Biocompatible Inkjet Resistive Sensors for Biomedical Applications

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Abstract— **A resistive sensor for strain measurements that uses inkjet technology for biomedical applications has been studied, designed, manufactured and tested. Preliminary experimental results of a single sensor are shown and commented. The inkjet printing process is based on the emission through a nozzle of a material in liquid phase in fixed quantity, usually called ink, in the form of microscopic droplets contained in a cartridge. The emitted drop falls on a substrate, forming a pattern. The liquid solidification can occur through the solvent evaporation, chemical modifications or crystallization. Often a post-processing is required, such as thermal annealing or sintering. For the realization of the resistive sensor, a nanocrystalline silver ink was chosen. The substrate is Kapton and several studies demonstrate its biocompatibility as well. In this paper, a preliminary analysis of the material, its compatibility with the desired printer, the design considerations and finally the experimental results with the calculation of the Gauge Factor are shown. The research purpose is to study sensors, thin, flexible, inexpensive, and biocompatible for applications within the human body.**

Index Terms—**Inkjet printing, strain measurement, biomedical application, resistive sensor.**

I. INTRODUCTION

In recent years, printed electronics has grown rapidly. The printed electronics is a low-cost technology, characterized by a high volume in production. The main techniques and processes used in printed electronics are: screen printing technologies and inkjet printing. Screen printing technique consists in the deposition of a film of a few microns in thickness in a single step using a mask. Recently, the research group has analyzed the screen printing for biomedical applications [1,2] and it is observed that this is a method that has low resolution [1]. Otherwise, inkjet printing is a non-contact method in which small droplets of material are deposited on the substrate accurately ensuring high resolution in the fabrication of the track geometry and high flexibility of the shape of the deposition. This allows realizing different devices for different applications. In the literature, different examples of devices made with this technique are reported. Kang et al. [3] have realized some passive components in inkjet printing, such as resistors, capacitors and inductors. Using different type of ink, the authors have obtained different types of layer: dielectric, conductive and ferromagnetic with the aim to achieve passive components. Finally, the authors have designed and fabricated a low pass filter by printing an electrical RC circuit. In the inkjet technology the deposition process depends on different factors: substrate, ink and application. For example, the inkjet printing requires a low viscosity, so in many cases, additives are added to the ink so as to reduce its viscosity during the deposition process. In this way, the processes of sintering or annealing are employed to increase ink's stability and conductivity. Furthermore, weather and drying conditions are important and depend on the ink type. The inkjet printing is one of the most recent techniques in Electronics and it is growing fast; in the literature, several recent studies describe sensors or electronic components obtained by inkjet printing. For example, T. Öhlund et al. [4] deposited a nanoparticle silver ink on paper substrates commercially available with different compositions, in order to select or construct a paper substrate to optimize the electrical performance in electronic applications on paper. A. Chiolerio et al. [5] investigated the best process using the silver ink on a substrate of Kapton to achieve a chipless RFID (Radio Frequency Identification), varying the size of the step drop, the number of printed layers, the track size and the annealing process. The inks used for inkjet printing differ in the characteristics and storage methods. PEDOT:PSS (poly(3,4-ethylenedioxythiophene)) poly(styrenesulfonate) ink and silver nanoparticles are frequently used in printed electronics. J. Rausch et al. [6] tried to use PEDOT:PSS to realize a strain sensor, while B. Andò et al. [7] proposed a strain sensor based on silver ink for strain measurements. A humidity sensor [8] was fabricated in polymeric PET (polyethylene terephthalate) with silver ink. K. Crowley et al. [9] have detailed the manufacture and performance of a sensor for analysis of ammonia gas by using the deposition of inkjet printed film of polyaniline nanoparticles

This research proposes a preliminary study of low-cost, light, flexible and biocompatible sensors for medical devices, using a nanocrystalline silver ink (Aldrich-719048) deposited by inkjet printing. Target applications can be different; first of all these sensors can be used in wearable systems measuring different human parameters, such as hearth rate, respiration rate or movements [10, 11]. Furthermore, these sensors can be used in implantable systems inside the human body, in passive devices or connected to power harvesting systems [12]. The

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biocompatible material is an important aspect in the case of implantable medical devices. The device proposed in this paper is simply composed of Kapton substrate and silver-based dressing, both biocompatible as reported in the literature. A.P. Supp et al. [13] and R. Rustogi [14] tested the absence of cytotoxicity in-vivo. The Kapton biocompatibility is confirmed by Y. Sun et al. [15].

