LASER SCRIBING OF p-i-n/p-i-n “MICROMORPH” (a-Si:H/μc-Si:H) TANDEM CELLS

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ABSTRACT: In view of large-area industrial manufacturing, the feasibility of the monolithic electrical series connection becomes a key issue for the micromorph tandem thin-film solar cells. The application of the well-established laser scribing technique for thicker micromorph (a-Si:H/μc-Si:H) tandem solar cells is indispensable. In first experiments described here a micromorph module (A= 23.6 cm^2) of 6 segments has been fabricated with an initial aperture efficiency of 9.3 % (V_{oc} = 8.025 V, FF = 70 %, I = 39 mA).
Keyword: laser processing –1: thin-film –2: tandem - 3

1. INTRODUCTION

The micromorph (a-Si:H/μc-Si:H) tandem concept is at present to be considered as one of the most promising thin-film solar cell. This cell concept represents a “true” tandem structure (with spectral sharing) with a ~0.3 μm thick amorphous silicon (a-Si:H) top cell and a 1-3 μm thick microcrystalline (μc-Si:H) bottom cell. Sofar, stabilised cell efficiencies between 11 and 12 % have been obtained on laboratory scale of around 1 cm^2 [1 - 5].

An important question for every thin-film solar cell concept is the application of the integrated series connection technique [6], in order to fabricate entire large-area (1 m^2) modules. Compared to conventional crystalline wafer-based modules, the application of this technique allows a reduction of the costs for thin-film solar cell module manufacturing. In case of amorphous silicon based solar cells, the laser-scribing method has already been well-established in the fabrication of ~m^2-size modules. Therefore, it is of particular interest to know if patterning of the much thicker micromorph pin/pin tandems is applicable, by the standard laser scribing technique, without damaging the cell. In this work, we present first results on laser patterning of ~3μm thick micromorph tandem cells.

2. EXPERIMENTAL

Micromorph p-i-n/p-i-n cells have been deposited by the Very High Frequency Glow-Discharge (VHF-GD) technique [1-3, 7] on glass/TCO substrates. The electrode area of these VHF reactors and, thus, the available deposited cell area is 8x8 cm^2.

For the patterning of the test cells, a Nd:YAG laser with a wavelength of 532 nm (TEM_{00}-mode) was available operating at a pulse frequency of 20 Hz. This laser was originally acquired as a tool for accelerated light degradation of amorphous silicon; its pulse frequency is, indeed, somewhat low compared to industrial lasers used for a-Si:H module manufacturing. Small test cells of 0.25 cm^2 area have first been prepared. Hereby, we investigated both the laser scribing both from the film-side as well as from the transparent glass substrate side.

The first step in the fabrication of a mini-module, consisting of several segments, is to electrically isolate the different segments of the front TCO. This front contact scribe is realised here by an infrared laser of 1064 nm wavelength (Nd:YAG, 100-10 kHz) and illustrated as Pattern #1 in Fig. 1. To form the series connection, the Patterning #2 and #3 were performed with the 532 nm laser.

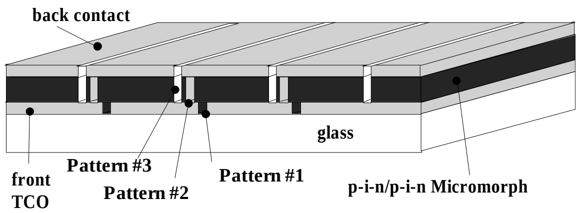

Figure 1: Different steps of patterning for the monolithic series connection in the micromorph thin-film solar cells modules.

The laser light optics was adjusted to obtain scribe line width in the range of 30 -50 μm, for both the 1064 nm and 532 nm wavelengths. For the scribing, an X-Y table controlled by a computer was used. With this table set-up, we have furthermore the possibility to perform Light Beam Induced Current (LBIC) measurements by scanning the areas of the patterned test cells. Hereby, a laser diode with a wavelength of 670 nm was used. This LBIC characterization gives information about the quality of the cell borders. The induced current is mapped in a 3-dimensional image. Apart from monitoring the properties of the cell borders, the LBIC images allow, furthermore, to identify inhomogeneities, as originating e.g. from pinholes, within the cell area.

