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Novel Stretchable Printed Wearable Sensor for Monitoring Body Movement, Temperature and Electrocardiogram, along with the Readout Circuit

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NOVEL STRETCHABLE PRINTED WEARABLE SENSOR FOR MONITORING BODY MOVEMENT, TEMPERATURE AND ELECTROCARDIOGRAM, ALONG WITH THE READOUT CIRCUIT

by

Ali Eshkeiti

A dissertation submitted to the Graduate College in partial fulfillment of the requirements for the degree of Doctor of Philosophy
Electrical and Computer Engineering Department
Western Michigan University
August 2015

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NOVEL STRETCHABLE PRINTED WEARABLE SENSOR FOR MONITORING BODY MOVEMENT, TEMPERATURE AND ELECTROCARDIOGRAM, ALONG WITH THE READOUT CIRCUIT

Ali Eshkeiti, Ph.D.

Western Michigan University, 2015

Conformal and stretchable wearable sensors provide vital real time information about individual’s health conditions. In this work, Traditional printing methods are used for fabrication of stretchable and wearable sensors which can be mounted on the human skin for the purpose of health tracking. In addition, screen printing technology was utilized to develop printed and flexible electronic circuit board which can be used as a readout circuit along with fabricated wearable sensors. The dissertation is organized and pursued in three projects.

In the first project, screen printing was used to fabricate multi-layer PCBs using printed deposited materials on three distinct substrates. The different characteristics of PET, paper and glass as a substrate for PCBs were analyzed. A method for populating electronic components onto the printed PCB pads was established and demonstrated. Different analysis such as effect of the roughness of the substrates on the electrical performance of the printed lines and effect of the bending on the resistivity of the printed lines were performed. The capability of the printed hybrid PCB circuit to correctly operate and drive an LCD was shown.

In the second project, a new method for fabrication of wavy lines and structures was devised for formation of stretchable and flexible wearable sensors.
Thermoplastic polyurethane (TPU) was used as a substrate in this project. Different wavy structure designs were printed and analyzed to determine the best design rules. Silver (Ag) and Carbon Nano Tubes (CNTs) were used for fabrication of wavy lines. The printability, bendability and stretchability of all printed lines were tested and analyzed. Different design rules and parameters such as the ratio of the width of the lines to their radius (W/r) and the length of the extended line to the diameter of the arc (L/D) were tested and analyzed. Printed wavy structures using CNTs showed below 35 % change in the resistance when it was stretched and 50 % strain was applied on the structure. 40 % change in the resistance of the lines printed using silver was obtained when 10 % strain was applied. The results obtained demonstrated that CNTs showed a promising potential to be used for fabrication of strain wearable sensors.

In the third project, a novel wearable sensing platform for the detection of disorder in body movement, temperature and ECG was fabricated. Both wavy structure and non-wavy structure were implemented in these devices. Silver and CNTs inks were used for the fabrication of different sensing parts on the PDMS and tattoo paper as substrates. The strain sensor fabricated on tattoo paper and PDMS were tested towards bending of finger to angles of 10, 20, 30 and 40 degree. 3.66 %, 4.7 % and 4.18 % change was observed in the resistance for each step for sensor 1, sensor 2 and sensor 3, respectively, on tattoo paper. The printed sensor on the PDMS demonstrated average change of 2.7 %, 2.2 % and 2.8 % for sensor 1, sensor 2 and sensor 3, respectively, for each step of bending of finger. The printed sensor on the PDMS was successfully implemented as temperature sensors for tracking of the skin
temperature. Mixture of silver and silicone was used for fabrication of flexible electrocardiogram sensor on PDMS. The devices’ response demonstrates the feasibility of printed multi-functional wearable sensors for health monitoring applications.
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CHAPTER I

INTRODUCTION

1.1. Motivation

Research on the development of flexible, stretchable, conformal and wearable sensors which can be mounted on the human skin has been gaining increasing interest [1-5]. These sensors are capable of providing real time information about the vital signs of an individual’s health and physical condition. There have been reports on the use of these sensors in health tracking devices [6-9], hydration level measurement sensors [10-13] and as an electronic nose [14-16]. The various applications of wearable sensors range from monitoring parameters, such as body movement, body temperature, electrocardiogram (ECG), electroencephalogram (EEG) and blood pressure for different uses in the biomedical, medical skin care and military industries [17-20].

Disorder in movement of the body is a common problem among the elderly as well as injured patients. There have been studies on the fabrication of different types of strain sensors for body movement tracking [2, 21-23]. A major challenge faced by these sensors is the ability to achieve a better contact with the body to collect accurate data while maintaining the ease and comfort of the patient. Also, body temperature measurements as well as ECG monitoring provide important information regarding the health monitoring of the elderly, athletes and soldiers in the field [24].

Wearable devices are typically fabricated using traditional CMOS based electronic manufacturing techniques, which are often expensive and laborious [25-27]. These devices are
not suitable to being attached to the body for a long time as they are rigid and quickly cause discomfort. The drawbacks associated with the fabrication of wearable sensors can be overcome by employing traditional printing techniques such as gravure, screen, flexo and inkjet for deposition of different materials on the flexible substrates such as plastic and paper. [28-30]. Reducing the wastage of materials during fabrication, low temperature operation, fast and easy processes as well as cost efficiency are some of the advantages of employing printing methods for the fabrication of electronics [31, 32].

Printed electronics (PE) is a quickly growing technology with noteworthy commercial potential that is attracting significant investments into the research and development of flexible electronics [33, 34]. In this technology, electronic components and devices are fabricated on different flexible substrates, such as plastic, paper, and textiles. The components and devices consist of electrically functional materials and inks forming metallization, dielectric, semiconductors and different sensing layers and are deposited using standard printing processes such as screen, gravure, flexo and inkjet printing. Some examples of already fabricated electronic devices include organic thin film transistors (OTFT) [35, 36], organic light emitting diodes (OLED) [37, 38], photovoltaics (PV) [39, 40], radio frequency identification tags (RFID) [41, 42], and biochemical sensors [43, 44]. The main advantage of PE technology is the additive nature of the deposition processes. All the layers having different designs are selectively printed, which excludes the need for masking and etching, resulting in less usage of material and faster fabrication processes. In addition, printers are generally low cost compared with conventional silicon based fabrication equipment. All the advantages of PE makes it a promising technology for fabrication of a variety of next generation electronic ranging from fully printed wearable devices to touch screen display applications.
Over the last decades, a steady and considerable effort has also been directed towards the development of materials and strategies to enable electronic devices and sensors to be transferred directly onto the human skin [2, 4, 22, 45]. However, most of the materials that are compatible with human skin require time consuming methods for synthesis and preparation [46, 47]. Even though there are flexible and stretchable wearable sensors reported in the literature, they are usually fabricated using silicon based techniques and must often be transferred using complicated methods onto a flexible substrate or directly on the skin [2, 22, 45]. The problem of transferring and mounting the sensor directly on the skin can be solved by employing a sacrificial layer which can be used as a temporary holder for the sensor during the fabrication process. The sensors can be directly printed on the sacrificial layer and then after fabrication, the sensor can be readily removed from the substrate by dissolving the sacrificial layer. All the improvements in PE and the availability of compatible materials/substrates with human skin have motivated the author to focus on design, fabrication and analysis of printed, stretchable and flexible wearable sensing systems for human health monitoring applications.

1.2. Author’s Contributions

The author’s research work has resulted in thirty seven conference publications, two intellectual property (IP) disclosures, one patent application and five high-quality peer-reviewed journal publications as given in the list of publications in Appendix A. The articles directly related to the research work presented in this dissertation have been marked with “*”, in the Appendix A. The outcomes of this research have been published and accepted to be published in prestigious journals such as IEEE Transactions on Components, Packaging and Manufacturing Technology and Sensors and Actuators: B Chemical. The author has also contributed in presenting the result of the projects at several international conferences. The
conference papers have been published in the proceedings of the *IEEE Sensors Conference* (2012, 2013, 2014); *International Meeting for Chemical Sensors (IMCS)* (2012, 2014); and *Eurosensors Conference* (2011). The author has been also awarded the **All-University Graduate Research and Creative Scholar Award** for 2011-12, **Departmental Graduate Research and Creativity Scholar at the doctoral level for 2014**, the prestigious **Kenneth W. Knight Award to Graduate students** for 2012 and **Graduate Research Award (2011, 2012, 2013, 2014)** by **Western Michigan University**. The author also has achieved **First Place in the Graduate Research Poster Competition (WMU College of Engineering and Applied Sciences)** for 2014 as well as a **Third Place in the Student Poster Presentation, at the FlexTech conference** for 2014.

### 1.3. Organization of the Dissertation

In this dissertation, the author provides details on the development of a wearable sensing system that employs traditional printing methods for the fabrication of stretchable and wearable sensors, which can be mounted on human skin for health tracking. In addition, the author presents the capability of employing conventional screen printing technology to develop a printed and flexible multi-layered electronic circuit board, which can be used as a readout circuit along with the fabricated wearable sensors. This work is organized and was pursued as three distinct projects with unique contributions that may be brought together to provide an even significant research outcomes.

In chapter 2, a comprehensive literature review is provided. Introductions to the fabrication of electronic devices using printing methods as well as a summary of the history of wearable sensors are presented. A discussion covering different types of sensors and their working principles and an introduction to wearable electronic devices and their applications is
included. A review of the previous work in the area of wearable flexible sensors as well as theirs strength and weakness; including, the complexity of their fabrication process is discussed in detail. This is followed by an introductory explanation of traditional printing methods and their ability to be employed as alternative techniques for the manufacturing of electronic device and sensors.

In Chapter 3, screen printing is used for the fabrication of multi-layer PCBs using PE deposited materials on three distinct substrates. The different characteristics of PET, paper and glass as a substrate for PCBs is analyzed. A method for attaching electronic components onto the printed PCB pads is established and demonstrated. The capability of the printed hybrid PCB circuit to operate correctly and to drive an LCD is shown. The results obtained showed the potential use of printed PCBs as the readout circuit for printed sensors.

In Chapter 4, screen printing is used as a new method for the fabrication of wavy lines and structure that allow the formation of stretchable and flexible wearable sensors. Thermoplastic polyurethane (TPU) is used as a substrate for this project. Different wavy test structures are printed and analyzed to determine appropriate design rules and the best design configuration. Different materials including silver (Ag) and Carbon nano tubes (CNTs) are deposited in this process. The printability, bendability, and stretchability of all printed lines are tested and analyzed. This work demonstrates the capability of printing techniques to provide low cost strategies for the fabrication of wearable sensors.

In Chapter 5, a novel wearable sensing platform to be used for the detection of disorder in body movement, temperature, and ECG is developed using both wavy an non-wavy structures. Different inks including Ag and CNTs are used for the fabrication of different sensing elements. Polydimethylsiloxane (PDMS)/ tattoo paper is used as the substrate for fabrication of these
sensors. Different methods are developed for transferring and attaching the sensors onto human skin. The measured responses of the system demonstrate the feasibility of printed multi-functional wearable sensors for use in health monitoring applications.

Finally in Chapter 6, the author presents the summary of the dissertation activities and accomplishments along with suggestions for future work.
1.4. References


CHAPTER II

LITERATURE REVIEW

2.1. Introduction

In this chapter, the author provides a comprehensive literature review on wearable and stretchable sensors, their fabrication mechanism and PE. The background review on the history of wearable and health monitoring sensors will provide a vision into the science behind the design, fabrication and challenges of manufacturing of skin like sensors. The author then presents an introduction and review of different forms of printing as alternative methods for deposition of active material layers used in the fabrication of electronic devices. A detailed review on the development of new materials, as well as strategies for building wearable sensors using PE will also be presented.

2.2. Sensors

2.2.1. Introduction to Sensors

Sensors are used for detection of different parameters such as physical, chemical or biological changes. These devices are capable of transmitting and receiving signals based on changes in a system which makes them capable of responding to physical phenomenon such as light, heat, pressure, magnetism or motion and send out the appropriate signal.

According to Merriam-Webster’s Dictionary, “… a sensor is a device that responds to a physical stimulus (as heat, light, sound, pressure, magnetism, or a particular motion) and transmits a resulting impulse (as for measurement or operating a control) …” [1]. The human
body is an amazing example of a sensing system that is composed of different sensors, which can provide information. The common sensors found in a human being are the five traditional senses; sight, hearing, smell, taste and touch [2].

Advancement in the semiconductor industry and the discovery of addition functional materials has assisted the development of new and different sensors and sensing systems [3-13]. On a daily basis, many old and new sensing devices are being used to improve and facilitate our life. Temperature controllers, health monitoring devices, automated car fuel alarm system, touch screen devices, among others systems, are examples of sensors utilized on a daily basis. The role of these sensors can be classified in detecting the information, generating an output which results on the helping in decision making and generating an output signal. Combining multiple sensors together of distributing the information to existing systems can improve or enhance decision making and actions. On the simplest level, examples of input/output signals are illustrated in Figure 2.1. For example, when the resistive temperature sensor is subjected to the heat the impedance of the sensor will be changed.

2.2.2. Types of Sensors

The capability of sensing devices, for use in different applications, is identified by the sensor detection modes. The different classes of detection modes include thermodynamic, mechanical, acoustic, chemical and biological stimuli, each of which has its own unique characteristics.

2.2.2.1. Thermal Sensors

Thermal sensors are used for detection of changes in temperature or energy (heat). Thermal sensors are classified in two forms, contact and non-contact, based on their modes of
detection. A good example of the contact mode is a thermometer [14]. Figure 2.2 represents a typical structure for a thermometer, consisting of three main components; the bulb which is usually made of glass, the temperature sensitive liquid which responds to increasing and decreasing temperature, and a scale which is used for identifying the temperature changes. The thermometer is used frequently due to ease of use and accuracy. The change in the temperature is detected based on fluctuations in the air or material placed in contact with the bulb. The bulb is loaded with temperature sensitive liquid, typically mercury or red alcohol. The difference between the volumetric reversible thermal expansion of the liquid and glass is used to change the liquid level and measure the relative change in temperature. For a faster response the bulb should
be small and thin. The scale is a representation of degrees, which are etched or printed in the glass of the thermometer as markings once calibrated based on the liquid and the size of the glass capillary tube used. As the temperature fluctuates, the heat sensitive liquid increases or decreases in volume and level due to gravity and capillary action. The measurement of Infrared (IR) radiation is an example of a non-contact thermal sensor.

![Figure 2.2: Liquid in thermometer [14].](image)

### 2.2.2.2. Mechanical Sensors

Mechanical deformation or deflection of sensitive material is used for generating the output for mechanical sensors. Some of the different parameters that are detected by mechanical sensors include; changes in position, pressure, stress, acceleration and flow rate. A schematic representation of a mechanical pressure sensor is shown in Figure 2.3. The capacitive pressure sensor shown is composed of two conductive plates and a spacer. When a pressure is applied on
The sensor, a deformation will be generated in one or both plates and the dielectric layer causing the thickness or distance between the two conductive electrodes to change. As a result, the capacitance will be increased and the change in applied pressure can be detected.

![Diagram of a pressure sensor as a mechanical sensor](image)

**Figure 2.3: Pressure sensor as a mechanical sensor [14, 15].**

The ratio of the capacitance of a non-deflected structure and the deflected structure can be used to calculate the deflection distance and determine the applied pressure [14, 15].

