Chapter 5

Technological Integration in Printed Electronics

Almudena RivadeneyraFlorin C. LoghinAniello Falco

Additional information is available at the end of the chapter

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Abstract

Conventional electronics requires the use of numerous deposition techniques (e.g. chemical vapor deposition, physical vapor deposition, and photolithography) with demanding conditions like ultra-high vacuum, elevated temperature and clean room facilities. In the last decades, printed electronics (PE) has proved the use of standard printing techniques to develop electronic devices with new features such as, large area fabrication, mechanical flexibility, environmental friendliness and—potentially—cost effectiveness. This kind of devices is especially interesting for the popular concept of the Internet of Things (IoT), in which the number of employed electronic devices increases massively. Because of this trend, the cost and environmental impact are gradually becoming a substantial issue. One of the main technological barriers to overcome for PE to be a real competitor in this context, however, is the integration of these non-conventional techniques between each other and the embedding of these devices in standard electronics. This chapter summarizes the advances made in this direction, focusing on the use of different techniques in one process flow and the integration of printed electronics with conventional systems.

Keywords: printing techniques, process flow, compatibility, final systems, interconnects

1. Overview of printing techniques

1.1. Introduction to printing

The beginning of printing techniques can be followed back to ancient history [1]. Here the use of stencils was used to define patterns as part of cave paintings. As time progressed, techniques that are more complex were developed, with the most common being seals used to pattern clay and wax [2]. The idea behind was to replicate patterns that were commonly used. The seal is an inverted image that is pressed into a soft material to create the desired pattern. Such a technique requires the material to be malleable as such with a similar idea, block printing was developed where a pre-defined carved block is inked and then brought into contact with the samples, in early times this being cloth and later following, paper. While this method allowed for the fast multiplication of the single block, it required a long time to alter the master block. Following this, it gave rise to the movable type where a big block would be composed of smaller blocks that could be permutated to create various designs. This along with the invention of the printing press gave rise to the printing revolution in Europe. With the tremendous technological advances of the twentieth century, fully automated printing technologies were developed leading to the digital household printers becoming the norm. Making use of these advances, throughput for printed media surged.

From an electronic point of view, inorganic electronics are predominantly used due to the inherent material properties of naturally found elements. Transition metals such as copper, gold or silver, display very good electrical conductance while silicon, germanium and III–V elements (among others) are employed as semiconductors in elements such as transistors and diodes. Although these materials offer ideal electrical characteristics, they have certain drawbacks when it comes to mechanical and or optical features. In terms of processing, these materials also tend to have limiting factors such as high processing temperatures, require high vacuum and/or involve chemical processes that are environmentally unfriendly. To overcome these shortcomings organic and nanomaterials have been developed, in the past decades, with the promise to enhance and cover the gaps in terms of possible devices. While extending the portfolio of material properties, the aforementioned materials can in most cases be brought into solution usually in form of a dispersion lending themselves to processing techniques widely used in printed technology. Such techniques have inherent advantages in comparison to commonly used CMOS technologies, both in terms of processing condition as well as throughput potential. In the following sub sections commonly used printed techniques used in the printed electronics community will be explored accompanied by state of the art devices fabricated herewith.

1.2. Gravure and flexographic printing

Gravure printing is one of the most common printing techniques and shares similarities to flexographic printing. The main difference is in the application of the ink to the substrate. Flexographic printing is a relief printing technique that employs a soft plate similar to stamping. In gravure printing the image is etched or laser written into a metal plate essentially creating pockets into which the ink can be filled. **Figure 1** displays the two processing techniques with their core components as well as the inking of the printing roll and transfer onto the substrate. Both these processes excel when it comes to throughput in comparison to other printing techniques. In terms of printed electronics gravure and flexographic printed have been employed to fabricate a plethora of devices spanning from organic photovoltaic (OPV) [3], transparent conductive films (TCFs) [4], thin-film transistors (TFTs) [5] and organic light emitting diodes (OLEDs) [6]. In addition Kraus et al. [7] have used gravure printing to deposit nanoparticles in the sub 100 nm range. As such proving that gravure printing not only profits from high throughput but can also provide very good resolution. A general drawback of this printing technique are the required costs in setting up the production in comparison to, for example, ink jetting where the pattern can be altered digitally.

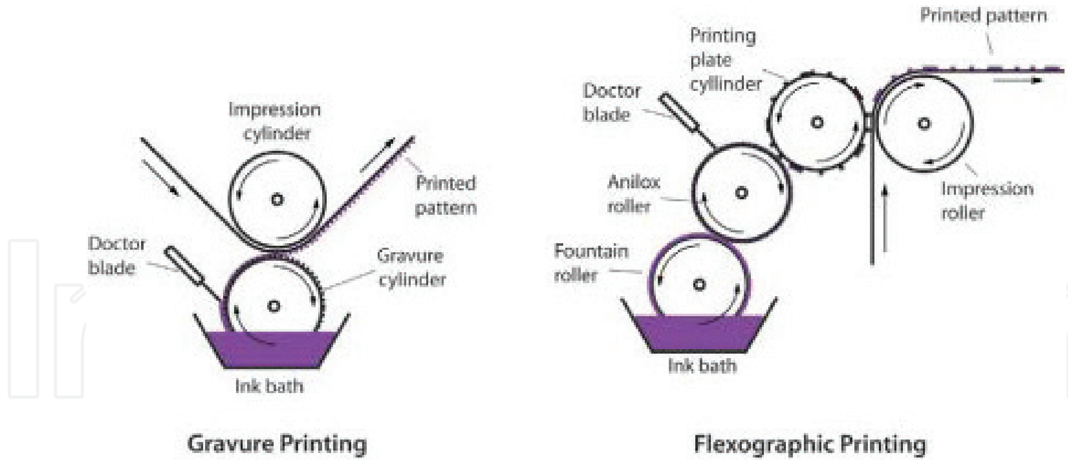

Figure 1. Schematic displaying the core principle of (left) gravure printing and (right) flexographic printing as well as the inking of the printing cylinders and transfer to the substrate (adapted from [3] with authorization).

