THE EFFECT OF ELASTOMER ON THE MECHANICAL PROPERTIES OF ELECTRICALLY CONDUCTIVE POLYMER



UNIVERSITI TEKNIKAL MALAYSIA MELAKA

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UNIVERSITI TEKNIKAL MALAYSIA MELAKA

JANUARY 2024

DECLARATION

I declare that this project report entitled "The Effect of Elastomer on The Mechanical Properties of Electrically Conductive Polymer" is the result of my own work except as cited in the references.

K.Hesaraaj Signature . HESARAAJ A/L KUICHALAN Name 5/2/2024 Date : UNIVERSITI TEKNIKAL MALAYSIA MELAKA

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 AALAYSIA Dr. Mizah Binti Ramli Name of Supervisor : 31/1/2024 Date UNIVERSITI TEKNIKAL MALAYSIA MELAKA

DEDICATION

To my beloved mother and father whose constant understanding and support made the journey possible. Throughout this quest, their support and faith in my abilities helped to keep me motivated. I also want to express my sincere gratitude to my mentor, Dr Mizah Binti Ramli, whose invaluable guidance and expertise helped shape the direction of this project. Their mentorship inspired me to think critically and complete my project. Finally, I would want to express my gratitude to my friends for their support and comprehension during tough moments.

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ABSTRACT

The research project aims to investigate the impact of adding elastomers to electrically conductive polymers (ECP) to enhance their mechanical properties and suitability for various applications. The need for flexible electronic devices and the potential of ECP in this domain, focusing on their mechanical flexibility and electrical conductivity. It emphasizes the limitations of pure ECPs and the benefits of incorporating elastomers to improve mechanical performance and electrical conductivity, broadening the range of applications for these materials. the preparation of the ECP with varying concentrations of elastomers, cyclic bending tests, electrical characterization, and morphology characterization using ImageJ analysis and light microscopic images. The results of the study demonstrate the relationship between the concentration of added silicone (elastomer) and the mechanical and electrical properties of the conductive polymer. The resistivity of the samples was measured at different cycle intervals, revealing a consistent trend of increasing resistance as the number of cycles increases. The data also showed the development of cracks and voids in the conductive polymer after cyclic bending tests, indicating a decrease in mechanical properties. The microscopic images depict the evolution of cracks and voids in the samples, further supporting the findings. Based on the results, the study concludes that varying concentrations of elastomers in ECP affect its mechanical and electrical properties, especially under cyclic loading conditions.

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ABSTRAK

Projek penvelidikan bertujuan untuk menyiasat kesan penambahan elastomer kepada polimer konduktif elektrik (ECP) untuk meningkatkan sifat mekanikal dan kesesuaian mereka untuk pelbagai aplikasi. Keperluan untuk peranti elektronik yang fleksibel dan potensi ECP dalam domain ini, memfokuskan pada fleksibiliti mekanikal dan kekonduksian elektriknya. Ia menekankan batasan ECP tulen dan faedah menggabungkan elastomer untuk meningkatkan prestasi mekanikal dan kekonduksian elektrik, meluaskan julat aplikasi untuk bahan ini. penyediaan ECP dengan pelbagai kepekatan elastomer, ujian lenturan kitaran, pencirian elektrik, dan pencirian morfologi menggunakan analisis ImageJ dan imej mikroskopik cahaya. Hasil kajian menunjukkan hubungan antara kepekatan silikon tambahan (elastomer) dan sifat mekanikal dan elektrik polimer konduktif. Kerintangan sampel diukur pada selang kitaran yang berbeza, mendedahkan trend peningkatan rintangan yang konsisten apabila bilangan kitaran meningkat. Data juga menunjukkan perkembangan retak dan lompang dalam polimer konduktif selepas ujian lenturan kitaran, menunjukkan penurunan sifat mekanikal. Imej mikroskopik menggambarkan evolusi keretakan dan lompang dalam sampel, seterusnya menyokong penemuan. Berdasarkan keputusan, kajian menyimpulkan bahawa kepekatan elastomer yang berbeza-beza dalam ECP mempengaruhi sifat mekanikal dan elektrikalnya, terutamanya di bawah keadaan pemuatan kitaran. SIAMELAKA

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LIST OF ABBEREVATIONS

2D	2 Dimensional
3D	3 Dimensional
AMCHAL	Advanced Material Characterization Laboratory
CNT	Carbon Nanotubes
CVD NALAYS	Chemical Vapour deposition
DMSO	Dimethyl Sulfoxide
ECP	Electrically Conductive Polymer
EG BANNIN	Ethylene-glycol
FeCI3 مالاك	Ferric Chloride
GIC	Graphite Intercalated Compound
OLED	Light Emitting Diodes
PA	Polyacetylene
PANI	Polyaniline
PEDOT:PSS	Poly(3,4-ethylene dioxythiophene) polystyrene sulfonate
PET	Polyethylene Terephthalate
PPY	Polypyrrole
TPU	Thermoplastic Polyurethane
UTeM	Universiti Teknikal Malaysia Melaka

LIST OF SYMBOLS



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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Today's technology is more focusing to improve device performance while also reduce the size of the electronic device in order to make it more adaptable and flexible to be used on the electronic devices. In order to increase the flexibility, typical solid-state technology poses such as wires need to be eliminated and a new technology such electrically conductive polymer must be invented. This new technology has been introduced in some of the industries. Due to their remarkable combination of mechanical flexibility and electrical conductivity, electrically conductive polymers (ECP) as shown in Figure 1.1 have drawn a lot of demand. This makes them appealing for a variety of applications, including flexible electronics, sensors, actuators, and energy storage devices. Researchers have looked into adding elastomers to electrically conductive polymer composites to improve their mechanical characteristics and make sure they are suitable for a variety of applications.

Elastomers have exceptional mechanical qualities such high elongation at break, robustness, and toughness. They are known for their great elasticity and capacity to withstand significant deformations while recovering to their original shape. Elastomers and electrically conductive polymers can be combined to create materials that have both better mechanical performance and electrical conductivity, broadening the range of applications for these materials.

ECPs' natural brittleness is one of the main obstacles to using them in real-world situations. Pure electrically conductive polymers frequently have low fracture toughness, very little elongation at break, and are vulnerable to crack under mechanical stress. These restrictions may prevent their use in structural applications and flexible devices where mechanical toughness is crucial.

Elastomers' inclusion in ECP has a number of benefits. The elastomer phase, which distributes stress and stops cracks from spreading within the composite material, first acts as a mechanical reinforcement. This reinforcement effect enhances the composite's tensile strength and fracture toughness, enabling it to withstand greater mechanical stresses without breaking. Elastomers also increase the elongation at break, giving the ECP composites more flexibility and making them more resistant to deformation and mechanical fatigue.

