Control of Deposition Parameters in ITO Films: Figure of Merit

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Abstract

Indium tin oxide films were deposited on unheated PET substrates by DC reactive magnetron sputtering of In-Sn (90-10 wt%) metallic alloy target. Electrical and optical properties of as-deposited films were systematically studied by control of the deposition parameters such as working pressure, DC power, and oxygen partial pressure. The figures of merit are important factors that summarize briefly the relationship between electrical and optical properties of transparent conducting films. The formulae of T/R_{sh} and T^{10}/R_{sh} are expressed as a function of transmittance and sheet resistance. The best values of those figures of merit were approximately 38.6 and 8.95 ($\times 10^{-3}\ \Omega^{-1}$), respectively.

Key Words : ITO, Magnetron sputtering, PET substrate, Metallic alloy target, Figure of merit

1. Introduction

Indium tin oxide (ITO) films have received attractive attention as an excellent candidate among the various transparent conducting oxides. ITO is commonly treated as a degenerate n-type semiconductor material. The electrical conduction of ITO depends upon oxygen vacancies and bivalent indium or tin atoms that are incorporated during film growth.[1] The low electrical resistivity of the film with the range of $\sim 10^{-4}\ \Omega$cm is resulted from this conduction mechanism. The carrier concentration is larger than 10^{20} cm^{-3} and the mobility is as large as 10 to 30 cm^2/Vs. On the other hand, these excellent conductive ITO films have been mainly used as a transparent electrode for optoelectric devices and flat panel displays such as solar cells, liquid crystal display (LCD), electrochromic display (ECD), electroluminescent display (ELD) and so on.[2] It has been recently required that ITO films are deposited on polymeric substrates instead of the conventional glass substrate for the transparent conducting applications. That is, these devices using glass substrate are somewhat heavy and can break easily, while those of polymeric substrate have significantly light and flexible properties. The substrate temperature and/or post-heat treatment of ITO films deposited on polymeric substrates is very restricted because polymers can not withstand high temperature. Therefore, the deposition methods of ITO films prepared at low temperature are important technology.[2,3] Nevertheless, the electrical and optical properties in ITO films on polymeric substrates should be almost similar with those on glass. ITO films for the transparent conducting devices are required at least higher optical transmittance than 80 % and low electrical resistivity as much as $\sim 10^{-4}\ \Omega$cm.

It is necessary to optimize simultaneously the electrical and optical properties for the transparent conducting applications. Therefore, figure of merit, which can explain in an easy

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manner as a relation between sheet resistance and optical transmittance, has been proposed sometimes to estimate the performance of transparent conducting films. Moreover, some researchers have defined and discussed the figure of merit in several approaches.[4,5,6] In order to evaluate the electrical and optical properties of ITO films with broad applications, we have systematically studied the electrical and optical properties with control of deposition conditions such as operating gas pressure, DC power and oxygen partial pressure (PO_2). The dependency of these deposition parameters on the sheet resistance and optical transmittance of as-deposited films is investigated by figure of merit.

2. Experiments

ITO films were deposited on polyethylene terephthalate (PET) substrate by DC reactive magnetron sputtering of metallic alloy target. The substrate temperature was not applied during the film deposition as well as post annealing treatment for as-deposited ITO films was not performed. Prior to ITO deposition, all substrates were ultrasonically cleaned for 5 min using methanol as a solvent. The deposition parameters such as the DC power, working pressure, and oxygen partial pressure (PO_2) were controlled. PO_2 in the operating gas mixture of total pressure was expressed as $[O_2]/([Ar]+[O_2])$ percentage and its ranges from 8 to 12 % were used. A disk In 90 wt%-Sn 10 wt% target, supplied by Cerac, with 2 inch diameter and 1/4 inch thick was used. A serious problem in the reactive sputtering of metallic alloy is the oxidation of metal target surface, well known as a poisoning phenomenon. Therefore, the target surface should be cleaned necessarily before every sputtering run. Moreover, the target was pre-sputtered in argon atmosphere for about 10 min in order to remove the oxidizing surface and impurity layer which may have formed during exposure to air.