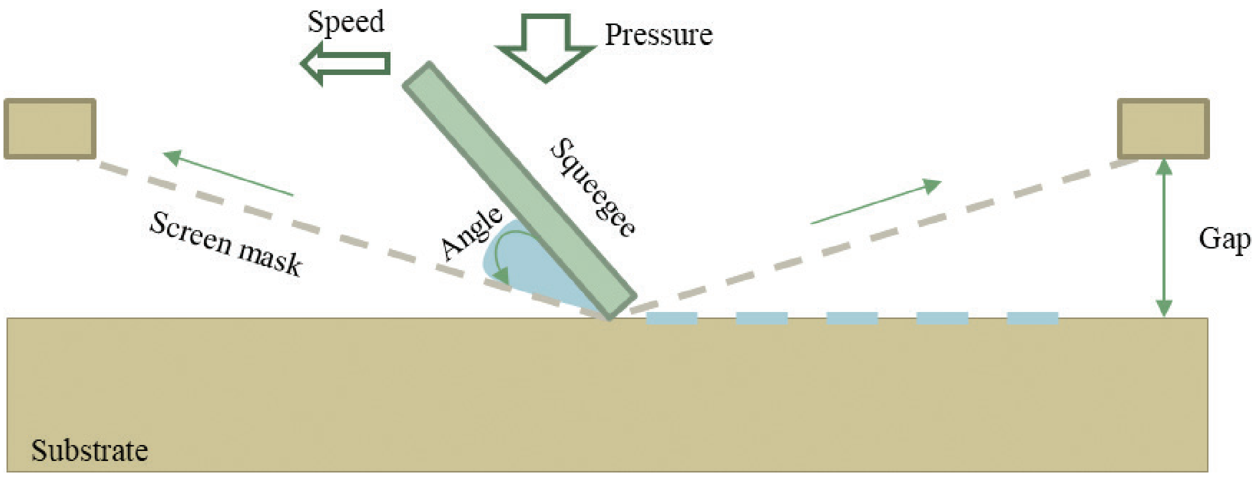

Figure 2. Schematic drawing of screen printer during a printing process. Key components as well resulting pattern are depicted.

1.3. Screen printing

Screen printing is a contact printing method that makes use of a patterned mesh to define structures on a variety of substrates. Highly viscous ink is pushed through the mesh that supports an ink-blocking stencil, with the aid of a squeegee. A typical printing process consists of inking the screen followed by a pass over with the squeegee. Due to the force exerted on the screen, by the squeegee, the screen is brought into contact with the substrate and the ink passes through creating a pattern. **Figure 2** displays the main components of the screen printer while in operation. Resolution is limited by ink formulation, thread thickness and density. Although commonly used in the printing of labels, signs as well clothing, screen printing has been widely used in flexible and printed electronics for a variety of devices including conductors [8], TFTs [9], RFID antennas [10]. An impressive work was done by Krebs et al. [11], who presented a fully screen printed, flexible solar cell based on a blend of organic acceptor and donor materials. The cells were integrated into household items to show the feasibility of such devices. Due to the possibility of integration into R2R framework, screen printing can be easily scaled to an industrial scale.

1.4. Inkjet

Inkjet is a widespread technology in the printing world, commonly employed in personal small printers. Although limited in terms of throughput, in comparison to technologies such as gravure printing, inkjet printing provides an affordable technology that offers itself especially to quick prototyping and alterations in print design. The functioning principle of this technology is the 'jetting' of individual droplets from a print head. Although there are a multitude of techniques to generate the individual droplets, the core principle is shared. Ink is brought into a chamber and through the addition of either thermal or mechanical energy, the fluid is perturbed. This creates a droplet that is released from the printing head. **Figure 3** displays the core components of an inkjet printer and its operation mode. In order to create closed layers droplets are overlapped and tessellated in order to form desired shapes. The processing speed can be dramatically increased with the use of a multitude of print heads simultaneously working. A difficulty arising from this is the sensitivity to clogging of individual nozzles leading to missing droplets and openings in the film. A further differentiation can be made in processing between drop on demand and continuous-mode. The name is indicative of the processing where drop are released as is required by the source image while the other mode jets continuously.

Due to the flexibility in terms of processable ink, inkjet printing has been successfully employed in the printed electronics world with great success. Devices presented include interconnects [12], chemical sensors [13], capacitors [14], OPV [15] and TFTs [16].

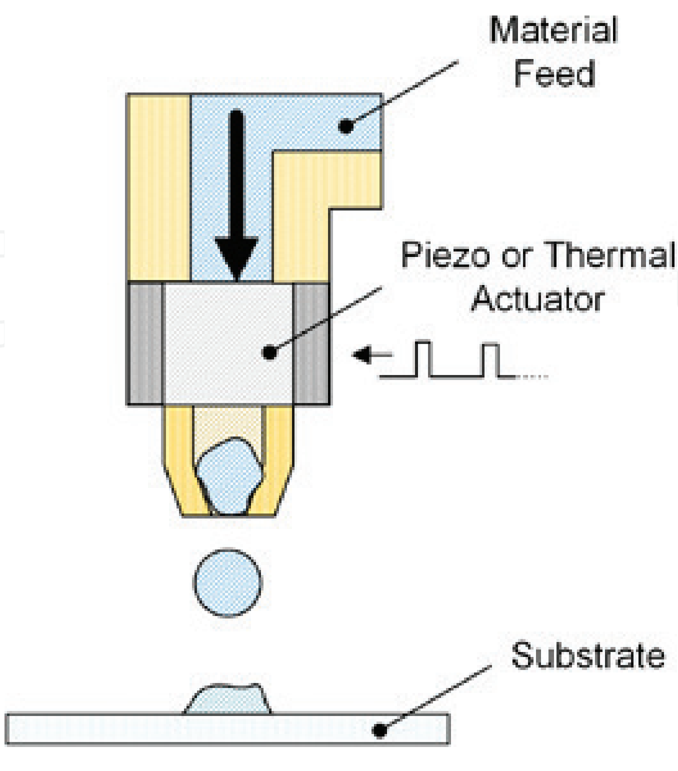

Figure 3. Schematic of an inkjet printer displaying key components and displaying operational mode.

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1.5. Spray deposition

Although spray technology has a variety of applications ranging from humidification to combustion, the more relevant for printed electronics is its use as surface coating. Although spray deposition inherently is a coating technique, it can easily be enhanced to fit the criteria of printing with the aid of a shadow mask. Spray deposition is the deposition of, usually a material in liquid state, with the aid of a gas stream. The bulk liquid is separated into droplets; this process is known as atomization and subsequently carried to the substrate in a mix of gas and a stream of droplets. The atomization can be achieved by either mixing with an air stream (air-assisted atomization) or with kinetic energy (ultrasonic atomization). The two aforementioned will be briefly discussed below.

Air-assisted nozzles make use of a high velocity gas stream to produce atomization. The liquid is fed into the nozzle either under pressure or as a gravity fed alternative. At the orifice, the liquid is mixed with the gas stream, which disrupts the liquid causing atomization. **Figure 4** displays a standard air assisted nozzle with the inset displaying the point of atomization. The droplet size is dependent on many factors such as the velocity of the gas stream, the ratio of gas to fluid, fluid properties as well as nozzle dimensions.

