chemosensors

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Review

Inkjet-Printed Wireless Chemiresistive Sensors—A Review

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Abstract: Microelectronic devices have great potential to be integrated into the Internet of Things, bringing benefits to the environment, society, and economy. Especially, microscaled chemical sensors for environmental monitoring are of great interest since they can be manufactured by cost, time, and resource efficient inkjet printing technology. The aim of the present literature review is a reflection of state-of-the-art inkjet-printed chemiresistive sensors. It examines current material approaches used to realize printed chemiresistors, especially the challenges in the realisation of accurate electrode patterns as well as the deposition of various sensing materials by inkjet printing technology. The review will be completed by an overview of current research activities dealing with the integration of chemiresistive sensors into wireless applications. The result of this review confirms that during the last decades, the number of publications covering inkjet-printed chemical, especially chemiresistive, sensors and their introduction into the Internet of Things is growing. Furthermore, it reveals the need for further research regarding material science and printing technology compatibility to achieve reliable and reproducible chemiresistive sensors.

Keywords: Inkjet printing (IJP); chemiresistive sensor; wireless; Internet of Things (IoT)

1. Introduction

The chemical sensors market is expected to expand at a compound annual growth rate (CAGR) of 8.1%, and in 2024, reaching USD 40.8 billion globally. The integration of chemical sensors in electronics will be the major driving force of this market growth. Safety purposes in the industrial sector as well as environmental monitoring programs lead to a rising demand of advanced monitoring technologies for environmental protection, remediation, and restoration, resulting in the introduction of chemical sensing microsystems into today's market [1].

Chemical sensing electronics are highly variable, complex, and interdisciplinary, leading to extensive application possibilities [2]. Especially, miniaturized arrays of sensors are of great interest to detect various environmental changes simultaneously. Thin-film sensor elements are conventionally deposited by thermal evaporation, sputtering, spray coating, chemical, physical vapour, or atomic layer deposition. Further technologies used, especially for patterning, are laser ablation and lithographic processes [3]. Most of these methods are less flexible and less resource efficient as well as cost and time intensive. Vapour deposition processes, for instance, are mostly temperature based and work under high vacuum. Sputter deposition is mainly performed under an argon atmosphere. Sometimes, the film deposition is also enhanced by an addition of reactive gases. Processes conventionally applied to generate patterned films (e.g., interdigitated electrodes) require many process steps: Either sputtering of a deposited film through a mask (only rough structures can be achieved) or removing parts of an

even film by lithographic processes comprising structuring of a photosensitive polymer by illumination and development, followed by etching of the underlying film [4]. Inkjet printing (IJP) technology has great potential to replace the mentioned complex and time-consuming processes. Benefits of the inkjet technology are the additive and contactless deposition of small dimensioned and thin layers, the possibility of patterned and flexible layouts, as well as the use of various material and substrate combinations under an ambient atmosphere [2,5–10]. Compared to conventional techniques usually employed in sensor manufacturing, inkjet-printing enables the manufacturing of every single sensor layer by one deposition method by simply changing the specific material (ink) to be deposited by the printer.

In 2013, Komuro et al. reviewed inkjet-printed chemical sensing devices, with a brief overview of different transduction mechanisms, applications, inkjet-printed features, printing devices, and types as well as substrates used in different publications. The overview demonstrated that at this time, only few publications were dealing with fully inkjet-printed devices. Most of the fully digital-printed sensors were optical sensors [11]. However, their results already showed that further research on fully inkjet-printed chemical sensors will follow. Moya et al. demonstrated in their review article of 2017 that healthcare applications are still one of the main drivers in the development of printed sensors. Research activities in the fields of the environment, food, and agriculture as well as energy and transport are comparatively low [12]. Due to this fact, further research on printed chemical sensors is desired to cover especially the market of environmental monitoring. The statistical development of publications in the field of chemical inkjet-printed sensors shown in Figure 1 is demonstrating an exponential growth. However, regarding chemiresistive inkjet-printed sensors, the number of publications is low. Due to the shown evolvement, further research, especially on fully inkjet-printed chemiresistors, is recommended.

