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DEPTH SELECTIVE LASER SCRIBING OF THIN FILMS FOR ROLL-TO-ROLL PRODUCTION OF SILICON SOLAR CELLS

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Abstract

Significant cost reductions for thin-film silicon solar cells are expected from a transition to roll-to-roll production. However, in contrast to state-of-the-art batch-type fabrication of glass based products, for thin-film photovoltaic modules on foil substrates no standard processes for one essential production step – the monolithic series interconnection - are presently available. Laser scribing is the preferred technology here as it allows fast, non-contact, local and precise removal of the thin films. ECN is currently developing the technology and setting up a pilot line for the production of 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, 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 which are then filled by insulating and electrically conductive inks. In this contribution, we present the latest status of our process development on nanosecond pulsed lasers with three different wavelengths to achieve depth selective scribing of these flexible thin-film silicon solar cells. To gain more insight into the selectivity of the process, the ablation thresholds of the different layers have been determined. Then, continuous lines were scribed by systematically varying the pulse energy and spot overlap. The required depth selective scribes could be obtained with all employed lasers (wavelengths of 355 nm, 532 nm, and 1064 nm).

Introduction

Thin film amorphous/microcrystalline silicon tandem solar cells (so-called 'micromorph cells') are an emerging PV technology as a cheap alternative to the more traditional wafer-based crystalline silicon solar cells since they can be produced using low-cost manufacturing methods [2]. An inherent advantage of thin-film PV technology is the ability to directly produce series interconnected modules on the substrate by laser structuring the PV active layers into stripes (leaving the substrate as carrier intact) which are monolithically series interconnected during the further device processing. Recently, many production lines for thin-film silicon PV modules based on glass substrates have become operational. Production capacity is expanded worldwide as turn-key fabrication equipment for this technology is available on the market, including the laser scribing tools and processes. However, the applied interconnection processes require three separate deposition steps (for TCO, silicon layers, and rear contact, respectively), each of which is followed by a laser scribing step in atmosphere [3]. This implies several handling steps of the glass substrates, and pump-down cycles for the vacuum deposition equipment.

Therefore, an important further decrease in production cost is expected when moving to high-throughput roll-to-roll production, where handling is limited to coils carrying kilometres of substrate foil which is further processed to PV laminates more compact production tools requiring less floor space. Besides, roll-to-roll production of thin film Si solar cells has several further advantages over batch-type reactor systems, for instance the opportunity to make lightweight and flexible products. Flexible and lightweight PV modules gear up to building integrated PV: the most important market for PV in densely populated, developed countries [4, 5].

However, in contrast to production lines based on glass substrates, no standard equipment is currently available for R2R production of thin-film silicon solar cells and modules. For the series interconnection, no standard concept has emerged yet, while some players are working on proprietary solutions.

To overcome these limitations, ECN is currently developing the technology and setting up a pilot line for the production of low-cost and high efficiency 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 barrier layer is required. On top of this barrier layer, a sputtered back contact is applied, followed by PECVD of the silicon layers and the front TCO sputtering. In order to further reduce the substrate handling during the manufacturing, in the ECN concept first all solar cell layers are deposited, and then the monolithic series interconnection is realized in one single process step by three depth selective laser scribes (P1, P2, and P3) which are subsequently filled by insulating and electrically conductive inks, see Figure 1.

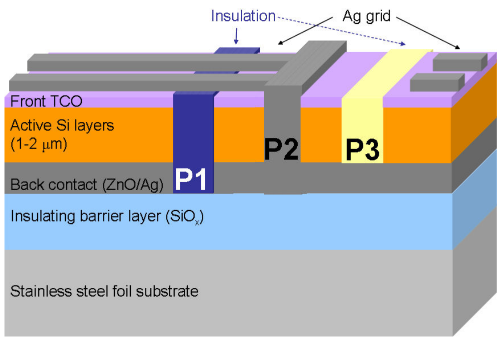


Figure 1. Thin-film silicon PV Module concept on electrically insulated steel foil substrate.

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. 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.

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

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 [3] 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.

