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Scribing of a-Si Thin-Film Solar Cells with Picosecond Laser

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Abstract. The thin-film technology is the most promising technologies to achieve a significant cost reduction in solar electricity. Laser scribing is an important step to preserve high efficiency of photovoltaic devices on large areas. The high-repetition-rate laser with the pulse duration of 10 ps was applied in selective ablation of multilayer thin-film a-Si solar cells deposited on flexible and rigid substrates. Two types of solar cells with flexible and rigid substrates had been investigated. The first type of solar cells was made of 400 nm a-Si layer coated on both sides with 2 μm transparent ZnO:Al contact layers deposited by CVD technique on the glass plate. The second type of solar cells was made of a flexible polyimide substrate coated with the Al back-contact, a-Si light absorbing layer and the ITO top-contact. Selection of the right laser wavelength is important to keep the energy coupling in a well defined volume at the interlayer interface. Well-defined shapes of scribes were produced by laser ablation through layers of the solar cell on the glass substrate. Localization of the coupled energy at inner interface led to the “lift-off” type process rather than evaporation of the top ITO layer when the 355 nm radiation was applied. All laser scribes did not indicate any material melting or other thermal damage caused by laser irradiation. Ultra-short picosecond pulses ensured the high energy input rate into absorbing material therefore peeling of the layers was possible without the influence on the remaining material.

PACS. 52.38.Mf Laser ablation; 81.05.Gc Amorphous semiconductors; 89.30.Cc Solar power; 42.62.Cf Industrial laser applications; 68.37.Hk Scanning electron microscopy

1 Introduction

Low material consumption, the possibility to deposit on large areas, use of cheap and flexible substrates make the thin-film silicon photovoltaic elements as one of the most promising technologies to achieve a significant cost reduction in solar electricity [1]. Efficiency of the thin-film solar cells with a large active area can be maintained if small segments are interconnected in series in order to reduce photocurrent in thin films and resistance losses. By alternating the layer deposition and layer patterning it is possible to produce integrated series connections. The structuring is accomplished by three critical scribing processes called P1, P2, and P3. The P1 scribe must penetrate completely through the full thickness of the contact layer next to a substrate. This cut defines and isolates the individual cells with an effective resistance of tens of megaohms. The P2 scribe through the active layer is important for formation of the series interconnects between cells. The integrity and continuity of the P3 scribe are as critical as of P1 scribe. Cutting through both the top-contact and semiconductor layers, the P3 scribe isolates adjacent cells.

Selective removal of the films in multilayer structures of modern solar cells is crucial for performance of the devices. Lasers are the technology of choice for these processes, delivering the desired combination of high throughput and narrow, clean scribes [2]. Accuracy in the ablation depth and a high scribing speed are required for efficient and cost-effective production of solar cells of this type. Laser scribing rates have to be in the range of 2 m/s.

In case of a-Si thin-film solar cells based on glass substrates laser scribing could be arranged through the glass side by so-called material lift-off process. Instead of melting, vaporizing or atomizing all the target material, the laser beam vaporizes a small amount of material at the film interface, removing the overlaying layers entirely by micro-explosive effect [2]. This minimizes thermal

effects, increases the layer selectivity and process efficiency because the required laser power for material removal is lower compared to direct laser ablation. An intensive process characterization has shown that low overlap of about 25% is desired during the scribing process in order to avoid peeling of the layers induced by the laser pulses [3]. In case of a-Si thin-film solar cells based on flexible polymer substrates laser scribing could be arranged only through the front side by direct laser ablation process.

Usually, Q-switched nanosecond lasers are applied for thin-film scribing in amorphous Si solar cells. Long laser pulses caused local heating of the material in areas adjacent to the scribing line, which strongly influenced the I/V characteristics of the cells [1]. Comparison of laser scribing with different pulse duration from nanosecond to femtosecond range in the thin-film a-Si solar cells on glass was performed in [4]. Front-side ablation with picosecond laser with the wavelength in IR and green did not get acceptable quality of scribing, while the results of back-side irradiation were considerably better. There are only fragmental results on laser scribing in the thin-film a-Si solar cells on flexible substrates.

