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To cite this article: Caden Tyler Sandry *et al* 2023 *Electrochem. Soc. Interface* **32** 61

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Progress in Inkjet-Printed Sensors and Antennas

by Caden Tyler Sandry, Sharmin Shila, Leobardo Gonzalez-Jimenez, Sebastian Martinez, and Praveen Kumar Sekhar

Within the last five years, flexible sensors and antennas have become increasingly common and used for a wide variety of applications. While flexible sensors and antennas can be fabricated through different methods, including screen printing and 3D printing, inkjet printing is notable in that it is cost effective and allows the production of precise sensors and antennas that do not degrade when bent. Though inkjet printing can be used for other applications, such as making solar cells and LEDs,¹ and there are many forms of inkjet printing, like piezoelectric and thermal,² this article focuses on inkjet printing for sensors and antennas.

Inkjet printing is convenient and relatively accessible while still allowing for a high-quality product. The applications of flexible sensors and antennas range from electronic skin³ to gas sensors. Inkjet antennas are generally used with sensors to transmit data, which is commonly used for remote biomedical applications or RFID tagging when paired with a sensor.⁴ There are also less common and more unique applications of inkjet devices since they are not as traditionally limited as rigid devices. One example is an inkjet antenna used on an origami robot, where the antenna must be light and flexible to attach to a paper surface.⁵ Inkjet sensors may also be used in intelligent packaging systems for food, in which the sensor may be used for freshness indication or hazardous substance detection.⁶

Several challenges are introduced when making a flexible device compared to more rigid ones, such as strain on the sensor or antenna while it bends. Bending can cause the device to degrade⁷ if not properly accounted for and must be compensated for in the circuit's material design to allow a device that performs adequately under any reasonable form of stress, strain, or bending. Another challenge that will be focused on in later sections is the coffee ring effect, which is an issue unique to inkjet printing. This involves the ink droplets drying in a certain formation that is essentially a circle of dried ink, which decreases the conductivity of the printed circuit. This unwanted effect can be dealt with through Marangoni flow⁸ or by altering the ink composition. This paper will not focus on suggesting solutions, but rather will discuss challenges and optimal solutions that are already present or in development.

This article will discuss the applications of flexible inkjet-printed sensors and antennas in the last five years, the challenges the field faces, and the fabrication process of these devices, as well as the general outlook for and possible advances in inkjet devices. Flexible devices have a clear focus in several concentrated areas, mostly wearable, biomedical, and environmental (gas sensing) applications,¹¹⁻⁴⁰ which will be explored in both common and novel applications to provide a complete review the field.

Fabrication of Inkjet Devices

In a general sense, inkjet printing allows for very high customization.⁴¹ As shown by the variety of applications in this paper, it is clear that there are very many different uses for inkjet-printed devices. This is one of the appeals of fabricating through the inkjet printing process since designs can be changed to meet the demands of both common and unique implementations. Different parameters like circuitry, substrate, ink type, and so on can be controlled to suit the needs of the sensor or antenna. Being able to do all of this from an inkjet printer is very convenient from both a manufacturing and a research perspective.

An important aspect in the review of inkjet devices is the fabrication process for both sensors and antennas. The inkjet device fabrication process goes through four major steps, which are pretreatment, inkjet printing, curing, and sintering.¹ These four processes (Fig. 1) are broken down further in each subsequent part of this fabrication section. Figure 2 shows a four-step diagram of sample preparation for inkjet printing. Traditional silicon-based processing and inkjet printing processes are contrasted in Fig. 3.

For sensors and antennas, an inkjet printer is used to print conductive ink onto a substrate. Substrate materials range from simple and cheap materials like paper to more specific materials like PET. Inkjet printing can produce high resolution patterns⁴³ using conductive inks such as copper, gold, and silver.⁴⁴

Nanoparticles range in size from ~1 to 100nm.⁴⁵ Thin film layers are created with low viscosity inks to fabricate the product.⁴⁶ Carbon nanotubes can also be used and are recyclable,⁴⁷ reducing overall manufacturing waste. However, nanotubes can be affected negatively during oxidation and other processes.⁴⁸ Graphene, with its strong mechanical properties, can also be used.⁴⁹ Nanoparticle inks can be created in a couple of ways, the most consistent of these being chemical processes in which metal salts are reduced to create particles of uniform size.⁵⁰ It is possible to create nanoparticles of metal with physical grinding; however, this can result in non-uniform