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Elastomers can also strengthen the adhesion between conductive polymer particles, resulting in a more conductive network that is interconnected. This improved interconnectivity makes it easier for electrical charges to move efficiently through the composite material, which improves electrical conductivity. The mechanical and electrical properties of the composite material can be adapted to match particular application demands by adjusting both the type and concentration of the elastomer phase.

The compatibility of various elastomers with electrically conductive polymers has been researched, including that of polyurethane, silicone, natural rubber, styrenebutadiene rubber, and thermoplastic elastomers. Each type of elastomer has particular mechanical characteristics that can be adjusted to meet particular applications, such as changing stiffness, toughness, and elongation. The overall mechanical and electrical properties of the material are greatly influenced by the elastomer applied and its concentration inside the composite.

It has been found that adding elastomers to electrically conductive polymers is a successful method for enhancing the mechanical properties of these materials. The resulting ECP composites have improved flexibility, elongation at break, tensile strength, and fracture toughness, making them suitable for a wider range of applications.



Figure 1.1 : Example of Electrically conductive polymer

1.2 PROBLEM STATEMENT

The electrically conductive polymer (ECP) is a revolutionized for rigid conductive ink where its serve the same purpose which is conducts electricity. This revolutionized is related to the limitations of conventional conductive ink that has been used in industry for many years, such as the fact that it has a permanent shape, rigid and anti-vibration. Electronic devices experience advanced applications that need ECP to be used into to ensure better performing. As a result, demand for ECP is growing fast over the past few years. To have high quality ECP, it must be able to withstand with complex structures, have high adhesive strength with the substrate and to ensure electrical conductive performance under flexibility condition. However, the existing ECP has a limitation which cannot be well performed under complex structures. Therefore, it is crucial to do research on effect of elastomer on the flexibility of ECP.

Next, ECP undergo certain limitation when it is being used under cyclic loading. In order to improve the quality of electrically conductive polymer, it must be capable of being used under cyclic loading. Therefore, this research was conducted to explore on the void formation of ECP following with compatibility of the substrate. It is very important to explore on void formation of ECP as this is one of the factor that impact the adhesion of ECP with the substrate.

1.3 OBJECTIVE

The objectives of this project are as follows:

- 1. To study the effect of elastomer on mechanical and physical properties of electrically conductive polymer.
- 2. To analysis the void formation of electrically conductive polymer subjected to cyclic loading.
- 1.4
 SCOPE OF STUDY

 The scopes of this project are:

 Image: Description of the scope of this project are:
 - 1. Evaluating the properties of electrically conductive polymers used as adhesives, such as their conductivity, mechanical strength and flexibility.
 - 2. Make a study on electrically conductive polymer behavior before and after adding elastomer.
 - 3. Analyzing the causes of failures and identifying strategies to improve the strength, elasticity and reliability of the electrically conductive polymer on flexible substrates.

CHAPTER 2

LITERATURE REVIEW

2.1 Conductive Ink

Conductive ink refers to an ink formulation that contains conductive materials, such as conductive polymers, metal nanoparticles, or carbon-based materials (e.g., carbon nanotubes, graphene). Conductive inks are used to print or deposit conductive traces or patterns onto various substrates, including flexible substrates like plastic or paper. Conductive ink is a key enabler for stretchable electronics. It is an ink that result in a patterned object which is the main purposed is to conducts electricity (Claypole, Kilduff, & Gethin, 2021). ECP have emerged as a new and exciting way to improve manufacturing of electronic component. These conductive inks enable the industry to bring up the improvement in printed electronic devices, which has considerable benefits over traditional silicon-based electronic devices (Kamarudin, Mustapha, & Kim, 2020). Aside from being less expensive and more functionality, ECP also have other appealing characteristics such as flexibility, ability to miniaturize and lightweight (Kamarudin, Mustapha, & Kim, 2020).

The interest in study to improve and produce new technologies in conductive ink has grown not only in academy but also in industry. Number of research in conductive inks has increased significantly in recent years to improvise the current properties of conductive ink (Saidina, Eawwiboonthanakit, Mariatti, Fontana, & Hérold, 2019). Another appealing feature of conductive ink is the remarkable versatility, which have been used to fabricate numerous devices, including printed circuits, wearable sensors, flexible electrodes, flexible displays and organic light-emitting diodes (OLEDs) (Ferri, Llinares Llopis, Moreno, Vicente Lidén-Roger, & Garcia-Breijo, 2020). These devices are generally fabricated by printing conductive ink onto a substrate using several printing processes, using different techniques which are flexography, inkjet printing, screen printing, and stencil printing (Gomes, Tama, Carvalho, & Souto, 2020). All of these methods have advantages and disadvantages, but they were all created to give a simple, rapid, efficient and economical way to generate conductive traces on flexible substrates (Tran, Dutta, & Choudhury, 2018).

Conductive inks are being produced by solvent that comprise metallic fillers and substrate materials. In addition to improve electrical conductivity, conductive ink should be affordable and easy to prepare, with love viscosity, good stability and flexibility, and adhesion to variety of substrates.

2.2 Material Filler

The demand for stretchable devices has been ever growing since new technology fields like stretchable electronics have emerged, the wave of searching for new materials that can afford high electrical conductivity and also good mechanical elasticity has surged. Although a variety of conducting polymers, such as polyacetylene (PA), polyaniline (PANI), polypyrrole (PPY), and poly(3,4-ethylene dioxythiophene) (PEDOT) have been developed for diverse applications, their wide-spread use is limited by their poor mechanical properties. some conductive fillers typified by a family of carbon matters, such as carbon blacks, graphite, and carbon nanotubes (CNTs) have been introduced to transform the resin from an insulator to a conductor. However, this approach requires a significant amount of filler to be added, even though the degradation of elasticity can be minimized for CNT-elastomer composites (Jin-Seo Noh, 2016).

2.2.1 Graphite

Graphite is a naturally developing form of carbon with great properties and a distinctive structure with a wide range of industrial and technological uses. Graphite can be classified as a layered structured that allows other types of atoms and molecules to insert between the layers of it. Due to that, a compound was created that known as graphite intercalated compound (GIC). Intercalation is the process of introducing molecules or atoms between the stratified layers of graphite (Van Heerden & Badenhorst, 2015). Graphite can be categorized into two categories which is natural graphite and synthetic graphite (Yoon et al., 2015), Natural graphite is graphite generated naturally by the Earth and it also be categorized into three type which is natural amorphous graphite, natural flakes graphite and high crystalline natural graphite as shown in Figure 2.1.