Lasers with a shorter, picosecond pulse duration were successfully applied in scribing the monolayer thin film structures deposited on glass [5, 6] and polymer substrates [7]. The technique was also applied in scribing films for the CIGS solar cells [8]. The experiments revealed potential of picosecond lasers in selective structuring of thin films when the wavelength of laser radiation was adjusted depending on optical properties both of the film and the substrate.

New results in application of picosecond lasers for scribing of two different multilayered a-Si solar cell systems are presented.

2 Samples and Experimental procedures

The first type of solar cells was made of 400 nm a-Si layer coated on both sides with 2 μm transparent ZnO:Al contact layers. The 0.5 mm thickness glass plate was used as a substrate. Samples from three different production stages were used in experiments for developing the laser scribing processes. The first sample was a single ZnO:Al layer deposited by chemical vapor deposition (CVD) on glass, the second sample was a multilayer structure made of glass/ZnO:Al/a-Si and the third sample was a complete multilayer Solar cell made of glass/ZnO:Al/a-Si/ZnO:Al. All laser scribes with this structure were performed through the glass (back) side (Fig. 1).

The second type of solar cells was made of a flexible polyimide substrate coated with the Al back-contact, a-Si light absorbing layer and the indium-tin oxide (ITO) top-contact. The complete multilayer structure of the solar cell was used in experiments and the front-side laser scribing was applied (Fig. 2).

The picosecond laser PL10100 (pulse duration 10 ps, pulse repetition rate 100 kHz) made by Ekspla UAB was used in the ablation experiments. The picosecond laser was chosen for the experiments because the short pulse duration might prevent thermal damage and degradation of materials, enabling a selective high quality ablation of the films. More details on the experimental setup are in [8].

The laser spot overlap along a scanning line was controlled by the translation speed at a constant pulse repetition rate. Various combinations of pulse energy, beam overlap and wavelength were used for selective ablation of the films. Optimal regimes for laser processing of every layer were estimated depending on the wavelength (1064 nm, 532 nm, 355 nm, 266 nm). The beam was focused either with the $f = 50$ mm (1064 & 532 nm) or $f = 100$ mm lenses (355 & 266 nm). The beam overlap played an important role in the processing selectivity because the ablation threshold was sensitive to accumulation of the irradiation dose. The laser processing parameters for selective removal of every layer were estimated.

The quality of processing was evaluated with an optical microscope and the scanning electron microscope (SEM) JSM 6490LV (JEOL).

3 Results

Two types of a-Si solar cell structures were investigated - deposited on the glass substrate and on the flexible polyimide substrate. Below are results of laser scribing in the structures for various stages of the solar cell manufacturing process.

3.1 Laser scribing of thin-film a-Si solar cell based on glass substrate

3.1.1 Formation of the ZnO:Al back-contact

The back-contact was made of the ZnO:Al film, directly deposited on the glass substrate. Structuring of the back-contact is the first laser process in a production line. A homogeneous film of the ZnO:Al should be divided into stripes by local removal of the film and forming isolation trenches in it. Good isolation between the nearby contact lines and the diminishing effect on the substrate are the main requirements at this stage.

To achieve better material selectivity the laser scribes were ablated through the glass (back) side. 1064 nm laser radiation was used at this stage because of good absorbance by the ZnO:Al layer and good transmittance by the glass substrate in the IR range. The experiments were conducted varying laser power and scanning speed for scribing. Good results were achieved for the speed from 500 to 800 mm/s, when the laser power was 0.8 W at the pulse repetition rate of 100 kHz. The lower laser power was not high enough for complete film ablation.

In the P1 process with the 1064 nm wavelength, balance between the complete film removal and preventing the substrate damage should be found. The laser beam was well absorbed at the interface between the glass substrate and the ZnO:Al layer causing vaporization and micro-explosion of the back-contact. The ZnO:Al film was completely removed without damage to the underneath glass substrate (Fig. 3). Only slight redeposition on a cleaned area was observed.