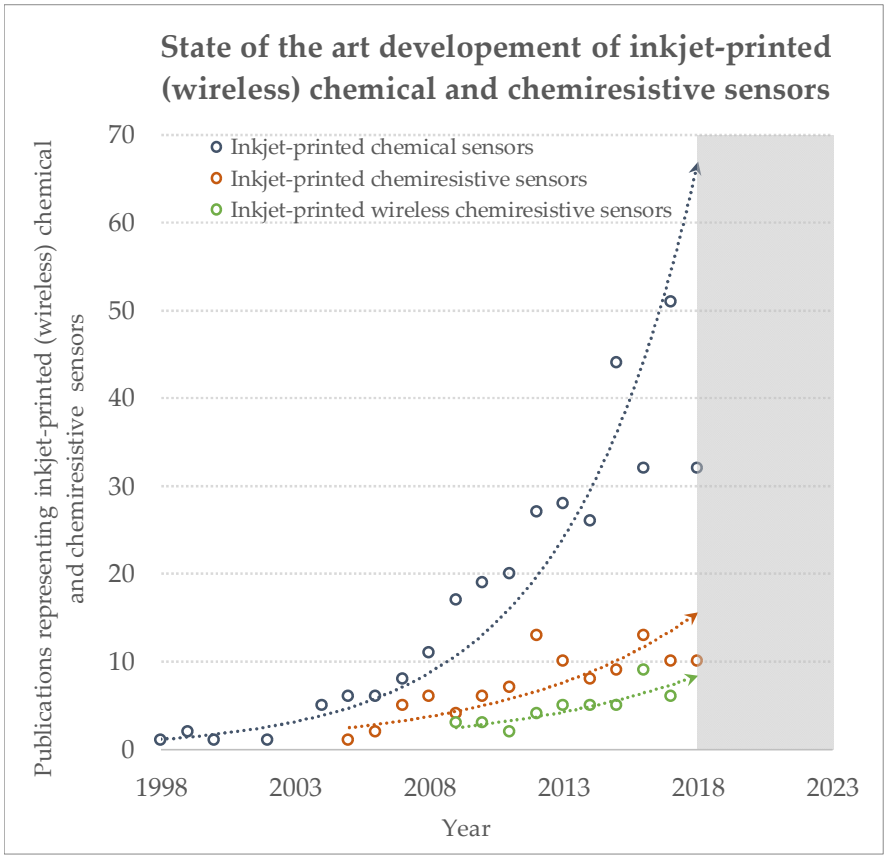

Figure 1. State of the art Development of inkjet-printed (wireless) chemical sensors (Scopus, 22 November 2018).

Figure 1 additionally reveals the statistical development of publications covering wirelessly used inkjet-printed chemiresistive sensors and the potential of further research activities in this field. Wirelessly used chemiresistive sensing applications are of great interest regarding long term in situ monitoring, large distance usage, regular measurements at hard-to-access and hazardous locations, as well as mobile implementation due to their low power consumption [13]. Hester et al. and Alreshaid et al. gave a brief overview on printed sensors for IoT wireless networks, covering an analysis of IoT system requirements as well as methods for their production, particularly by additive manufacturing [14,15]. The present review article should continue the previous literature reviews, with a focus on current fully inkjet-printed chemiresistive sensor devices as well as chemiresistors used for the wireless detection of volatile organic compounds (VOCs) in air.

The following Section 2 will focus on the structure and transduction mechanism of chemiresistive sensors. Section 3 examines state-of-the-art substrate, electrode, and sensing materials followed by a description of selected publications dealing with partly as well as fully inkjet-printed chemiresistors. Section 4 reviews the development in the field of inkjet-printed wireless chemiresistive sensor applications, followed by Section 5, which summarizes the presented results of the literature review as well as fabrication challenges. Additionally, it points out the prospective role of inkjet-printing used for the manufacturing of wireless chemiresistive sensors.

2. Structure and Transduction Mechanism

Chemiresistive sensors are mostly based on an interdigitated electrode (IDE) and a sensing layer on top (Figure 2). They are especially used for monitoring chemical changes in the environment. If the sensor is exposed to different concentrations of an analyte, the resistance changes due to the interaction between the sensing layer and the analyte.

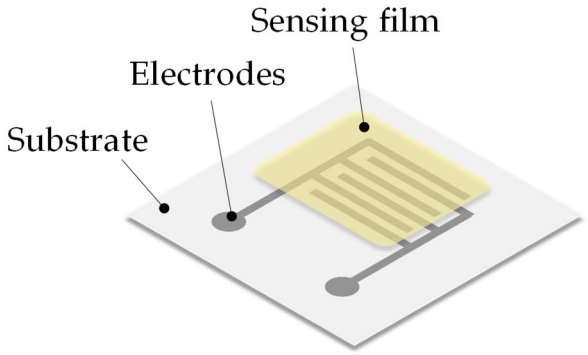

Figure 2. Structure of a chemiresistive sensor.

Due to fast progress in micro- and nanotechnology, traditional resistive chemical sensors are developing more and more in sensitivity, power consumption, response time, and miniaturization.

Electrical resistance is the easiest and most cost-effective electrical parameter, which can be measured with less power consumption. The systems are reliable and their resolution can be adjusted. One further beneficial property of resistive sensors is that they can be assembled as an array of individual resistors due to their simple construction, which leads to the use of several sensors with different sensitive layers in the same device [16–18].

