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Fabrication of 3D Temperature Sensor Using Magnetostrictive Inkjet Printhead

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Abstract. *Recently, the three-dimensional (3D) printing technique has attracted much attention for creating objects of arbitrary shape and manufacturing. For the first time, in this work, we present the fabrication of an inkjet printed low-cost 3D temperature sensor on a 3D-shaped thermoplastic substrate suitable for packaging, flexible electronics, and other printed applications. The design, fabrication, and testing of a 3D printed temperature sensor are presented. The sensor pattern is designed using a computer-aided design program and fabricated by drop-on-demand inkjet printing using a magnetostrictive inkjet printhead at room temperature. The sensor pattern is printed using commercially available conductive silver nanoparticle ink. A moving speed of 90 mm/min is chosen to print the sensor pattern. The inkjet printed temperature sensor is demonstrated, and it is characterized by good electrical properties, exhibiting good sensitivity and linearity. The results indicate that 3D inkjet printing technology may have great potential for applications in sensor fabrication.* © *2020 Society for Imaging Science and Technology.*
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1. INTRODUCTION

The downsizing of electronic devices is one of the fields of research that has attracted continuous interest up to the present time. Current electronic devices have a structure comprising a plastic housing and a printed circuit board (PCB). However, with the ongoing interest in downsizing electronic devices, existing PCBs face the constraints of wasted space when combined with the housing of electronic devices. To resolve this issue, three-dimensional molded interconnect device (3D-MID) technology, which first appeared in the 1980s, has gained a lot of attention because it can reduce the wasted space of PCBs and housings [1]. The 3D-MID technology allows the addition of electronic functionality on three-dimensional (3D) objects without the use of traditional cabling, thereby effectively producing more attractive products that are especially suitable for automotive electronic applications [2, 3]. On the other hand, 3D-MID has a high production cost because an additional mold is required for metal wiring. Furthermore, there is a concern that the waste liquid used in the plating process may adversely affect the environment.

Considering these constraints, various methods for electronic wiring on the surface of 3D objects without plating have been studied. The use of aerosol is considered the most promising alternative [4, 5]. But direct molding techniques for 3D objects, such as 3D-MID and aerosol jet deposition, have limitations on cost or processing speed.

Recently, new printing methods that can be applied to 3D objects have been proposed: screen–pad printing, gravure offset printing, and inkjet printing. Among them, inkjet printing has several advantages such as high ink use efficiency and non-contact, digital on-demand process nature [6]. Here, we introduce “magnetostrictive inkjet” (MagJet) printing technology, developed by our laboratory, which utilizes a magnetostrictive material as an actuating mechanism [7]. The magnetostrictive material used is Terfenol-D, which changes its dimensions according to the magnetic field. Yoo et al. developed and characterized the first two-dimensional (2D) magnetostrictive inkjet head [7, 8].

Among the sensing technologies, the temperature sensor is probably the most widely employed [9]. From the state of the art in temperature sensors on flexible substrates, the most commonly reported temperature sensors are resistive temperature detectors. In these kinds of sensors, a change in resistance is observed with variation in temperature. They have typical characteristics such as high accuracy, short response time, small volume, and simple fabrication [10]. Good sensitivity, linearity, and signal level simplify the design of the sensor interface [11].

In this article, we present the fabrication and characterization of an inkjet printed low-cost 3D temperature sensor on a 3D-shaped thermoplastic substrate using a magnetostrictive inkjet printhead. We fabricate the temperature sensor by three different dimensions to study the effect of size. The subject of this study is the investigation of factors that influence temperature measurement via the measurement of the corresponding resistance with varying temperature in the range 30 ° C–100 ° C for an inkjet printed low-cost 3D temperature sensor.

