Diamond-like carbon based micro-pressure sensor with ultra-thin sensitive membrane

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***Abstract*—in this study, diamond-like carbon (DLC) piezoresistive film and ultra-thin sensitive membrane structure (580 nm thick Si_3N_4/SiO_2) were used for the micro-pressure sensors to improve the sensitivity. High power impulse magnetron sputtering (HiPIMS) process was used to deposit DLC film with high gauge factor (GF), and the wet-etching process was used to fabricate the ultra-thin sensitive structure. Based on Raman spectra, the size of sp^2 clusters slightly increased after the release of the internal stress, which might reduce the GF of the DLC film. However, the DLC based sensor still showed high sensitivity of 3.2×10^{-4}/kPa, good non-linearity of 2.4% FS and satisfied repeatability. This work showed an efficient and economical method to improve the performance of the micro-pressure sensors.**

Keywords—diamond-like carbon; piezoresistive; micro-pressure sensor; ultra-thin structure; internal stress

I. INTRODUCTION

Micro-pressure sensor is one of the core components of consumer electronics and medical/aviation/meteorological facilities[1-4]. Among kinds of micro-pressure sensors, the piezoresistive sensor is widely used for it is simple to design, economical and has high performance[5, 6]. To improve the sensors' sensitivity, various new materials and thinner sensitive structures are attempted in recent years. Graphene and nanocrystalline diamond film are fabricated into self-supporting films with nanoscale thickness[7, 8]. And the polysilicon film is also used for the sensitive/mechanical membrane in micro-pressure sensor[9]. However, during those sensors preparation procedure, transfer of the sensitive films, high-temperature growth or ion implantation processes are needed, which increases process complexity and restricts their development. Fortunately, diamond-like carbon (DLC) films have attracted great attention, since they have high piezoresistive gauge factor (GF) within the range of -3200 to 1200[10-12], can be directly deposited on silicon, SiO_2, glass and many other substrates. Besides, the DLC has wonderful mechanical, anti-corrosion performance and good compatibility with micro-electromechanical systems (MEMS)[13].

Therefore, in this work, we applied DLC films as piezo resistors that were directly deposited on 580 nm thick Si_3N_4/SiO_2 sensitive membrane. The ultra-thin sensitive membrane was designed to improve the sensor's sensitivity, and the main preparation procedure of this sensor was simple and economical wet-etching process, which was based on the self-stopping phenomenon. The high adhesion between DLC and Si_3N_4/SiO_2 layer and anti-corrosion performances of DLC films improved the ratio of the finished sensors. Besides, the impact of the release of the internal stress of DLC film was preliminarily investigated, since the stress release would cause curvature/wrinkle on such thin structure and might change the microstructure of the film.

II. DESIGN AND FABRICATION OF THE SENSOR

A. Design of the Sensor

As shown in Fig. 1, to improve the sensitivity of the sensor, we designed a sensitive membrane with large width/thickness ratio (~3448). The overall size of the sensor was 4×4×0.5 mm, and the dimension of the sensitive membrane was 2 mm×2 mm×580 nm. Here, 280 nm thick Si_3N_4 and 300 nm thick SiO_2 films were selected for the sensitive membrane. As for the DLC piezo resistors, the whole dimension was 60 μm×20 μm×60 nm. And the dimension of the effective area (excluding the overlap area) was 20 μm×20 μm×60 nm.

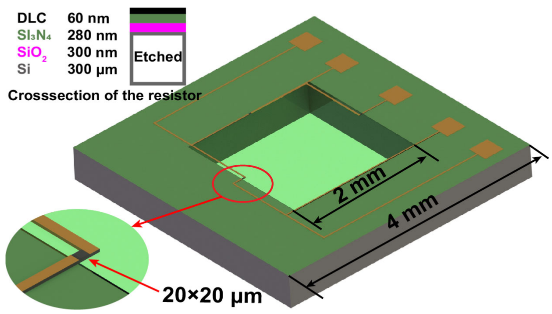

Fig. 1. Illustration of the micro-pressure sensor.

