Printed electronics and their applications

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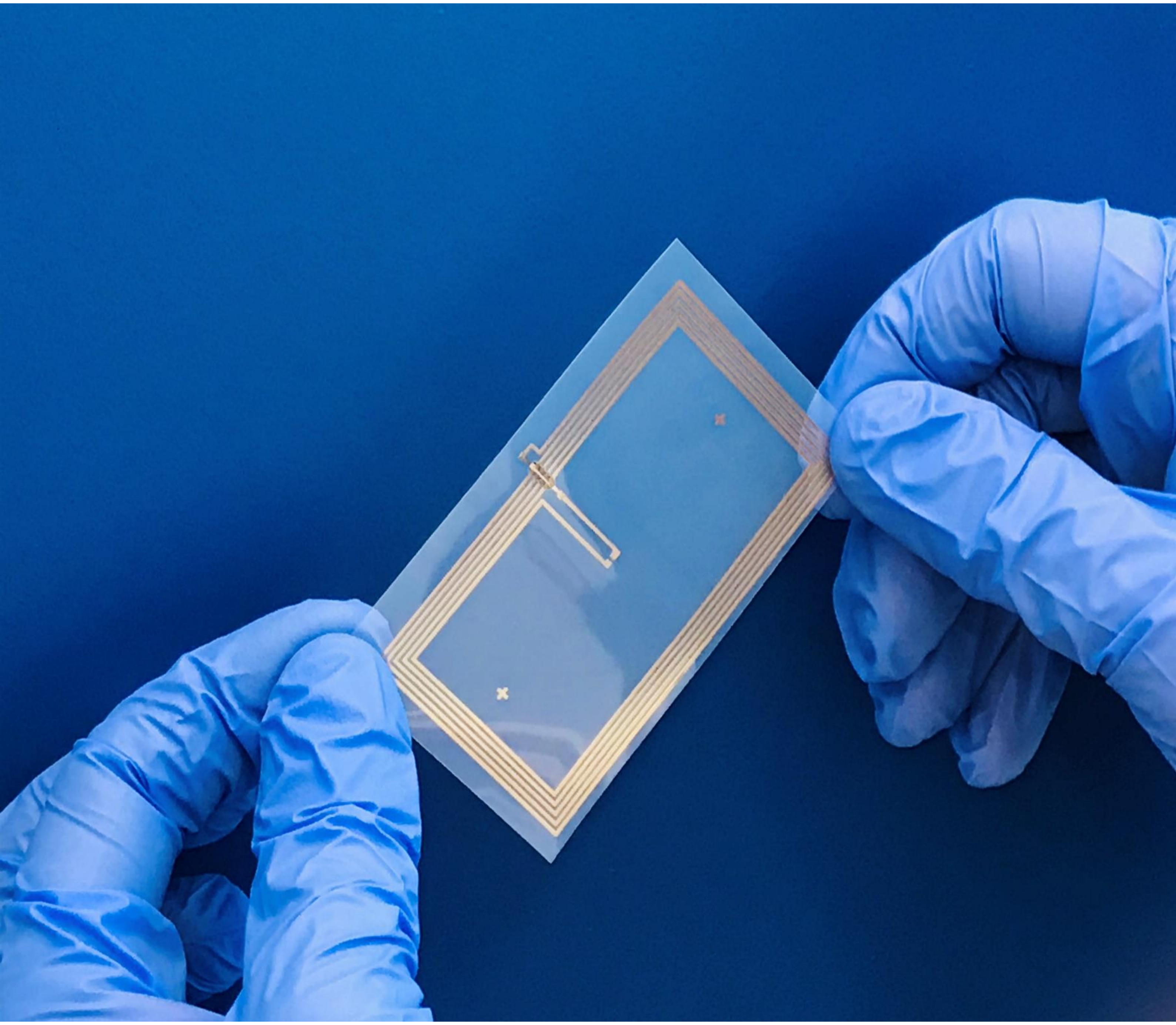

Introduction

Electronic devices have been manufactured for more than 60 years using a multiple-step sequence of photolithographic and chemical processing, creating in the end electronic circuits on silicon or other semiconductor material.

Printed electronics (PE) technology refers to an alternative process for electronics manufacturing, in which standard graphic arts printing processes are used to produce various kinds of electronic devices. This is done by fabricating conductive traces on a usually organic, rigid or flexible substrate. Sensors that are printed on flexible substrates represent a growing market and it is estimated that the market for fully printed sensors will reach $7.6 billion by 2027 [1].

The technology offers some unique characteristics, such as novel form factors (ultra-thin, flexible, stretchable), a variety of substrates (plastics, textiles, paper), a simple manufacturing process, and inexpensive mass production. These properties create the potential for a wide range of novel and promising applications in several areas, such as consumer electronics, packaging or pharmaceuticals.

In addition to the systems using exclusively printed electronics or traditional electronics, hybrid systems can also be built. In fact, these are almost the only option today, because all-printed integrated circuits for the wireless communications and signal processing are not yet widely available, if available at all.

The hybrid systems combine the best of the two worlds, silicon-based IC's for performance combined with flexible, printed components and substrates. Typically, one or more silicon-based chips are utilized in combination with printed peripherals, such as sensors, actuators, or antennas. All these are assembled on flexible, thin and organic substrates, where also the wiring is done.

The current whitepaper provides an overview of the technology and provides insights into some novel applications that it enables.

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1 Printed Electronics - Applications

In chapter 2, an overview of the Printed Electronics (PE) technology will be given, presenting what types of devices can be manufactured and the potential benefits for the manufacturer and the end-users of the products and/or services. However, as in any innovation the focus should be on the application of the emerging technologies. This section therefore focuses on providing insight into how the technology can be applied.

