DOI: 10.1007/s12541-013-0197-5

Electrical and Optical Properties of Indium-tin Oxide (ITO) Films by Ion-Assisted Deposition (IAD) at Room Temperature

Mansour S. Farhan[1], Erfan Zalnezhad[2], Abdul Razak Bushroa[2,#], and Ahmed Aly Diaa Sarhan[2]

1 College of Engineering, Wasit University, Iraq
2 Center of Advanced Manufacturing and Material Processing, Department of Engineering Design and Manufacture, Faculty of Engineering, University of Malaya, Kuala Lumpur, 50603, Malaysia
Corresponding Author / E-mail: bushroa@um.edu.my, TEL: +60-7967-4593, FAX: +60-7967-5330

KEYWORDS: IAD, ITO thin films, Electrical properties, Optical properties

Indium-tin oxide (ITO) films have been traditionally deposited at elevated substrate temperature of 400ºC to achieve low resistivity and high transmission. In some cases, films deposited at low substrate temperatures can be annealed at higher temperature to achieve lower resistivity. In this paper, thin films of ITO with various oxygen flow rates are prepared by ion-assisted electron beam evaporation at room temperature. Electrical, optical and structural properties of ITO thin films have been investigated with the function of oxygen flow rate, rate of deposition and layer thickness. Low resistivity of 7.5 × 10-4Ω-cm, high optical transmittance of 85% at wavelength 550 nm, optical band-gap of 4.2 eV and crystalline ITO films can be achieved at room temperature almost one order smaller than that prepared by other method.

Manuscript received: March 25, 2013 / Accepted: May 26, 2013

1. Introduction

A distinctive class of transparent oxide films comprises electrically conducting. While most oxides are fine insulators, some are wide band-gap semiconductors. Indium tin oxide (ITO) thin films are widely utilized in numerous industrial applications due to the unique combined properties of transparency to visible light and electrical conductivity.[1] Coatings on glass with highly transparent conductive oxide films (TCO) are mostly performed with indium tin oxide layers (ITO). This oxide material is very common in applications where both high electrical conductivity and optical transmittance are essential. ITO films are reactively sputtered with single magnetron sputter sources of different sizes. The aim of ITO process technology development is to obtain stable film properties for large-area coatings with exceptionally low resistivity and high transmittance within the visible spectrum range.

ITO films may be prepared in several ways including reactive evaporation[8-10] or sputtering, DC magnetron reactive[10,11] or RF sputtering,[12-14] as well as Ultralow-Pressure Sputtering[15] and sol-gel.[16] All of these processes involve a reactive oxygen background. The oxygen level during the procedure is a critical component of controlling film quality.

ITO films are highly degenerate n-type semiconductors, and have low electrical resistivity (10^{-4}Ω-cm) along with high carrier concentration. Furthermore, ITOs have a wide band-gap (Eg > 4.1 eV) and high transmittance (> 85%) in the visible range.[2] This unique combination of electrical and optical properties has prompted numerous researchers to thoroughly investigate ITO film growth and characterization. ITO finds potential applications in a number of devices, such as flat panel displays, solar cells, gas sensors, camera lenses, anti-reflection coatings, heat reflection mirrors and surface heaters for automobile windows.[3] In the last 22 years, considerable data has been reported on ion sources[4] utilized for both substrates pre-cleaning and to assist with thin film deposition and growth processes.[6,7] Currently a plethora of ion sources are available for commercial use besides countless improvements of older designs. Ion-assisted deposition (IAD) modifies many of the physical characteristics of thin films. Since visible transmission and electrical conductivity are fundamentally in conflict with each other, ITO seems one of the better film materials available for such applications. However, as an oxygen-deficient material it behaves like metal, becoming conductive, optically absorbing and highly reflective in the infrared region.

Traditionally, superior films (i.e. low resistivity, high transmission) are deposited at elevated temperatures.[9-11] Honda, et al[17] studied the oxygen content of deposited films at a range of substrate temperatures from ambient room temperature to 400°C. In some instances, films deposited at low temperatures can subsequently be annealed at higher temperatures to achieve lower resistivity.[9,10] Applying a broad-beam ion source would be ideal since it runs on pure oxygen. ITO has a refractive index with a real part of roughly 2.05.[4,9,18] All applications allow for a low-index, quarter-wave outer layer to increase transmission. The higher resistivity applications have no limitations to film structure. Therefore, ITO into a multi-layer anti-reflection structure, and for this reason it is desirable to fully characterize the films' optical properties.

In this study, ITO films were deposited at room temperature by electron-beam evaporation and ion-assisted deposition (IAD). The effects of oxygen flow rate, deposition rate and layer thickness on the electrical, optical and structural properties of deposited ITO films on glass substrate at room temperature are investigated.

