

T.R.
GEBZE TECHNICAL UNIVERSITY
GRADUATE SCHOOL

GRAPHENE BASED STRETCHABLE ELECTRONICS



BERKCAN ZULFIKAR

A THESIS OF MASTER OF SCIENCE
DEPARTMENT OF
NANOSCIENCE AND NANOENGINEERING

ASSIST. PROF. NIHAN AYDEMİR

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*To my Family and
all of my Co-workers
and my beloved professor
Nihan Aydemir*

ABSTRACT

Stretchable electronic components are electronic components that, unlike traditional rigid electronics, can withstand mechanical stress when subjected to stretching forces. They have become important with the advent of wearable technology, which requires compliant electronics. Various material designs are being investigated to ensure structural extensibility, such as Wavy, island and Kirigami-inspired designs. Material selection is critical in stretchable and conductive composites, which commonly use elastomers filled with nanomaterials such as metals, carbon nanotubes, and graphene. One particular material design that has attracted attention is laser-induced graphene, which is produced using different laser wavelengths on substrates such as polyimide. This method offers potential advantages in terms of scalability and manufacturing. The aim of the present thesis is to discuss the development of stretchable electronics and explore new designs using laser-induced graphene (LIG) and Kirigami-inspired patterns. To achieve this goal, LIG is characterized using advanced techniques such as Scanning Electron Microscopy (SEM), Energy Dispersive X-Ray Spectroscopy (EDX), Raman spectroscopy and X-Ray Photoelectron Spectroscopy (XPS) to analyze its morphology, composition, defects, and bonding properties. In addition, various Kirigami-inspired designs, including a unique design created specifically for this thesis, were subjected to mechanical testing to evaluate their performance. Once an appropriate sample was selected, two different device designs were subjected to electrical performance testing. The results of the characterization tests showed the successful production of LIG. The mechanical tests highlighted the high mechanical performance of the uniquely created design. Performance evaluation revealed that the line pattern exhibits less change in resistance when subjected to stretching forces, although both designs showed an increase in resistance over cycles due to substrate deformation.

Keywords: Stretchable Electronics, Graphene, Scanning Electron Microscopy, X-Ray Photoelectron Spectroscopy, Raman Spectroscopy.

ÖZET

Esnek elektronik bileşenler, geleneksel sert elektroniklere karşı, gerilme kuvvetlerine maruz kaldıklarında mekanik stresle başa çıkabilen elektronik bileşenlerdir. Giyilebilir teknolojinin ortaya çıkmasıyla birlikte, uyumlu elektroniklere olan ihtiyaçları nedeniyle önem kazanmışlardır. Dalgalı, ada ve Kirigami'den ilham alan tasarımlar gibi yapısal genişletilebilirlik sağlamak için çeşitli malzeme tasarımları araştırılmaktadır. Esnek ve iletken kompozitlerde malzeme seçimi kritik öneme sahiptir; bu genellikle metaller, karbon nanotüpler ve grafen gibi nanomalzemelerle doldurulmuş elastomerler kullanılarak gerçekleştirilir. Dikkat çeken özel bir malzeme tasarımı, poliimid gibi substratlar üzerinde farklı lazer dalga boyları kullanılarak üretilen lazer kaynaklı grafendir. Bu yöntem, ölçeklenebilirlik ve üretim açısından potansiyel avantajlar sunar. Bu çalışmanın amacı, esnetilebilir elektroniklerin gelişimini tartışmak ve lazer kaynaklı grafen (LIG) ve Kirigami'den ilham alan desenler kullanarak yeni tasarımları keşfetmektir. Bu hedefe ulaşmak için LIG, morfolojisini analiz etmek için Taramalı Elektron Mikroskobu (SEM), Enerji Dağılımı Spektrometresi (EDX), Raman Spektroskopisi ve X-Işını Fotoelektron Spektroskopisi (XPS) gibi ileri teknikler kullanılarak karakterize edilir. Bileşimi, kusurları ve bağlanma özellikleri incelenir. Ayrıca, bu çalışma için özel olarak oluşturulan benzersiz bir tasarım da dahil olmak üzere, Kirigami'den ilham alan çeşitli tasarımlar, performanslarını değerlendirmek için mekanik testlere tabi tutuldu. Uygun bir örnek seçildikten sonra, iki farklı cihaz tasarımı elektriksel performans testine tabi tutuldu. Karakterizasyon testlerinin sonuçları, LIG'nin başarılı bir şekilde üretildiğini gösterdi. Mekanik testler, benzersiz olarak oluşturulan tasarımın yüksek mekanik performansını gösterdi. Performans değerlendirmesi, çizgi deseninin gerilme kuvvetlerine maruz kaldığında dirençte daha az değişiklik gösterdiğini ortaya koyarken, her iki tasarımın da alt tabaka deformasyonu nedeniyle döngüler boyunca dirençte bir artış gösterdiğini ortaya çıkardı.

Anahtar Kelimeler: Esneyebilir Elektronikler, Grafen, Taramalı Elektron Mikroskobu, X-Işını Fotoelektron Spektroskopisi, Raman Spektroskopisi.

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LIST OF SYMBOLS AND ABBREVIATIONS

μm	: Micrometer
mm	: Milimeter
S	: Siemens
CH_4	: Methane
CO_2	: Carbon dioxide
H_2	: Hydrogen
$(\text{NH}_4)_2\text{SO}_4$	: Ammonium Sulfate
CE	: Counter Electrode
CVD	: Chemical Vapor Deposition
EDX	: Energy-Dispersive X-Ray Spectroscopy
FEA	: Finite Element Analysis
GO	: Graphene Oxide
LIG	: Laser Induced Graphene
PCB	: Printed Circuit Boards
PDMS	: Polydimethylsiloxane
PI	: Polyimide
PU	: Polyurethane
rGO	: Reduced Graphene Oxide
SEM	: Scanning Electron Microscopy
WE	: Working Electrode
XPS	: X-Ray Photoelectron Spectroscopy

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1. INTRODUCTION

This first chapter contains an introduction to the concept of stretchable electronics as well as a thorough description of what they are and how to make them. How and from what sources stretchable electronics can be made are explored.

The second section describes the short list of applications for these devices. The last material discussed is graphene. Properties are explained along with the fabrication processes.

The thesis also describes laser induced graphene (LIG), a more recent variety of graphene. Due to its advantages during the fabrication process, this material can lead to new possibilities in stretchable electronics.

1.1. Stretchable Electronics

Current developments in materials science and technology point to a shift away from rigid substructures to stretchable electronic components. This area of study drew a lot of attention for the last decade, which had a big impact on the research and commercial pathways. The need for electrical devices to have larger mechanical properties to withstand frequent deformation has become more apparent with the rise in popularity of wearable smart electronics. In order to meet the demands of wearable electronics, advanced raw materials and challenging manufacturing processes are required for stretchable devices, which can be seamlessly incorporated into textiles or clothing to power electrical devices. In the decade, researchers and engineers have continuously carried out research and development on novel materials and design strategies for stretchable electrodes as well as traditional inorganic materials to meet the demands of the next generation of wearable electronics [1].

The main goal of using stretchable electronics is to incorporate electronics in places where using rigid materials is not practical such as wearable technology. For instance, in the field of artificial skin technology, scientists are concentrating on the development of stretchable electronics. Alongside the development of flexible electronics, there has been progress in the field of stretchable electronics. Studies carried out in 2006 laid the first foundation for the discovery of stretchable electronics

[2]. These studies can be considered as the continuation of earlier investigations into stretchable electronic devices that have higher mechanical strength requirements. Since then, a wide range of stretchable electronics designs have been explored, utilizing various materials [3].

1.1.1. Brief Definition

Stretchable electronics are electronic components that can handle mechanical stress when subjected to opposing forces. This property distinguishes them from flexible electronics, which only resist bending and twisting. In contrast, stretchable materials retain their properties even under tension. The development of stretchable electronics began in 2006, following research on flexible electronic devices that required more mechanical strength. Different materials have since been studied for designing stretchable electronic systems. In principle, the stretchable substrate and the conductive layer are two essential parts that make stretchable electronics work, indicated in **Figure 1.1**. Because it gives the conductive layer structure and support, the substrate is essential. To manage large loads, it's crucial to choose resilient materials with elastic qualities. While polyimide can be made stretchable through other techniques, substrates such as PU, PDMS, and PEDOT:PSS can be utilized as they are intrinsically flexible and stretchable to some extent. Depending on the needs of the device, liquid metals, metal wires, or nanoparticles can also be used to create the conductive layer. Additionally compatible with stretchable electronics are graphene and carbon nanotubes. To build durable and functional stretchable electronics, the right materials must be selected for each component [3].

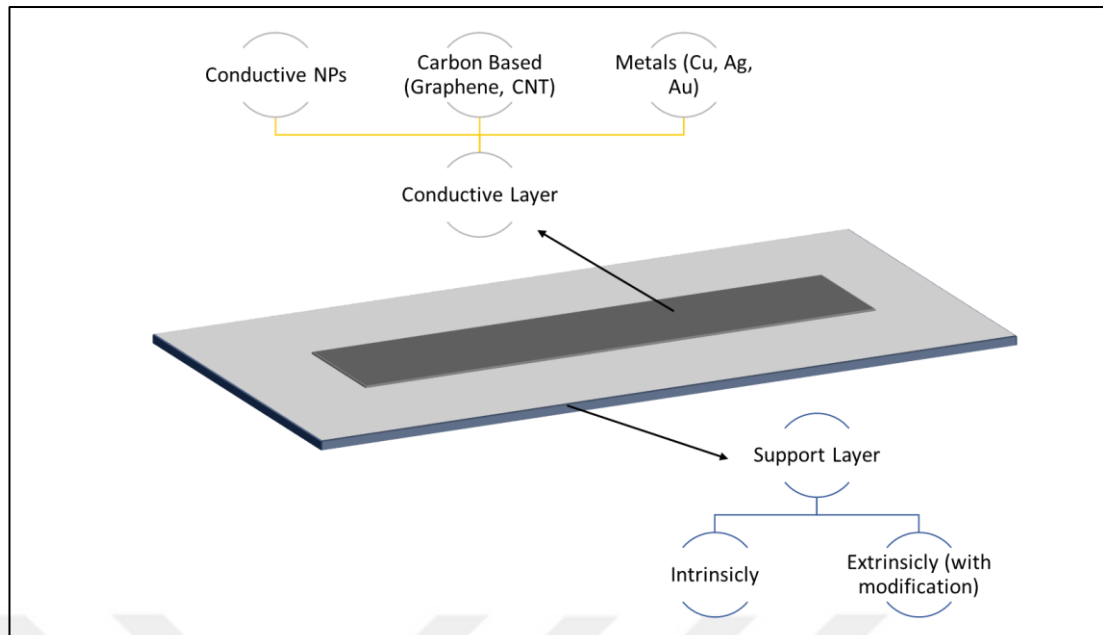


Figure 1.1: A simple representation of stretchable electronics.

The foundation of stretchable electronics lies in the material selection, but since the materials used in the conductive layer might not be strong enough to withstand mechanical strain, other strategies are required for device fabrication. A certain amount of conductivity loss is frequently the outcome of such strains [4]. That being said, it is also necessary to consider the product's design factor. Examples of structures that have been widely used to create structural stretchability including spiral or wavy-like structures, interconnected islands, fractal designs, and structures that are inspired by Kirigami is shown in **Figure 1.2**. With the use of curvatures on a second dimension, buckling structures allow for the loading of more material in one dimension than straight planes. Because of this, applying pulling in a lengthwise direction result in less stresses on the atomic bonds. Structures that resemble spirals or waves typically consist of two layers, each of which is shaped like a wave running the length of the structure. Stretchability in both one and two dimensions can be achieved with this design. With rigid materials, buckling structures can also be used. The linked island design adds two distinct structures together to maximize their strengths and minimize their weaknesses, much like composites do. According to this design, conductive bridges or liquid metals arranged geometrically on a stretchable substrate connect the rigid island structures. With increased stretchability without sacrificing conductivity, the stiff islands offer high connectivity for devices. In designs with geometric

configurations, patterns that will be covered later can be included, such as wave-like structures running the width. Stretchability is possible in two dimensions with the connected island design. Some creative designs have been investigated to replace conventional conductive designs, like horseshoe structures and rounded zigzag (also called "serpentine"), since the idea of stretchability in highly ductile materials is essentially based on depositing more material in a confined area. Space-filling curves serve as a major source of inspiration for the fractal design field that has seen recent study flourish. Stretchability and strain on the material are increased as a result of these curves' filling more lines within a defined area. The amount to which stretchability is enhanced has been investigated for a number of fractal patterns. Additionally, fractal designs have been used in studies that attempt to provide stretchability in multiple dimensions. Stretchable electronics can be greatly enhanced by fractal designs as well as Kirigami-based designs. Stretchability is achieved through mechanical processes like cutting and folding, which are achieved by geometrically shaping the material. Obtaining an ordered cut pattern on the material is one of the most popular Kirigami-based designs [5].

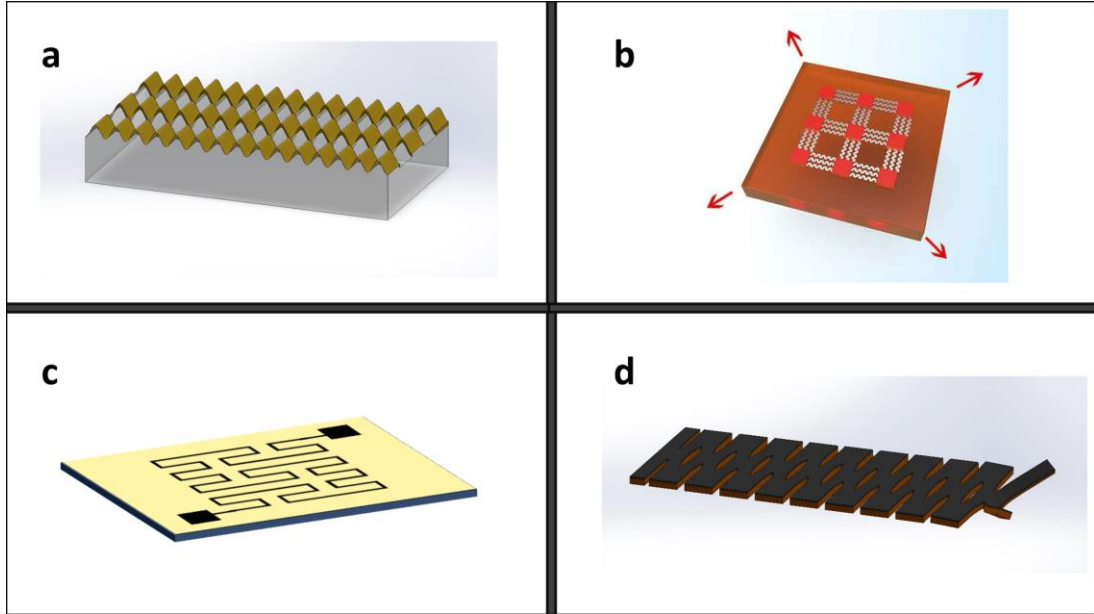


Figure 1.2: Different designs for fabrication of stretchable electronics: (a) wavy-like structures, (b) interconnected island design [5], (c) fractal design (peano curve), and (d) Kirigami inspired design (diamond shape).

