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Introduction

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Chapter 1

Introduction

Abstract This chapter showcases the significance of sensors, explaining the ideology behind the usage of printed flexible sensors, their fabrication techniques and some of their applications.

1.1 Flexible Sensors

The utilization of sensors for daily activities has made a prominent impact on human being's life. Sensors are being employed to monitor and detect the changes taking place in the surrounding environment. The use of sensors for different applications is increasing every day. They are installed or connected to different objects and operated via control engineering from distant locations. They have been used to collect, store and analyze data that are difficult to obtain from inaccessible and partially accessible locations without much human intervention and for security purposes. The use of sensors has been done for more than 2000 years (Soloman 2009). Technically, a sensor can be defined as a device that can detect and respond to the changes happening in its ambiance. Even though the first commercial sensor was a thermostat, there was a prominent rise in the usage of sensors around the early 19th century (Oberg et al. 2006). As the demand for commercial sensors gradually increased, work had been done to improve the quality of existing sensors (Muro 2013). The utilization of sensors has almost tripled in the last two decades (Wang 2001). Currently, almost all the applications are somewhat connected with sensing systems (Meixner et al. 2008). The types of any sensor are mainly dependent on the application for which they are to be used. The current sensors different among the current sensors lie in their operating principle, size, sensitivity, etc. Some of the popular types of sensors are magnetic, electrical, thermal, chemical, etc. The cost of a sensor depends on the price of the processed materials, the fabrication technique and post-processing costs. These characteristics reflect the properties of the sensor which in turn dictates the applications for which are to be used for. Initially, when the researchers started using sensors for measurement purposes, prototypes having rigid substrates were used for measuring different industrial (Nag et al. 2016b; Nag et al. 2016c; Zia et al. 2011) and healthcare (Mainwaring et al. 2002; Otto et al. 2006; Szewczyk et al. 2004) applications ubiquitously. Until the end of the last decade, single-crystal silicon has been the dominant semiconductor material to develop the substrates for the sensors. Some of the distinct advantages of using rigid silicon sensors include their inexpensiveness, high sensitivity, and low leakage current, which is as a result of the high potential barrier in silicon. Even though these sensors are used largely to form sensors on a large-scale, there are certain disadvantages associated with them like the high cost of fabrication, high input power for operation, mechanical damage and stiffness, which opts for alternative options. Due to these limitations, flexible sensing prototypes are more and more preferred for different applications (Segev-Bar and Haick 2013). Some of the limitations mentioned above are rectified by flexible electronics. Thin-film transistor circuits were developed around fifty years ago, which at that time, formed a new emerging segment for forming sensors. With time, the circuits were enhanced regarding their performances, cost of fabrication and efficiency. This was subsequently followed by microelectromechanical systems (MEMS), which were developed in the late 20th century. MEMS cover a wide range of systems with sizes varying from a few microns to a few millimeters. MEMS have significantly improved regarding size, efficiency, and power consumption compared to the earlier devices.

After the advent of utilizing the sensors for continuous monitoring (Sze 1994) for different applications in daily life, there has been an ever rising demand for their commercial availability. They have revolutionized the quality of human life via their employment in a dynamic range of applications. Earlier, it took hours to study or monitor an event but can be tackled in minutes or even seconds via smart sensing systems. The dynamic applications of sensors have led to an ever-rising modification of the existing sensors. Nowadays, almost every industrial, domestic and environmental sector utilizes sensors for improving the quality of life (Nag and Mukhopadhyay 2014; Nag et al. 2016a; Nag et al. 2016b; Rahman et al. 2014; Rahman et al. 2013; Zia et al. 2014). They have been deployed for different sectors including gas-sensing (Nag et al. 2016b; Nag et al. 2016c), environmental-monitoring (Suryadevara et al. 2012; Yunus and Mukhopadhyay 2011), determining the individual constituents in the food and other edible products (Mukhopadhyay and Gooneratne 2007; Zia et al. 2014; Zia et al. 2013) and physiological parameter monitoring (Nag et al. 2016a).

