Development of Strain and Pressure Sensors on Flexible and Stretchable Platforms

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DEVELOPMENT OF STRAIN AND PRESSURE SENSORS ON FLEXIBLE AND STRETCHABLE PLATFORMS

by

Mohammed Mudher Mohammed Ali

A thesis submitted to the Graduate College
in partial fulfillment of the requirements
for the degree of Master of Science in Engineering
Electrical and Computer Engineering
Western Michigan University
June 2016

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DEVELOPMENT OF STRAIN AND PRESSURE SENSORS ON FLEXIBLE AND STRETCHABLE PLATFORMS

Mohammed Mudher Mohammed Ali, M.S.E
Western Michigan University, 2016

The capability of the human brain to operate in conjunction with human senses and muscles enables us to become powerful autonomous beings. By using these organs, humans can interact with the surrounding environment. Similarly, the combination of sensors with the signal processing of modern electronics enables the interaction with the non-electrical environment.

In this thesis, the work focuses on the design and fabrication of flexible and stretchable sensors which have been receiving an increased interest for applications such as human body movement, tracking in the biomedical industry, object detection, fingerprint sensor as well as for monitoring deformations or structural changes in civil infrastructural assets. This thesis is organized in two projects.

In the first project, a printed strain sensor was successfully fabricated, based on a metal-metal composite based strain sensor on a flexible and stretchable thermoplastic polyurethane (TPU) substrate. A silver nanowire (Ag NW)/Ag flake composite ink was screen printed on the TPU substrate as the metal-metal composite. Silver nanowires were chosen as the stretchable filler because of its ability to maintain electrical conductivity under tensile strains. A silver flake was chosen due to its viscous nature (12 Pa.s) and good adhesion properties, and both materials are compatible with the screen printing process. The capability of the fabricated strain sensor was demonstrated by investigating the electro-mechanical response to elongations of 1 mm, 2 mm and 3 mm.

In the second project, a novel flexible capacitive pressure sensor was successfully developed for detecting applied pressure. The sensor was fabricated by creating PDMS based electrode channels that were filled with Eutectic Gallium-Indium (EGaIn) liquid metal. The master molds for the electrode channels were manufactured using conventional PCB technology. Then two separate PDMS layers were bonded together by
corona discharge treatment, at room temperature and atmospheric pressure before the liquid metal is injected. The capability of the fabricated pressure sensor was demonstrated by investigating the capacitive based response of the device for varying applied pressures, ranging from 0.25 MPa to 1.1 MPa.
ACKNOWLEDGEMENTS

First and foremost, I would like to express my deepest appreciation and gratitude to my Committee Chair and advisor, Prof. Massood Atashbar, Director of the Center for Advanced Smart Sensors and Structures, for his continuous support and encouragement of my master study and research, and for his patience, motivation, enthusiasm, and immense knowledge. His guidance and vast knowledge helped me during all the time of research and writing of this thesis. I really appreciate his confidence and trust in my knowledge and abilities. I could not have imagined having a better advisor and mentor for my master study.

My sincere thanks also go to all the members on my committee, Dr. Bradley J. Bazuin and Dr. Margaret K. Joyce for their encouragement, insightful comments, and support of my thesis.

I also would like to thank Dr. Paul D. Fleming for his valuable time spent with me to clear my doubts and for his guiding my research. His valuable feedback contributed greatly to this thesis.

I owe a large thanks to Mr. David Florida of the Department of Electrical and Computer Engineering, Mr. Matthew Stoops of the Department of Chemical and Paper Engineering and Mr. Glenn Hall of the Department of Mechanical and Aeronautical Engineering, at Western Michigan University, for their help in providing technical support with the instruments used throughout the work of this thesis.

Many thanks to my fellow lab members, Dr. Binu Baby Narakathu, Dr. Ali Eshkeiti, Dr. Sai Guruva Reddy Avuthu, Amer Chlehaiwi, Sepehr Emamian, Farah Aljanabi, Zeinab Ramshani and Dinesh Maddipatla for their advice and great support in the Sensors Technology Laboratory (STL), the Center for Advanced Smart Sensors and Structures (CASSS) and the Center for the Advancement of Printed Electronics (CAPE).

Also, I want to thank everyone in the Electrical and Computer Engineering (ECE) Department, Chemical and Paper Engineering (ChP) Department for the support and all resources provided to me during the course of this thesis work.

Last but not least, I would like to give love and thanks to my parents, Prof. Mudher and Dr. Shatha, and the rest of my family and friends. Furthermore, I wish to thank my wife for her patience and encouragement, which was needed for me to reach
this point of my life. I would like to extend special thanks to my sister in law Ms. Noor Aljanabi for her immeasurable support.

Mohammed Mudher Mohammed Ali
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CHAPTER I

INTRODUCTION

1.1 Motivation

The idea of sensing is as old as life itself, humans experience sensing every day. Humans’s sensory organs interact with the surrounding environment and transform sensory input into stimuli that allow us to act and react. Depending on the stimuli, it may warn us of danger, discomfort or allow us to do some activity [1]. However, this sensory system has natural limitations, involving both the presence of a person and the ability of human nervous system to receive and analyze particular phenomenon [2]. Researchers are trying to gain more insight and understanding of the world around them by searching deeper into its physical nature. However, due to limitations of our senses, there is a great need for new devices, sensors, which could help in continuing our quest. Examples of sensors include: the infrared sensor which can interact with colors beyond the ability of human eyes; an ultrasound sensor which has the ability to communicate with sounds that are considered higher than the human ear’s capability [3]; and antennas which allow us to listen to deep space.

The rapid evolution of sensors has led the author to investigate the design and development of strain sensors, which have been gaining an increased interest for various applications such as health tracking devices in the biomedical industry [4], hydration sensors [5] as well as for monitoring deformations or structural changes in civil infrastructure and assets [6]. Generally, there are different materials which are used to fabricate strain sensors, for instance by depositing metal layers such as gold (Au) [7], polymer such as Carbon nanotubes (CNTs) [8], metal-polymer composites such as ionic polymer/metal composites (IPMCs) [9] as well as polymer-polymer composites such as polymer nanocomposite with multiwalled carbon nanotube (MWNT) [10].

Recent achievement in the field of printed electronics (PE) has demonstrated the development of flexible and stretchable electronic devices for applications in the wearable devices [11] and the robotics industry [12], and for monitoring temperature [13], electrocardiogram (ECG) [14] and electroencephalogram (EEG) [15].
The advantages associated with PE material deposition using inkjet [16], gravure [17], flexography [18] and screen printing [19], include additive manufacturing techniques that reduce the wastage of materials and low manufacturing temperatures in comparison to silicon based technology, which often involves photolithographic patterning techniques along with high-vacuum and high-temperature deposition processes. In addition, these devices cannot be mounted on the body for a long time due to their rigidity. Therefore, the development of printed strain sensors on flexible and stretchable substrates is bound to have a significant impact in the field of wearable electronics.

In this era of industrial modernization, pressure sensors have also been a longstanding aim of researchers in several applications such as object detection [20], tactile sensing for mechatronics [21] and aerospace implementations [22]. There are three main kinds of pressure sensors [23]: piezoelectric [24], piezoresistive [25], and capacitive pressure sensors [26]. The capacitive pressure sensor has been receiving more attention due to its capability to provide a stable and repeatable response along with its low sensitivity to both temperature and humidity [23]. Typically, the sensitivity of a capacitive pressure sensor depends on the amount of capacitance change under applied pressure. The magnitude of the capacitance change is measured based on changes in the dielectric constant, the thickness of the dielectric layer and the surface area of an electrode [23].

There have been different flexible materials used to design pressure sensors such as PDMS [27] and Ecoflex [28]. To allow permanent bonding of the polymer surfaces, studies have shown various techniques can be used, including oxygen plasma treatment [29], heating in a standard microwave oven [30] and corona treatment [31]. Recently, the development of stretchable interconnects has been shown using liquid metal such as Gallium based alloys [32], eutectic Gallium-Indium [33] and Mercury [34]. These results have produced a considerable interest for flexible electronics due to potential sensor softness, durability, and conductive retention during stretching and bending tests. There are several methods for patterning Ga-In depending on the applications of the sensor [32], such as lithography e.g. photolithography [35], injection [36], vacuum filling [37], laser and patterning [38] and direct write [39]. With the remarkable interest that liquid metal has been gaining in recent years, the author was interested to explore the
potential of using stretchable substrate along with liquid metal to manufacture a pressure sensor.

1.2 Author’s Contributions

The author’s research work has resulted in two conference publications (one published and one submitted) and three high quality peer-reviewed journal publications (one submitted and two in progress for submission). The publications directly related to the research performed for this thesis have been marked with “*”. The author was also awarded the Leaders Advancing and Helping Communities (LAHC) Award for 2015-2016.

Journal Papers:

Conference Papers:

1.3 Thesis Organization

In this thesis, the author presents in details two research projects that were performed during the course of his master studies. The first project includes the development of printed flexible and stretchable strain sensor that employs traditional screen printing technology, based on metal-metal composite of silver nanowire (AgNW) / silver (Ag) flake on thermoplastic polyurethane (TPU) substrate. The second project, the author developed a flexible capacitive pressure sensor based on polydimethylsiloxane (PDMS) substrate and eutectic Gallium- Indium (Ga-In) liquid metal, along with traditional printed circuit board (PCB). The rest of the thesis is organized in five chapters.

Chapter 2 includes an introduction to sensors as well as their various types, working principles and characteristics. Chapter 3 discusses an introduction to different printing techniques which are used in the fabrication of electronic devices with emphasis on the importance of screen printing technology. Chapter 4 provides a detailed description of the development of printed, flexible and stretchable strain sensor based on screen printing. Two configurations, straight and wavy lines, were designed and fabricated using a metal-metal composite of (Ag NW) / Ag flake. The capability of the fabricated strain sensor was demonstrated by investigating the electro-mechanical response obtained for various elongations tests. Chapter 5 presents the development of flexible pressure sensor along with the use of conductive liquid metal (Ga-In). This includes the design and fabrication of the pressure sensor. The experimental setup, testing and results obtained are also described. Chapter 6 deals with the conclusions for this work as well as suggestions for future work.
1.4 References


CHAPTER II
INTRODUCTION TO SENSORS

2.1 Introduction

In this chapter, the basic concepts and definitions of a sensor are introduced with their types and characterizations. The past several years have brought a tremendous rise in the visualization of sensors, along with a significant increase in terms of the number of applications [1]. A sensor is a device that converts energy, which is derived from a physical phenomenon (non-electrical input) such as heat, light, sound, pressure, etc. into an appropriate electrical signal output. Sensors provide the interface between the real world and the electronic circuit [2].

Humans are always attempting to increase their capabilities. In the beginning, they increased their mechanical powers by inventing new things such as the steam engine, combustion engine, and electrical motor, which leads to the industrial revolution of the mechanization. Next, they tried to increase their brain capabilities by inventing the computer and the internet which are developing more and more every day without predicting the end result of this revolution. The third important invention was sensorization, humans are knowing how to artificially increase their senses. The third industrial revolution of full automation and robotization will be brought by combing mechanization, information and sensorization as shown in Figure 2.1 [3].

Figure 2.1: History of Industrial Automation [3].
Advanced Safety Vehicles (ASV) which were developed by Nissan, is a good example of a vehicle that has various sensors, information and actuators altogether combined in one system [4]. This car is equipped with different types of sensors to improve the safety levels for all passengers. Outside the vehicle, there are different sensors which perform different tasks such as an emergency braking advanced advisory system which includes a microwave, ultrasonic and infrared measuring sensors to activate the break light indicator during the emergency to give attention to the driver to take an action. Also, it may have an adaptive cruise control system that decreases the car’s speed automatically to leave a suitable distance for safety purposes. For night driving, there is a pedestrian monitoring system that detects and notifies the driver to the presence of pedestrians. Moreover, inside the vehicle, there are some sensors such as a drowsiness warning system, drowsiness relieving system, driver head inclination detector and tire air pressure sensor detector. The whole system of mechanics, computers and sensors allow the car to drive on autodriver.