3. Inkjet-Printed Sensors

3.1. Substrate and Electrode Materials

In general, it can be stated that the combination of low-cost substrates and sensor materials with inkjet-printing can reduce the overall cost of a chemical sensing system. The cost of a final sensor is determined by the measurement electronics rather than the substrate or sensing materials [11,19]. Substrates used to apply printed chemiresistive sensors are rigid ones, like glass [20–23] or

silicium [24,25]. Furthermore, the use of flexible substrates, like polyethylene terephthalate (PET) [26,27], polyethylene naphthalate (PEN) [28–30], Kapton [31–36], coated paper [25,37–40], or even textiles [41], are demonstrated. Flexible substrates have great potential to enhance application possibilities of chemiresistive sensors. Flexible sensors could conformably cover objects with irregular surfaces, adding new functionalities to daily use or even wearable devices [28,29,42]. Inkjet-printing technology allows the manufacturing of electrodes as well as complete devices on exotic substrates (e.g., water soluble ones), increasing the application possibilities of printed sensors [43]. A challenge inkjet-printing is often faced with is the realization of precise, reproducible IDEs with desired dimensions and distances. There are numerous research activities dealing with inkjet printing challenges, like pattern accuracy, minimum feature sizes, process stability as well as ink and substrate interactions [44–48]. In 2010, Stringer et al. already investigated the formation and stability of lines produced by inkjet printing. They revealed the conditions of stable line formation with a constant width and parallel straight edges influenced by upper and lower bounds of drop widths predictable through simple mechanism models. The prediction can lead to a stable track formation, compatible with a wide range of inks, but limited to inks based on low vapor pressure solvents [45]. Recently, Tao et al. reported on the impact of the spreading and drying of a colloidal ink on printed pattern accuracy. They analyzed the spreading and drying behavior of printed multicomponent mixtures (in their case, a silver ink) and the impact of jetting frequency, drop spacing, and substrate pre-treatment. They came to the conclusion that a phase separation phenomenon occurs during ink spreading, having a negative impact on the pattern accuracy [47]. Furthermore, Molina-Lopez et al. discussed the difficulty of poor placement accuracy of inkjet-printing systems [49]. Researchers try to overcome these challenges by adjusting the IDE distances to the specific ink (e.g., silver ink) [24] or by digital adjustment of the IDE layout (e.g., with bitmap masking) [50]. Smallest IDE distances of about 25 µm achieved by inkjet-printing was demonstrated by Alshammari et al. and of 57 µm by Rivadeneyra et al. [33,51]. Silver and gold nanoparticle-based inks are mostly applied for IDEs of printed chemical sensors [20,21,24,26,34,49,52–56]. Furthermore, IDEs based on silver nanowires are recently reported, potentially used for stretchable and wearable sensors [42,57].

3.2. Partly Inkjet-Printed Chemiresistors

Sensing materials, which are often used for resistance-based chemical sensors, are semiconductors, like metal oxides, organic macro-molecule-metal complexes, conducting polymers, and carbon black-polymer mixtures. The advantages of metal oxide-based chemical sensors are their easy manufacturing, simple operation, and low cost. Their main disadvantages are the higher power consumption due to heating of the device as well as the low selectivity, especially in mixed gas environments. Gases of no interest influence the overall signal response [17,58,59]. Another semiconducting material very often applied as a sensing material in inkjet-printed chemical sensors are carbon-nanotubes (CNTs) [20,21,28,29,31,35,60,61]. CNTs have, on the one hand, a high surface area and can be functionalized for chemical specificity. Hester et al., for instance, could reach a sensitivity to dimethylmethylphosphonat (DMMP) of 20%/10 ppm with their CNT-based sensor [31]. However, on the other hand, CNT processing is very challenging due to insolubility in most solvents, low material processing control, scalability, device reproducibility, manufacturability, and long-term stability [3,40,62–64]. Another well-known material for gas sensing approaches is polyaniline (PANI) [24,26,55], which is in fact a highly versatile conducting polymer and is suitable for various sensing applications, especially ammonia (NH_3) detection. The sensor approach of Lee et al., for example, has high sensitivity in the low level of NH_3 concentration (detection limit: 25 ppm) [24]. However, the material is very challenging regarding the solubility in water and other common organic solvents [11,65], enabling the liquid processing by inkjet-printing technology. An additional material often used as a sensitive layer in gas sensors is poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS) or PEDOT:PSS compounds (e.g., with graphene) [52,65]. The PEDOT:PSS based gas sensor of Tseng et al. reached a sensitivity of 0.7%/100 ppm to CO_2 [65]. PEDOT:PSS is a high

transparent conductive polymer with low redox potential and good processing properties [52]. However, it is also known that conducting polymers have high susceptibility to ambient humidity and reactivity to oxygen [64]. Additionally, alcohol vapor can rapidly penetrate into the thin films of PEDOT:PSS, causing an irreversible breakdown of electrical conductivity [11]. Furthermore, the choice of conducting polymers is limited regarding the formation of sensor arrays.

