Developing Reliable Foam Sensors with Novel Electrodes

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***Abstract*— This paper presents an ultra-light, highly compressible, resistive sensor based on open-cell polyurethane foam coated with PEDOT:PSS. A novel electrodes configuration is developed to eliminate the unstable contact resistance, providing reliable electrical and mechanical connections for foam-based sensors. Thereby, the proposed sensors have a low resistance of 15 ohm, and can detect small strain variations (<0.1%) with negligible hysteresis (4%). Multiple samples were characterized and analyzed. The resistance only increases 4% after 100 cycles of 70% compression. The proposed foam sensor provides a low-cost, easy-to-implement, robust sensing solution for real-world applications in robotics and wearable systems.**

Keywords*— *Soft sensors; conductive foam; contact resistance; electrodes; porous material

I. Introduction

Soft mechanical sensors [1] are highly demanded in robotics [2, 3] and wearable systems [4] for tactile sensing and motion monitoring. In the last two decades, researchers have explored various transducer mechanisms (resistive [5], capacitive [6], magnetic [7], inductive [8], optical [9] etc.), and novel materials and smart structures [10] to develop better soft sensors [2]. Among all these transducer mechanisms, resistive sensors have the simplest read-out electronics and design flexibility. Many nanocomposite materials (elastomer with nano/micro fillers) [11, 12] have been developed for soft sensing, while they usually present significant hysteresis and long response time [13]. Liquid-metal-based sensor became a popular solution for stretchable sensing [14, 15] despite the complex micro-channel fabrication. Nevertheless, most of these resistive sensors are sensitive only to tensile strain due to the transducer mechanism and/or the incompressibility.

In recent years, a new type of resistive sensors based on 3D conductive porous structures [16] have been explored for highly compressible strain and pressure sensing. in which the overall resistance changes due to variations of conductive pathways between micro-fibers. In particular, commercial foams have been exploited as compressible materials for soft sensors by coating them with conductive ink. One foam body can be used for 3D multimodal deformation sensing by using specific electrodes configurations [17]. Metal and carbon-based conductive nano-materials are commonly used as fillers for nanocomposites and as conductive coatings for foam-based sensors [18]. However, the conductivity is rather low and the bonding between the carbon nanomaterials and the polymer foam fibers is poor, a stabilization process is required to reduce the typical peeling-off effect. Very recently, PEDOT:PSS was used as conductive polymer coating on melamine foam [19], showing relative low resistance (200 Ω) and good mechanical bonding. However, melamine foam is very fragile and the copper electrodes are mechanically unstable, significantly limiting the application. In this work, we exploit the high conductivity of PEDOT:PSS and the superior mechanical properties of commercial polyurethane (PU) foam to fabricate soft sensors. In addition, a reliable electrode for foam sensors is developed to eliminate contact resistance. The proposed foam sensor shows highly repeatable measurement of compressive strain (up to 70%) with negligible hysteresis.

II. Conductive Foam

Cylindrical PU foam samples (16 mm diameter, 12.7 mm thickness, 0.11 g) were cut from large sheet (8643K549, McMaster-CARR, Chicago, USA) through a laser cutter. The PEDOT:PSS ink was prepared by mixing 95% PEDOT:PSS (Clevios PH1000, solid content 1.3%, Hereaus), 5% dimethyl sulfoxide (DMOSO, 99.9%, Sigma Aldrich), and 1% 4-dodecacylbenzenesulfonic acid (90%, Sigma-Aldrich). The foam samples were dipped in the PEDOT:PSS ink for 30 minutes, with a few times of compression-release cycles to

