Low Resistivity Transparent Conducting Oxide Thin Films Prepared by Pulsed Laser Deposition

Akio SUZUKI, Tatsuhiko MATSUSHITA, Takanori AOKI, Hideaki AGURA and Masahiro OKUDA*

Abstract

In a bid obtain resistivity of on the order of 10^{-5} Ω·cm, we fabricated a series of transparent conducting films from indium tin oxide (ITO) and aluminum-doped zinc oxide (AZO) by pulsed laser deposition (PLD) using an ArF excimer laser (λ =193 nm). With this method, a magnetic field generated by powerful permanent magnets of rare-earth (NdFeB: 1.25 T) was applied perpendicularly to the plume generated between the target and substrate. The flying particles and clusters subjected to Lorentz force are thought to be associated with complicated evaporation processes. Using this method, we obtained an ITO film with a resistivity of 7.2×10^{-5} Ω·cm was obtained.

However, the film resistivity obtained by this method was not always reproducible. In an attempt to improve the reproducibility, we adopted a target-to-substrate (T-S) distance of 10 mm instead of the 40～80 mm distance used beforehand. Under this new condition, the substrate was instantaneously exposed to the plume at high temperature. Upon receiving the thermal energies within the plume, the crystallization properties of the films improved and the values of carrier concentration increased. Statistically, our method had a 75 % probability of obtaining ITO films with a resistivity on the order of 10^{-5} Ω·cm. In the fabrication of AZO films, a resistivity of 8.54×10^{-5} Ω·cm was obtained by optimizing the applied magnetic field, T-S distance, and other preparation conditions.

Keywords

Low resistivity; Indium tin oxide films; Al-doped zinc oxide film; Pulsed laser deposition; Surface flatness; Interaction between plume and magnetic field; Target-to-substrate distance; Liquid crystal transparent electrode; Organic electroluminescence transparent anode; High deposition rate

Received October 10, 2003

Department of Electrical Engineering and Electronics, Osaka Sangyo University

* Department of Physics and Electronics, Osaka Prefecture University

1. Introduction

With the rapid advancement of electronic devices, the transparent conducting oxide (TCO) films utilized as electrode materials are now subject to far stricter performance demands. When TCO films are applied to liquid crystal displays, for example, the realization of films with lower the resistivity will be crucial for the successful manufacture of large displays exceeding 30～40 inches. Application in the field of organic electroluminescence also requires a lower film resistivity, as well as highly flattened electrode surface only attainable by polishing the surface after evaporation. In an earlier effort to meet these requirements, Tak and colleagues took a new look at the method used for TCO film preparation [1]. In addition the technology to grow of films at low temperature has become indispensable, and manufacturers are required to consider the heat-resistant property of the organic substrate when attempting film growth at low temperatures [2-4].

Various fabrications methods have been used to grow indium tin oxide (ITO) films. In recent experiments to grow ITO films by pulsed laser deposition (PLD), a resistivity on the order of 10^{-5} Ω·cm has been achieved [5]. However, this PLD method employed a substrate made from yttria-stabilized zirconia (YSZ) and quartz instead of glass, in order to keep the substrate temperature above 500 ℃. For this reason, the method was unsuitable for practical use.

To cope with these challenges, we tried to grow a series of low resistivity TCO films onto glass substrates (soda-lime), using an originally designed PLD method performed in the presence of a magnetic field applied perpendicularly to the plume generated between the target and substrate. By optimizing the deposition conditions, we succeeded in fabricating ITO and aluminum-doped zinc oxide (AZO) films with smooth surface morphologies and resistivities on the order of 10^{-5} Ω·cm.

In the experiments to fabricate the ITO film, we used an ArF excimer laser that provides relatively small power (40 mJ) and low repetition rate (10Hz). To apply a magnetic field perpendicular to the plume, three rare-earth permanent magnets (NdFeB), each with a flux density of 1.25 T were placed at intervals of every 120°. The composition of the target was In_2O_3 doped with 5 % SnO_2 [ITO (5 wt. %)] (99.999 % purity Furuuchi Co., Ltd.). In a series of films with a thickness of approximately 30 nm grown at a substrate temperature (T_{SUB}) of 300 ℃ in oxygen with a partial pressure of 10^{-3} Pa, the lowest resistivity obtained was 7.2×10^{-5} Ω·cm and the average transmittance was more than 90 % in the visible light wavelength range (more than 85 % at 400 nm) [6]. However, several limitations made this method infeasible for practical use: the results were not always reproducible, and the long T-S of 80 mm reduced the deposition rate to a mere 1.5 nm/min, making it difficult to stabilize the parameters required for fabrication. To surmount these limitations, we attempted a new series fabrications using an ArF excimer laser that provided larger power (300 mJ) and higher repetition rates (～50 Hz), with the T-S distance shortened to 10 mm. These efforts proved successful, and the deposition rate increased by 290 times compared to that observed earlier with the longer T-S distance of 80 mm. However, the oxygen deficiency in this revised fabrication method

ended up coloring the films. When the same process was repeated with the partial pressure of oxygen raised to the extreme degree (~10 Pa), we produced films with a thickness of approximately 300 nm, an average transmittance in the visible wavelength range of more than 90 %, and an average roughness on the film surface (Ra) of 1.26 nm. The lowest resistivities of the new films was 8.45×10^{-5} Ω·cm and the statistical probability of obtaining a resistivity on the order of 10^{-5} Ω·cm was 75 %.

