An Inkjet-printed Strain Sensor with a Carbon-Silver-Polyimide Topology

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I. Summary And Motivation

This paper presents a fully printed strain sensor consisting of carbon ink [1] coating layer and interdigitated shape silver (Ag) ink electrodes solidified on a polyimide (PI) substrate. The carbon ink provides an output of an increase in resistance when the substrate is bent because the occurred cracks break electrical conducting pathways in the solidified ink layer [2]. Improving on the works with only single carbon ink layer [2], an addition of the Ag ink electrodes brings extra resistance increase due to the occurrence of metallic cracks. A 1.5 × 1.5 cm size strain sensor is fabricated to verify the performance of our proposed topology. The results show that the maximum resistance change ratio of the sensor with interdigitated electrodes reaches 7.9%, which is ~12.5% higher than that using carbon ink alone. Because of the low-cost fabrication and the improved sensing capability, our proposed strain sensor can be further optimized for wearable electronics and structure health monitoring applications.

II. Advances over Previous Works

Flexible sensors are attracting increasing research interests and its quick development benefits the growing demands of implantable sensors [3], strain detection [4], biomedical electronics [5-8], artificial human skin [9], *etc*. Conventionally, the fabrication of a flexible sensor includes steps like spin-coating, photolithography, deposition, and lift-off [10-11]. Apparently, these steps are complicated, mandate expensive instruments, and produce a large amount of toxic waste. Compared to the conventional sensor fabrication processes, the inkjet printing approach is simple and of low-cost as it does not require any mask to produce different layers [12]. During printing, it allows precise ink quantity/volume control to achieve the desired layer thickness. Moreover, the sensor's substrate does not need to contact with any contamination sources, showing great advantages to fabricate biosensors and chemical sensors using such a printing approach.

For strain sensing, carbon shows similar electrical and mechanical properties to the costly graphitic materials such as graphene, graphene oxide and carbon nanotube [13]. This is highly desirable when used for large-scale deployment where low-cost is of utmost importance [14-16]. Carbon ink prepared by mixing carbon particles and polymeric stabilizers is observed to show stable piezoresistivity [13]. Using printing technologies, carbon inks can be easily coated on a flexible substrate, like polyimide (PI), to function as a piezoresistive strain sensor. As reported in [17], the carbon ink (Methode 3801, Methode Electronics, Inc., Richardson, TX, USA) was inkjet-printed on C_{10}^{F}-treated Canson Vellum paper (Model No. 702-442, Canson Vellum, France) to act as a deflection sensor.

In this work, the PI film is used as a substrate for direct transfer of the patterned Ag ink and then coated by the carbon ink layer. The interdigitated shape Ag ink electrodes acts as a connection bridge for the carbon ink conductive paths, while the deformation of the PI substrate causes cracks on both carbon and Ag inks, resulting in an improved resistance change ratio ($\Delta R/R$). The reconnection/disconnection of the crack fracture surfaces is the main reason causing the strain-dependent variation in the output of the resistance. This design shows higher $\Delta R/R$ than the case with carbon ink layer alone under same experimental conditions. Moreover, it allows direct patterning, showing simple and cost-efficient manufacture, which enables the applications of this strain sensor on the large-scale surface and to the fields where the production cost is of importance.

III. Results and Methodology

Following the similar interdigitated electrodes' design as reported in [18-19], the proposed strain sensor design and fabrication process are illustrated in Fig. 1. Using this design, Ag ink (purchased from Sigma-Aldrich) was printed on the PI substrate (thickness: 120 μm) via the inkjet printing machine (Printer DMP-2850, FUJIFILM Dimatix Inc.). After the inkjet printing was finished, the patterned PI substrate was placed inside a heating oven (~100 °C) for 1 hour for the drying of the ink. The electrodes' prototype was shown in Fig. 2 (a), with a magnified view of ink drops on the edge of the electrode as depicted in Fig. 2 (b). The average thickness of the inkjet-printed electrodes was ~4 μm. Following the drying processing, the carbon ink was brushed to the substrate and covered the whole interdigitated part of the electrodes. Again, the substrate was

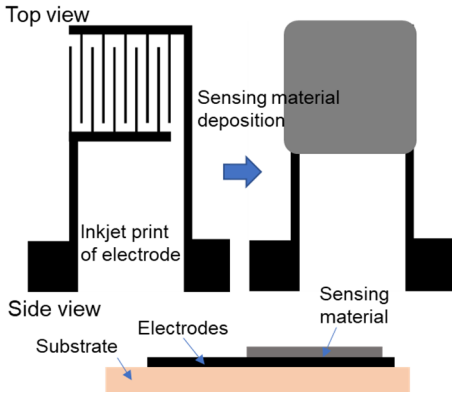

Fig. 1: Schematic design of the proposed piezo-resistive sensor.