Figure 2.1 : Types of Graphite

2.2.2 Graphite Intercalated Compound (GIC)

GIC is formed by intercalating molecules or atom in between graphite layers. Due to their advanced properties such as high thermal and electrical conductivity, graphite or graphene has been selected as a first choice to be implement in semiconductor industry. According to (Saidina et al., 2019), electrical and thermal conductivity of GIC is higher than those metals due to GIC design which is has simple hexagonal lattice. Thus, electrons can easily transfer through it to allow electricity to flow freely. Ferric chloride (FeCl₃) as shown in Figure 2.2— GCI has been formed by inserting FeCl₃ into the interlayer or graphite element, GCI are technologically useful functional materials and potentially to be used as main material for fillers (Tan et al., 2021). Figure 2.3 shows the simplified process of GIC formed.

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Figure 2.2 : 2D Chemical structure of FeCl₃



Figure 2.3 : Process of GIC formed

2.2.3 Graphene

For this research, Graphene was selected to be the filler of the stretchable conductive ink. Graphene is one of the next-generation conducting materials that have the potential to replace existing materials such as gold, platinum, silver, iron and so on due to their exceptional properties. (Tan et al., 2021). With two-dimensional substance composed of carbon atoms organized, it can make graphene more electrical conductivity, transparency, flexibility and high mechanical strength that make it promising for many applications. For conductive ink applications, high conductivity, excellent thermal stability, and layered structure make graphene a perfect option.

Graphene gain more interest among semiconductor big company to be implemented in their product as it can be processed in solution, allowing for the low-cost fabrication of electrical and optical devices. The conductive ink is based on the oxygen free graphene ink. The compositions of GCI are 30-40 wt% conductive polymer, 5-15 wt% ethanol, 2-10 wt% diethylene glycol, and <I wt% graphene (Chen and Zhang, 2021). With the oxygen free graphene components, it will increase 5-7 times of the conductivity from normal base polymer ink. Due to quick evaporation of the solvent, resulting ink is easily coated on substrates compare to chemical vapour deposition (CVD) graphene (Han et al., 2013).

2.2.4 Graphene Properties

Graphene is a graphite layer composed of an atomic layer of carbon atoms arranged in a hexagonal lattice arrangement (Xu et al., 2017). Despite the fact that graphene only an atomic layer of graphite, it is very rigid and strong in comparison to most metal and non-metal compounds. Another advantage of graphene also has a large surface area, high Young's modulus, large mechanical strength and high thermal conductivity, as indicated in Table 2.1 below (Xu et al., 2017).

 Table 2.1 : Properties of Graphene

Property	Approximated value of graphene
Surface Area (m^2/g)	2630
Young Modulus (GPa)	1000
Mechanical Strength (GPa)	130
Charge Carrier Mobility (cm ² /V.s)	اويبو مرسيخ بت
Thermal Conductivity (Wm / K)	5000
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With thickness of only 0.334nm, graphene can be classified as the world's thinnest substance. Excellent carbon structure, bonding system, and infinite repetition of 2D plane structure, provide it with a variety of characteristics. As a result, it has a huge potential of applications in semiconductor material as semiconductor industry need the material that can works under high temperature (Ren, Rong and Yu, 2018).

2.2.5 Thermoplastic Polyurethane (TPU)

Thermoplastic Polyurethane (TPU) may be option to develop formulation for stretchable ink since it has been filled with conductive particles (Suikkola et al., 2016). In this research, TPU was chosen because it provides combination of favorable properties such as excellent elongation, high impact strength, good thermal conductivity and good elasticity (Chen et al., 2015), Adhesion between ink and the substrate is important for mechanical properties of finalized conductive ink, thick ink coating are often less flexible than the substrate it is printed on leading poor adhesion (Lee and Nah, 2012). TPU have higher abrasion resistance and surface energy than other elastomer that brings resulting in much better adherence to the conductive ink. TPU can also be incorporated into conductive ink formulations to create flexible and stretchable conductive traces or patterns. By adding TPU to the ink formulation, it is possible to enhance the ink's flexibility and stretchability, making it suitable for applications that require mechanical deformability.

2.3 Printing Process

Ink patterning has been evolved using a variety of processes, including inkjet, aerosol, screen printing, and direct writing. Screen printing is the most popular and commonly used approach due to high efficiency of thick conductor traces that carry large currents. The drawback of this method is it cannot produce line width less than 80-100um (Walker and Lewis, 2012). Figure 2.4 shows the typical flat-bed screen printing method. First, the ink was distributed onto the substrates with a squeegee through the open pores of the screen (G. Hu ct al., 2018).



Figure 2.4 : Schematic figures showing a flat-bed screen printing

2.4 Curing Process

Following the printing of the conductive ink, a post-treatment known as the "curing process" is carried out. During this process, the hardener and epoxy resin's epoxide group react chemically to create a strong, cross-linked, three-dimensional network (3D) with excellent creep resistance, high modulus, and high temperature performance (Saidina et al., 2019). The curing process can be utilized to improve the adhesion between the ink and substrate as well as enhance the binding between the filler, binder, and hardener particles.

2.5 Bending Test

Cyclic bending tests are widely used to evaluate the mechanical durability and reliability of various materials, including electrically conductive polymer composites (Brostow et al., 2020). These tests involve applying cyclic stresses to the material specimens and monitoring their performance under repeated bending. These tests can help determining the material's suitability for applications involving bending or deformation, such as stretchable conductors, flexible electronics, and sensors. There are many ways of bending tests, such as guided bend testing, semi guided bend testing and cyclic loading. In this project, bending testing which is a mechanical testing that apply force on a sample and see how it react in terms of stress and strain is used. The sample will be clamped at its two end part and being pushed slowly based on the speed test. As the samples being pushed, its structure and how much cyclic loading test it can withstands can be found out.

The main objective of bending testing is to determine the material's resistance after cyclic loading. Several experiments from previous studies have been designed and used to determine the performance of deformed flexible electronics. The Majority of the work involves stretching (Lu et al.) and cyclic loading and uniaxial loading (Glushko et al.). There is also an ASTM standard for a uniaxial loading or bending test. Until now, most mechanical testing for flexible electronics only focuses on simple deformations (uniaxial stretching and bending) (Glushko et al.). Even more complicated ones, such as twisting or biaxial stretching, may not accurately represent the load that a flexible electronic would undergo during usage. Therefore, a test procedure for increasingly complicated loadings must be developed and able to apply complicated deformations such as cyclic loading (Glushko et al.) in order to ensure the maximum stress of flexible electronic can withstand.

