DEPTH-SELECTIVE LASER ABLATION FOR MONOLITHIC SERIES INTERCONNECTION OF FLEXIBLE THIN-FILM SILICON SOLAR CELLS

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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. 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 (P1, P2, and P3) which are then filled by insulating and electrically conductive inks. We present here the latest status of our laser process development on state-of-the art solid state lasers with three different wavelengths. To gain more insight into the depth selectivity of the 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. Confocal microscopy combined with optical microscopy, SEM and EDX are used as the main tool to analyse the obtained laser scribes.
Keywords: Laser Processing, Flexible Substrate, Thin Film Solar Cell

1 INTRODUCTION

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 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, first all layers of the solar cell are deposited in sequential vacuum processes, 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.

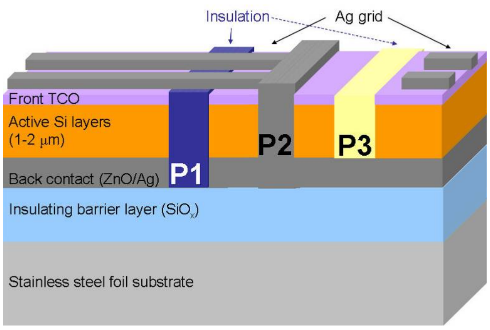

Figure 1. Module concept on electrically insulated steel foil substrate.

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 rear contact. The main challenge is to have no remaining bridges of the rear 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 rear contact of the adjacent cell. This scribe should remove all silicon layers, but leave the ZnO/Ag rear contact unaffected. The insulating scribe P3 can in principle be obtained with the same process as P2.

2 EXPERIMENTAL

2.1 Sample fabrication

The investigated samples were fabricated by spray-coating of a thermally curing SiOx 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 has been applied by RF magnetron sputtering.

2.2. Laser scribing

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. Scanner speed, laser frequency, the pump diode current, and the output power could 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.

2.3 Characterisation and Analysis

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

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).

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

The laser fluence H represents the power density during the pulse and therefore increases linearly with increasing pulse energy.

3 RESULTS AND DISCUSSION

The required depth-selective scribes have been obtained with all three employed DPSS-lasers (wavelengths of 355 nm, 532 nm, and 1064 nm). Some interesting and initially unexpected results were found and are described in the following.

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 Figure 2.

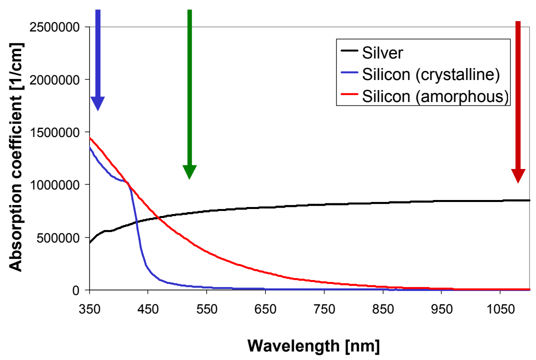

Figure 2. Absorption spectra of the materials involved in the depth selective laser processes. Arrows indicate the standard YAG laser wavelengths of 355, 532 and 1064 nm.

Therefore, first experiments have been performed with a nanosecond pulsed UV (355 nm) laser which allows a careful control of the ablated material volume because of the small optical penetration depth in silicon at this wavelength. In Figure 3 the diameter of ablated spots obtained with different pulse energy is plotted versus the pulse energy, and the ablation thresholds are determined from a fit of the data to equation (1). For the same optical configuration, we found that the ablation threshold for the rear contact without silicon layer on top is only ¼ of the threshold for the ablation of the Si layer itself.

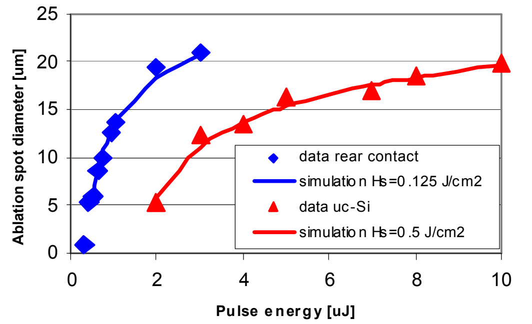

Figure 3 Ablation diameter versus pulse energy for isolated spots ablated with the 355 nm laser on a steel/barrier layer substrate with only the ZnO/Ag rear contact, and one sample with rear contact plus 1 µm of microcrystalline silicon.

