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Technical Paper

Femtosecond laser scribing of Mo thin film on flexible substrate using axicon focused beam

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ABSTRACT

Ablation experiments of molybdenum (Mo) thin film on flexible polyimide (PI) substrate are conducted using femtosecond laser pulses focused by an axicon lens. The purpose is to assess the capability of axicon lens in producing narrow grooves and how robustness the scribing process is. We first obtain the damage threshold of Mo and PI and then characterize the spatial beam profile produced by the axicon lens through both theoretical calculations and experimental measurements. Then scribing experiments are performed with different pulse energy, scanning speed, and the distance between the axicon tip and the sample's surface. Optical microscope and atomic force microscope are used to examine the microgrooves from the experiments. It is shown that high quality narrow scribes can be produced with axicon focused beam which can tolerate large height fluctuations of moving flexible substrate expected in an industrial setting.

1. Introduction

The multilayer $CuIn_xGa_xSe_{2y}S_y$ (CIGS) thin film solar cell technology has drawn considerable attention due to its unique advantages of low production cost and high photovoltaic energy conversion efficiency. CIGS has been recognized as the most efficient thin-film solar cell technology with conversion efficiency of 20.4% reached in 2013 in a research lab [23]. The material cost of CIGS thin-film cells can be very inexpensive since it requires few raw materials. The manufacturing cost can be reduced with an efficient, scalable roll-to-roll process. The conventional scribing process for monolithically integrated CIGS modules in production lines typically involves three steps: laser patterning of the Mo back conductor (P1), followed by mechanical patterning of the absorption layer (P2) and finally laser patterning of the front conductor layer (P3) [1]. Currently there is a push for establishing all laser-scribing in thin-film solar panel production.

Q-switched DPSS (diode pumped solid state) lasers emitting at 1064 nm or 355 nm (third harmonic) has been commonly used in industry for P1 scribe [2]. The P2 and P3 processes are typically performed by a frequency-doubled DPSS laser emitting at 532 nm. The pulse duration is usually around several tens of nanoseconds. Despite the popularity of ns lasers in thin film solar cell production, thermal damage due to melting, recast and microcrack formation such as shown by Haas et al. [3] limits the scribe quality and line width to >20 μm. The problem is more severe for CIGS type cells on flexible metal/polymer substrate because of the extreme heat sensitivity of the materials [2]. Excessive melting of CIGS and deposition of molybdenum on scribe walls were found to reduce the photovoltaic efficiency considerably [4].

To overcome the shortcomings of ns lasers, ultrafast lasers with ps and fs pulses have been used to scribe CIGS solar cells. It was reported that all P1, P2 and P3 scribing can be performed by ps lasers with desired selectivity of different layers [5,6]. However, thermal effect was shown to be a problem even at this pulse duration (1–10 ps): periodic melting of the molybdenum (Mo) layer and damage to the substrate (especially polyimide) was observed in P1 scribing, electrical shunts were created near scribe edge, and non-uniform ablation leads to residuals in the groove [7–9]. Studies using ultrashort pulses of a few hundred femtoseconds have been conducted and non-thermal ablation with narrow line width was reported for thin film scribes [10,11]. In addition, a few comparative investigations demonstrated unambiguously the advantages of fs pulses over ns and ps pulses in reduced thermal effects, minimal interdiffusion between multi-layers, improved electrical performance, and narrow line width [12–14]. Recent research in ultrafast laser scribing has extended to use of pulse shaping in both spatial and temporal domain. Square top-hat beam profile has shown advantages such as reduced damage at groove center, smooth scribe edge and insensitiveness to beam quality [15]. Bursts

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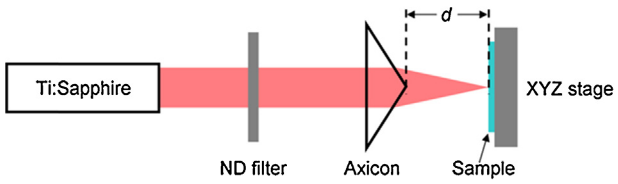

Fig. 1. Experimental setup.

Table 1
Experimental condition with fixed distance and different pulse energy and scanning speed.

Parameter	Value
Pulse energy (μJ)	10, 15, 20, 25, 30, 35
Laser scanning speed (mm/s)	0.1, 0.2, . . ., 0.9, 1.0
Axicon tip to sample distance (mm)	Fixed at 9 mm

of low energy pulses were found to reduce melt areas in the scribe zone [16].

Despite the advantage femtosecond laser offers in scribing CIGS solar cells, it faces one serious limitation: small depth of field. For example, the Rayleigh length for a laser with wavelength of 1 μm focused to a 10 μm spot size (in diameter) is less than 0.1 mm, which means consistent narrow line width during scribing is impossible to achieve when the height variation for a large moving flexible substrate is expected to be up to 3 mm [17]. In view of the fact that common beam shaping from Gaussian to flattop distribution renders an even shorter depth of field based on the study by Tamhankar et al. [17], the purpose of this paper is to study fs laser scribing with axicon focused beam. Use of an axicon lens can generate an intense beam pattern which is referred to as a near-nondiffracting beam, i.e., a beam with much larger depth of focus in comparison to that generated by a conventional focusing lens. Although the goal is to achieve all three patterning processes (P1, P2, P3) with an single fs laser source, the focus of this study is on P1, i.e., scribing Mo thin film on a flexible polyimide (PI) substrate.

