Optics and Lasers in Engineering 69 (2015) 35–39

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng

Rear-side picosecond laser ablation of indium tin oxide micro-grooves

Peng Liu, Wenjun Wang*, Xuesong Mei, Bin Liu, Wanqin Zhao

State Key Laboratory for Manufacturing Systems Engineering, Xi'an Jiaotong University, Xi'an 710049, China

ARTICLE INFO

Article history:
Received 27 March 2014
Received in revised form
7 January 2015
Accepted 5 February 2015
Available online 25 February 2015

Keywords:
Picosecond laser
Indium tin oxide
Rear-side ablation
Scan speed

ABSTRACT

A comparative study of the fabrication of micro-grooves in indium tin oxide films by picosecond laser ablation for application in thin film solar cells is presented, evaluating the variation of different process parameters. Compared with traditional front-side ablation, rear-side ablation results in thinner grooves with varying laser power at a certain scan speed. In particular, and in contrast to front-side ablation, the width of the micro-grooves remains unchanged when the scan speed was changed. Thus, the micro-groove quality can be optimized by adjusting the scan speed while the groove width would not be affected. Furthermore, high-quality micro-grooves with ripple free surfaces and steep sidewalls could only be achieved when applying rear-side ablation. Finally, the formation mechanism of micro-cracks on the groove rims during rear-side ablation is analyzed and the cracks can be almost entirely eliminated by an optimization of the scan speed.

1. Introduction

Indium tin oxide (ITO) is widely used as a transparent electrode material for the fabrication of thin film solar cells, liquid crystal displays and organic light emitting devices (OLED) because of its high optical transmittance in the visible spectral range and its high electrical conductivity [1–7]. In order to reduce the resistive losses and maximize the active area of the solar cells, a high resolution-patterning of the ITO thin films is required for the formation of interconnect lines and the assembly of the thin film solar cells [8]. Wet chemical etching is typically used for the conventional patterning of the ITO films. However, this method presents some problems such as the large number of steps involved in the process and the necessity for the disposal of the chemical waste solution [9]. Therefore, nanosecond laser ablation has recently started to replace the traditional wet chemical etching for the patterning of high resolution micro-grooves into ITO thin films. But high ridges remain at the rims of the grooves due to the obvious effect of the heat during nanosecond laser ablation and these ridges can lead to a shunt in the device that decreases the photovoltaic efficiency [10,11]. Compared with long-pulsed lasers, ultra-short-pulsed lasers for ablation result in a very limited region affected by the heat. Therefore, picosecond lasers and femtosecond lasers have been utilized to scribe micro-grooves on ITO for the fabrication of solar cells [12–18]. Furthermore, rear-side ablation turned out to be a very effective method to selectively remove the ITO layer without inflicting noticeable thermal damage, enabling the fabrication of grooves with almost rectangular cross section, very steep edges and a flat bottom located at the initial position of the ITO interface [19–22]. However, so far no studies have been reported on the detailed investigation of the effects of the process parameters on the micro-groove width during rear-side laser ablation. Also, an optimal strategy to improve the micro-groove quality when applying rear-side picosecond laser ablation has not been reported as well.

Therefore, in this paper, we report on the investigation of the influence of the process parameters during rear-side picosecond laser ablation in order to obtain high-quality ITO micro-grooves. Different laser powers and laser scan speeds were applied in order to precisely control the widths of the grooves and improve the groove quality. The optimal process parameters for the realization of high-quality micro-grooves are presented which might play a great role in the improvement of thin film solar cells.

2. Material and methods

A schematic illustration of the experimental setup for the laser ablation of the ITO films is shown in Fig. 1. A neodymium-vanadate (Nd:VAN;Austria) laser delivering pulses with a duration of 10 ps, and a power of 2 W at a tunable repetition rate between 1 and 100 kHz was used for the irradiation. The laser beam quality factor was 1.3 and a 150 mm focal length plano-convex spherical lens was used to focus the beam on the sample. A good facula quality was achieved by using a pinhole diaphragm. The ITO thin film used in the experiments is commercially available and has a resistance

* Corresponding author. Tel.: +86 2982663870; fax: +86 2982663870.
E-mail address: wenjunwang@mail.xjtu.edu.cn (W. Wang).

http://dx.doi.org/10.1016/j.optlaseng.2015.02.001
0143-8166/

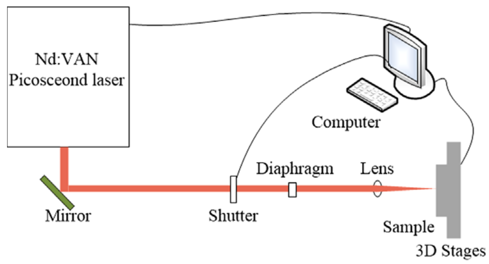

Fig. 1. Schematic illustration of the experimental setup for the laser ablation of the ITO films.

of 16 Ω/cm^2. The thickness of the ITO layer coated on the glass substrate was 180 nm.

