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Laser-Surface-Treatment for Photovoltaic Applications

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Abstract

To increase the overall efficiency of photovoltaic systems, such as solar cells or modules, different laser surface treatments have been adopted. In this article laser processing is applied to reduce the reflectivity on silicon solar cells, to reduce structure sizes for patterning processes applied for thin film solar modules, and to improve the opto-electrical properties of front-contact cathodes for thin-film solar modules.

Keywords: Laser ablation; Process parallelization; Patterning; Thin films; TCO

1. Introduction

The lack of fossil energy and the overturning of earth biosphere forces humans to solve their energy generation- as well consumption-problems by applying "green" energy principles. Different approaches are today adopted, like generation of electrical energy using the solar energy, via photovoltaic or solar thermal energy, or using kinetic energy of wind as well as of water for off-shore wind farms and hydro-electric power plants. Additionally to the development of new concepts to generate emission-less electrical energy current technologies have to be improved, too.

One approach to increase the overall efficiency of photovoltaic systems, such as solar cells or modules, is by laser surface treatment. Conventionally silicon solar cells are today textured by etching techniques increasing the active area and the number of reflections on the surface for sun light absorption. Thin-films of solar modules are machined using laser radiation for electrical purpose and different layers are also treated changing physical properties. In this article new approaches will be presented using laser technology to reduce the reflectivity and the structure size, and to improve opto-electrical properties.

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2. Experimental

Lasers in the photovoltaic industries have to feature typical production conditions, like long-time operation with nearly unchanging radiation properties, and low-cost budget at rough environmental conditions. For wafer-based photovoltaic applications with lasers use scanning technologies in order to operate at large processing speed > 1 m/s on large areas up to m².

In this investigation an overview of the activities at the LZH in the area of laser processing for photovoltaic applications is given demonstrating the potential of laser technology to improve photovoltaics. A standard set-up for photovoltaic applications using different laser sources, beam-guiding via dielectric mirrors and beam expander, and finally the scanning system with the focusing optics will be applied. F-Theta objectives optimized for selected wavelengths are used as focusing optics enabling focused radiation with diameters of about 10-40 µm with nearly unchanged beam quality offering additionally nearly-orthogonal irradiation on the target as well as a planar image plane. The used scanning systems are coupled to the f-Theta objectives featuring a focal length up to 300 mm and resulting in an image plane of up to 300×300mm².

3. Results and Discussion

Applications using laser surface-treatment are manifold. In this publication a survey on following topics for photovoltaic applications will be given. Large-area silicon structuring reducing the reflectivity, precise electrical series connection of cells in a module by laser scribing reducing the structure size, and annealing of thin films improving opto-electrical properties of transparent conductive oxides (TCO).

3.1. Reflectivity decrease

The efficiency of multi-crystalline silicon (mc-Si) solar cells can be improved by reducing the amount of reflected solar radiation. Today common techniques are 1. isotexture etching for mc-Si, 2. applying antireflective coatings, and 3. anisotropic etching for mono-crystalline silicon solar cells for pyramid structures. A reduction in reflectivity by laser surface treatment of different materials, also silicon, with ultra-short laser radiation has been demonstrated, too [1].

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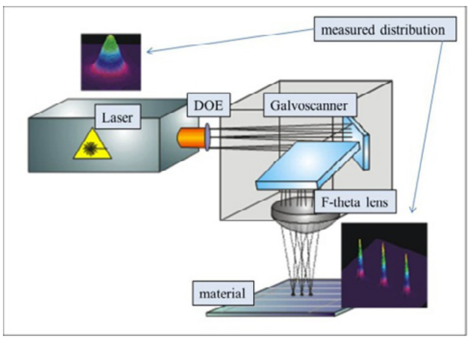