Extrinsic stretchable electronics have a significant drawback when higher mechanical strength is required. The bond between the stretchable base and conductive layer can be separated under high mechanical strain, reducing performance. In these cases, intrinsic stretchable electronics can be used to achieve conductivity without compromising stretchability and durability. Intrinsic stretchable electronics can be a composite form (**Figure 1.3a**), or they can be a single material used as a stretchable conductive substrate (**Figure 1.3b**). Stretchable conductors are typically composites of elastomer polymer and conductive nanomaterials in this case. Conductive nanostructured composites, such as metal nanoparticles and nanowires, carbon nanotubes, graphene, and conductive polymers, are commonly used as fillers. The shape and size of fillers, dispersibility, and percolation threshold are important properties to consider. Establishing conductive percolation paths is easier with long and thin nanomaterials, so metal nanowires and carbon nanotubes are often used. Graphene also shows promise due to its high electrical and mechanical properties. The concentration of conductive fillers must reach a threshold level to form a filler network and allow direct current flow. The percolation threshold concentration should be as low as possible to create a conductive composite. Increasing filler concentration

decreases stretchability and transparency, so it must be carefully balanced with the composite's electrical, mechanical, and optical characteristics [6].

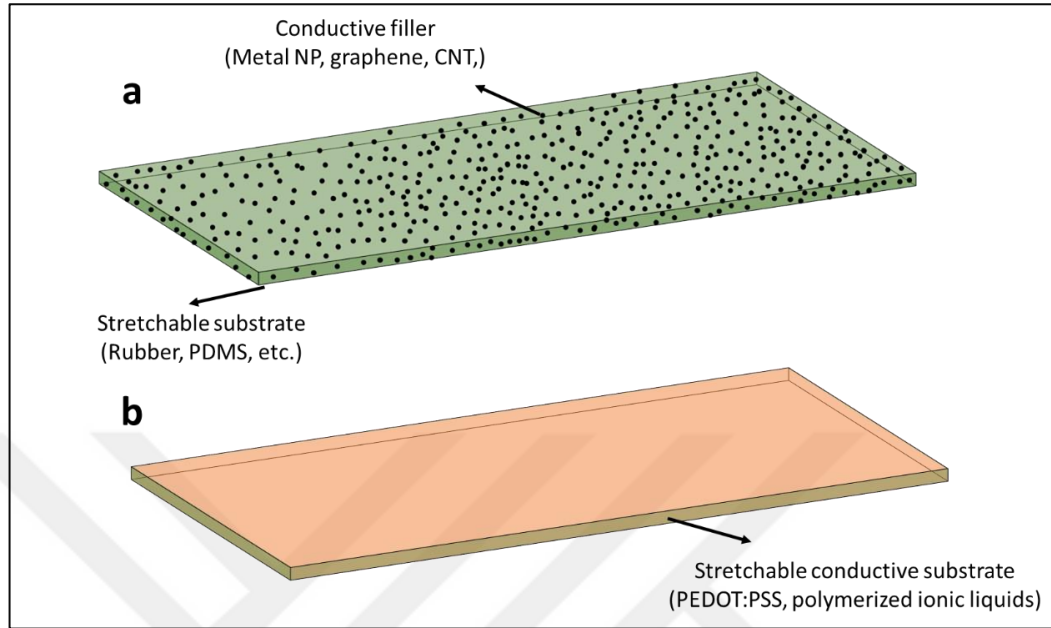


Figure 1.3: A simple representation of extrinsic designs for stretchable electronics: (a) composite structure and (b) stretchable conductive substrate only.

1.1.2. Applications

In **Figure 1.4**, stretchable electronics, as previously indicated, consists of just two layers for its main structure. This design works well enough to function as a simple stretchable circuit or conductive platform. For this reason, conductors and electrodes are the primary targets of stretchable electronics' initial applications. Printed circuit boards (PCBs) and other interconnection devices are currently being used in these fields, along with ongoing investigations into specific designs like stretchable heaters. Studies on energy production and storage devices that use graphene's properties are also being carried out. Transistors and sensors have shown to be the areas where flexible electronics has advanced the most. Strain and tactile sensors serve as notable instances of stretchable sensors. Integrating electronic devices in locations where rigid materials are impractical is the main goal of employing stretchable electronics. Hence, the development of stretchable electronics in artificial skin technology is accepted as a focus area for scientists. Artificial skin technology mimics natural skin structure to enhance sensory capacities by creating artificial contact and gathering information

about strain, humidity, and pressure variations in order to send electrical signals to processors. Stretchable sensors, supercapacitors, transistors, and solar panels can all be integrated to realize this idea [5], [7].

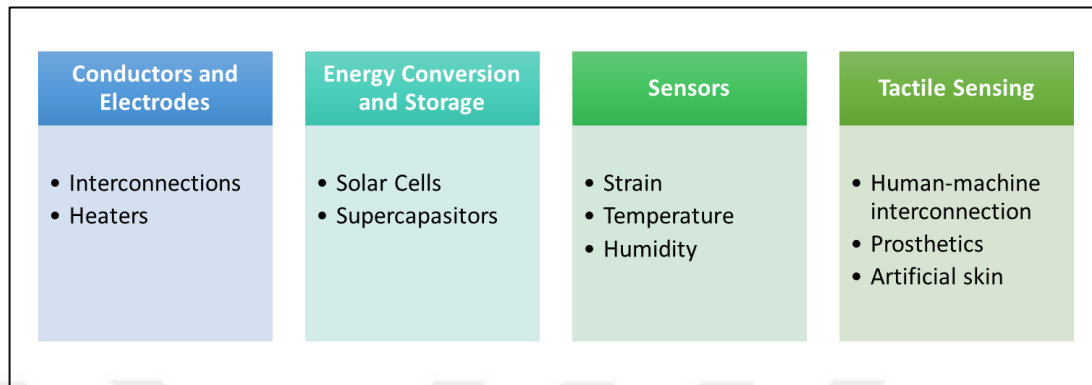


Figure 1.4: Various applications for stretchable electronics.

1.2. Graphene

The past ten years have seen a notable increase in interest in graphene due to its electrical conductivity, super capacitance, improved mechanical qualities, and high thermal conductivity. This focus stems from its potential applications in a broad spectrum, such as solar cells, Li-ion batteries, biosensors, field effect transistors, and supercapacitors. Scientists have investigated and created a number of techniques for producing graphene in order to satisfy the need for these applications. Mechanical exfoliation techniques and chemical synthesis are two top-down approaches to the fabrication of graphene. Conversely, methods like chemical vapor deposition (CVD) and pyrolysis are part of the bottom-up strategies. Scholars have various options to produce graphene with desired properties and characteristics thanks to these different fabrication methods. The field of graphene research and its potential applications have therefore advanced significantly as a result of the study and development of these techniques [8].

1.2.1. Properties

Graphene is a nanostructured hexagonal lattice allotrope of carbon, where each atom in a single layer is connected to its three nearest neighbors by σ -bonds and a delocalized π -bond, represented in **Figure 1.5**. Due to the intersection of valence band and conduction band, graphene's electrical properties are quite impressive. It is an excellent conductor of electricity, surpassing traditional materials like copper. The high electron mobility in graphene allows for fast electron transport, making it invaluable for electronic devices. Moreover, its unique band structure and quantum Hall effect at room temperature contribute to its potential use in quantum computing. The exceptional thermal conductivity of graphene, exceeding that of most materials, opens avenues for applications in heat dissipation and thermal management [8].

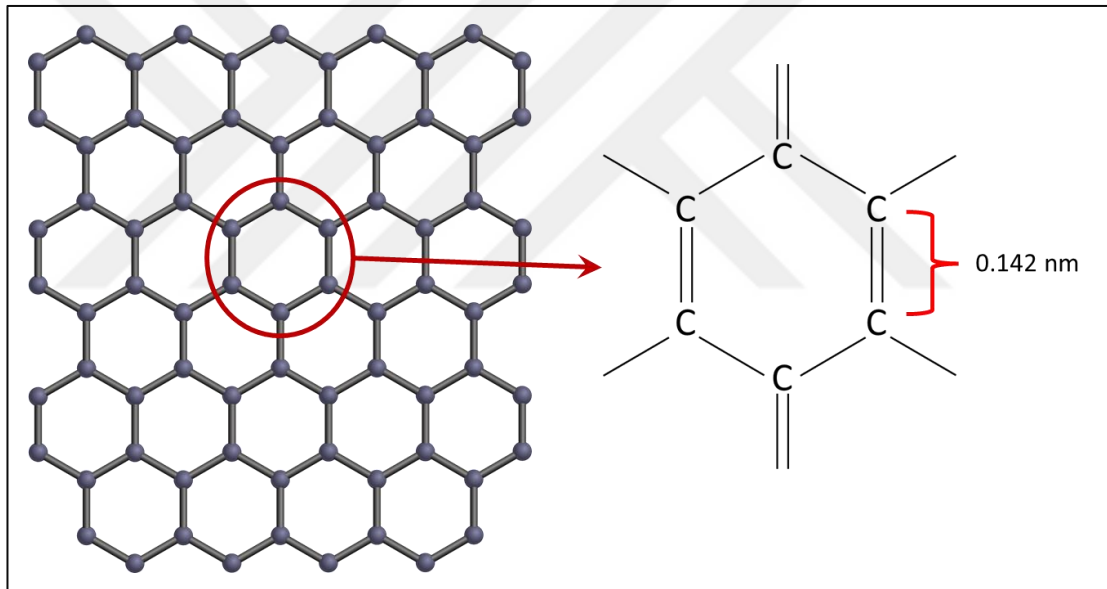


Figure 1.5: A representative structure of graphene.

Beyond its mechanical and electrical prowess, graphene exhibits fascinating optical properties. It is nearly transparent, absorbing only 2.3% of visible light, making it suitable for transparent conductive films [9]. Additionally, graphene's optical response is nonlinear, enabling applications in ultrafast lasers and nonlinear optics. The surface area of graphene is another noteworthy aspect. With a specific surface area of around 2629 m²/g [10], it provides a vast area for interactions with other substances, making it a promising material for sensors and catalysis. However, pure graphene is super

hydrophobic and gas impermeable due to its structure. Hence, it needs to be activated in order to interact with solutions for sensor applications [11].

While these properties make graphene a material of immense potential, challenges remain in large-scale production and integration into existing technologies. Researchers are actively exploring methods to produce graphene at a lower cost and exploring innovative applications across various industries.

1.2.2 Fabrication methods

Figure 1.6 summarizes the exfoliation method, the first graphene fabrication processes. The originally proposed approach involved using an adhesive tape to mechanically peel graphene sheets away from graphite. This process required successive stick and pull movements on subsequent surfaces, resulting in the deposition of a few graphene layers. Such a deposition proved sufficient to study the applications of this remarkable material. Although this particular study was deemed worthy of receiving the prestigious Nobel Prize in 2010, it is evident that a more robust, repeatable, and scalable methodology is required to facilitate further research in this area. In the field of electrochemical exfoliation method, platinum rods are used as the counter electrode (CE) and graphite rods as the working electrode (WE). After carefully inserting the two previously mentioned electrodes into an electrolyte solution containing $(\text{NH}_4)_2\text{SO}_4$, a 10V direct potential is carefully applied for three to five minutes. This careful use produces a large amount of scattered graphene flakes on top of the mixture [12].

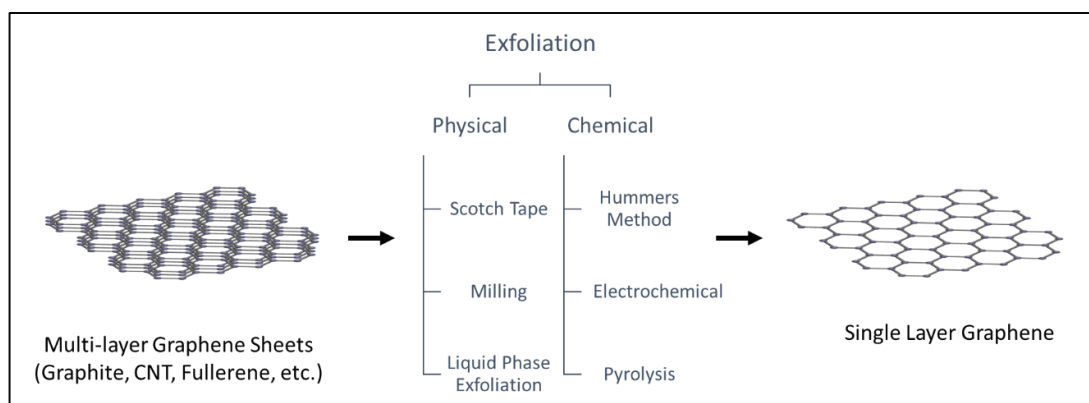


Figure 1.6: A simple representation of exfoliation method for fabrication of graphene.

Another noteworthy strategy that has been discovered is the the Hummers method, which involves chemically peeling graphite in the presence of potent oxidants to yield graphene oxide (GO) [13]. In **Figure 1.7**, the resulting graphene oxide is then exposed to reducing agents, effectively converting it into reduced graphene oxide (rGO). This alternative approach offers potential advantages in terms of increased reliability and ease of implementation, thus proving to be a valuable avenue for future investigations. Importantly, it should be noted that graphene obtained by the Hummers' method and electrochemical exfoliation is dry and powdery, requiring further steps and materials to make film production easier [14].



Figure 1.7: Chemical conversion of graphene to GO and rGO [15].

Chemical Vapor Deposition (CVD) is a promising development in the field as it allows for the fabrication of single or few layers of graphene layers, indicated in **Figure 1.8**. The substrate used in this technique is either copper (Cu) or nickel (Ni) film, providing a strong base for the deposition process. A carefully blended mixture of H_2 and CH_4 is used to purge the CVD chamber, establishing a regulated atmosphere that supports the

growth of graphene. Because of the breakdown of CH_4 at increasing temperatures, carbon atoms (C atoms) dissolve in the Ni or Cu substrate. The C atoms then diffuse until they finally gather on the substrate surface, where they create complex hexagonal graphene structures—a feature that is unique to graphene—once the chamber is sufficiently cooled. A lot of research and documentation have been done on this interesting phenomenon. Multiple layers of graphene are obtained through the CVD process in the case of Ni substrate, according to research investigations. On the other hand, one can effectively grow a single layer of graphene when a Cu substrate is used. The differences in the two substrates' characteristics and behaviors, which in turn influence the development and growth of graphene films, can be used to explain the discrepancy in the results. Graphene films of remarkable quality with controlled thickness and high conductivity are produced by the CVD method, which is worth mentioning. Due to their enormous potential for use in a variety of fields, including electronics, energy storage, and sensing devices, these qualities are extremely important. It is imperative to recognize that, notwithstanding the manifold benefits bestowed upon the CVD methodology, certain constraints must be taken into consideration. A primary disadvantage of this approach is the need for costly equipment, which limits its applicability to a small number of academic and commercial institutions. Furthermore, the extensive labor and expertise required for the CVD process limits its widespread use in the short term. It is therefore essential to investigate substitute techniques that can get around these obstacles and allow for the large-scale synthesis of graphene films. To fully utilize graphene and enable its incorporation into a wide range of technological applications, it will be imperative to develop scalable and economically viable methods [16].

