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Design and development of ITO/Ag/ITO spectral beam splitter coating for photovoltaic-thermoelectric hybrid systems

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ABSTRACT

ITO/Ag/ITO (IAI) multilayer coatings were designed for spectral beam splitter applications and these coatings were deposited on glass substrates by magnetron sputtering method. The thicknesses of the component layers, namely, Ag and ITO were varied to achieve high visible transmittance, high NIR-IR reflectance and optimum cut-off wavelength. The optimized ITO/Ag/ITO exhibits high visible transmittance (~88%) and high NIR-IR reflectance (>90%) with an optimum cut-off wavelength (~900 nm). A novel chemical etching method was used to improve the transmittance of the plain glass substrate. The optimized IAI multilayer coating deposited on single side etched glass substrate resulted in increase in transmittance (~91%), which is due to the nano-porous morphology of the etched glass substrate. The angular and polarization dependence studies of IAI multilayer coatings were also studied in detail.

1. Introduction

The scarcity of conventional energy sources forced to find out new sources of energy and energy saving methods. Therefore, in the last few decades, active and passive use of solar power got much attention for the global energy production. It has been reported that hybrid solar power conversion by combining different solar energy conversion methods can be used to improve the efficiency of total solar energy conversion (Mojiri et al., 2013; Soule and Wood, 1986; Uzu et al., 2015). Hybrid photovoltaic (PV)-thermoelectric (TE) system is one of the established technology used to increase the efficiency of total solar energy conversion (Chendo et al., 1987; Chow, 2010; Hamdy et al., 1985; Herrando and Markides, 2016). Many works have been carried out in this field to improve the efficiency and finding the new areas of applications (Jradi et al., 2011; Vorobiev et al., 2006; Wang et al., 2011; Yang and Yin, 2011). It has been reported that majority of the photovoltaic solar cells' spectrum response is most efficient when the energy of a photon is near to solar cell band-gap energy, the remaining lower and higher wavelength regions of the solar spectrum are only partially utilized. So, by spectrum splitting and directing the solar radiation not in the range of given solar cell's band gap to the thermo-electric generator (TEG) for producing electricity by thermoelectric effect will increase the efficiency of total solar conversion. Moreover, it can reduce the heat from the solar cell (Ju et al., 2012). Ju et al. have found that the optimum generated power of the PV/TE hybrid system is achieved when the spectrum splitter has a cutoff wavelength (λ_c) around 900 nm (Ju et al., 2012).

Different types of solar spectrum splitting methods for hybrid PV/TE system have been suggested over the years (Imenes and Mills, 2004). They include: solar beam splitting transparent heat mirrors, holographic concentrators, liquid absorption, rugate filters, etc. (Imenes and Mills, 2004; Mojiri et al., 2013). Solar beam splitting transparent heat mirrors are investigated for many years (Lambert, 1981; Pracchia and Simon, 1981; Shou et al., 2012; Soule and Wood, 1986). Transparent heat mirrors (THM) use a thin coating on a substrate of glass which can transmit the visible region and reflect the near-infrared (NIR) and infrared (IR) region of the solar spectrum (Fan and Bachner, 1976). An ideal THM should possess maximum transmittance in the visible region and maximum reflectance in NIR and IR regions (Lambert, 1981). Because of the unique properties of THMs, they can be used for various applications such as solar flat-plate collectors for solar heating and cooling, solar hybrid systems, energy efficient windows, thermal insulators for many structures, etc. (Al-Kuhaili et al., 2009; Granqvist, 1981). However, to achieve high visible transmittance

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(T_{vis}) and high NIR and IR reflectance together is a difficult task. Many previous works have been done to achieve the maximum transmittance in the visible region and maximum reflectance in the NIR and IR wavelength regions (Al-Kuhaili et al., 2012; Dalapati et al., 2016; Pracchia and Simon, 1981).

It has been reported that transparent and conducting film can be used for THM application due to its wide band gap and high charge density which gives high reflection in NIR and IR regions (Arfsten, 1984; Granqvist, 1981; Griffiths et al., 1992). Among these materials, tin-doped indium oxide (ITO) is considered as a premium one because of its high transmittance in the visible region and high reflectance in the NIR and IR regions due to its high charge carrier density. ITO is one of the most extensively investigated material for the applications, including heat mirror, solar cells, transparent electrodes, display of various kinds, etc. (Granqvist and Hultaker, 2002). ITO films with excellent uniformity can be prepared in a large area by sputter deposition. Moreover, by adjusting the preparation parameters such as thickness, oxygen content, etc., we can enhance the transmittance in a particular wavelength range (Guillen and Herrero, 2009). However, to further enhance the spectral selectivity, multilayer structures of ITO and a high reflecting metal layers are used (Kusano et al., 1986). A thin layer of Ag, Au, Cu, etc. was sandwiched between two thin ITO layers, and this type of multilayer system gives better selectivity than a single layer ITO (Lambert, 1981; Pracchia and Simon, 1981). In addition, the visible transmittance, NIR and IR reflectance and the λ_c of the solar spectrum can be adjusted by varying the thicknesses of ITO and metal layers. For the middle metal films, Ag is considered as a suitable candidate for the multilayer THM application, because of its high reflectance in NIR and IR regions and lowest refractive index and lowest absorption in the visible region of the solar spectrum (Durrani et al., 2004; Lee et al., 1996). Many researchers have investigated ITO/Ag/ITO (IAI) multilayer layer system for solar spectrum splitting and transparent electrode applications (Choi et al., 1999; Granqvist, 2007; Jeong and Kim, 2009; Kusano et al., 1986). Kusano et al. have studied the thermal stability of IAI multilayer system and found that IAI multilayer coating is more stable than the other multilayer heat mirror (i.e., ZnO/Ag/ZnO) at higher temperatures (Kusano et al., 1986).