Next, based on our experience fabricating the ITO films, we tried to fabricate AZO films [7] with resistivities on the order of 10^{-5} Ω·cm using a PLD method with the same magnetic field applied in a similar configuration. However, with the AZO films, we employed a split target joined with two semicircles, one side made from zinc oxide doped with 1 wt. % Al_2O_3 [AZO (1 wt. %)] and the other side made from zinc oxide doped with 2 wt. % Al_2O_3 [AZO (2 wt. %)]. The optimized preparation conditions were as follows: laser power of 15~40 mJ, repetition rate of 10 Hz, T-S distance of 25 mm, T_{SUB} of 230 ℃, and base pressure of 3×10^{-4} Pa in vacuum. As a result, we obtained a series of AZO films with a thickness of 280 nm, an average transmittance more than 91 % in the visible light wavelength range (more than 90 % at 400 nm), and nadiral resistivity of 8.54×10^{-5} Ω·cm.

2. Experimental

Figure 1 shows a schematic diagram of the pulsed laser deposition system employed in this experiment. Table 1 lists the preparation conditions. The deposition was performed using

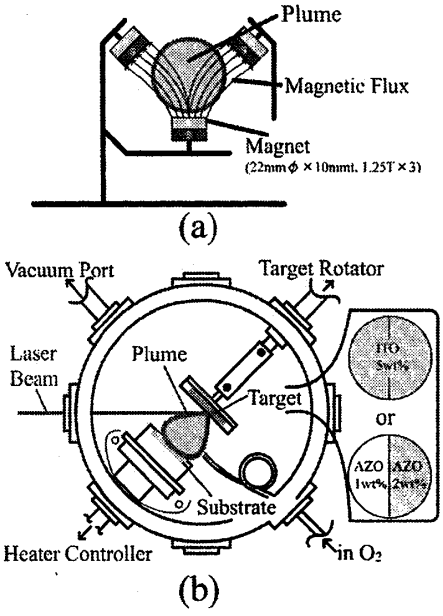


Fig. 1. Pulsed laser deposition system used for the ITO (5 wt. %) films: (a) the arrangement of the permanent magnet and (b) schematic diagram of the chamber.

Table 1. Preparation conditions for ITO films fabricated with magnetic field.

Laser	ArF Excimer Laser (λ = 193nm)
Laser Energy	15~300 mJ
Repetition Rate	1~50 Hz
Target to Substrate Distance	10~80 mm
Target	In_2O_3 : SnO_2 (5wt%) , ZnO : Al_2O_3 (1.5~2.0wt%)
Substrate	Corning #7059
Substrate Temperature	25~450 ℃
Base Pressure	10^{-5} Pa
Gas Pressure	~10^{-3} Pa (in O_2)
Ablation Time	0.5~40 min

an ArF excimer laser (λ =193 nm) that delivered 40 mJ pulses for 12~16 ns durations at repetition frequency of 10 Hz (LAMDA PHISIK, COMPex 200, LPX-305i). The deposition cell was initially evacuated to ~10^{-5} Pa and film deposition was performed at a working pressure of 10^{-3} Pa by adjusting the flow rate of oxygen. Corning #7059 glass substrates measuring 38 ×26 mm were used at T_{SUB} = 25~300 ℃. After setting the target 40 mm from the substrate, the laser beam was focused to a point measuring approximately 1.8 mm in diameter using a spherical quartz lens, delivering energy at a density of 1.5 J/cm^2 directly onto the target. During the laser irradiation, a computer-controlled pulsed motor moved the target along two axes (up-down and right-left) and rotated it at a speed of one revolution per minute in order to avoid the formation of deep craters that could modify the material ejection. The film thickness was measured with a high accuracy using three devices: a stylus instrument (KLA TENCOR, P-10), a high-resolution SEM (HITACHI, S-4700), and an ellipsometry instrument (HOSIN, AE-1100). The resistivity, carrier concentration, and Hall mobility were measured by the van der Pauw method (BIO-RAD, Hl5500PC). The transmittance through the films was measured in a wavelength range of 300~1000 nm using a spectrophotometer(HITACHI, U-3500) with Corning #7059 glass as reference. The crystal orientation was evaluated by an X-ray diffractmeter (Shimadzu, XRD-6000 for the thin-film method, XRD-6100 for the θ-2θ method), and the surface morphology of the film was observed by a high-resolution field emission scanning electron microscope (FE-SEM) (HITACHI, S-4700). The surface roughness of the film was measured by an atomic force microscope (AFM) (Topometrix, TMX-2000).