2.6 Four Point Probe Test

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Resistance and resistivity are the most significant characteristics in electrical measurement. The measured resistance is frequently translated to resistivity and then compared to the bulk resistivity of the conductive materials (Salam, Lai et al. 2011). If the material is constructed of two types of conductive material, the resistivity will be compared to the material with lowest resistivity value.

A four-point probe test is a basic instrument used to measure the resistivity of semiconductor samples. The substrate resistivity may be measure by supplying a current through outside probes and measuring the voltage via the inner probes.

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CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter will be discussing the steps and the process flow involved in this research study. This project starts by finding and studying related research articles to this project. Then the preparations of conductive polymer take place by adding the elastomer with grapheme ink on thermoplastic polyurethane (TPU). The variable in this project is the percentage of elastomer added to the graphene ink to analysis the effect on mechanical and electrical properties. This chapter also presents the preparation of electrically conductive polymer and the analysis on conductive polymer.

3.2 Research methodology flow chart UNIVERSITI TEKNIKAL MALAYSIA MELAKA

This section will provide all the work done that has been go through during the research and the experiment conducted in the Advanced Materials and Characterization Laboratory (AMCHAL), Faculty of Mechanical Engineering, Universiti Teknikal Malaysia Melaka (UTeM). The Figure 3.1 below shows the experimental flow chart.



Figure 3.1 : Methodology Flowchart

3.3 Materials

In this research, material that were used are Polystyrene sulfonate, Dimethy sulfoxide (DMSO), Ethylene-glycol (EG), Triton X-100, Thermoplastic polyurethane(TPU) and Graphene nanoplatelets and silicone solution. Research was conducted on the effect of elastomer on mechanical properties of electrically conductive polymer.

3.4 Optimum formulation for Electrically Conductive Polymer

The materials for preparation for 4 g conductive polymer contains 3 parts which is graphene with 0.4 g (10 wt%) as shown in Table 3.1, Poly(3,4-cthylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) solution with 3.6 g (90 wt%) as shown in Table 3.2 and the percentage of elastomer added. The material were used in this sample preparation are Polystyrene sulfonate, Dimethyl sulfoxide (DMSO), Ethylene-glycol (EG), Triton X-100, Thermoplastic polyurethane (TPU) and graphene nanoplatelets. Below are the compositions of 0.4 g graphene nanoplatelets and 3.6 g PEDOT:PSS solution.

Hybrid graphene size (3:1)	Mass, g	
25 µM Graphene nanoplatelets	0.3	
5 µM Graphene nanoplatelets	0.1	

 Table 3.1: Composition of 0.4g Graphene nanoplates

PEDOT : PSS solution	Mass, g	Wt%	
Polystyrene sulfonate (P:PSS)	3.234	89.82	
Dimethyl sulfoxide (DMSO)	0.2153	5.98	
Ethylene-glycol (EG)	0.1436	3.99	
Triton X-100	0.00716	0.199	

Table 3.2: Composition of PEDOT : PSS solution

For mixing and curing parameters are shown in Table 3.3 as below:

Table 3.3 : Mixing and curing parameters

	714		
Mixing speed, rpm	Mixing time, min	Curing temperature, °C	Curing time, min
2000	10	60	15
LUST		JIEIV	

3.5 Conductive Polymer Preparation

To form the 4 g conductive polymer, 0.4 g graphene nanoplatelets were combined

with 3.6 g Poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) and silicone solution of 0.01g, 0.02g and 0.03g. To get the gross weight, the binder was weighed on an analytical balance. The weight of the mixture should be in between the tolerance of ± 0.05 g that have been set by using analytical balance. Mixture of 3.6 g Poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) was kept in place for a few second to allot the unit to stabilize. Mixture of PEDOT: PSS was mixed in mixer for 10 minutes with 2000 rpm. Graphene nanoplatelets were weighed at 0.4 g with 3:1 ratio (0.3 g of 25 μ M and 0.1g of 5 μ M). Mixture of Graphene and PEDOT: PSS was mixed.

3.6 Sample Preparation of Thermoplastic Polyurethane (TPU)

Here, the uncured conductive polymer was printed into a rectangle shape of 140 mm x 40 mm Thermoplastic Polyurethane (TPU) via the stencil printing method shown in Figure 3.2. As seen in Figure 3.3, four points were marked into the TPU substrate, with 10 mm between each point. The resistivity at each location is determined using the point in the four-point probe test. Electrically conductive polymer was printed into rectangle shape. Complete pattern was developed with a length of 50 mm by 10 mm. Sample preparation process began with the cutting of a 140 mm x 40 mm TPU substrate. Scotch tape with 0.05 mm thickness was attached to the side of TPU. Then the stencil is placed firmly on the TPU substrate. Conductive polymer was applied on the stencil where it produces a design in rectangle shape. Finally, the stencil and the scotch tape were removed away from the TPU. For this research, curing process has been conducted at 60°C for 15 minutes inside a universal oven. By preheating the oven early, the printed specimen can be placed in the oven immediately after the printing process was done. By this way, printed specimens were not exposed to room temperature that can be tampering the result. After curing process was done, the printed specimens can be dry completely at room temperature and prior to testing. The Figure 3.4 shows the conductive polymer on TPU after curing process. There are 3 samples made for each parameter of elastomer percentage added which results in total of 12 samples of electrically conductive polymer made.


Figure 3.3 : Sample of Conductive Polymer



Figure 3.4 : Conductive Polymer on TPU after curing

3.7 Cyclic Bending Test

The purpose of this test is to investigate the conductive polymer's behavior under cyclic fatigue. This test was conducted using an instrument from the Advanced Materials Characterization Laboratory (AMCHAL). As seen in Figure 3.5, the sample is first fastened to a holder and made flat before the test is conducted. The motor is powered by the power supply, and the test instrument's counter has been reset to zero. The power supply is turned on once the setup is complete. The sample was bent for 180 degrees at a rate of one cycle per second. The samples were bent for a total of 4000 cycles, and resistivity readings were collected both before and after each test cycle of 1000. After that, the morphology of the sample was examined before and after 4000 cycles.



Figure 3.5 : Setup for Cyclic Bending Test

3.8 Electrical Characterization

This test used an inclined four-point probe (Jandel RM3000 + Test Unit with an input range of 10 μ A to 100 mA) as indicated in Figure 3.6. This test was conducted using an instrument from the Advanced Materials Characterization Laboratory (AMCHAL). In order to ensure that it would not move during the testing, the sample was initially placed underneath and secured in place with tape. Till a reading was obtained, the probe pin was gradually lowered onto the conductive polymer's surface. The sample was re-positioned once the setup was complete in order for the pin to detect the resistivity at the locations shown in Figure 3.3. Three readings were obtained at each point, for a total of 12 readings for each sample, and the average was then determined.



