DEPTH SELECTIVE LASER SCRIBING FOR THIN-FILM SILICON SOLAR CELLS ON FLEXIBLE SUBSTRATES

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ABSTRACT

Roll-to-roll production facilitates flexible PV modules and a significant decrease of production cost for thin-film silicon solar cells. However, no standard processes for monolithic series interconnection on opaque foil substrates are readily available. In this contribution, we present different approaches to achieve depth selective laser scribing of thin-film silicon solar cells on electrically insulated steel foil. Besides paving the way to series interconnection on opaque flexible substrates, this concept also allows to significantly reduce the number of process steps during module manufacturing.

The required depth selective scribes can be obtained with all three employed Diode Pumped Solid State-lasers (wavelengths of 355 nm, 532 nm, and 1064 nm). Actually, several laser parameter combinations (wavelength, pulse energy, spot overlap, single/multi-pass) have been found to make scribes that meet the requirements of the device architecture. Currently, the electrical validation of the observed scribes is in progress. In a next step, fully series interconnected modules will be manufactured following the presented device and processing concepts.

INTRODUCTION

Roll-to-roll production facilitates flexible PV modules and a significant decrease of production cost for thin-film silicon solar cells. ECN is currently developing the technology and setting up a pilot line for the production of single junction and tandem solar cells based on microcrystalline and amorphous silicon on steel foil substrates [1]. To allow monolithic series interconnection on these electrically conducting substrates, an insulating layer is required. In the presented module concept (see Fig. 1), first all layers of the solar cell are deposited, and after that series interconnection can be realized in one process step by three depth selective laser scribes (P1, P2, and P3) which are then filled by insulating and electrically conductive inks, see Figure 1. P1 has the function to separate the cells from each other electrically. Thus, all the layers of the full cell have to be ablated here, including the back contact. The main challenge is to have no remaining bridges of the back contact in the scribe, while the insulating layer should be unaffected as well. The laser scribe P2 is necessary for the actual connection of the front contact of one cell to the back contact of the adjacent cell. This scribe should remove all silicon layers, but leave the ZnO/Ag back contact unaffected. The insulating scribe P3 can in principle be obtained with the same process as P2.

We present here the latest status of our laser process development on state-of-the art solid state lasers with three different wavelengths.

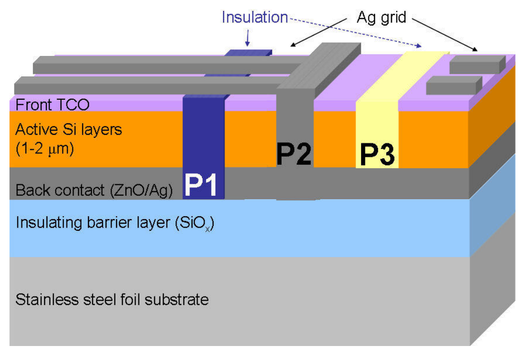

Fig. 1. Module concept on electrically insulated steel foil substrate.

EXPERIMENTAL

The investigated samples were fabricated by spray-coating of a thermally curing SiO_x based sol-gel lacquer on stainless steel foil substrates, followed by magnetron sputtering of Ag and ZnO:Al layers. Amorphous and microcrystalline Si layers were deposited by linear remote microwave PECVD. As front TCO, 80 nm of ITO have been applied by RF magnetron sputtering.

Laser scribing experiments have been performed with nanosecond pulsed diode pumped solid- state YAG lasers equipped with galvo-head scanners to guide the laser over the substrates resulting in locally isolated spots, or, when overlapping subsequent spots, in continuous lines. Besides the direct parameters scanner speed, laser frequency and the pump diode current, the output power could also be directly controlled by an external attenuator.

To gain more insight into the selectivity of the ablation process, the ablation thresholds of the different layers involved have been determined. Then, the laser parameters have been systematically varied, yielding a pulse energy / spot overlap matrix. Also multi-pass scribing, (2 or more scribing lines on top of each other) has been investigated.

The resulting laser spots and scribes have been analysed by optical microscopy, confocal microscopy, SEM and EDX.

RESULTS AND DISCUSSION

From conceptual considerations, an ideal depth selective ablation process would be 'self-regulating' in depth, e.g. due to differences in absorption and/or thermo-mechanical properties of the involved layers. A good example for such a 'self-regulating' process is the removal of a silicon layer from a TCO/glass substrate [2] with a green laser, which is practically not absorbed by the TCO, so that a clean removal of the Si from the TCO can be obtained.