2. EXPERIMENTAL SETUP

2.1 *Materials and Methods*

The substrate used to print the temperature sensor is a 3D-shaped thermoplastic, polyether ether ketone (PEEK). Its thermal properties are sufficient for the PEEK substrate to withstand the sintering conditions under which the ink is used. The melting point and the short-term continuous

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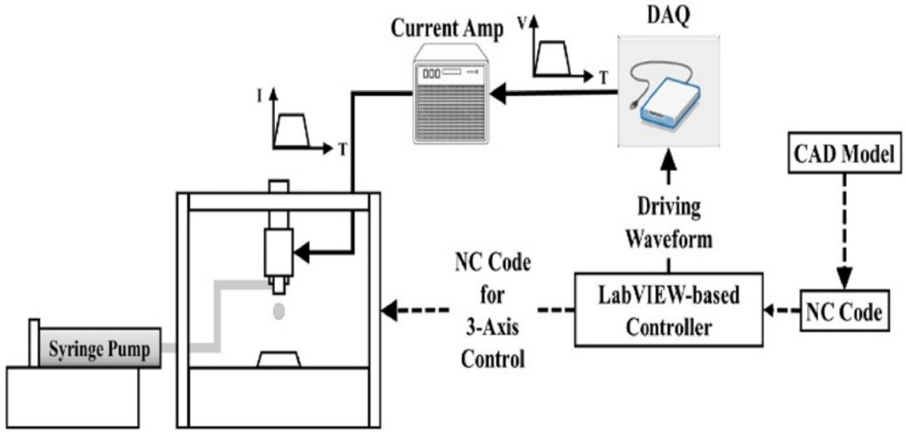

Figure 1. Schematic for experimental setup.

operating temperature of the PEEK substrate are 340 and 310 ° C, respectively. The shape of this substrate is changed from 2D to 3D at an angle of inclination 10°. An organic silver complex compound is used as the functional ink to generate the designed pattern on the 3D-shaped thermoplastic substrate. The functional conductive silver nanoparticle ink is purchased from InkTec (TEC-IJ-010, InkTec Co., Ltd, Korea). The ink contains 15 wt% of silver. The ink's surface tension and viscosity are approximately 30–32 dyne/cm and 9–15 cPs, respectively, and it requires a sintering temperature of 120–150 ° C as per the supplier specification.

A magnetostrictive inkjet printing system (MagJet) developed in the laboratory is used to deposit silver nanoparticle ink onto the thermoplastic PEEK substrate. The system consists of a 3D moving magnetostrictive inkjet printhead, a droplet formation monitoring system, a steady stage, and a LabVIEW-based control system integrated with the UCCNC software as shown in Figure 1. The entire system is computer-controlled. The diameter of the nozzle is 200 μm. A square-shaped driving waveform is set with 10 μs as the ejection time, 300 μs as the holding time, and 10 μs as the breaking time. The jetting frequency of the ink is 5 Hz; the continuous flow rate of the ink is approximately 5 μL/min. A moving speed of 90 mm/min is selected from several experiments to print the temperature sensor patterns.

Figure 2 shows the schematic process for the printing of a 3D temperature sensor on the PEEK substrate. The process of printing the 3D temperature sensor on the 3D-shaped substrate starts with the creation of a 3D model using computer-aided design (CAD) software. Moreover, a CAD program is used to generate a 3D temperature sensor model with different sizes on a 3D substrate. Then, an NC code for the temperature sensor model is generated through a CAM system, which is shown in Fig. 2.

The schematics and photos of 3D printed temperature sensors of different sizes are shown in Figures 3 and 4. The meander-shaped sensor patterns are printed with five lines, and the distances between two lines are 2 mm, 3 mm, and 4 mm. The patterns are named 2 mm, 3 mm, and 4 mm, respectively. The average width of the lines is calculated as 620 ± 20 μm. The average spaces between two lines after printing for 2 mm, 3 mm, and 4 mm are 1.21 ± 0.3 mm, 2.23 ± 0.3 mm, and 3.25 ± 0.3 mm, respectively.

