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Piezoresistive response of ITO films deposited at room temperature by magnetron sputtering

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Abstract Indium tin oxide (ITO) thin films have been deposited on (100) Si substrates by RF magnetron sputtering from a compact target (90% In_2O_3–10% SnO_2 in weight) with 6 in. in diameter. In order to perform electromechanical characterizations of these films, strain gauges were fabricated. An experimental set-up based on bending beam theory was developed to determine the longitudinal piezoresistive coefficient (π_l) of the strain gauges fabricated. It has been confirmed that electrical resistance of the strain gauges decreases with load increases which results a negative gauge factor. A model based on the activation energy was used to explain the origin of this negative signal. The influence of the temperature on piezoresistive properties of ITO films was also evaluated.

Introduction

Indium tin oxide (ITO) thin films produced by RF magnetron sputtering technique are degenerate semiconductor materials, with wide band gap and high conductivity, which exhibit strong piezoresistive properties comparable to N-type monocrystalline silicon which become then promising for strain sensors applications [1, 2].

Several deposition techniques have been used to produce ITO thin films. Among these techniques, magnetron sputtering is one of the most attractive because of the good reproducibility of the film properties, low temperature deposition, and good uniformity in large areas [3]. New substrates with thermally unstable behavior such as plastic and organic materials require very low substrate temperatures during the deposition process.

The literature [1, 4, 5] shows that one of the main applications of ITO films is in the development of liquid crystal displays. Besides this, these films have been employed in a vast number of active and passive electronic and optoelectronic devices [6, 7].

In the last years, the ITO films and other transparent oxides started to be used in the development micro-electromechanical systems (MEMS) devices because of the sensitivity of these materials to mechanical, electrical, and thermal stimuli [8].

In this context, some studies have been performed on piezoresistive properties of ITO thin films [9]. The piezoresistivity effect refers to a material property that is defined as resistivity change due to the applied mechanical stress. The possibility of produced ITO films at low temperature with appropriate properties is important for strain sensors applications. In this work, we investigate the piezoresistive properties of ITO thin films deposited on Si substrates at room temperature by RF magnetron sputtering of an ITO target in Ar + O_2 atmosphere. Strain gauges were fabricated on the films produced. In order to determine piezoresistive coefficient and gauge factor of these films, one strain gauge was bonded near the clamped end of a stainless steel cantilever beam and different loads were applied on free edge.

Experimental procedure

ITO films were prepared in an RF magnetron sputtering system, equipped with a turbo molecular pump and a

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mechanical vane pump, using a compact ITO target (90% In_2O_3–10% SnO_2 in weight) on the following deposition conditions: pressure (5×10^6 Torr), RF power (75 W), argon flow rate (24 sccm), deposition time (120 min), and distance target–substrate (100 mm). Three different film compositions were obtained by varying oxygen concentration in gas mixture from 0 up to 10%. The p-type silicon wafers with 3-inch in diameter and 10 Ω cm resistivity were used as substrate. These wafers were cleaned in a standard Piranha solution ($H_2SO_4/H_2O_2 \rightarrow 4:1$), during 10 min at 115 °C, and subsequently in hydrofluoric acid ($H_2O/HF \rightarrow 20:1$). The film thicknesses were measured using a Dektak 3030 high-step meter and the resistivity was determined by free-carrier density and Hall mobility using four-point probe technique and H-50 Hall-Van Der Pauw Controller. Influence of deposition parameters on structural of ITO films were studied in previous work [10].

In this work, we fabricate strain gauges to perform the electromechanical characterization of ITO films using an experimental set-up based on bending beam method as shown in Fig. 1.

The strain gauges consist of one ITO thin-film resistor with one silver pad at each extreme as shown in Fig. 2. Strain gauges were cut and glued with epoxy on a stainless steel cantilever beam (1.08 mm of thickness, 32.23 mm of width, and 138.41 mm of length). The samples were submitted to cure process at 150 °C for 90 min in a climatic chamber under nitrogen environment.

An Agilent 34411A digital multimeter was used to measure the electrical resistance of the strain gauges for each applied load on beam. A microcontrolled-climatic chamber was used to characterize the influence of the temperature on piezoresistive properties of ITO thin films.

