Nanosecond pulsed laser scribing of fluorine-doped tin oxide coated on glass substrate

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Abstract

Laser is a promising tool for scribing fluorine-doped tin oxide (FTO) film coated on a substrate, in which the individual unit cells have to be completely isolated for the manufacturing of perovskite solar cells. A clean-cut channel without remarkable damage on and underneath the laser-scribed surface is highly desired in order to enhance the efficiency of energy conversion of the produced solar cells. This study aims at investigating the influences of laser fluence, scan speed and side of ablation on the width and depth of cut channel as well as electrical resistance between the scribed unit cells. A nanosecond pulse laser was employed to scribe a 700-nm FTO film coated on a glass substrate. According to the experimental results, the FTO film was completely isolated by the laser without causing remarkable damage when the ablation was performed through the backside of the substrate. The suggested machining condition was the laser fluence of 5 J/cm^2 and a scan speed of 160 mm/s.

Keywords: *Laser, Scribing, Fluorine-doped tin oxide, Solar cells*

1. Introduction

Fluorine-doped tin oxide (FTO) is a transparent conductive oxide (TCO) used as an electrically conductive layer in perovskite solar cells, touch screens and light-emitting diodes (LEDs). This is due to its good resistance to heat and cheap that make it available for solar cell and microelectronic applications (Baek et al, 2010). According to the perovskite solar cells, the FTO film coating on a solar cell substrate must be scribed into several units before the subsequent coating of other active layers for making the solar cells. The Laser is a promising tool to scribe the FTO film coated on the substrate, in which the individual unit cells have to be completely isolated without causing any significant damage. Kim et al. (2009) used an Nd: YAG laser to etch the FTO thin film with the feed speed of 6.08 mm/s and overlapping rate of 62% that one may reduce the proportion area of FTO. Kim et al. (2017) performed the laser scribing of FTO film by using a Bessel beam, which provides a better cut result than a Gaussian beam. Kim et al. (2016) and Doan et al. (2016). Studied the Nd: YAG laser-induced backward ablation with a single laser shot on the FTO film, and the plasma shielding effect is found to play a significant role in the ablation process. Canteli et al. (2013) investigated the Nd: YVO_4 laser scribing of SnO_2: F film and the width and depth of grooves are small when ablating the film on its backside. Wang et al. (2019) studied the femtosecond pulsed laser etching of FTO films and no obvious crack is found on the cut surface.

Despite the cut morphology, the electrical resistance over the laser scribed units and substrate damage are also the important indicators of solar cell quality. Typically, the electrical resistance between the isolated cells should be greater than 100 MΩ (Wang et al, 2019) to prevent a short circuit. Due to the lack of intensive study on these issues, this work aims at examining the effects of laser fluence, scan speed and side of the workpiece for the laser scribing on the cut features, electrical resistance, and substrate damage. The significance of this study could enable a better understanding of the laser scribing process for the FTO as well as other TCO films, where the cut dimensions, resistance and substrate damage are acceptable for the manufacturing of perovskite solar cells.

2. Objectives

1. To understand the influence of laser fluence, scan speed and side of the workpiece on the cut features, electrical resistance, and substrate damage in the laser scribing of FTO film.

2. To determine a suitable laser scribing condition causing a fine quality cut, high electrical resistance and low substrate damage.

3. Materials and Methods

A nanosecond pulse laser was used in this study to scribe a 700-nm thick FTO film prepared by a spray pyrolysis method on a glass substrate. The laser emitted a wavelength of 1064 nm, and it was focused by a 100-mm focusing lens providing a beam diameter of 37.66 µm at $1/e^2$ regarding the Gaussian profile. The laser pulse duration and pulse repetition rate were kept constant at 100 ns and 100 kHz, respectively. In this study, the effects of laser fluence, laser scan speed and side of ablation on the cut width, depth, electrical resistance and substrate damage were experimentally examined. The relevant process parameters are listed in Table 1. The laser fluence (F) is a function of average laser power (P), beam diameter (d) and pulse repetition rate (f) and it is calculated by using:

$$F = \frac{4P}{\pi d^2 f} \quad (1)$$

Table 1 Experimental parameters used in this study

Parameter	Value	Unit
Pulse duration	100	ns
Pulse repetition rate	100	kHz
Focal length	100	mm
Beam diameter	37.66	µm
Laser fluence	2, 3, 4, 5, 6	J/cm^2
Average laser power	2.23, 3.34, 4.46, 5.57, 6.68	W
Scan speed	80, 100, 120, 140, 160	mm/s
Side of ablation	On the film side (Figure 1(b)), Through the backside of the substrate (Figure 1(c))	
FTO thickness	700	nm
Substrate thickness	3	mm

