Recent developments of inkjet-printed flexible sensing electronics for wearable device applications: a review

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Abstract

Purpose – This paper aims to encompass the technological advancements in the area of flexible sensing electronics fabrication particularly for wearable device development applications. In the recent past, it is evident that there is a tremendous growth in the field of flexible electronics and sensors fabrication technologies all around the world. Even though, there is a significant amount of research has been carried in the past decade, but still there is a huge need for exploring novel materials for low temperature processing, optimized printing methods and customized printing devices with accurate feature control.

Design/methodology/approach – The author has done an extensive literature survey in the proposed area and found that the researchers are showing significant interest in exploring novel materials, new conductive ink processing methods suitable for additive manufacturing, and fabrication technologies for developing the plastic substrate-based flexible electronics for the on growing demands of wearable devices in the market.

Findings – The author has consolidated some of the recent advancements in the area of flexible sensing electronics using the inkjet-printing platform carried out by the researchers. The novel customized inkjet-printing technology, materials selections for device development, compatibility of the materials for the inkjet-printing process and the interesting results of the devices fabricated are highlighted in this paper.

Originality/value – The author has reported the novel inkjet-printing platforms explored by researchers in the recent past for various applications which primarily includes gas sensing. The author has consolidated in a crisp manner about the technology, materials compatible for inkjet-printing, and the exciting results of the printed devices. The author has reported the advantages and challenges of the proposed methods by the researchers. This work will bridge the technical gap in the inkjet-printing technology and will be useful for the researchers to take forward the research work on this domain to the next level.

Keywords Wearable devices, Flexible sensors, Inkjet-printing, Nano conductive inks, Printing technologies

Paper type Literature review

1. Introduction

Thick film and thin film methods can be used for sensors fabrication as shown in Figure 1, but these methods have got certain major drawbacks. The drawbacks of these two methods are listed in the Table 1. In this regard, there is a great necessity to explore new sensor fabrication methods which can overcome the drawbacks of the conventional methods. In the recent past, people are doing extensive research work on establishment and optimization of reliable inkjet-printing technology for the sensor fabrication purpose. The strong motivation this research work is to develop a flexible gas sensor element for a wearable device application by exploring a reliable and cost-effective inkjet-printing technology.

Inkjet-printing technology can be considered as one of the most promising alternatives to the conventional thick and thin film fabrication methods, by which the conductive materials in the form of lines/layer can be drawn (printed) onto the substrate in one step. There are two important components of the inkjet-printing technology which are mentioned below:

1 Mechanical system (printer).
2 Conductive material (ink).

The studies were focused by various researchers on the formation of droplets, accurate control of dropping location and printing parameters (Meinhart and Zhang, 2000; Huang and Kim, 2001; Tseng *et al.*, 2002; Perçin and Khuri-Yakub, 2003; Azucena *et al.*, 2008; Yang *et al.*, 2009; Ahn *et al.*, 2011; Yung *et al.*, 2014; Huang *et al.*, 2014; Dang *et al.*, 2014). On the research of conductive ink, several materials were studied including molten metal, conductive polymer and metallic nanoparticle suspension (Calvert, 2001). Among all the above-mentioned materials, metallic nanoparticle suspension gained a significant interest in recent years because it can be operated at room temperature (Chou *et al.*, 2005) unlike the molten metals and also has due to their better performance in terms of conductivity compared with conducting polymers. The metal used for developing nanoparticle-based inks include gold (Au), Silver (Ag) and Copper (Cu). Bulk silver has got the lowest

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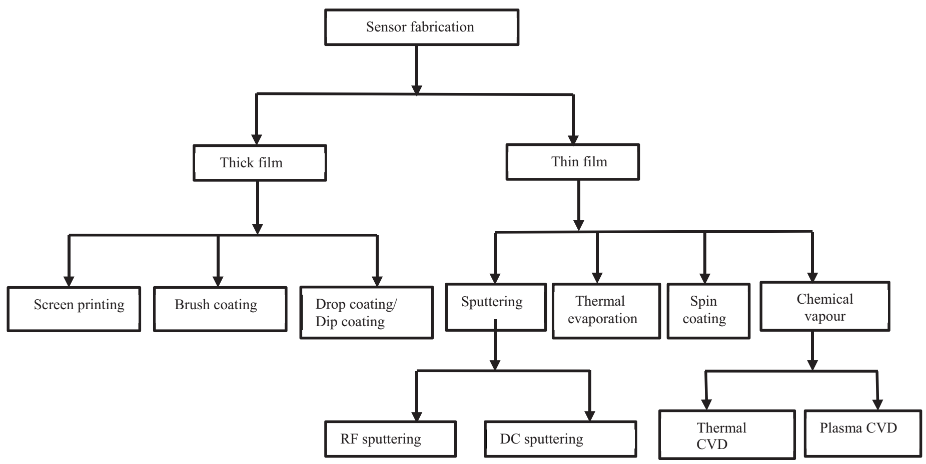
Table 1 Drawbacks of thick film and thin film fabrication technologies

Sr. No.	Thick film method	Thin film method
1	Problem in controlling the thickness of film deposition on the substrate	Very expensive to develop films using this method
2	More wastage of raw materials	Fewer yields and more wastage of raw materials
3	Lengthy manufacturing process	Time-consuming process
4	Slow production rate	Not feasible for mass production of electronics/sensors
5	Limitations in printing the complicated patterns	Restriction of target materials

Figure 1 Classification of conventional sensor fabrication method



resistivity (1.6 $\mu\Omega$ cm), whereas copper nanoparticles oxidize spontaneously in air and gold is very expensive and hence silver has been identified as a potential material for the research works in the recent past (Huang *et al.*, 2014).

Viscosity and surface tension are the two most important properties of general printing inks; hence, we need to concentrate more on matching the viscosity and surface tension properties of the metallic nanoparticle ink on par with general printing inks. Size, dispersion and the stability of metallic nanoparticles are also crucial for the conductive ink system because the nozzle of the printer would be clogged with larger particles or due to the agglomeration of nanoparticles in the conductive ink. In addition, the physical properties of metallic nanoparticles undoubtedly affect the performance of the ink to a great extent. Due to their high conductivity and thermal stability, gold and silver nanoparticle suspensions were widely adopted in the studies of conductive ink. The operating parameters considered in prior works (Fuller *et al.*, 2002; Szczech *et al.*, 2002; Bieri *et al.*, 2003; Chung *et al.*, 2004; Bieri *et al.*, 2004; Szczech *et al.*, 2004; Azucena *et al.*, 2008; Ahn *et al.*, 2011; Huang *et al.*, 2014; Yung *et al.*, 2014; Dang *et al.*, 2014; Lee *et al.*, 2005) are listed in the following Table 2 for comparison.