During the experiments, an emission wavelength of 1064 nm and a pulse repetition rate of 1 kHz were employed. A series of experiments were performed on the ITO thin films. Micro-grooves were fabricated by applying laser pulses with different laser powers in the range from 30 mW to 150 mW at scan speeds in the range from 1 mm s^{-1} to 10 mm s^{-1} to the front side and the rear side of the sample, respectively. The beam diameter was calculated using the following equation:

$$2\omega = \frac{4\lambda f_0 M^2}{\pi d} \quad (1)$$

where ω is the radius of the beam waist, λ is the wavelength, f_0 is the focal length of the lens, d is the diameter of the incident beam and M is the beam quality factor [23]. In this study, the diameter of the incident beam was 3.5 mm resulting in a beam diameter of approximately 102.8 μm according to Eq. (1). In addition, the beam overlaps are 103, 26 and 10 for scan speeds of 1 mm s^{-1}, 4 mm s^{-1} and 10 mm s^{-1}, respectively, as calculated from the following equation:

$$N = \frac{2\omega f}{v} \quad (2)$$

where N is the beam overlap, ω is the radius of the beam waist, f is the repetition rate of the laser pulse, and v is the scan speed [24].

The microstructure and width of the grooves were analyzed by scanning electron microscopy (SEM) and laser scanning confocal microscopy (LSCM). It is worth mentioning that in this study, the groove width includes the ripple zone but does not include the crack zone. The resistance of the laser scribed grooves was measured using a VICTOR VC890D digital multimeter with a maximum measurement range of 20 MΩ. The laser power was measured by a power meter.

3. Results and discussion

3.1. Variation of micro-groove widths for front- and rear-side ablations

Fig. 2 shows the groove width as a function of laser power at a scan speed of 1 mm s^{-1}. The groove width increases with the laser power for both the front-side and the rear-side laser ablation. When the laser power increased to a certain level, the groove width gradually reached a plateau and then remained constant. At the same time, as shown in Fig. 2, the micro-grooves scribed from the rear side are narrower than those scribed from the front side independent of the change in laser power. As the laser power increases from 30 mW to 80 mW, the difference in width between the micro-grooves scribed from the front side and the rear side decreases from 28 μm to 10 μm; when the laser power was further increased, the difference in width did not change significantly. The difference in groove width between the two methods of laser ablation can be attributed to the different beam propagation and material removal processes. In front-side ablation, laser beam eradiates on the surface of ITO layer. As the laser beam moves linearly, micro-groove is formed with the evaporation of ITO material. In rear-side ablation, a nonlinear absorption process occurs in ITO. In the beginning, only a thin layer of ITO material close to the glass is ablated and high pressure is formed in the confined place between ITO layer and glass substrate because of the gasification of ITO material. Then, with the increase of the number of pulses, the pressure increases and the outer layer of ITO will eventually completely dissected [19,21,25]. Based on the results, rear-side ablation should be the method of choice for obtaining more narrow grooves during the patterning of the ITO films.

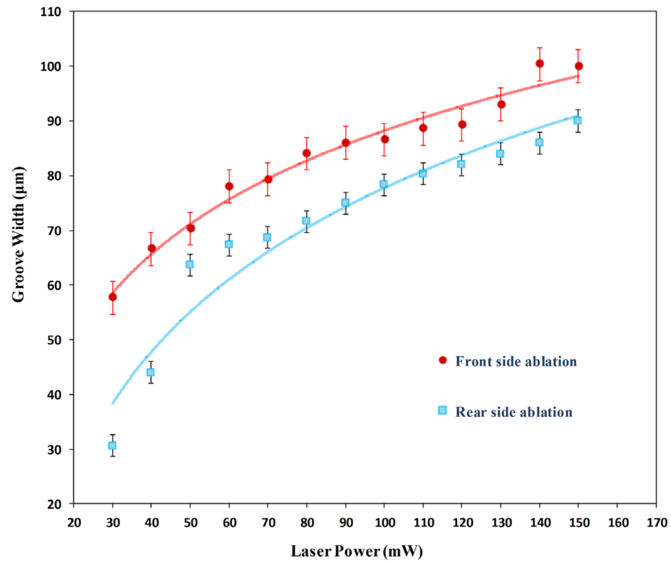

Fig. 2. Micro-groove width plotted over the laser power at a scan speed of 1 mm s^{-1}.

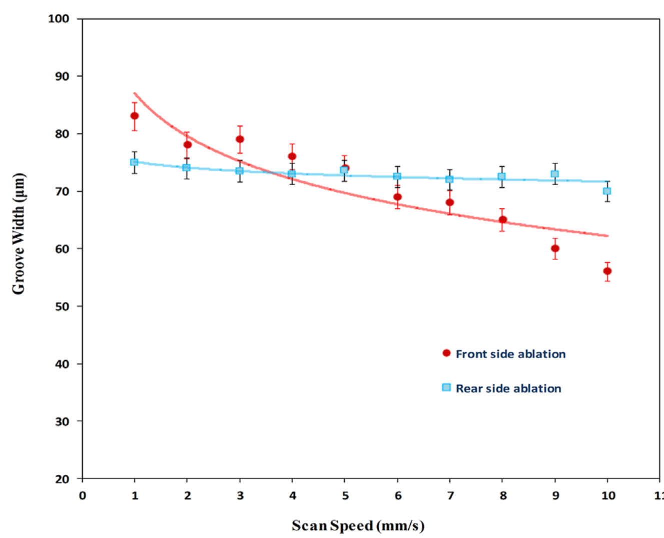

Fig. 3. Micro-groove width plotted over the scan speed at a laser power of 80 mW.

Fig. 3 shows the groove width as a function of the scan speed. In order to explore the potential of improving the processing efficiency, different scan speeds of 1 mm s^{-1} to 10 mm s^{-1} were chosen at a fixed laser power of 80 mW. In contrast to the impact of the laser power, for rear-side laser ablation, the groove width