Due to the drawbacks and challenges, especially in printing of the before mentioned sensing materials, alternatives must be investigated. One material increasingly used as a sensing layer in printed chemiresistive sensors is graphene or graphene oxide (GO) [31,36,40,52,66]. It has a comparably high electrical conductivity (reduced GO: 0.05–2 S/cm) and can easily be dispersed in water, making it suitable for a wide range of solution processing-based manufacturing methods, like printing [64,67]. The graphene-based material can be organically functionalized to enable different sensitivities of the sensitive films. Sensitivities, such as 2.8%/10 ppm and 6%/500 ppm to NH_3 or 8.5%/800 ppb to nitrogen dioxide (NO_2), can be achieved with GO-based chemiresistive sensors [31,36,66].

Further potential materials are, for instance, platinum (Pt)- and gold (Au)-based sensing layers [68–71]. Until now, these material approaches are less investigated in inkjet-printed chemiresistive sensors. Especially, Au nanoparticles (NPs) have great potential to be used for the detection of a wide range of analytes due to their large surface-to-volume ratio, enhancing the detection sensitivity to chemical vapors [72]. Benefits of Pt NPs are their catalytic characteristic improving the gas reaction. Additionally, adding Pt NPs can significantly decrease the operating temperature as well as the response time, increasing gas sensitivity as well as selectivity [56,73,74]. Raguse and Chow et al. realized a chemiresistive gas sensor comprising of an inkjet-printed Au NP-based sensing layer, with a response time below 3 min, a good repeatability, and a high sensitivity down to 0.1 ppm. However, the sensor was not fully inkjet-printed since the electrodes were fabricated by sputtering and standard photolithography. Furthermore, the sensing area was only micro-dropped and not patterned [22,23]. Figure 3a demonstrates the sensor structure. Claramunt et al. used Au NPs for decorating their carbon nanofiber (CNF)-based sensing layer, but the layer was spray coated on top of inkjet-printed silver (Ag) IDEs (see Figure 3b). The optimum response they reached was around 3%/500 ppm to NH_3 with a response time of around 5 min. It should be noted that their sensor approach must be heated for optimal operation [32]. One further example of a partially inkjet-printed chemical sensing approach was investigated by Ramírez et al. (see Figure 3c). They used tungsten oxide (WO_3) nanowires decorated with Pt NPs as the sensing material for their resistive gas sensor, which was applied by aerosol assisted chemical vapor deposition (AA-CVD) on inkjet-printed Ag NP-based electrodes. The sensitivity of their sensor (ΔI~30/500 ppm) to hydrogen is comparable to standard silicon transducers [34]. Since only a small number of publications address fully inkjet-printed chemiresistive sensors based on platinum and gold containing sensing layers, one can assume that further research is desirable in this field.

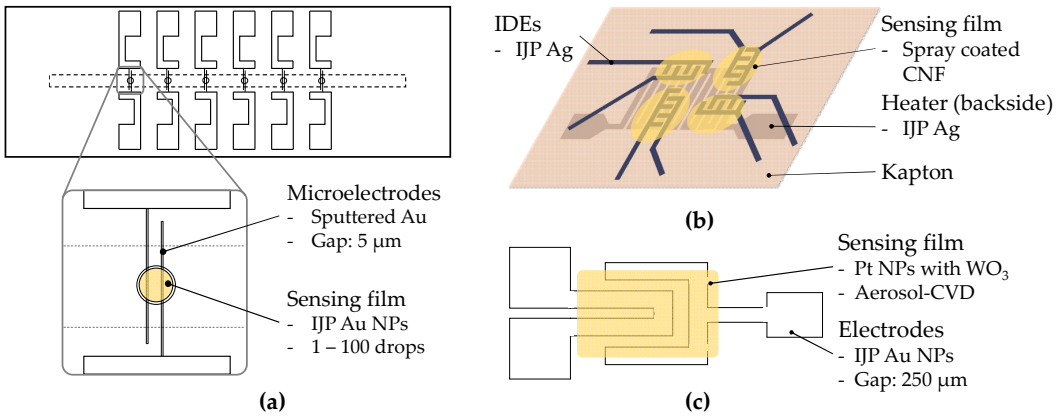

Figure 3. Partly printed sensors using Au and Pt as the sensing material: (**a**) Au NP-based sensing film [22,23]; (**b**) Au NP decorated sensing film [32]; (**c**) Pt NP-based sensing film [34].

As previously shown, numerous chemical sensors are manufactured by inkjet-printing. However, the literature review confirms that most sensor approaches based on inkjet-printed layers are often combined with other manufacturing methods. In many cases, only one layer is inkjet-printed, either the electrode or the sensing layer. Electrodes are often screen-printed and only the sensing layer is digitally printed [26,52] or the electrodes are inkjet-printed and the sensing layer is drop-casted [24,75], spray-coated [32,49,54], or screen-printed [33].

3.3. Fully Inkjet-Printed Chemiresistors

This chapter will point out a selection of three research activities that focus on fully inkjet-printed chemical sensors that operate by the resistive transduction mechanism.