### 2.2.2.3. Acoustic Sensors

Acoustic sensors are capable of sensing the physical phenomenon of waves propagating throughout different materials such as lithium niobate, lithium tantalate, quartz, etc. When the wave travels through or along the surface of well-defined classes of material, the properties of the material might affect the characteristics of the wave such as velocity or amplitude. These changes can be detected by measuring the frequency or phase in sensors. Based on the mode of the wave traveling in the material, these sensors are categorized into two forms, bulk or surface wave sensors. In bulk acoustic wave sensors, the wave travels through the volume of the material. In the second form, which is called surface acoustic wave sensor, the wave travels on the surface of the sensor. This class of acoustic sensors is divided into shear horizontal waves or shear vertical waves based on the mode of propagation. Piezoelectric material is generally used...
in acoustic devices to generate acoustic waves. An acoustic gas sensor is depicted in Figure 2.4 [14].

![Schematic of acoustic gas sensor.](image)

**Figure 2.4: Schematic of acoustic gas sensor.**

The gas sensing film in placed on the surface of the device. When this film is exposed to the gas, the properties of the sensing film (mechanical and electrical) will change which results in the change in the oscillation frequency of the sensor. In the case of electrical change, the conductivity of the sensing material can change when it is exposed to the gas which results in change in the oscillation frequency. For the mechanical change, concentration of adsorbed gas into the bulk of the sensing film can also cause a change in the oscillation frequency of the sensor.

2.2.2.4. **Chemical Sensors and Biosensors**

Chemical sensors and biosensors are devices that transform the chemical information of a measurand to an output electrical signal. This chemical information can be the result of a chemical reaction of the analyte or the binding between two molecules in a sample. Usually, a chemically sensitive layer is integrated into both chemical sensors and biosensors. Transducer along with associated electronics or signal processing components is commonly present on chemical sensors. A basic diagram for chemical sensor is represented in Figure 2.5 [15]. The
A diagram shows an array of interdigitated electrodes (IDTs) that has a sensing layer coated on them. When the sample contacts the sensing area, chemical or biological reaction will occur and continue to be accrued. The reaction causes change in the capacitance or impedance of IDTs, which arrives at a steady-state and can be used for detection of the test sample.

Figure 2.5: Schematic of an array of chemical or biosensor [15].

2.2.2.5. Optical Sensors

The functionality of optical sensors is based on detecting the change in the measurand using light as a stimulus. Optical sensors consist of optical waveguides and optical fibers. Optical fibers are made up of a core and cladding. Figure 2.6 shows a simple example of an optical sensor, which consists of cylindrical cladding layer and a circular core. Figure 2.7 illustrates the basic structure and physical parameters of an optical fiber utilized in optical sensors. To prevent light propagation losses into the fiber and accomplish complete internal reflection, the angle of incident light should be higher than the critical angle. The critical angle ($\phi_i$) is obtained by the following equation 1, where $n_i$ is the refractive index of the core in the optical fibers and $n_p$ is that for the cladding’s [16, 17].

$$\phi_i = \sin^{-1} \frac{n_p}{n_j}$$

(1)
As the light enters the optical fiber, if the angle of introduced light into the optical fiber is more than the critical angle it will continue traveling through the fiber, reflecting at the core boundary, for a significant distance without propagation loss.

Figure 2.6: Schematic of optical fiber guide.

Glass and plastic are the main types of raw materials utilized to fabricate and develop optical fibers for wavelengths in the visible light region. Material such as glass and plastic, along with reflective and polished coated hollow tubes, are used for channeling light in the near and far infrared regions [16, 17].

Figure 2.7: Basic structure of optical fiber.
Optical sensors are typically non-electric based as well as contactless sensing devices, which provides the advantage of remote sensing. Such devices are resistant to radio frequency and electromagnetic interference and they don’t bother the environment.

A summary of different types of sensor and their stimulus is presented in table 2.1.

<table>
<thead>
<tr>
<th>Type of Sensor</th>
<th>Stimulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acoustic</td>
<td>Wave, Wave Velocity</td>
</tr>
<tr>
<td>Thermal</td>
<td>Temperature, Thermal Conductivity</td>
</tr>
<tr>
<td>Chemical and Biological</td>
<td>Chemical or biological reaction causing change in: Conductivity, Mass, Density</td>
</tr>
<tr>
<td>Optical</td>
<td>Refractive Index, Absorption, Transmission, Reflection</td>
</tr>
<tr>
<td>Mechanical</td>
<td>Pressure, Mass, Position, Density, Force, Strain, Stress, Shape</td>
</tr>
</tbody>
</table>

In the following sections, the author presents the details of wearable sensors and their applications as well as previous works on design, strategies for fabrication and analysis of wearable sensors. The advantages and disadvantages of different fabrication methods and their applications are also provided.
2.3. Wearable Electronics and Applications

2.3.1. Introduction to Wearable Electronics

Wearable electronic devices, which can be mounted on the skin or garment, have gained in interest over the last few decades [19-28]. Development of the technology which made electronic devices mobile and portable has provided new application for electronic devices such as smart phones, small music players and different personal access devices. While the wrist watch and small portable radios may be categorized as first generation of wearable electronics, in 1960s, one of the first recognized wearable devices was made by Edward Thorp and Claude Shannon for prediction of numbers in roulette [29].

Advancements in computing systems, along with the miniaturizing of the size of the devices, have enabled the users to carry sophisticated systems and have access to data and information almost everywhere. Wearable computers are defined as miniaturized version of desktop computers that can be carried during operation [30]. These wearable computers are either used for a specific target, such as heart rate monitoring or for general support and assistance in daily life. The wearable computing systems can be attached to cloth, such as a jacket or belt, as well as a human body. The term, wearable electronics refers to that type of electronic devices that are worn or mounted on the human body or clothing for an extended period of time [30]. Wearable devices can be divided into two forms, 1) those which are attached to clothing and 2) those which are mounted on the body.

Sensors and sensing systems have become pervasive during last few decades. For example, sensors are being inserted widely into our daily lives including in cars, cameras, cell phones and even in clothing and buildings. There has been a serious need for the development of
flexible and stretchable wearable electronic systems to overcome the drawbacks of ambulatory methods for monitoring the vital signs of individuals. These devices should be capable of monitoring of the patient over weeks or even months. Such devices can be used in biomedical, epidermal, military and environmental monitoring application [31-43]. Flexibility and stretchability can improve the functionality of these devices while they are attached on the body. During the last decade, the improvement of wearable electronic devices has led to an increasing interest in the design and fabrication of health monitoring, wearable sensors [44-51].

An important challenge faced by development of wearable electronic devices is ability to maintain ease and comfort of the [52-59]. In this chapter, some of the previous works that have concentrated on design and fabrication of flexible wearable sensors and their challenges will be discussed. Problems associated with the fabrication of these wearable sensors will be analyzed.

2.3.2. Previous Works

Most fabricated electronic devices are made of single-crystal, inorganic materials such as silicon, which is rigid. In the case of flexible and stretchable sensors, the interfaces for these devices with the human body play an important role in the sensitivity and the operation of the devices. While most efforts during the last few decades were directed toward reducing the size of the electronic devices and increasing the operational speed, new applications of electronics require new form factors and focus such as flexibility and stretchability, which can make the electronics conformal. Most of the newer devices are fabricated on non-wafer substrates such as plastic and paper. Stretchability to some extend can help and plays an important role in performance of conformal and flexible sensors [60-64]. There has been a significant amount of
research and development of methods and materials to improve flexibility and stretchability of sensors [65-78].

One strategy to overcome these drawbacks is to fabricate electronic devices using rigid components that are connected using stretchable connectors such as gold and silver, which have been frequently reported [65-68]. This form of electronics is suitable for devices that don’t have too many active components. John Rogers and his group have reported different methods and strategies for fabrication of stretchable and flexible electronic devices [68, 79-81]. Building of a ribbon structure in form of a coil, or helix is one of the reported methods for fabrication of stretchable interconnections. This ribbon acts like a spring and enables the device to stretch. This kind of semiconductor ribbons can be fabricated on the single-crystal wafers. The strained multilayered film is grown on these wafers. These ribbons are then cut using lithography into nano ribbons and they will be released from their supporting substrate by dissolving the sacrificial layer [79, 81]. After releasing from the supporting substrate, the strained layers in the ribbons cause them to bend upward and make a tube shape [68, 79-81] which is shown in Figure 2.8 (a). The geometry of the fabricated structures depends on properties of the substrate and the thickness of deposited material [67, 68, 79-81]. Another method for fabrication of stretchable interconnections is based on the use of ripple configurations, which are illustrated in figure 2.8 (b, c) [67, 68, 79-81]. Fabrication steps for these nano-ribbons start by deposition of material on a source or host wafer using silicon based technologies. Poly methyl methacrylate (PMMA), a sacrificial layer, is cast coated on the source wafer. Then the conductors or semiconductors are deposited on the substrate and formed in parallel arrays of ribbons. Next, the sacrificial layer is etched. After this step, pre-strained PDMS, stretched from length of L to L+ΔL which results in pre-strain of ΔL/L, will be placed in contact with the ribbons, and, by applying pressure, the
ribbons will become attached to the PDMS. The ribbons are attached to the surface of PDMS based on the van der Waals chemical bonding [67, 68, 79-81]. Releasing the strain in the PDMS results in the formation of wavy/buckled ribbons, as shown. The ribbons are then transferred onto a final flexible substrate. Deposition of material and patterning in the desired form can be done using different conventional methods based on the properties of different materials [62-66, 70, 71].

![Figure 2.8: a) spring form of interconnections, b) and c) wavy form of interconnections (i) chemical bonding along the ribbon and (ii) chemical bonding in the selected areas, courtesy of [68].](image)

Discussing this fabrication method in more depth, if the surface of PDMS is oxidized only in selected areas, after releasing the pre-strain, the ribbons form buckled shapes, which are completely separated from the PDMS in non-oxidized areas. PDMS is made of polymeric chain with the repeating unit of −(CH₃)₂SiO−. Low surface energy as well as low Young’s modulus enables the PDMS to form a conformal contact with almost any substrates. Exposing PDMS to the ozone changes the hydrophobic properties of the surface to hydrophilic by oxidizing the −
CH₃ of the surface and generating –Si–OH. After this conversion, the surface of PDMS can react and make a chemical bond with different materials. The wavelength and the amplitude of the fabricated lines can be predicted using the following formulas [68, 79-81].

\[ \lambda_0 = \frac{\pi * h}{\sqrt{\varepsilon_c}} \]  

(5)

\[ A_0 = h \sqrt{\frac{\varepsilon_{pre}}{\varepsilon_c} - 1} \]  

(6)

\[ \varepsilon_c = 0.52 \sqrt[3]{\frac{E_{PDMS} * (1 - v_x^2)}{E_x * (1 - v_{PDMS}^2)}} \]  

(7)

where \( \varepsilon_c \) is the critical strain for buckling, \( \varepsilon_{pre} \) is the level of prestrain, \( \lambda_0 \) is the wavelength, and \( A_0 \) is the amplitude. The Poisson ratio is \( v \), the Young’s modulus is \( E \), and the subscripts refer to properties of the PDMS or deposited material (\( x \)). The thickness of the deposited material is \( h \).

Usually, three different techniques are used for pre-straining the PDMS. In the first method, PDMS is mechanically rolled after bringing it in contact with the deposited material on the holder substrate (usually silicon wafer). The wavy structure made using this method does not show uniform wavelength and amplitude. In the second method the PDMS is exposed to a 30 °C to 180 °C temperature before bringing it in contact with the deposited material on silicon and it is cooled down in next step. The wavy lines show uniformity in a large area with high reproducibility. In the third method, the PDMS is stretched using mechanical stage and pre-strain is physically released after removal from the wafer. Fabricated structures have been used for fabrication of range of electronic components and sensors having diverse applications in health monitoring as well as epidermal electronics [68, 79-81].
John Rogers and his group [81] reported the fabrication of multifunctional epidermal electronics, which can be directly transferred onto the human skin by employing the strategies discussed above. This device consists of multiple sensors for measuring temperature, strain, ECG and EMG as shown in Figure 2.9 [81]. All of these sensors are fabricated using lithography to form of wavy and buckled lines. After fabrication, the device was transferred onto polyvinyl alcohol (PVA), a flexible substrate, or directly onto skin. Wavy lines with different width were fabricated to determine the best interface with the human body and to overcome potential breakage due to the roughness of skin. Challenges in transferring the sensor directly onto the skin were analyzed and reported. The authors have provided results of different sensors, which look promising for use as wearable devices [81].

In a separate article, John Rogers’s group [82] reported fabrication of another set of epidermal electronics, which includes sensing systems as well as transmission components, as shown in Figure 2.10. Interconnections as well as some components are fabricated by employing
wavy structures. This device was transferred onto the forearm and forehead of a human test subject and the effects of body motion on the stability of the device were analyzed. Mechanical properties of the fabricated device were also analyzed, which showed sufficient strength and a good tolerance for stress based on the movement of the body and the continued operation of the device [82].

Figure 2.10: Epidermal wearable electronics, courtesy of [83].

Fabrication of differential impedance sensors for skin hydration monitoring, using transfer printing of the device on a flexible substrate, was also reported by John Roger’s group. These devices include different forms of sensors; circular, meander and interdigitated. For each form of Sensor, the identical structures were used for both reference and measurement electrodes. The fabrication of a complete device was started by spin coating of PMMA and polyimide (PI) on a silicon wafer. Photolithography was used for patterning the deposited material to form interconnections. The final device was transferred onto a layer of PVA as a temporary
flexible substrate. The sensor was transferred onto the skin and was attached to the skin by Van Der Waals forces. The device showed stability towards applied stretching in different directions. The lines were connected to an external data acquisition instruments. The change in the impedance of the sensors was obtained by changing the hydration of the skin, which showed the capability of the stretchable and flexible sensor to monitor the hydration level of the skin [83].

In another work, the Dae-Hyeong Kim group [84] used the same principle as Rogers' group for fabrication of wearable and stretchable devices. The device includes a data storage unit, a diagnostic section and a drug delivery section in stretchable form as shown in Figure 2.11. The fabricated wearable patch is capable of measuring movement disorders as well as delivering a drug to the surface of the skin. Strain sensors were used for the detection of disorder in movement. The monitored data were stored in the flexible memory and analyzed. Based on defined criteria, feedback in the form of drug delivery was provided. Implementation of different stretchable sensors and electronic parts, fabricated on a light weight and thin patch, can play an important role in the future of flexible sensing systems. As shown, the various elements and sensors of this device were tested and the functionality and limitation of each part has been discussed [84].
There are additional reports on the fabrication of flexible electronic components, such as transistors and diodes [85-92]. Even though, all these devices showed potential to perform under compressive and tensile stress the problem associated with fabrication of these devices is the complicated process of fabrication. The silicon based technologies are time consuming, expensive and require expertise used for fabrication of these devices on the rigid substrate. In the next step, complicated processes are used to transfer the final device onto the flexible substrate. Therefore, there is a need for an alternative method to overcome these drawbacks. Printing technologies, which will be discussed in the next section, can be used as alternative methods for deposition of functional materials required for the fabrication of electronic devices. Some of the advantages of these methods are fast processing, less waste of material, and the deposition of material at room temperature.