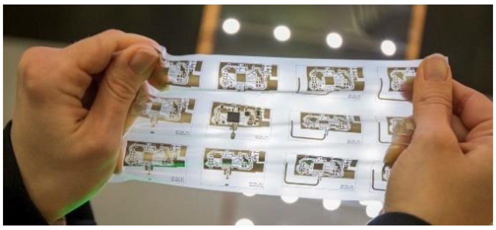
When the PE technology emerged, it was initially regarded as a substitution of the traditional electronics. But it soon became apparent that PE is a complementary technology and its applications can be entirely different. PE devices and systems cannot compete with their silicon-based counterparts in terms of performance. However, being many times more cost-effective, having unique form factors and offering the possibility to be printed on unconventional materials, PE enable abundant possibilities to integrate electronic functionality into several product applications that serve a variety of markets.

The following table presents some examples of applications that could be realized with the PE technology.

Application	Description
E-skin for over-strain detection during pipe transportation	Buried pipelines for gas, oil or water should be in a perfect state before putting them underground. A flexible plastic foil containing hundreds of printed strain sensor can be wrapped around the pipelines at all times between manufacturing and deployment. Such system could detect if the pipelines have been bended or strained beyond the allowed limits, even if this has happened only instantaneously. This could help detecting weaknesses in the supply chain and ensure high quality of the delivered products.
Multi-point surface temperature measurements for batteries	A thin array of temperature sensors can be printed either directly on a battery pack or first on a plastic foil that will then be attached to the battery. By constantly measuring the surface temperature the system will be able to detect situations where the batteries are overheating due to malfunctioning. Being able to measure the temperature value across multiple points as well as the temperature gradient, as opposed to a single-point measurement of a single sensor is a key benefit of such a system. At the same time, the printed electronics technology lowers the overall cost and offers the chance to produce fully customizable and scalable sensor arrays to fit any given battery pack size and shape.
Smart container with liquid level sensor	Thin humidity sensors printed with biodegradable materials on the inside of liquid containers can provide monitoring of the liquid level. Such a system can be implemented as a passive NFC tag, where an external reader (such as a smart mobile phone) provides power wirelessly to it, and then initiates a measurement and reads the results. These smart containers can be used for various everyday products such as milk bottles or liquid detergents
Portable device for monitoring the concentration of multiple hazardous and toxic gases	In settings such as underground mines, laboratories, military operations and fire accidents in petrochemical areas or areas where hazardous chemicals are stored, it is essential for the well-being of the people involved (mine workers, firefighters, etc.) that the presence of hazardous and toxic gases can be detected. The existing portable monitoring systems are bulky, expensive, and the consume a lot of power. Furthermore, many of those systems have to be carried at the same time, each for a specific type of gas. A portable multi-gas monitoring system based on printed sensors will give a huge benefit, since a) it can be very small and thin, b) it can detect multiple gas types, and c) it will be very low power, inexpensive and lightweight. Such a system can be implemented on thin foils that are then attached on clothes when necessary and can be disposed of afterwards. Connected wirelessly to a central communication point, can provide a very localized view of the situation, even if there is a gas leakage far away. Or connected to someone's own communication device or mobile phone it can rapidly warn of a hazardous or toxic gas detection.

Wireless health patch for human respiration monitoring	A thin piece of flexible plastic or textile can be manufactured that will contain printed strain sensors. Attached on a human's chest such a system can detect the inhales and exhales of breathing. In such a way, monitoring of the respiration or breath rate is possible. The patch can be used to detect changes in the normal respiration rate, as a result of a developing pneumonia, cough, bronchitis, asthma, etc. The patch can deliver health data to healthcare providers to flag potential issues before they turn serious and alert them before people become seriously sick. Such a patch can also be helpful to monitor the breathing rate of athletes and help them improve their performance.
Smart bandage for wound monitoring	Smart bandages can contain electronics for monitoring the wound status in the healing process. Flexible sensors can be directly printed on the bandage or a thin foil that is then attached on the bandage and monitor physiochemical markers such as temperature, humidity, pressure and pH. The system could be supplied from a printed, flexible and ultra-thin battery so that data are constantly logged. Alternatively, it can be passive and transmit the instantaneous wound condition when needed. Such a bandage could assist the caregivers in deciding if it is time to use a new bandage without prematurely uncovering the wound, or in adjusting the administered treatment according to the healing progress.
Stock-Level Monitoring Smart Shelve	In this application a matrix of multiple printed pressure sensors could be used to monitor the stock level present on a shelve of a supermarket or warehouse. The sensors could either be printed on the shelve itself or manufactured as a separate thin and lightweight foil that is then attached to the shelve. The shelve collects data continuously and relays this information wirelessly to a central server, so that the stock level can be monitored remotely in real time. This can have multiple benefits: unnecessary time spent from the store or warehouse personnel in finding out which product needs to be replenished is avoided, shortages are predicted before they happen, and a big pool of data is available for statistical analyses of any kind.
RFID logger for perishable goods supply chain	Monitoring of perishable goods in the logistic chain during transportation is important for many different products, such as pharmaceuticals and agriculture products. A cheap and disposable NFC tag with multiple printed sensors and powered by a printed battery would provide a smart solution to this need. The tag can be attached on a container, pallet, box or individual product like a thin label and after its activation, data from all sensors will be periodically logged in a non-volatile memory throughout the transportation duration. The logged data can then be retrieved and uploaded to the cloud through any NFC-compatible smart phone or other customized NFC reader. The gathered information can then be used for a variety of things, such as to ensure the high quality of the transported goods, to accurately determine how long the goods can be stored and ultimately, to optimize the logistic chain management.
RFID humidity and temperature logger for cigar packet	A thin, flexible and cheap active RFID logger featuring temperature and humidity sensors can be put inside each cigar packet. This can provide an indication of exposure to very low or very high humidity conditions, which would impact the quality of cigars. The logger will be supplied by a thin printed battery and will be activated right after the cigars are packed. It will then periodically log measurements until the product's end of life. Anyone with an NFC-compatible smart phone or other custom NFC reader can download the gathered measurement data from the tag, get any under- or over-threshold alarms that may have occurred and even upload the data to the cloud for further analysis.

