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Optical and electrical properties of ITO thin films sputtered on flexible FEP substrate as passive thermal control system for space applications

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ABSTRACT

ITO thin films were deposited on flexible fluorinated ethylene propylene (FEP) substrates by pulsed direct current reactive magnetron sputtering system using an In:Sn (90%–10% wt.) alloy target. The influence of the deposition parameters (argon and oxygen flow rates, and substrate temperature) and effect of coating thickness on the optical, electrical, structural and microstructural properties of ITO thin films deposited on FEP was investigated. The thickness of the ITO coatings was varied from 5 to 180 nm. The optimized ITO coating (10 nm thick) exhibited high IR emittance (79%) on FEP substrate with high average solar transmittance (94.0%) and moderate sheet resistance (3 kΩ/sq.). We also investigated in detail the angular dependence of reflectance as well as haze factor of thin ITO coatings. Our results suggest that 10 nm thick ITO coating exhibits an average haze factor of 8.6%. The high value of IR emittance, moderate sheet resistance and high solar transmittance along with low haze factor indicate the suitability of ITO thin films on FEP substrates as flexible optical solar reflector for space applications.

1. Introduction

Electrically conducting and optically transparent flexible substrates have vast applications in the field of solar, space, flexible displays and many more [1–6]. Generally, most of the transparent materials are intrinsically insulators, but by surface modification and by incorporating an additional conducting coating we can change the properties of these materials to make them electrically conducting yet optically transparent. Fluorinated ethylene propylene (FEP) is a commercially available transparent sheet with high optical transmittance, high IR emittance (ε), good thermal insulating and mechanical properties [7–10]. FEP sheet coated with Ag or Al thin film is used as flexible optical solar reflector (FOSR) [3,7,11–13]. The metallic coating reflects the incident radiation, whereas, FEP helps to radiate heat owing to its high IR emittance [3,11–13]. For low earth orbit space applications, the FOSR needs to be electrically conducting while retaining all other optical properties as there is a buildup of electrostatic charges (20–30 kV), which may affect the performance of satellite [13,14]. Therefore, a very thin layer of transparent indium tin oxide (ITO) is applied on metalized FEP substrate to bleed off the electrostatic charges [3,13]. ITO coated metalized FEP substrate is used in most of the satellites stationed in geostationary earth orbits (GEO) as passive thermal control system by radiating back the incoming solar radiation [11–13]. Fig. 1 shows the schematic representation of FEP based FOSR with ITO coating.

ITO coating is one of the premium transparent and conducting thin films, which shows lower electrical resistance and very high transmittance over the solar spectrum region [15–18]. An efficient FOSR for GEO satellite application should have high thermal emittance ($>75\%$), high solar transmittance ($>88\%$) and sheet resistance in the range of 2–10 kΩ/sq. [3,11–13]. The high transmittance of ITO in FOSR can be obtained by reducing the thickness of ITO coating to few nanometers [3,13,14]. Therefore, there is a need to critically optimize the process parameters and hence the properties of ITO thin films for FOSR applications.

Thin films of ITO have been deposited using a variety of deposition methods such as: sputtering, CVD, thermal evaporation, pulsed laser deposition, etc. [1–5,15–19]. Sputter deposition is considered as the most suitable method to prepare high quality ITO thin films [16]. Sputtering is commonly used as an industrial production technique. The advantages of sputtering are: we can control the thickness of the films very precisely, and we can systematically control all the deposition parameters to achieve required properties in ITO thin films [15–17,20,21]. The ITO films prepared by sputtering are highly

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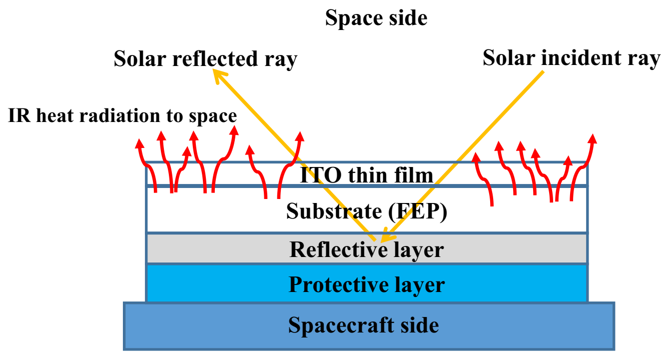

Fig. 1. Schematic representation of FEP based flexible optical solar reflector.

uniform and free from impurities, and also have good mechanical and adhesion properties [15,20].

In an attempt to develop ITO based FOSR for GEO satellite applications, we have studied in details the effect of various process parameters such as: argon flow rate, oxygen flow rate, substrate temperature, sputtering power and thickness, which affect the optical and electrical properties of ITO thin films during the deposition on flexible thin FEP sheets by reactive pulsed direct current (DC) magnetron sputtering. We also investigate the structural and microstructural characteristics of ITO coatings deposited on FEP substrates. Our studies indicate that ~10 nm thick ITO film on 127 µm thick FEP substrate exhibits IR emittance of 79%, average solar transmittance of 94% and sheet resistance of 3 kΩ/sq., suitable for passive thermal control in satellites stationed in lower earth orbits. This work also has potential to be used in futuristic flexible electronics devices, including organic photovoltaics.