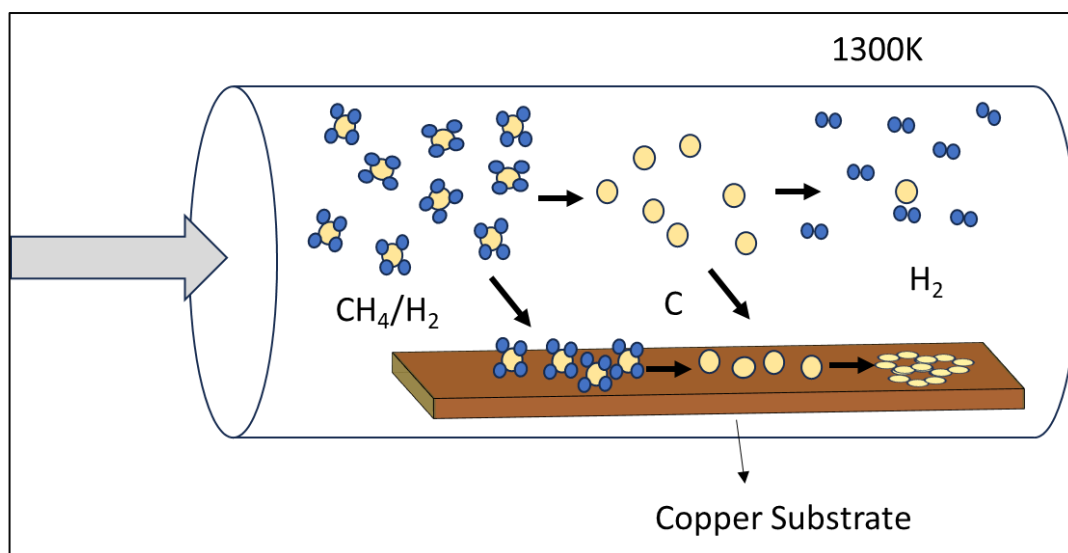


Figure 1.8: A simple representation of CVD method for graphene.

The development of Laser Scribed Graphene (LSG) or Laser Induced Graphene (LIG) has allowed a variety of organic materials to be used in the production of graphene films by applying various types of lasers, thereby addressing the need for a more efficient and labor-saving manufacturing method. In addition to facilitating the in-situ production of devices in conjunction with the graphene film fabrication process, the use of computer-controlled lasers guarantees that the resulting films can be obtained in any desired shape, design, or pattern. The successful production of graphene films is based on the laser reduction mechanism, which is based on three essential elements. First, the material absorbs the light from the laser, and the concentrated and localized energy causes the functional groups to break down. As a result of this process, the carbon atoms are removed. Ultimately, hexagonal graphene sheets are formed when the carbon atoms realign. The need for scalable and labor-saving fabrication techniques is met by this multi-stage process, which produces graphene films with high precision and efficiency [17].

1.2.3. Laser Induced Graphene

The operational mechanism of LIG is shown in **Figure 1.9**, as it is predicated on the absorption of the laser light and the ensuing molecular transformations, such as the breaking of chemical bonds due to the assimilated energy, as well as the expulsion of certain molecules as gaseous byproducts, followed by the reorganization of the

residual atoms. Once the laser beam reaches the surface, the energy is assimilated by the polyimide (PI) film, leading to the rupture of the bonds of functional groups. Consequently, the remaining carbon atoms amalgamate to form graphene. It is worth noting that the intrinsic color of the PI is amber; however, regions subjected to laser engraving undergo a color transition, turning black. It is important to acknowledge that it is typically impracticable to entirely eliminate all the functional groups, thereby resulting in a small amount of nitrogen and oxygen potentially persisting as defects [17], [18].

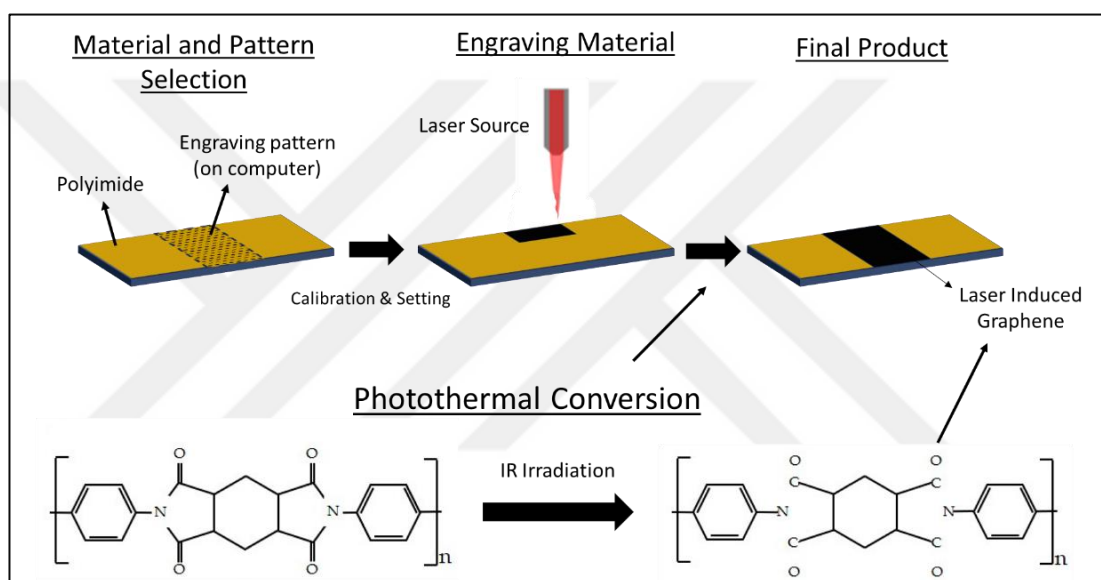


Figure 1.9: A simple representation of Laser Induction method for LIG.

Within the field of laser scribed graphene, El-Kady and Kaner presented the first example. In this experiment, a spin coating technique was used to apply graphene oxide (GO) solution onto PET substrates. The material was subsequently reduced using a 405 nm DVD writer laser [19]. The energy needed to convert graphene is directly impacted by laser absorption of the material. It is important to remember that different materials absorb laser light within specific wavelength ranges, so different materials require different wavelengths of lasers. For instance, in 2014, the first LIG fabrication from PI was demonstrated, along with its supercapacitor application. In this experiment, the Kapton PI material was induced using a CO₂ laser with a wavelength of 10.6 μm [20]. This particular laser was utilized by the researchers to accomplish the

intended conversion of graphene. Several supercapacitor applications were made expertly with this specific film. Furthermore, the application of a CO₂ laser was highly significant in the lignin film treatment process, which in turn produced graphene films. After forming, these new graphene films were applied as electrochemical biosensors, mainly for alcohol, lactate, and glucose screening [21].

Figure 1.10 shows the characterization results of the initial discovery of LIG in 2014. The finished product of the film consisted of densely packed graphene flakes in a porous film with a thickness of approximately 30 μm . Three different peaks that the first order enabled, G peak at about $1,580\text{ cm}^{-1}$, the 2D peak at about $2,700\text{ cm}^{-1}$, which came from second order zone boundary phonons, and the D peak at about $1,350\text{ cm}^{-1}$, which was caused by interference defects or bent sp² carbon bonds were visible in Raman spectroscopy of LIG films. These peaks indicate information about the properties of the graphene formed and show the existence of graphene-like structures. From the XPS spectra, it can be observed that the oxygen and nitrogen peaks in LIG were significantly reduced due to the laser conversion of PI to LIG. Since the C-N, C-O and C=O peaks of PI were significantly reduced, the C 1s spectra show that the C-C peak dominates in LIG. The C=O peak in LIG is less pronounced than the C-O peak in the O 1s spectra. The laser irradiation that produced LIG also significantly reduced the peak intensity of N 1s [20].

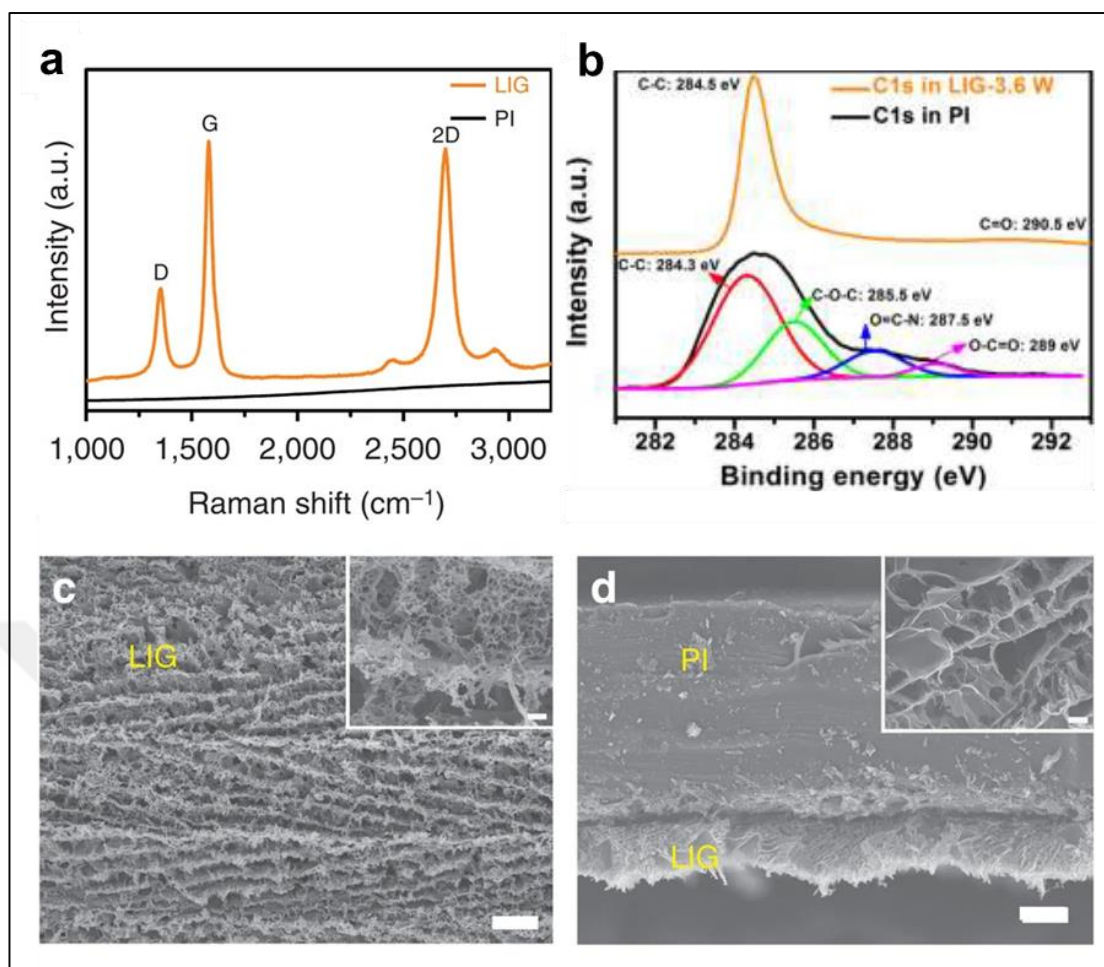


Figure 1.10: Results of literature characterization for LIG; (a) Raman spectroscopy results, (b) XPS results, (c, d) SEM results.

2. BACKGROUND THEORY

This chapter begins with a discussion of the concept of Kirigami designs in stretchable electronics while discussing ideas for Kirigami designs and how they can be used with stretchable electronics to increase stretchability. This gets around traditional rigid electronics' drawbacks.

Second, parameters related to material selection, fold and cut geometry, cross-section density, and their effects on mechanical and electrical properties are discussed in relation to designing Kirigami patterns. Additionally mentioned are elements such as the materials utilized, their mechanical qualities, their stability in various conditions, and the geometry and fold patterns of the cuts and folds that affect the distribution of stresses.

Finally, the assessment of these designs' performance via testing techniques such as finite element analysis, fatigue testing, and tensile testing is presented. A thorough evaluation of the mechanical, electrical, and functional aspects is required.

2.1. Kirigami Designs for Stretchable Electronics

Stretchable electronics benefit from the innovative applications of Kirigami, a traditional Japanese art form that involves the precise cutting paper. The use of Kirigami-inspired designs offers a unique and creative approach to stretchable electronics, where the ability to conform to uneven surfaces and withstand mechanical stress is critical. By incorporating Kirigami principles, which involve strategically placed cuts and folds, it is possible to achieve controlled deformation and stretchability of electronic materials that are initially non-stretchable, thereby overcoming limitations and advancing progress in stretchable electronics. Researchers have successfully demonstrated improved stretchability and flexibility in a variety of electronic components, including circuits, displays, and sensors, through the strategic implementation of cuts and patterns in flexible materials [22]. Kirigami's ability to withstand significant deformation without compromising electrical performance is a notable advantage when it comes to stretchable electronics. This is achieved by creating patterns that efficiently distribute mechanical stresses and prevent the material from failing locally. The design and optimization of Kirigami structures for stretchable

electronics requires consideration of numerous parameters to achieve the desired mechanical and electronic properties. These principles can be used not only to improve these designs but also to create new designs [23].

2.2. Parameters For Designing

The selection of materials for both the electrical components and the flexible substrate is crucial. The material must have the appropriate mechanical properties such as stretchability and flexibility as well as good overall electrical performance. Therefore, elastomers and polymers with specific mechanical properties are often used. Kirigami structures used in the field of stretchable electronics are also often exposed to various environmental conditions. Stability is therefore important to ensure the long-term functionality of the devices even against variables such as temperature, humidity, and chemical exposure. Therefore, selecting high-performance polymers like PI, PMMA, or elastomers such as PDMS serves as excellent alternatives.

A critical factor influencing the material's response to stress is the geometry of the Kirigami pattern, which is determined by various parameters. The size, shape, and placement of cuts and folds in the material play a pivotal role in shaping how stresses are distributed within the structure. The interaction of these parameters influences the overall mechanical behavior of the material, impacting its ability to stretch, compress, and deform. The cutting angles and orientation of the Kirigami pattern are additional parameters that significantly affect the mechanical response of the material during stretching. Although certain designs demonstrate their mechanical stability (see **Figure 2.1**), the long-term objective is to maximize the stretchability of the material while simultaneously minimizing the stress concentration in local areas. This optimization process is essential to enhance the overall performance and durability of the material when subjected to deformation [23].

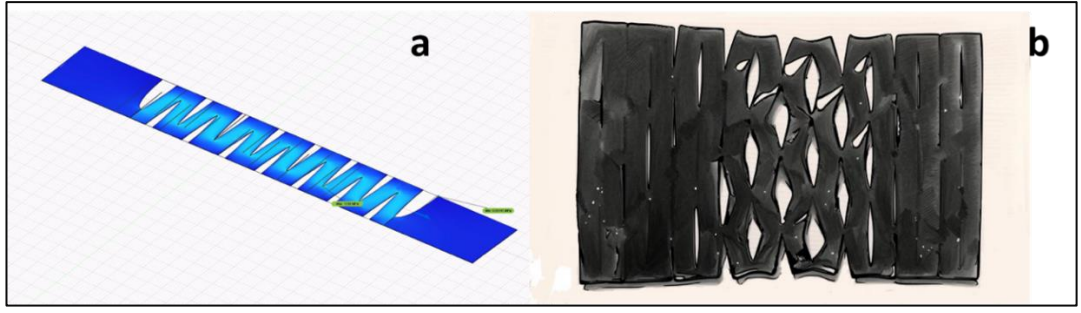


Figure 2.1: Most common examples of Kirigami designs in stretchable electronics: (a) serpentine design and (b) diamond design.

