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Indium-tin-oxide thin film deposited by a dual ion beam assisted e-beam evaporation system

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Abstract

Indium-tin-oxide (ITO) thin films were deposited on polycarbonate (PC) substrates at low temperatures (<90°C) by a dual ion beam assisted e-beam evaporation system, where one gun (gun 1) is facing ITO flux and the other gun (gun 2) is facing the substrate. In this experiment, effects of rf power and oxygen flow rate of ion gun 2 on the electrical and optical properties of depositing ITO thin films were investigated. At optimal deposition conditions, ITO thin films deposited on the PC substrates larger than 20 cm × 20 cm showed the sheet resistance of less than 40 Ω/sq., the optical transmittance of above 90%, and the uniformity of about 5%.

Keywords: ITO; PC; IBAE; Oxygen ion beam; Radical

1. Introduction

Recent technical developments in flat panel displays using indium-tin-oxide (ITO) thin film as transparent conductive electrode are favoring low process temperature to use organic substrates instead of glass. Several techniques such as pulsed laser deposition (PLD) [1], dc (or rf)-sputtering [2] and evaporation [3] have been studied to deposit low temperature ITO thin films. Among these techniques, sputtering technique is the most widely applied to industrial applications, however, ion beam assisted evaporation (IBAE) could be a promising technique for low and room temperature deposition because it offers several advantages such as more flexibility in controlling the beam and hence the film properties. These are the flux and the energy of the ion beam, the uniformity of the beam, the distance and the angle between ion gun and substrate, etc.

In this study, among the various parameters of IBAE, rf power and oxygen flow rate to the ion gun facing the substrate were varied and their effects on the electrical and optical properties of deposited ITO were investigated for a dual oxygen ion gun assisted e-beam evaporation system.

2. Experimental conditions

The deposition system used in the experiment was consisted of an e-beam evaporator and two

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internally mounted oxygen ion guns. Both of the oxygen ion guns were driven by rf inductively coupled plasma (13.56 MHz) and two grids were attached for the extraction and acceleration of the ions generated. To study the effect of the flux of the oxygen ion beam irradiated to substrate, one of the oxygen ion guns (ion gun 2) was facing the substrate and the flux was varied by changing the rf power (200–400 W) and the flow rate (3–6 sccm). The voltages applied to accelerator grid and extraction grid were +1.8 kV and −100 V, respectively. The other oxygen ion gun (ion gun 1) was located near the ITO evaporator and irradiated oxygen ion beam towards ITO flux not to the substrate. The condition of the ion gun 1 was fixed with rf power of 250 W, oxygen flow rate of 4 sccm, acceleration voltage of +1.2 kV, and extraction voltage of −100 V. The deposition rate of deposited ITO thin films was kept at 0.05 nm/s. Optical emission spectroscopy (OES) was used to investigate the plasma species in the oxygen ion source chamber as a function of rf power and oxygen flow rate to ion gun 2; and the irradiated oxygen ion flux was measured by a Faraday cup located near the substrate holder. The properties of the deposited ITO films were measured using a four-point probe, an UV-spectrophotometer, and a Hall probe.

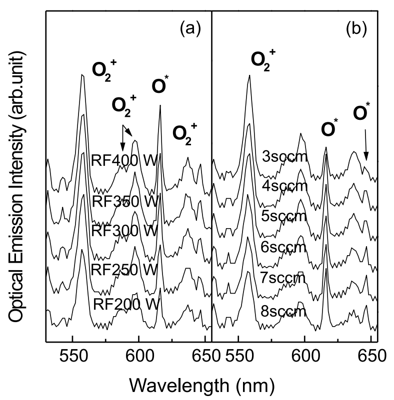

Fig. 1. OES of oxygen plasma in the ion source chamber of the ion gun 2 measured by OES as a function of rf power (a) and oxygen flow rate (b).

3. Results and discussion

Fig. 1 shows OES data of oxygen atoms and ions (O and O_2^+) measured inside gun 2 as a function of rf power and oxygen gas flow. As shown in the figure, the increase of rf power to the gun at a fixed gas flow of 4 sccm increased both oxygen ion density and oxygen atom density. However, the increase of oxygen gas flow to the gun at a fixed rf power of 250 W continuously decreased the oxygen ion density even though the oxygen atom density was increased with the increase of oxygen gas flow.

The change of oxygen ions inside gun 2 observed using OES as a function of oxygen gas flow and rf power could be also confirmed by measuring oxygen ion current extracted through extraction and acceleration grids using a Faraday cup located near the substrate position. Fig. 2 shows the oxygen ion current measured by the Faraday cup as a function of rf power and oxygen gas flow to the ion gun 2. As shown in the figure, the oxygen ion flux to the substrate as a function of oxygen gas flow was varied depending on the rf power to the gun. When the rf power to the gun was lower than 250 W, the oxygen ion current measured by the Faraday cup was decreased with the increase of oxygen gas flow to the gun as observed by OES. However, when the rf power to the gun was higher than 300 W, the oxygen ion current increased initially with the increase of oxygen gas flow to the gun and, at a high oxygen flow to the gun, the ion current de-

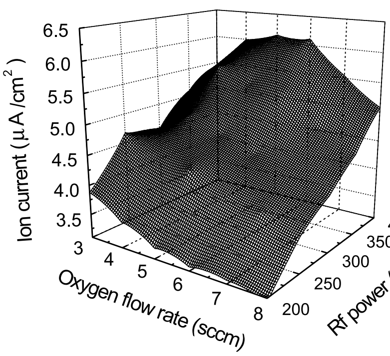

Fig. 2. Variation of the oxygen ion current measured by a Faraday cup as a function of rf power and oxygen flow rate to ion gun 2.