Figure 3.6 : Four Point Probe

3.9 Morphology Characterization

Selected samples were examined under a scanning electron microscope (SEM) to analyze the surface and void formation based on different particle sizes and the effect of the cyclic bending test on the sample. The findings were correlated with its electrical properties.

CHAPTER 4

RESULT AND ANALYSIS

4.1 Introduction

This chapter focused on the results and discussions of the electrically conductive polymer using graphene as filler and adding silicone solution as variable parameters which include resistivity of conductive polymer and void formation subjected to cyclic loading.

4.2 Data and Graph of 0.01 g of Silicone

Table 4.1 : Average Resistance of 0.01g Si After cycle

Cycles	Sample	Resistance	Average Resistance (Ω)	Standard Deviation	
Before	S1 S2	0.802 0.878	ALAYSIA MEL	AKA 0.370	
	S3	1.623			
	S 1	0.853			
1000	S2	1.040	1.258	0.447	
	S3	1.880			
	S1	0.930			
2000	S2	1.045	1.273	0.406	
	S3	1.844			
	S1	0.997			
3000	S2	1.283	1.281	0.240	
	S3	1.564			
4000	S1	0.997			
	S2	1.090	1.292	0.353	
	S 3	1.790			



Figure 4.1 : Resistance vs Cycle for 0.01 g of Silicone

The trend in the average resistance for 0.01 g Si at different cycle intervals shows a consistent pattern of change. The average resistance values for 0.01 g Si increases as the number of cycles increases. Specifically, the average resistance values for 0.01 g Si at 1000 cycles are lowest than those at 2000 cycles, which are in turn lower than those at 3000 cycles. Finally, the average resistance for 0.01g Si at 4000 cycles is 1.292 Ω which is highest than at 3000 cycles. This indicates a general trend of increasing resistance for 0.01g Si as the number of cycles increases. The 0.01 g Si added has the lowest average resistance compared to the other two parameters. When the resistance is lower, the higher the current flow in the circuit. So, there will be less current loss in the circuit in order to function efficiently.

4.3 Data and Graph of 0.02 g of Silicone

Cycles	Sample	Resistance	Average Resistance (Ω)	Standard Deviation	
	S1	0.778			
Before	S2	0.834	2.022	1.719	
	S2	4.453			
	S1	0.864			
1000	S2	0.632	2.120	1.943	
	S3	4.864			
	S1	1.012		2.106	
2000	S2	0.983	2.487		
	S3	5.465			
	S1	1.081		2.545	
3000	S2 4	1.253	2.966		
	S3	6.564			
M.	S1	1.157		2.645	
4000 🛗	S2	> 1.100	2.999		
7	S3	6.740			

 Table 4.2 : Average Resistance for 0.02 g Si After cycle



Figure 4.2 : Resistance vs Cycle for 0.02 g of Silicone

The average resistance for 0.02 g Si varies over different cycle intervals. The data shows that at 1000 cycles, the average resistance for 0.02 g Si is 2.120. This value increases to 2.487 at 2000 cycles and further to 2.966 at 3000 cycles. Finally, at 4000 cycles, the average resistance for 0.02g Si reaches 2.999. Therefore, the trend indicates an overall increase in average resistance for 0.02 g Si as the number of cycles increases. The average resistance for 0.02 g Si at 4000 cycles is 2.999 Ω which is highest than the 0.01 g and same as 0.03 g silicone added. This shows that there will be a higher loss of current when the 0.02 g and 0.03 g of silicone added conductive polymer used.

4.4 Data and Graph of 0.03 g of Silicone

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			Average Resistance	Standard	
Cycles	Sample	Resistance	(Ω)	Deviation	
61	S1	1.821			
Before 🦳	S2 S2	1.510	1.528	0.233	
	S3	1.252			
LIN	IVE SLITI	3.390	ALAYSIA MELAI	KΔ	
1000	S2	1.577	2.093	0.923	
	S3	1.313			
	S1	3.754			
2000	S2	1.657	2.345	0.997	
	S3	1.623			
	S1	5.184			
3000	S2	1.799	2.913	1.606	
	S3	1.757			
	S1	5.357			
4000	S2	1.762	2.999	1.668	
	S3	1.879			

Table 4.3 : Average Resistance for 0.03 g Si After cycle



Figure 4.3 : Resistance vs Cycle for 0.03 g of Silicone

The trend in the average resistance for 0.03 g Si at different cycle intervals shows a escalating pattern of change. The average resistance values for 0.03 g Si increases as the number of cycles increases. The average resistance values for 0.03 g Si at 1000 cycles are lowest than those at 2000 cycles, which are in turn lower than those at 3000 cycles. Finally, the average resistance for 0.03 g Si at 4000 cycles is 2.999 Ω which is highest than at 3000 cycles. This indicates a general trend of increasing resistance for 0.03 g Si as the number of cycles increases.

4.5 Graph at Different Cycle



4.5.1 Resistance vs Added Silicone at Before Cycle

Figure 4.4 : Resistance vs Added Silicone at Before Cycle

This figure shows the average resistance at before cycle test of added silicone of 0.01 g, 0.02 g and 0.03 g. At the beginning of test the average resistance of 0.02 g is highest compare to the other two. This suggests that there is a relationship between the amount of added silicone and the initial resistance levels. As the amount of added silicone increases, the average resistance also increases at the start of the test. This trend is important to consider when analyzing the impact of silicone on the resistance properties of the material being tested.



4.5.2 Resistance vs Added Silicone at 1000 Cycle

This figure shows the average resistance at 1000 cycle of bending test of added silicone of 0.01 g, 0.02 g and 0.03 g. After the 1000 cycle of test, still the average resistance of 0.02 g is higher compare to the other two. The 0.01 g Si increases slightly with 0.157 Ω shows that it can sustain the 1000 cycles whereas the 0.02 g Si also increases slightly with the value of 0.098 Ω but because of the highest resistance at beginning itself indicates that 0.02 g Si is least durable.



4.5.3 Resistance vs Added Silicone at 2000 Cycle

This figure shows the average resistance at 2000 cycle of bending test of added silicone of 0.01 g, 0.02 g and 0.03 g. After the 2000 cycle of test, still the average resistance of 0.02 g is higher compare to the other two. The 0.01 g Si increases slightly with 0.015 Ω shows that it can sustain the 2000 cycles. As the cycles increase, microscopic cracks or defects develop, causing a reduction in the sample's overall resistance to deformation as we can see from the value of 0.02 g Si and 0.03 g Si.