Ultrasonic-assisted nozzles utilize a vibrating body based on a piezoelectric transducer that vibrates at ultrasonic frequencies. When this body is brought into contact with the body of fluid the liquid becomes unstable generating a mist of droplets. In most cases, this mist is mixed with a carrier gas that transports the droplets to the surface. Based on the applied frequency the droplet size can be varied. As with air-assisted nozzles the droplet formation also depends on a multitude of factors, both nozzle as well as fluid related. For further detail on spray technology the reader is referred to the work of Lefebrve [17].

In terms of printed electronics, spray deposition has been used for a multitude of device. Both conducting as well as semiconducting devices being produced. Some of these devices include TFTs [18], TCFs [19], chemical/bio sensors [20, 21], OPVs [22] as well as OPDs [23] to name a few. Falco et al. [24] presented a fully spray deposited, TCO free, flexible OPD based

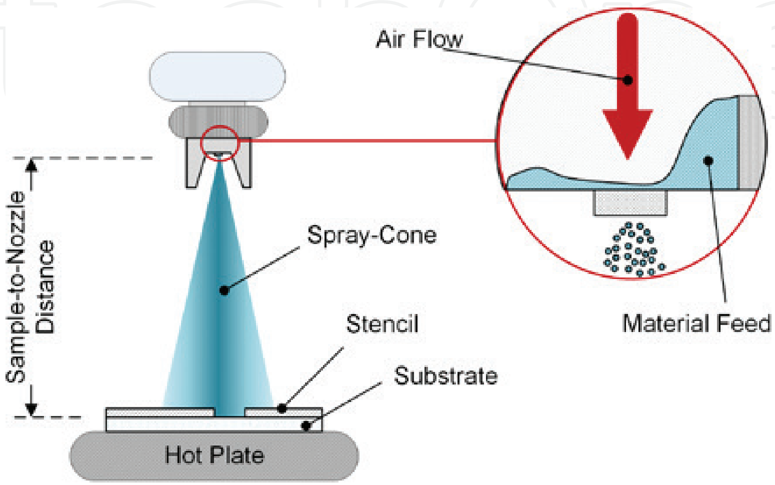

Figure 4. Schematic displaying a typical air-assisted atomization nozzle including key elements in a spray deposition setup. The insert displays the point of atomization.

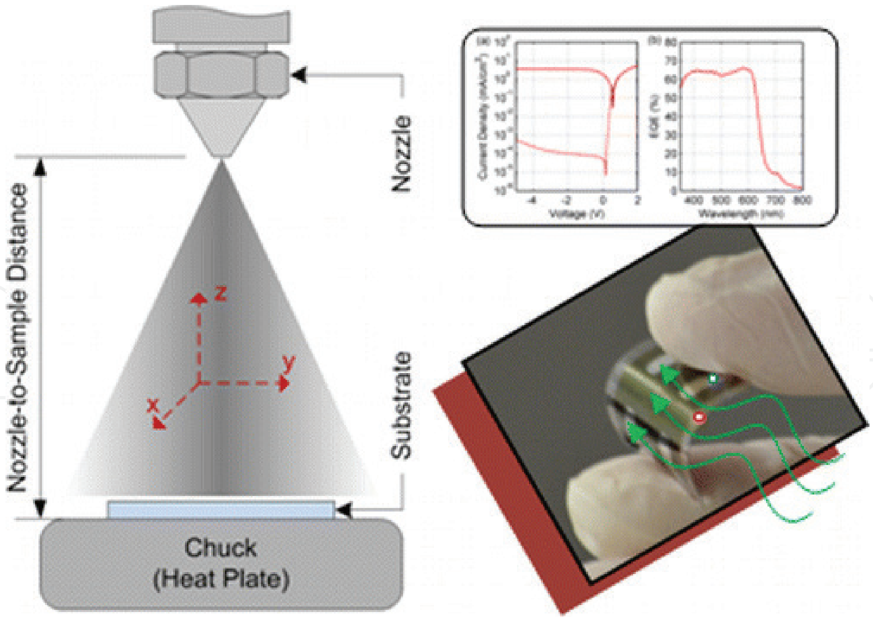

Figure 5. Summarizing figure displaying spray deposition setup used for the fabrication of fully-sprayed, flexible OPDs, the final device as well as key electrical characteristics (adapted from [24] with authorization).

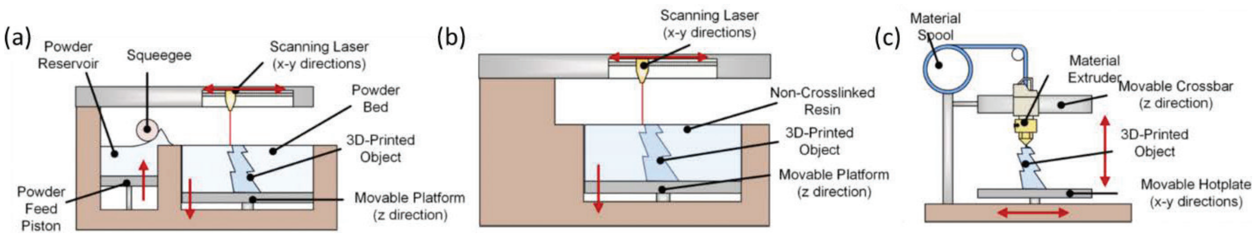

Figure 6. Schematic depictions of common 3D processing techniques of (a) Selective Laser Sintering and (b) Stereolithography and Fused Deposition Modeling.

on a blend of regioregular poly (3-hexylthiophene-2,5-diyl) and [6,6]-phenyl C61 butyric acid methyl ester (PCBM). It demonstrated the feasibility of spray deposition as a method for printed organic electronics especially since all layers were successively deposited by the same technology. **Figure 5** summarizes the work displaying the setup used, the final device as well as key electrical performance.

1.6. 3D printing

3D printing is a term used to encompass additive manufacturing techniques that aim at fabricating solid objects through the deposition of material. Although only recently having gained broad awareness, due to the surge in available privately affordable devices, 3D printing patents date back to 1986 [25]. Used mostly for rapid prototyping and in research the main fabrication was limited to static objects with limited mechanical features. With the increase research of nano-based materials, 3D printing has moved beyond creating scaffolds for electrical devices with the integration of electrical characteristic being embedded into the 3D structure [26–28].

Leigh et al. employed a carbon black filler embedded in a biodegradable polyester to produce an electrically conductive filament [26]. This led to the fabrication of flex sensors as well as embedding it into a 3D printed glove to monitor finger movement. Most commonly, there are three types of processing techniques. Stereolithography (SLA) and Selective Laser Sintering (SLS) use the principle of solidification of a base material while Fused Deposition Modeling (FDM) melts a solid material, which is extruded through a nozzle. **Figure 6** depicts the aforementioned 3D processes marking critical components.