Lorwongatrool et al. realized an all inkjet-printed chemiresistive sensor approach already in 2012. The sensor successfully reacts on ammonium hydroxide (NH_4OH) and VOCs, like ethanol, acetone, trimethylamine, or tetrahydrofuran. For their sensor approach, they used two different layer stacks: On the one hand, the sensing layer was divided into separate layers of water based multi-wall-CNTs (MWCNTs) and a polymer, and, on the other hand, they used a composite of these two materials in one single layer (Figure 4). The sensing layer was applied by digital printing technology (Microdrop system) on top of inkjet-printed silver nanoparticle-based IDEs (Dimatix Materials Printer DMP 2831), with a gap size of 200 µm deposited on glass substrates. The composite approach provided a high value of reference resistance while the separate layer approach led to high selective response to NH_4OH [20,21].

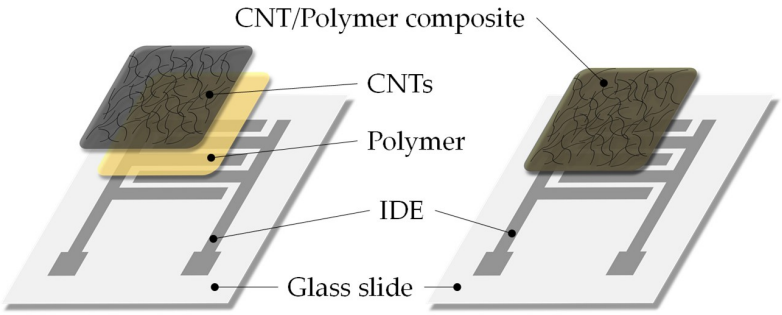

Figure 4. All inkjet-printed chemical gas sensor based on polymer and CNT networks [21].

Further research was done by Hester et al. who demonstrated a resistive fully inkjet-printed ammonia and DMMP sensor. The NH_3 sensor was based on graphene oxide as the sensing material and the DMMP sensor was based on CNTs. After the deposition of the sensing material on the very complex pre-treated Kapton substrate, silver IDEs with a gap size of 350 µm were applied by inkjet-printing technology as well (Figure 5a). The final sensitivity of the sensor was found to be 2.8%/10 ppm for NH_3 and 20%/10 ppm for DMMP. They state that their sensor has great potential for wireless sensing in IoT applications [31].

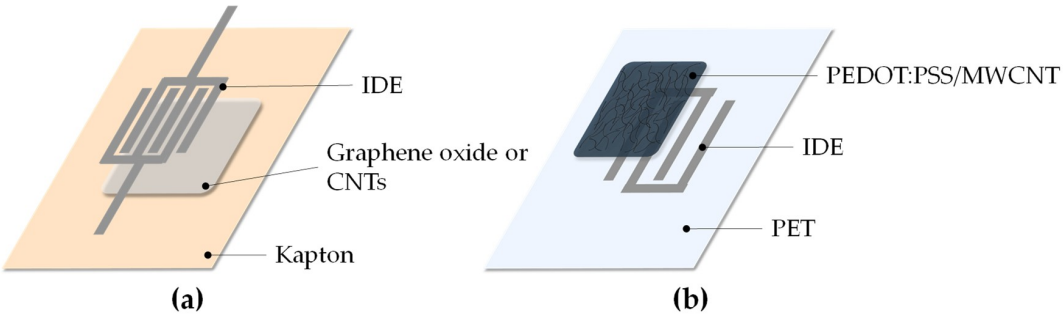

Figure 5. All inkjet-printed chemical gas sensor based on: (**a**) Graphene oxide or CNTs [31]; (**b**) PEDOT:PSS/ MWCNT) [51].

Recently, Alshammari et al. demonstrated a fully inkjet-printed gas sensor for improved ethanol sensing. They built up their sensor on the PET substrate with inkjet-printed silver electrodes covered by inkjet-printed PEDOT:PSS/MWCNT as the sensing film (Figure 5b). They could enhance the sensitivity and response time by the polymer functionalized CNTs compared to previous presented CNT-based sensor approaches. The response time for 1000 ppm ranged between 8 s and 25 s. The detection limit of their sensor was found to be about 13 ppm [51].

Table 1 summarizes selected publications of partly as well as fully inkjet-printed gas sensing devices.

Table 1. Selection of research works reporting on inkjet-printed chemiresistive sensors.