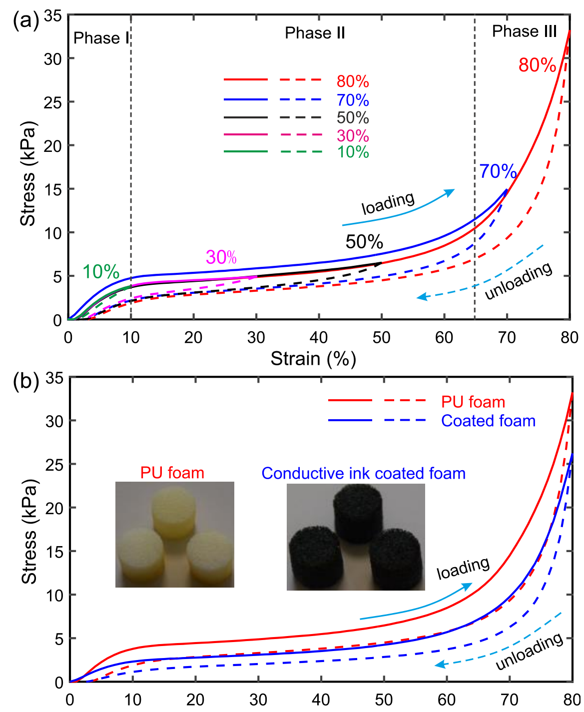

Fig 1. Mechanical characteristics of the foam samples. (a) Stress-Strain curves of a cylindrical foam sample (D×H: 16 mm × 12.7 mm) at different maximum strains. (b) Stress-strain curves of a foam sample before and after coating it with conductive ink. Inset: photos of three uncoated and coated foam samples. (Solid lines for loading, dashed lines for unloading).

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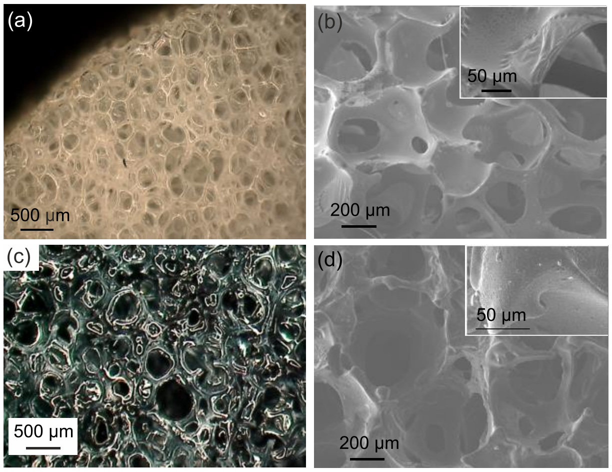

Fig. 2. Optical (a) and SEM (b) images of PU foam surface; Optical (c) and SEM (d) images of a PEDOT:PSS coated PU foam surface; Surface morphology of both coated and non-coated PU fibers are shown in the insets.

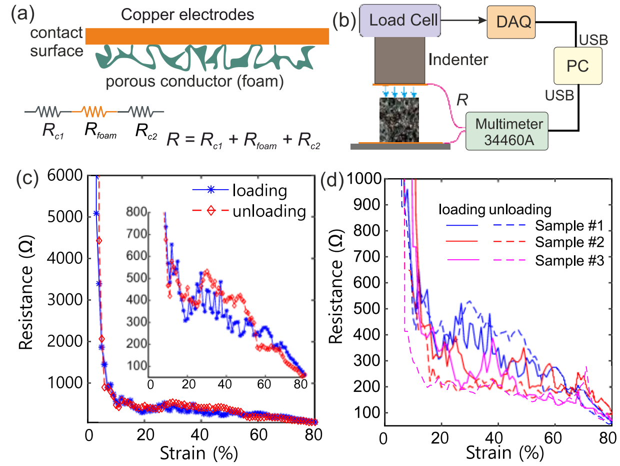

Fig. 3. (a) Contacts between porous conductor and solid electrodes; (b) Experimental setup (c) Resistance variation of the foam sample under compression loading up to 80% strain. Inset: resistance at 10% to 80% strain; (d) Resistance of three foam samples at a cycle of 80% compression.

ensure full soaking. After dipping, the samples were squeezed to remove extra ink, then were hung with needles in a vacuum oven at 100 °C for 1 hour to dry.

Mechanical characteristics of the PU foam and PEDOT:PSS coated foam were tested by using a customized setup which consists of a motorized linear stage (M-111.1DG1, Physik Instrumente, Germany) and a 6-axis load cell (Nano17, AIT Industrial Automation, USA). As shown in Fig. 1a, the samples were compressed at maximum strains from 10% to 80%. Fig. 1a shows a maximum hysteresis of 15% at 70% strain. The stress-strain curves can be distinguished into three phases: phase I (0-10%) is almost linear elastic; phase II (10-65% strain) is highly viscoelastic and softer; phase III (>65% strain) demonstrates much stiffer behavior since micro-fibers start packing together. Despite the increased thickness of these micro-fibers due to coatings, Fig. 1b shows that the coated foam samples are softer (21.1% lower stress at 80% strain) than the uncoated ones, which could be a result of structure changes or damages of these micro-cells in the dipping and drying process. As shown in Fig. 2, both optical and SEM images were acquired to characterize the cell structures of the foam (cell size varies from 300 μm to 600 μm), and surface morphologies of the PU fibers (~50 μm) and conductive coatings. Fig. 2(d) indicates that the conductive coating added a rough layer on the surface of PU fibers.