2. Inkjet-printed physical and chemical sensors

In 2019, Delibozov and Spasova, stated that microsensor printing systems include improved materials, low-cost manufacturing processes and improved compatibility with standard manufacturing techniques (Delibozov and Spasova, 2019). Because of their various applications, the interest in flexible sensors is growing. Due to low-cost manufacturing, fast processing and flexibility and low weight of printed devices, printed electronics is suitable technology for the realization of flexible sensors.

Various printing techniques (inkjet, engraving, screen printing and dip-coating) may be used in the realization of printed temperature sensors. The resistive response of an interdigitated electrode is used for the humidity sensor. It is made of silver nanoparticle ink with a response time of approximately 3 min (Delibozov and Spasova, 2019).

Working principle of inkjet-printed humidity sensor may be based on capacitive changes. Those changes lead to different levels of humidity. Specific strain sensors are the most important instruments used in safety control, damage detection and prevention of failure. About half of all manufactured pressure sensors are based on the strain gauge principle. Low price, simple circuits and easy configuration are the key benefits of strain gauge. Specific technologies can be used in strain sensor manufacturing processes. Traditional manufacturing process includes products made from Pt and NiCr. Inkjet-printing uses inks which contain the nanoparticles of silver.

Silver, gold, carbon nanomaterials (including graphene) and conductive polymers are the most used conductive materials in the chemical sensors printed by inkjet technology. Monitoring environmental, industrial and biological parameters requires accurate, real-time and inexpensive sensing of liquid pH values. Carbon nanotubes can be used as a pH sensitive material. As stated by Delibozov and Spasova, in 2019, they are attractive due to their high mechanical stability and tunable electric properties.

Table 2 Summary of prior works on metallic nanoparticle conductive ink

Sr.No.	Particle/Size (nm)	Solvent	Concentration (wt%)	Curing Condition	Line width (μm)	Line thickness (nm)	Resistivity (Ω-cm)	References
1	Ag/(5–7)	A-terpineol	10	(100–300)°C	80	100	3 x 10^{-6}	Fuller *et al.* (2002)
2	Ag/(1–10)	Toluene	30–35	300°C	120	1000	3.5 x 10^{-5}	Szczech *et al.* (2002)
3	Au/(2–4)	Toluene	30	(300–400) °C	20	50	1.4 x 10^{-5}	Bieri *et al.* (2003)
4	Au/(2–5)	Toluene	30	(200–1000) mW (Laser curing)	17	20–200	1.4 x 10^{-5}	Bieri *et al.* (2004)
5	Au/(5–20)	Toluene	30	300°C	1000	600	1 x 10^{-5}	Szczech *et al.* (2004)
6	Au/(2–4)	Toluene	30–35	(50–500) mW (Laser curing)	123	250	4.5 x 10^{-6}	Chung *et al.* (2004)
7	Ag/(10–50)	Water-DEG	25	(150–260) °C	130	532	1.6 x 10^{-5}	Lee *et al.* (2005)
8	Ag-CCI-300 ink	Ethylene glycol	19–21	(200–300) °C	750	Not Specified	1.3 x 10^{-5}	Azucena *et al.* (2008)
9	Ag/((5–50)	Ethylene glycol	70–85	250°C	Not specified	Not Specified	1 x 10^{-5}	Ahn *et al.* (2011)
10	Ag/($\leq$30)	Water-Ethylene glycol	20	150°C	Not specified	Not specified	1.26 x 10^{-5}	Huang *et al.* (2014)
11	Ag/(5–20)	Methyl alcohol	30	(50–250) °C	Not specified	200	Not specified	Yung *et al.* (2014)
12	Ag/(<10)	Ethanol-Ethylene glycol-2-iso-propoxyethanol-glycerin	20	(100–200) °C	Not specified	Not specified	Not specified	Dang *et al.* (2014)

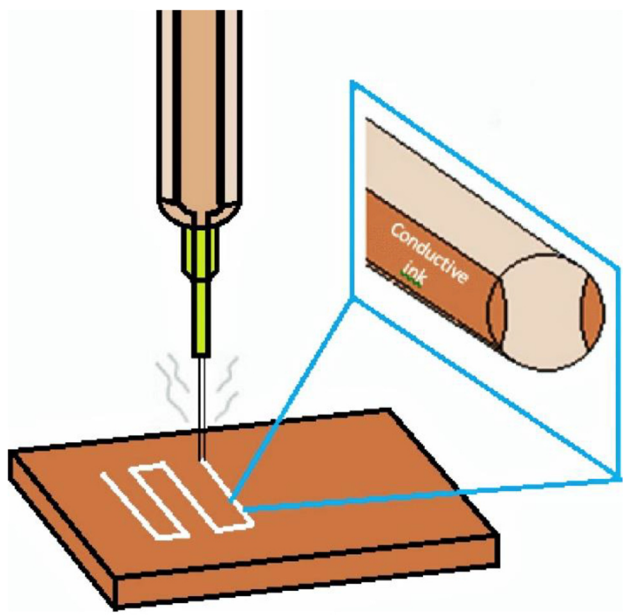
2.1 Temperature sensors

A temperature can be measured using electrically conductive materials that depend on the ambient temperature (Molina-Lopez *et al.*, 2012). Components with an electrical resistance dependency on temperature with positive (PTC) and negative (NTC) temperature coefficients can also be applied (Bali *et al.*, 2016). The resistors in the sensor are meander-shaped and can be manufactured on thick films using inkjet-printing with silver nanoparticles ink (Figure 2). Printing lines with a width of 85 μm and a pitch of 115 μm on the foil make up the resistors.

The range of temperatures usually measured is from 15°C and 45°C. Various printing techniques (inkjet, gravure, screen printing and dip-coating) can be used to realize temperature sensors (Bali *et al.*, 2016). Temperature sensors that can work within a range of 10°C-150°C can be manufactured using nanoparticles based on ink (Lin and Liao, 2016). The bridge's output voltage in an inkjet-printed temperature sensor based on a combination of NTC and PTC materials has good linearity, good repeatability and ~4 mV/° C sensitivity (Bali *et al.*, 2016).