2.2 *Measurement Protocols*

Two electrodes are printed at the end of mender patterns. The size of the electrodes is 5 × 5 mm^2. Copper wires are connected to the electrodes using conductive epoxy and then dried at room temperature overnight. For evaluating the temperature response, the printed sensor is placed on the digital hot plate with easy-to-use controls. A Fluke digital multimeter is used for resistance measurement from temperature sensors. The temperature is increased by 10 ° C from 30 ° C to 100 ° C. After each increment, the temperature is maintained constant for 5 min. Then the resultant values are recorded.

3. RESULTS AND DISCUSSION

In general, the electrical resistance of conductive materials is dependent on the temperature. In a certain range and for a large variety of materials, the change in resistance can be approximated linearly as a function of the temperature $R(t)$ as described in Eq. (1) [12]:

$$R(t) = R_0.[1 + \alpha.(t - t_0)]. \tag{1}$$

Here, R_0 equals the resistance at a certain defined temperature t_0 (commonly defined as $t_0 = 25°$ C or $t_0 = 0°$ C). The material-dependent constant α corresponds to the temperature coefficient of resistivity (TCR). For metals, such as silver, the TCR is positive, resulting in increasing resistance with rising temperature. This fundamental principle is utilized for sensor fabrication within the scope of this work [12].

Figure 5 shows the relationship between the resistance and the input temperature of silver-based temperature sensors of different dimensions. The observed resistance

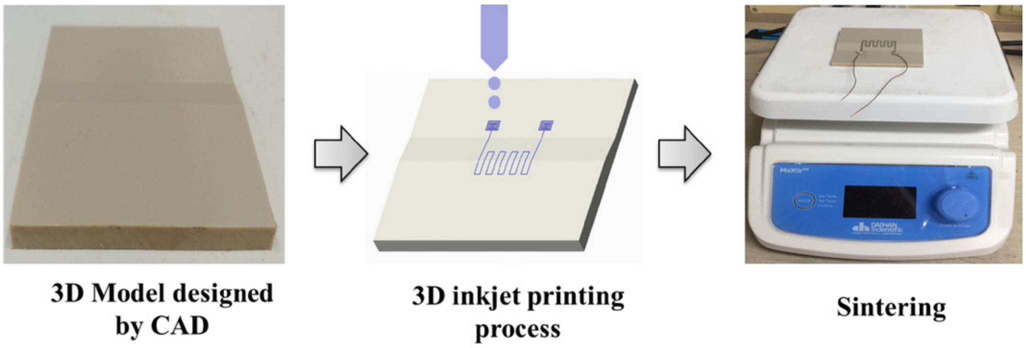

Figure 2. Schematics of fabrication process for the printed temperature sensor.

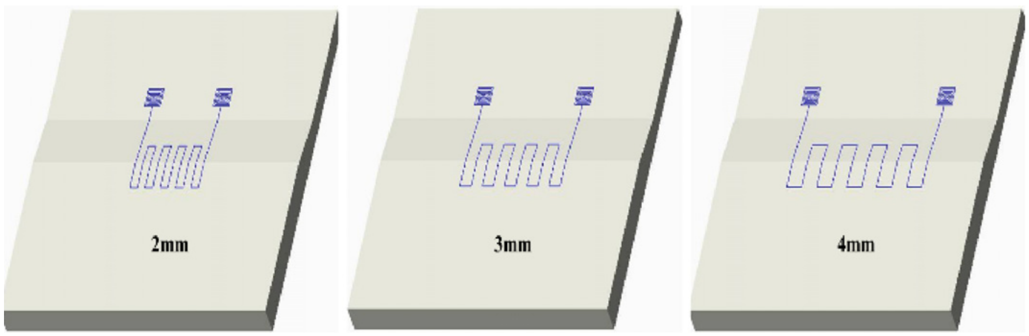

Figure 3. Schematics of 3D printed temperature sensors.

