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Short communication

Temperature sensor realized by inkjet printing process on flexible substrate

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ABSTRACT

The objective of this study is to realize a printed and flexible temperature sensor to achieve surface temperature measurement of the human body. The sensor is a thermistor composed silver (Ag) deposited on a Polyimide substrate (Kapton HN). The meander was patterned by inkjet printing with a drop-on-demand Jetlab4 (Microfab Technologies Inc.). The resistance temperature coefficients have been studied in the temperature range of 20–60 °C with a range of voltage between 0 and 1 V. The stability versus time has also been measured without a sensor layer protection. The sensitive area of the sensor, silver lines width and the gap between the electrical conductors were, respectively 6.2 cm^2, 300 μm, 60 μm. The mean temperature sensor sensitivity found was $2.23 \times 10^{-3}\,°C^{-1}$. The results show a good linearity and less than 5% hysteresis in the extended measurement.

1. Introduction

Lately, research on the development and implementation of electronic components on flexible substrate has been grown: for example, flexible proximity sensors composed of a ZnO layer sandwiched between a flexible aluminum sheet and a nano silver top electrode layer [1], or inductive angular position sensor composed of meandering silver coils [2] were fully fabricated on a flexible substrates using inkjet technology.

Inkjet printing of silver nanoparticles was also used to developed Flexible biosensors [3] and flexible polymer humidity sensor [4] on different flexible substrates.

More recently [5] ozone gas sensors based on ZnO nanoparticles have been realized by standard photolithography and femtosecond laser ablation processes on flexible substrate with Ti/Pt interdigitated electrodes.

Flexible substrates were identified for manufacturing sensors with the following features: very low manufacturing costs, flexibility, lightweight, stretchability and large area applications compared to the silicon [6–8]. In printed electronics industry, the commonly flexible substrates used are mainly polyethylene terephthalate (PET), Polyethylene naphthalate (PEN) and polyimide (PI). The sensor fabrication on PET, PEN or PI can allow reducing the production costs due to the use of large area and low-cost substrates [9–11].

Different printing methods such as inkjet, screen, etching or flexography printing have attracted much attention. Recently inkjet printing has been a driving technology for the manufacturing of sensors on flexible substrate. This manufacturing technique provides a way for direct printing without the need of intermediate tools and contact with the substrate. Inkjet printing is an alternative to screen printing or flexography [12–14] because this is a digital and additive technology.

Among the sensing technologies, the temperature sensor is probably the most widely employed [15]. In the state of the art of temperature sensors on flexible substrate, the most common reported temperature sensors are the resistive temperature detectors (RTDs). In these kinds of sensors, change in resistance is observed upon varying the temperature. They have typical characteristics of by high accuracy, short response time, small volume and simple fabrication [16]. A good sensitivity, linearity and signal level simplify the design of the sensor interface [17].

Bielska et al. [18] have developed a sensor dedicated to human body temperature measurements. The temperature sensor is based on polymer film deposited by the fine-mesh screen-printing technique on Kapton substrate ensuring good adaptation to textile applications. Sensor resistance is measured from 30 to 42 °C with a relatively linear response.

Briand et al. [19] used silver ink-jet printing in combination with thick Ni electroplating to develop flexible resistive temperature sensors on PET foils. The resistive temperature detectors exhibited good linearity, in the range of −10 to 140 °C, with a

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temperature coefficient of resistance for the electroplated lines of about $4.27 \times 10^{-3}\,^{\circ}C^{-1}$.

Meier et al. [20] report on the investigation of printed PEDOT:PSS films for temperature sensing devices. Gravure printing with the advantage of low cost production was used to prepare thin films on a flexible foil substrate. The suitability of these printed films for an application as temperature sensors was studied by measuring the change of resistance under thermal cycling. Due to a drift of the resistance, which depends on time, temperature and samples, the usage for direct measurement of temperature is not possible.

In this paper, we report the fabrication and characterization of a temperature sensor printed by an inkjet process on a flexible substrate intended for medical applications. The novelty of our work compared to literature is the fact that the sensor must be supplied under a bias voltage of 1 V and require the lowest possible current. It means the sensor must have the highest nominal resistance. The printed sensor will be integrated into a patch with heavy constraint in design (patch dimensions, sensor nominal resistance, very low bias current, adjustment electronics, interconnection, encapsulation, ...). The conductive track must be as long as possible in a constrained size (2 cm × 3 cm) while the thickness, width and spacing of the track are set by the inkjet process. This required a specific work in order to get a stable inkjet process and patterns without defects (short-circuits or open-circuits).

The inkjet printing parameters were optimized to have a consistent droplet formation and well defined patterns. The electrical properties of the designed temperature sensor were examined. The results were discussed and compared to the existing state of the art of the printed temperature sensors on flexible substrate.