Sensors can be classified according to the conversion principle, the quantity being measured, the technology that is used or the application. Typically, sensors may be operated either passively or actively according to the signal conditioning viewpoint [2,5]. A sensor that requires an external source of excitation is called an active sensor such as a thermistors and resistive strain gage pressure sensor, without the external excitation potential, there is no output from the sensor. On the other hand, a passive sensor generates its own energy or derives it from the phenomenon being measured, so that there is no need for external power supply, such as thermocouples, photodiodes and piezoelectric. Table 2.1 [6] shows some examples of the typical sensors and their outputs according to the types of the input.

There is another way to classify sensors according to the simplicity and complicity of the output [4]. A direct sensor can be characterized as a simple sensor that can convert the stimulus excitation into an electrical signal by the physical effect, whereas a complex sensor requires additional transducers before performing the same operation. Furthermore, sensors can be categorized depending on the selected reference, into Absolute and Relative. An absolute sensor can sense the stimulus in reference to an absolute physical scale which is independent on the condition of measurement such as an
absolute pressure sensor which provides signal in reference to vacuum (an absolute zero on a pressure scale). Whereas, a relative sensor generates a signal which is related to specific case such as a relative pressure sensor which produces a signal with respect to a specific baseline (non-zero pressure as the atmospheric pressure).

Table 2.1 Examples of Some Sensors and their Outputs [6].

<table>
<thead>
<tr>
<th>Property</th>
<th>Sensor</th>
<th>Input type (Active/Passive)</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceleration</td>
<td>Accelerometer</td>
<td>Active</td>
<td>Capacitance</td>
</tr>
<tr>
<td>Temperature</td>
<td>Thermocouple</td>
<td>Passive</td>
<td>Voltage</td>
</tr>
<tr>
<td></td>
<td>Silicon</td>
<td>Active</td>
<td>Voltage/Current</td>
</tr>
<tr>
<td></td>
<td>RTD</td>
<td>Active</td>
<td>Resistance</td>
</tr>
<tr>
<td></td>
<td>Thermistor</td>
<td>Active</td>
<td>Resistance</td>
</tr>
<tr>
<td>Light Intensity</td>
<td>Photodiode</td>
<td>Passive</td>
<td>Current</td>
</tr>
<tr>
<td>Position</td>
<td>LVDT</td>
<td>Active</td>
<td>AC Voltage</td>
</tr>
<tr>
<td>Force/ Pressure</td>
<td>Strain Gauge</td>
<td>Active</td>
<td>Resistance</td>
</tr>
<tr>
<td></td>
<td>Piezoelectric</td>
<td>Passive</td>
<td>Voltage</td>
</tr>
</tbody>
</table>

2.2 Sensing Systems

A sensor is a device that detects or measures a physical stimulus such as heat, light, pressure, sound or motion, and converts it to an electrical signal. Transducer is another term that is related to the sensor, it can be defined as a device that converts energy from one form to another form. The difference between sensors and transducers is that sensors perform a transducing action, and the transducers sense some physical quantity [7]. Whereas, an actuator can perform as well as sensor but in the opposite way, by converting the signal which is usually electrical to another action such as mechanical output. Therefore, sensors and actuators are forms of transducers [8].

As an example, when considering the system in Figure 2.2 [7], the power supply is connected to the sensor, modifier and transducer. The sensor is used as a modulating
sensor. In such a sensor, an energy flow supplied from the source which is the power supply, is modulated by the measurand such as a photoconductive cell. The cell will respond to the energy from the input light, but it cannot produce a usable signal without the energy of the power supply. Applying a voltage and analyzing the resulting current will produce the signal. There is no need for the power supply if the sensor is self-generating such as a photodiode, due to the effect of the photovoltaic that stimulates the photodiode to generate voltage by itself. For instance, the photovoltaic effect can convert the radiant energy into an electrical signal. The modifier is used to modify the signal such as amplifying the small electrical signal or converting the analog to digital signals. For the transducer part, the digital signal is converted into a radiant signal by using a light emitting diode display panel as an example. Therefore, there is a possibility to read, analyze and discover the properties of the radiant signal visually.

Figure 2.2: General Measurement System [7].

The output signals from most sensing elements are low level and it may be subjected to different signal interfacing sources, as shown in Figure 2.3 [9]. Therefore, electrical output signals are preferred for most measurement devices. Self-generating sensors such as piezoelectric sensor which do not require a secondary source to generate an output signal. However, non-self-generating sensor such as sensors based on resistive and capacitive sensing elements require a secondary excitation signal to produce an output signal.
Figure 2.3: A Generalized Model of Transducer [9].

After the development of the microelectronics technology, smart sensors have been introduced by combining the function of sensors and their interfaces in one design. These functions include sensing, analog to digital conversion (ADC), signal conditioning, data processing and bus interfacing. For instance, considering the smart office building which offers a high level of automation. As shown in Figure 2.4, the building requires the interconnection of several systems [9]. In offices, any changes in the environment can be captured by the sensing nodes, which send the status and a control message to other nodes. Power nodes open or close dampers, change fan speed and make other adjustments based on the available information. In addition, there are other aspects of these systems such as self- diagnostics, fire detection, data logging, sprinkler systems and security monitoring.
Figure 2.4: Office/Building Automation.

2.3 Types of Sensors

The conversion of energy from one form to another is key to the classification of sensors. Therefore, it is useful to consider the various forms of sensors such as temperature sensors, pressure sensors, mechanical sensors, chemical and biological sensors, acoustic sensors and optical sensors. The major types of sensors are discussed in this section.

2.3.1 Thermal Sensors

Thermal sensors depend on the change that occurs in materials as their temperature change. In thermal sensors, the input signal is transduced into the output signal in two steps: the input signal which can be described as a physical quantity, which is transduced into a thermal quantity as the first step, then later transduced into an electrical quantity. The concept of thermal sensors can be clearly explained by considering a medical thermometer [10]. Medical infrared thermometry is used for the measurement of the body and the skin surface temperatures. The skin measurements are
used for the estimation of the internal body temperature as well as for specific diagnostics. It depends on the skin blood perfusion and the condition of the environment. As a result, it can be independently correlated with the internal temperature only with some perceivable error. Moreover, the surface IR thermometer sensors are very popular due to the ease of use for detecting a fever. On the other hand, the more accurate way to measure the internal body temperature is by placing the probe of an IR thermometer into an ear canal [11]. The tympanic membrane inside the canal, has a temperature which is very close to that of the blood. A simple block diagram of the thermometer is shown in Figure 2.5 [10,12].

![Figure 2.5: (a) Heated Infrared Sensor in a Medical Ear Thermometer and (b) Braun-Thermoscan Ear Thermometer [10].](image)
A thermopile IR sensor is encapsulated inside a metal header which is attached to a heater. The heater warms up the IR sensor from room temperature up to 37 °C which is the normal body temperature, before using it for a patient. The thermal gradient between the patient and the sensor is close to zero for a healthy patient. However, for a patient with a fever, the temperature gradient is only 2-4 °C and this range is still substantial, which makes this thermometer highly accurate.

2.3.2 Mechanical Sensors

Mechanical sensors operate based on the principle of detecting the deformation and deflection of the materials in terms of converting them to electrical signals. Some properties such as acceleration, stress and pressure of the materials, position and angle of substances placed on the sensor and the flow rate of substances can be measured by using the mechanical sensors.

Consider the accelerometer as an example of the acceleration [10]. Acceleration is used to measure the accelerometer and it is an important parameter for absolute motion measurement and vibration sensing. It can be operated in a harsh environment according to its small size, it is light in weight, rugged and robust. There are two configurations that can be used as active or passive sensor. In addition, the active accelerometer cannot be used for a static or DC measurement, so that the selection of active or passive depends on the applications. An accelerometer has some properties that make it more preferable over other types of sensors such as a high range of frequency, more suitable with destructive force than the velocity or displacement sensors and the ease of measuring the transients and shocks compared to other sensors. Figure 2.6 shows a typical deflection type seismic accelerometer [10].

In this case, the seismic mass is suspended by a spring inside a rigid frame. The frame is connected to the vibrating structure; hence when the vibration takes place, the mass trends to remain fixed such that the relative displacement can be picked up. For practical purposes, the accelerometer can also be classified as mechanical or electrical, depending on whether the restoring force or other mechanical properties such as the law of motion, distortion of a spring, fluid dynamics, or on electrical or magnetic forces.
2.3.3 Acoustic Sensors

Acoustic sensors are devices that employ elastic waves at different frequencies in the megahertz to gigahertz range to measure physical, chemical or biological quantities. It is attractive for chemical vapor and gas sensing due to its sensitivity. Based on the introduction of sonar in 1918, acoustic waves have been successfully used to determine the velocity, position and orientation of underwater objects in both commercial and military applications [1,13]. The development of acoustic pyrometry into a commercial technology has been underway since 1984. Nowadays, these systems have been used in many applications such as the online continuous temperature measurement of gas temperature and velocity in a hostile furnace. The technique provides an average line of sight measurement between an acoustic transmitter and receiver. The speed of the sound is a function of the temperature that the sound wave travels. In ranging systems, the variation in the sound speed is considered as an error that requires an appropriate correction. However, the changes in sound speed provide the desired measurement in acoustic sensors. The determination of temperature requires the measurement of the flight time of an acoustic pulse over a known distance. The result will be then the average
temperature of the entire acoustic path. The speed of sound in a gas is related to gas temperature by the following equation [5]:

\[
C = \sqrt{\frac{\gamma RT}{M}}
\]  

(1)

Where,

\(C\) = Speed of sound,

\(\gamma\) = Ratio of specific heats,

\(R\) = Gas constant = 8.314 J/mole-K,

\(T\) = Temperature, K,

\(M\) = Molecular weight, Kg/mole.

Figure 2.7 shows an example of a single path acoustic pyrometer. All that is required to install a sound source is a transmitter which is placed in one side of the boiler and a receiver that is placed on the other side. A sound pulse is emitted from the transmitter and then, received by the receiver. It is possible to calculate the intermediate temperature of the path traversed by the acoustic pulse because the value of the distance is known and fixed.

Figure 2.7: A Single Path Acoustic Pyrometer using Air Bursts as Source of Sound [5].
2.3.4 Optical Sensors

Optical sensors are used for the measurement of radiation properties such as intensity, polarization and spectral distribution. There are two types of optical sensors. First, thermal detectors, also known as the absorbing detectors, which are basically a tandem transducer, hence the energy associated with the impinging radiation is first absorbed and the temperature increased due to the measurement of the heat generated using one of the contact sensors. Second, photon detectors, also called quantum detectors, which enables the conversion of photons into electron-hole pairs, the concentration of which can be directly electrically measured [3].

An electrooptical cardiac sound sensor is used as an optical sensor in medical healthcare. The analysis of the frequency content of this sensor is widely used as a clinical diagnosis tool. An optical reflection scheme has been developed by Yeung et al [14,15] as shown in Figure 2.8

![Figure 2.8: A Simplified Diagram of Optical Components which are employed in the Electrooptic Cardiac Sound Sensor [14].](image)

Light from three simultaneously excited LED’s is reflected from the skin back to an array of eight phototransistors connected in parallel. The multiple number of
transmitter and receivers is used to rise the signal to noise ratio and decrease the sensitivity to specific skin reflection characteristics. During the vibration of the wall chest, a time varying amount of light will be detected, obeying the inverse square law with distance. As a result of the practical experiment, the minimum detectable motion which is determined by electrical sensitivity was found to be 0.225 mm. The advantages of this technique include a wide bandwidth about 3 to 9 KHz, cost, small size and light weight.

2.3.5 Chemical and Biological Sensors

Chemical and biological sensors are defined as measurement devices which use chemical or biological reactions to detect and quantify a specific analyte or event [16]. Such sensors differ, therefore from physical sensors that measure physical parameters. These sensors are the evolved products of many measurement systems and many different technologies. Sensors represent multidisciplinary hybrid products of the physical, chemical and biological sciences according to the physical transduction methods and drawing on diverse disciplines such as polymer chemistry, physics, electronics and molecular biology, chemical and biological. As a result, chemical and biological sensors are able to recognize a specific molecular species and then convert this recognition event into an electrical signal output [16].

