Chapter

Inkjet Printing of Functional Inks for Smart Products

Cláudia Buga and Júlio C. Viana

Abstract

Inkjet printing is a recent promising technology for direct patterning of solution-based materials over different substrates. It is particularly interesting for applications in the flexible electronics field and smart products manufacturing, as it allows for rapid prototyping, design freedom, and is compatible with conductive, semiconductive, and dielectric inks that can be cured at low temperatures over several types of substrates. Moreover, the inkjet process allows for ink economization, since great electrical conductivity can be achieved despite the deposition of small volumes of ink. This chapter describes the overall process, the main inks and their features, the critical process variables, and its limitations. Applications related to inkjet printing of functional materials and smart products are highlighted. New technology advancements and trends are finally addressed.

Keywords: inkjet printing, functional inks, process parameters, printing process optimization, inkjet printed devices, smart products

1. Introduction

Inkjet printing (IJP) is a widespread technology used in personal and industrial printers. Recently, it has started to gain traction as a new promising technology for the direct patterning of solution-based functional materials. IJP relies on a non-impact dot-matrix printing technology in which droplets of ink are flown from small openings, called nozzles, directly to a designated position on a media to produce an image. The printed patterns are digitally defined and directly transferred to the printer. The nozzles or the substrate holder move accordingly to a pre-programmed pattern, which allows the printing of virtually any pattern [1, 2].

IJP technique is particularly interesting for applications in the printed electronics field as it allows for rapid prototyping and is compatible with various substrates, and conductive, semiconductive, and dielectric inks that can be cured at low temperatures. As a result, several application examples of this technology have already been advanced in the literature [3–9]. IJP methods are widely employed in the manufacture of sensors and actuators, and many electrically conductive inks are already commercially available and optimized according to specific characteristics that make them suitable for IJP [10]. Since IJP relies on the use of computer software, it allows for rapid prototyping and freedom of design combined with tunable resolution [11]. Throughout the literature, some examples include IJP temperature sensors [12–14], humidity sensors [15–17], and pressure and strain sensors, that can be capacitive [18, 19], piezoresistive [20, 21], and piezoelectric [22–24]. These sensors and actuators can be integrated into novel smart products.

According to recent technical reports, printed electronics (PE), particularly IJP and its enabling technologies (functional printing and inks) show an increased market interest and growth. **Table 1** presents the market expectations related to these technologies.

PE market will continue to expand over the coming years, with a strong emphasis on energy harvesting and storage for electronic cars, gadgets, equipment, components, and other industries that rely on PE to reduce total energy usage. The PE market will be driven by low production costs, environmentally friendly technologies, a diverse choice of substrates, and a rising demand for flexible electronics applications. PE has allowed printing of electronic and electrical components on lightweight, cost-efficient and flexible materials (like cloth, paper, or polymeric films) in conventional electrical circuits. This PE market will continue to expand mainly driven by [29]: (a) the increasing development of smart and connected devices, as demanded by Internet of Things (IoT); (b) the rising demand for energy-effective, thin, and flexible consumer electronics; (c) the substantial costs reduction provided by PE; and (d) the importance of environmentally sustainable technologies.

The increased demand for low-cost and high-volume production of electronics will boost the functional printing market. This is supported by the increased availability of a wide range of substrates, high-throughput manufacturing technologies (e.g., R2R for large-area electronics processing), and a reduced environmental impact (e.g., thin and flexible electronics) [30]. This will be fostered by the development of new products/applications, the introduction of added functionalities into multiple products, and the emergent widespread of digital manufacturing techniques.

After a huge pace of growth, the IJP market is becoming mature, and high-speed inkjet printing devices with enhanced quality and higher productivity are already available. Notwithstanding, the initial costs of equipment are still rather high. Major applications of IJP have been related to graphic communication and packaging labeling, but functional substrates and objects driven by PE and functional printing applications are fostering IJP market. Principal drivers for the adoption of IJP technologies

	Printed electronics [25]	**Functional printing** [26]	**Inkjet Printing** [27]	**Functional inks** [28]
2020 market value, B$	7.9	8.9	40.8	0.87
2027 market value, B$	22.7	23.9	49.2	1.3
CAGR, %	21.5	15.1	3.11	5.3
Typical applications	Batteries, sensors, sign boards, labels, PCB, touch panels, LED panels, solar cells	Sensors, displays, batteries, RFID tags, lighting, photovoltaic, electronic components	Flexible OLED displays, wearables, photovoltaic, sensors, PCB	PCB, MEMS, security printing, smart textiles, displays, smart packaging, RFID tags, photovoltaics, biochips

Table 1.
Market values and growth rates for different related technologies: Printed electronics, functional printing, inkjet printing, functional inks, and smart products.

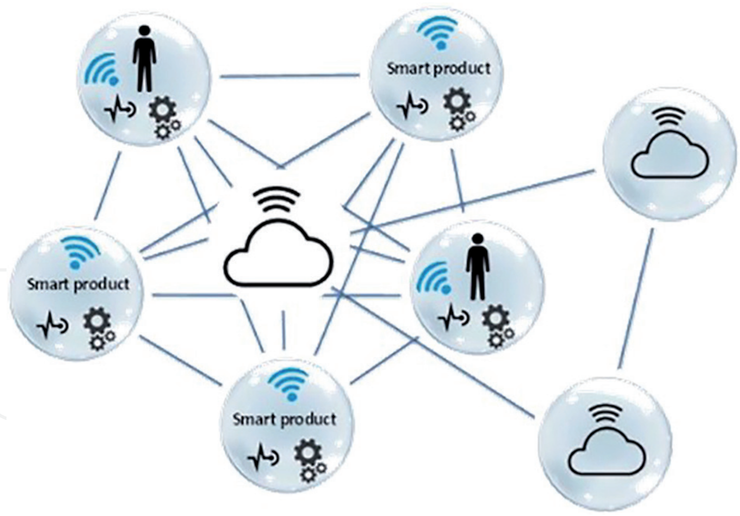

Figure 1.
System of smart products.

are OLED displays, products/processes digitalization, IoT, Cyber-physical systems (CPS), and Big Data.

Functional inks can be electrically conductive, resistive, dielectric, semi-conductive, or have other special functions, such as thermal conductivity, electroluminescence, light-diffusing, or piezoelectric. Functional inks are key enablers for PE applications. They must combine their functionality with being flexible, processable at low temperature, adhere to a wide range of substrates, in some cases transparent, and straightforward to manufacture. Novel functional inks include suspensions of organic or inorganic nanomaterials, or particle-free solutions of organic materials, which are inherently stretchable, and suitable for applications in e-textiles and in-mold electronics [31].

Smart products are physical objects equipped with sensors, embedded artificial intelligence, communication ability, and information technology. They bridge the physical and digital worlds, sharing information about themselves, their environment, and their use, being supported by emergent technologies of CPS, IoT, and artificial intelligence (AI). Furthermore, smart products are now connected and able of forming product eco-systems; they interact with the user, adding a social layer to these eco-systems. This allows a paradigm shift in the business world: from selling products to offering services, to the "servitization" of products (**Figure 1**). This transformation towards novel smart products is enabled by the development of emergent technologies simultaneously in both the physical (hardware) and digital (software) worlds, and their interfaces. This chapter focuses attention on product manufacturing (hardware) technologies for smart products, namely those based on PE and functional printing, and more specifically on inkjet printing of functional inks.

2. Inkjet printing of functional inks

2.1 Inkjet printing process

IPJ is an additive manufacturing technique that encompasses an ink reservoir that is connected to a print head device and responsible for jetting ink droplets over a pre-determined substrate. IJP allows for high-resolution 2D patterning, ink

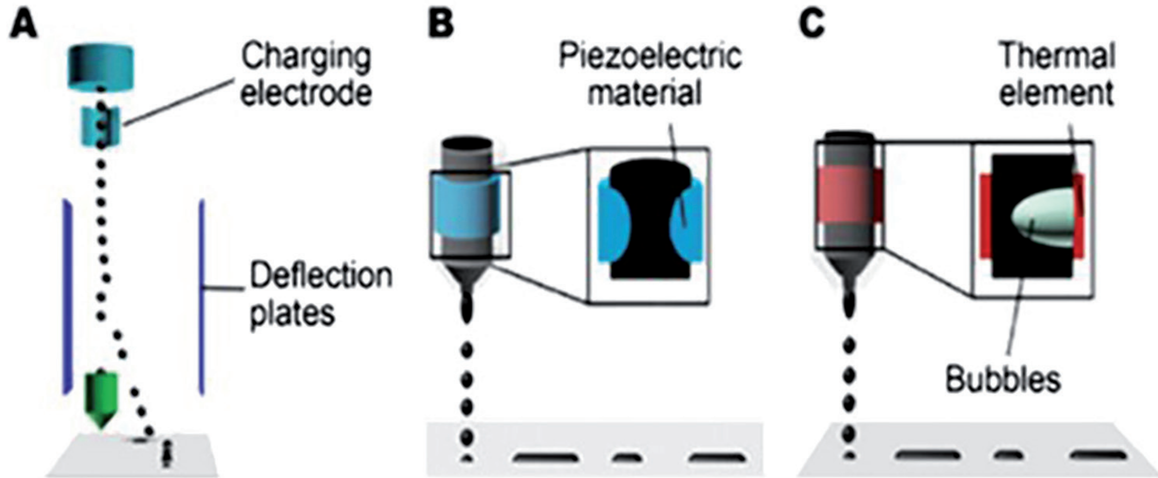

Figure 2.
IJP methods: (a) CIJ, and DOD inkjet printing with (b) piezoelectric and (c) thermal head [34].

economization, and non-contact deposition via a micrometer-sized inkjet nozzle head [32, 33]. Inkjet can be divided into two main distinct processes (**Figure 2**): Continuous inkjet (CIJ) printing and Drop-on-demand (DoD) printing technologies [35]. As the name suggests, in CIJ printing the droplets are continuously generated and deposited when subjected to an electrostatic field, caused by a charging electrode. DoD printing, on the other hand, relies on the selective activation of the print-head through impulses that can be acoustic, electrostatic, thermal, and piezoelectric (the latter two are the most reported cases) [35].

The CIJ process is mainly used in industrial printers, mostly for packaging and graphical applications. In this case, the ink droplets are continuously expelled due to the effect of an electric field that actuates the piezoelectric crystal of the print-head. Although this process can be used for PE it is majorly directed at continuously printing large volumes of nonfunctional inks [36]. Concerning DoD inkjet printing, several sub-methods can be identified. The most disseminated ones are piezoelectric and thermal inkjet printing, nonetheless, there are other methods whose popularity is increasing and can also grant high-quality printing of functional inks [36]. Among those, electrohydrodynamic (EHD)-IJP [37–39], aerosol jet printing [40], drop impact printing [41], and acoustic printing [42], can be highlighted.

In the piezoelectric IJP method, the ink reservoir is coupled with piezoelectric constrictors that load and expel the ink (print head). In this process, the dimensions of the ink droplet can be controlled, so the ink consumption is very low. To avoid clogging the nozzles, the functional inks must be produced taking into account specific properties, such as particle size, ink viscosity, surface tension, and density [35]. The nozzle is designed to be resistant to organic solvents and is therefore compatible with a wide range of solvents for ink formulation [2]. **Table 2** summarizes the main characteristics of the inks that are compatible with each one of the inkjet printing methods and sub-methods. Comparing the different printing sub-methods, it is clear that the thermal and the piezoelectric ones are much more limited in terms of suitable ink viscosity range. Nonetheless, they are still currently the most approachable methods in terms of affordability and widespread commercial availability of the equipment.

Except for the jetting method, the overall process of printing is common to all CIJ and DoD IJP techniques. The printed patterns are digitally generated (CAD software)

Printing Method	Sub-method	Particle size (nm)	Viscosity (cP)	Surface Tension (dynes/cm)	Resolution (μm)
CIJ	—	<1000	1–10	25–70	
DoD	Thermal	<1000	5–30	35–70	2–100
	Piezoelectric	<300	1–30	35–70	2–100
	EHD	3–300	1–4000	35–70	0.2–1
	Aerosol	10–30	0.5–2500	20–70	5–20
	Acoustic	<100	0.5–25,000	15–650	10–20
	Drop impact	<20,000	0.5–33	32–70	40–960

Table 2.
CIJ and DoD printing characteristics [2, 35, 37–43].

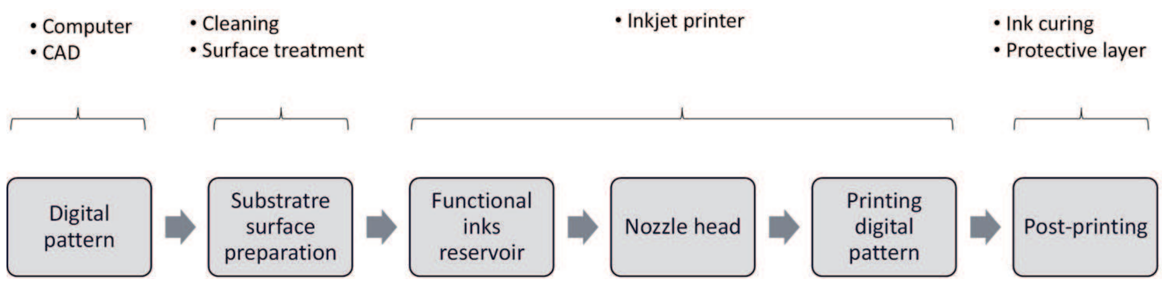

Figure 3.
Inkjet printing steps.

and can be easily changed, which makes this printing technique an ideal choice for prototyping and design optimization. **Figure 3** depicts the main stages in IJP:

1. Digital pattern—A CAD software (or other graphic software) is used to digitally generate the printed pattern.

2. Substrate surface preparation—the substrate surface is cleaned with an appropriate cleaning agent; a surface treatment can be selected for better ink adhesion.

3. Ink preparation—ink can be filtered to remove impurities; ink viscosity can be changed by using an adequate solvent; a surface treatment technique can be applied (e.g., plasma, corona discharge); the ink must be stirred for better particle suspension dispersion.

4. Inkjet printing—the file is uploaded in the printer software; the reservoir is filled with the ink; the ink can be preheated before printing; the printing parameters are defined, mainly for controlling the printing head (see next section); then, printing takes place.

