Study of the Laser Scribing of Molybdenum Thin Films Fabricated using Different Deposition Techniques

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ABSTRACT

Monolithic cell interconnection is a technique used in solar devices to allow for interconnection of adjacent cells through patterning of the thin films during fabrication. In the case of $CuIn_{1-x}Ga_xSe_{2-y}S_y$ (CIGS) solar cells, Molybdenum is commonly used as the back contact. Patterning of this layer is required in the interconnection scheme to electrically isolate adjacent cells. Laser scribing has been adopted for patterning of this layer. This paper reports on the effect of the molybdenum thin film deposition technique, and the resulting film properties, on the characteristic of the laser scribe. Films were deposited using DC magnetron sputtering over a range of working gas pressures and powers as well as in single and multilayer configurations. It was found that the residual stress within the film lead to significantly different laser ablation processes. This required independent tuning of the laser processing parameters to create a clean, defect free scribe for different samples. Experimentation was carried out using both film-side and glass-side processing. It was shown that glass-side processing leads to a reduction in cracks and delamination originating from the scribe. The processing conditions that produced successful scribe lines for the various films are presented and discussed.

Keywords: CIGS, Molybdenum Thin Film, Thin-Film Solar Cells**,** Laser Scribing, Monolithic Integration, Photovoltaics

1. INTRODUCTION

Thin-film solar cells, specifically $CuIn_{1-x}Ga_xSe_{2-y}S_y$ (CIGS) based devices, provide an alternative to Silicon based solar cells with the potential for lower production cost while maintaining comparable conversion efficiencies[1]. In order to realize these lower production costs, the implementation of a monolithically integrated device is essential. Monolithic cell interconnections require three independent scribes commonly referred to as P1, P2 and P3 as shown in figure 1. The P1 scribe is performed on the cell back contact and is required to electrically isolate back contacts of adjacent cells. Molybdenum thin films remain the most suitable back contact for CIGS thin-film solar cells, due to their high melting point and low reactivity[2]. Laser scribing has been adopted for performing this scribe due to successful processing for a wide range of laser pulse lengths and wavelengths[3,4].

Laser scribing is commonly used in the solar industry for production of CIGS thin-film solar modules[5,6]. Several groups have reported on the effect of the laser processing parameters on the laser scribing process, such as the pulse length[3] and fluency requirements[7]. There are few reports on the fundamental film properties as it relates to the laser ablation process. This paper focuses on the physical properties of the film including the internal stress and microstructure, and how these properties effect the laser-film interaction. Discussion of processing parameters is also provided as it relates to successful laser scribing.

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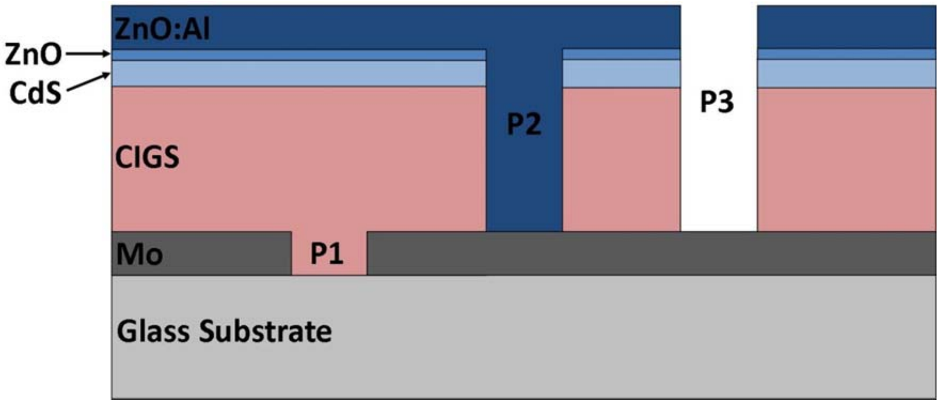

Figure 1: Schematic of a monolithically integrated CIGS solar cell with P1, P2, and P3 scribes.

