Printed and Flexible Sensor Technology

Fabrication and applications

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Fabrication and applications

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Preface

The intervention of sensing systems within the modern world has revolutionized the quality of human life. Almost every aspect of day-to-day activities in today's world involves the implementation of sensors in some way. Their presence has not only made our lives easier, but has also allowed humanity to progress on a technological level. The sensing systems as we use them today are being developed and characterized mostly in academic and industrial contexts. Following the sensorial pyramid, different kinds of prototypes have been fabricated, varying in terms of their processed materials, operating principles, and respective applications. Each of these prototypes is being specialized to have high efficiency in terms of sensitivity and robustness for the targeted application. The advancement in technology has allowed highly functionalized equipment to be developed that can be mass-produced for point-of-care sensing systems. Among the sensors that are currently available, the flexible sensors have been able to perform in a much more dynamic manner in comparison to the conventional MEMS-based silicon sensors. The additional wearable nature of flexible sensors has allowed them to be used for ubiquitous monitoring purposes. These flexible sensors have been fabricated using a range of printing techniques, each of which has the capability to form high-quality thin-film sensors. These prototypes have revolutionized the world of flexible sensors due to their simple fabrication techniques, quick roll-to-roll production, and simple operating mechanisms. The choice of printing technique primarily depends on the specifications of the sensors, which in turn depend on their applications.

In recent times, with the conjugation of nanotechnology and printing techniques, these flexible sensors have increased their dynamicity for real-time applications. The developed printed and flexible sensors have been exploited successfully in biomedical, industrial, and environmental applications. With the advent of nanotechnology these printed flexible sensors have attained further heights with respect to their performance. Nanomaterials have been included in various forms using the available printing mechanisms to enhance the resultant functionality. 1D and 2D conductive materials have been utilized thoroughly to enhance the sensitivity and selectivity of prototypes. Flexible printed sensors have allowed us to further formalize entire systems to determine the interfacing circuits for conditioning and transmitting the sensed data. Market surveys have also presented a great need for these sensors, not only to increase the multifunctional nature of the sensing systems but improve their impact on the chosen application. The exponential increase of these printed flexible sensors in the near future can be justified by the need in automated systems for detection in sectors of prioritized significance.

This book contains a structured overview of the fabrication techniques of the various printed flexible sensors that have been formulated and devised. It also contains some of the significant applications of these printed flexible sensors, conducted in controlled and real-time scenarios. This book contains chapters contributed by experts in their respective fields who have studied and operated printed flexible sensors via designing and employing them. It also presents the technological growth in the field of printed flexible sensors by presenting current trends. Each of the presented works will not only allow the reader to obtain an understanding of this field but will also assist the reader to improvise and innovate something of their own. This book is organized in the following manner.

