Recent advances in printed sensors on foil

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In this review paper, we summarise the status and trends in the research and development of printed sensors on foil substrates. Our focus includes sensor technologies that have some of their elements printed with a special interest for fully printed structures. The paper reviews the two large physical and chemical sensor families addressing different transduction principles. The paper concludes with a short notice on status and perspectives in the field with some words on the commercial maturity and trends of printed sensors on foil.

Introduction

In recent years, there has been a tremendous increase of the number of sold microsystem sensing units. Among others, Micro Electro-Mechanical Systems (MEMS)-based accelerometers, gyroscopes, magnetometers, microphones, and pressure, temperature, and humidity sensors have reached the consumer market with notably a massive penetration in mobile phones. And from the analysts and actors in the field, this is only the beginning of the emergence of a new sensor era. The establishment of the Internet of Things, the networking of smart objects, is in progress and will drive the implementation of sensors into industrial and also our daily life objects. TSensors (Trillion Sensors) movement was founded to accelerate and coordinate the development of the trillions of sensors that are expected to be needed for the development of a new generation of smart sensing systems. The latter will be deployed in several fields of applications including biomedical, energy, environment, gaming, logistics, manufacturing, personal health care, telecommunication, transport, etc.

Silicon sensors technology will be of course expanding to meet this demand but one can expect organic and printed electronics (OPE) to strongly complement silicon technology. OPE enables the development of sensors and smart sensing systems with unique characteristics such as flexibility, conformability, transparency, biocompatibility and possibility of fabrication over a large area. The materials and processes used to fabricate OPE devices are progressing towards greener electronics systems, being environmentally friendly, thanks to the use of additive processes and reduced infrastructure and thermal budget. Besides these unique functionalities, of high interest for better design integration into various kind of wearable and consumer products, OPE is also very attractive for the large area manufacturing at very low-cost of this extremely high number of sensing components or intelligent sensing surfaces. When dealing with such a high number of items and products, environmental impact becomes also a critical issue especially when considering their end of lifetime. OPE is here again well positioned to ensure their safe disposal, this by doing the right selection/development of materials. However, one should stay aware that in several cases, OPE sensors performances do not match those of silicon sensors, due the lack of resolution of the patterned features and to non-availability of on-chip integrated powerful Complementary Metal-Oxide-Semiconductor (CMOS) electronics for signal processing.

But there is still plenty of Research & Development (R&D) work ahead of us for the large deployment of OPE sensor technology. Indeed, fully printed sensing devices and surfaces are still at their infancy age and, in most cases, smart sensing systems are being demonstrated using a hybrid integration approach involving silicon components. Screen printing technology is already well established for the fabrication of sensors on rigid substrate such as alumina ceramic, but when looking at sensors processing on flexible polymeric and cellulosic foils, combination of lithographic and printing processes is commonly used. However, when

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relevant, the tendency is being towards the implementation of an all printed approach.

In this article, we summarise the status and trends in the research and development of printed sensors on foil. Our focus includes sensor technologies that have some of their elements printed with a special interest for fully printed structures. For a detailed description concerning the working principle of the printing techniques mentioned in this paper, with particular emphasis on sensors fabrication, the Reader is invited to refer to [1]; another excellent review on printing fabrication techniques can be found in [2]. The paper reviews the two large physical and chemical sensor families addressing several transduction principles such as capacitive, resistive, amperometric, voltametric, optical, piezoresistive, piezoelectric, photoelectric, and pyroelectric. Finally we will conclude with a short notice on status and perspectives in the field with some words on the commercial maturity and trends of printed sensors on foil.

Physical printed sensors

This section reviews the current state-of-the-art of printed sensors for the detection of physical quantities, that is, temperature, position, light and mechanical stimuli (pressure and strain).

Temperature sensors

Temperature is one of the most important physical quantities, as it appears explicitly in the most basic physical laws and affects almost any typology of measurements. Sensors able to detect temperature variations and quantify them according to a previously defined scale are usually called thermometers [3].

Most of the printed thermometers presented in the scientific literature consist of metallic printed resistors and rely on the variation of resistance with temperature, defined with a known equation within the temperature range of interest [4]. Different types of materials, substrates and fabrication techniques have been utilised so far; the majority of examples reported in the literature describe resistors realised with metallic inks on flexible, plastic substrates.

