Strain sensing capabilities of Ag-sandwiched ITO as transparent thin film resistor

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Abstract: Strain sensors with good sensitivity and high optical transparency are of notable use in smart and transparent electronics which demands optoelectromechanical application. In this work, strain sensing capabilities of thin film resistor with high optical transparency is evaluated. Transparent Thin Film Resistor (TFR) was prepared by sputtering trilayer of Indium Tin Oxide (ITO) and Silver (Ag) on flexible polyethylene terephthalate (PET) substrate. ITO thin film was optimized to achieve resistivity of \( \sim 5.5 \times 10^{-4} \, \Omega \cdot \text{cm} \) with \( \sim 91\% \) optical transmission in visible wavelength. Insertion of thin silver film (\( \sim 10 \, \text{nm} \)) between ITO films by sputtering at room temperature produced film resistivity \( \sim 6 \times 10^{-5} \, \Omega \cdot \text{cm} \) and resistance \( \sim 4 \, \text{K} \, \Omega \) to serve as strain sensing layer. Longitudinal piezoresistive response was evaluated by cantilever beam bending method. Gauge factor of 3.5 \( \pm 0.3 \) and optical transmission of \( \sim 87\% \) in 400-800 nm wavelengths (visible region) was measured on the transparent TFR. Piezoresistive response was linear and reproducible with minimal hysteresis for strains up to 280 \( \mu \varepsilon \) for the measurements carried out at ambient conditions.

1. INTRODUCTION

Electronic devices are evolving continuously to catch up with the ever increasing consumer electronic demands. The research interest in the development of transparent electronics has soared in the recent years to meet the needs of futuristic devices. The existing sensors, however, are opaque due to the property of the materials employed in device fabrication. Opaque sensors have limitations in applications such as display panels, wearable electronics, transparent electronics etc. Several studies on transparent electronics have been reported [1-5]. Conductive transparent films are essential for photosensitive electronic devices such as thin film solar cells, touch screens, display technologies, wearable electronics and so on [1]. In the last decade, transparent conductive oxides are used in development of MEMS devices and tactile sensors because of its sensitivity to mechanical, electrical and thermal stimuli [2-5]. An arrangement of high optical transparency and low resistivity can be attained in two classes: (i) extremely thin films (< 10 nm) of highly conductive metals, like Ag or Au. The optical transmission can go up to 50%, and higher. Film resistivity would be couple of order higher than the bulk, (ii) wide band gap semiconductors like indium tin oxide (ITO) and Al doped Zinc oxide (AZO) exhibit good electrical conductivity and low absorption of light. The optical transmission can go up to 90% and higher. Film resistivity ranges from \( 10^{-3} \) to \( 10^{-4} \, \Omega \cdot \text{cm} \) [6,7]. Injudiciously increasing the film thickness to enhance film would in-turn increase the optical absorption too.

ITO is a promising candidate for active strain elements due to its excellent electrical and chemical stability at high temperature and relatively large piezoresistive response [8]. Piezoresistive sensors base their operating principle on the piezoresistive effect experienced by some classes of materials.
upon elastic deformation. Piezoresistive sensors are used to perform direct measurements of
dynamometric and geometric parameters. These include force, displacement, deformation, mass,
pressure, flow, level, height, torque, acceleration, cracks, creep, and fatigue [9]. Different materials,
such as pure metals or alloys, commonly nickel and copper are involved in the technological
processes for the manufacturing of piezoresistive sensors [10, 11]. More sophisticated processes are
based on thin–film, thick–film and solid state technologies. Thin film resistor with continuous
conductive film possesses the advantage of exhibiting resistance high enough for reliable measurements,
without having to increase the resistor path length. Since the resistance must follow the strain
reversibly, stability of thin film resistor is necessary to demonstrate minimal hysteresis and produce
promising repeatability [12]. In this work, thin film resistors are fabricated with high optical
transmission to evaluate its response to static strain along with stability and repeatability analysis.
Transparent strain sensor finds application in camouflaged mounting on windows, doors, windshields
to monitor structural stability, strain, vibration, shock, impact etc