Chapter 1 presents an overview of the sensors and fabrication techniques that are currently available. It also presents a brief overview of the sectors in which these prototypes have been deployed. This is followed by chapter 2, which exemplifies the utilization of printed flexible sensors for a range of research-based applications. It also categorizes the applications, providing the advantages and reliability related to each of them. Chapter 3 highlights the work done on the fabrication of printed flexible sensors in terms of their issues and resolution. It deals with the fabrication of printed flexible sensors via highlighting some of the challenges related to their fabrication techniques and possible corresponding solutions. Chapter 4 showcases the potential of 3D wax printing technology to create sophisticated biomedical devices. It also explains the application of printable devices for point-of-care testing and various biosensing purposes and details some recommendations and future directions for improving sensing accuracy and robustness. Chapter 5 summarizes some of the laser induced graphene preparation methods and their broad-spectrum applications, in particular in electrochemical and biosensing. It also focuses on the future outlook and research gaps in the reported literature. Chapter 6 provides an overview of the significant development in wearable microfluidic devices in terms of their fabrication and characterization. It also shows different categories for its use in physical property and body fluid sampling, manipulation, and detection. Chapter 7 reviews the recent developments in assembly techniques, including printing processes for forming films or networks of single-walled carbon nanotubes (SWNTs). The challenges related to the processing and performance of SWNTs, along with the potential research that can be performed with SWNTs, are also presented. Chapter 8 presents the fabrication and implementation of flexible strain sensors using graphene and its composites. It analyzes the capability of the remarkable material graphene in developing high-quality flexible strain sensors. Chapter 9 presents an overall review of screen-printed electrochemical and impedance biosensors. This is achieved by presenting different cases involving the estimation of environmental contaminants, food toxins, protein molecules, bacteria, and viruses. Chapter 10 deals with the properties of cellulose paper and its use for flexible electronic device applications. It explains the design and technology of flexible electronics produced using cellulose paper. Chapter 11 explains the synthesis and characterization methods for printing/fabricating graphene-based implantable electrodes for various neural recording and stimulation processes. This is followed by chapter 12 which shows the work done on screen-printed electrode-based sensors for the detection of biological and chemical species. It highlights the potential of electrochemical methods of screen-printed electrodes for accurate measurements of trace level biochemical species in a sample solution using a rapid and cheap analysis method. Chapter 13 provides a brief overview of the role of 3D printing in microfluidic enzymatic biofuel cells, along with related recent work in upcoming research areas. Chapter 14 presents the work done on the use of an array of interdigitated electrodes for developing novel incontinence sensing systems. These devices consist of simulation using ANSYS finite element analysis (FEA) and printing of the conductive polymer PEDOT:PSS on PET substrates. Chapter 15 presents an experimental study carried out to develop a transparent thin-film strain sensor (TFSS) using an unconventional substrate (PET with a pre-applied thin pressure-sensitive adhesive layer) and to investigate its response to static and dynamic strain environments. Insights into the fabrication of high figure of merit transparent thin films at room temperature and the methodology to develop a transparent TFSS, along with its performance evaluation, are described in this chapter. Chapter 16 reports the work done on high-performance radio frequency (RF) magnetron sputtered cerium oxide (CeO_2) thin-film-based oxygen sensors by optimizing the film thickness. Chapter 17 presents the fabrication of a metal oxide (MOX) trace moisture sensor on a flexible substrate. The sensors are parallel-plate capacitors with nanoporous alumina hydrophilic sensing films, deposited on polyimide using the solution method. Chapter 18 discusses the importance of droplet detection and the need for improvements in sensor geometry for precise and accurate detection of microdroplets. A novel type of printable and flexible sensor is introduced for droplet detection, which utilizes the capacitive transduction principle and the detection is contactless, thus increasing the lifetime of the detection system. Chapter 19 focuses on flexible and conformal antennas for wireless communication and sensing applications.

The chapters contributed to this book have been written with the utmost care and detail in order to present the work in a simple and efficient manner. The valuable research ideas imparted by the contributing authors have allowed us to present the high-quality research taking place in the microelectronics industries. Each of the presented research works will help the reader understand the functionality of printed flexible sensing systems at both the basic and advanced levels. The compilation of this interesting and useful book would not have been possible without the priceless contribution of the authors and their willingness to participate in this journey.

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Chapter 1

Printed and flexible sensors: a review of products and techniques

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Sensors are playing an increasingly important role in our day-to-day lives and are helping us to lead safer and more secure lifestyles. Different types of sensors are used in different spheres in our lives, including healthcare, environmental monitoring, industrial applications, and many other fields. Printing is not a new technique in the sensor industry, in fact some types of sensors have always been printed. However, with the development of new and high quality materials and the advancement of technologies, a new generation of printed sensors is now emerging from various research and development activities with a wide range of applications. In recent times flexible sensors have emerged as another new paradigm of sensor research and application. This chapter will review the different available sensor products and will discuss the techniques used to fabricate such sensors.