2.4. Printed Electronics

Current research and the growth of interests in flexible electronic devices and sensors is due to their potential applications in different aspects of daily life and the need for an alternate,
simple methods for fabrication. The fabrication method of choice for flexible devices in this research involves traditional printing methods. The capability of printing technology for the manufacturing of electronic devices come from the additive deposition of multiple layers in the form of thin films in a simple and cost-effective way as compared to existing electronics production processes. Overall, PE offers the implementation of new form factors, such as flexibility and stretchability, and the fabrication of new types of electronics based on the deposition of active materials on flexible and stretchable substrates. The advantages of PE in manufacturing of electronic devices include: cost efficiency, flexibility, lightweight, fast production and less waste of material. The origins of the printed electronics manufacturing come from the membrane switch and Electroluminescence lamp (EL) which used printing as a manufacturing technique [93]. PE can promise simple manufacturing process for flexible large-area devices, which can be disposable. PE has been growing gradually over last 30 years and more recently by advancement in the printing of nanomaterials; an emerging industry that has shown the potential to revolutionize numerous products in the market.

Merging traditional printing methods with conventional electronic fabrication process has also shown potential for high volume electronic manufacturing. In contrast with lithography based subtractive methods, the additive properties of PE offer lower cost processes for electronic manufacturing. In comparison with other methods PE does not require large amounts of material and the waste of resources during fabrication is reduced due to deposition of material only on the desired areas. The development and improvement of different inks such as conductive, dielectric and semi-conductive along with advancement of ink deposition methods for fabrication of electronics have also enabled the integration of PE processing steps to be incorporated in current electronics
fabrication processes. Similar to all technologies, PE faces a range of difficulties and challenges. Some of these challenges include the stability, durability and yield of the fabricated devices. Functionality and feature sizes of the printed devices are additional limitation for this emerging industry as compared with silicon based devices. The standards for this field as well as design rules are some of the ongoing research areas that require further study and development.

2.4.1. Types of Printing

Printing processes are categorized into two classes: (a) impact printing and (b) non-impact printing [101]. Non-impact printing does not require a mask or image carrier. It can be used for printing on rigid or flexible substrates. In this method the image is mainly controlled digitally. In impact printing, the image is transferred onto the substrate by using an image carrier. Different forms of printing are summarized in Figure 2.12.

Printed techniques can be classified into four traditional methods which are used in the fabrication of PE devices: screen printing, inkjet printing, flexo printing and gravure printing. Flexography and gravure printing techniques are identified as roll-to-roll printing, due to the fact that the printing process is typically performed on a continuous sheet of substrate delivered from a large roll of material. Inkjet printing, in contrast, is considered for thin film printing and non-contact nature; while screen printing is known for printing thick film layers. Further details of the printing methods will be discussed in the following section. A summary of the characteristics of these four printing process is shown in Table 2.2 [93, 95]. The ink viscosity, expected thickness of the layer, the resolution and the roughness of the layer play an important role in selection of proper printing methods for fabrication of electronic devices.
2.4.1.1. Screen Printing

The main components used for screen printing are the image carrier which is called screen printing plates and the squeegee for applying the pressure on the ink. Material which is used for fabrication of squeegees include rubber or other polymeric materials. The screen plate has two parts 1) frame and 2) the stencil. The frame is used to hold the screen mesh and the stencil in the image carrier. The frame is generally made of steel or aluminum for their strength and rigidity as well as the ease of cleaning. The material used for the screen fabric and the stencil
depends on the ink solvent. Ease and comfort of the cleaning also plays a role in choice of material for fabrication of frame.

Table 2.2: Different characteristics of printing methods [95].

<table>
<thead>
<tr>
<th>Method</th>
<th>Lateral Resolution (µm)</th>
<th>Ink Film Thickness (µm)</th>
<th>Viscosity (Pa.s)</th>
<th>Printing speeds (ft/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexography</td>
<td>15</td>
<td>0.5-2</td>
<td>0.05-0.05</td>
<td>300-1000</td>
</tr>
<tr>
<td>Gravure</td>
<td>15</td>
<td>0.5-8</td>
<td>0.05-0.2</td>
<td>1500-3000</td>
</tr>
<tr>
<td>Screen</td>
<td>15</td>
<td>3-60</td>
<td>0.5-50</td>
<td>300-500</td>
</tr>
<tr>
<td>Inkjet</td>
<td>20</td>
<td>0.05-0.50</td>
<td>0.001-0.04</td>
<td>500 (for 600×600 dpi)</td>
</tr>
</tbody>
</table>

Screen printing is considered a push through process. The ink is applied on the screen and ink passes through the screen mesh and is transferred onto the substrate when the ink is swept by the squeegee. Figure 2.13 illustrates the typical screen printing process [94].

2.4.1.2. Inkjet Printing

Inkjet printing is a non-impact printing process that does not use image carrier or mask. The image is usually formed digitally. This process is divided into two types of printing techniques: 1) continuous inkjet and 2) drop on demand inkjet. Drop on demand inkjet printing include 1) thermal and 2) piezoelectric actuation. Figure 2.14 a, b and c illustrates the difference between these classifications.
In continuous inkjet printing, a continuous stream of ink droplets is generated during the printing process. This stream is electronically controlled in a process where a high voltage, electrostatic field is formed that can deflect ink droplets from an image area to a non-image area. The deflected ink is directed back into the printer. In comparison, a drop on demand inkjet printing generates ink droplets only on the desired locations to form the images. Drop on demand inkjet printing techniques use either thermal or piezoelectric techniques to jet individual drops of ink [94].
2.4.1.3. Flexographic Printing

Flexographic printing is a roll-to-roll printing technique that became popular in the 20th century. The main components of this printing process are a plate cylinder, which is made of rubber or photopolymers, an impression cylinder, an anilox roll, and an inking unit. The imaged areas on the plate cylinder are raised with respect to the overall surface of the plate cylinder. The image is transferred from the plate cylinder to a substrate through the use of an inking unit. The inking unit first transports the ink particles onto the anilox roll, which is metered with the assistance of a doctor blade that wipes the excess ink from the surface of the anilox roll. In the next step, the raised parts of the plate cylinder will receive the ink from the anilox roll. Because the non-image areas are not raised with respect to the surface of the cylinder they don’t receive...
the ink. The image on the plate cylinder is transferred to the substrate by the use of an impression cylinder. Figure 2.15 shows the Flexographic printing process [94].

![Figure 2.15: Flexographic printing](image)

2.4.1.4. Gravure Printing

Figure 2.16 illustrates different components of gravure printing method which include an image carrier that is called the gravure cylinder, impression cylinder for helping in transfer of the image, an ink container which is called ink fountain and a wiping part which is called doctor blade and. Steel having the coating of copper on the surface is a typical material for fabrication of the image carrier. In order to create the image on the cylinder, small recessed cells that are made using engraving onto the copper which is chrome plated and it can provide wear resistance.
The impression cylinder is manufactured with materials like rubber. The rotation of the gravure cylinder in the ink fountain results in the filling of the cells on the cylinder. Doctor blade wipes off the remaining excess ink on the surface of the image carrier. The ink in the cells is imprinted onto the substrate with the help of the impression cylinder [95, 96].

Printing techniques have shown their ability for fabrication of electronic devices and components, such as electrochemical sensors [97, 98], strain gauges [99, 100], pressure sensors [101, 102], substrate for Raman spectroscopy [103], TFTs [104-107], and solar cells [108, 109], paper based devices, [110, 111]. There has been an increasing interest in utilizing printing methods for fabrication of wearable and stretchable electronics. Some of the major works will be discussed below.

**Figure 2.16: Gravure printing**

Ongoing research on fabrication of stretchable and wearable sensors using PE can be divided into two categories, the development of material and the development of strategies. There have been some researches on development of stretchable and mechanically strong inks to be used in this area [110-119].
In most fabricated devices, silver or gold are used as a metallization layer. Both of these two materials are not stretchable and when placed under tensile strain the structure will break. To overcome this problem silver nano wires (AgNWs) are a good choice of material. Shanshan Yao and Yong Zhu [120] fabricated multi-functional wearable sensor using AgNWs. This sensor is capable of detecting strain and pressure, including a finger touch with high sensitivity and a fast response time. Feng Xu and Yong Zhu [121] reported fabrication of stretchable silver nanowire conductors. In this work, first AgNWs are drop-casted on substrates such as silicon (Si) wafers, glass slides, or plastic materials prior to being dried. Next liquid PDMS is casted on the NWs and cured at 65 °C for 12 hours. The AgNWs/PDMS composition is peeled off of the substrate. This mixture shows promising properties as a conductor for the fabrication of wearable and stretchable electronic devices [121].

Carbon Nano Tube (CNTs) based inks are one the most popular materials in the field of PE and wearable sensors. CNTs are mechanically strong and they can tolerate to some extent applied strain on their structures; therefore, they offer promising properties for stretchable materials. Usually CNTs are not highly conductive, which can be a drawback for some devices where high conductivity is needed. For these applications, a mixture of CNTs with other conductive materials is being used. For example, Kyoung-Yong Chun demonstrated printable and stretchable hybrid composites consisting of silver flakes, multi-walled carbon nanotubes and self-assembled silver nanoparticles [114]. They reported that the maximum conductivities of these composites were 5,710 S cm$^{-1}$ at 0% strain and 20 S cm$^{-1}$ at 140% strain, at which point the film ruptured.

Along with the development of stretchable materials, there have been a significant amounts of work on the development of new strategies for fabrication of flexible wearable
sensors using printing methods [122-132]. Some of the accomplishments will be discussed in following section.

Yang Wei and his coworkers employed screen printing for the fabrication of printed cantilever structures used for wearable motion detection applications. Polyester cotton-fabric was used as a substrate. To reduce the roughness of the fabric, a UV curable polymer was deposited and used as an interface material. After this step, the electrodes and sacrificial layer were printed on the substrate to form the cantilever structure. The picture of the sensor is shown in Figure 2.17. The fabricated sensor was placed on the arm of a human and motion was detected. While promising, as the authors suggested, there is a need to encapsulate the sensor and to perform additional design modifications to reduce the size of the sensor and also test the sensor at a lower frequencies. Also future work in this paper suggests printing of circuit board directly on the fabric to integrate the full system on the flexible substrate. [133].

![Printed cantilever structure](figure2_17.png)

**Figure 2.17: Printed cantilever structure courtesy of [133].**

There have been multiple attempts into the fabrication of printed strain sensors for movement measurement. Various materials, such as silver, carbon nanotube, and PEDOT:PSS
have been used as metallization layers. All these printed sensors showed ability to measure motion to some degrees. However, a weak response to applied strain on the fabricated devices has been one of their major problems. When these devices are stretched, the lines often break. Therefore, there is a need for alternative materials and strategies to enable printed sensor to be functional while being stretched [134-136].

Wataru Honda and his coworkers [136] reported fabrication of multi-functional, wireless health monitoring wearable devices using a macro scale printing methods. The devices consist of a screen printed LC circuit, as a proof of concept for wireless communication, a temperature sensor, and a microfluidic channel fabricated using a conventional method for drug delivery. The performance of different parts of the device was analyzed and reported. While this device is not fully printed and other methods were involved in the fabrication of the device, the concepts and results are useful and interesting [137].

Hydration level sensors are an example of wearable devices that have been fabricated using PE on different substrates, such as plastic and tattoo paper. Joseph Wang and his co-workers [138, 139] have reported fabrication of tattoo-paper based sensors for epidermal PH monitoring. A picture of the printed sensor is shown in Figure 2. 18. Screen printing was used as deposition method for this sensor. The device was printed on a tattoo paper and transferred after fabrication onto human skin. The device was mounted on lower back, neck and wrist of the human body and tested for real-time measurement of the pH levels of perspiration during exercise. Motion and deformation of the body during the exercise did not affect the performance of the sensor [138, 139].
Different materials such as silver (Ag), gold (Au) and aluminum (Al) have been used and analyzed for the fabrication of printed wearable sensors. The major focus of most of the reported devices was on the flexibility and bendability of the sensors but, as mentioned before in this chapter, stretchability plays an important role in functionality when the sensors are attached to the human body. There are only a few reports on the development of stretchable materials or strategies for applications in wearable devices fabricated using printing methods. Therefore, there is a significant need for further study, characterization of new materials, and strategies for the printing of stretchable and wearable electronics.

In this work, the screen printing was used for the fabrication of multi-functional, flexible and stretchable sensors that can be directly transferred onto the skin. The author utilized both stretchable materials and developed strategies for the fabrication of stretchable devices to design and fabricate fully printed wearable sensors. The performance of these devices was studied and analyzed. In the following section the applications of PE in wearable sensors and predicted market for them is presented.
2.4.2. Applications of PE in Fabrication of Wearable Electronics

There are different commercialized wearable devices in the market ranging from google glass to health monitoring bracelets [140-149]. PE and especially the field of printed sensors have the potential to revolutionize fabrication of such devices. Based on an IDTechEx report, printed sensors are emerging from R&D stages to the market [150]. IDTechEx predicts the market for printed sensors will be above $8 billion by 2025. As an example of commercialized printed devices, printed Glucose sensors have a market of greater than $8 million per year. Figure 2.19 represents the expected growth of market and demand for printed sensors over the next 10 years [150].

![Graph showing market growth for printed sensors]

Figure 2.19: Market growth for printed sensors [150].

The market size for different wearable sensors by 2025 is illustrated in Figure 2.20. It shows that chemical sensors will have the largest share of the market for wearable sensors in 10 years. Figure 2.21 illustrates the prediction for growth of the market for
different types of wearable sensors. As it can be seen stretchable strain and pressure sensors are expected to grow rapidly over the next 10 years [151].

Figure 2.20: Market share for wearable sensors [151].

Figure 2.21: Predicted growth of market to different types of wearable sensors [151].
2.5. Summary

In this chapter, the author presented a comprehensive literature review that includes a detailed introduction to sensors and PE. A discussion covering different types of sensors and their working principle is presented. An introduction and review of the types of wearable electronic and sensors which have been designed, fabricated and tested as part of this dissertation was also presented. The major works accomplished by other research groups on the fabrication of wearable sensors was explained and the strengths and weaknesses of these devices were analyzed. This was followed by an introduction to PE, the different forms of printing used, and their characteristics. The application of PE to the fabrication of wearable sensors and stretchable devices was introduces and some of the previous work in this area were discussed. The next chapter discusses a project that involved the use of screen printing for the fabrication of a multi-layered printed electronic circuit board on non-conventional substrates which can be used as a readout circuit for fabricated sensors. The background for this work, design of the circuit, fabrication process, and analysis of the printed lines is discussed. A method for electronic component attachment on the printed pads is also established and presented.
2.6. References


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CHAPTER III

SCREEN PRINTING OF MULTI-LAYERED HYBRID PRINTED CIRCUIT BOARDS (PCB) ON DIFFERENT SUBSTRATES

3.1. Introduction

As embedded electronics have become common in an ever widening array of products and applications, the form factors, flexibility and materials used to construct circuit boards must evolve to support emerging applications. As a result, there has been an increasing demand for further development and understanding of the characteristic traits pertaining to the printing of flexible electronic circuits and components. Printed electronic (PE) devices, created using traditional printing techniques such as; gravure [1, 2], inkjet [3, 4], flexography [5, 6] and screen printing [7, 8], have shown the ability to produce circuits and sensors for many applications [9-13]. Some examples of printed electronic devices are organic thin film transistors (OTFT) [14, 15], flexible displays [16, 17], flexible printed solar cells [18, 19] and substrates for surface enhancement Raman spectroscopy [20], which have shown varying levels of applicability for use in commercial applications.