2 Printed electronics – An overview



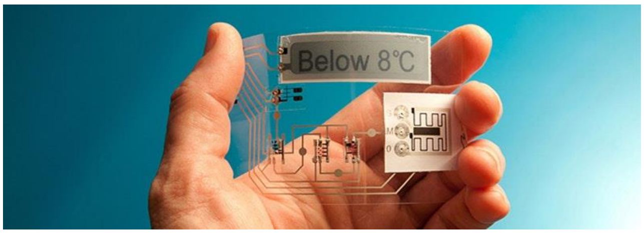


Figure 1: Examples of printed electronics

[sources: eeDesignIt.com, printedelectronicsworld.com]

2.1 Fabrication Process

The fabrication of traditional electronics requires a variety of physical and chemical processes to make conductive paths on a specific type of substrate (e.g. semiconductor wafer for Integrated Circuits or fiberglass for Printed Circuit Boards). The fundamental technology to these processes is photolithography, i.e. light exposure of a circuit image through a mask, much like a negative image in standard photography.

Contrary to this photolithographic fabrication process, creating material structures on the substrate using a print process of materials is a straightforward, two-step process. First, the printing material is deposited directly on the substrate and only on the desired areas. Since the printing material is usually an ink or a paste, this is usually in a wet state after the deposition. After printing an appropriate post-deposition treatment is necessary to bring the printing material in its functional state. This curing or sintering process results in the evaporation of any solvent and may also sinter the pigments or any other particles that are located in the printing material together, in order to make the conductive tracks and improve conductivity.

2.2 Printing Technologies

Several well-known printing techniques from the graphic arts industry are applied for PE, for example gravure, flexographic, offset, screen and inkjet printing. The printing technologies can be classified into template, and non-template (or digital) ones.

2.2.1 Template Printing Technologies

All template-based processes use some type of printing template, which comes in direct contact with the substrate. One of the most commonly used process nowadays is screen printing, which is mostly used to print solar cell electrodes. Another common technique is the flexography, typically applied for higher volume products such as printed Radio Frequency Identification (RFID) tags. However, both of these techniques require the printing equipment to be adapted to each type of device that is printed. For example, in screen printing, a new screen must be fabricated for each layer of an electronic device and in flexography a new printing cylinder is required each time. This inherently means a less flexible and more expensive process.

2.2.2 Non-template Printing Technologies

On the other hand, the non-template or digital techniques are much more flexible. They allow fabrication directly from a digital model created with any Computer Aided Design tool. Furthermore, the substrate only gets in contact with the deposition material. This leads to an enormous increase in flexibility regarding substrate choice, simplification of the switching process between different printed devices, as well as cost and waste reduction. This makes these technologies very promising for PE.

The most popular digital printing technologies is inkjet printing. It is a relatively new printing technique and is thus not widely used in industrial settings for printing of electronics. However, it is attracting growing interest from the scientific community and shows a lot of potential for the future of PE. It stands out for its simple and digital nature, the high variety of compatible substrates and low consumption of raw materials. Because the processed images are digital, products can be easily varied and personalized according to customer needs.

2.3 Substrate and Printing Materials

Although the printing technology for some technologies such as screen printing is very mature, where the technological readiness level is 10, i.e. full production capability. There are still challenges in other printing technologies such as ink jet and flexogravure is TRL5-6, i.e. that there are demonstrators available, but the full market introduction is still waiting. In respect to this the main challenge lies in the development of functional materials and inks for PE, especially when it comes to printing on unconventional materials such as textiles, and this is where the researchers focus on today.

2.3.1 Conductive Inks

The conductive inks are a very important factor for producing PE devices and have therefore increasingly gathered attention in the last decades. As PE applications continue to emerge, conductive inks will grow further in the future.

Unavoidably, a large variety of materials have been explored for PE, both organic (such as polymers) and inorganic. The organic inks are used either as active layers for active devices, such as Organic Light Emitting Diodes and Organic PhotoDiodes, or they are employed for batteries, passive components, sensors, etc. The inorganic inks, which usually contain metallic particles, are typically used for passive components and sensors.

There are three constituents for the conductive inks: a conductive pigment that makes the ink electrically conductive, a binder material that gives the ability to adhere to the substrate, and some solvents as a carrier for the mixture to give the liquid state and make it printable.

The conductive pigment can contain either microparticles (micro-ink) or nanoparticles (nano-ink). Micro-inks tend to be more porous when laid on the substrate, due to the bigger particles that they contain and thus less conductive than nano-inks. Using nano-inks can save a lot of material because the conductivity will be better and thus less material needs to be deposited to achieve the same target resistance. Furthermore, nano-inks, due to the conducting pigment's large surface area, have much lower sintering temperatures compared to micro inks, thus requiring less energy in post processing.

Despite the benefits associated with the nano inks, there are still many challenges to use nano inks for commercial purposes. For instance, it is much more expensive to produce the nano particles than it is to produce the micro particles from the bulk metal. As a result, most of the commercial products in PE nowadays still use micro inks.

