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Printed Strain Sensors Based on an Intermittent Conductive Pattern Filled with Carbon Nanotube Ink Droplets

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Abstract

In this study, we demonstrate a strain sensor fabricated as a hybrid structure of a conductive intermittent pattern with embedded single droplets of a functional resistive ink. The main feature of our proposed sensor design is that although the intermittent pattern comprises the majority of the entire sensor area, the strain sensitivity depends almost selectively on the resistive droplets. Although the intermittent conductive pattern comprises over 90% of the entire sensor, its contribution to the measured resistance change was only approximately 1%. This is the key feature of the developed strain sensor. This opens up the possibility for fast and inexpensive evaluation of sensors manufactured from various functional materials. As the use of resistive ink was limited to single droplets deposition, the required ink amount needed to build a sensor can be considerably reduced. This makes the sensors cost-effective and simple for fabrication. The developed strain sensors were tested during bending deformations demonstrating linear output signal no hysteresis within the investigated strain range.

1. Introduction

Strain sensors have a long history of being used in various engineering fields. Aside from aerospace and automotive applications, strain sensors are also widely used to monitor civil infrastructures. Conventional metal foil strain sensors are typically made of a copper-nickel alloy, commonly known as constantan. Constantan-based sensors are of particular interest, mainly owing to their low thermal coefficient of resistance. Such sensors are generally fabricated using a photolithography etching process that involves several fabrication steps and materials. Nonetheless, strain sensors have significantly evolved during the last years. Recent progress in additive manufacturing, widely used for flexible printed electronics, opens up new possibilities for the cost-effective fabrication of sensors using diverse materials. As printable constantan-based inks are not commercially available, printed strain sensors are generally manufactured from other strain-sensitive materials based on graphite, silver, PEDOT:PSS, graphene, carbon nanotubes or composites of these materials. All above-mentioned research shows great promise for future practical applications. However, although the previously reported printed strain sensors differ in terms of materials used and shapes associated with their specific target applications, all these sensors have one common feature. They are entirely constructed using a strain-sensitive material that defines both

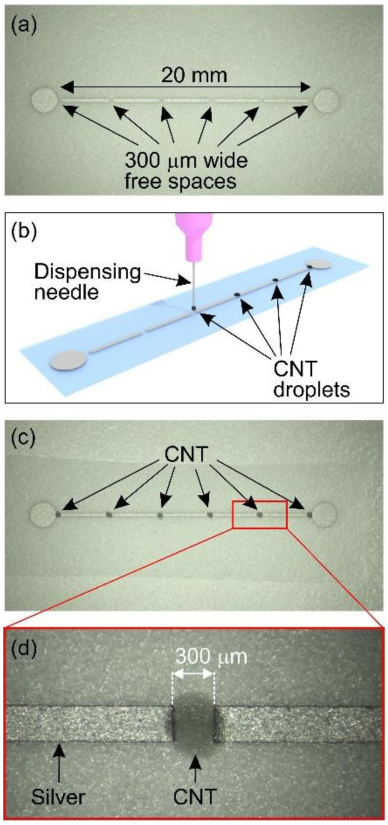

Fig. 1 (a) Printed pattern of the intermittent structure made of silver ink. (b) Deposition of single droplets of the resistive carbon nanotube ink. (c) Top view on the fabricated strain sensor. (d) Zoom in dried droplets made of the resistive carbon nanotube ink.

the sensor shape and sensing properties. In this study, we evaluate an alternative concept for a strain sensor whose design is based on a hybrid construction of a conductive intermittent pattern with embedded single droplets of resistive functional ink, i.e., an ink used to build electrically resistive elements in the sensor structure providing strain sensitivity. The principle of operation of the sensor is similar to the conventional sensors and is based on monitoring of the electrical resistance changes in the entire sensor structure subjected to mechanical deformations. However, for the proposed sensor design, the electrical resistance of the intermittent conductive pattern was much lower than the resistance of resistive elements. We demonstrate that owing to such a configuration, the sensitivity of the entire sensor depends almost selectively on the properties of the resistive elements. This is the key feature of the developed strain sensor. The resistive functional inks define sensor sensitivity while the intermittent conductive patterns specify the sensor shape or, in other words, a path along which strain is measured in the points corresponding to the positions specified by the resistive elements.