4.5.4 Resistance vs Added Silicone at 3000 Cycle

This figure shows the average resistance at 3000 cycle of bending test of added silicone of 0.01 g, 0.02 g and 0.03 g. After the 3000 cycle of test, the average resistance of 0.02 g is reached to 2.966 Ω , the highest compare to the other two. The 0.01 g Si is the lowest with 1.281 Ω shows that it can sustain the 3000 cycles.



4.5.5 Resistance vs Added Silicone at 4000 Cycle



This figure shows the average resistance at 4000 cycle of bending test of added silicone of 0.01 g, 0.02 g and 0.03 g. After the 4000 cycle of test, the average resistance of 0.02 g and 0.03 shows the same average value of 2.999 Ω . The 0.01 g Si shows the lowest value of 1.292 Ω . Finally we can concluded that the suitable parameter to add in the conductive polymer is 0.01 g of silicone as it shows minimum deformation and less average resistance value compared to other two parameter.

4.6 Void Formation

4.6.1 ImageJ Analysis of 0.01 g Si of Conductive Polymer

Total Area (cm ²)	Mean	Max	Total Area of Void (%)	Average Void Area (%)
18.750	11.317	255	4.438	
18.750	9.292	255	3.644	4.084
18.750	10.632	255	4.170	

Table 4.4 : ImageJ Analysis 0.01 g Before Test

 Table 4.5 : ImageJ Analysis 0.01 g After Test

(cm ²)	Mean	Max	Total Area of Void (%)	Average Void Area (%)
18.750	21.874	255	8.578	
18.750	20.095	255	7.881	8.821
18.750	25.512	255	10.005	

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4.6.2 ImageJ Analysis of 0.01 g Si of Conductive Polymer

Total Area (cm ²)	Mean	Max	Total Area of Void (%)	Average Void Area (%)
18.750	12.858	255	5.042	
18.750	20.078	255	7.874	6.510
18.750	16.868	255	6.615	

 Table 4.6 : ImageJ Analysis 0.02 g Before Test

 Table 4.7 : ImageJ Analysis 0.02 g After Test

Total Area (cm ²)	Mean	Max	Total Area of Void (%)	Average Void Area (%)
18.750	28.544	255	11.194	
18.750	35.876	255	14.069	12.931
18.750	34.505	255	13.531	

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4.6.3 ImageJ Analysis of 0.01 g Si of Conductive Polymer

Total Area (cm ²)	Mean	Max	Total Area of Void (%)	Average Void Area (%)
18.750	20.310	255	7.965	
18.750	18.098	255	7.097	7.256
18.750	17.099	255	6.705	

Table 4.8 : ImageJ Analysis 0.03 g Before Test

 Table 4.9 : ImageJ Analysis 0.03 g After Test

Total Area (cm ²)	Mean	Max	Total Area of Void (%)	Average Void Area (%)
18.750	40.657	255	15.944	
18.750	35.875	255	14.065	14.511
18.750	34.500	255	13.523	
سيا ملاك	کل ملیہ	ڪنيد	بيۆمرسىيتى تىچ	او

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4.7 Light Microscopic Images

Light microscopy was performed on the sample to observe the conductive polymer on a microscopic level, which captured for all the surface of samples of different silicone added and cycles. For the purpose of comparison, only the worst resistivity of samples in each parameter are going to compared. Figure 4.9 until Figure 4.14 shows surface of conductive polymer in normal images and microscopic images before cyclic bending test at 5x magnificent for 0.01 g, 0.02 g and 0.03 g of silicone added. This figures shows the conductive polymer surface has a smooth surface without crack and bumps.



Figure 4.9 : Conductive Polymer of 0.01 g of Silicone Added



Figure 4.10 : Conductive Polymer surface for 0.01 g Si added before Cyclic Bending Test at 5x magnificent



Figure 4.11 : Conductive Polymer of 0.02 g of Silicone Added



Figure 4.12 : Conductive Polymer surface for 0.02 g Si added before



Figure 4.13 : Conductive Polymer of 0.03 g of Silicone Added



Figure 4.14 : Conductive Polymer surface for 0.03 g Si added before Cyclic Bending Test at 5x magnificent

Figure 4.15 until Figure 4.20 shows the growth of cracks after cyclic bending test is applied for 4000 cycles for 0.01 g, 0.02 g and 0.03 g of silicone added. The cracks continue to develop until failure of the sample when increasing the value of cycle to 4000 to 5000 cycles as shown in Figure 4.21.



Figure 4.16 : Conductive Polymer surface of 0.01 g Si after 4000 Cyclic Bending Test at 5x magnificent

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Figure 4.17 : Conductive Polymer of 0.02 g Si added after 4000

Cyclic Bending Test



Figure 4.18 : Conductive Polymer surface of 0.02 g Si added after 4000

Cyclic Bending Test at 5x magnificent



Figure 4.19 : Conductive Polymer of 0.03 g Si added after 4000

Cyclic Bending Test



Figure 4.20 : Conductive Polymer surface of 0.03 g Si added after 4000

Cyclic Bending Test at 5x magnificent



Figure 4.21 : Conductive Polymer testing failure at 5000 cycle



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Figure 4.22 shows how number of cycles affect the cracks formation. The cracks continue to occur as the number of cycles increases. Cracks area is seen in Figure 4.22 along with a gap between polymer particles resulting in less contact surface between particles as well as lower conductive routes produced on the TPU substrate. Less contact surface will increase the resistivity of conductive polymer. Microscopic analysis will obtain the exact location of defects located that increase the resistivity of samples.



Figure 4.22 : Conductive Polymer surface after 4000 cycles of Cyclic Bending Test at 10x magnificent

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Introduction

The electrically conductive polymer using graphene fillers are fabricated by print screen method on TPU substrates. The sample were cured at 60°C for 15 minutes in universal oven and let at the room temperature for 10 minutes to 20 minutes before test. The cyclic bending test was measured to determine the relationship between number of cycles and resistance. Resistivity of samples was measure by using four-point probe test. 3 samples were made for each parameter of 0.01 g Si, 0.02 g Si and 0.03 g Si. 3 readings were taken at each point marked on TPU. From the 12 readings measured we calculate the average resistivity of each sample. Resistance were used to identified the relationship between resistivity and number of cycles . The results indicated that resistivity of 4000 cycles for 0.02 g Si and 0.03 g Si produced the highest resistivity at 2.999 Ω . Result shows that the current sample of 0.02 g and 0.03 g of silicone added conductive polymer has less mechanical and conductivity properties when being tested until 4000 cycles since it produced high resistivity that indicate low conductivity that is important for semiconductor component. In terms of trend, increasing the number of cycles will increase the resistivity and decrease the conductivity. It can be concluded that number of cycles is directly proportional to resistivity, while inversely proportional to conductivity.