Silver is the most well-known and most commonly used material for the metallic particles. This is due to its very low bulk resistivity and to the fact that even the oxides of silver are conductive. Alternative materials are being investigated and one of the most promising materials is copper. This is the case because copper is much cheaper and more available than silver, while its resistivity is not very much different from the one of silver. The big challenge is that the copper oxides are not conductive. Copper inks are slowly becoming commercially available and the future of PE is believed to be in copper. The company *Copprint* has developed an oxidation free nano copper ink at very low cost, rapid post-processing stage and high conductivity. The company *Novacentrix* also provides copper-oxide inks, which require a photonic curing sintering stage in order to reduce the copper oxide into conductive copper.

2.3.2 Substrates

Substrates play a big role when designing a PE device. From its compatibility with the printing technique and ink, to its thermal behavior and suitability with the intended application, choosing a wrong substrate can make the difference between a product being manufacturable or not.

The substrates of PE can be either rigid or flexible and are usually of organic material. Although the choice between the two is dictated by the application, the possibility of using flexible materials offers many advantages compared to the hard semiconductor materials used for traditional electronics that is of high importance for the development of new application areas for PE. The flexible substrate materials, however, set very specific requirements for the ink and matching the ink with the substrate is one of the challenges of PE.

Some examples of printing substrates that can be used are paper, textiles and fabric, glass, metal, wood, polymers, biomaterials and even 3D printed objects.

Glass is often used in the laboratory environment for qualifying and quantifying the behavior and properties of functional inks. Since it is a non-porous and neutral material, it doesn't influence this process. The challenge for printing on glass is the low roughness of the surface, as it becomes difficult to get the printing material to adhere to the glass, therefore it is often necessary to dehydrate and passivate the surface prior to printing.

Paper substrates show increasing popularity as base materials for PE, mainly because they are flexible, available and of low cost. Due to the roughness of the surface it is easy to have the printing material to adhere to the paper. The challenge for printing on paper is the porosity of the paper, since this can lead to nanoparticles entering the paper, therefore paper can be coated which then decreases the diffusion, making the process easier to manage.

Polymers are the most commonly used flexible substrates and various types have been proposed. Polyimide substrates have been in use for decades because they provide high performance and durability under the harshest of conditions. Other options include semi-crystalline polyethylene terephthalate (PET) and polyethylene naphthalate (PEN). Research is currently active in this field, trying to find new polymers that are even better suited to applications of flexible PE devices.

PE on textiles are becoming more and more popular with both researchers and wearable companies, since they provide a revolutionary expansion of functionality. According to reports [12] the consumer electronics market for medical wearables is expected to grow very fast in the next years and researchers are exploiting the development of new smart textiles with completely new technical functionalities.

Finally, biomaterials have also gained increasing focus for the fabrication of PE [13], mainly due to their mechanical robustness as well as biocompatibility and biodegradability.

2.4 Pros and Cons

From the discussion so far, it is apparent that PE come with some very strong benefits that make them attractive for certain application domains. There of course some disadvantages and challenges as well and this section will try to give an overview of the pros and cons of PE.

Pros	Cons
Straightforward and fast manufacturing process	Performance
Lower cost / Less waste	Reliability
Highly customizable	Feature size
Mass-production compatible (R2R process)	
Unique and novel form factors	
Variety of substrates	
Lightweight	
Possibility to be biodegradable	
Functionality	

Table 1: Pros and Cons of printed electronics

2.4.1 Main Benefits

As it was discussed earlier in the document, PE are manufactured using printing technologies that are straightforward and require only two processing steps. This manufacturing process by itself results in many benefits.

First, it is very fast to manufacture PE. Traditional silicon-based integrated circuits require a fabrication time of around 3 to 4 months due to the complexity of the process. On the contrary PE with a process time in the order of magnitude of minutes are nowhere near that.

Moreover, the costs involved in manufacturing PE are massively lower than the conventional electronics, which makes the produced devices much more affordable. Many different aspects contribute to this benefit. The manufacturing tools are much cheaper, since the printing methods are straightforward and easy, and because only low temperatures are involved the energy consumption is also kept minimal. The possibility to use low cost substrates, like paper or plastic, as well as doing roll-to-roll manufacturing and creating electronic devices on a roll, are factors that contribute to the low overall cost.

Thanks to the ease of production and low cost, PE can be highly customizable. In particular, when it comes to the digital inkjet technique, in theory every part can be different with no additional cost of designing and handling different printing masters. As a result, the PE technology makes it possible to mass-produce highly customized electronic devices in large volume and high speed.

Another important advantage for which PE stand out over traditional electronics lies in their form factor. Because it is possible to print on many surface types, unique form factors can be achieved that people had never thought before. For example, PE has the ability to make very thin and flexible electronics, which can fit small and tight spaces, and also to print electronics on polymeric films that are afterwards bended in a 3D shape (in-mold electronics). Because of the possibility to print on very thin films, PE can be made very lightweight. Furthermore, being able to use substrates from biomaterials can make PE biodegradable and thus sustainable. All this results in another big benefit of PE, which is its functionality: doing things that otherwise would be impossible or very difficult and expensive with the traditional electronics.

2.4.2 Challenges

Despite being a fast-growing technological field, PE technology is not without its challenges.

One of the main challenges is the development of new ink formulations that are suitable and optimal for the target application and usage. There is still a significant amount of research into developing functional conductive inks and materials for PE applications in a cost-effective manner. Rapid advancements in material science, such as the nanomaterials, support the researcher efforts in this direction.

The compatibility of the ink and the substrate is a complex interaction which depends on many parameters and constitutes another main research challenge. If this interaction is not optimized, then the final resolution and repeatability of printed patterns and devices is strongly affected.

Another drawback of PE devices is that they are not necessarily the most performant compared to the traditional silicon-based electronics. But it is clear that the target applications of the two worlds are different. The PE technology paves the way for novel applications that do not require the high speeds of the traditional electronics applications.