5. Post printing—after printing the printed pattern must be sintered/cured (by temperature, photonic, UV light, plasma); a protective layer can be applied (e.g., by lamination, spray coating)

The IJP technology for PE applications and its technical-scientific developments have been reviewed over the last decades. Hue P. Le [44], 1999, reported the developments in the various IJP technologies, noting the significant growth rate of inkjet printers market. New ink formulations and new printhead designs were recognized as relevant for new applications. In 2010, the state-of-the-art of IJP of functional materials was reviewed by Raje and Murmu [45]. Improvements in process throughput remained the major challenge. In the same year, Derby reviewed the current understanding of the mechanisms of drop formation and the interactions between drops and the substrate, with a focus on the fabrication of structures for structural or functional materials applications [46]. Two years later, in 2012, Cummins and Desmulliez conducted a review in IJP of conductive materials [47]. IJP process, substrate properties, and types of conductive inks are the various factors that affect the quality of inkjet-printed products and their increasing relevance to the fields of electronics manufacturing, packaging, and assembly. In 2019, Nayak et al. reviewed the IJP of electronic devices, mainly addressing the fluid dynamics of inks and main properties (e.g., viscosity, surface tension, Weber number, Reynolds number, and Ohnesorge number) and their effects on defects appearance (coffee ring formation) [48]. The use of functional inks in sensors, thin-film transistors, and energy storage devices is presented. Ke Yan et al. revised the state-of-the-art related IJP strategies and functional inks for wearable electronic devices (e.g., sensors, displays, transistors, and energy storage devices) [49]. They highlighted the need of having available more intrinsically flexible and stretchable inks for avoiding, cracking, and delamination on highly flexible/stretchable substrates. Also, IJP technology development shall solve nozzle clogging issues for a more stable printing process. Kye-Si Kwon et al. reviewed piezo-driven IJP for PE. Other printing methods for high viscosity ink are also considered and compared (e.g., electrohydrodynamic jet, aerosol jet, and micro-plotter printing) [50]. There is a high demand for high-resolution printing of high viscosity inks for PE. In this case, the functionality of the device is more important than graphism perception, and the development of suitable inks for IJP remains one of the key issues. More recently, Muhammad Ali Shah reviewed the classifications and applications (textile, displays, and wearable devices) of IJP with more attention paid to piezoelectric IJP due to its higher relevance [36]. Various driving-voltage waveforms approaches are compared. Recently published studies on applications of IJP are summarized. Again, high high-viscosity IJP technologies are revised. The performance of IJP shall be improved by the development of new printheads with ink-recirculation and new techniques for printing high viscosity inks.

2.2 Functional inks for IJP

The use of inks has been around for almost as long as there is human life. It empowered evolution and was responsible for cultural and sociological developments whose footprints can be traced from the Paleolithic to this day [51]. The methods to dispense inks have also evolved with them and the first inkjet-type apparatus was patented in 1858 by William Thomson and Abbe Nollet [52]. The concept of printing functional conducive inks emerged some years later, in the 20th century, and was patented by Albert Hanson [53]. Nonetheless, research in IJP of functional inks exploded only nearly 100 years later, at the turn of the 21stcentury, thanks to the breakthrough development of organic conducting polymers by Heeger, MacDiarmid, and Shirakawa, which rendered them the 2000 Chemistry Nobel Prize [54, 55]. This led to several advancements in the field of PE, including the development of the first high-resolution printed all-polymer transistor circuits [56–58]. The fact that polymeric inks are more stable, easier to formulate, manipulate, and print was mostly responsible for this paradigm shift [43]. Nonetheless, with the technical developments experienced in this field, metallic-based inks started to be printed shortly after, thanks to the use of stable solvent systems and other additives that allowed to stabilize the metallic particles into homogeneously dispersed formulations with tunable surface tension and viscosity. Thereby, nowadays several base materials can be selected, depending on the final device desired functionality.

Functional inks for inkjet printing can be divided into, conductive, semi-conductive, and dielectric. Conductive inks are usually applied in the development of conductive tracks, vias, and electrodes. They generally rely on the dispersion of metallic nanoparticles, namely Ag [59], Cu [60], and Au [61], on organic or water-based solvents. To aid in the dispersion and grant long-term stability of these inks, surfactants, stabilizers, humectants, and other additive compounds are demanded [32]. To further tune the ink properties conductive nanofillers such as CNT can also be added. Although less conductive than metals, some polymers, metal-oxides, liquid-metal alloys, MXenes, perovskites, quantum-dots, and metal–organic-decomposition inks can also be used in the development of conductive inks. Currently, indium tin oxide (ITO) is still the most used material to produce transparent electrodes for thin-film devices (organic light-emitting diodes, OLED; field-effect transistors, OFET; photovoltaic devices, OPV) [62, 63]. However, the deposition o ITO is usually done by resorting to physical vapor deposition (PVD) which is much more expensive and energy-demanding than printing technologies. Moreover, its over-exploitation is damaging to the environment, and it is only recyclable through energy-consuming processes [64]. MXenes, quantum dots, and perovskites are examples of alternative base materials that can be used to develop inks for inkjet printing transparent electrodes for the above-mentioned applications. As a result, even though they have lower power conversion efficiency, their popularity is increasing [65, 66]. Despite being known for their higher electrical conductivity most inorganic inks are expensive, become brittle after curing, have limited flexibility, and might experience oxidation and loss of performance, if not properly encapsulated. As a result, organic conductive polymers such as poly(3, 4-ethylenedioxythiophene)-poly(styrenesulfonate) (PEDOT:PSS) [10, 67, 68], poly(3-hexylthiophene-2,5-diyl) (P3HT) [69, 70], and oxidized polyaniline (PANI) [71] are also being used as alternative materials for printing electrodes and conductive tracks. Other highly conductive inks can be developed using carbon allotropes, such as single-walled and multi-walled carbon nanotubes (SWCNT and MWCNT) [72–76], graphene [77, 78], and fullerenes [79].

Semiconductors have an electrical conductivity that can vary between the conductor and the dielectric. They can be n-type or p-type, depending on the doping atomic impurities added to the structure of the semiconductor. These impurities define the electrical properties, with highly doped semiconductors presenting conductivity values similar to metals. When the semiconducting material is less doped, its conductivity departs further from the conductive range. These semiconductors are crucial for the performance of the final device since their characteristics usually change with environmental physical, or chemical conditions [43, 72]. Less doped inorganic semiconductors include zinc-oxide (ZnO), zinc tin oxide (ZTO), and indium-zinc-oxide (IZO). Another interesting material for the development of semiconductor inkjet inks is the amorphous indium-gallium-zinc-oxide (a-IGZO), as it is processable at low temperatures, being vastly used in thin-film-transistors and solar cells [80]. On the other hand, organic semiconductors can be PEDOT: PSS, rubrene, pentacene, poly(diketopyrrolopyrrole-terthiophene) (PDPP3T), diphenylanthracene (DPA) [43]. PEDOT: PSS and CNT-based composites are vastly

Ink	Description	Examples
Conductive	Composed of highly conductive materials, mostly metals, metal-based composites, metal oxides, metallic alloys, highly doped conductive organic polymers in solvents, metal-oxide particles suspended in binders or organic-metallic blends	Metallic nanoparticle-based inks; Conductive polymers; Graphene inks; Perovskites; Mxenes; Quantum dots; Metal oxide-based inks; Eutectic liquid metals
Semi-conductive	Composed of semiconducting organic polyme*rs in solvents, inorganic nanoparticles (Group III-V, II-VI and IV semiconductors and carbon nanotubes) suspended in carrier fluids, or organic–inorganic blends; Also composed of less doped polymers that can be reinforced with carbon nanotubes or wires.	Metal-oxide inks; Semi-conductive polymers; Carbon-based inks
Dielectric	Organic polymers in solvents, organic polymer thermosets or ceramic-filled organic polymers	Ceramics; Metal–organic materials; Dielectric polymers; Piezoelectric polymers

Table 3.
Summary of ink types, their description, and some examples.

used as pressure sensors (piezorresistive materials) [81, 82], and temperature sensors (thermoresistive materials) [83, 84].

Finally, dielectrics exist in the less conductive boundary of the conductivity spectrum. They are used in electrical applications that demand high capacitance and insulation. Some dielectrics inks can be made from metal–organic materials such as aluminum oxide (Al_2O_3), zirconium oxide (ZrO_2), hafnium oxide (HfO_2), and yttrium oxide (YO2). Nevertheless, organic dielectric inks can also be formulated from polyvinylpyrrolidone (PVP), Polyvinyl alcohol (PVA), and Polymethyl methacrylate (PMMA), polydimethylsiloxane (PDMS), Polyvinylidene fluoride (PVDF) and its copolymer, polyvinylidene fluoride-trifluoroethylene (PVDF-TrFE). PVDF-based inks are of extreme importance since they are ferroelectric and enable piezoelectric applications. Another inkjet ink is the electrostrictive P(VDF-TrFE-CTFE) terpolymer, which can be used for energy harvesting applications [85–87]. **Table 3** summarizes the different types of printable inks.

2.3 Inkjet printing process variables

Both CIJ and DoD printing demand the use of inks with particle size under 1 μm (ideally <300 nm). In the particular case of the piezoelectric DoD method, their viscosity should be in the range of 1-20 cP, and their surface tension between 35 and 70 $mN.m^{-1}$ [35]. IJP requires no mask, has a low ink waste rate, and typical linewidth resolution of 30-50 μm [88]. DoD has established itself as the main IJP technology, with piezoelectric method being the most widely employed when it comes to IJP printing of functional inks, as it allows less ink consumption [49]. Hence, inks are specifically formulated to meet the requirements of the printing process [49].

To achieve the best possible printing quality, several factors need to be taken into account and studied from an optimization-driven perspective. For instance, the rheological properties of the ink (viscosity, surface tension, and density) interplay with each other and cannot be individually assessed. Similarly, the parameters of the printing process themselves cannot be individually studied. Thus, the printing resolution, printhead speed, printhead height, waveform profile, droplet size, and printhead temperature also influence one another and, as a result, before high-quality printing

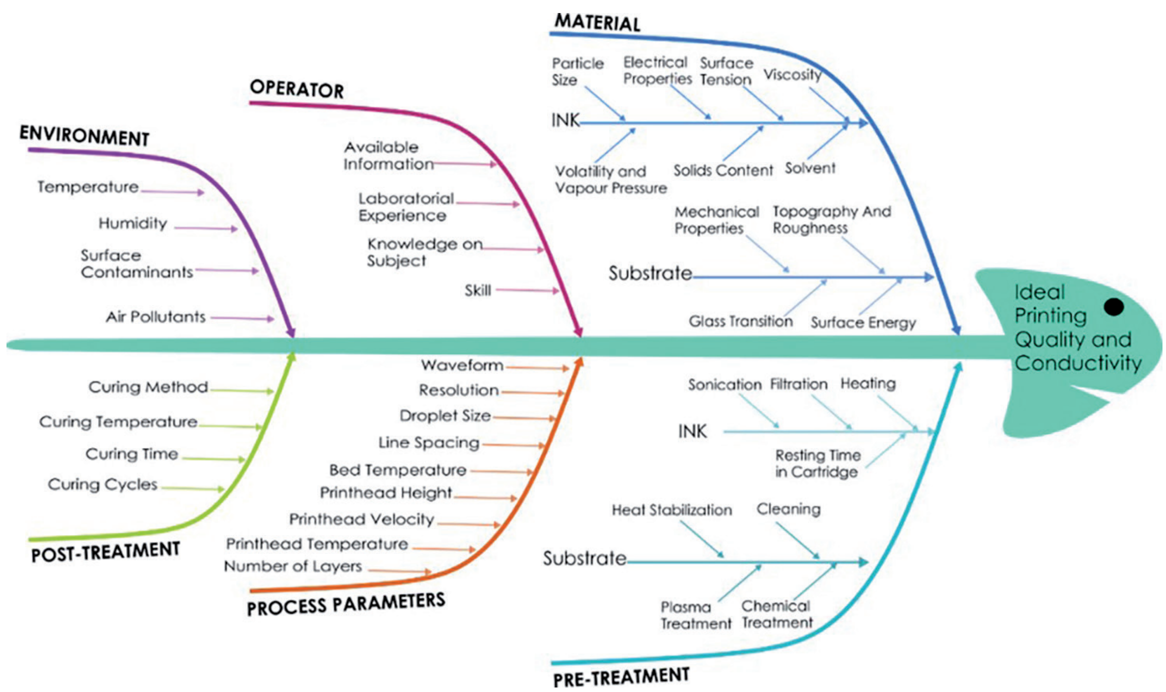

Figure 4.
Potential cause-effect factors influencing printing quality and conductivity.

can be attained, a series of optimization studies need to be conducted for each combination of ink/substrate. Other variables include the pre and post-treatment of the ink, substrate, and printed outputs. The operator experience and the environmental conditions will ultimately also influence the printing process. In **Figure 4**. the main print quality affecting parameters are summarized in a Fishbone diagram. Since several factors need to be simultaneously studied, a design of experiments approach is frequently performed by researchers aiming to rapidly optimize the process [59, 89–91].

Even after all parameters are optimized, some issues can still occur during the printing process namely nozzle clogging, printing deficiencies (coffee-ring effect, satellite drops, random electrical interference that causes droplet jetting oddness, missing droplets), loss of ink dispersibility, presence of dirt or dust particles in the ink system or substrate, among other issues [92]. As a result, to use IJP to develop electronic devices in industrial settings in-line quality control methods should be performed as a way of assuring functionality. To prevent the effect of environmental variables, which are often uncontrollable, the printing process should be performed in a controlled clean-room area.

2.3.1 Inks properties

Inks intended for inkjet printing should have linear Newtonian behavior and low viscosity, within a specific range. The drop formation and dynamics of the ink are ruled by three dimensionless numbers, that are related to the ink rheological and physical properties, namely the Reynolds number (R_e), the Weber number (W_e), and the Ohnesorge number (Oh) [49]:

$$\mathrm{R_e} = \frac{\upsilon \rho d}{\text{ç}}; \mathrm{W_e} = \frac{\tilde{o}^2 \rho d}{\tilde{a}}; Oh = \frac{\sqrt{\mathrm{W_e}}}{\mathrm{R_e}} = \frac{\text{ç}}{\sqrt{\gamma \rho d}}; \mathrm{Z} = \frac{1}{Oh} \qquad (1)$$

where, υ is the velocity, ρ is the density, η is the dynamic viscosity, γ the surface tension, and d the characteristic length. To assure the ink is printable, its characteristics must obey some critical parameters and fall within certain limits. Most reports indicate that the optimum range to print a stable droplet is $1 < Z < 10$, as represented in **Figure 5** [49]. Z values above 10 relate to fluids with insufficient energy for drop formation, whereas Z values below 1 generally belong to fluids that are too viscous for printing, because the capillary force at the nozzle prevents its ejection. Also, to avoid the formation of satellite drops, the Weber number should be in the range of $2 < We < 25$. Nonetheless, these boundaries are not universal laws, with some authors reporting slightly broader ranges for ink printability [93, 94]. When the overall properties of the ink do not fall within these boundaries, the jetted fluid will not be able to form stable and consistent drops with adequate velocity to overcome the surface tension barrier at the tip of the nozzle, caused by the fluid/air interface. In this case, several break-up regimes can be identified from the Rayleigh break-up (insufficient velocity to form jets of ink) to the complete atomization (disintegration of the ink jets due to exaggerated velocity) [95].

