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Highly reproducible printable graphite strain gauges for flexible devices

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ABSTRACT

A growing area for the electronics industry is the development of flexible components for novel devices. Controlling the flexibility of such devices requires the precise and reliable measurement of strains in a manner compatible with the form and function of the device. In this article, we demonstrate the fabrication and characterization of printed strain gauges with a gauge factor as high as 19.3 ± 1.4, fast signal response and high reproducibility. The device is made of graphite ink deposited by screen printing on a plastic substrate. The flexible printed sensor is capable of precisely measuring repetitive tensile and compressive bending strain changes. An approach for eliminating the temperature-induced errors of strain gauges based on neutral axis engineering is also described.

1. Introduction

Recent developments in organic and printed electronics are paving the path for the creation of commercially viable flexible devices [1,2]. Such devices will need a number of sensors with quick signal response and reliability for the precise measurement of their flexibility. In particular, strain gauges systems, whose electrical resistance changes in proportion to the amount of strain, are necessary for measuring mechanical deformations in a precise manner [3]. Strain measurement supports determining the state of the device and accomplishing certain operations that are associated with flexibility, for instance, new possibilities of input and output interactions between the user and the device [4]. Printable and flexible strain gauges offer distinct advantages over conventional rigid sensors, such as mechanical flexibility, smaller dimensions, and higher sensitivity [5,6]. Wearable computing requires multiple sensors integrated into small devices and the manufacture of multiple sensors in layers and arrays will be enabled by the development of new printable electronic circuits and manufacturing techniques.

Conventional strain gauges made of metal foils and semiconductor slabs are not suitable for use in system-in-foil technologies due to their inability to conform to curvilinear surfaces and accommodate large deformations. A number of advanced materials for manufacturing highly flexible and stretchable strain sensors have been previously reported, including silicon nanomembranes [7], silver nanoparticle ink [8,9], thin films of carbon nanotubes [6,10], graphene films [11,12], PEDOT:PSS [13,14], BEDT-TTF salts [15], and electrically conductive composites mainly based on PDMS with different fillers such as carbon black [5], graphite [16], carbon nanotubes [17], or metallic nanoparticles [18,19]. Such materials are attractive because they are capable of measuring deformations as large as 100–150% with a gauge factor ranging from 2 to 30. However, only a few of these can be utilized in printing processes that allow affordable mass-production, furthermore, reliability and robustness of such printed strain gauges is still an issue.

This article reports the design and demonstration of a bidirectional strain gauge that is suitable for manufacture at high scale and consists of graphite conducting ink printed on a flexible plastic substrate. The strain gauge can be manufactured by screen printing and then thermal curing. To improve the speed of

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manufacture, a photonic flash curing of printed graphite ink was developed as an alternative to conventional thermal processes. The printed strain measurement device with large gauge factor exhibits quick response and high reproducibility to both tensile and compressive bending strains. The sensor can be reversibly bent resulting in about 0.7% strain for more than 100,000 cycles without performance degradation. Temperature-induced errors are eliminated by employing a second compensating strain gauge made of identical material and located at the strain-free neutral axis of the mechanical plane.

2. Experimental

2.1. Printing and curing processes

Strain gauges were fabricated using screen printing. The graphite ink 26-8203, a black high viscosity paste, was supplied by Sun Chemical and used as described by the manufacturer. The substrate was 125 μm thick poly (ethylene naphthalate) (PEN) foil that lacks surface features (Teonex Q65FA, DuPont). The hand screen printer was purchased from EuroPrint and used according to the manufacturer's instructions. The ink was deposited using a polyester screen mesh of 70 threads/cm with the thread diameter of 31 μm, and a squeegee with the hardness of 75 Shore A.

Feature printing was followed by a curing step. The wet graphite ink was initially cured on a hot plate at 120 °C for 30 min according to the supplier recommendation. For high volume production faster post-processing is advantageous so an alternative technique was developed. Photonic flash curing was performed using a xenon flash lamp tool UIS-100 (Aeromed LLC). The apparatus consisted of a power supply, a discharge unit, a controller, and a lamp housing which included a xenon flash lamp with forced air cooling, an elliptical reflector with reflectivity of >98%, and an adjustable table for samples. A linear xenon flash lamp was placed in one of the focus lines of an elliptical reflector. The reflector projected an image of the lamp on the second focus line, resulting in an illumination area of about 20 × 250 mm. An adjustable table allowed setting a projected image with desirable light intensity. The lamp had an emission spectrum ranging from 200 to 900 nm. The system had an average electric power of about 1000 W with a pulsed peak power of about 2.2 MW. The pulse energy was adjustable in the range of 12–108 J, the pulse frequency varied from 1 to 50 Hz, and the pulse duration was 50 μs.

