SIMULATION AND EXPERIMENTAL INVESTIGATIONS FOR MECHANICAL STRUCTURING OF CIGS THIN FILM SOLAR CELLS

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Abstract: Despite all research attempts to optimize materials and efficiency, the mass production of CIGS thin film solar cells is still employing mechanical scribing to obtain P2 and P3 structures which are required to achieve the monolithic serial interconnection between neighboring cells. However, mechanical scribing results in random lift-offs and chipping, remaining material at the chip-off locations and increased non-productive area ‘dead zone’ thereby resulting in the loss of active solar cell area. Moreover, the non-deterministic nature of the material removal mechanism yields wide, irregular scribe lines that necessitate large spacing between adjacent scribes. As a result, the CIGS modules suffer decreased efficiency. The key challenge will be how to reduce this loss of power generation and enhance the performance of the patterning processes. In this work the mechanical scribing of CIGS thin film solar cells was investigated by experimental and numerical methods. In the experimental investigation, mechanical scribing of CIGS solar cell is done with the help of a tungsten needle and finally a half-symmetric Finite Element model for the crack initiation is presented for the numerical analysis of the mechanical scribing process. The initial crack probably propagates very close to the contact point between the spherical tip and the CIGS layer specimen and forms a circular crack before lift-off which is representing the scribe.

1 Introduction

Thin film solar cells have shown a big potential to decrease cost of manufacturing for photovoltaic power generation. CIGS has become an exciting material for the production of thin film photovoltaic (PV) panels. CIGS thin film solar cells on glass now hold the laboratory world record of 20.8% energy conversion efficiency [1]. Among other advantages commercial CIGS PV modules are relatively non-toxic and environmentally benign and have a very stable performance over time and environmental exposure and hence the future for CIGS looks bright. While laser scribing has long been the process of choice to form amorphous Silicon and CdTe monolithic interconnects [2], the mass production of CIGS thin film solar cells is still employing mechanical scribing to obtain P2 and P3 structures which are required to achieve the monolithic serial interconnection between neighboring cells. However, mechanical scribing results in the loss of active solar cell area. As a result, the CIGS modules suffer decreased efficiency [3, 4]. The key challenge will be how to reduce this loss of power generation and enhance the performance of the patterning processes. This paper presents an experimental and numerical investigation of mechanical scribing on the CIGS solar cell. In the experimental investigation, P3 mechanical scribing of CIGS solar cell is done with a flat tip tungsten needle 50 µm in radius. To understand the fracture mechanical behavior of CIGS layer during scribing, a static finite element (FE) analysis of crack initiation is done for the mechanical scribing.

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2 Specimen Geometry and Experimental Procedure

To perform the P3 mechanical scribing on the CIGS thin film solar cell, a laser station ‘3D-Micromac microSTRUCT C’ which was adapted with a mechanical scribe head by ‘Jenoptik’ was used. For experimental investigations 100 × 100 × 3 mm³ CIGS solar cell specimen was used. Scribing is done with a flat tip tungsten needle 50 µm in radius. Mechanical scribing is performed in order to produce the P3 scribes on the CIGS solar cell specimen. Mechanical scribing parameters such as force normal to the specimen and the scribing speed were systematically varied in order to achieve different scribes on the same specimen (see Table 1). All the scribes are 9 cm long. Optical microscope image analysis of the different scribes is done in order to obtain the correlation between the scribe parameters and the scribing characteristics.

Table 1: Variation of mechanical scribing parameter

<table>
<thead>
<tr>
<th>Scribing speed (mm/s)</th>
<th>Force normal to the specimen (N)</th>
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<td>0.81</td>
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<td></td>
<td>1.59</td>
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<td>3.55</td>
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<tr>
<td>10 scribe 1</td>
<td>scribe 2</td>
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<tr>
<td>100 scribe 4</td>
<td>scribe 5</td>
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<td>200 scribe 7</td>
<td>scribe 8</td>
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3 Numerical Finite Element Model

In order to understand what happens in the CIGS layer during the scribing process, a numerical FE model comprising the CIGS layer and the spherical tip was constructed considering the static aspects of the problem. Engineering simulation software ANSYS was used. Due to the symmetry of the scribing test configuration, a top view 2-dimensional half-symmetric FE model was constructed to spare calculation time (see Figure 1) assuming plane stress conditions. CIGS layer has the length and width of 0.2 mm each. To model the CIGS layer, a 2-D 8-Node structural solid element was used, the spherical tip was modeled as 2-D target segment and the contact surface between the CIGS layer and the tip was modeled with 2-D 3-Node surface-to-surface contact elements. The spherical tip is 50 µm in radius as is in the experimental investigation. The mesh was refined in the contact region to consider the Hertzian contact stress behavior. An elastic material model was used for the CIGS material. The mechanical properties such as Young’s modulus and Poison’s ratio for the CIGS material are not available in the literature. However, the experimental calculations have been done for the mechanical properties of CIS material in the past [5, 6, 7]. In the present work, Young’s modulus (E) of 75 GPa and Poisson’s ratio of 0.4 have been assumed for the CIGS material. The spherical tip is modeled as rigid target.