In SLS, a pulsed laser source is employed to solidify a base powder that can originate from plastics, resins and metals. Material is fed from a powder reservoir while the sample stage is moved downwards to expose more material to the laser spot. This process is continued until the desired object is finalized. The remaining material is removed and can be reused as such there is very limited waste material. Due to the sensitive interaction at the powder laser interface, precise calibration is required as to not cause unwanted sintering. Conceptually SLA is similar to SLS, employing a laser to crosslink photosensitive resins. Energetically such an approach is significantly advantageous in comparison to SLS. The limiting factor being the base material for SLA while both techniques suffer from a difficulty in further integration in in-line processes. FDM can cover these shortcomings, albeit at a cost in resolution as well as stability. In the FDM the melted filament is extruded through a nozzle and lines are overlapped and tessellated to create desired structures.

2. Synergy of printed electronics

After reviewing the main fabrication techniques for printed electronics, it is clear that each of them have potential to define different electronic components. For example, antennas require thicker metallic layers in order to enhance their performance. Although the desired thickness could be achieved with any of the described technologies, the most efficient one is screen printing because we can achieve tens of μm selecting a coarse mesh with only one turn. The same thickness would need 20 layers in case of using inkjet printing, resulting in a very time consuming process because it is needed to wait until the layer is dried and the area to cover is quite large. In the case of spray deposition, also the stack of several layers would be mandatory. This technique is much faster than inkjet printing but the pattern definition is poorer in comparison to screen printing.

Another example is the definition of interdigitated electrodes (IDE) for capacitive structures. If the IDE is going to be used to build a capacitive sensor, the distance among consecutive fingers determines the sensitivity of the sensors: the closer they are placed, the higher its sensitivity can be. In this sense, the resolution of the printing technique limits the performance of the device.

Therefore, each technique can be more suitable for different electronic components, as highlighted in the previous examples. As the ultimate goal is to fabricate a fully working and efficient electronic system, it is mandatory to properly combine manufacturing techniques to fulfill it. In the last years, some authors have worked in this director, using different printed techniques to design electronic circuits on flexible substrates.

Some authors have already illustrated how the fabrication of each component of a final device or system should be carefully selected in order to optimize its performance. In particular, Salmerón et al. described two ultrahigh frequency (UHF) radio frequency identification (RFID) tags with sensing capabilities [29]. As demonstrated before [30], they used screen printing to define the antenna in order to achieve a better performance in the RF link. The sensing capabilities comes from the substrate (a polyimide), whose electrical permittivity changes with the moisture content. To exploit this feature, they printed an array of planar capacitive structures. In one of the tags, the electrodes were fabricated with inkjet printing, whereas screen printing was employed in the other design. These tags include an UHF RFID chip with an in-built temperature chip and a sensor frontend capable of measuring capacitive sensors. Although both tags covered a 30% of relative humidity (RH) and showed very low thermal drifts (below 0.05%RH/°C), their features were different. In the case of the inkjetted capacitive array, the sensitivity achieved was 100 fF/RH%. Whereas in the case of the screen printed ones, the sensitivity was about the half (54 fF/RH%). The tag with the inkjetted sensor exhibited a higher performance than the screen printed one in terms of area saving and higher humidity sensitivity. The screen printed sensors approach can be fabricated with just one step but a much bigger area was needed (see **Figure 7a**).

Another device manufactured with two printing techniques was a hybrid sensor for simultaneous vapor determination of RH and toluene concentration [31]. They exploited two strategies to provide with sensing capabilities their device. The RH was measured again by changed in the selected substrate, whereas the toluene concentration was measured by a sensing layer deposited on top of the electrodes. The chosen electrode layout is shown in **Figure 8**, assuring that there was no electrical path between the capacitive electrode and the resistive electrode. Although other electrode configurations present higher, they do not allow the integration of more functionalities in the same side of the device with virtually no interference between them [32]. Inkjet printing was selected to define the electrodes, whereas screen printing was used to deposit the sensitive resistive composite. Inkjet printing allows better resolution, and

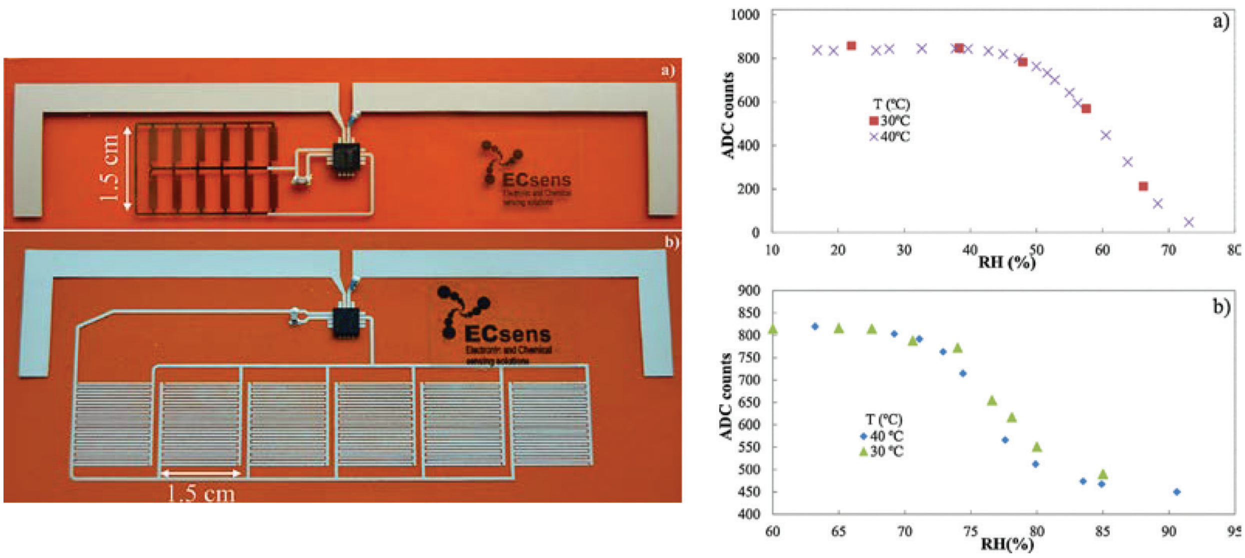

Figure 7. Left: (a) RFID tag with inkjetted serpentine sensors and (b) RFID tag with interdigitated sensors by screen printing. Right: (a) ADC counts of tag with inkjetted serpentine sensor and (b) ADC counts of screen printed tag with IDE sensors. Images adapted from [29] with authorization.