2. LASER SCRIBING EXPERIMENT

Molybdenum thin films were deposited using DC magnetron sputtering on 3mm thick soda-lime glass. It has been shown that through varying of the DC power and working gas pressure, the residual stress within the films can be controlled[8]. Stress free films were obtained by depositing subsequent layers of compressive and tensile films. For this study, both stress free and films with tensile stress having a thickness of 600 nm were used. Additionally, a commercially available molybdenum coated soda-lime glass was used for comparison. Samples sizes up to 10 cm by 10 cm can be processed.

Laser processing was carrying out using a Diode Pumped, Q-switched Nd:YAG laser of 532 nm wavelength. A Gaussian beam profile was used for this study. The pulse repetition rate was variable from 2.5 kHz to 10 kHz and the scanning speed ranged from 50 mm/s to 15 mm/s. Pulse length were near 100 ns and the fluency of each pulse was controlled through changes in the spot size. A schematic of the system used is shown in figure 2.

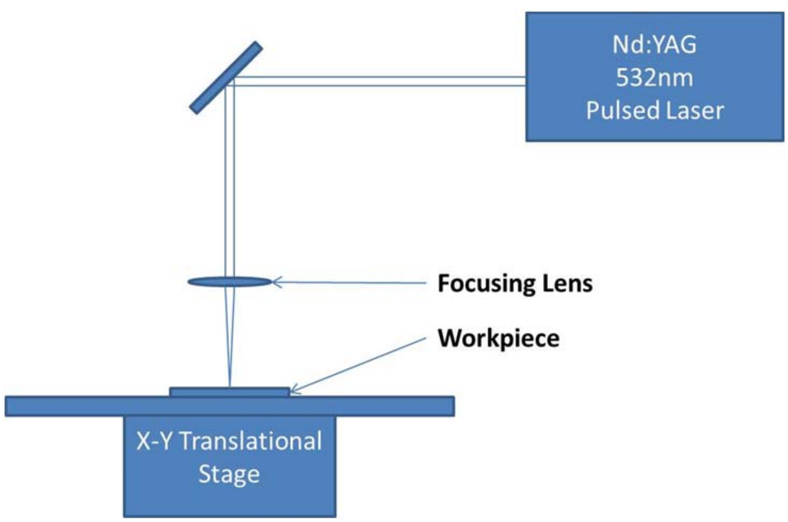

Figure 2: Diagram of laser processing setup including the laser source, focusing optics, and motorized translational stage.

3. RESULTS AND DISCUSSION

3.1 Effect of processing parameters

Figure 3 shows optical micrographs of various laser scribe lines on stress-free molybdenum thin films. Experimentation was carried out to optimize the fluency (energy per unit area) and pulse overlap to create defect free scribes. It was observed that at very high overlap, utilizing scanning speeds below 5 cm/s, significant damage occurred near the edge of the scribe. Similarly, at high levels of levels of fluency, flaking and cracking of the film was observed. Optimal laser processing, identified by minimal damage, sharp edges and high reproducibility, was obtained at speeds in the range of 7.5-12.5 cm/s with a beam diameter of 130-150 μm.

When incorporating laser processing into the production of CIGS modules, it is essential to insure that there is no opportunity for a conductive path to form between two sides. Therefore, it was found that a significant overlap in each laser scribe would limit the possibility of shunt type defects forming. On the other hand, excessive overlap resulted in an increase in the heat affected zone and the formation of microcracks and delamination of the film at the scribe edges. These damaged areas, depending on their nature, may become electrical defects, such as recombination centers, that will limit the resulting solar cell performance. A careful balance of these two effects is required for ideal scribing.

