PROGRESS ON DECREASING THE OPTICAL SHADOWING OF GRID LINES BY VOLUME OPTICS IN EVA MADE BY FS-LASER STRUCTURING

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ABSTRACT: An innovative approach for decreasing the optical shadowing of grid lines of solar cells is to form volume optics in the encapsulating Ethylene-vinyl acetate (EVA) layer by femtosecond (fs-)laser structuring. Recent results on this ongoing research topic are presented. In particular, the chemical changes of the EVA material upon interaction with a fs-laser pulse were investigated by applying confocal Raman microscopy. Moreover, a careful investigation on the optical properties of the EVA volume optics was performed: (i) experimentally on the basis of goniometric measurements of diffractive micro-structures, as well as (ii) theoretically by applying optical modeling and optimization procedures. This resulted in a better understanding of the effectiveness of the optical volume elements in decreasing the shadowing of metal grid lines on the active cell surfaces. Moreover first results of mini-modules with incorporated volume optics are presented. Results of optical simulation and Laser Beam Induced Current (LBIC) experiments show that the losses due to grid fingers can be reduced by about 50% by creating micro-optics in the volume of the EVA by fs-laser structuring.

Keywords: Optical Losses; Module; Laser Processing

1 INTRODUCTION

About 7 to 9% of the front surface of c-Si solar cells with screen printed electrodes is covered with metal. Light impinging onto these grid fingers is reflected and absorbed. When the solar cells are encapsulated a part of the reflected light can be “recycled” by total internal reflection at the glass-air surface of the module. The amount of the recycled light can be increased by increasing the scattering of the front side metallization.

Optical losses at grid fingers can be reduced by applying different approaches [1],[2],[3],[4]. One rather new approach was presented at the 28th EU-PVSEC and is relying on the formation of micro-optical elements within the volume of EVA by fs-laser structuring [5] (see also [6]). These micro-optical elements are found to be able to deflect light away from the grid fingers and consequently to decrease their optical shadowing.

In this paper we present progress on this new method. The material properties of the micro-optical elements were investigated by confocal Raman-microscopy. These results allow estimation about the local changes in the chemical and optical characteristics of the EVA due to the laser process treatment. Based on the estimations of the optical properties a coupled wave-optical and ray-tracing simulation was conducted in order to create a better understanding on the light deflecting properties of the micro-optics.

2 EXPERIMENTAL

fs-laser set-up:

For the laser scribing of volume optics in the bulk of the polymeric encapsulation material a commercial 1-kHz fs Ti:Sapphire laser amplifier (Spitfire, Spectra Physics) was used – operation wavelength = 800 nm. The laser beam has to pass through the glass plate before focussing into the encapsulation. Consequently a microscopic objective (LUCPLFLN 60X/numerical aperture of 0.7, Olympus) specially designed for focussing through a glass plane of at least 1 mm was applied. This objective enables a high resolution and minimal aberration in the laser focus for the desired application. Samples are mounted on a XYZ positioning stage (AEROTECH ALS-130), in order to enable a high precision laser scribing process.

Confocal Raman-microscopy set-up:

A confocal Raman-microscope from Horiba Jobin Yvon Labram 800 HR with an Olympus LUCPlanFL 40/0.60 objective with cover glass correction was used for the material characterization.

Test sample set-up:

Test samples (mini-modules) were manufactured in order to investigate the potential of micro-optical structures to decrease the optical shadowing of metal grid fingers. In particular a sandwich structure comprising of two glass sheets and a 2x2 cm² solar cell laminated within a sheets of commercial EVA were made. The width of the grid fingers is 100 µm and the spacing of the fingers is 1 mm. Within the volume of the EVA, above the grid fingers, volume micro-optics was created. The test sample set-up is sketched in Figure 1.

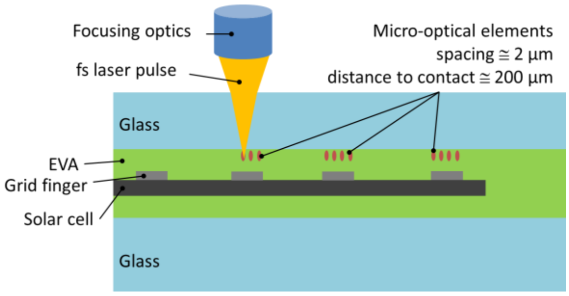

Figure 1: The test sample set-up is sketched.

In addition simple test samples comprising of two sheets of glass (1 mm) laminated with one sheet of commercial EVA were manufactured (for material tests).

Electro-Optical characterization:

The angular resolved transmission was measured with a Gon360 goniometer (Instrument Systems). The lab-scale modules are characterised by applying the Laser Beam Induced Current (LBIC) method at Fraunhofer ISE using a LOANA solar cell analysis system from pv-tools.