Throughout the printing process of the sensors and the lamination techniques, flexible polymer may be used as a substrate to encapsulate them at foil level (Molina-Lopez *et al.*, 2012). Inkjet-printed temperature sensors enable the manufacture of low-cost flexible sensors with large arrays (Molina-Lopez *et al.*, 2012). Conventional temperature sensors are formed by patterning gold on parylene (e-beam evaporated) and using polyamide as a sensing layer (Molina Lopez, 2014). Printed temperature sensors with inkjet can be used extensively in industrial applications.

Figure 2 Resistor printing of a temperature sensor



Source: Delibozov and Spasova (2019)

2.2 Humidity sensors

The changing of the electrical properties of a system is one of the basic concepts in the humidity sensor. The ambient humidity is influencing that change (Quddious *et al.*, 2016). Working principle of humidity sensor printed by inkjet technology can be based on capacitive changes. Those changes respond to different levels of humidity. In the capacitive humidity sensor the capacitor's dielectric material can diffuse and adsorb water vapour. In that way, it equilibrates with the world around the sensor. The dielectric "dry" constant is much lower than water's. The electric capacitance increases as the dielectric absorbs water. This increase is reflective of the surrounding humidity (Gaspar *et al.*, 2017). The sensor is a built-in electrode printed on a paper substrate (Figure 3).

This paper substrate provides baseline conductivity (Quddious *et al.*, 2016). The increase in humidity from 18 to 88% contributes to a decrease in electrode resistance from Mega-ohms to kilo-ohms. The interdigital electrode is made of ink with silver nanoparticles. This type of sensor isn't made up of discrete components (Quddious *et al.*, 2016).

The conducting electrodes are produced using industrial Ag inkjet-printing (Gaspar *et al.*, 2017). As paper is used as the sensing medium and substratum, this sensor can reveal moisture changes (40 per cent-100%) with almost linear behaviour and slight hysteresis (Gaspar *et al.*, 2017). Graphene Oxide can also be used to base the low-cost humidity sensor (Nikolaou *et al.*, 2016). Using antenna-based UHF RFID sensors as wireless sensors (Gao, 2013), humidity can be sensed remotely. The RFID sensor can work in the low frequency (LF) or high frequency (HF) band with humidity sensing.

In RFID humidity sensing, a sensing material is applied to the coil antenna. This moisture sensing type has a limited reading distance of 10 cm. The use of traditional humidity sensing materials cannot meet the requirements of the latest applications (Feng, 2015). Inkjet-printing is manufacturing techniques which are maskless and non-contact (Feng, 2015). Due to their simple structure, low cost, adaptability to circuits of different types and easy manufacturing and miniaturization, the most popular humidity sensors are the resistive and the capacitive type (Feng, 2015). Inkjet-printed humidity sensors may be used for monitoring the environment. They can be incorporated into a mark or tag. Intelligent packaging of the products is another possible use.

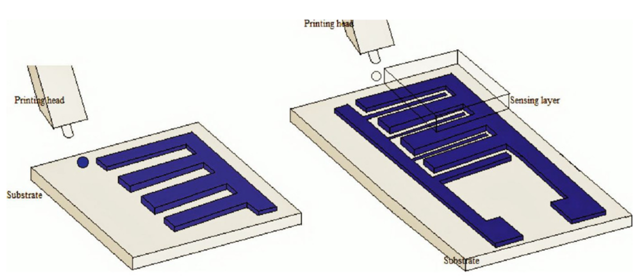
2.3 Strain gauge sensors

When a strain is applied to certain materials the resistance of such materials is modified. That resistance change can be easily measured. Devices in which their resistance is modified as a result of pressure applied or force are called strain gauge sensors. Inkjet-printing is a high-speed process efficiently using ink materials. A pattern with thin film can be printed on flexible substrates at low cost. Here, the inkjet-printing uses polyamide substrates and inks that contain silver nanoparticles. The type and content of the ink indicated the quality of the printing process (Zlebic *et al.*, 2016). In the process of printing inks that include carbon nanotubes and copper nanoparticles can be used (Figure 4) (Ravikumar *et al.*, 2013).

The CNT-based strain sensors have a gage factor (GF) of up to 25, whereas metal gauges only have a gage factor of 1.2. The enhanced gauge factor can detect smaller variations in the strain (Ravikumar *et al.*, 2013). CNT-based strain sensors have greater biocompatibility compared to the metallic gauges (Andò *et al.*, 2015). Different technologies can be used to manufacture stress sensors.

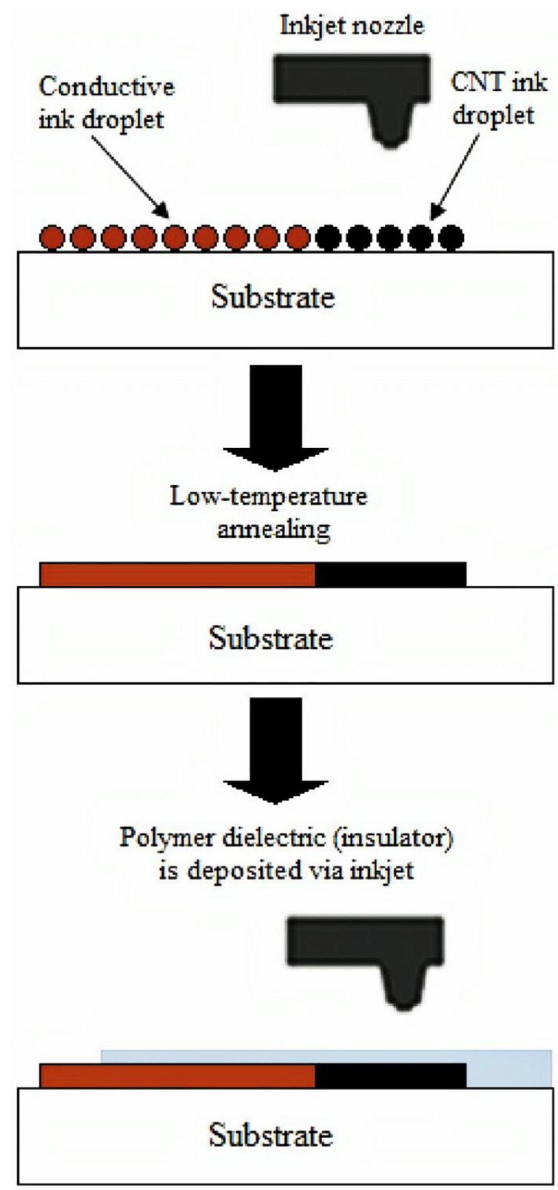
Pt and NiCr are used in the traditional manufacturing process, and photolithographic pattern is used with lift-off process. Pt thin film sensors have a GF 1.7 gage factor (Zlebic *et al.*, 2016). Using the printing technology, strain sensors can be impressed on carbon fiber in mask-less deposition. It allows composites to be manufactured with inherent sensing capabilities. Those sensors have GF in the 2.2 ± 0.06 range. About half of all manufactured stress sensors rely on the strain gage principle.