B. Fabrication Process

The fabrication process mainly contained DLC deposition and ultra-thin membrane fabrication. As shown in Fig. 2(a), 4-inch silicon wafer (100) with Si_3N_4 and SiO_2 films on both sides was used. In Fig. 2(b, c), photoresist was directly used as mask for the fabrication of DLC resistors. The DLC film was deposited using high power impulse magnetron sputtering (HiPIMS) process to improve the sp^3 content and GF, the relation between those two parameters was shown in our former work[14]. The sputtering power was about 1.5 kW, the duty cycle was 0.1 and the working pressure (Ar gas) was about 8 mTorr. Besides, -100 V bias voltage was applied to the substrate during the deposition.

Then, as shown in Fig. 2(d), 20 nm Cr and 200 nm Au were successively deposited and then fabricated into wires by lift-off process. In Fig. 2(e), inductively coupled plasma (ICP) etching process was used to etch Si_3N_4 and SiO_2 films on the backside of the wafer to fabricate the mask for wet-etching. Then the sensitive components were carefully protected by photoresist/PDMS/glass, as shown in Fig. 2(f). Finally, in Fig. 2(g), the silicon substrate was etched by KOH etchant (33% in mass fraction, 90 °C). The etching process will self-stop when the etchant contact with the SiO_2 film and then the fabrication of the sensitive membrane was finished. Finally, the protection layers were removed and the sensor chips were cleaned with deionized water, acetone and alcohol, successively.

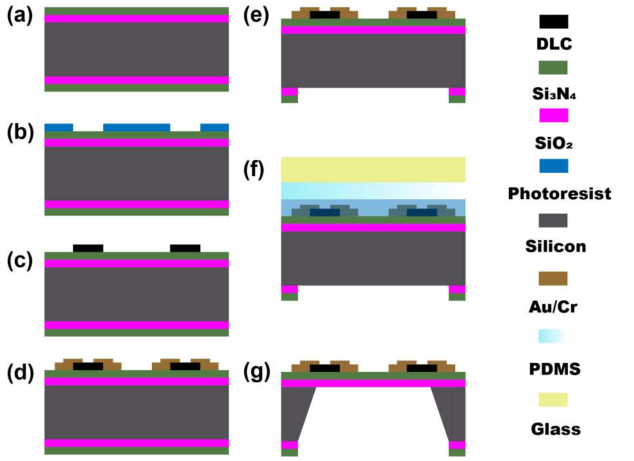

Fig. 2. Diagram of the fabrication process. (a) Silicon wafer with Si_3N_4 and SiO_2 films on both sides. (b) Photolithography and the photoresist was used as mask. (c) Deposition of the DLC film and then lift-off process was used to fabricate the resistors. (d) Fabricating Au/Cr wires. (e) Using ICP etching process to fabricate mask for wet-etching. (f) Protecting the sensitive components. (g) Wet-etching and then remove the protection.

The DLC-based micro-pressure sensor was shown in Fig. 3. During the package process, the sensors were pasted onto PCB board and then they were pasted onto a 3D printed shell with a cavity inside. The compressed gas will be introduced into the cavity and then applied to the backside of the sensitive membrane, which was transparent in the photo because of its ultra-thin thickness. The inset figures showed both the sensitive membrane (the left one) and the DLC piezo resistors (the right one).

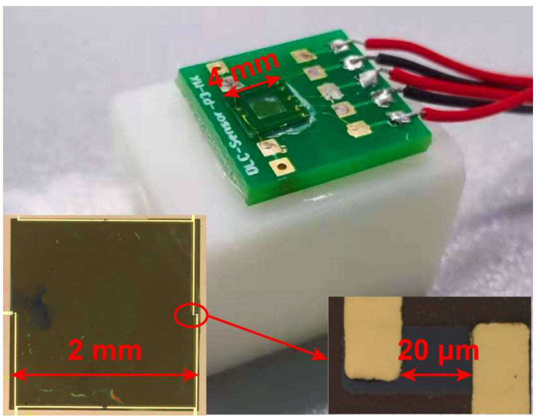

Fig. 3. Packaged sensor and the micrographs of the sensitive membrane and piezo resistors were shown in inset figures.

III. RESULTS AND DISSCUSSION

A. Deflections of the film and the curvature caused by stress

The deflections of the center line of the sensitive membrane during the test were measured by confocal microscopy, which was shown in Fig. 4 (the center line was shown in the inset figure). We should note that the transparent performance of the film caused the noise in the figure. From the curves, the film swelled evenly when the pressure was applied, which is good for the linearity of the sensor. The maximum deflection was about 49.0 μm, and the corresponding ratio between the deflection and the thickness was about 84.5. Therefore, the deformation of the sensitive membrane confirmed with the large-amplitude model.