For the P1 scribe of the interconnection concept presented here, one has to take into account that the investigated laser wavelengths are absorbed very effectively in the steel substrate. Potential damage or even ablation of the substrate surface is critical as it may induce damage to the insulating barrier layer. Thus, despite the high transparency of the barrier layer itself, the P1 scribing process cannot be self-regulating and has to be optimized to just ablate the back contact, with minimal exposure of the barrier layer and back contact to the laser radiation.

For the P2/P3 scribes, when neglecting the absorption in the TCO layers, the most critical selectivity is expected between the silicon layers and the Ag layer in the back contact. In first instance, the 355 nm wavelength appeared most interesting for these scribes, as the silicon layers show very high absorption exceeding the values for the Ag layer, see Fig. 2.

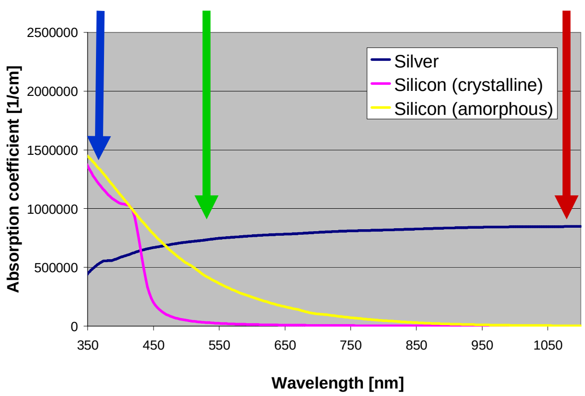

Fig. 2. Absorption spectra of the materials involved in the depth selective laser processes. Arrows indicate the standard YAG laser wavelengths of 355, 532 and 1064 nm.

The small optical penetration depth in silicon at this wavelength allows for careful control of the ablated material volume per laser pulse by tuning the pulse energy. For the analysis and understanding of the ablation process the Gaussian intensity profile is used as an important property of the laser pulses. Assuming a certain ablation threshold H_s (in J/cm^2) and a diameter of the Gaussian beam in focus d_f, the resulting ablation spot will have a diameter d_{abl} which increases with increasing laser fluence H following equation (1).

$$d_{abl} = d_f \sqrt{\frac{1}{2} \ln \frac{H}{H_S}} \qquad (1)$$

Solving this equation for the ablation threshold H_s allows to determine this specific parameter by varying the pulse energy of the laser and measuring the corresponding ablation diameters d_f:

$$H_S = H \exp\left(-2\left(\frac{d_{abl}}{d_f}\right)^2\right) \qquad (2)$$

Fig. 3 shows the dependence of the ablation diameter on the pulse energy for the back contact and the silicon layers. For the same optical configuration, we found that the ablation threshold for the back contact without silicon layer on top is with a value of 0.125 J/cm^2 only ¼ of the threshold for the ablation of the Si layer which amounts to approximately 0.5 J/cm^2.

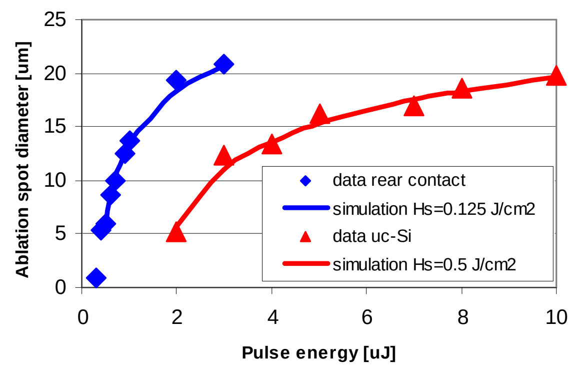

Fig. 3. Ablation diameter versus pulse energy for the back contact and the μc-Si layer. Fitting of these curves yields the ablation thresholds of the corresponding layers for the 355 nm laser.

Thus, the removal of the silicon layers from the back contact is not a self-regulating process. Only slightly too high pulse energy will lead to a removal of the back contact together with the silicon layers. Consequently, the scribing depth has to be controlled by the laser process itself (i.e. pulse energy, spot overlap, etc). The process window for a clean removal of only the silicon from the back contact is rather narrow, see Fig. 4. At only slightly too large or too little pulse energy or spot overlap, locally either the back contact is removed, or Si remains that bridges the scribe. Scribing in multiple passes did not improve the quality of the scribes, nor could we increase the process window.

With the same 355 nm laser, a robust P1 scribe can be accomplished straightforwardly, for example in single and double pass mode, as shown in Fig. 5.