2. Experimental setup and procedure

The experimental setup is shown in Fig. 1. A Ti:Sapphire femtosecond laser system delivers pulses with full-width-at-half-maximum (FWHM) pulse duration of 60 fs, center wavelength of 800 nm, maximum pulse energy of 4.3 mJ, beam diameter ($1/e^2$) of 10 mm, and repetition rate of 1 kHz. The pulse energy is attenuated by a variable neutral density (ND) filter. The attenuated beam is focused by an axicon lens (Doric Lenses). This axicon lens is made from fused silica, and has a base angle of 25° and a tip angle of 130°. The thin-film sample used in this study consists of a back contact layer (molybdenum, Mo) and a PI substrate. The thicknesses of the Mo layer and the PI layer are ~220 nm and 25 μm, respectively. The Mo thin film was deposited on the PI substrate using electron beam evaporation. The sample is mounted on a motorized XYZ stage (Newport).

Laser scribing experiments are performed on the sample by scanning it across the focal spot. Scribing conditions include pulse energy, scanning speed, and the distance (d) between the axicon tip and the sample's surface. We first place the sample at a fixed distance of 9 mm from the axicon tip, scribe grooves with various combinations of pulse energy and scanning speed, and examine groove quality using optical and atomic force microscopes. Then we apply the optimal combination of energy and speed found above and scribe grooves at different axicon-sample distances. The corresponding experimental conditions are shown in Tables 1 and 2, and the results are shown in Sections 3.3 and 3.4, respectively. Before conducting the scribing experiments, laser damage threshold of Mo and PI are determined and axicon focused beam profile is characterized to assist in the selection of laser scribing conditions.

Table 2
Experimental condition with fixed pulse energy and scanning speed at different distances.

Parameter	Value
Pulse energy (μJ)	Fixed at 15
Laser scanning speed (mm/s)	Fixed at 0.6
Axicon tip to sample distance (mm)	1, 2, 3, . . ., 18 mm

3. Results and discussion

3.1. Single pulse damage threshold

Damage threshold is a characteristic dependent on the wavelength, pulse width and type of material. It is ideally defined as the laser fluence at which irreversible damage occurs in the material by removing a monolayer of material. It is actually determined by visual examination, ablation depth measurement, plasma radiation monitoring etc. In this work the damage threshold is estimated by recording the diameter (D) of the ablated craters using SEM and then using the following relationship between the square of the crater diameter and the logarithm of the laser fluence (F) [18]:

$$D^2 = 2w_0^2 \, ln\left(\frac{F}{F_{th}}\right) \quad (1)$$

where w_0 and F_{th} are fitting variables, representing focal spot $1/e^2$ radius and damage threshold, respectively. A plot of the square of damage diameter, D^2, against the logarithm of laser fluence is made to obtain both w_0 (from the slope of the line) and F_{th} (from the extrapolation of D^2 to zero value) as shown in Fig. 2. The Mo and PI damage threshold at 60 fs were found to be 0.18 J/cm^2 and 0.75 J/cm^2, respectively. The Mo damage threshold slightly increases with increased pulse duration, which is consistent with the previous research of fs laser ablation of Cu and Al film and fs laser ablation of fused silica [19,20]. Since the damage threshold of PI is higher than that of Mo, it is possible to only remove the Mo layer while not damaging the PI substrate by choosing a laser fluence in between of these two thresholds. The optimal operating parameters (including pulse energy and scribing speed) are determined in the following scribing experiments.

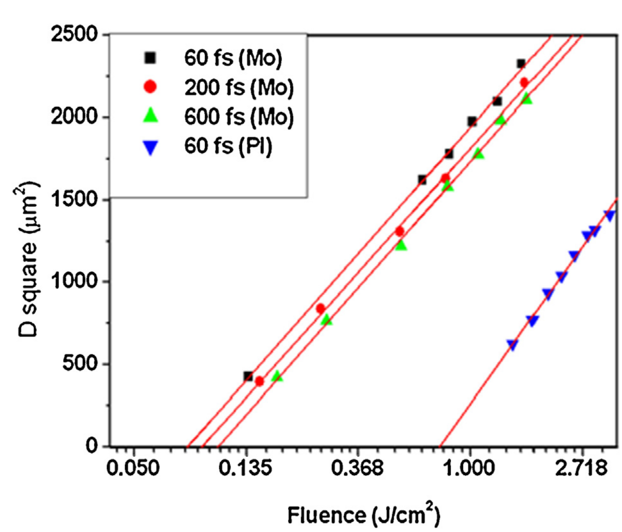

Fig. 2. Single pulse damage threshold of Mo and PI at various pulse durations.