EVALUATION OF THE PERFORMANCE OF PIEZORESISTIVE STRAIN SENSORS BASED ON DIFFERENT SEMICONDUCTOR THIN FILMS

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Abstract. *The increasing demand for microelectromechanical systems (MEMS) piezoresistive sensors with capability to operate at high temperature mainly for automotive, petrochemical and aerospace applications has stimulated the research of materials to substitute the silicon in the fabrication of these sensors. It is known that silicon sensors have low performance in aggressive environments. Motivated by this, here we have reported the fabrication and characterization of strain sensors based on undoped and nitrogen-doped silicon carbide (SiC) and diamond-like carbon (DLC) thin films for high temperature applications. The structure of each sensor consists of four thin-film resistors, configured in Wheatstone bridge, with Ti/Au electrical contacts fabricated by photolithography, lift-off and reactive ion etching (RIE) processes. The strain sensors were characterized by beam-bending experiments where one sensor of each type was glued near the clamped edge of a stainless steel cantilever beam and on the free edge were applied different loads. The electrical resistance of each sensor was measured without applied load on the beam and during subsequent tensile load. The temperature coefficient of resistance (TCR) measurements were also carried out to evaluate the performance of the sensors up to 250ºC . It was observed that the DLC strain sensor exhibits greater GF and smaller TCR that the strain sensors based on SiC. Besides, it was observed that the types of materials used exhibit smaller TCR that the silicon which indicate that use them can be a good alternative to better the performance of piezoresistive sensors at high temperatures.*

Keywords*: silicon carbide, diamond-like carbon, nitrogen doping, piezoresistive strain sensors*

1. INTRODUCTION

Semiconductor thin films materials with a large piezoresistive effect are suitable materials for the development of strain sensors due to their low-cost fabrication, compatibility with integrated circuits and possibility of deposition on different substrate types (Neumann, 2001). Nowadays, strain sensors are used in several fields of experimental stress analysis such as deformation monitoring of components as a building, pressure data collecting in gas turbine engines, high-pressure fuel systems and even aerospace applications (Stauffer et al., 2006). Moreover, testing of components using strain sensors are commonly employed in automotive and aeronautics industry (Gregory et al., 1997). A piezoresistive strain sensor operates on the principle that its electrical resistance changes when it is elastically deformed by an applied stress. A limitation to use some semiconductor materials, as for example the silicon, as piezoresistive sensing elements is that their resistance also changes as the temperature changes. An alternative to solve this limitation is use semiconductor materials for high temperature applications such as silicon carbide (SiC) and diamond-like carbon (DLC).

In previous works (Fraga et al., 2010a, b), we showed the influence of the temperature on piezoresistive properties of undoped and nitrogen-doped SiC films obtained by PECVD (plasma enhanced chemical vapor deposition). Besides, we compare the results of these sensors with the based on SOI (Silicon-On-Insulator) substrates (Fraga et al., 2010c). In our most recent study, we compare the performance of strain sensors based on TiO_2, DLC and SiC films produced by RF magnetron sputtering (Fraga et al. 2011). Here we extend this study by evaluating sputtered nitrogen-doped DLC and SiC films. The structure of each strain sensor is composed of four SiC (or DLC) thin-film resistors, configured in Wheatstone bridge, with Ti/Au electrical contacts fabricated on thermally oxidized Si substrates. Two types of measurements were performed to evaluate the performance of the sensors: gauge factor (GF) and temperature coefficient of resistance (TCR).

2. EXPERIMENTAL

2.1. Sample preparation

Silicon carbide and DLC thin films were deposited onto thermally oxidized p-type (100) Si substrates by magnetron sputtering. In Table 1 are summarized the deposition conditions of the films. Doping of each film type was achieved by nitrogen gas addition during deposition process.