Reliability is another concern of printed electronics. Although a printed sensor is cheap to manufacture and probably easy to replace, it is not very clear how long such a sensor can last or when and how it will fail. Are PE systems resistant to heat exposure and other harsh conditions or are they going to start cracking and delaminating more easily than the regular printed circuit board electronics? Therefore hybrid systems are often developed, where the parts that are most challenged by long term reliability are fabricated as printed circuit boards, and the advantages for the printed electronics in the other parts.

Lastly, the feature size (or how small things can be) of the PE devices can be limited, whereas traditional semiconductor electronics can have features up to 3 orders of magnitude smaller. This is attributed entirely to the different manufacturing method, as printing technologies have more difficulties in this aspect than the photolithography.

2.5 Types

"Printed electronics" is an umbrella term that is used to describe electronics in general that are printed on usually flexible and organic materials. But what kind of electronics do we actually mean? In fact, several different types of electronics can be printed, from individual system components to the systems themselves.

2.5.1 Sensors & Transducers

Sensors that are printed on flexible substrates represent a growing market and it is estimated that the market for fully printed sensors will reach $7.6 billion by 2027 [1].

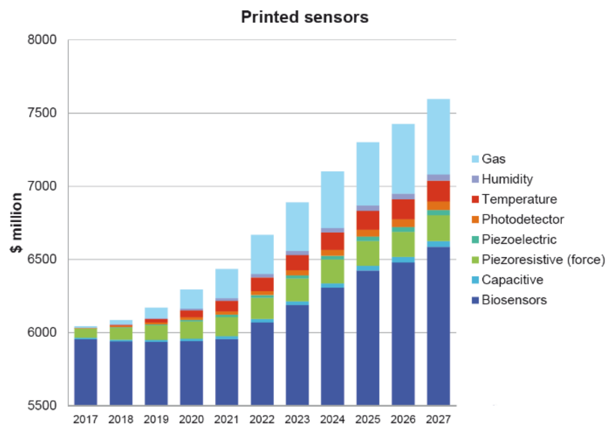


Figure 2: Market predictions of Printed Sensors 2017-2027
[source: IDTechEx "Printed and Flexible Sensors 2017-2027: Technologies, Players, Forecasts"]

Several types of sensors and transducers can be printed. Some of them are already mature and others are being established. The former category includes glucose test strips, force sensors and capacitive sensors. Some sensors are easier to manufacture, consisting of a very simple structure with a few electrodes only, and others are more complex and require the deposition of multiple layers.

Each sensor may have different perspectives based on the exact application that it is being used for. For example, a strain gauge can be used for measuring a variety of mechanical quantities, such as force, tension, weight and pressure. A gas sensor can be used in numerous applications to detect a variety of gases, such as O2, CO2 or CO, depending on the material that is deposited on the sensor surface. Biosensors can detect and track different biomarkers.

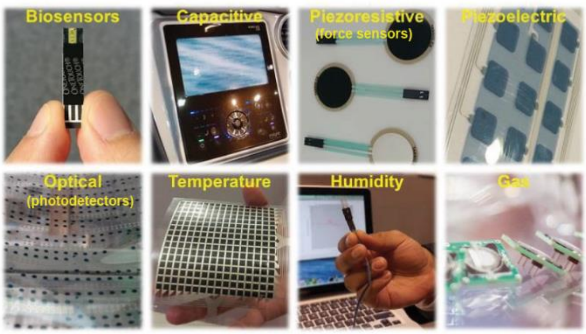


Figure 3:Different types of printed sensors
[source: IDTechEx]

A short overview of the different types of sensors is given below.

Temperature sensors

Printed temperature sensors are one of the easiest types to manufacture and the most widely employed. Resistive Temperature Detectors (RTD) are the most commonly reported and demonstrated on various substrates temperature sensors. They typically consist of a single, long, and meander-shaped conductive pattern. Their operating principle is that a change of resistance is detected when the temperature is varying. In practice, an electrical current is transmitted through the RTD sensor, which is located close to the area where the temperature is to be measured. Subsequently, the voltage drop across the RTD is measured and its resistance value is calculated and correlated to temperature based upon the known temperature coefficient of the RTD material.
Apart from the general benefits of PE we have discussed, the printed temperature sensors have some additional ones. The use of very thin substrates where the sensors are fabricated on, with almost negligible thermal mass, ensures that these sensors have very short response time and good sensitivity.

Due to the low cost of printed temperature sensors, it is very easy to build flexible temperature arrays that can be applied for multi-point surface temperature measurements or for measurements in confined spaces with narrow areas where typical silicon sensors cannot fit.

Humidity sensors
Humidity is one of the widely monitored parameters in the environmental, medical, food and other industries. PE technology can be used to print humidity sensors. Many types of humidity sensors have been reported in the literature [19], both on paper and on other flexible substrates such as polyimide and PET. For self-compensation reasons, it is beneficial to combine humidity and temperature sensors on the same substrate and this can be easily achieved with PE.
A printed humidity sensor is usually either resistive or capacitive, with the former being the most commonly implemented type as such sensors are easier to be integrated and they also use relatively simpler electronics to monitor. A resistive printed humidity sensor usually consists of an interdigitated electrode array. The operating principle is that the electrical resistivity of the electrode material is strongly dependent on the absorbance of water vapors, therefore relative humidity levels can be extracted by measuring the electrical resistance between the two electrodes. This resistance will change when the humidity levels change, as more (or less) water molecules are absorbed.