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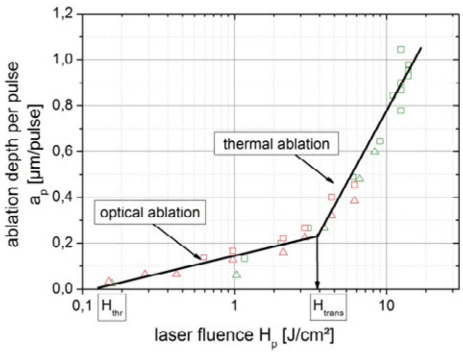
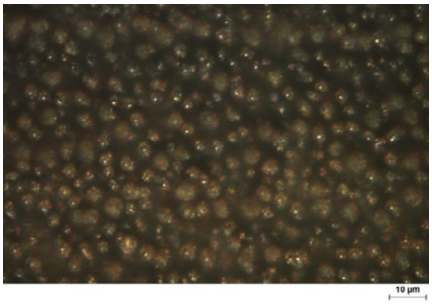
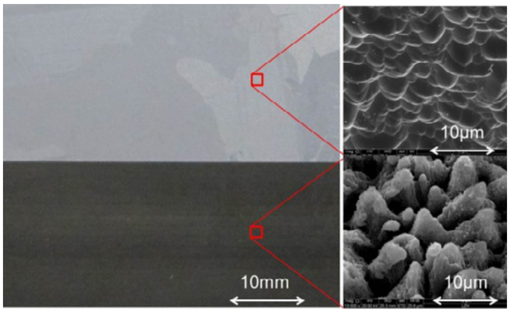


Fig. 1. (a) optical setup for parallel processing of 5" silicon wafers (b) ablation depth per pulse as a function of the laser fluence at picosecond laser pulse duration

Here an alternative approach being industrial applicable is demonstrated. Picosecond laser radiation (t_p = 7 ps, λ = 515 nm, $f_p \leq$ 400 kHz) is formed by DOE to multiple beams, guided through a galvano-scanner and focused onto the silicon surface to a beam diameters $\omega \approx$ 25 µm. Processing, here high-repetition rate ablation, is done by scanning on meandrian trajectories the focused radiation. Compared to the process described in [1-5], first, the process induced by picosecond laser radiation is much more stable due to a simplified processing approach without additive gases, and second using high-repetition rate laser radiation in the multi-100 kHz regime from an industrial laser, the productivity, expressed in m²/scan be driven into the productive range of 1 wafer per second at an appropriate mean laser power. Therefore processing is parallelized generating multiple laser spots using diffractive optical elements (Fig. 1a) [6].

Depending on the applied fluence two regimes for ablation are detected (Fig. 1b). In the optical regime at fluences below about 4 J/cm² a cone-like topology can be generated, whereas above 4 J/cm² ablation results in smooth structures being attributed to the thermal regime [7]. The surface is modified by ablation depending on the laser parameters in the optical regime of silicon generating cones with sizes of up to 10 µm (Fig. 2a) with dimensions in the range of a few µm. The reflectivity is reduced absolutely of about 11% over the spectral distribution of solar light in comparison to the standard isotexture surface on mc-Si solar cells (Fig. 2b).



(a)


(b)

Fig. 2. (a) Cone-like structures on Silicon, generated by picosecond laser radiation detected by light microscopy. (b) Partially laser structured silicon 5” wafer, top area unstructured, bottom area laser-structured; Inlet: surface topologies by SEM

3.2. Structure size reduction

Thin-film solar modules are today produced with different materials, being subdivided into two major material classes: the inorganic and the organic solar modules. In order to enhance the efficiency of thin-film solar modules the necessary electrical isolation between the different layers for monolithic series connection is achieved either by direct printing of deliberate structures, or by additional structuring of specific layers either mechanical or by laser radiation, the so called patterning P1, P2, and P3, see Fig. 3a [8, 9]. Patterning P2 und P3 of CIGS solar modules are today processed using a needle removing the layers mechanically. This approach results in structures with little reproducibility with partially damaged layers. Also a large dead area results by mechanical treatment (given by the sum of the areas of P1 –P3).

Using laser radiation for the P2 and P3 patterning enables to structure the CIGS with geometry widths as small as 50 µm without damaging the molybdenum (P2) and also removing CIGS and the TCO without damaging either the remaining layers (P3) [10,11].

