years, graphene has become popular as a hot research topic in nanotechnology and are intensively investigated. According to Moldovan et al. (2015), graphene is the name given to a two-dimensional sheet of sp2-hybridized carbon. Its extended honeycomb network is the basic building block of other important allotropes; it can be stacked to form 3D graphite, rolled to form 1D nanotubes, and wrapped to form 0D fullerenes. Moreover, graphene has the ability to conduct both heat and electricity with great efficiency. Graphene material main advantage are super-strong, super-light, durable-yet-flexible two-dimensional material. Most notably, they are quite cheaper than carbon nanotubes or silver nanowires (AgNWs) and have an abundant material source.

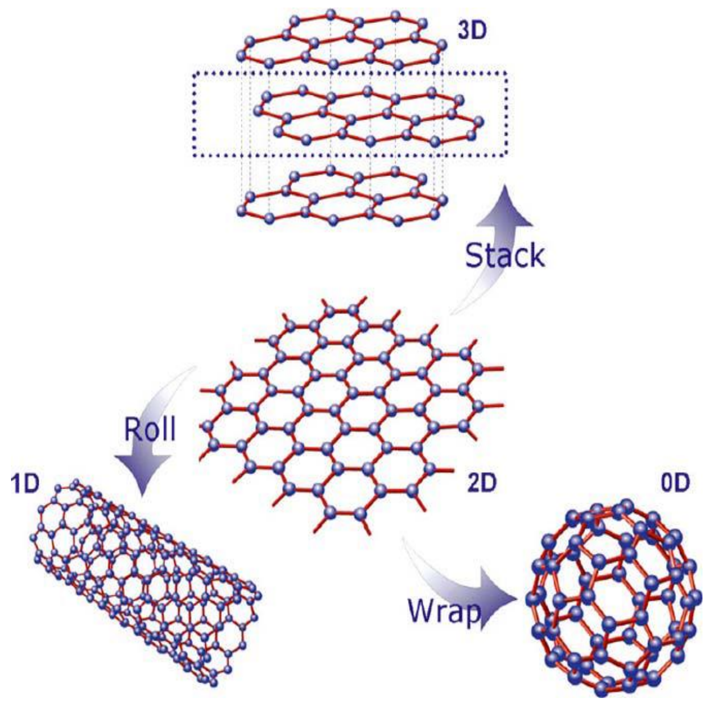

Figure 1.1: Graphene is the basic building block for other carbon allotropes (He and Tjong, 2016).

Polydimethylsiloxane which is silicon – based organic polymer has been choosen as substrate and extensively used in order to prepare printed circuit. According to Chuang and Wereley (2009), a mixture of a PDMS prepolymer and metallic powder shows higher conductivity. PDMS belongs to the group of silicones which are made of silicon, carbon, hydrogen and oxygen. PDMS consist of a flexible (Si-O) backbone and a repeating ($Si(CH_3)_2O$) unit (Seethapathy and Górecki, 2012).

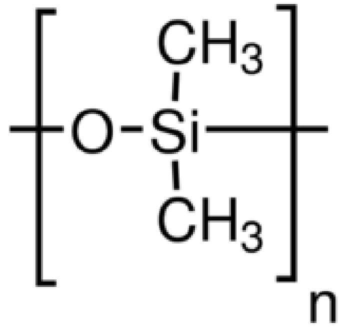

Figure 1.2: PDMS chemical structure
(Kricheldorf, 1996)

The speciality of PDMS are optically clear and generally inert, non-toxic, non-flammable and does not bio accumulate. It has very low glass transition temperature of -127 °C and a shear elastic modulus of 250kPa. In addition, it has low cost, ease of fabrication and biocompatibility (Seethapathy and Górecki, 2012). According to Samuel et al. (2016), PDMS is important in biomedical applications where flexibility and stretchability are required as it is biocompatible, chemically stable and transparent

1.2 Problem Statement

The challenges that need to be faced in this project is how to optimise the conductivity of the graphene ink. In order to prepare conductive ink, type of ingredient used must be determine first. The best formulation for the substrate and conductive ink need to be determine to produce the conductive graphene package. In order to determine the best formulation, a lot of rational trial is compulsory until the best formulation is achieved.

The elasticity and stretchable of the PDMS substrate can affect the length of the conductor and at the same time will change the value of the resistance. Conductivity of the elastomeric conductors printed on stretchable substrate of PDMS is the main concern when under mechanical deformation.

Besides that, the adhesion between the conductive ink and the substrate need to be good and the elastic modulus between both of them need to be comparable in order to prevent local rupture during stretching. Another intrinsic problem is the homogeneity of conductive filler in ink matrix.

Therefore, the aim of this project is to understand the graphene-based ink as a conductive ink printed on stretchable substrates that can open a new possibility for flexible and stretchable sensor applications due to its relationship between the resistance and stretch apply on the PDMS substrate. The outcome of this research may bring a lot of benefits and contribution into the electrical technology application.