The aim of this work was to develop a spectral beam splitter (i.e., ITO/Ag/ITO) which exhibits high transmittance and high reflectance in the visible and NIR/IR regions, respectively. In addition, the effects of ITO and Ag layer thicknesses on the visible transmittance, NIR/IR reflectance and also on the cut-off wavelength have been studied in detail. Further, a novel approach (i.e., chemical etching) was used to enhance the peak transmittance of IAI multilayer system. A nano-porous microstructure was formed on the plain glass substrate surface (i.e., single side), which acts as an antireflective layer and enhances the transmission. The IAI multilayer system exhibits high transmittance in the visible region ($T_{max} \sim 91\%$) and high NIR/IR reflectance (>90% for $\lambda \geqslant 2000$ nm) on single side etched glass substrates. The thicknesses of ITO and Ag layers have been varied in order to achieve the optimum λ_c (i.e., $\lambda_c \sim 900$ nm), which is very much required for the hybrid PV/TE system.

2. Experimental details

IAI multilayer coatings were deposited by a DC balanced magnetron sputtering system. The top and bottom ITO layers were deposited on glass substrate using an In:Sn (90%:10%) alloy target of diameter 0.076 m (purity: 99.99%) in argon and oxygen atmosphere. All the ITO depositions were done at 60 W pulsed DC power (pulse width = 2976 ns and frequency = 100 kHz). The middle Ag layer was deposited using a 0.076 m diameter Ag target of 99.99% purity in argon atmosphere using a 5 W DC power.

Borosilicate glass (from Borosil) of dimension: 17 mm × 25 mm × 1.25 mm were used as the substrates. The glass substrates were cleaned by ultrasonication in isopropyl alcohol and acetone for 10 min each. Some of the glasses were one side etched to enhance the visible transmittance, the details of which can be found elsewhere (Kumar et al., 2016). Prior to the deposition, the chamber was evacuated down to a base pressure 5×10^{-4} Pa using a turbo molecular pump backed with a rotary pump. The growth rates of ITO and Ag films were 1 and 0.5 nm/s respectively, which were calculated from the cross-sectional field emission scanning electron microscopy (FESEM, Supra 40 VP, Carl Zeiss) images and profilometer (NanoMap 500 LS) studies. Hereafter, films with required thicknesses were deposited by varying the deposition time. All the three layers were deposited without breaking the vacuum in the chamber. No substrate heating was used while sputtering.

UV–vis-NIR spectrophotometer (PerkinElmer, Lambda 950) was used for the solar spectrum transmittance, reflectance, angular reflection and optical haze measurements of the coatings. Transmittance and reflectance of single and multilayers were measured in a wavelength range of 250–2500 nm. Angular reflection was measured using the universal reflectance accessory at varying angles (8–68°). Haze measurements were done as per the ASTM 1003 standard (*Haze Measurements Using an Integrating Sphere, UV/VIS/NIR Spectroscopy Resource, Perkin Elmer*, n.d.), in the wavelength range 380–780 nm. FTIR transmittance was measured using PerkinElmer GX FTIR spectrometer. Atomic force microscopy (Bruker) was used to find out the roughness of plain and etched glass substrate.

3. Results and discussion

3.1. Design of ITO/Ag/ITO multilayer spectral beam splitter coating

Fig. 1 shows the schematic diagram of the spectral beam splitter deposited to split the visible and NIR regions separately for hybrid solar conversion. The IAI multilayer system acts as a spectral beam splitter which transmits the visible radiation and reflects the NIR-IR radiation. The sunlight coming through the concentrator falls on the multilayer filter coated on a glass substrate. The different components of hybrid solar conversion system are placed in such a way that the reflected rays of higher wavelength fall on the thermoelectric generator (TEG), and the transmitted visible light falls on the solar cell. The efficiency of the hybrid system will be the sum of the efficiency of TEG and the solar cell. Therefore, high transmittance in the visible region and high reflectance in the NIR and IR region with an optimum cut-off wavelength is necessary to increase the total efficiency of the hybrid system. These peculiar optical properties are produced due to the antireflection from the interface of the films of high and low refractive index materials stacked alternatively (Al-Kuhaili et al., 2009; Granqvist, 1981; Lee et al., 1996).

The genesis of selecting IAI as the spectral beam splitter has been corroborated by the reported admittance data of Ag and ITO (Hong et al., 2011; Kostlin and Frank, 1982; Kusano et al., 1986; Lee et al., 1996). From the admittance diagram technique, it is known that a highly reflecting metal film sandwiched between two high refractive index materials like ITO ($n_{ITO} \sim 2$) will show a high antireflection effect in the visible range with very high visible transmittance (Kostlin and Frank, 1982). Further, a highly conducting metal film exhibits high reflection in the NIR and IR regions due to its high electron density. Moreover, a metal film can also be transparent in the visible region if it has a refractive index near