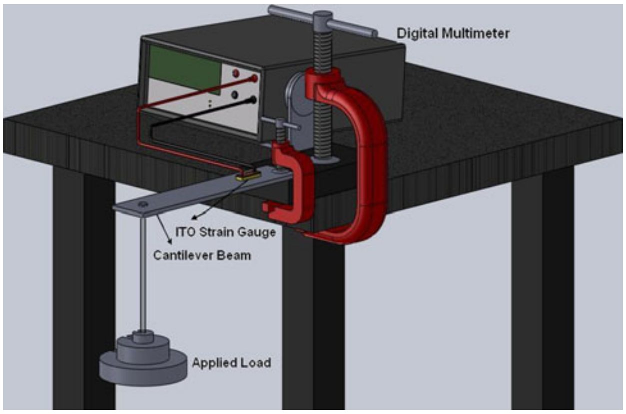

Fig. 1 Experimental set-up for piezoresistive characterization of ITO thin films

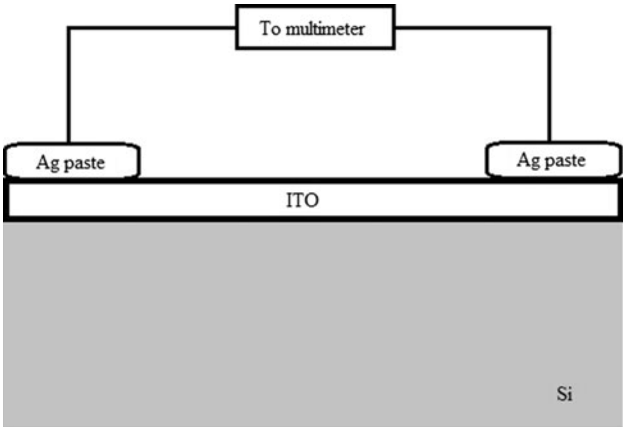

Fig. 2 Schematic diagrams of typical ITO strain gauge structure to determine the electrical, thermal, and mechanical characteristics

Results and discussion

The four-probe measurements show that the ITO films has resistivity of 7.37×10^{-4} Ω cm and by Hall effect was obtained 5.92×10^{-4} Ω cm. These values are similar to those typically reported in the literature for transparent electrode applications [4, 12]. A particular feature of these amorphous materials is that its electrical properties depend on the deposition conditions.

High values of carrier density (2.3×10^{20} cm^{-3}) and carrier mobility (53.4 cm^2/Vs) of the ITO films were obtained indicating that this material is degenerated.

After the strain gauges fabrication, the bending-beam method was used to investigate the response of ITO films to mechanical strain according to theory of small deflections [11]. Figure 3 shows the resistance change as a function of applied mechanical tensile strain. As can be

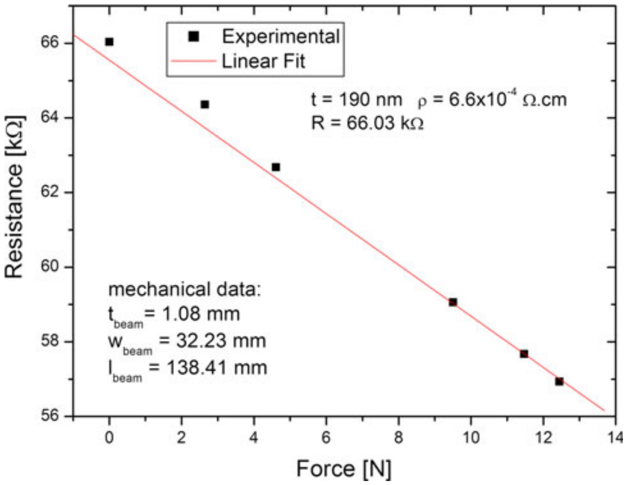

Fig. 3 Electrical resistance as a function of the mechanical applied force

observed a typical linear piezoresistance response was obtained.

It is known that amorphous films have no preferred orientation due to applied mechanical stress, therefore, they assume axial force direction. In the case of a particular device, to calculate its sensibility a combination of the applied mechanical stress and the relative resistance variation is considered.

In order to determine the gauge factor of the ITO thin film strain gauge, the cantilever beam was deflected by the applied load and the strain was determined through beam theory. The strain gauges were subjected to a maximum force equivalent to 9.5 N.

The piezoresistive coefficient of the ITO films resistor was obtained from equation that describes the piezoresistive effect:

$$\frac{\Delta R}{R} = \pi_l(1 - \nu)\sigma_l \qquad (1)$$

where σ_l is longitudinal mechanical stress and ν Poisson ratio.

The GF or mechanical sensitivity was calculated by the following equation:

$$\mathrm{GF} = \frac{\Delta R}{R}\varepsilon \qquad (2)$$

where $\Delta R/R$ is the fractional change in electrical resistance of the piezoresistor, ε is the strain calculated by

$$\varepsilon = \frac{\sigma}{E} \qquad (3)$$

where E is the elasticity modulus and σ is the mechanical stress.

The applied force (F) in the ITO film can be used to calculate the strain and stress at a given point on the beam from the knowledge of the beam geometry using the equation

$$F = \frac{wt^2}{6_l}\sigma \qquad (4)$$

where w, t, and l are the width, thickness, and length of the beam, respectively.