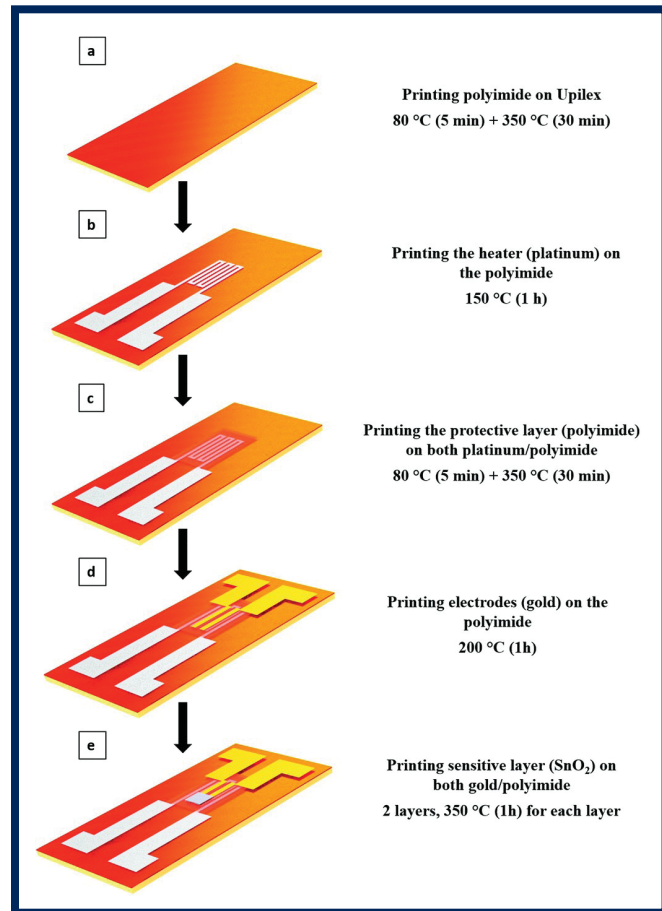


FIG. 1. Fabrication steps toward a fully printed gas sensor.⁴²

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particle sizes. Inconsistent particle sizes, especially larger ones, can cause nozzle clogging. Nozzle clogging is also possible with certain inks and should be carefully considered based on the inkjet printer

being used to prevent fabrication defects. This is discussed further in the challenges section.

Important aspects of fabrication are biodegradability and environmental safety, especially since many sensors are for medical use and will be disposed of after use. Silver nanoparticle ink is common for inkjet printing because it is conductive and relatively

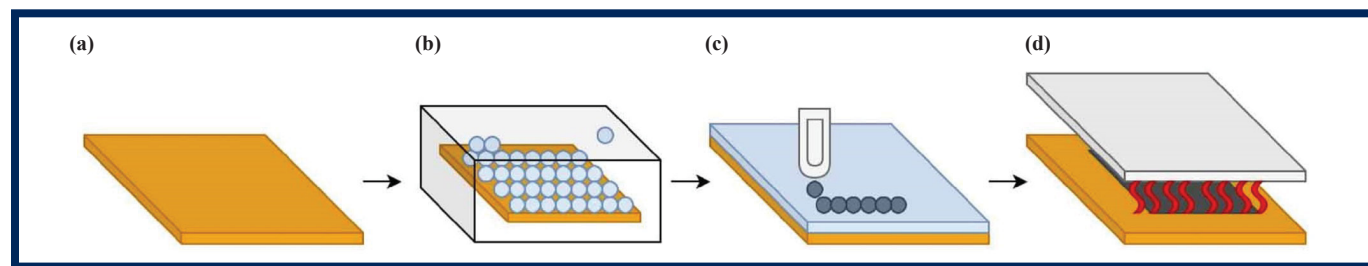


FIG. 2. Four step diagram of sample preparation: (a) Kapton; (b) plasma pre-treatment of Kapton; (c) inkjet printing of the pre-treated substrate; (d) sintering of the graphene ink.⁵³

