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Selective ablation with UV lasers of a-Si:H thin film solar cells in direct scribing configuration

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ABSTRACT

Monolithical series connection of silicon thin-film solar cells modules performed by laser scribing plays a very important role in the entire production of these devices. In the current laser process interconnection the two last steps are developed for a configuration of modules where the glass is essential as transparent substrate. In addition, the change of wavelength in the employed laser sources is sometimes enforced due to the nature of the different materials of the multilayer structure which make up the device. The aim of this work is to characterize the laser patterning involved in the monolithic interconnection process in a different configurations of processing than the usually performed with visible laser sources. To carry out this study, we use nanosecond and picosecond laser sources working at 355 nm of wavelength in order to achieve the selective ablation of the material from the film side. To assess this selective removal of material has been used EDX (energy dispersive using X-ray) analysis, electrical measurements and confocal profiles. In order to evaluate the damage in the silicon layer, Raman spectroscopy has been used for the last laser process step. Raman spectra gives information about the heat affected zone in the amorphous silicon structure through the crystalline fraction calculation. The use of ultrafast sources, such as picoseconds lasers, coupled with UV wavelength gives the possibility to consider materials and substrates different than currently used, making the process more efficient and easy to implement in production lines. This approach with UV laser sources working from the film side offers no restriction in the choice of materials which make up the devices and the possibility to opt for opaque substrates.

1. Introduction

Thin film a-Si:H solar cell technology has great potential to produce low cost modules. The cost reduction is determined by the scaling rate of the production capability, by means of the improvement of each step throughout the fabrication process. Regarding the monolithic interconnection process of the cells to form a module, laser-controlled ablation of individual layers is essential for the isolation and interconnection of the cells. Material ablation with minimum debris and small heat-affected zone with low processing cost, is one of the main challenges for the successful implementation of laser micromachining as a competitive technology in this field [2–5]. The three steps (P1, P2 and P3) for monolithic interconnection of solar cells within modules are nowadays defined by DPSS (diode pump solid state) laser sources working at IR ($\lambda = 1064$ nm) and VIS ($\lambda = 532$ nm) wavelengths for thin film module fabrication. These steps consist in removing the front contact layer usually a TCO (transparent conductive oxide) (P1), a-Si structure ablation (P2) and finally back contact removal (P3). It is important to highlight the back scribing configuration to carry out P2 and P3, where the laser attacks the material through the glass substrate, restricting the latter to be transparent to the laser radiation.

The laser process must be improved in order to minimize shunting problems which are closely related to the inherent thermal affection of laser irradiation at these wavelengths and nanosecond pulse duration. This work moves towards the possibility of performing the three laser steps with UV laser sources working at two different temporal ranges of pulse width (nanosecond and picosecond) in order to eliminate the thermal affectation and performing the process from the film side, which makes the process suitable for the two different configurations (superstrate and substrate) and other kinds of technologies (CIS/CIGS, CdTe) including opaque substrates [5]. Especially important is the picoseconds laser scribing evaluation, due to the lack of literature in this subject and the fact that these laser sources have become nowadays good industrial tools with high repetition rates, which allows the high processing speed required for industrial application.

This work presents the characterization of the three laser steps (P1, P2 and P3), focusing on the special difficulties of selective ablation from the film side of all the layers which make up these devices, in particular P2 and P3 steps, where the affectation of the silicon structure layer compromises the proper function of the same. In

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P2 a good control of energy is necessary to avoid damage on the layer underneath and the removed silicon may be redeposited on the edge of the grooves, leading to the formation of ridges that may affect the layer deposited on top. In P3, more important in terms of the behaviour of the final device, the back contact scribing may cause shunts between the layers, when the laser interacts with them due to the heat affectation. The change in the a-Si:H structure could lead to impoverishment of the electrical properties of the final module.

Laser ablation for the three steps will be discussed, focusing our study on the ablation threshold measurements and process-quality assessment by means of EDX, SEM images and Raman spectra in order to evaluate the heat affected zone in the amorphous silicon structure through the crystalline fraction calculation.

The success of this approach determines the suitability of the laser process on solar modules with opaque substrates. This leads to the possibility of using cheaper and more versatile materials. In previous works, we have demonstrated some of the advantages of using UV wavelengths for minimizing the thermal affectation, hence reducing the probability of shunting problems in the device [6,7].