Figure 4 shows the results obtained. In piezoresistive sensors, it is possible to obtain the relationship between the mechanical and electrical properties of the material when we assume that the change in resistivity is associated to mechanical deformation produced from a mechanical stress. Thus, the longitudinal piezoresistive coefficient (π_l) of the samples was then calculated using the Eq. 1 that describes the piezoresistive effect [13, 14].

To obtain the piezoresistive coefficients (π_l), we assumed that the ITO films have Poisson coefficient (ν) of 0.25 and Young modulus (E) of 49 GPa [15]. π_l values were obtained between (2.4–8.7) $\times$ 10^{-10} m^2/N that are correlated to a gauge factor range of −12 and −22, respectively. Besides, the results showed a significant change in the mechanical sensitivity when the oxygen content in the films varies. The calculated and measured parameters of ITO obtained under different oxygen concentrations are summarized in Table 1.

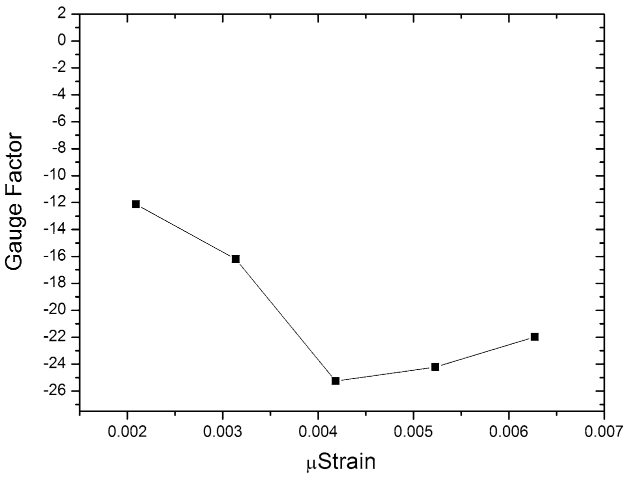

Fig. 4 Mechanical sensitivity according to the deformation of the films

Earlier studies [14, 19] reported that the signal of the gauge factor is a result of a complex competition between the bending loading conditions, Poisson ratio, wave function overlapping, and activation energy, E_a. Then, Fig. 5 shows calculated E_a as a function of GF of ITO deposited films at room temperature to provide its conduction mechanism. Theoretical models observed in the literature describe conduction in amorphous films concerning the thermal activation of electrons due to either the tunneling through a potential barrier or to a thermionic emission over the potential barrier [20, 21]. An exponential relationship was found between activation energy and gauge factor of ITO films.

The temperature effects over electrical properties were also measured in ITO films on stainless steel cantilever beam that were heated up to 245 °C in nitrogen environment are shown in Fig. 6. It was observed that the resistance decrease due thermal generation of electrons. This behavior is typical of N-type material.

Figure 7 shows the TCR measurements. For low temperature values, up to approximately 150 °C, the TCR presents high variations whereas in temperature range of 150–240 °C, it was found quasi-constant TCR value of approximately 1237.54 ppm/ °C.

As can be observed, the ITO films exhibit relatively large gauge factors, typically to semiconductors and also manifest a relatively large temperature coefficient of resistance, TCR. For mechanical stress devices, as pressure sensors, it is important to have positive and constant values

Table 1 Calculated and measured parameters of ITO films

Sample	ρ (Ω cm)	μ (cm^2/V s)	GF	π_l (m^2/N) × 10^{-10}
100% Argon	5.92–7.37 × 10^{-4}	53.4	−12 to −22	−2.4 to −8.7
5% Oxygen	4.45 × 10^{-2}	5.0	−0.07 to −0.18	−0.013 to −0.37
10% Oxygen	2.08 × 10^{-2}	5.6	−0.15 to −0.90	−0.03 to −0.18