Figure 3 Humidity sensor – electrode printing



Source: Delibozov and Spasova (2019)

Figure 4 Printing process of strain gauge sensor



Source: Delibozov and Spasova (2019)

Strain gage is a simple, low-price, measuring circuit (Zlebic *et al.*, 2016). Inkjet-printed strain gage sensors for monitoring purposes can be integrated into light weight structures.

2.4 Chemical sensors

The electrical conductance of a graphene layer is altered in this form of sensor when its surface adsorbs gas molecules (Andò *et al.*, 2015). Fully inkjet-printed electrochemical sensors cannot be produced because of difficulties with the inkjet techniques in printing all necessary components (Moya *et al.*, 2017). Electrochemical sensors may be constructed by inkjet-printing (Figure 5).

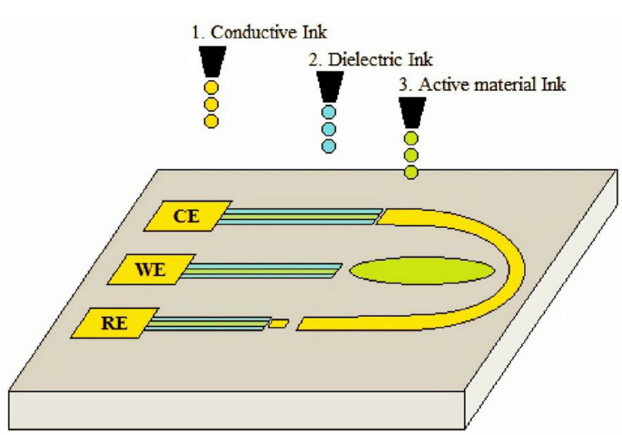
The inkjet-printing is digital technique as opposed to the production processes in which photomasks and stencils are used. The design adjustments can be done with a little expense. Silver, gold, carbon nanomaterials (including graphene) and conductive polymers are the most widely used conductive materials in inkjet-printed chemical sensors (Moya *et al.*, 2017). The inkjet-printing technology uses compatible materials such as polymers and silver nanoparticles which are conductive. Chemical sensor inks are based on silver nanoparticles (Andò *et al.*, 2015).

Chemiresistive sensors can sense the presence of gas in the inkjet-printing technology and can be printed on paper substrates. The mixture of water/isopropanol can be used here as a sensing ink. In the various manufacturing processes of the analog paper-based graphene sensors, CVD (chemical vapor deposition) grown graphene or inkjet-printed GO (graphene oxide) dispersion may be used.

In such a sensor, an aqueous graphene suspension is printed on versatile, low-cost substrates by inkjet-printing (Villani *et al.*, 2017). A graphene inkjet-printing is used for preparing chemiresistors on the pre-patterned substrate. The production cycle finishes with electric characterization [14]. Fully inkjet-printed electrochemical sensors cannot be produced due to inkjet techniques difficulty in printing all of the necessary components (Moya *et al.*, 2017).

Low-cost electronics and sensors can be developed using processes in the graphic industry. Printed devices are the cheapest when compared to traditional silicon electronics photolithographic manufacturing process. We can be extended

Figure 5 Chemical sensor – printing process



Source: Delibozov and Spasova (2019)

to low-cost products. One of the inkjet-printed chemical sensor applications is for gas sensing (carbon dioxide monitoring).

2.5 Ph sensors

The pH sensor is used to measure hydrogen ion (H^+) concentration in a solution, as well as to provide details on acidity or low alkalinity (Zea, 2016). Inkjet-printing technology can be used to create a pH-sensor. Iridium Oxide Film is printed on a flexible, plastic substratum which forms a modified platinum microelectrode. The pH sensor inks consist of Pt, Ag and SU8.

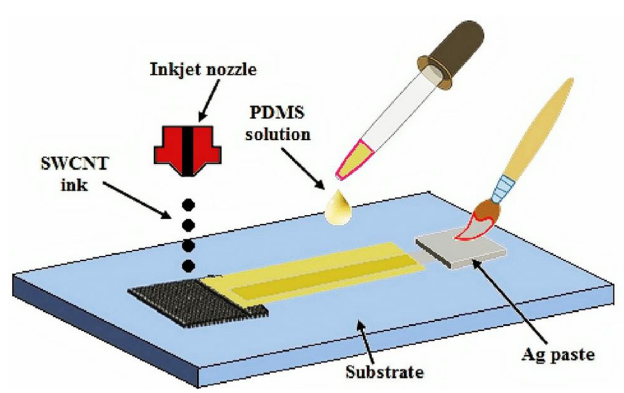
The inkjet-printed pH sensor response between pH 1 and 11 is linear with a mean slope of 0.065 V/pH. The speed of response is less than a second (Zea, 2016). Screen printing, flexography, engraving, offset lithography and inkjet are methods used in printed electronics. There is currently no pH sensor that is entirely made from inkjet technology. Partially, state-of-the-art pH sensors are rendered using inkjet and screen printing. The inkjet-printed part of the sensor (Figure 6) (Zea, 2016) is an electrode made from carbon nanotubes. Use single-wall carbon nanotubes, as electron conduction and pH sensitive layers.

The sensitivity here is using hydronium and hydroxide ions to dop and de-dop the carbon nanotubes. Glass substrate can be used to print electrodes which have a pH sensitivity of 48.1 mV/pH with an average response time of 7 s and a low 4 mV hysteresis (Qin *et al.*, 2016). The key component is the sensitive electrode within a potentiometric pH sensor. Here carbon nanotubes are the material which is sensitive to pH. Tunable electrical properties and a high mechanical stability have made the pH sensors so attractive.

