Single carbon fiber as a sensing element in pressure sensors

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The principal and innovative concept of this research is the replacement of piezoresistors in the current piezoresistive pressure sensors with carbon fibers. The piezoresistive characteristics of carbon fibers can play the same role as piezoresistors in current pressure sensors. The main structure of pressure sensors was built by back side etching on a silicon-on-insulator wafer to create a square diaphragm. Dielectrophoresis was used for the alignment and deposition of carbon fiber across the gap between two electrodes. The fabricated pressure sensors clearly showed linear response to applied pressure, so the feasibility of carbon-fiber-based pressure sensors was demonstrated.
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Pressure sensors are extensively used in many engineering fields. In general, all pressure sensors that are commercially available can be grouped into four categories according to their sensing principles: piezoelectric, piezoresistive, capacitive, and optical.[1,2] Among the many silicon-based microsensors, piezoresistive pressure sensors are one of the widely used products of microelectromechanical system technology. Piezoresistive pressure sensors use silicon's or germanium's piezoresistive effect that is greater than that of other metals. Piezoresistivity is a material property where an electric resistance of a material is influenced by the mechanical stress applied to the material. The basic structure of a piezoresistive pressure sensor consists of a thin silicon diaphragm with four diffused sensing piezoresistors in a closed Wheatstone bridge configuration. When pressure is applied, the force on the sensing element results in the deformation of the sensing element. This deformation changes the resistance of the element and the electrical output of the sensor. Compared to other types of pressure sensors, the piezoresistive transducer provides several advantages such as mechanical stability despite its lightweight and small size, inherent high gauge factors, and low output impedance. But it also has some drawbacks such as significant power requirement, large offset due to temperature dependency,[3–5] and nonlinearity.

This research reports the fabrication and characterization of a pressure sensor using a pitch-based carbon fiber as its sensing elements. The principal concept behind this type of pressure sensor is the replacement of the piezoresistors in the current piezoresistive pressure sensors with carbon fibers. Current piezoresistors are normally made from highly doped silicon thin films. The carbon fibers can play the same role as piezoresistors in the proposed pressure sensors.[6] Because the piezoresistors are replaced with carbon fibers, several advantageous characteristics of carbon fibers can be utilized. Compared with the conventional pressure sensors, the carbon-fiber-based pressure sensors may possess superior sensitivity because the piezoresistive behavior of carbon fibers is highly sensitive to very small deformations of the carbon fibers. The pressure sensing ranges can be extended by appropriate arrangement of different types and sizes of carbon fibers.

The basic structure of a carbon-fiber-based pressure sensor (4.0×4.0 mm^2) fabricated in the present work is shown in Fig. 1. It consists of a thin silicon diaphragm (1.5×1.5 mm^2) with carbon fibers deposited at locations where resistors used to be. The performance characteristics are expected to be strongly dependent on the electrical properties of carbon fibers as well as the geometry of the diaphragm, namely, its area and thickness, and the positions of carbon fibers. Among the many proposed techniques to produce uniform thickness in the whole region of the diaphragm, a simple and robust fabrication method based on silicon-on-insulator (SOI) substrates was adopted. The key point of the

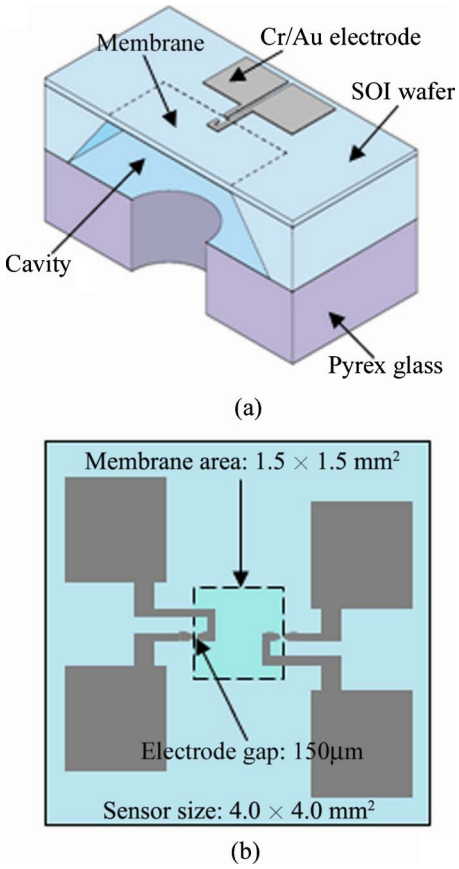

FIG. 1. (Color online) Schematics of the pressure sensor: (a) cross section view and (b) top view.