The test cells and the modules were characterised and compared by AM1.5 I-V measurement (WACOM solar simulator WXS-140S-10) and with spectral response (SR) measurements.

In order to obtain mechanical details of the scribe-trench Scanning Electron Microscopy (SEM) has been performed on the different samples.

3. RESULTS AND DISCUSSION

3.1 Film-side patterning

Although highest laser energies (0.5 – 1.5 mJ) were applied for the patterning (λ = 532 nm) from the layer-side it was not possible to remove completely the whole thickness of the micromorph cell by one single shot. Therefore, several repeated scribes (7–9 x) were performed to obtain an isolated test cell.

The I-V characteristics of such film-side scribed cells result in rather poor fill factors (FF < 50%) and open circuit voltage (V_{oc}) losses of approximately 300 mV. The close-up view of such scribed trenches is shown in Fig. 2 by a SEM micrograph. One observes in these scribes not a clean silicon-free separation, but still a lot of melted or redeposited cell material. The effect of such melted borders is evidenced by the LBIC measurement in Fig. 3. We observe that the induced current is much higher at the border zone than in the centre of the cell area. As the spectral response of the amorphous top cell at the LBIC wavelength of 670 nm is around a factor 4 lower compared to the microcrystalline bottom cell (see e.g. SR-measurements in [3]) we explain this enhanced LBIC

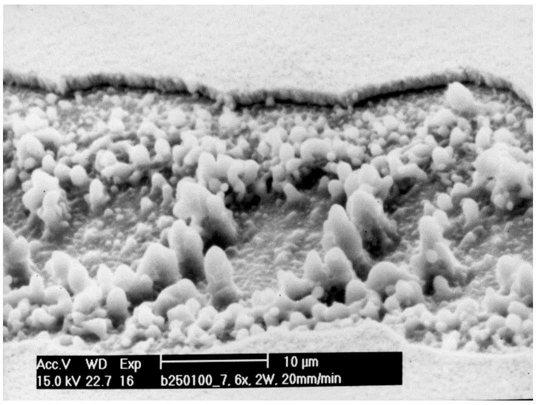

Figure 2: Typical film-side scribe (λ=532nm) of a micromorph cell by SEM.

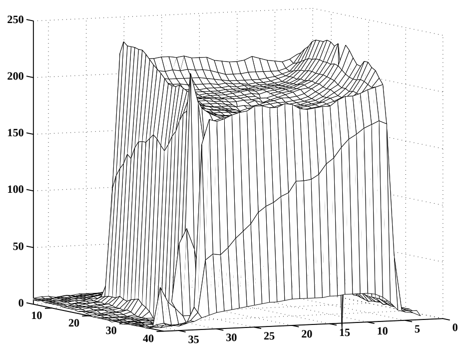

Figure 3: LBIC image (λ = 670 nm) of a micromorph cell patterned from the film-side

signal at the border zone by a shunting of the amorphous cell. The appearance of a high LBIC signal indicates that the µc-Si:H bottom cell (into which the laser scribe light λ = 532 nm enters first) is still working. Obviously, the µc-Si:H cell suffers less from the laser pulse than the amorphous top cell. A further indication of damage to the a-Si:H top cell is the fact that if the scribing is not deep enough to reach the amorphous cell (with e.g. only 6x repeated scribes) a better performance of the micromorph cell (FF = 61 %, V_{oc}= 1.32 V) can be observed. Although scribe tests with different pulse powers and different table speeds (spot overlapping) have been carried out, not even a single good solar cell could be prepared by film-side scribing.

3.2. Glass-side patterning

Another possibility to structure p-i-n configured thin-film solar cells is patterning by the laser through the transparent glass substrate [8]. In contrast to layer-side scribing, we found that the patterning from the glass-side offers the possibility of a direct explosive ablation of the entire 2-3 µm thick micromorph cell. Only one single pulse allows us to remove the thickness down to the bare front-TCO. This can clearly be seen in Fig. 4 where every pulse shot can be identified by the SEM picture. A closer look at the dark scribe borders reveals that beside the ablation of the back contact there must also be a removal of a part of the µc-Si:H bottom cell. As in this dark part the cell is no more active (due to the absence of the back contact) this defective area does not influence the performance of the micromorph cell. However, these dark stripes represent a scribe loss of approximately 20 µm width, which have to be added to the area losses of Pattern #3 in the series connection of a module.