Consequently, the process window for a clean removal of only the silicon from the rear contact is rather narrow. At only slightly too large or too little pulse energy or spot overlap, locally either the rear 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. P1 scribes could be obtained with the 355 nm laser in a broad process window.

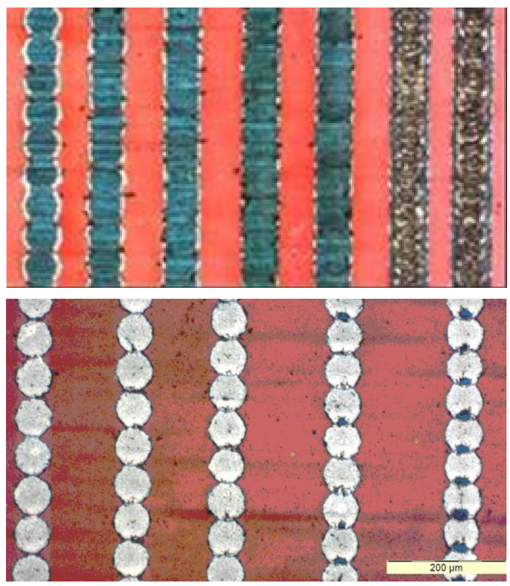

Figure 4. P1 (top) and P2 scribes obtained with the 1064 nm laser. In both pictures, the pulse overlap is increased from left to right, centered around the visually best scribe.

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 / rear contact samples.

Following this screening, we focused on the results obtained with a 1064 nm laser, and found excellent P1 and P2/P3 scribes of the complete stack including ITO deposited on the (amorphous) silicon, see Figure 4. An important observation is that the SiO_x barrier 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, as shown in Figure 5. The confocal microscope actually finds a strong signal for all reflecting interfaces that are illuminated during the scan. As the SiOx layer is transparent, the microscope measures a high intensity of reflected light at two different heights (right graph in Figure 5, corresponding to the surface of the steel substrate and the surface of the insulating layer. The appearance of these two peaks confirms the complete removal of the non-transparent rear contact. The distance between the peaks actually indicates the thickness of the undamaged insulating layer.

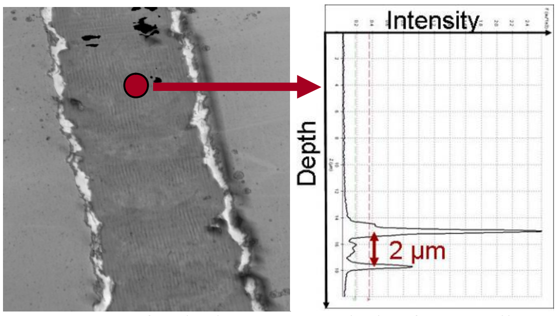

Figure 5. Confocal microscopy analysis of a P1 scribe.

Also for the P2/P3 scribe, an excellently flat surface of the groove has been observed, see the confocal image and cross section in Figure 6. Another 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.

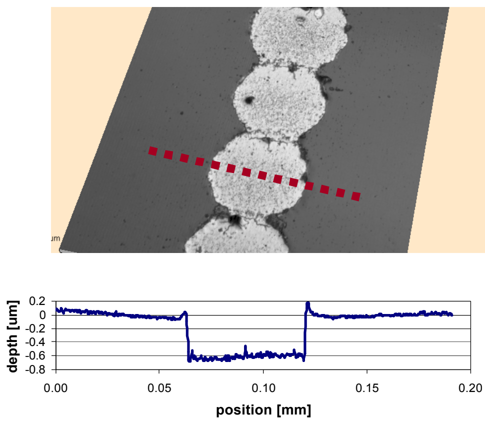

Figure 6. Confocal microscopy analysis of a P2 scribe.

4 CONCLUSIONS

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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