The range of parameters' values tested in this work was selected from our preliminary experiments, in which the FTO was able to be scribed without the presence of cracks and remarkable damage on the substrate and vicinity of cut channel. The experimental setup applied in this study is presented in Figure 1(a). The laser ablation was also performed on the film side and through the backside of the substrate as shown in Figure 1(b-c). It is anticipated that the latter technique could diminish the plasma shielding effect since the FTO film is to be cut on the backside and the plasma plume could not directly interfere with the incident laser beam during the ablation. After the scribing process, the cut samples were annealed at 450°C for 30 minutes in an oven to promote the crystallinity of fluorine. The groove width and depth of each cut were measured by a confocal microscope (Olympus LEXT OLS 4000). The electrical resistance of the cut region was also quantified by an avometer (ADCMT 7451A Digital Multimeter). Each scribing condition was repeated three times and the average measures were taken as the final reading.

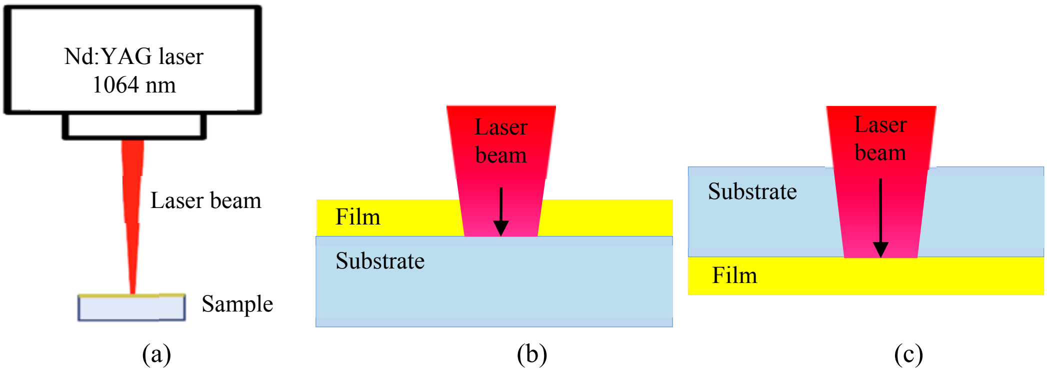


Figure 1 (a) Laser scribing of FTO film (b) Ablation on the FTO film side (c) Ablation through the backside of a glass substrate.

4. Results and Discussion

A clean and narrow groove on the FTO film was obtained when performing the laser ablation on the film side as shown in Figure 2. The width and depth of grooves produced by using the different processing conditions were measured and plotted in Figure 3. As per the results, the groove width was found to increase with the laser fluence, while the effect of laser scan speed on the width was not discernible in this study. The depth of the groove was slightly affected by the change of laser fluence, but the increase in laser scan speed tended to decrease the groove depth as shown in Figure 3(b). This is due to the short laser irradiating time under the high scan speed that introduces the shallow groove depth. When the laser scan speed of 80 mm/s was applied in the ablation, the obtained depth was greater than the FTO film thickness of 700 nm. This indicates that the FTO film along the machined groove was completed cut by the laser beam.

Laser fluence (J/cm^2)	**Laser scan speed (mm/s)**				
	80	**100**	**120**	**140**	**160**
2					
3					
4					
5					
6					

Figure 2 Surface morphology of laser scribed FTO film obtained after the ablation on the film surface.