In this work we have used piezoelectric Drop-on-demand (DOD) printers normally used at home to print documents. They are very cheap and the process is very simple and doesn't require the controls of environmental parameters. The inkjet printing is a non-contact method. It consists on the deposition of small droplets in two possible ways: continuous (CIJ) or Drop-On-Demand (DOD). In the first case, the droplets are ejected constantly from a nozzle and then directed by an electrostatic field on the substrate. In DOD printer, the droplets are ejected using piezoelectric or thermal systems. Commercially, professional printers properly created to print electronic devices exist but they are 2 orders of magnitude more expensive than general-porpouse DOD printer destined for home use. To test the performance of these materials, different geometric patterns were printed. In particular, a sensor for medical devices was fabricated printing multilayers of the same ink. The printed sensor pattern is similar of the traditional strain gauge and the resistance response under stress and the temperature influence have been tested. In this work we wanted to study a low-cost technology to developed biomedical sensors for measuring the force in a particular direction: these sensors must be light and the substrate must be flexible to be suitable for any kind of surface. Because they interact with the human being they must be also biocompatible. The inkjet printing is suitable for this purpose. The pattern of the sensor we have decided to study is similar to a strain gauge, which changes its electrical resistance when it is stretched.

II. SENSOR DESCRIPTION

The equipment used for the development of the sensor consists simply of a commercial inkjet printer and a series of refillable cartridges. The selected printer is the Epson Stylus SX430W, a commercial printer. It has 4 separate cartridges with 128 nozzles for black and 42 nozzles for each color; it has a print resolution of 5760x1440 dpi and can print with different qualities. The printer driver decides the amount of ink that will be used depending on substrate, resolution and quality. The substrate chosen for the sensor is made of Kapton (25 um thickness). The used ink is based on silver nanoparticles, with size less than 150 nm, permitting the particles go through the nozzle. Compared to PEDOT:PSS, the silver ink is simpler to use and it causes nozzle obstruction less frequently. In this way, it's possible to use the cartridge until the silver emptying, guaranteeing a more reproducibility of performance. The viscosity is around 10 cps and the tension surface 30 DYC. The ink is 20% wt dispersion in ethanol and ethanediol (Table. I).

TABLE I. INK AND SUBSTRATE MAIN PROPERTIES.

Sigma Aldrich 719048	
Concentration	in ethanol and ethanediol, 20% wt.
Volume resistivity	5-30 μΩ-cm after annealing @ 150-300 °C
Particle size	<150 nm (DLS)
Surface tension	28.0-31.0 dynes/cm
Viscosity	10-13 cP
DuPont HN100	
Thickness	25 um
Thermal coefficient of linear expansion	20ppm/°C
Glass transition temperature	360°C
Shrinkage @ 150°C, after 30 min	0.17%

The strain gauges were designed with the classic serpentine structure (Fig. 1). After the printing of three superimposed layers by inkjet, the sensor has been subjected to annealing which consists in heating the sample at a temperature of 150 °C for 30 minutes. Then the sensor was contacted at its ends with copper wires using a conductive silver paste (DuPont 5028).