2 OPTICAL MODELLING

Optical simulations of devices with dimensions larger than mm usually are done by classical ray-tracing methods. Since the geometric dimensions of the volume optical elements created by fs-laser processes typically are in the range of 10 µm and below, wave optical effects cannot be neglected and classical ray-tracing methods are no longer sufficient for a proper optical modelling. Thus, the optical simulation of volume optics was conducted with the Finite Difference Time Domain (FDTD) method which is solving the Maxwell Equations with a numerical algorithm [7]. An exclusive FDTD simulation of test devices such as these described in the experimental section (dimensions in the range of mm and cm) with a sub-µm resolution is usually not possible due to limitations in processing power and memory space. Consequently combined simulation of wave-optical elements and ray-tracing is not trivial. For the modelling of the volume optics within the EVA encapsulation a newly developed interface for FDTD Solutions (Lumerical) and the ray-tracer ASAP (Breault Research Organisation) was applied. Details about this interface can be found in another publication [8]. For investigating the deflection performance the amount of light deflected around a grid finger and impinged onto a detector located beneath was simulated (see Figure 2)

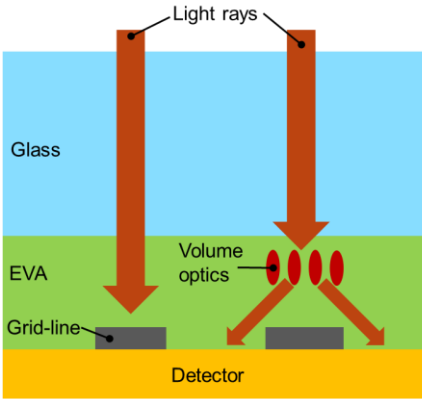

Figure 2: The simulation set-up for investigating the deflection performance of different micro-optics is sketched. In particular the increase in light detected on a surface beneath a grid-finger was used as figure of merit to evaluate the deflection performance.

3 RESULTS

A test sample comprising of volume optical elements created with different laser process parameters (average laser power and scanning speed) was manufactured (see Figure 3).

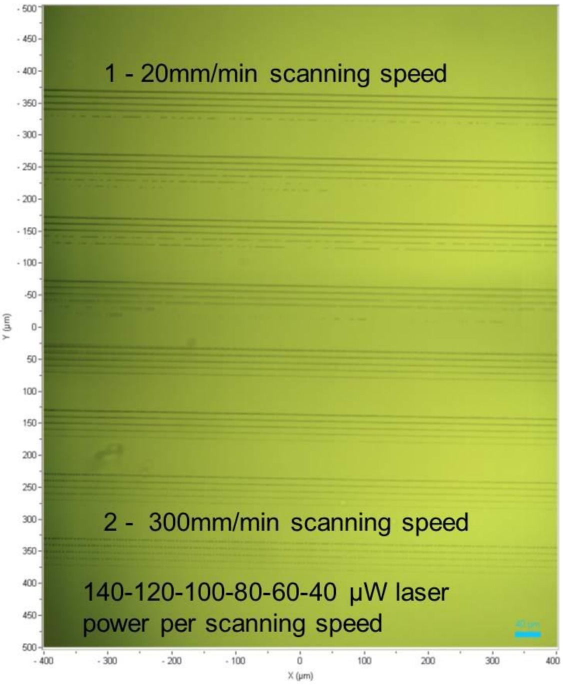

Figure 3: A light microscopic image of a test sample is shown comprising of a test series of different volume micro-optics made with varying laser process parameters. Positions 1 and 2 indicate the minimum and the maximum scanning speed.

In Figure 4 light microscopic pictures and the corresponding Raman images of two sample areas are shown. Different colours indicate variations in the Raman spectra.

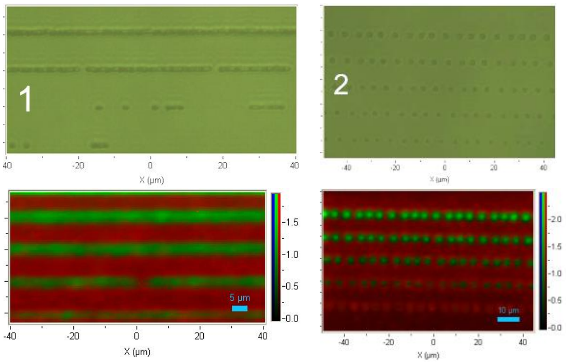

Figure 4: Microscope images and laterally resolved Raman spectra data are shown for volume optics created at different scanning speeds.

At the positions of the micro-optical elements a substantial increase in intensity of the Raman signals is found (relative to un-processed EVA). This corresponds to an increased fluorescence which indicates partial damage (degradation) of the polymeric EVA material. Moreover, in some voxels intense bands at 1350 und 1580 cm^{-1} were observed which are typical for a carbonization of the material, e.g. amorphous carbon shows similar bands. Since amorphous carbon has a refractive index (n) and an extinction (k) coefficient which are higher than those of EVA, one can expect that the optical constants of the EVA material are locally increased by the fs-laser process.