2.3.2 Adhesion between inks and substrates

Another parameter that demands the previous study when planning inkjet printing is the adhesion between ink and substrate. This may affect the final printing result and additional procedures might be needed to assure compatibility. For ink to adhere well to a substrate, it must present appropriate wettability and adhesive bondability [96], meaning the surface tension of the ink must be lower than the wetting tension of the substrate (surface energy). To test this parameter, the substrate must be completely dry and free of any contaminants to start with. If after cleaning the substrate it still presents low wettability, surface pre-treatments may be needed. Such treatments include surface modification resorting to chemical modification,

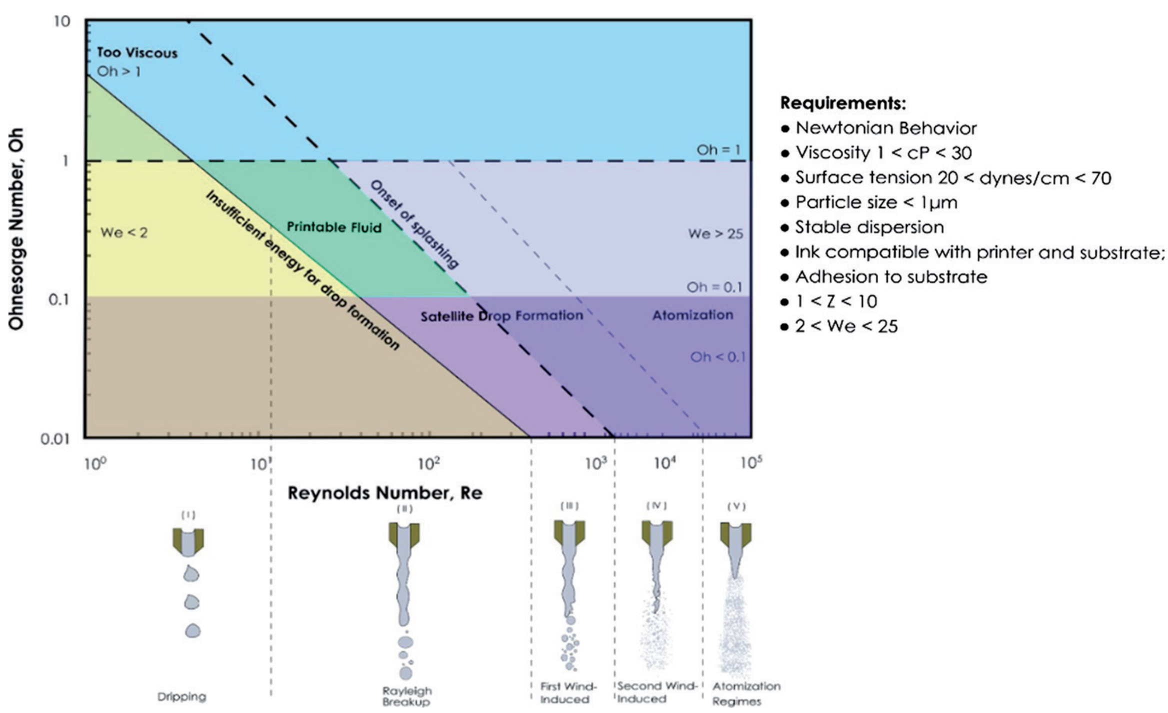

Figure 5.
Ohnesorge diagram, evidencing the fundamental characteristics of the printable fluid and the different drop break-up regimes responsible for printing errors, and requirements summary for developing a printable fluid.

coating with hydrophilic moieties (such as PVP and PVA solutions) [97, 98], plasma activation [98–100], mechanical abrasion, or superficial integration of nanoparticles or nanoclays [101], which increase surface roughness. Plasma activation is usually done by resorting to corona discharge plasma treatment and relies on the production of a high voltage electrical discharge that ionizes the molecules of the treated surface, positively changing its polarity (or oxidizing it) [99, 102, 103].

2.3.3 Pre- and post-treatments

To improve the printability of the ink some actions can be taken. Re-dispersion followed by filtration of the ink before use is effective in removing impurities and potential particle agglomerates that could clog the microscopic nozzles. The presence of trapped air bubbles in the ink is also damaging to the printing process. To prevent trapped bubbles, the ink should be degassed after filtering and left to rest for at least 30 minutes after filling the cartridge with it.

After printing, the ink must dry to become functional. When printing over paper and textiles, the ink is easily absorbed, and drying is not usually necessary, however, when using polymeric substrates it is preferable to promote the drying of the ink by thermal or UV curing [104]. In the case of thermal curing, heat is applied to facilitate the evaporation of the liquid ink carrier, which can be water or organic solvent. To render high printing quality and good electrical conductivity the curing temperature needs to be carefully chosen to prevent deformation, melting, or degradation of the substrate, as well as preserve the ink properties and avoid cracking [89]. To assure the homogeneous heating of the final printed patterns, an oven or an environmental chamber is usually used. Alternatively, cross-linkable inks are instantaneously cured using UV irradiation.

Regarding the drying of the ink itself, residual tensions might cause the ink not to dry homogeneously, leading to a phenomenon known as the coffee ring effect, which impairs the quality of the final print and is pictured in **Figure 6**. The coffee ring effect

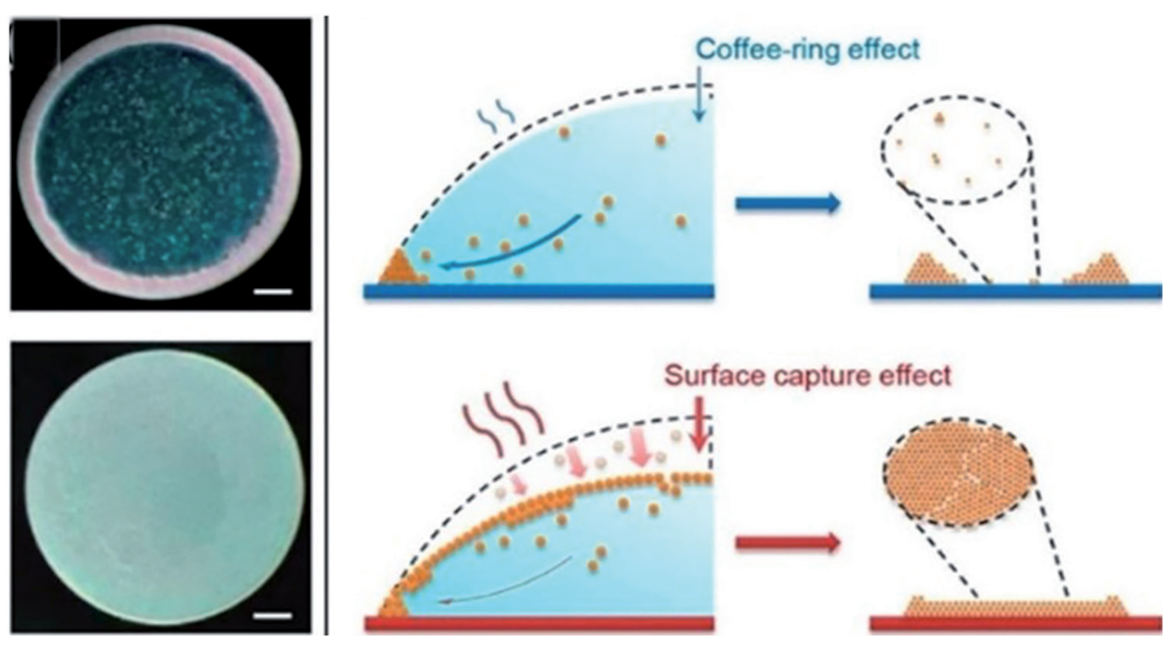

Figure 6.
Ring formation in colloidal droplets dried at room temperature versus uniform particle deposition of evaporating the same colloidal system in an environmental chamber at an elevated temperature. Reproduced with permission from refs. [105, 106]. Copyright © 2019 ACS.

is characterized by a ring-like morphology formed during ink evaporation, resulting from the solute segregation and accumulation along the drop periphery due to capillary flow. This issue occurs frequently when using nanoparticle inks and is caused by the convective macroscopic flow (Marangori flow) that occurs during the drying process and pushes the particles to the borders of the printed fluid [107], causing irregularities in thickness or coalescence between printed droplets.

Factors that influence the coffee ring effect are the evaporation rate and the particle concentration in the ink. A lower evaporation rate promotes ink homogeneity and can be reduced by lowering substrate temperature. Thus, the drying temperature and time also need to be optimized. Moreover, superficial cleaning, treatment, and heating must be performed homogeneously throughout the entire surface of interest. Since the ink starts its drying process as soon as it hits the substrate, the final curing step in the oven might not be sufficient to grant homogeneous drying. As a result, some printers encompass an integrated substrate heating feature, which can facilitate the bonding of the ink to the substrate and in between layers (when more than one layer of ink is printed). Using a solvent with a high boiling point, adding additives, reducing drop volume, and increasing the particle diameter can also help reduce the coffee ring effect.

2.3.4 Process and apparatus related parameters

Printhead model. Different inkjet printing systems demand different printhead models. The model of printhead also varies depending on the final application. Printheads for industrial IJP applications are more expensive, display a larger number of nozzles and allow for higher printing resolution. On the other hand, printheads intended for research and laboratory use are cheaper, have fewer nozzles, and print in lower resolution, as displayed in **Table 4** [50]. Regarding laboratory printing setups the most frequently used thorough the literature is the Dimatix Materials Printer, DMP series [50, 92, 108–112].

The general inkjet printer setup can be seen in **Figure 7a**. A 3-degree of freedom (DOF) system is the most frequently adopted and allows for efficient printing. Usually, the printhead only prints in one of the directions x-y directions (left-to-right).

In an inkjet printer the following parameters can be adjusted:

Resolution. The resolution should be chosen in accordance with the desired printed pattern, selected ink, and substrate material [109]. In multi-nozzle inkjet printers, the resolution is often controlled by the rotation of the printhead in predefined angles

		Features				
System Type	**Examples**	**Max. Jetting Frequency (kHz)**	**Print Width (mm)**	**Dropplet Volume (pL)**	**Resolution (dpi)**	**Number of nozzles**
Printheads for industrial applications	Xaar, Hitachi Ricoh, Konica Minolta, Kyocera	45–100	72–116	1.5–21	360–400	1024–5680
Laboratory and research systems	Microdrop,Microfab, Fujifilm Dimatix	30	64.96	12–33	1200	1024

Table 4.
Available inkjet printing systems [34, 50].

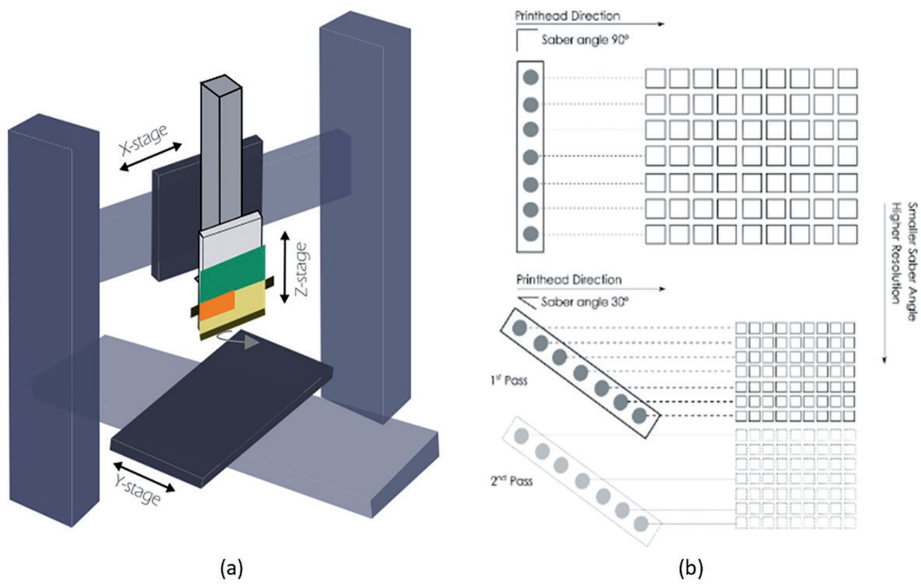

Figure 7.
(a) Illustration of the XYZ cartesian inkjet printing system with mounted printhead. (b) Depiction of the Printhead in its native position and rotated at a 30-degree angle [113].

(saber angles). To increase resolution, the printhead is rotated towards the movement direction axis. While the printhead is perpendicular to the printing direction, the resolution equals the native distance of the nozzles (lowest resolution). When the angular displacement is decreased, the distance between nozzles is diminished and the printed patterns achieve higher resolution (**Figure 7b**) [113]. In cases where the printhead is manually rotated, operator errors may occur, especially when dealing with small patterns with high resolution, which are more prone to displacement errors. For example, as seen in **Figure 7b**, many patterns demand more than one pass of the printhead be concluded and, if the direction is not perfectly aligned, the pattern will experience displacement between the two passes.

In practice, higher resolution is associated with a higher density of drops per area, which in turn, provides higher conductivity when printing conductive inks. Nonetheless, some issues might arise when the drops are too distanced (low resolution) or too overlapped (high resolution) and printing errors such as flooding, lack of superficial homogeneity, and loss of conductivity can occur, as illustrated in **Figure 8**. Moreover, if several passes are demanded additional attention must be given to assure correct angle alignment [109]. Some designs can also be prone to variability and errors, particularly if the image has sharp right-angle corners or lines whose width does not obey critical spacing rules [108].

Since inkjet printers usually print exclusively when moving in the left–right direction, different orientations of the same patterns may experience differences in the quality output, especially when higher resolutions are involved (> native resolution). This is particularly noticeable if the manual setting of the saber angle is not perfectly aligned. Considering this, to print the correct resolution in the precise position, the inkjet printer software is programmed to compensate for the angular displacement of the head. When this happens, even a slight imprecision during the printhead assembly can propagate printing errors across several printing passes (In **Table 5**, the major figures of merit that allow to identify the quality of printing are summarized, along with their description and observational examples).

Printhead Height. The height of the printhead, i.e., the distance between the nozzle and the substrate (the stand-off distance) can influence the splatter pattern

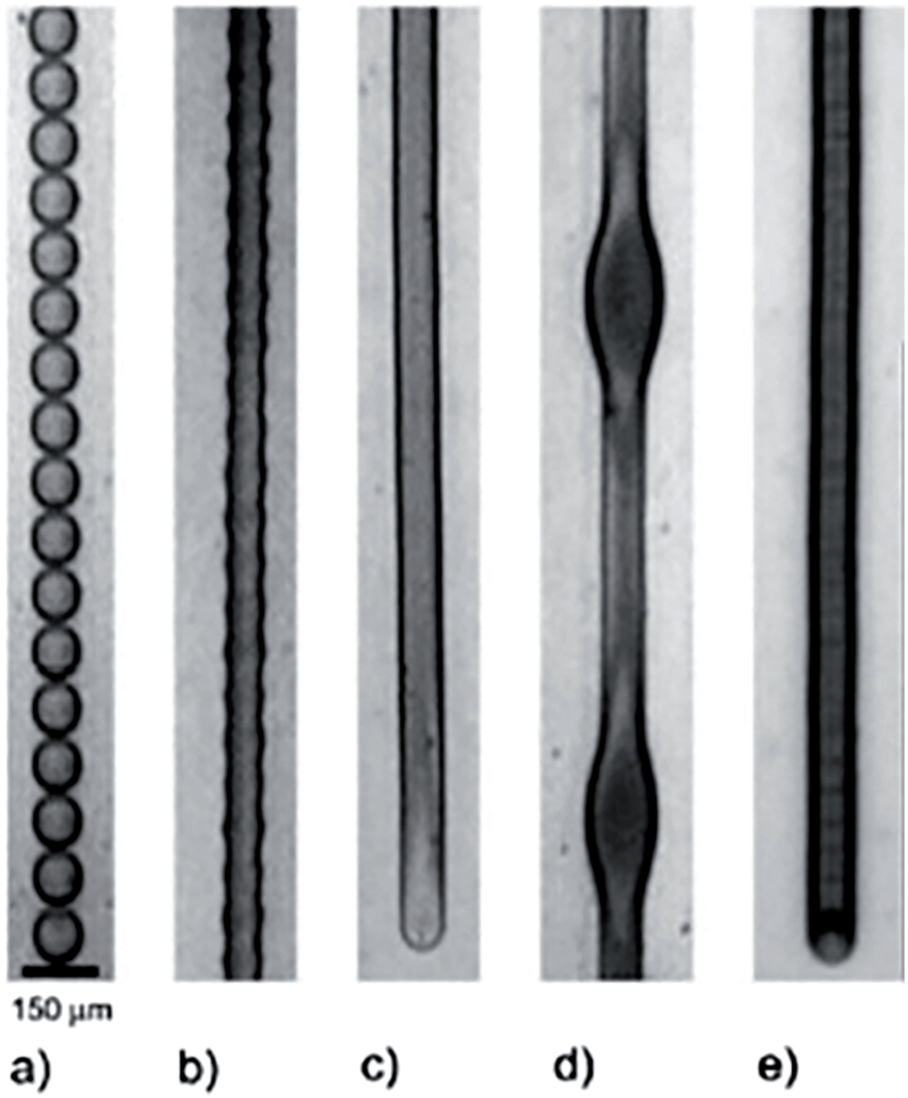

Figure 8.
Illustration evidencing the relationship between dot spacing and morphology of printed lines. (a) Large dot spacing caused drops to be isolated from each other. (b) Less drop spacing merges drops but their round edges are still visible. (c) Ideally merged drops forming a homogeneously printed line. (d and e) low drop spacing causing localized bleeding and coffee ring effect at the edges of the printed line, respectively. Reprinted with permission from [97]. Copyright (2022) ACS.

of the drops and their displacing accuracy. Because of this, higher printhead height is correlated with lower printing accuracy (higher prevalence of ink spraying and splatter). An optimum height should be found taking into consideration the type of ink used and the morphology the drops develop during the ejection phase. Some inks, especially metallic nanoparticle-based ones also demand heating of the printhead, as a way of helping the flow of the ink, as this promotes nanoparticle distancing and decreased viscosity, which avoids nozzle clogging [108, 109]. During printing, it is also essential to make sure the distance between the printhead and the substrate remains stable which in some printer models is assured through a vacuum-assisted bed that prevents substrate vibration and displacement [50].

