INFLUENCE OF INTERFACIAL $MoSe_2$ LAYERS ON ns LASER SCRIBING OF $Cu(In, Ga)Se_2$ SOLAR CELLS

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ABSTRACT: In many thin film photovoltaic technologies laser structuring is a common method to achieve the required monolithical series connection between neighboring cells. For CIGS solar cells P2 and P3 laser scribing using ultra short laser pulses (ps, fs)[1] has also been proven to be suitable but it is still not used in industry production. In this work, it is shown that nanosecond infrared laser pulses (1064 nm, 8 ns) are capable of removing the CIGS/CdS/ZnO layers from the underlying Mo substrate utilizing an explosive ablation process. SEM micrographs show that the resulting scribe edges exhibit clean fracture edges and are free of molten material for a broad distribution of laser parameters. The Mo layer remains completely intact. However, the outcome of the laser process strongly depends on the Mo/CIGS interface properties, like the presence of $MoSe_2$ or oxide layers. In particular, $MoSe_2$ layers are analyzed in terms of thickness and crystal orientation using TEM. Based on results from a quantitative pull test method, we found that the CIGS/Mo adhesion is crucial for successful laser scribing. Finally, mechanical and compositional interface properties are discussed and a model for the laser ablation based on the thermo-mechanical behavior of the CIGS layer stack under short pulse laser illumination is proposed.

1 Introduction

The optimization of the monolithical series connection has large potential for additional gain of efficiency of CIGS solar cells. The reduction of the dead zone by the use of smaller structures for electrical interconnection is directly connected to a rise of active solar cell area. Actually, laser scribing of CIGS solar cells is performed mainly in laboratory processing. In industry mechanical scribing is still the dominating technology. Different approaches of laser scribing of CIGS thin films include the use of short laser pulses in the range of ns or ultra-short pulses in the range of ps and fs range [2, 3]. It has also been proven that the use of 1064 nm pulses might be suitable to achieve the successful preparation of P3 like structures [4, 5]. In this work, 1064 nm laser pulses with a pulse length of 8 ns are used for P3 scribing with the goal to obtain a P3 scribe without any molten CIGS at the edges. Material properties like the presence of a $MoSe_2$ layer and adhesive forces between the CIGS and the Mo are investigated and related to characteristics of the resulting scribe structures.

2 Experimental

For the experiments 4 different samples 1a, 1b, 2a, 2b were used. CIGS was deposited in a coevaporation process (sample 1a, 1b Martin Luther University Halle Wittenberg; sample 2a, 2b industrial process). The layer structure is glass/Mo/CIGS/CdS and ZnO. Scribing of CIGS layers is performed with pulsed laser (8 ns) irradiation with a wavelength of 1064 nm utilizing an explosive ablation or lift-off process. Using shorter wavelengths leads to melting of the CIGS material on the surface due to the higher absorption coefficient for 532 nm and 355 nm irradiation. However, laser energy and spot size have been varied systematically in order to achieve ablation structures with fractured edges free of residual material. The scribes are investigated using optical microscopy and SEM. For adhesion measurements a pull test [6] is used. The samples were cut into small pieces of a size of approximately 10 x 10 mm². Metal cylinders with a diameter of 5 mm were glued on top and bottom. The pull test experiment was carried out with a Zwick Z005 instrument. During the test a force normal to the CIGS/Mo interface was applied. This force was increased till delamination took place. After this the delaminated area was measured to calculate the adhesion strength. Interface characterization of the CIGS/Mo interface was done using TEM. For this a TEM lamella was prepared with FIB techniques and the thickness and the crystallographic orientation of the $MoSe_2$ layer was measured.

3 Results

Based on the scribing results the following three step model is proposed **(Fig 1)**. In the first step (step a) heating up of the CIGS material causes thermal expansion and therefore tensile stress at the CIGS/$MoSe_2$ interface. A delamination (step b) at the CIGS/$MoSe_2$ occurs in the case of low adhesion. Due to the high fluence the CIGS melts and evaporates (step c) in the beam center. The delaminated CIGS is removed by an explosive lift-off mechanism. For successful scribing the delaminated area has to be larger in size than the molten area. Otherwise no removal of the whole CIGS/CdS/ZnO will occur. Since delamination of the CIGS from the Mo layer is required for forming clean scribes without molten CIGS the CIGS/Mo interface layer is investigated in greater detail. The measured adhesion stress for a successful ablation has to be below 10 N/mm².