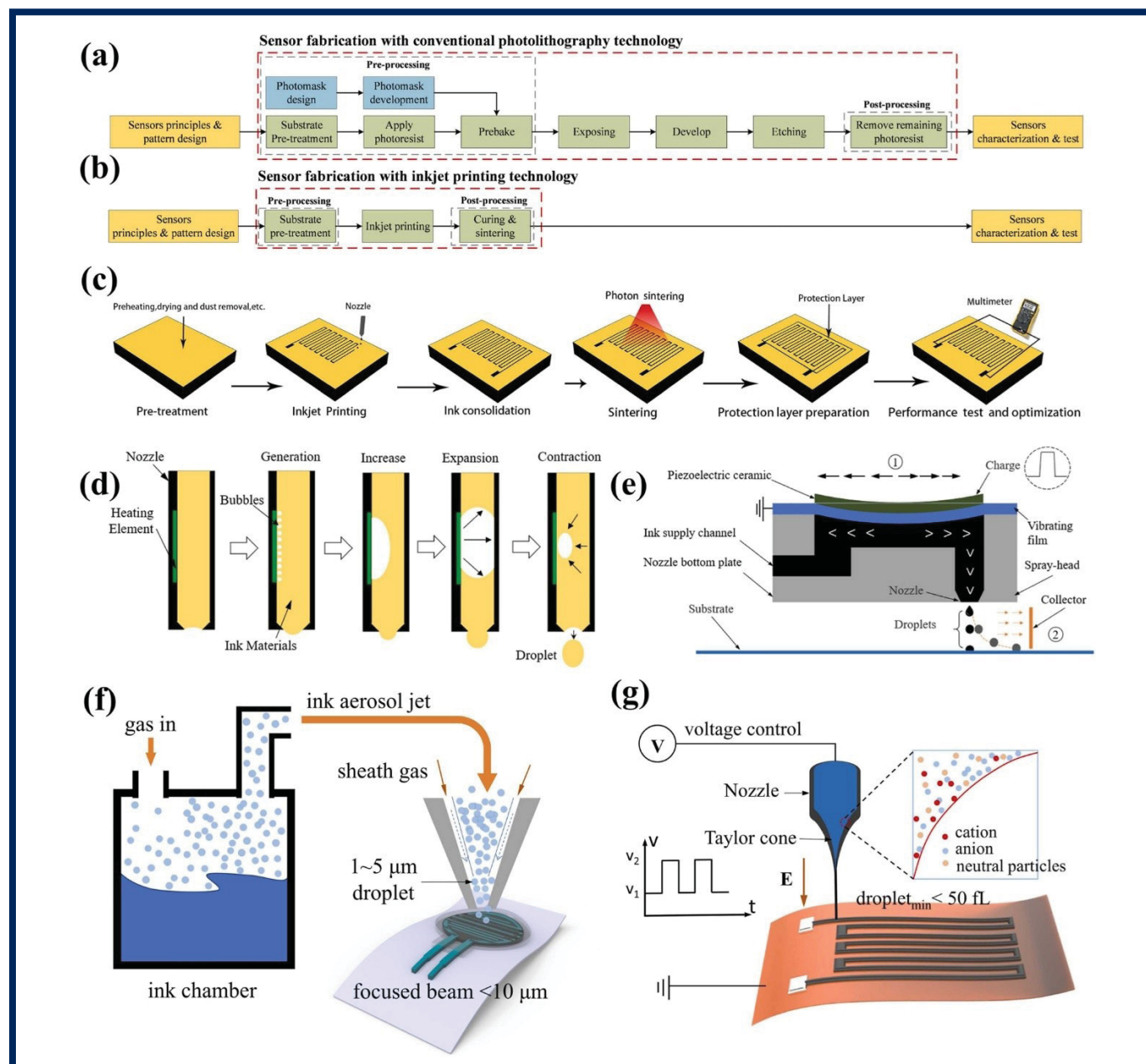


FIG. 3. Schematic illustration of inkjet printing. (a) Conventional silicon-based sensor fabrication with photolithography technology, (b) Flexible sensor fabrication with inkjet printing technology, (c) Process flow of inkjet printed flexible sensors, (d) Thermal inkjet printing, (e) Piezoelectric inkjet printing, (f) Aerosol jet printing, and (g) Electrohydrodynamic jet printing.¹

Table I. Biomedical sensors⁸⁸

Sensor	Ink Material	Sintering Method	Substrate	Functional Electrode Material	Detection Method	Sensitivity	Detection Limit	Ref.
pH	Pt, NP; Ag, NP	thermal, 180°C	PEN	IrOx	potentiometry	71.3 mV pH ⁻¹	-	151
Pb ²⁺	Bi, inorganic salt	plasma	PET	-	DPV	0.083 A*m ⁻¹ mm ⁻²	1 × 10 ⁻⁷ M	152
Hg ²⁺	Au, NP	thermal, 380°C	PI	-	potential impedance spectroscopy	566 Ohm ppm ⁻¹	0.01 ppm	153
Glucose	Au, NP	thermal, 130°C	PET	CuO	cyclic voltametry	850 μA mM ⁻¹ cm ⁻²	2.99 μM	151
AB42	Au, inorganic salt	plasma	PET	AB42 antibody	DPV	-	-	152
DNA	Au, inorganic salt	plasma	PET	hnRNP HI	DPV	-	-	154

inexpensive; however, using large amounts of silver in electronics can produce an equally large amount of waste.⁵⁴ Since one of the biggest appeals of inkjet printing is that it is easy and inexpensive to use as a manufacturing method on a wide scale, biodegradable materials are even more relevant. Replacing silver or other materials that are used for their conductive and electrical qualities with elements like magnesium, zinc, or iron can be much better for the environment. These elements can dissolve in water, which makes them much more suitable for disposable electronics.⁵⁴ This will be expanded upon in the challenges section.

Applications of Inkjet Sensors

Inkjet sensors and antennas are closely related but will be treated here in two separate sections for better comprehension. Since there may be overlap regarding the literature on these topics, devices that include both a sensor and antenna may be included in either section. The most common applications will be covered first, followed by the more unique applications.

Three of the most prominent applications of inkjet sensors are biomedicine,^{50, 55-62}, gas sensing,^{42, 61, 63-81} and temperature sensing.⁸²⁻⁸⁷ Other common uses are electronic skin and wearables, which can overlap with the above applications, such as a wearable temperature sensor.

Biomedical sensors are often wearable; thus they must be flexible and stable so that they can be attached to skin without affecting performance or data collection. Biomedical inkjet sensors vary, but generally serve the purpose of detecting abnormal levels of a substance, often through biomarkers. The goal of a wearable biomedical sensor is to provide accurate, useful medical information while being convenient and non-invasive for the user. Examples include human temperature sensors, glucose sensors, sweat analysis sensors that track K and Na levels,⁵⁴ and in some cases electronic skin. Biomedical research can also benefit from inkjet printing,⁸⁹ in which a sensor can be attached to the body to collect study data. Wearables have several specific requirements that are discussed later.