Analyte	Technology	Substrate	Interdigitated Electrode, Gap	Sensing Material, Thickness	Ref.
Ammonium Hydroxide, Ethanol, Acetone, Triethylamine, Tetrahydrofuran	Inkjet	Glass	IJP (DMP 2831) Ag, 200 µm	IJP (Microdrop) CNTs, 70.5–385 nm	[20,21]
Ammonia	Screen, Inkjet	Flexible, transp.	Screen printed Ag, 1 mm	IJP (Office printer) graphene-PEDOT:PSS, 402–407 nm	[52]
Ammonia	Inkjet, Drop casting	Silicon wafer	IJP (DMP 2800) Ag, 72–335 µm	Drop casted PANI	[24]
Ammonia	Inkjet, Spray coating	Kapton	IJP (Xenjet 4000) Ag	Spray coated carbon nano fibres, 300 nm	[31,32]
Ammonia, Dimethylmethyl-phosphonat	Inkjet	Kapton	IJP (DMP 2831) Ag, 350 µm	IJP graphene oxide, CNTs	[31]
Hydrogen Sulfide	Screen, Inkjet	PET	Screen printed Ag and carbon, 200 µm	IJP (DMP 2811) PANI, PANI-copper chloride	[26,27]
Hydrogen Sulfide	Lithograph, Inkjet	PET	Etched copper, 300 µm	IJP (DMP 2831) copper acetate	[27]
Toluene, Dichloromethane, Ethanol	Sputtering, Inkjet	Glass	Sputtered Au, 5 µm	IJP (Microdrop) Au NP, 600 nm	[22]
Hydrogen	Inkjet, AA-CVD	Kapton	IJP Au NP (DMP 2800), 250 µm	AA-CVD, Pt NP decorated WO_3	[34]
Nitrogen dioxide	E-beam evaporation Inkjet	Paper Silicium Aluminum	Evaporated Au, 350, 860 µm	IJP (DMP 2831) graphene, ~50–225 nm	[25,66]
Ethanol	Inkjet	PET	IJP Ag, ~25 µm	IJP (DMP 2831) PEDOT:PSS/MWCNT, 40 nm	[51,76]
Toluene	Inkjet, Screen	Kapton	IJP (DMP 2831) Ag, 57–163 µm	Screen printed graphite-polystyrene, 7 µm	[33]

4. Integration of Inkjet-Printed Chemiresistors into Wireless Applications

One of the first research groups to introduce inkjet-printed wireless gas sensors was Tentzeris et al., who have intensively publicized the topic since 2009 [60,61,77–79].

Le et al., for instance, were able to connect a fully inkjet-printed graphene oxide based chemical sensor to a fully passive, battery-free, and programmable radio-frequency identification (RFID) tag (868 MHz) and a microcontroller. They could reach a resistance change of 6% at an NH_3 concentration of 500 ppm within 15 min and achieve recovery without heating [36]. Their sensing system was further enhanced by connecting it to an inkjet-printed antenna and by the use of photo paper instead of expensive Kapton. The system measures the relation between the antenna power threshold and gas concentration during NO_2 exposure of 40 ppm and reached a difference of 9.18% in the backscattered power level [40]. The concept of the wireless sensor system can be seen in Figure 6a.

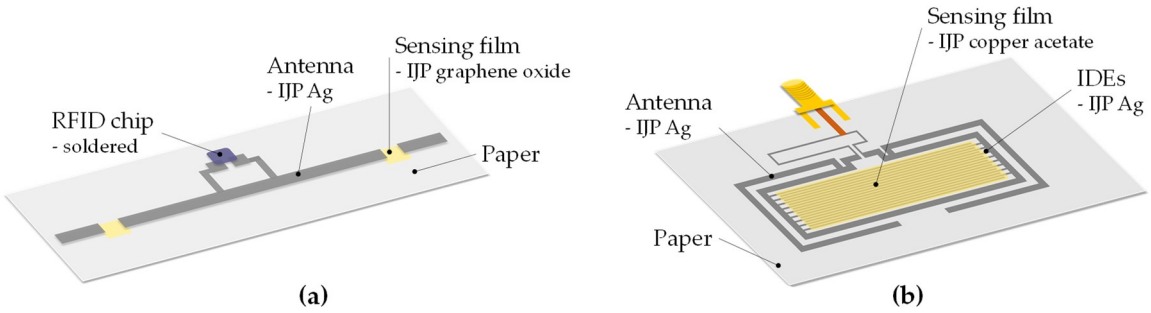

Figure 6. Fully inkjet-printed wireless gas sensors: (**a**) Graphene based sensing layer [40]; (**b**) copper acetate based sensing layer [38].

In 2016, an inkjet-printed and chipless RFID gas sensor was demonstrated by Quddious et al. The substrate used was photo paper with inkjet-printed Ag IDEs, with a copper acetate-based sensing film on top. The sensor was able to detect hydrogen sulfide (H_2S) concentrations of 5 ppm–10 ppm, with a fast response time of about 3 min. The measured resistances for varying H_2S concentrations were used to simulate the sensor behavior if connected to an antenna. The passively sensed frequencies should relate to a certain level of gas concentration [38]. The fully inkjet-printed sensor approach is demonstrated in Figure 6b.

Furthermore, Lorwongtragool et al. added their previously mentioned chemiresistive sensor [20,21] into a Zigbee-based wireless and wearable application for real time monitoring of ammonium hydroxide, acetic acid, acetone, and ethanol. The sensing area was arranged as an array of sensors that could change their resistance if exposed to single analytes. The substrate they used was polyethylene naphthalate (PEN), decorated with silver nanoparticle-based IDEs, which were covered by inkjet-printed sensing material based on CNTs combined with different polymers, either separately printed or blended (Figure 7). They state that the used sensor approach can clearly distinguish between ammonium hydroxide and acetic acid while it was difficult to determine between the electrical response of ethanol and acetone [28,29].