Table 1
Variation of sheet resistance, resistivity, electron concentration, Hall mobility, optical transmittance, and figure of merit as a function of oxygen flow rate to ion gun 2[a]

Flow rate (sccm)	Sheet resistance (Ω/sq.)	Resistivity (Ω cm)	Carrier concentration ($\times 10^{20}$ cm^{-3})	Hall mobility (cm^2/V s)	Transmittance (%)	Figure of merit (10^{-3} sq./Ω)
3	50.5	5.4×10^{-4}	3.26	43.6	93.66	10.31
4	39.7	5.1×10^{-4}	4.3	37.5	91.65	10.5
5	85	8.0×10^{-4}	1.25	45.6	93.7	6.13
6	110.5	1.2×10^{-3}	1.08	45.7	96	6.01

[a] RF power: 250 W.

creased again with the increase of oxygen gas flow. The decrease of ion density with the increase of oxygen gas flow at low rf powers appears to be from the higher probability of recombination than that of ion–electron formation as reported by Lee et al. [4]. Electrical and optical properties of ITO deposited as a function of oxygen gas flow to gun 2 were measured and the results are shown in Table 1 for the gas flow in the range from 3 to 6 sccm. For the deposition, the acceleration voltage and extraction voltage of gun 2 were also fixed at 1.8 kV and −100 V, respectively. Rf power to gun 2 was kept at 250 W for Table 1. As shown in Table 1, the increase of gas flow from 4 to 6 sccm increased the optical transmittance, however, decreased the conductivity. The increase of optical transmittance with the increase of oxygen gas flow appears to be from the improved stoichiometry of the ITO thin film by increased oxygen atom incorporation to the depositing ITO thin film. The decrease of conductivity with the increase of oxygen gas flow also appears to be related to the decrease of oxygen vacancies in the film due to the improved stoichiometry. The decrease of conduction electrons with the increase of oxygen gas flow can be seen from the carrier concentration data in Table 1. The increase of Hall mobility with the increase of gas flow appears to support the improved stoichiometry of the film by reducing oxygen vacancy related defects in the film. The decrease of oxygen gas flow rate from 4 to 3 sccm also decreased the conductivity and increased the optical transmittance. As shown in Figs. 1 and 2, the decrease of oxygen gas flow to gun 2 increased oxygen ion density in the gun and oxygen ion flux to the substrate. Therefore, the decrease of conductivity and the increase of optical transmittance by reducing oxygen gas flow from 4 to 3 sccm also appear to be from the net increase of oxygen incorporation to the film by increased oxygen ion flux even though oxygen atom flux was decreased with the decrease of oxygen flow rate. The decrease of carrier concentration and the increase of Hall mobility with the decrease of oxygen gas flow rate

Table 2
Variation of sheet resistance, resistivity, electron concentration, Hall mobility, optical transmittance, and figure of merit as a function of rf power to ion gun 2[a]

RF power (W)	Sheet resistance (Ω/sq.)	Resistivity (Ω cm)	Carrier concentration ($\times 10^{20}$ cm^{-3})	Hall mobility (cm^2/V s)	Transmittance (%)	Figure of merit (10^{-3} sq./Ω)
200	64.26	8.5×10^{-4}	2.61	27.9	88.8	4.33
250	39.7	5.1×10^{-4}	4.3	37.5	91.65	10.5
300	43	5.46×10^{-4}	3.43	33.3	94.8	13.6
350	43.6	5.6×10^{-4}	2.6	45.3	94.4	12.9
400	45.7	5.8×10^{-4}	2.75	42.9	95	13.1

[a] Oxygen flow rate: 4 sccm.

from 4 to 3 sccm appear to support the increase of oxygen incorporation in the film.

Rf power to gun 2 was also varied from 200 to 400 W and the effects of rf power on the electrical and optical properties of the deposited ITO thin film were also investigated. The extraction voltage, acceleration voltage, and oxygen flow rate to gun 2 were fixed at −100 V, 1.8 kV and 4 sccm, respectively. The results are shown in Table 2. As shown in the table, the increase of rf power from 250 to 400 W generally increased the transmittance and decreased the conductivity similar to the effect of oxygen gas flow rate. The increase of transmittance and the decrease of the conductivity with the increase of rf power also appear to be from the increase of oxygen incorporation into depositing ITO thin film as observed by the increase of oxygen ion flux and oxygen atom density shown in Figs. 1 and 2. When rf power was decreased from 250 to 200 W, the conductivity and the transmittance were both decreased and it appears to be from the increase of oxygen defect cluster which are not contributing conduction electrons. When the resistivity was measured along the 25 cm × 25 cm wide ITO deposited polycarbonate (PC), about 5% uniformity could be obtained on most of the ITO deposited substrates.

4. Conclusions

ITO thin films were deposited on PC substrates using a dual oxygen ion gun assisted e-beam evaporation system. In this experiment, rf power and oxygen flow rate to the gun facing the substrate was varied and their effects on the electrical properties and optical properties of deposited ITO thin film were investigated. The increase of oxygen flow to the ion gun increased the oxygen atom density, but it decreased the oxygen ion density. However, the increase of rf power to the gun increased both oxygen ion density and oxygen atom density. The electrical and optical properties of depositing ITO thin films were dependent on the oxygen ion flux and atom flux emitted from the ion gun. There were optimum ranges of rf power and gas flow rate which can optimize both conductivity and optical transmittance. The lowest sheet resistance obtained with 1200 A thick ITO was 39.7 Ω/sq. at 250 W of rf power and 4 sccm of oxygen gas flow and the optical transmittance at the condition was above 90% at 550 nm. When the resistivity was measured along the 25 cm × 25 cm wide ITO deposited PC, 5% uniformity of resistivity could be obtained in our deposition system.

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