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3D PRINTED GRAPHENE-COATED FLEXIBLE LATTICE AS PIEZORESISTIVE PRESSURE SENSOR

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ABSTRACT

Piezoresistive sponges represent a popular design for highly flexible pressure sensors and are typically fabricated using templating methods. In this work, we used stereolithography (SLA) to 3D-print an elastomeric body-centered cubic (BCC) lattice structure with a relative density of 21% and an elastic modulus of 31.5 kPa. The lattice was dip-coated with graphene nanoplatelets to realize a piezoresistive pressure sensor with excellent performance (gauge factor = 3.25, sensitivity = 0.1 kPa^{-1}), high deformability (up to 60 % strain), and repeatability. The novel approach outlined in this work offers greater control over the microstructure and can be used to fabricate sensors with tunable properties.

KEYWORDS

3D printing, stereolithography, pressure sensor, lattice, piezoresistivity, graphene.

INTRODUCTION

3D printing technology (also referred to as additive manufacturing, rapid prototyping, or freeform fabrication) offers unprecedented design freedom that allows the user to fabricate parts directly from a digital computer-aided design (CAD) file in a tool-less processing workflow. The technology especially offers value during the fabrication of complex shapes, where the high cost and low speed of 3D printing (compared to traditional subtractive manufacturing) are offset by its ability to realize complex and intricate designs that are difficult or impossible to fabricate using conventional machining processes. An example of this is a lattice structure that offers unique advantages such as light weight, high energy absorption, and local tunability of mechanical properties such as stiffness — fabricating a lattice structure of a desired geometry is difficult or impossible using subtractive manufacturing but is rather straightforward using 3D printing [1].

A cellular structure (e.g. foam) is a popular design for flexible pressure sensors, allowing much higher accommodation of strain and lighter weight compared to traditional silicon-based sensors. Further, the bulk porosity is known to enhance the response time and reduce hysteresis in viscoelastic sensors [2]. Several methods of fabricating elastomeric (usually polydimethylsiloxane or 'PDMS') sponges, such as direct templating (e.g. using sugar cube scaffolds), emulsion templating, gas forming, and so on have been reported in the literature [3]. The sponges are subsequently coated with conducting materials such as thin metal films [4], carbon nanotubes (CNT) [5], graphene nanoplatelets [6], liquid metal [7] etc. to develop pressure sensors with capacitive or piezoresistive sensing principles. The sensors fabricated using these processing workflows showed high deformability, good sensitivity, and repeatability over thousands of cycles of dynamic loading, making them suitable for applications in wearable electronics such as breath [5] and gait monitoring [6].

Although elastomeric conductive sponges have shown promise as pressure sensors, the aforementioned fabrication methods often afford limited control over microstructural features such as pore size and relative density [3] due to the limitations of the template used to fabricate the lattice. For instance, preparing an ordered structure (e.g. body centered cubic lattice) is not possible using sugar cube templating. Such highly ordered structures can offer greater flexibility and control over the resulting mechanical properties, sometimes even offering interesting possibilities such as negative Poisson's ratios with proper lattice design. Although 3D printing is an ideal candidate to fabricate intricate lattice designs owing to its 'complexity is free' paradigm, the printing of PDMS or PDMS-like materials is often complicated by the low Young's modulus of the uncured soft polymer [3]. Chen *et al.* [8] fabricated a silicone rubber foam using 3D printing by using custom-made inks comprised of a dispersion of sodium chloride in silicone precursor. Yu *et al.* [9] used fused deposition modeling (FDM) to fabricate a simple lattice using a thermoplastic elastomer (styrene-ethylene-butylene-styrene block copolymer) comprised of a simple line infill design, and coated it with CNT to develop wearable pressure and strain sensors with high stretchability.

In this work, we used high-resolution stereolithography (SLA) 3D printing to fabricate a body centered cubic (BCC) lattice structure using a PDMS-like elastomer. The lattice was dip-coated with conductive graphene nanoplatelets (GNP) to realize a piezoresistive pressure sensor. We performed a comprehensive characterization of the sensor using both static and dynamic compression tests. Unlike previous methods of fabricating spongy pressure sensors, the approach proposed in this work offers greater control over the cellular design (and consequently the resulting mechanical properties) that can be used to develop highly deformable sensors with tunable characteristics.