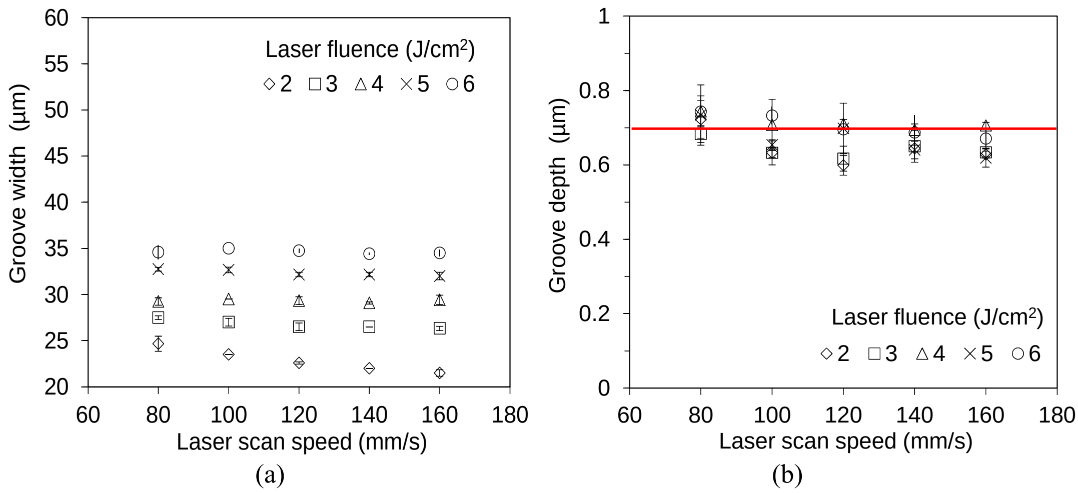


Figure 3 Laser etched groove (a) width and (b) depth obtained when scribing on the film side

The surface morphology of groove scribed by the laser through the backside of the substrate is presented in Figure 4, demonstrating that a wider groove is obtained when using a higher laser fluence and a slower scan speed. Per contra, under this condition, micro-cracks were explicitly presented on the laser-ablated surface. Such crack formation was not remarkably found when the ablation took place on the film side (Figure 2). It is anticipated that the incident laser beam is not significantly attenuated by the plasma and vaporized material plumes during the ablation so that the laser energy absorbed by the film is more prominent than the front-side ablation technique. In addition, the absorption of laser energy typically takes place at the FTO-substrate interface when performing the backside ablation rather than at the top surface of FTO film or air-FTO interface. This importantly causes detrimental to both the FTO film and glass substrate, where cracks are substantially formed on the substrate due to the thermal shocking effect.