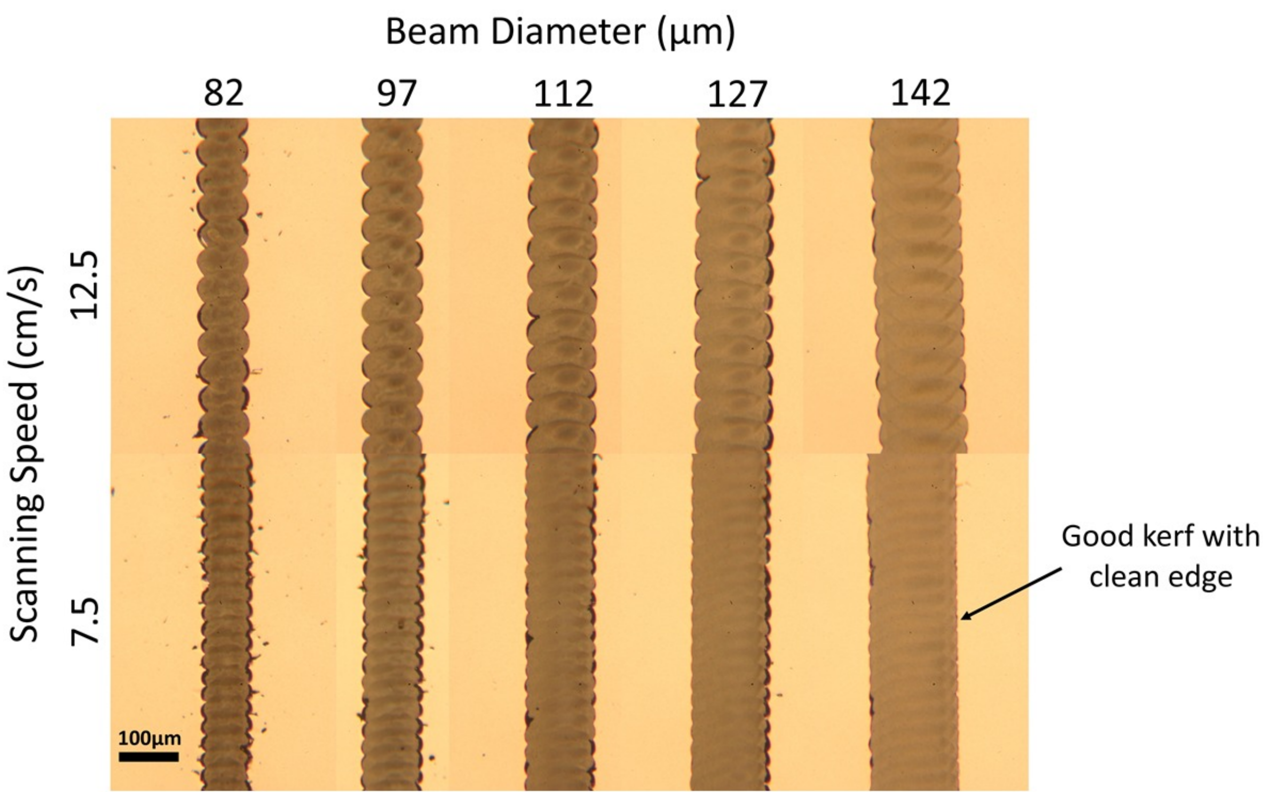

Figure 3: Optical images of laser scribes on Molybdenum thin films showing a trend of decreasing fluency from left to right (or increasing spot size) at two selected scanning speeds.

