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Fabrication and Characterization of Inkjet Printed Flexible Fractal-type Temperature Sensor

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Abstract. In the present research, we have presented the fabrication and characterization of inkjet printed temperature sensor. The sensor was designed as a Sierpinski curve of width 300 µm and 9, 27 and 81 fractals. The sensors were printed with an inkjet printer on Kapton, a thermally stable flexible substrate using silver nanoparticles based ink. The width of the printed sensor was 318 µm ± 2 µm as measured by profiler. The elemental analysis of printed sensors confirmed the presence of 98 wt% of silver nanoparticles. The electrical resistance of the sensors was measured at temperature (30-100) °C and results indicated the linear relation of resistance with temperature. The performances of Sierpinski curves were compared by measuring sensitivity and temperature coefficient. Higher sensitivity and temperature coefficient of resistance is 0.3760 (Ω/°C) and 0.009 ($°C^{-1}$) for the sensor with 81 fractals. These fractal-based sensors on flexible substrate can find promising application in on-body health sensors.

Keywords: Fractal Sierpinski, flexible sensor, electrical resistance

Introduction

Wearable sensor technology are gaining popularity and have a wide range of application in personal medical care [1]. They offer mechanical robustness, reusability, and comfort when compared to typical rigid sensors. The qualities required by flexible sensors differ depending on the application [2]. In case of wearable temperature sensors, the main purpose is to measure the continuous body temperature in direct contact with skin. Flexible temperature sensors are gaining significant interest in applications of electronic skin. These sensors have also been explored together with different sensing devices for the improvement of industrial and social robots [3],[4].

Temperature sensing is a crucial function of human body which indicates the body's metabolism. It will have an impact on practically all physiological functions in the body [5]. For decades, any variation in body temperature has been considered as a sign of illness. A normal temperature of body does not indicate that a person is healthy; nonetheless, a person may be unwell if the body temperature range is exceeding or reduced.

The average human body temperature is between 37 to 37.5 °C [6]. Skin temperature is often easily monitored by hard temperature transducers such as thermometers. The basic problem, however, is the employment of these rigid sensors in an enclosed environment (such as within garments or prosthetic parts) where pressure is generated against the skin. Additionally, since thermometers cannot be easily positioned under the arm as needed, this approach is not appropriate for children. For accurate temperature measurement, it is preferable to have a direct contact of sensor with human body. Traditional thermometers, on the other hand, cannot make conformal contact with uneven surfaces. To overcome this problem, temperature sensors should be flexible, biocompatible, lightweight, robust, and non-irritating to skin surface [7].

Many physical parameters depend on temperature such as, vapor pressure, change in volume expansion and resistance. As a result, temperature-related physical stimuli are incorporated in the development of temperature sensors. The temperature is determined from modeling, based on the measurement principle. The most common temperature sensors are thermistors, thermocouples and resistance temperature detectors. Different methods have been described on the fabrication of flexible sensors to detect the temperature. The printing of temperature sensitive materials on flexible substrates is one of those approaches [8].

Printed techniques have gained a lot of interest in the development of wearable and flexible electronics. Wearable sensors are fabricated using a variety of processes, including inkjet [9], screen [10] and gravure printing [11]. The present research focuses on silver nanoparticles-based inkjet printing. With this technology, direct printing is possible without the use of additional processes like lithography and etching. The functionality of the printed temperature sensor was investigated by testing it to temperatures ranging from ambient temperature to 100 °C. The sensor was designed as Sierpinski space filling curve. The curve path length is optimized by measuring the temperature coefficient of resistance (TCR) and sensitivity.

Materials and Methods

Design of temperature sensor

The model tested for temperature sensor was in the geometrical shape of the Sierpinski fractal. The width of the conductive path was chosen to be 300µm. The advantage of using a fractal shape is that, within the same 2D space, the length of the printed conductive path can be increased by incorporating higher order fractals. It is expected for the resistance of the resistive structure to increase with the increase of the length of the conductive path for fixed width of the conductive path. At the same time for same length of the path, the resistance increases with the decrease of the width. Use of Sierpinski fractal gives us the flexibility to choose a reference resistance, relative to which the fractional resistive change proportional to temperature is seen to be maximum. This, in turn, means that the temperature sensitivity, $\Delta R/\Delta T$, can be maximized.

