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Research paper

Hand-drawn variable resistor and strain sensor on paper

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ABSTRACT

Paper electronics pave the way to a new generation of cheap and flexible gadgets. In this paper, we present a paper variable resistor by repeated folding completely using commercially available commodity materials, such as paper, brush pen, and electronic paint. The working principle of the variable paper resistor is investigated. Based on the mechanism of contact resistance, a strain sensor is developed.

1. Introduction

Flexible electronics can lay a solid foundation for many new applications such as chemical device [1–4], power source [5–7], electronic components [8,9] and mechanical parts [10]. Especially, using paper as a substrate for electronics has obvious advantages of low cost, flexibility and ease of disposal [11]. For electronics utilizing paper as a substrate to be feasible, the circuits need to include all types of components. It is necessary to fabricate useful paper components in order to realize the full potential for paper as a substrate.

Therefore, research works have been extensively carried out to fabricate various paper components. Paper ultraviolet (UV) sensors and transistors were fabricated based on handwriting of ZnO nanoparticles [12]. Fabrication of variable resistor was achieved based on the mechanism of flow-assisted displacement transducer [13]. On the other hand, strain sensing components are important considering the measurement of mechanical quantities. Although paper strain sensors have been demonstrated [14,15], further expansion of fast and simple solutions are required.

In this paper, we report a novel variable resistor for paper electronics, a hand-drawing process for texturing paper surface, and a folding/pressing process for constructing the resistor. Besides, hand-drawn paper strain sensors have been demonstrated with advantages of fast and simple fabrication. The proposed method presents a low-cost, versatile and simple fabrication approach for paper-based variable resistor and strain sensor.

2. Experimental details

The electronic paint is based on vulcanized rubber and contains approximately 66 wt% Ag nanoparticles. The electronic paint is applied to paper by hand drawing with brush pen. The typical scanning electron microscope (SEM) image of the surface of the conductive paint after curing is shown in Fig. 1. The sheet resistance of conductive ink is approximately 50 Ω/sq. at 50 μm film thickness.

After curing and multiple folding of paper substrate, a flexible resistor is achieved, as shown in Fig. 2a. The force is applied by a pressure gauge together with a plastic plate. The resistance is measured when all the facets of the resistor are in contact. The measured resistance can be adjusted by changing the value of applied force, as shown in Fig. 2b.

In comparison, we investigate the resistance changes of the unfolded pattern under force, as shown in Fig. 3.

A novel paper strain sensor is proposed as shown in Fig. 4. Paper substrates with cured electronic paint were attached to magnet sheet with double-sided tape. Then, two fabricated components were held together by magnet sheet. A separation force was applied to deform the upper paper substrate. The resistance changes were measured as upper paper substrate deforms.

3. Results and discussion

Paper resistors can be made by folding the paper substrate with conductive paste and the resistance can be adjusted with varied pressing force, which, for the sake of demonstration, has been used for

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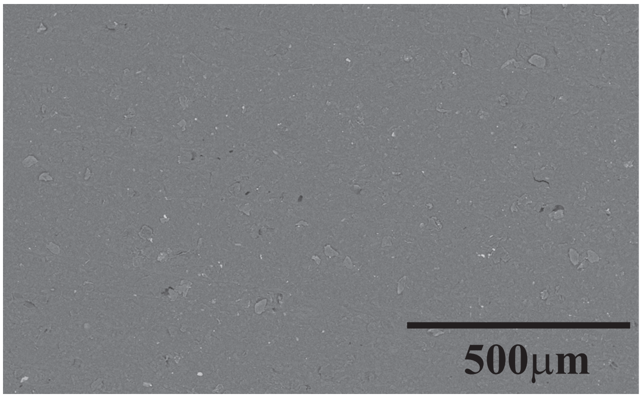

Fig. 1. Typical SEM image of the surface of the conductive paint after curing.

controlling the brightness of a light-emitting diode (LED). Fig. 5a shows the schematic of the circuit. Before pressing, the LED dimmed, as shown in Fig. 5b. After pressing, the LED operated normally, as shown in Fig. 5c. The changes of light intensity are associated with the variation of resistance.

The ratio of measured resistance (R_{m0}) to initial resistance (R) is obtained after 1 cycle of pressing under various applied pressing force (Fig. 6). The average resistance value for R is 9 kΩ. It shows a large decrease in resistance in proportion to pressing force: the resistance decreases by approximately 50%, 68% and 88% under 50 N, 100 N and 200 N pressing force, respectively. It is obvious that large pressing force significantly decrease the resistance.