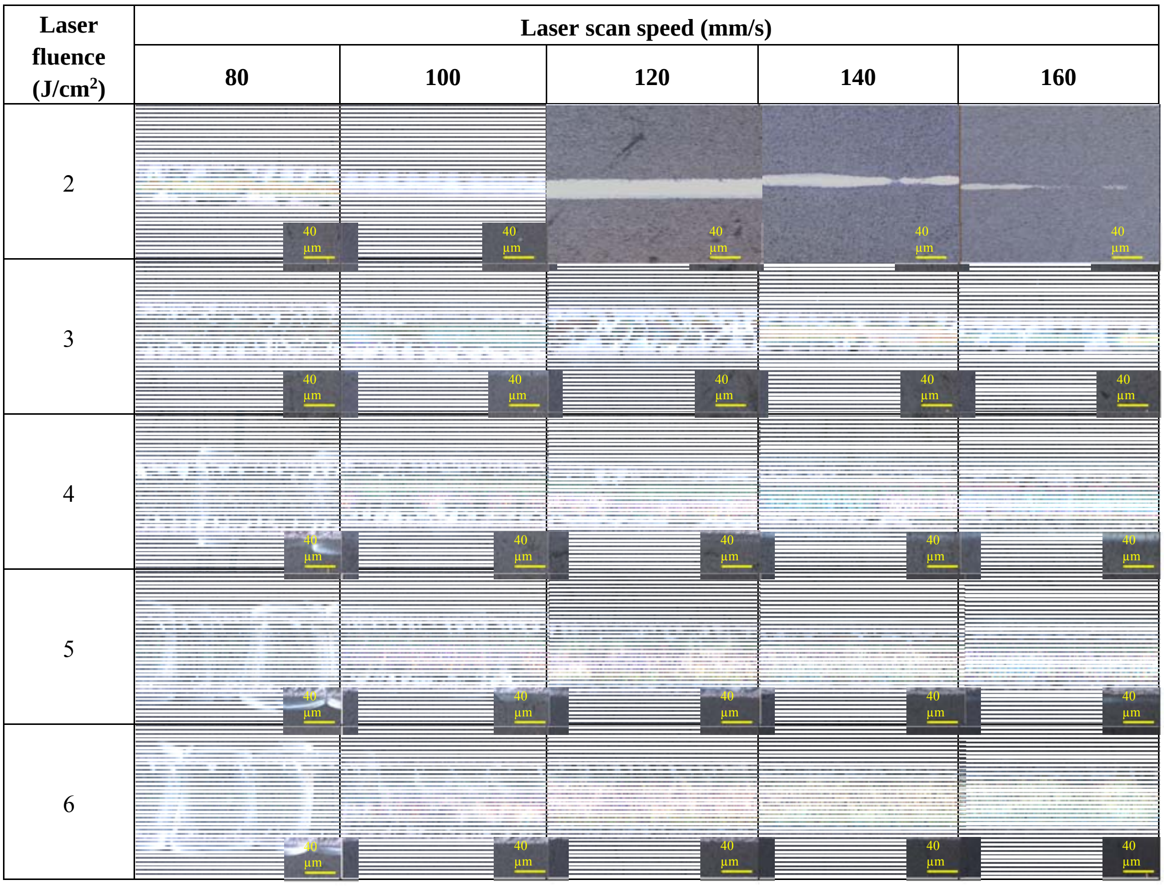
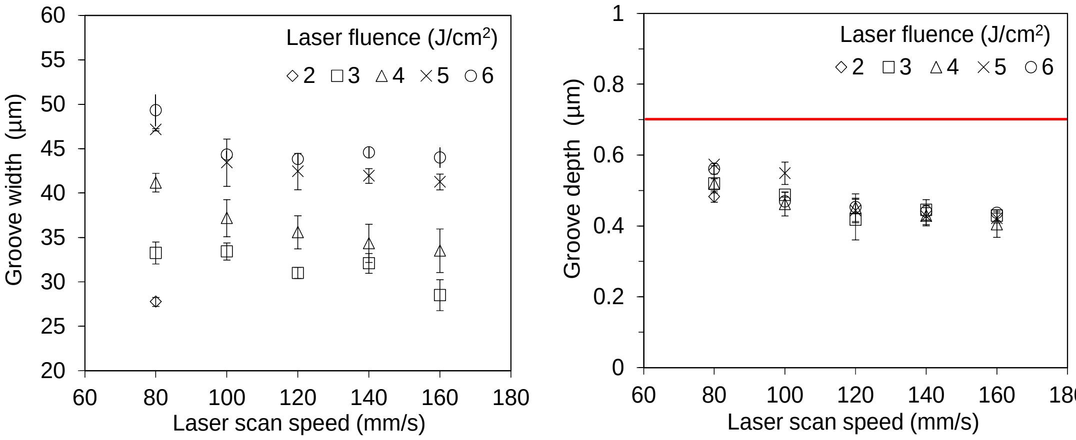


Figure 4 Surface morphology of laser-scribed FTO film obtained after the ablation through the backside of the substrate.

According to Figure 4, there was no groove created under the combinations of 2-J/cm^2 laser fluence and the scan speed of equal or greater than 100 mm/s. This could be due to the refraction of the laser beam in the 3-mm thick glass substrate that significantly off focuses the beam and makes it unable to effectively ablate the FTO film on the backside. The change of focal position also enlarges the beam diameter for the ablation as evidenced in the large kerf results (Figure 4). The larger the beam diameter, the weaker the energy density is applied in the laser scribing of FTO film. Hence, using too low laser fluence together with high scan speed is of less potential for producing a groove on the FTO film.

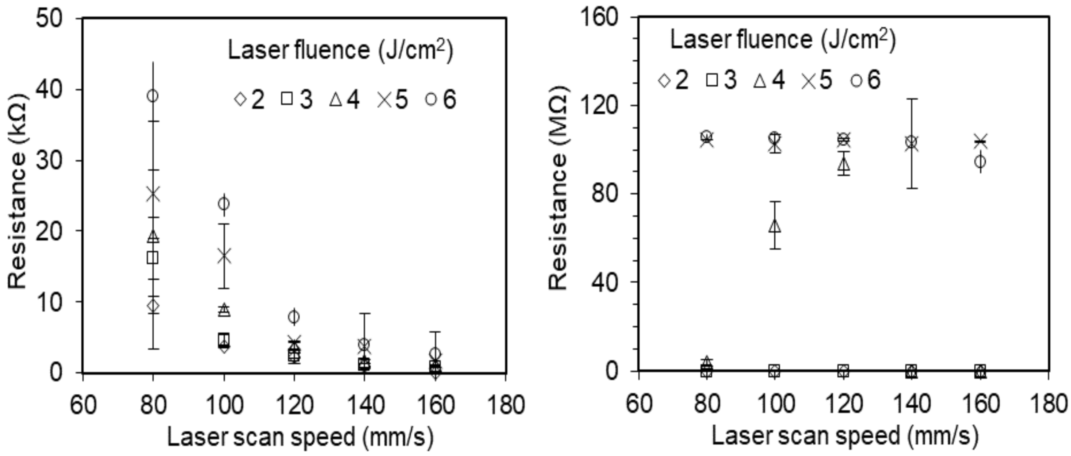
The effects of laser fluence and scan speed on the groove width and depth are presented in Figure 5, noting that the increase in laser fluence significantly increases the groove width but not the depth. By comparing to the groove dimensions obtained from the front-side ablation (Figure 3), the groove fabricated by the backside technique was wider and shallower. The cut depth was found to be less than the film thickness of 700 nm, and the FTO film seemed to be incompletely cut by the laser when considering these results. In order to verify the isolation of the conductive layer, the electrical resistance over the laser-scribed units was measured and accounted for in this study.