MATERIALS AND METHODS

Sensor fabrication

The pressure sensor design was in the form of a cube (20 mm × 20 mm × 20 mm) comprising a BCC lattice structure. The lattice was modeled in Netfabb (Autodesk Inc.) with a unit cell of 3 mm × 3 mm × 3 mm and a strut diameter of 700 μm, resulting a relative density of 21%. The model was 3D-printed using a commercial SLA printer (Form 3, Formlabs Inc.) with a proprietary 'Elastic Resin' offered by Formlabs Inc. The cured resin had a Shore A hardness of 50 and resembled PDMS in its appearance and mechanical properties [10]. The 3D-printed lattice cube

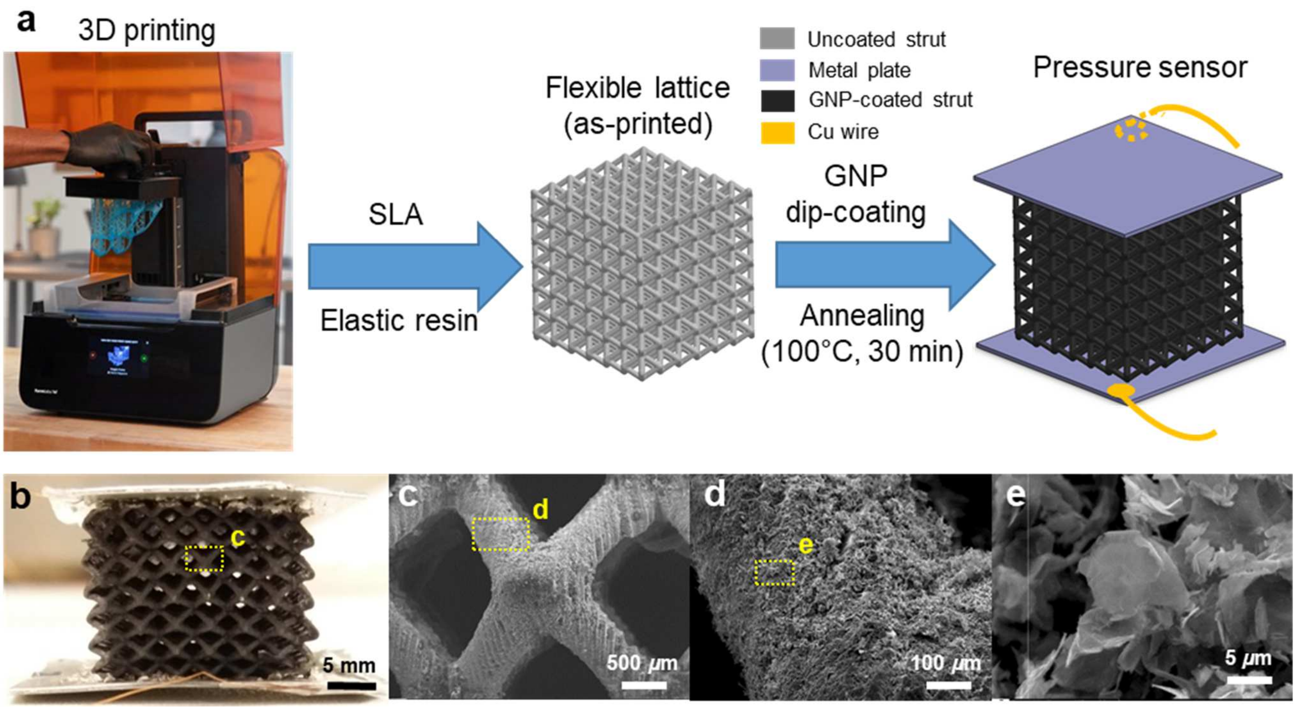

Figure 1: a) Processing workflow comprising SLA 3D printing and GNP dip-coating to fabricate piezoresistive pressure sensor, b) sensor photograph, c-e) scanning electron micrographs (SEM) of GNP-coated lattice struts.