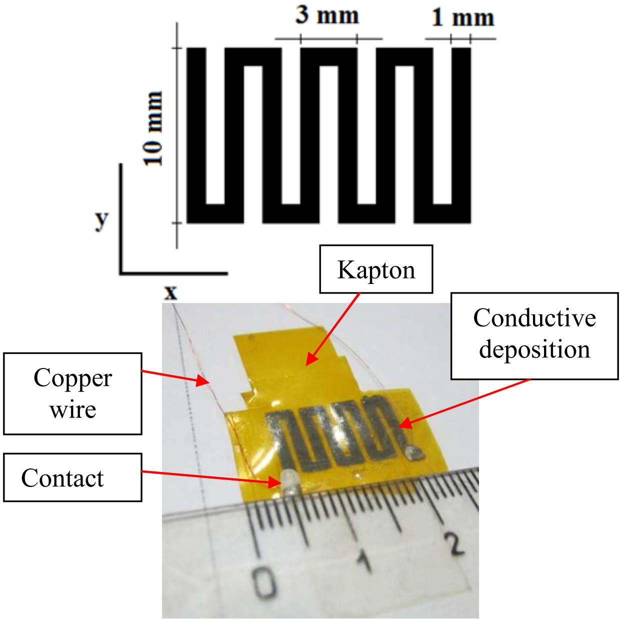

Fig. 1. Images of the realized strain gauge and dimensions.

In Fig. 1 a final device picture is reported and in Fig. 2 an enlargements of its track are shown. The pictures are obtained using an optical microscope at 50x and show the border of the track obtained by the inkjet printer with one printed layer, Fig. 2 (a), and two printed layer Fig. 2 (b). It is clear that after two depositions, the track is more uniform. The chosen pattern is comparable to a traditional strain gauge used for deformation measurements. As a traditional strain gauge, which is usually made of metallic foil, the sensor is fabricated printing a metallic layer, whereas, with respect to the printed strain gauges, conventional strain gauges are larger and are less suitable to be attached on curvilinear surfaces and to measure large deformations.

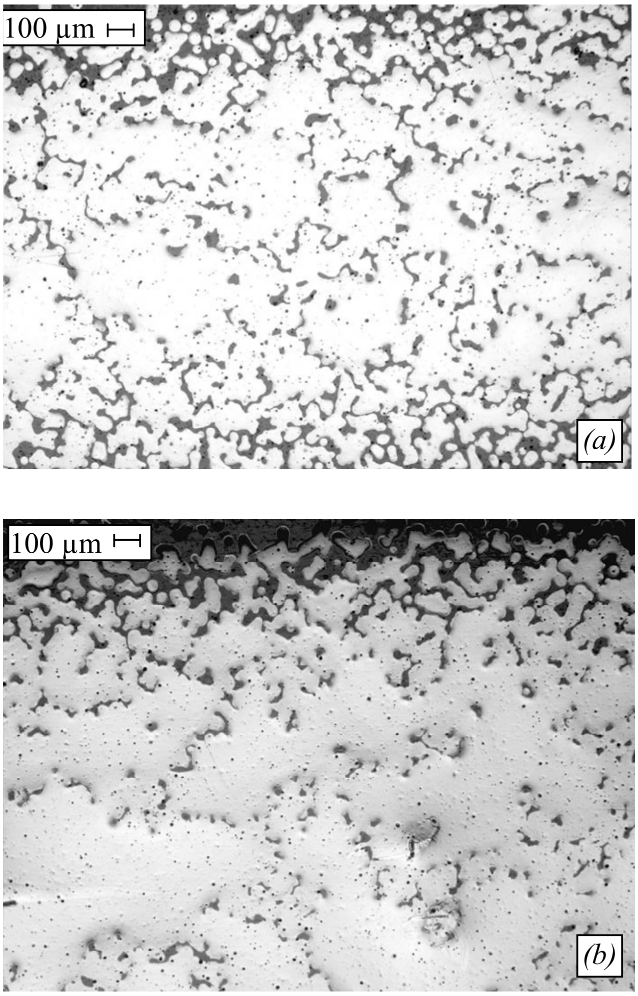

Fig. 2. Images of the realized depositions. (a) One printed layer; (b) two printed layers.

III. PRELIMINARY EXPERIMENTAL RESULTS

With the aim of analyzing the resistance obtainable by the deposition method, different conductors of rectangular shape having different length (from 2 mm to 25 mm), but equal width (3 mm) and thick (three layers of printing), were fabricated with the printing process described in the previous paragraph. The conductor resistances were measured with the 4-wire classical connection using a multimeter (HP34401A) and then the average value of the resistance was calculated, which is about 7.4 Ω / cm (Fig. 3). The measured data show good linearity and the calculated value is in agreement with that measured for the realized sensor (about 498 Ω). Tests were then performed to evaluate the temperature dependency. The thermal drift of the sensor at rest is obtained using a climatic chamber Perani UC 150/70. The measurements were carried out in conditions of constant humidity at 20% and varying the temperature from -20 ° C to 90 ° C, with a step of 5 °C (Fig. 4). The resistance variation due to temperature variation is almost linear and the trend is in accordance with expectations; it follows the classical behavior of metal conductors.