The overall stretchability of the Kirigami structure is not solely reliant on the geometry of the cuts and folds but is also contingent on the quantity and quality of these features. The term "stretchability" refers to the material's ability to undergo extension or stretching. Higher cross-sectional densities, achieved through an increased number of cuts, generally contribute to higher ductility. Ductility is the material's capacity to undergo significant deformation before rupture. However, it is crucial to note that while higher cross-sectional densities enhance ductility, this comes with trade-offs. Other mechanical and electrical properties of the material can be compromised in the process. Factors such as strength, conductivity, and stiffness may be adversely affected as a consequence of increasing the density of cuts.

The aspect ratio of the Kirigami pieces, including cuts and folds, has a significant impact on how the material deforms when pressure is applied. As shown in **Figure 2.2** and equations (2.1) and (2.2), achieving these ratios allows the number of connections between cuts to be varied, which in turn improves overall ductility and mechanical robustness [24].

$$\alpha = (w - 0.5b)/L_0 \quad (2.1)$$

$$\beta = (0.5d - c)/L_0 \quad (2.2)$$

Connection design is of significant importance in the realm of stretchable electronics. This is to distribute stress and provide resistance to deformation. Undoubtedly, it is crucial to have a comprehensive understanding of how the load is distributed throughout the Kirigami structure. It is crucial to ensure that electronic components

can withstand mechanical deformation without losing functionality. Through the effective use of Kirigami patterns, stretchable connections can be created that maintain electrical conductivity even when deformed. Basic factors changing the performance of the device are the spacing and arrangement of the connections [24].

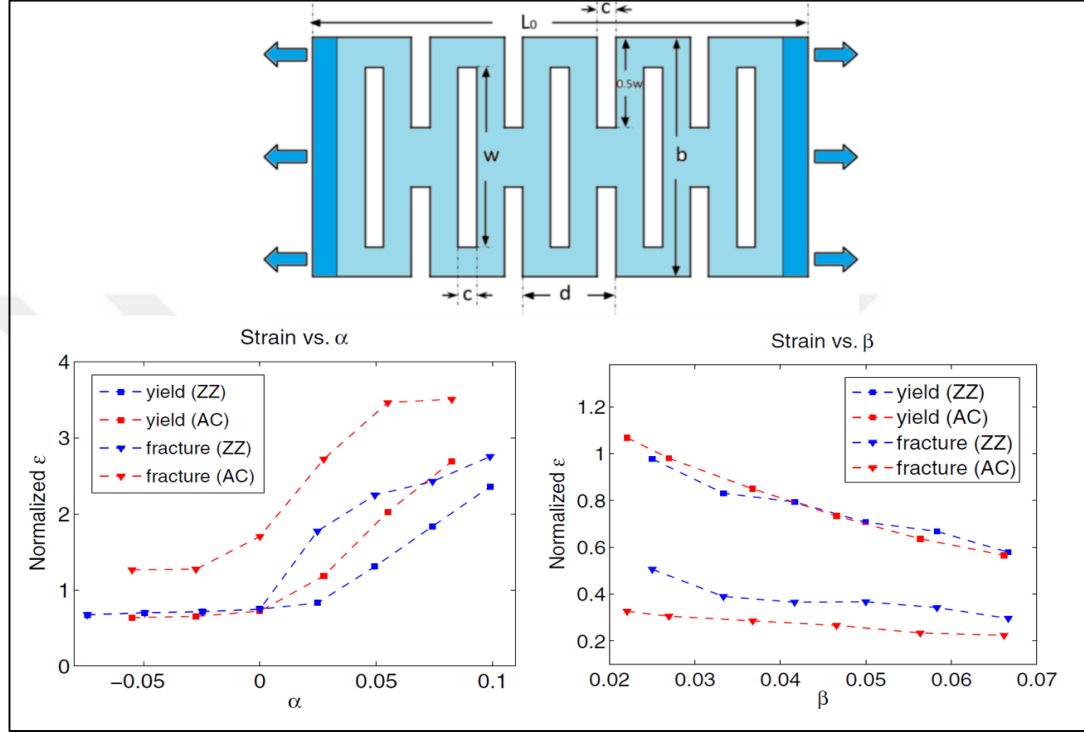


Figure 2.2: Example of the effect of aspect ratio in Kirigami designs in different patterns (AC and ZZ are called “armchair” design and “zigzag” design, respectively) [25].

In the realm of Kirigami designs, the manner in which the cuts are arranged and the degree of density of these cuts within the material have the potential to exert an influence over the electrical conductivity characteristics of said material. A greater number of cuts may introduce a certain level of disruption within the flow of electrical current, thus increasing the resistance and decreasing the overall electrical performance of the material is compromised. The cuts in the material can disrupt the continuous paths for electrical conductivity. Each cut introduces additional resistance to the electrical current. As the density of cuts increases, there may be more interruptions in the conductive paths, leading to a higher electrical resistance. In areas with high cross-sectional densities, where there are numerous cuts, stress concentrations can occur during deformation. This stress concentration may lead to

localized damage, especially for those materials that are not intrinsically stretchable due to the plastic deformation around the cuts. With higher cross-sectional densities, the cumulative effect of increased resistance from multiple cuts can be significant, hindering the electrical conductivity of the material. This can result in decreased efficiency and performance in electrical devices [25].

Another important factor to consider is how feasible it would be to create Kirigami inspired stretchable electronics. Key parameters such as cost-effectiveness of the manufacturing process, reproducibility and scalability need to be considered to meet real-world applications.

2.3. Performance Evaluation

Performance testing of Kirigami designs in the realm of stretchable electronics is a multifaceted process that has a significant importance in guaranteeing the optimal functionality and reliability of devices when subjected to various deformations and strains. This testing involves a comprehensive assessment of mechanical, electrical, and functional characteristics to effectively address the challenges that arise from integrating Kirigami patterns into flexible electronic systems indicating, as shown in **Figure 2.3**.

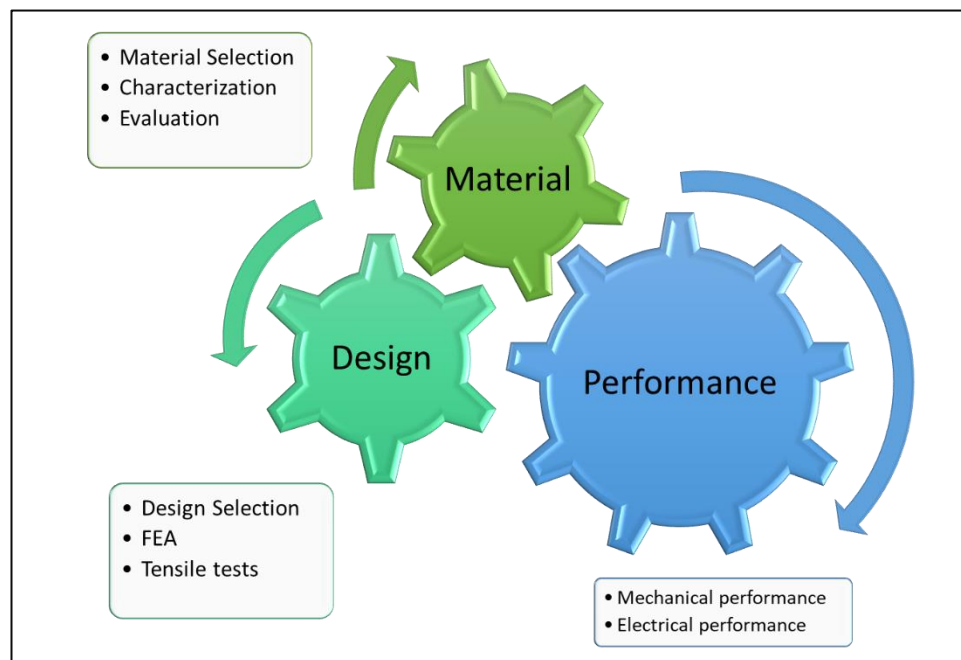


Figure 2.3: Framework for evaluating the performance of stretchable electronics using test methods.

The evaluation of mechanical performance forms the cornerstone of performance assessment, with a particular focus on key parameters such as tensile strength, stretchability, and durability. Tensile testing, for instance, serves as a valuable tool in measuring the material's ability to withstand stretching forces, thereby providing essential data on its mechanical strength and elasticity. Additionally, cyclic loading tests allow for the simulation of repetitive deformations, effectively mimicking real-world conditions and providing valuable insights into the material's fatigue behavior. Furthermore, fatigue testing helps in evaluating the long-term performance and durability of Kirigami structures that are subjected to repeated mechanical stress. Therefore, comprehending how Kirigami patterns respond to these mechanical tests is of utmost importance, as it enables the optimization of their design to meet the demands of diverse applications.

Finite Element Analysis (FEA) emerges as a pivotal tool in the performance testing of Kirigami designs, as it offers researchers the ability to simulate the mechanical behavior of Kirigami structures under various deformation scenarios. This computational approach provides a virtual platform that allows for the prediction of stress distribution and the identification of potential failure points. Consequently, FEA aids in the iterative design optimization of Kirigami patterns by enabling researchers to fine-tune the geometry and arrangement of cuts, thereby enhancing mechanical robustness and stretchability. Notably, studies conducted have extensively used FEA to model the mechanical behavior of kirigami-inspired structures, demonstrating its effectiveness in accurately predicting complex deformation patterns [26]. However, it is important to mention that this analysis requires significant expertise and knowledge in modeling and simulation. This is due to the fact that the cuts behave as fractures in the material, and the deformation mode that occurs is out-of-plane shear rather than opening mode. Specifically, the mode is Mode III instead of Mode I. Therefore, in this thesis, the FEA was not conducted correctly since the stress and strain values of the patterns under tension were incorrect.

In the evaluation of Kirigami-based stretchable electronics, electrical performance assumes equal importance. This encompasses the evaluation of conductivity, resistance, and the reliability of interconnects within the Kirigami patterns. In order to achieve this, specialized materials with tailored electrical properties are often employed in these structures, and performance tests must be conducted to verify the

integrity of these materials when subjected to deformation. For instance, conductive inks, flexible substrates, and stretchable conductive materials represent integral components of Kirigami-based electronics, and their electrical performance is subject to stringent scrutiny in order to ensure consistent conductivity even during deformation [4].



3. MATERIAL CHARACTERIZATION

The current chapter first explains in detail how the LIG sample is prepared for characterization. The materials, equipment and techniques used in this research project are explained in detail.

The results from Energy-Dispersive X-Ray Spectroscopy (EDX) and Scanning Electron Microscopy (SEM) on the sample are then discussed. In addition, a summary of the basic ideas of SEM and EDX is provided in the discussion.

Following, an analysis and discussion of the results obtained by applying Raman spectroscopy to the sample. A description of the theoretical principles and concepts of Raman spectroscopy is also included.

Finally, the findings from the application of X-ray photoelectron spectroscopy (XPS) to the sample are explained. To enhance the reader's understanding, a brief summary of the basic ideas and techniques related to XPS is also provided.

3.1. LIG Fabrication

The VLS 3.60 CO₂ laser engraver was purchased from the Universal Laser Systems (see in **Figure 3.1**). The adhesive-free Polyimide (PI) films (Dupont Kapton HN Film, TapeCase) utilized in the thesis were used. No additional cleaning procedures were required after these films were obtained in their original state. A significant observation is that the films were 125 μm thick, an important dimension to take into account for both experimentation and further analysis. After that, a variety of advanced tools were employed in the characterization experiments in order to acquire precise and trustworthy measurements. For the SEM measurements, the Zeiss SUPRA 50 VP instrument was employed. The XPS measurements, on the other hand, were conducted using the Phoibos 100, SPECS GmbH instrument. Additionally, the Raman measurements were performed utilizing the WITec alpha300 R Raman Microscope and Spectrometer. By utilizing this combination of these instruments, the researchers were able to gather comprehensive data and obtain valuable insights into the characteristics and properties of the materials under investigation.



Figure 3.1: VLS 3.60 (40W, 10600 nm), Universal Laser Systems.

The CO₂ Laser engraver/cutter used in this thesis is shown in **Figure 3.1**. The system consists of multiple components, including a 40W CO₂ laser tube, optics that transfer and focus the laser beam onto the substrate, software, a computer, and a sample stage. It's vital to remember that this specific kind of laser has three different modes of operation: cutting, vector rastering and engraving. The engraving mode is the recommended option when it comes to the fabrication of graphene films, while vector rastering is much more suitable for line designs. This thesis used the Inkscape software to draw the designs and facilitate laser control while ULS, the laser's own software, for laser operations. Two main variables affecting the fabrication of graphene are the laser power and scan speed, both of which are software modifiable. To fabricate the device, all of these parameters should be predetermined. In addition, the design must

be drawn with suitable color due to the color-coding system of laser's software, determining which operation mode will be active during fabrication. As standard, black is for engraving, red is for cutting and blue is for vector rastering. Therefore, the sample shown in **Figure 3.2** was fabricated in engraving mode with a power and write speed setting of 12.5% and 10%, respectively. These parameters are selected from the literature suitable for this research because other parameters are either unable to produce graphene films or are too strong, causing erosion of the substrate, and adjusted to the best electrical conductivity result, without changing the power-speed ratio.

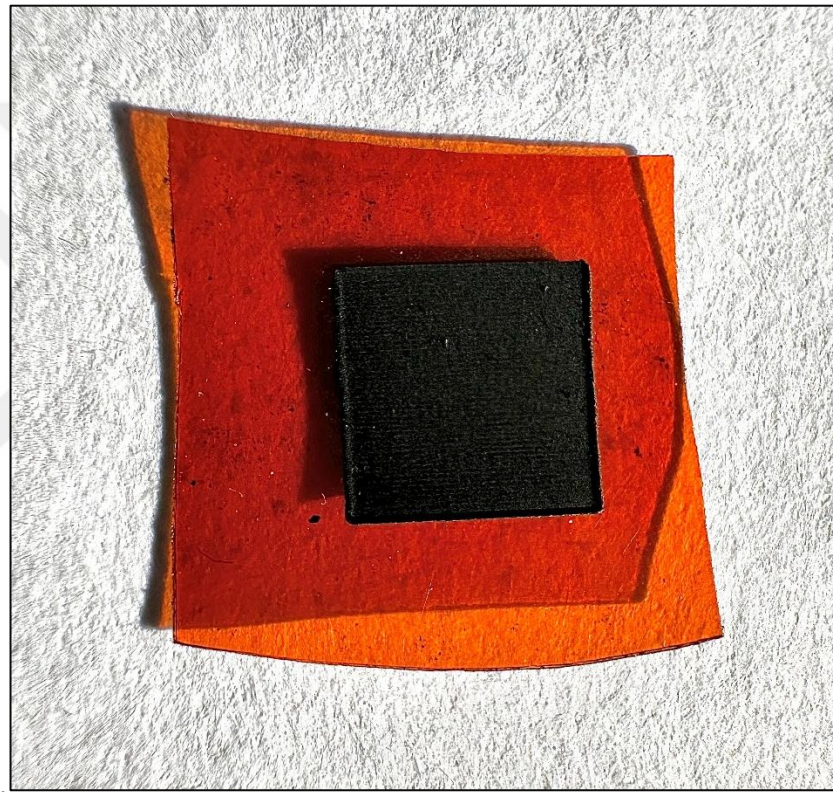


Figure 3.2: The LIG sample for characterization tests.