2. Construction and analysis of the sensor

The proposed hybrid construction for the strain sensor differs from that for the standard sensors. Instead of one resistive sensor structure, several small resistive elements (made of carbon nanotubes) were connected in series within the intermittent pattern made of a good electrical conductor (silver). The electrical configuration of such a sensor is illustrated in Figure 2.

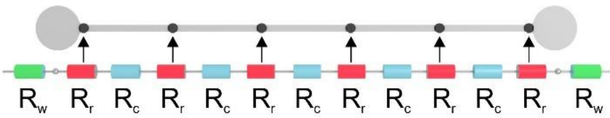

Fig. 2 Electrical configuration of the developed strain sensor. Rc is the electrical resistance of single segments of the intermittent structure, Rr resistance of a single resistive element, Rw resistance of wires attached to the sensor.

The preparation of the strain sensors begins from the printing of the intermittent conductive pattern demonstrated in Fig.1(a). Silver ink was screen-printed onto polyethylene terephthalate (PET) substrate and cured in a conventional convection oven. In the next step, the free spaces of the intermittent structure were filled with carbon nanotubes-based ink. According to the proposed concept, the resistance of the sensing elements should be higher than the conductive intermittent pattern. The functional ink was used in a very small quantity through a single droplet deposition using a dispenser (Musahi ML-5000XII). The dispenser had adjustable pressure and discharge time. The pressure of 0.35 MPa and discharge time of 70 ms were set to form droplets sufficiently large to fill the 0.3 mm wide free spaces in the intermittent pattern and to provide electrical contact between the consecutive silver segments (Fig.1(c)). For comparison, additional sensor entirely made of CNT was prepared.

The sensors were analyzed by measuring the variations in electrical resistance when the sensors attached to a steel plate were subjected to mechanical deformations. During the analysis, bending cycles up to approximately 700 microstrain were implemented. The measured output signal was compared with strain recorded by a reference conventional strain gauge. Figure 3 demonstrates a comparative analysis of the sensor with the intermittent construction and sensor entirely made of CNT. The results show that within the investigated strain range, both sensors reveal similar linear output signal and no hysteresis. The calculated average gauge factor (GF) were similar. Despite the amount of CNT ink needed to build the sensor with the hybrid structure was reduced by over 90%, the properties of both sensors were almost the same.

On the other hand, because the silver intermittent pattern

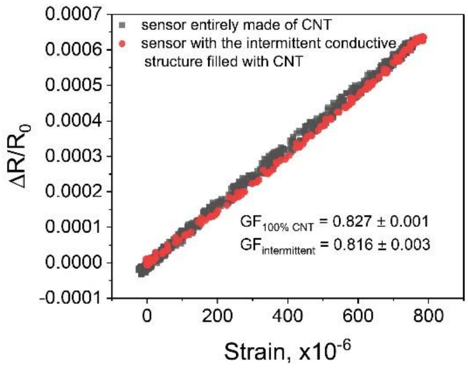

Fig. 3 Analysis of a sensor with the intermittent hybrid construction intended to evaluate the linearity of the measured output signal.

comprises over 90% of the sensor area, assessing its contribution to strain sensitivity of the entire hybrid sensor structure was crucial. Moreover, assessing the contribution related to contact resistances between Rr and Rc was necessary. Performed additional analysis revealed that the influence of contact resistance changes was negligible and because the electrical resistance of carbon nanotube ink was higher than the resistance of the silver pattern, the sensitivity of the entire sensor structure depended mainly on the properties of the resistive elements fabricated from carbon nanotubes. It enables combining various resistive functional inks that define the sensor sensitivity with the intermittent conductive structure that specifies the sensor's shape. Moreover, the ink amount needed to build a sensor can be significantly reduced. Such a fabrication process may be especially interesting for materials like that exhibits good mechanical properties and are yet relatively expensive.

3. Conclusions

In this study, the proposed sensor design was based on a hybrid construction composed of conductive intermittent pattern with embedded single droplets of resistive carbon nanotube-based ink. The key feature of the demonstrated sensor is that although the conductive pattern comprise the majority of the entire sensor area, the strain sensitivity depends almost selectively from the resistance changes in the small resistive elements. As the deposition of functional ink was limited to several single droplets, the amount of ink needed to build a sensor can be significantly reduced. It makes the sensors cost-effective and simple for fabrication. Our current research focuses on the analysis of other resistive functional materials and analysis of intermittent structures with diverse shapes.

Acknowledgements

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