The interconnections were fabricated over the printed and cured graphite track by screen printing with a mesh count of 165 threads/cm using a silver ink (26–8204, Sun Chemical). The silver ink was sintered using a hot plate at 120 °C for 30 min. For testing the performance of the strain sensors, two copper wires were soldered at the end pads of printed structures by means of thermosetting conductive adhesive based on silver (Elecolit 3653, Eurobond Adhesives). The lamination of two graphite tracks on plastic foils stacked one on top another for the temperature compensation measurements was performed using UV curable adhesive (9008, Dymax).

2.2. Characterization techniques

The printed samples were inspected by optical microscopy. The thickness was measured by means of white-light interferometer MicroXAM-100 from KLA-Tencor. The morphology of graphite film was studied by a LEO 1530VP field-emission scanning electron microscope (SEM). The adhesion was evaluated by scratch tests and cross-cut tape tests based on the standard ASTM D 3359. The electrical resistivity and the sheet resistance values were calculated based on standard 2-point and 4-point probe measurements, respectively, using the Agilent 34410A digital multimeter. Mechanical properties of printed tracks were studied by applying a tensile and compressive bending stress with the radius of curvature from 120 to 10 mm. Repeated mechanical deformation tests were conducted in 2-point and 4-point bending modes with the maximum bending radius of 25 mm using a custom-made apparatus [20]. More than 100,000 bending cycles were performed for each sample. Temperature-induced change of resistance in heating and cooling modes was studied by means of the hot plate IKA S7 and the Agilent 34410A multimeter.

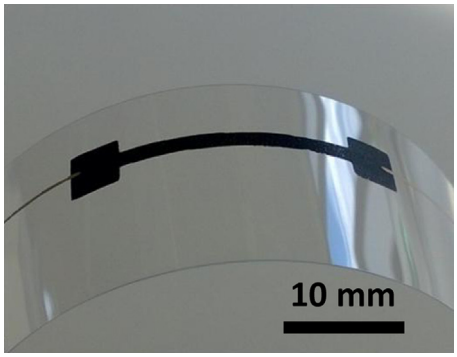

Fig. 1. Graphite strain gauge printed on PEN.

3. Results and discussion

3.1. Fabrication

Fabrication techniques were developed to improve the ability to print graphite-based inks on plastic substrates to obtain thin, flexible conducting surface features. A graphite track with strong adhesion to PEN had a linear geometry with a length of 20–30 mm, a width of 0.5–1.5 mm, and an average thickness of 6.6 ± 0.4 μm (Fig. 1). Screen printing supports reproducible fabrication of the patterns with a spacing of approximately 200 μm between lines. Conventional thermal curing of the ink resulted in an electrical resistivity of 60 mΩ cm. However, the thermal process is incompatible with large scale production such as roll-to-roll manufacturing, which demands fast and efficient low-temperature techniques. An alternative method known as a photonic flash sintering based on xenon flash lamp irradiation was investigated due to its simplicity and high efficiency. Metal nanoparticle inks such as silver and copper inks printed on plastic substrates can be photo-cured into high conductive structures within seconds, in contrast to minutes and even hours needed for conventional thermal processes. The principle of this technique is the selective heating of the ink by the absorption of xenon high-intensity pulsed light for which the substrate is transparent [21,22]. This paper is the first report that this photonic flash curing is also an efficient method for curing printed structures made from graphite inks. The graphite material strongly absorbs light in the range from 200 to 900 nm where the xenon flash lamp usually emits [23]. The exposure to the ink causes a significant local temperature rise in the wet graphite layer that inevitably leads to rapid curing. The curing process involves a cross-linking of polymeric matrix concomitant with the evaporation of solvent. The benefit of photonic curing approach is similar to that for the sintering of metal nanoparticles in that it allows effective curing of the carbon ink on low-melting-point plastic substrates at room temperature within seconds. Fig. 2 shows that the complete curing of relatively thick graphite layer indicating the sheet resistance of about 50 Ω/□ can be achieved within 20 s at the average power of 918 W (the pulse energy of 27 J, the frequency of 34 Hz) instead of 30 min at 120 °C on the hot plate.