3.2. Scanning Electron Microscopy and Energy-Dispersive X-Ray Spectroscopy

Scanning electron microscopy (SEM) has been a commonly used imaging technique since the mid-20th century. SEM enables detailed insights into surface morphology and composition by enabling high-resolution, three-dimensional imaging of a variety of materials. The basic idea of SEM is to scan the surface of a substrate with a

concentrated electron beam and create interactions that lead to the emission of different signals. These signals – which include backscattered electrons, secondary electrons, and characteristic X-rays – are then found and used to create finely detailed photos with exceptional depth of field. SEM is an important tool for studying materials at the micro and nanoscale due to its main advantage: it can achieve nanoscale resolution. It is a tool commonly used in materials science to characterize the microstructure of materials. That enables detailed imaging of biological samples such as cells, tissues, and microorganisms, helping to advance the study of topics such as pathology and cell biology [27].

For elemental analysis of materials, energy-dispersive X-ray spectroscopy, also known as EDS or EDX, is a frequently used analytical method in conjunction with scanning electron microscopy, or SEM. Developed as an extension of SEM, EDX allows researchers to determine the elemental composition of a substrate by measuring the emitted characteristic X-rays during high-energy electron bombardment. Both qualitative and quantitative analysis are made possible by the energy and intensity of these X-rays, which are indicative of the elements found in the sample. EDX is a widely used analytical tool in scientific fields, such as geology, biology, materials science, and nanotechnology. It offers important insights into the composition and elemental distribution of a large number of materials at the micro- and nanoscales [28].

Following the fabrication process, the obtained films were subjected to SEM and EDX analyses in order to inspect their characteristics. In **Figure 3.3** we can observe the distinct morphological difference between the polyimide (PI) film and the graphene films. The PI film exhibits a remarkably smooth and flat surface, while the graphene films take on a foam-like form, displaying an extremely porous nature and consisting of flakes with a thickness of only a few nanometers (as depicted in **Figure 3.3c** and **Figure 3.3d**). These nanoflakes are densely packed within the foam-type film, which has approximate thickness of 30 μm (with a standard deviation of $\pm 2 \mu\text{m}$) (see **Figure 3.3e**). It is worth noting that the graphene foam obtained through the LIG (laser-induced graphene) method showcases a porous film structure comprising interlinked nanoflakes, which is consistent with previous observations reported in the literature [29].

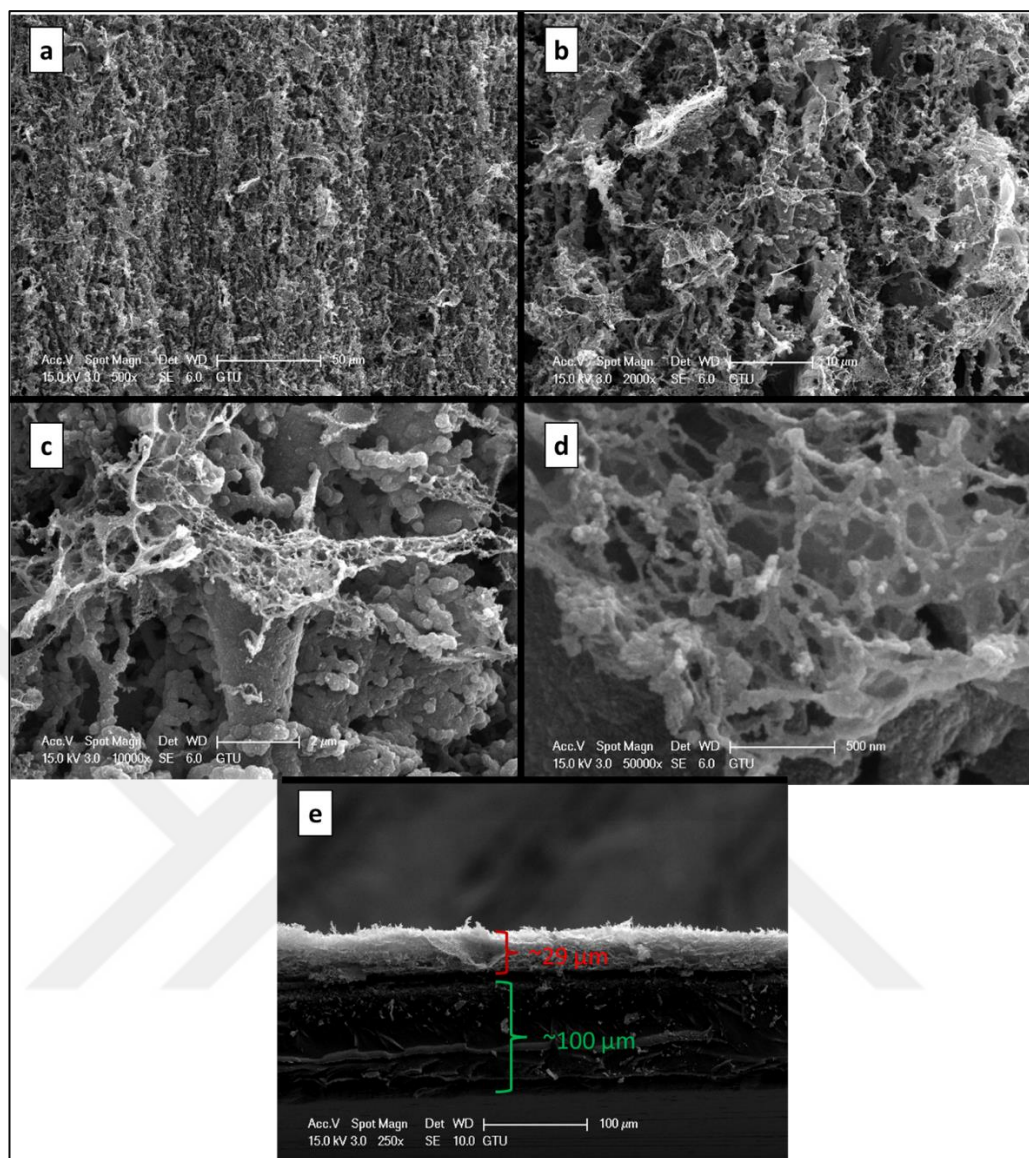


Figure 3.3: SEM results of LIG-PI sample; magnified by (a) 500x, (b) 2000x, (c) 10000x and (d) 50000x, (e) thickness of LIG film on PI substrate.

In the EDX results, carbon, oxygen, and nitrogen are present in LIG, detailed in **Figure 3.4** and **Table 3.1**. Due to the defect structure of LIG, a high proportion of carbon and a low proportion of oxygen atoms are expected. EDX also shows small amounts of nitrogen, which may be due to the chemical composition of the nitrogen-containing PI film. Considering the nature of photothermal conversion in the manufacturing process, this suggests that low nitrogen residues are present in the LIG sample.

Table 3.1: EDX results for LIG-PI sample.

Element	Weight %	Atomic %	Net Int.	N.I. Error
C K	91.43	93.08	2035.34	0
N K	3.42	2.99	5.82	0.14
O K	5.15	3.93	35.14	0.04

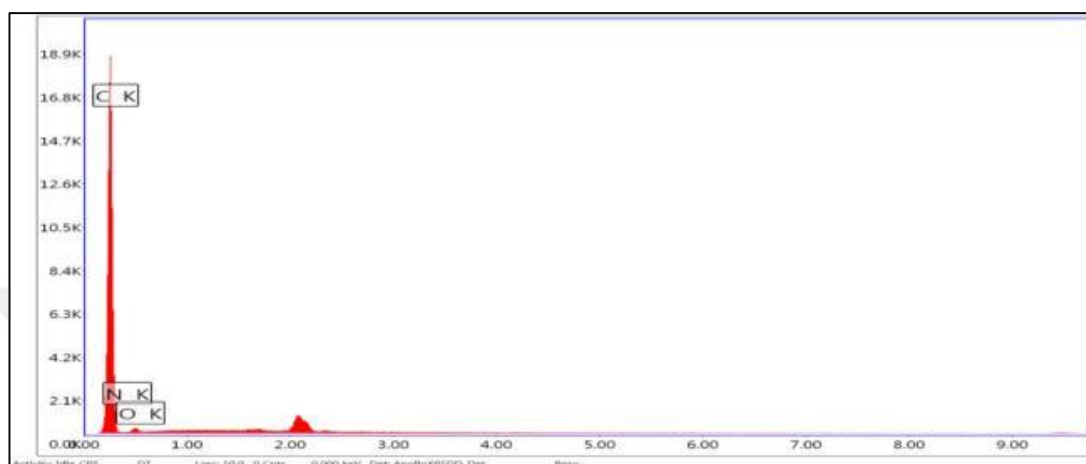


Figure 3.4: EDX results of LIG-PI sample in comparison.

3.3. Raman Spectroscopy

Raman spectroscopy is a technique for analyzing molecular vibrations. It is widely used in various scientific disciplines. It is based on the scattering of light and provides information about molecular composition and structure. An advantage of Raman spectroscopy is its non-destructive nature, which makes it valuable for studying sensitive materials. It can be used for both qualitative and quantitative analysis, identifying compounds, and studying structural changes. The Raman spectrum shows peaks indicating bond lengths, angles, and functional groups. Interpretation often requires expertise in vibrational spectroscopy, but computational methods have facilitated analysis. Advances in Raman instrumentation have expanded its capabilities. Confocal Raman microscopy enables detailed chemical information from specific regions. Surface-enhanced Raman spectroscopy amplifies the signal and allows detection of trace amounts. Raman spectroscopy has applications in pharmacy, biology, environmental science, and cultural heritage analysis [30].

Turning our attention to the Raman spectrum of the LIG, it predominantly exhibits three peaks known as the D, G, and 2D bands (as seen in **Figure 3.5**). The presence of the D band, in the absence of the D' band, indicates the presence of edges with a high density, which may underline the foamy nature of the LIG. The D band is also indicative of the defects within the graphene structure, which corroborates the findings from the XPS survey, highlighting the presence of a small amount of oxygen within the LIG. The G band, on the other hand, corresponds to the stretching vibration of the sp² carbon lattice. Finally, the 2D band represents the secondary D band, arising from the stacking of graphene sheets. By calculating the I_D/I_G ratio, a value of 0.59 was obtained, which further supports the notion of a high-density edge structure within the foamy LIG.

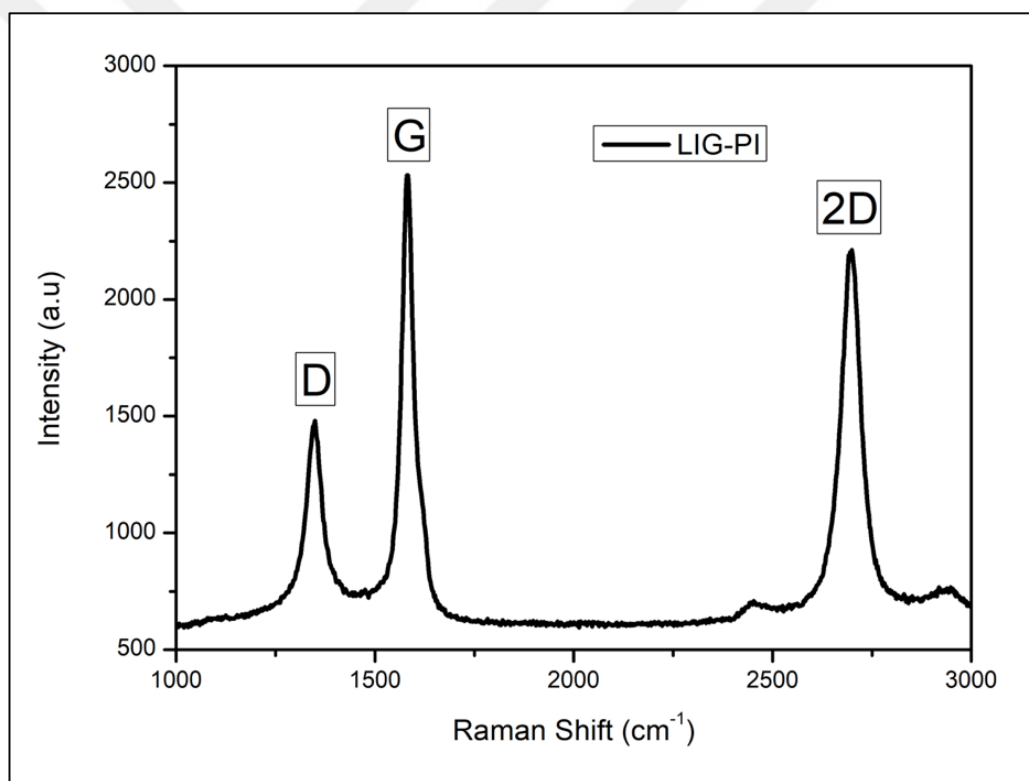


Figure 3.5: Raman results of LIG-PI sample.

3.4. X-Ray Photoelectron Spectroscopy

X-ray photoelectron spectroscopy (XPS) is a surface analysis technique used in materials science, chemistry, physics, and related fields. In XPS, a substrate is irradiated with monochromatic X-rays, causing photoelectrons to be ejected from the atoms within the sample. The amount of electrons that are ejected, and their kinetic energies are measured and provide information about the binding energy of the electrons as well as the elemental composition and chemical state of the sample. XPS is very sensitive to surface composition and can analyze the outermost layers of a material, making it valuable for studying thin films, coatings, and surfaces of heterogeneous materials. XPS can distinguish between different oxidation states of an element and is non-destructive. It can be used to characterize a large amount of materials including metals, polymers, semiconductors, and biological samples. XPS has applications in various scientific and industrial areas. In materials science, it is used in the surface chemistry of catalysts, to analyze thin film interfaces, and to study corrosion processes. In the semiconductor industry, XPS provides important information about device surfaces and interfaces. In biomaterials research, XPS is used to study the interaction between biological molecules and surfaces. Environmental sciences benefit from XPS by characterizing pollutants and understanding surface interactions [31].

The XPS (X-ray photoelectron spectroscopy) survey spectrum provides valuable insights into the composition of the film (as depicted in **Figure 3.6a**), revealing the predominant presence of carbon at an energy level of 286 eV, corresponding to sp² carbons (C1s). Additionally, a small amount of oxygen is detected at 534 eV, corresponding to O1s, which aligns with the values reported in the existing literature. Interestingly, no peak indicating the presence of nitrogen is observed, indicating the dissociation of the N-C bonds and subsequent removal of nitrogen as a gaseous byproduct. Further analysis of the C1s peak (as shown in **Figure 3.6b**) elucidates the presence of an aromatic C bond at 284.6 eV, C-O bonds at 286.9 eV, and C=O bonds at 291.3 eV, which collectively signify the existence of graphene with inherent defects. These defects contribute to the increased hydrophilicity of graphene, making it particularly desirable for applications involving biosensors and liquid phase supercapacitors that operate in aqueous media. Quantitatively, the oxygen content was

found to be approximately 19.58%, while the carbon content accounted for the remaining 80.42%, calculated by determining the area under each respective peak.