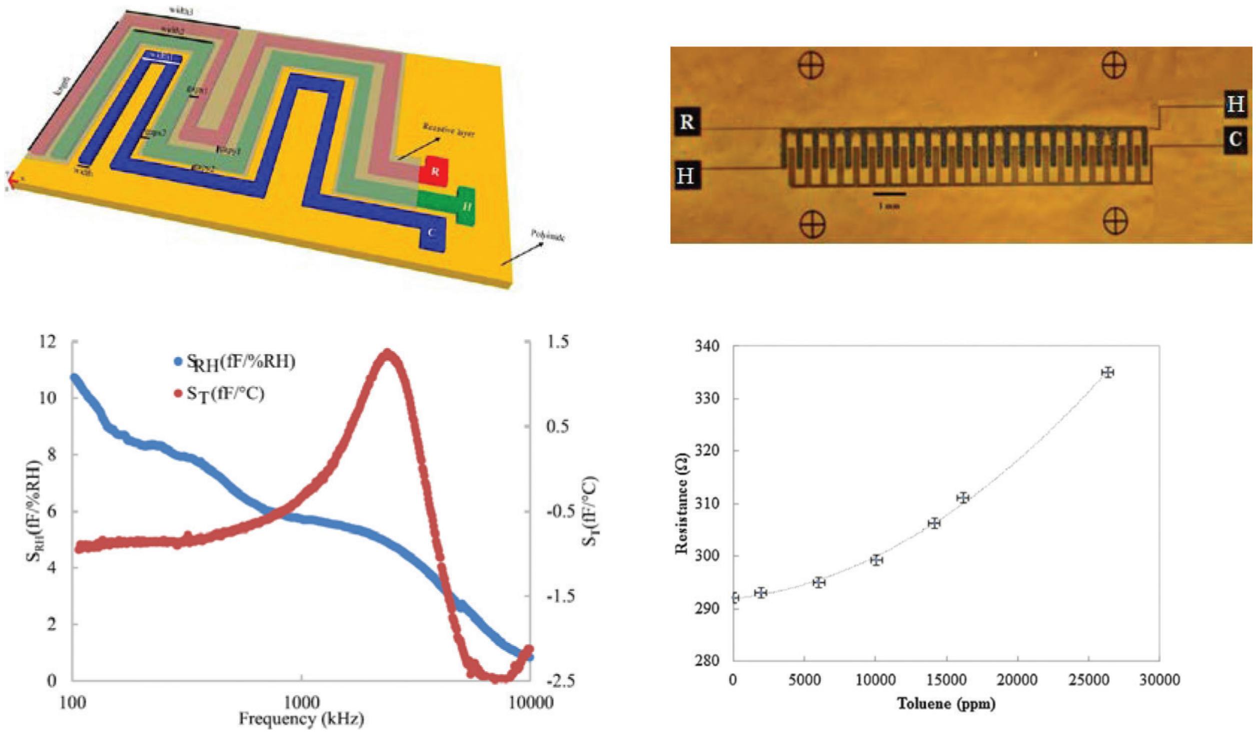

Figure 8. (a) Layout of the novel designed hybrid capacitive-resistive sensor indicating the notation of the dimensions. R corresponds to resistive terminal, C for capacitive sensor, and H corresponds to the common terminal. (b) Image of the hybrid sensor. The resistive element is shown in the upper part of the device, defined between the terminals R and H. The capacitive element is measured between the terminals H and C. (c) Experimental relative humidity and temperature sensitivities as a function of frequency, measuring between H and C. (d) Resistance vs. toluene concentration, measuring between H and R. Images adapted from [31] and [32] with authorization.

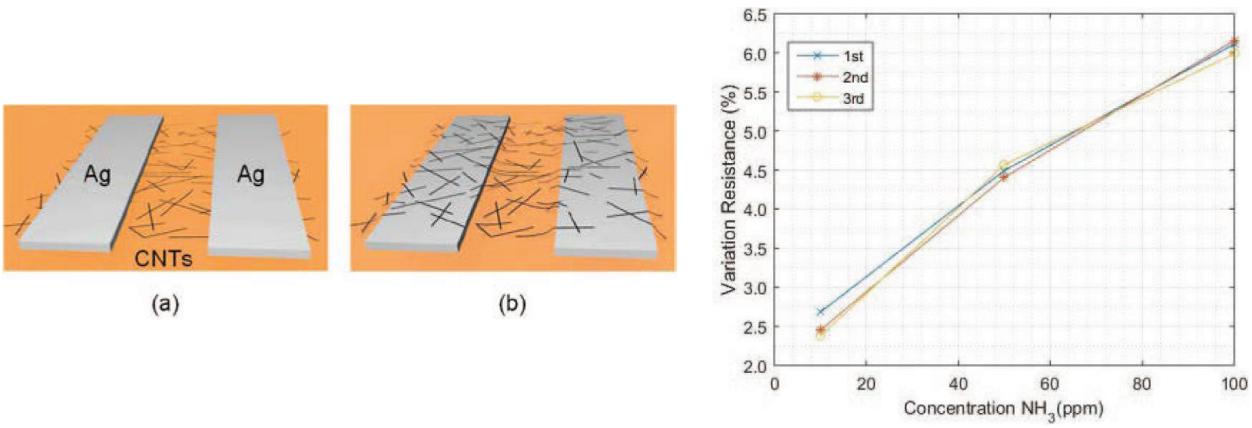

Figure 9. Left: schematics of the two fabricated sensors: (a) electrodes on top of CNT film; (b) CNT film on top of the electrodes. Right: normalized response under different values of NH_3 concentrations. Images adapted from [33] with authorization.

therefore, electrodes can be placed closer, increasing the sensitivity, especially of the capacitive part. But the viscosity of the resistive composite sensitive to toluene was too high to be deposited by inkjet printing, and therefore they employed screen printing to define this layer on top of the electrodes.

Another example of mixing PE techniques was illustrated by Abdelhalim et al. [33]. They showed a fully printed ammonia sensor on a flexible substrate. The electrodes were fabricated by inkjet printing of silver nanoparticles whereas the sensitive film was made of carbon nanotubes (CNT) deposited by spray by an air atomizing nozzle. Two different approaches were followed to manufacture the sensors: first, spraying the CNT solution on top of the electrodes (**Figure 9a**) (conventional approach) and second, printing the electrodes on top of the sprayed CNT film (**Figure 9b**). In the case of conventional approach, the resistance values were one order of magnitude higher than in the case inverted method (printing the electrodes on top of the sensing layer). This can be explained by the fact that the thickness of the silver layer and the mean value of the CNT are about the same value (~450 nm), therefore, the establishment of an electrical path between the CNT is more difficult in the classical approach than in the inverted one.

The results obtained for NH_3 sensing showed a good performance in terms of sensitivity and time response to the test gas, with performance comparable with that obtained with evaporated metal electrodes and conventional approach [34].