A field of homogeneously distributed micro-optical elements was created in EVA laminated between to glass sheets. The spacing between the individual elements was about 3 µm; the total area of the volume-optics field is about 1.5x1.5 cm². Goniometric transmission measurement results through this area of micro-optical elements are shown in Figure 5.

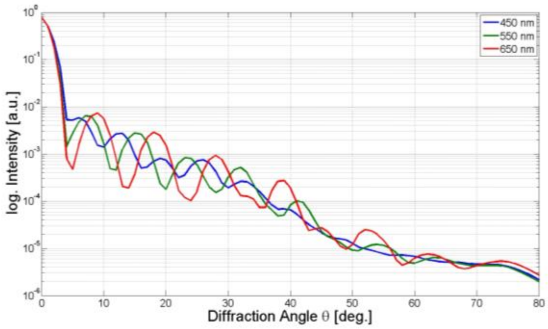

Figure 5: Results on goniometric transmission measurements through an area of micro-optical elements are shown for three different wavelengths.

A light beam transmitting though an area of volume optical elements is deflected in different angles. In particular different orders of diffraction can be identified which depend on the wavelength and on the spacing of the individual elements.

Using coupled wave-optical and ray-tracing simulations the influence of different micro-optics on the deflection performance was investigated. In Figure 6 simulation results on a micro-optics with a feature size of 2 µm is shown. Based on the results of the Raman measurements the refractive index (n) was estimated to correspond to 2 which is in between that of EVA (1.5) and that of amorphous carbon (2.4). The simulation is conducted for two different extinction coefficients (k).

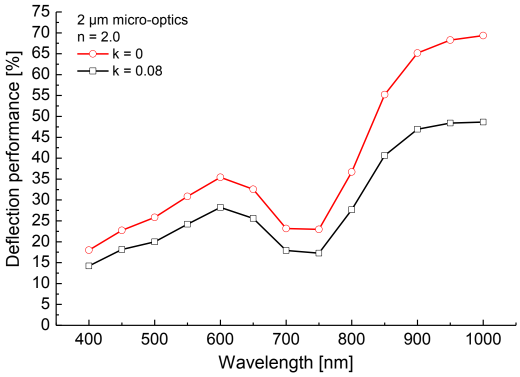

Figure 6: Optical simulation results on the deflection performance of a micro-optics with a feature size of 2 µm is shown. The calculations are conducted for two different extinction coefficients.

Obviously the simulated deflection performance is depending on the wavelength. The reason for this is that the “lattice constant” of the volume optics is about 2 µm which is relative large compared to the wavelengths plotted in Figure 6. For short wavelengths the diffraction efficiency is lower than for longer ones. The dip in deflection performance at around 700 to 800 nm is a result of interference effects at the voxels and more light is reflected in the 0 order. From the optical simulations shown above one could expect an optical deflection efficiency of up to 50%. A comparison of the simulation results for two different extinction coefficients shows, that absorption substantially limits the optical performance. In particular the parasitic losses due to absorption within the voxels range from 5 to 20% (depending on the wavelength).

An LBIC measurement of lab-scale modules (test samples) shows, that the photocurrent (which is directly related to the EQE) at grid fingers is reduced and the reflection is increased (relative to values of the active cell surface). However, grid fingers which have micro-optics above show significantly less decrease in EQE and an increase in reflection (see Figure 7)

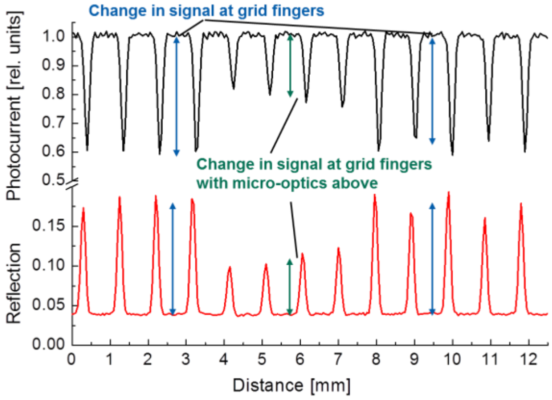

Figure 7: A LBIC line scan (780 nm) of a test sample is shown. The photocurrent is normalised to this measured at the active solar cell.

A comparison of the change in signal (EQE and reflection) for grid fingers with and without volume micro-optics shows that the volume optics decreases the loss in EQE by about 50% and the increase in reflection by about 60%.

4 CONCLUSIONS

The results of the confocal Raman microscopy measurements show that the fs-laser pulses locally damage and/or carbonise EVA. The light deflection of the micro-optics can be related to diffraction effects. Results of optical simulation and LBIC experiments show that the losses due to grid fingers can be reduced by about 50% when creating micro-optics in the volume of the overlying EVA by fs-laser structuring.

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