1.1 Introduction

Humans are blessed with five excellent sensing organs—the eyes, ears, nose, tongue, and skin—along with the control centre, the brain, to organize and respond to all activities. To make our lives safer and more comfortable, the exploration, design, and development of different types of sensors are never-ending. Printing technology in the field of sensors began many decades ago and with time it has become smart, efficient, and productive. It allows many sensors to be printed within one fabrication step. Various types of sensors are manufactured partially by screen printing, in which the transducer is a printed layer of either a polymeric or ceramic material. This technology has been used in the sensor industry for many years. Progress in printed electronics now enables more sensors to be printed in their entirety. Since sensors have a much simpler structure than other electronic components such displays or logic circuits, the manufacturing learning curve is therefore less steep compared to many other printed electronics applications. In most cases, these new

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printed sensors can be fabricated on plastic substrates with the advantages of mechanical flexibility, thinness, and light weight [1–4]. Printed sensors are eco-friendly in nature and have the ability to fit onto various small, differently shaped electronic devices for different applications. Printed sensors eliminate the use of silicon and metal oxides, instead, with the help of innovative printing technologies, printed sensors can be manufactured on various flexible substrates such as paper, plastics, and foils [1–4].

Printed sensors and sensing devices find applications in various industries, including the automotive industry, environmental testing, consumer electronics, medical devices, smart packaging, building automation, and industrial equipment [1, 2]. The demand from some fields, in particular from smart packaging, is expected to grow at a high rate owing to the ability of sensors to enable manufacturers to keep track of inventory. The growing adoption of printed sensors in this industry to enhance the quality, visibility, hygiene, and safety of a product is anticipated to enhance the market growth of printed sensors. Printed sensors are being used increasingly in the food and beverage industries to monitor the temperature, gas, and humidity of sensitive products. With time many new exciting and challenging applications will find use for flexible and printed sensors.

Planar printed sensors can be of different shape, structure, and fabrication to cater for a certain application. In the early 2000s different types of sensors, mainly meander and mesh type configurations, were designed and developed [5–12]. The size and configuration were modelled and the experimental performance was evaluated. Planar printed sensors have been applied in many applications, for example, the determination of the quality of meat, in particular protein and fat content, is reported in [13], and consistent performance in the design of saxophone reeds is reported in [14]. The processing of leather, making use of planar electromagnetic sensors of interdigital type, is reported in [15] and the determination of the contamination of nitrate in water is described in [16]. The report in [17] describes the measurement and performance evaluation of novel planar interdigital sensors for different chemicals related to food poisoning. The contamination of phthalate leaching from plastic bottles is reported in [18]. The operating mechanism and preliminary results of using printed interdigital sensors to detect the leakage of liquefied petroleum gas are reported in [19] and the effects of particle size, composition, and coating layer thickness on its performance are reported in [20]. During the last few years, flexible sensors have been fabricated for different applications. Laser-ablated metallized PET films for tactile sensing are reported in [21], and a laser-induced graphene sensor has been designed and fabricated for salinity testing [22]. Printed sensors based on flexible materials as well as silicon based fabrication to detect water contamination and environmental monitoring are reported in [23] and [24], respectively.

A significant amount of research on printed and flexible materials is taking place in different parts of the world and many sensors are being developed. Although there remain many challenges, such as developing sensors with very small sized and adequate mechanical strength, selective detection, environmental friendliness, long lifetimes, and so on, the investigation of smart technology, new materials, and novel applications will continue in future.

1.2 Major manufacturers

Currently, many companies are involved in the design and development of printed and flexible sensors. Some of the major global players are included in the following with a short description, some elements of which have been quoted from their websites. There are also other manufacturers who are involved in the design, development, and production of printed and flexible sensors.

1.2.1 Interlink Electronics

Founded in the mid-1980s, 'Interlink Electronics has evolved into a leading provider of printed electronics, HMI devices, and sensor solutions' [25]. The company offers 'a full range of standard products as well as the ability to create custom solutions by leveraging the expertise in prototyping, materials science, firmware and software development, sensor fusion, system integration, and manufacturing' [25]. The company has developed sensor applications for numerous and diverse industries, such as the automotive, medical, industrial, and robotics fields. Interlink is also active within the burgeoning Internet of Things (IoT) sector, adopting the essential role of a full-service system integrator for IoT applications due to their membership in the LoRa Alliance ecosystem.