A chemical and biological sensor consists of three basic components: (1) a chemically or biologically active surface which specifically interacts with the analyte to be measured; (2) a transducer which detects the chemical/biochemical event happening between the surface and the analyte; and (3) support electronics/software which amplify and report the output signal from the transducer as shown in Figure 2.9, which clarify the basic components of a chemical/biological sensor [16]
The nature of the surface active layer determines the type of the sensor. Chemical sensors utilize polymeric membranes by itself or containing specific, low-molecular-weight doping agents. In most cases, the polymeric layer is the active component of the sensor which interacts with the target analyte. On the other hand, biological sensors can also contain polymeric layers and membranes, however all biosensors have a biomolecule (such as an enzyme, antibody, or receptor) as the active component which interacts with the target analyte. According to the preceding definition and as shown in Figure 2.10, a true chemical sensor or biosensor thus incorporates both the detection and quantification systems into the same device.

2.4 Sensors Characteristics and Terminology

The main aim of this section is to clarify the relationship between the input stimuli into sensors and the output electrical signals, according to the various conversion steps, which sensors may have before generating an output signal. The characteristics of sensors will be explained in details, regardless of its physical nature or the number of conversion that may occur. The characteristics of a sensor can be categorized as being
either static, or dynamic. These parameters are essential in high fidelity mapping of output against input. Static characteristics are those that can be measured after all transient effects, which have stabilized to their final or steady state. However, dynamic characteristics describe the sensor’s transient properties by analyzing the response to an impulse, step or ramp function.

2.4.1 Static Characteristics

2.4.1.1 Sensitivity

The sensitivity of a sensor is defined in terms of the relationship between the input physical signal and the output electrical signal. Generally, it is the ratio between the small change in electrical signal to the small change in physical signal. For example, it can be expressed as the slope of the output electrical curve ($\Delta y/\Delta x$) as shown in Figure 2.10, or as a derivative of the transfer function with respect to physical signal [2].

In addition, there is another term that is called the sensitivity error. It is also shown in Figure 2.10 (dotted curve), which is the departure from the ideal slope of the characteristic curve.

![Figure 2.10: Ideal and Sensitivity Error Curves [2].](image)
2.4.1.2 Selectivity

A sensor’s ability to measure a single component in presence of other components is known as its selectivity. Oxygen sensors for example, does not produce a response to other gases such as CO, CO$_2$ and NO$_2$, may be considered as selective [17]. The following relationship is obtained when the sensor is sensitive to measurands $x_1, x_2, ..., x_n$ [18].

\[
    y = y_0 + \frac{\sigma y}{\sigma x_1} \Delta x_1 + \cdots + \frac{\sigma y}{\sigma x_n} \Delta x_n \tag{2}
\]

\[
    y = y_0 + S_1 \Delta x_1 + \cdots + S_n \Delta x_n \tag{3}
\]

Where,

- $y$ = the output of the sensor in the presence of measurands,
- $y_0$ = the output of the sensor in the absence of measurands,
- $S$ = sensitivities to different measurands.

In addition, the selectivity to a specific measurands such as $x_1$ is expressed by the following equation:

\[
    Sel_{x_1} = \frac{\sigma y / \sigma x_1}{\sigma y / \sigma x_j} \quad \text{When } j \neq 1 \tag{4}
\]

If an array of $m$ sensors is employed with each sensor sensitive to $n$ different measurands, which leads to the useful result for each sensor. Hence, the sensitivity of the array is defined in Eq. (5):

\[
    S = \begin{bmatrix}
    \frac{\sigma f_1}{\sigma x_1} & \cdots & \frac{\sigma f_1}{\sigma x_n} \\
    \vdots & \ddots & \vdots \\
    \frac{\sigma f_m}{\sigma x_1} & \cdots & \frac{\sigma f_m}{\sigma x_n}
    \end{bmatrix} \tag{5}
\]

In the same manner, the selectivity of the array can be described as well as the selectivity of the single sensor, in terms of the ability of the array to retrieve the value of $n$ quantities. When the matrix is diagonal, that means the maximum selectivity, which represents the case when the array is composed of $n$ specific sensors.

2.4.1.3 Resolution

Resolution or discrimination is the minimal change of input parameter necessary to produce a detectable change at the output. It is strongly limited by any noise in the
signal [19]. When the input continuously changes over the range, the output signals of some type of sensors will not be perfectly smooth, even under the no noise conditions. The output may change in minimal steps in some applications such as potentiometric transducers, occupancy infrared detectors with grid masks, and other sensors where the output signal change is allowed only upon a specific degree of input variation. The amplitude of the input variation, which obtained in the output lowest step is specified as resolution under specific conditions [4].

### 2.4.1.4 Accuracy

The accuracy of the sensor can be defined as the maximum difference that will exist between the actual value and the indicated value at the output of the sensor. It is the quality that characterizes the capacity of a measuring instrument for obtaining results that are close to the ideal value of the measured quantity [2]. The exact or ideal value is given when measurements are created by using an ideal method. The accuracy of a sensor is calculated by means of a static calibration process. It consists of keeping constant all sensor inputs except that to be studied. This input is changed too slowly, thus measuring successive constant values along the measurement range. The successive sensor output results are then recorded. The resulting plot against input values represents the calibration curve. The difference between the true value for the measured quantity and the instrument reading is called an error. Furthermore, the difference between instrument reading and the true value is called an absolute error. It can be expressed as a percentage of the maximum value that can be measured with the instrument or with respect to the difference between the maximum and the minimum measurable value which is the measurement range as shown below [19]

\[
\text{Absolute error} = \text{Result} - \text{True value}
\]  

(6)

### 2.4.1.5 Linearity

Linearity explains the closeness between the calibration curve and a specific straight line. It is measured as the maximum deviation of any calibration point from a
specific straight line during one calibration cycle [7]. The linearity of the sensor can be specified in different ways as shown in Figure 2.11 [19].

- **Independent linearity**: this method usually gives the best quality. The straight line is defined by the least squares criterion. With this system, the maximum positive error and minimum negative error, are equal, as shown in Figure 2.11 (a).

- **Zero based linearity**: this method also depends on the straight line, which is defined by the least squares criterion. However, there is an additional restriction of passing through zero, as shown in Figure 2.11 (b).

- **Terminal based linearity**: the straight line is described by the output corresponding to the lower input and the theoretical output when the higher input is applied, as shown in Figure 2.11 (c).

- **End point linearity**: in this method, the straight line is defined by the real output when the input is the minimum of the measurement range and the output when the input is the maximum of the measurement range, as shown in Figure 2.11 (d).

- **Theoretical linearity**: the definition of the straight line depends on the theoretical prediction when the sensor is fabricated, as shown in Figure 2.11 (e).

As a conclusion, the linearity of the curve indicated as to what extend the sensor’s sensitivity is constant. In order to accept the sensor, it is not necessary to have a high linearity. The interest in linearity takes place when the sensitivity is constant.
2.4.1.6 Noise

Noise refers to random fluctuations which occur when the measurand is not changing at the output signal, its cause may be external to the sensor such as mechanical vibrations, electromagnetic signals which includes radio waves and electromagnetic noise from power supplies and surrounding temperature to the sensor or internal to the sensors. All sensors generate some noise along with their outputs. If the noise is less than the fluctuations of the input (the physical signal), it can be considered not important. On the other hand, there are some other cases in which noise limits the performance of the sensors and it cannot be ignored.

2.4.1.7 Saturation

Saturation defines the performance limits of all sensors. At this stage, the output does not respond to the input, even if the sensor has linear characteristics for some steps.
of the input as shown in Figure 2.12. The output in the saturation region will not respond to any increment in the input [18].

\[ \text{Figure 2.12: Linear and Saturation Response Regions [18].} \]

### 2.4.1.8 Hysteresis

Hysteresis occurs when some sensors do not return to the same output when the input stimulus is cycled up or down. The width of the expected error in terms of the measurand quantity is defined as hysteresis [6]. Figure 2.13 shows a typical hysteresis curve; it matters from which direction the change is happening. Approaching a fixed input value such as point B from a higher value such as point P, will produce a different output from that obtained by approaching the same value from a lesser value such as point Q. In addition, point B can be represented by \( F(x)_1 \), \( F(x)_2 \), or \( F(x)_3 \) depending on the immediate previous value; it is obvious that there is an error due to hysteresis [2].
2.4.1.9 Calibration

Sensor calibration is important to ensure the accuracy of the measurement. The limitation of calibration is different from one sensor to another. It is essential to be performed in the environment where the sensor is going to be used to collect an accurate measurement from the sensor. The process begins by applying an input \(x\), then plotting the sensor output response \(y\), corrected for a background signal \((y_0)\) against the value of the input which is \((x)\) or \(\log(x/x_0)\), where \((x_0)\) is the reference for the input. For a steady state calibration curve, the sensitivity and the linear range is calculated from a plot of \((y - y_0) / x\) versus \((x/x_0)\). On the other hand, for a transient calibration curve, the sensitivity and the linear range is calculated by plotting \((dy/dt)_{max} / x\) versus \(\log(x/x_0)\). For both cases, sensitivity is measured from the slope of the calibration curve in the linear input curve.

Occasionally, cross-calibration is performed with an alternate input such as gas sensors, calibration is performed by using a gas that is readily available and easier to
handle than the actual gas. Moreover, when cross-calibration is performed by using another gas, the output of the sensor is normally multiplied by a response factor to account for the difference in response for both gases [17].

2.4.1.10 Dead Band

Dead band means that the sensor is insensitive during a specific range of the input signal as shown in Figure 2.14. During this period, the output of the sensor may stay close to a certain value or zero.

![Figure 2.14: Dead Band Zone.](image)

2.4.1.11 Dynamic Range or Span

All sensors are designed to perform over a specified range. The dynamic range is the total range of operation for the sensor from the minimum to the maximum values [2], as shown in Eq. (7).

\[ R_{dyn} = y_{max} - |-y_{min}| \] (7)
This range of input signals that will result in a meaningful output for the sensor. Signals outside of this range might be considered as unintelligible, inaccuracies, and may even cause irreversible damage to the sensor [17].

2.4.1.12 **Repeatability**

Repeatability is defined as the ability of the sensor to reproduce the same output signal under the same conditions and direction, when the same measurand is applied to it consecutively.

Repeatability error is caused by the inability of the sensor to perform the same value under identical condition. It can be expressed as the maximum difference between output readings as determined by two calibrating cycles, expressed as a percentage of the full scale output (Eq. (8)) of the sensor [4,18]

\[
\sigma_r = \frac{\Delta}{FS} \times 100\% 
\]

Where,

\( \sigma_r \) = repeatability error

\( \Delta \) = the difference in the sensor output in two calibration cycles

\( FS \) = full scale output

Thermal noise and material properties are examples which cause the repeatability error.

2.4.2 **Dynamic Characteristics**

The sensor response to variable input signals is different from that exhibited when input signals are constant, which is described by means of the static characteristics in the previous section. The reason is the presence of energy storing elements such as internal elements and capacitances.

The behavior of a sensor when variable input signals are applied is described by means of dynamic characteristics [19].

It is better to use linear and time invariant mathematical representation for sensing system due to the ease of extracting information about the sensing system to the users.
The relationship between input and output of any linear time invariant measuring system can be shown in the following formula [18]:

\[
\begin{align*}
& a_n \frac{d^n y(t)}{dt^n} + a_{n-1} \frac{d^{n-1} y(t)}{dt^{n-1}} + \cdots + a_1 \frac{dy(t)}{dt} + a_0 y(t) = b_m \frac{d^{m-1} x(t)}{dt^{m-1}} + \\
& b_{m-1} \frac{d^{m-2} x(t)}{dt^{m-2}} + \cdots + b_1 \frac{dx(t)}{dt} + b_0 x(t)
\end{align*}
\]  

(9)

Where,

- \(x(t)\) = Input signal
- \(y(t)\) = Output reading
- \(a_0, \ldots, a_n\) = Constants
- \(b_0, \ldots, b_n\) = Constants

\(x(t)\) can have different values, it may be considered as a step change as shown in Figure 2.15.