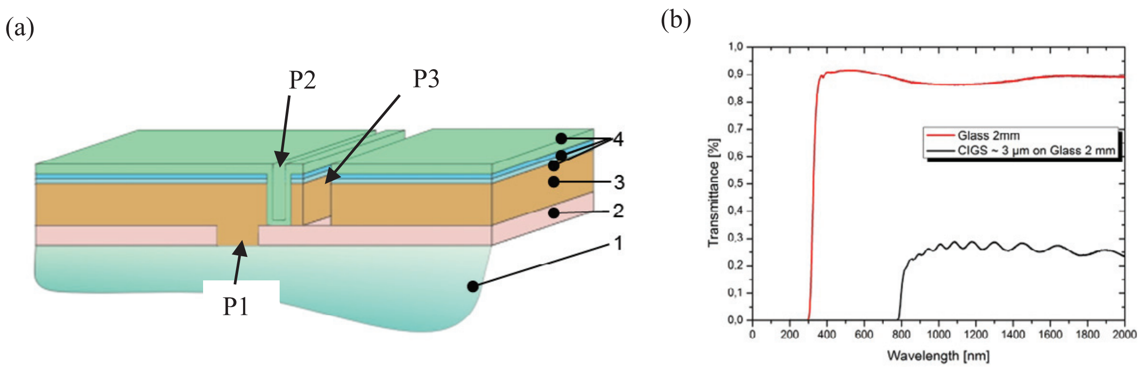


Fig. 3.(a) Schematic setup of CIGS Solar module with series connection. 1 Substrate, 2 Molybdenum, 3 CIGS, 4 TCO. Patterning P1, P2, and P3. (b) Transmittance of the glass substrate and the CIGS layer with glass substrate

Here results on laser patterning P2 and P2 for CIGS ($Cu(In,Ga)(S,Se)_2$) solar modules are presented, demonstrating the increase in active area by reducing the connection gap to about 75 µm. The choice for the laser radiation wavelength can be deduced from the transmission spectra for the substrate and the CIGS: between 300 and 800 a large processing window is given (Fig. 3b). Patterning is achieved using sub-nanosecond laser radiation at a wavelength λ = 532 nm, a pulse duration t_p = 500 ps, and a repetition rate f_p = 50 kHz; the layer thicknesses and the required geometry dimensions are given in table 1.

Table 1. Materials and dimensions for laser structuring

structuring step	Layer	material	Function	thickness	required line width [µm]
	1	Glass	Substrate	2 [mm]	
P1	2	Molybdenum	Back contact	~ 0,5 [µm]	< 75
P2	3	CIGS	Active layer	2 [µm]	< 75
P3	4	ZnO:Al; ZnO; CdS	TCO	0,5 - 1 [µm]	< 75

P2 laser structuring

A selective ablation of the CIGS layer has been demonstrated without damaging the molybdenum layer (Fig. 4). The lines have been processed with several loops at low pulse energy (E_p = 2µJ, v = 100/mm/s). Also visible in the inlet is re-solidified CIGS.

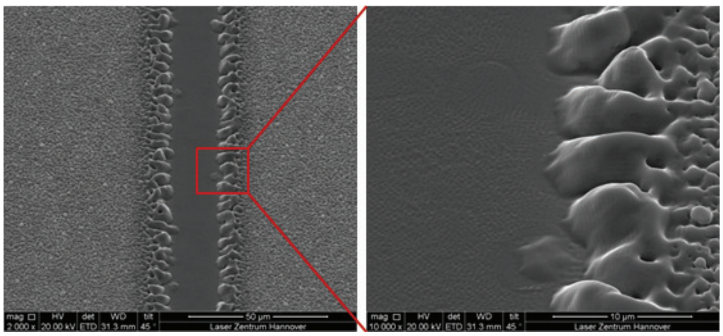


Fig. 4. P2 structured line in the CIGS layer (SEM, λ = 532 nm, t_p = 500 ps, E_p = 2 µJ; v = 100 mm/s; 9 loops)

Single loop ablation of the CIGS layer results in incompletely removed and re-solidified material (Fig. 5). The conductivity of the resulting CIGS has been increased enabling after deposition of the TCO a contact between TCO and molybdenum.