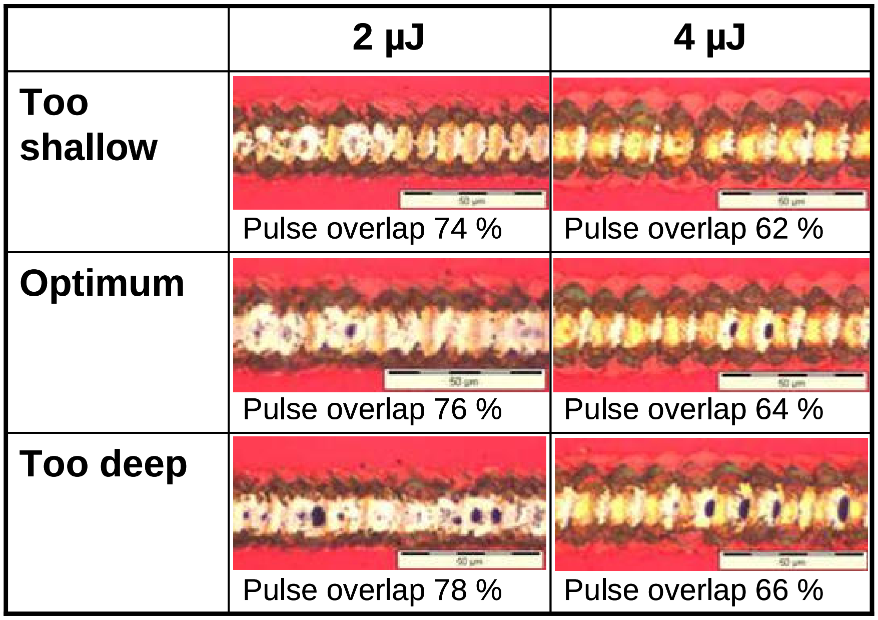

Fig. 4. Pulse energy / pulse overlap combinations to achieve P2 scribes with the UV ns laser.

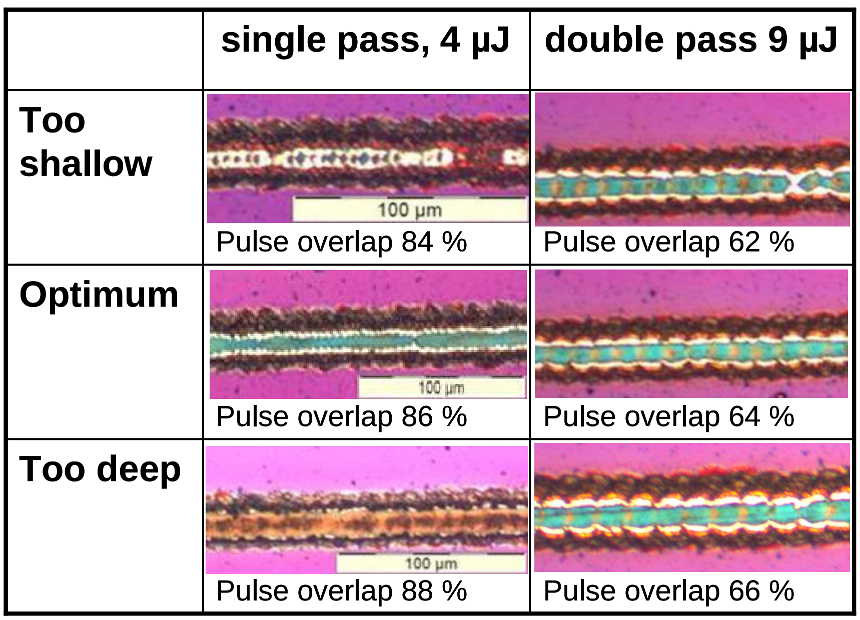

Fig. 5. Pulse energy / pulse overlap combinations to achieve P1 scribes with the UV ns laser in single and double pass.

In search of a larger process window especially for the P2 scribe, also 532 nm and 1064 nm lasers have been applied, and actually all scribes (P1, P2, P3) have been realized on stacks including either amorphous or microcrystalline silicon on top of the steel / barrier / back contact samples, see Fig. 6.