The printing surface had an area of 24.3 mm × 24.3 mm, where 24.3 mm has been chosen because of the fact that it is a power of 3 multiplied by 0.1 mm, and the printed model's complexity rises each time by 3. With the goal of increasing the length of the path, but staying within the border of the mentioned surface, the method of Sierpinski tiling arrowhead was applied as presented in Figure 1.

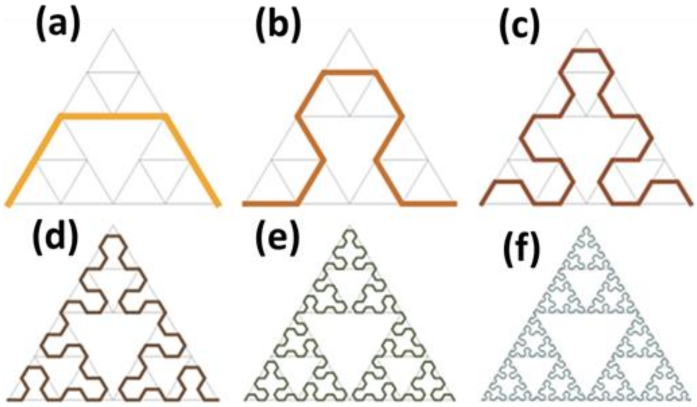

Fig. 1. Sierpinski tiling arrowhead; Iterations from 1 to 6

The higher limit for choosing the complexities of the model was the printing surface and the success of the printed structure, on the other hand, the lower limit is defined by the low resistance of the printed structure. With that in mind, the structures chosen for printing are the ones with the double, triple and quadruple iterations (in Figure 1, they are labaled with b, c and d.

Materials

In the present research, the commercially available SmartInk S-CS01130 conductive ink was purchased from Sigma Aldrich to print the temperature sensor design on flexible substrate. The substrate used was Kapton, a polyimide film with a thickness of 125 µm.

Inkjet Printing of Temperature Sensor

The Sierpinski fractal sensor was printed using the inkjet printing technology. The Dimatix DMP 3000 printer is used to print. According to the data sheet provided by company, the silver nanoparticle ink was sonicated for 15 min to avoid any agglomeration. About 3 mL of ink injected into cartridge and placed in the static state for approximately 30 min. The Sierpinski temperature sensor was designed using AutoCAD software and converted to desired pattern file (. ptn) using the pattern Editor (Bitmap images) on the DMP program. The number of printing layers, drop spacing and image resolution were set in accordance with design requirement.

Resistance measurement with Temperature

The change in resistance of printed sensor was measured between (30-100) °C with the increment of 5 °C. The sensor was place on the hotplate and connected with digital multimeter to record the change in resistance with respect to temperature. Figure 2 depicts the experimental setup.

Fig. 2. Experimental setup for measuring the resistance of the sensor with increasing of the temperature

Printed Sensor surface characterization

The morphology of printed temperature sensor was performed by Hitachi TM3000 tabletop scanning electron microscope. 3D Optical Profilometer (Huvitz BioImager® HRM-300) with Huvitz microscope and Panasis software was used to analyze the surface of printed sensor.

Results and Discussion

Surface Morphology of Printed Sensor

The printed sensor SEM image is shown in Figure 3(a), whereas elemental analysis, EDX of printed image is presented in Figure 3(b). The EDX shows the presence of silver nanoparticles is 98 wt%. The width of the printed Sierpinski structure was 318 µm ± 2 µm as showed by profiler image in Figure 3(c).