3. Results and discussion

3.1. Preparation of ITO films with magnetic field

The deposition rate was reduced to one-half to one-third with the application of magnetic field, and the film thickness was reduced from 50~75 nm without magnetic field to about 20 nm with magnetic field. Figure 2 shows the influence of substrate temperature (T_{SUB}) on

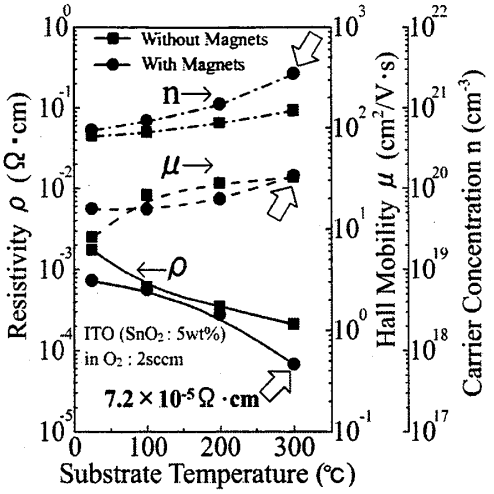
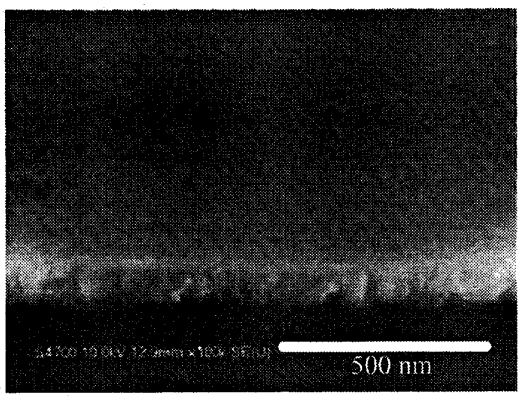


Fig. 2. Substrate temperature dependencies of electrical properties of ITO (5 wt. %) deposited on glass substrates.

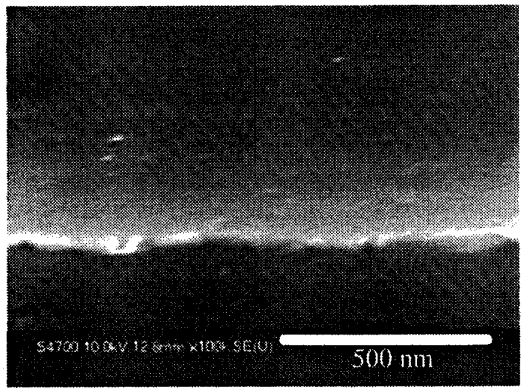
resistivity (ρ), carrier concentration (n) and Hall mobility (μ) in ITO (5 wt. %) films grown under the conditions listed in Table 1. The resistivity decreased as TSUB increased, and the application of the magnetic field resulted in a substantially reduced resistivity. The lowest resistivity observed under the magnetic field, 7.2×10^{-5} Ω·cm, was half that obtained at TSUB = 300 ℃ (see arrows in the figure) and nadiral among all ITO films deposited onto the Corning #7059 glass substrate. The carrier concentration substantially increased with the application of magnetic field at TSUB = 300 ℃, rising to value of 2.5×10^{21} cm^{-3}, or close to the maximal carrier concentration expected in the visible transmission wavelength range. On the other hand, the application of magnetic field produced no observable effect on the Hall mobility. Based on the findings above, we concluded that the very low resistivity obtained at TSUB = 300 ℃ was attributable to the high carrier concentration obtained by the application of magnetic field. The only explanation proposed for these experimental results involve a complicated model of carrier movement [8] derived from atoms, molecules, and clusters excited by Lorentz force. However, no definitive solution has been reached. Several yeas ago, an average transmittance of more than 90 % in the visible light wavelength range (more than 85 % at 400 nm) was obtained [6]. Figure 3 shows FE-SEM micrographs of the surfaces and cross-sections of ITO films prepared at TSUB = 300 ℃ (a) without and (b) with magnetic field. In Fig. 3 (a), columnar structures growing up from the substrate can be observed in the cross section of the film with a poly-crystalline structure of about 30~50 nm on the film surface. In Fig. 3 (b), the formation of only tiny crystallites resulted in very smooth film surfaces. This was highly suggestive of a complicated movement of carriers resulting from the magnetic field in the deposition process, as described in Fig. 2.

in O_2 : 2sccm T_{SUB} : 300 ℃
Without Magnets



(a)

With Magnets



(b)

Fig. 3. High-resolution SEM images of ITO (5 wt. %) films fabricated (a) without and (b) with magnetic field.