2. Experimental procedure

2.1. Laser systems

For the direct-scribing experiments two different laser sources, with pulse durations of nanosecond and picoseconds, have been used. The former is a DPSS laser operating at 355 nm wavelength (HIPPO SPECTRA PHYSICS), with pulse duration of 15 ns, and the latter is a picosecond DPSS emitting at 355 nm wavelength and pulsewidth of 8 ps (LUMERA SUPER RAPID). The typical pulse energy distribution of both sources is Gaussian. The power of both lasers is adjusted by an external attenuator with the maximum power set through the excitation current of the respective pump sources. The beams have been delivered through a scanner head in order to achieve high speed processing. VIS wavelengths of DPSS lasers have not been used, given the fact that this work does not consider back-scribing processes and is focussed only in direct writing from the film side.

2.2. Sample preparation

Two types of samples have been processed. For studying the ablation thresholds, single-layers of material have been deposited on glass. For the laser scribing study, non-finished solar cells were deposited for the different steps in the superstrate configuration (AZO/a-Si:H/ASAHI-U (TCO)/glass). The amorphous-silicon layers have been deposited by PECVD (plasma-enhanced chemical-vapor deposition) in an MVSystems capacitive-coupled reactor yielding highly uniform films with thicknesses in the range 500–600 nm. For TCO single layer ablation we used commercial Asahi-U (SnO_2:F) and in-house-prepared ITO (SnO_2:In_2O_3) and AZO (ZnO:Al) samples were prepared in a RF sputtering plant using a MVSystems device.

2.3. Measurement and characterization techniques

Ablation-profile measurements and morphological characterization have been made using a confocal laser scanning microscope (CLSM) Leica ICM 1000. Additional SEM (scanning electron microscopy) (Hitachi S-3500N) and EDX (energy dispersive X-ray (spectroscopy)) (Röntec QX2) profile analysis images are included for a better comprehension of the morphology and selective-ablation process of the scribes. Combining these three techniques, the ablation or elimination of material from the layer is demonstrated. The EDX profiles provided by line scans analysis show the composition along the transversal section of the laser scribe. EDX line scans profiles are generated by the counts of electrons with different energies corresponding to different materials obtained from the scan of the electron beam from the SEM over a selected line in the sample. By the representation of these counts the profiles of the materials involved in the sample are obtained. This information is correlated with the amount of material present in the sample. Confocal topographical profiles show the height profile of the laser scribe, confirming the material removal by the laser scribing process. For ablation threshold calculations, a confocal topographical image has been used in order to measure the crater diameters (see Refs. [8,9] for further details). In order to assess the heat affected zone in the second laser step, Raman spectra were run with a Renishaw Micro-Raman System. The deconvolution of Raman spectra that yields quantitative information regarding crystallinity can, thus, be correlated to the material damage by means of the heat affected zone generated during the laser scribing. In that sense, due to the high temperatures reached by the a-Si:H layer during the interconnection steps (P2 and P3), a heat affected zone, mostly associated with morphological changes induced in the material, could be generated around the ablated portion. In order to get this additional quantitative information, Raman crystallinity fraction, ϕ_c, can be evaluated from the deconvoluted Raman spectra as the ratio of the area under the peaks related to crystalline parts over the total area of the silicon related peaks.

Table 1
Ablation threshold for thin-film materials (J/cm^2).

Materials	ϕ_{th} (J/cm^2)	
	355 nm 15 ns	355 nm 8 ps
Asahi-U® (SnO_2:F)	1.42	0.47
ITO (SnO_2:In_2O_3)	0.21	0.36
ZnO:Al	0.18	0.32
a-Si:H	0.12	0.22
Al	0.62	0.14

3. Ablation thresholds calculation

In laser selective ablation processes it is important to determine the appropriate energy density values that lead to effective material removal with minimum side effects. Ablation thresholds are very helpful for establishing limiting values for potential parametric windows. Ablation thresholds are obtained by measuring the increasing value of the ablation crater diameter as a function of the beam fluencies, a variable directly related to the ablation threshold [8,9].

A summary of the threshold energy densities for single pulse ablation is presented in Table 1. The ablation thresholds correspond to single pulse radiation for the two different lasers and the materials which make up the solar cell. At 355 nm and 15 ns pulses the ablation thresholds tendency is similar to the ones obtained at 355 nm and 8 ps pulses, except for the case of Asahi-U and the aluminium. This suggests that the effect of the pulsewidth is not so relevant for the temporal range in which the study is centred. In the case of aluminium and the high conductive TCO Asahi-U, the dependency with the pulsewidth is higher, given the absorption mechanisms involved in metals [10].

4. Laser scribing processes

The experiments have been carried out in unfinished solar cells, where each laser step has been assessed with the appropriate deposition of layers. For the first step (P1), a unique layer of transparent