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Xe-arc flash annealing of indium tin oxide thin-films prepared on glass backplanes

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ABSTRACT

Using a Xe-arc flashing of 0.4 ms, indium tin oxide (ITO) thin-films widely applied to fabricate transparent conducting electrodes for solar cells and displays are annealed at room temperature in order to improve their electric conductance and optical transmittances. ITO thin-films of 100 nm in thickness are deposited on a glass substrate of 500 μm in thickness by the magnetron sputtering method. Ray-tracing calculation estimates that heat absorbed in the thin-film during flash lamp annealing (FLA) process with using an additional back-reflector increases by about 2.8 times greater than that without using the back-reflector. Simulation based on one-dimensional conduction/radiation heat transfer model shows that the film temperatures during the FLA process exceed the crystallization point of the ITO material, indicating that its physical properties have been varied accordingly. Undergoing the short experimental FLA process, resistivity of the specimen has been decreased by about 30%, which is comparable to the ones obtained from conventional furnace annealing at temperatures ranging 200–300 °C for an hour, while the transmittances in the visible light range have been slightly increased. Morphological features of the films are investigated using XRD, XPS, AFM, and SEM, indicating that the specimens treated by the FLA or in furnace have crystallites larger than that of the as-received.

1. Introduction

Indium tin oxide (ITO) thin-films have been widely used in optoelectronic industries, especially for flat panel displays, solar cells, gas sensors, and organic light emitting devices due to their unique optical and electrical characteristics [1–4]. Since the ITO material is one of heavily-doped n-type semiconductors with wide band gaps of 3.3–4.3 eV, it has high optical transmittances over the visible wavelength range. High carrier concentrations in the ITO thin-films caused by oxygen vacancies and substitutional tin dopants result in low electrical resistivities of 2×10^{-4}–4×10^{-4} Ω-cm. Furthermore, they are mechanically strong and chemically stable, resisting relatively high process temperatures [5,6].

ITO thin-films have been manufactured using a variety of processing methods, such as magnetron sputtering [7], sol–gel deposition [8], electron beam evaporation [9], chemical vapor deposition [10], pulsed laser deposition [11], and spray pyrolysis [12]. Since crystallization of ITO starts at temperatures between 150 °C and 180 °C [13,14], every deposition technique requires either a deposition process at higher temperatures of 200–650 °C [15–17] or a post-deposition annealing treatment at higher temperatures with a process longer than an hour after the deposition at low temperatures. Since the current trend in the fabrication of the ITO thin-films utilizes thinner glass backplanes or polymer materials as the substrate for realizing flexible solar panels or displays economically, we have to lower the deposition or the post-annealing temperatures to minimize the thermal damage of the substrate.

Various methods for post-deposition annealing of the ITO thin-films have been developed, such as conventional furnace annealing (CFA), excimer laser annealing (ELA), electron plasma annealing, oxygen plasma treatment, and rapid thermal annealing [18–21]. In all the methods except the ELA, the annealing processes are considerably time-consuming and the thin-film is treated thermally simultaneously with the substrate. That is, the substrate can be damaged thermally, if the substrate is vulnerable to high process temperatures. On the contrary, the ELA method is known to anneal the thin-film without incurring the thermal damage of the substrate due to the extremely short process time of tens of nanoseconds, but the overall ELA process becomes extremely expensive compared with other methods. Therefore, it is necessary

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to develop the furthermore inexpensive and short-duration annealing process sufficient to induce the selective heating of the ITO thin-film only.

In order to heat the ITO thin-film on glass substrate selectively, this study will apply the flash lamp annealing (FLA) process, in which the thin-film can be annealed within a process time less than 1 ms with the use of a Xe-arc flash lamp. In general, the FLA has been investigated as one of the candidates for replacing the ELA process of amorphous silicon (a-Si) thin-film [22–28] for the fabrication of low-temperature poly-silicon (LTPS). It has not been, however, applied to anneal the ITO thin-film, since the ITO material has relatively low values of imaginary part of the refractive indices in the visible light spectrum, resulting in extremely ineffective heating of the thin-film.

Table 1 briefly compares the strengths and the weaknesses of the typical ITO annealing methodologies with the FLA to understand the current stage of the annealing technologies in the fabrication of the large-window displays and solar cells. Furthermore, millisecond annealing techniques with flash lamps, recently, have attracted noticeable attentions in the display or semiconductor manufacturing process, since the FLA process can provide the sufficient time delay for incubation or activation and can minimize thermally-induced damage as well [32–34].