Voltage Waveform. The waveform is the parameter that causes the piezoelectric crystal to deform, generating negative pressure at the printhead nozzles, and causing the ink drops to be jetted. To complete the drop ejection process, a bipolar voltage waveform is responsible for the fill/fire pulses (**Figure 9a**). The higher the voltage, the higher the speed of the generated droplet. This occurs because the pressure

Figures of merit	Description	Observations
Uniformity and homogeneity	Uniformity relates to ink thickness and width irregularities (e.g., line width, raggedness, blurriness). Homogeneity is linked to distribution of ink in the printed pattern area.	Coffee ring effect is an ink inhomogeneity feature. The size of a printed line depends on drop volume and droplet-substrate interactions. Typically, printed line width is higher that the design value. Ink thickness is measured by profilometry or confocal microscopy. Its morphology by optical or SEM. Image analyzer are used for quantitative characterization. Inconsistency due to misfiring, nozzle-plate flooding and satellite drop formation (related to the ink rheology and surface tension)
Consistency	Consistency of ink flow guaranteeing a constant process (drop volume, full dot drop)	
Resolution	Capacity to reproduce printed pattern details	Addressability (dpi, lpi of a inkjet printer or npi of a printhead); dot spacing; sharpness and contrast;
Drop placement error	Difference between the target and impact locations, related to printing accuracy and precision.	Error influenced by the precision of the nozzle manufacturing and the nozzle-substrate distance.
Repeatability	Agreement between successive measurements of drop placement	Can be tested through observation or electrical conductivity measurements (consistent for the same patterns over different prints)
Wettability	Preference of a fluid to maximize the surface contact with the substrate and spread over it	Weber number, Z number, contact angle, surface tension
Adhesion	Adhesion of the ink to the substrate and cohesion between layers	Surface tension, surface energy of the substrate, topography of substrate
Electrical resistivity	Can be measured as surface or volume resistivities	Two-point probes method or Van der Paw method (for better accuracy)
Electromechanical behavior	Deformability of the printed pattern	Gauge factor; geometrical layout of printed pattern
Ink fracture	Crackling of the deposited ink	Optical analysis
Flexibility/ stretchability	How much the ink is able to deform and return to its native state without losing its properties	Intrinsically flexible/stretchable inks; Flexible/ stretchable substrates; design of patterns to withstand repetitive stress loading

Table 5.
Summary of figures of merit used to classify the quality of the inkjet printing process.

created inside the chamber is consequently superior [116]. To recreate the desired image, the inkjet printer is connected to adequate computer software that supports the upload of the image and allows for the printing settings to be defined. In the case of the piezoelectric DoD method, a voltage is applied across a piezoelectric crystal under a pre-defined time and amplitude pattern, which generates the voltage

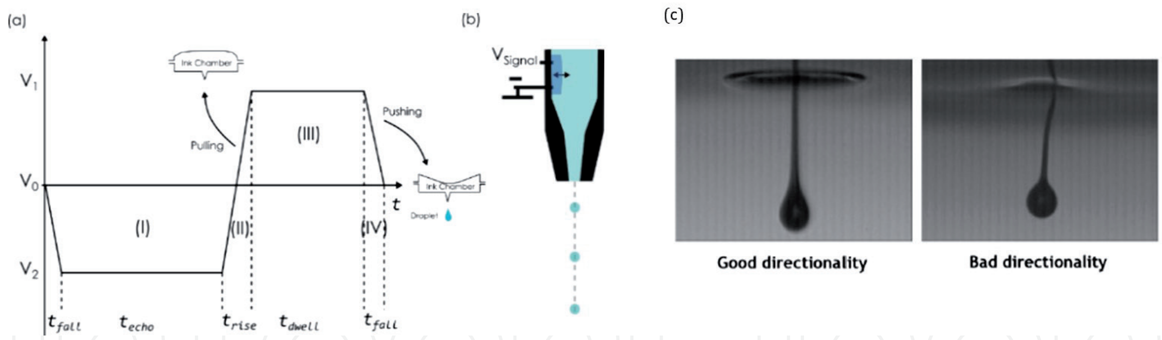

Figure 9.
(a) Simple depiction of a waveform. (I) Negative pulse that eliminates residual oscillations after each drop ejection; (II) and (III) are the pressurization and ejection phase, respectively; (b) nozzle pressure chamber as the piezoelectric crystal (darker blue) deforms due to step (III) [114, 115]; (c) jet straightness images obtained from a high-speed camera. Reprinted from [50].

waveform [114]. As depicted in **Figure 9a**, the waveform has four main phases – the damping and relaxation period that prepares the chamber to start the cycle (phase I, or t_{echo}), then, the pressurization (phase II) causes the ink chamber and nozzles to fill and defines the volume that will be ejected. During the next phase (phase III, or dwell time) there is a slight pause for stabilization of the ink inside the chamber. The cycle ends in phase IV, with the ejection of the ink droplets due to the pushing pressure caused by the piezoelectric crystal. Depending on the characteristics of the ink, the waveform can be optimized, and the best jetting performance is associated with fast, round, and stable droplets without tails [114]. To achieve this, the total waveform duration, number of phases, and the individual phase amplitude, durations, and slew rates (slopes), can be manually adjusted [114]. Recent inkjet printers are already equipped with waveform tuning ability, and in some cases encompass real-time drop-watcher high-speed cameras that capture images such as the ones in **Figure 9c** [108, 109]. This allows for simultaneous tracking and optimization of the profile of the jetted ink drops.

Jetting Frequency and Printhead Speed. The frequency in which the piezoelectric crystal is actuated is intimately related to the waveform and the printhead speed, which can be varied, affecting the rate at which droplets are jetted. If the printhead moves at a low speed the printhead nozzles will be actuated at a lower frequency. By generating waveforms with longer echo and dwell times, the jetting frequency will also be stalled, and vice-versa. As a result, this parameter can be simultaneously studied with the voltage and printhead speed to obtain higher quality printing. As seen in **Figure 10**, the shape of the jetted drops is dependent upon the jetting frequency and varies with the ink characteristic (viscosity, rheology, surface tension).

Number of printed layers. It is also a frequently studied parameter, particularly in what concerns its influence on electrical conductivity. To illustrate this, Rihen et al. studied the effects of the number of printed layers (1–5 layers), drop spacing (1016 DPI – 1693 DPI), and curing temperature (75–120°C) in the final conductivity of an Ag ink [89]. In this study, they found that the best conductivity was obtained for 3 printed layers, 1270 DPI, and a curing temperature of 120°C. It was also found that the number of printed layers strongly affected the final conductivity and that when too many layers were printed, excessive ink ejection ended up causing bleeding of the ink during printing and cracks after the heat-treatment was conducted. Hence, when possible, the number of printed layers should be limited to an "optimum minimum"

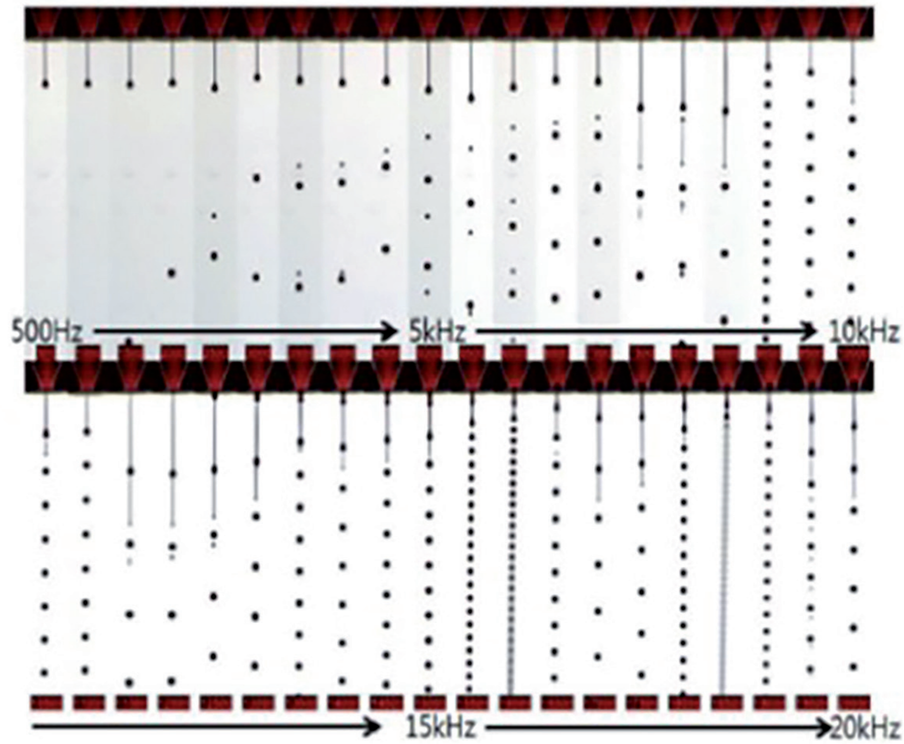

Figure 10.
Jetting behavior with increasing frequency. Reprinted from [117] with permission of AIP publishing.

as it can end up affecting conductivity and printing quality in a negative manner. Moreover, by finding a compromise between resolution and number of layers the printing process can become more economical in terms of ink used.

Design-related variables. The layout of the circuit designs to be printed needs to obey specific rules that depend upon the type of circuit, inkjet printer, printhead, and ink. The process of developing a certain circuit to be printed starts by defining the schematic circuit design in CAD, and after making sure it obeys the rules it is converted to bitmap for printing (**Figure 11a**) [118]. Design-related variables include the minimum resolution, horizontal/vertical line drop spacing, horizontal/vertical line width, horizontal/vertical line thickness, orientation of the design, and the angles of the line connections and design borders [118]. As depicted in **Figure 11c**, different line spacing between two consecutive lines can cause the lines to overlap. Hence, by managing the way the design is created, different results can be obtained depending on the final objective. Moreover, by anticipating the probability of flooding or coffee ring effect of the ink in specific areas, the design can be manipulated to prevent them through pattern compensation methods, as advanced by Vila et al. [119].

2.3.5 Inkjet printing quality indicators

Fabrication of PE devices using IJP faces a series of challenges for enhancing the technology merit indicators, which are application dependent. These relate mainly to printing quality indicators (printed pattern homogeneity, resolution, consistency), electrical conductivity, mechanical durability, and device flexibility/stretchability. In IJP, the printing quality involves complicated interactions between many factors including the printer, the printhead, the substrate, and the ink [49].

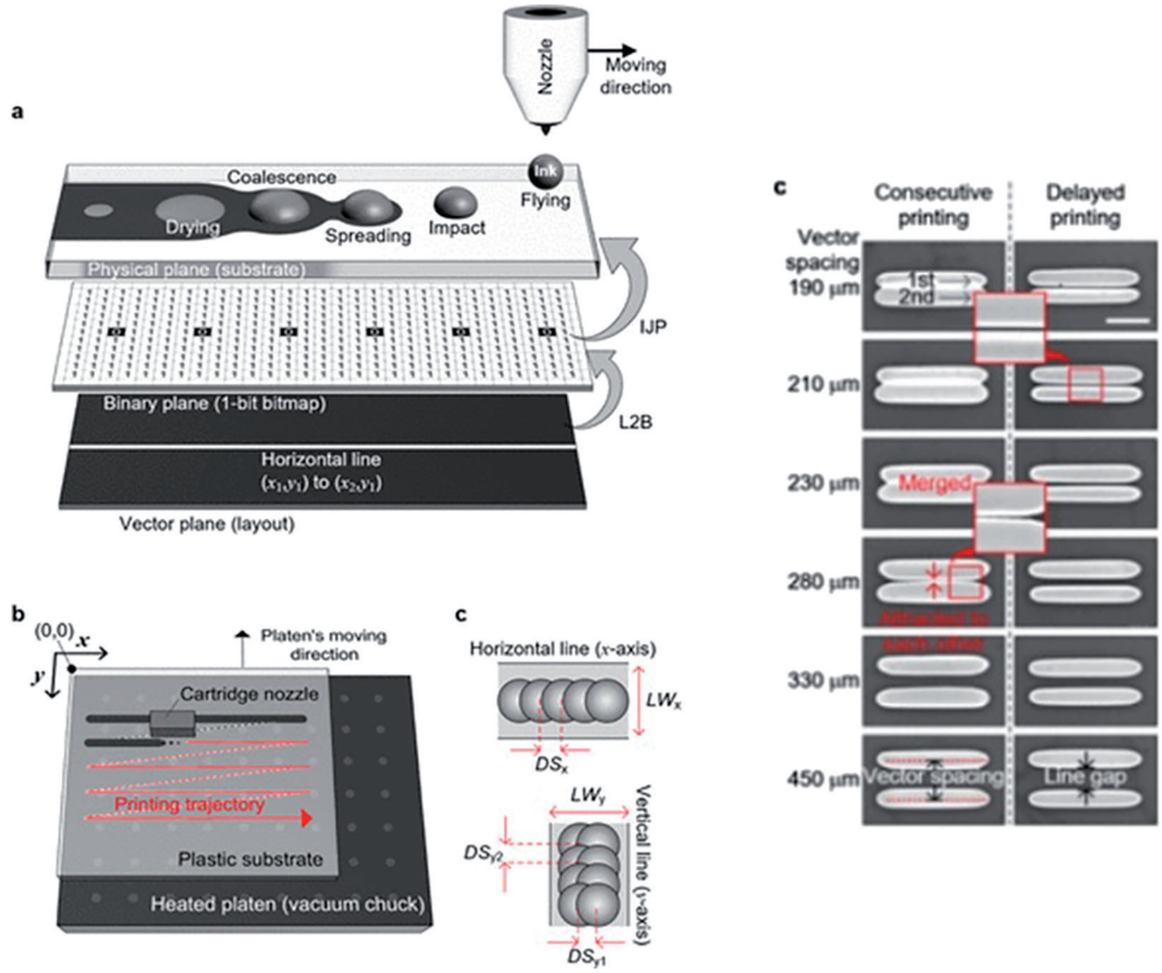

Figure 11.
(a) IJP metal track generation along the x-axis (mask-less): From a CAD layout drawing (a vector file) to a binary plane (a bmp file) and from the binary plane to a physical substrate surface. (b) a unidirectional IJP system. (c) Microscopic images of the two printed lines with varying vector spacings from 190 to 450 μm (scale bar is 500 μm).

