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Development of highly stabilized efficiency micromorph tandem solar cells

Y. LIU, J. K. RATH[*], R. E. I. SCHROPP
Utrecht University, Faculty of Sciences, SID-Physics of Devices, P.O.Box 80.000, 3508TA Utrecht, The Netherlands

Micromorph silicon (a-Si:H/μc-Si:H) tandem solar cells on Asahi U-type substrates have been fabricated by very high frequency (VHF) PECVD in a high vacuum multichamber system called ASTER. The microcrystalline silicon (μc-Si) intrinsic layer (i-layer) was deposited using a shower head cathode at high pressures and under silane depletion conditions, at a high deposition rate of about 0.5 nm/s. The best optoelectronic quality μc-Si i-layer was found at the transition phase from amorphous to crystalline. An initial efficiency of 9.9% for a single junction μc-Si cell in a p-i-n configuration on texture-etched ZnO:Al was achieved. We measured a stabilized efficiency of 10% (Voc = 0.52V, FF = 0.74) after light soaking. The best tandem efficiency based on this single cell was achieved with 12% initial and 11.4% stabilized values. To fully exploit the benefit of the high stability of the μc-Si single junction cell, we made micromorph cells with a bottom cell limited structure. These tandem cells delivered an initial efficiency of 10.3% (Voc = 1.32V, FF = 0.69). To further study the independent influences of light illumination and thermal heating, annealing treatment was carried out for such μc-Si:H single junction cells and tandem cells. It was found that light soaking does not increase recombination in the μc-Si:H i-layer, and annealing treatment can improve the cell contact.

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1. Introduction

A "micromorph" tandem solar cell is composed of a hydrogenated microcrystalline silicon (μc-Si:H) bottom cell and a hydrogenated amorphous silicon (a-Si:H) top cell. Therefore, it can take advantage of a broader solar spectrum.

In recent years, most groups reported degradation of μc-Si:H single junction cells after light soaking [1,2]. In our group, a μc-Si:H single cell of 9.9% initial efficiency was achieved with an i-layer deposition rate of 0.45nm/s, by combining very high frequency PECVD (VHF-PECVD) and source gas high pressure depletion (HPD) conditions. The μc-Si:H i-layers were deposited in the amorphous to microcrystalline transition phase, as reported by several groups [3,4]. It was found that the light soaking process could upgrade the cell performance, and result in a record high stabilized 10% efficiency [4,5]. Meanwhile, light soaking has light induced and heating effects. In order to understand the improvement of performance by light soaking and find out the independent influences from these two effects, an annealing experiment was done for μc-Si single junction cells and micromorph tandem solar cells.

In this paper, the light induced influence from light soaking and the thermal influence from annealing for μc-Si single junction cells and micromorph tandem cells are discussed.

2. Experimental

The a-Si:H and μc-Si:H i-layers, as well as the p and n layers of the micromorph tandem cell, were deposited in separate chambers of the ultra high vacuum multichamber ASTER system by VHF-PECVD at 60 MHz. The μc-Si i-layer, specifically, was deposited by using a shower head cathode with gas inlets at high pressures and under silane depletion conditions, at a high deposition rate of around 0.5 nm/s. In this chamber, the electrode structure includes a 170 cm^2, powered electrode and a ground electrode to which the 10×10 cm^2 substrate holder is transported by an automatic robot arm. The electrode distance can be varied from 5 to 27mm. The ZnO:Al layer used as a back reflector is made by our rf magnetron sputtering setup called SALSA.

The micromorph tandem cells were deposited on 10cm × 2cm size Asahi U-type substrates. The deposition was done in the sequence of top a-Si:H p-i-n cell and then bottom μc-Si:H p-i-n cell. The a-Si:H i-layer of ~250 nm was deposited by VHF PECVD at 50 MHz, with a silane to hydrogen ratio of 1:1. The μc-Si:H layer, 1.5 μm thick, was deposited by VHF-PECVD at 60 MHz, with a hydrogen dilution d_H (d_H=H_2 flow/SiH_4 flow) of 28. The substrate temperature was chosen to be around 180 ^oC. The cell area was determined by 0.4×0.4 cm^2 back contacts of metal silver and aluminium layers, which were deposited by sputtering in the SALSA.