![Figure 2.15: A Step Change.](image)

When the input signal is a step change, Eq. (9) can be simplified as:

\[
\begin{align*}
& a_n \frac{d^n y(t)}{dt^n} + a_{n-1} \frac{d^{n-1} y(t)}{dt^{n-1}} + \cdots + a_1 \frac{dy(t)}{dt} + a_0 y(t) = b_0 x(t)
\end{align*}
\]  

(10)

As all derivatives of \(x(t)\) with respect to \(t\) are zero. The input does not change with time except at \(t=0\). On the other hand, if the output shows an instantaneous response to the input, then all \(a_1, \ldots, a_n\) coefficients except \(a_0\) are zero.

\[
a_0 y(t) = b_0 x(t)
\]

(11)
or \( y(t) = Kx(t) \) \( (12) \)

Where \( K = \frac{b_0}{a_0} \) is defined as the static sensitivity. Such a response represents a perfect zero order system. However, if the system is not perfect and the output does show a gradual approach to its final value, then it is called a first order system such as the charging of a capacitor with a voltage supply, whose rate of charging is exponential in nature. The first order system is described as:

\[
\tau \frac{dy(t)}{dt} + y(t) = b_0 x(t) \tag{13}
\]

\[ or \quad \frac{a_1}{a_0} \frac{dy(t)}{dt} + y(t) = \frac{b_0}{a_0} x(t) \tag{14} \]

By defining \( \tau = \frac{a_1}{a_0} \) as a time constant, the equation will be considered as the form of a first order ordinary differential equation (ODE):

\[
\tau \frac{dy(t)}{dt} + y(t) = Kx(t) \tag{15}
\]

The ordinary differential equation can be solved by obtaining the homogenous and particular solutions. By solving this equation, the output \( y(t) \) in response to \( x(t) \) will change exponentially. In addition, \( \tau \) is the time taken for the output to reach 63\% of its final value, hence:

\[
1 - \frac{1}{e^{-1}} = 0.6321 \tag{16}
\]

As seen in a typical output of a first order system in Figure 2.16

\[ Figure 2.16: \text{First Order System with Time Constant} \ [19]. \]
However, the response of a second order system to a step change can be defined as the following:

\[ a_2 \frac{d^2 y(t)}{dt^2} + a_1 \frac{dy(t)}{dt} + a_0 y(t) = b_0 x(t) \]  

(17)

By defining the undamped natural frequency \( \omega = \frac{a_0}{a_2} \), and damping ratio \( \varepsilon = \frac{a_1}{2a_0a_2} \), Eq. (16) reduces to:

\[ or \frac{1}{\omega^2} \frac{d^2 y(t)}{dt^2} + \frac{2\varepsilon}{\omega} \frac{dy(t)}{dt} + y(t) = Kx(t) \]  

(18)

The damping ratio has a pivotal role in the shape of the response as seen in Figure 2.17.

- If \( \varepsilon = 0 \), there is no damping and the output is a constant oscillation, with the solution being a sinusoid.
- If \( \varepsilon \) is small, then the damping is low, and the oscillation gradually diminishes.
- If \( \varepsilon = 0.707 \), the system is critically damped. A critically damped system converges to zero quicker than any other without oscillating.
- If \( \varepsilon \) is large, the response is high damped or over damped.

Most of sensing systems follow the second order equations. For such systems responses that are not close the critically damped condition \((0.6 < \varepsilon < 0.8)\) are highly undesirable which systems may be either slow or oscillatory.

![Figure 2.17: Second Order System Response to a Unit Step [19].](image)
2.5 Summary

In this chapter, the introduction of sensors has been explained along with the sensing systems and the classification of sensors. A brief discussion was dedicated for the different types of sensors. In addition, the sensor characteristics were presented as static and dynamic according to the behavior of the sensor. The next chapter will include an introduction and brief details about printed electronics which play an important role in the development of sensor technology.
2.6 References


CHAPTER III
INTRODUCTION TO PRINTING TECHNIQUES

3.1 Introduction

Printing technique can be defined as a process of reproduction of an image from a printable surface by contact impression, which leads to transferring ink onto polymer sheets, paper, and other type of substrates. Printed and flexible devices can be created physically and mechanically compatible with applications, which need an ability of stretching, bending, and folding [1].

In recent years, there has been an increasing interest in the development of flexible and printed electronic (PE) devices, according to the valuable advantages such as high process efficiency, large scale patternability, environmentally friendly, reduction in weight, low fabrication cost and reduction in material use [2-5]. These benefits of printed electronics have opened new areas for researchers to explore new avenues for materials processing to develop sensors on even non-planar surfaces, which otherwise are difficult to realize with the conventional wafer-based fabrication techniques such as a silicon (Si) wafer [6].

Consider the following example of the development in printing electronic technology which can be implemented in many applications around the world [7], new future homes which can include the following facilities: (1) large screen TV hangs on the wall, the advantage of this TV is that it is thin, lightweight and flexible. The TV panel is expected to be made of a self-light-emitting organic light-emitting diode with an active matrix back plane created by organic transistors with metallic nano ink circuits. (2) Walls of the house can be patterned using a dye-sensitized solar cell that has the ability of recycling electrical energy from the lighting inside the room. (3) Tables have cells which are able to charge any electronic device wirelessly placed on it such as cell phones and laptops by the communication sheet on the table, which can also be wirelessly connected to the internet. (4) for a walking robot inside the house, it is recommended to have some specifications such as soft skin with sensors embedded on it, to avoid any damage to furniture or injury to people. (5) The outside face of a curtain can be made of an organic
thin-film type of solar cell, and the inside face of the curtain made of an OLED lighting panel. The solar cell generates electricity to the internal lighting. The curtain works as a standalone flexible device. (6) On the roof of a home, there could be a solar cell that can be made of a thin-film inorganic type of module such as a copper–indium–gallium–selenium (CIGS).

3.2 Types of Printing Techniques

Printed techniques can be classified into four types in terms of the action of the image carrier which is used in producing the image, inkjet [8], gravure [9] and flexography [10] screen printing [11,12]. They are also applicable to many advanced PE products. Depending on the nature of the PE products, one should make a suitable choice regarding the ink, substrate, designed device structure, manufacturing speed, pattern geometry, yield and production cost [7]. Table 4.1 shows a summary of the characteristics of four types of printing processes. The viscosity of the ink, layer thickness and roughness has an important functionality in the selection of the proper printing techniques [13].

Table 3.1 Characteristics of Various Printed Techniques [13].

<table>
<thead>
<tr>
<th></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>Flat Bed 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>0.05-0.5</td>
<td>0.001-0.04</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(for 600×600 dpi)</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>Flexography</td>
<td>15</td>
<td>0.5-2</td>
<td>0.05-0.5</td>
<td>300-1000</td>
</tr>
</tbody>
</table>
3.2.1 Screen Printing

The primary strength of the screen printing is its ability to print on virtually any surface. It is difficult to address every product and substrate that can be used by the screen printing process due to the widespread usage of this type of printing. Screen printing is a stencil process wherein the image area is open and the non-image area is closed [14]. Ink is moved through the stencil by a flexible squeegee. Screen printing is entirely different from other methods of printing for many reasons [12,14]. It is the most versatile among others due to the ability of printing on virtually any surface such as paper, cardboard, plastic, textiles and other materials. In addition, this method of printing is used when a heavy ink film is required.

Moreover, the screen printing process is based on six basic components: stencil, screen fabric, screen frame, squeegee, ink and substrate as shown in Figure 3.1 [12,15], each plays a specific role in the process. The frame, fabric and stencil work together to form the image carrier for this process. The squeegee’s task is to force the ink through image areas onto the substrate. The ink deposited can be adjusted to produce anything from a thin film to very thick film as needed, by making a change in the fabric, stencil, or squeegee.

![Figure 3.1: Schematic of the Screen Printing Process.](image-url)
3.2.2 Inkjet Printing

Inkjet printing is defined as an automated deposition method based on the expulsion of picoliter droplets of a liquid ink, from a nozzle. However, the print-head is moving above the substrate. It allows non-contact patterning on almost any type of substrate [16,17]. Inkjet printing is a highly material-efficient process for the additive manufacture of electronic materials by use of a drop-on-demand material deposition system. This additive process differs from the typical methods of electronic fabrication; hence there is no need for cleanroom environments, hazardous chemical waste and expensive photolithography masks [18,19].

Inkjet printers can be classified by the transferring method used as continuous inkjet or drop-on-demand inkjet. A continuous inkjet printer as shown in Figure 3.2 (a), produces a continuous stream of ink, hence it is charged due to the image and electronically controlled. The charged droplets are deflected by a high voltage source. However, the non-deflected ink is transferred onto the substrate. A large part of the deflected ink is fed back into the system. Drop-on-demand inkjet printer, produces ink droplets only in the image areas by using a piezoelectric technique as shown in Figure 3.2 (b) [20].
3.2.3 Gravure Printing

Gravure printing is one of the promising processes for electronics manufacture due to its high quality at high speeds. It is used widely in the graphics and packaging industries. The principle of operation of the gravure printing process is based on the transfer of low viscosity ink solutions from small cells of an engraved cylinder, by the pressure of a rubber cylinder, to the substrate [21-23]. The engraved cylinder is refilled with ink continuously after transferring the ink and the surplus is taken away by a doctor blade [24]. The quality of printing depends on substrate wettability, smoothness and porosity; ink properties such as viscosity, ink chemistry and drying; the process parameters such as doctor blade pressure and angle, impression pressure and speed [25].

Figure 3.3 illustrates the mechanism of this type of printing [26]. In the beginning, the ink is placed on an engraved imaged roll, and the surplus ink is removed with a doctor
blade which is made of steel. During printing, ink is transferred to a transfer roll that is subsequently transferred onto the substrate due to the applied pressure. It is possible to use this method for printing patterns on 3D surfaces with high height steps due to the softness of the rubber layer on the transfer roll.

![Gravure Printing Diagram](image)

**Figure 3.3: Gravure Printing [26].**

### 3.2.4 Flexographic Printing

Flexo printing is a rotary printing method process that applies fast drying fluid inks and prints to flexible plates of photopolymer or rubber that have the image designed in relief [27,28]. This type of printing is suitable for flexible substrate due to the lighter printing pressure which is involved in this process, moreover, it has been applied in large area; thin and uniform coating due to the low viscosity of inks compared with other types of printing.

The mechanism of flexo printing is shown in Figure 3.4, the low viscosity ink distribution systems begin by transferring inks to the surface of printing plate through an anilox roll, and hence the surface is screened with cells that hold ink. The angle, shape and depth of the cells affect ink deposit and print quality. The polymer or rubber plate is
attached to the printing plate cylinder. Subsequently, ink is transferred to the substrate according to the pressure of the impression cylinder. A reverse angle doctor blade wipes the roller, putting inks in the recessed areas of the cells. The roller becomes in contact with the image carrier to deliver a uniformly metered ink film on the surface of the substrate which maintains ink density regardless of press speed [12,20].

![Diagram of Flexography Printing](image-url)

**Figure 3.4: Flexography Printing [20].**

### 3.3 Why Screen Printing?

Screen printing is the most versatile technique compared with other types of printing such as flexography, gravure and inkjet printing. This type of printing can be used for printing on different substrates such as paper, cardboard, wood, plastic, textile, ceramic, metal, leather and other materials [14]. The process of printing can be accomplished not only on flat surfaces, but on different shapes of surfaces such as round, convex, and irregular shapes. The ability of mesh to conform to surface characteristics is unchallenged by other direct printing processes.
Recently, emerging technology has impacted all of the printing processes and introduced nonimpact printing. As a result, flexography, inkjet and gravure printing have experienced shifting markets [15]. On the other hand, screen printing could maintain a modest stable sharing with traditional markets continuously.

Screen printing controls the ink film thickness by changing the diameter of the fiber that forms the mesh. There is a possibility to apply a very thick ink film. The ink range from those used in typical graphic arts applications to conductive inks that are used in electronics [15]. On the other hand, the gravure, and flexographic processes require different formulation of the inks that are more complex.

### 3.4 Challenges in Printed Electronics

In the near future, printed electronics technology is predicted to be widely used due to the ability to overcome traditional expensive and rigid silicon based electronics to fabricate a wide range of devices on flexible substrates. Today, the market of printed electronics is almost double compared with the traditional (Si) technology [29,30].

On the other hand, due to the difference in the manufacturing process for producing the printed electronics, some unforeseen environmental impacts may happen during the life cycle when it is compared to the traditional electronics [29]. An additional consideration to be addressed is the high sintering temperatures that are not compatible with common polymer foils such as polycarbonate (PC) or polyethylene terephthalate (PET), due to their relatively low glass transition temperatures. This restriction leads to the choice of more expensive polymer such as polyimide (PI) where both the temperature and the time required for sintering need to be minimized [30-32].