1.3 Research Objectives

This research aims,

i) To prepare a stretchable conductive ink based on graphene on PDMS substrate.

ii) To study the electrical characteristic of the graphene conductive ink.

iii) To study the mechanical properties of the PDMS substrate and graphene ink.

1.4 Thesis Structure

This thesis basically consists of five chapters.

Chapter 1 highlights the brief introduction about the stretchable electronics and conductive ink. Problem statement, research objectives, and structure of thesis are also presented in this chapter.

Chapter 2 discusses the literature review study.

Chapter 3 covers the details of material, formulation and methodology in this research. All the testing and characterization methods are presented in this chapter.

Chapter 4 focuses on the experimental results and discussion.

Chapter 5 conclude about the significant findings. There are also a few suggestion and recommendation that can be used in future work.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Nowadays, most electronics appliances are bulky and rigid since they are fabricated on rigid substrates such as glass. In future, most electronics will be fabricated on polymeric foil so that it going to be flexible and stretchable. An increasing interest in stretchable electronics has developed in the area of electrical and electronic system. Stretchable composites suitable for use in electric circuits, interconnects and electrodes. There have been a wide variety of efforts in order to develop conductive elastomers that can provide good mechanical stretchability and electrical conductivity, so those stretchable and wearable devices can be produced (Someya, 2012).

According to Someya (2012), the traditional solid electronics will be replaced by the electronic that are as flexible as films and as stretchy as rubber sheets. The latest advances in conductive inks and printing technologies have enabled engineers to design and construct a large variety of mechanically flexible and stretchable electronic devices. Electrical properties of the ink are determined by conductive particles such as silver mixed into the ink solution and the way they 'connect' in the cured ink. The most preferred method for fabricating stretchable electronic components or circuits is by depositing conductive inks on organic or inorganic layers. This method is chosen due to its low cost (Tekin et al., 2008).

According to Mohammed and Pecht (2016), development of screen printable stretchable electronics (SE) consist of stretchable conductive inks screen printed on stretchable substrates. Based on their research, the conductive ink is a mixture of metallic particles contained within a solvent and contain three different component of materials. The first component is the group of materials that will determine the functionality of the ink which is metallic powders like Ag, Au, or Cu. The second component, consisting of polymer binders, plays a critical role in attaching the metallic powders to the substrate during and after the sintering process. The last component is volatile solvents and nonvolatile organic polymers. This group is important to generate the rheological properties necessary for screen printing. It also acts as the carrier for the metallic powders and the polymer binders during the screening process and the sintering process.

Stretchable ink should be able to be strained by at least 20% of its original length, for at least 500 cycles and the resistance should not increase by more than 30 times its original resistance while maintaining electrical and mechanical integrity. Based on their research, it suggests that ink with only nano-silver spheres will have higher conductivity, but it cannot enhance the stretchability of the ink. However, the stretchability can be increased with a multi-modal mixture of fine and large-diameter silver flakes. Flakes that smaller in size will increase the conductivity and lower the sintering temperature while flakes that have larger size promote ohmic connectivity during stretching. Figure 2.1 shows the multi-modal flake distribution increases connection points while enhancing packing density (Mohammed and Pecht, 2016).

