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Periodic surface structures on the surface of indium tin oxide film obtained using picosecond laser

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ABSTRACT

Ultrafast laser-induced surface modification of materials has attracted significant attention in recent years. The mechanism of formation of ultrafast laser-induced periodic surface structures (LIPSS), which were evenly distributed over the large area of indium tin oxide, was studied both theoretically and experimentally. Films were deposited using 10-ps 1064-nm laser. Resistance and transmission characteristics of LIPSSs on ITO film were analyzed. The resistance of LIPSSs increases with the increasing of transmittance in infrared band within a certain range. The paper reports the optimal processing parameters for the realization of LIPSSs on ITO films established based on the resistance and transmission properties of the film. The film with the optimized structure can significantly improve the infrared transmittance function of ITO while ensuring the low resistance, which can greatly improve the power generation efficiency of the thin film solar cells.

1. Introduction

Indium tin oxide (ITO), notable for its high transmittance in the visible light range and its low resistivity, is widely used as a transparent electrode for thin film solar cells, liquid crystal displays, organic light emitting devices (OLED), etc [1–7]. Ultrafast laser processing has been demonstrated as a novel approach for micro- and nano-machining of bulk material surfaces and internal modification of transparent materials [8–11]. Ultrafast laser-induced periodic surface structures (LIPSSs) can improve the characteristics of ITO film. Due to the periodic protrusions and depressions structures on the surface, the textured ITO film being beneficial for photons generated in the multiple quantum wells (MQW) [12], this leads to a decrease in light reflectance and increases the light transmittance correspondingly. Untreated ITO films have low IR transmittance, which significantly reduces the light absorption efficiency of thin film solar cells [13,14]. The LIPSSs on the surface of ITO film might enhance the light transmittance in IR band, making them useful for application for the film solar cells and OLED devices.

However, preparation of large area LIPSSs on the ITO film by 1064 nm picosecond laser has not been reported. The relationship among the LIPSSs, light transmittance and resistance, which is important for ITO thin films, has not been understood well. In this paper, we report the processing method of LIPSSs on ITO films with emphasis on large-scale uniform LIPSSs as well as analysis of the energy distribution and overlap rate of ultrafast laser spot. The effect of different scan speeds on the surface resistance of different ITO structures as well as their transmission characteristics are discussed in detail, as well as the relationship between them. Resistance and transmission characteristics of ITO film in solar cells were obtained, which helped to establish the optimal processing parameters for the realization of LIPSSs on ITO films to produce improved thin film solar cells.

2. Experimental techniques and procedures

The schematic of the experimental setup is shown in Fig. 1. The apparatus consisted of a laser, a 3-D moving workbench, laser transmission system, control system and other associated instruments. A neodymium-vanadate (Nd: VAN; Austria) laser, delivering 10-ps pulses and a maximum power of 2 W at a tunable repetition rate between 1 and 100 kHz, was used to obtain the LIPSSs on the ITO film surface. Laser transmission system consisted of a plano-convex lens with the focal length of 150 mm. An aperture slot was used to block the edge of the laser beam. An electromechanical shutter was controlled by the computer. Meanwhile, horizontal and longitudinal movements as well as

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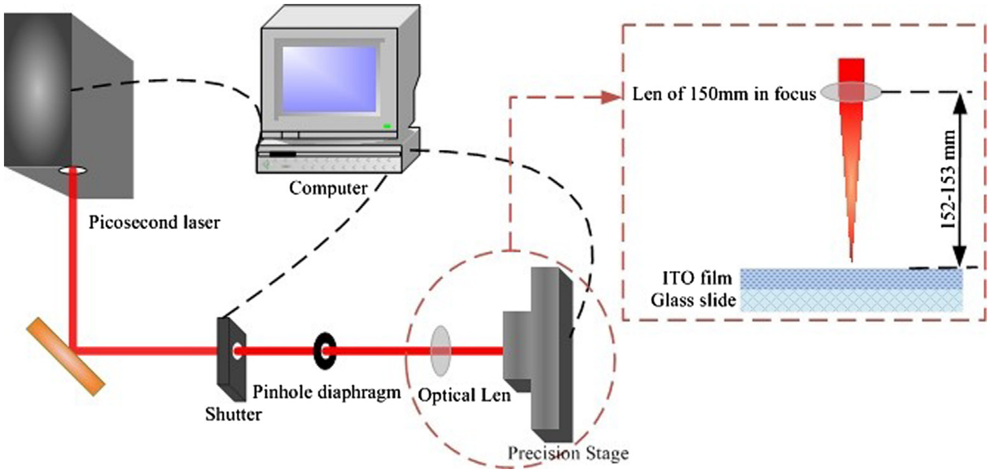

Fig. 1. Schematic of the experimental setup for the LIPSSs deposition on the ITO films.

accurate positioning of the ITO film was controlled by a three-axis servo platform (100 nm in resolution).