Molina-Lopez et al. [5] described the fabrication of inkjet-printed silver meander-shaped resistors on flexible plastic foils (namely, polyethylene terephthalate – PET) (Fig. 1). These devices, in the considerer range of temperatures [-10 °C, +60 °C], exhibit an extremely linear behaviour (coefficient of determination to a linear fit higher than 0.999) and are characterised by a Temperature Coefficient of Resistance (TCR) up to $(6.52 \pm 0.05) \times 10^{-4}$ °C^{-1}.

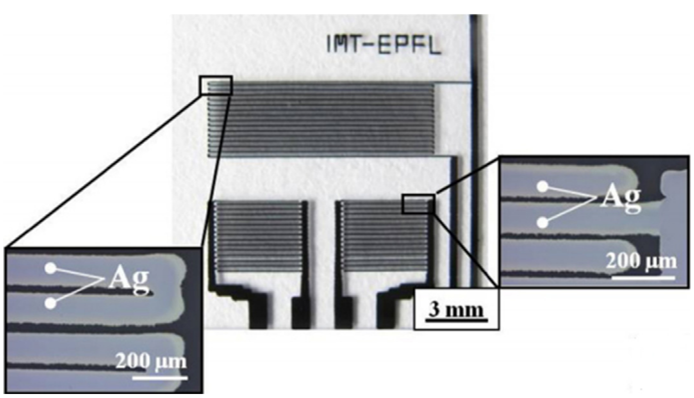

FIGURE 1

Scheme of the inkjet-printed temperature sensors (Molina-Lopez et al.). The picture refers to a system composed of humidity and temperature sensors; the thermistor is the device on the top, with an inset shown on the left.

Another interesting example of printed temperature sensor was presented by Aliane et al. [6]. In this case the Authors described screen printed resistors fabricated on flexible polyethylene naphthalate (PEN) or polyethylene terephthalate (PET) foils. First of all, electrical connections were fabricated by sputter deposition of a thin layer of gold (30 nm) which was subsequently patterned by photolithography. For the fabrication of the temperature sensors, two different types of temperature-sensitive pastes were used: a Positive Temperature Coefficient (PTC) and a Negative Temperature Coefficient (NTC), the latter being based on antimony tin oxide (ATO). Printed layers had a thickness between 8 and 10 μm and were cured at 130 °C for 20 min after printing. Finally, A CYTOP-like fluoropolymer layer (~1 μm thick) was deposited on the top of the sensors as protection layer, also by screen printing. The PTC and NTC printed resistors could be used either alone or combined together within a Wheatstone bridge circuit, in order to increase the system's sensitivity. When tested alone, printed resistors exhibited a TCR of 0.05 C^{-1} and 0.006 C^{-1}, respectively, for PTC and NTC pastes, within the temperature range of 20–80 °C. When used together in a Wheatstone bridge configuration, the system reached a maximum sensitivity of 0.54 V/°C at a temperature of 60 °C (input voltage V_{in} was kept at 48 V). Finally, the authors demonstrated the possibility of transferring their fabrication technology into a large-area fabrication process by realising 12 × 12 matrices of devices on PEN foils (38 cm × 32 cm) for thermal mapping or temperature threshold detection.

Britton et al. [7] described a procedure to fabricate nanoparticulate silicon-based inks, starting by bulk silicon (either n-type or p-type doped) milled and reduced into thin nanoparticles powder (maximum nanoparticles diameter: 50 nm) which were subsequently suspended in ethanol; the addition of polymeric binders (such as cellulose acetate butyrate – CAB – or acrylic screen printing pastes) to the suspension was necessary to obtain the ideal viscosity for screen printing. These inks were utilised for the room temperature fabrication of thick film silicon-based resistors, screen printed on the top of low-temperature substrates such as paper; this technology was later patented [8]. These resistors are all screen printed: the silicon-based ink is printed on the top of interdigitated silver electrodes (length of electrodes: 16 mm, gap between electrodes: 0.25 mm), to obtain resistors of approximately 100 kΩ. These temperature sensors, tested between 20 and 60 °C, showed a negative temperature coefficient (NTC) with a beta value of 2000 ± 100 K. In 2010, PTS Sensors Ltd started the commercialisation of these sensors and very recently (March 2014) they have entered into a Purchase and Licence agreement with Thin Film Electronics ASA for the production of temperature-sensing smart labels where PTS printed resistors will be integrated within Thin Film Electronics printed radio-frequency (RF) circuits with near field communication functionality.

Infrared and light sensors

Radiation sensors are detectors able to interact with the electromagnetic radiation and produce an output signal as a response to