The TCR (Temperature Coefficient of Resistance) has been calculated with the following formula (1).

$$TCR_{\%} = \frac{1}{R_{\max}} \frac{\Delta R}{\Delta^{\circ} t} \% \qquad (1)$$

Where ΔR is the resistance variation in ohm and $\Delta^{\circ} t$ the temperature variation in celsius.

The sensitivity with respect to temperature is of 0.042% / °C. The strain gauge has been subjected to deformation by an experimental setup consisting of a micrometer screw (Fig. 5) and the corresponding resistance values were measured.

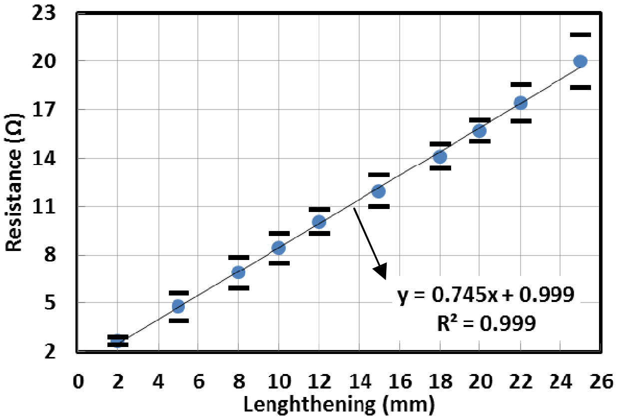

Fig. 3. Resistance values for different conductor lengths.

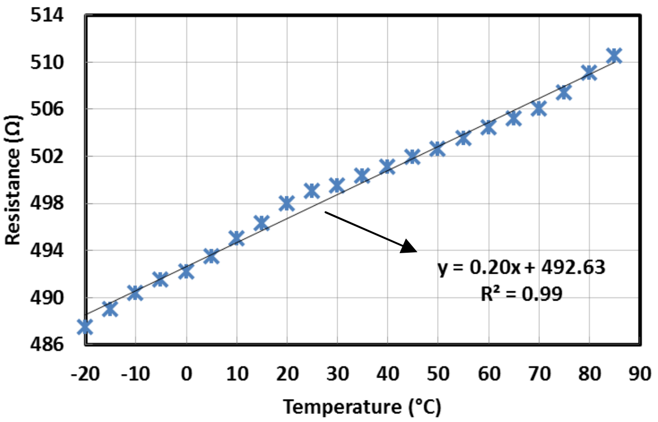

Fig. 4. Variation of the strain gage resistance vs. temperature.

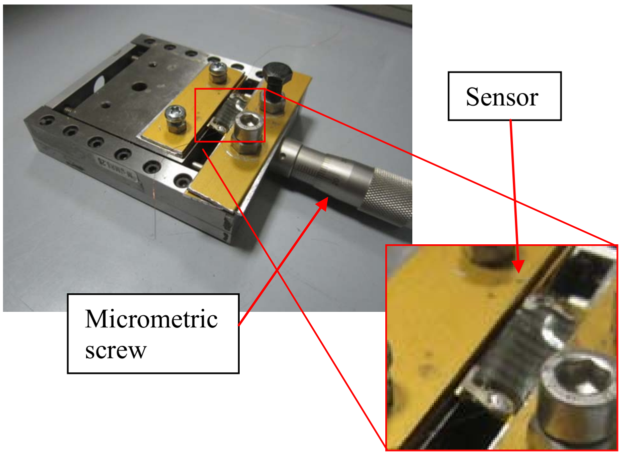

Fig. 5. Images of the realized strain gauge and dimensions.

The gauge has been gradually stretched along the direction of its y-axis with a pitch of 50 μm. The data relating to the calculation of the gauge factor are shown in the graph of Fig. 6.