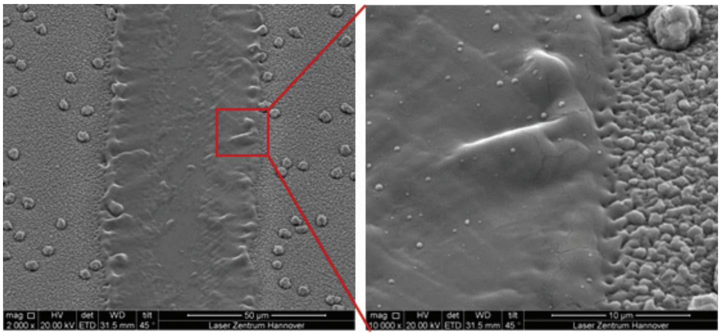


Fig. 5. P2 structured line in the CIGS layer (SEM, λ = 532 nm, t_p = 500 ps, E_p = 24 µJ; v = 100 mm/s)

P3 laser structuring

Patterning P3 is achieved with two different strategies, firstly by removing only the TCO layer, and secondly by removing the TCO- and the CIGS-layers. In the first case good visible structuring can be detected (Fig. 6). Complete modules have been set-up with P3-patterning (TCO-only) resulting in a fill factor FF comparable to mechanical patterning P3 of FF = 68-70 %.

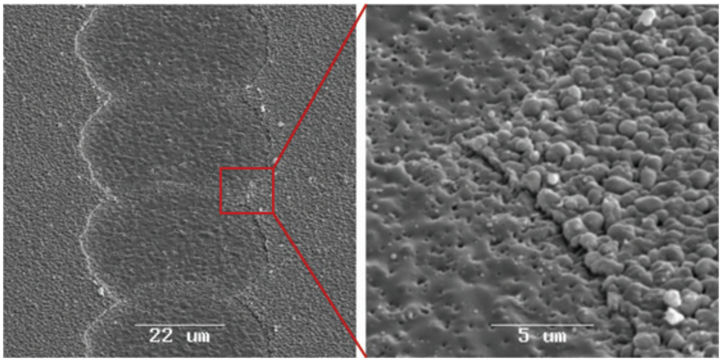


Fig. 6. P3 structured line in TCO layer (SEM, λ = 532 nm, t_p = 500 ps, E_p = 4 µJ; v = 1,75 m/s)

The second approach for P3 with laser radiation, structuring the TCO and CIGS layers, results in a visible molten CIGS layer at the edge at both sides of the lines (Fig. 7). The processing speed is actually too small for being relevant for industrial production purposes. This processing may also create electric shortcuts in between TCO and Mo layers. More investigations are needed.

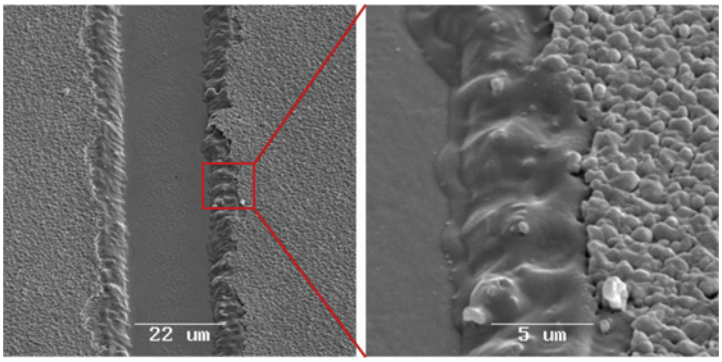


Fig. 7. P3 structured line in TCO and CIGS layers (SEM, λ = 532 nm, t_p = 500 ps, E_p = 2 µJ; v = 10 mm/s)

3.3 Improvement of electrical conductivity & optical transparency

New TCO designs for front-contact cathodes of a-Si/µ-Si thin-film solar modules (Fig. 8a) suffer from the limited optical and electrical properties. One candidate is aluminum doped zinc oxide being more and more applied as a cost-effective alternative to ITO in thin-film electronics. Laser surface annealing of TCO's [12 - 14] enables to change fundamental physical parameters, like the electron mobility and carrier density of e.g. a ZnO:Al-thin film.