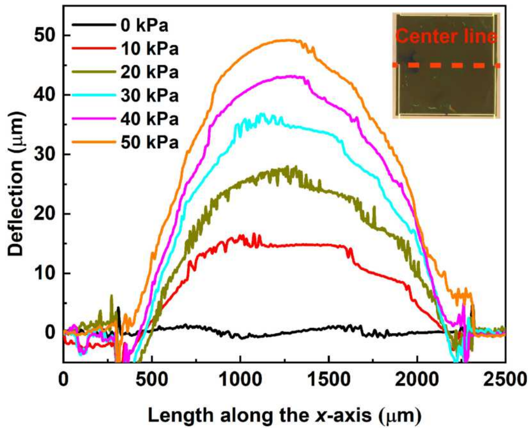

Fig. 4. Deflections of the center line of the sensitive membrane during test.

DLC films usually have a large internal stress during deposition process. As shown in Fig. 5, from the 3D AFM image, the stress caused curvature with the maximum deflection about 448.5 nm. The curve was smooth, which implied that no fracture appeared in the DLC film. Besides, the internal structure and content might have slight change, and a proper characterization method was needed for further analyzation.

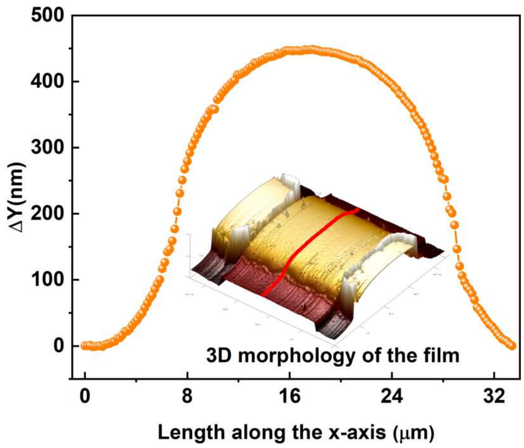

Fig. 5. Curvature caused by the stress of the DLC film.

B. Impact of the stress release to the internal structure of DLC film

The Raman spectra of the DLC piezo resistor before and after the stress release were shown in Fig. 6. During the test, 532 nm laser source was used and the signal within 800-2000 cm^{-1} was collected. Before the release, in Fig. 6(a), the peak from silicon substrate could be found within 900-1000 cm^{-1}. And in Fig. 6(b), it disappeared after the release, which implied that the silicon was completely etched after the wet-etching process. The G peak position, full width at half maximum (FWHM) of G peak of the DLC resistor before the release were 1548.1 cm^{-1} and 198.87 cm^{-1}, separately. After the release, the data were 1553.5 cm^{-1} and 178.6 cm^{-1}, separately. Besides, the sp^2 cluster size can be calculated by the intensity of D peak and G peak (I_D and I_G), the value of I_D/I_G increased from 1.68 to 1.87, which meant that the sp^2 clusters slightly increased[15]. This result showed that the stress release had a small effect on the internal structure of the DLC resistor. Based on the thick-film resistor model that was reported on former works, the GF will have a little loss [14, 16]. However, the sensitivity of the sensor still had a significant improvement, which was shown in the following sector.

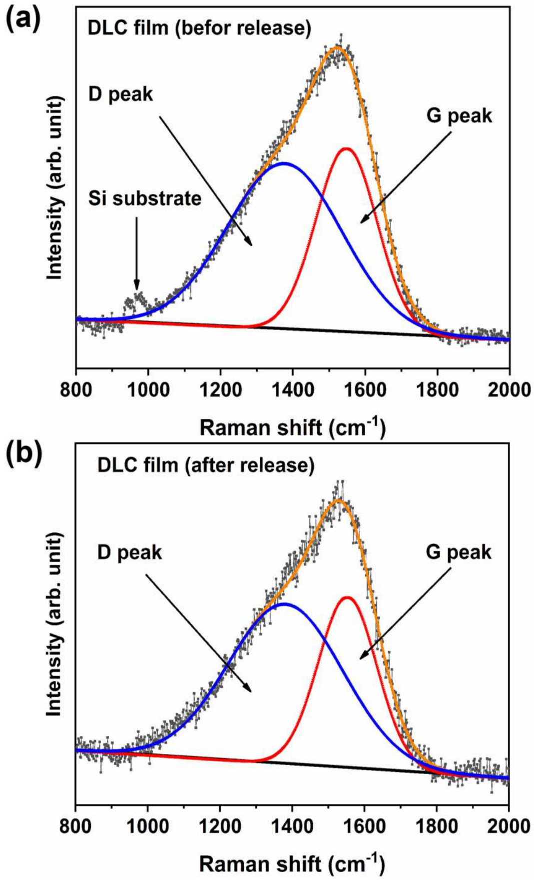

Fig. 6. Raman spectra of the DLC film before and after the release.