3.1.2 Back-contact exposure to strip the a-Si absorber layer

The integrity of the P2 scribe is critical in forming the series interconnects between cells. Any active-layer material remaining over the contact layer will impose contact resistance, resulting in parasitic losses and a decreased electrical power output of the module [2].

The experiments with the P2 process were performed using the 532 nm laser wavelength since the underlying ZnO film is highly transparent at this wavelength. The laser energy absorbed by silicon started to affect the films notably, when the laser power exceeded 250 mW. The cracks appeared in the a-Si film and it was removed partially in the central part of the irradiated path. The best scribing results were achieved when the laser power was kept at the 0.4 W level and the scribing speed was high (900 mm/s) to ensure small overlap of laser pulses. SEM picture of typical scribe at that regime is shown in Fig. 4.

Overlap of laser pulses was carefully controlled to avoid micro-cracking and peeling of the upper layer induced by the laser pulses as it was found by Haas et al. [3].

3.1.2 Cell isolation/top-contact formation

The P3 process requires laser scribing by removal of two upper layers: a-Si and upper ZnO:Al films isolating the adjusted p-n junctions and completing formation of the integral interconnection between them. Therefore, the experiments were performed on complete structures of the solar cells with all layers deposited.

The “green” laser working at the 532 nm wavelength was used to irradiate the structure through the glass substrate. Because of the high absorption of silicon, the excitation was localized at the inner interface between the back-contact and a-Si. The “lift-off” process triggered by evaporation expelled both upper layers. When the laser power was 0.4 W both films were removed at the scribing speed as high as 900 mm/s. However, quite a lot of debris was located close to the scribe. Reducing the laser

power to 0.2 W helped to diminish the debris formation. SEM picture of the scribe in both a-Si and upper ZnO:Al layers is shown in Fig. 5.

In both P2 and P3 cases, the layers were removed with sharp edges like a tear-away, without any marks of heating on the rims.

3.2 Laser scribing of thin-film a-Si Solar cell on flexible substrate

Polyimide used as a substrate for flexible solar cell has sufficient absorption in infrared to ultraviolet spectral range to exclude the back-side irradiation geometry in laser scribing. Moreover, the metal film used as a back contact is not transparent to any light. Therefore, only the front-side irradiation can be used in experiments on scribing the top-contact layer in the PI/Al/a-Si/ITO solar cell structure. The wavelength of laser radiation was selected in UV (355 or 266 nm) to ensure high absorption in outer layers and to prevent the effect of laser processing to underneath layers.

The ITO top-contact had high absorption at the 266 nm wavelength and it was possible to ablate the film layer-by-layer until the a-Si film was opened (Fig. 6). However, due to the Gaussian spatial distribution of the laser energy in the irradiated spot, the ITO film was ablated completely only by the central part of the spot. Material at the peripheries of the laser spot was melted or exfoliated only due to lower local irradiation dose. The “melt” ring formation even was not prevented by scanning the beam at a high speed to ensure small overlap of the spots (Fig. 7).

ITO is transparent to the 355 nm radiation, and the laser energy was absorbed at the ITO/a-Si interface. Localization of the coupled laser energy at the inner interface led to the “lift-off” type removal process due to rapid thermal expansion rather than evaporation of the top ITO layer. Therefore, the a-Si film was cleanly opened (Fig. 8). The scribe had no smooth edges because of the specifics of the removal process, however the rims were sharp and without any marks of heating or melting. Further optimization of the scribing parameters is required to reduce chipping of the films.

Photo-mechanical model of such material removal in the a-Si/SnO₂/glass structure was discussed in [9] in case of the back-side irradiation with nanosecond laser. Picosecond laser pulses increased the energy input rate and local transient stress to the film which facilitated the upper film separation and removal. Selection of the right laser wavelength is important to keep the energy coupling in a well-defined volume at the interlayer interface and might be a way to achieve the selective removal of layers even in the front-side irradiation geometry which is only acceptable for solar cells on flexible substrates.

4 Conclusions

Lasers with the picosecond pulse duration were applied in structuring the thin-film solar cells. The wavelength of laser radiation was adjusted depending on optical properties both of the film and the substrate.