Transparent conducting films have two important factors; that is, electrical resistivity and optical transmittance. These two qualities have sometimes duality characteristics each other which is inversely or linearly related with several deposition ways and film nature. With broad application fields, only lower electrical resistivity neglecting high optical transmittance may be required, or vice versa. No matter which side chooses, these two factors are significantly used in many cases, and therefore the figure of merit which involves simultaneously the electrical and optical properties has greatly meaningful.

First, Fraser and Cook[7] developed figure of merit based on the sheet resistance (R_{th}) and transmittance (T) of transparent conducting films; i. e. defining as a formula of T/R_{th}. The higher value in figure of merit becomes, the better film quality signifies owing to the requirement of high transmittance and low sheet resistance. However, transmittance and sheet resistance in the formula are actually expressed as a function of film thickness. The transmittance becomes generally lower with an increase of film thickness due to absorption in the films. It has been known that the electrical properties of ITO films sensitively depend on the thickness.[8] On the other hand, it was reported that the resistance for the as-deposited films prepared at room temperature was no significant difference with a variation of film thickness below 300 nm.[2,9] All films in this work were the as-deposited state without any heat treatment, and film thickness was about 120 ± 5 nm. Another figure of merit developed by Haache[10] was more emphasis on the transparent properties in the films, although it had similar formation to Fraser and Cook's formula. The figure of merit is defined as a T^x/R_{th}, where x is larger integer than 1 and the value chosen in this work is 10.

3. Results and discussion

Fig. 1 shows the figures of merit for ITO films on PET substrate with a variation of DC power. The figures of merit, T/R_{th} and T^{10}/R_{th},

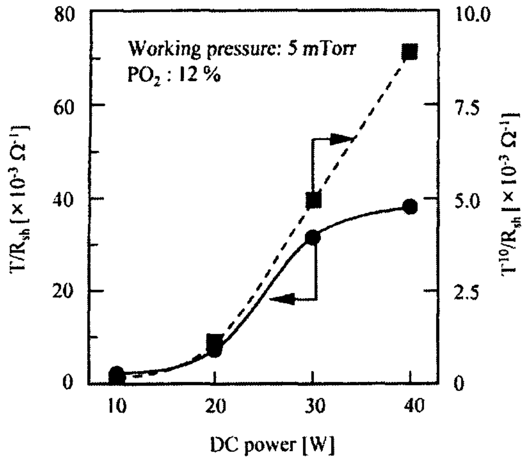

Fig. 1. Figures of merit for ITO films on PET with an increase of DC power.

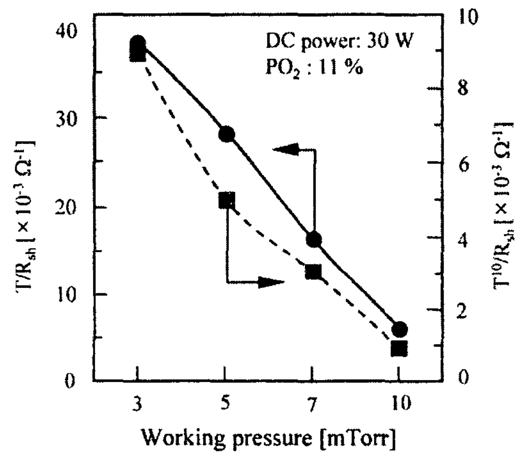

Fig. 2. Figures of merit for ITO films on PET as a function of working pressure.

increase with an increase of DC power, particularly T/R_{th} grows up from 2.1 to 38.6 ($\times 10^{-3}\ \Omega^{-1}$). The reason is mainly caused by the reduction of sheet resistance which is probably related to an increase of oxygen vacancies[2], as the DC power is increased. It is considered that the mechanism of electrical conduction in ITO films depends critically on oxygen vacancies. The optical transmittance increases slightly from 80 to 85 % at 550 nm wavelength with a variation of DC power. But the PET substrate