2. Experimental details

ITO thin films were deposited on flexible FEP substrates by reactive sputtering using a DC balanced magnetron sputtering system. The sputtering target used for deposition was In:Sn (90%:10% wt.) alloy with purity of 99.99% and a diameter of 0.076 m. FEP substrates of 40 mm × 40 mm size were used in all the experiments. Before introducing into the chamber, FEP substrate was cleaned with iso-propylene alcohol in ultrasonic agitator for 5 min and then blown dried with nitrogen gas. The process parameters were optimized before the deposition of these coatings. Hereafter, the substrate was loaded and the vacuum chamber was then evacuated down to a base pressure of 5.0×10^{-4} Pa using a turbo molecular pump backed by a rotary pump. The sputtering gases used in the experiments were argon and oxygen. The flow rates of oxygen and argon were controlled separately by mass flow controllers. Prior to all deposition, the target was cleaned under argon plasma for 1 min. All the depositions were done using pulsed DC power supply (frequency = 100 kHz and pulse width = 2976 ns) which was kept constant at 60 W power. In order to study the influence of argon and oxygen partial pressures on the ITO deposition the flow rates were varied from 11 to 17 sccm and 1.8 to 3 sccm for argon and oxygen, respectively. While for all other depositions the flow rates of argon and oxygen were kept constant at 11.5 sccm and 2.0 sccm, respectively. Substrate temperature was varied from room temperature to 140 °C. However, all the optimized coatings were deposited at a substrate temperature of 140 °C. By varying the deposition time, ITO thin films with different thicknesses were prepared. ITO thin films were also coated on silicon and glass substrates at optimized parameters to measure the roughness, thickness and work function of the coating.

2.1. Characterization of the coating

The crystal structure and phase of the ITO films with various thicknesses on FEP substrates were measured using X-ray diffractometer (XRD, Bruker, D8 Advance) with a CuK_{α} source in thin film mode. The optical transmittance and reflectance spectra of the ITO thin films coated on FEP substrates were recorded by a PerkinElmer, Lambda 950 UV–vis–NIR spectrophotometer. IR emittance of the coatings was measured using a solar spectrum emissometer (Model AE) of M/s. Devices and Services. FTIR reflectance was measured using GX FTIR spectrometer (PerkinElmer). The sheet resistance of the ITO thin films was measured using a four-point technique (Model M-700A, Magne-Tron Instruments). Chemical composition of ITO thin films was determined utilizing X-ray photoelectron spectroscopy (XPS, SPECS), using non-monochromatic AlK_{α} radiation. The morphology of the ITO coating on FEP substrates was studied by high-resolution field emission scanning electron microscopy (FESEM, Supra 40 VP, Carl Zeiss). ITO film thicknesses were measured from cross-sectional FESEM images and also from 3D surface profilometer (NanoMap 500 LS). Atomic force microscopy (AFM-Bruker) was used to evaluate the roughness of the ITO coatings. A Kelvin probe (Model SKP 5050) was used to find out the work function. The calibration was done using a standard gold sample provided by KP Technology. Gold tip with a diameter of 2 mm was used for the work function measurements. Adhesion test by tape peel off method has been performed. For this, the samples were fixed on a flat surface by sticking adhesive tapes on four sides, after that using a 3 M Scotch® tape the peel off test was performed as per ASTM D903 standard [22].

3. Results and discussion

3.1. Optimization of deposition parameters

To achieve highly transparent, conducting and adherent ITO thin films on flexible FEP substrate was a challenge because of its low melting point. Therefore, various process parameters were optimized systematically. In our experiments we noticed that the ITO thin films prepared at low target power (i.e., < 30 W pulsed DC), the optical and electrical properties were not stable in atmosphere than the films deposited at higher target power. But we observed that increasing target power caused deformity and warpage of the FEP substrate because of its low safe operating temperature (~200 °C). So, for compromising both the problems we used 60 W pulsed DC power for our experiments.

Among all the deposition parameters, the flow rates of oxygen and argon are the most influential parameters for obtaining transparent and conducting ITO thin films [20,21]. The influence of oxygen and argon gas flow rates during the reactive sputtering on the optical properties of ITO thin films on FEP substrate has been studied. ITO thin films were deposited at different oxygen and argon flow rates, keeping film thickness at 30 nm and substrate temperature at 140 °C. The oxygen flow rate was varied from 1.8 to 3 sccm while keeping the argon flow rate at 11.5 sccm. From the transmittance spectra shown in Fig. 2(a) it is clear that varying oxygen flow rate during the deposition changes the optical transmittance of ITO films on the FEP substrate. At higher oxygen flow rate (3.0 sccm) the average transmittance of ITO on FEP was excellent (93.7%), even the transmittance at NIR region was almost equal to the transmittance of uncoated FEP substrate. But the sheet resistance was very high (~2 MΩ/sq.), (data not shown) for these coatings. Upon decreasing the oxygen flow rate the transmittance and sheet resistance were also found to decrease. In ITO thin films the charge carriers are originate through oxygen vacancy ($V_0^{\bullet\bullet}$) and