Printed pattern resolution and uniformity are determined by droplet-substrate interactions, ink solvent evaporation rate, and capillary flow inside the ink droplet. The printed lines' dimensions, namely their width, depend upon the drop spacing and coalescing time. There is a relationship between drop spacing, line width, and electrical resistance. The electrical resistance is directly proportional to the drop spacing and inversely proportional to the line width.

3. Inkjet printing of smart products

IJP is already ubiquitously employed for printing decorative layers of products. In addition to this, during the past decade, it has also started to establish itself as a low-cost manufacturing process for large-area electronics applied to smart devices [43, 50]. As previously stated, potential markets include the development of electrodes and charge transport layers for thin-film devices, energy storage devices, electronic textiles, wearables, and smart tags and sensors for remote monitoring and logistics of marketable goods. In some of these cases, technological advancements have already allowed products to emerge and enter the market [120, 121].

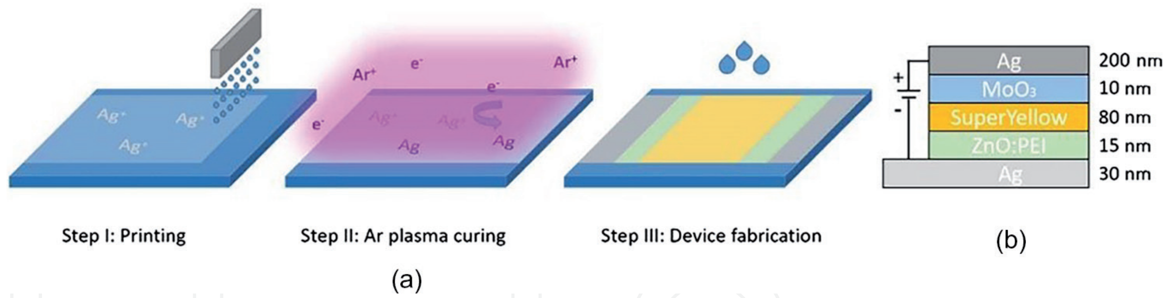

Figure 12.
Overview of the device fabrication. Reproduced from [123].

3.1 Flexible OLED and QLED

Many devices nowadays encompass screens made from transparent electrodes. These are usually obtained using metal oxides (such as ITO) and employed in light-emitting diodes (LED) devices. As stated above, however, ITO is brittle, and its exploitation and end-of-life cycle processing damaging to the environment. Hence, organic and hybrid alternatives, such as OLED and quantum-dot light-emitting diode (QLED) displays are starting to dominate the markets [122]. Thanks to the characteristics of the employed materials, inkjet printing is often a great manufacturing pathway to develop these devices [123]. As seen in **Figure 12**, ITO-free OLED can be obtained using inkjet-printed and low-temperature plasma-sintered Ag electrodes. A MOD ink was used to optimize the reduction effect of the plasma treatment, and the emissive layer of Super yellow was spin-coated.

Regarding organic printable materials capable of replacing the ITO electrodes, PEDOT:PSS is the favored organic semiconductor. Jürgensen et al. studied the tuning of a PEDOT:PSS solution with surfactants, as a way of inkjet printing green electrodes in OLED with reduced surface tension [124]. Moreover, Cinquino et al. concluded that by granting a surface tension value of28 – 40 mN/m and adding 40 vol.% of a low-boiling-point co-solvent proper substrate wetting was granted [125]. As for inorganic materials, perovskite nanocrystal (PeNC) solutions have also been investigated as inkjet printable color conversion layers (CCL) in PeNC/OLED hybrid displays [126]. These displays are used universally in entertainment devices, including augmented and virtual reality devices with enhanced performance. Another field of application of these displays respects healthcare devices and photomedicine, in particular, in the development of displays for photodynamic therapy (PDT), which vows to attack cancer cells using specific light-emitting wavelengths [127].

3.2 Organic photovoltaic (OPV) cells

Similarly, regarding OPV cells, the tendency is also to replace metal-oxide alloys with more environmentally friendly and easy to process materials. As an example, Alamri et al. developed fully-inkjet-printed hybrid perovskite photodetectors using Graphene/Perovskite/Graphene [128]. Schackmar and co-workers also came up with an approach to develop all-inkjet-printed absorbers and change transport layers [129]. As seen in **Figure 13a**), a p–i–n-perovskite solar cell architecture was created. The triple-cation perovskite absorber layer (TCP, brown) and

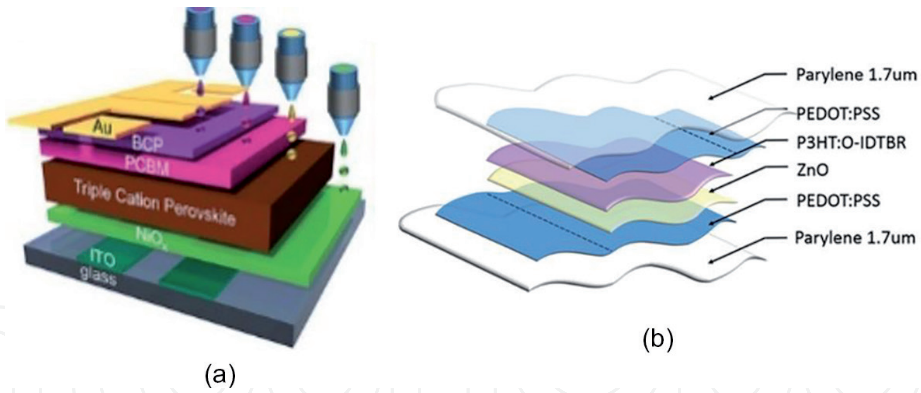

Figure 13.
(a) Schematic of the p–i–n-perovskite solar cell architecture with printed absorber and extraction layers. Reprinted from [129]; (b) schematic of the layer-by-layer composition of the solar cells made from PEDOT:PSS inkjet-printed electrodes. Reprinted from [69].

the double layer ETL made of PCBM and BCP (pink and purple, respectively) were deposited by inkjet printing. Bihar et al. also developed a fully-inkjet printed alternative to develop OPV in which PEDOT:PSS was used to develop the electrodes (**Figure 13b**) [69].

3.3 Energy storage applications

Inkjet printing technology is being vastly employed in the development of supercapacitors (SC), triboelectric nanogenerators, and batteries. Even though many challenges still have to be overcome for these devices to reach competitive performance, promising alternatives already exist [130]. For example, graphene-based solutions are vastly studied throughout the literature for IJP of supercapacitors [131, 132]. Li et al. inkjet printed disposable micro-supercapacitors (MSC) on paper using conductive inks based on the ternary composite of PEDOT:PSS, graphene quantum dots, and graphene [133]. In **Figure 14**, the resulting MSC are pictured in different array dispositions.

Giannakou and colleagues developed 3D conformable supercapacitors intended for epidermal energy storage. To achieve this, they inkjet-printed nickel (II) oxide active electrodes over PVA substrate. As a proof-of-concept, the SC was used on the skin of test subjects, and energy from their movements was successfully harvested to light a LED [134]. Energy harvesters can also be printed over textiles as a way of obtaining self-powered garments with sensing and monitoring abilities [135].

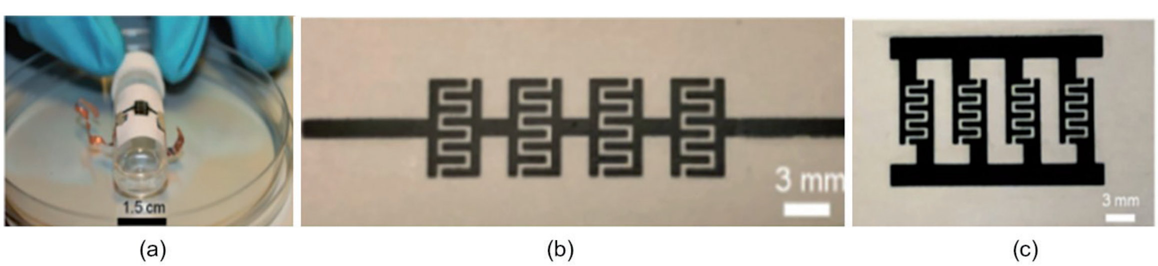

Figure 14.
(a) Microsupercapacitor (MSC) printed on photo paper for flexibility performance test, (b) fully-printed MSC array with 4 MSC connected in series on carton paper, (c) fully-printed MSC array with 4 MSC connected in parallel on carton paper. The bus lines were printed with 17 passes. Reprinted from [133].

VARTA company has recently started to apply inkjet printing to the development of batteries to power sensors, and smart tags for intelligent packaging applications. Different electrochemical systems and electrodes can be printed in a stacked or co-planar manner depending on the envisioned design of the battery [136].

3.4 Sensors, e-textiles, and biomonitoring devices

Sensors are vital to transduce physical changes into readable data. Several inkjet-able materials can be used as the functional part of sensors, whose electrical conductivity varies according to those changes and is later processed into digital outputs for monitoring. The most frequently developed physical sensors measure mechanical (pressure, force, strain), temperature, and humidity changes. Metal nanowires [137], metallic nanoparticles [138], polymer micro/nanostructures [139], CNT, and graphene have been applied to the design of piezoresistive flexible tactile sensors [140–142]. To work efficiently, the latter ones must be homogeneously dispersed in an elastomeric matrix, in concentrations above the electrical conductivity percolation threshold [143]. To produce piezoelectric pressure sensors the most used materials are piezoelectric ceramics, ceramic/polymer composites, and single crystals [144, 145]. As for capacitive sensing applications, SWNT/PDMS electrodes are effective options [145, 146]. Inkjet printing has also been extensively used to produce temperature, and humidity sensors that can be applied in standalone settings or, thanks to the development of the IoT can work as scattered sensor networks for remote and connected monitoring applications. Thanks to their inherent conformability, low-cost, biocompatibility, tunability, accuracy, and adequate sensing range, the pressure, temperature, and humidity printable sensors, have started to be applied in e-textiles and biomonitoring applications. As an example, Farooqui et al. successfully developed a smart bandage to remotely monitor chronic wounds through inkjet printing of a resistive sensor sensitive to pH [147].

Wearables and electronic textiles can be used for applications ranging from human-machine interaction (HMI), fashion, haptics, and biomonitoring. Regarding biomonitoring, different sensors can be inkjet-printed over textiles or conformable polymeric substrates (PDMS, PET, PEN, PEEK) and retrieve accurate biological data, thanks to the close proximity to the body. Pressure, strain [67], temperature [148], and humidity sensors [17], are the most frequently printed, nonetheless, photoplethysmography (PPG), electrocardiography (ECG), and electroencephalogram (EEG)

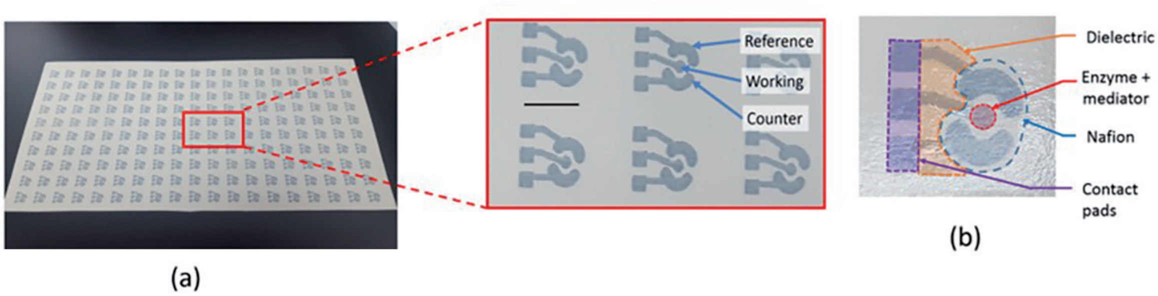

Figure 15.
(a) Inkjet-printed glucose biosensors; (b) fully printed biosensor and identification of the different printed layers, namely the electrode (PEDOT:PSS), the dielectric, the biological coating containing the enzyme and the mediator, and the encapsulation layer. Reprinted from [156].

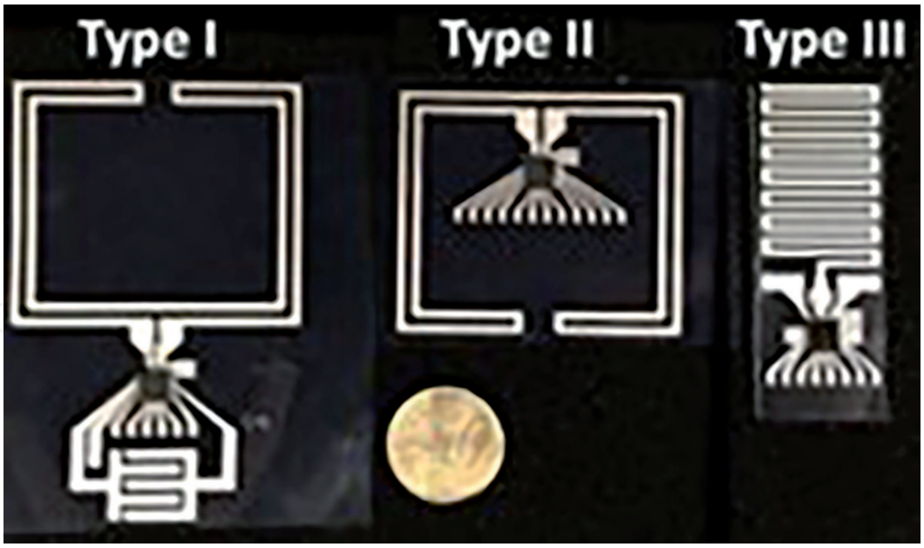

Figure 16.
Three types of printed, passive tags on a flexible substrate for operation in the UHF RFID band (902–928 MHz). Reprinted from [161].

sensors can be inkjet-printed as well [49, 135, 149–152]. Electroluminescent devices can also be printed over textiles to enhance their functionality [153].

Flexible printed and biocompatible sensors placed in direct contact with the human body are also valuable for sensing specific biomarkers. This can be achieved by IJP of enzyme-functionalized inks [154]. Mass et al. enzyme-functionalized silica nanoparticles and mixed them with SWCNT to create a bio-ink with catalytic activity [154]. Biocompatible graphene-based biosensors can be printed as well to monitor the effect of antiviral drugs through impedance analysis [155]. Bihar and colleagues also developed a disposable glucose sensor by inkjet printing PEDOT:PSS as electrodes, and a glucose oxidase solution as the sensing material [156]. A dielectric ink was printed to isolate the electrode interconnects as depicted in **Figure 15**.

3.5 Smart tags and logistics

Inkjet printing can be used in the development of antennas, radio frequency identifier (RFID) chips, and near-field communication (NFC) chips, which can work as smart labels and sensor tags. Temperature, humidity, and strain sensors are usually paired with these labels to develop intelligent packaging and/or tracking applications [157, 158]. For this purpose, paper is one of the most used substrates [159]. Another important application for smart tags is food quality monitoring. By combining humidity, ammonia, temperature, and volatile organic compounds (VOC) sensors the state of perishable goods can be evaluated and the food supply chain optimized accordingly [160]. For this purpose, Quintero et al. developed a multi-sensing platform where an RFID chip was integrated with inkjet-printed sensors (ammonia, humidity, and temperature) over a PEN substrate [160]. Baubauer and co-workers also studied the printing of different types of passive tags over flexible substrates, when integrated with a rigid RFID chip, as illustrated in **Figure 16** [161]. In this case, the purpose of the tags was to serve as user-interactive touch sensors. One interesting asset of these types of labels is the fact that they can be reset and reprogrammed.