The classification of sensors can be done in two categories depending on the type of materials used to fabricate them, flexible (Segev-Bar and Haick 2013) and non-flexible (Unno et al. 2011). The flexible prototypes are the ones which are fabricated from the materials which are malleable to a certain extent without changing their properties, whereas the latter ones are made from materials which are rigid and non-malleable. The non-flexible sensors were developed earlier among which the ones developed with silicon substrates are the most popular ones. Even though sensors of this kind are employed for a wide field of applications, there are certain limitations like their brittle nature, stiffness, which deters their usability. These disadvantages are more prominent, especially when the sensing system is deployed for monitoring physiological parameters of a person or any other uses which involves any strain applied on the sensor. This results in to opt for an alternative approach where the electrical and mechanical properties of the sensor would be dynamically used, thus negating any inconvenience caused to the person or protecting the sensor from damage for any specific application. Apart from this, lower fabrication cost, lighter weight, enhanced mechanical and thermal properties are some of the advantages of the flexible sensors in comparison to the non-flexible ones which make them a better option. Figure 1.1 shows a schematic of a monitoring system to sense physiological parameters like the heart rate and respiratory rate of a person and simultaneously transmit the data wirelessly to the cloud server via any information gateway (Patel et al. 2012). This is a quick and efficient real-time system as any abnormality of the person would be reflected in the transmitted data, which would give a notification to the healthcare provider or family members.

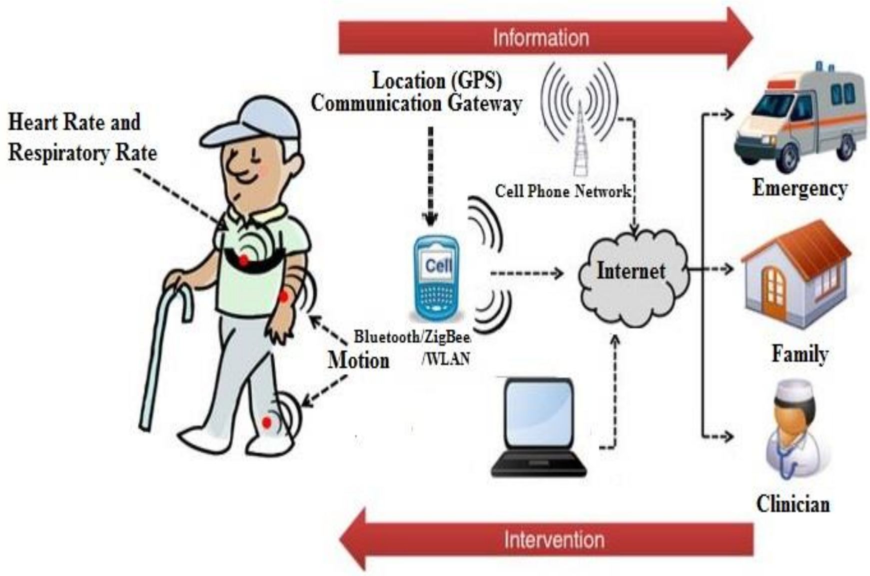

Figure 0.1 Schematic representation of the use of wireless sensors for physiological parameter monitoring (Patel et al. 2012).