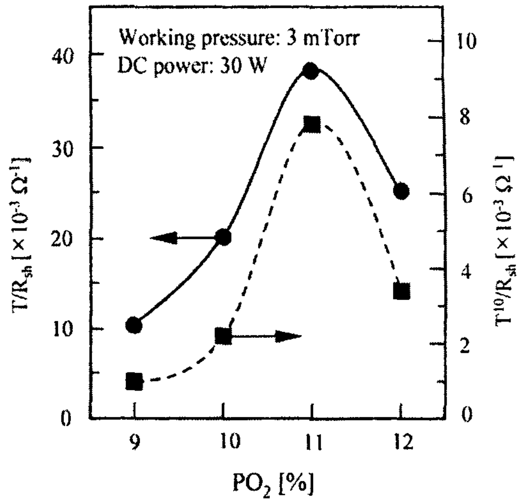

Fig. 3. Figures of merit for ITO films on PET as a function of PO_2.

of 100 μm thick using in this work was bended occasionally at higher power than or same to 40 W because of the raising temperature effect on substrate generated by ejected atom from target.

Fig. 2 expresses the figures of merit of the films as a function of working pressure under the following deposition conditions: DC power of 30 W and PO_2 of 12 %. T/R_{th} and T^{10}/R_{th} decrease with an increase of working pressure. As the working pressure increases, the sheet resistance shows the increasing trend abruptly and the transmittance increase slowly. As the results, it seems that the figure of merit depends upon the sheet resistance, rather than the slowly increasing effect of transmittance. It is noticed by Kumar and Mansingh[11] that the carrier concentration of ITO films deposited at low working pressure is larger than that at high working pressure. Therefore, the figure of merit goes down at higher working pressure because the electrical conduction of the films is decreased at higher working pressure.

Fig. 3 shows the figures of merit with a variation of PO_2 at the working pressure of 3 mTorr for 30 W. The figures of merit increase gradually with the increasing PO_2, while they decline sharply above the PO_2 of 11 %. That is,

Table 1. Figures of merit in ITO films prepared on the various substrates at low temperature by several papers.

Substrate	Deposition methods	Thickness (nm)	Substrate Temp. (°C)	Sheet resistance (Ω/sq.)	Transmittance (% at 550 nm)	Figures of merit (mΩ^{-1})		Ref.
						T/R_{sh}	T^{10}/R_{sh}	
Glass	FTS	100-300	RT	<40	>85	21.3	4.92	9
Glass	DCS	115	RT	55	84	15.2	3.18	1
AC	RFMS	390	50	19.06	74	38.6	2.58	5
PC	RFMS	-	<50	27.3	90	32.9	12.7	4
PET	Evaporate	230	>80	52	83	20.0	2.98	12
Glass	RFMS	500	RT	3.1	~56	180	1.0	13
PET	DCMS	125	RT	22	85	38.6	8.95	Ours

AC=acrylic, PC=polycarbonate, PET=polyethylene terephthalate, FTS=face target sputter, and RT=room temp.

the maximum point is obtained at 11 %. As the PO_2 increases, the sheet resistance shows inversely similar curve with figure 3. The sheet resistance decreases until the PO_2 of 11 % and then increases. It is considered that this trends of sheet resistance and figure of merit with a variation of PO_2 is due to the optimum requirement of oxygen content for excellent ITO films. The optical transmittance increases slowly up to 84 % at PO_2 of 11 % and then reduces into 81 %.

From the above results, the best values of those figures of merit are approximately 38.6 and 8.95 ($\times 10^{-3}$ Ω^{-1}), respectively. Table I shows the figures of merit in ITO films prepared on the various substrates at low temperature by some papers.

4. Conclusions

ITO films were deposited on polyethylene terephthalate substrate by DC reactive magnetron sputtering of metallic alloy target. The figures of merit are important factors that summarize briefly the relationship between electrical and optical properties of transparent conducting films. The formulae of T/R_{sh} and T^{10}/R_{sh} are expressed as a function of transmittance and sheet resistance. The best values of those figures of merit were approximately 38.6 and 8.95 ($\times 10^{-3}$ Ω^{-1}), respectively.

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