Moreover, there are more challenges in terms of implementation such as the complexity of ink formulation, compatibility of the printed substrates, consistency and material selections [33]. All those issues are the focus of researchers in areas of printed electronics.
3.5 Summary

In this chapter, various printed techniques have been presented. The advantages of using screen printing were described. There are some challenges for using printed electronics compared with the traditional Si technology. These were addressed as important issues to be considered during the fabrication of different types of systems.

The upcoming chapter will present the design and fabrication of a flexible and stretchable strain gauge by using screen printing to deposit an ink onto a flexible substrate.
3.6 References


CHAPTER IV
PRINTED STRAIN SENSOR BASED ON SILVER NANOWIRE/SILVER FLAKE COMPOSITE ON FLEXIBLE AND STRETCHABLE TPU SUBSTRATE

4.1 Introduction

Over the past decades, strain sensors have been receiving an increased interest for applications such as human body movement tracking in the biomedical industry as well as for monitoring deformations or structural changes in civil infrastructural assets [1]. Typically, strain sensors have been developed by depositing metal layers such as silver (Ag), gold (Au) and copper (Cu) [2-4]. However, these sensors are often fabricated on substrates that are not stretchable and are thus prone to mechanical failures due to their limited stretchable capabilities. Research has also demonstrated the development of strain sensors using metal-polymer composites such as thermoplastic elastomer (Evoprene)/carbon black nanoparticle [5], silver nanoparticles/elastomeric fibers [6], metal coated carbon nanofiller/epoxy [7] and silver nanowire/polymer [8] as well as polymer-polymer composites such as graphene composite films [9], polycarbonate/multiwall carbon nanotube [10] and UHMWPE/PANI [11]. The major drawback associated with these sensors is the reduction in conductivity due to the use of polymeric materials. The use of metal-metal composite based strain sensors on flexible and stretchable substrates, which could potentially overcome these disadvantages, has not yet been investigated. The fabrication of these novel strain sensors is thus a promising solution for applications in the biomedical and civil infrastructural industries.

Recent advancements in the field of printed electronics (PE) has demonstrated the development of flexible and stretchable electronic devices for applications in the biomedical [12-14], military [15] and tactile robotic industries [16]. The advantages associated with PE include additive manufacturing techniques, minimal usage of resources and low manufacturing temperatures in comparison to silicon based technology, which often involves photolithographic patterning techniques along with high-vacuum and high-temperature deposition processes. PE devices such as solar
cells [17], displays [18], electrochemical sensors [19] and piezo resistive sensors [20] have been fabricated using traditional printing processes such as gravure [21], inkjet [22], flexography [23] and screen printing [24]. Moreover, the flexible and stretchable capabilities, made possible by the use of PE, can help in the implementation of wearable electronic devices for monitoring temperature [25], hydration [26], electrocardiogram (ECG) [27], electromyography (EMG) [28] and human body movement. Wearable devices require flexible and stretchable electrodes that provide high conductivity and mechanical stability under varying strains [29]. Therefore, the development of printed strain sensors on flexible and stretchable substrates is bound to have a significant impact in the field of wearable electronics.

In this work, the author has successfully fabricated a metal-metal composite based strain sensor on a flexible and stretchable thermoplastic polyurethane (TPU) substrate. A silver nanowire (Ag NW)/Ag flake composite was screen printed on the TPU substrate as the metal-metal composite. Silver nanowire was chosen as the stretchable filler because of its ability to maintain electrical conductivity for tensile strains ranging from 16% - 50% [30, 31]. Silver flake was chosen due to its viscous nature (12 Pa. s) and good adhesion capabilities, and both materials are compatible with the screen printing process [32]. The author demonstrated the capability of the fabricated strain sensor by investigating the electro-mechanical response for elongations of 1 mm, 2 mm and 3 mm.

4.2 Experimental

4.2.1 Chemicals, Materials and Sample Preparation

Flexible and stretchable TPU (ST604) from Bemis Associates, Inc, was used as a substrate for the fabrication of the strain sensor. The metal-metal composite was prepared using Ag NWs (Blue Nano SLV-NW-90, 1.25 % AgNW and 98.75 % ethanol), with 25 µm length and 90 nm diameter, and Ag flake ink (Electrodag 479SS, 74.6 % Ag and 25.4 % carbitol acetate) from Henkel.
4.2.2 Design of Strain Sensor

Schematics of the strain sensors are shown in Figure 4.1. The author chose multiple sensor designs based on standard straight line and wavy line configurations, to investigate the effect of structural changes on the electro-mechanical response of the sensor. The straight line (Fig. 4.1 (a)) has a width of 0.8 mm with overall dimension of 28 mm × 4 mm. For wavy design, it has been reported that a smaller ratio of width to radius of the wavy line segments (w/r), result in more stretchability due to reduced stress on the sensor as well as reduced resistance change [33]. The parameters for the wavy line were thus chosen with an aim of maintaining a smaller w/r ratio and with similar overall dimensions as that of the straight line, for comparison purposes. The wavy line (Fig 4.1(b)), which is formed with two half circles connected to each other [25], was designed with a width of 0.8 mm, radius of 2 mm and overall dimension of 28 mm × 4 mm which results in a w/r ratio of 0.4.

![Schematic of (a) straight line and (b) wavy line (Not to Scale).](image)

4.2.3 Fabrication of Printed Strain Sensor

0.4 g of Ag NWs was mixed with 5 g of the Ag flake ink by magnetically stirring it on a hot plate (VWR Professional series 7x7), at 400 rpm speed and at 70 °C for 30 minutes. This results in a composite of 0.13 % Ag NW in Ag flake ink. The prepared Ag NW/Ag flake composite ink was then screen printed at room temperature using a screen
printer (AMI MSP 485) from Affiliated Manufacturers Inc. on the flexible TPU substrate. A stainless steel screen from Microscen® with 325 mesh count and 12.7 µm thick MS-22 emulsion was used. The printed sample was then thermally cured in a VWR 1320 oven for 30 minutes at 120 °C to obtain the strain sensor (Figure 4.2). Figure 4.3 shows the 3D profilometry images of the printed samples measured using a Bruker vertical scanning interferometer microscope (CounterGT). An average thickness of 18.18 µm (Figure 4.3(a)) and 19.82 µm (Figure 4.3(b)) was measured for the straight and wavy lines, respectively.

### 4.2.4 Experimental Setup

The experiment setup is shown in Figure 4.4. The strain sensor (printed straight/wavy lines) was placed in between the clamps of a force gauge (Mark-10 ESM 301 motorized test stand), with a vertically movable platform. The platform, capable of moving upwards and downwards, was used to apply the varying elongations of 1 mm, 2 mm and 3 mm. Ag conductive epoxy paste (CircuitWorks® CW2400) was used to bond connecting wires to the contact pads of the printed lines. The wires were then connected to an Agilent E4980A precision LCR meter using alligator clips. A cyclic elongation test was performed on the sensor, at 3 Hz operating frequency. The electro-mechanical based response of the strain sensor was acquired using a custom built LabVIEW™ program installed on a computer. The resistance change of the printed sensors was recorded during each stretch-release cycle and the dynamic range was determined for each sensor.

![Figure 4.2: Screen printed (a) straight and (b) wavy line configuration based strain sensors on flexible and stretchable TPU substrate.](image)
Figure 4.3: 3D Profilometry Scan of the (a) straight line showing an average thickness of 18.18 µm and (b) wavy line showing an average thickness of 19.82 µm.
4.3 Results

The author demonstrated the performance of the printed strain sensors by investigating the electro-mechanical response obtained for elongations of 1 mm, 2 mm and 3 mm, at 3 Hz operating frequency. Tests were performed on three different sensors for each of the straight and wavy line configurations.

Figure 4.5 shows the response of the printed strain sensor during the stretch-release cyclic elongation test, for 1 mm (Figure 4.5 (a)), 2 mm (Figure 4.5 (b)) and 3 mm (Figure 4.5 (c)). The average resistance, over 100 cycles, changed from $7.48 \pm 0.56 \, \Omega$ to $15.34 \pm 0.37 \, \Omega$, $17.14 \pm 3.70 \, \Omega$ to $47.53 \pm 8.52 \, \Omega$ and $38.44 \pm 5.41 \, \Omega$ to $130.30 \pm 2.80 \, \Omega$ for the 1 mm, 2 mm and 3 mm elongations, respectively. A drift in the base-line resistance was observed after the sensor was subject to every 100 cycles of stretch-release tests. This can be attributed to the fact that the sensor was getting fatigued, a phenomenon demonstrated in several research studies [18,25,33]. The average change in resistance for the 1 mm, 2 mm and 3 mm elongations was calculated to be $7.86 \pm 0.93 \, \Omega$,
30.39 ± 12.20 Ω and 91.86 ± 28.20 Ω, respectively (Figure 4.6). The strain on the sensor and average percentage changes in resistance were mathematically calculated using Eq. (1) and Eq. (2), respectively.

\[
\frac{\Delta R}{R_0} \% = \left( \frac{R_1 - R_0}{R_0} \right) \times 100\% \\
\varepsilon = \frac{\Delta L}{L_0}
\]

where, \( R_0 \) is the average base resistance, \( R_1 \) is the average value of the resistance after stretching the sensor over 100 cycles, \( L_0 \) is the initial length of the strain sensor and \( L_1 \) is the final length of the strain sensor after stretching. The results thus correspond to a 104.88 %, 177.30 % and 238.97 % average change of the resistance in response to 3.5 %, 7 % and 10 % strains, respectively (Figure 4.7). A sensitivity of 21.02 % resistance change for every 1 % strain, with a correlation coefficient of 0.9982, was thus obtained.

Similarly, cyclic stretch-release tests were performed on the printed strain sensor with the wavy line configuration, for 1 mm, 2 mm and 3 mm elongations. It was observed that the average resistance, over 200 cycles, changed from 13.99 ± 2.56 Ω to 20.54 ± 2.06 Ω, 21.21 ± 6.78 Ω to 51.22 ± 12.52 Ω and 55.41 ± 17.72 Ω to 190.43 ± 44.10 Ω for the 1 mm, 2 mm and 3 mm elongations, respectively. A base-line drift in resistance, similar to that of the sensor with the straight line configuration, was observed for this sensor as well after every 200 cycles of stretch-release tests, due to the effect of sensor fatigue. The increase in number of cycles is because of the capability of the wavy design to perform better, in terms of stretchability while maintaining conductivity, when compared to the sensor with a straight line configuration [25,33]. The average change in resistance for the 1 mm, 2 mm and 3 mm elongations was calculated to be 6.55 ± 4.62 Ω, 30.01 ± 19.30 Ω and 135.02 ± 61.82 Ω, respectively (Figure 4.8). These results correspond to an average change of 46.80 %, 141.42 % and 243.66 %, for a strain of 3.5 %, 7 % and 10 %, respectively on the printed strain sensor (Figure 4.9). For the strain sensor with the wavy line configuration, a higher sensitivity of 33.27 % resistance change for every 1 % strain, with a correlation coefficient of 0.995, was obtained.
Figure 4.5: Electro-mechanical response of printed strain sensor, with straight line configuration, when subject to cyclic stretch-release test, for elongations of (a) 1 mm, (b) 2 mm and (c) 3 mm; at 3 Hz for 100 cycles.
Figure 4.6: Average change in resistance of printed strain sensor, with straight line configuration, for elongations of (a) 1 mm, (b) 2 mm and (c) 3 mm; at 3 Hz for 100 cycles.

Figure 4.7: Effect of strain applied on printed strain sensor, with straight line configuration.
Figure 4.8: Average change in resistance of printed strain sensor, with wavy line configuration, for elongations of (a) 1 mm, (b) 2 mm, (c) 3 mm; at 3 Hz for 100 cycles.

Figure 4.9: Effect of strain applied on printed strain sensor, with wavy line configuration.

The hysteresis curves of the printed strain sensors for increasing and decreasing elongations of 1 mm, 2 mm and 3 mm. A maximum hysteresis of 2.94 Ω and 2.07 Ω was observed at 1 mm for the sensors with the straight line (Figure 4.10) and wavy line (Figure 4.11) configurations, respectively. The results obtained from the electro-
mechanical responses of the printed sensors demonstrate that the sensor with the wavy line configuration is better suitable for strain monitoring applications since the change in resistance was greater when compared to that of the sensor with the straight line configuration. It can also be concluded that the sensor with the wavy line configuration can be implemented for applications that require a stretchable form factor.

