Micro Pressure Sensors Based on Ultra-thin Amorphous Carbon Film as both Sensitive and Structural Components

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***Abstract*— Amorphous carbon(a-C) is a promising material for Micro Electro-mechanical System (MEMS) due to its significant piezoresistive effect, in-situ large-area deposition and outstanding mechanical performance. In this work, a micro pressure sensor based on ultra-thin sensitive film layers (a-C/Si_3N_4/SiO_2) is proposed. In order to measure the micro pressure change, an ultra-sensitive rectangular a-C film piezo resistor with thickness of 300 nm, width of 300 µm and length of 900 µm and an ultra-thin rectangular sensitive structure with thickness of 785 nm, width of 400 µm and length of 600 µm are designed and fabricated. The simulation and testing results show that the resistance response of the ultra-thin film, with a linear relation of differential pressure, is highly sensitive. This work shows that a-C is a potential piezoresistive material for micro pressure change detection.**

Keywords—amorphous carbon film; ultra-thin sensitive structure; pressure sensors; piezoresistive effect; wet-etching

I. Introduction

Piezoresistive micro pressure sensor is one of the most commonly used sensors in industrial field, which can easily convert the micro applied pressure into electrical signals. In order to gain higher sensitivity, many new materials like graphene [1], carbon fiber cement paste [2] and silicon nanowires [3] are used as the sensitive material or structure. However, these new materials are expensive and difficult to fabricate or in-situ large-area deposit. At the same time, researchers try to innovate the sensor's structure to obtain higher sensitivity [4]. There are still some shortages of traditional fabrication methods: the process of SOI (silicon-on-insulator) and the technique of dry etching cost a lot, sensitive element in the scale of submicron is difficult to fabricate. Thus, it's important to find a new material as the sensitive element in the piezoresistive pressure sensor which can be easily processed in MEMS.

Amorphous carbon (a-C) is a competitive material: firstly, it's gauge factor can be very high, which up to 1200 according to reports [5], 5 times as much as doped silicon. So that it can be used as sensitive element in piezoresistive pressure sensor. Then, it has very attractive properties such as good heat

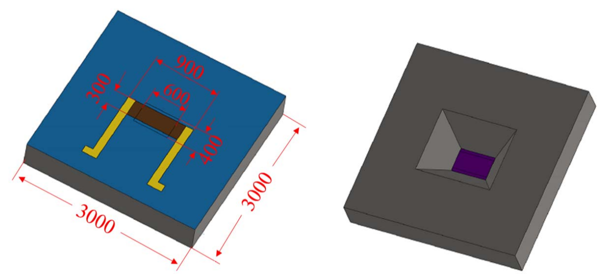

Fig. 1. 3D model and dimensions of the micro pressure sensor. (units: µm).

resistance and corrosion resistance, which is suitable in wet etching [6]. Finally, the film deposition is much more simpler than silicon's ion implantation process which is widely used in piezo-resistors fabrication. In this paper, firstly, a micro pressure sensor with a 785 nm thick film as sensitive structure is designed, the thinner the film is, the greater the stress generates under the same pressure, so that the higher sensitivity is obtained. A finite element software is utilized to analyze the structure and prove that the design can realize the measurement of the micro pressure. Then, a sensor chip is fabricated. Finally, the micro pressure sensor is packaged and tested.

II. Design And Fabrication

A. Sensor's Sensitive Structure Design

As shown in Fig. 1, a micro pressure sensor based on ultra-thin (785 nm) sensitive film layers(a-C/Si_3N_4/SiO_2) is presented, 20 nm Cr and 200 nm Au films are deposited on the amorphous carbon film to form electrical connection. There is a rectangular hole in the silicon substrate with a width of 400 µm and a length of 600 µm which is fabricated by KOH wet-etching process. The dimensions of the silicon substrate and the piezo resistor (patterned amorphous carbon film) are shown in Fig. 1.

As shown in Fig. 1, with this sensitive structure, the resistance of the amorphous carbon film changes when pressure load is applied to the film. To evaluate the

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piezoresistive effect of the material, the gauge factor (GF) is generally used and defined as [7]:

$$G = \frac{dR}{R}\frac{1}{\varepsilon} \quad (1)$$

A schematic drawing of the film without and with pressure load is shown in Fig. 2(a) and Fig. 2(b). The film deflects when a pressure is applied, the in-plane strain (ε) is determined by measuring pressure (P) and the deflection (h) of the center of the film. For a long rectangular film, the in-plane strain and the deflection in the center of the film can be calculated from the pressure and deflection data using the following formulas [8-9]:

$$\varepsilon = \frac{P(a^2 + h^2)}{2Eht} \quad (2)$$

$$h = [\frac{6Pa^4(1-\nu^2)}{8Et}]^{\frac{1}{3}} \quad (3)$$

Here, a is a half of the film window width, E is the Young's modulus of the film, t is the film thickness, ν is the Poisson ratio of the film, respectively. Then the resistance variation induced by the applied pressure can be written:

$$\frac{\Delta R}{R} = G[0.55P^{\frac{2}{3}}a^{\frac{4}{3}}E^{-\frac{2}{3}}t^{-\frac{2}{3}}(1-\nu^2)^{-\frac{1}{3}} + 0.454P^{\frac{4}{3}}a^{\frac{4}{3}}E^{-\frac{4}{3}}t^{-\frac{4}{3}}(1-\nu^2)^{-\frac{1}{3}}] \quad (4)$$