Strain & piezoresistive sensors
Strain sensors are used for diverse applications, from structural monitoring to healthcare and in most cases strain gauges are employed. A strain gauge is a sensor whose resistance varies with applied force. It can convert a variety of mechanical quantities (such as force, pressure, tension, and weight), into a change in electrical resistance which can then be measured. A strain gauge measures "strain", which can be any expansion or contraction that may occur by many external influences or internal effects of the material itself.
Strain gauges take advantage of the physical property of electrical conductance and its dependence on the conductor's geometry. A typical strain gauge consists of a long conductive strip in a zigzag or meander pattern of parallel lines, being quite similar to a temperature sensor.

Accurate strain gauges with different force sensing ranges are reported and can be produced on flexible paper or PET substrate. Although not all-printed strain sensors can achieve sensing performance comparable to the one of silicon-based sensors, they are massively superior in optical transparency, weight, flexibility, and fabrication cost. This paves the way for novel applications, such as artificial skin, movement detection, flexible touch panel, etc.

Biosensors
Biosensors are devices that can detect biological molecules (such as nucleic acids (DNA and RNA), proteins, antibodies, and antigens) in air, water or blood. They are widely used in medical monitoring and diagnostics, among other sectors. One of the most known and widespread application is the monitoring of blood glucose concentration for diabetics. In fact, printed biosensors and especially glucose test sensors hold the biggest part of the printed electronics market. With a globally aging population, the need for non-invasive remote monitoring and self-diagnosis is increasing, and smart systems collecting data from wearable biosensors are essential for this. Many cases of printed biosensors have been reported in the literature, such as an inkjet-printed disposable glucose sensor on paper [9], a DNA biosensor based on nanomaterials [10], an all-printed biosensor for fast detection and classification of pathogens [11] and many more.

Electrochemical sensors
Electrochemical sensors are sensors that convert biochemical activity of any kind into measurable energy events. For example, such sensors are used to detect toxic chemicals or chemical warfare agents. Printed electrochemical sensors are of special interest for wearable systems in healthcare, industrial and security fields. Much of the success of these sensors is attributed to research in material science and the development of novel inks comprising of new nanomaterials, polymers and composites. One very promising application field of printed, thin and flexible electrochemical sensors is in wearables and healthcare for the non-invasive monitoring of biomarkers, such as electrolytes and heavy metals in sweat, saliva and tears.

Gas sensors
Gas sensors have numerous potential applications in several areas, such as industrial manufacturing, personal safety protection and environmental monitoring, where detecting hazardous and toxic gases (e.g. hydrogen sulfide H_2S, nitrogen dioxide NO_2, etc.) is essential for the protection of human health. Traditional sensors of this type are not very compatible with low cost, battery-powered, flexible devices intended for IoT applications. Thus, the research attention towards using organic materials and printing technologies to produce organic-based electrochemical gas sensors is rapidly increasing. The forecasts for the next years predict that gas sensors, which are now gradually moving into mass production, are expected to have the largest growth among printed and flexible sensors.

Organic electrochemical gas sensors can have very low power consumption in the μW range and are flexible and cost-effective, which makes them very attractive for IoT applications. Their operation is based on measuring the concentration of a target gas through electrochemical interaction (oxidation or reduction) between the gas and the sensor surface, which generates electric current. The target gas does not need to be hazardous or toxic. Instead, it can be any type of gas, such as oxygen or methane.

Photodetectors

Photodetectors (also called photosensors) convert light pulses into electrical signals and are fundamental blocks for any opto-electronic system. They have widespread technological applications, such as image sensors or digital X-ray sensors, which would greatly benefit from the cost-effective fabrication processes enabled by PE technology. Organic semiconductors are the materials that have received the most focus for printed photodetectors, with the resulting devices being organic photodiodes and organic phototransistors. Although their resolution is not very high, organic photodiodes offer, apart from the typical PE benefits, novel functionalities such as wavelength tunability or transparency and at the same time have comparable performance with the silicon-based photodiodes [7]. Printed photodetectors will contribute to the development of cost-effective optical detection systems.

Touch sensors

Touch sensors are another type of printed sensors available today and one of the most common sensing methods is capacitive sensing. In the capacitive touch sensors, touch activity is defined by detecting minor changes in electrical charge (capacitance) between two conductors, generated by the contact with a finger. Such sensors are usually constructed as narrow strips of interdigital electrodes. The most typical application of printed touch sensors is to replace mechanical buttons, because of their unique benefits. First, they are not subject to wear and tear, and second they can be manufactured on any surface, even molded on 3D objects and curved surfaces.

Piezoelectric sensors & actuators

A device or material is characterized as piezoelectric when it generates an electric charge when mechanically deformed. Conversely, when an external electric field is applied to piezoelectric devices they mechanically deform and thus act as actuators. Rapid advances in materials science enable the construction of piezoelectric systems in thin, flexible and stretchable form factors [8]. Such systems can be applied for mechanical energy harvesting, sensing or actuation in wearable or implantable systems, for sustainable power sources in consumer electronics, etc. The company *Meggitt* has developed a screen printable, low temperature piezoelectric ink, called PIEZOPAINT, and has demonstrated integration into flexible foils and textiles [15].

2.5.2 PTC Heaters

Traditional heaters can be heavy and bulky and are prone to failures due to potentially faulty wires or coils. Printed PTC (Positive Temperature Coefficient) heaters are circuits printed on a thin and flexible substrate using printing techniques and can be used in various industries to deliver heat much more efficiently. One of the biggest benefits of the PTC heaters is that they are self-regulating; they maintain their target temperature without external intervention. Therefore, all safety risks, hot spots and external diagnostic circuits are eliminated. Other characteristics of the PTC heaters are that they provide uniform heating and the turn-on time is very short, consuming at the same time less energy than the traditional ones. PTC heaters are already an established printed element and find application in many industries, such as automotive and aerospace. Examples include seat, mirror and steering wheel heating, as well as wing heating and de-icing. *GGI Solutions*, *Henkel* and *Quad industries* are some examples of manufacturers that provide PTC heaters.