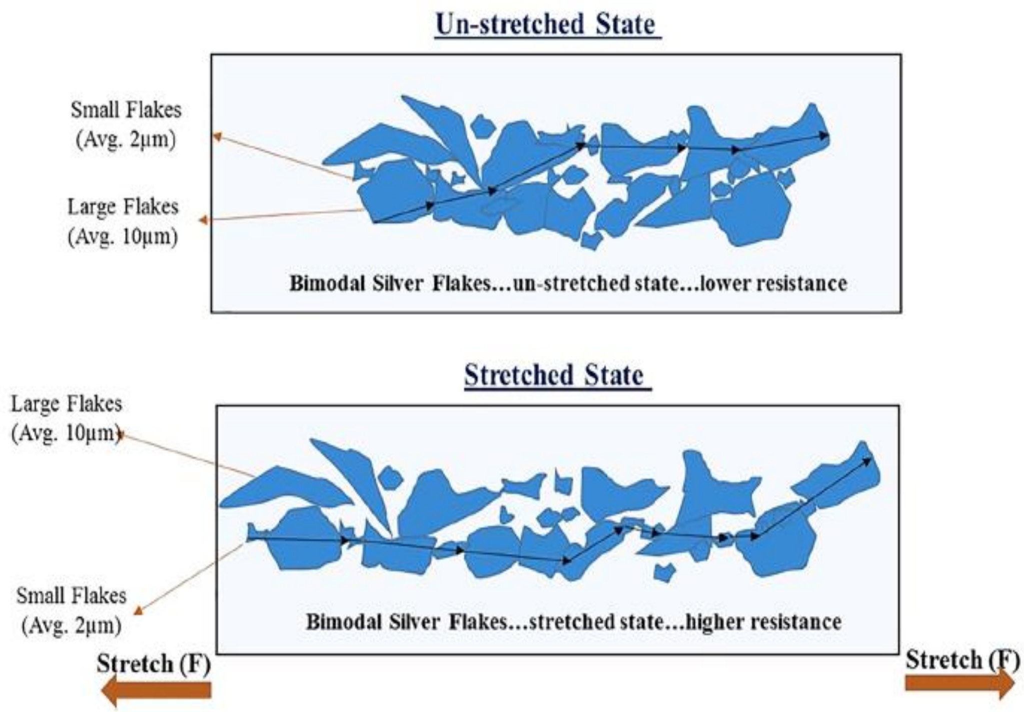

Figure 2.1: A conceptual approach- Bimodal flake distribution maintaining ohmic connectivity during stretching (Mohammed and Pecht, 2016).

Normally, the conductive ink consists binders such as polymeric, epoxy, siloxane, or resin binders. This is because granular powders alone cannot form a continuous film without linkages of them. However, Huang et al. (2015) stated that binders need to be decomposed or evaporated through high-temperature thermal annealing. This high-temperature process prevents the ink from printed on flexible substrates such as papers and textiles. However, binders also act as an insulator that causes ink has a lower conductivity. A binder-free strategy is developed in order to achieve both low-temperature processing and high conductivity. In addition, it also combines with rolling compression to enhance printed ink conductivity.

2.2 Conductive Material

Conductive filler is the main material in the preparation of conductive ink. The conductive filler includes silver, gold, copper, nickel, aluminum, carbon nanotube (CNT), indium tin oxide (ITO) cobalt powder and graphene. Among all these conductive fillers, the gold powder has the excellent chemical stability and conductivity. It is the best conducting particle in the conducting resin. But it is very expensive and only can be used in the products that require extremely high stability and reliability.

In recent years, indium tin oxide (ITO) was used in order to prepare flexible electronic applications. The advantages of ITO are it offers both optical transparency and it also has good electrical conductivity. However, because of the limited supply of indium, the cost of indium rapidly increased and it is not suitable for the flexible electrodes since ITO thin films are brittle in nature. Due to the following non-ideal properties, ITO is not a suitable candidate for future high performance, low cost and flexible electronic devices (Kumar et al., 2013).

To overcome these drawbacks, silver conductive fillers also can be used as an alternative in order to fabricate conductive ink. Due to its high electrical, good thermal conductivities and good chemical stability, silver is the metal fillers that most commonly used. Wang et al. (2016) reported their research of low-temperature sintering nano-silver conductive ink printed on cotton fabric as printed electronics. Figure 2.2 shows the preparation of nano-silver conductive ink and its application on cotton fabric. In this project, in-situ synthesis method in an aqueous solution has been used to produce silver nanoparticles conductive ink. They also studied the effect of size distribution of the Ag nanoparticles with conductivity.

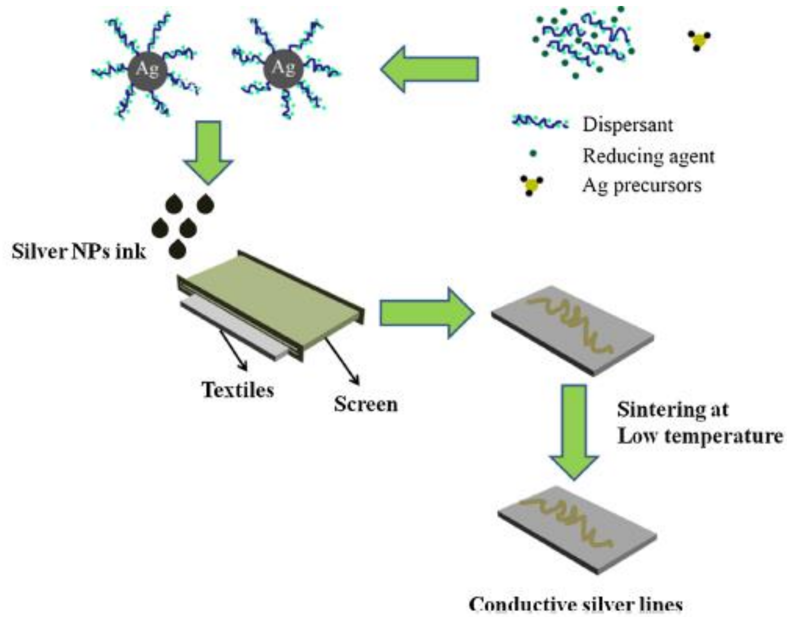

Figure 2.2: The preparation of nano-silver conductive ink and its application on cotton fabric (Wang et al., 2016).