Using inkjet-printing technique, a network of conductive polymer nanowires can be realized on a flexible film. Polymer nanowires can be used in the formation of a conduction path. The large surface area and porosity made the morphology of the nanowire network suitable for the sensing material. Polyaniline is one of the conductive polymers studied most widely (Song *et al.*, 2015).

Complicated and costly are pH sensors that use actual masks. Inkjet-printing is a low-cost process. One of the applications in the biomedical field of inkjet printed pH sensors is. The pH sensors are also widely used in chemical and

Figure 6 pH sensor – printing of sensitive layer



Source: Delibozov and Spasova (2019)

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biological applications such as food quality, measurements of the blood pH and measurements of the laboratory pH.

3. Experimental work on inkjet-printed flexible sensing electronics

In 2015, Andò *et al.* developed a low-cost CO_2 sensor made on a plastic substratum. By depositing a double layer of PEDOT/PSS and Graphene on Interdigited electrodes printed on a PET (Poly Ethylene Terephthalate) substrate, the sensor was realized. The interdigited electrodes were developed using a commercial EPSON inkjet printer to print a conductive pattern of a silver nano-particle solution (Andò *et al.*, 2015).

The sensor's sensing theory exploits the improvement in graphene's electrical conductivity due to adsorption of the gas molecules. A device responsivity of 45μOhm/ppm was obtained at 30°C, and a sensitivity of 100 ppm respectively. The authors are claiming that the inkjet-printed device presented in their work has advantages in relation to its low cost, flexibility and low demanding manufacturing compared to the solutions proposed in the recent past. They have also stated that flexibility of the device is important for applications that allow the device to form irregular surfaces, such as clothing or food packaging.

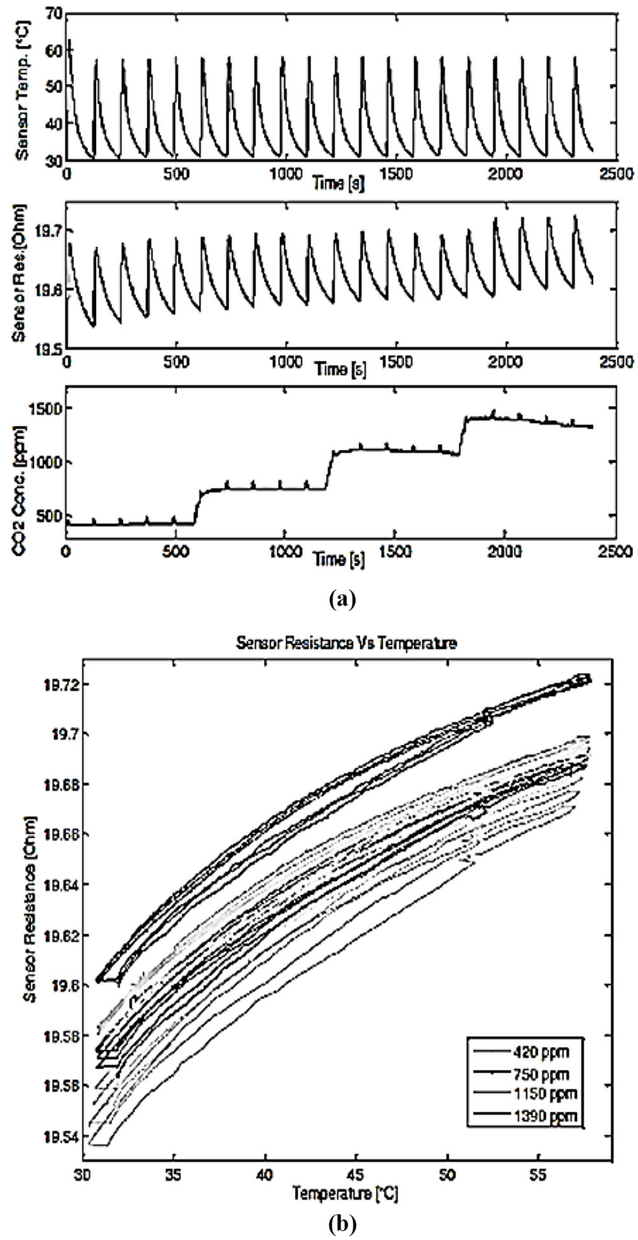
The system developed by Andò *et al.* (2015) consists of a PET substratum, where a low cost inkjet printer and a silver nanoparticle-based ink were created to construct an IDT structure. A calibrated spreader (12 μm) deposited an ink of PEDOT/PSS, prepared to dilute the starting solution with distilled water (1:1, v/v), onto a silver electrode and heated at 80°C for 50 min. A further layer (12 μm) of a solution obtained by dispersing graphene in water (using sonication followed by centrifugation) was subsequently deposited across the PEDOT/PSS layer.

Figure 7(a) depicts the sensor's time domain response proposed in 2015 by Andò *et al.*, while Figure 7(b) displays the sensor behaviour as a function of the heating temperature to increase gas concentration values inside the chamber. The results obtained from the experiment demonstrate the functionality of the proposed sensor and encourage the development of CO_2 sensors using the suggested sensing strategy.

In 2016, Quddious *et al.* developed an inkjet-printed, fully passive sensor capable of sensing either moisture or gas. The sensor consists of an interdigited electrode, an ink sensitive to custom printable gas, and a specialized wireless dipole sensing antenna. The interdigital electrode printed on a paper substrate provides the basic conductivity that differs throughout the phase of sensing. A rise in relative humidity from 18 to 88%, supported by the porous nature of the substrate, decreases the electrode resistance from a few Mega-ohms to the kilo-ohm range.