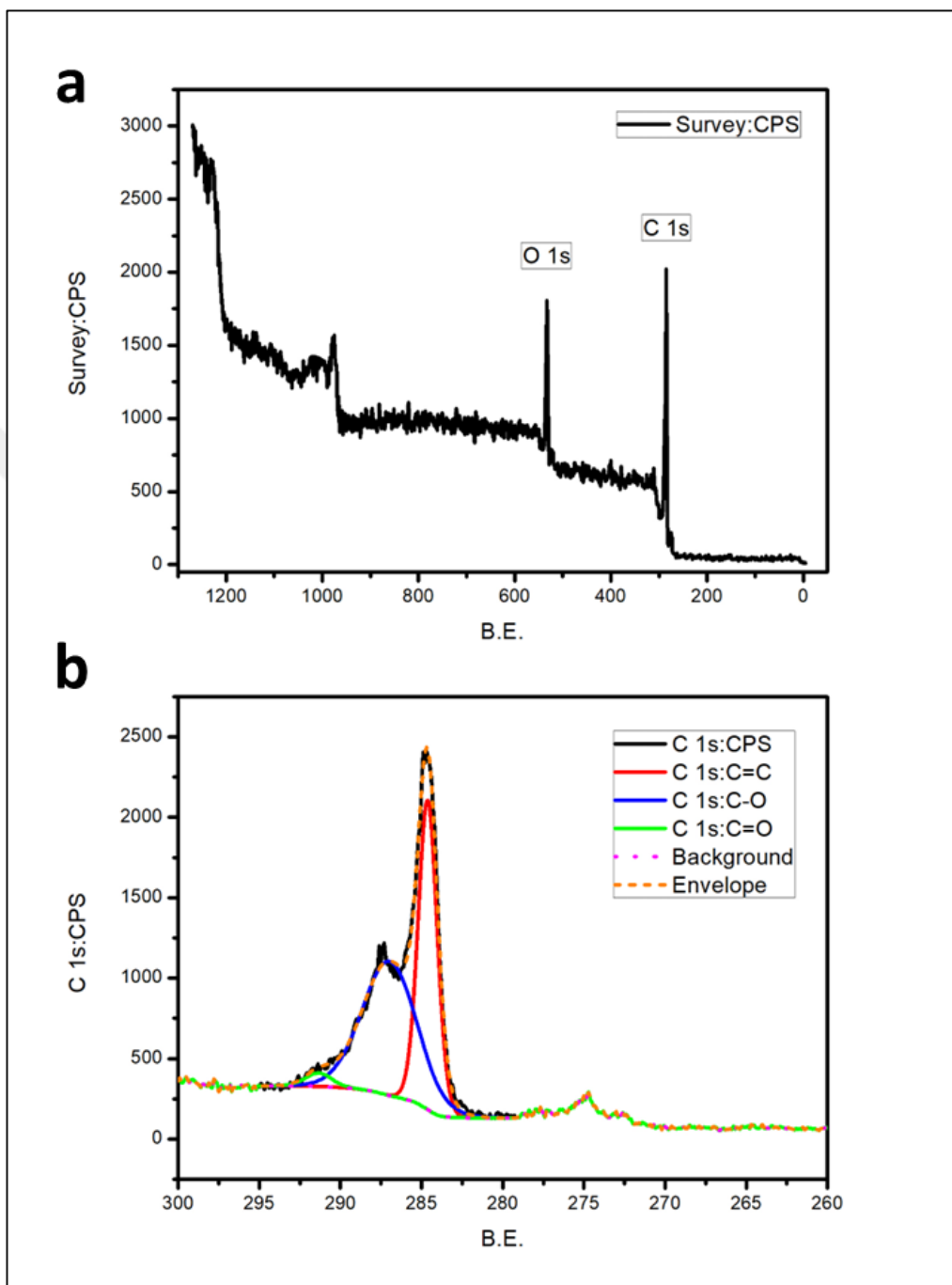


Figure 3.6: XPS results of LIG-PI sample; (a) survey scanning and (b) C1s scanning.

4. DEVICE FABRICATION and PERFORMANCE TESTS

The first section of this chapter focuses on conducting mechanical investigations of various Kirigami patterns to determine the most suitable one. A comprehensive analysis and evaluation of these mechanical tests is carried out.

The subsequent part delves into the fabrication of two distinct designs for Kirigami-inspired devices through the utilization of laser cutting techniques. The objective is to assess the mechanical and electrical performance of these designs and discern which one exhibits superior characteristics.

Finally, an evaluation is carried out for the electrical performance and resistance variations of the above structures when subjected to controlled tensile tests and stretches to failure. Comparisons are made between the resistance changes observed in the two device designs.

4.1. Mechanical Tests and Design Selection

It is crucial to address the selected designs in detail in order to apply the field of stretchable electronics before beginning the examination of mechanical tests. Six carefully selected designs are shown in the illustrious **Figure 4.1** for review and analysis. These patterns include the well-known serpent and diamond patterns, which have position as the most common designs for stretchable electronics made with Kirigami. In addition, the designs of triangles and squares, which are well-known for their capacity to stretch two dimensions, are noticeable. Moreover, the two remaining designs are also important. A modified version of the square designs, specifically made for this thesis to allow for one-dimensional stretching ability, is one of these designs. On the other hand, the other design—named the arrow design—is a unique creation made especially for this thesis. The concept behind the arrow design was to take the diamond design and curve the cuts upward to increase the cut density of the design. In the end, this resulted in the tips of these curves being longer and the curves being given angles to create a whole new design.

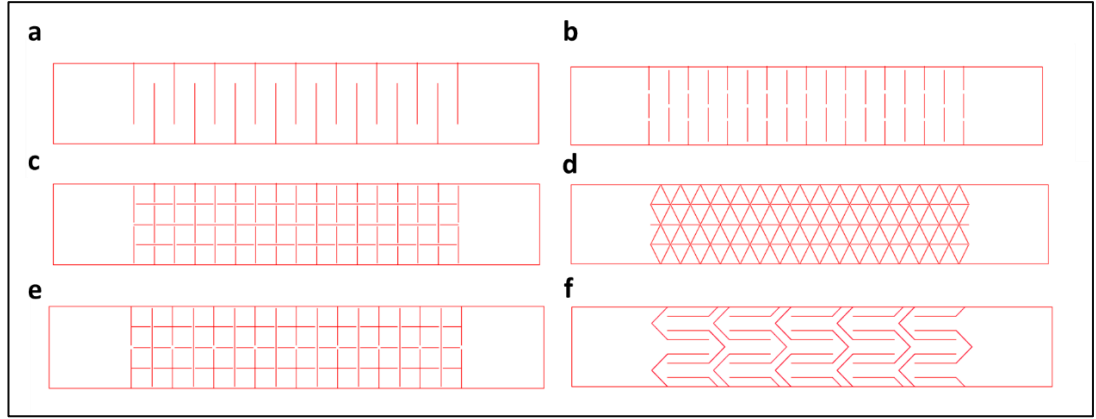


Figure 4.1: Kirigami patterns for tests; (a) serpent, (b) diamond, (c) square, (d) triangle, (e) modified fractal square and (f) unique arrow designs.

The designs are fabricated using the cutting mode with the same CO₂ laser cutter that was discussed in Chapter 3. **Figure 4.1** provides a detailed illustration of the drawn patterns in machine's software. Since these patterns are designed to be cut, they are drawn in red. In order to achieve an excellent cut, the cutting parameters are adjusted to 50% power and 40% laser speed. Following the specifications of the test apparatus, the sample's dimensions were 120 mm in length and 20 mm in width. These designs are then put through the demanding process of tensile testing, which allows for a thorough assessment of their mechanical characteristics. The ÇEKO Tensile Tester (Labomar) was the tensile tester utilized in this investigation. In order to determine which design should be chosen and pursued for additional research and exploration within the parameters of this study, a thorough analysis has been conducted.

The results of the tensile test performed on the structures under investigation are shown in **Figure 4.2**, which is presented in the section that follows. It is important to note that every sample used in this experiment had a consistent connection size because each one was thoughtfully designed. This decision was justified by the fact that the evaluation of electrical conductivity was the main objective of this thesis. These samples were also put through the demanding process of tensile testing three times in total.

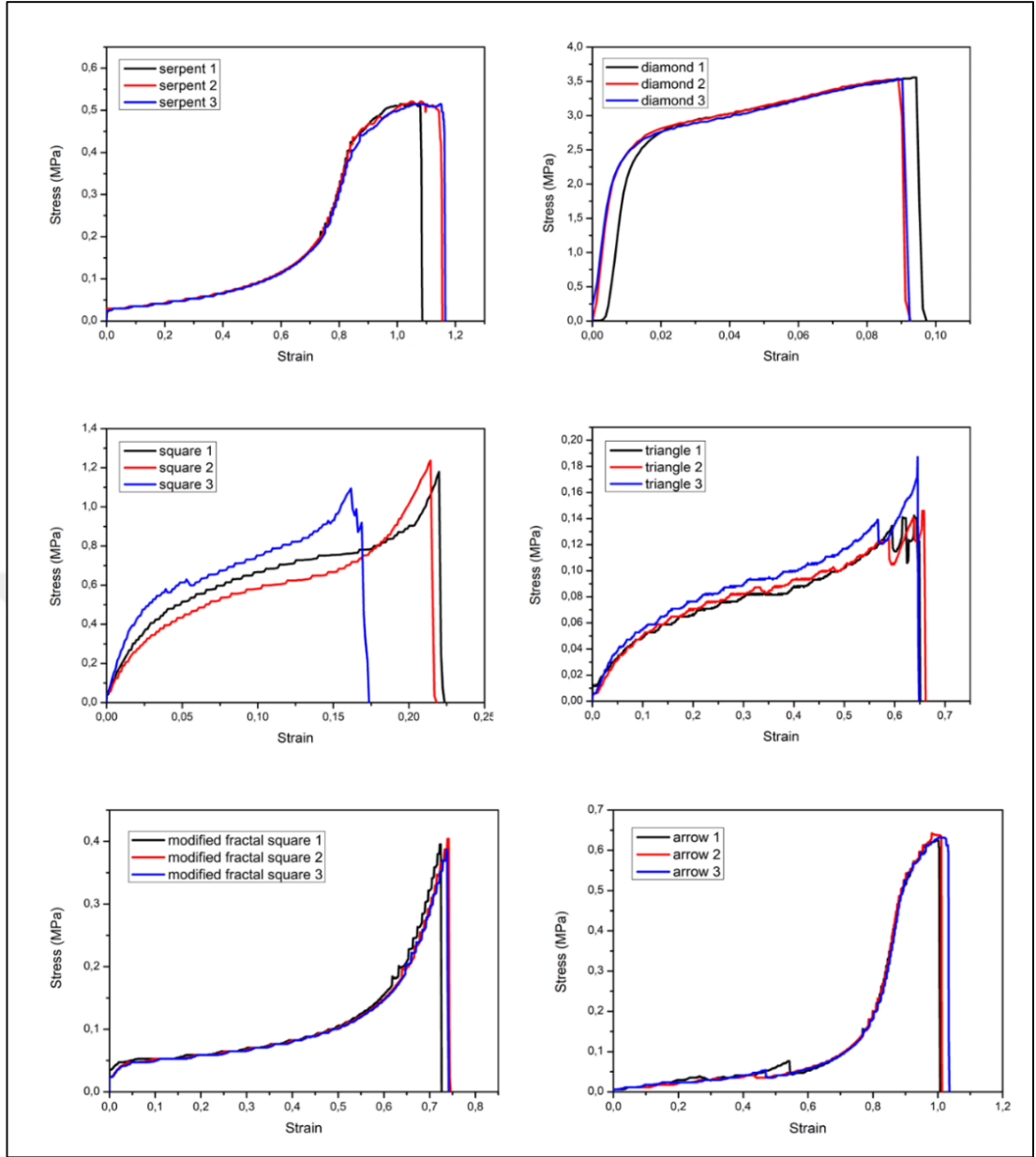


Figure 4.2: Tensile tests for the samples.

After a thorough examination of the data, as shown in **Figure 4.3**, it is possible to deduce that the arrow design, which has a distinctive configuration, has exceptional mechanical strength and comparable stretchability to the serpent design. However, it is crucial to emphasize that the arrow design's extensibility is similar to the serpent designs. The fact that the serpent design is recognized as one of the most flexible Kirigami patterns—it can stretch the substrate up to four times its original length—makes it especially remarkable. As a result, the arrow design has the capacity to maintain its mechanical strength in the face of large loads. As such, it is reasonable to state that the arrow design is the most appropriate option to be investigated in this thesis.

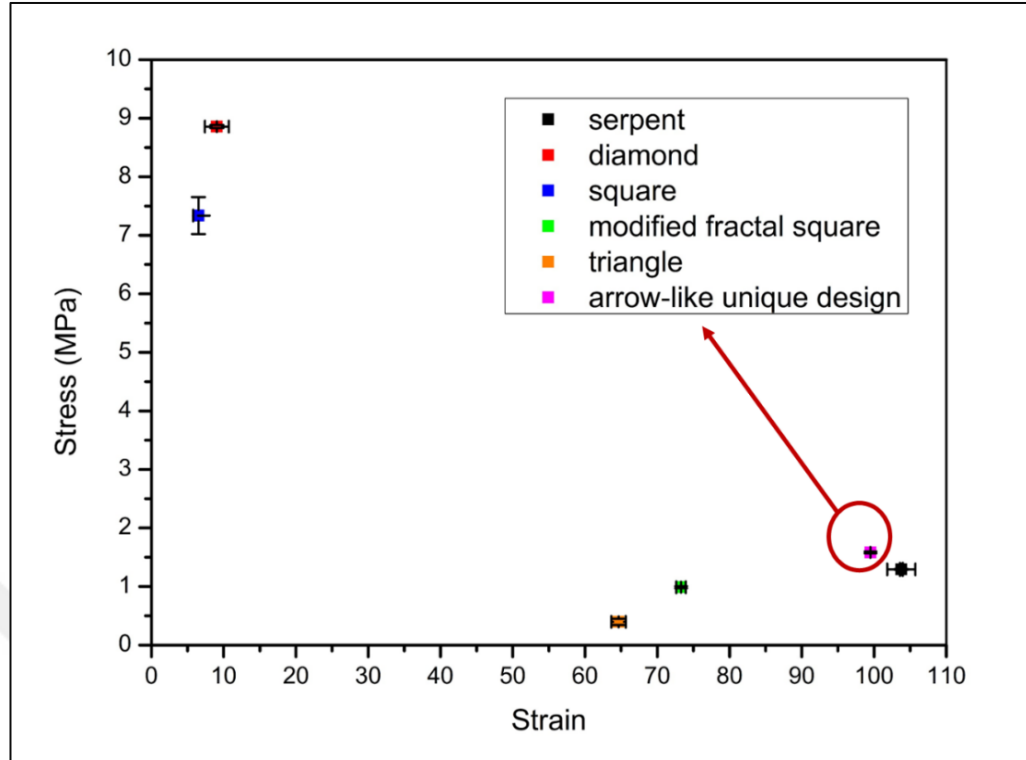


Figure 4.3: Comparison between Kirigami designs in mechanical strength.

4.2. Device Fabrication

After selecting the suitable Kirigami design, two device designs are fabricated by the same laser cutter with same parameters as fabrication patterns is given in **Figure 4.4**. Vector engraving is the other process mode for the cutter that is indicated by the blue lines on device A2. This mode guarantees that the engraving is done along with the vector drawn in pattern. Therefore, the vector engraving mode's parameters are the same as those of the previously mentioned normal engraving mode.