According to He and Tjong (2016), other than silver, copper also one of the promising candidates of conductive fillers. This is due to its low resistivity, low cost, and good electromigration performance. Moreover, the price of copper is 20 times cheaper than silver. However, the main drawbacks of using copper for fabricating the conductive inks is copper easily oxidizes when exposing to the atmosphere due to the reaction with oxygen. In order to overcome the easily oxidize problem, Nishikawa et al. (2010) studied the effects of silver coating covered with copper filler on electrical resistivity of electrically conductive adhesives (ECA).

The copper particles were coated with silver and the effect of silver coating on the electrical resistivity of ECA was investigated. Electroless plating was used to coat the copper particles with silver. Four different types of conductive adhesives were prepared. ECA-1 contain only pure copper fillers with a spinous shape and phenolic resin as a polymer matrix. ECA-2 was composed of silver-coated copper fillers with a spinous shape and resin. ECA- 3 composed of silver-coated copper fillers with a spherical shape and resin and lastly ECA-4 was composed of silver-coated copper fillers with a spherical shape and resin. The result shows that the electrical resistivity of conductive adhesives that filled with silver coated copper much lower than the pure copper filler.

In printed circuit technology, graphene is a promising next-generation conducting material with the potential to replace traditional materials such as gold, platinum, silver, tin, iron, etc (Jo et al., 2012). Graphene is a 2D material made of carbon atoms, arranged in a honeycomb lattice resembling the hexagons that bees make to store honey (Weiss et al., 2012). It is the thinnest and strongest material known to man. Graphene has characteristics that make it interesting for industrial applications, such as electrical conductivity, transparency, flexibility, mechanical strength and environmental stability. These properties make graphene a promising candidate in order to produce multiple products such as flexible and transparent electronics, high-performance computing, composites, photonics, conductive inks, light-emitting devices, touch screens, etc (Moldovan et al., 2015)

Graphene has superior properties. The main advantages of graphene are super strong, super light, flexible and it also has higher conductivity. The addition of graphene to a matrix will give higher mechanical properties with promising applications in many industries, such as aerospace, electronics, structural and mechanical, environmental, medicine, and food and beverage. However many improvements still need to be done. Structure control, dispersion of graphene in the matrix, interfacial interaction between the graphene and matrix, and contact between individual graphene is the technical barrier must be taken into account to realize the wide application of these wonder material (Du and Cheng, 2012).

Recently, Ji et al., (2013) described how graphene can be produced and then use it to produce conductive ink for inkjet printing. The graphene is produced by exfoliation of graphite flakes in dimethylformamide. In order to study the electrical properties such as resistivity value, conductive value, the graphene line length, width, and thickness (proportional to the number of printing passes) can be adjust, in this research, the graphene conductive ink is print with different number of layer which is 10, 15 and 20 layers. The result shows that as the number of graphene layer increase the resistivity value will decrease.

Huang et al. (2015) prepared a highly conductive and highly flexible printed graphene for wireless wearable communications applications by using graphene nanoflakes. The graphene ink prepared was printed on the conventional paper that acts as the substrate. After that, rolling compression process was used to obtain highly dense graphene laminates by using compression roller. The conductivity and surface resistance of the printed graphene under various compression ratios were measured. From this research, it can be seen that as the compression ratio increase, the conductivity will increase and the sheet resistance decreases accordingly. The conductivity of the printed graphene is 8.3×10^2 S/m at 0% compression ratio while the conductivity increases to 4.3×10^4 S/m at 80% compression ratio.

According to Chen et al. (2013), fabrication of lightweight 3d graphene foam composite can be done by growing the graphene on copper or nickel foam substrate by using chemical vapor deposition process. Then, a thin layer of PDMS was coated on the surface of graphene and continued with etching away the metal template. This etching process needs a longer time. This process will give the graphene composite a foam-like structure. The electrical conductivity of the graphene foam composite is as high as 2 S/cm with 0.8 wt% graphene loading. It also has higher mechanical flexibility and the electrical conductivity does not show any obvious performance degradation even after repeatedly bending 10000 times. The graphene foam embedded in elastomer can be stretched up to 95% before undergoing fracture.

2.3 Substrate Materials

Both mechanically rigid and flexible polymeric materials have been widely used in electronics as substrate materials that used to mount chips or other electrical components. Various types of organic materials including paper impregnated with phenolic resin, woven or non-woven glass cloth, polyimide or polyester can be used as base material in flexible electronics depending on the physical characteristics required by the application, such as operating temperature, frequency or mechanical strength. Besides that, low cost and ease of manufacture are other parameters that need to be considered in order to choose the substrate materials.

Hocheng and Chen (2014), stated that there are three types of substrates that commonly used in electronic devices. The first one is the solid substrates. Most of the traditional electronic devices use solid substrates due to their high strength against bending and impacts. Besides that, solid substrates also possess the highest reliability. The second one is the flexible substrates. One of the drawbacks of this flexible substrate is it has limited bendability and little stretchability. If someone folds the flexible circuit for a thousand cycles, the circuits will decrease its lifetime drastically.

