High throughput laser-scribing processes for industrial production of flexible CIGS thin-film solar modules

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Abstract: Robust high-throughput laser scribing processes for monolithic interconnection of $Cu(In,Ga)Se_2$ absorber based thin-film solar cells were developed, validated and assessed for industrial roll-to-roll production of photovoltaic modules. Here we present results of the FP7-project APPOLO.

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1. Introduction

Absorber layers based on $Cu(In,Ga)Se_2$ are attractive for solar cell production because of their potentially high maximum efficiency and tunable band gap. This high potential resulted in best of class efficiencies above 20 percent for small single cells, e.g. ZSW 22.6%[1]. In recent years tremendous efforts have been made to up-scale the thin-film deposition processes to industrial production capacities while conserving as much as possible of the high conversion efficiency. CIGS thin-film technology is compatible with roll-to-roll production thanks to available low-temperature deposition processes[2]. An important step when moving from single solar cells to modules is the electrical series interconnection of the cell strips. Laser scribing is key enabling technology to the monolithic interconnection of cells into modules on flexible substrate because traditional techniques such as needle scribing, etching or shindling are either not applicable or not desirable.

Our research consortium previously investigated several different process regimes including lift-off, induced lift-off, and direct ablation for P1 (electrical separation of the back contact), P2 (electrical connection between back- and front contact), and P3 (electrical separation of the front contact). Promising scribing processes were validated in mini modules produced on glass substrate. Best performance demonstrated was 16.6 percent conversion efficiency (aperture area) for a purely laser-structured grid-less 8-cell mini module[3] (certified by Fraunhofer ISE).

3. Scope of the project

In the frame of the FP7 project APPOLO (Hub of Application Laboratories for Equipment Assessment in Laser Based Manufacturing) we aim to transfer our optimized scribing processes to industrial scale and to flexible substrates. The consortium involving all key partners along the value chain followed a three stage assessment process: i) optimization and validation of the laser source, ii) optimization and validation of scribing processes at industrially relevant throughput, and iii) assessment of laser equipment and scribing processes in industrial module production. The industrial scenario used was as follows: in-line scribing integrated in a roll-to-roll production line with a production rate of 0.5 to 1 m/min and a roll width of 0.5-1 m. Scribing velocities requested in this scenario are 1-2 m/s. The modules were produced in substrate configuration e.g. with the following full-stack order: substrate/Mo/Cu(In,Ga)Se2/CdS/ZnO/ZnO:Al (substrate/back contact/absorber/buffer/transparent front contact).

4. Scribing processes

The well-established P1 lift-off process is a low overlap process with illumination of the molybdenum back contact layer through the transparent substrate [4]. Scaling of the process throughput to several meters per second by increasing the laser pulse repetition frequency was demonstrated and no degradation was observed. Typical scribing parameters for P1 and subsequent scribing processes are given in Table 1.

The classical P2 process, where the absorber layer is directly ablated with high pulse-to-pulse overlap, is the most critical for up-scaling. Increasing the laser pulse repetition frequency leads to heat accumulation in the absorber layer, an unwanted effect that limits the scribing velocity to <100 mm/s on the material used in this study. Our solution to the problem is energy scaling of the process: a high energy laser pulse is focused to a narrow line with a top hat profile in direction of scribing. In this way, laser fluence and pulse to pulse overlap and pulse repetition frequency can be kept constant. The scribing velocity scales approximately proportional to the aspect ratio: length to width of the focal line. Based on this technique linear scalability with laser pulse energy was demonstrated and scribing velocities up to 1750 mm/s were realized[5].

For P3 process two scenarios were investigated: the complete removal of front contact and absorber layer by direct ablation and an induced lift-off process removing only the front contact. Electrical quality of the lift-off P3 process was found to be equal or superior to ablation of front contact and absorber. A full paper covering the comparative study on different P3 scribing processes is accepted for publication and will be available at the time of the conference.

5. Experimental

Functional mini modules were produced on Flisom roll-to-roll machine up to the deposition of the ZnO layer. For technical reasons not related to scribing, modules had to be cut out from the roll and P2-patterned on a dedicated scribing machine. Then the ZnO:Al front contact was deposited at Empa followed by P3 scribing at BUAS. Electrical characterization was done according to Flisom standards at their facilities. Scribing parameters used during experiments are given in Table 1.

Table 1 Scribing process parameters and laser sources used in this study

process	*wavelength*	*fluence*	*frequency*	*velocity*	*spot size*	*laser model*
P1 lift-off	1064 nm	0.31 J/cm^2	50 kHz	1750 mm/s	diam. 50 µm	onefive Katana HP10
P2 ablation	1064 nm	0.16 J/cm^2	10 kHz	500 mm/s	3500 x 60 µm^2	onefive Genki XP
P3 lift-off	532 nm	0.10 J/cm^2	100 kHz	2000 mm/s	diam. 35 µm	onefive Katana HP05

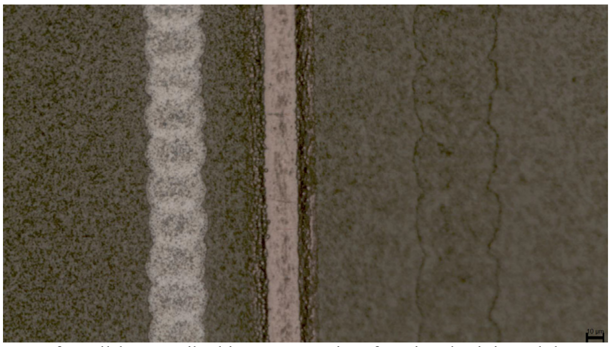

Figure 1 Optical microscope image of an all-laser scribed interconnect in a functional mini-module manufactured on flexible substrate.

6. Results

High quality scribes were produced as shown in the overview image of an interconnect presented in Fig. 1. Electrical characterization of the first batch of functional modules done at Flisom has shown high conversion efficiencies above 15 percent (designated illumination area).

7. Conclusions

Successful up-scaling of optimized laser scribing processes for a scenario of roll-to-roll manufacturing of CIGS thin-film solar modules was demonstrated. Processes were validated successfully in the production of functional 8-cell mini modules on industrially produced sample material. High quality of scribes was confirmed by measured module efficiencies above 15 percent.

8. References

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