Lastly, the surface of conductive polymer also been observed and found out that there are the highest crack and hole in the sample of 0.03 g of silicone added at 4000 cycles due to poor abilities of graphene and silicone mixture, and conductive polymer to withstand high number of cycles. Due to low ability to withstand under high number of cycles, it will affect the resistivity as it is directly proportional to number of cycles. Long crack will form an air trap on the surface of the conductive polymer, that reducing the mechanical properties.

5.2 Recommendation for Future Research

For the future work recommendation on the electrically conductive polymer using graphene fillers.

- 1) Prepare the electrically conductive polymer on PET substrates.
- 2) Prepare the conductive polymer in the inert environment and analysis the properties of electrically conductive polymer.
- 3) Prepare the electrically conductive polymer using rubber and do comparison between the elastomer.
- 4) Run the cyclic load test under various temperature and number of cycles to obtain maximum cyclic stress the conductive polymer can withstand

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APPENDIX A

Average Resistance of Silicone Added

Sample	Point	Resistance 1	Resistance 2	Resistance 3	Resistance	Average Resistance
	1	0.953	0.955	0.956	0.955	
S 1	2	0.834	0.831	0.832	0.832	0.802
	3	0.745	0.758	0.772	0.758	
	4	0.652	0.659	0.676	0.662	
	1	1.062	1.090	1.053	1.068	
S2	2	0.880	0.902	0.876	0.886	0.878
	3	0.791	0.835	0.837	0.821	
	4	0.749	0.732	0.730	0.737	
	1	2.411	2.498	2.465	2.458	
S3	2	1.634	1.640	1.660	1.645	1.623
	3	1.286	1.261	1.290	1.279	
	4	1.087	1.114	1.122	1.108	

Average Resistance for 0.01g Si at Before cycle

0.0

UNIVERSITI TEKNIKAL MALAYSIA MELAKA Average Resistance for 0.01g Si at 1000 cycle

Sample	Point	Resistance 1	Resistance 2	Resistance 3	Resistance	Average Resistance
	1	1.030	1.086	1.088	1.068	
S 1	2	0.875	0.899	0.905	0.893	0.853
	3	0.759	0.785	0.784	0.776	
	4	0.670	0.678	0.679	0.676	
	1	1.254	1.259	1.285	1.266	
S2	2	0.930	0.931	1.059	0.973	1.040
	3	1.004	1.025	1.015	1.015	
	4	0.894	0.911	0.898	0.901	
	1	3.283	3.273	3.390	3.315	
S3	2	1.538	1.574	1.656	1.589	1.880
	3	1.439	1.493	1.494	1.475	
	4	1.129	1.130	1.162	1.140	

Sample	Point	Resistance 1	Resistance 2	Resistance 3	Resistance	Average Resistance
	1	1.102	1.171	1.170	1.148	
S 1	2	0.978	1.034	1.032	1.015	0.930
	3	0.864	0.870	0.895	0.876	
	4	0.674	0.681	0.673	0.676	
	1	1.342	1.332	1.406	1.360	
S2	2	0.959	0.999	1.002	0.987	1.045
	3	0.944	0.978	1.003	0.975	
	4	0.873	0.883	0.809	0.855	
	1	2.364	2.345	2.419	2.376	
S3	2	1.747	1.757	1.752	1.752	1.844
	3	1.718	1.768	1.804	1.763	
	4	1.471	1.493	1.485	1.483	

Average Resistance for 0.01g Si at 2000 cycle



Average Resistance for 0.01g Si at 3000 cycle

Sample	Point	Resistance 1	Resistance 2	Resistance 3	Resistance	Average Resistance
	1 —	1.127	1.160	1.162	1.150	
S1	2 U	1.183	TE 1.247 AL	MA1.290 SIA	1.240	0.997
	3	0.794	0.815	0.813	0.807	
	4	0.778	0.799	0.794	0.790	
	1	1.854	1.916	1.959	1.910	
S2	2	1.068	1.059	1.054	1.060	1.283
	3	1.058	1.112	1.148	1.106	
	4	1.037	1.045	1.082	1.055	
	1	2.027	2.132	2.102	2.087	
S3	2	1.660	1.754	1.785	1.733	1.564
	3	1.457	1.464	1.426	1.449	
	4	0.975	0.972	1.011	0.986	

Sample	Point	Resistance 1	Resistance 2	Resistance 3	Resistance	Average Resistance
	1	1.151	1.147	1.145	1.148	
S 1	2	1.039	1.067	1.046	1.051	0.997
	3	0.991	0.992	0.987	0.990	
	4	0.783	0.799	0.817	0.800	
	1	1.244	1.308	1.315	1.289	
S2	2	1.163	1.227	1.197	1.196	1.090
	3	0.971	0.978	0.832	0.927	
	4	0.914	0.948	0.951	0.938	
	1	2.605	2.694	2.810	2.703	
S3	2	1.842	1.897	2.026	1.922	1.790
	3	1.463	1.510	1.583	1.519	
	4	1.017	1.021	1.006	1.015	

Average Resistance for 0.01g Si at 4000 cycle



Average Resistance for 0.02g Silicone Added

Sample	Point	Resistance 1	Resistance 2	Resistance 3	Resistance	Average Resistance
	1	1.129	0.947	0.900	0.992	
S1	2	0.666	0.669	0.653	0.663	0.778
	3	0.713	0.712	0.741	0.722	
	4	0.728	0.735	0.742	0.735	
	1	1.293	1.254	1.241	1.263	
S2	2	0.735	0.735	0.877	0.782	0.837
	3	0.595	0.610	0.696	0.634	
	4	0.662	0.664	0.678	0.668	
	1	4.379	4.549	4.530	4.486	
S3	2	4.426	4.426	4.456	4.436	4.453
	3	4.380	4.520	4.517	4.472	
	4	4.440	4.459	4.351	4.417	

Average Resistance for 0.02g Si at Before cycle



Sample	Point	Resistance 1	Resistance 2	Resistance 3	Resistance	Average Resistance
	1 —	0.826	1.039	1.364	1.076	
S1	2 U	0.693	0.865 AL	MA0.782 SIA	0.780	0.864
	3	0.920	0.917	0.900	0.912	
	4	0.695	0.682	0.682	0.686	
	1	0.112	0.114	0.112	0.113	
S2	2	0.833	0.853	0.892	0.859	0.632
	3	0.806	0.832	0.825	0.821	
	4	0.744	0.736	0.725	0.735	
	1	4.785	4.897	4.967	4.883	
S3	2	5.189	5.213	5.225	5.209	4.864
	3	4.269	4.306	4.307	4.294	
	4	4.956	5.069	5.182	5.069	