Although the current performance of PE devices does not match the switching speed, density and higher current handling of traditional solid-state devices, produced using conventional manufacturing techniques, there are several advantages of using printing techniques for the fabrication of less demanding devices. These include a lower-cost of manufacturing, lower-processing temperatures and a reduction in resources used during fabrication. These advantages have facilitated the need for the production and manufacturing of PE products on a
commercial scale [21, 22]. Moreover, printing techniques, which lend themselves to roll-to-roll (R2R) processes, enable electronic devices to be produced in high volumes at high speeds without the intricate process requirements associated with conventional silicon manufacturing technologies, such as complicated photolithographic patterning procedures, high temperatures and vacuum deposition methods.

Although many researchers have shown the ability to produce electronic components and devices on flexible substrates [23-28], there have been very few reports involving the printing of PCBs on flexible and rigid substrates such as paper, polyethylene terephthalate (PET) and glass. Most of the currently available flexible PCBs are fabricated using methods such as spin coating, sputtering, and spray coating [29]. These processes are typically used for the deposition of the conductive materials onto the substrate [29]. Some of the disadvantages associated with these methods include increased production time and material waste, which can be overcome by employing printing methods. To date, there are only a few reports on the printing of PCBs, however, none of these involved the screen printing of a multi-layer hybrid PCB prototypes with integrated electronic components on flexible substrates [30, 31].

Both plastic and paper could play an important role in the future of light-weight and flexible PCBs. Plastic offers the advantages of high smoothness, transparency and low porosity [32, 33]. Even though plastic is not very amenable to the use of different solvents, it has been one of the main materials used in conventional flexible electronics [34, 35]. In comparison to plastic, paper is more temperature resistant, stiffer, more renewable and may be less susceptible to moisture problems [36]. Currently, paper is the material of choice for many products used on a daily basis, and therefore, the fabrication of PCBs on paper may open new market opportunities for PEs and paper. The ability to produce flexible PCBs on paper and PET enable them to be
placed on and conform to different form factors and surfaces, where spacing or shape would prohibit the placement of a rigid conventional circuit board. Alternately, for some applications, such as the auto industry, a rigid transparent PCB on glass would be beneficial to enable devices to be integrated into the windshields or mirrors of cars. Moreover, glass offers the added advantages of heat stability, transparency and smoothness [37].

In this work, the author has employed screen printing to fabricate multi-layer PCBs on PET, paper and glass. Pick and place equipment was used to attach solid state components onto the boards to produce a working hybrid PCB. The ability to fabricate a PCB incorporating an embedded microcontroller to drive a $160 \times 100$ pixels LCD display with $+3V$ power supply was demonstrated.

3.2. Background

The initial objective for this study was to define and construct a proof of concept for the fabrication of high yield, multi-layer electronic circuit boards on flexible substrate as well as glass. This section summarizes the key activities and result of this research work. The first generation of PCBs was printed using gravure printing methods on polyethylene terephthalate (PET). In this work Silver nano particle ink (Inktec) was used as a metallization layer (top and bottom layers) and UV clear from ecology was used as a dielectric layer. Figures 3.1 (a) and (b) show the top and bottom layer printed individually on PET. The component attachment was done using the facility of Finetech Company. A Martin dot liner 06.6 was used for dispensing of the silver epoxy (Figure 3.2 (a)) and Fine tech placement instrument was used for attachment of the component. (Figure 3.2 (b)).
These instruments provided high accuracy in dispensing of the silver epoxy as well as attachment of the electronic components. The final sample after printing of three layers as well as component attachment is illustrated in Figure 3.1 (c).

After component attachment, the PCB was tested. A few problems were observed. Due to spreading of the ink after printing on PET, some of the lines were shorted. The DC to DC convertors was electrically shorting and some of the component came off in this section due to small dimension of the pads. When voltage was applied to the circuit, this voltage was seen across the components but there was a problem in programing the microcontroller. Based on
these problems, the author modified the design and chose another method for fabrication of the printed PCDs which is explained in details in following sections.

![Image](a) ![Image](b)

**Figure 3.2: (a) Martin dot liner 06.6 (b) Fine tech placement instrument**

### 3.3. Objectives

#### 3.3.1. Materials and Sample Preparation

Three different substrates were of interest; 130 μm thick flexible PET film (Melinex ST 506) from DuPont Teijin Films, plate glass from Corning and paper (NB-RC3GR120) from Mitsubishi. Some of the important characteristics of the different substrates are summarized in Table 3.1. For example, glass demonstrated a higher surface energy when compared with paper and PET. Adhesion of the silver ink employed for traces on all of these substrates was good, thereby showing promise as substrates for the fabrication of PCBs. The roughness of paper, PET and glass was measured to be 0.175 μm, 0.015 μm and 0.005 μm, respectively, using a WYKO RST-plus optical profiler. Based on these measurements, both glass and PET have relatively smooth surfaces, making them good substrates for printing thin conductive traces. In comparison to the glass and PET, paper is considerably rougher, although this paper is very smooth by paper standards. However, unlike PET and glass, paper is more absorptive, which can reduce the amount of ink spreading after printing. Since the thickness of a
printed ink film depends on the amount of ink spreading and absorption, if both properties are controlled, highly conductive lines can be produced on paper. The roughness and absorptive properties of paper could also be an added advantage for ink adhesion. Hence it is worthy of study, since it is flexible, readily available, tunable and of low cost.

Metal and Dielectric: There are different materials such as silver (Ag), gold (Au), and copper (Cu) that can be employed for the fabrication of electronic circuit boards. In this paper, a Ag flake ink (Electrodag 479SS) and a UV acrylic-based ink (Electrodag PF-455B) from Henkel were used as the metallization and dielectric layers, respectively. All layers were printed using an AMI 485 semiautomatic screen printing press at room temperature.

After construction of the PCB, components must be attached to the contact pad location using a conductive adhesive. A commercially available Ag conductive epoxy (H20E), was purchased from Epoxy Technologies Inc. and was used to attach the surface mounted devices (SMD) to the different substrates. The epoxy was screen printed onto the pads prior to placement of the electronic components with an automated pick and place instrument (MY100sxe) from My Data Inc.

Table 3.1: Summary of different characteristics of substrates including surface energy, thickness and roughness

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Surface energy [dynes/cm]</th>
<th>Thickness [µm]</th>
<th>Roughness [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paper</td>
<td>53.9</td>
<td>177±12</td>
<td>0.175</td>
</tr>
<tr>
<td>PET</td>
<td>43.8</td>
<td>127±1</td>
<td>0.015</td>
</tr>
<tr>
<td>Glass</td>
<td>58.21</td>
<td>629±1</td>
<td>0.005</td>
</tr>
</tbody>
</table>
3.3.2. Design of the Circuit

In order to demonstrate that the hybrid PCB would work once fabricated, a microcontroller based circuit was designed to control an externally attached LCD and a three-layer PCB layout pattern was produced. The circuit design consisted of a DC to DC convertor, microcontroller and other necessary passive components. The design layout was done using PCB123® design software and then transferred to a multilayer Adobe Illustrator file for screen generation. The layout of the design that consists of two conducting layers and an insulating layer, which prevents shorting between the top and bottom Ag layers, is shown in Figure 3.3.

Figure 3.3: The layout of PCB design created in PCB123® design software. This design consists of the pads for a DC to DC convertor, a microcontroller and necessary passive components. (Red Layer – Bottom Electrodes; Green Layer – Dielectric Layer; Yellow Layer – Top Electrodes).
3.3.3. Screen Printing of PCB

The conductive and dielectric materials were screen printed onto the substrates using an AMI 485 semi-automatic screen printing press, at room temperature. A 320 mesh count screen was used for printing the materials on the various substrates. After printing the first or bottom metallization layer on all three substrates, the ink was cured for 20 min in a VWR 1320 temperature-controlled oven at 120 °C. The thickness of the ink film on paper, glass, and PET was measured to be 14.8, 10, and 12.8 μm, respectively, using a Bruker vertical scanning interferometer microscope (CounterGT) [Figure. 3.4 (a), (c), and (e)]. All PCB lines were found to be continuous (no breaks) and conductive. Next, the dielectric layer was screen printed over the first metal layer. The printed layer was then cured using a UV fusion drying system equipped with a D bulb. Figure. 3.4 (b), (d), and (f) show the dielectric layer printed over the Ag layer on paper, glass, and PET, respectively.

The thickness of the dielectric layer on paper, glass, and PET was measured as 14.00, 9.46, and 8.62 μm, respectively. As shown, the dielectric layer was printed uniformly, thereby preventing any shorting between the top and bottom Ag layers. Finally, the top metallic layer was printed and thermally dried in an oven. A photograph of three printed layers on PET is provided in Figure. 3.5 (a).

The operational circuit was fabricated by attaching SMD components to defined pad areas on the PCB. The silver epoxy, previously described, was screen printed onto the pads using a 200-μm mesh screen and polymer squeegee of 80D hardness. The components were then placed onto the epoxy using an automated pick and place instrument from My Data Inc. The samples were then initially cured at 130 °C for 10 min followed by a second cure at 120 °C for 5 min. A photograph of the completed PCB on paper is shown in Figure. 3.5 (b).
3.4. Results
3.4.1. Analysis of Printed Lines

The widths of the printed lines were measured with an ImageXpert (KDY Inc.) image analyzer. The results are shown in Figure 3.6 (a). The patterned 300 and 600 μm lines on paper printed as 263 and 566 μm, which correlate to a −13.3% and −5.6% loss, respectively. The negative gains are attributed to ink absorption by the paper. On PET, the line widths are measured as 323 and 625 μm, which correlate to a gain of 7.6% and 4.16%, respectively. The
increase in linewidth is attributed to the wetting and spreading of the ink on the PET film. For glass, the line widths were measured to be 295 and 608 μm, producing a negative gain of −1.6% and positive gain of 1.3%. Fig. 3.6 (b) shows the vertical scanning interferometer images of the printed lines for the microcontroller contact pads. It was observed that these lines were printed uniformly, with complete separation from one another. The picture of the pads for the microcontroller with 500 μm spacing is shown in Fig. 3.6 (c). The separation of the pads can be attributed to the lack of ink spreading.

Figure 3.5: (a) Photograph of three layers of printed PCB on PET and b) A photograph of the completed PCB on paper.
Figure 3.6: (a) Summary of line width measurement on different substrates; (b) 3D profilometry picture and (c) optical microscope image of printed lines for microcontroller contact pads.

Figure 3.7 shows a comparison of the effect of substrate roughness on the resistance of the printed lines. For example, it was seen that the lowest resistance (1.06 Ω) was obtained on paper, for the 600 μm lines. This is because paper absorbs the ink, thereby keeping the particles
in close contact with one another, and hence the lines are more conductive. The printed lines on the glass substrate exhibited lower resistance (1.13 Ω) than the printed lines on PET (1.16 Ω) due to the lower roughness of glass creating a more consistently larger cross-sectional area for the line. It was observed that higher roughness affected the uniformity of printed lines and decreased the conductivity due to variations in ink film thickness at some points. Figure 3.7 shows that the printed lines on the PET are slightly higher in resistivity when compared to those on glass. This is due to the higher roughness of the PET producing a less consistent and effectively smaller cross-sectional area.

![Resistance Vs. Roughness](image)

Figure 3.7: Effect of roughness on resistivity of printed lines.

### 3.4.2. Electrical Analysis

**Line Resistivity:** The effect of the resistivity of the lines on the performance of the circuit was also investigated. The LCD was driven, with a series of conventional resistances and it was observed that the LCD worked with line resistances of up to 3.7 kΩ. Since the resistance of all
the printed lines was measured to be below 10 Ω, it was determined that the performance of the LCD would not be affected by the resistance of the printed lines. The summary of this test is shown in Figure 3.8.

<table>
<thead>
<tr>
<th>Series Resistance (Ω)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td></td>
</tr>
<tr>
<td>330</td>
<td></td>
</tr>
<tr>
<td>1k</td>
<td>LCD works fine</td>
</tr>
<tr>
<td>2.2k</td>
<td></td>
</tr>
<tr>
<td>3.3k</td>
<td></td>
</tr>
<tr>
<td>3.7k</td>
<td></td>
</tr>
<tr>
<td>4.0k</td>
<td>Distorted Display</td>
</tr>
<tr>
<td>4.2k</td>
<td>No Display</td>
</tr>
<tr>
<td>4.7k</td>
<td></td>
</tr>
<tr>
<td>7.6k</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 3.8: Summary of the effect of the resistivity of the lines on the performance of the circuit**

Effect of Bending: The effect of bending of the substrate on the resistance of the lines was also analyzed using a force gauge (Mark-10). The PCB was mounted on the support of the 3-point test fixture and subjected to 10000 cycles of 5-mm elongation. After 10 000 cycles of bending, a 1.8% increase in the base resistance was observed. This is negligible for the given above stated tolerance of the line resistance. The scanning electron microscope (SEM) images of the printed lines were acquired using a Hitachi S-4500 model SEM, with Quantax 200 software package before and after bending. Figure 3.9 (a)–(d) shows the SEM images of the printed lines before and after bending, respectively. It was observed that even though there were some small cracks, the printed lines were conductive after bending.
3.4.3. LCD Operation

The printed PCB circuit was then energized and used to drive an LCD display. The codes for the microcontroller, a low-power Texas Instruments (TI) MSP430 processor, were written using TI’s Code Composer Studio. Figure 3.10 shows the performance of the printed PCB when 3 V was applied to it. The preloaded software executing on the microcontroller produced a graphic message (CAPE), as shown, on the LCD. This effectively demonstrated that the embedded microcontroller driving an attached device suggest numerous other small battery-operated applications. This includes low cost R2R electronic circuit boards for consumer electronics (e.g., in packaging industry) and medical wearable devices that can be attached to the
human skin, postal security systems (printed directly to packages and envelopes), and very-light-weight circuit boards for aircrafts or automobiles.

![Photograph of powered, operating microcontroller and passive electronics on the printed glass substrate driving an LCD display.](image)

**Figure 3.10:** Photograph of powered, operating microcontroller and passive electronics on the printed glass substrate driving an LCD display.

### 3.5. Summary

In this chapter, the author presented an introduction to new substrates and fabrication methods for electronic devices and the need for fabrication of flexible and low cost electronic circuit boards for different applications such as biomedical and auto industry. In addition, the background and details of previous work that have led to the current project was presented. This includes the fabrication of first generation of printed PCBs using gravure printing methods, and the difficulties that were seen during the process. This was followed by an improved methodology, a detailed explanation of screen printing for PCBs an various substrates and the analysis of results and performance of the printed PCBs.