![Figure 1: Half-symmetric 2-D FE model with plane stress of the crack initiation for the mechanical scribing including CIGS layer and spherical tip](image)
The CIGS layer is fixed in x and y directions along the bottom edge and in x direction along the right edge. As a symmetric condition, the layer is fixed in x direction along the left edge. The spherical tip is fixed in x direction at the center. An initial vertical crack of 5 µm length is assumed to be present in the CIGS layer. The spherical tip is pressed along the surface of CIGS layer with a scribing force of 1 N in order to simulate the experimental results qualitatively. The position of initial crack (x direction) is varied along the top edge of CIGS layer starting from 5 µm and going up to 60 µm. As failure criteria pure mode I of stress intensity is assumed for CIGS.

4 Experimental Results

Figure 2(a) shows the topography of one of the P3 structure performed by mechanical scribing. It can be seen that the scribe width increases due to the chippings. Figure 2(b) shows histograms for the variation of pixel frequency with scribe width for the upper side of the scribes performed with different values of normal force. Pixel frequency describes the number of pixels which have the scribe width that lies in the particular range such as 0-5 µm or 5-10 µm up to 100 µm. It can be seen from the histograms that the variation in normal force does not influence the scribe width. The scribe width distribution is almost same for the different force values. Almost the same trend is observed for the lower side of the scribes. Figure 2(c) shows that there is no correlation between the scribe parameters such as force normal to the specimen and the minimum width of the scribe. The minimum width describes the minimum possible width of the scribe in the absence of chippings. Further investigations of the end of the scribe by the optical microscope image analysis revealed the circular shaped crack in the CIGS layer at the end of the scribe in front of the needle as shown in Figure 2(d).

Figure 2: (a) Topography of a P3 structure performed by mechanical scribing, (b) Pixel frequency as a function of scribe width for upper side of the scribes, (c) Minimum width as a function of normal force, (d) Optical microscope image of the circular crack at the end of a scribe
5 Numerical Results of Simulation

Figure 3(a) shows the distribution of first principal stresses in the CIGS layer in the half-symmetric FE model without a crack. It can be seen that following the Hertzian contact regime, the tensile stresses are present near the contact point between the spherical tip and the CIGS layer which indicate that the initial cracks can propagate in the region of the contact point. In the next step, the half-symmetric model with crack is used to find out the mode-I stress intensity factor ($K_I$) values by varying the position of initial crack (x direction) from the contact point. The CIGS layer with an initial crack of 5 \( \mu m \) is pressed by a spherical tip with the scribing force of 1 N. The $K_I$ values obtained from numerical simulation for cracks in different x-positions are plotted in Figure 3(b).

![Stress field of the first principal stresses with tensile stresses near the contact point (without a crack), Mode-I Stress Intensity Factor ($K_I$) plotted against the position of initial crack along top edge of the CIGS layer](image)

It can be seen that the stress intensity increases as we move more towards the contact point. It suggests that the initial crack most likely propagates near the contact point which may later on be chipped away in the form of a circular shape crack (cf. experimental results) leading to the removal of the material as a result of mechanical scribing.

6 Discussion

In this paper first principal experiments and the FE simulations for mechanical scribing on the CIGS thin film solar cells were performed. It was observed that the mechanical scribes are broadened because of chipping. The scribe width was found to be independent of the normal force and scribing speed. If it is assumed that the needle touches the Mo layer in every experiment, then the load case is nearly the same in every experiment and the results are similar. No correlation was found between the scribe parameters and the minimum width of the scribe which indicated that the outcome of mechanical scribing process was independent of the scribe parameters. A circular shaped crack was observed in the CIGS layer at the end of the scribe in front of the needle as a result of the mechanical scribing. Thus, the mechanism of mechanical scribing seems to be a subsequent crack initiation, defined circular crack forming and lift-off (chipping). In Figure 2(a), the result of subsequent circular cracks can be seen as a wavy scribe topology. Numerical simulations indicated that the initial crack most likely propagates near the contact point which fits qualitatively well to the experimental observations. Though, since there is no value available in the literature regarding the critical stress intensity factor for the CIGS material, a detailed position of crack propagation cannot be determined. Nevertheless, the qualitative analysis showed interesting results and the present model can be used to model the propagation path of the crack.
7 Conclusion

Mechanical scribing of the CIGS thin film solar cells results in the loss of active solar cell area because of lift-offs and chipping thereby decreases the efficiency. In this paper the mechanical scribing was investigated by experiments and numerical models. It could be shown in the experiments that P3 mechanical scribe was broadened because of chipping. Variation in scribe parameters such as normal force and scribing speed does not influence the scribing characteristics such as scribe width. The circular shaped crack was observed in the CIGS layer at the end of the scribe in front of the needle. Thus, the mechanism of scribing is repetition of crack initiation due to pressure of the needle, circular crack forming in front of the needle, and lift-off of the circular chips. These experimental results were correlated to the numerical results of the half-symmetric FE model without a crack which showed the presence of tensile stress field near the contact point and with a crack which showed the continuous increase in the KI value towards the contact point. This suggested that the initial crack most likely propagates near the contact point. In future work, the experimental data obtained could be utilized to validate the advanced FE model for the simulation of crack propagation and a comprehensive understanding of the mechanical scribing process. These results can be used for the optimization of mechanical scribing process and the design of scribing setups.

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References