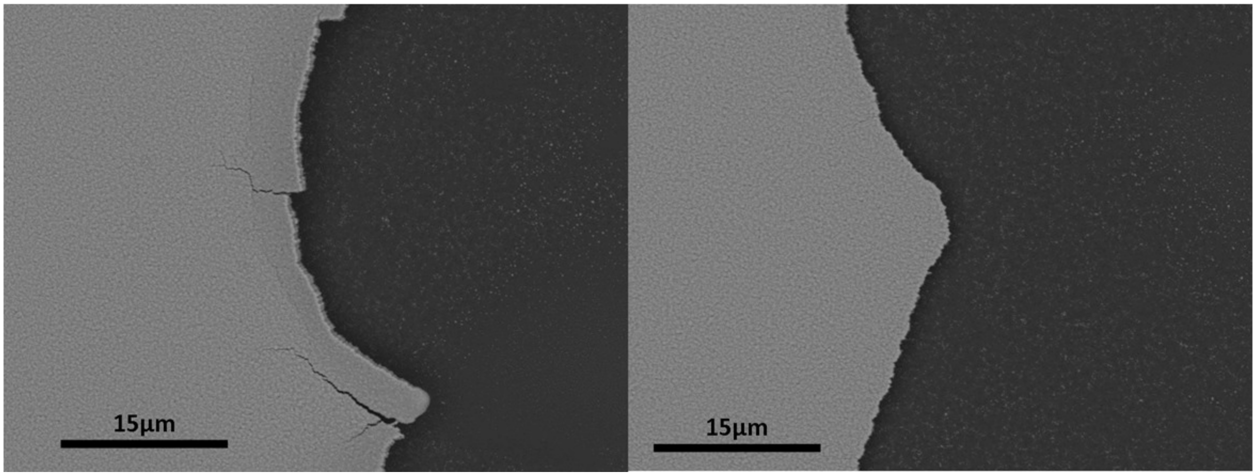

Figure 4: SEM micrographs showing laser ablation of a molybdenum film with excessive damage (left) and minimal damage (right)

Under conditions that resulted in damage at the scribe edge, detailed investigation was carried out to understand the nature of the defects. Figure 4 shows scanning electron microscope (SEM) images of two scribe lines both with and without damage. It can be seen that during the ablation process, if there is a non-uniform intensity distribution, incomplete removal of the film is observed. Several cracks were found to propagate through the film and there remained regions of delaminated film. In contrast, sharp defect free edges are observed when the beam intensity and profile are optimized. In order to obtain high quality scribes with a large depth of focus, a top hat type beam profile may be used. However, in this study, optimization of a Gaussian beam profile itself did yield defect free scribes.

Commercially available molybdenum films were also employed in this study. It is assumed these films are in a stress-free configuration. It was observed that these films exhibited a much larger heat affected zone than films deposited at our facility, under similar laser-processing conditions. As noted in the literature, processing through the substrate was identified to reduce the heat-affected zone[7]. However, this effect was not observed with films deposited at our facility as processing from both substrate and film-side lead to damage free scribes.

3.2 Effect of film properties on laser interaction

In order for molybdenum thin-films to be used as the back contact for CIGS solar cells, a film with good adhesion and high conductivity is required. Multilayer films were developed so as to achieve these optimal film properties[9]. The residual stress must also be considered in the development of high quality molybdenum films. It was observed that films with internal stresses exhibited different ablation properties that resulted in poor quality scribe lines.

For films with internal stresses that are tensile in nature, there is a tendency for the film to crack and delaminate when exposed to temperatures below the threshold for laser ablation. This results in sections, or strips of the film remaining and extending both within the scribe and upwards away of the film. The result is shown in figure 5. Under identical processing conditions, the damage resulting from residual tensile stress can be seen.

The residual stress within a film has been identified as a concern for reliability of thin-film devices as it may lead to delamination as a device is subjected to temperature cycling in real-world condition. This condition may be accelerated due to laser scribing, as the scribe edges will act as nucleation sites for delamination. Therefore, a stress free film must be used for production of high quality CIGS devices.