An example of a biomedical sensor is one that can detect the level of glucose in the blood of a person with diabetes.⁹⁰ It is possible to detect glucose using inkjet sensors and urine samples as well.⁹¹ When an inkjet sensor is developed for measuring data outside of the human body, flexibility may not be as much of a concern. The glucose sensor designed to be used in urine, for example, did not need to resist large and frequent amounts of bending or strain. Inkjet printing is simply cost-effective and well suited for printing very small sensors, which are still benefits for non-flexible applications. Wearable glucose inkjet sensors have been printed using gold ink and copper oxide nanoparticles,⁹² as well as other inks and nanoparticles. This type of sensor is disposable and wearable, which is both convenient and cheap for the user. These factors are important when considering biomedical applications, as their purpose is to be easier to use, cheaper, and at least as accurate as already existing methods. Inkjet sensors can also monitor glucose levels through sweat,⁹³ and in this case, provide a fantastic alternative to traditional methods of monitoring glucose levels. The sensors are almost as accurate as commercial blood glucose monitors. If further developed to become wearable, glucose monitoring like this example could become very cheap and convenient for remote healthcare applications. This is

also a prime example of what inkjet sensor technology should strive to accomplish; the sensor achieved the same goal as the traditional blood collection kit while advancing otherwise, meaning that inkjet printing technology is rapidly approaching wider availability and usability. Another paper found that an inkjet-printed sensor for glucose biomonitoring was sensitive, disposable, low cost, and customizable to meet the user's needs.⁹⁴ A selection of these sensors is presented in Table I, which covers the type of sensor, substrate, functional electrode material, detection method, ink and sintering method, and performance.

Temperature sensors are another example of inkjet-printed flexible devices. Traditional temperature sensors are typically rigid and thus not applicable as wearables that must maintain skin contact.⁸⁷ With inkjet-printed sensors, temperature sensors can be used in biomedical applications when paired with an antenna,⁹⁵ though they currently face challenges like poor operation range and conductivity. Carbon-based sensors are common in temperature sensing, primarily for their high conductivity and mechanical strength.⁸⁴ Flexible polymer-based temperature sensors are also common; the conductivity in the material changes with changes in temperature.⁸⁴ Since temperature sensing is essentially a category of biomedical sensors, comfort and durability are not just desired, but essential. Table II presents some of the reported temperature sensors along with information on their materials, production details, and performance.

The third common use for inkjet-printed sensors is gas sensing. Carbon inks are sensitive to gas, which means they can detect aspects of an environment such as humidity.¹ One of the most common uses of a gas sensor is for sensing ammonia, which can overlap with biomedical sensors. One such ammonia sensor is used to detect dangerously high levels of ammonia in human blood, which can help prevent seizures. Current tests for hyperammonemia require specialized equipment and are slow.⁸⁰ Wearable ammonia sensors would enable much more convenient and earlier hyperammonemia detection. Research on ammonia sensors is relatively recent, and development is ongoing.⁹⁶ Currently, ammonia detection is most commonly used in environmental hazard detection in industrial applications, in cars, and in houses.⁸⁸ Workplace ammonia detection alerts if the concentration of ammonia is too high.²² Incorporating such a sensor into a small, inexpensive wearable may better protect employees because a wearable is easy to use and more effective for detecting individual exposure. Table III is a summary of inkjet-printed gas sensors.

Another feature of flexible inkjet gas sensors is that they operate at room temperature. Rigid semiconductor oxide-based sensors are usually brittle, expensive, and require a relatively large amount of power to operate, as well as operating at a higher temperature than that of the average room.³⁵ Thus, inkjet sensors are operable under wider conditions.

Tactile sensing and pressure sensors are another category of flexible inkjet sensors.⁹⁷ For example, electronic skin⁹⁸ is essentially a wearable, multifunctional sensor. Electronic skin, or e-skin, can be viewed as a combination of the sensors explored above, including detection of temperature, pressure, humidity, gas, and strain. Although such multifunctional sensors are currently relatively under-researched, inkjet printing certainly could play a role in their development.

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Table II. Temperature sensors

Ref., Year	Substrate Material	Sensing Material	Contacts/ Electrodes	Temperature	Sensitivity [TCR] (%/°C)
140, 2020	paper	AgNP & PEDOT: PSS	A.J.M.	25 - 45°C.	$9.389 \times 10^{-4} \text{ } ^\circ\text{C}^{-1}$ & $-0.0139 \text{ } ^\circ\text{C}^{-1}$
141, 2019	paper	AgNP	A.J.M.	20-80°C	$1.625 \times 10^{-3} \text{ K}^{-1}$
142, 2020	PET	AgNP	A.J.M.	30-100°C	$0.086 \text{ } ^\circ\text{C}^{-1}$
143, 2021	PI	G & f-rGO	AgNP	30-83°C & 30-100°C	$-1.94 \times 10^{-3} \text{ K}^{-1}$ & $-1.64 \times 10^{-2} \text{ K}^{-1}$
144, 2021	nylon taffeta fabric	MWCNT	A.J.M.	25-50°C	10.4×10^{-3}
145, 2021	paper	AgNP	A.J.M.	-20 - 60°C	$1.713 \times 10^{-3} \text{ K}^{-1}$
82, 2019	cellophane tape	Ag	A.J.M.	25 - 45°C	$2.15 \times 10^{-3} \text{ } ^\circ\text{C}^{-1}$
85, 2021	taffeta	CNT	Ag yarns	25-50°C	$0.15 \text{ } ^\circ\text{C}^{-1}$
85, 2021	taffeta	PEDOT: PSS	Ag yarns	25-50°C	$0.41 \text{ } ^\circ\text{C}^{-1}$
85, 2021	taffeta	CNT/PEDOT: PSS	Ag yarns	25-50°C	$0.31 \text{ } ^\circ\text{C}^{-1}$
146, 2019	Kapton	carbon	AgNP IDEs	28-50°C	$0.00375 \text{ } ^\circ\text{C}^{-1}$
147, 2019	PET	PEDOT: PSS	AgNP IDEs	20-70°C	$-0.8 \text{ } ^\circ\text{C}^{-1}$
148, 2020	FR-4 board	PZT-PDMS	AgNP IDEs	25-120°C	$18.111 \text{ kHz/} ^\circ\text{C}$
149, 2021	PET	rGO/AgNPs	AgNP	30-100°C	$0.086 \text{ } ^\circ\text{C}^{-1}$
150, 2020	PET	MWCNT/AgNP	AgNP	30-150°C	$8 \text{ } \mu\text{V/} ^\circ\text{C}$
83, 2020	polymer substrate	CdSe/ZnS quantum dots	-	20-70°C	$109 \text{ pm/} ^\circ\text{C}$
86, 2022	PI	PEDOT: PSS	AgNP	28-70°C	$0.13 \text{ } ^\circ\text{C}^{-1}$
86, 2022	photo paper	PEDOT: PSS	AgNP	28-50°C	$-1.67 \text{ } ^\circ\text{C}^{-1}$