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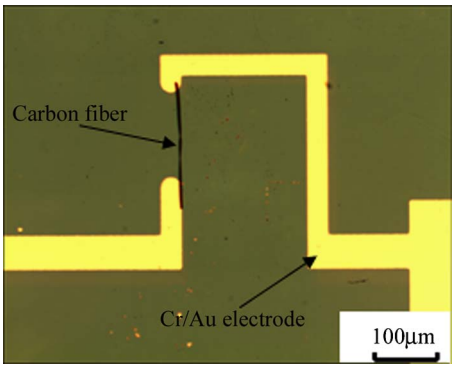

FIG. 2. (Color online) Carbon fiber assembled between two electrodes (D =7.22 μm, L=203 μm).

adopted method is the use of the buried oxide in SOI wafers as an etch-stop layer. The structure of SOI wafers consists of two silicon layers on the top and bottom separated by a silicon dioxide layer. The top silicon layer constitutes the diaphragm of the sensor. Considering the different ranges of applied pressure, pressure sensors with two different thicknesses of the diaphragm, namely, 3 and 21 μm, were fabricated.

The geometric configuration of the carbon fiber location will strongly affect the characteristics of the pressure sensors. An optimal position of the carbon fiber on the diaphragm for maximum sensitivity was determined by numerical analysis using a commercial program, ANSYS. The distributions of stress, strain, and deflection of the diaphragm were analyzed. The results showed that the diaphragm exhibited maximum stress at the middle edge of the diaphragm. Hence, the carbon fibers were designed to be oriented from the middle edge toward the center of the diaphragm between two electrodes of 150 μm gap distance and 0.1 μm thickness. The diaphragm deflection for the 21 μm diaphragm thickness increased linearly by 0.5 μm/bar at applied pressure between 0 and 3 bars. For the 3 μm diaphragm thickness, the deflection was 80 μm/bar at applied pressure between 0 and 1 bar; this deflection amount was about 160 times higher than that for the thicker diaphragm. The deflection of the diaphragm was measured by a laser vibrometer having a resolution of 10 nm. The laser was focused on a point 110–120 μm away from the middle edge of the diaphragm between the two electrode gaps. The measured diaphragm deflection by the laser vibrometer showed good agreement with that by the numerical analysis.

The fabrication of pressure sensors was accomplished in two steps. The main structure without carbon fibers was fabricated by the following process sequence. A 250 nm thick layer of Si_3N_4 was deposited on both sides of a 4 in SOI wafer by using low pressure chemical vapor deposition. Next, a layer of Au/Cr with thickness of 1500/300 Å was e-beam evaporated on top of an AZ-5124 photoresist pattern, and the gold electrodes were structured with a lift-off process. The back side nitride was patterned by photolithography and removed by reactive ion etching. Next, the back side silicon was etched with tetramethylammonium hydroxide solution. This etching process was automatically stopped at the SiO_2 buried layer. The buried oxide layer was removed by wet etching in buffered hydrogen flouride solution.

After the main structure was made, the principle of dielectrophoresis[7–9] was utilized to attract and orient carbon fibers across the microscale gap between the two electrodes. Carbon fibers used in the present work were pitch-based carbon fibers obtained from heat treatment at 1000 °C, and they were conductive with a specific resistivity of about 6.0 $\times 10^{-3}$ Ω cm. The carbon fibers were dispersed in an ethanol solution, and the suspended solution of the carbon fibers was sonicated for several hours to disentangle and disperse the fibers in the solution. A drop of the solution was applied on the gap between the electrodes where the biased ac electric field was applied. Positive dielectrophoretic forces were induced from the higher polarizability of the carbon fibers surrounded by a lower polarizable medium (ethanol) with a nonuniform electric field. This method is much cheaper and simpler than the complex fabrication processes of current piezoresistors, and it can be performed at room temperature. A carbon fiber (L=203 μm, D=7.22 μm) deposited between two metal electrodes is shown in Fig. 2. The contact between the carbon fibers and electrodes is not good because the carbon fibers were positioned smoothly between the electrodes. To reduce the contact resistance, Au was selectively deposited on top of the carbon fiber. After this deposition, the resistance of the carbon fiber shown in Fig. 2 reduced by about six times, namely, from 2.567 to 0.492 kΩ.