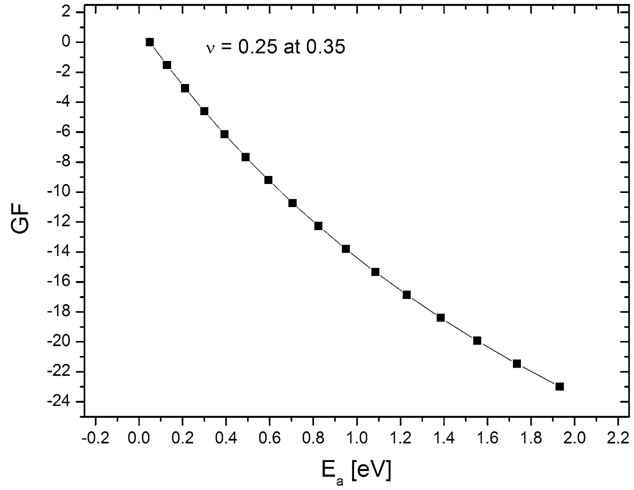

Fig. 5 Gauge factor as a function of activation energy, E_a

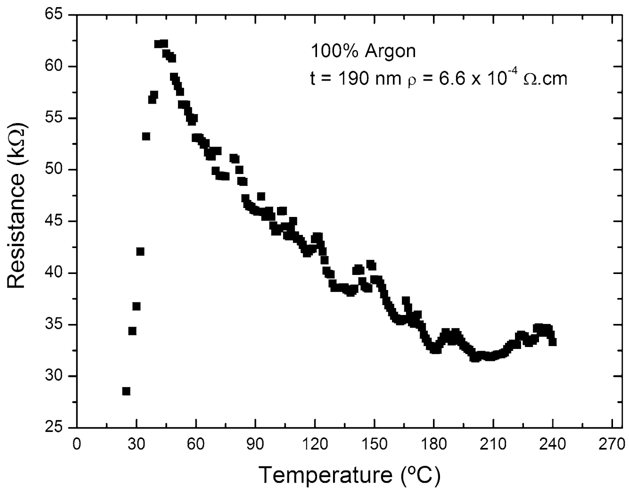

Fig. 6 Electrical resistance of ITO films as a function of operation temperature

of TCR. It makes it possible to use simple signal conditioning techniques.

In terms of piezoresistive response, the gauge factor of a metal ($2 \leq GF \leq 12$) depends mainly on its dimensional changes. However, to semiconductors ($5 \leq GF \leq 175$) as ITO, the piezoresistivity response depends largely on the variations in its energy band structure due to mechanical stress, which modify the mobility and carrier concentration values [12, 13].

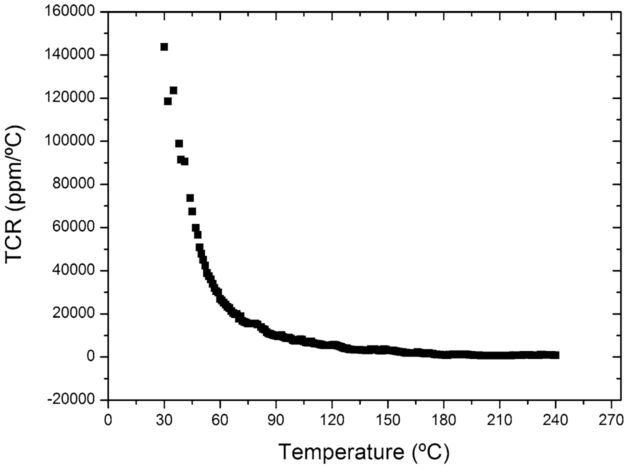

Fig. 7 Temperature coefficient of resistance, TCR, as a function of applied temperature to ITO deposited films

Gauge factor values of monocrystallyne silicon measured at high temperatures (around 100 °C) are normally in the range of 40–60, and they are dependant of the doping level. Gauge factor of n-type β-SiC varies between −3.7 and −31.8 and due to its deposition parameters (process pressure, dopant gas flow, plasma power, etc.) a positive gauge factor of around +19.2 is also possible [16, 17]. For polysilicon, the gauge factor range is from 15 to 27. However, depending on the materials doping concentration and annealing temperature its gauge factor can be influenced [18].

Deposition conditions of ITO films such as deposition rate, dopant gas flow, RF power, distance between electrodes, target quality, and pressure influence drastically the characteristics of the deposited material. To major sensing devices applications, ITO films must present as lower as possible TCR values, which are also highly influenced by deposition parameters. Wide bandgap semiconductors typically exhibit a large negative TCR while most heavily doped semiconductors end metals exhibit a much smaller positive TCR.

Conclusion

ITO films were deposited on silicon substrates by RF magnetron sputtering at room temperature. The electrical and piezoresistive properties of the ITO strain gauges were investigated using the bending beam theory. It was observed that the electrical resistance of ITO strain gauge decrease as a function of tensile stress, which indicates a typical behavior of N-type material. Besides, it was obtained gauge factor in the range of −12 to −22 and a longitudinal piezoresistive coefficient in the range of −2.4 to -8.7×10^{-10} m^2/N. The temperature coefficient of resistance (TCR) was determined and it was observed that in the temperature range of 150–240 °C present almost constant value of 1237.54 ppm/ °C, which shows the potential of ITO films to work in this temperature range. These results suggest that ITO films should be used in the fabrication process to sensing devices for relatively high temperature applications.

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