For gas sensing, an additional customized ink based on copper acetate was printed on top of the electrode which changes both the optical and the electrical properties of the electrode upon reaction with hydrogen sulphide gas (H_2S). At room temperature, a rapid response time of 3 min is achieved for an H_2S concentration of 10 ppm at 45% relative humidity (RH). The sensor's sensing capacity for humidity was analysed in their work. Without the chemi-resistive ink, the bare

Figure 7 (a) The time domain response of the inkjet printed sensor, the operating temperature and the reference sensors and (b) the sensor behaviour as a function of the heating temperatures for different concentration of CO_2

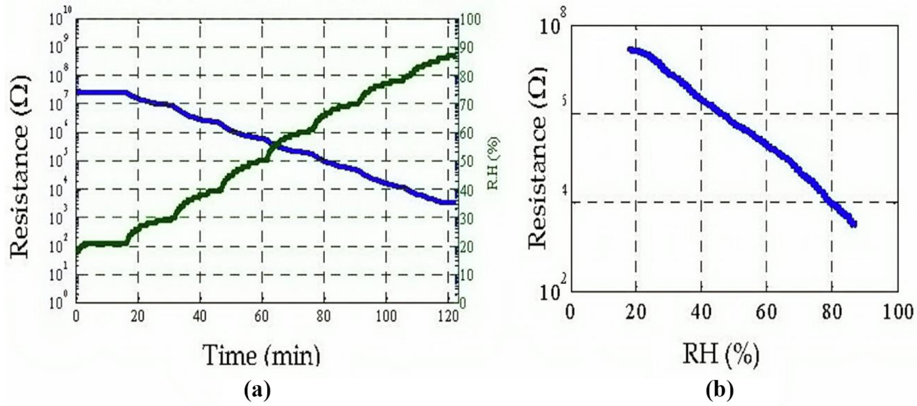


Source: Andò *et al.* (2015)

interdigited electrode was placed in the chamber, and relative humidity (RH) was increased over time.

As the paper substrate appears to absorb moisture, the electrode's conductivity was predicted to increase as a result of the initiation of ion conduction as described in (Tobjörk and Österbacka, 2011). That has been verified, as shown in Figure 8(a, b), by a reduction in resistance from 10 M to a few tens of km as the RH increased from 18 to 88%. The decrease in resistance was measured by the LCR meter began at approximately 20 minutes and continued to decline linearly as the RH increased.

Figure 8 Humidity sensing results



Notes: (a) Measured resistance (Blue) of sensor for different humidity levels (Green) with respect to time; (b) measured resistance of sensor with respect to varying humidity only
Source: Quddious *et al*. (2016)

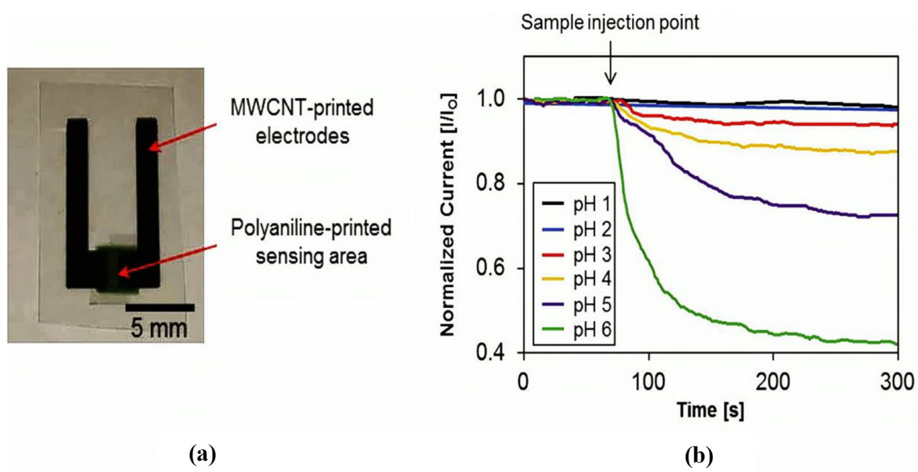
In 2015 Song *et al.*, reported an inkjet-printing technique to pattern a conductive polymer nanowire network on a flexible film for chemical sensing applications [Figure 9(a)]. The authors claim that this work's novelty lies in the patterning ability of polymer nanowires to form a conducting path. In an aqueous solution, polyaniline nanowires were chemically synthesized and a surfactant was added to lower the surface tension which enabled the nanowires to be printed using a commercially available inkjet printer (Song *et al.*, 2015).

The patterns based on the nanowire network were printed on a flexible transparency film, and their characterization of morphology, patterning ability and the electrical properties were investigated by them. There were two types of sensors manufactured by them: a pH sensor and a hydrogen peroxide sensor. The authors claim that the sensors developed can be used as low-cost, removable and easily printable chemical sensors. The proposed technology may be used for potential use in point-of-care diagnostics in developing a simple print-and-use biochemical sensing kit.

Because polyaniline's conductivity is pH-responsive, the printing of a polyaniline layer between two electrodes can develop a simple chemiresistive pH sensor (Song *et al.*, 2015). The low-sheet resistance electrodes were also developed using a similar technique by printing 15 layers of multi-walled carbon nanotubes (MWCNTs) onto a transparency film by Song *et al.*, in 2014. The sensing area based on polyaniline nanowire was formed by printing 20 layers of the polyaniline ink to ensure highly interconnected nanowire networks.

The transparency film dimensions on which the nanomaterials were printed were about 2 × 1 cm, with a film

Figure 9 A fully printed polyaniline-based pH sensor



Notes: (a) image of the sensor showing printed polyaniline nanowire network as a sensing area and MWCNT-printed electrodes as electrical contacts; (b) pH sensing results showing changes in conduction current through the polyaniline with respect to the initial current value (Io) for each pH sample solution
Source: Song *et al*. (2015)

thickness of 145 μm (Song *et al.*, 2015). The printed device's pH response was obtained by initializing the sensor with a strong acid to establish a maximum current and exposing the sensor to different pH buffering solutions. The sensor was initially exposed to pH 1 buffer before stable current measurement was obtained between the two electrodes influenced by MWCNT. The apparatus was then immersed in a sample solution with a particular pH value.

Figure 9(b) depicts the current conduction response of the printed polyaniline material whose conductivity depends on the pH of the environment. As shown in their plot, polyaniline conductivity decreases with increasing pH levels. This shows that even after the inkjet-printing process, the imprinted polyaniline nanowires retain their electroactivity.

The printed sensor has got longer response time may be because the polyaniline becomes non-conductive at neutral pH, and it may take longer time to regain conductivity by protonation. To fully recover the conductivity of polyaniline, a sufficient quantity of protons must be adsorbed onto the polyaniline polymer chains to produce abundant mobile charging carriers.