was then washed in isopropyl alcohol for 10 minutes and manually squeezed multiple times to ensure that no uncured resin remained within the lattice. The uncured lattice cube was then immersed into a solution of commercially obtained (Graphene Supermarket) conductive graphene dispersion (23 wt. % GNP, average nanoplatelet thickness ~ 7 nm) diluted with ethanol (1:10 by volume) and ultrasonically agitated for a period of 30 minutes to coat the lattice struts with GNP. The GNP-coated lattice was subsequently heated in a furnace at 100° C for 30 minutes to serve the twofold purpose of curing the lattice (to improve its mechanical strength) and annealing the GNP percolation network (to improve its conductivity). Finally, two opposing faces of the lattice cube were affixed to aluminum plates (25 mm × 25 mm) using conductive silver epoxy (EPOTEK H20E). The fabrication workflow is summarized in Fig. 1a, and a photograph of the sensor is shown in Fig. 1b. Scanning electron microscopy (SEM) confirmed the uniform adherence and coating of GNP on the lattice struts (Figs. 1c-e). Copper wires soldered to the aluminum plates were connected to an external Wheatstone bridge circuit to measure (National Instruments DAQ USB6003) and acquire (NI Signal Express) sensor resistance data at 100 Hz sampling frequency during testing. It must be noted that this manner of connecting the sensor to the external circuit ensured that the connection points (i.e., wire soldered to the top and bottom aluminum plates) did not experience any stress during the test. Hence the measured resistance change could be solely attributed to the piezoresistivity of the GNP-coated lattice. The base resistance of the unstrained sensor was ~ 100 kΩ.

Compression testing apparatus

The pressure sensor was tested in compression using a universal tensile testing machine (MTS 810). Special T-shaped fixtures were machined and clamped to the fixed and moving heads of the MTS 810 machine and the pressure sensor (sandwiched between the two aluminum plates) was attached to the lower (fixed) head of the machine, as shown in Fig. 2 (inset). The displacement and frequency of motion of the upper head could be controlled, and the force and displacement data during the compression tests were acquired at a frequency of 10 Hz. Both static and dynamic (1 Hz) tests were conducted by loading the sensor up to 60% strain, and the force, displacement, and resistance values were logged simultaneously.

RESULTS AND DISCUSSION

Mechanical properties

The lattice structure was subjected to 50 cycles of loading and unloading at a deformation rate of 2.4 mm/s to obtain its mechanical properties. The BCC lattice is a bending-dominated structure whose stress-strain curve typically consists of three characteristic regimes: elastic deformation (where the struts elastically bend), stress plateau (where the struts elastically buckle), and finally cell densification (where opposite struts collapse onto each other) [11]. In the stress-strain curve obtained in this work (Fig. 2), the elastic deformation and stress plateau regimes seemed to be merged since the stress increased linearly till a strain of around 30% after which densification occurred. The elastic modulus of the BCC lattice was calculated to be 31.5 kPa (equal to the slope of the curve till 30% strain averaged over 50 load-unload cycles). According to the Gibson-Ashby model [11] for lattice structures,

$$\frac{E_L}{E_S} = C\left(\frac{\rho_L}{\rho_S}\right)^2 \qquad (1)$$

where E_L is the elastic modulus of the lattice, E_S is the elastic modulus of the strut material, C is a proportionality constant, ρ_L is the the density of the lattice and ρ_S is the density of the strut material. Substituting $E_L = 31.5$ kPa, E_L

= 2.45 MPa (estimated from a shore hardness of 50A using Gent's equation [12]), and ρ_L/ρ_S = 0.21 (reduced density calculated in Netfabb), the constant C was calculated to be 0.3 which was within the expected range of 0.1 – 4 [13] for open foam lattice structures. Using the knowledge of the constant C, Eq. 1 can be used as an analytical tool to design lattice structures of the desired stiffness.