III. Contact Resistance

As illustrated in Fig. 3a, only small protrusions (fiber tips) of the porous conductor (conductive foam) are in contact with a flat electrode (copper tape), which would result in highly random, pressure-dependent, large contact resistance [20, 21], given the high porosity (96%) of the foam. In order to investigate the contact resistance effect of the foam sensor, an experimental setup (Fig. 3b) was built to measure the total resistance ($R_{total}= R_{foam} + R_{c1} + R_{c2}$) between two copper electrodes when they were in contact with the top and bottom surfaces of a coated foam sample. A high precision multimeter (34460A, Keysight, Santa Rosa, USA) was used to monitor the resistance when the foam was under compressive loading. At the initial contact phase (0-5% strain), the total resistance is extremely unstable, decreasing from 100 kΩ to 1 kΩ level drastically when pressure increases. As shown in Fig. 3c, the resistance further decreases to 100 Ω level when the foam was compressed to 80%. The amplified view (inset of Fig. 3c) highlights the large fluctuations of resistance caused by unstable contact resistance. Fig. 3d shows the results of three samples from the same fabrication batch, indicating that the large noise and uncontrollable characteristics would make it very difficult to use foam sensors without reliable electrodes.

IV. Foam Sensor Development

A. Reliable electrodes for foam sensor

Since the contact resistance is highly sensitive to pressure [22] and could be affected by many unpredictable contact conditions, stable mechanical connections between the electrodes and the foam body are crucial to make the foam sensor stable and repeatable. In this paper, we propose a novel solution for fabricating contact electrodes for foam-based sensors. A thin top/bottom surface layer of the porous structure was filled with a stretchable silver conductor (PE873, DUPONT, Midland, USA) as an electrode. As highlighted in Fig.4a, the silver paste only penetrated into approximately 1 mm of the foam surface, covering all fibers' surface, and partially filling some hollow space of the cell structures. The stretchable silver conductor was stably bonded with the conductive foam fibers through large contact area, eliminating the contact resistance and providing compliant, strong mechanical connections. After the silver paste was dried in a ventilated oven for 20 mins at 120 °C, a small drop of Ag paste was used as conductive adhesive to glue wires to the electrodes. Fig. 4b shows a complete foam sensor sample on a glass slide. Three samples were fabricated using the same batch of conductive foam as those samples tested in Section III; then they were tested under cyclic loading (up to 70% compression, Fig. 4c). Despite showing a slight difference of the initial resistance (might be caused by the electrodes fabrication process), the resistance to strain curves are exactly the same (Fig. 4c, 3rd cycle of a continuous cyclic loading).

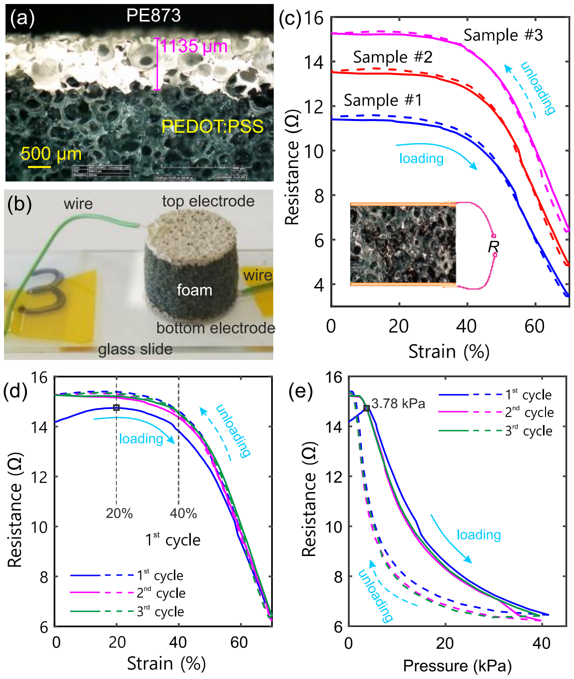

Fig. 4. (a) Optical microscope image of the stretchable silver electrodes for foam sensors; (b) Photo of a foam sensor sample with top and bottom electrodes and connected wires; (c) Resistance variations of three foam sensor samples under cyclic compression loading (maximum strain 70%); inset: sketch of the electrodes and wiring configuration for foam sensor; Response of the 1st, 2nd, and 3rd loading and unloading cycles (d) Resistance to strain curves; (e) Resistance to pressure curve. (Solid lines represents the loading process, dashed lines are for unloading process).