The materials chosen for developing flexible sensors are processed with different techniques, depending on the dimensions of the final prototype. For example, for sensors with tiny dimensions having a few microns to a few millimetres, processes like photolithography (Revzin et al. 2001), screen printing (Chang et al. 2009), 3D printing (Muth et al. 2014), ink-jet printing (Wang et al. 2010), laser cutting (Schuettler et al. 2005) are commonly used. Photolithography is one of the frequently used techniques for microfabrication. Spin-coating of a photo-sensitive material called the photoresist is done on the substrate, to generate a geometrical pattern followed by the exposure of the substrate to the ultra-violet (UV) light. Two types of photolithographic processes occur, masked and maskless. The former one consists of a patterned mask through which the light passes on the substrate to imprint the design on the substrate. The maskless one does not involve any photomask but rather forms the patterns directly on the substrate, depending on the design uploaded on the system. Exposure of the photoresist to light polymerizes it on the patterned locations. Followed by the exposure to UV light to form the patterns, the residual photoresists are removed by an etching process. Two types of etching namely ionic or dry and chemical or wet etching, are performed for removing the photoresists. Screen printing is one of the earliest techniques that has been employed to develop devices with finer dimensions. This process is similar to photolithography apart from the fact that smaller dimensions can be obtained with a photolithographic technique. In screen printing, a pattern is generated on a stencil through which the ink or any liquid is transferred to a substrate to obtain the developed pattern. The design is formed on a mesh where the ink is poured to develop the mesh design on the substrate. The design is formed on polymers where the mesh is fixed to a frame for support. Ink is dropped or squeezed by a squeegee to develop the pattern on the substrate. 3D printing is a relatively newer technique that has been used to generate three-dimensional objects by printing them. This method was developed in the early 1980s. The shapes or geometries formed by this approach are designed using a range of computer-aided modeling techniques. The designs are saved with a file extension that is compatible with the 3D model printer. The design or model is then subsequently divided into a series of thin layers which produces the G-code. These codes are specific to each instrument and represent the specific actions that are used to develop the designed object. This process has many industrial applications like metal wire processing and lamination. Inkjet printing is another process which was developed in the late 20th century to develop different types of small-scale printed devices. This technique has certain advantages like fine resolution, no warm-up time, low per-dye costs and improved picture quality in comparison to other printing technologies. Two types of drop-on-demand (DOD) processes are employed for this process: thermal and piezoelectric. The former one consists of a series of chambers with each one having a heater. When a pulse of current is passed through the heating element of the chamber, the ink vaporizes and subsequently forms a bubble. This increases pressure of the chamber, thus ejecting one droplet on the substrate. The piezoelectric sensors change their dimensions with pressure, with an input voltage, thus creating a rise in pressure which forces the bubble out of the nozzle. Laser cutting is a process developed in the early 1960s when this technique was mainly used to develop holes in the diamond. Two different types of laser cutters namely CO_2 and Nd/Nd-YAG lasers, where the former one is more used than the latter one for research purposes. The laser material is stimulated which results in total internal reflection to the partial mirror as a result of which, a stream of monochrome coherent light generates out of the laser nozzle. The techniques used for laser cutting primarily include vaporization, melt-and-blow and reacting cutting. This approach has certain edges over other techniques like small sample preparation time, reduced contamination of the developed sample, final dimensions up to a few microns of the sample, low thermal influence, clean-cut edges, and smooth final product. Laser cutting devices are commercially available having a range of input powers which are decided by the sample to be sliced or ablated.

A wide range of materials has been employed for developing substrates and electrodes for developing different flexible sensing prototypes. The materials that are selected for different prototypes depends upon their inherent properties. For example, commercially available tapes are cheaper than many of the organic polymers, but they would not form a very efficient substrate regarding the flexibility, due to their high Young's modulus (E). Similarly, the electrical conductivity of gold is than aluminum but so is its brittle nature. Their breaking point threshold would be lower than that of aluminum electrodes. Thus, a material chosen for fabrication has to offer a balance between its cost of availability and extraction, its electrical, mechanical and thermal properties, and ultimately, its use as a sensing material.

Some of the substrates commonly used to develop flexible sensors are Polydimethylsiloxane (PDMS) (Jo et al. 2000), Polyethylene Terephthalate (PET) (Mannsfeld et al. 2010), Polyethylene Naphthalate (PEN) (Cai et al. 2009), Polyimide (PI) (Engel et al. 2003), Poly(3,4-ethylene dioxythiophene):Polystyrene sulfonic acid (PEDOT:PSS) [22], etc. PDMS is an organic polymer which is developed from the repetition of the siloxane monomers. It is most commonly used to develop flexible substrates for applications having rheological requirements. Some of its advantages are its transparency, non-toxicity, non-flammable and hydrophobic nature. Apart from this, one of the biggest advantages of using PDMS is its ability to form strong interfacial bonding with any nanomaterials during the formation of nanocomposites. PET is a carboxylate-group polymer that is mainly prepared for synthetic fibers. It is developed from ethylene glycol and dimethyl terephthalate. It is a semi-crystalline resin and is a more viscous polymer in comparison to PDMS. A few of the most common things made from PET are plastic bottles, packaging of foods and beverages. PEN is a polymer similar to PET but has higher dimensional and temperature stability. It is developed form carboxylate polymer and ethylene glycol. Its main uses include piezo-resistive tapes, for packaging, and solar-cell protection. PI is one comparatively of the oldest polymers and has been mass produced for its applications. The reaction between a diamine and dianhydride is commonly done to form these polymers. It mainly exists in two forms, a heterocyclic structure, and a linear structure. It is mostly used to create commercial tapes due to its high chemical resistance and excellent mechanical properties. PEDOT: PSS is one of the popular conductive polymers available in the market. It is developed from the two isomers of sulfonate and polystyrene groups. It is a transparent, flexible polymer, which makes it suitable for certain applications like printing and electrolytic capacitors.