**Figure 4.10:** Hysteresis curve for the printed strain sensor with straight configuration for elongations of 1 mm, 2 mm and 3 mm.

**Figure 4.11:** Hysteresis curve for the printed strain sensor with wavy line configuration for elongations of 1 mm, 2 mm and 3 mm.
4.4 Summary

In this chapter, the author discusses the need for a flexible and stretchable strain sensor based on metal-metal composite. A detailed account of the experimental tasks included in this work was described. This includes the chemicals, materials and sample preparation; design; fabrication process; and experimental setup. Finally, the results obtained are also presented.

A novel printed strain sensor was successfully fabricated by screen printing a Ag NW/Ag flake composite on a flexible and stretchable TPU substrate. The capability of the fabricated strain sensor, printed in two design configurations: straight line and wavy line, was investigated by studying its electro-mechanical response towards varying elongations of 1 mm, 2 mm and 3 mm. For the printed sensor with the straight line configuration, average resistance changes of 104.88 %, 177.30 % and 238.97 %, over 100 cycles, were observed for the 1 mm, 2 mm and 3 mm elongations, respectively. However, the printed sensor with the wavy line configuration demonstrated a better dynamic range over 200 cycles with average resistance changes of 46.80 %, 141.42 % and 243.66 % for elongations of 1 mm, 2 mm and 3 mm, respectively. In addition, the wavy line strain sensor showed a better performance (33.27 % change in resistance for every 1 % strain), in terms of sensitivity, when compared that of the straight line strain sensor (22.02 % change in resistance for every 1 % strain). The results obtained thus demonstrate that the wavy line strain sensor configuration was better suited for applications that require a flexible and stretchable form factor.
4.5 References


CHAPTER V

FLEXIBLE CAPACITIVE PRESSURE SENSOR BASED ON PDMS SUBSTRATE AND Ga-In LIQUID METAL

5.1 Introduction

In recent years, the development of pressure sensors has been a major focus of researchers for applications such as object detection [1] and fingerprint sensors [2] as well as health care and medical diagnostics [3]. The three common types of pressure sensors are based on piezoelectricity [4,5], piezoresistivity [6,7] and capacitance [8-10]. The capacitive based pressure sensors have been receiving more interest due to its low sensitivity to both temperature and humidity along with its capability to provide a stable and repeatable response [11,12] capacitive pressure sensors have been fabricated using traditional silicon manufacturing technology [13] as well as conventional printing processes such as screen [14], gravure [15] and inkjet printing [16]. The silicon based pressure sensors are often fabricated on rigid substrates and are therefore prone to mechanical failures due to its limited physical flexibility. Even though, the printed pressure sensors have been fabricated on flexible substrates and use functional inks, these devices are still subject to mechanical failures because the cured inks result in a solid electrode. The use of liquid metal based electrodes is envisioned as a promising solution for overcoming the limitations associated with capacitive based pressure sensors, manufactured using silicon technology and printing processes.

The use of liquid metal such as eutectic gallium-indium (EGaIn), for the development of stretchable interconnects and electrodes, has attracted a considerable interest for flexible electronic applications such as tactile robotic skins [17] and radio antennas [18]. The major advantages of liquid metal electrodes are its capability to remain conductive during stretching, bending and stressing. It also has the added advantage of enabling an inexpensive and faster manufacturing process, at room temperature, by employing microfluidic injection [19] when compared to other EGaIn patterning techniques such as photolithography [20], vacuum filling [21], laser patterning [22] and direct write [23]. In addition, the EGaIn liquid metal can be
encapsulated in soft elastomeric materials, thus enabling an increased flexibility and stretchability. Therefore, the development of capacitive pressure sensors that integrate liquid metal electrodes using elastomeric materials is important.

PDMS, an elastomeric polymer, is a common material that has been used for the fabrication of flexible devices due to its properties such as highly chemical and thermal stability with low elastic modulus, low surface energy, low glass transition temperature, capability of detecting pressure under compression, strain and bending [24-26] as well as its ability to bond to itself without any adhesive [27-29]. The nature of the surface treatment prior to bonding is found to be a major influence for effective bonding of polymers [30]. Durable bonding between PDMS layers has been demonstrated using surface treatment methods such as oxygen plasma treatment [31], plasma guns [32] and standard microwave oven [33]. However, oxygen plasma treatment is relatively expensive, requires bulky equipment and often requires a vacuum chamber. Even though the plasma gun method eliminates the need for the vacuum chamber, it retains the use of controlled gas flows to achieve the desired plasma. Also, the microwave oven method requires sample treatment at high temperatures. In order to overcome these drawbacks, a corona treatment can be employed as a more effective and inexpensive bonding method [34-36]. The advantages of using the corona treatment method are that it does not require vacuum pumps or gas cylinders and can be performed at room temperature and atmospheric pressure. Therefore, the use of PDMS elastomeric polymer, bonded using a corona treatment is expected to advance the development of novel pressure sensors that use liquid metal electrodes, for flexible and stretchable applications.

In this work, the author was successfully developed flexible a capacitive pressure sensor with PDMS based electrode channels that were filled with EGaIn liquid metal. The master molds for the electrode channels were manufactured using conventional PCB technology. The PDMS layers were bonded together after using a corona discharge treatment, at room temperature and atmospheric pressure. The author demonstrated the capability of the fabricated pressure sensor by investigating the capacitive based response of the device for varying applied pressures, ranging from 0.25 MPa to 1.1 MPa.
5.2 Experimental

5.2.1 Chemicals and Materials

PDMS (Sylgard® 184 Silicone Elastomer kit) from Dow Corning was used for the fabrication of the dielectric, top and bottom layers. Aluminum blocks were machined and used for the base of the master molds. The electrodes of the pressure sensor were created using EGaIn liquid metal (495425) from Sigma–Aldrich® Chemical Company. Tubing, with an inner diameter of 0.01” and outer diameter of 0.0625”, and tube connection accessories from Upchurch Scientific Company were used for the sample transfer.

5.2.2 Pressure Sensor Configuration

A schematic of the pressure sensor configuration is shown in Figure 5.1. The pressure sensor consists of three layers of PDMS with an overall dimension of 3.8” × 2.5” × 0.26”. The top and bottom layers have a dimension of 3.8” × 2.5” × 0.1”. The dielectric layer, sandwiched between the top and bottom layers, has a dimension of 3.8” × 2.5” × 0.06”. The top layer has two symmetrical shapes that form the top electrode channels, which is 1.18” long, 1” wide and 0.004” high. The bottom layer also has two symmetrical shapes that form the bottom electrode channels, which is 1.96” long, 0.6” wide and 0.004” high. The top and bottom electrode channels form four overlapping electrode areas which result in four capacitors: C1, C2, C3 and C4. When a pressure is applied on the sensor, the distance between the top and bottom electrodes will be reduced as a result of the change in dielectric layer thickness. This leads to a change in the capacitance according to the change in the cross-section of the channels during compression.
5.2.3 Design and Fabrication of Master Mold

The base for the master mold was fabricated by machining a 3.8” × 2.5” × 0.2” volume from the aluminum block which had an overall dimension of 4” × 3” × 0.7” (Figure 5.2). The PCB, with an overall dimension of 3.8” × 2.5” × 0.062”, was designed in ExpressPCB™ software for the top (Figure 5.3(a)) and bottom (Figure 5.3(b)) layers, respectively of the pressure sensor. The electrode designs on the PCB were designed using two symmetrical shapes with dimensions of 1.18” × 0.98” × 3.93” and 1.96” × 0.59” × 3.93” for the top and bottom electrodes, respectively. The PCB was fabricated using conventional technology for the top (Figure 5.3(c)) and bottom
(Figure 5.3(d)) layers, respectively with a copper thickness of 0.00197” (0.05 mm), which is typically used in the PCB manufacturing process and represents the height of the electrodes. The fabricated PCBs were then placed in the machined area of the aluminum base for the top (Figure 5.4(a)) and bottom (Figure 5.4(b)) layers, to form the master mold.

Figure 5.2: (a) Dimensions of aluminum block with machined area (Not to Scale) and (b) aluminum block after machining.

Figure 5.3: (a) Schematic of master mold designed in ExpressPCB™ software for the (a) top and (b) bottom electrode layer. Fabricated PCB based master molds for the (c) top and (d) bottom electrode layers.
5.2.4 Preparation of PDMS Layers

The heat curable PDMS Sylgard® 184 Silicone Elastomer kit consists of a prepolymer (base) and cross-linker (curing agent). The liquid PDMS prepolymer base was manually mixed vigorously with the cross-linker curing agent at a ratio of 10:1 (w/w), for 10 minutes. The mixing introduces bubbles in the solution that were removed by placing the mixture aside at room temperature for 1 hour.

PET films, with dimensions similar to that of the electrode designs and thickness of 50 µm, were placed on each electrode to increase the height of the electrode channels. The prepared liquid PDMS was poured into the fabricated master molds and the whole setup was cured at 110 °C for 7 minutes in a VWR 1320 oven. The cured PDMS was peeled off from the PCB master mold (Figure 5.5). Inlet and outlet ports, with a diameter of 1 mm, were cored out using a biopsy puncher (33-31AA) from Miltex®. For each electrode channel, five holes were cored out: one at the center for injecting the liquid metal and four at each corner to degas the air. The thickness of the electrode channels was measured to be 102 µm and 103 µm for the top (Figure 5.6(a)) and bottom (Figure 5.6(b)) layers, respectively using a Bruker GTL-EN-61010 profilometer. In addition, a third PDMS based dielectric layer, with thickness of 0.006”, was fabricated by pouring liquid PDMS directly into the aluminum base, without the PCB.
Figure 5.5: Fabricated PDMS (a) top and (b) bottom layers.

Figure 5.6: 3D Profilometry scan of the (a) top layer showing an average thickness of 102 µm and (b) bottom layer showing an average thickness of 103 µm.
5.2.5 Fabrication of Microchannels

Initially, the PDMS based bottom and dielectric layers were cleaned with isopropyl alcohol (IPA) and placed on a non-conducting surface, with the bonding side up. A corona discharge treatment was performed by passing back and forth a laboratory corona treater (Model BD-20AC, Electro-Technic Products Inc.), approximately ¼ inch above each bonding surface, for approximately 30 seconds. The electrode channels were masked with a piece of PDMS, during the corona treatment to prevent treatment of the channels. The treated surfaces were then pressed together and left undisturbed overnight for the bonding to take effect. Then, the bonded bottom and dielectric layer as well as the PDMS based top layer were cleaned with IPA and placed on a non-conducting surface, with the bonding side up. The corona treatment, under similar conditions, were performed on these two surfaces. The two pieces were then pressed together and left undisturbed overnight for effective bonding. A programmable syringe pump (KD Scientific KDS210) was connected to the inlet port of the four electrode channels to inject the liquid metal, while the outlet ports were used to degas the air (Figure 5.7(a)). After the electrode channels were filled with the liquid metal, connecting wires were inserted into the inlet ports. Liquid PDMS was used to fill the inlet and outlet ports. Finally, the whole device sample was cured in the VWR oven for 15 minutes and thus formed the pressure sensor with four liquid metal electrodes (Figure 5.7(b)).

![Figure 5.7: (a) Liquid metal injection process and (b) Filled top and bottom electrode layers.](image)
5.2.6 Circuit Design

The timing diagram for the measurement is shown in Figure 5.8(a). Each capacitor in the pressure sensor (C1, C2, C3 and C4) was measured for 30 seconds. In order to differentiate among the responses of the four capacitors, a fifth known capacitor (C5 = 339 nF) was introduced and measured for a duration of 5 seconds between each capacitor. The overall time for measuring C1, C2, C3, C4 and C5 is 140 seconds.

A timing and switching circuit was designed to control the measurement time and selection of the capacitors, in the pressure sensor (Figure 5.8(b) and (c)). The circuit consists of a power supply, an Arduino UNO microcontroller, relays, buffers, transistors, capacitors (C1, C2, C3, C4 and C5), LEDs and an ON/OFF switch. A Tektronix, PS280 DC power supply was used to provide power to the timing and switching circuit. The microcontroller was programmed to control the measurement time and selection of the capacitors (C1, C2, C3, C4 and C5) through the switching relays (OMRON G5V-2). The buffers (74HCT541N 3-State Octal Buffer) were used to protect the microcontroller from feedback signals or high voltages. The transistors (2N3904 NPN) were implemented to drive the switching relays. The LEDs were used to visually identify the selected capacitor during measurement. The ON/OFF switch was used to turn on and off the electronic circuit.