2. Experimental techniques

This study was conducted in a fully automated turbo-pumped coating chamber equipped with resistive sources, 6-pocket 270°, 14 kW electron beam gun (E-gun) with a quartz crystal rate/thickness controller. The "Kaufman" ion source is characterized by placing a Faraday probe into the tooling around the outer radius. A general view of the equipment can be seen in Fig. 1. The evaporation source material is ITO, 10% tin oxide and 90% indium oxide. The pressure during the evaporation process was around 5×10^{-6} mbar and was initiated at ambient temperature. Film thickness and evaporation rate were monitored for all films by a quartz-crystal monitor. During deposition, the ion current density and ion energy were maintained at 90 μA/cm^2 and 150 eV, respectively.

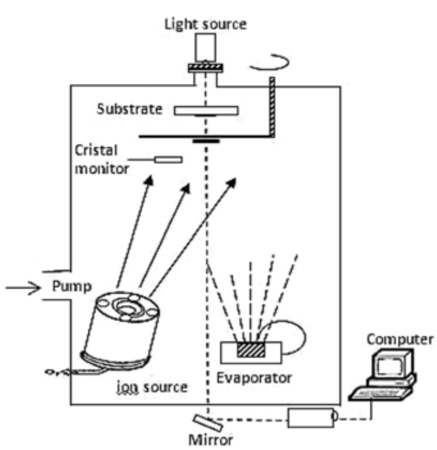

Fig. 1 Schematic diagram of the deposition system

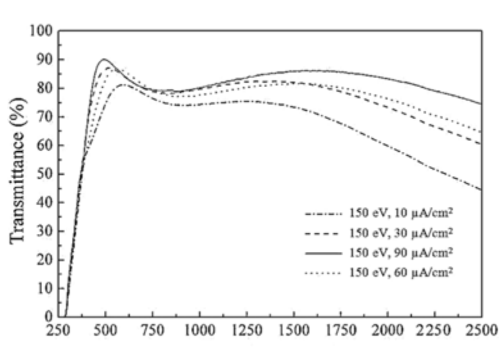

Fig. 2 Transmission spectra of ITO films

Oxygen flow rate was regarded as a variable parameter, and hence configured at 20, 25 and 30 sccm flow rates monitored by a mass flow controller (MKS). The electrical sheet resistance of the ITO films was measured through the four-point probe method, while the transmittance spectra were measured with a UV-NIR spectrophotometer (Perkin-Elmer Lambda 900) in double-beam configuration. The crystalline quality of the ITO films was determined via X-ray diffractometer (XRD) analysis at room temperature using Cu K_α radiation. Prior to loading the glass substrates, cleaning by an ultrasonic washer with acetone, alcohol, and de-ionized water was done to remove organic contamination after which they were blown in dry nitrogen gas.

3. Results and discussions

The influence of oxygen ion-beam density on optical transmission is presented in Fig. 2. All films have thickness of 200 nm 0.6 nm/sec rate of deposition and were deposited at 150 eV ion-beam energy and 0.6 nm/sec rate of deposition. Clearly, the ITO film prepared by oxygen ions bombardment during deposition and becomes transparent due to the high oxygen ion source beam reactivity. At the same ion energy, irradiation with high ion-flux density improves the transparency, indicating that the ratio of O/(In + Sn) approaches the sesquioxides.

Figure 3 shows the optical transmittance behavior of ITO thin films deposited at 0.6 nm/sec deposition rate, 140 nm thickness, 150 eV ion energy, 90 μA/cm^2 ion density and 20 sccm oxygen flow rate as a function of wavelength. The ITO thin films obviously have excellent optical transmission in the visible range, and at 550 nm the wavelength is 85%.

The refractive index (n) and extinction coefficient (k) values of ITO films in the wavelength range of 400-800 nm are calculated from the interference pattern of the transmission spectra.[19] The technique for determining the optical constants of the thin films based on the measurements of the transmitted light intensity[20-22] was utilized to develop a computer program to calculate the n and k values. Explicit expressions for n and k were derived from the fringe pattern of the transmission spectrum of a thin transparent film assumed to be surrounded by non-absorbing media. The maxima and minima from the

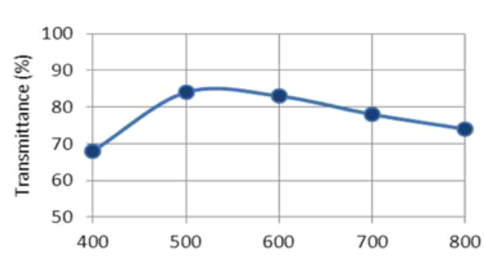

Fig. 3 Optical transmittance versus the wavelength