A range of flexible conductive materials has been used to develop flexible sensors. Some of them are Carbon Nanotubes (Karimov et al. 2015), silver (Yao and Zhu 2014), copper (Kim et al. 2009), gold (Gong et al. 2014), iron (Alfadhel et al. 2016), etc. The conductive materials chosen to develop the electrodes depends on the fabrication technique and application of the sensors. For example, conductive inks are used to develop the electrodes with the ink-jet printing technique. Nanotubes are cylindrical structures in nanoscale level with extraordinary electrical, thermal and mechanical properties. The tubes are bonded with sigma bonds, which makes them much stronger than their macro-counterparts. Nanowires have a high aspect ratio, where the ratio between its length to width is greater than 1000. These nanowires are synthesized by a range of techniques like vapor-liquid-solid method, solution-phase synthesis, and non-catalytic growth. But, the conductivity of nanotubes is greater than the nanowires as a result of their lower mean free electron path than that of the later.

Also, the electrical conductivity of the nanotubes is higher than the nanowires due to the ballistic transport of electrons.

1.2 Printed Electronics

The recent progress in printing technology has brought a leap of advancements in the sensing world of electrical and electronics field. Printed technology has been adapted to develop sensitive electronic systems (Secor et al. 2014; Yin et al. 2010) as a result of certain advantages like their simplified processing steps, limited material wastage and overall low cost of fabrication. These features make it a very popular choice to use them for the development of large-area multifunctional electronic circuitries. The deployment of printed electronics has taken a major part for the fabrication of microelectronics using standard printing methodologies. Two of the major categories based on their fabrication techniques, namely contact and non-contact processes, are involved in printing technology. The contact process involves the physical contact of certain patterned inked surfaces with the substrates on which the electrode design has to be imprinted. Some of the common technologies of contact printing include R2R processing, flexographic and gravure printing.

Figure 0.2 Fabrication of flexible sensors using various printing techniques. (a) Direct printing using an ink-jet printer to coat gallium indium alloy on the paper. The wires developed from printed alloys are attached to the LED. (b) Optical images of the printed sensor for various components like Inductance coil and RFID antenna. (c) Schematic diagram of nano-printing done using a silicon mould. After the flowing of the molten precursor, demoulding is done followed by heating the sample at 250 °C. Three different types of nano-printing: hierarchical patterning, transfer stacking and polymer transfer are shown to demonstrate the differences in their techniques to develop sensors. (d) Schematic diagram of micro-contact printing. The pre-polymer is poured and cured on the pre-structured master to develop the elastomer stamp. The stamp is peeled off the master, cut into small pieces and used as a printing ink to stamp the replicated shape on a surface. (e) Transfer printing is done using the conformal stamp of a polymeric stamp with silicon wires. The wires are peeled off and transferred to the final substrate. (e) Screen printing of pressure sensors done on large flexible polymer films (f) with bumped structures on the top of the film (Khan et al. 2015).

Table 0.1 Features and challenges of some of the commonly used printing techniques to develop flexible electronic systems (Khan et al. 2015).

Printing Type	Features	Challenges
Screen	• Conventional printing technique. • Fast and controlled deposition of solutions. • The open area of the mesh is defined with pre-structured patterns.	• Resolution greater than 30 microns cannot be obtained. • The occurrence of spreading and bleeding of printed solutions. • Deteriorated patterns due to the spreading of the inks.
Inkjet	• Lower viscosity of solutions compared to screen printing. • Specific deposition of droplets. • Lower material wastage compared to other techniques.	• Unequal distribution of dried solute is causing a coffee-ring effect. • High chances of clogging because of misfringing. • Pixilation-related issues due to drop-on-demand.
Gravure	• The substrate should be smooth, have compressible porosity and wettability. • The ink should be high viscosity, solvent evaporation, and drying rate.	• Expensive process. • Detect and pick up related challenges due to contact printing. • Proper ratio of cell spacing to cell width.
	• A popular technique for printing on hard surfaces.	• Degree of solvent absorption effects the width of the printed line.