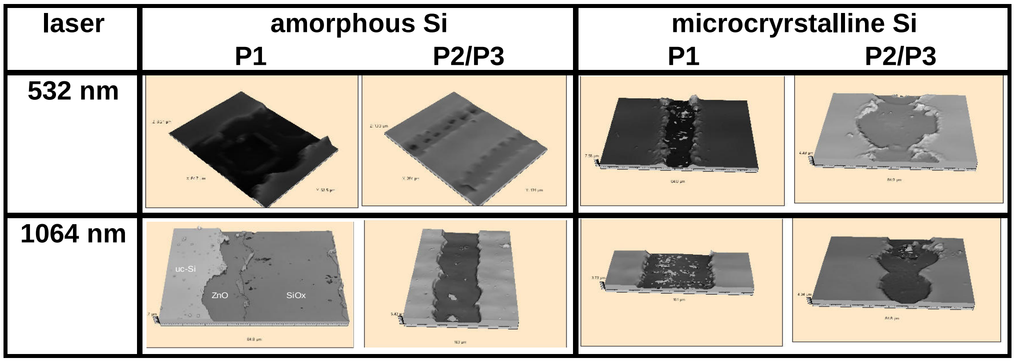

Fig. 6. P1 and P2/P3 scribes achieved with 532 nm and 1064 nm lasers on amorphous or microcrystalline silicon layers deposited on top of steel / barrier layer / back contact samples.

In the following, we focused on the results obtained with a 1064 nm laser, and found excellent P1 and P2 scribes of the complete stack including ITO deposited on the (amorphous) silicon, as shown in Fig. 7 and Fig. 8, respectively. In both pictures, the optimum scribes can be found in the center. An important observation is that the SiO_x layer still has a very flat surface after laser scribing of P1, indicating that there is no significant damage to this layer. This is confirmed by a closer analysis of the confocal microscopy results. The confocal microscope actually finds a strong signal for all reflecting interfaces that are illuminated during the measurement.

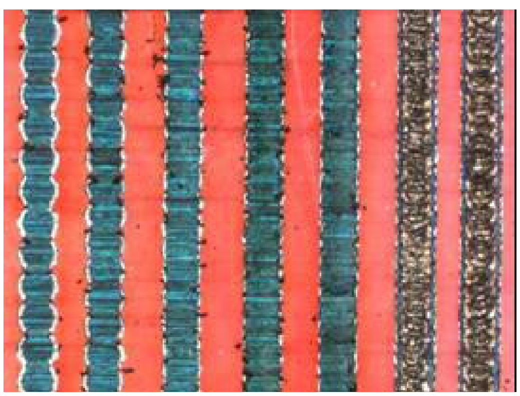

Fig. 7. P1 scribes obtained with a 1064 nm ns pulsed laser. From left to right the spot overlap was increased

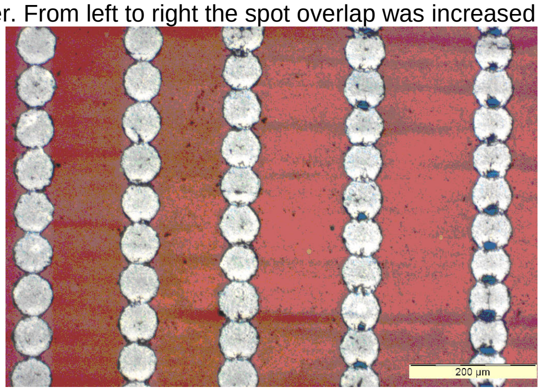

Fig. 8. P2 scribes obtained with a 1064 nm ns pulsed laser. From left to right the spot overlap was increased.

As the SiO_x layer is transparent, the surface of the steel substrate and the surface of the insulating layer are visible in the P1 scribe. The appearance of these two peaks confirms the complete removal of the non-transparent back contact, and the distance between the peaks indicates the unchanged thickness of the insulating layer.

An important observation for the P2 scribe is that obviously the back contact remains fully unaffected at places where the silicon and ITO are removed. In EDX analysis, we found Zn in the P2 scribes, and a Zn/Ag ratio comparable to the value outside the scribe. This indicates that the ZnO is still present on top of the easily visible Ag layer.

CONCLUSIONS AND OUTLOOK

Depth selective laser scribing is a crucial process step towards monolithic series interconnection of thin-film silicon solar cells on opaque flexible foils. We have demonstrated that the required depth selective scribes can be obtained with all three employed DPSS-lasers (wavelengths of 355 nm, 532 nm, and 1064 nm). Several laser parameter combinations (pulse energy, spot overlap, single/multi-pass) have been found to make scribes that meet the requirements of this monolithic device architecture. Currently, the electrical validation of the observed scribes is in progress. In a next step, fully series interconnected modules will be manufactured following the presented device and processing concepts.

ACKNOWLEDGEMENTS

We would like to thank Matthias Fahland (Fraunhofer Institute FEP Dresden, Germany) for supplying the sputtered Ag / ZnO:Al layers, and Claudia Finck and Michael Wutz (Rofin) for the fruitful cooperation on part of the presented laser process development.

Part of this work has been financed by the European Commission under contract EU FP-6 Energy 2004 – 019948 (FLEXCELLENCE project) and by the Dutch Ministry of Economic Affairs (contract TSIN3043).

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