Selective removal of thin layers in both samples on the glass and polyimide substrates was achieved. All laser scribes have not indicated any material melting or other thermal damage caused by laser irradiation. Ultra-short picosecond pulses ensured the high energy input rate into absorbing material, therefore peeling of the layers was possible without influence on the remaining material.

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Figures captions

Fig.1. Configurations of the experimental procedures for laser scribing of the thin films on the glass substrate. P1 - back-contact formation; P2 - back-contact exposure to strip a-Si layer; P3 - top-contact formation.

Fig.2. Configuration of the experimental procedure for the laser scribing of the thin films on the polymer substrate.

Fig.3. Scribe in the ZnO:Al back-contact on glass, made by the back-side irradiation with the picosecond laser. Wavelength 1064 nm; average power: 0.8 W; scribe speed: 800 mm/s.

Fig.4. Scribe in the silicon film in the glass/ZnO:Al/a-Si structure by the back-side irradiation with the 532 nm wavelength. Laser power: 0.4 W; scribe speed: 900 mm/s.

Fig.5. Scribing absorber and top-contact films for cell isolation in the glass/ZnO:Al/a-Si/ZnO:Al structure by the back-side irradiation with the 532 nm wavelength. Laser power: 0.2 W; scribe speed: 900 mm/s.

Fig.6. The spot ablated by a single laser pulse in ITO layer of the Polyimide/Al/a-Si/ITO solar cell structure. Wavelength 266 nm; pulse energy 4 μ J.

Fig.7. Scribe in ITO layer with the wavelength 266 nm. Pulse energy 4 μ J; pulse repetition rate 5 kHz; scribing speed 120 mm/s.

Fig.8. Scribe in ITO layer with the wavelength 355 nm. Pulse energy 1.8 μ J; pulse repetition rate 50 kHz; scribing speed 650 mm/s.

Figures

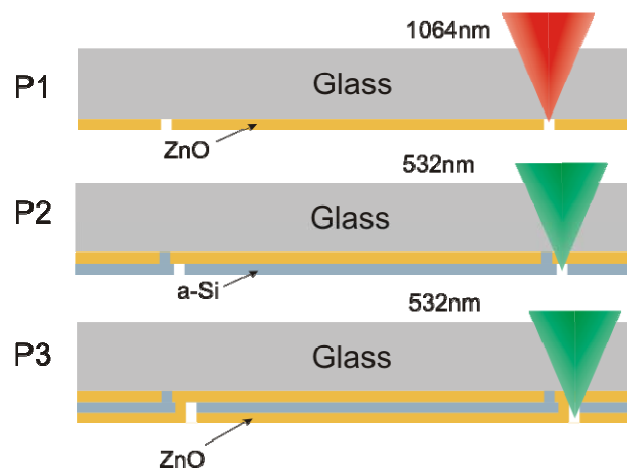


Fig. 1 Configurations of the experimental procedures for laser scribing of the thin films on the glass substrate. P1 - back-contact formation; P2 - back-contact exposure to strip a-Si layer; P3 - top-contact formation.

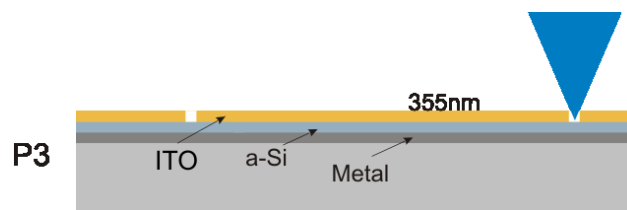


Fig. 2 Configuration of the experimental procedure for the laser scribing of the thin films on the polymer substrate.