1.2.2 Tekscan

'Tekscan technology encompasses sensor technology, data acquisition electronics, and processing and analysis software. FlexiForce force sensors are ultra-thin and flexible printed circuits, which can be easily integrated into force measurement applications' [26].

1.2.3 PST Sensors

'Founded in 2010, PST Sensors is a Cape Town based technology company focussed on printed electronics and sensors. The letters PST stand for Printed Silicon Technology which forms the company's innovative base, and the word Sensors represents the team's passion for providing cutting edge temperature sensing solutions far beyond today's approaches' [27].

1.2.4 GSI Technologies

Established in the 1980s, the company has '40 years of experience with precision printing, use conductive inks to create durable, high-performance RFID antennae, electrodes, medical diagnostic sensors, drug delivery patches, organic photovoltaics, electro-chromatic and thermo-chromatic displays, smart cards, and many other applications across various industries. GSI is a leading provider of medical diagnostic electrodes, RFID antennas, printed heaters, printed sensors, EL lamps, and many other printed electronic applications' [28].

1.2.5 KWJ Engineering

KWJ Engineering ‘builds products for detecting and monitoring a variety of gases including carbon monoxide, ozone, hydrogen sulfide, and other environmental pollutants. The developed instruments and modules are used in many industries including Smart Cities, Smart Homes, Personal Wearables, and IoT applications’ [29].

1.2.6 Peratech Holdco

‘Force-sensing HMI/MMI Solutions Company, founded in 1996 and inventor/developer of proprietary of Quantum Tunnelling Composites materials, providing next-generation Touch/Force-Sensing solutions. QTC® materials today are custom developed screen-printable inks, in both opaque and clear formulations, printing at only a few microns thick. These new incarnations of the material replace the legacy sheet materials, opening up many new opportunities for the technology as the key enabler. Peratech QTC® technology has been integrated in over one million devices, in areas such as smartphones, electronic whiteboards, cordless drills and even NASA robots’ [30].

1.2.7 ISORG

‘The company’s core technology successfully integrates printed photodiodes on different substrates to enable large-area image sensors for the smartphone and security markets and extended applications in medical x-ray imaging, non-destructive testing and stock management. The company has strong knowledge in integration of printing-based photodiode on different substrate (glass, polyamide i.e. PI, …) allows us to do image sensor of different size and shape dedicated to several applications’ [31].

1.2.8 Fujifilm

‘Starting in the 1980s, the use of digital technologies spread across a wide range of industries. From the beginning, Fujifilm was a digital pioneer, rapidly generating major digital advances in the fields of medicine, photography, printing, and more.

In the field of medicine, Fujifilm developed Fuji Computed Radiography (FCR), the world’s first digital x-ray diagnostic system. In the field of photography, Fujifilm developed the DS-1P, the world’s first digital camera, as well as the world’s first digital minilab. In the field of printing, Fujifilm developed highly innovative computer-to-plate (CTP) systems.

To create all of these fundamental technologies, Fujifilm have developed strong fundamental technologies in electrical engineering, electronics, image analysis, imaging, and software. The core technologies that arose from these efforts remain one of Fujifilm’s key strengths today’ [32].

1.2.9 Canatu

‘Canatu’s solutions have brought the design freedom and user experience to the next level for 3D shaped touch devices. Canatu develops and manufactures innovative

3D formable and stretchable films and touch sensors, which are integrated into plastic, glass, textile or leather enabling 3D touch displays, smart switches and other intuitive user interfaces in automotive and consumer electronics' [33].

1.2.10 PolyIC

'PolyIC develops and markets products based on the platform technology printed electronics: In the course of this PolyIC focusses on individually manufactured transparent and flexible metal-mesh touch sensors. Touch sensors based on the PolyTC® technology offer transparent, conductive and flexible possibilities for touch screens and capacitive keys in any variants. The highlight is the possibility to combine decoration and function to achieve a maximum of design flexibility' [34].

1.2.11 MC10

'MC10's proprietary BioStamp® system wearable health tech creates comfortable, discreet sensors that can be applied anywhere on the body for targeted data collection. The wearable sensors are wireless and rechargeable via the included Link Hub. A dedicated mobile phone plus Link Application designed for remote data collection guides users through sensor application, prescribed activities, and eCOA' [35].