On the sample group 1 (samples 1a, 1b) successful ablation was achieved using pulse energies in the range of 89 µJ to 120 µJ (see **Fig. 2**). In this case a spot size of about 100 µm was used. The scribes are homogeneous without large variation in width. The best result was achieved with pulse energies of 104 µJ. The Mo surface is free from residuals near the scribe edges. There are droplets of recrystallized material towards the center of the scribe. This leads to the conclusion that the ablated CIGS area is larger than the area in which melting of the CIGS occurs. The edge itself is free from molten material and provides clean cracks throughout the complete layer stack. The Mo surface is not damaged without traces, cracks or other visible structural defects.

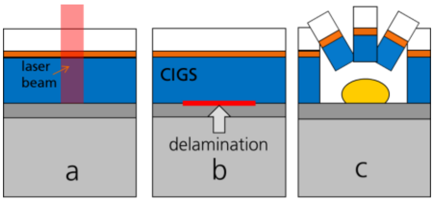


Fig. 1, Laser scribing process schematically, step a: heating of CIGS, step b: delamination, step c: explosive lift-off process with molten CIGS residual (yellow)

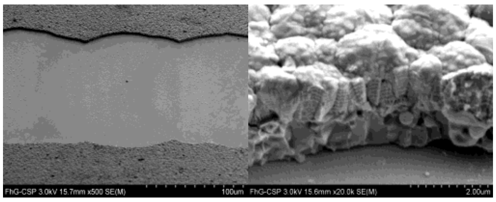
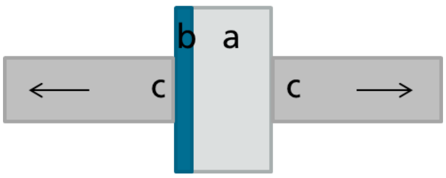


Fig. 2, SEM micrographs of the P3 scribe edge. The left figure shows an overview of the scribe. The scribe edges and the bottom of the scribe nearby are free from molten CIGS or other residuals.

Reducing the spot size to less than 30 µm leads ultimately to a selective ablation of the ZnO. At the bottom of the scribe the Mo layer is not visible. Instead the surface of molten and recrystallized CIGS is identified. Since reducing the spot size leads to an increase of the laser fluence, the ZnO delaminates from the underlying layer because of evaporating CIGS. The ZnO forms flat floe shaped pieces that are redeposited at the surrounding surface (not shown here). On sample group 2 (samples 2a, 2b) no selective ablation of the CIGS/CdS/ZnO layer stack was possible. Scribing with large and small beam diameter caused no ablation of the layer stack. Molten CIGS remained on the Mo. ZnO was removed at small beam diameters of about 30µm.

Using a pull test method (shown schematically in **Fig. 3**) the adhesion stress was measured between the CIGS and the Mo layer. The experiment was repeated 8 times for each of the samples. The results show large differences between samples from group 1 (samples 1a, 1b) and from group 2 (sample 2a, 2b) (see **Fig 4**).



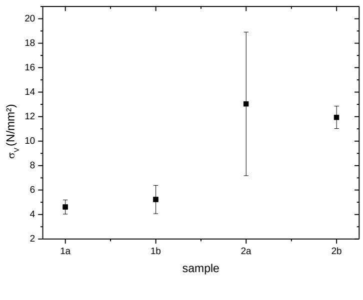


Fig. 3, Pull test schematically, a glass, b CIGS, c metal cylinders glued on the sample surface, the arrows indicate the applied forces.

Fig. 4, Adhesive stress from pull test measurements with samples of group 1 (1a, 1b) showing reduced adhesive forces in than to samples of group 2 (2a, 2b).

Adhesion of group 2 was significantly higher than in group 1 (1a: 4.6 N/mm², 1b: 5.2 N/mm², 2a: 13.0 N/mm², 2b: 11.9 N/mm²). However, sample 2a shows a high variation for σ_V. Possible reasons are inhomogeneities at the CIGS/Mo interface. However, the orientation and the thickness of the $MoSe_2$ of sample 2a and 2b were different (not shown here). Sample 2a showing a thin $MoSe_2$ layer with the dense lattice parallel to the interface, wheras sample 2b exhibits a thick $MoSe_2$ layer without any preferential lattice orientiation. Accordingly, it is assumed that $MoSe_2$ thickness and crystal orientation is not the main reason for different adhesive forces of the CIGS/Mo interface.

4 Conclusions

Successful laser scribing was achieved on samples with low CIGS adhesion for pulse energies 90 µJ to 120 µJ. A pull test setup was used to measure the adhesion quantitatively: delamination/laser ablation of CIGS from the Mo may be performed for $\sigma_V < 10$ N/mm². Systematic TEM investigations of the thickness and crystal orientation show that these $MoSe_2$ properties like thickness and orientation are not crucial for the ns ablation. Therefore the structural, chemical and mechanical properties of this interface are determining the adhesive forces.

5 Acknowledgements

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