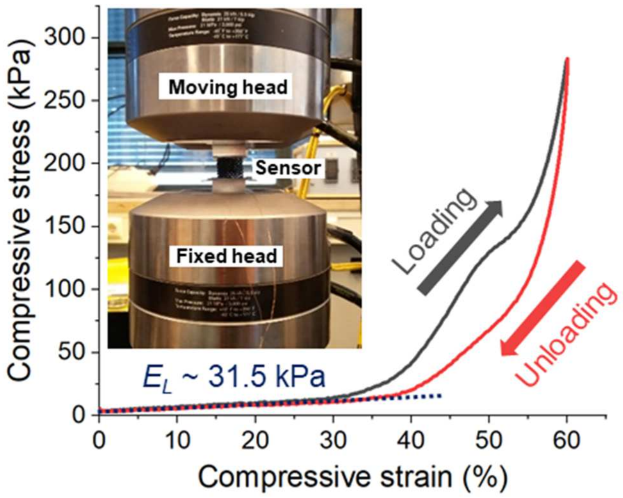

Figure 2: Stress-strain curve of lattice (averaged over 50 load-unload cycles) with testing apparatus in inset.

Static compression test

In the static test, the sensor was compressed in steps of 2 mm till a total displacement of 12 mm (60% strain). The displacement at each step (i.e., 2, 4, 6, 8, 10, and 12 mm) was held at 2 minutes before ramping to the next value. The sensor was then gradually unloaded in the reverse order from 12 mm to 0 mm in steps of 2 mm with the same hold time at each step. The complete loading-unloading cycle lasted 25 min and was conducted three times to get statistically meaningful data. Each GNP-coated strut in the BCC lattice represented a flexible piezoresistor that changed its resistance when it experienced strain. Upon compression, the equivalent resistance change in the 3D network of conductive struts was measured between the top and bottom aluminum plates.

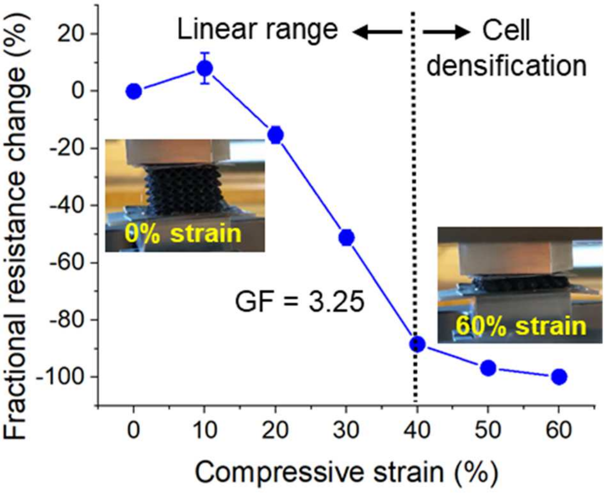

Figure 3: Piezoresistive response during static loading (average of three load-unload tests).

Fig. 3 shows the fractional resistance change measured in the lattice at each strain step during the loading stage. Interestingly, the resistance showed a slight increase till a compressive strain of 10%, implying a negative piezoresistive effect that has also been observed in spongy pressure sensors in the literature [14], [15]. The sensor exhibited a linear resistance decrease in the 10–40 % strain range, beyond which the fractional resistance change started to saturate at -100%, making the lattice almost completely conducting at the highest applied strain of 60%. Observed in the context of the stress-strain curve presented in Fig. 2, it can be seen that the linear behavior of the pressure sensor coincided with the elastic deformation regime of the lattice. Once cell densification occurred (strains > 40%), the struts in each unit cell contacted each other and made the lattice fully conducting, thus driving the resistance change to -100%.