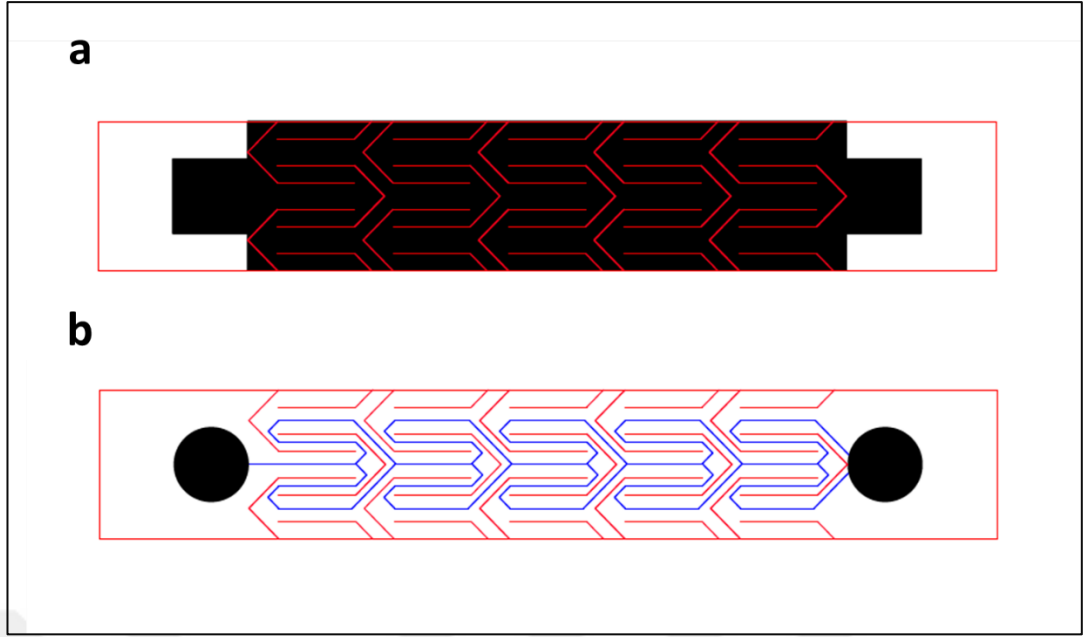


Figure 4.4: Device patterns identified as (a) device A1 and (b) device A2.

The stress generated at the tip of the cuts during stretching can significantly impact a device's electrical conductivity, as was discussed in Chapter 2. Therefore, we sought to find out how to modify the design process to either prevent or lessen this effect [2]. To improve conductivity efficiency, stretchable electronics made with LIG are currently implemented by covering the entire operating surface. It is inevitable that conductivity will be impacted by stress because electric current will always choose the shortest path through stress concentration areas of cuts in this case. This can be lessened, though, by creating a conductive path around these locations, as the current will be forced to follow this route. Consequently, it is anticipated that, in comparison to device A1, device A2 will have less resistance change as stretching.

4.3. Performance Tests and Comparisons

Before the manufacturing process to test the devices, it is important to evaluate the electrical conductivity of the laser-induced graphene (LIG) specifically intended for the manufacturing process, as mentioned earlier. To achieve this, the four-point probe method is employed using the M-3 portable digital four-probe tester (see in **Figure 4.5**). This methodological approach enables the precise measurement of the electrical conductivity of a material. After carrying out the necessary calculations, considering the dimensions of LIG film as 10 mm x 10 mm x 29 μm , the resulting electrical conductivity value for the LIG material is determined to be $1.83 \times 10^6 \text{ S/mm}$ [32].

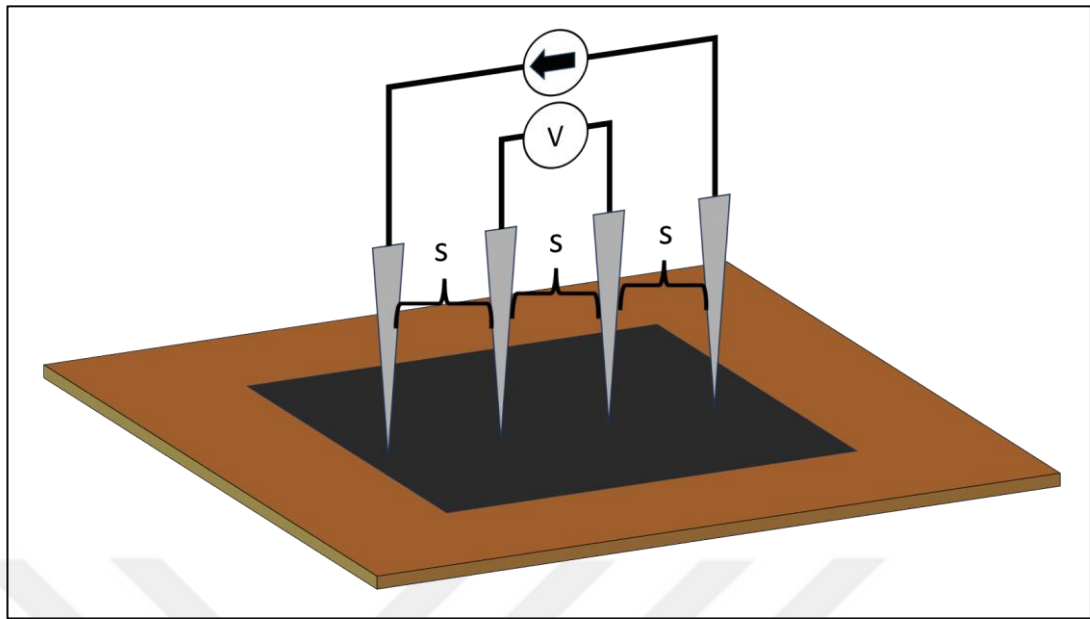


Figure 4.5: A schematic for Four Point Probe Measurement.

A custom setup is used for the performance test, which includes the use of a digital caliper and a Keithley 2400 SourceMeter with a voltage capacity of 1100V. **Figure 4.6** shows the configuration. The sample has been securely attached to each endpoint of the caliper and conductive copper tape is attached to each end of the electrodes to ensure optimal contact with the SourceMeter. The main goal of this test is to measure the change in resistance when the devices are subjected to a controlled load. This controlled stretching is achieved by stretching the devices ten times, at stretching intervals of 25%, 50%, and 75%, respectively, all within the limits of a controlled speed of 2 mm/s. The devices are then loaded to the final point of failure. After reviewing the data, a comprehensive analysis is carried out to examine the complex relationship between the resistance change and the corresponding strain of the devices. This research was intended to provide knowledge into the behavior and performance of these devices.

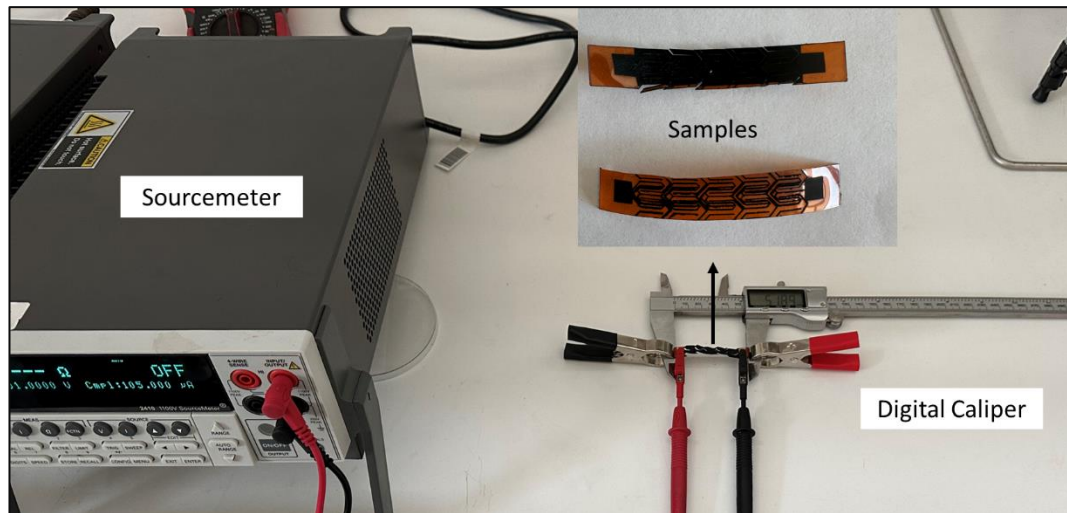


Figure 4.6: The configuration of performance test.

Figures 4.7, 4.8 4,9 and 4.10 show the results of the performance tests. You can see some irregularities based on the lines in the diagram. The two main causes of these irregularities are the failure of proper opening during stretching and the relaxation caused by plastic deformation in the stretching process. What is noteworthy, however, is that despite these anomalies, common behavior exists. Due to the stress of the residual deformation of the substrate and the stress at the interface between the PI and LIG materials, this behavior is manifested by an increase in resistance with each cycle.

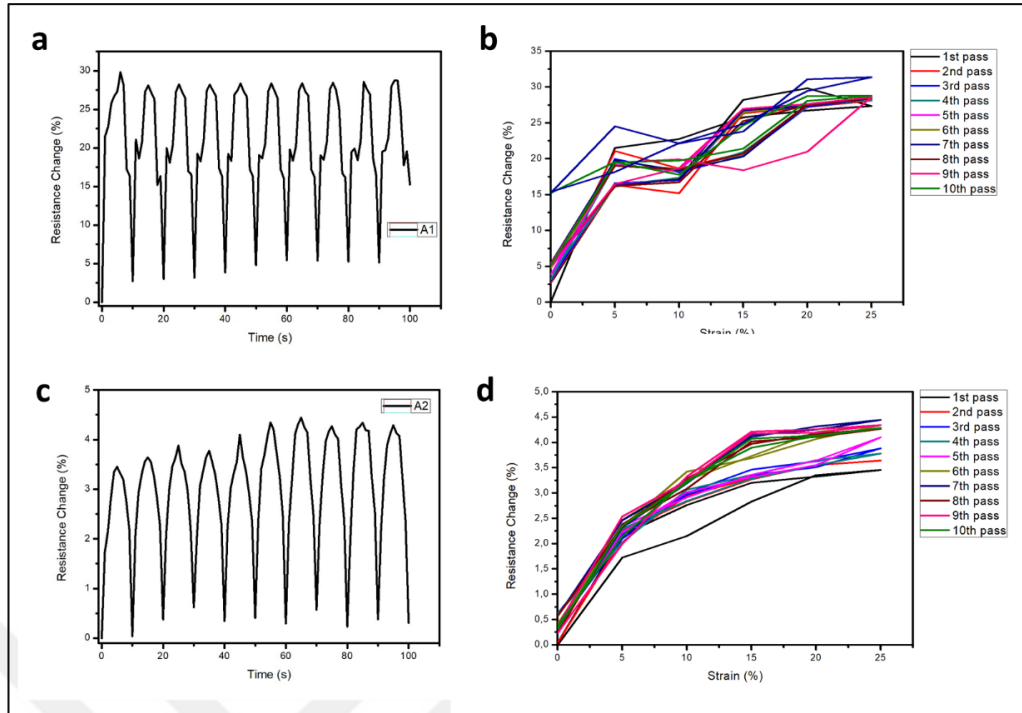


Figure 4.7: Device A1 and A2 performance tests up to 25% strain (a, b) and (c, d) respectively.

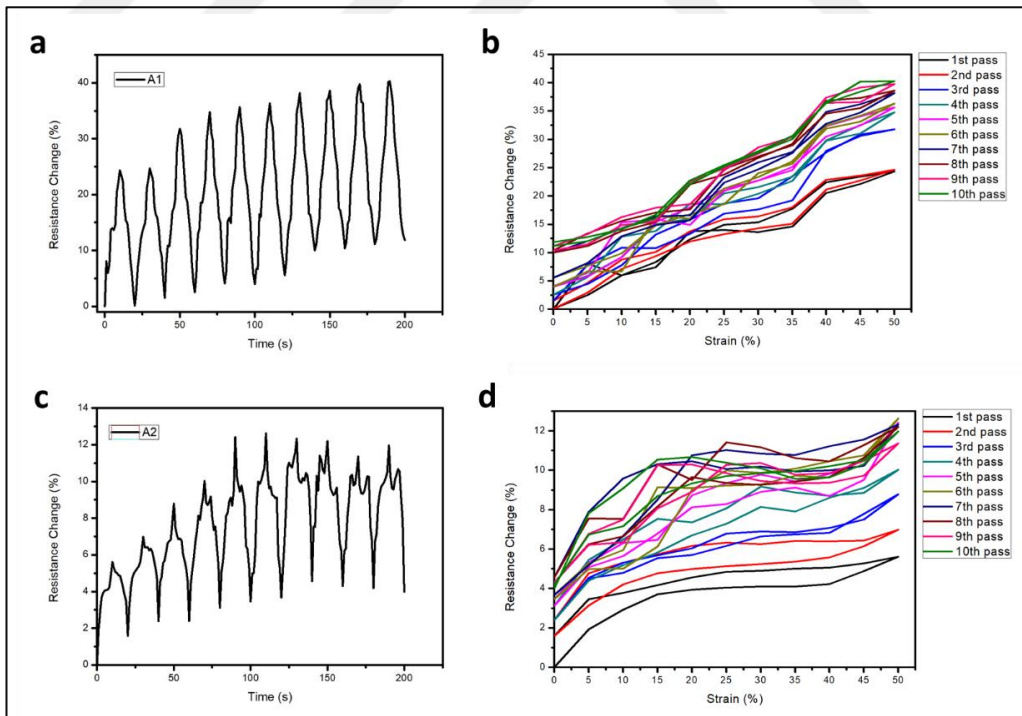


Figure 4.8: Device A1 and A2 performance tests up to 50% strain (a, b) and (c, d) respectively.

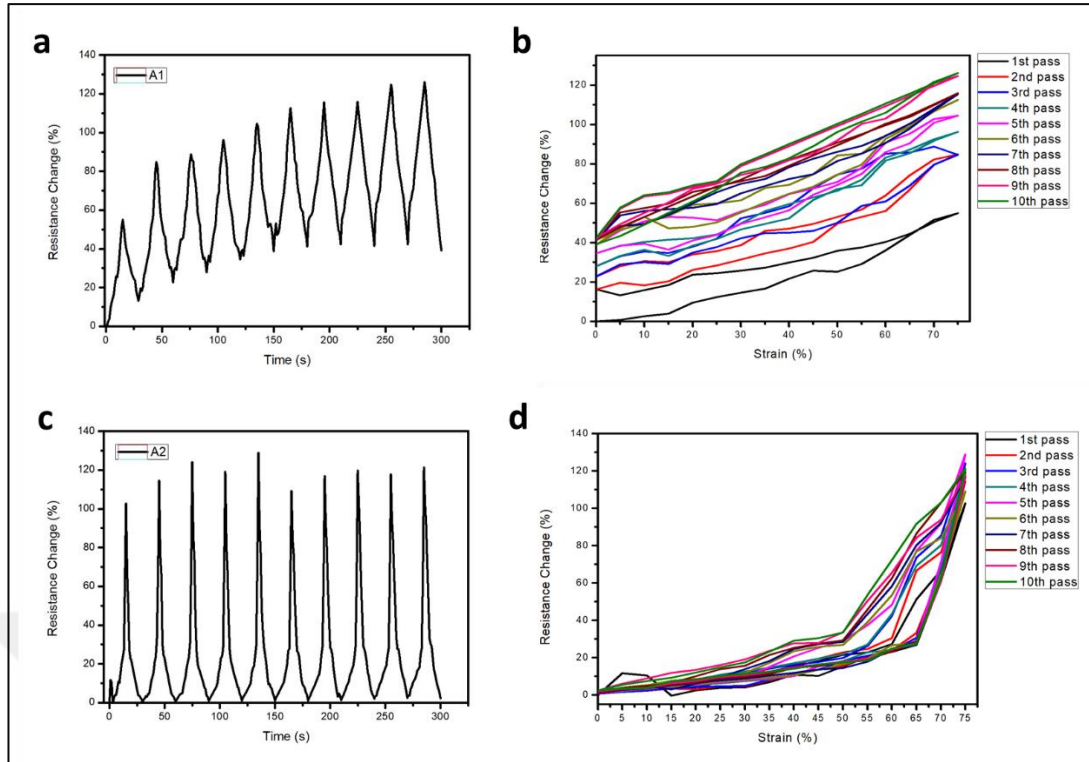


Figure 4.9: Device A1 and A2 performance tests up to 75% strain (a, b) and (c, d) respectively.