Pressure sensors can be categorized as capacitive, piezoelectric, triboelectric, or piezoresistive, and in one example, a sensor was created using silver ink in a capacitive sensor with a dielectric material in between two plates.⁹⁹ The traditional fabrication process for this sort of sensor takes lots of time and uses dangerous chemicals;⁹⁹ thus inkjet printing can reduce workplace hazards and manufacturing time. In this example, not only were the manufacturing time and work environment improved, but the sensor's performance also improved. The sensor was able to detect pressures lower than 1 kPa and at 50 kPa, so it can be used in many systems surrounding skin.⁹⁹ With a capacitive sensor like this one, a dielectric is placed between two plates in the fabrication process. With a piezoresistive pressure sensor, the dielectric can be replaced with a conductive layer that changes resistivity when pressure is applied, allowing it to measure pressure change.¹⁰⁰ Manufacturing steps need be only partially altered to change from a capacitive to a piezoresistive sensor, as the dielectric layer can be altered and replaced to form a different sensor. This sort of pressure sensor can be used for tactile sensing as it conforms to a surface. Figure 4 shows the schematic to implement an inkjet-printed tactile sensor.

Applications of Inkjet Antennas

Inkjet antennas by themselves are limited to data transmission, which is why they are usually paired with a sensor. Inkjet antennas are similar to inkjet sensors in that they can be flexible and allow for bending stress, which means that they can be placed on skin, clothing, or other nonplanar surfaces as wearables.¹⁰¹ One application of inkjet-printed antennas is RFID tagging.¹⁰²⁻¹⁰⁸ In biomedical applications, RFID tagging is used for smart blood storage/blood bag tagging and patient monitoring.¹⁰⁹ The tags are combined with a sensor, such as a strain sensor, to monitor patient parameters and transmit them to providers. Common issues with these devices include balancing transmission range and size. Figure 5 shows an inkjet-printed antenna on textile and Fig. 6 shows RFID tags on apples.

In one example, an inkjet-printed antenna and an RFID were used as a dosimeter tag for irradiation of blood for transfusions.¹¹⁰ Since the antenna is used in blood, it had to be optimized for this lossy environment. The antenna was integrated with biomedical sensors to automate the process of irradiation during blood transfusion and reduce loss of blood by increasing efficiency. RFID tagging can also be used in security.¹⁰² This unique application relies on the natural randomness that is inherent to inkjet printing, meaning that patterns can be created that are difficult to reproduce. This means that these RFID tags can be used as a high-level security measure simply because of the nature of inkjet printing. RFID tagging can also be used in the form of an inkjet-printed sticker, allowing inkjet antennas to be used in food packaging and monitoring.¹¹¹ Prototypes are approximately double the length of the stickers already used on produce.

In another example, an inkjet and screen-printed antenna was incorporated into a bandage for wireless wound monitoring.¹¹² Like other wearable antennas in this article, it had to be flexible and bendable while remaining functional, and it could not be intrusive. In this example, the antenna was able to conform to the body properly, which demonstrates that it is already possible to meet these demands in making biomedical wearables. It should be noted, however, that strain and bending reduced both the gain and the bandwidth of the antenna, which will be discussed further in the challenges section.

Nonmedical wearable antennas also require a great degree of flexibility and stability while bending. This strain can cause performance losses and must be accounted for in fabrication. A wearable antenna¹¹³ designed using a Teflon substrate can track body movement with RF sensing. This application is rarer in the field of flexible antennas, but it is certainly one that logically could be incorporated with an inkjet antenna. Current research on inkjet antennas is often nonspecific and used to verify that inkjet antennas have a promising place in the advancing world of electronics. In one study, for example, an antenna not used for a specific application reached an efficiency of 84%.¹¹⁴