2. EXPERIMENTAL DETAILS

Thin film resistors are fabricated on PET substrates. Meandering structure is patterned on substrates
by direct writing lithography method (Heidelberg Mask Writer). Radio frequency magnetron
sputtering (using Tecport Sputter Coater) is performed in the pressure range of 0.5 Pa by introducing
argon gas to deposit ITO/Ag/ITO (50/10/50 nm) trilayer (as seen in figure 1) at room temperature on
patterned substrates. The power densities employed for ITO target is 1.97 W/cm² and of Ag is 0.65
W/cm². Deposition followed by lift off of photoresist in acetone and IPA produced desired resistive
patterns on substrates with resistance ~4 KΩ. Thin copper wires are bonded to contact pads using
silver epoxy, at room temperature. M-Bond 200 adhesive is used to cement TFR firmly on a stainless
steel (SS) specimen. Cantilever beam bending method is adopted to evaluate longitudinal
piezoresistive response of transparent TFR. To study device response to the longitudinal tensile stress,
bending moment is applied to the cantilever beam by fixing one end of the stainless steel specimen to
a mechanical wise and deflecting the other end progressively using a height gauge (figure 2). The
known deflection of the beam is converted into respective force and strain values. The SS test
specimen is 29 mm in length, 20 mm wide and 0.3 mm thick. UV-Vis spectroscopy is performed to
measure the optical transmission of films in visible spectrum and sheet resistance is measured using
four probe technique.

3. RESULT AND DISCUSSIONS

ITO sputtered at room temperature with afore-optimized pressure and power condition produced ITO
films with resistivity ~5.5 x 10⁻⁴ Ω.cm (for 100 nm films). Substrate heating while sputtering is
usually employed to enhance the surface diffusion on the substrate surface to yield resistivity in the
order of ~10⁻⁵ Ω.cm. PET substrates have low thermal budget thus restricts the maximum process
temperature. To overcome such limitations of thin films on polymeric substrates, multilayer
transparent conductive films are developed in literatures [17,18]. In this work, ITO/Ag/ITO films are
sputtered on PET substrate to achieve desired electrical and optical properties. Sputtering ITO (50
nm)/Ag (10 nm)/ITO (50 nm) produces sheet resistance of ~6 Ω/□, whereas individual ITO (100 nm)
film produced sheet resistance of ~55 Ω/□ (Table 1). Electrical insulation exhibited by PET substrate
is greater than 9999 MΩ at 50 volts DC, hence avoiding the need for any passivation between
stainless steel specimen and TFR on PET substrate.
Table 1. Single layer and trilayer film details.

| Sputtered layer(s) on PET substrate | Thickness (nm) | Sheet resistance (Ω/□) | Resistivity (Ω.cm) | Optical transmission (%) |
|-----------------------------------|---------------|-------------------------|--------------------|--------------------------|
| ITO single layer                  | 100           | 55.4                    | 5.54 x 10^-4       | 91 (400 nm -800 nm)      |
| ITO/Ag/ITO trilayer              | 50/10/50      | 5.5                     | 6 x 10^-5          | 83 (400 nm -800 nm)      |

The sheet resistance of Ag-inserted ITO can be estimated by equation (1)

\[
\frac{1}{R_{s(Eff)}} \approx \frac{1}{R_{s(Ag)}} + \frac{2}{R_{s(ITO)}}
\]

Where \( R_{s(Eff)} \) is effective sheet resistance of Ag-inserted ITO film, \( R_{s(Ag)} \) is sheet resistance of silver layer and \( R_{s(ITO)} \) is sheet resistance of ITO layer.

Figure 1. (a) Trilayer ITO/Ag/ITO film on 130 µm PET substrate attached to a test specimen and (b) Cross sectional view of effective sheet resistance \( (R_{s(Eff)}) \) exhibited by Ag-inserted ITO films.

3.1 Piezoresistive response

When an object attached to strain sensor undergoes deformation, the strain is transferred from the measurement object (SS) to the adhesive layer (M-Bond 200), then from the adhesive layer to the sensing layer carrier (PET) and at last from the carrier to the sensing layer (ITO/Ag/ITO film). The tensile strain causes the resistance to increase; therefore \( \Delta R/R \) is positive (where \( R \) is the initial resistance and \( \Delta R \) is relative change in the resistance due to strain \( \varepsilon \)). Cantilever beam is deflected using height gauge to a maximum of 300 µm corresponding to strain of 278 x 10^-6. Beam deflection causes change in length \( (\Delta l) \) of specimen attached to the thin film resistor. Applied strain is well within the fracture limit depicted by linear relation of stress and strain in the inset of figure 3. Resistive response \( (\Delta R/R) \) of TFR is in the order of \( 10^{-3} \) to \( 10^{-4} \) (figure 3).