Where R is the initial resistance value of the film, ΔR is the change of R, G is the GF of the film. Equation (4) notes that the relative change of the resistance of the amorphous carbon film is linearly related to the applied pressure load. So that, the applied pressure load can be measured according to the resistance change.

To verify the design of the micro pressure sensor, a commercial software, Comsol multiphysics, is used to simulate the mechanical and electrical behavior of the structure. The result of the finite element method(FEM) is shown in Fig. 3, which shows the change of the resistance of the amorphous carbon film is perfectly linear to the applied pressure, which is consistent with the expectation.

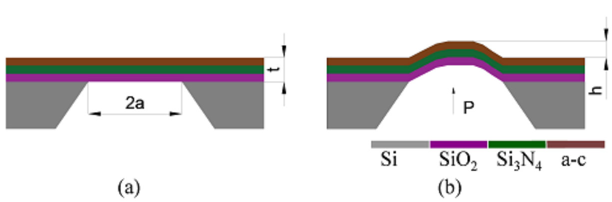

Fig. 2. Schematic of film without (a) and with (b) applying pressure load.

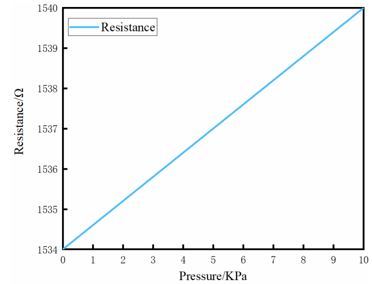

Fig. 3. Resistance changes as a function of pressure.

B. Sensors Materials and Fabrication

In this work, the structure is fabricated using 4-inch silicon wafer (100) with SiO_2 and Si_3N_4 layers on both sides. And the thickness of silicon wafer is 500±5 μm, the thicknesses of SiO_2 and Si_3N_4 layers are 200 nm and 285 nm, respectively. Only three masks are needed in the whole procedure, one for the fabrication of a-C piezo-resistor, one for the metal electrode, and another for etching the rectangular hole in silicon substrate.

Fig. 4. shows the process flow of the fabrication of the micro pressure sensors: (a) the substrate is cleaned by acetone and absolute ethanol; (b) spin-coating photoresist and then photoetching on the top side, depositing 300 nm a-C film by direct current (DC) sputtering; (c) using acetone to do lift-off process and getting the patterned a-C piezo-resistor; (d) photoetching on the top side, depositing 20 nm Cr and 200 nm Au, and then getting the electrode by lift-off process; (e) photoetching on the bottom side; (f) etching the SiO_2 and Si_3N_4 on the bottom side by inductively coupled plasma (ICP) process; (g) finally, the exposed silicon is etched by KOH etchant at a temperature of 80 ℃, this etching process is self-stopped when the 500 μm silicon is etched over and the KOH etchant contact with the SiO_2 layer, thus the structure for measuring the micro pressure load is obtained. The fabricated micro pressure sensor is shown in Fig. 5(a).

III. EXPERIMENTS AND RESULTS

A. Packaging and testing of the pressure sensor

The fabricated micro pressure sensor is glued on a printed circuit board (PCB) and then the PCB is glued on a 3D printed mold as shown in Fig. 5(b). In this process, epoxy glue is

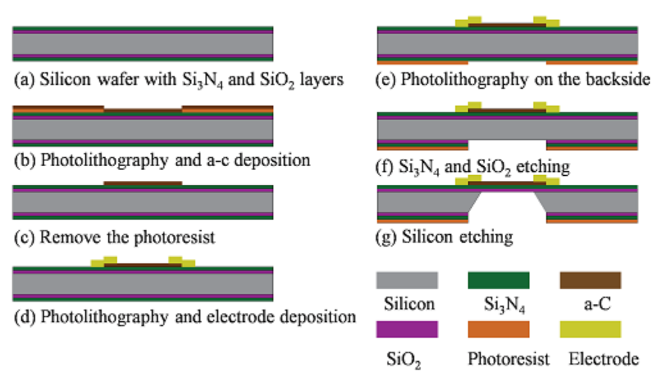

Fig. 4. Fabrication process of the micro pressure sensor.