Table III. Gas sensors

Ref., Year	Substrate Material	Sensing Material	Target Gases	Detection Range/Gas Concentration	Working Condition
42, 2019	polyimide (PI)	SnO ₂ -based ink	C ₂ H ₅ OH, NH ₃ , CO	dry and wet air	300
63, 2022	PET	rGO/CuCoO _x	NO ₂	50 ppb	room temperature
64, 2019	flexible & transparent	PEDOT: PSS/MWCNTs-N ₂	formaldehyde (CH ₂ O)	10-200 ppm	room temperature
66, 2020	photo paper	MWCNTs	ammonia and methylalcohol	0.05 g/L	room temperature
67, 2019	pMOSFET	WS ₂ nanoparticles	NO ₂ , H ₂ S, NH ₃ , and CO ₂	10 ppm	100°C
68, 2022	photo paper	molecular-imprinted polymer (MIP)	propenoic acid	3-48 ppm	room temperature
69, 2019	thin substrate	graphene	NO ₂ and NH ₃	10 ppm NH ₃ , 20-200 ppb NO ₂	250°C
70, 2019	Epson photo paper	PEDOT: PSS-MWCNTs	VOCs, ethanol, toluene	RH 32%, 0-1300 ppm	26°C
71, 2021	plastic	SnO ₂ nanoparticle ink	O ₂	55% RH, 0.7% w/v	21°C
72, 2019	Kapton	ZnO	NO ₂	50 ppm	110°C
73, 2021	photo paper	molecularly imprinted sol-gels (MISGs)	volatile organic acids (HA, HpA and OA), hexanoic acid (HA), heptanoic acid (HpA), and octanoic acid (OA)	19.56, 15.92, and 11.78 ppm	room temperature
74, 2019	paper	molecular imprinted polymer (MIP)	propanoic acid (PA), hexanoic acid (HA), heptanoic acid (HPA) and octanoic acid (OA)	-	-
75, 2021	Kapton	PEDOT: PSS-MWCNT	ethanol	40-50% RH, 500-1300 ppm	room temperature (25°C)
76, 2022	CLTE-MW	CNT	NH ₃	300-700 ppm	room temperature
77, 2021	silicon wafer	MWCNTs	benzene, toluene, and xylene (BTX)	30 - 500 ppm	room temperature
78, 2020	quartz glass	hydrogen-terminated nanocrystalline diamond (NCD)	NH ₃ and NO ₂	10-50 ppm	150°C
80, 2022	PET	YSZ dielectric	NH ₃	0, 200 and 500 μM	room temperature

A proposed application of an inkjet antenna that is currently quite relevant is an inkjet-printed 5G antenna.¹¹⁵⁻¹¹⁸ Mass production of inkjet-printed antennas for 5G is likely appealing for its manufacturing ease and lower cost. 5G inkjet antenna applications include wearables and transportation.¹¹⁹ Their lower weight, smaller size, and flexibility allows these antennas to be used on aerial vehicles such as small UAVs, which benefit aerodynamically from a flexible antenna. For niche applications in which a UAV uses flapping wings to fly, flat

and flexible sensors or antennas can attach to the wings or a curved surface. UAVs may also require omnidirectional antennas,¹²⁰ which can be created with inkjet printing.

More common vehicles like cars can also use inkjet antennas. An inkjet-printed antenna can conform to the surface of a car or military vehicle.¹²¹ Paired with other qualities like water resistance, certain flexible antennas can be implemented as a full replacement and upgrade to other, bulkier antennas. WLAN and WiMAX are another application of inkjet antennas, which allows for data connectivity with high speeds.¹²² Like previous applications, this is simply a more cost-effective approach in making technology that already exists. This technology is used for wireless devices like computers and phones,¹²² meaning that mass production is required, and manufacturing will benefit greatly from a simpler and cheaper production process. A unique application of inkjet-printed antennas is for wireless power transfer,¹²³ though this application is still uncommon and its usefulness as a manufacturing method is not yet clear.

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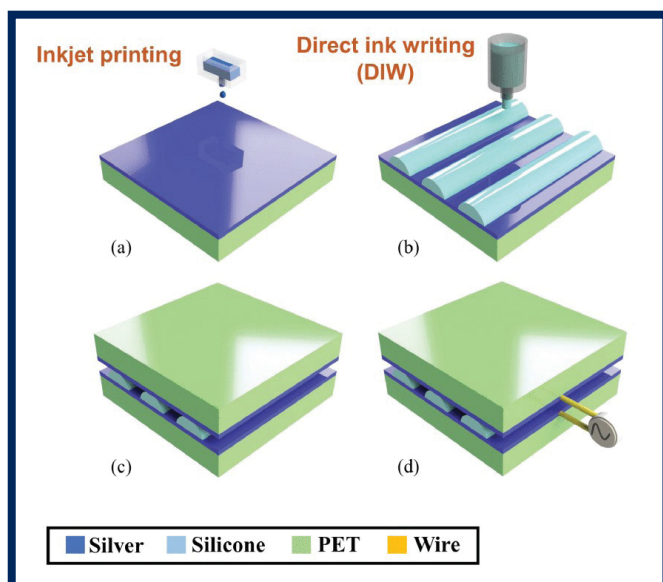


Fig. 4. Fabrication procedure to implement a flexible tactile sensor: (a) Inkjet printing for the silver electrodes on a PET substrate. (b) DIW printing for the silicone-based insulating ink (or CNT/PDMS conductive ink) on the bottom electrode. (c) Bonding between another electrode obtained by repeating (a) and the printed structure obtained in (b). (d) Wire bonding to the electrodes for capacitance (or resistance) readout.¹⁰⁰

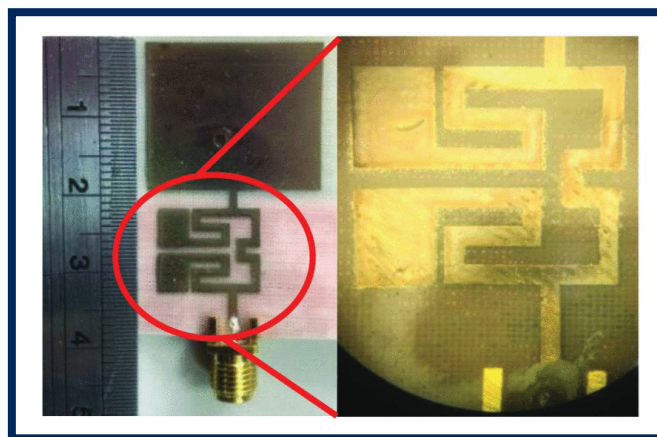


Fig. 5. Photographs of inkjet-printed filtering antenna on a textile.¹⁰¹

A frequent trend in inkjet antennas applications is that many of the applications already exist, they just currently use traditional antennas (e.g., WLAN and WiMAX, 5G, and RFID). However, inkjet printing's cost-effectiveness makes it useful regardless of how new or unique the application, and there are new applications, especially in wearables.