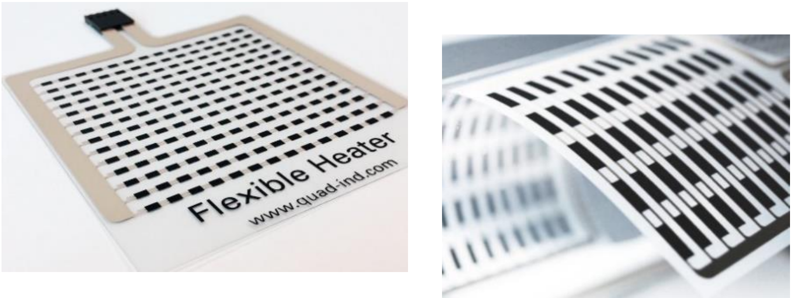


Figure 4: Printed PTC heaters

[sources: QUAD industries, GGI Solutions]

2.5.3 Light and Displays

Organic electroluminescent devices offer a serious alternative to their inorganic counterparts, as they are thinner, more flexible, more efficient and have extremely lower cost production, as inexpensive roll-to-roll printing processes can be used. The first and most common organic electronic lighting products in the market have been the organic light-emitting diodes (OLED's). However, OLED's have some important drawbacks. They are very sensitive to the thickness of the multiple coating layers of different organic materials that are applied, and they also use expensive and rare metals for coating these layers, therefore pushing the low-cost limits of the printing techniques.

An alternative technology that is slowly emerging is the light-emitting electrochemical cell (LEC or LEEC) technology. This is very similar to the OLED technology but has the advantage of using only one light-emitting material layer between the two conductive electrodes and is relatively insensitive to the thickness of the active layer and the properties of the electrodes. Furthermore, LEC's can be manufactured all-organic by using organic conductive materials for the electrodes. This makes their manufacturing easier and the end devices recyclable, as for example the company *LunaLEC* is doing.

Printed displays are mainly used in the consumer electronics market, such as for wearables and mobile devices. The need for very thin and flexible displays for these applications, has led to the development of printed displays by leading manufacturers, who mainly use the organic light-emitting diodes (OLED) technology. Nowadays PE manufacturers can make a great variety of flexible LED displays on paper, fabric, and plastic film, including transparent film with good transparency of the circuit.

Another type of printed displays that is quite promising is the electrochromic type. Electrochromic materials are organic or inorganic substances that change color or opacity when charged with electricity. The color change is persistent, and energy needs only be applied to effect a change. This technology has been extensively used in dimmable glass applications or "smart glass", such as rear-view mirrors in automotive and airplane windows (like the Boeing 787 Dreamliner for example) and building windows for heat control. Many PE manufacturers (such as *PEA*, *ynvisible*, and *rdot*) have developed printed electrochromic displays, mostly on flexible conductive polymers, that can be integrated into any smart product as a visual interface. Such a display can be used in packaging or other similar devices that require the display's unique features: its ultra-thinness, flexibility, robustness and ultra-low power consumption.

Figure 5: Examples of printed electrochromic displays

[sources: Rdot Displays, ynvisible]

2.5.4 Power

Three sub-categories can be identified here: printed batteries, thin film solar cells and supercapacitors.

Batteries are obviously a very important building block of portable electronics and in recent years they are moving to new form factors, such as printed, ultra-thin and flexible [1], mainly thanks to the rise of Internet of Things, wearables and environmental sensors. These market sectors have a need for functionality that the traditional batteries cannot provide. The industry is changing rapidly, as new developments are constantly announced. The printed batteries usually have a chemistry based on zinc and thus are not rechargeable. Some commercially available printed batteries are as thin as paper and offer typical standard form factors of 1.5 V or 3.0 V, capable of delivering tens of mAh of energy, with peak currents of at least several mA [2], [3]. Those batteries are suitable for low power disposable devices, which require flexible and thin properties, and can be customized according to requirements.

Figure 6: Examples of printed batteries

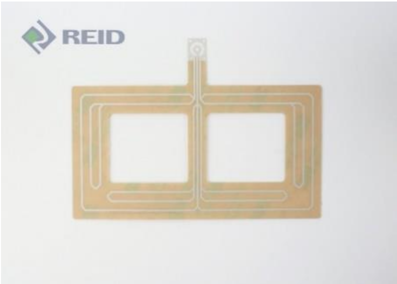
[sources: Enfucell, Blue Spark, Imprint Energy]

In the photovoltaics field, the organic or plastic solar cells (OSC) and the dye sensitized solar cells (DSSC) are examples of flexible and inexpensive PE power sources. Compared to traditional silicon-based devices, these cells are lightweight and highly customizable, allowing unique shapes and looks to be used. They also offer the potential to exhibit transparency, suggesting many novel applications in windows, cars etc. The biggest challenges in this space is further reducing costs and optimizing lifetime and efficiency.

Supercapacitors can also be printed, providing an excellent promising option for temporary energy storage in applications that use low energy harvesting or for energy buffers for wind power, photovoltaics and more. One example of printed supercapacitors are the ones from the company *Printed Electronics Arena (PEA)*, which are made from wood derivates.

2.5.5 Antennas

Another type of PE that can be manufactured are antennas, which can affect applications in various industries, such as hand-held consumer devices, automotive and aircrafts. All these applications could benefit from smaller and cheaper antennas with less weight and PE can help realize these goals.