Table 1. Deposition conditions of the SiC and DLC films

Sample	Target	Ar flow (sccm)	N_2 flow (sccm)	CH_4 flow (sccm)	Target-substrate distance (mm)	Power (W)	Deposition time (min)
1	SiC	7.0	-	-	75	200	120
2	SiC	7.0	0.7	-	75	200	120
3	graphite	4.5	-	0.5	90	150	60
4	graphite	4.0	0.5	0.5	90	150	60

The composition, thickness, resistivity and elastic modulus of the films were investigated respectively by Rutherford back scattering (RBS), profilometry, four-point probe and nanoindentation techniques. The RBS measurements were carried out using a 2MeV He^+ beam and the RBS spectra were analyzed using a RUMP code (RBS spectroscopy analysis package). The thickness of each sample was obtained by measuring step heights using a TENCOR Alpha-Step 500 profilometer. A four-point probe type VEECO FPP-5000 was used to measure the resistivities of the samples. Elastic modulus of the films were determined by nanoindentation technique using a Hysitron triboindenter. In this technique, a controlled load was applied to a diamond tip in contact with the surface. The continuos measurement of the tip displacement as the applied allowed the construction of load-unload curves. The nanoindentation depth did not exceed 10% of the film thickness.

2.2. Fabrication of the strain sensors

The process of fabrication of the strain sensors is illustrated in Figure 1 and it can be summarized in the following steps:

a) Thermal oxidation of Si substrates;

b) Deposition of the SiC or DLC thin film by magnetron sputtering;

c) A layer of 35 nm of Ti was sputtered onto the film. Subsequently, a layer of 250 nm of Au was sputtered onto the Ti layer.

d) The next step was to define the geometry and the size of the Ti/Au electrical contacts by standard lithographic procedure.

e) Unwanted Ti and Au were etched using etchant solution.

f) After the fabrication of the contacts, a second litography was done to define the geometry and the size of the thin-film resistors.

g) The film on the regions not protected with photoresist was etched by reactive ion etching using SF_6+O_2 gases mixtures.

h) Strain sensor final structure.

In Figure 2 is shown the optical image of one DLC strain sensor fabricated. For each film type deposited on SiO_2/Si substrate (1/4 of 3 in. wafer), it were fabricated 50 strain sensors. Some sensors were fabricated using photolithographic techniques in conjunction with lift-off processes. In this case the fabrication sequence shown in Figure 1 is changed; the photolitography step to define the electrical contacts is performed before deposition of Au and Ti layers. After the deposition, the lift-off is performed by immersing the samples in acetone.