Nowadays, the use of stretchable substrate starts to increase. Stretchable substrates can sustain large bending and stretching actions, and they also can be placed on any non-planar surface. However, stretchable substrates also have their own disadvantage which is their lifetime is the lowest among the three, due to the working conditions that force them to be bent and stretched constantly. Stretchable substrates can be divided into three types which are the coplanar type, compound type, and non-coplanar type.

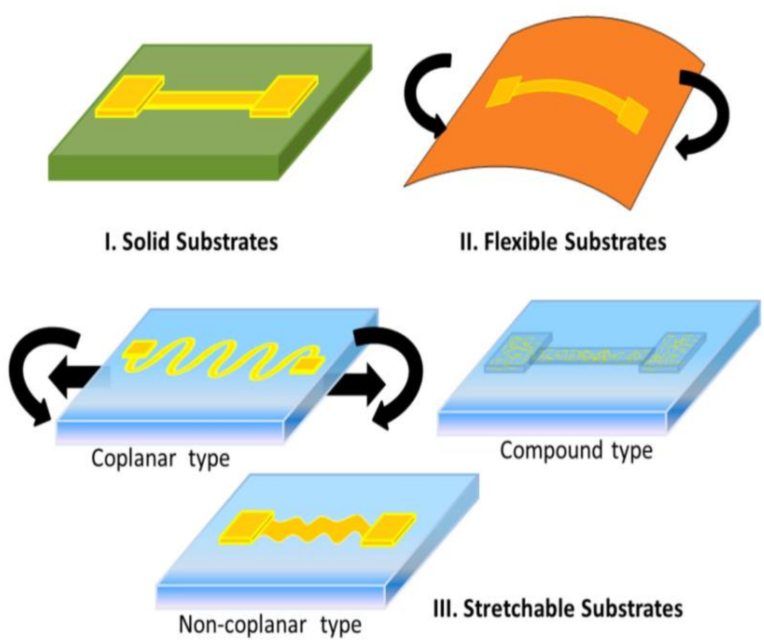

Figure 2.3: Solid substrates, flexible substrates, and stretchable substrates (Hocheng and Chen, 2014)

There are differences between flexible and stretchable. Flexibility is the ability of a material to be bent, such as rolling up a poster, while stretchability relates to the ability to pull on a material, such as pulling on a rubber band (Onorato et al., 2017). A few research have been done toward this goal began by fabricating stretchable electronics on polymeric substrates, such as Polymethyl methacrylate (PMMA), polyethylene terephthalate (PET) and polydimethylsiloxane (PDMS). Among them, PDMS is the highly flexible since it has the flexibility that can be tuned continuously by changing the volume ratio of PDMS precursor and curing agent (Chuan-Wei et al., 2015).

Silicones have many applications in many areas of life. Polydimethylsiloxane (PDMS), which belongs to the class of silicones, has been extensively used in the field of electronic due to its properties. In the PDMS structure, the (-Si-O-Si-) backbone is highly flexible compared to many other rubbery polymers. PDMS is highly transparent and also has good flexibility and biocompatibility. PDMS is made of the hydrophobic structure and it is chemically inert material. Combining conductive patterns with PDMS will provide a way to fabricate various high-performance devices, such as stretchable conductors, wearable devices and electronic skins (Sun et al., 2016).

However, silicone elastomers have a very low modulus, resilience and tear strength. Polymer blending can be done to increase the mechanical properties. Besides that, to produce silicones with sufficient mechanical properties requires the incorporation of particulate fillers. Reinforcing fillers can be used to increase tensile strength, tear strength and abrasion resistance, providing a several-fold. The most common fillers that usually used in order to increase the mechanical properties of silicone elastomers are colloidal silica. The reinforcement capability of silica fillers is highly dependent on the particles surface area and the van der Waals and hydrogen bonding between fillers and polymer (Agar, 2011). Figure 2.4 shows an example of PDMS substrate.

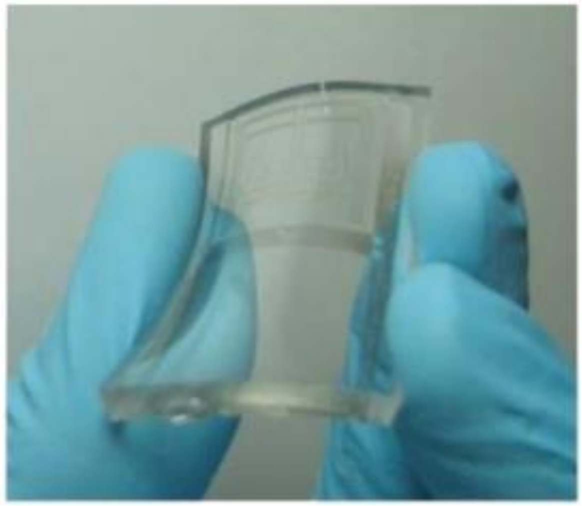

Figure 2.4: Photograph of transparent and flexible graphene films transferred on PDMS substrate (Ahn and Je, 2012).