Offset	• The goal is for 100% transference. • Speed and pressure and the main process parameters.	• Spreading of the line during the set process. • High rolling resistance due to the fast rolling speed.
Flexographic	• Patterns are raised on the low-cost flexible plate using photolithography. • Better pattern quality concerning the contact printing methodologies.	• Layer cracks and non-uniform films. • Tensile stress is occurring due to solvent evaporation or high temperature. • Divergence from nominal specified values with speeding.
Micro-contact	• The stamp is inked and pressed against the substrate surface to transfer the design. • They are used for biological sciences to develop micro and nano-structured surfaces.	• Hydrophobic problems of some polymers like PDMS with the polar inks. • Change in the pattern sizes due to swelling to the stamp during the inking process.
Nano-imprinting	• The master material is pressed into a polymeric material cast at a specific temperature and pressure. • Creating a thickness in contrast to the polymeric material.	• Damage to the fragile nanostructures while removing the cast material. • Time-consuming technique compared to other contact printing process.

		• Difficult to replicate structures with resolution below 50 nanometers.
Transfer	• Transfer and printing occur through solution casting. • Combined techniques of photolithography and micro-contact printing.	• Misalignment of neighboring strips during undercutting. • Maintaining the surface quality of the backside of the flipped transferred structures is difficult.

The second type of printing approach is the non-contact printing, which allows the solution to be distributed on the substrate through openings in a mask in a defined pattern to form the electrodes. The substrate below the mask is adjusted in a pre-programmed manner to define the pattern of the designed electronic device. Some of the commonly used printing technologies adapting this process are screen and ink-jet printing. The non-contact printing approach is more advantageous than that of the contact one as a result of their higher resolution of the patterns, speed, and reduced material wastage. Figure 1.2 shows various types of sensing materials developed with the contact and non-contact processes (Khan et al. 2015). Even though the non-contact approach has certain advantages over the contact ones, there are certain challenges that need to be addressed in both techniques. Table 1.1 provides a summary of some of the advantages and disadvantages of the contact and non-contact processes obtained from work done in this area to develop a range of flexible electrical and electronic systems.

Apart from the approaches of the printing methodology, other classifications such as the choice of conductive inks to develop the colloidal solution have also been analyzed to determine the rheological properties of the solutions. Different types of materials including conducting (Leenen et al. 2009; Subramanian et al. 2008;

Tobjörk and Österbacka 2011), semiconducting (Dahiya and Gennaro 2013; Nomura et al. 2003; Zhang et al. 2009) and dielectric (Choi et al. 2010; Pease and Chou 2008; Subramanian et al. 2008) materials have been opted for, to form pure and hybridized printed electronic systems along with organic and inorganic polymers. The choice of a material to develop printed sensing prototypes depends on their capability to obtain optimality for some of the parameters like surface tension, viscosity, flexible and malleable compatibility, electrical and thermal conductivity and affinity of the resultant colloidal solutions. There are three main categories of conductive materials that are used for printing technologies till date. In the first category, metallic elements like silver (Li et al. 2005), gold (Luechinger et al. 2008), and copper (Lee et al. 2008) inks are used to design the electrode part of the circuit. Apart from the high cost of these materials, the oxidation in room temperature for some of the metallic pastes like copper and aluminum limits their range of applications. To tackle this limitation, some of the organic conductive polymers have been used (Blanchet et al. 2003; Zhou et al. 2012) along with these metals along with a range of printing technologies. These resultant conducting polymers are in different forms, which depends on the level of doping. Along with the use of the intrinsic ones (Kamyshny and Magdassi 2014), the doping level is varied with the n-type and p-type dopants, to have the resultant work function close to that of the semiconductors. Some of the common conducting polymers that are used for printing technology are polyacetylene (Sawhney et al. 2006), polyaniline (Crowley et al. 2008), polythiophene (Li et al. 2007), PEDOT: PSS (Sriprachuabwong et al. 2012), etc. Although these conducting polymers are employed on a large scale to fabricate printed electronic devices, the electrical conductivities of these polymers are much lower than for the conductive metals, which curbs their applications. Another favorable choice of conductive materials for the printing technology is the formation of nanocomposite using nano-fillers of a range of metallic nanoparticles and organic elastomers at the varied ratio. The amount of nanofillers in the polymer matrix depends on the percolation threshold of these mixed nanofillers, which eventually defines their dispersion in the matrix. Although the electrical, thermal and mechanical properties of the resultant nanocomposites is dependent on the number of nano-fillers mixed in the polymer matrix, the agglomeration of the nanoparticles with the matrix affects the rheological properties of the subsequent nanocomposite. This is somewhat optimized using a range of surfactants and volatile additives along the nanoparticles. Among the semiconducting materials, the ability of the transduction of the free carriers of some of the materials like crystalline silicon (Dahiya et al. 2012) and certain oxides of transition metals (Nomura et al. 2003) makes them a very favorable choice for printing technology. Similar to that of the organic conducting polymers, the organic semiconducting polymers (Fortunato et al. 2008) are also employed to a certain extent to form colloidal solutions as a result of their solubility and capability to optimal dispersal solutions. For the utilization of the dielectric materials to synthesize the colloidal solutions of the printed devices, the organic materials are favored over the inorganic ones as a result of their low-cost and capability to diffuse in different solvents and solutions.