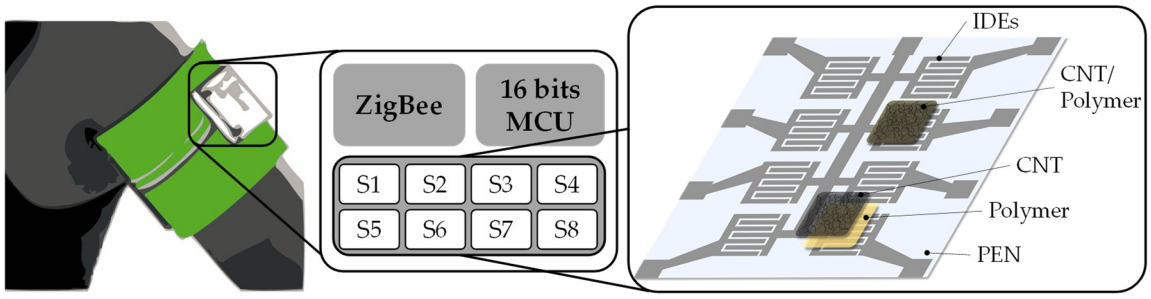

Figure 7. CNT based wireless, flexible inkjet-printed chemical sensor array [29].

Quintero et al. created an RFID enabled multisensor system for humidity and ammonia sensing. The platform consists of capacitive as well as resistive sensors, which can be read out simultaneously. All IDEs of the sensor array were inkjet-printed with silver nanoparticle-based ink and covered either by inkjet-printed cellulose acetate butyrate (CAB) for capacitive humidity sensing or drop casted PANI/carbon nanocomposite for chemiresistive NH_3 sensing. The sensor system was applied on the PEN substrate and connected to a screen-printed RFID label (13.56 MHz), a power source, and a microcontroller (Figure 8). The chemiresistive ammonia sensor showed a linear response to NH_3 with a sensitivity of 5.4 $\pm$ 0.2%/ppm retrieved by the RFID label and displayed on a user interface [30].

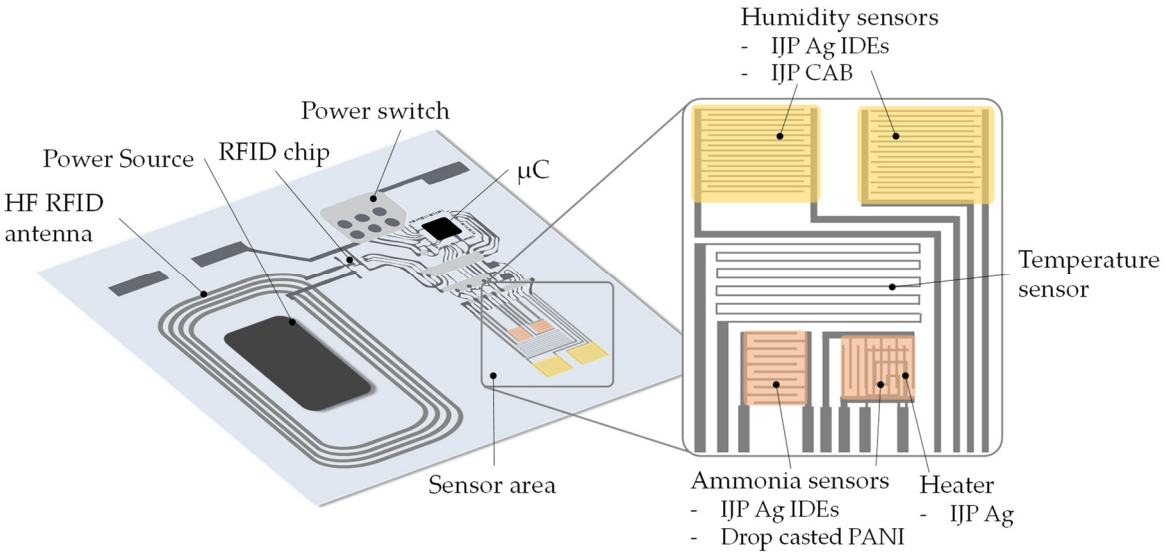

Figure 8. RFID enabled printed multisensor system [30].

Recently, Farooqui et al. demonstrated a disposable, wireless sensor system for large area monitoring. The components of the sensor were arranged three-dimensionally (Figure 9). The H_2S sensor consisted of an inkjet-printed CNT based sensing film with inkjet-printed silver IDEs on top. It could detect H_2S levels as low as 3 ppm, with a high selectivity compared to hydrogen, methane, and sulfur dioxide, representing the first H_2S sensor fully inkjet-printed on a 3D printed substrate. The sensor was connected to an inkjet-printed antenna operating at 2.4 GHz, microelectronic components, and powered by a thin lithium-polymer battery. The system was able to communicate regardless of its orientation and within a distance up to 100 m [80].