Xu and Zhu (2012) reported an embedding process where a stretchable conductor with Ag-NWs was embedded in the surface layer of poly(dimethylsiloxane) (PDMS). The top surface of the conductive layer is a composite of AgNWs and PDMS. Initially, AgNWs suspension is drop-casted onto a precleaned substrate. The substrate could be silicon (Si) wafer, a glass slide or plastic materials. After drying process, liquid PDMS is cast on top of the AgNW film, followed by curing at 65 ° C for 12 h. After the substrate is peeled off, the AgNW film is bonded to the cured PDMS. The AgNW film is actually buried just below the PDMS surface.

A good adhesion of Ag-NWs to the PDMS substrate was achieved due to the embedding of Ag-NWs within the PDMS. A good adhesion between Ag-NWs with the PDMS substrate is important in order to achieve higher stretchability. However, the embedded Ag-NW networks still could be damaged upon a high stretching deformation and cause the electrical stability of the conductors under stretching was relatively low. The conductivity and resistance of AgNW/ PDMS package before and after undergo stretching was studied.

The result shows that the Ag nanowires (AgNWs) embedded in the surface layer of PDMS achieved a high conductivity of 5285 S/cm in a tensile strain range of 0%–50%. Figure 2.5 shows that the surface of the AgNW/PDMS layer is flat without any noticeable undulation before stretching. When the PDMS was stretched, the surface morphology did not show obvious change; see Figure 2.5b as an example for 80% strain. When the AgNW/PDMS layer is released, the AgNWs slide back by certain degree but cannot slide back to the original state because of the friction force between the NWs and the PDMS matrix. The surface buckling started to appear in the stretching direction at 50% strain (Figure 2.5c). More buckles appeared with the further release of the strain (Figure 2.5d). No cracking was observed until the fracture the PDMS up to a strain of more than 100% (Xu and Zhu, 2012).

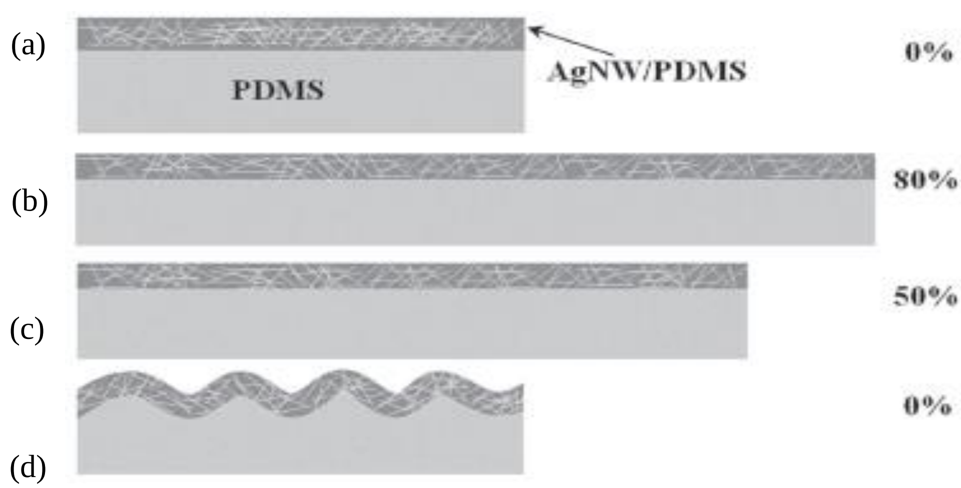

Figure 2.5: A Schematic showing the deformation of AgNW/PDMS layer during the normal (a) stretching (-c) and releasing (d) condition

On the other hand, Lee et al. (2016) demonstrated that the surface roughness and adhesion of AgNW films can be strengthened by a direct spray coating on uncured PDMS. They fabricated nanowire (AgNW) films on polydimethylsiloxane (PDMS) substrates for the applications of a stretchable and transparent electrode. The penetration of AgNWs into the uncured PDMS by a nozzle pressure can improve the adhesion of AgNW films and PDMS. It does not require any laser irradiation, a coating of a buffer layer, and a peeling-off process. However, the standalone AgNW films show an unstable resistance under tensile strain. We have therefore employed a conductive polymer/ poly(3,4-ethylenedioxythiophene): poly(styrene sulfonate) (PEDOT:PSS), which is coated on the AgNW film. The structure shows very stable resistance under tensile strain.