As apparent from what we have described so far, the integration of different printing techniques can bring to innumerable benefits, and lets the designer exploit the advantages of each method. Conventional printing, however, constrains the degrees of geometrical freedom two, limiting the possibilities of integration to an *in plane* approach. It is, nevertheless, possible to push the boundaries of technological integration, embedding 2D thin film devices into 3D structures, in order to create *electronic objects,* more than just electronic devices. One of the possible approaches for the obtainment of such structures is 3D printing of scaffolds, in which discrete electronics are cast and embedded. The 3D printed object and the electronics can be designed separately and the only major concern would be the attachment and interconnection of the devices in the 3D housing. Opposed to this approach, Falco et al. demonstrated the facile integration of conformal organic electronics devices in 3D printed structures, where the device is directly fabricated on or in the printed object [35]. The 3D printing technique of choice was FDM, because of its low cost, ease of use and high customizability. The major caveat, though, is the elevated RMS roughness (tens of microns) of the objects produced with means of this method. As the typical active layers employed in organic and printed electronics have thickness of few hundreds of nanometers, it was necessary to also develop a high throughput, sustainable and easy-to-integrate planarization process.

In this work the authors exploit spray deposition not only for the definition of the active materials (i.e. conductive polymers, silver nanowires, carbon nanotubes), but also to achieve the required planarization **Figure 10**.

The spray-planarization is obtained dissolving the 3D printable material itself in an organic solvent, and spraying it on the rough as-printed structure in a wet deposition regime. In this manner, it is possible to re-utilize some wastes of the 3D printing process (material employed to prime the nozzle or to print the outskirts of the pieces), while preparing the structure for successive thin film deposition. Their results outperform alternative methods presented in previous works, and yield RMS roughness of the substrate lower by one order of magnitude with respect to literature [36, 37]. In order to test the viability of this method as preparation tool for printed electronics, the authors deposited and characterized thin films of a conducting polymer (PEDOT:PSS), silver nanowires and carbon nanotubes. Remarkably, the sheet resistance of the layers deposited on planarized samples were up to ten times lower than what

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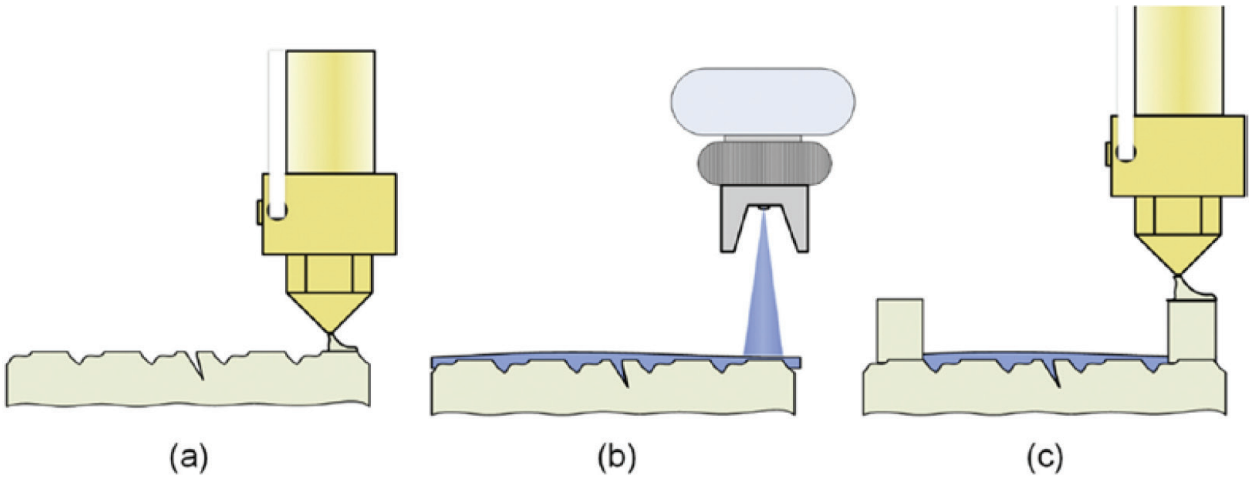

Figure 10. Proposed schematic for multi-technology integration. The substrate is printed with FDM printing technology (a). Spray deposition—or other printing techniques—is employed to deposit a functional layer (b), and (c) the upper stacks of the 3D printed object are realized on top of the spray deposited thin film. Image adapted from [35] with authorization.

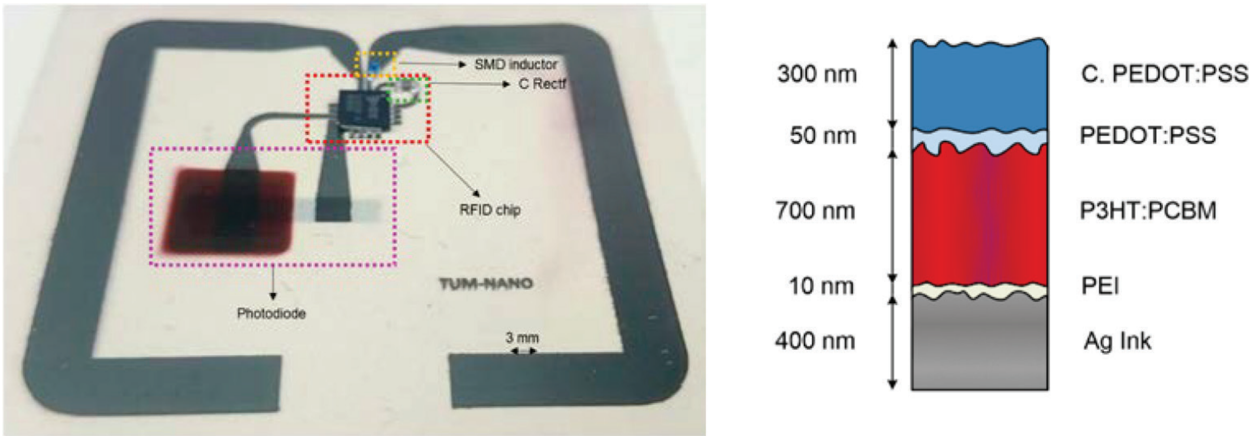

Figure 11. Left: image of the tag with all its elements labeled; right: cross-sectional view of the OPD. An inkjet-printed Ag line modified with spray-coated PEI. Both images adapted from [38] with authorization.

could be measured on the as-printed ones, and comparable to the reference material on glass. Finally, they show an application of 3D print and spray concept, by designing a semitransparent 3D printed heating chamber, which represents the first example of a fully-printed and cost effective functional object.

One last example of combination of PE techniques is a printed passive radiofrequency identification (RFID) tag in the UHF band for light and temperature monitoring [38]. In this case, the antenna and interconnects were realized with silver nanoparticles via inkjet printing. Temperature measurements came from an in-built sensor in the silicon RFID chip whereas the light monitoring was performed by a sprayed photodetector. This work showed for the first time the feasibility of the embedment of large-scale organic photodetectors onto inkjet-printed RFID tags. To succeed in the fabrication process, it was necessary to spray polyethylenimine (PEI) thin layer on top of the inkjetted silver electrode to obtain a working photodiode. In this case, they claimed that the antenna was done by inkjet printing instead of screen printing for simplicity of the process but in order to obtain an antenna with larger read range, screen printing would be the optimal process **Figure 11**.