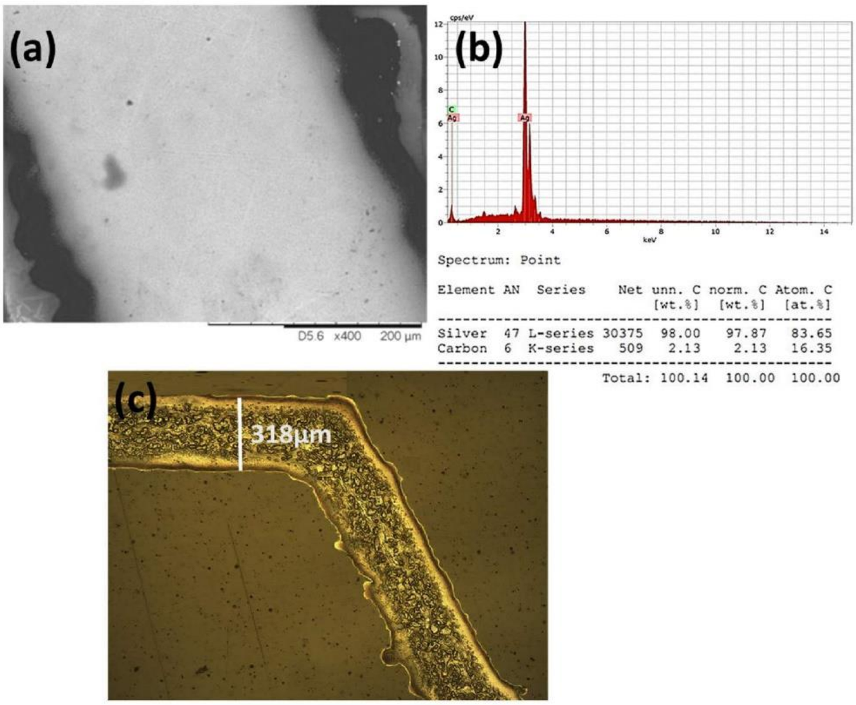

Fig. 3. Inkjet printed lines (a) SEM image, (b) EDS, and (c) profiler thickness of printed Sierpinski structure

Design optimization

The printed structures of width 300µm are shown in Figure 4.

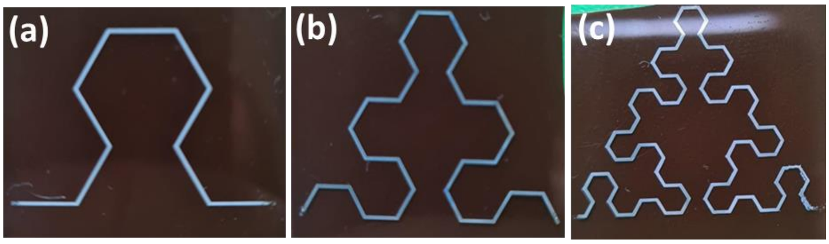

Fig. 4. Printed Sierpinski structures of sensor with length (a) 54 mm, K_03_9, (b) 108 mm, K_03_27, (c) 218.7 mm, K_03_81

K_03_09 represents the Kapton substrate (K), 300µm width and 9 fractals, K_03_027 and K_03_81 shows the 27 and 81 fractals, respectively.

To optimize the sensor design, the experiments were done, where the resistance was measured in the temperature range from 30 °C to 100 °C with the increment of 5 °C.

After the hotplate heated up, before measuring the resistance there was a time window of around 3 min, so that the sample would heat up. The 3minute time was set to have a stable temperature of hot plate. The hot plate and sensor temperature was monitored by infrared camera for accuracy of temperature. (Heat conductivity is high in Kapton and silver, so even 3 min were enough). The resistance changes with temperature for each printed sensor are presented in Figure 5, and linear regression has been applied.