To summarize, Screen-printed multilayered PCBs using PE-deposited materials on three distinct substrates were successfully fabricated. The different characteristics of PET, paper, and glass as the substrates for PCBs were analyzed. A method for populating electronic components onto the printed PCB pads was defined and demonstrated. The capability of the printed hybrid
PCB circuit to operate correctly and to drive an LCD was shown. The fabrication of PCBs on flexible substrates such as paper and PET opens numerous opportunities for the development of low-cost and light-weight circuit boards for embedded electronic devices and applications that may include the requirement for conformal shapes or surfaces. At the same time, the fabrication of PCBs on flexible or rigid glass may lead to new designs for automotive and aerospace applications.

In the following chapter, the author presents a project that includes design, simulation, fabrication and analysis of the wavy lines for fabrication of stretchable sensors as well as interconnections of stretchable systems. The measurement set-up, testing and results obtained are also presented.
3.6. References


CHAPTER IV

DESIGN, FABRICATION AND ANALYSIS OF PRINTED WAVY LINES FOR STRETCHABLE ELECTRONIC DEVICES

4.1. Introduction

There have been steady efforts in semiconductor and device technology working towards increasing the operation speed of transistor and electronic devices and reducing the dimensions of end device for almost half a century [1-4]. Over the last two decades, there has been an increasing interest in the fabrication of electronic devises on light weight and flexible substrates, such as paper and plastic for enabling the manufacturing of large area electronics [5-15]. The flexibility of electronic devices improves the placement and interfacing of such devices with their surrounding environment. Some examples of these devices include flexible sensors [16], paper like displays [17], thin film transistors [18], radio frequency identification tags [19] and wearable electronics [20]. Development of this new type of electronic devices requires new forms of materials and strategies that are mechanically strong enough to tolerate the applied strain and stress. A large number of materials, when deposited on a thin substrate or close to neutral plane in a thin layer form, can flex properly [21-25]. For specific applications, the amount of stress that these devices experience can remain below the fracture limit. Fabricated stretchable electronic devices, which can be stretched to some point, have shown many applications in unconventional electronics, especially in health monitoring devices [26- 30].

There has been numbers of reports on stretchable lines for the fabrication of flexible electronics [21, 22, 31-33]. Most of these fabricated devices have used conventional electronic
device manufacturing techniques that are then transferred onto a final flexible substrate. These methods are also time consuming and require expensive instruments and complicated procedure for fabrication. These drawbacks can be surpassed by employing printing methods for the deposition of functional materials in stretchable forms. As explained in chapter 2 section 2.4, these methods have advantages such as fast, low cost and low temperature fabrication processing. There are a few reports on the fabrication of stretchable lines using carbon nanotubes and silver nanowires deposited using printing technologies [34, 35]; however, to the best of the author’s knowledge, there are no reports on the fabrication of wavy lines using printing methods. Wavy lines have shown many applications in epidermal electronics. In this work screen printing was employed for the fabrication of flexible and stretchable lines for use as health monitoring devices that will have a better interface with the human body. The goal of this chapter is to fully characterize the design and fabrication of wavy lines and determine the important design parameters for the stretchability of these lines.

4.2. Experimental

4.2.1. Design and Fabrication of Wavy Lines

One method used for the fabrication of stretchable sensors is the design of interconnects and sensors in the form of wavy or meander lines on a stretchable substrates. There have been many reports on different challenges and parameters in the design and analysis of wavy lines. The major designs are divided in in three categories: 1) wavy lines formed with two half circle connected to each other; 2) wavy lines having extended lines between two half circles; and 3) horse-shoe designs. The design parameters for wavy structure are shown in Figure 4.1. A wavy line has parameters such as r (radius of arc), Θ (arc angle), L (straight section of wavy lines), W (width of wavy lines), and D (diameter if the arc).
Figure 4.1: Design parameters of wavy lines.

Figure 4.2: Schematic of wavy structure a) two half circles connected to each other (design 1), w=800 µm r=2000µm, b) two half circles connected to each other (design 1), w=800 µm r=4000µm, and c) two half circles connected through a straight line w=800 µm r=4000µm L/D=1/2 (design 2) and c) two half circles connected through a straight line w=800 µm r=4000 µm L/D=2 (design 2).

In order to study the effect of the applied strain on the resistance of wavy stretchable lines different structures having the widths of 400 µm, 800 µm and 1600 µm were designed in different
forms based on the three categories described. The effects of the W/r ratio and L/D ratio, important design parameters related to stretchability, have been studied.

Figure 4.2 a) and b) illustrate the design of wavy structure (which will be called design 1) having two half circles connected to each other. These lines were designed having line widths of 1600 µm, 800 µm and 400 µm and with varying radii of 2000 µm, 4000 µm, 6000 µm and 8000 µm. The schematic of wavy lines having extended lines with Θ=90 (design 2) are shown in Figure 4.2 c) and d).

The wavy structures with extended lines in form of horse-shoes (design 3) and with different lengths of extended lines are shown in Figure 4.3.

![Schematic of horse show (design 3) wavy lines (Θ=80) a) L/D=1/4, b) L/D=1/2, c) L/D=3/4, d) L/D=1.](image)

The schematic of horse show form with different Θ is presented in Figure 4.4. To analyze the effect of the angle on the stretchability of the printed lines different horse-shoe structures having angles of 30, 45 and 60 degree were designed.
4.2.2. Simulation

Three different meander structures were simulated and the effect of applying stress to them was analyzed using CoventorWare®. All of the designs have a line width of 400 µm and radius of 4000 µm. In the simulation the lines were formed using copper. The effect of the substrate on the stretchability of the lines was neglected. 10 µm, 100 µm and 500 µm displacements were applied to the meander structures. Figure 4.5 a) shows the result of applying a 10 µm displacement to design 1. High levels of stress are observed in the crest of the wavy structure. This stress could lead to breakage in the curves. By increasing the applied displacement, the amount of stress applied on the structure increased. The amount of stress on the crest was 0.54 MPa when the structure was stretched 10 µm. Figure 4.5 b) and c) show that the stress increased to 54 MPa and 260 MPa when the line was stretched for 100 µm and 500
µm, respectively. To avoid high concentration of stress in the crest of the waves the straight extended lines were added to the design (design 2). Figure 4.6. a), b) and c) represent the effect of applying 10 µm, 100 µm and 500 µm displacements to design 2. Adding the extended lines to the design offers a better distribution of stress in the structure as compared with design 1. By direct comparison to design 1, the applied strain on the crest on the waves for all three displacements has been reduced to 0.18 MPa, 2 MPa and 97 MPa, respectively when the structure was stretched for 10 µm, 100 µm and 500 µm. The straight vertical line might limit the deformation of the wavy lines in cases that biaxial deformation is needed. To overcome the limitation of the deformation causes by straight lines, they have been changed to the horse shoe form for design 3. The results obtained for this simulation are illustrated in Figure 4.7 a), b) and c). As it can be seen from the image, the stress is distributed all over the curved part as well as the extended line. In comparison with design 1, the amount of stress applied is decreased to 0.24 MPa, 1.9 MPa and 140 MPa.

In all of the designs, failure can happen in the regions that have a higher concentration of stress. The zoomed in pictures of those points are shown in Figure 4.8 a), b) and c). The simulations have shown that adding extended line to the design of meanders has helped the stretchability, reducing the induced strain in the structures. For example in case of applying 10 µm displacement to different designs the maximum strain tolerated by the structure was decreased 66% and 56 % and for design 2 and design 3 as compared with design 1.

In the next section the author will explain the details of fabrication as well as the resulting characteristics, in particular the mechanical and electrical performance of the printed lines.
Figure 4.5: Simulation results obtained for the stretching of lines (design 1) a) 10, b) 100 and c) 500 µm
Figure 4.6: Simulation results obtained for the stretching of lines (design 2) a) 10, b) 100 and c) 500 µm
Figure 4.7: Simulation results obtained for the stretching of lines (design 3) a) 10, b) 100 and c) 500 µm
4.2.3. Chemicals, Materials and Sample Preparation

Thermoplastic polyurethane (TPU) from Bemis Associates, Inc, was used as a substrate for the fabrication of wavy lines. Silver (Ag) ink (Electrodag 479SS from Henkel) as well as
Carbon nano tubes (CNTs) ink (VC101 from SWENT) were used for the fabrication of wavy lines.

4.2.4. Fabrication of Printed Wavy Lines

A semi-automatic screen printing press (AMI 485) was used for the fabrication of wavy lines on a TPU substrate. The screens provided by Microscreen® were of a stainless steel mesh count of 325 and MS-22 emulsion thickness of 12.7 μm. The wire diameter of the screen was 28 μm with an angle of 22.5 degrees. The printing process was performed at room temperature and three runs of printing, depositing three layers, was used to deposit the conductive materials. Deposited silver ink was cured in a VWR 1320 temperature-controlled oven at 120 °C for 20 min. The same structures were printed on TPU using CNTs. Isopropyl alcohol was used as a cleaning agent. Printed CNTs were cured in the oven for 10 min at 120 °C. The thickness of lines having 400, 800, 1600 μm line width were measured to be 24, 25, and 23 μm, respectively, using a Bruker vertical scanning interferometer microscope (CounterGT). (Figure 4.9 a), b) and c))

Figure 4.9: 3D vertical scanning interferometer images of a) design 1, b) design 2 and c) design 3.
4.2.5. Experiment Setup

The experiment setup is shown in Figure 4.10. The printed wavy lines were placed between a force gauge (Mark-10 model M5-200) and vertically movable platform (Mark-10 ESM 301 motorized test stand). The lines were subjected to different displacements ranging from 1 mm to 8 mm for 100 cycles. The resistance of the lines was measured after each step and change in the resistance was recorded. The failure point for each structure was determined.

![Experiment Setup](image)

Figure 4.10: Experiment setup.

4.2.6. Results

Figure 4.11 represents the effect of the different stretching tests on the resistance of the wavy lines (design 1). Figure 4.12 illustrates the change in resistance of the lines versus applied strain. The resistance of all lines increased more than 100 % in response to applied strain. For W=1600 μm, r=4000 μm by stretching the line for 1 mm, 2 mm, 3 mm, and 4 mm the resistance increased from 1 Ω to 1.4 Ω, 1.9 Ω, 2.4 Ω and 3.4 Ω which corresponds to 34 %, 84 %, 131 % and 218 % change in the resistance. For the line with W=1600 μm, r=8000 μm the base resistance was 2.1 Ω. After stretching the line for 1 mm, 2 mm, 3 mm, 4 mm and 5 mm, the resistance increased to 2.5 Ω, 2.9 Ω, 3.6 Ω, 4.2 Ω and 5.2 Ω, respectively, which corresponds to 16 %, 36 %, 69 %, 95 % and 141 % changes in the base resistance of the line. In the case of wavy structure with W=800 μm, r=2000 the resistance increased from 1 Ω to 1.6 Ω, 2.4 Ω and 3.4 Ω which is equal to 53%,
128 % and 221 % changes in the resistance the line when it was stretched 1 mm, 2 mm, and 3 mm. The wavy line having W=800 μm, r=4000 μm with the base resistance of 2.2 Ω was subjected to stretching for 1 mm, 2 mm and 3 mm. The resistance increased to 2.7 Ω, 4.7 Ω and 5.5 Ω. This shows 20 %, 110 % and 146 % changes in the resistance of the line. The line with W=800 μm, r=6000 μm was also stretched for 1 mm, 2 mm, 3 mm and 4 mm. The base resistance of 3.3 Ω was increased to 3.5 Ω, 5 Ω, 5.8 Ω and 6.5 Ω, respectively, which correspond to 5 %, 52 %, 74 % and 96% changes. The wavy line having the width of 1600 μm and radius of 8000 μm showed the maximum tolerance toward applied strain, which was calculated to be 12 %. The applied strain can be mathematically calculated using:

\[ \varepsilon = \frac{\Delta L}{L_0} \]  

where the \( \Delta L \) is change in the length of the sensor and \( L_0 \) is the initial length of the sensor.

The ratio of width to radius of waves (W/r) is one of the important parameters in analysis and design of the wavy lines. It has been reported that the smaller this ratio the less strain is applied on the line during stretching [36]. Figure 4.13 a) and b) presents the effect of the W/r on the stretchability of the lines. Figure 4.13 a) shows three lines having the width of 800 μm with different radius of 2000 μm, 4000 μm and 6000 μm which correspond to W/r ratio of 0.4, 0.2 and 0.13. It can be seen that the lower W/r ratio shows less change in the resistance of the printed lines when the stress is applied. For example when the lines are stretched 3 mm, the line having W/r=0.13 showed 74 % change in the resistance where the lines with W/r= 0.2 and W/r= 0.4 showed 146% and 221%. Figure 4.13 b) compares stretchability of two lines having the width of 1600 μm and radius of 4000 and 8000 μm. It is seen that the smaller W/r results in a less strain and more stretchability. Both of the lines were stretched 1mm, 2mm, 3mm, and 4 mm and in all steps the line having W/r= 0.2 showed less change in the resistance of the line. For
another test the radius of the arc was kept constant (r=4000 µm) and two lines having width of 400 and 800 µm and extended line (L=4000 µm) were printed. Figure 4.13 c) shows that the smaller W/r ratio revealed smaller change in the resistance of the line when displacement was applied to the line.

Figure 4.11: Effect of displacement on the resistance of lines with different sizes a) W=1600 µm, r=4000 µm, b) W=1600 µm, r=8000 µm c) W=800 µm, r=2000 µm d) W=800 µm, r=4000 µm e) w=800 µm, r=6000 µm.
Figure 4.12: change in the resistance of lines having different sizes a) W=1600 μm, r=4000 μm, b) W=1600 μm, r=8000 μm c) W=800 μm, r=2000 μm d) W=800 μm, r=4000 μm e) W=800 μm, r=6000 μm.
Figure 4.13: analysis of W/r ratio on stretchability of the lines. a) W=8000 μm, r= 2000, 4000 and 6000 μm (W/r=0.4, 0.2 and 0.13), b) W=1600 μm, r= 4000 and 8000 μm (W/r=0.2 and 0.4) c) r= 4000 μm, W=400 and 800 μm (W/r =0.2 and 0.1)
According to the previous simulations explained in Section 4.2.3, wavy lines having straight extended lines (design 2) show better stretchability, which is based on the distribution of the strain through the crest and added extended line. Figure 4.14 a) and b) shows the results obtained after stretching the lines for 1 mm, 2 mm, 3 mm, 4 mm and 5 mm. For wavy line with W=800 μm, r=4000 μm, L=4000 μm and Θ=90 ° the base resistance increased from 1.9 Ω to 2.1 Ω, 2.3 Ω, 2.8 Ω, 3.3 Ω and 3.6 Ω which correspond to 10 %, 22 %, 48 %, 72 % and 89 % increase of resistance. Resistance of line with W=800 μm, r=4000 μm, L=16000 μm and Θ=90 ° was increased from 2.6 Ω (base resistance) to 3.1 Ω, 3.6 Ω, 4 Ω, 4.4 Ω and 5.4 Ω. This corresponds to 19 %, 37 %, 52 %, 68 % and 107 % increase of the base resistance for 1 mm, 2 mm, 3 mm, 4 mm and 5 mm displacement. Figure 4.14 c) shows that the percentage changes in the resistance of the lines were decreased in comparison with design 1. This can be related to the effect of adding the extended straight line to the structure of the wavy lines. It helps in distribution of the strain through the crest as well as extended line and decreases the chance of breakage on the curved part of the structure.
Figure 4.14: Effect of the displacement on the resistance of lines having different sizes a) W=800 μm, r=4000 μm and L/D=1/2, b) W=800 μm, r=4000 μm, L/D=2, c) Change in the resistance of lines. The line with L/D smaller than one shows less change in the resistance.