Laser surface annealing has been achieved focusing cw-laser radiation (λ=1070 nm, P_{av} =50 W) with a spot diameter of 1.6 mm on the substrate, and moving the focused beam via scanning technology at processing velocities up to 60 mm/s. Areas are processed by definite scanning strategy. The TCO has been annealed at ambient atmosphere and alternatively covered during laser processing by silicone oil and a glass plate. This procedure, called capping, protects the TCO from any atmosphere interaction (Fig. 8b). The electrical sheet resistivity is measured by the four point method and the transmittance is detected by UV Vis spectroscopy.

a) b)

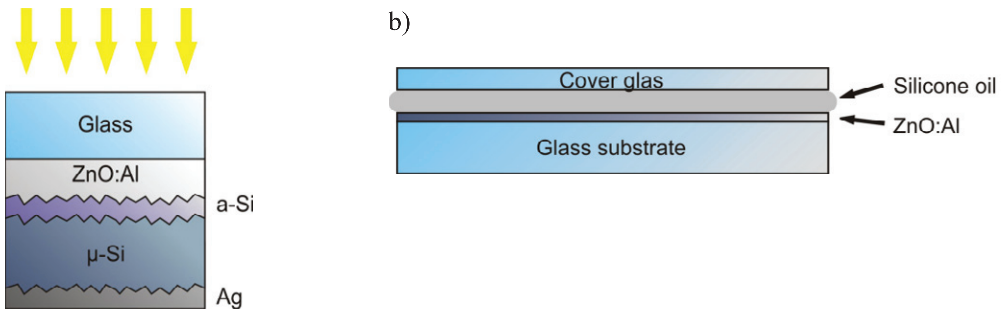
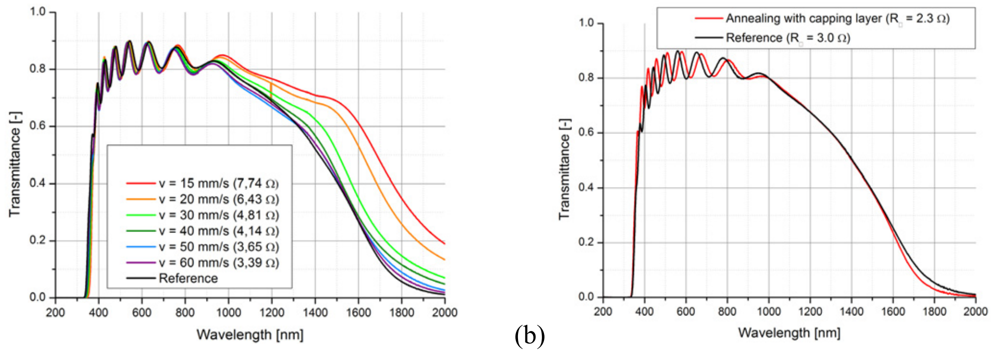


Fig. 8. (a) schematic set-up of an a-Si/µ-Si Solar cell; (b) principle set-up for laser-annealing with capping layer

The transmittance is increased by laser annealing at ambient atmosphere with increasing resistivity with decreasing processing velocity. The resistivity could not be improved from the reference value of 3.0Ω. Mainly the carrier concentration has been decreased by laser annealing (Fig. 9 a). The already good crystal properties of the reference ZnO:Al thin film, which was deposited at high substrate temperatures, can be tuned and further improved by laser treatment. Processing with capping layer, here the silicon oil, the transmittance remains nearly unchanged, but the resistivity has been decreased by laser annealing from 3.0 Ω to 2.3 Ω. This is attributed to an increase of electron mobility (Fig. 9 b).

This approach features an electrical improvement by annealing being comparable to thermal annealing [15, 16], but being flexible in deliberate area processing.



(a) (b)

Fig. 9. Transmittance of CW laser radiation treated ZnO-thin films: (a) at ambient atmosphere for different processing velocities and resistivities (b) with "silicon oil" capping

4. Conclusion

Laser technology is applied at the Laser Zentrum Hannover e.V. in different processes for photovoltaic production. Using ultrafast laser radiation the surface topology of silicon is modified reducing the overall reflectivity by 11%. CIGS Solar module have been laser processed with sub-nanosecond laser radiation in P2 and P3 with success resulting in solar modules with a fill factor comparable to mechanical processing of about 70%. New TCO layers substituting the cost-intensive ITO have been investigated treating them with CW laser radiation changing the optical and the electrical properties. The resistivity of ZnO:Al layers have been reduced by 22% compared to a reference ZnO:Al layer of FZ Jülich.

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