1.2.12 QUAD Industries

'Quad Industries uses its expertise in high-precision, fully automated screen printing-techniques to integrate functionality directly on various lightweight and flexible materials such as plastics, textiles, TPU and on paper. This allows the integration of a wide range of electronics—sensors, connectivity, heating—in any object, irrespective of its shape, size or material. Printed electronics not only enhance flexibility, they are also less harmful to the environment and more cost-effective to manufacture' [36].

1.2.13 Terabee

'Terabee develops and manufactures a wide range of sensor modules, including 2D infrared LED time-of-flight distance sensors, 3D time-of-flight depth cameras, and thermal cameras' [37]. The developed 'products are easy to use, compact, lightweight and offer great performance over a wide range' [37].

These major market players are involved in strategies, such as acquisitions, new product launches, and partnerships, to expand their reach in the market. For example, Thin Film Electronics ASA signed a distribution agreement with CymMetrik, China. This agreement focuses on sales expansion in India, China, and Taiwan. The printed sensors market ecosystem comprises raw material vendors, manufacturers, and end users. Some of the raw material vendors include T+ink, FlexEnable, Palo Alto Research Center, Brewer Science, and DuPont.

1.3 Materials for printed and flexible sensors

Manufacturing cost is an important consideration, but other than the cost of fabrication there are many other factors which need to be considered for the selection of materials for different parts of printed and flexible sensors. The size, mechanical strength, long-term performance, resistance to harsh environments, repeatability, reusability, and non-toxic and non-hazardous nature are the main requirements for the materials used in fabricating sensors.

Traditional printed sensors are based on silicon technology—an oxidized silicon wafer is spin coated with photoresist. A photoresist is a light-sensitive material used in several industrial processes, such as photolithography and photoengraving, to form a patterned coating on a surface. Different chemicals are used to give a material the desired permanent property variations. Materials such as poly(methyl methacrylate) (PMMA), poly(methyl glutarimide) (PMGI), phenol formaldehyde resin (DNQ/Novolac), and SU-8 are used. The materials are all applied as a liquid and are generally spin-coated to ensure uniformity of thickness.

Dry film stands alone amongst the other types in that the coating already exists as a uniform thickness, semi-solid film coated onto a polyester substrate and the user applies that substrate to the workpiece in question using lamination.

Gold sputtering is usually adopted on the side opposite to the sensing surface and it acts as a ground plane for single-sided measurement. The duration of sputtering depends on the density of the material sputtered and the thickness of the sputtered layer.

For flexible printed sensors the electrodes are usually printed on a substrate material. Different types of materials are currently available to be used as substrate materials. Although polydimethylsiloxane (PDMS) is extremely popular in research and development, other materials are also used. The comparative advantages and disadvantages of the different materials used as substrates are shown in table 1.1 [38–41].

Table 1.1. Comparative advantages and disadvantages of different substrate materials.

	Polydimethylsiloxane (PDMS)	Polyethylene terephthalate (PET)	Polyimide (PI)
Advantages	• Inert • Non-toxic • Non-flammable • Hydrophobic	• Inexpensive • Good chemical resistance • High resistance to temperature • High flexibility	• High flexibility • Good chemical and thermal resistance • High mechanical toughness
Disadvantages	• Difficult to integrate electrodes • Deposition needs to be carried out directly on its surface	• Very susceptible to heat degradation • Poor impact strength	• Expensive • Poor resistance to alkalis • Low impact strength

Table 1.2. Comparative advantages and disadvantages of different electrode materials.

	CNTs	Graphene	Aluminum
Advantages	• Better dispersion with a mixed polymer • Better compatibility • Higher flexibility	• High surface-to-volume ratio • Excellent electrical conductivity • High carrier mobility and density • High thermal conductivity	• Corrosion resistant • Strong in low temperatures
Disadvantages	• Low purity • Short lift time • Expensive growth process	• Does not have a band gap • High quality graphene is expensive and requires a complex process • Graphene exhibits some toxic qualities	• Growth of an oxide layer • More expensive than steel • Abrasive to tooling

The electrodes in flexible sensors are usually made of different materials, the most common among them are graphene, carbon nanotubes, aluminium, etc. The relative advantages and disadvantages of these materials are provided in table 1.2 [38–42].