Challenges in Inkjet-printed Sensors and Antennas

Regarding the challenges that inkjet devices face, it is important to consider the alternatives that inkjet printing may be in competition with. One such alternative is general 3D printing, which can allow a wider variety of structure fabrication than inkjet printing. Inkjet printing can be pursued in 3D; however, the challenge is that inkjet structural printing tends to fracture and is not as strong as 3D printing with common materials such as plastic.¹²⁴ This is a challenge that can be met by identifying and testing different materials. For RF sensors, inkjet printing also does not have multilayer printing capabilities, while DIW 3D printing does.¹²⁵ In addition, inkjet printing must be performed on a flat surface. If the ink is released onto a curved surface, it may flow away from the intended printing area and cause the device to malfunction, as the circuit design will not match the theoretical design. This is unique to inkjet printing in that the printer is depositing liquid onto a substrate, but it can be avoided in two ways. The first method is to simply not use curved surfaces in the design of a device. This is limiting in the creation of the device but still provides many design options. The second way is to print layer-by-layer, which can build surfaces that are not entirely flat but can be printed on without changing the intended design of the device.¹²⁴

The materials used for inkjet printing may provide some disadvantages. Specific materials are needed that can be printed onto the substrate at a certain viscosity, as the material must be put through the curing and sintering processes. Sintering can be done with an infrared lamp¹²⁴ to broaden the material selection, but this still presents limitations for inkjet printing sensors and antennas. A problem with some inkjet-printed devices is that the stress of being bent may reduce the lifespan of the sensor or antenna.¹²⁶ Though many of these devices are optimized to perform well under different conditions and forms of stress, their durability over time under these forces is not yet widely tested. Generally, the electrical aspect is highly researched and tested to ensure that the device will function properly when bent or flexed, but these devices typically are not put under this strain for long periods of time to test their structural integrity. Using something such as a wearable sensor on a piece of clothing or skin may cause the device to crack or fracture over long periods of time. All factors related to this issue are subject to change depending on the material used. For example, PTFE is a polymer that has limited use in flexible antennas, as the bandwidth is reduced under bending, and it is electrically unstable when bent as well as being more difficult to bend than other materials.¹²⁷ Bending can also change the bandwidth of an antenna.¹²⁸ Inkjet antennas can also be costly and bulky if the transmission range must be large, and tagging certain surfaces like skin, water, and metal may reduce antenna performance¹⁰⁹.

With a rigid antenna, different amounts of metal can be used to prevent some forms of damage and wear¹²⁹. This protection cannot be implemented on flexible antennas because they are either too small for mechanical protection or the protective material is not suited for the bending and constant strain of a flexible antenna.

Medical sensors entail particular safety, privacy, and performance requirements. Parameters such as selectivity and sensitivity must reach a certain threshold to be medically useful.¹³⁰ With components that are extremely small, this can be tricky to manage. Often this will mean testing and redesigning sensors before they meet these standards. These requirements also mean that certain antennas and sensors may not be the designed to be the best possible devices available, but rather ones that function adequately while still being small and flexible. Some flexible antennas are designed to work



Fig 6. Fabricated prototype of RFID tag on two different apple samples.¹¹¹

well under a specific bandwidth, but not necessarily a very large bandwidth for all applications.¹³¹ A more general issue that inkjet-printed devices face is the risk of manufacturing defects, which can affect device sensitivity.⁷⁵ This is a challenge that comes with many other electronic components and is certainly not unique to inkjet-printed devices but is still worth noting, especially because sensitivity is particularly important in medical sensors.

Nozzles can clog when using metal nanowires, which can slow down printing time and limit how much of a particular nanowire material can be used. In addition, an inkjet printer alone cannot print patterns $>30\text{ }\mu\text{m}$ ¹³². Carbon nanotube ink can clog nozzles as well, which is caused by their inherent structure. Inks that are water-based can have another problem entirely, as the possibility of high surface tension can reduce printing consistency.⁸⁷ These are all very important factors to consider when choosing materials to fabricate a sensor or antenna with inkjet printing, as clogging and inconsistencies in printing can result in wasted time, funding, and materials. The coffee ring effect is one of the more common problems that inkjet printing faces, which involves particles forming in a circle on the substrate while the printed ink is drying, causing conductivity changes in the resulting circuit. One method of reducing the effects of the coffee ring effect is to add ethanol to the solvent, which promotes a lower contact angle between the ink and the substrate.¹³³ This is essentially through Marangoni flow, which involves changing the surface tension of solvents in the ink.⁸ The reduced contact angle on the droplet lowers the surface tension, which can help reduce the coffee ring effect.