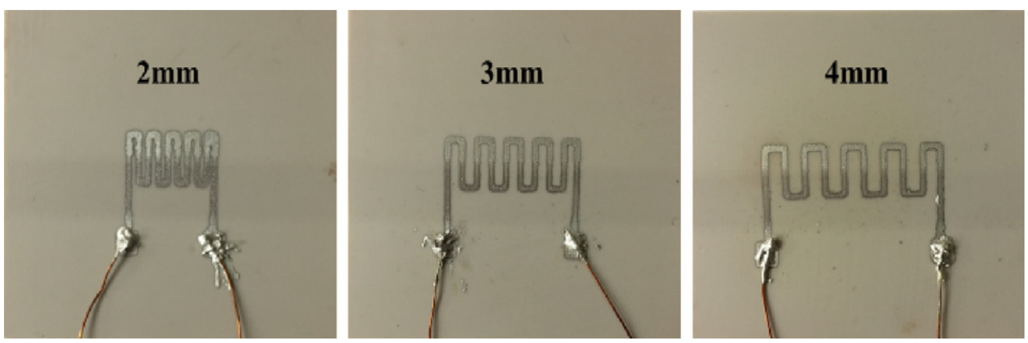

Figure 4. Photos of 3D printed temperature sensors.

of the sensor increases linearly with increase in input temperature for the specified ranges. The curves show a clear increase in sensor resistance with increasing temperature. The sensor of size 2 mm shows a linear increase in resistance from 100.6 Ω to 113.9 Ω for input temperatures from 30 ° C to 100 ° C. It works on the principle of resistance temperature detector. The temperature coefficient of resistance is $2.101 \times 10^{-3}\ C^{-1}$ in ascending order of measurement (Fig. 5(a)). The temperature sensor of size 3 mm shows a linear increase in resistance from 80.5 Ω to 84.9 Ω for input temperatures from 30 ° C to 70 ° C and non-linear behavior in the temperature range from 80 ° C to 100 ° C. The temperature coefficient of resistance is $1.691 \times 10^{-3}\ C^{-1}$ in ascending order of measurement (Fig. 5(b)). The temperature sensor of size 4 mm exhibits a linear increase in resistance from 63.5 Ω to 67.7 Ω for input temperatures from 30 ° C to 70 ° C and non-linear behavior in the temperature range from 80 ° C to 100 ° C. The temperature coefficient of this sensor is $1.645 \times 10^{-3}\ C^{-1}$ in ascending order of measurement (Fig. 5(c)).

Figure 6 shows that all the 3D printed temperature sensors exhibit the same behavior in ascending and in descending order of measurement; but in descending order, the resistance decreases slightly. Fig. 6 shows the comparative results of the 3D printed temperature sensors of size 2 mm, 3 mm, and 4 mm in ascending order of measurement. The temperature sensor of size 2 mm shows a high change in resistance and higher sensitivity than the sensors of size 3 mm and 4 mm, which may be due to the smaller size of the printed area.