Since packaging is meant to be disposable, by recovering and reprogramming the tags they can be reused in other applications before being ultimately recycled [162].

4. Advanced inkjet printing techniques

IJP is a mature technology and recently has been used to print functional inks for PE devices. This novel use demanded developments in terms of new printing equipment and inks. As a result, advanced IJP technologies have emerged, responding to the requirements of novel applications. These advanced technologies are focused on increasing printing resolution and speed, printing of high viscosity inks (with higher electrical conductivity), printing over non-planar substrates, and enlarging the range of materials that can be printed.

A novel double-shot IJP technique has been developed, which allows for the deposition of two types of inks at the same position [163]. In this way, conductive and dielectric inks can be printed at the same position, allowing the construction of devices. Reactive inkjet printing, which also uses two nozzles, combines the processes of material deposition and chemical reaction to print over a substrate material, enlarging the type of ink materials.

EHD-IJP allowed high-resolution printing, paving its use in micro/nano manufacturing of electronic devices [45]. EHD-IJP is a direct patterning technique that can also be used as a thin film deposition technique (e.g., electrospraying, electrospinning). Furthermore, multi-nozzle implementation has been proposed, but nozzle density is still low [50]. EHD-IJP also allows printing of high viscosity inks and consequently has huge potential for fabricating 3D patterns [163].

Needle-based printing is a recent technology to dispense relatively high viscosity ink through a fine nozzle [50]. Droplets are ejected from the nozzle exit by the motion of the needle, which can be operated by air pressure or piezoelectric actuator. This technique can handle high viscosity inks.

Micro-plotter is a technology that also allows dispensing of relatively high viscosity ink through a fine nozzle [50]. The dispensing mechanism is based on the ultrasonic pumping action at the core of the micro-plotter head, a micropipette. The mechanism is capable of depositing ink droplets with dot size of less than 2 μm, which is smaller than an inkjet system, even when using relatively high viscosity inks (up to 450 cP).

Other droplet-based techniques have been developed, mainly for printing on non-planar substrates, such as aerosol jet printing, surpassing the limitations of both inkjet and EHD-IJP techniques. Aerosol jet printing uses high-speed ejection of aerosols instead of liquid droplets [164, 165]. The aerosol is produced by atomization of ink, which produces very small droplets with diameters in the range of 1 to 5 μm. Due to the aerodynamic effect, it also allows higher resolution for fabricating micro- and nanoscale devices. Furthermore, aerosol jetting allows different inks to be conformably printed onto the substrate.

High-resolution 3D patterning combines IJP with 3D printing technologies [166]. High-resolution insulating and conductive layers can be printed using multiple printheads in the same printing system. However, this requires a high degree of deposition precision that can be achieved by the use of phase-change inks (activated by chemical or thermal triggers) with no solvents. 3D structures can also be produced by IJP, by deposition of layer-by-layer of two reactive components, followed by polymerization. This is a technology of current intense research and fast growth.

5. Concluding remarks and future trends

In this chapter, the main topics concerning the IJP manufacturing of printed electronics have been discussed. Being an additive manufacturing technology, some of its advantages concern lower associated costs, material economization, and design freedom. Since its establishment as an alternative for electronics manufacturing, different variations of this technology have emerged, nonetheless, piezoelectric IJP is the most widespread method. Many functional inks have already been optimized for IJP and are commercially available. Despite this, several factors linked to the printing process can still negatively influence the printing output in terms of both printing quality and electrical conductivity and demand optimization.

As for IJP application in the current PE market, there is an undeniable growing tendency. However, it is still early to anticipate the potential of IJP technology in the long run because of all the other options currently being developed. Because of the drawbacks associated with piezoelectric IJP, namely the tendency for nozzles to clog, the limited ink viscosity range (and consequently limited electrical conductivity), and the elevated number of factors that influence the printing process, it is possible that IJP gets to be used in specific niche applications, whereas needle-based and EHD-IJP might ultimately transcend piezoelectric IJP in terms of applicability.

Acknowledgements

This work has been supported by NORTE-06-3559-FSE-000018, integrated invitation NORTE-59-2018-2041, aiming Hiring of Highly Qualified Human Resources, co-financed by the Regional Operational Programme North 2020, thematic area of Competitiveness and Employment, through the European Social Fund, and by the scope of projects with references UIDB/05256/2020 and UIDP/05256/2020, financed by FCT—Fundação para a Ciência e Tecnologia, Portugal.

Author details

Cláudia Buga[1,2] and Júlio C. Viana[1,2]*

1 IPC/LASI—Institute for Polymers and Composites/Associated Laboratory for Smart Systems, University of Minho, Guimarães, Portugal

2 DTx Colab—Digital Transformation, University of Minho, Guimarães, Portugal

*Address all correspondence to: jcv@dep.uminho.pt

References

[1] Cruz SMF, Rocha LA, Viana JC. Printing technologies on flexible substrates for printed electronics. In: Rackauskas S, editor. Flexible Electronics. Rijeka: IntechOpen; 2018. DOI: 10.5772/intechopen.76161

[2] Khan S, Lorenzelli L, Dahiya RS. Technologies for Printing Sensors and Electronics over Large Flexible Substrates: A review. IEEE Sensors Journal. 2015;**15**(6):3164-3185

[3] Matsui H, Takeda Y, Tokito S. Flexible and printed organic transistors: From materials to integrated circuits. Organic Electronics. 2019;**75**:105432

[4] Correia V, Mitra KY, Castro H, Rocha JG, Sowade E, Baumann RR, et al. Design and fabrication of multilayer inkjet-printed passive components for printed electronics circuit development. Journal of Manufacturing Processes. 2018;**31**:364-371. DOI: 10.1016/j.jmapro.2017.11.016

[5] Castro HF, Correia V, Sowade E, Mitra KY, Rocha JG, Baumann RR, et al. All-inkjet-printed low-pass filters with adjustable cutoff frequency consisting of resistors, inductors and transistors for sensor applications. Organic Electronics. 2016;**38**:205-212

[6] Correia V, Oliveira J, Perinka N, Costa P, Sowade E, Mitra KY, et al. All-printed Piezoresistive sensor matrix with organic thin-film transistors as a switch for crosstalk reduction. ACS Applied Electronic Materials. 2020;**2**(5):1470-1477. DOI: 10.1021/acsaelm.0c00214

[7] Franco M, Alves R, Perinka N, Tubio C, Costa P, Lanceros-Mendéz S. Water-based graphene inks for all-printed temperature and deformation sensors. ACS Applied Electronic Materials. 2020;**2**(9):2857-2867. DOI: 10.1021/acsaelm.0c00508

[8] Yap YL, Wang C, Sing SL, Dikshit V, Yeong WY, Wei J. Material jetting additive manufacturing: An experimental study using designed metrological benchmarks. Precision Engineering. 2017;**50**:275-285. DOI: 10.1016/j.precisioneng.2017.05.015

[9] Krykpayev B, Farooqui MF, Bilal RM, Shamim A. A WiFi tracking device printed directly on textile for wearable electronics applications. In: IEEE MTT-S International Microwave Symposium Digest. 2016. p. 4

[10] Ma S, Ribeiro F, Powell K, Lutian J, Møller C, Large T, et al. Fabrication of novel transparent touch sensing device via drop-on-demand inkjet printing technique. ACS Applied Materials & Interfaces. 2015;**7**(39):21628-21633

[11] Ando B, Baglio S, Castorina S, Crispino R, Marletta V. An inkjet printed pressure sensor for applications in active ageing monitoring. In: SAS 2019-2019 IEEE Sensors Applications Symposium, Conference Proceedings; 2019

[12] Dankoco MD, Tesfay GY, Benevent E, Bendahan M. Temperature sensor realized by inkjet printing process on flexible substrate. Materials Science & Engineering, B: Solid-State Materials for Advanced Technology. 2016;**205**:1-5

[13] Vuorinen T, Niittynen J, Kankkunen T, Kraft TM, Mäntysalo M. Inkjet-printed graphene/PEDOT:PSS temperature sensors on a skin-conformable polyurethane substrate. Scientific Reports. 2016;**6**(1):35289. DOI: 10.1038/srep35289

[14] Katerinopoulou D, Zalar P, Sweelssen J, Kiriakidis G, Rentrop C, Groen P, et al. Large-area all-printed temperature sensing surfaces using novel composite thermistor materials. Advanced Electronic Materials. 2019;**5**(2):1-7

[15] Popov VI, Kotin IA, Nebogatikova NA, Smagulova SA, Antonova IV. Graphene-PEDOT: PSS humidity sensors for high sensitive, low-cost, highly-reliable, flexible, and printed electronics. Materials. 2019;**12**(21):1-9

[16] Jung M, Lee J, Vishwanath SK, Kwon OS, Ahn CW, Shin K, et al. Flexible multimodal sensor inspired by human skin based on hair-type flow, temperature, and pressure. Flexible and Printed Electronics. 2020;**5**(2):16

[17] Barmpakos D, Segkos A, Tsamis C, Kaltsas G. A disposable flexible humidity sensor directly printed on paper formedical applications. Journal of Physics Conference Series. 2017;**931**(1): 012003

[18] Cruz S, Viana JC, Dias D, Rocha LA. Pressure sensing platform for health monitoring. In: 2014 IEEE International Symposium on Medical Measurements and Applications (MeMeA); 2014. pp. 1-5

[19] Salim A, Lim S. Review of recent inkjet-printed capacitive tactile sensors. Sensors. 2017;**17**(11):2593

[20] Chiolerio A, Rivolo P, Porro S, Stassi S, Ricciardi S, Mandracci P, et al. Inkjet-printed PEDOT:PSS electrodes on plasma-modified PDMS nanocomposites: Quantifying plasma treatment hardness. RSC Advances. 2014;**4**(93):51477-51485. DOI: 10.1039/C4RA06878E

[21] Mohammed MG, Kramer R. All-printed flexible and stretchable electronics. Advanced Materials. 2017;**29**(19):1604965. DOI: 10.1002/adma.201604965

[22] Seipel S, Yu J, Periyasamy AP, Viková M, Vik M, Nierstrasz VA. Characterization and optimization of an inkjet-printed smart textile UV-sensor cured with UV-LED light. IOP Conf Ser. Materials Science and Engineering. 2017;**254**(7):072023

[23] Gardner SD, Haider MR, Islam MT, Alexander JID, Massoud Y. Aluminum-doped zinc oxide (ZnO) inkjet-printed piezoelectric Array for pressure gradient mapping. Midwest Symposium on Circuits and Systems. 2019;**2019**:1101-1104

[24] Fang M, Li T, Zhang S, Rao KV, Belova L. Design and tailoring of inks for inkjet patterning of metal oxides. Royal Society Open Science. 2020;**7**(4):200242. Available from: https://royalsocietypublishing.org/doi/abs/10.1098/rsos.200242

[25] Printed Electronics Market 2021: Industry Size, Regions, Emerging Trends, Growth Insights, Development Scenario, Opportunities, and Forecast By 2027 [Internet]. 2021. Available from: https://www.marketstatsville.com/printed-electronics-market

[26] Functional Printing-Global Market Trajectory and Analytics. 2021

[27] Inkjet Printing Market-Growth, Trends, Covid-19 Impact, and Forecasts (2022-2027) [Internet]. 2021. Available from: https://www.mordorintelligence.com/industry-reports/inkjet-printing-market

[28] Functional Inks-Global Market Trajectory and Analytics [Internet]. 2021. Available from: https://www.researchandmarkets.com/reports/5302023/

functional-inks-global-market-trajectory-and

[29] Global Printed Electronics Market-Industry Trends and Forecast to 2028 [Internet]. 2021. Available from: https://www.databridgemarketresearch.com/reports/global-printed-electronics-market

[30] Global Functional Printing Market-Industry Trends and Forecast to 2027 [Internet]. 2020. Available from: https://www.databridgemarketresearch.com/reports/global-functional-printing-market

[31] IDTechEx. Materials for Printed/Flexible Electronics 2021-2031: Technologies, Applications, Market Forecasts. 2021. IDTechEx Research finds, the most interesting emerging technologies

[32] Cruz SMF, Rocha LA, Viana JC. Printing technologies on flexible substrates for printed electronics. Rackauskas S, editor. Flexible Electronics. London: IntechOpen; 2018. p. 25

[33] Rivadeneyra A, Loghin FC, Falco A. Technological integration in printed electronics. In: Rackauskas S, editor. Flexible Electronics. Rijeka: IntechOpen; 2018. DOI: 10.5772/intechopen.76520

[34] Beedasy V, Smith PJ. Printed electronics as prepared by inkjet printing. Materials. 2020;**13**(3):704. Available from: https://pubmed.ncbi.nlm.nih.gov/32033206

[35] Sattler KD. 21st Century nanoscience—A handbook: Design strategies for synthesis and fabrication Sattler KD, editor. Vol. 1st ed. United Kingdom: Taylor & Francis; 2019. p. 496

[36] Shah M, Lee D-G, Lee B-Y, Hur S. Classifications and applications of inkjet printing technology: A review. IEEE Access. 2021;(9):140079-140102

[37] Kwon H, Hong J, Nam SY, Choi HH, Li X, Jeong YJ, et al. Overview of recent progress in electrohydrodynamic jet printing in practical printed electronics: Focus on the variety of printable materials for each component. Advanced Materials. 2021;**2**(17):5593-5615. DOI: 10.1039/D1MA00463H

[38] Yu M, Ahn KH, Lee SJ. Design optimization of ink in electrohydrodynamic jet printing: Effect of viscoelasticity on the formation of Taylor cone jet. Materials and Design. 2016;**89**:109-115. Available from: https://www.sciencedirect.com/science/article/pii/S0264127515305505

[39] Cai S, Sun Y, Wang Z, Yang W, Li X, Yu H. Mechanisms, influencing factors, and applications of electrohydrodynamic jet printing. Nanotechnology Reviews. 2021;**10**(1):1046-1078. DOI: 10.1515/ntrev-2021-0073

[40] Skarżyński K, Krzemiński J, Jakubowska M, Słoma M. Highly conductive electronics circuits from aerosol jet printed silver inks. Scientific Reports. 2021;**11**(1):18141. DOI: 10.1038/s41598-021-97312-5

[41] Modak CD, Kumar A, Tripathy A, Sen P. Drop impact printing. Nature Communications. 2020;**11**(1):4327. DOI: 10.1038/s41467-020-18103-6

[42] Foresti D, Kroll K, Amissah R, Sillani F, Homan K, Poulikakos D, et al. Acoustophoretic printing. Science Advances. 2018;**4**:eaat1659

[43] Buga CS, Viana JC. A review on materials and technologies for organic Large-area electronics. Advanced Materials Technologies. 2021;**6**(6):2001016. DOI: 10.1002/admt.202001016

[44] Le HP. Progress and trends in ink-jet printing technology. Journal of Imaging Science and Technology. 1998;**42**:49-62

[45] Raje P, Murmu NC. A review on electrohydrodynamic-inkjet printing technology. International Journal of Emerging Technology and Advanced Engineering. 2014;**4**(5):174-183