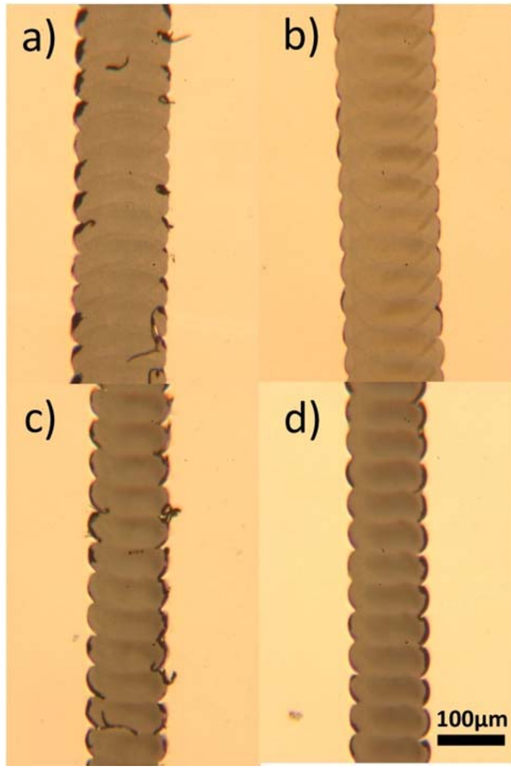

Figure 5: Optical micrographs showing laser ablation under identical processing conditions using film-side processing for (a) tensile film and (b) stress free film, and using glass-side processing for (c) tensile film, and (d) stress free film.

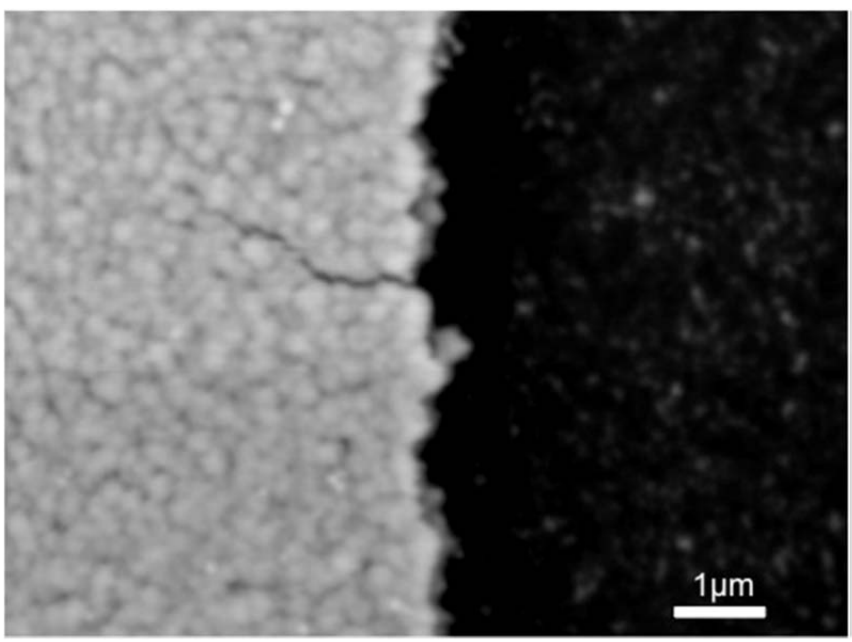

Figure 6: SEM micrograph displaying a microcrack initiating at the kerf edge and propagating along the grain boundaries in the molybdenum film. The roughness at the kerf edge is also defined by the size of the grains in the film. In this case the average grain size is approximately 300 nm.

The microstructure of the film will determine how the excess heat will affect the remaining film. Figure 6 shows a crack that has developed on a clean scribe edge along the grain boundaries in the Molybdenum film. This effect is what causes excessive internal stress to result in highly damaged scribe edge. Even the edge of the scribe is defined by the microstructure of the film, as the kerf edge follows the contours of the individual grains. Therefore, the grain size and shape will have a significant effect on the laser ablation process. In this case, the kerf is practically smooth since the roughness is in the nanometer range.

4. CONCLUSION

Molybdenum thin films are commonly used as the back contact for CIGS thin-film solar cells. For production of monolithically integrated solar devices laser scribing must be performed on this layer of the film. The process parameters to create defect free scribes must be independently controlled to match the properties of the film. We have shown the physical properties of the film including the microstructure and internal stress impact the laser ablation process significantly. It has been shown the small grained, stress free films allow for the largest range of successful processing parameters. For other films advanced techniques such as beam shaping may be required to allow for high quality scribe lines.

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