2. Experimental procedure

2.1. Substrate material and ink preparation

The standard Kapton® type HN with a thickness of 125 μm was used in this work. Kapton® type HN was used successfully in applications at temperature between −269 and 400 °C [21]. The high temperature stability makes it a good choice in printed electronics application.

Glass was used as a reference for some experiments. Although these samples were not meant to investigate a change in resistance due to a temperature, they did prove useful for the general electrical characterization of the printed thin film resistive temperature sensor. Standard microscope slides were taken as substrates in this case.

Prior to the deposition, cleaning of Kapton® substrates was done to completely remove any residual grease or particles and organic contaminates on the surface. The samples were stored in a closed box to protect them from dust until deposition experimental setup is ready to print the intended pattern.

An organic silver complex compound (TEC-IJ-010 from Inktec Co. Ltd., South Korea) was used as the functional ink to generate designed pattern on cleaned Kapton and glass. The viscosity of the ink was 9–15 cps at 25 °C. The silver ink was sonicated for 10 min to avoid nozzle clogging, increase suspension stability and remove large particles.

2.2. Inkjet process

A customized direct-write inkjet system JetLab® 4 (MicroFab Technologies) was used to deposit silver complex ink onto the Kapton substrates. The system consisted of a pneumatic controller, drop ejection drive electronics (JetDriveTM III), JetLab® software with waveform amplifier, a drop visualization system, and precision *X*, *Y*, *Z* motion control. The dispensing device (print head assembly, MJ-AL-01-050) consists of a glass capillary tube, with a 50 μm diameter orifice coupled with a piezoelectric element.

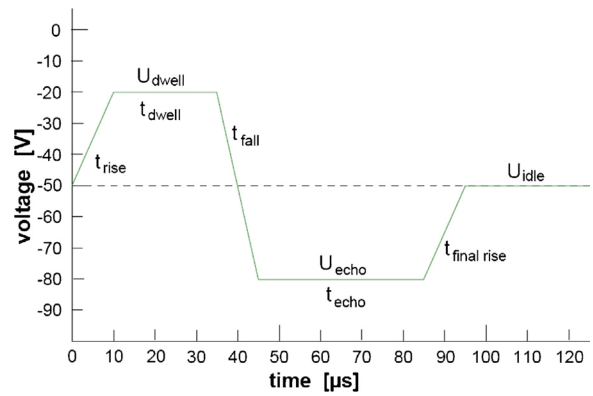

Fig. 1. Pulse waveform of the JetLab® interface.

Determining optimal jetting parameters requires trial-and-error. Using the JetLab® interface, the appropriate pulse waveform for consistent droplet formation was characterized by manipulating the rise, dwell, and fall times (see Fig. 1), as well as the voltage and pressure.

These pressure oscillations propagate through the printing fluid in the tube, resulting in the ejection of microdroplets. Stable droplet ejection is achieved by visually observing expelled microdroplets and adjusting voltage pulse parameters and capillary fluid backfill pressure to create an "ideal" drop. Drops are visualized using synchronized strobe illumination and a charged coupled device (CCD) camera. Fig. 2 shows the droplet formation sequence from the nozzle of the inkjet printer.

Printing was performed at a jetting frequency of 400 Hz with a droplet velocity of ~4.5 m/s. It was observed that, droplet velocities between 4 and 6 m/s are ideal for printing homogeneous patterns. Droplet velocities less than 1 m/s may result in inaccurate drop placement. Thus, conditions that provide the highest drop velocity without satellite droplet formation are desired [22]. The motion control component and pattern monitor allowed for precise control of the length, width, and thickness of the coating by adjusting the pitch distances between droplets. In order to obtain smooth conductive patterns with high resolution by ink-jet printing, various printing conditions, including the step (inter-spacing distance between dots) and drop diameter (sizes), the printing speed which is related with frequency, and the driving wave form was also optimized to obtain smooth and homogeneous coating layers.

2.3. Thermal curing

The resulting printed silver lines (see Fig. 3) on the cleaned Kapton substrate was first heated to 130 °C on a hot plate, and held at this temperature for 10 min to convert the deposited silver nanoparticles into a conductive silver film.

This consists of two steps thermal curing procedure recommended by the ink supplier: a drying step to remove solvent and obtain a continuous structure.

Then a second sintering at 150 °C for 30 min was done in a classical oven to obtain high conductive structure.

The Electrical functionality of the printed pattern was measured using a 4-point probes method after thermal curing. And a sheet-resistance and a resistivity of 0.163 Ω/sq and 5.9 μΩ cm, respectively are obtained. These results are similar to those values reported in the datasheet of the ink supplier.