Sustainable manufacturing is another common topic in inkjet devices, as it is in our best interest to facilitate recycling of inkjet antennas and sensors. This means that, to be sustainable, the parts used to make a sensor or antenna, which includes the substrate and any electronic components used for the device, must be created efficiently and be recyclable or biodegradable.¹³⁴ This may be difficult as a researcher to be directly involved in, but it should be worth noting that it is very much possible to create recyclable and biodegradable inkjet devices that are still functional for their intended purpose. The specific problem that comes with using biodegradable materials for ink, like magnesium, is that they do not provide as much conductivity compared to materials that are not as easy to dispose of without harming the environment.⁵³ Currently, electronics manufacturing creates massive amounts of waste. This is something that is difficult to change at a consumer level but is still important for researchers to further investigate to provide large-scale methods of reducing waste in the industry. It is also something that may not be implemented, even if it is possible, due to cost. Money is often going to be a major deciding factor when it comes to production, possibly meaning that this challenge will be around for a while.

In general, inkjet printing is a low-cost method of manufacturing electronics. This is true most of the time, but extremely sensitive devices that are beyond the typical goals and scope of inkjet devices can be too expensive to be implemented reasonably. For example, RF platforms in pH sensors for meat packaging are very sensitive and provide stable communication options; however, currently they are too expensive to manufacture to be considered worth the price.¹⁵³

For inkjet-printed antennas, a notable challenge to overcome is the operating range. Research on inkjet antennas shows that it is very possible to make a flexible antenna whose performance is not affected by bending stress, but the operating range is often too low for certain important applications. One of these applications is biomedical sensors paired with an antenna, which when fabricated with a PEDOT:PSS substrate, do not provide an operating range that is suitable for biomedical temperature sensing.¹³⁶ There is little research in the combination of a temperature sensor and antenna that are both inkjet-printed, which means that the development of a fully optimal combination will likely not be implemented into any system very soon. Like many of the other challenges discussed in this section, the optimal solution is simply to research and test more designs and materials. Some antennas have been found to provide better efficiency than that of traditional antennas while under bending stress, so it is very likely possible to solve the issue of transmission range.

Most of the issues that inkjet-printed sensors and antennas face do not seem impossible to overcome. The average cost and variety of use of these devices while still retaining quality means that inkjet-printed sensors and antennas are a technology that cannot be ignored. There are already many examples of working sensors and antennas fabricated through inkjet printing,¹³⁶⁻¹³⁹ demonstrating their promise and sustainable use.

Conclusion and Outlook

Overall, inkjet printing shows great promise and use in electronics manufacturing. Inkjet sensors and antennas can be used for a variety of applications while being cost-effective in their fabrication technique. Fabrication can be performed with materials that allow disposable sensors to be biodegradable, holding potential for being more environmentally friendly than traditional manufacturing methods. Inkjet printing holds great promise for biomedical systems as well as temperature and gas sensors, and even more applications.

Inkjet antennas can either be paired with a sensor for uses like biomedical applications and RFID tagging or can be used independently for virtually any basic data transmission. Inkjet printing also allows for the sensors and antennas to be highly customizable while still being convenient to make and use. Much of the research on inkjet-printed devices shows that it is very possible to make them flexible while being bend and strain resistant, resulting in these devices being applicable to many applications. Flexibility allows for the relatively newer usage of wearable sensors and antennas, since the devices can bend, fold, and basically follow the skin or clothing of a moving person. This is especially important for biomedical sensors, and it is equally important with inkjet antennas, as they may need to attach to and bend with a surface. Bending in this way allows antennas to attach to unique surfaces like wings, due to both the shape changes and better aerodynamic properties when acting as a flat surface instead of a rigid stick or other shape. Benefits also include being operable under relatively normal conditions, like room temperature.

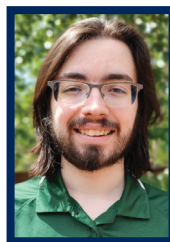
Though inkjet-printed sensors still face challenges like fabrication defects, the coffee ring effect, and effective lifespan, and inkjet antennas still face range limitations and other challenges, the benefits outweigh the downsides. Challenges like fabrication defects are uncommon and can be minimized by material choice and circuit design. Most importantly research is working to find new ways to either compensate for these problems or solve them completely.

It is unlikely that the inkjet-printing fabrication process will change much in the coming years. Some steps have been slightly altered in recent research, but the overall process remains the same. Changing the materials used and ink composition as well as different methods for treating, curing, and sintering are all common, but these are forms of customization, rather fundamental advances. Some applications are certainly more promising than others, however, as the amount of research on biomedical sensors appears to be much more common than research on some of the other topics, such as food processing. Regardless, it is evident that the use of inkjet printing in electronics manufacturing will only increase, and is poised to find niche applications in the era of internet of things (IoT).

Acknowledgments

Sebastian Martinez and Leobardo Gonzalez-Jimenez were funded by the National Science Foundation, under grant #2104513. 
© The Electrochemical Society. DOI: 10.1149/2.F12234IF

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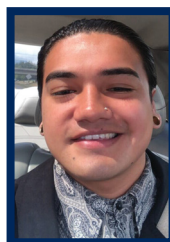
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(continued on next page)

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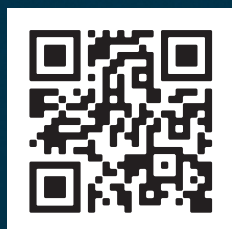
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