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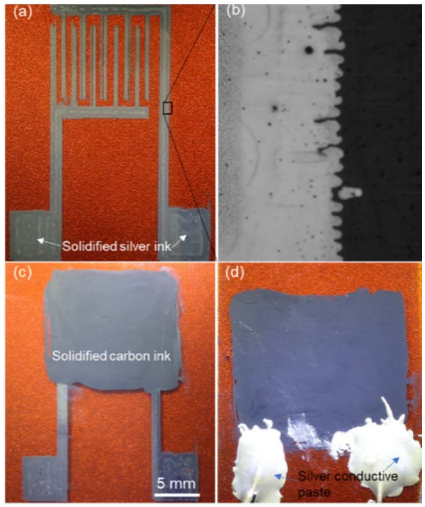

Fig. 2: (a) Drop map of inkjet-printed Ag nanoparticles; (b) optical magnified view; (c) sensor with carbon ink coating layer; (d) strain sensor without interdigitated electrodes.

sent into the heating over (~100 °C) for 30 minutes for drying of the carbon ink and lowering its resistance. The thickness of the solidified carbon ink layer was about 20 µm. The final strain sensor's prototype including the Ag ink formed electrodes and carbon ink conductive layer is shown in Fig. 2 (c), with initial resistance of about 8.9 Ω at its flat state. As a comparison, a second strain sensor with the same carbon ink layer size (1.5 cm × 1.5 cm) coated on the PI substrate was fabricated. For benchmarking, the second sensor did not include the interdigitated electrodes [Fig. 2 (d)], its nominal resistance was 40 Ω, which reveals the addition of the interdigitated electrodes provides additional conductive paths, thereby lowering the entire resistance in our proposed design.

In order to compare the piezoresistivity of the strain sensors with and without the interdigitated electrodes, the proposed design and its counterpart were bent at the same angles, and their $\Delta R/R$ were recorded as shown in Fig. 3. As expected, with the application of the interdigitated electrodes, the sensor shows an improved sensitivity to the bending angle (or strain). More specifically, the sensor with the interdigitated electrodes shows 1.42× higher gauge factor than the other one with a bending angle of 15°. The reason for this improvement attributes to the broken conducting paths on the electrodes formed by silver nanoparticles. The next, the proposed sensor was bent towards upward and downward directions, to demonstrate its flexibility and sensitivity to directions. When it deforms, the change in resistance versus the bending angles (upwards and downwards directions) was measured as depicted in Fig. 4. It indicates a linear and monolithic response when it deforms in one direction, while the resistance change at different direction shows similar performance. This implies that our work can be applied to the surfaces to which the direction of the applied force (or strain) is unpredictable. Consequently, our work exhibits wider application fields than the one with only single directional sensitivity. Finally, to demonstrate the repeatability of the sensor, the fabricated strain sensor was adhered to the hand wrist and was bent for 80 times. The resistance change ratio was recorded in the Fig. 5, giving a range of 1.6% to 2.3%. In current experimental conditions, we did not note detectable lamination and ink peeling off from the PI substrate. To some extent, the fabrication process and the design reported in this work may be suitable for mass manufacturing and repeatedly used over an extended period. However, this will need in-depth and careful analysis and will be part of our future work following the current feasibility study.

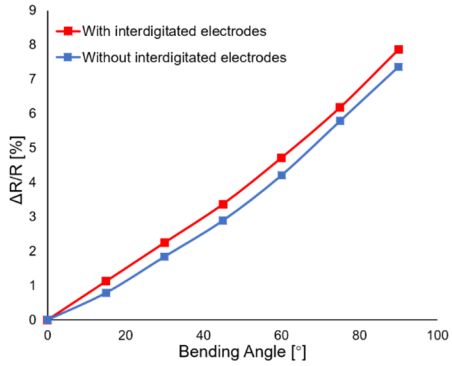

Fig. 3: Resistance change ration comparison between the sensor with and without the interdigitated electrodes. ΔR is the maximum change in the resistance of the sensor during the bending and R is the baseline resistance.

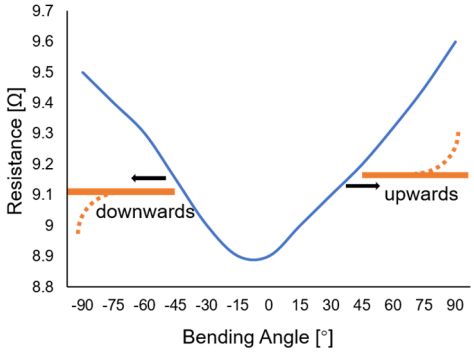

Fig. 4: Resistance change of the proposed strain sensor versus upwards and downwards bending angles.

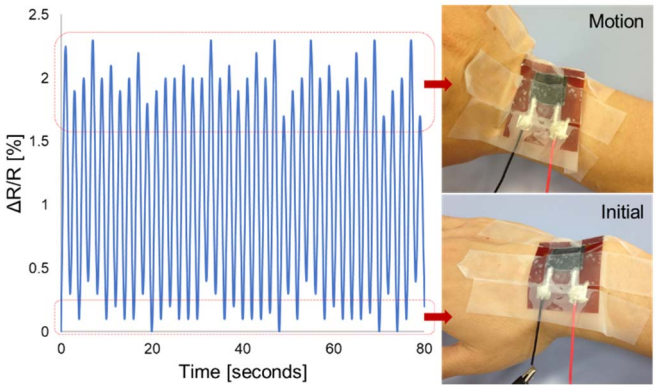

Fig. 5: Relative changes in resistance of the sensor versus time for hand wrist motion including flat and bent states.

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