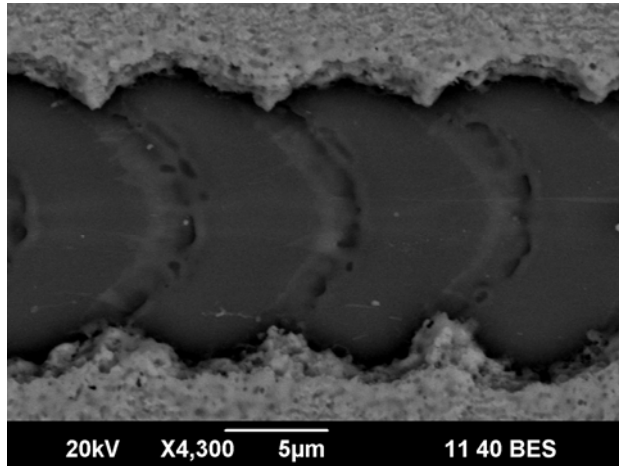


Fig. 3 Scribe in the ZnO:Al back-contact on glass, made by the back-side irradiation with the picosecond laser. Wavelength 1064 nm; average power: 0.8 W; scribe speed: 800 mm/s.

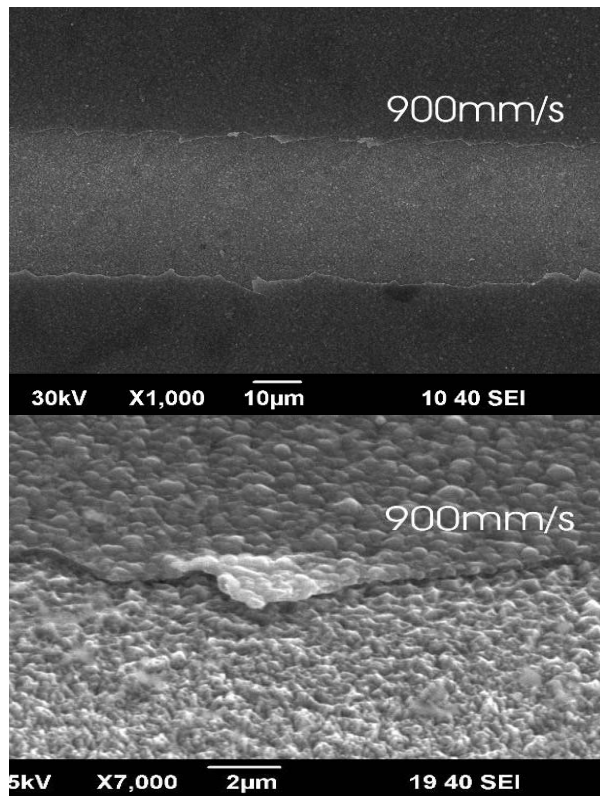


Fig. 4 Scribe in the silicon film in the glass/ZnO:Al/a-Si structure by the back-side irradiation with the 532 nm wavelength. Laser power: 0.4 W; scribe speed: 900 mm/s.

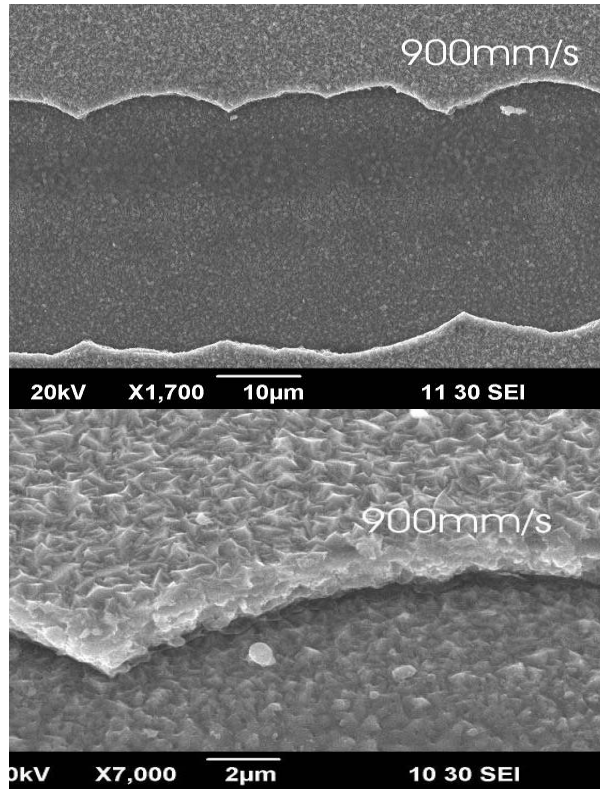


Fig. 5 Scribing absorber and top-contact films for cell isolation in the glass/ZnO:Al/a-Si/ZnO:Al structure by the back-side irradiation with the 532 nm wavelength. Laser power: 0.2 W; scribe speed: 900 mm/s.