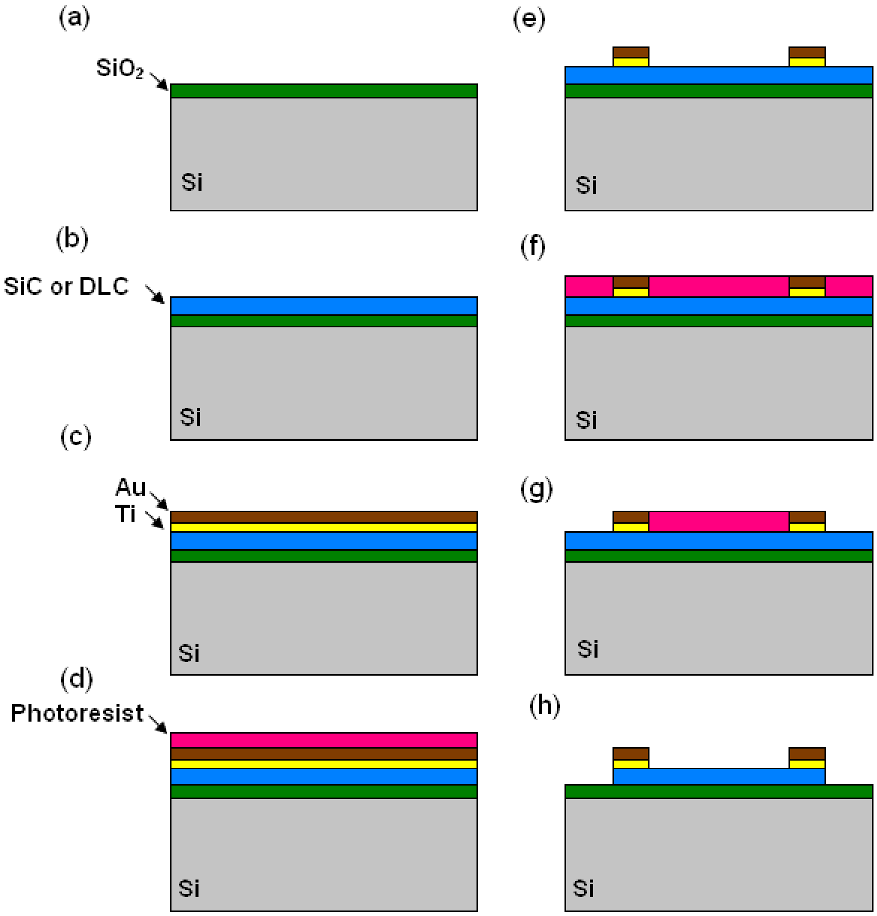

Figure 1. Fabrication steps of the SiC or DLC strain sensors

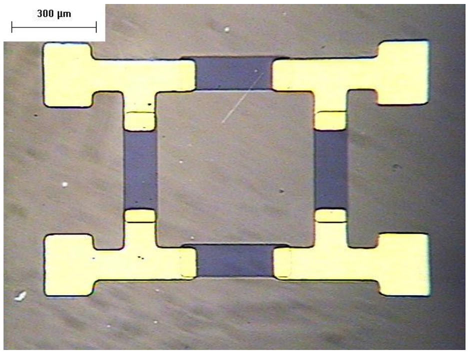

Figure 2. Image of the DLC strain sensor obtained by optical microscopy

2.3. Characterization of the strain sensors

The strain sensors fabricated were characterized using the beam-bending method. One strain sensor of each type was glued with epoxy onto a stainless steel cantilever beam (120 x 25 x 1.2 mm) and cured at temperature of 120 ºC during for 30 min. Calibrated weights are applied to the free end of the beam (see Figure 3). The beam bending produces a uniaxial surface strain across the lenght of the beam. The electrical resistance of each strain sensor was measured without applied load on the beam and during subsequent tensile loading using a digital multimeter. The electrical resistance changes were then calculated by:

$$\frac{\Delta R}{R} = \frac{R_f - R_0}{R_f} \tag{1}$$

Where R*o* and R*f* are is the electrical resistance without and with applied load on the beam respectively. The piezoresistive coefficient of each thin-film resistor can be obtained from equation that describes the piezoresistive effect (Singh et al., 2001)

$$\frac{\Delta R}{R} = \pi_l (1 - \upsilon)\sigma_l \tag{2}$$

Where π_l is the piezoresistive coefficient, υ is the Poisson's coefficient and σ_l is the longitudinal mechanical stress.

In the case of the cantilever beam clamped at one end and free at the other, the longitudinal mechanical stress is defined by (Beer and Russel, 1995)

$$\sigma_l = \frac{6FL}{bt^2} \tag{3}$$

Where F is the weight of the block placed on free end of the beam, L, b and t are the lenght, width and thickness of the beam respectively. The sensitivity of a strain gauge is generally termed the gauge factor. This is a dimensionless quantity and is given by (Jahsman, 1979)

$$GF = \frac{\Delta R}{R}\frac{1}{\varepsilon} \tag{4}$$

Where ε is the strain that can be calculated by the equation:

$$\varepsilon = \frac{\sigma_l}{E} \tag{5}$$

Where E is the elastic or Young's modulus.

Figure 3. Photograph of the experimental setup for characterization of the strain sensors

3. RESULTS AND DISCUSSION

3.1. Properties of the SiC and DLC thin films produced

Table 2 summarizes the properties of the SiC and DLC thin films produced. It was observed that the introduction of N_2 reactive gas in the deposition process promotes a decrease in Si and C atom concentrations (approx. stoichiometric to sample 1) in the SiC film. It can be also observed that undoped SiC film presents higher resistivity and lower elastic modulus that the DLC films. Moreover, the XRD analysis showed that all the film types produced are amorphous.

Table 2. Properties of the SiC and DLC films

		Composition					
Sample	Film	Si (%)	C (%)	N (%)	Thickness (nm)	Resistivity (Ω.cm)	Elastic modulus (GPa)
1	SiC	51	49	-	810	2.5×10^5	40
2	doped SiC	28	24	46	750	2.27×10^5	60
3	DLC	-	93	-	360	1.0×10^5	85
4	doped DLC	-	77	21	420	4.2×10^3	78

3.2. Gauge Factor (GF) of the strain sensors fabricated

The change in resistance as a function of the applied stress on the beam is showed in Figure 4. For all types of sensors, the resistance constantly increases as the applied stress increases. In Figure 5 is given the gauge factor (GF) obtained by the slope of the relative change in resistance (ΔR/R) plotted as a function of the strain. It was obtained a GF of 64 for the strain sensor based on undoped DLC thin film and GF of 20 for the based on SiC film.