The classification in a range of materials utilized to form the substrates of the flexible electronics is depended on their physical, chemical and optical properties that include their dimensional and thermal stabilities, bendability to a certain extent, transparencies and radiation properties. Thin glass, metallic foils and various plastics with different bendability are the three major types of substrates that are chosen to develop flexible systems. In accordance to the disadvantages of the intrinsic brittle property of the thin glass and the surface roughness to a certain degree of the metal foils, the plastics possess advantages over these two limitations in comparison to the other two types. Among the different plastics that are used as substrates for printing technologies, amorphous and semi-crystalline polymers are the most popular ones. A few examples of these types of plastics include Polycarbonate (PC), Polyethersulfone (PES) and Polyethylene Terephthalate (PET), Polyethylene Naphthalate (PEN), and Polyether ether ketone (PEEK) respectively. In a comparison between two types, the semi-crystalline ones are more advantageous that the amorphous ones as a result of their higher glass-transition (T_g) temperature.

1.3 Conclusion

The chapter showcases a brief introduction to flexible sensors and the associated printing technologies used to develop them. Initially, the raw materials used to fabricate the flexible sensors was explained along with their background, followed by the elucidation of the individual electrode and the substrate parts. In continuation of this, some of the commonly used fabrication techniques used to develop the flexible sensors are explained in this chapter. The commonly used printing techniques are explained in the second section, which is utilized to develop flexible electronic and electrical systems. The importance of printed electronics has also been highlighted regarding the different printing technology available to develop flexible sensors along with the features and challenges while operating them. Among the range of fabrication techniques available in printing technologies, laser and 3D printing are some of the commonly used techniques as a result of to their low fabrication cost, easy sample preparation and the capability to form smooth and flexible cuts of the final prototypes. The sensor patches developed with the laser cutting and 3D printing techniques are eventually utilized for varied applications like monitoring of the environment, industrial and health parameters. The utilization of different sensor prototypes for their subsequent applications as a result of their physiochemical suitability for that particular use. The advancement in the field of microfabrication of sensors has been focused along with their potential to be deployed for practical work.

1.4 The aim of the book

Flexible sensors have showcased enormous potential to be deployed for monitoring purposes in the field of healthcare, environment, and industrial applications. The full-blown use of this category of sensors is yet to be done to generate an influence on the quality of life of people. The presented work shows great potential in the utilization of sensors in the real world. Among the various types of fabrication techniques that are utilized to generate flexible sensors differing regarding dimension, cost and resolution, the use of printing technology have been done on an enormous scale. The research work on printed flexible sensors has been constantly expanding as a result of their advantages of low-cost, enhanced electrical, mechanical and thermal properties. In this book, the explanation of the novel flexible printed sensors was done which were formulated using laser cutting and 3D printing techniques. Four different types of printed flexible sensor prototypes were developed, characterized and utilized for different applications. The purpose behind the formation of each of these sensor prototypes can be attributed to highlight their low cost of fabrication, simple operating principle, and multifunctional capabilities. The electrical behavior of the electrodes was based on a parallel-plate capacitor as a result of their interdigitated shapes. Electrochemical Impedance Spectroscopy was used in association with the sensor prototypes to determine the output concerning the corresponding changes in the input signals. The distinctions among these prototypes were based on their individualistic characteristics as a result of the different raw materials that have been processed to fabricate them. Multi-Walled Carbon Nanotubes, graphene, aluminum, and graphite are some of the conductive materials that were processed to form the electrodes of the sensor prototypes because of their light weight, high electrical conductivity, durability and high aspect ratio. Polydimethylsiloxane, polyethylene terephthalate, and polyimide are some of the polymeric materials that were processed to form the substrates of the sensor prototypes because of their low-cost, biocompatibility, low Young's modulus and capability to form flexible, bi-layer structured devices. The sensor prototypes were utilized for different applications like monitoring of movements of different body parts, respiration and taste sensing in the point of view for healthcare, salinity and nitrate sensing for the environment, and low-force and tactile sensing for industrial applications.