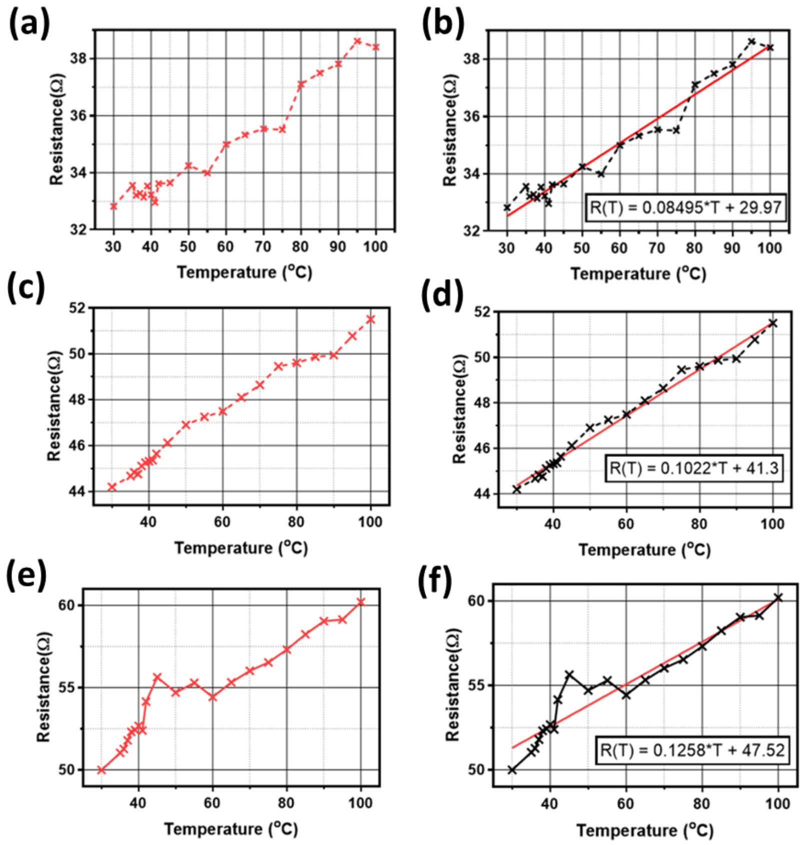

Fig. 5. Resistance change with temperature for printed structures (a) K_03_09 (b) model equation of K_03_09 (c) K_03_27 (d) model equation of K_03_09 (e) K_03_81 (f) model equation of K_03_81

The increase in resistance with temperature is linear which shows the positive temperature coefficient of resistance (TCR) value of the printed material.

Temperature coefficient and sensitivity

From the graphs plotted in the previous section, sensitivity and temperature coefficients of the printed structures have been calculated to optimize the design. The temperature coefficient of resistance (TCR, α is a vital parameter to evaluate sensitivity of the resistance based temperature sensing elements. The high TCR value confirms high sensitivity [12]. It is defined by the following expression:

$$\alpha = \frac{1}{R_0}\frac{\Delta R}{\Delta T} \tag{1}$$

Whereas sensitivities of the printed sensors are calculated using the following equation:

$$S = \frac{R_{max} - R_{min}}{T_{max} - T_{min}} \tag{2}$$

R_{max} is the resistance at maximum temperature which is 100 °C and R_{min} is the resistance value at minimum temperature which is 30 °C. T_{max} and T_{min} are maximum and minimum temperatures, in the studied temperature range.

The calculated values of TCR and sensitivities for the printed sensors are presented in Table 1.

Table 1. The TCR and sensitivity of printed sensors

Sample	α (°C^{-1})	Sensitivity (Ω/°C)
K_03_9	0.001	0.0546
K_03_27	0.003	0.1386
K_03_81	0.009	0.3760

The sensitivity of sensor depends on the path length if external pressure is constant. As mentioned in section 2.1, Sierpinski fractals can maximize sensitivity of the temperature sensor by maximizing the fractional resistive change proportional to the temperature. Hence, the Seirpinski sensor K_03_081 has higher α (0.009 °C^{-1}) and sensitivity (0.3760 Ω/°C) which proves the effect of fractals number on the sensor's sensitivity.

Conclusions

In the present research, we have fabricated inkjet printed Seirpinski fractal temperature sensors. The sensor fractals are optimized by measuring the sensitivity and temperature coefficient of resistance for the temperature range (30-100) °C. The sensitivity of K_03_81 was highest and equal to 0.3760 as compared to other two sensors, which shows that, for same width of the strip, longer length achieved through fractals will have higher sensitivity, where fractals ensure increasing length within a fixed area. It proves that by keeping the width constant, fractal numbers effect the sensitivity of the sensor. In, our future research, we will perform repeatability test for the optimized sensor and also test it for some biomedical application as these printed flexible temperature sensors have application potential in bio medical devices to monitor temperature.

Acknowledgements

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