Therefore, the manufacturing choice will depend on the restrictions of each application, in terms of printing technology availability, performance, area and materials and processes compatibility.

3. Towards on-chip integration

Integrating the different deposition techniques on one single substrate constituted the final step towards the obtainment of fully printed and hybrid circuits, with tuned capabilities and functionalities. Flexible tags, as the one presented earlier, however, are characterized by an inherently weaker link: the connection between the integrated circuits and the printed devices. Research in solving the interconnection issues, or eliminating them by realizing inherently flexible circuits, has seen a tremendous surge in the last decade.

In every application, in which it is not possible to construct an entirely flexible circuit, the necessity to solder (or, more correctly, to "attach") monolithic integrated circuits to the printed tag arises. The immediate problematics to be faced are mainly three: attaching the component with no harm to the flexible substrate, achieving a low contact resistance and retaining the flexibility of the overall circuit, at no performance loss. The most straightforward approach for the integration of ICs onto flexible circuits, is the adaptation of industrial soldering processes, with the employment of low-temperature soldering alloys. In a systematic and well-presented work by Andersson et al. [39], a series of SMD components with different packaging was soldered keeping the reflowing temperature below 150°C. The study showed mixed results: on the one hand, it proved the feasibility of soldering on paper with standard industrial devices, obtaining contact resistances in the order of few ohms; on the other hand, it was partially inconclusive, as it showed the inevitable presence of cracks after soldering and bending (shown in **Figure 12a**). Furthermore, the soldering yield was rather low (ca. 80% for the smallest packaging, much lower for bigger components), which might be a serious issue in commercial applications. An apparently more complicated—although much more appealing and promising—solution, stems out from treating flexible electronic chips for what they are: non-classical electronic systems, with the need of dedicated solutions. In this avenue, a very interesting work from Quintero et al. compares two technologies with a similar common denominator: the employment of conducting adhesive layers [40]. In particular, the present a selective etching of an isotropic conductive adhesive and the stencil-printing of Anisotropic Conductive Adhesives (ACAs), applied to the bonding of two separate flexible chips. The latter approach, extensively studied and applied in many material combinations, is the one that, so far, has been attracting the highest interest. ACA-based interconnects are obtained in a simple three-step procedure: first, the adhesive conducting film is deposited through a stencil, then the target component is placed on top of it, finally, the temperature of the substrate is raised to the bonding temperature (usually lower than 150°C). When the resin is heated up, it creates an electrical bond between carrier substrate and component, and creates a mechanically stable link. Nilsson et al. [41], present a remarkable application of printed circuits with ACA

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connected chips: a semipassive RFID chip, used to log eventual intrusions in carton packages. The system includes a resistive sensing network, an active microcontroller used to record and log the sensor data, powered up by a flexible battery, and a passive communication system. The connecting lines were ink-jet printed and screen-printed, while the hybrid interconnections were obtained with means of a commercial ACA, as shown in **Figure 13**. An extensive study on the stability and reliability of similar solutions has been presented, already in 2014, by Happonen et al. [42], who thoroughly investigated the resiliency of conducting adhesives employed for the connection of separate flexible foils. They explored different bonding solutions and performed a live measurement of the DC 4-wires resistance during several thermal and bending cycles. Interestingly, they show that the stability of hybrid interconnections is enhanced by the presence of supportive, non-conductive adhesives. These hybrid structures can undergo more than 1000 thermal cycles (0–100°C and back to 0°C in 1 h) and bending cycles (with bending radius down to 20 mm). The number of samples and the statistical analyses behind this analysis are solid and prove how flexible to flexible interconnects can be sufficiently reliable for consumer electronics applications. In spite of such promising results, however, the interconnections remain a significant point of failure.

An altogether different approach, however, could reduce the problematics of interconnection technology to their minimum terms. The newest research in flexible electronics, in fact, shows how it is possible to develop complex and fully functional circuits, with the employment of metal-oxide n-type and carbon based p-type semiconductors. Complete circuital systems, which are inherently flexible, would restrict the need for interconnects to very few and controllable points. These points can be designed to be in positions subject to minimal mechanical stress, hence reducing the probability of failure. Most of the effort in this direction has been put in the realization of only n-type semiconducting circuits, given the superior stability of metal oxides with respect to carbon based materials [8]. Although limited by the high power consumption of unipolar circuits, these studies show the avenue to follow to reach flexible and integrated electronics with the minimal interconnection technology. A remarkable work in this context is the one presented by Hung et al. [43], where an ultra-low power RFID tag is developed on plastic foil. All the components of the tag, including logic gates, decoders,

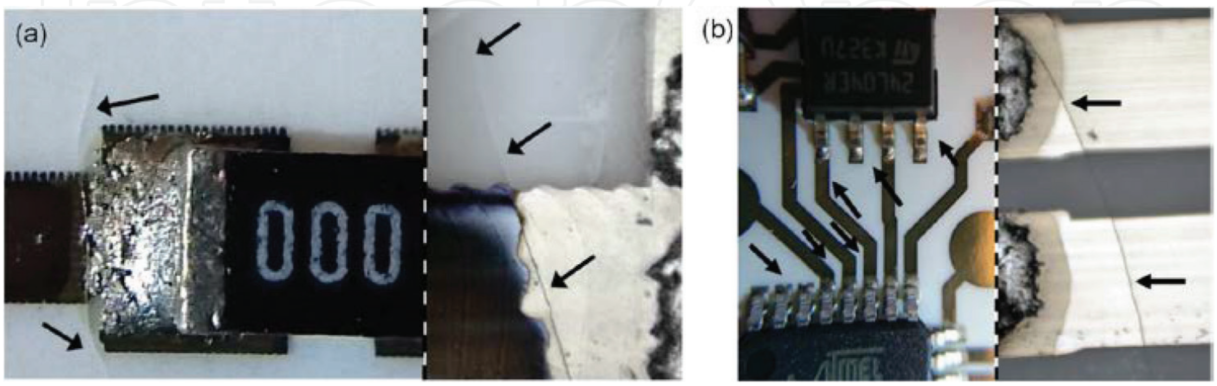

Figure 12. (a) Cracks left on the paper coating, on the printed lines and at the soldering, indicated by arrows, for a 0805 packaging component (b) similar issues for QFP and SOP packages, showing that the problematic is insensitive of packaging type and, up to a certain extent, size insensitive. Image adapted from [39] with authorization.