[46] Derby B. Inkjet printing of functional and structural materials: Fluid property requirements, feature stability, and resolution. Annual Review of Materials Research. 2010;**40**(1):395-414. DOI: 10.1146/annurev-matsci-070909-104502

[47] Cummins G, Desmulliez MPY. Inkjet printing of conductive materials: A review. Circuit World. 2012;**38**(4):193-213. DOI: 10.1108/03056121211280413

[48] Nayak L, Mohanty S, Nayak SK, Ramadoss A. A review on inkjet printing of nanoparticle inks for flexible electronics. Journal of Materials Chemistry C. 2019;**7**(29):8771-8795. DOI: 10.1039/C9TC01630A

[49] Yan K, Li J, Pan L, Shi Y. Inkjet printing for flexible and wearable electronics. APL Materials. 2020;**8**(12):120705. DOI: 10.1063/5.0031669

[50] Kwon K-S, Rahman MK, Phung TH, Hoath S, Jeong S, Kim JS. Review of digital printing technologies for electronic materials. Flexible and Printed Electronics. 2020;**5**:043003

[51] Halverson J. The first pictures: Perceptual foundations of Paleolithic art. Perception. 1992;**21**(3):389-404. DOI: 10.1068/p210389

[52] Wijshoff H. Structure and fluid dynamics in piezo inkjet printheads. Integrated Assessment. The Netherlands: Univ. Twente, Enschede; 2008

[53] Hanson A. British Patent 4.681; 1903

[54] The Nobel Prize in Chemistry 2000. [cited 2020 Nov 28]. Available from: https://www.nobelprize.org/prizes/chemistry/2000/summary/

[55] Brédas JL, Marder SR, Salaneck WR, Heeger AJ, MacDiarmid AG, Shirakawa H. Macromolecules. 2002;**35**(4):1137-1139. DOI: 10.1021/ma0118973

[56] Fan H, Lu Y, Stump A, Reed ST, Baer T, Schunk R, et al. Rapid prototyping of patterned functional nanostructures. Nature. 2000;**405**(6782):56-60. DOI: 10.1038/35011026

[57] Sirringhaus H, Kawase T, Friend RH, Shimoda T, Inbasekaran M, Wu W, et al. High-resolution inkjet printing of all-polymer transistor circuits. Science. 2000;**290**(5499):2123-2126. Available from: https://www.science.org/doi/abs/10.1126/science.290.5499.2123

[58] Evans JRG. Direct ink jet printing of ceramics: Experiment in teleology. British Ceramic Transactions. 2001;**100**(3):124-128. DOI: 10.1179/096797801681332

[59] Mypati S, Dhanushkodi SR, McLaren M, Docoslis A, Peppley BA, Barz DPJ. Optimized inkjet-printed silver nanoparticle films: Theoretical and experimental investigations. RSC Advances. 2018;**8**(35):19679-19689. DOI: 10.1039/C8RA03627F

[60] Li W, Li L, Gao Y, Hu D, Li C-F, Zhang H, et al. Highly conductive copper films based on submicron copper particles/copper complex inks for printed electronics: Microstructure, resistivity, oxidation resistance, and long-term stability. Journal of Alloys and Compounds. 2018;**732**:240-247. Available from: https://www.sciencedirect.com/science/article/pii/S0925838817336290

[61] Cui W, Lu W, Zhang Y, Lin G, Wei T, Jiang L. Gold nanoparticle ink suitable for electric-conductive pattern fabrication using in ink-jet printing technology. Colloids and Surfaces A: Physicochemical and Engineering Aspects. 2010;**358**(1):35-41. Available from: https://www.sciencedirect.com/science/article/pii/S0927775710000403

[62] Kim MG, Kanatzidis MG, Facchetti A, Marks TJ. Low-temperature fabrication of high-performance metal oxide thin-film electronics via combustion processing. Nature Materials. 2011;**10**(5):382-388. DOI: 10.1038/nmat3011

[63] Que M, Guo W, Zhang X, Li X, Hua Q, Dong L, et al. Flexible quantum dot-sensitized solar cells employing CoS nanorod arrays/graphite paper as effective counter electrodes. Journal of Materials Chemistry A. 2014;**2**(33):13661-13666. DOI: 10.1039/C4TA02052A

[64] Dang MT, Lefebvre J, Wuest JD. Recycling indium tin oxide (ITO) electrodes used in thin-film devices with adjacent hole-transport layers of metal oxides. ACS Sustainable Chemistry & Engineering. 2015;**3**(12):3373-3381. DOI: 10.1021/acssuschemeng.5b01080

[65] Guo Y, Zhong M, Fang Z, Wan P, Yu G. A wearable transient pressure sensor made with MXene Nanosheets for sensitive broad-range human-machine interfacing. Nano Letters. 2019;**19**(2):1143-1150

[66] Shi L, Meng L, Jiang F, Ge Y, Li F, Wu X, et al. In situ inkjet printing strategy for fabricating perovskite quantum dot patterns. Advanced Functional Materials. 2019;**29**(37):1903648. Available from: https://onlinelibrary.wiley.com/doi/abs/10.1002/adfm.201903648

[67] Cruz S, Dias D, Viana JC, Rocha LA. Inkjet printed pressure sensing platform for postural imbalance monitoring. IEEE Transactions on Instrumentation and Measurement. 2015;**64**(10):2813-2820

[68] Wang Y-F, Sekine T, Takeda Y, Yokosawa K, Matsui H, Kumaki D, et al. Fully printed PEDOT:PSS-based temperature sensor with high humidity stability for wireless healthcare monitoring. Scientific Reports. 2020;**10**(1):2467. DOI: 10.1038/s41598-020-59432-2

[69] Bihar E, Corzo D, Hidalgo TC, Rosas-Villalva D, Salama KN, Inal S, et al. Fully inkjet-printed, ultrathin and conformable organic photovoltaics as power source based on cross-linked PEDOT:PSS electrodes. Adv. Materials and Technologies. 2020;**5**(8):2000226. Available from: https://onlinelibrary.wiley.com/doi/abs/10.1002/admt.202000226

[70] Valentini L, Cardinali M, Grkovic M, Uskokovic PS, Alimenti F, Roselli L, et al. Flexible transistors exploiting P3HT on paper substrate and graphene oxide film as gate dielectric: Proof of concept. Science of Advanced Materials. 2013;**5**(5):530-533

[71] Feast WJ, Tsibouklis J, Pouwer KL, Groenendaal L, Meijer EW. Synthesis, processing and material properties of conjugated polymers. Polymer. 1996;**37**(22):5017-5047. Available from: http://www.sciencedirect.com/science/article/pii/0032386196004399

[72] Garlapati SK, Divya M, Breitung B, Kruk R, Hahn H, Dasgupta S. Printed electronics based on inorganic semiconductors: From processes and materials to devices. Advanced Materials. 2018;**30**(40):1707600. Available from:

https://onlinelibrary.wiley.com/doi/abs/10.1002/adma.201707600

[73] Chen C-B, Kao H-L, Chang L-C, Cho C-L, Lin Y-C, Huang C-C, et al. Fabrication of inkjet-printed carbon nanotube for enhanced mechanical and strain-sensing performance. ECS Journal of Solid State Science and Technology. 2021;**10**(12):121001. DOI: 10.1149/2162-8777/ac40d4

[74] Aziz A, Bazbouz MB, Welland ME. Double-walled carbon nanotubes ink for high-conductivity flexible electrodes. ACS Applied Nano Materials. 2020;**3**(9):9385-9392. DOI: 10.1021/acsanm.0c02013

[75] Akindoyo JO, Ismail NH, Mariatti M. Development of environmentally friendly inkjet printable carbon nanotube-based conductive ink for flexible sensors: Effects of concentration and functionalization. Journal of Materials Science: Materials in Electronics. 2021;**32**(9):12648-12660. DOI: 10.1007/s10854-021-05900-y

[76] Ervasti H, Järvinen T, Pitkänen O, Bozó É, Hiitola-Keinänen J, Huttunen O-H, et al. Inkjet-deposited Single-Wall carbon nanotube micropatterns on stretchable PDMS-Ag substrate–electrode structures for Piezoresistive strain sensing. ACS Applied Materials & Interfaces. 2021;**13**(23):27284-27294. DOI: 10.1021/acsami.1c04397

[77] Pandhi T, Chandnani A, Subbaraman H, Estrada D. A review of inkjet printed graphene and carbon nanotubes based gas sensors. Sensors. 2020;**20**(19):5642

[78] Saidina DS, Eawwiboonthanakit N, Mariatti M, Fontana S, Hérold C. Recent development of graphene-based ink and other conductive material-based inks for flexible electronics. Journal of Electronic Materials. 2019;**48**(6):3428-3450

[79] Huckaba AJ, Garcia-Benito I, Kanda H, Shibayama N, Oveisi E, Kinge S, et al. Inkjet-printed TiO2/fullerene composite films for planar perovskite solar cells. Helvetica Chimica Acta. 2020;**103**(5):e2000044. DOI: 10.1002/hlca.202000044

[80] Winarski DJ. Development of zinc oxide based flexible electronics. Bowling Green State University; 2019

[81] Mirza F, Sahasrabuddhe RR, Baptist JR, Wijesundara MBJ, Lee WH, Popa DO. Piezoresistive pressure sensor array for robotic skin. Popa D, MBJ W, editors. Sensors for Next-Generation Robotics III. Baltimore, Maryland, United States: SPIE; 2016. pp. 168-179

[82] Wang L, Peng H, Wang X, Chen X, Yang C, Yang B, et al. PDMS/MWCNT-based tactile sensor array with coplanar electrodes for crosstalk suppression. Microsystems & Nanoengineering. 2016;**2**(1):16065. DOI: 10.1038/micronano.2016.65

[83] Wang Y-F, Sekine T, Takeda Y, Yokosawa K, Matsui H, Kumaki D, et al. Fully printed PEDOT:PSS-based temperature sensor with high humidity stability for wireless healthcare monitoring. Scientific Reports. 2020;**10**:2467

[84] Ozioko O, Kumaresan Y, Dahiya R. Carbon nanotube/PEDOT: PSS composite-based flexible temperature sensor with enhanced response and recovery time. In: 2020 IEEE International Conference on Flexible and Printable Sensors and Systems (FLEPS); 2020. pp. 1-4

[85] Yin Z, Tian B, Zhu Q , Duan C. Characterization and application of

PVDF and its copolymer films prepared by spin-coating and langmuir-Blodgett method. Polymers. 2019;**11**(12):2033

[86] Haque RI, Vié R, Germainy M, Valbin L, Benaben P, Boddaert X. Inkjet printing of high molecular weight PVDF-TrFE for flexible electronics. Flexible and Printed Electronics. 2015;**1**(1):15001. DOI: 10.1088/2058-8585/1/1/015001

[87] Hu X, Ding Z, Fei L, Xiang Y, lin Y. Wearable piezoelectric nanogenerators based on reduced graphene oxide and in situ polarization-enhanced PVDF-TrFE films. Journal of Materials Science. 2019;**54**(8):6401-6409. DOI: 10.1007/s10853-019-03339-5

[88] Suganuma K. Introduction to Printed Electronics. 1st ed. New York: Springer New York; 2014. p. 124

[89] Riheen MA, Saha TK, Sekhar P. Inkjet printing on PET substrate. Journal of the Electrochemical Society. 2019;**166**:B3036-B3039

[90] Ball AK, Das R, Roy SS, Kisku DR, Murmu NC. Experimentation modelling and optimization of electrohydrodynamic inkjet microfabrication approach: A Taguchi regression analysis. Sadhana-Academy Proceedings in Engineering Sciences. 2019;**44**(7):1-16. DOI: 10.1007/s12046-019-1146-5

[91] Bucciarelli A, Adami A, Chandaiahgari CR, Lorenzelli L. Multivariable optimization of inkjet printing process of Ag nanoparticle ink on Kapton. In: 2020 IEEE International Conference on Flexible and Printable Sensors and Systems (FLEPS); 2020. pp. 1-4

[92] i Garcia ER. Inkjet printed microelectronic devices and circuits. Bellaterra, Catalonia: Universitat Autònoma de Barcelona; 2014

[93] Liu Y, Derby B. Experimental study of the parameters for stable drop-on-demand inkjet performance. Physics of Fluids. 2019;**31**(3):32004. DOI: 10.1063/1.5085868

[94] Delrot P, Modestino MA, Gallaire F, Psaltis D, Moser C. Inkjet printing of viscous monodisperse microdroplets by laser-induced flow focusing. Physical Review Applied. 2016;**6**(2):24003. Available from: https://link.aps.org/doi/10.1103/PhysRevApplied.6.024003

[95] Du Z, Yu X, Han Y. Inkjet printing of viscoelastic polymer inks. Chinese Chemical Letters. 2018;**29**(3):399-404. Available from: https://www.sciencedirect.com/science/article/pii/S100184171730373X

[96] Lee C, Kang BJ, Oh JH. High-resolution conductive patterns fabricated by inkjet printing and spin coating on wettability-controlled surfaces. Thin Solid Films. 2016;**616**:238-246. Available from: https://www.sciencedirect.com/science/article/pii/S0040609016304497

[97] Soltman D, Subramanian V. Inkjet-printed line morphologies and temperature control of the coffee ring effect. Langmuir. 2008;**24**(5):2224-2231. DOI: 10.1021/la7026847

[98] Trantidou T, Elani Y, Parsons E, Ces O. Hydrophilic surface modification of PDMS for droplet microfluidics using a simple, quick, and robust method via PVA deposition. Microsystems & Nanoengineering. 2017;**3**(1):16091. DOI: 10.1038/micronano.2016.91

[99] Eom JS, Kim SH. Plasma surface treatment of polyimide for adhesive Cu/80Ni20Cr/PI flexible copper clad laminate. Thin Solid Films. 2008;**516**(14):4530-4534. Available from: https://www.sciencedirect.com/science/article/pii/S0040609008001077

[100] Yang S-Y, Yang H-X, Hu A-J. Chapter 4- super engineering plastics and forms. Advanced Polyimide Materials. In: Yang S-Y, editor. Amsterdam, Netherlands: Elsevier; 2018. pp. 137-193

[101] Cruz S, Rocha L, Viana J. Enhanced printability of thermoplastic polyurethane substrates by silica particles surface interactions. Applied Surface Science. 2015;**360**:198-206

[102] Abu-Khalaf J, Al-Ghussain L, Nadi A, Saraireh R, Rabayah A, Altarazi S, et al. Optimization of geometry parameters of inkjet-printed silver nanoparticle traces on PDMS substrates using response surface methodology. Materials. 2019;**12**(20):3329

[103] Podhajny RM. Corona treatment of polymeric films. Journal of Plastic Film & Sheeting. 1988;**4**(3):177-188. DOI: 10.1177/875608798800400303

[104] Schlozer R. The top 4 drying methods for inkjet. Inkjet Insight. 2020. Available from: https://inkjetinsight.com/knowledge-base/the-top-4-drying-methods-for-inkjet/ [Internet]

[105] Li Y, Yang Q, Li M, Song Y. Rate-dependent interface capture beyond the coffee-ring effect. Scientific Reports. 2016;**6**(1):24628. DOI: 10.1038/srep24628

[106] Al-Milaji KN, Zhao H. New perspective of mitigating the coffee-ring effect: Interfacial assembly. Journal of Physical Chemistry C. 2019;**123**(19):12029-12041. DOI: 10.1021/acs.jpcc.9b00797

[107] Majumder M, Rendall CS, Eukel JA, Wang JYL, Behabtu N, Pint CL, et al. Overcoming the "coffee-stain" effect by compositional Marangoni-flow-assisted drop-drying. The Journal of Physical Chemistry. B. 2012;**116**(22):6536-6542. DOI: 10.1021/jp3009628