C. *Test result of the micro-pressure sensor*

During the test of the micro-pressure sensor, a manual pump was used to apply gas pressure load and it was calibrated by a commercial piezometer. The pressure was controlled within 0-50 kPa and the interval was 10 kPa, as shown in Fig. 7(a).

The signal of $\Delta R/R$ of the DLC piezo resistor was measured and the result showed that the sensor had a high sensitivity of 3.2×10^{-4}/kPa (the GF of the DLC film was about 22.3). As shown in Table I, it had an obvious improvement, compared with graphene/nanocrystalline diamond-based sensors, in which these films were also used to fabricate an ultra-thin sensitive structure. Although the sensitive membrane was ultra-thin and the ration of width/thickness was about 3448 and deflection/thickness was about 84.5. The signal still had a small non-linearity of 2.4 % FS. Besides, the sensor also had good repeatability, which was shown in Fig. 7(b). Furtherly, Wheatstone full-bridge sensitive circuit will be completed and stress concentration structure will be designed for the ultra-thin film to improve the sensitivity.

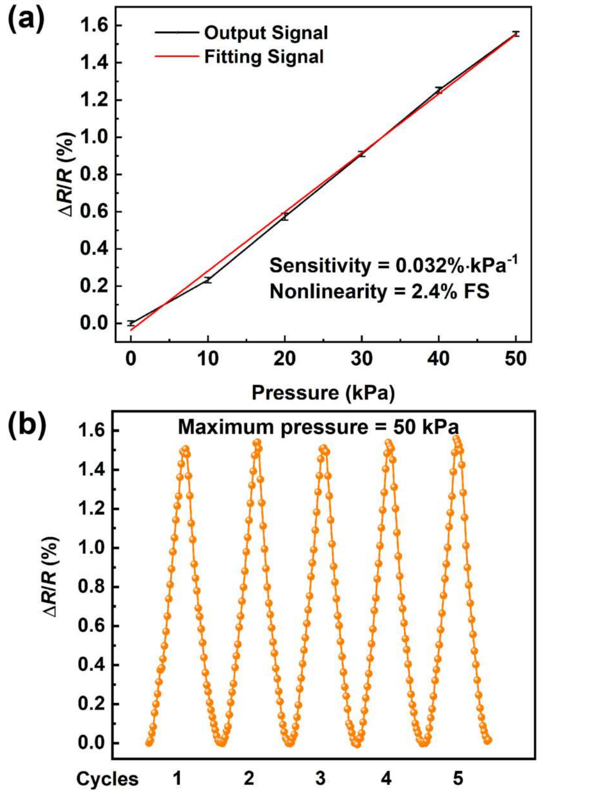

Fig. 7. Test result of the micro-pressure sensor. (a) Output signal and the fitting result. (b) Repeatability test result.

Table I. Comparation between related works.

Refs.	Normalized sensitivity	Thickness
Graphene[7]	2.97×10^{-5}/kPa	0.335 nm
Nanocrystalline diamond[8]	6×10^{-5}/kPa	150 nm
DLC (this work)	3.2×10^{-4}/kPa	580 nm

IV. Conclusion

A DLC piezoresistive film based high-sensitivity micro-pressure sensor with ultra-thin sensitive structure was presented in this work. An economical fabrication process that was mainly based on HiPIMS deposition and wet-etching processes was also shown. Using Raman spectra and AFM, we preliminarily discussed the impact caused by the release of the internal stress. Finally, the test of the micro-pressure sensor showed a high sensitivity of 3.2×10^{-4}/kPa, good non-linearity of 2.4% FS and satisfied repeatability. The design and the fabrication process can be used to improve the performance of the micro-pressure sensor and reduce the process cost.

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