Figure 2. Cross sectional view of cantilever beam bending measurement setup.

Figure 3. Relative resistance change as a function of applied strain.
3.2 Strain sensitivity

The strain sensitivity of the gauges can be calculated by measuring the change in relative resistance for a known amount of strain on the specimen under test. The measure of sensitivity of the strain gauge is called gauge factor. Generally, ITO-Ag strain gauges exhibit gauge factor around 4 to 7 [13] depending on the composition of materials in the sensing layer. In this work, Ag is stacked with ITO, not doped; and longitudinal strain sensitivity of trilayer film is measured. The gauge factors reported in the literatures not only depend on the type of resistive material(s) used but also on the conditions of deposition, its resistivity and substrate imperfections. TFR prepared by sandwiching Ag in ITO films resulted in gauge factors in the range of 4 ±0.4 for lowest strain applied and 3.5 ±0.3 for higher strain as shown in figure 4.

To arrive to the strain values from the deflection applied, equation (2), (3) and (4) are used. Equation (2) converts cantilever beam deflection into applied force at any point on a suspended beam. Equation (3) converts the force into appropriate stress and equation (4) gives the strain value calculated from the stress using Hooke’s law and the Young’s modulus of stainless (190 GPa).

\[
F = \frac{6Eb^2t^3(\text{Deflection})}{12a^4(3l-a)}
\]  
\[
\sigma = \frac{6Fa}{bt^2}
\]
\[
\varepsilon = \frac{\sigma}{E}
\]

(where \(\sigma\) = stress on the beam, \(\varepsilon\) = (\(\Delta l/l\)) strain on the beam, \(E\) = Young’s modulus of SS specimen, \(F\) = force applied, \(l\) = length of the beam, \(a\) = length of beam from fixed end to point of force applied, \(t\) = beam thickness, \(b\) = beam width)

3.3 Optical transmission

The transmittance of ITO films deposited on PET is highest, averaging ~91% over the spectral range of 400-800 nm. The decrease in transmission (~83% in 400-800 nm wavelengths) for trilayer film on PET can be attributed to enhancement in carrier density in the film [14]. The higher carrier density and presence of silver particles between ITO layers is expected to increase the optical scattering and absorption in the visible region. The optical transmission for meander patterned TFR is ~87%. Figure 5 shows the optical transmission spectra of deposited films and TFR. The average transmission of transparent TFR improves by ~4% as compared to blanket coated trilayer films, due to minimal absorption on baseline referred PET substrate with no trilayer film. The picture at inset of figure 5 shows transparent thin film resistor held against light. Transparent TFR with PET substrate camouflages when attached to the test specimen, thus it can be employed in strain or impact sensing applications needing high optical visibility of the mounted device on transparent test objects.
3.4 Repeatability

Mechanical integrity of ITO/Ag/ITO thin film resistor as strain sensor is investigated by repetitive loading/unloading of force on the cantilever beam for several cycles. Repeatability of resistive response is shown in figure 6 and gauge factor repeatability is shown in figure 7. Usually, thin film strain gauges have tendency to develop cracks when subjected to multiple straining cycles. The resistance change of cracked/discontinuous thin film is higher than that of continuous thin films [15,16]. The order of magnitude of change in resistance with strain is observed to be repeating for all test cycles, which is suggestive of stable behaviour of thin film and its suitability for measuring strain. All the measurements were carried out at room temperature in ambient conditions.

4. CONCLUSION

Silver sandwiched Indium Tin Oxide based transparent thin film resistor has been evaluated for measuring static strain. Trilayer ITO/Ag/ITO films were deposited using RF magnetron sputtering on PET substrate, at room temperature. Transparent TFR of 110 nm thickness exhibited resistance ~4 KΩ on meandering structure patterned on PET. Piezoresistive response in the order of $10^{-4}$ to $10^{-3}$ Ω
and longitudinal gauge factor of $3.5 \pm 0.3$ was measured using cantilever beam bending method. Investigation on repeatability of resistive response suggested good stability of thin film resistor which can be employed for strain sensing in applications needing camouflaged installations on transparent test objects in academic or commercial applications.

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