[108] Chuang MY. Inkjet printing of Ag nanoparticles using dimatix inkjet printer, No 2. technical report. United States: University of Pennsylvania; 2017

[109] Abbas A, Bajwa I. Inkjet printing of Ag nanoparticles using Dimatix inkjet printer, No 1. Technical Report. United States: University of Pennsylvania; 2017

[110] Mujal J, Ramon E, Diaz E, Carrabina J, Calleja Á, Martínez R, et al. Inkjet printed antennas for NFC systems. In: 2010 IEEE International Conference on Electronics, Circuits and Systems ICECS 2010- Proceeding; 2010. pp. 1220-1223

[111] Sowade E, Mitra KY, Ramon E, Martinez-Domingo C, Villani F, Loffredo F, et al. Up-scaling of the manufacturing of all-inkjet-printed organic thin-film transistors: Device performance and manufacturing yield of transistor arrays. Organic Electronics. 2016;**30**:237-246. Available from: http://www.sciencedirect.com/science/article/pii/S156611991530238X

[112] Ramon E, Sowade E, Martínez-Domingo C, Mitra KY, Alcalde A, Baumann RR, et al. Large-scale fabrication of all-inkjet-printed resistors and WORM memories on flexible polymer films with high yield and stability. Flexible and Printed Electronics. 2021;**6**(1):15003. DOI: 10.1088/2058-8585/abdb40

[113] Scattareggia S. Inkjet application process development using functional fluids. IARIGAI: The International association of research organizations for the information, media and graphic arts industries. Finland: Aalto University; 2015. p. 23

[114] Lindh M. Inkjet Deposition of Electrolyte: Towards Fully Printed Light-Emitting Electrochemical Cells. Umeå University; 2013

[115] Patnaik DN, Subramanian V, Salahuddin SS. Three-dimensional structure formation via inkjet-printed metal nanoparticles: Ink and application development. Berkeley: University of California; 2018

[116] Hamad AH, Salman MI, Mian A. Effect of driving waveform on size and velocity of generated droplets of nanosilver ink (Smartink). Manufacturing Letters. Elsevier. 2020;**24**:14-18

[117] Kwon K-S, Jang M-H, Park HY, Ko H-S. An inkjet vision measurement technique for high-frequency jetting. The Review of Scientific Instruments. 2014;**85**(6):65101. DOI: 10.1063/1.4879824

[118] Kwon J, Baek S, Lee Y, Tokito S, Jung S. Layout-to-bitmap conversion and design rules for inkjet-printed Large-scale integrated circuits. Langmuir. 2021;**37**(36):10692-10701. DOI: 10.1021/acs.langmuir.1c01296

[119] Vila F, Pallarès J, Ramon E, Terés L. A systematic study of pattern compensation methods for all-inkjet printing processes. IEEE Transactions on Components, Packaging and Manufacturing Technology. 2016;**6**(4):630-636

[120] Solar Cells Reimagined. [cited 2020 Sep 7]. Available from: https://sauletech.com/

[121] Connolly KB. Johnnie Walker 'Smart Bottle' Performs for Consumers and Supply Chain [Internet]. 2015. Available from: https://www.packagingdigest.com/beverage-packaging/johnnie-walker-smart-bottle-performs-for-consumers-and-supply-chain150306

[122] Jia H. Who will win the future of display technologies? National Science Review. 2018;**5**(3):427-431. DOI: 10.1093/nsr/nwy050

[123] Hengge M, Livanov K, Zamoshchik N, Hermerschmidt F, List-Kratochvil EJW. ITO-free OLEDs utilizing inkjet-printed and low temperature plasma-sintered Ag electrodes. Flexible and Printed Electronics. 2021;**6**(1):15009. DOI: 10.1088/2058-8585/abe604

[124] Jürgensen N, Pietsch M, Hai X, Schlisske S, Hernandez-Sosa G. Green ink formulation for inkjet printed transparent electrodes in OLEDs on biodegradable substrates. Synthetic Metals. 2021;**282**:116930. Available from: https://www.sciencedirect.com/science/article/pii/S0379677921002368

[125] Cinquino M, Prontera CT, Zizzari A, Giuri A, Pugliese M, Giannuzzi R, et al. Effect of surface tension and drying time on inkjet-printed PEDOT:PSS for ITO-free OLED devices. Journal of Science: Advanced Materials and Devices. 2022;**7**(1):100394. Available from: https://www.sciencedirect.com/science/article/pii/S2468217921000708

[126] Lee SY, Lee G, Kim DY, Jang SH, Choi I, Park J, et al. Investigation of high-performance perovskite nanocrystals for inkjet-printed color conversion layers with superior color purity. APL Photonics. 2021;**6**(5):56104. DOI: 10.1063/5.0044284

[127] Triana MA, Hsiang E-L, Zhang C, Dong Y, Wu S-T. Luminescent nanomaterials for energy-efficient display and healthcare. ACS Energy Letters. 2022;**7**:1001-1020

[128] Alamri AM, Leung S, Vaseem M, Shamim A, He J-H. Fully inkjet-printed photodetector using a graphene/perovskite/graphene Heterostructure. IEEE Transactions on Electron Devices. 2019;**66**(6):2657-2661

[129] Schackmar F, Eggers H, Frericks M, Richards BS, Lemmer U,

Hernandez-Sosa G, et al. Perovskite solar cells with all-inkjet-printed absorber and charge transport layers. Adv. Materials and Technologies. 2021;**6**(2):2000271. Available from: https://onlinelibrary.wiley.com/doi/abs/10.1002/admt.202000271

[130] Sajedi-Moghaddam A, Rahmanian E, Naseri N. Inkjet-printing Technology for Supercapacitor Application: Current state and perspectives. ACS Applied Materials & Interfaces. 2020;**12**(31):34487-34504. DOI: 10.1021/acsami.0c07689

[131] Sollami Delekta S, Laurila M-M, Mäntysalo M, Li J. Drying-mediated self-assembly of graphene for inkjet printing of high-rate Micro-supercapacitors. Nano-Micro Letters. 2020;**12**(1):40. DOI: 10.1007/s40820-020-0368-8

[132] Sollami Delekta S, Adolfsson KH, Benyahia Erdal N, Hakkarainen M, Östling M, Li J. Fully inkjet printed ultrathin microsupercapacitors based on graphene electrodes and a nano-graphene oxide electrolyte. Nanoscale. 2019;**11**(21):10172-10177. DOI: 10.1039/C9NR01427F

[133] Li Z, Ruiz V, Mishukova V, Wan Q, Liu H, Xue H, et al. Inkjet printed disposable high-rate on-paper Microsupercapacitors. Advanced Functional Materials. 2022;**32**(1):2108773. DOI: 10.1002/adfm.202108773

[134] Giannakou P, Tas MO, Le Borgne B, Shkunov M. Water-transferred, inkjet-printed Supercapacitors toward conformal and epidermal energy storage. ACS Applied Materials & Interfaces. 2020;**12**(7):8456-8465. DOI: 10.1021/acsami.9b21283

[135] Huang T-T, Wu W. Inkjet-printed wearable Nanosystems for self-powered technologies. Advanced Materials Interfaces. 2020;**7**(12):2000015. DOI: 10.1002/admi.202000015

[136] VartaAG. Printed Electronics for Medical and Lesiure Use. 2020 [cited 2021 Aug 24]. Available from: https://www.advancedbatteriesresearch.com/articles/20633/printed-electronics-for-medical-and-lesiure-use

[137] Gong S, Schwalb W, Wang Y, Chen Y, Tang Y, Si J, et al. A wearable and highly sensitive pressure sensor with ultrathin gold nanowires. Nature Communications. 2014;**5**:1-8

[138] Yang Z, Wang D-Y, Pang Y, Li Y-X, Wang Q, Zhang T-Y, et al. Simultaneously detecting subtle and intensive human motions based on a silver nanoparticles bridged graphene strain sensor. ACS Applied Materials & Interfaces. 2018;**10**(4):3948-3954. DOI: 10.1021/acsami.7b16284

[139] Pan L, Chortos A, Yu G, Wang Y, Isaacson S, Allen R, et al. An ultra-sensitive resistive pressure sensor based on hollow-sphere microstructure induced elasticity in conducting polymer film. Nature Communications. 2014;**5**(1):3002. DOI: 10.1038/ncomms4002

[140] Shi J, Li X, Cheng H, Liu Z, Zhao L, Yang T, et al. Graphene reinforced carbon nanotube networks for wearable strain sensors. Advanced Functional Materials. 2016;**26**(13):2078-2084. DOI: 10.1002/adfm.201504804

[141] Cardenas JA, Andrews JB, Noyce SG, Franklin AD. Carbon nanotube electronics for IoT sensors. Nano Futures. 2020;**4**(1):12001. DOI: 10.1088/2399-1984/ab5f20

[142] Mousavi S, Howard D, Zhang F, Leng J, Wang CH. Direct 3D printing of highly anisotropic, flexible, constriction-resistive sensors for multidirectional

proprioception in soft robots. ACS Applied Materials & Interfaces. 2020;**12**: 15631-15643

[143] Zare Y, Rhee KY. Simulation of percolation threshold, Tunneling distance, and conductivity for carbon nanotube (CNT)-reinforced nanocomposites assuming effective CNT concentration. Polymers. 2020;**12**(1):114. Available from: https://www.mdpi.com/2073-4360/12/1/114

[144] Chen Z, Wang Z, Li X, Lin Y, Luo N, Long M, et al. Flexible piezoelectric-induced pressure sensors for static measurements based on nanowires/graphene Heterostructures. ACS Nano. 2017;**11**(5):4507-4513. DOI: 10.1021/acsnano.6b08027

[145] Chen S, Wu N, Ma L, Lin S, Yuan F, Xu Z, et al. Noncontact heartbeat and respiration monitoring based on a hollow microstructured self-powered pressure sensor. ACS Applied Materials & Interfaces. 2018;**10**(4):3660-3667. DOI: 10.1021/acsami.7b17723

[146] Lipomi DJ, Vosgueritchian M, Tee BC-K, Hellstrom SL, Lee JA, Fox CH, et al. Skin-like pressure and strain sensors based on transparent elastic films of carbon nanotubes. Nature Nanotechnology. 2011;**6**(12):788-792. DOI: 10.1038/nnano.2011.184

[147] Farooqui MF, Shamim A. Low cost inkjet printed smart bandage for wireless monitoring of chronic wounds. Scientific Reports. 2016;**6**(1):28949. DOI: 10.1038/srep28949

[148] Kuzubasoglu BA, Sayar E, Bahadir SK. Inkjet-printed CNT/PEDOT:PSS temperature sensor on a textile substrate for wearable intelligent systems. IEEE Sensors Journal. 2021;**21**(12):13090-13097

[149] Lo L-W, Zhao J, Wan H, Wang Y, Chakrabartty S, Wang C. An inkjet-printed PEDOT:PSS-based stretchable conductor for wearable health monitoring device applications. ACS Applied Materials & Interfaces. 2021;**13**(18):21693-21702. DOI: 10.1021/acsami.1c00537

[150] Ryu G, You J, Kostianovskii V, Lee E, Kim Y, Park C, et al. Flexible and printed PPG sensors for estimation of drowsiness. IEEE Transactions on Electron Devices. 2018;**65**(7):2997-3004

[151] Gupta R. Biomedical sensors and their interfacing. Smart Sensors, Measurement and Instrumentation. 2017;**25**:219-248

[152] Welch KC, Kulkarni AS, Jimenez AM, Douglas B. Wearable sensing devices for human-machine interaction systems. In: 2018 United States National Committee of URSI National Radio Science Meeting (USNC-URSI NRSM); 2018. pp. 1-2

[153] Liao Y, Zhang R, Wang H, Ye S, Zhou Y, Ma T, et al. Highly conductive carbon-based aqueous inks toward electroluminescent devices{,} printed capacitive sensors and flexible wearable electronics. RSC Advances. 2019;**9**(27):15184-15189. DOI: 10.1039/C9RA01721F

[154] Mass M, Veiga LS, Garate O, Longinotti G, Moya A, Ramón E, et al. Fully inkjet-printed biosensors fabricated with a highly stable ink based on carbon nanotubes and enzyme-functionalized nanoparticles. Nanomaterials. 2021;**11**(7):1645

[155] Schultz A, Knoll T, Urban A, Schuck H, von Briesen H, Germann A, et al. Novel cost-efficient graphene-based impedance biosensor for the analysis of viral Cytopathogenicity and

the effect of antiviral drugs. Frontiers in Bioengineering and Biotechnology. 2021;**9**:718889. Available from: https://pubmed.ncbi.nlm.nih.gov/34381768

[156] Bihar E, Wustoni S, Pappa AM, Salama KN, Baran D, Inal S. A fully inkjet-printed disposable glucose sensor on paper. npj Flexible Electronics. 2018;**2**(1):30. DOI: 10.1038/s41528-018-0044-y

[157] Wang L, Wu Z, Cao C. Technologies and fabrication of intelligent packaging for perishable products. Applied Sciences. 2019;**9**(22):4858

[158] Urbano O, Perles A, Pedraza C, Rubio-Arraez S, Castelló ML, Ortola MD, et al. Cost-effective implementation of a temperature traceability system based on smart RFID tags and IoT services. Sensors. 2020;**20**(4):1163

[159] Zikulnig J, Hirschl C, Rauter L, Krivec M, Lammer H, Riemelmoser F, et al. Inkjet printing and characterisation of a resistive temperature sensor on paper substrate. Flexible and Printed Electronics. 2019;**4**(1):15008. DOI: 10.1088/2058-8585/ab0cea

[160] Quintero AV, Molina-Lopez F, Smits ECP, Danesh E, van den Brand J, Persaud K, et al. Smart RFID label with a printed multisensor platform for environmental monitoring. Flexible and Printed Electronics. 2016;**1**(2):25003. DOI: 10.1088/2058-8585/1/2/025003

[161] Baumbauer CL, Anderson MG, Ting J, Sreekumar A, Rabaey JM, Arias AC, et al. Printed, flexible, compact UHF-RFID sensor tags enabled by hybrid electronics. Scientific Reports. 2020;**10**(1):16543. DOI: 10.1038/s41598-020-73471-9

[162] Machiels J, Appeltans R, Bauer DK, Segers E, Henckens Z, Van Rompaey W, et al. Screen printed antennas on Fiber-based substrates for sustainable HF RFID assisted E-fulfilment smart packaging. Materials. 2021;**14**(19):5500

[163] Huang Q, Zhu Y. Printing conductive nanomaterials for flexible and stretchable electronics: A review of materials, processes, and applications. Advanced Materials Technologies. 2019;**4**(5):1-41

[164] Abdolmaleki H, Kidmose P, Agarwala S. Droplet-based techniques for printing of functional inks for flexible physical sensors. Advanced Materials. 2021;**33**(20):2006792. DOI: 10.1002/adma.202006792

[165] Wiklund J, Karakoç A, Palko T, Yiğitler H, Ruttik K, Jäntti R, et al. A review on printed electronics: Fabrication methods, inks, substrates, applications and environmental impacts. Journal of Manufacturing and Materials Processing. 2021;**5**(3):89

[166] Guo Y, Patanwala HS, Bognet B, Ma AWK. Inkjet and inkjet-based 3D printing: Connecting fluid properties and printing performance. Rapid Prototyping Journal. 2017;**23**(3):562-576. DOI: 10.1108/RPJ-05-2016-0076