3.2. Preparation of ITO films without magnetic field

The results of the above-described fabrication method for ITO films were not always reproducible, and the long T-S distance of 80 mm reduced the rate of deposition to a mere 1.5 nm/min, making it difficult to stabilize the parameters required for fabrication. These limitations ruled out the feasibility of this method for practice use. In an effort to surmount these limitations, we attempted a new series of fabrications using an ArF excimer laser that provides larger power (300 mJ) and higher repetition rates (~50 Hz), with the T-S distance shortened to 10 mm. These efforts proved successful, and the deposition rate increased by 290 times compared to that observed earlier with the longer T-S distance of 80 mm.

Next, we describe a method capable of fabricating ITO films with resistivity on the order of 10^{-5} Ω·cm with excellent reproducibility. Table 2 lists preparation conditions with a high deposition rate in the absence of magnetic field. Figure 4 shows the influence of the T-S distance on electrical properties (ρ, n and μ) and the deposition rate (D.R.) in ITO (5 wt. %) films prepared under the following conditions: T_{SUB} = 400 ℃, laser power = 300 mJ, repetition

Table 2. Preparation conditions for ITO films fabricated without magnetic field.

Laser	ArF Excimer Laser (λ = 193nm)
Laser Energy	300 mJ
Laser Energy Density	6 J/cm^2
Repetition Rate	1～50 Hz
Target to Substrate Distance	10～80 mm
Target	ITO (5wt% SnO_2)
Substrate	Corning #7059
Substrate Temperature	400 ℃
Base Pressure	～10^{-4} Pa
Gas Pressure	10^{-1}～10 Pa (in O_2)
Ablation Time	30～900 sec

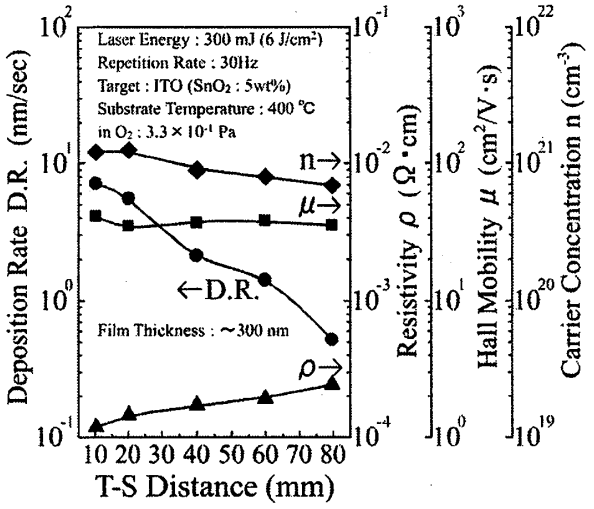


Fig. 4. The influence of the target-substrate distance on the resistivity, carrier concentration, Hall mobility and deposition rate on in ITO (5 wt. %) films of approximately 300-nm-thickness. The substrate temperature was kept at 400 ℃ and the oxygen pressure was kept at 3.3×10^{-1} Pa during deposition.

rate = 30 Hz, working pressure = 3.3×10^{-1} Pa in oxygen. In order to obtain ITO films with a thickness of approximately 300 nm, the ablation time was adjusted to between 30 and 900 s. At the T-S distance grew shorter, the deposition rate (D.R.) increased, resulting in 15-fold increase in the D.R from 0.5 nm/s at the T-S distance of 80 mm to 7.3 nm/s at the T-S distance of 10 mm. A decreasing T-S distance was also associated with a monotonous decrease in the resistivity due to an increase in the carrier concentration, and a resistivity of 1.15×10^{-4} Ω·cm was obtained at the T-S distance of 10 mm. However, the average transmittance in the visible light wavelength range of 400~700 nm was only 74.2 % for the 300-nm-thick ITO films obtained at the T-S distance of 10 mm.