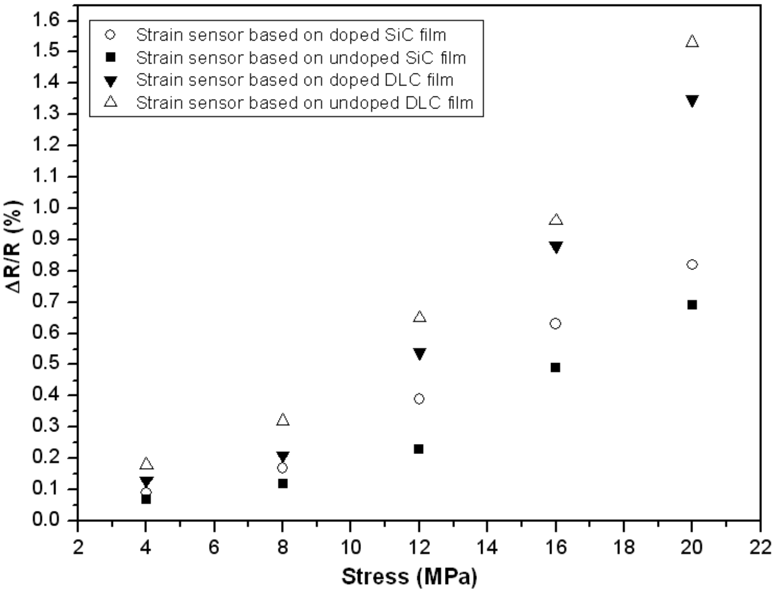

Figure 4. The relative change in resistance (ΔR/R) of the strain sensors as a function of the applied stress

It was observed that the nitrogen doping reduces the GF of the DLC thin film for 62 and increases the of the SiC film for 24. This result obtained for sputtered SiC film is similar to that observed in our previous work on the influence of nitrogen doping on the piezoresistive properties of PECVD SiC film (Fraga et al., 2010b) .

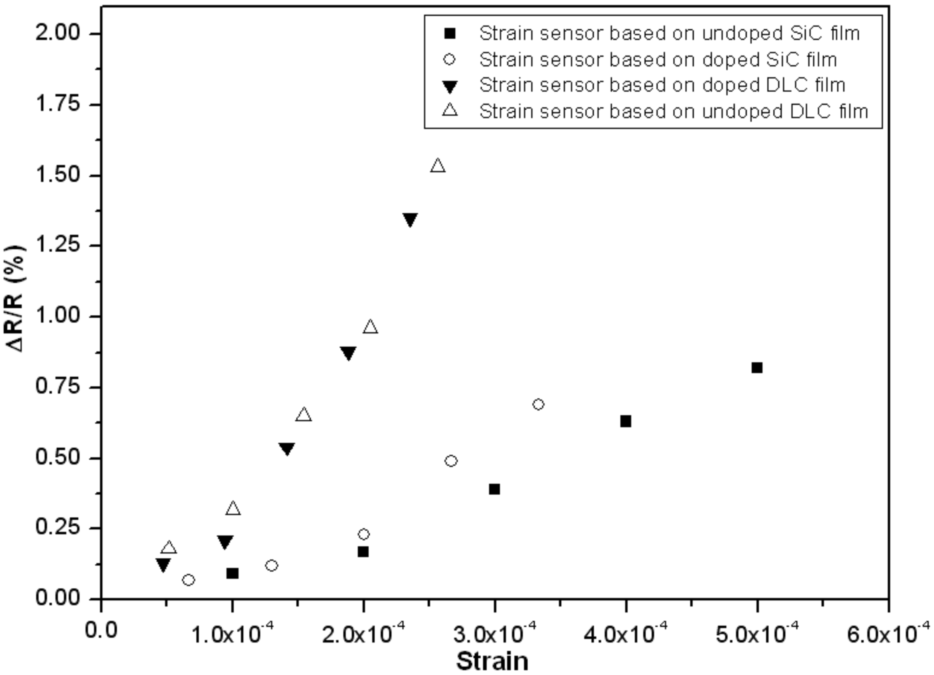

Figure 5. Gauge factor measurements, the relative change in resistance (ΔR/R) as a function of the applied strain (ε).