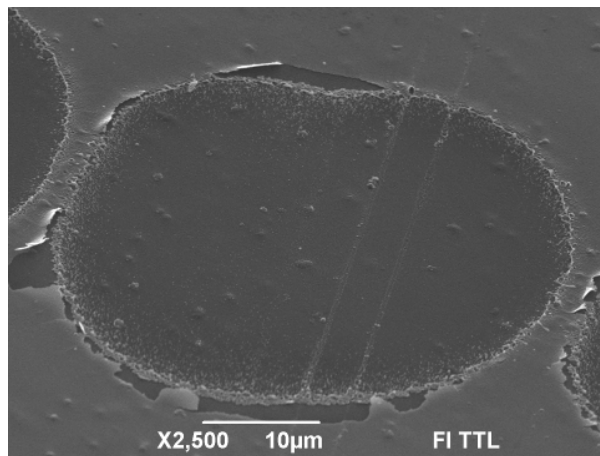


Fig. 6 The spot ablated by a single laser pulse in ITO layer of the Polyimide/Al/a-Si/ITO solar cell structure. Wavelength 266 nm; pulse energy 4 µJ.

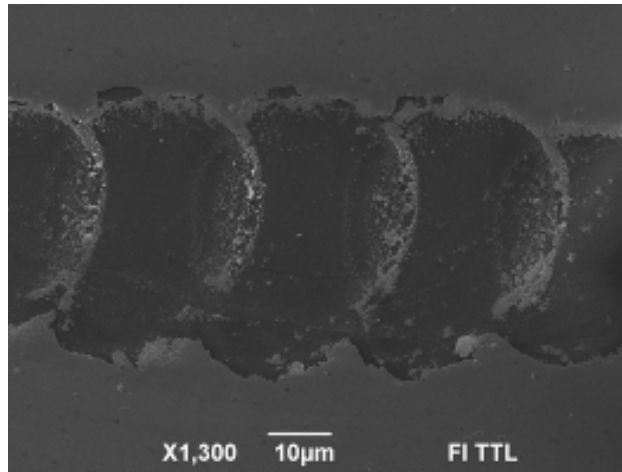


Fig. 7 Scribe in ITO layer with the wavelength 266 nm. Pulse energy 4 μ J; pulse repetition rate 5 kHz; scribing speed 120 mm/s.

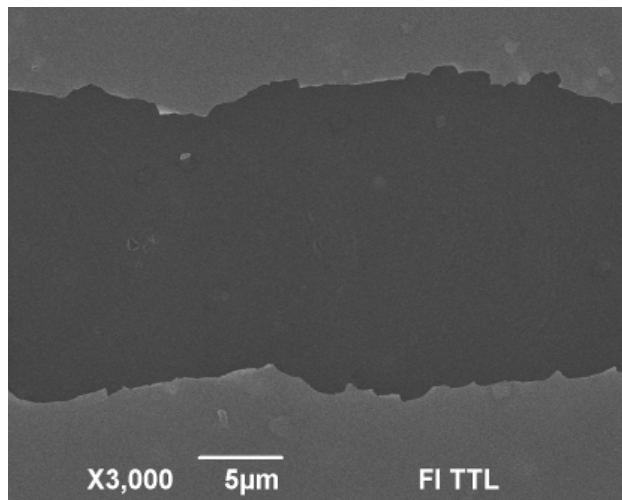


Fig. 8 Scribe in ITO layer with the wavelength 355 nm. Pulse energy 1.8 μ J; pulse repetition rate 50 kHz; scribing speed 650 mm/s.