Next, to investigate the cause of this low transmittance, the surface morphologies of the ITO films fabricated by changing the T-S distance were observed by FE-SEM and AFM. On the basis of these results, we attributed the low transmittance in the visible range in the films fabricated at the T-S distance of 10 mm to the scattering caused by deterioration of the film surface, a phenomenon that may have stemmed from the lack of oxygen gas [9]. To investigate further, we examined the surface morphologies of ITO films fabricated at a high partial oxygen pressure of 10 Pa at the same T-S distance of 10 mm. Figure 5 shows the (a)

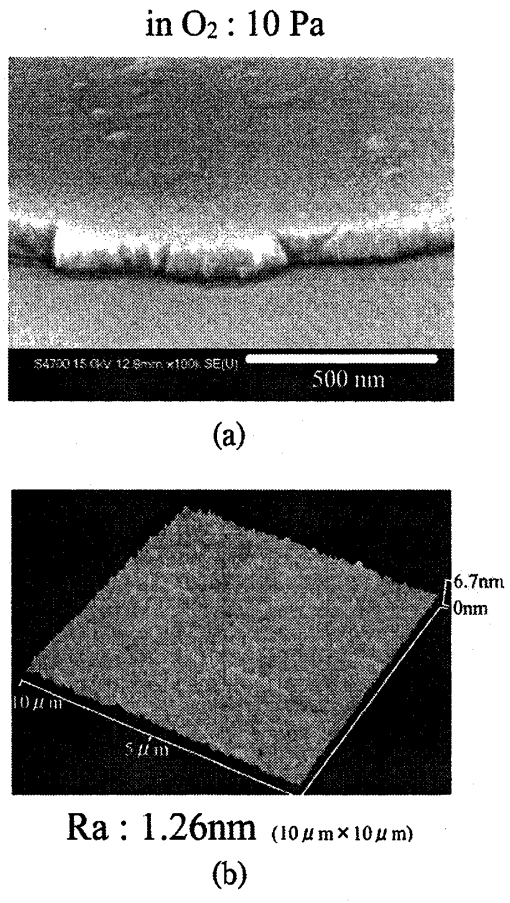


Fig. 5. High-resolution SEM image (a) and AFM image (b) obtained of ITO (5 wt. %) film deposited at a T-S distance of 10 mm under an oxygen pressure of 10 Pa.

FE-SEM and (b) AFM images of an approximately 300-nm-thick ITO film grown at a T-S distance of 10 mm under an oxygen partial pressure of 10 Pa. The film fabricated under these conditions had a surface roughness (Ra) of only 1.26 nm, or about the same roughness as that obtained at the T-S distance of 40~80 mm (see Fig. 3). Figure 6 shows the optical transmittance spectrum for the ITO films and a photograph of the real thing. These ITO films had an average transmittance of more than 80 % in the visible range (near 80 % at 400 nm) and their transmittance was proved to be very high in the visible range, as shown in the inset of Fig. 6. Table 3 summarizes electrical and optical properties of the ITO films

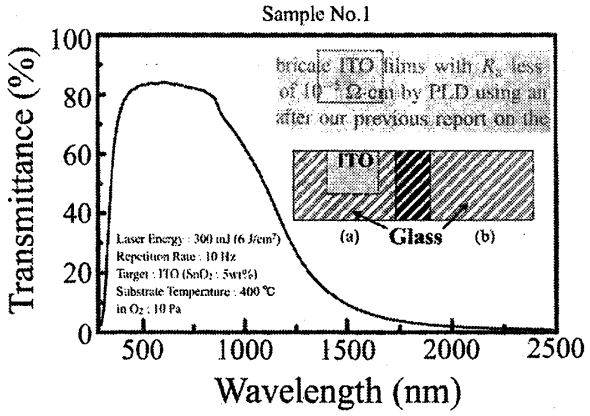


Fig. 6. Optical transmittance spectra of sample No.1 listed in Table 3. The inset gives the proof of the high transmittance.

Table 3. Electrical and optical properties of ITO (5 wt. %) film grown at a T-S distance of 10 mm under an oxygen pressure of 10 Pa.

Sample number	Resistivity (Ω·cm)	Hall Mobility ($cm^2/V \cdot s$)	Carrier Concentration (cm^{-3})	Average Transmittance [a] (%)	Thickness (nm)
1	8.45×10^{-5}	53.5	1.38×10^{21}	84.7	315
2	9.72×10^{-5}	58.9	1.09×10^{21}	83.7	321
3	8.78×10^{-5}	51.6	1.38×10^{21}	91.7	281

[a] The average value in the visible range of 400-700 nm.

grown at the T-S distance of 10 mm under the oxygen partial pressure of 10 Pa. The measurements were performed four times for each of three samples and data showing resistivity values on the order of 10^{-5} Ω·cm were adopted. According to these data, the 300-nm-thick ITO film reproducibly obtained a resistivity on the order of 10^{-5} Ω·cm (75 % probability). Next, in order to clarify why these ITO films acquired excellent electrical and

optical characteristics when fabricated at a short T-S distance under a high oxygen partial pressure, we measured the temperatures in the plume using a simple method with thermocouples. Figure 7 shows a photograph of the plume (left-hand) corresponding to the