1.5 Research Contributions

The important contributions of this work lie in the fabrication, characterization, and utilization of four types of flexible sensing prototypes. The novelty in this work can be defined to be the usage of the processed materials and the fabrication techniques. The working principle of the flexible sensor prototypes was studied and presented along with the electrical and mechanical changes taking place during their experimentation. The sensor prototypes were used in different sectors including healthcare, environmental and industrial applications. The fundamental purpose of these sensors is for the advancement of the micro and nano-electronics for monitoring multiple applications ubiquitously.

The major contributions of this research can be summarised as follows:

1. A brief introduction is given regarding the fabrication and implementation of wearable, flexible systems. It showcases the use of some common materials along with different techniques used to process them to form prototypes that are significant for the electronic world.
2. A detailed background study of the work done on the development of sensing prototypes with conductive materials like CNTs and graphene is done. The sensors fabricated using CNTs and graphene are categorized into different applications, based on their electrochemical, strain and electrical nature. The challenges faced by the current sensors along with some of the possible remedial solutions are also explained in the paper.
3. The detailed explanation of the working principle of all the fabricated sensor prototypes is also done in the book. The interdigitated structure of all the sensors prototypes worked on planar capacitive principle. Usage of electrochemical impedance spectroscopy (EIS) in conjugation with the impedance analyzers at different experimental setups is also elucidated in the paper. The sensors were connected to the analyzers via probes to determine the response concerning different inputs at specified frequencies.
4. The design, fabrication, and implementation of the first sensor prototype were done in the succeeding chapter. Carboxylic acid functionalized Multi-Walled Carbon Nanotubes (MWCNTs) and Polydimethylsiloxane (PDMS) were used as the conductive and substrate materials respectively. Laser cutting technique was used to curve the electrodes from a nanocomposite (NC) layer formed

with the mixing of MWCNTs and PDMS at definite proportions. The developed were used for monitoring physiological movements like limb movements and respiration. They were also employed for measuring low-pressure tactile sensing to determine their capability to be used for prosthetic applications.

5. The succeeding chapter describes the formation and implementation of the second sensor prototypes formed with metalized polymer films. Polyethylene terephthalate (PET) films being metalized with aluminum on one side was used as the singular processing material. The electrodes were carved via laser inducting from the the aluminum side of the metallized polymer films to form the sensor prototypes. The developed sensors were used for tactile sensing via applying different pressure ranges through the index finger, thumb and palm.
6. Highlight on the fabrication and employment of laser-induced graphene sensors was given in the succeeding chapter of the book. Commercial polymer films were laser-induced for the photo-thermal formation of graphene. This conductive material was transferred to the Kapton tapes to form the electrodes of a sensor. These sensors were used for monitoring the amount of salinity and nitrate content in different water bodies. They were also used as taste sensors where five different chemicals about individual tastes were experimentally tested to determine the differences in the responses.
7. The fourth and final sensor prototype, developed from Graphite and PDMS was underscored to highlight their fabrication and application. 3D printed molds were used as templates for casting and curing of Graphite and PDMS at defined heights to form the electrodes and substrates respectively. The formed sensors were used for strain-induced applications like monitoring of limb movements, by connecting them to different bendable locations of the body like knee, elbow, neck, and finger. They were also used for low-pressure sensing by applying low forces on the sensing area of the prototypes.
8. The conclusion of the explained work is drawn in the final chapter of the book which summarizes the work explained in the preceding chapters. It also highlights some of the future applications that can be done with the fabricated sensors, along

with the possibility of forming new sensing prototypes with a range of raw materials.

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