5.2.7 Experiment Setup

The experiment setup is shown in Fig. 9. The pressure sensor was placed on the base compression plate of a motorized test stand (Mark-10 ESM 301). A digital force gauge (Mark-10 M5-200), with a vertically movable rubber-tip attachment, was used to apply varying pressures ranging from 0.25 MPa to 1.1 MPa. The connecting wires from the pressure sensor were connected to the switching relays in the electrical circuit. The output from the electrical circuit was then connected to an Agilent E4980A precision LCR meter using alligator clips. A custom built LabVIEW™ program, installed on a computer and connected to the LCR meter via USB, was used for acquiring and for post-processing of the capacitive response of the pressure sensor. All experiments were performed at room temperature. Calibration for the wires was done before taking measurements.
Figure 5.8: (a) Timing diagram, (b) schematic of timing and switching circuit and (c) realization of circuit bread board.
5.3 Results

The author demonstrated the performance of the pressure sensor by investigating the capacitive response of the device for varying applied pressures, ranging from 0.25 MPa to 1.1 MPa. Tests were performed on three different sensors (S1, S2 and S3), for three times each. The pressures were applied individually on each capacitor and the corresponding effect on the remaining capacitors, which were not under pressure, were also studied.

Figure 5.10 shows the average capacitive response of S1 when pressure is applied to C1 (Figure 5.10(a)), C2 (Figure 5.10(b)), C3 (Figure 5.10(c)) and C4 (Figure 5.10(d)). It was observed that the capacitance increased from 14.90 pF to 16.59 pF, 15.20 pF to 16.40 pF, 15.20 pF to 16.40 pF and 12.85 pF to 14.30 pF as the pressure was increased from 0.25 MPa to 1.1 MPa for C1, C2, C3 and C4, respectively. Simultaneous capacitance measurements on the capacitors, which were not under pressure, showed that there was no effect of the applied pressure and the capacitance values were stable. The
results thus demonstrated that an average capacitance change of 1.69 pF, 1.20 pF, 1.20 pF and 1.45 pF was obtained for C1, C2, C3 and C4, respectively for pressures varying from 0.25 MPa to 1.1 MPa. These results thus correspond to an average change in capacitance from 2.55% to 10.14%, 2.75% to 11.56%, 2.75% to 11.57% and 1.90% to 11.82% as the pressure was increased from 0.25 MPa to 1.1 MPa for C1 (Figure 5.11(a)), C2 (Figure 5.11(b)), C3 (Figure 5.11(c)) and C4 (Figure 5.11(d)), respectively when compared to the base values of the capacitors.

Figure 5.10: Capacitive response of pressure sensor S1 when pressure is applied on (a) C1, (b) C2, (c) C3 and (d) C4.
Figure 5.11: Change in capacitive response of pressure sensor S1 when pressure is applied on (a) C1, (b) C2, (c) C3 and (d) C4.

Similar tests were performed on S2 and for varying pressures applied on C1, C2, C3 and C4. It was observed that the capacitance increased from 13.70 pF to 15.29 pF, 15.35 pF to 16.90 pF, 12.70 pF to 14.10 pF and 14.31 pF to 15.80 pF as the pressure was increased from 0.25 MPa to 1.1 MPa for C1 (Figure 5.12(a)), C2 (Figure 5.12(b)), C3 (Figure 5.12(c)) and C4 (Figure 5.12(d)), respectively. Simultaneous capacitance measurements on the capacitors, which were not under pressure, showed that there was no effect of the applied pressure and the capacitance values were stable. The results thus demonstrated that an average capacitance change of 1.59 pF, 1.55 pF, 1.40 pF and 1.49 pF was obtained for C1 (Figure 5.13(a)), C2 (Figure 5.13(b)), C3 (Figure 5.13(c)) and C4 (Figure 5.13(d)), respectively for pressures varying from 0.25 MPa to 1.1 MPa. These results thus correspond to an average change in capacitance from 2.23% to 13.91%, 2.31% to 11.48%, 2.39% to 12.80% and 2.98% to 13.66% as the pressure was increased from 0.25 MPa to 1.1 MPa for C1, C2, C3 and C4, respectively when compared to the base values of the capacitors.
Figure 5.12: Capacitive response of pressure sensor S2 when pressure is applied on (a) C1, (b) C2, (c) C3 and d) C4.

Figure 5.13: Change in capacitive response of pressure sensor S2 when pressure is applied on (a) C1, (b) C2, (c) C3 and (d) C4.
Similar tests were performed on S3 and for varying pressures applied on C1, C2, C3 and C4. It was observed that the capacitance increased from 13.70 pF to 15.00 pF, 14.70 pF to 16.30 pF, 13.51 pF to 14.80 pF and 12.60 pF to 14.11 pF as the pressure was increased from 0.25 MPa to 1.1 MPa for C1 (Figure 5.14(a)), C2 (Figure 5.14(b)), C3 (Figure 5.14(c)) and C4 (Figure 5.14(d)), respectively. Simultaneous capacitance measurements on the capacitors, which were not under pressure, showed that there was no effect of the applied pressure and the capacitance values were stable. The results thus demonstrated that an average capacitance change of 1.30 pF, 1.60 pF, 1.29 pF and 1.51 pF was obtained for C1 (Figure 5.15(a)), C2 (Figure 5.15(b)), C3 (Figure 5.15(c)) and C4 (Figure 5.15(d)), respectively for pressures varying from 0.25 MPa to 1.1 MPa. These results thus correspond to an average change in capacitance from 2.21% to 11.94%, 2.79% to 12.38%, 2.38% to 12.12% and 3.28% to 13.90% as the pressure was increased from 0.25 MPa to 1.1 MPa for C1, C2, C3 and C4, respectively when compared to the base values of the capacitors.

Figure 5.14: Capacitive response of pressure sensor S3 when pressure is applied on (a) C1, (b) C2, (c) C3 and (d) C4.
The effect of the varying applied pressures on the capacitance change in pressure sensors (S1, S2 and S3) is summarized in Figure 5.16. An average change in capacitance from $2.33 \pm 0.06\%$ to $12.00 \pm 0.24\%$, $2.62 \pm 0.02\%$ to $11.81 \pm 0.82\%$, $2.51 \pm 0.04\%$ to $12.16 \pm 0.00\%$ and $2.72 \pm 0.06\%$ to $13.12 \pm 0.09\%$ was observed as the pressure was increased from 0.25 MPa to 1.1 MPa for C1, C2, C3 and C4, respectively when compared to the base values of the capacitors. From these results, a cross sensitivity of 8.02% which is estimated to be negligible, was calculated by comparing the response of the capacitor under pressure with the response of the capacitors with no pressure.

A linear fitted curve was obtained for the average capacitance change with a sensitivity of 0.11%/MPa, and correlation coefficient of 0.9975 (Figure 5.17).
Figure 5.16: Average change in capacitance of three different pressure sensors: S1, S2 and S3 when pressure is applied on (a) C1, (b) C2, (c) C3 and (d) C4.

Figure 5.17: Linear fitting curve of normalized change in capacitive response for S1, S2 and S3.

The capacitance of sensor S1 was measured again for varying pressures after two months, to study the repeatability of the sensor response. Figure 5.18 shows the change in capacitance of sensor S1 before and after two months. It was observed that, after two
months the average change in capacitance ranged from 2.30% to 11.26%, 3.11% to 12.66%, 2.58% to 11.89% and 2.17% to 12.08% as the pressure was increased from 0.25 MPa to 1.1 MPa for C1 (Figure 5.18(a)), C2 (Figure 5.18(b)), C3 (Figure 5.18(c)) and C4 (Figure 5.18(d)), respectively when compared to the base values of the capacitors. The results thus demonstrate a good repeatability of the sensor with a maximum difference in capacitance change of 1.39%, 1.10%, 1.18% and 0.95% for C1, C2, C3 and C4, respectively, before and after two months.

Figure 5.18: Change in capacitive response of pressure sensor S1, before and after two months, when pressure is applied on (a) C1, (b) C2, (c) C3 and (d) C4.

Figure 5.19 shows a linear fitted curves which were obtained for the average capacitance change for the first sensor (S1) before and after two months. A sensitivity of 0.10%/MPa and 0.11%/MPa as well as a correlation coefficient of 0.9908, and 0.9975 was calculated for the pressure sensor before (Figure 5.19(a)) and after (Figure 5.19(b)) two months respectively. The results thus show a stable and reproducible performance of the fabricated pressure sensors.
Figure 5.19: Linear fitting curve of normalized change in capacitive response for S1 (a) before (b) after, two months.
5.4 Summary

In this chapter, the author introduced a novel flexible pressure sensor based on PDMS and EGaIn liquid metal for detecting applied pressure. A detailed account of the experimental tasks included in this work was described. This includes the chemicals and materials; design; fabrication process; and experiment setup. Finally, the results obtained are also presented.

The sensor was fabricated with PDMS polymer based electrode channels that are filled with EGaIn liquid metal. The liquid metal based electrodes were designed to form four capacitors (C1, C2, C3 and C4). Conventional PCB technology was used to manufacture the master mold to form the electrode channels. Corona discharge treatment was employed to bond the PDMS layers, at room temperature and atmospheric pressure. The author demonstrated the capability of the fabricated pressure sensor by investigating the capacitive response of the device under varying applied pressures. A maximum average capacitance change of 12.00%, 11.81%, 12.16% and 13.12% was obtained for C1, C2, C3 and C4 respectively, when pressures ranging from 0.25 MPa to 1.1 MPa were applied. A linear fitted curve was obtained for the average capacitance change with a sensitivity of 0.11%/MPa, and correlation coefficient of 0.9975. The results obtained thus demonstrate the feasibility of employing liquid metal based electrodes for the fabrication of flexible pressure sensing devices.
5.5 References


CHAPTER VI

CONCLUSION AND FUTURE WORK

6.1 Conclusion

Through this thesis work, the author has successfully demonstrated the development of a printed strain sensor based on metal-metal composite of silver nanowire (Ag NW)/Ag flake ink, on a flexible and stretchable thermoplastic polyurethane (TPU) substrate, using screen printed technique. In addition, a flexible pressure sensor was also demonstrated that employs a conductive liquid eutectic gallium-indium metal (Ga-In) on a polydimethylsiloxane (PDMS) substrate. The accomplishments of both projects are listed below:

In the first project, the author was successfully designed and fabricated a printed strain sensor, based on metal-metal composite for applications in the biomedical and civil infrastructural industries. The sensor was fabricated by screen printing a silver nanowire (Ag NW)/Ag flake composite on a flexible and stretchable thermoplastic polyurethane (TPU) substrate in two design configurations: straight line and wavy line. The capability of the fabricated strain sensors was investigated by investigating its electro-mechanical response towards varying elongations. Average resistance changes of 104.88 %, 177.30 % and 238.97 %, over 100 cycles, and 46.80 %, 141.42 % and 243.66 %, over 200 cycles, were obtained for the sensors with the straight and wavy line configurations at elongations of 1 mm, 2 mm and 3 mm, respectively. A sensitivity of 21.02% and 33.27%, in resistance change for every 1% strain, was calculated for the printed strain sensors with the straight and wavy line configurations, respectively. The results obtained thus demonstrate the feasibility of employing conventional screen printing process for the development of strain sensors for applications that require a flexible and stretchable form factor.

In the second project, the author was successfully demonstrated a novel flexible capacitive pressure sensor with PDMS based electrode channels that were filled with EGaIn liquid metal. The liquid metal based electrodes were designed to form four capacitors (C1, C2, C3 and C4). The master molds for the electrode channels were
manufactured using conventional PCB technology. The PDMS layers were bonded together by using corona discharge treatment, at room temperature and atmospheric pressure. The author demonstrated the capability of the fabricated pressure sensor by investigating the capacitive based response of the device under varying applied pressures, ranging from 0.25 MPa to 1.1 MPa. A maximum average capacitance change of 12.00%, 11.81%, 12.16% and 13.12% was obtained for C1, C2, C3 and C4 respectively, when pressures ranging from 0.25 MPa to 1.1 MPa were applied. A linear fitted curve was obtained for the average capacitance change with a sensitivity of 0.11%/MPa, and correlation coefficient of 0.9975. The results obtained thus demonstrate the feasibility of employing liquid metal based electrodes for the fabrication of flexible pressure sensing devices.