Here, we apply a Xe-arc flash lamp of pulse duration, 400 μs, for post-annealing of the ITO thin-film deposited on glass substrate, based on the multiple absorption of the light in the film in a highly reflective enclosure. Refractive indices of the as-received ITO thin-film are estimated from the measurements of optical transmittances and reflectances in the visible wavelength spectrum, which are used to predict the thermal field in the ITO thin-film/substrate and to confirm that the peak temperature reaches the point sufficient to anneal the thin-film. The experimental system has been modified from the one used for the annealing of a-Si thin-film on glass in our previous studies [27,28] with the addition of a flat reflector at the backside of the substrate, as shown in Fig. 1. The enclosure composed of the back-reflector and the reflector for the lamp induces the multiple reflection of the flash beam and thus the multiple absorption in the thin-film. The ITO thin-films obtained from the FLA post-process were compared with those from the CFA process through optical spectra, electrical resistivities, X-ray diffractions (XRD), X-ray photoelectron spectroscopy (XPS), atomic force microscope (AFM) and scanning electron microscope (SEM) images, to assure the effectiveness of the FLA process for post-annealing the almost-transparent material, ITO.

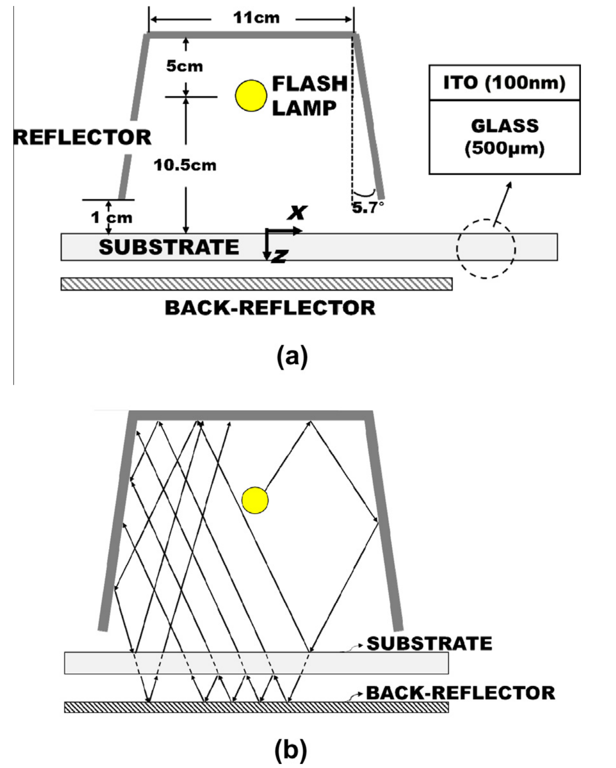

Fig. 1. (a) Flash lamp annealing (FLA) system for the ITO thin-film deposited on glass substrate and (b) tracing of light emitted from the lamp.

2. Experimental

2.1. Optical characterization

To assure the selective heating of the ITO thin-film using the FLA process, we have to estimate the optical properties of the thin-film, especially the imaginary part of the refractive index, from the measurements of transmittances and reflectances over

Table 1
Important characteristics of the representative methodologies for ITO annealing [18,20,24,29–31].

Characteristics	Continuous furnace annealing (CFA)	Eximer laser annealing (ELA)	Flash lamp annealing (FLA)
Process time	>1 h	~30 ns	~1 ms
Process temperature	>200 °C	Room temperature	Room temperature
Process window	Whole panel	Extremely narrow (~0.5 mm × 500 mm)	Wide (~100 × 2000 mm)
Glass panel size	~8th generation	~6th generation	~8th generation
Process uniformity	Highly uniform	Highly non-uniform, requiring a great number of scanning and overlapping	Moderately uniform, probably a couple of scanning and overlapping
Thin-film heating selectivity	Non-selective	Selective	Selective
Process continuity	Batch	Semi-continuous	Continuous
Mechanical stability for glass substrate	Good	Good	Good
Mechanical stability for polymer substrate	Poor	Good	Moderate
Light spectrum	Infrared	UV	UV–visible
Oxygen adsorption to degrade electric conductivity	High	Low	Low
Thermal budget	High	Low	Low
Price	Low	Highly expensive	Moderate
Technical readiness for ITO annealing	Widely applied	Rarely applied	Not available in literature