In 2016, Nikolaou *et al.*, reported inkjet-printing as an alternative deposition method for low-cost gas or humidity sensors based on Love wave devices coated with graphene oxide (GO). The authors believe that inkjet-printing method paves the way for massive, large-scale industrial production of multi-layered GO chemical sensing films for volatile organic compounds and for the detection of relative humidity (RH). GO vapor adsorption resulted in sensitivities of 30 Hz/ppm, 24 Hz/ppm, and 2.4 kHz/1% ethanol (C_2H_6O), toluene (C_7H_8) and RH, respectively in their work. The authors claim that the GO-based inkjet-printing process is one of the most promising features for affordable and high-speed patterning tools for high demanding gas trace or RH sensing applications (Nikolaou *et al.*, 2016)

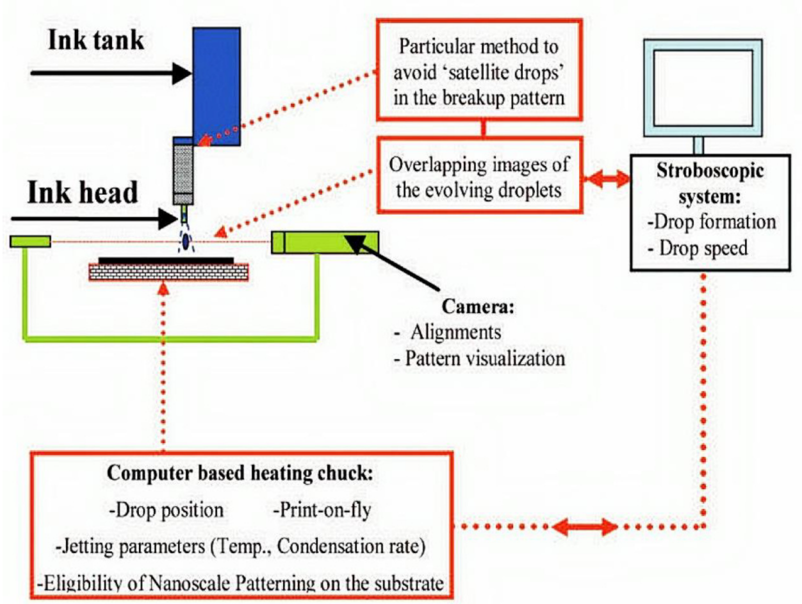
In this study, authors (Nikolaou *et al.*, 2016) have investigated the delimitations and characteristics of directed Shear Horizontal Surface Acoustic Wave (SH-SAW) or Love Wave sensors coated by inkjet-printed GO layers, in which the efficiency of this platform for trace-gas detection applications was enhanced. They have stated that the sensitive film deposited on the acoustic device is of primary importance, which must be effective for target immobilization/recognition, lossless with respect to the acoustic wave, reproducible and satisfy friendly properties with regard to industrial processability.

Drop on demand (DOD) inkjet-printing process was used by Nikolaou *et al.*, in 2016 to deposit graphene oxide solutions on the SH-SAW guided devices. In addition, microfabrication print head assemblies as subsystems were incorporated into a customized commercial inkjet system (Alta-Drop), as shown in Figure 10.

The authors have subjected the inkjet-printed GO sensor devices for detecting C_2H_6O and C_7H_8 vapors with a vapor generator (PUL 110). A constant flow rate (0.112 L/min) of nitrogen was selected by them as a carrier gas and a conventional sequence of different concentrations of C_2H_6O and C_7H_8 were circulated directly on both acoustic path delay lines, which were placed in a specific hermetic cell. The cycling process started with 30 ppm of each target analyte (ethanol or toluene) and this concentration was further used as the base line for the bare and coated devices, respectively. The maximum concentration concentrations for both substances were selected for up to 750 ppm as shown in their detection responses in Figure 11(a) and 11(b).

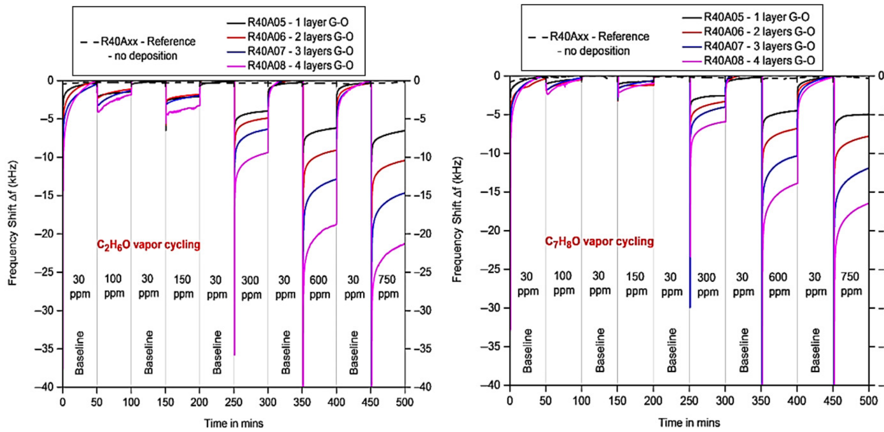
In 2017 Gaspar *et al.*, developed an inkjet-printed relative humidity sensor based on capacitive changes that respond to different humidity levels in the environment. The configuration of inkjet-printed silver interdigitated electrodes on the paper substrate enabled the production of a functional proof-of-

Figure 10 Inkjet - Printed graphene oxide process overview



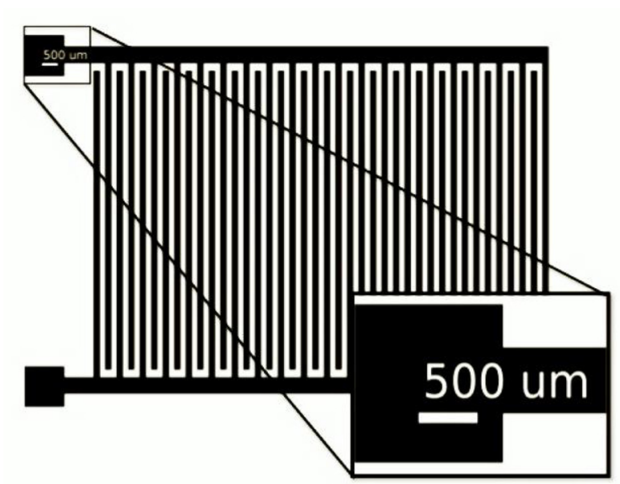
Source: Nikolaou *et al.* (2016)