B. *Characteristics of foam sensor*

Figure 4c indicates that resistance-strain curves during the loading and unloading process are almost completely overlapped with a negligible hysteresis of less than 4% for 70% compression, which is a promising feature for accurate strain measurement. As shown in Fig. 4d and Fig. 4e, in the loading process of the first cycle, the resistance increased about 4% at 20% strain (at 3.78 kPa pressure), then slowly decreases between 20% to 40% strain, which could be due to some micro-cracks formed on the PEDOT:PSS coating when the PU fiber was deformed. Similar phenomena have been reported in literature [18]. When the strain is larger than 40%, resistance decreases linearly, with a sensitivity of -0.281 Ω/1% strain (Gauge factor equals to 2). The resistance measurement noise (standard deviation) is as low as 0.53 mΩ, which indicates an high resolution of strain variation detection (<0.1% strain). The second and all the following cycles are almost completely overlapped given that the micro-cracks will not re-connect under continuously loading. Fig. 4e indicates that the foam sensor can be used for pressure sensing as well, with a sensitivity of -0.313 Ω/kPa, which means it can detect small pressure variations of 10 Pa. However, the foam sensor is not suitable for accurate absolute pressure measurement given its large hysteresis (>25%) due to the inherent mechanical properties (Fig. 1) of the porous structure itself.

To evaluate the long-term stability and repeatability of the proposed foam sensor, sample #3 was tested under 100 cycles loading of 70% maximum compression (in 2 hours). Fig. 5a

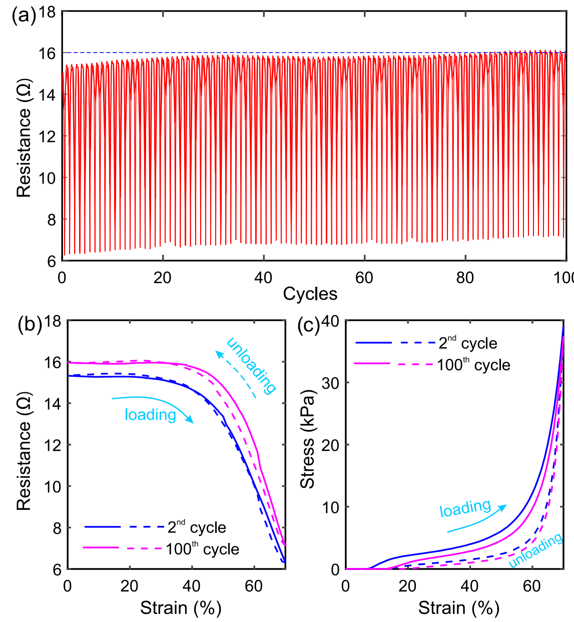

Fig. 5. Long-term stability and repeatability test (sample #3) (a) Resistance variations of 100 cycles loading at 70% compression; (b) Resistance to strain curves of the 2nd and 100th cycles; (c) Stress to strain curves of at the 2nd and 100th cycles.

shows highly repeatable response, with the unloaded resistance slightly increased by 4.1% (0.64 Ω). The resistance to strain curves of the 2nd and the 100th loading-unloading cycles are exactly similar except for the small change of the absolute resistance (Fig. 5b); and the resistance variation decreased only 1.6% after 100 cycles 70% compression. As shown in Fig. 5c, the foam sensor became a little bit softer (4.3% smaller stress at 70% strain) after 100 cycles loading, which could be caused by damaged cell structures and plastic deformation of the foam body. Results from tests conducted in one week later shows that absolute resistance increased by 8%, which could be caused by changes of temperature, humanity or conductivity of the coated PEDOT:PSS.

V. Conclusions and Future Work

In summary, we presented a low-cost, ultra-light, robust, highly compressible strain sensor based on commercial PU foam coated with PEDOT:PSS. The presented foam sensor has a low resistance in the range of 10 to 20 Ω. Highly repeatable results (1.6% degradation after 100 cycles loading of 70% compression) were achieved by eliminating the contact resistance through the novel stretchable silver electrodes. Both the electrical and mechanical behaviors of the foam sensors were characterized and analyzed. The presented results and discussions give us a better understanding of the advantages and drawbacks of this type of sensors. The presented foam electrodes provide a practical solution for developing robust sensors based on any porous materials. To better understand all aspects of the foam sensors and to make it robust in various conditions and applications, temperature and humanity affect, modeling techniques should be investigated. In the near future, we intend to further investigate this low-cost, versatile sensing solution for 3D multimodal sensing, and to explore it in soft robotics and wearable applications.

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