(a) (b)

Figure 5 Laser etched groove (a) width and (b) depth obtained when scribing through the backside of the substrate

All cut samples were undergone the annealing process at 450°C for 30 minutes to promote the crystallinity of fluorine before examining their electrical resistance. A relationship between the laser fluence, scan speed and electrical resistance over the laser scribed units is presented in Figure 6, showing that the resistance is high when using high laser fluence and slow scan speed. On the other hand, the effect of laser scan speed on the resistance was not discernible in the case of backside ablation. Furthermore, it is interesting to note that the grooves scribed by the laser through the backside of the substrate provided the resistance of about 100 MΩ when the laser fluence of 5 or 6 J/cm^2 was employed together with all scan speeds examined in this study. The maximum resistance obtained from the front-side ablation was only 40 kΩ when 6-J/cm^2 laser fluence and 80-mm/s scan speed were used. Regarding the results, the laser ablation of FTO film through the backside of the substrate possessed a higher resistance than the front-side ablation, although the quality of the groove surface obtained from the backside approach was relatively poor.



(a) (b)

Figure 6 Resistance between the laser scribed cells when ablating (a) on the film side and (b) through the backside of the substrate

By considering the results of electrical resistance and groove depth, the grooves produced by the backside ablation were shallower than the film thickness (700 nm), but their resistance was much higher than that of the front-side ablated grooves. The formation of grooves whose depth was less than the film thickness might not be attributed to the incomplete isolation of FTO film, but it may be subjected to the recast structure of glass substrate protruding from the groove bottom and then resulting in the shallow cut. The presence of recast is due to the substantial melting of glass at the FTO-substrate interface during the backside ablation, while this effect contributes less in the front-side ablation. Additionally, the rapid solidification of molten glass can cause thermal cracking to the laser-ablated surface, and this is hence a reason for the formation of micro-cracks on the cut surface. According to the experimental findings, the laser fluence of 5 J/cm^2 and a scan speed of 160 mm/s are likely to be a suitable setup for scribing the FTO film coated on the glass substrate since it can isolate fewer micro-cracks on the substrate surface and short processing time. These characteristics are in general desired for the manufacturing of perovskite solar cells as well as other high-density systems.

5. Conclusion

The laser scribing of a 700-nm thick fluorine-doped tin oxide (FTO) film coated on glass substrate was investigated in this study. A nanosecond pulse laser was applied for ablating the FTO film on the front side and through the backside of the glass substrate under the different laser fluence and scan speed. The effects of these processing parameters on the width, depth, surface morphology and electrical resistance of cut channels were experimentally examined. The results proved that a large and deep groove was obtained when using high laser fluence and slow scan speed. A larger groove and more cracks on the machined surface were apparent in the ablation taking place through the backside of the substrate. However, the electrical resistance over the laser-scribed units can reach about 100 MΩ when the backside ablation was applied. Based on the obtained surface quality and electrical resistance of the laser-scribed units, the backside ablation technique associated with the laser fluence of 5 J/cm^2 and scanning speed of 160 mm/s was suggested for scribing the FTO film. In conclusion, the findings of this study could be an essential guideline for the cutting and scribing of FTO as well as other TCO films, in which the cut dimensions, resistance and substrate damage are of concern for the manufacturing of perovskite solar cells and other high-density systems.

6. Acknowledgments

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