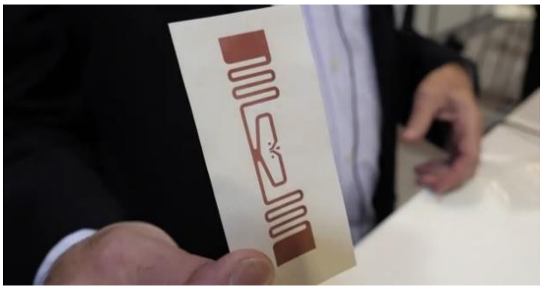


Figure 7: Examples of printed RFID antennas

[sources: REID, printedelectronicsworld.com / Copprint]

2.5.6 Building Components

In order to realize the vision of electronic systems constructed entirely with PE, it is necessary to replicate all components of conventional rigid electronics in a printable form. Passives (such as are resistors and capacitors) and active components (such as diodes and transistors) are the most basic but necessary building blocks.

Resistors

Using ink to print conductive resistors has been a proven method of PE. Printed resistors of any shape, form and accuracy can be used in applications, such as potentiometers or fixed resistors. Printed power resistors can withstand and conduct high power and thus, high power densities can be achieved. These power densities can be used either to dissipate power or to generate heat in heating elements, for example, in applications like seat heating or local heating for printed sensors.

Capacitors

Printed capacitors are not so advanced as the printed resistors. However, active research on the field reports promising results for the future [16][17]. The challenge is yet again to find the most suitable ink and substrate combination to achieve desirable performance.

Diodes

Contrary to diodes for photovoltaics or light (e.g. OLED), as of today, little emphasis has been put on fabricating purely electronic diodes with PE technology, but these could be integrated into a variety of circuits for applications like rectification or energy harvesting [4]. The literature shows that researchers have managed to print solution processed and organic diodes from a wide range of organic and inorganic materials.

Transistors

Transistors are undoubtably one of the most fundamental building components used today in electronic circuits. With the development of appropriate printing inks and organic semiconductors, as well as the vast improvement of the respective material properties lately, more research attention has been paid to fabricate organic printed transistor devices of adequate performance to be used in PE applications. For example, recent improvements in the performance, stability and reproducibility of printed organic thin-film transistor (OTFT) devices [5] mean that the future, where printed analog circuits will be a reality, is not very far. One very important building block for sensor applications, that is the operational amplifiers, will be available along with a variety of signal processing (such as active filters, amplifiers, impedance converters etc.) will open the door to new and exciting applications. Wearable smart biosensors are one of the most promising applications in this regard. Other transistors that have received attention in the area of PE devices are the organic field-effect transistor (OFET) devices. Research has sought to achieve comparable device performance, as such devices are considered as a key component for organic printed integrated circuits. In addition to their typical use as switching elements for logic circuits, OFET devices can also play an important role in realizing large-area, flexible and low cost printed sensors, including chemical, biological, photo, as well as pressure and temperature sensors [6].

2.5.7 Other Components

Other printed, low transistor-count components that involve logic are also starting slowly to appear in the literature [14], and researchers are trying to manufacture a complete IC using printing techniques, but it will probably be a while before such an achievement is reached.

Stand-alone re-writable memory manufactured by a printing process is still behind compared to other printed components and not yet widely available, but it will certainly become so in the future. When this is the case, the cost is expected to be significantly lower compared to existing technologies, particularly for small volumes of memory. *Xerox®* Printed Memory uses a thin film of adhesive plastic as a substrate to make 36 bits of rewritable memory available. This can be used for example to hold various product information such as lot and serial numbers, expiration dates etc.

2.5.8 Circuit Interconnects

We have seen that PE technology provides the possibility to deposit conductive materials into a patterned structure on various substrates. It thus goes without saying that fabricating the connection tracks between the various components of an electronics system comes inherently and can be easily achieved. However, this is true only for the two surface sides of the substrate, top and bottom. Printing interconnects in multiple layers, as it is common practice for the traditional Printed Circuit Boards (PCB), is still quite challenging but not entirely impossible. For example, the company *NanoDimensions* manufactures and sells a machine that can ink-jet print multi-layer PCBs, with the targeted use case being rapid prototyping and design validation. Nevertheless, even the two layers of connections are more than enough for most, if not all, electronics of the targeted PE applications.

2.5.9 Hybrid Systems

In addition to the systems using exclusively printed electronics or traditional electronics, hybrid systems can also be built. In fact, these are almost the only option today, because all-printed integrated circuits for the wireless communications and signal processing are not yet widely available, if available at all.

The hybrid systems combine the best of the two worlds, silicon-based IC's for performance combined with flexible, printed components and substrates. Typically, one or more silicon-based chips are utilized in combination with printed peripherals, such as sensors, actuators, or antennas. All these are assembled on flexible, thin and organic substrates, where also the wiring is done.

3 Conclusions

It is unlikely that printed electronics will be able to compete with conventional silicon-based electronics when it comes to performance, reliability and ability to handle complex designs. However, printed electronics open up new possibilities for applications that are not feasible with the silicon-based electronics, due to the unique characteristics of the technology.

Some advantages of printed electronics that the present investigation has found are the following:

- Cost – Lower manufacturing and production costs compared to traditional silicon-based solutions for some applications
- Flexibility – Electronics can be printed on various substrates in unique and novel form factors
- Customizability – Electronic devices can be easily tailored to the specific need of the application
- Speed – The fabrication time of printed electronics is much less than the traditional electronics

According to the predictions, the electronics industry will increasingly use printed electronics technology in the future. It is still an emerging field and there are many things to figure out. However, the possibility of embedding electronics in any object and shape and at a low cost is very attractive.

4 Revision History

Revision	Author	Revision date	Description
1.0	N. Agianniotis	30-11-2020	Released
1.1	N. Agianniotis	10-12-2020	Corrections to the first and second pages

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