We used 1064 nm emission wavelength and 1 kHz repetition rate. Commercial ITO film with the resistance of 16 Ω/cm^2 was used. The thickness of the ITO layer coated on the glass substrate was 180 nm.

The nanostructure of samples was analyzed using scanning electron microscopy (SEM). The transmission rate was tested using Violet-visible spectrophotometer with the 260–2600 nm bandwidth.

Laser energy should be limited to the value above its ablation threshold and below its excessive ablation. The laser power was fixed at 30 mW and the distance of the focus away from the surface of ITO film was 2 mm (see Fig. 2). Spot radius can be calculated using Eq. (1):

$$r_0 = \frac{w_f}{2}\left[1+\left(\frac{z}{d}\right)^2\right]^{\frac{1}{2}}, \tag{1}$$

where z is the off-focus distance, d is Rayleigh length of laser system expressed as $\pi(w_f/2)^2/\lambda$ [15,16] and w_f is spot beam radius at the focus, which can be expressed using the following equation:

$$w_f = \frac{4M^2\lambda f}{\pi w_0}, \tag{2}$$

where w_0 is laser beam radius before focus, M^2 is the beam quality, f is the focal length and λ is the wavelength [17,18]. The experiment was performed with fixed vertical distances between the two laser scanning lines (equal to 70% of laser spot diameter) to ensure large enough energy accumulation to efficiently produce continuously uniform LIPSSs (see Fig. 2).

3. Mechanism of the nanostructure fabrication using picosecond laser

Different surface morphologies were observed on the ITO film due to the Gaussian distribution of laser energy. The irradiated zone with high pulse energy could be divided into three regions (see Fig. 3). Laser fluence in the center of the spot was large enough to ablate the whole ITO material. Second area had ring-arranged holes arrays. Therefore, only the energy in the outmost region was suitable to produce LIPSSs [19–21]. Thus, the laser fluence had to be reduced in the center of beam to avoid random holes and ring-arranged holes arrays embedded in LIPSSs. The laser energy had to be attenuated to the desired value if the single pulse laser energy density was not enough to produce ring-arranged hole arrays, which was slightly below the ablation threshold of ITO. The ablation threshold of ITO were calculated experimentally using Liu's method [22]:

$$D^2 = 2w_f \ln\left(\frac{F_0}{F_{th}}\right), \tag{3}$$

where D is the diameter of the damaged area measured by the optical microscope, w_f is spot beam radius at the focus, F_{th} is the ablation threshold fluence and F_0 is peak fluence calculated from Eq. (4):

$$F_0 = \frac{2E_p}{\pi w_f^2}, \tag{4}$$

where E_p is laser pulse energy. The ablation threshold fluence is $F_{th} = 0.5920\ J/cm^2$.

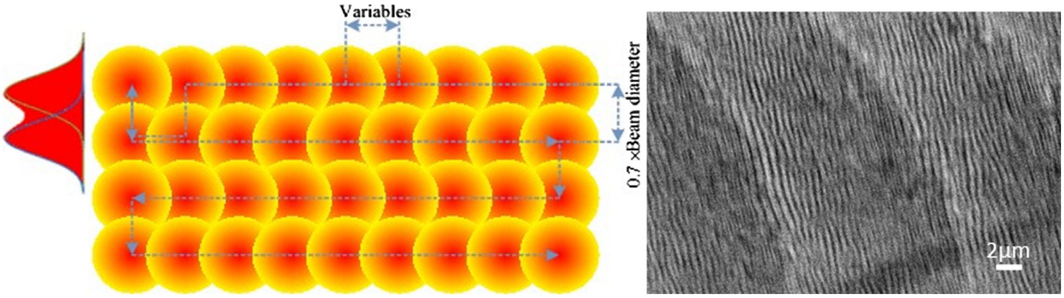

Fig. 2. Schematic and SEM image of the overlapping laser beam.