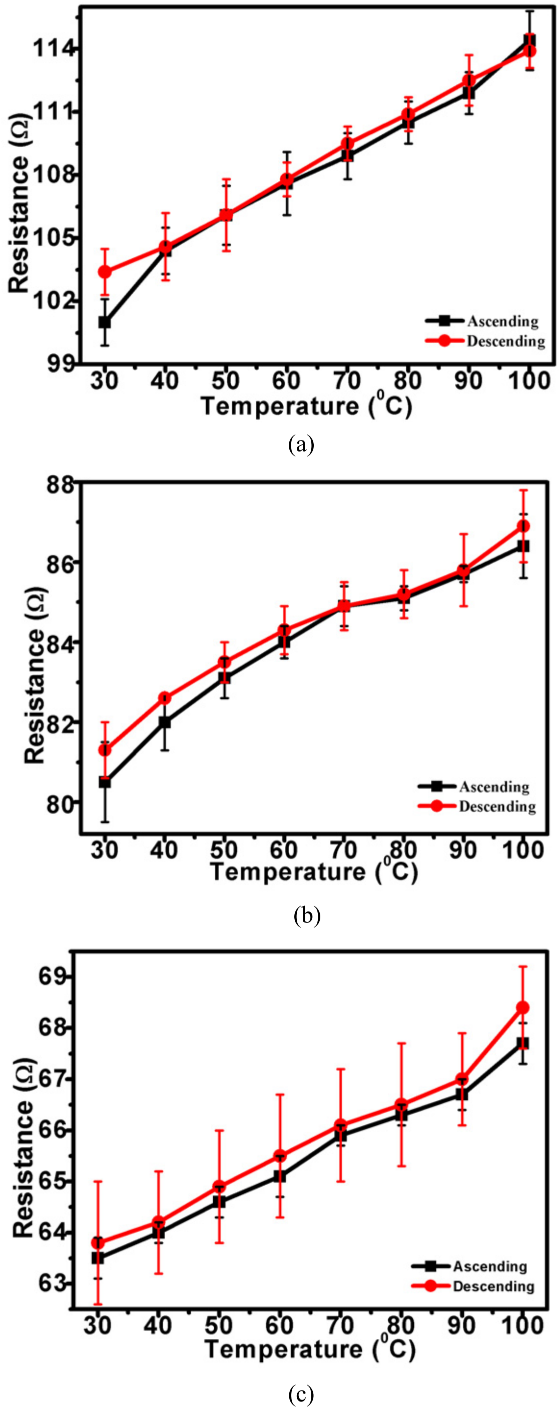

Figure 5. Temperature response of printed temperature sensors in ascending and in descending order: (a) 2 mm, (b) 3 mm, and (c) 4 mm.

4. CONCLUSIONS

In this study, positive temperature coefficient thermistor characteristics of 3D printed silver temperature sensors were investigated. The 3D temperature sensors of different sizes were inkjet printed on a PEEK substrate using a magnetostrictive inkjet printhead. The resistances of the printed temperature sensors were stabilized by thermal treatment at 150° C for 30 min. The 3D printed temperature

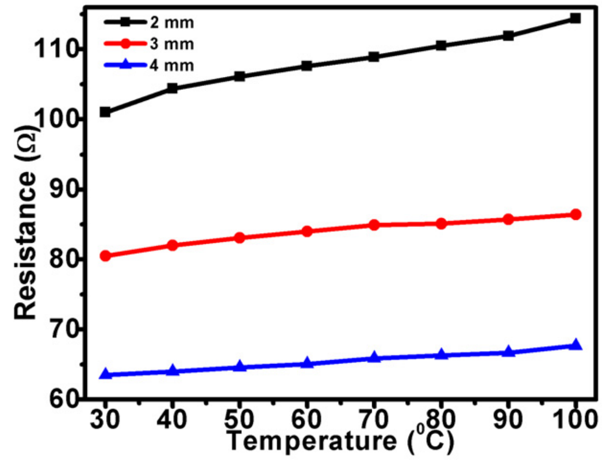

Figure 6. Temperature response of the printed temperature sensor in ascending order.

sensors of size 2 mm showed a linear change in resistance for a linear change in temperature and sensors of size 3 mm and 4 mm showed a linear change in resistance from temperatures 30° C to 70° C. The temperature coefficient values were 2.101 $\times$ 10^{-3} C^{-1}, 1.691 $\times$ 10^{-3} C^{-1}, and 1.645 $\times$ 10^{-3} C^{-1} for 2 mm, 3 mm, and 4 mm in ascending order of measurement, respectively. The sensor of size 2 mm showed a high change in resistance with input temperature; the sensitivity was also higher than the 3 mm and 4 mm size temperature sensors. To improve the stability and the performance, the sensors should be built in smaller size, which should be maintained in the following stages of the process.

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