Indeed, our I-V measurements confirm high fill factors of over 70 % indicating that shunt effects due to the scribing process are not present. The micromorph tandems patterned by glass-side scribing reveal their full solar cell performance with respect to open circuit voltage as well as with respect to the short circuit current.

Furthermore, our LBIC measurements show that no disturbances at the scribed border zones of the cells are present. This is demonstrated in Fig. 5 where a flat signal over the whole cell area is observed.

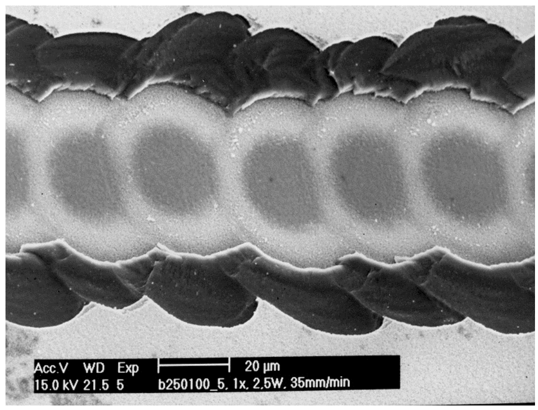

Figure 4: Typical glass-side scribe (λ=532nm) of a micromorph cell by SEM.

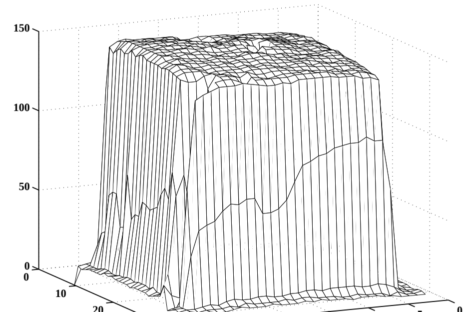

Figure 5: LBIC image (λ = 670nm) of a micromorph cell patterned from the glass-side.

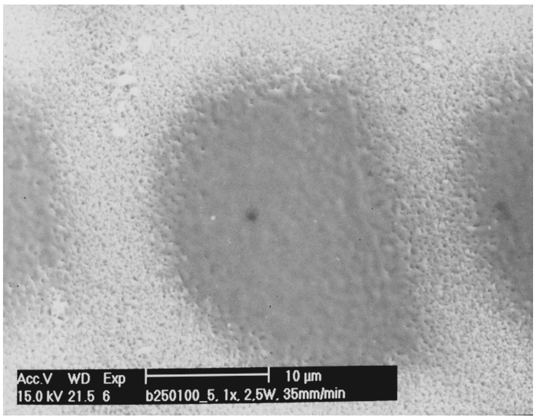

Figure 6: Close-up of the front TCO after a laser pulse through the glass substrate.

A closer look by SEM of the laser scribe (Fig. 4) reveals a change of the surface texture of the front TCO in the centre of the shot (grey areas in Fig. 6). It seems that the incoming laser pulse melts, by its high energy (creation of a plasma, [9]), the textured TCO producing, thus, a more flat material. This melting zone is, however, only present in the inner part (around 20 µm in diameter) of the ablation spot (30-50 µm) and is always observed even if we reduce the laser pulse power to get an incomplete ablation of the cell. This modification of the front TCO could, in principle, modify the contact to the front of the scribed cell resulting, thereby, in such a way that the cell performance would be adversely affected in a reduced fill factor (e.g. due to an increase of resistance of the melted front TCO). Our results, however, do not sofar give any evidence of such effects. Therefore, it may also be the case that this melted zone enhances the conductivity of the front TCO.

Another important point we observed is the high yield obtained, for good, working micromorph cells when applying glass-side scribing.

The positive results achieved here by glass-side patterning may suggest that this method probably takes advantage of the same momentum transfer of the exploded material and of the laser pulse direction. The glass-side patterning may, thus, favour the cell ablation by a more explosive process than in the case of the film-scribe.

4. FABRICATION OF MICROMROPH MODULES

Based on the encouraging results of test cell patterning as described above, first micromorph modules with integrated monolithic series connection have been explored within the disposable deposition area of 8x8 cm^2. Patterning #2 and #3 have, here, been performed through the glass-side.