Sample	Point	Resistance 1	Resistance 2	Resistance 3	Resistance	Average Resistance
	1	0.911	1.071	1.312	1.098	
S1	2	0.992	1.065	1.022	1.026	1.012
	3	0.980	1.066	1.225	1.090	
	4	0.779	0.829	0.890	0.833	
	1	1.444	1.386	1.382	1.404	
S2	2	1.160	1.153	1.133	1.149	0.983
	3	0.669	0.666	0.658	0.664	
	4	0.717	0.717	0.704	0.713	
	1	4.914	4.762	4.879	4.852	
S3	2	6.035	6.297	6.289	6.207	5.465
	3	4.654	4.718	4.848	4.740	
	4	5.928	6.119	6.135	6.061	

Average Resistance for 0.02g Si at 2000 cycle



Average Resistance for 0.02g Si at 3000 cycle

		No.				
Sample	Point	Resistance 1	Resistance 2	Resistance 3	Resistance	Average Resistance
	1	1.099	1.071	1.226	1.132	
S1	2	1.178	1.269	1.201	1.216	1.081
	3 —	1.136	1.144	1.015	1.098	
	4 U	0.822	0.883	0.933 514	0.879	
	1	1.798	1.816	1.884	1.833	
S2	2	1.192	1.192	1.255	1.213	1.253
	3	0.945	0.938	0.941	0.941	
	4	0.982	1.014	1.077	1.024	
	1	6.231	6.393	6.543	6.389	
S3	2	6.550	6.563	6.560	6.558	6.564
	3	5.059	5.165	5.212	5.145	
	4	8.060	8.197	8.235	8.164	

Sample	Point	Resistance 1	Resistance 2	Resistance 3	Resistance	Average Resistance
	1	1.815	1.834	1.211	1.620	
S1	2	1.012	1.066	1.072	1.050	1.157
	3	1.260	1.183	1.039	1.161	
	4	0.761	0.821	0.810	0.797	
	1	1.089	1.089	1.128	1.102	
S2	2	1.314	1.412	1.437	1.388	1.100
	3	1.019	1.079	1.092	1.063	
	4	0.813	0.864	0.868	0.848	
	1	5.619	5.720	6.883	6.074	
S3	2	7.576	7.511	7.529	7.539	6.740
	3	5.957	6.038	6.054	6.016	
	4	7.616	7.165	7.203	7.328	

Average Resistance for 0.02g Si at 4000 cycle



Average Resistance for 0.03g Silicone Added

Sample	Point	Resistance 1	Resistance 2	Resistance 3	Resistance	Average Resistance
	1	2.194	2.416	2.305	2.305	
S1	2	1.932	1.873	1.905	1.903	1.821
	3	1.733	1.727	1.707	1.722	
	4	1.357	1.363	1.341	1.354	
	1	1.757	1.945	2.095	1.932	
S2	2	1.415	1.452	1.490	1.452	1.510
	3	1.308	1.376	1.442	1.375	
	4	1.226	1.312	1.311	1.283	
	1	1.788	1.815	1.885	1.829	
S3	2	1.190	1.196	1.252	1.213	1.252
	3	0.950	0.934	0.941	0.942	
	4	0.987	1.010	1.079	1.025	

Average Resistance for 0.03g Si at Before cycle



Average Resistance for 0.03g Si at 1000 cycle

Sample	Point	Resistance 1	Resistance 2	Resistance 3	Resistance	Average Resistance
	1	4.639	4.468	4.680	4.596	
S1	2	3.289	2.971	2.698	2.986	3.390
	3	3.580	3.709	3.728	3.672	
	4	2.206	2.365	2.338	2.303	
	1	1.913	1.988	1.996	1.966	
S2	2	1.465	1.618	1.625	1.569	1.577
	3	1.379	1.389	1.416	1.395	
	4	1.338	1.380	1.416	1.378	
	1	1.810	1.824	1.701	1.778	
S3	2	1.080	1.060	1.052	1.064	1.313
	3	1.250	1.173	1.140	1.188	
	4	1.160	1.198	1.310	1.223	

Sample	Point	Resistance 1	Resistance 2	Resistance 3	Resistance	Average Resistance
	1	5.598	5.507	6.362	5.822	
S 1	2	3.185	3.190	3.218	3.198	3.754
	3	2.220	2.192	2.185	2.199	
	4	3.681	3.849	3.856	3.795	
	1	1.998	2.017	2.054	2.023	
S2	2	1.320	1.357	1.370	1.350	1.657
	3	1.862	1.895	1.834	1.864	
	4	1.325	1.430	1.419	1.391	
	1	2.400	2.490	2.460	2.450	
S3	2	1.635	1.650	1.650	1.645	1.623
	3	1.290	1.271	1.285	1.282	
	4	1.107	1.114	1.122	1.114	

Average Resistance for 0.03g Si at 2000 cycle



Sample	Point	Resistance 1	Resistance 2	Resistance 3	Resistance	Average Resistance
	1 —	7.644	7.615	7.861	7.707	
S1	2 U	3.447	1E 3.170 A	A3.033 SIA	3.217 CA	5.184
	3	4.269	4.220	4.343	4.277	
	4	5.723	5.372	5.508	5.534	
	1	2.498	2.588	2.023	2.370	
S2	2	1.327	1.397	1.418	1.381	1.799
	3	1.433	1.459	1.480	1.457	
	4	1.864	1.991	2.107	1.987	
	1	2.344	2.345	2.319	2.336	
S3	2	1.647	1.657	1.652	1.652	1.757
	3	1.712	1.764	1.802	1.759	
	4	1.270	1.290	1.280	1.280	
Sample	Point	Resistance 1	Resistance 2	Resistance 3	Resistance	Average Resistance
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	1	8.825	9.176	8.417	8.806	
S 1	2	5.504	5.360	5.546	5.470	5.357
	3	3.021	2.987	3.171	3.060	
	4	4.131	4.076	4.073	4.093	
	1	2.237	2.509	2.442	2.396	
S2	2	1.377	1.394	1.353	1.375	1.762
	3	1.544	1.596	1.626	1.589	
	4	1.647	1.706	1.708	1.687	
	1	3.183	3.173	3.280	3.212	
S3	2	1.538	1.574	1.656	1.589	1.879
	3	1.439	1.493	1.494	1.475	
	4	1.229	1.230	1.262	1.240	

Average Resistance for 0.03g Si at 4000 cycle



APPENDIX B

SAMPLE OF IMAGEJ ANALYSIS