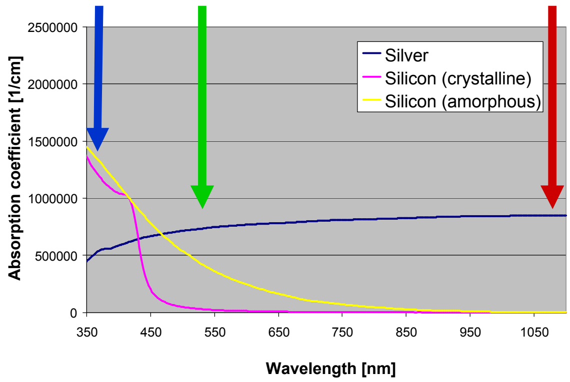


Figure 2. Absorption spectra of the materials involved in the depth selective laser processes. Arrows indicate the

standard YAG laser wavelengths of 355, 532 and 1064 nm.

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 Figure 2.

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 the determination of this specific parameter by varying the pulse energy of the laser and measuring the corresponding ablation diameters d_f:

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

Figure 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.

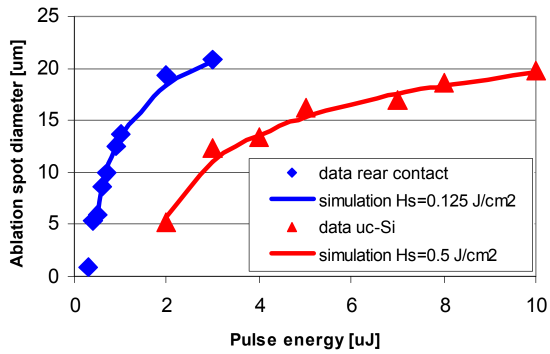


Figure 3. Ablation diameter versus pulse energy for the back contact and the µc-Si layer. Fitting of these curves yields the ablation thresholds of the corresponding layers for the 355 nm laser.

Thus, the removal of the silicon layers from the back contact at a laser wavelength of 355 nm 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 Figure 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 or double pass mode, as shown in Figure 5.

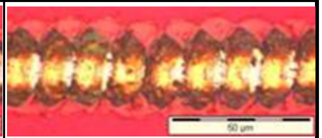
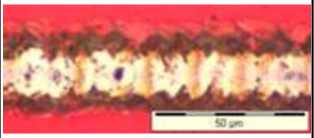
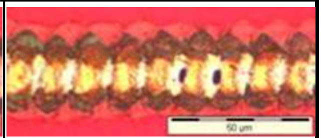
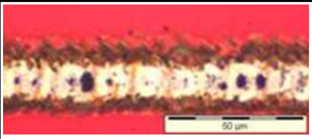
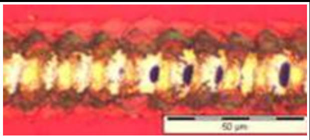
	2 µJ	4 µJ
Too shallow	 Pulse overlap 74 %	 Pulse overlap 62 %
Optimum	 Pulse overlap 76 %	 Pulse overlap 64 %
Too deep	 Pulse overlap 78 %	 Pulse overlap 66 %

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

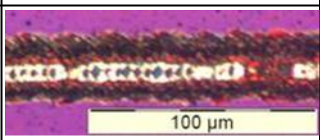
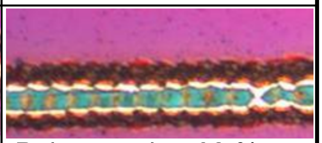
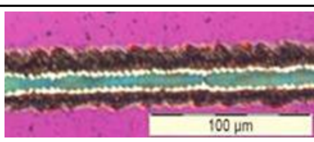
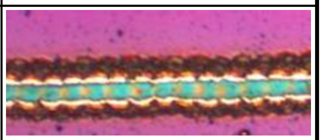
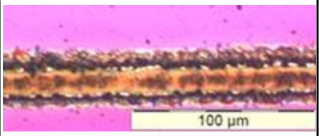
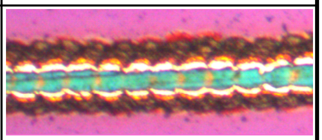
	single pass, 4 µJ	double pass 9 µJ
Too shallow	 Pulse overlap 84 %	 Pulse overlap 62 %
Optimum	 Pulse overlap 86 %	 Pulse overlap 64 %
Too deep	 Pulse overlap 88 %	 Pulse overlap 66 %

Figure 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 Figure 6.