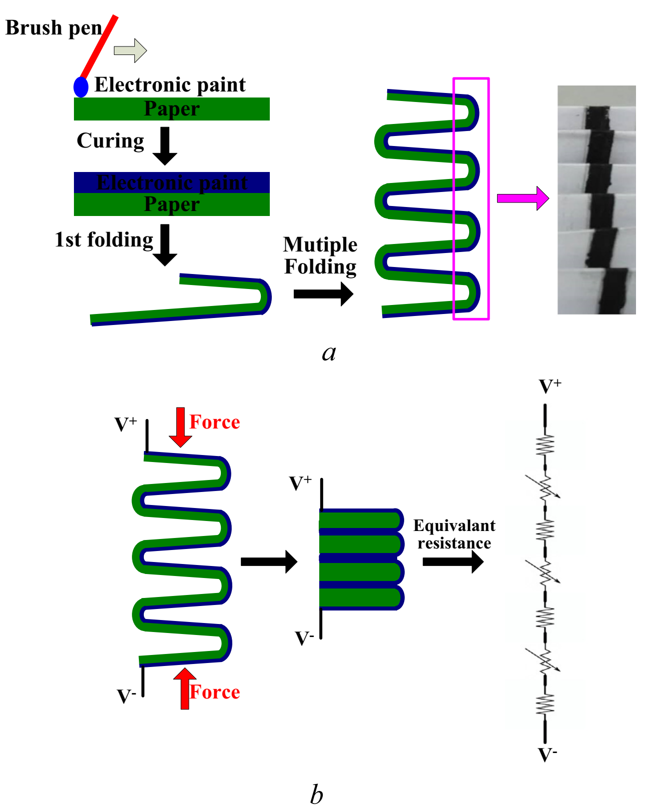

Fig. 2. Fabrication process and working principle of variable resistor. a Fabrication process of variable resistor based on hand-drawing and folding. b Working principle of variable resistor based on pressing.

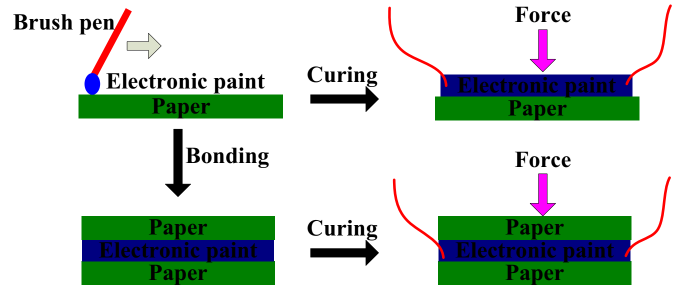

Fig. 3. Schematic of the resistance measurement structure of the unfolded pattern under force.

The piezoresistive effect was modeled and discussed. Since the electrical conductivity of Ag nanoparticle is much larger than the conductivity of polymer, it can be approximated that the electrical conductivity of the polymer is zero. The composite is approximated as perfect elastomer and we suppose that Ag nanoparticles are evenly distributed in the composite. Based on reference [16], we can obtain the relationship between electrical resistance and pressure, which is shown as follows.

$$\frac{R}{R_0}=(\Phi_0-\Phi_c)^t\left[\Phi_0\exp\left(\frac{1-2\nu}{E}P\right)-\Phi_c\right]^{-t}\times\exp\left(-\frac{1+2\nu}{E}P\right)\quad(1)$$

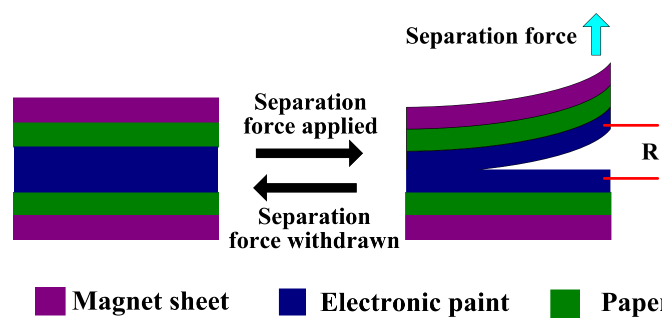

Fig. 4. Schematic of proposed paper strain sensor.

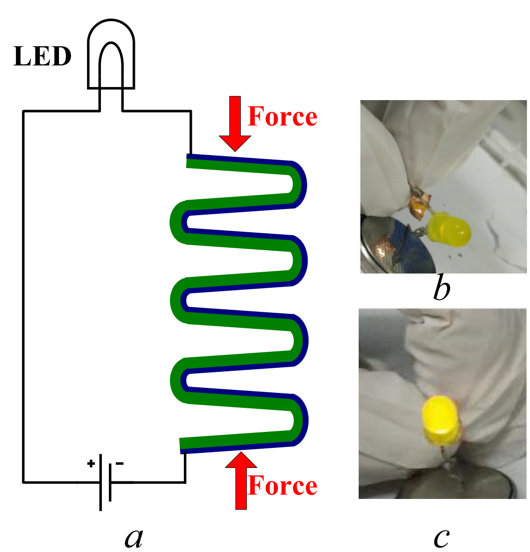

Fig. 5. Demonstration of proposed paper variable resistor. a Schematic of the circuit. b Photo of LED before pressing paper resistor. c Photo of LED after pressing paper resistor.