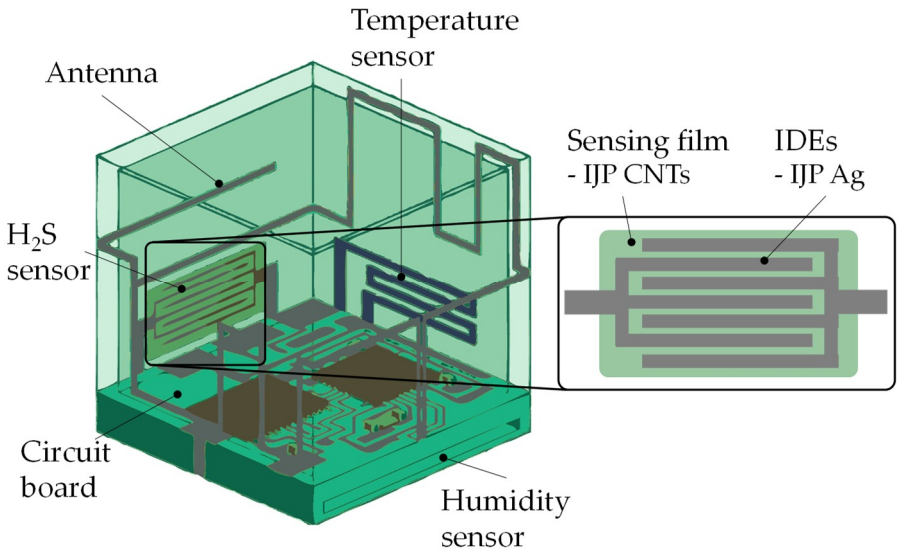

Figure 9. 3D wireless sensor system for large distance environmental monitoring [80].

To summarize the topic, an overview of several further inkjet-printed wireless sensor approaches is given in Table 2.

Table 2. Selection of research works reporting on wireless inkjet-printed chemiresistive sensors.

Analyte	Technology	Substrate	Interdigitated Electrode	Sensing Material	Wireless System	Ref.
Hydrogen sulfide	Inkjet (DMP 2831)	Photo Paper	IJP Ag	IJP copper acetate	RFID	[38]
		3D printed polymer	IJP Ag	IJP CNTs	ZigBee	[80,81]
		Coated paper	IJP Ag	IJP copper acetate	RFID	[39]
Ammonia	Inkjet (DMP 2800)	Kapton	IJP Ag	IJP graphene oxide	RFID	[36,40]
Carbon dioxide	Inkjet (DMP 2831)	Kapton	IJP Ag	IJP SWCNTs	RFID	[35]
Ammonia, acetic acid, acetone, ethanol	Inkjet (DMP 2831 Microdrop)	PEN	IJP Ag	IJP CNTs	ZigBee	[28,29]
Humidity, ammonia	Inkjet (DMP 2831), Drop Casting	PEN	IJP Ag	IJP CAB, drop casted PANI	RFID	[30]

5. Conclusions and Outlook

This review illustrates that a growing number of publications is dealing with printed chemiresistive sensors followed by research on fully digital-printed devices. The fundamental research on inkjet-printed sensors have evolved to multisensor platforms connected to microelectronic devices, like antennas, batteries, and microchips, enabling a wireless and real-time readout. Especially, the presented research articles in the field of wireless environmental monitoring will lead to an improvement of everyday life in the era of the Internet of Things. These sensors are particularly required for long-term and large distance monitoring at partially hard-to-access and hazardous locations. On the one hand, it is shown that the inkjet printing technology has great potential for the manufacturing of chemiresistive sensors since it is an additive, flexible, and contactless method with no need of a printing form. Furthermore, the sensors can be deposited on flexible substrates, leading to versatile applications, like wearable sensor systems or the possibility of covering objects with irregular surfaces. On the other hand, it is demonstrated that further investigation is needed.

Interdigitated electrode designs must be refined regarding the accuracy and finger distances to further minimize the sensor size. Sensing materials must be further investigated to ensure reliability and process stability, especially due to the application in industrial mass-manufacturing processes. Furthermore, improvement of the response time, selectivity, and sensitivity while taking the dependency of the used materials and substrate combinations into account is required.

Since the number of research articles covering basic research on sensor materials and manufacturing technology as well as integration of printed sensors into wireless applications has been constantly growing over the last decades, one can assume that further research in this field will follow. In the future, chemical systems, particularly chemiresistive sensor systems that can detect different environmental changes simultaneously, might be completely manufactured by digital printing technology. This would lead to significant material, time, and cost savings compared to conventional manufacturing and integration methods.

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Conflicts of Interest: The authors declare no conflict of interest.

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