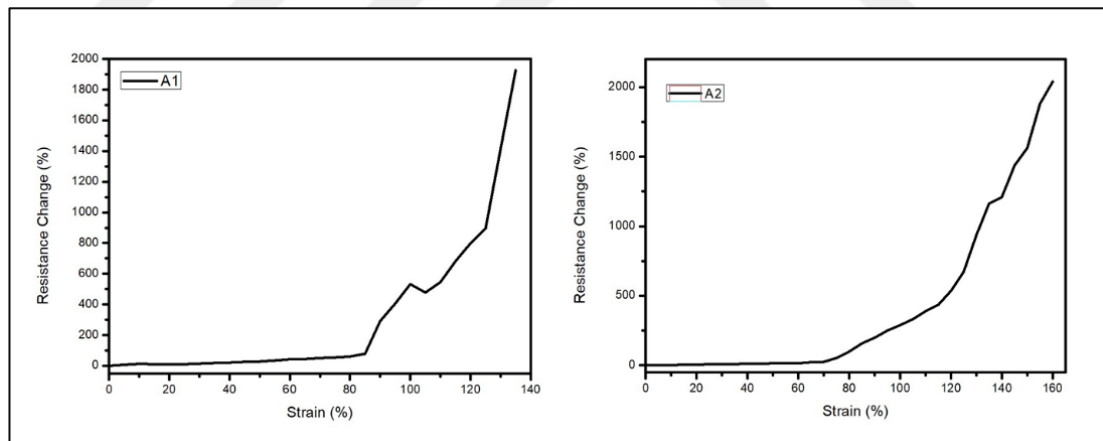


Figure 4.10: Device A1 and A2 performance tests up until the failure (a, b) and (c, d) respectively.

As previously mentioned, the performance test results provide evidence to support the claim that A2's line design exhibits less resistance change compared to A1 (see **Figure 4.7, 8, 9** and **10**). However, it is important to recognize that the change in resistance observed during the rupture test shows similarities between the two designs. This phenomenon can possibly be attributed to the fact that the deformation occurring at

the transition point of the cuts increases as the deformation progresses. Consequently, the region of stress concentration expands significantly, exerting a significant impact on the A2 design and resulting in a large increase in resistance due to the relatively small cross-section that LIG possesses. Nevertheless, it should be noted that Device A1 remains a viable option for surgeries that require minimal conduction change under stretch. Additionally, Device A1 may be significantly more suitable for sensing applications as it has the potential to effectively detect minute changes due to the significant resistance variation observed during smaller deformations.



5. CONCLUSION

The discussion in this chapter revolves around the thorough examination of the results obtained in this investigation at the outset. This section explains the main results obtained, concentrating on the devices that are being studied.

The next section explores possible improvements for the previously mentioned devices, detailing alternate configurations that are worth trying as well as alternate options that could be used.

5.1. Main Results

Ultimately, the main goal of this thesis was to gain an insight for developing stretchable electronics through the use of laser-induced graphene (LIG) and Kirigami designs. The process of LIG production involved using a CO₂ laser engraver/cutter to engrave the graphene onto polyimide films. Various techniques were used to characterize the resulting LIG films and study their structure and properties.

Examination of the LIG films using scanning electron microscopy (SEM) showed that they had a porous, foam-like structure made of densely packed graphene nanoflakes. Furthermore, energy dispersive X-ray spectroscopy (EDX) confirmed that the elemental composition of the films was predominantly carbon with small amounts of oxygen and nitrogen. In addition, Raman spectroscopy showed the presence of characteristic D, G and 2D bands, indicating the existence of graphene with defects. X-ray photoelectron spectroscopy (XPS) further supported these results by detecting the presence of carbon, oxygen, and defects in the structure.

During sample preparation and testing, the samples were subjected to tensile tests. These tests were performed three times to evaluate the mechanical properties of the samples and determine the optimal design. The samples were progressively stretched at intervals of 25%, 50%, and 75% of their original length, all within controlled speed limits. The samples were then loaded to failure to investigate their mechanical behavior under tensile loading. During these tests, the unique arrow design was found to have greater mechanical strength compared to the other patterns. Consequently, this successfully created sample was selected for performance testing.

Before fabricating the devices, the conductivity of the LIG films was measured to be 1.83×10^6 S/mm. Two Kirigami device designs were then manufactured using the same laser cutter, namely devices A1 and A2. Device A2 incorporated a conductive path design aimed at minimizing the change in resistance upon stretching compared to Device A1.

Extensive performance testing was performed on the devices, including cyclic stretching, and measuring resistance changes using a source gauge and digital caliper. The tests showed that, as expected, device A2 had fewer resistance fluctuations than device A1 under the same loads. However, in both designs there were significant increases in resistance near the fracture point due to the stress concentration at the intersections.

In summary, this thesis successfully demonstrated the fabrication of LIG films on polyimide and their application in Kirigami-based stretchable electronics. The conductive path design of device A2 improved its electrical performance under strain compared to device A1 (See in **Figure 5.1**). While both designs showed promise, Device A1 may be better suited for applications requiring minimal line change or for sensing purposes. Further optimization of the design could potentially improve the stretchability and mechanical robustness of the devices.

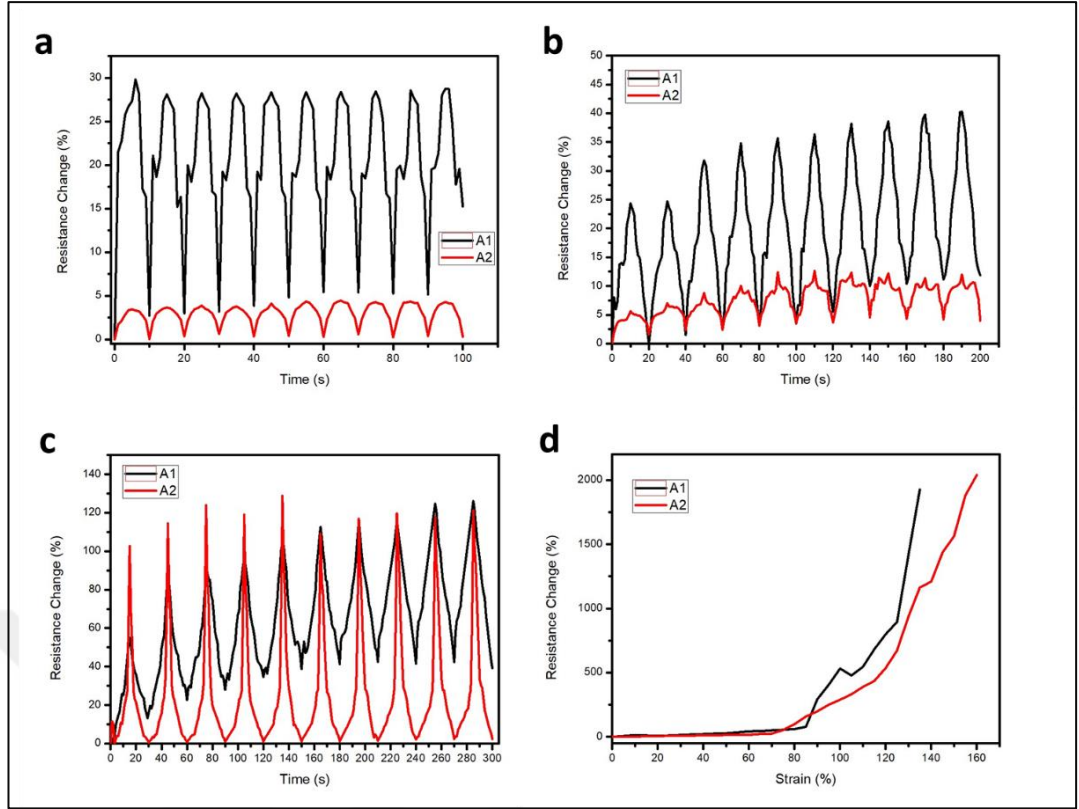


Figure 5.1: Comparison between A1 and A2; (a) up to 25% strain, (b) up to 50% strain, (c) up to 75% strain and (d) up until the failure.

5.2. Discussion

According to the results of the tests, performance of these devices drastically changes at high strain rates. The effect of stress and plastic deformations on devices is very high at this point. Hence, reducing this effect can improve the mechanical and electrical performance of these devices by applying several improvements. They can be grouped as material and design improvements.

Although the arrow design that has been uniquely created exhibits a high level of performance, it is important to note that the angular curvature of the design as well as the relatively small cutting width can give rise to entanglement within the structure. This entanglement, in turn, has the potential to disrupt the conductivity of the material during stretching. As such, it would be highly beneficial to explore potential improvements in the design shown in **Figure 5.2**, that could help mitigate these entanglement issues and ensure smooth operation.

One possible design improvement that could be implemented is the increase in the cutting width. By doing so, it would be possible to prevent friction from occurring between the cutting faces, thereby eliminating any further disturbances that may arise. In addition to this, it is also worth considering the incorporation of a small circular hole at the tip of the cuts in the design. This particular modification would serve to inhibit the concentration of stress that occurs during stretching, consequently minimizing the impact of stress on both the conductivity and mechanical properties of the material. Furthermore, another potential improvement that could be made involves increasing the curvature at the tip of the arrow. This adjustment would effectively eliminate any additional entanglements that may arise during operation. Additionally, it is worth noting that in certain cases where a greater degree of stretchability is required, the inclusion of more arrows in a vertical orientation rather than a horizontal one could prove advantageous. However, it is important to acknowledge that such an approach may lead to a decrease in both the mechanical strength and conductivity of the material. Nevertheless, it is worth considering this option as it has the potential to facilitate the handling of stresses that are associated with larger strain rates.

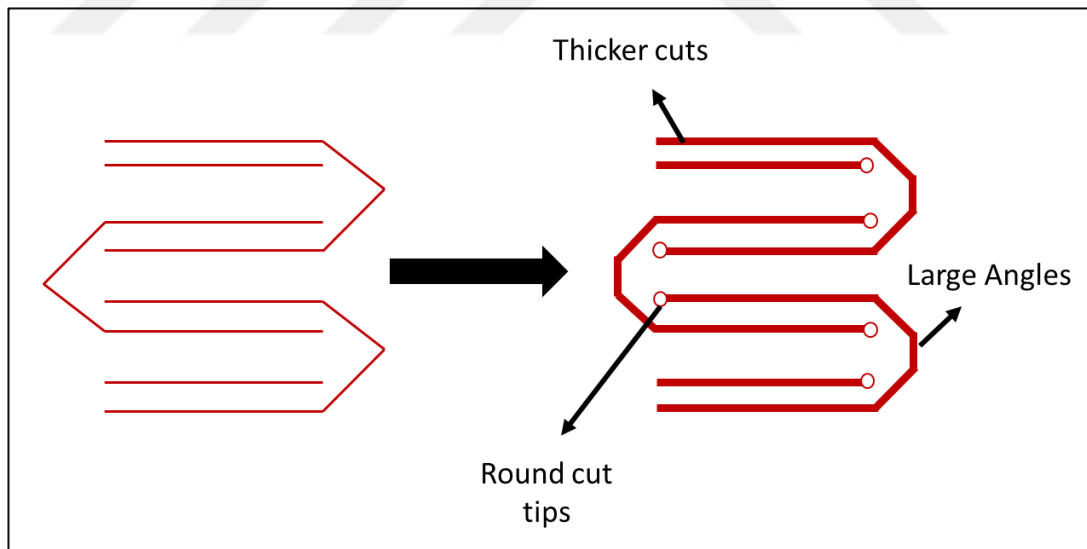


Figure 5.2: Ideas for design improvement.

The film of LIG on devices possesses the potential to undergo deformation and fracture from the underlying substrate as a result of the stress exerted on the device and the interface. This occurrence arises due to the absence of any coating or surface protection

during the fabrication process of these devices. Consequently, this deformation has the capability to induce a decline in the electrical performance of the LIG film. In order to prevent the fracturing of the LIG film, it is imperative to apply a protective surface treatment, such as an elastomer coating or the application of adhesive tape (see in **Figure 5.3**). By incorporating these protective measures, the material can be effectively held together, ensuring the stability of the film's structure, and thereby maintaining its connection. An example of such a protective measure is the utilization of coatings containing ecoflex, which has been successfully employed in certain research studies [4]. Furthermore, alternative protective materials, such as PDMS and rubber, can also serve as viable options for safeguarding the LIG film. These materials can be applied through dip coating or spray coating techniques. Another effective means of protection for these devices is the utilization of a sandwich structure, where adhesive PI tape is employed. Subsequent to fabricating the LIG pattern, the adhesive tape can be applied, after which the cutting operation can be carried out.

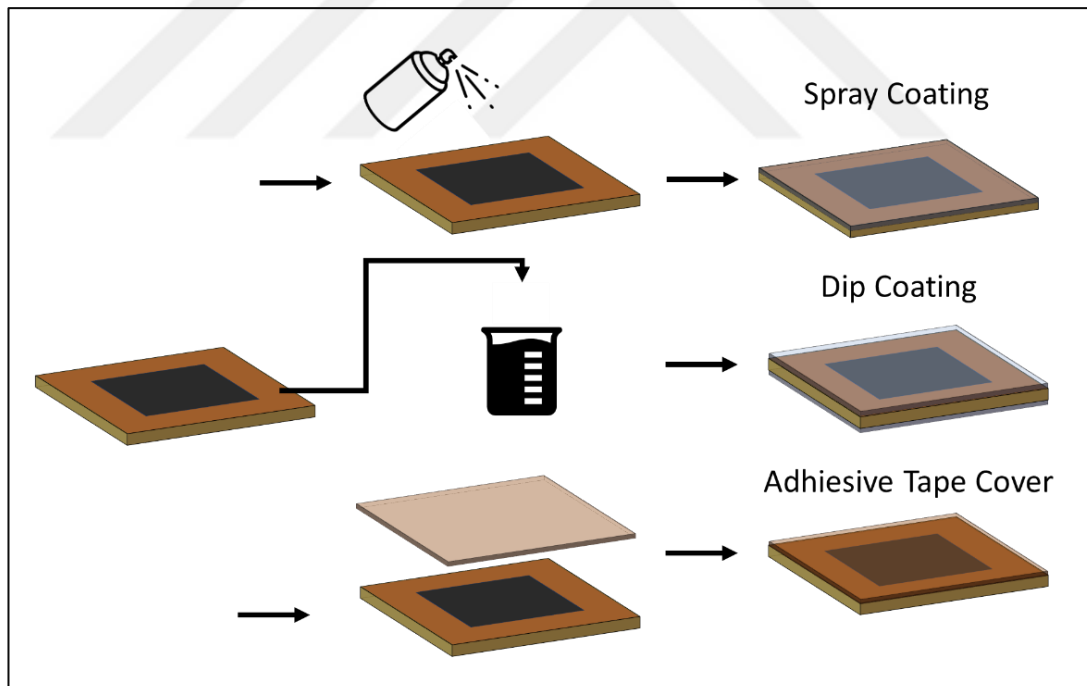


Figure 5.3: Surface protection techniques.

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