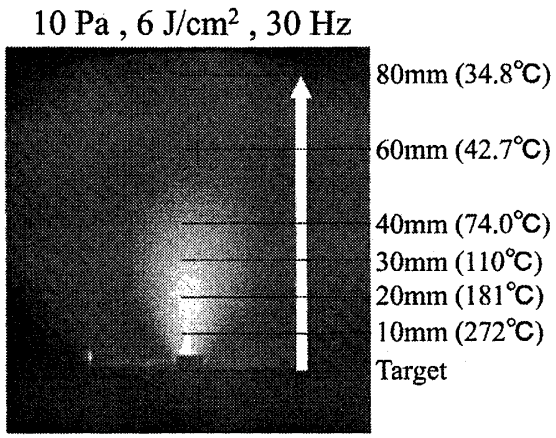


Fig. 7. The influence of the T-S distances on plume temperatures measured with thermocouple.

dependence of plume temperatures on the T-S distance (right-hand). As the T-S increased, the plume temperature gradually decreased in the region from 40 to 80 mm, where a condensation process was allowed to proceed due to the minimal influence of the collision process between ambient gas and flying particles. In contrast, the plume temperature rapidly decreased in the region from 0 to 40 mm, where a complicated collision process among electrons, ions and atoms following the interaction between the target material and laser beam resulted in a plasma reaction. Consequently, we conjecture that in the region from 0 to 10 mm largely deficient states of oxygen will appear near the substrate when the fabrication is performed at low partial pressure of oxygen, due to the oxygen-consumption-process caused between the plume and materials ejected from the substrate with strong momentum. Thus, we conclude that in the fabrication process performed at this time, the sufficient supply of oxygen into the region irradiated by the high-energy laser beam of 300 mJ and the enhanced ionization of the spices inside the plume, namely, the increase in plasma density, gave rise to the low resistivity state by increasing carrier concentration. Turning now to a different issue, the cause of the low resistivity, we need to consider the large values of mobility listed in Table 3, since the carrier concentration does not approach the limit ($\sim 2.5\times10^{21}$ cm^{-3}) derived from the visible light wavelength range. However, numerous points related to ionization scattering and neutral impurity scattering must be clarified to account for the large mobility values observed when particles with high energy in the vicinity of the target become constituent elements of films under high oxygen partial pressure of 10 Pa. These issues are currently under study in our laboratory.

3.3 Preparation of AZO films with magnetic field

Next, we describe the fabrication process of aluminum-doped zinc oxide (AZO) films, grown in vacuum (base pressure 3×10^{-4} Pa) by PLD using ArF excimer laser (15 mJ, 10 Hz), a device that works without the rare metal element, indium. Two point are noteworthy here: the use of the split target composed of AZO (1 wt. %) and AZO (2 wt. %) as shown in Fig. 1 (b) and the adoption of a T-S distance of 25 mm. Figure 8 shows the dependence of electrical

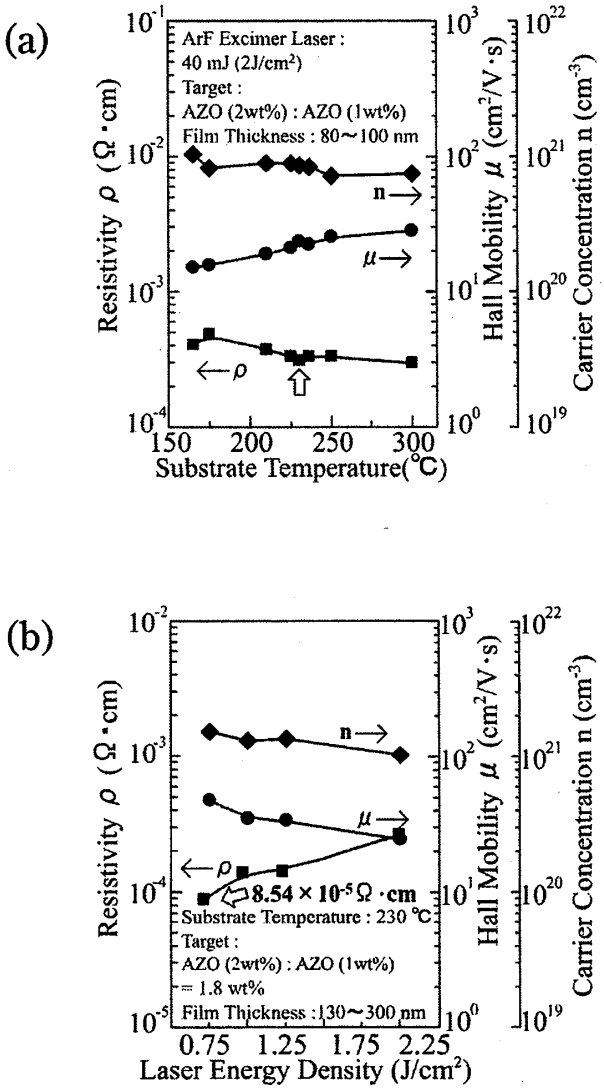


Fig. 8. Electrical properties of AZO (1.8 wt. %) films deposited on glass substrates: (a) substrate temperature and (b) laser energy density dependences.