The experimental setup consisted of the gas supply system to the cavity, a laser vibrometer to measure the deflection of the diaphragm, and a measurement system of the resistance change of the carbon fiber. The fabricated pressure sensor was bonded to Pyrex glass by anodic bonding method and was sealed completely by epoxy bonding to prevent gas leakage. The applied pressure to the cavity from high pressure N_2 cylinder was minutely controlled by a pressure regulator. The electrodes on the diaphragm were connected to contact pads on the board by using a wire bonder. With applied pressure, both the diaphragm and accordingly the carbon fiber experience deformation, changing the resistance of the carbon fiber. The resistance change was measured by using a sourcemeter, supplying a constant 1 mA current to the carbon fiber. The experimental conditions and characteristics of the carbon fibers used are shown in Table I.

The resistance change of the carbon fibers are shown in Fig. 3, which clearly shows the linear response to the applied

TABLE I. Experimental conditions and characteristics of carbon fibers.

Case	Length (μm)	Diameter (μm)	Resistance at 22 °C (R_0, kΩ)	Diaphragm thickness (μm)	Pressure range (bar)
A-1	250	13.42	1.9835	21	0–3
A-2	172	8.54	1.7122	21	0–3
A-3	193	7.07	2.1123	21	0–3
B	246	8.25	0.4927	3	0–1

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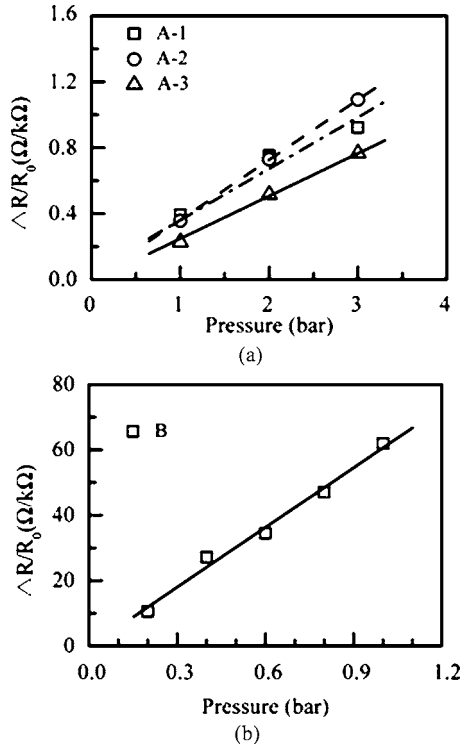

FIG. 3. Change in resistance of a carbon fiber according to applied pressure: (a) $t=21$ μm, and (b) $t=3$ μm.

pressure. This result clearly demonstrated feasibility of carbon-fiber-based pressure sensors. The sensitivity of pressure sensors, S ($\Omega/k\Omega$ bar), is defined as follows:

$$S = \frac{\Delta R}{R_0}\frac{1}{\Delta p}. \tag{1}$$

Here, $\Delta R(\Omega)$ is the change of resistance, R_0 is the initial resistance (kΩ), and Δp is the pressure difference (bar). The calculated sensitivities of pressure sensors with 21 μm diaphragm thickness were 0.31, 0.35, and 0.25 $\Omega/k\Omega$ bar for the cases of A-1, A-2, and A-3, respectively. For the pressure sensor with 3 μm diaphragm thickness, the sensitivity was 61.8 $\Omega/k\Omega$ bar, which was 200 times higher than that for the pressure sensor with thicker diaphragm. The thinner diaphragm deformed more for the same applied pressure, resulting in higher deformation and resistance change of the carbon fibers.

The gauge factor K is defined as

$$K = \frac{\Delta R}{R_0}\frac{1}{\varepsilon}. \tag{2}$$

Here, ε is the strain of the piezoresistors. Pressure sensors with higher gauge factors have superior sensitivity. The gauge factor of conventional piezoresistive pressure sensors is approximately 100. It is difficult to obtain the gauge factor of carbon fiber resistors because the exact strain value of a carbon fiber cannot be known. Using the strain value of the diaphragm instead of that of the carbon fiber, the calculated gauge factor was approximately 50, which was on the same order as that of conventional piezoresistive pressure sensors.

The effect of temperature on the resistance of a carbon fiber was also investigated. As the temperature changes from room temperature to 250 °C, the resistance of a carbon fiber decreases by about 8.5% from that at room temperature. Silicon piezoresistive pressure sensors cannot be properly operated beyond 150 °C due to the rapid increase of leakage current through the p-n junction.[10] On the other hand, in the present pressure sensor, no current leaked between carbon fibers and the wafer because of the insulating nitride layer.

In conclusion, carbon-fiber-based pressure sensors, which were fabricated and tested in the present research, showed satisfactory sensing characteristics with cheap, fast, and simple fabrication processes adopting SOI wafers and dielectrophoresis method. The results demonstrate the feasibility of carbon-fiber-based pressure sensors as future pressure sensors.

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