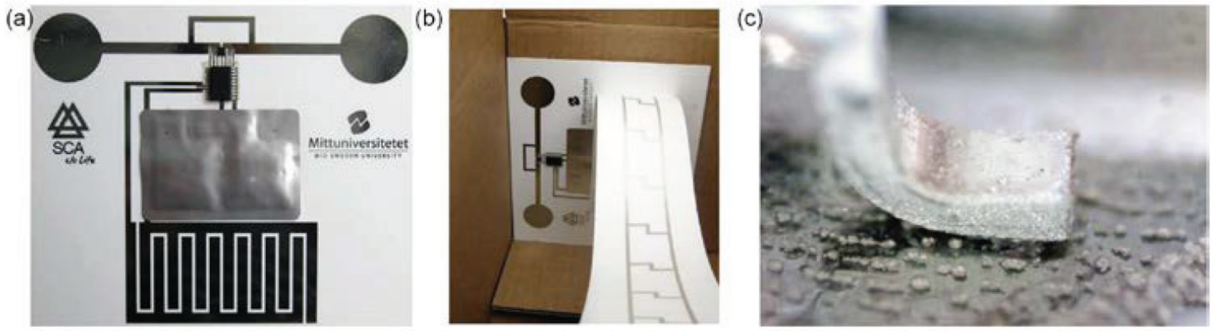

Figure 13. (a) A complete tag with RFID chip, antenna and flexible battery for a complete sensing kit (b) realization of an anti-intrusion system with sensing elements integrated in the sealing tape (c) photo of chip connected to printed line with an ACA. Figure adapted from [41] with authorization.

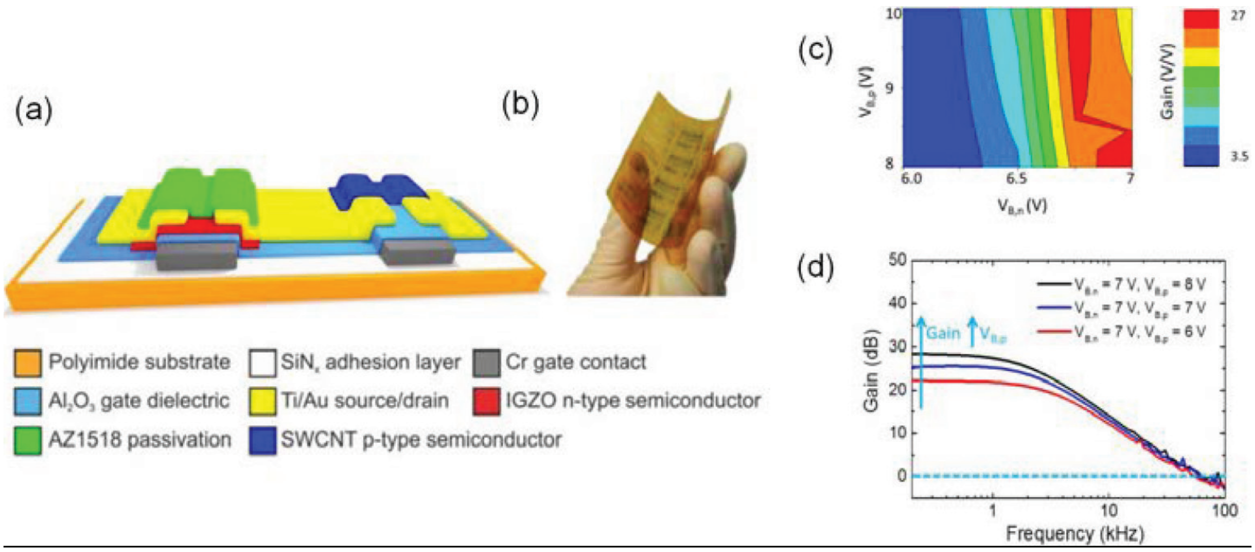

Figure 14. (a) Cross-section of the CMOS amplifier, with the different layers emphasized in different colors (b) photograph of a flexible substrate with many devices (c) voltage gain as a function of bias voltages, measured in ambient air (d) bode plot for different bias voltages, showing how the gain can be gate tuned. Figure adapted from [47] with authorization.

memory and clock generator were fabricated employing amorphous-IGZO FETs and were functioning at 1 V. Such systems, does not need any external driving element, and, thus, no further interconnection is necessary. In a similar direction, Myny et al. presented a flexible NFC barcode tag, with direct clock division circuit, which is compliant with ISO14443-A [44].

To further extend the spectrum of possibilities of printed, interconnectionless electronics, the group led by Prof. Jan Genoe, for instance, has demonstrated the feasibility of flexible control, driver and conversion electronics for photovoltaics-powered micro LCD screens, suggestively integrated onto a contact lens [45]. In this article they demonstrate the great potential of oxide-based electronics, fabricating a system which would have needed a high number of interconnects, and it would have not been realizable without this enabling technology. Finally, although flexible sensors have been often presented in many works, their biggest limitation was the necessity to connect them to external amplifiers and read-out electronics. Recent efforts in literature have shown how stable and reliable amplifier can be obtained employing a-IGZO FETs [46], although they still present the classic limitation of unimodal pseudo-CMOS logics. Significant breakthroughs are, nevertheless, achieved with a steady pace. Petti and co-workers recently reported a flexible full-CMOS amplifier, with a gain bandwidth product of 60 kHz, realized with sputtered IGZO and spray-deposited CNTs as n-type and p-type semiconductors, respectively [47]. The structure and characteristics of these devices are presented in **Figure 14**. The resulting amplifier is stable in ambient conditions, completely flexible and easy to integrate in other circuits, and it also shows the remarkable adaptability of solution processing (in this particular case, spray-deposition) to different substrates and pre-existent circuits. Albeit in this work the n-type material is sputtered, the specialized literature is abundant with reports of solution-processed IGZO transistors [48, 49], which could be readily employed for the realization of fully printed circuits.

The achievement of a complete set of electronic blocks—such as flexible oscillators, controllers, diving circuits, and amplifiers—is certainly a significant milestone towards a future of flexible electronics. However, considering their performances, it is also evident how printed and oxide-based circuits do not aim at substituting traditional silicon-based electronics for computationally intense tasks. What appears certain, though, is that with a careful and considerate interconnection of classical ICs and energy harvesters, with the exploitation of the advantages of each solution-processing technique, and with a systematic understanding of the underlying processes, flexible circuits will soon be able to permeate our lives.

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Conflict of interest

Authors declare no conflict of interest.

Author details

Almudena Rivadeneyra[1]*, Florin C. Loghin[1] and Aniello Falco[2]

*Address all correspondence to: almudena.rivadeneyra@tum.de

1 Institute for Nanoelectronics, Technical University of Munich, Munich Germany

2 Faculty of Science and Technology, Free University of Bolzen-Bolzano, Bolzen Italy

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