properties (ρ , n and μ) on the substrate temperature (a) and laser energy density (b). After taking the fabrication process for various devices into account, we adopted a substrate temperature of 230 ℃ [see arrows in (a)]. The lowest resistivity observed, 8.54×10^{-5} Ω·cm, was obtained in an approximately 280 nm-thick-AZO film at what we surmise to be a laser energy density near the threshold value required for film fabrication, namely, 0.75 J/cm^2 [see arrows in (b)]. At this time, the film composition was estimated to be AZO (1.8 wt. %) by the trace ratio (the ratio of time required to irradiate each part of the split target). Figure 9 shows the transmittance spectrum for the AZO films with the lowest resistivity. An average

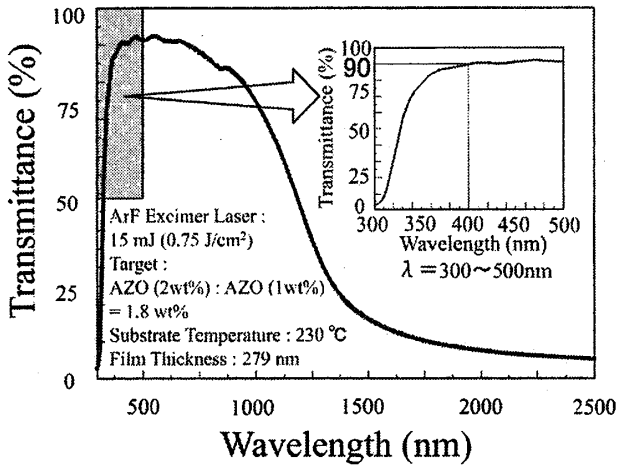


Fig. 9. Optical transmittance spectra of the AZO (1.8 wt. %) film with approximately 280-nm-thickness. The inset gives the proof of the high transmittance near the ultra violet wavelength region (90 % at 400 nm).

transmittance of more than 91 % in the visible range (near 90 % at 400 nm from the inset of the figure) was obtained and that the AZO film fulfilled its function as the TCO film in the visible range. At this point, we carried out a cross-sectional TEM observation in to clarify why the AZO film as acquired a low resistivity on the order of 10^{-5} Ω·cm. Figure 10 shows TEM images obtained for the 280 nm-thick-AZO film with a nadiral resistivity of 8.54×10^{-5} Ω·cm under two conditions: (a) without magnetic field and (b) with magnetic field. In these images, the columnar structures with the c-axis orientation stemming from the interface between the substrate and the film [including (002) and (004) facets], are disarranged in the film fabricated without magnetic field. This corresponded well with the X-ray measurements, which showed a large peak (002) and (004) in the film fabricated with magnetic field, versus only a small peak (002) in the film fabricated without magnetic field. Moreover, the regularity

in the crystal growth emerged from different points in the two films, namely, immediately from the interface between the substrate and the film in the fabricated with magnetic field, and from near the center of the film in the film fabricated without magnetic field. This may have been due to the difference in mobility observed between the films (47.6 $cm^2/V \cdot s$ with magnetic field vs. 36.7 $cm^2/V \cdot s$ without magnetic field).