Figure 11 (a) Dynamic response of inkjet – printed GO based love wave sensors towards C_2H_6O (ethanol) vapour; (b) inkjet-printed GO based love wave sensors towards C_7H_8 (toluene) vapour



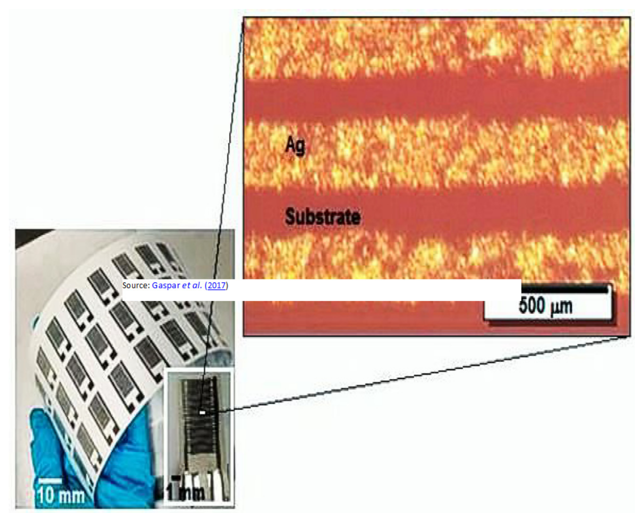
Source: Nikolaou *et al.* (2016)

Figure 12 Schematic of the printed interdigitated electrodes (IDE) sensors, with 40 fingers (scale bar represents 500 m)



Source: Gaspar *et al.* (2017)

Figure 13 Digital picture of an array of inkjet-printed Ag interdigitated finger electrodes structure and the magnified view of one device and the electrodes (5 magnification)



Source: Gaspar *et al.* (2017)

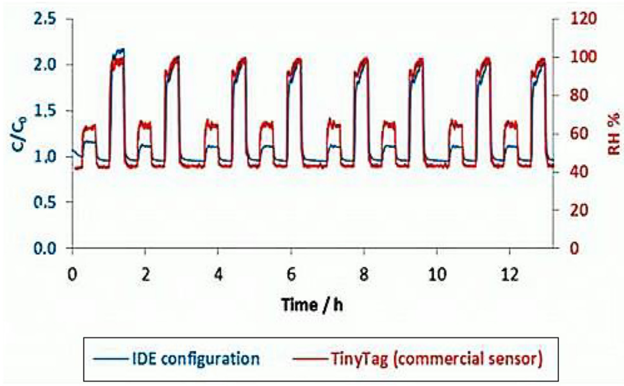
concept of the relative humidity sensor by using the paper itself as a sensing material. The authors are claiming that the sensor's sensitivity was calculated to be around 2 pF/RH per cent in terms of relative humidity changes. They also claim that the response time of the proposed sensor against different temperature steps from 3 to 85°C was fairly constant (about 4–5 min) and a smart label was considered quick for the intended application (Gaspar *et al.*, 2017).

The authors (Gaspar *et al.*, 2017) have done the Inkjet-printing using a Dimatix piezoelectric multi-nozzle (Santa Clara, CA, USA, DMP-2831) printer, with 10 pL cartridges. The spacing from the drop was about 30 m. While printing, the temperature of the substrate was set to 60°C to improve solvent evaporation from the droplets that were ejected. The authors are stating that the ink-jetted structures were imprinted without any pretreatment on the substrates. The line width of the finger structure (40 fingers in total, 20 fingers for each electrode) was set at 200 m in the IDE configuration, with a distance of 150 m and a length of 900 m, occupying a total area of 1 × 2 cm as shown in Figure 12.

Gaspar *et al.* (2017) used an IR-oven Infrared IC heater T-962 Puhui (from Puhui Electric Technology Co., Ltd., Taian, China) with 800Woutput capacity, infrarrot (IR) was used to sinter the printed devices. After the structures were printed, the substrates were inserted for 7 min in an IR-oven at 160°C. Typically a sensing material is required for the conventional manufacturing process, either deposited or printed on top of the IDE, but no such layer was introduced in their work and instead used the paper as substrate and as material for sensing.

They have analysed the quality of the printed lines visually after the inkjet-printing of the IDE structure. They are claiming that the manufacturing yield in a sheet-to-sheet output mode

Figure 14 Dynamic response of an IDE configuration printed sensor (in blue) against a commercial sensor, at a fixed frequency of 100 kHz



Source: Gaspar *et al.* (2017)

was between 60 and 70%. On paper substrates, after sintering, the optical microscope images were taken from the surface of the IR-sintered lines (Figure 13).

The reproducibility of their (Gaspar *et al.*, 2017) printed sensor at room temperature is shown in Figure 14, during a minimum period of 12 h when exposed to alternating levels of humidity. From Figure 14, it is evident that the dynamic response of the printed sensor by Cristina *et al.* to the commercial sensor response shows that the printed sensor response approaches and almost matches the commercial sensor response at high humidity rates (over 60 RH per cent). In addition, the sensor response does not match the commercial sensor for lower humidity rates (less than 60 RH %).

4. Conclusion

In the recent past, it is evident that there is a tremendous growth in the field of flexible electronics and sensors fabrication technologies all around the world. The researchers are showing significant interest in exploring novel materials, conductive ink processing methods and fabrication technologies for developing the plastic substrate based flexible electronics for the on growing demands of wearable devices in the market. The fabricated inkjet-printed temperature sensors by the researchers can be used to realize flexible sensors in combination with the foil manufacturing process. Compared with conventional techniques, the principal advantage of printed components is that they are low cost, easy to develop, mass production and less material wastage. Inkjet-printing is the manufacturing technique which is mask less and non-contact printing process. Inkjet-printing may be used to build flexible physical and chemical sensors which can be conformally shaped on the human body for measuring the physiological parameters in the form of wearable gadgets. In the inkjet-printing method, the changes may be made to the digital image file which has got the geometry of the sensor components and layers with a little cost and less time. The author has done extensive research on the development of flexible electronics development process. The devices fabricated by the author from the proposed method are most promising and reliable and these devices can be used in the wearable devices for many applications. Extensive research work has to be carried out further to optimize the device parameters, printing parameters and to explore novel materials.

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