6.2 Future Work

The author believes that there are various possibilities to improve the current projects by the following suggestions for future work.

- **Printed Strain Sensor Based on Silver Nanowire/Silver Flake Composite on Flexible and Stretchable TPU Substrate:** Future work may include further research to investigate the potential of increasing the sensitivity and dynamic range of the printed sensors and to enhance the device lifetime to more than 100 and 200 cycles for the straight and wavy line configurations, respectively based on one or more of the following steps.(1) Varying the Ag NW/Ag flake composite ratio, which results in more flexibility and stretchability. (2) Mixing other metal-metal composites such as copper/copper nanowires or gold/gold nanowires and test for better performance. (3) Alternate thinner line widths could be designed to allow for optimization in terms of cost, material usage and better characteristics [1]. (4) Different printing techniques such as gravure, flexography or inkjet, could be implemented to fabricate strain sensor, which will result in a change of the printed characteristics such as viscosity, thickness and resolution [2]. (5) Encapsulate the strain sensor (straight/wavy configurations) by using flexible materials such as PDMS, which can enhance the performance of the
sensors in terms of the conductivity and the elongation, by reducing the applied stress on the sensor. (6) Develop a Calibration procedure for compensating baseline drifts in sensor response.

- **Flexible Capacitive Pressure Sensor Based on PDMS Substrate and Ga-In Liquid Metal:** Future work may involve more investigation to increasing the performance of the pressure sensor based on the following ideas. (1) Changing the design of the channels, which can reduce the number of holes for injecting liquid metal and degassing the air [3] (2) Different printing techniques such as gravure, screen, flexography or inkjet, could be used to fabricate electrodes [4]. (3) Different methods such as oxygen plasma treatment, plasma guns or standard microwave oven, could be used to test the bonding performance [5]. (4) The PCB base master mold can be fabricated using screen, inkjet or gravure printing processes, all of which are relatively cost efficient and rapid methods when compared to the PCB manufacturing technique. (5) Implementing different methods for patterning liquid metal such as lithography, vacuum filling (freezing), laser patterning or direct write, which can be performed, depending on design and applications’ needs [6]. (6) Using different liquid metal such as gallium based alloys, which can result in different properties. (7) Develop an electronic circuit with algorithm for selective detection of individual capacitors.
6.3 References


APPENDIX A

Arduino Microcontroller Code

The Microcontroller Arduino UNO was connected to the timing and switching circuit to control the measurement time and selection of the capacitors (C1, C2, C3, C4 and C5), in the pressure sensor. For example, it was programmed to collect the value for the first capacitance for 30 seconds, and then the microcontroller selects the fifth capacitance for 5 second and so on. Therefore, the following code was used to specify which capacitor value should collect at a specific time.

```c
int val = 0;

void setup()
{
    pinMode(2, OUTPUT);  // sets the digital pin 2 as output
    pinMode(3, OUTPUT);  // sets the digital pin 3 as output
    pinMode(4, OUTPUT);  // sets the digital pin 4 as output
    pinMode(5, OUTPUT);  // sets the digital pin 5 as output
    pinMode(6, OUTPUT);  // sets the digital pin 6 as output
    pinMode(7, OUTPUT);  // sets the digital pin 7 as output
    pinMode(8, INPUT);   // sets the digital pin 8 as input
    pinMode(9, OUTPUT);  // sets the digital pin 9 as output
    pinMode(10, OUTPUT); // sets the digital pin 10 as output
    pinMode(11, OUTPUT); // sets the digital pin 11 as output
}

void loop()
{
    while(1)
    {
```
val = digitalRead(8); // read analog input

if (digitalRead(8)==HIGH) { // reset

    // C1 control switch
    digitalWrite(2, LOW); // sets the relay 1 off
    digitalWrite(3, LOW); // sets the relay 2 off
    digitalWrite(4, LOW); // sets the relay 3 off
    digitalWrite(5, LOW); // sets the relay 4 off
    digitalWrite(6, HIGH); // sets the LED 1 on
    digitalWrite(7, LOW); // sets the LED 2 off
    digitalWrite(9, LOW); // sets the LED 3 off
    digitalWrite(10, LOW); // sets the LED 4 off
    digitalWrite(11, LOW); // sets the LED 5 off
    delay(30000); // waits for 30 seconds for C1

    if (digitalRead(8)==LOW)
        { break; }

    // C5 control switch
    digitalWrite(2, LOW); // sets the relay 1 off
    digitalWrite(3, LOW); // sets the relay 2 off
    digitalWrite(4, LOW); // sets the relay 3 off
    digitalWrite(5, HIGH); // sets the relay 4 on
    digitalWrite(6, LOW); // sets the LED 1 off
    digitalWrite(7, LOW); // sets the LED 2 off
    digitalWrite(9, LOW); // sets the LED 3 off
digitalWrite(10, LOW);   // sets the LE D4 off
digitalWrite(11, HIGH);  // sets the LED 5 on
delay(5000);             // waits for 5 seconds for C5
if (digitalRead(8)==LOW)
{
  break;
}

// C2 control switch
digitalWrite(2, HIGH);   // sets the relay 1 on
digitalWrite(3, LOW);    // sets the relay 2 off
digitalWrite(4, LOW);    // sets the relay 3 off
digitalWrite(5, LOW);    // sets the relay 4 off
digitalWrite(6, LOW);    // sets the LED 1 off
digitalWrite(7, HIGH);   // sets the LED 2 on
digitalWrite(9, LOW);    // sets the LED 3 off
digitalWrite(10, LOW);   // sets the LED 4 off
digitalWrite(11, LOW);   // sets the LED 5 off
delay(30000);           // waits for 30 seconds for C2
if (digitalRead(8)==LOW)
{
  break;
}

// C5 control switch
digitalWrite(2, LOW);    // sets the relay 1 off
digitalWrite(3, LOW);    // sets the relay 2 off
digitalWrite(4, LOW); // sets the relay 3 off
digitalWrite(5, HIGH); // sets the relay 4 on
digitalWrite(6, LOW); // sets the LED 1 off
digitalWrite(7, LOW); // sets the LED 2 off
digitalWrite(9, LOW); // sets the LED 3 off
digitalWrite(10, LOW); // sets the LED 4 off
digitalWrite(11, HIGH); // sets the LED 5 on
delay(5000); // waits for 5 seconds for C5
if (digitalRead(8)==LOW)
{
    break;
}

// C3 control switch
digitalWrite(2, LOW); // sets the relay 1 off
digitalWrite(3, HIGH); // sets the relay 2 on
digitalWrite(4, LOW); // sets the relay 3 off
digitalWrite(5, LOW); // sets the relay 4 off
digitalWrite(6, LOW); // sets the LED 1 off
digitalWrite(7, LOW); // sets the LED 2 off
digitalWrite(9, HIGH); // sets the LED 3 on
digitalWrite(10, LOW); // sets the LED 4 off
digitalWrite(11, LOW); // sets the LED 5 off
delay(30000); // waits for 30 seconds for C3
if (digitalRead(8)==LOW)
{
}
break;
}

// C5 control switch
digitalWrite(2, LOW);   // sets the relay 1 off
digitalWrite(3, LOW);   // sets the relay 2 off
digitalWrite(4, LOW);   // sets the relay 3 off
digitalWrite(5, HIGH);  // sets the relay 4 on
digitalWrite(6, LOW);   // sets the LED 1 off
digitalWrite(7, LOW);   // sets the LED 2 off
digitalWrite(9, LOW);   // sets the LED 3 off
digitalWrite(10, LOW);  // sets the LED 4 off
digitalWrite(11, HIGH); // sets the LED 5 on
delay(5000);            // waits for 5 seconds for C5
if (digitalRead(8)==LOW)
{
  break;
}

// C4 control switch
digitalWrite(2, LOW);   // sets the relay 1 off
digitalWrite(3, LOW);   // sets the relay 2 off
digitalWrite(4, HIGH);  // sets the relay 3 on
digitalWrite(5, LOW);   // sets the relay 4 off
digitalWrite(6, LOW);   // sets the LED 1 off
digitalWrite(7, LOW);   // sets the LED 2 off
digitalWrite(9, LOW);   // sets the LED 3 off
digitalWrite(10, HIGH); // sets the LED 4 on
digitalWrite(11, LOW); // sets the LED 5 off
delay(30000); // waits for 30 seconds for C4

if (digitalRead(8)==LOW)
{
  break;
}

// C5 control switch
digitalWrite(2, LOW); // sets the relay 1 off
digitalWrite(3, LOW); // sets the relay 2 off
digitalWrite(4, LOW); // sets the relay 3 off
digitalWrite(5, HIGH); // sets the relay 4 on
digitalWrite(6, LOW); // sets the LED 1 off
digitalWrite(7, LOW); // sets the LED 2 off
digitalWrite(9, LOW); // sets the LED 3 off
digitalWrite(10, LOW); // sets the LED 4 off
digitalWrite(11, HIGH); // sets the LED 5 on
delay(5000); // waits for 5 seconds for C5

if (digitalRead(8)==LOW)
{
  break;
}

}}}
APPENDIX B

Matlab Code to Separate Output

The outputs of the pressure sensor, were saved in one file due to the use of the LabVIEW™ software. Matlab code was used to separate these values which were collected from the sensor that represented the capacitor value of (C1, C2, C3, C4 and C5). Then each capacitor was plotted separately due to the place of applied pressure. The following matlab code demonstrates the separation process.

close all
clear all % To clear all previous operations
clc

%% C5: Constant Capacitor

C5_nom = 339e-9; % Constant Capacitor (C5) is Used to Separate Data for Each Capacitor

%%
data; % Recorded Data Form The Experiment
size_Cap = size(Cap); % Size of the Recorded Data
C1 = zeros(1000,1); % Initializing C1
C2 = zeros(1000,1); % Initializing C2
C3 = zeros(1000,1); % Initializing C3
C4 = zeros(1000,1); % Initializing C4
C5 = zeros(1000,1); % Initializing C5
C1(1) = Cap(1); % First Data Point Belongs to C1
aa = 1; % C1 Counter
bb = 0; % C2 Counter
cc = 0; % C3 Counter
dd = 0; % C4 Counter
ee = 0;
ff = 0;
kk = 1;
i = 2; % Loop Counter
j = 1;
while i < (size(Cap(1) + 1)
i
if Cap(i) > 1e-7
  ee = ee + 1;
  kk = kk + 1;
  while Cap(i) > 1e-7
    ff = ff + 1;
    C5(ff) = Cap(i,1);
    i = i + 1;
  end
  if i > size(Cap,1)  % Loop Break
    break;
  end
end
if ee == 4
  ee = 0;
  kk = 1;
end
if kk == 1
  if i > size(Cap,1)  % Loop Break
    break;
  end
  while Cap(i) < 1e-7
    aa = aa + 1;  % C1 Counter
    C1(aa) = Cap(i);  % C1 Data
    i = i + 1;
    if i > size(Cap,1)  % Loop Break
      break;
    end
  end
end
end
if kk == 2
while Cap(i) < 1e-7
bb = bb + 1;  % C2 Counter
C2(bb) = Cap(i);  % C2 Data
i = i + 1;
if i > size(Cap,1)  % Loop Break
break;
end
end
end
end
if kk == 3
while Cap(i) < 1e-7
cc = cc + 1;  % C3 Counter
C3(cc) = Cap(i);  % C3 Data
i = i + 1;
end
end
end
if kk == 4
while Cap(i) < 1e-7
dd = dd + 1;  % C4 Counter
C4(dd) = Cap(i);  % C4 Data
i = i + 1;
if i > size(Cap,1)  % Loop Break
break;
end
end
end
end

%% Plotting
% Plotting C1 Data
subplot(2,2,1)
plot(C1)
title('C1')
ylabel('C1 (F)')

% Plotting C2 Data
subplot(2,2,2)
plot(C2)
title('C2')
ylabel('C2 (F)')

% Plotting C3 Data
subplot(2,2,3)
plot(C3)
title('C3')
ylabel('C3 (F)')

% Plotting C4 Data
subplot(2,2,4)
plot(C4)
title('C4')
ylabel('C4 (F)')

%%%% Save Data

save C1
save C2
save C3
save C4