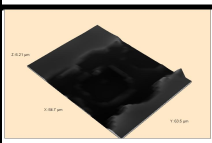
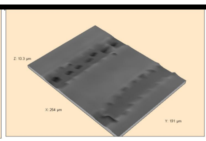
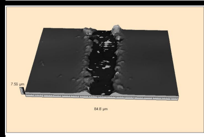
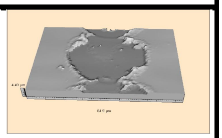
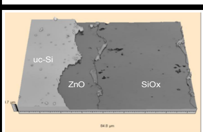
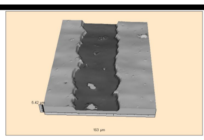
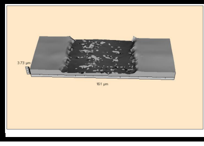
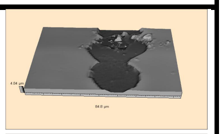
laser	amorphous Si P1	amorphous Si P2/P3	microcryrstalline Si P1	microcryrstalline Si P2/P3
532 nm				
1064 nm				

Figure 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 Figure 7 and Figure 8, respectively. In both pictures, the optimum scribes can be found in the center.

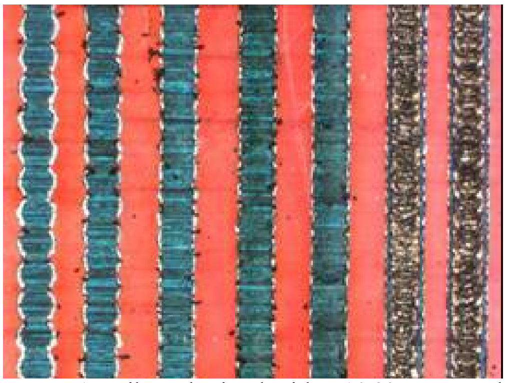


Figure 7. P1 scribes obtained with a 1064 nm ns pulsed laser. From left to right the spot overlap was increased

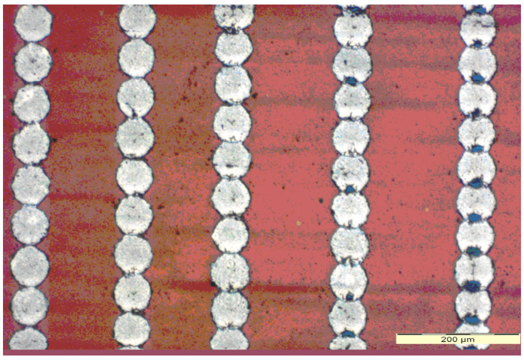


Figure 8. P2 scribes obtained with a 1064 nm ns pulsed laser. From left to right the spot overlap was increased.

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 presented in Figure 9.

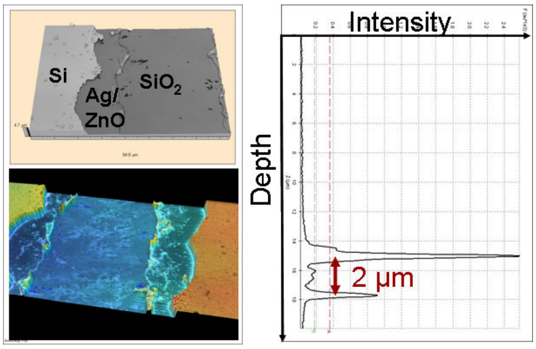


Figure 9. Confocal microscopy analysis of the P1 laser scribe.

The confocal microscope actually finds a strong signal for all reflecting interfaces that are illuminated during the measurement. 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 of 2 µm 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.

A possible explanation for the initially unexpected selective ablation obtained at 1064 nm (see discussion above and the absorption spectra in Figure 2) is an ablation mechanism governed by pressure induced ejection, where the pressure may be built up by the silicon layer itself, e.g. due to the formation of hydrogen gas as a result of heating [6], or by the expansion of the rear contact.

Conclusions and Outlook

ECN is developing a novel fabrication process for thin film silicon solar cells on foil. Steel foil is a suitable substrate and when a proper barrier layer is applied, monolithic series interconnection of cells can be accomplished *after* the deposition of all functional layers of the cell.

Depth selective laser scribing is a crucial process step towards monolithic series interconnection of thin-film silicon solar cells on such 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.

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