The most common plastic substrates are polycarbonate (PC), polyethylene terephthalate (PET), polyethylene naphthalene (PEN), polyarylethersulfone (PES), polyamideimide (PAI), polyimide (PI), and polyethylene (PE).

1.4 Printing technologies

Many technologies are available and under development for printed and flexible sensors. In this section a few technologies will be described in brief. Some of the techniques will be used in combination to produce a printed sensor.

1.4.1 Thick-film technology

Thick-film technology is a common method used by many industries 'to produce electronic devices such as surface mount devices (SMD), hybrid integrated circuits, heating elements and sensors' [43, 44]. 'The complete method involves deposition of several successive layers of conductors, resistors and dielectric layers onto an electrically insulating substrate using a screen-printing process. The whole thick-film process usually consists of the following stages: lasering of substrates [45], preparation of ink [46], screen printing [47], drying/curing [48], firing [49], abrasive trimming [50] and laser trimming [51].

1.4.2 Thin film technology

Wikipedia defines a thin film as 'a layer of material ranging from fractions of a nanometer (monolayer) to several micrometers in thickness. The controlled synthesis of materials as thin films (a process referred to as deposition) is a fundamental step in many applications'. Thin film sensors 'are produced by directly depositing material onto fixtures in a vacuum deposition chamber by a process known as sputtering. A sputtering system allows for process control so that films may be produced with a high degree of repeatability' [52–54].

1.4.3 Inkjet printing

According to Wikipedia, the 'concept of inkjet printing originated in the 20th century, and the technology was first extensively developed in the early 1950s. The world first inkjet printer was invented by Ichiro Endo, who worked for Canon in Japan. In the late 1970s, inkjet printers that could reproduce digital images generated by computers were developed, mainly by Epson, Hewlett-Packard (HP) and Canon. In the worldwide consumer market, four manufacturers account for the majority of inkjet printer sales: Canon, HP, Epson and Brother' [55]. Inkjet printing is a type of digital or non-contact printing that recreates a digital image by propelling droplets of ink onto paper and plastic substrates [55].

1.4.4 Photolithography

Lithography is derived from the Greek words *litho* for stone and *graph* for drawing. Photolithography, also called optical lithography or ultra-violet (UV) lithography, is a process used in microfabrication to pattern parts on a thin film or the bulk of a substrate [56]. It uses light to transfer a geometric pattern from a photomask onto a photosensitive chemical photoresist on the substrate. The steps involved in the photolithographic process are wafer cleaning; barrier layer formation; photoresist application; soft baking; mask alignment; exposure and development; and hard-baking [57].

1.4.5 Masked photolithography

A photomask is made by exposing, or writing, the designer's pattern onto a resist coated chrome mask blank [58]. The latent image in the resist is then developed to form the required pattern. This resist image acts as a mask during the etching process. The pattern is transferred into the chrome film when the resist layer is removed. 'Photolithography uses three basic preparation steps to transfer a pattern from a mask to a wafer: coat, develop, expose. The pattern is transferred into the wafer's surface layer during a subsequent process. In some cases, the resist pattern can also be used to define the pattern for a deposited thin film. The wafer is exposed by UV (ultraviolet) from a light source traveling through the mask to the resist. A chemical reaction occurs between the resist and the light. Only those areas not protected by the mask undergo a chemical reaction' [58].

1.4.6 Maskless photolithography

The process of maskless photolithography, which does not use an intermediate static mask, utilizes methods that transfer the information directly onto the substrate. There are some advantages as well as disadvantages to this method compared to masked photolithography, which are detailed in [58, 59]. A key advantage of maskless lithography is the ability to change the lithography patterns from one run to the next, without incurring the cost of generating a new photomask [60].