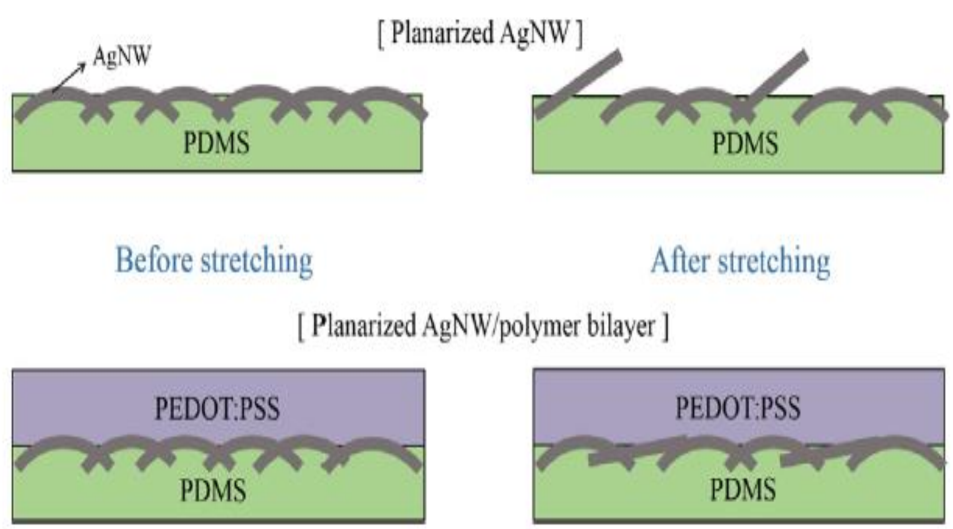

Figure 2.6: Schematic view of the mechanism for the stable resistance by AgNW/polymer bilayer electrodes (Lee et al., 2016).

2.4 Type of Printing

In order to produce stretchable printed electronic devices, the conductive ink needs to be onto the substrate first. Photolithography is one of the technologies that commonly used to fabricate conductive metal lines. However, it is a time-consuming process and requires complex process (Yin et al., 2008). Various new technologies have emerged in order to produce flexible electronics and devices such as spray coating, (Lee et al., 2016), inkjet printing, (Secor et al., 2013), non-vacuum deposition, screen printing etc. (Pardo et al., 2000). Among these technologies, inkjet printing has gained more and more attention in order to fabricate conductive lines.

According to Tekin et al. (2008), inkjet printing has become an important technology due to its low-cost, low material and energy consumption and programmable control. Furthermore, by using inkjet printing, contamination can be minimized since inkjet printing is a non-contact deposition method. Inkjet printing is a kind of technology that can be used to create patterns or images by propelling ink droplets onto different substrates, such as paper, photo paper, PET, PI, PDMS films, etc. The ink formulation must be compatible with the particular ink-jet system chosen for deposition. The particles used should be small with no agglomeration so that clogging can be avoided.

Huang et al. (2011) has been studied series of inkjet printing processes using graphene-based inks. In this research, two types of graphene materials, namely single-layered graphene oxide (GO) and few-layered graphene oxide (FGO) were used in order to study the ink jet printing parameters. The thickness of the printed patterns can be controlled by printing the patterns different numbers of times. The result shows that as the number of times the pattern was printed increased the conductivity of the patterns also increased. This is due to higher number of printing times will cause a higher number of ridges. This ridges that made of graphene will become thicker and better connected to each other.

Besides that, under the same printing number, the patterns printed using FGO ink showed a higher electrical conductivity than those printed using GO ink due to their higher integrity. They suggest that content of oxygen-containing groups in FGO is lower than that in GO. To demonstrate the mechanical flexibility of the graphene patterns produced using inkjet printing various high image quality patterns with controllable line width and thickness are prepared on different commercial flexible substrates by the direct inkjet printing method. The conductivity of the patterns on various substrates before and after bending cycles was measured. After hundreds of bending cycle, no decrease in conductivity was observed (Huang et al., 2011).

Besides inkjet printing, screen printing is one of the most promising alternatives and has been widely used to fabricate conductive lines. This method involves the transfer of ink by moving a squeegee blade across a screen mesh. Screen printing is a method realized by pressing an ink through a patterned stencil by using a squeegee. This technique is very simple, low cost and versatility (Pardo et al., 2000). Besides that, screen printing is suitable to print conductive lines onto a various substrate in one step. According to Yin et al. (2008), it is quite hard to achieve screen printing by using a silver nanoparticle suspension with low silver content since screen printing needs an appropriate viscosity of the ink.