It has been reported that changing the angle of the extended line might help improve the stretchability of the wavy structure [36]. Based on the simulation this can help in distribution of the stress through the structure. For this purpose four different structures having the extended line with the angle of 30, 45, 60 and 80 were designed and tested. The results obtained are illustrated in Figure 4.15.
Figure 4.15: Effect of the displacement on the resistance of lines having different angles a) \( \Theta = 80 \) b) \( \Theta = 60 \) c) \( \Theta = 45 \) d) \( \Theta = 30 \)

Figure 4.16: Percentage change in the resistance of lines having different angles.

This result shows that comparing with design 1 the amount of strain has been reduced and the stretchability of the line increased. For example when the design 1 (\( W = 800 \) μm, \( r = 4000 \)
µm) was stretched, the line broke after stretching 3 mm but in case of design 2 having Θ = 45, 60, and 80) it was possible to stretch them up to 6 mm. The percentage change in the resistance of the structures has also decreased comparing the design 1. The change in the resistance up to applying 8 % strain is below 50 % (Figure 4.16) where in design 1 after stretching 2 mm the change in the resistance was 110 %.

The length of the extended line has an impact on the stretchability of the wavy structure. In order to analyze this effect the ratio of L/D (ratio of length of the extended line to the diameter of arc) is used as a design parameter. To analyze this parameter, horse shoe structure having the angle of 80 degree with 4 different ratios of L/D (1/4, 1/2, 3/4 and 1) were designed. The width, radius and angle were kept constant (w=800 µm, r=4000 µm, Θ=80) for all the lines. Figure 4.17 presents the effect of applying stretching tests to these lines. The change in resistance of these lines was below 50 % until 6 mm of stretching. It has been reported that if this ratio is kept below 1 the lines can tolerate more strain [36]. Comparing with the result presented in Figure 4.14 c) all these lines having the L/D ratio below one show less strain comparing with the L/D ratio bigger than one. For example when the line having L/D=2 was stretched 4 mm a 40 % change in resistance was observed (Figure 4.14 c) but for L/D less than one all of the samples showed a change in resistance of less than 20 % when they were stretched by 4 mm. When L is higher than D, the extended line becomes stiff and does not allow the structure to stretch more, and, as a result, it can lead to breakage of the structure.
In order to analyze the effect of the thickness of the line on the stretchability, one, two and three deposition layers for a wavy line ($W=400 \, \mu m$ and $r=4000 \, \mu m$, $\Theta=80$) were printed and then subjected to different displacements, as shown in Figure 4.18. It shows that the change in the resistance of the three layers line was lower compared with one and two layers for all applied strain. For example when a 5 % strain was applied on the line having three layers, a 12 % change was obtained in the resistance. Applying the same strain on one layer and two layered lines resulted in 19 % and 17 % changes in the resistance, respectively. It can be attributed to the fact that stretching the lines in vertical direction results in compressive strain to the lines in the horizontal directions. This extra strain can cause a breakage in the lines. When the line is formed with a greater thickness, it reduces the effect of the compressive strain on the structure.
Figure 4.18: Analysis of the effect of thickness on the stretchability of the structure. The with three layered sample shows less change in the resistance of line in compare with one layer and two layered sample.

3D vertical scanning interferometer images of the wavy lines were taken in order to monitor the changes in the structure. The line with W=800 µm, r= 4000 µm and Θ=80 was subjected to 100 cycles stretching for 1 to 11 mm. A profilometry picture of the line both in the curve and in the straight section were taken after each step. Figure 4.19 shows the effect of strain on the structure of the line after stretching 1 mm, 5mm, 7mm and 11 mm. The line did not break until it was stretched 6 mm. After this point, first the curved part of the waves started showing some breakage and then the straight part broke at 11mm of stretching. Based on the simulation result presented in section 4.2.3 the high level of stress was applied on the crest part of the wavy structure. Profilometry pictures have shown that the first part of the structure, which showed failure during applying strain, is the curved part of the line.
Figure 4.19: 3D vertical scanning interferometer images of a) curved part of the line after a) 1mm (no breakage), c) 5 mm (no breakage), e) 7 mm (started breaking), g) 11 mm (broken), straight part of the line after b) 1mm (no breakage), d) 5 mm (no breakage), f) 7 mm (no breakage), h) 11 mm (started breaking).

CNTs were used to print two forms of wavy line with W= 400 µm, r= 4000 µm Θ=80 (design 3) having L/D= 1/4 and L/D=3/4. The result of the stretching test is shown in Figures 4.20 and 4.21. In comparison with Ag, CNTS showed a higher strachability with less change in the base resistance of the lines. Printed lines using Ag ink showed failure after stretching of 7 mm (design 3) but the lines printed using CNTs with the same design parameters were stretched
until 40 mm and the line was still connected and functional. On the other hand it was observed that the change in the resistance of the line was below 10 % when the lines were stretched 10 mm. The line with w= 400 µm, r= 4000 µm Θ=80 (design 3) having L/D= 1/4 was stretched up to 40 mm. When the same line was stretched 1mm, 2 mm, 3 mm, 4 mm, 5 mm, 6 mm, 7 mm, 8 mm, 9mm, and 10 mm the resistance of the line was increased from the base (176 kΩ) to 176.8 kΩ, 177.6 kΩ, 178.8 kΩ, 180.2 kΩ, 181.6 kΩ, 184.2 kΩ, 186 kΩ, 191.1 kΩ, 192.9 kΩ and 196 kΩ, respectively. This result in 0.4 %, 0.9 %, 1.5 %, 2.4 %, 3.2 %, 4.6 %, 5.7 %, 8 %, 9.6 % and 11.3 % changes in the observed resistance. The results show, based on the stronger mechanical properties of the CNTs, that there is less change in the resistance when the lines are subjected to strain. Figure 4.21 illustrated the result of the stretching tests on the wavy line printed using CNTS with w= 400 µm, r= 4000 µm Θ=80 (design 3) having L/D= ¼. The line was stretched to 40 mm and the percentage change in the resistance was calculated. Similar to the other line having (L/D= ¼), this structure showed higher stretchability when compared with the printed lines using silver. The amount of the change in resistance remained below 10 % when a 20 % strain was applied on the line. This performance suggests that CNTs can offer better functionality when they are subjected to strain and the chance of failure in the functionality of the lines is less. On the other hand, for applications such as stretchable PCBs which generally are not subjected to high amount of strain, silver can be a better candidate based on better conductivity.
Figure 4.20: a) Effect of the displacement on the resistance of line ($L/D = \frac{1}{4}$), b) Change in the resistance of the line ($L/D = \frac{1}{4}$).
Figure 4.21: a) Effect of the displacement on the resistance of line (L/D = 3/4), b) Change in the resistance of the line (L/D = 3/4).
4.3. Summary

In this chapter, the author discusses the need for a detailed study on the design and fabrication of printed wavy lines. A detailed account of the experimental tasks involved in this work was presented. This included design, fabrication and analysis of wavy line on the TPU as a stretchable substrate using Ag ink and CNT ink.

In this work, different forms of wavy structures were designed and fabricated. The effect of displacement on the stretchable lines was analyzed. Different parameters which have an impact on the stretchability of the lines were discussed. It was shown that smaller ratios of W/r result in more stretchability and a reduced amount of change in the resistance of the lines. The effect of adding extended straight line segments on the performance of the patterns under applied stress was presented. The result showed that adding the extended line helps in the distribution of the stress in the line and reduces the chance of failure and breakage. Three different thicknesses were also tested to determine the effect of thickness on the stretchability of the structures. It was seen that the three layered sample showed more tolerance regarding the applied stress in comparison with one layer and two layers printed lines. CNT ink was also used for printing wavy lines based on their stronger mechanical properties. The printed samples showed less change in the resistance when they were stretched.

In the following chapter, the author presents an application of printed wavy lines in design and fabrication of stretchable wearable sensors for health monitoring devices. The measurement set-up, testing and results obtained are presented.
4.4. References


CHAPTER V

FABRICATION OF WEARABLE SENSORS USING PRINTING METHODS

5.1. Introduction

With advancements in material science and printing technology along with the development of prosthetics and wearable devices, much effort have been dedicated to the design and fabrication of flexible wearable sensors on thin film substrates [1-9]. Flexibility allows a conformal human-device interface, which improves the sensitivity of measurements. Stretchable sensors, unlike flexible devices, have shown stronger mechanical properties, which is a very important factor for wearable, skin mountable sensors. Among various important sensing parameters, strain, temperature, and ECG (electrocardiogram) can provide very important information about the vital signs of a wearer. The interface of the sensor with the skin has a significant impact on the sensitivity of the device. Tensile and compressive strain applied to the sensor based on the movement of the body affect the accuracy of the measurement. As an example, the strain sensor is used for movement measurement and the strain is directly applied on the structure of the sensor. Fabrication of wearable devices, which are both flexible to have a conformal interface with body and stretchable to be able to tolerate the applied strain, offer a potential for wide use in the medical devices market.

In this work, the author uses conventional screen printing techniques to fabricate a fully printed, stretchable, multi-functional sensor for strain, temperature, and ECG measurement. A thin layer of Polydimethylsiloxane (PDMS), as well as temporary tattoo paper, has been used as
a substrate. CNT ink was used for printing the strain and temperature sensor, and a mixture of silicone and silver was used for fabrication of ECG pads. The author demonstrated the capability of the fabricated device to be used as a multi-functional wearable sensor.

5.2. Experimental

5.2.1. Chemicals, Materials and Sample Preparation

PDMS (Sylgard® 184 Silicone Elastomer from Dow Corning) was used as a substrate for the fabrication sensors. The liquid PDMS pre-polymer was mixed thoroughly with a curing agent at a ratio of 10:1 and degassed for 1 hour. Polyvinyl Alcohol (PVA) substrate (Watson QSA 2000) was used as a sacrificial layer for transferring the sensor directly onto the skin. Temporary tattoo paper (Papolio) was also used as a substrate. CNT ink (VC101 from SWENT) was used for the fabrication of resistive strain and temperature sensors. EXP-06335, a screen-printable silicone+ Silver (Protavic America) was used for deposition of ECG pads.

5.2.2. Fabrication of Printed Strain Sensor on Tattoo Paper

Multiple sensors consisting of both wavy shape, having an 800 μm line width and overall dimension of 3 cm × 0.4 cm, and straight line, having a width of 800 μm and length of 2 cm, were screen printed using CNT ink on temporary tattoo paper. The CNT ink was cured in a VWR oven at 100 °C for 10 minutes. Different steps associated with the fabrication of the strain sensor on the tattoo paper are shown in Figure 5.1. The sensors were printed using a Semi-automatic screen printer (AMI MSP 485) from Affiliated Manufacturers Inc. The screens, for fabrication of the sensors, were fabricated at Microscreen® with a stainless steel mesh count of 325 and MS-22 emulsion thickness of 12.7 μm. The wire diameter of the screen was 28 μm at an angle of 22.5.
Initially, the tattoo paper was cleaned using an air gun (Figure 5.1(a)) and the strain sensor was printed on the tattoo paper (Figure 5.1(b)). A 4 cm × 1 cm PDMS dielectric layer was then screen printed on top of the sensor (Figure 5.1(c)). In the next step, the sticky part of tattoo paper was attached on the finger and the printed sensor on the tattoo paper was placed on the sticky part. Finally, the sensor was transferred onto the skin by wetting the tattoo paper (Figure 5.2). The structure of the skin-device when the sensor is transferred onto the body is shown in Figure 5.1 d).

![Fabrication steps of strain sensor on tattoo paper](image_url)

**Figure 5.1: Fabrication steps of strain sensor on tattoo paper** a) tattoo paper in cleaned using air gun b) the sensor is printed on the tattoo paper substrate c) thin layer of PDMS is screen printed on the sensor d) the structure of skin-sensor after attaching onto the skin
5.2.3. Experiment Setup

The experiment setup is shown in Fig. 5.3. Printed strain sensors were mounted on the human finger. The resistive response of the sensor was then tested by bending the finger to different angles. The sensor was connected to an Agilent E4980A precision LCR meter with wires attached using a mixture of silicone and Silver (Protavic America) epoxy paste.

5.2.4. Results

5.2.4.1. Strain Sensor on the Tattoo Paper

The resistance of the fully printed strain sensors in both wavy and straight forms was measured after bending the finger to different angles including 10, 20, 30 and 40 degrees. Three
different sensors were tested for each configuration. Each sensor was subjected to three cycles of bending the finger to different angles and bringing it back to the original position. This test was repeated three times for each sensor. Figure 5.4 shows the change in resistance of the strain sensor (sensor 1) printed in a wavy form when it was subjected to the finger positions described. The base resistance of this sensor after mounting on the finger was measured as 255 kΩ. After bending the finger to 10, 20, 30 and 40 degrees in test 1 the resistance was increased to 265.6 kΩ, 275 kΩ, 284.6 kΩ and 295 kΩ, respectively which corresponds to 3.8 %, 7.5 %, 11.2 % and 15.3 % changes in the resistance of the sensor. In the next phase of the test the finger was moved back to 30, 20, 10 degrees and the original position (zero degrees) of the finger. The resistance of the sensor was decreased to 284.3 kΩ, 275.3 kΩ, 265.3 kΩ and 256 kΩ, which showed 11.6 %, 7.5 %, and 3.7 % changes in the resistance of the strain sensor. The base resistance was increased 0.2 % in comparison with the original resistance of the sensor. All Figures show the average of three cycles of bending the finger and bringing the finger back to the original position. After 20 minutes rest, the sensor was tested again by the bending of the finger. The base resistance for test 2 was measured as 250 kΩ. The finger was bent to 10, 20, 30, and 40 degrees and the resistance of the strain sensor was increased to 258.3 kΩ, 266.3 kΩ, 275 kΩ and 285.6 kΩ which corresponds to 3.1 %, 6.3 %, 9.8 % and 14.1 % changes when compared to the initial base resistance. Then it was progressively brought back to the original position, and for each step the resistance of the sensor was decreased to 274.3 kΩ, 265.6 kΩ, 258 kΩ and 250.7 kΩ which are equal to 9.5 %, 5.9 % and 3 % changes in the resistance of the strain sensor. The base resistance for test 2 was increased 0.2 % when the finger was brought back to the original position. The sensor was left in the rest position for 20 minutes and the same measurement was repeated for a third time. When the finger was bent to 10, 20, 30 and 40 degrees, the resistance was increased
from 256 kΩ to 265.2 kΩ, 275.3 kΩ, 285.6 kΩ, and 294.6 kΩ and when it was brought back to the original position the resistance was measured as 285.3 kΩ, 275.3 kΩ, 265.6 kΩ and 256.5 kΩ. This measurement showed 3.6 %, 7.3 %, 11.4 %, 14.9 %, 11.3 %, 7.3 %, and 3.6 % changes compared to the resistance of the wavy strain sensor at rest. The base resistance was increased 0.1 % after this test compared with the base resistance of the sensor. The average of each round of measurements is shown in Figure 5.4 for sensor 1. Figure 5.5 illustrates the percentage change in the resistance of the sensor at each degree of bending as compared with the base resistance.