For these first module fabrication experiments we have chosen a module design consisting of 6 segments. Hereby, the widths of the segments were 8-12 mm: a choice that needs, of course, further optimisation. One of our fabricated micromorph mini-modules is shown in Fig. 7.

Because of our present technical possibilities the space width of around 0.2 mm between the different scribe lines (Pattern #1 - #3, in Fig. 1) is sofar not optimised for electrical performance. Further equipment would be needed for a better positioning of the glass substrate.

The analysis of the scribed area by an optical microscope shows that we loose thanks, due to the monolithic series connection, an area of approximately 5 % of the total module area.

The I-V characteristics of such a micromorph mini-module is shown in Fig. 8. This module of an area of 23.6 cm^2 has a conversion efficiency under AM1.5 illumination of 9.3 %. The high fill factor of around 70 % proves that the series connection works indeed, well, also in the specific case of thick micromorph tandem cells. A comparison with test cells of 1 cm^2 from the same deposition run indicates further a rather good homogeneity over the deposited area of 8x8 cm^2. J_{sc} and V_{oc} values correspond relative well between, module segments (V_{oc} = 6 x 1.34 V; J_{seg} = 10.3 mA/cm^2) and test cells (V_{oc} = 1.34 V; J_{sc} = 10.6 mA/cm^2).

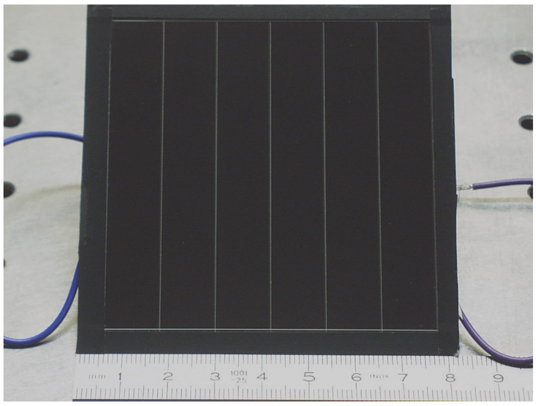

Figure 7: Picture of a micromorph module (8x8 cm^2) in the "superstrate" configuration.

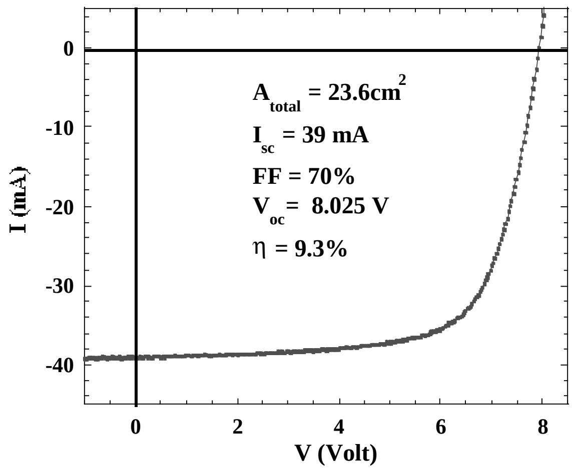

Figure 8: I-V curve (AM1.5) of a 6-segmented micromorph tandem cell module.

5. Conclusions

In this paper we present for the first time micromorph p-i-n/p-i-n solar cell modules which were fabricated by the well-established laser-scribing technique as generally used for monolithic series connection. By applying our small-size VHF-GD reactor we obtained in a mini-module (area of 23.6 cm^2) with an initial conversion efficiency of 9.3 % (V_{oc} = 8.025 V, FF = 70 %, I = 39 mA). The different patterning steps were successfully performed with Nd:YAG lasers (λ = 532 nm and 1064 nm), even for the 2-

3 μm thick micromorph tandem cell.

These first results are very encouraging because they prove that the application of the monolithic series connection technique to the micromorph solar cell concept is possible and can, thus, contribute to cost reduction as compared to crystalline wafer technologies, with special relevance for the case of industrial mass production. Further optimisation with respect to cell deposition as well as to module design and laser-scribing rather in precision will lead us to stable micromorph modules of 10 %.

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