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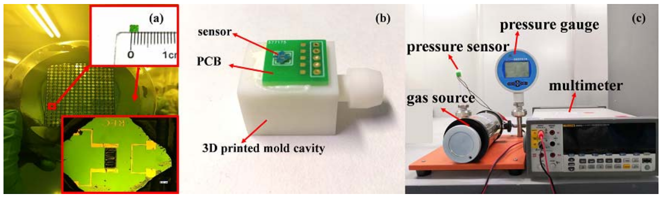


Fig. 5. (a) Fabricated micro pressure sensor. (b) Packaged pressure sensor; (c) Setup to characterize the pressure sensor.

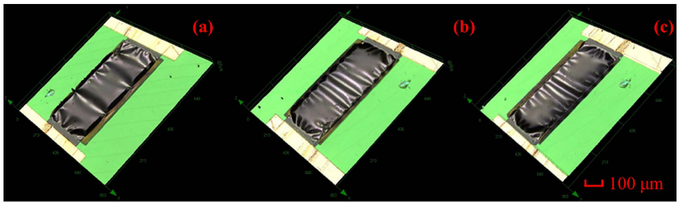


Fig. 6. The film's appearance when the (a) Δp=0; (b) Δp>0 and (c) Δp<0.

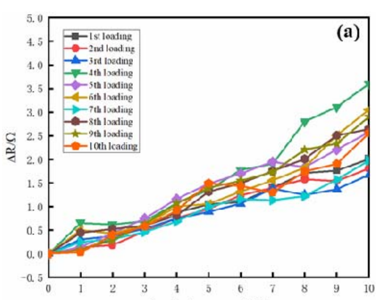
utilized to ensure air tightness. Then gold wires are used to connect the pads on chip and PCB. The experimental setup to characterize the micro pressure sensor is shown in Fig. 5(c).

In order to observe the change of the film appearance, the micro pressure sensor is placed under the Confocal Laser Scanning Microscope. When air is squeezed into or withdrawn from the cavity of the 3D printed model, a pressure difference Δp generates between the outside and inside surfaces of the film. Fig. 6.(a)-(c) show the film's appearance when Δp=0, Δp>0 and Δp<0, respectively. Compared with the normal state, the film expands when air is squeezed into the cavity and shrinks when air is extracted.

When the pressure load is applied, the resistance of the a-C film will change because of its piezoresistive effect. To test the sensor's performance, a multimeter (FLUKE 8846A) is used. Fig. 7(a) shows the resistance signal of the sensor, while the applied pressure started from 0 KPa to 10 KPa for 10 times. Fig. 7(b) shows the resistance signal of loading and unloading testing, each step is 1 KPa. Thus, the sensitivity of the micro pressure sensor is 0.289 Ω/KPa.

B. Analysis of the wrinkles

As shown in Fig. 6(a), the film without applied pressure has several wrinkles instead of perfect flat surface. It is suspected that the wrinkles may be caused by the release of internal compressive stress which is generated during the DC deposition of the a-C. For the purpose of exploring the origin of the wrinkles, FEM method is used to verify the assumption, as shown in Fig. 8, when an initial internal compressive stress



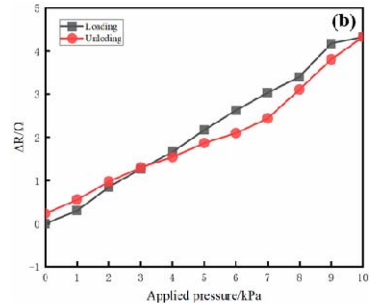


Fig. 7. The resistance signal of the micro pressure sensor.

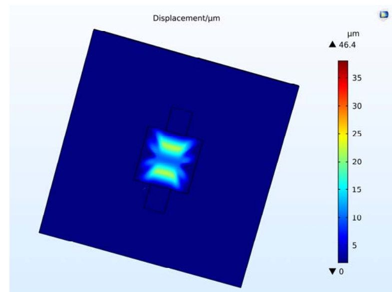


Fig. 8. Wrinkles caused in the film by initial internal compressive stress in the simulation.

is applied to the a-C film in the simulation process, the same wrinkles appear as in the actual experimental situation, which proves that the previous assumption is correct.

According to the testing results, the micro pressure sensor can still detect the change of micro pressure sensitively although the existence of the wrinkles. Sensor's performances may be affected by wrinkles, but it can be eliminated by leaving dozens of microns of silicon beneath the film.

IV. CONSLUSION

A micro pressure sensor based on ultra-thin (785 nm) sensitive film layers (a-C/Si_3N_4/SiO_2) has been presented in this paper, in which the a-C film(300 nm) is sensitive elements. The design method, fabrication process and testing result have been reported. According to the testing results, although there are several wrinkles appear in the film, within the range 0-10 KPa, a sensitivity of 0.289 Ω/KPa is obtained. These results demonstrate the effectivity of the design and fabrication technology of the micro pressure sensors and indicate that a-C is a potential sensitive and structural material to apply in MEMS field.

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