Gauge factor (GF) and sensitivity (S) are two commonly adopted metrics to characterize the performance of piezoresistive pressure sensors, and are defined as the fractional resistance change of per unit applied strain and applied stress, respectively. GF was measured by calculating the slope of the linear (10–40 % strain) region and was found to be 3.25 as shown in Fig. 3. S can be calculated as GF/E_L and was estimated to be 0.1 kPa^{-1}. As shown in Table 1, the obtained values compared favorably to the ones reported in the literature for spongy piezoresistive pressure sensors [5], [14], [15] within a similar strain range of 10–40 %.

Table 1: Comparison with sensors in the literature.

Ref.	**GF**	**S (kPa^{-1})**	**Materials**
This work	3.25	0.1	Formlabs elastic resin lattice + GNP
Ref. [14]	0.38	0.023	Polyurethane sponge + carbon black
Ref. [15]	1.58	N/A	Polyurethane sponge + cellulose/Ag nanowire
Ref. [5]	N/A	0.033	PDMS sponge + CNT

Dynamic compression test

The dynamic response of the sensor was evaluated by compressing the lattice at different amplitudes (2–12 mm in steps of 1 mm) at a frequency of 1 Hz for a total of 120 cycles. Due to an initial clearance of 1.5 mm between the moving head and the top plane of the lattice sensor before the test, the total displacements of the cube were in the range of 0.5–10.5 mm. Fig. 4 (inset) shows the sensor resistance variation over time for a total strain of 52 %. It can be seen that the sensor showed repeatable behavior over 120 cycles and recovered back to its original resistance at the end of the test. The clearance between the moving head and the sensor caused a 'spring back' effect of the lattice whenever the moving head lost contact with the sensor at the end of each cycle, causing mild fluctuations in resistance peaks as seen in Fig. 4. However, the sensor response remained stable in compression, e.g. ~ -50% in Fig. 4 (inset). To quantify the effect of varying amplitude on the sensor output, a fast Fourier transform (FFT) operation was undertaken on the time series data of the sensor output at different displacements. The FFT peak (in kΩ) amplitude at 1 Hz was normalized by the mean resistance and plotted against the total strain applied during the test (Fig. 4). The sensor output showed linear behavior in the strain range of 15–45 % with a ‘dynamic’ GF of 3.15 as shown in Fig. 4, similar to the results obtained in the static test (Fig. 3).

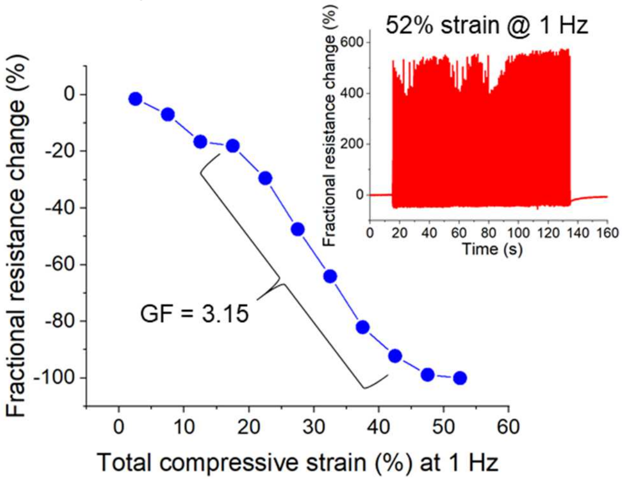

Figure 4: Sensor response (FFT peak magnitude at 1 Hz normalized by mean resistance) during dynamic loading at 1 Hz. Inset shows exemplar time series data for 52% strain.

CONCLUSIONS

In this work, we developed highly deformable piezoresistive pressure sensors designed in the form of a BCC lattice cube. The lattice structure was fabricated in a low-cost desktop SLA 3D printer using a PDMS-like elastomeric material, following which it was dip-coated with graphene nanoplatelets. The pressure sensor exhibited excellent performance in both static and dynamic compression tests, comparing favorably to similar spongy pressure sensors reported in the literature. The lattice design (easy to realize using 3D printing) can enable better control over the sensor properties (e.g. tunable stiffness, density, pore size, etc.) compared to prior methods of fabricating spongy sensors.

ACKNOWLEDGEMENTS

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