![Resistive Response of the Strain Sensor Towards Bending of the Finger](image)

Figure 5.4: Resistive response of the sensor towards bending of the finger for different angles (Sensor 1).
Figure 5.5: Percentage change in the resistive response of the fully printed strain sensor towards bending of the finger for different angles (Sensor 1).

The same measurement was repeated for sensor 2 and sensor 3. The measured resistances as well as percentage change of the resistances are presented in Figures 5.6, 5.7, 5.8 and 5.9.

Figure 5.6: Resistive response of the sensor towards bending of the finger (Sensor 2).
Figure 5.7: Percentage change in the resistive response of the fully printed strain sensor towards bending of the finger for different angles (Sensor 2).

Figure 5.8: Resistive response of the sensor towards bending of the wrist (Sensor 3).
Figure 5.9: Percentage change in the resistive response of the fully printed strain sensor towards bending of the finger for different angles (Sensor 3).

Figures 5.10 and 5.11 represent the average of all the measurement on each sensor. For sensor 1, 3.5 %, 7 %, 10.8 %, 14.7 %, 10.6 %, 6.9 %, 3.4 % changes in resistance were observed for each step of the measurement. A 0.2 % change in the base resistance of the sensor was observed. In case of sensor 2, 4.8 %, 9.9 % 14.6 %, 19 %, 15.5 %, 10 % and 5 % changes were measured in response to the bending of the finger. The base resistance showed a 0.4 % increase when compared with the resistance of the sensor before bending. Finally, 3.9 %, 8.3 %, 12.4 %, 16.8 %, 12.4 %, 8.5 % and 4.3 % changes were observed in the resistance of the printed strain sensor 3 in response to bending the finger.

The changes in the resistance of the sensors between each step of bending were calculated and presented in Figure 5.12. Average changes of 3.66 %, 4.7 % and 4.18 % for each step were calculated for sensor 1, sensor 2 and sensor 3, respectively. All changes in the resistance of the sensor can be attributed to the effect of applied strain on the sensor due to the
Figure 5.10: Resistive response of the sensor towards bending of the finger for different angles.

Figure 5.11: Percentage change in the resistive response of the fully printed strain sensor towards bending of the finger for different angles.

bending of the finger. When a finger is in a bent position, the sensor is subjected to tensile strain that increases the resistance of the sensor. These changes can be used to predict the angle of bending of the finger when the change in the resistance is measured.
The strain sensor was printed on the tattoo paper in the form of a straight line to compare with the wavy structure. The sensor was subjected to the same test as the wavy sensor. Figures 5.13, 5.14 and 5.15 show the result obtained for the straight strain sensor. Sensor 1 tested towards bending of the finger. During the third round of measurement, sensor 1 was broken and it did not respond to the test after the second cycle of the third test. Sensor 2 and sensor 3 both showed failure during the second round of testing. Figures 5.16 and 5.17 represent the performance of sensor 1 (straight line). Changes of 4.8 %, 83.5 %, 12.3 %, 16.4 %, 12.3 %, 7.9 % and 3.6 % for each step were observed. The base resistance increased 0.4 % as compared to the base resistance prior to test 1. For test 2, changes of 3.5 %, 7.5 %, 12.5 %, 16.4 %, 12.3 %, 7.9 % and 3.6 % were observed. The sensor failed during test 3.

The wavy structure showed better performance in tolerating the repeatedly applied stress caused by bending of finger as compared with the straight line. This can be due to the fact that when the strain is applied on the wavy structure, the amplitude and wavelength of
the waves are changed, which results in better stretchability of the structure. Based on the results presented in the chapter 4, CNT ink showed a very good tolerance toward applied stress. On the other hand, wavy structures showed a better stretchability in comparison with the straight line. Combination of using wavy structure and mechanically strong and stretchable material (CNTs) has shown a promising performance for fabrication of stretchable strain sensors for body movement measurements.

Figure 5.13: Resistive response of the straight line sensor towards bending of the finger for different angles.
Figure 5.14: Resistive response of the straight line sensor towards bending of the finger for different angles.

Figure 5.15: Resistive response of the straight line sensor towards bending of the finger for different angles.
Figure 5.16: Resistive response of the straight line sensor towards bending of the finger for different angles (Sensor 1 in a straight form).

Figure 5.17: Percentage change in the resistive response of the fully printed strain sensor towards bending of the finger for different angles (Sensor 1 in a straight form).
5.2.4.2. Strain Sensor on PDMS

The strain sensor with a wavy structure (W=800 µm, r=2000 µm) was screen printed onto PDMS sheet with thickness of 254 µm using CNT ink. The picture of the fabricated sensor is shown in Figure 5.18. The sensor was tested similar to the strain sensor printed on tattoo paper, which was explained in section 5.2.4.1. The resistive response of the strain sensor towards bending of the finger is shown in Figure 5.19. The resistance of the sensor after mounting on the finger was 270 kΩ. After bending of the finger to 10°, 20°, 30° and 40° the resistance was increased to 276 kΩ, 282.6 kΩ, 292.6 kΩ and 301.6 kΩ which correspond to changes of 1.8 %, 4.2 %, 7.9 %, and 11.2 % in the resistance of the sensor compared with the base resistance. Then, the finger was brought back to the original position in steps of 10 °. The resistance was measured as 293 kΩ, 282.6 kΩ, 276 kΩ, and 271.6 kΩ. This showed changes of 8 %, 4.2 %, and 1.8 % in the resistance. The base resistance was increased by 0.2 % when compared with the original resistance of the sensor. This test was repeated three times and the result are illustrated in Figures 5.19 and 5.20. Sensor 2 and sensor 3 were subjected to the same measurement and the results are presented in Figures 5.21, 5.22, 5.23 and 5.24.

Figure 5.18: Photograph of the printed strain sensor on the PDMS (w=800 µm, r=2000 µm).
Figure 5.19: Resistive response of the sensor towards bending of the finger (Sensor 1 on PDMS).

Figure 5.20: Percentage change in the resistive response of the printed strain sensor towards bending of the finger for different angles (Sensor 1 on PDMS).
Figure 5.21: Resistive response of the sensor towards bending of the finger (Sensor 2 on PDMS).

Figure 5.22: Percentage change in the resistive response of the fully printed strain sensor towards bending of the finger for different angles (Sensor 2 on PDMS).
Figure 5.23: Resistive response of the sensor towards bending of the finger (Sensor 3 on PDMS).

Figure 5.24: Percentage change in the resistive response of the fully printed strain sensor towards bending of the finger for different angles (Sensor 3 on PDMS).
Figures 5.25 and 5.26 represent the average of all three measurements for each sensor. For example for sensor 3, the average of base resistance was measured as 272 kΩ. After bending of the finger 10, 20, 30 and 40 degree this resistance increased to 279.6 kΩ, 287.7 kΩ, 294.4 kΩ and 303.1 kΩ which correspond to changes of 2.6 %, 5.6 %, 8.2 % and 11.2 % in the resistance of the sensor. Then the finger was brought back in steps of 30, 20, and 10 degrees and the first position and the resistance was measured as 294.7 kΩ, 287.7 kΩ, 279.5 kΩ and 272.6 kΩ. This showed changes of 8.1 %, 5.6 %, 2.5 % and 0.1 % in the resistance of the sensor. The average change of 2.7 %, 2.2 % and 2.8 % between each step of bending was calculated for sensor 1, sensor 2 and sensor 3, respectively (Figure 5.27).

![Resistive Response of the Strain Sensor Towards Bending of the Finger](image)

**Figure 5.25:** Resistive response of the sensor towards bending of the finger for different angles.
Figure 5.26: Percentage change in the resistive response of the fully printed strain sensor towards bending of the finger for different angles.

Figure 5.27: Comparison of the percentage change of each step for different sensors.
Another group of Strain sensor (w=400 µm, r=4000 µm) was printed on PDMS as shown in Figure 5.28 using CNT ink. The sensor was mounted on the knee by help of the sticky part of tattoo paper. The strain sensor was subjected to movement of the knee (downward for 20 degrees and upward to original position) and the resistive response of the sensor was obtained. For this purpose, three different sensors were fabricated and tested. The results are presented in Figures 5.28, 5.29 and 5.30. The base resistance of sensor 1 after multiple downward and upward movements increased from 7.09 MΩ to 7.3 MΩ corresponding to a 2.9 % change in the resistance. The base resistance of the sensor showed a 0.1 % change in comparison with the original resistance (Figure 5.29). It was observed that the average resistance of sensor 2 increased from 8.34 MΩ to 8.50 MΩ, for multiple downward and upward movements, which corresponds to a 1.19 % change in the sensor response. The base resistance of the sensor increased for 0.2 % after multiple movements (Figure 5.30). The base resistance of sensor 3 when mounted on the knee was measured as 7.32 MΩ. After subjecting the sensor to downward movement of the knee this resistance was measure as 7.52 MΩ. The base resistance was increased to 7.36 MΩ which is equal to 0.5 % change in the base resistance of the sensor.

![Figure 5.28: Strain sensor printed on PDMS (w=800 µm, r=4000 µm).](image)
Figure 5.29: change in the resistive response of the fully printed strain sensor towards bending downward and upward of the knee (Sensor 1).

Figure 5.30: change in the resistive response of the fully printed strain sensor towards bending downward and upward of the knee (Sensor 2).
Figure 5.31: change in the resistive response of the fully printed strain sensor towards bending downward and upward of the knee (Sensor 3).

Sensor three remained attached for 6 hours on the knee. The response of the sensor towards bending of the knee was measured after 3, 4, 5 and 6 hours. The base resistance of the sensor increased to $9.2 \, \text{M}\Omega$, $9.4 \, \text{M}\Omega$, $10.6 \, \text{M}\Omega$ and $11.4 \, \text{M}\Omega$ after 3, 4.5 and 6 hours, respectively. For each test, again the sensor was subjected to downward and upward movement of the knee and the resistive response of the sensor was measured. An average change of 2.2 % in the resistance of the sensors was obtained due to downward and upward movement of the knee when the sensor was tested after 3 hours for each bending. Changes of 1.8%, 6.4 % and 10.1 % in the resistance compared to the base resistance were obtained after subjecting the sensor to downward and upward movement of the knee after 4, 5, and 6 hours, respectively. It was observed that even though the base resistance of the sensors changed after remaining attached on the knee for a few hours, the sensor was able to respond to the movement of the knee (Figure 5.32).
The strain sensor (horse-shoe design shown in Figure 5.28) attached on the knee was tested towards bending of the knee for different angles. The knee was bent 20, 40, 60 and 80 degree. The resistance increased further for different angle of bending applied on the sensor. Changes of 3.1 %, 5.2 %, 10.1 %, and 14.14 % in resistance were obtained in the first measurement. The based resistance decreased when the knee was brought back the original position. The same test was repeated again and changes of 3.3 %, 5.7 %, 10.9 %, and 14.6 % were observed (Figure 5.33).

![Response of the Sensor after 3,4,5, and 6 hours](image)

**Figure 5.32:** Performance of the sensor after 3, 4, 5 and 6 hours.
There is a report on fabrication of capacitive strain sensor using silver nano wires which was able to detect the bending of the finger (up to 50 % strain) [10]. The results presented in this section show the capability of printed strain sensor towards detection of the bending of finger and knee for multiple movement and bending. The silver nano wires show better conductivity compared with CNT, but for the applications such as strain sensor, the printed resistive sensors showed a very good performance and high tolerance towards applied strain.

5.2.4.3. Strain Sensor on PVA

The sensor, in a wavy shape having 800 μm line width and overall dimension of 3 cm × 0.4 cm, was screen printed using CNT ink (SWeNT CV100) on a water-soluble polymer based PVA substrate (Watson QSA 2000) (Figure. 5.34(a)). The CNT ink was cured in a VWR oven at 100 ºC for 10 minutes. The skin was wetted and the printed sensor was mounted on the left forearm (Fig. 5.34(b)). The sacrificial PVA layer was then washed away using water and the
sensor transfer onto the skin was complete. The average thickness of the printed CNT layer was measured as 5.6 μm using a Bruker Contour GTL EN 61010 profilometer (Figure. 5.35). An Agilent E4980A precision LCR meter was used for recording the change in the resistance of the sensor due to flexion and extension movements of the elbow. It was observed that the average resistance of the sensor increased from 32.8 kΩ to 36 kΩ for multiple flexion and extension movements of the elbow, which corresponds to a 10 % change in the sensor response (Figure 5.36). In addition, a 2 % change in the base resistance of the sensor was observed, when the elbow was brought back to the original position after 10 cycles. A high possibility of failure in performance of the sensors was observed after mounting directly on the skin. The thickness of the printed sensor is 5.6 μm and when it is transferred on the human body, a high chance of breakage was observed due to the roughness of the skin. The yield of functional sensors that were directly mounted on the skin was below 10 %. As the author explained before in this chapter, as an alternative method for fabrication of printed body movement sensors, it seems promising to fabricate the sensor on the thin layer of substrate and then transfer it onto the skin.

Figure 5.34: Screen printed stretchable sensor: (a) on PVA substrate, and (b) after transferring onto the forearm.
5.2.4.4. Temperature Sensor on PDMS

The resistive temperature sensor in a wavy form with W=800 µm and r=2000 µm was printed on the PDMS using CNT ink. The printed CNTs were then cured in the oven for 10 minutes at 100 °C. Interconnects were printed in wavy form using Ag ink on the TPU substrates and were attached to the sensor using a mixture of silicone and Silver (Protavic America). Printed Ag ink showed a resistance of 0.8 Ω. Due to the much smaller resistance of interconnects, no change was
observed in the resistance of the sensor after attaching it to the interconnect lines. The picture of the fabricated sensor along with interconnects is shown in Figure 5.37. The effect of temperature on the printed temperature sensor was investigated. The change in resistance was obtained by increasing and decreasing of the temperature from 25 °C to 50 °C in steps of 1 °C and vice versa using a hot plate, which is shown in Figure 5.38. The initial resistance of the sensor was measured as 474 kΩ. Results of this test yield a linear relationship between resistance and change in temperature. It was observed that the resistance of the sensor decreased about 0.36 % when the temperature was increased by 1 °C. In a separate test the effect of increasing and decreasing the temperature on another sensor (R₀=575 kΩ) was investigated. The average of the change in the resistance of the sensor by changing the temperature is shown in Figure 5.39, which is equal to 0.33 %. The temperature sensor showed an approximate sensitivity of 2 kΩ per °C.

After stand-alone testing, the sensor was transferred onto skin and was exposed to hot air using a hair dryer. Three sensors were exposed to hot air for 10 seconds and the resistance of the sensors was recorded 3 seconds after removal of the hot air. Figure 5.40 presents the results obtained for these sensors. The results show averages decreases in resistance of 1.68 %, 1.44 %, 1.49 % for sensor 1, 2 and 3 respectively, which is indicated by average 3.7 °C, 4 °C and 4.5 °C increases in the temperature. Before and after exposing the sensor to hot air, the skin temperature was measured using an infrared thermometer which showed a temperature increase of 4 °C, 3.83 °C and 3.77 °C.

