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Applied Surface Science 252 (2006) 3428–3435

applied surface science

www.elsevier.com/locate/apsusc

# Electron scattering mechanisms in indium–tin-oxide thin films prepared at the various process conditions

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Received 30 November 2004; received in revised form 15 March 2005; accepted 24 March 2005

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## Abstract

The carrier concentrations and mobilities of indium–tin-oxide (ITO) thin films by DC magnetron sputtering at the various process conditions were measured by means of the Hall technique. The relationship between the carrier concentration and mobility showed two distinct features: (i) roughly up to the carrier concentration of $9.0 \times 10^{20}/\text{cm}^3$, both the carrier concentration and mobility increased together; (ii) above the carrier concentration of $9.0 \times 10^{20}/\text{cm}^3$, the carrier mobility decreased as the carrier concentration further increased. The distinct behavior of the carrier concentration and mobility was due to the transition of the dominant electron scattering mechanism. ITO thin film with a low degree of crystallinity was governed by the grain boundary scattering. However, the ionized impurity scattering was dominant in ITO thin film with a high carrier concentration over $9.0 \times 10^{20}/\text{cm}^3$. The overall characterizations related to the carrier concentration and mobility were also performed using X-ray diffractometer, UV–vis–NIR spectrometer, scanning electron microscope, atomic force microscope.

*Keywords:* Indium–tin-oxide (ITO); DC magnetron sputtering; Hall measurement; Carrier concentration; Carrier mobility; Surface roughness; Scattering

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## 1. Introduction

Thin films with both the optical transparency and the electrical conductivity have been intensively investigated for many applications such as transparent electrode in various kind of displays, solar cells, electrochromic devices, heatable glasses and so on. Both the high transparency and conductivity could be achieved largely in two types of materials [1–3].

First, an extremely thin film of metal, especially of Ag, Au or Cu, could be possible. Not only a metal single layer film with about 50% luminous transmittance but also a ITO-Metal-ITO (IMI) multilayer system [4–6] to improve the transparency have been widely investigated.

Second, the wide-band gap oxide semiconductor is also possible, where indium–tin-oxide (ITO) is the

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0169-4332/$ – see front matter
doi:10.1016/j.apsusc.2005.03.203

most used and widely studied transparent conductor among the various oxides. However, although it has been found for about 40 years that ITO has both the excellent electrical and optical properties [7,8], the theoretical understanding of ITO has been limited, especially because of the complex crystal structure of ITO thin film, which exhibits a bixbyite structure with a unit cell containing 40 atoms and two non-equivalent cation sites.

Until now, many researches on ITO thin film were mainly focused on the deposition condition [9–11], the post-treatment such as heat annealing [12], plasma treatment [13], and the substrate effect [14,15] to improve the electrical and optical properties of ITO thin film. In addition, the electron carrier transport and scattering phenomena were widely investigated. It has been reported that there are several electron scattering mechanisms in ITO thin film such as the grain boundary scattering, the ionized impurity scattering and the neutral impurity scattering [11,15–18].

However, to the best of our knowledge, the detailed scattering mechanisms in ITO thin films at the various process conditions such as coating time (film thickness), DC power density, process temperature have not been reported. In this study, the overall investigation on the electron scatterings in ITO thin films at the various process conditions was performed.

## 2. Experimental

ITO thin films were deposited by a commercial batch-type DC magnetron sputtering system. The target was an indium–tin alloy with $In_2O_3$ and $SnO_2$ in a weight proportion of 9:1 with a purity of 99.99%. The substrates used were the alkaline-free glasses. Generally, the vacuum chamber was evacuated down to pressure $1.0 \times 10^{-3}$ Pa prior to deposition. After evacuation, argon gas was introduced into the chamber and the required pressure ($4.0 \times 10^{-1}$ Pa) was set. The flow rate of oxygen reactive gas was fixed at 0.5 vol.% of argon flow rate. Before sputtering, the target was presputtered (4.30 W/cm$^2$ DC power) for about 10 min with a shutter covering the target in order to remove the surface oxide layer. Then the shutter was opened and the sputtering process was started. Each gas flow of argon and oxygen was controlled by a mass flow controller. The DC power density during the sputtering was set 1.08–3.24 W/cm$^2$ DC power. The

Table 1
The process conditions for the sample preparation and the various properties of ITO thin films

| Number | | Process conditions | | | | Properties | | | |
|---|---|---|---|---|---|---|---|---|---|
| # | Series | Temperature (°C) | Thick | Power (W/cm$^2$) | Target used | SR (μΩ cm) | CC ($10^{20}$/cm$^3$) | CM (cm$^2$/V s) | rms $r$ |
| 1 | T1 | 70 | 3212 | 2.15 | 3 | 1044 | 5.25 | 12.0 | 18.9 |
| 2 | T2 | 100 | 3230 | 2.15 | 3 | 685 | 5.84 | 15.7 | 40.4 |
| 3 | T3 | 150 | 3324 | 2.15 | 3 | 392 | 6.10 | 27.4 | 57.0 |
| 4 | T4 | 200 | 3384 | 2.15 | 3 | 246 | 7.52 | 34.1 | 67.6 |
| 5 | T5 | 250 | 3323 | 2.15 | 3 | 203 | 8.06 | 38.6 | 62.0 |
| 6 | T6 | 300 | 3358 | 2.15 | 3 | 160 | 9.23 | 43.4 | 54.6 |
| 7 | T7 | 350 | 3270 | 2.15 | 3 | 135 | 11.0 | 43.2 | 39.1 |
| 8 | T8 | 380 | 3277 | 2.15 | 3 | 130 | 11.6 | 41.5 | 33.4 |
| 9 | t1 | 350 | 2450 | 2.15 | 3 | 134 | 11.1 | 42.5 | 40.5 |
| 10 | t2 | 350 | 1619 | 2.15 | 3 | 137 | 11.0 | 42.7 | 23.6 |
| 11 | t3 | 350 | 825 | 2.15 | 3 | 141 | 9.86 | 44.8 | 14.0 |
| 12 | t4 | 350 | 388 | 2.15 | 3 | 149 | 9.10 | 46.1 | 11.7 |
| 13 | P1 | 350 | 830 | 1.08 | 3 | 136 | 11.0 | 43.1 | 15.3 |
| 14 | P2 | 350 | 800 | 3.24 | 3 | 146 | 9.43 | 45.3 | 16.3 |
| 15 | P3 | 350 | 810 | 1.08 | 2 | 138 | 10.6 | 43.8 | 14.8 |

T1–T8: process temperature series (others fixed constant); t1–t4: film thickness series (others fixed constant); P1–P3: power density: target used series (others fixed constant). Fixed conditions: (1) base pressure = $1.0 \times 10^{-3}$ Pa; (2) presputtering = 10 min @ $4.0 \times 10^{-1}$ Pa (Ar only) and 4.30 W/cm$^2$ DC power; (3) working pressure = $4.0 \times 10^{-1}$ Pa [$O_2$/Ar = 0.5/100]. SR: specific resistivity (μΩ cm); CC: carrier concentration ($10^{20}$/cm$^3$); CM: carrier mobility (cm$^2$/V s); rms $r$: root-mean-square roughness.