The GF (Gauge Factor) has been calculated with the following formula (2).

$$GaugeFactor = \frac{\Delta R / R_0}{\Delta L / L_0} \qquad (2)$$

Where ΔR is the resistance variation and ΔL the length variation and L_0 and R_0 are length and resistance without strain.

The hysteresis has been calculated with the following formula (3).

$$H_{\%} = \frac{\Delta R_{\max}\big|_{\varepsilon}}{FSS}\% \qquad (3)$$

Where ΔR is the resistance variation, ε is the strain and FSS is the full-scale span. The measured data permit to calculate the gauge factor that is about 6.2 with a hysteresis of 36%. Conversely, the GF of the metallic strain gauges is about 2 and the GF of the semiconductor strain gauges is higher. Fig. 7 shows the resistance variation due to strain variation for a cycle. The data show a hysteresis of 36%. The research work has allowed us to realize a biocompatible resistive sensor with the inkjet printing technique. Further research work on different geometries for improving reproducibility and resolution is ongoing.

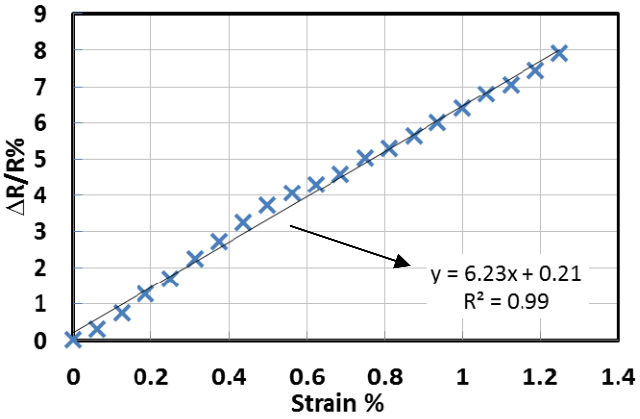

Fig. 6. Percentage change of the resistance vs. strain.

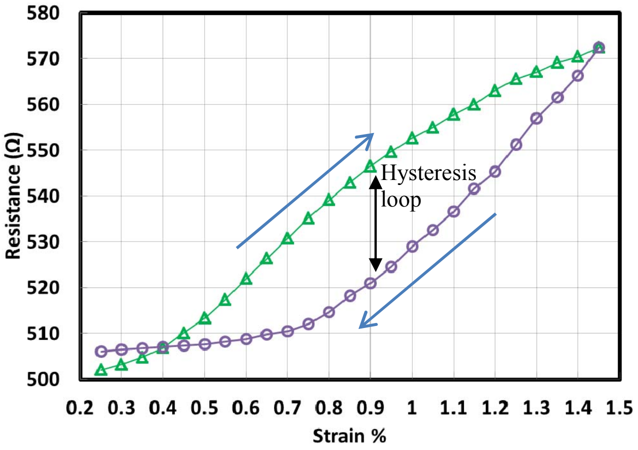

Fig. 7. Hysteresis loop measured at different strain values.

IV. CONCLUSIONS

In this paper, sensors realized through inkjet technology with commercial printers are described. We have studied the inkjet printing method for biomedical purposes using a conventional inkjet printer. In particular we have found a good solution to guarantee the correct adhesion and conduction of the silver ink on Kapton substrate. The adopted substrate is biocompatible. The preliminary experimental results show the behavior of the sensor that has been achieved. We established the number of printings of the same pattern to build a conduction path. The resistivity is constant all over the strip and the process is reproducible despite of the non-uniformity deposition at millimetric scale. Furthermore, some tests were carried out by varying the applied voltage and measuring the resistance and the results show a high gauge factor. The results of the temperature dependence are shown as well. An analysis of the values obtained experimentally is in progress. Experimental trials are underway to evaluate both different geometries and different deposition parameters. The technique developed for the sensor fabrication can be used for the design of devices for different biomedical applications, for example, in wearable systems for measuring different human parameters, such as heart rate, respiratory rate or movements. Furthermore, such sensors can be used in implantable systems within the human body, in passive devices or systems connected to power harvesters.

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