3.3. Temperature coefficient of resistance (TCR) of the strain sensors fabricated

In order to evaluate the influence of the temperature, the resistance of each strain sensor type was measured incrementally from room temperature up to 250ºC. This experiment allowed to determine the temperature coefficient of resistance (TCR). This coefficient is defined by :

$$TCR = \frac{\Delta R}{R}\frac{1}{\Delta T} \tag{6}$$

Where ΔT is the change in temperature. The TCR describes the parts per million change in resistance for every one degree change in temperature.

TCR measurements are presented in Figure 6. It can be observed that all strain sensors exhibited a positive TCR values and that the strain sensor based on doped DLC thin film present the smaller value. It was observed that the addition of nitrogen in deposition process reduced the TCR of the DLC films whereas increases othe SiC film. The films investigated in this work have TCR between 32 and 53 ppm/ºC. It was known that the the silicon has TCR of the order of 1000 ppm/ºC (Ku, 1977) which show that DLC and SiC films are more appropriate than the silicon for high-temperature applications.

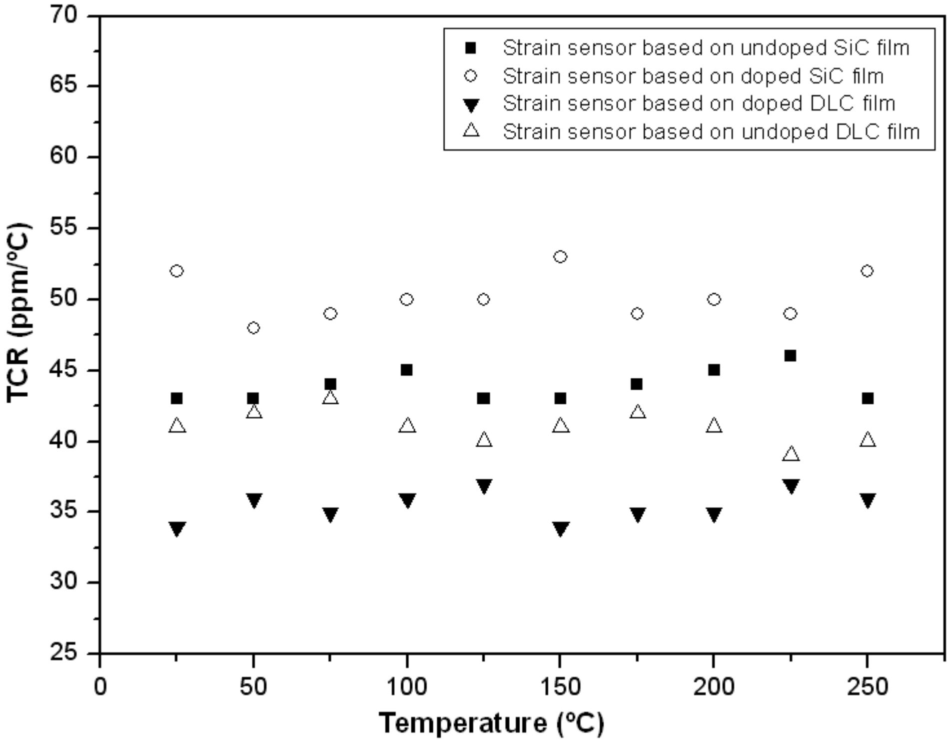

Figure 6. TCR measurements of the strain sensors fabricated

4. CONCLUSIONS

In summary, this work reported the fabrication and characterization of piezoresistive strain sensors based on SiC and DLC films produced by RF magnetron sputtering. The measurements results of the sensors indicate that among the films used the undoped DLC film exhibits the greater gauge factor (GF) whereas the nitrogen-doped DLC film the smaller temperature coefficient of resistance (TCR) up to 250ºC. In addition, it was observed that the four film types used exhibited TCRs significatively smaller that the silicon. These preliminary results indicate that the films studied in this work can be a good alternative to silicon for the development of high temperature strain sensors.

5. ACKNOWLEDGEMENTS

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