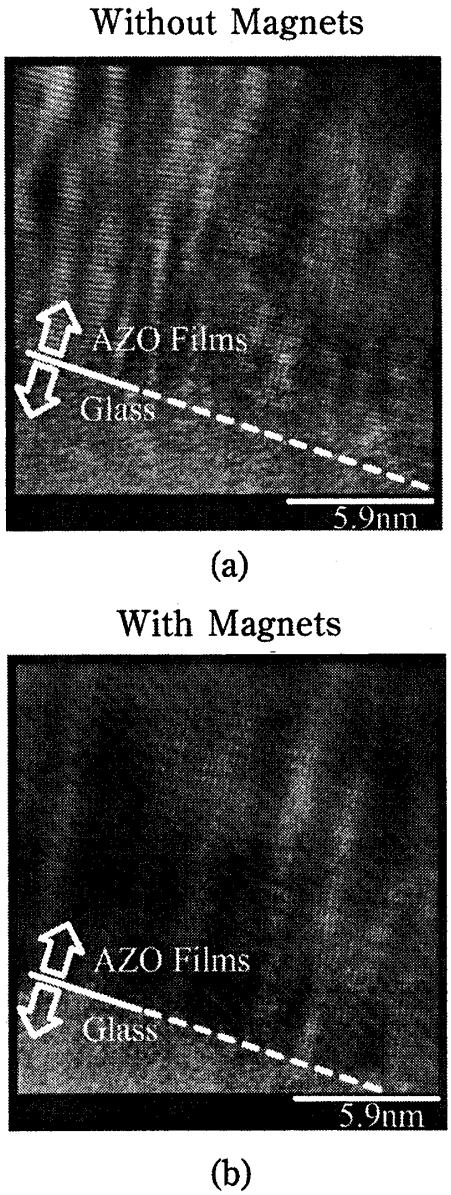


Fig. 10. High-resolution TEM images of the AZO (1.8 wt. %) film fabricated (a) without and (b) with magnetic field.

4. Conclusions

The following results were obtained for the ITO films;

(1) ITO films were deposited on glass substrates at a T-S distance of 40 mm in the presence of a magnetic field applied perpendicularly to the plume generated by PLD using an ArF excimer laser (40 mJ, 10Hz). In ITO (5 wt. %) films grown to a thickness of about 20 nm at T_{SUB} = 300 ℃ in oxygen under a partial pressure of 10^{-3} Pa, we obtained nadiral resistivity of 7.2×10^{-5} Ω·cm and an average transmittance of more than 90 % in the visible range (400 ~700 nm). According to our measurement of the Hall effect, the very low resistivity was attributable to the increase in the carrier concentration by the application of magnetic field. In our FE-SEM observation the surfaces of the films fabricated with magnetic field were very smooth due to the formation of only small crystallites.

(2) ITO films were deposited on glass substrate at T-S distance of 10 mm in the absence of magnetic field using an ArF excimer laser (300 mJ, 30 Hz). In ITO (5 wt. %) films grown to a thickness of about 300 nm at T_{SUB} = 400 ℃ in oxygen under a partial pressure of 10 Pa, we obtained a resistivity on the order of 10^{-5} Ω·cm with a good reproducibility of 75 %. In these films, we obtained a nadiral resistivity of 8.45×10^{-5} Ω·cm, surface roughness of 1.26 nm and average transmittance of more than 80 % in the visible range (400~700 nm) .

(3) We attempt to explain two issues: why the plume temperature depended on the distance, and why resistivity on the order of 10^{-5} Ω·cm was reproducible with probability of 75 %. The essential mechanism to explain these results is now under investigation.

The following results were obtained for the AZO films;

(1) AZO films were grown on glass substrates at a T-S distance of 25 mm in the presence of a magnetic field applied perpendicularly to the plume generated by PLD using an ArF excimer laser (15 mJ, 10 Hz, 0.75 J/cm^2). In the approximately 280 nm-thick-AZO film (1.8 wt. %) grown at T_{SUB} = 230 ℃ in vacuum, we obtained a nadiral resistivity of 8.54×10^{-5} Ω·cm and an average transmittance of more than 91 % in the visible range.

(2) Based on the cross-sectional TEM observation and the XRD spectrum images, the success in reproducibly obtaining a low resistivity on the order of 10^{-5} Ω·cm appeared to be the effect of the magnetic field in suppressing the disorder in the crystal due to originating in the vicinity of the interface between the substrate and film. By imposing a preference towards the c-axis-orientation, the magnetic field increased the mobility.

References

[1] Y.H. Tak, K. B. Kim, H.G. Park, K.H. Lee, J.R. Lee, Thin Solid Films 411 (2002) 17.

[2] H. Izumi, T. Ishihara, H. Yoshioka, M. Motoyama, Thin Solid Films 411 (2002) 32.

[3] F.O. Adurodija, H. Izumi, T. Ishihara, H. Yoshioka, Appl. Phys. Lett. 74 (1999) 3059.

[4] D.C. Paine, T. Whitson, D. Janiac, R. Beresford, C.Ow Yang, J. Appl. Phys. 85 (1999) 8445.

[5] H. Ohta, M. Orita, M. Hirano, H. Tanji, H. Kawazoe, Applied Phys. Lett. 76 (2000) 2740.
[6] A. Suzuki, T. Matsushita, T. Aoki, Y. Yoneyama, M.Okuda, Jpn. J. Appl. Phys. 40 (2000) L401.
[7] A. Suzuki, T. Matsushita, T. Fukuda, H. Fujiwara M. Okuda, Trans. IEE of Japan 117 (1997) 405.
[8] M. Tachiki, T. Kobayashi, Jpn. J. Appl. Phys. 38 (1999) 3642.
[9] S. Takayama, A. Tanaka, T. Sugawara, T. Himuro, Jpn. J. Appl. Phys. 41 (2002) L619.