The temperature coefficient of the material is defined as the amount of change in the resistance as a function of change in the temperature, which can be calculated using the formula below

\[ R_{new} = R_{old} (1 + \alpha \Delta T) \]
Where the $R_{\text{old}}$ is the original resistance, $R_{\text{new}}$ is the new resistance after a change in the temperature; $\Delta T$ is the change in the temperature, and $\alpha$ is the thermal coefficient of the resistor. In this work the thermal coefficient of the sensor was measured to be 0.36 and 0.33 °C$^{-1}$.

Figure 5.37: Photograph of printed temperature sensor attached on the shin

![Photograph of printed temperature sensor attached on the shin](image)

Figure 5.38: Resistance of the sensor versus temperature and the computed linear response using linear regression method.

![Graph showing change in resistance vs. change in temperature](image)
Figure 5.39: Resistance of the sensor versus temperature and the computed linear response using linear regression method.

Figure 5.40: Resistance vs heat transferred on the skin.
As a final test, the sensor was attached onto human skin and the change in the temperature after eating spicy food by the wearer was analyzed. The food was covered with blazin sauce which contains habanero peppers. This pepper has a scoville heat unit of 100K-350K which is categorized as a hot and spicy food. After eating any type of food, for maintaining the body temperature some amount of heat will be released which causes a change in the temperature of skin [11]. The body temperature was measured using a thermometer before and after eating the food as 29.2 °C and 31.4 °C, respectively. The resistance of the sensor decreased from 480 kΩ to 475.4 kΩ (Figure 5.41) which shows a change of 0.95 % in the resistance. This change indicates a 2.6 ° increase of the temperature. This change can be compared to the 2.2 °C increase when measured with the thermometer. One potential difference in measured temperatures using the printed sensor and a thermometer may be due to the lack of proper attachment of the sensor to the skin. Another factor might be changes in the resistance of the sensor resulting from moisture on the skin due to sweating after eating spicy food. This moisture can affect the properties of CNTs and make slight changes in the resistance of the printed sensor.

![Resistance vs Temperature](image)

Figure 5.41: Change in the temperature after eating spicy food measured by resistive sensor.
5.2.4.5. Electrocardiogram Sensor (ECG)

A mixture of silicone and Silver (EXP-06335 from Protavic America) was prepared and screen printed on a PDMS substrate to fabricate ECG measurement pads. The picture of printed pads is shown in Figure 5.42 a). After deposition of the mixture it was cured in the oven for 40 minutes at 100 °C. It was observed that the printed ECG pads showed a very good adhesion on the PDMS. The thickness of the printed pads was measured using a Bruker vertical scanning interferometer microscope (CounterGT) as 32 µm as shown in Figure 5.42 b).

Figure 5.42: a) Photograph of printed ECG pads on the PDMS b) 3D vertical scanning interferometer images of Pads.
In order to obtain an ECG signal, three identical sensors were placed on the left hand, right hand and right leg of a healthy volunteer (35 years old). In the next step, the printed pads were connected to the data acquisition device, which had been previously developed. The active electrode, AC coupler, instrumentation amplifier, driven right leg amplifier (DRL), and active filter were used for recording the ECG signal. The active electrodes include two input buffers and two resistors for providing the high impedance input for the instrumentation amplifier. An AC coupler including bio potential amplifier and an Analog Devices INA 2128 chip was employed as the instrumentation amplifier. The feedback to achieve a high common mode rejection ratio (CMRR) was provided to the human body by the DRL amplifier, which consisted of a two stage amplifier. In order to record the ECG signals the ECG pads were connected to a Tektronix TDS 5104B Digital Phosphor Oscilloscope. A notch filter was used to eliminate 60 Hz power line interference. A schematic of the setup is presented in Figure 5.43. The obtained ECG signal is shown in Figure 5.44 a). Next, the ECG pads were connected close to the left and right shoulders on the chest and the third electrode was connected to lower-left edge of the rib cage. The ECG measurement obtained is shown in Figure 5.44 b). For the third measurement, the ECG electrode from the lower-left edge of the rib cage was removed and attached onto the right leg. The ECG signal recorded is shown in Figure 5.44 c).
The heart cells are polarized. The inside of heart muscle cells are negatively charged and the exterior of the cells are positively charged. Depolarization and repolarization of these cells lead to muscle contractions that circulate blood throughout the body. When some of the positive ions move through the membrane, this decreases the potential difference between exterior and interior of the heart muscle cells which results in depolarization. After depolarization, positive ions move back to their first position and increase the potential difference between exterior and interior of the heart muscle cells, which causes repolarization. In ECG signals, P-wave illustrates the depolarization of the two atrium chambers of the heart. The Q, R and S waves are used to characterize the depolarization of the two ventricle chambers of the heart. The T wave shows the repolarization of the two ventricle chambers. In the measured ECG signals obtaining, it was possible to identify the typical ECG characteristic components, which include the QRS complex and the T-wave (Figure 5.44) [12].
Figure 5.44: ECG signals obtained for a) Left hand, right hand and right leg b) chest close to left and right shoulders and lower-left edge of the rib cage c) chest close to left and right shoulders and right leg.

All three types of sensors developed; strain, temperature and ECG; can be printed onto PDMS to be used as a multi-functional wearable sensor to detect the movement of the body, temperature of the skin, and ECG signal. A picture of the resulting device is presented in Figure 5.45

Figure 5.45: Picture of multi-functional wearable sensor fabricated on PDMS
5.3. Summary

In this chapter, the author presented an introduction that discusses the importance of developing a fully printed, flexible and stretchable sensing system that can be mounted onto the skin. A detailed account of the experimental tasks involved in this work including chemical, materials, and different sensors fabricated and tested was presented.

To summarize, screen printing techniques were employed to fabricate fully printed strain sensors. Different methods were tested for transferring the device onto the skin including printing the sensors on tattoo paper, PDMS, and PVA as well. CNT ink was used for fabrication of sensors while silver ink was employed for the printing of interconnects. The printed sensors on the tattoo paper were attached on the finger and were subjected to finger bending at angles of 10°, 20°, 30° and 40°. For sensor 1, changes in resistance of 3.5 %, 7 %, 10.8 %, 14.7 %, 10.6 %, 6.9 %, 3.4 % were obtained for each step of the measurement. A 0.2 % change in the base resistance of the sensor was recorded. For sensor 2, 4.8 %, 9.9 %, 14.6 %, 19 %, 15.5 %, 10 % and 5 % changes were observed in response to the bending of the finger. The base resistance showed a 0.4 % change when compared with the base resistance of the sensor. Finally, 3.9 %, 8.3 %, 12.4 %, 16.8 %, 12.4 %, 8.5 % and 4.3 % changes were measured in the resistance of the printed strain sensor 3 in response to bending the finger. Average changes of 3.66 %, 4.7 % and 4.18 % for each step were calculated for sensor 1, sensor 2 and sensor 3, respectively. Also, the strain sensor printed on PDMS was mounted on the skin and tested by bending the finger. The average change of 2.7 %, 2.2 % and 2.8 % between each step of bending was calculated for sensor 1, sensor 2 and sensor 3, respectively. The printed strain sensor on the PMDS was placed on a knee and the response of the sensor towards downward and upward movement of the knee.
was recorded. Changes of 2.9 %, 1.19 % and 2.7% in the resistance of the sensor were observed after each movement of the knee.

A resistive temperature sensor was printed using CNT ink on PDMS substrates. A mixture of silver and silicone was used as a metallization layer for fabrication of ECG sensors. One of the most important challenges that the author was able to overcome in this chapter was the deposition of conductive material on the PDMS. The mixture of silver and silicone as well as CNT ink showed proper adhesion on the surface of PDMS. The effect of exposing the temperature sensor to the hot air was tested. The sensitivity of the temperature sensor was measured as 2 kΩ °C⁻¹. A strain sensor was also printed on PVA as a sacrificial layer. After printing it was transferred onto the skin and the PVA was washed away using water. A high chance of breakage in the sensor was observed due to roughness of the skin. The yield of functional devices transferred onto the skin was below 10 %. The mixture of silver and silicone was used as a metallization layer for fabrication of ECG pads. These ECG pads were placed on the human skin and the ECG signals were successfully obtained.

In the following chapter, the author concludes this dissertation with a summary of the projects performed and also provides some suggestions for possible future work.
5.4. References


CHAPTER VI

CONCLUSION AND FUTURE WORK

6.1. Conclusion

Through this dissertation work, the author has successfully described and demonstrated the fabrication of printed electronic circuit boards and established a method for the attachment of electronic components on the printed lines. The author has demonstrated designs and design techniques for the fabrication of flexible, stretchable conductive lines and sensing devices. And, extended this work, the ability of conventional printing technologies to be utilized for the fabrication of multi-functional stretchable and wearable sensing systems for health monitoring applications was demonstrated. The accomplishments of each of the three research projects are listed below:

In the first project, the author successfully fabricated multi-layer electronic circuit board on paper, glass and PET using the screen printing methodologies. The design of the board consists of an LCD, microcontroller and other necessary components. Silver ink was used as a metallization layer and a dielectric ink was printed between top and bottom layer to prevent electrical shorting. The widths of the printed lines were measured with an ImageXpert (KDY Inc.) image analyzer. The maximum gain was measured on PET as 7.6% and the maximum loss was measured on paper as −13.3%. The effect of the substrate roughness on the resistance of the printed lines was analyzed. The lowest resistance of 1.06 Ω was obtained for the 600 μm lines printed on paper. The effect of the resistance of the lines on the performance of the circuit was determined. It was observed that the resistance of all lines was below 10 Ω which would not affect the functionality of the circuit. The effect of bending of the substrate on the resistance of
the printed lines was also tested. After 10,000 cycles of 5-mm elongation a negligible change in
the resistance was obtained. A method for attachment of electronic components onto the printed
PCB pads was established and demonstrated. The author also tested the capability of the printed
PCBs toward driving an LCD display. The preloaded software executing on the microcontroller
generated a graphic message (CAPE) on the LCD. Based on the results obtained, the author
showed the capability of the printing methods for manufacturing of multi-layered hybrid
electronic circuit boards and electronic systems.

In the second project, the author designed and fabricated different forms of wavy lines
using screen printing to analyze the effect of stretching test on them and determine the best
configuration. The design of wavy lines were divided into three groups 1) wavy lines with two
half circle connected to each other, 2) wavy lines having extended lines between two half circles
and 3) a horse-shoe design. Silver and CNTs were used for printing of the wavy lines on TPU as
a stretchable substrate. Different configurations were subjected to multiple displacements and
changes in the resistance of the lines were recorded. Different dimensionless design parameters
such as the ratio of the width of the lines to their radius (W/r) and the length of the extended line
to the diameter of the arc (L/D) were analyzed. The lower W/r ratio lines show better
stretchability and less change in the resistance when they were subjected to the strain. It was
observed that if the ratio of L/D is below one the lines show better stretchability. The effect of
the thickness of the lines on the stretchability was also analyzed. The printed lines having three
layers of silver ink showed better performance compared with one layer and two layers. The
change in the resistance of the lines (L/D=3/4) printed using CNTs were below 35 % when 50 %
strain was applied on the lines, while the silver printed lines having the same design parameters
showed 40 % change in the resistance when 10 % strain was applied. The results obtained
demonstrated that wavy lines having extended line segments between two semi-circles have better stretchability. In addition, CNTs demonstrated a better capability in comparison with silver to be used for the fabrication of stretchable electronic devices.

In the third project, the author successfully fabricated a novel, fully printed, stretchable sensor for strain, temperature, and ECG measurements using screen printing. The sensor was successfully printed on a PDMS, as well as tattoo paper, using CNTs for strain and temperature and mixture of silver and silicone for ECG electrodes. The sensor printed on tattoo paper and PDMS was subjected to bending on a human finger to angles of 10, 20, 30 and 40 degree. The resistive response of the sensor demonstrated average changes in resistance of 3.66 %, 4.7 % and 4.18 % for each step for sensor 1, sensor 2 and sensor 3, respectively, on tattoo paper. For the sensor printed on PDMS the average changes observed were 2.7 %, 2.2 % and 2.8 % between each step of bending for sensor 1, sensor 2 and sensor 3, respectively. PVA was used as a sacrificial layer to help transfer the sensor directly onto skin. The yield of the fabricated devices using the sacrificial layer was below 10 %. The ECG pads were placed on the skin and ECG signals were successfully observed and recorded. The author thus demonstrated the feasibility of employing traditional printing techniques for the fabrication of flexible, stretchable, multi-functional wearable sensors.

6.2. Future Work

The author believes that there are several possibilities and opportunities to improve upon the current projects. Some suggestions for future work are now discussed.

- **Screen Printing of Multi-Layered Hybrid Printed Circuit Board (PCB) on Different Substrates:** Alternate conductive materials, such as copper, can be used for printing PCB traces and tested for lower resistance and better performance. This may also aid in lowering
the cost of printed PCB fabrication. The effect of encapsulation on the performance of printed PCBs can be analyzed. Alternative substrates such as poly imide can be used for manufacturing the PCBs. Finally, the printed PCB can be fabricated using stretchable lines and the effect of the applying strain on the performance of the PCBs, including component attachment, can be tested. Combining a flexible, stretchable PCB with wearable sensors would allow a complete sensor system to be attached to a human body.

- **Design, Fabrication and Analysis of Printed Wavy Lines:** The material used in this work for printing wavy lines could be replaced by other functional inks such as copper, gold, platinum, or nickel and tested for performance. Different line widths, especially thinner lines, could be printed and tested, allowing optimization for material cost, resistance, and other performance characteristics. Both gravure and flexo printing techniques could be employed to fabricate the wavy structures. The wavy line using CNTs can be printed on PDMS with different thicknesses to analyze the effect of the substrate on the stretchability of the lines. Encapsulation of the wavy lines could help reduce the applied stress on the line. A thin layer of spin coated PDMS or poly imide could be used for encapsulation of the wavy structures.

- **Fabrication of Wearable Sensors Using Printing Methods:** The effect of encapsulation on the performance of the strain sensor should be investigated. As an alternate configuration, an array of sensor could be fabricated for strain mapping on the body. The use of alternate materials such as platinum could be used for printing the temperature sensor. An array of sensors could be printed for temperature mapping on the skin. ECG signals could be obtained during physical activates to investigate the effect of body motion on the performance of the sensors. A thicker layer of CNT may be printed on the PVA to analyze the effect of the line thickness on the functionality of the sensor after transferring directly onto skin.
• **Wearable Sensors Systems:** Combining printed, flexible and stretchable PCBs with appropriate stretchable line interconnects to wearable sensors would allow a complete monitoring system to be mounted on an individual and wirelessly transmit vital signs and condition to nearby receivers. This system can be consisted of strain, temperature and ECG sensors. Such systems could readily support both military and medical applications, where untethered monitoring can provide continuous measurements during physical activity or patient transfers.
APPENDIX A

LIST OF PUBLICATIONS

A1. Inventions


A2. Journal Papers


investigation of electron transfer between thiol functionalized viologen and gold clusters”,


A3. Conference Papers