1.4.7 Screen printing

The complete process of screen printing is explained in detail in [61]. Screen printing is a multidimensional process, and it becomes complex when micro- to nano-level electronics devices are to be printed precisely on a flexible or bendable substrates. The properties of substrates, such as surface roughness and chemical, mechanical, thermal, optical, thermo-mechanical, electrical, and magnetic properties, have to be studied in detail. The correct properties need to be chosen for optimum utilization. In the case of screen printed antennas, consistency in maintaining the required 'planarity' of the flexible or non-flexible underlying substrate will be of utmost importance.

1.4.8 Sputtering

According to Intlvac '[s]puttering can be described in a number of ways: cathodic sputtering, diode sputtering, RF or DC sputtering, ion-beam sputtering, reactive sputtering—but all of these are essentially describing the same physical process. Sputtering is a thin-film manufacturing process widely used across many industries including semiconductor processing, precision optics, and surface finishing. Sputtered thin films have excellent uniformity, density and adhesion making them ideal for multiple applications.

The target (source) material and substrate (destination) are placed into a vacuum chamber and a voltage is applied between them so that the target is the cathode and the substrate is attached to the anode. A plasma is created by ionizing a sputtering gas, usually an inert gas such as argon or xenon. Inert gases are typically employed as the sputtering gas because they tend not to react with the target material or combine with any process gases and because they produce higher sputtering and deposition rates due to their high molecular weight.

The sputtering process occurs when the target material is bombarded with the sputtering gas and the resulting energy transfer causes target particles to escape, travel and deposit on the substrate as a film. For the sputtering process to produce an effective coating, a number of criteria must be met. First, ions of sufficient energy must be created and directed towards the surface of the target to eject atoms from the material. The interaction of the ions and the target are determined by the velocity and energy of the ions. Since ions are charged particles, electric and magnetic fields can control these parameters. The process begins when a stray electron near the cathode is accelerated towards the anode and collides with a neutral gas atom converting it to a positively charged ion' [62, 63].

1.4.9 Direct laser writing

Prem Prabhakaran at l3dw.com defines direct laser writing (DLW) as '3D printing for the microscopic world. This techniques goes beyond the smallest shapes and sizes that can be accomplished by garden variety 3D printing. The highest resolution that can be achieved by DLW is typically [in the] few micron to sub-micron range. To put this into perspective, the average human hair has a cross section of 70–100 μm so we can imagine [...] the 3D structures [sitting] nicely [...] by the dozen across the cross-section of a hair. This technique allows 3D drawing of complex shapes with fine features (μ to few nm). The complexity of shapes that can be achieved by this technique are limited only by [the] photochemistry of [the] materials used for fabrication, and the limits of the optical setup' [64].

1.4.10 Direct dry printing of carbon nanotubes

As Binghao Liang *et al* explain 'in the direct dry printing of carbon nanotubes, a porous CNT block [is] used as both the seal and the ink; and Ecoflex film...serve[s] as an object substrate. Well-designed CNT patterns can be easily fabricated on the polymer substrate by engraving the target pattern on the CNT seal before the stamping process. Moreover, the CNT film can be directly used to fabricate [an] ultrathin (300 μm) strain sensor. This strain sensor possesses high sensitivity with a gauge factor (GF) up to 9960 at 85% strain, high stretchability (>200%) and repeatability (>5000 cycles)' [65].

1.4.11 Hybrid printed electronics

According to Holstcentre 'The hybrid printed electronics technology opens new possibilities for electronics applications. Combining printed circuits and devices with traditional electronic components like LEDs and chips, it enables large-area, flexible and freeform applications that can be manufactured in high volumes using roll-to-roll printing and assembly processes' [66, 67].

1.5 Conclusion

The chapter has described the progress of printed and flexible sensors over the last few decades. The demand for small sizes, smart devices, high performance, and critical applications is keeping the research and development of the field exciting. Many different sensors have been reported and a lot of work is in progress. With time new sensors will be available for use and will help us to live a better, healthier, and more comfortable life. New challenges, such as COVID-19, will be faced by humanity in the future and researchers will find ways to tackle these problems and find appropriate solutions.

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