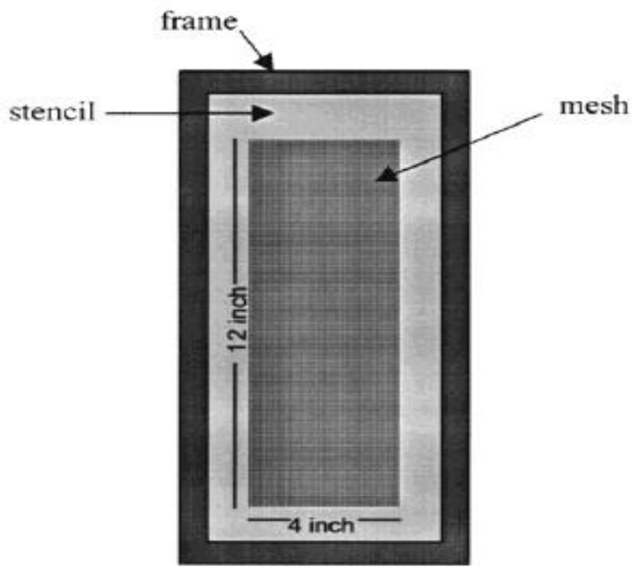

Figure 2.7: A schematic of the image carrier showing the mesh, stencil, and frame (Pardo et al., 2000).

Screen printing is a stencil printing method which has the ability to improve printing quality. There are many parameters that can affect the printing process such as ink composition, screen count, scratching force, ink viscosity, printing speed, angle and geometry of the squeegee, the distance between the screen mask and substrate. Figure 2.8 shows the general principle for screen printing. A screen is the core component to produce the designed pattern. Firstly, a substrate is placed under the screen, and after that, the ink was dropped on a blank area of the board away from the pattern. A squeegee is used to push the ink to cover the whole pattern region. The ink transfers through the screen openings and adheres to the substrate. After drying, the pattern is printed on the substrate (Goldberg et al., 1994).

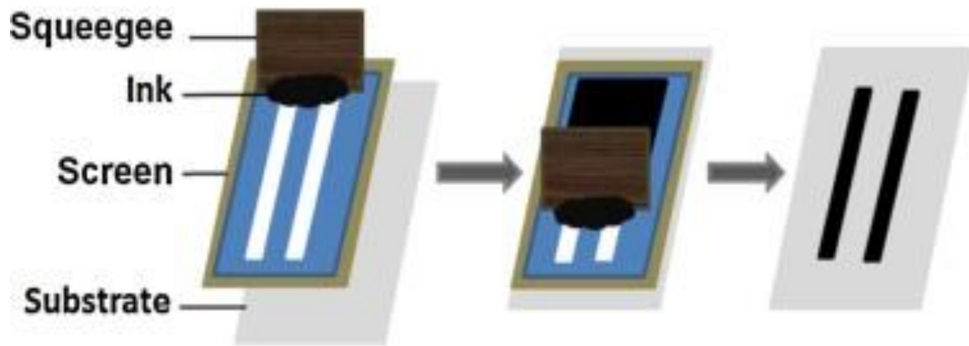

Figure 2.8: Schematic of the work principle for screen-printing technology (Chu et al., 2016).

2.5 Stretchable Electronic Application

In recent years, a wide variety of flexible devices for application in wearable and electronic uses have developed. Many application such as in sports and healthcare industry where recently a remote monitoring of physiological parameters can revolutionize healthcare in the healthcare industry where a device enables the monitoring of physiological parameters. The past decade has been an active research corresponding to the methods and material for the wearable device where it needs to be lightweight, unobtrusive and conform to complex surfaces and stretch with body’s motion. It is vital in power electronic to uses passive components such as inductor, capacitors, and resistor to perform functions such as filtering, short-term energy storage, and voltage measurement in many other applications.

The process of fabricating printed device and sensor arrays on stretchable substrates enable the development of a wide range of new technologies, such as flexible displays, radio-frequency (RF) identification tags, sensor tapes, artificial skin, and more. There are two major application fields for stretchable electronic systems can be identified at present which is electronics close to the human body and electronics attached to three-dimensionally curved (free form) surfaces. The first application field can be further subdivided into medical and textile electronics. They should be able to withstand cyclic stretch of a 3 - 5 percent and be robust against moisture due to body liquids or repeated washing (Löher et al., 2009).

Stretchable Electronics that can be bent or twisted can benefit biomedical applications such as electroencephalograms (EEGs), electrocardiograms (ECGs), photodetectors, and implantable medical devices (Mohammed and Pecht, 2016). Besides that, it also can be applied to wearable healthcare devices and a sensor for skin. In order for the electronic devices to perform effectively inside, and on the human body, they need to be compatible with the human body since the human body is stretchable, soft, and curvaceous. Conventional integrated circuits tend to be rigid, planar, and inflexible so it is uncomfortable to wear.

The device should preferably be comfortable and unnoticeable. When conventional circuits are deployed within the human body for monitoring the heart, brain, or the muscles, the body identifies and eventually rejects them as foreign materials, leading to tissue scarring. To achieve better wearability, we need to transform the flat rigid device into a flexible or stretchable electronics device that can better follow the shape of the human body (Van den Brand et al., 2015). Figure 2.9 shows epidermal electronic system (EES) attached at the human neck to measures neck Electromyography (EMG).