The solar cells were tested by J-V measurements under simulated AM 1.5 light (a calibrated Wacom dual beam solar simulator) with an intensity of 100 mW/cm^2, and in dark at 25 ^oC. The intensity calibration was done using detectors calibrated at NREL (USA). The accuracy of the J-V measurement was confirmed by comparing the efficiency of an amorphous silicon cell measured with this set-up with that at NREL under recognized standard conditions.

The annealing experiment for μc-Si:H and micromorph solar cells was carried out at 150°C for 2 hours in a nitrogen rich environment. Annealing data used in this paper all involved measurements within 1 hour before and after the 2 hour annealing process.

3. Results and discussion

The J-V characteristics from light soaking experiments are given in Fig.1, and the corresponding data for five cells measured before and after annealing are shown in Fig. 2. The cells used in Fig. 2 were made in another deposition series than Fig. 1, but were made under the same conditions. Cells in both series have the same FF, implying similar material qualities. The lower efficiency in the latter series (Fig. 2) is only due to lower current, which is caused by the slightly thinner i-layers in these cells. It is certain from these figures that the solar cell efficiency and FF are improved relatively by 3% and 1.4% respectively with heat treatment.

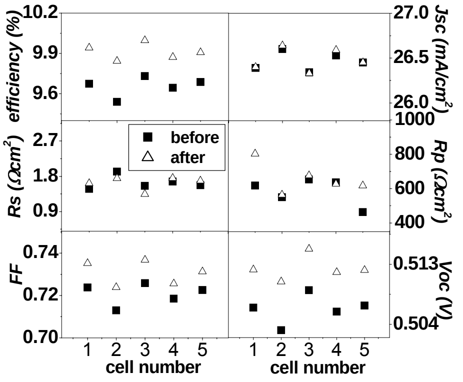

Fig. 1. Light J-V parameters of a μc-Si:H single junction cell before and after light soaking.

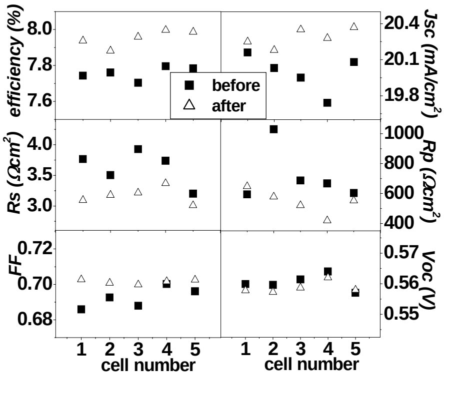

Fig. 2. Light J-V parameters of μc-Si:H single junction cell before and after annealing treatment.

It is found in Fig 1 that after light soaking, the open circuit voltage (Voc) increases on average by about 1%. The short circuit current density (Jsc) stays nearly constant for each cell. This correlates to the almost unchanged Rs values. Rp values do not decrease with light soaking. The improvement in solar cell performance mainly originates from the increased Voc and FF.

In Fig 2, the Voc keeps roughly the same value after the annealing process, and even decreases a little. On the other hand, the Jsc values in all five cells indicate an increase. Meanwhile, Rs reveals a clear drop averaging 14.3% in all five cells. In the annealing case, the cells show improvement by the dramatically reduced Rs, and thus the enhanced Jsc.

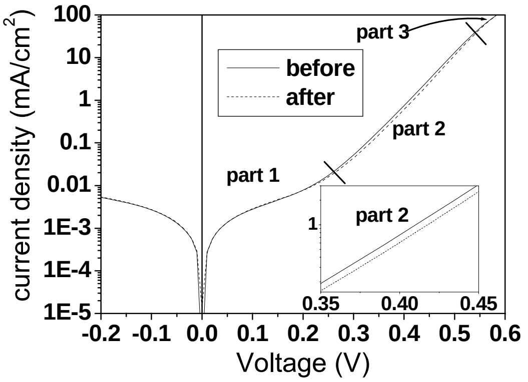

Fig. 3. Dark J-V curve of a μc-Si:H single junction cell before and after light soaking.

To further confirm the above inference, dark J-V curves for both cases were plotted and studied. Fig. 3 shows the dark J-V curves of cell number 3 before and after light soaking. The perfect overlaps of part 1 and 3 indicate that the light soaking process has no significant effect on Rp and the cell contacts. In part 2 (also see the inset), the curve dropped after light soaking. We presume that the drop is because light illumination could reduce the defect density, and therefore result in a lower reverse saturation current parameter J_0 (confirmed by our data, but not shown) and diode quality factor n, giving rise to a drop in the slope in part 2.

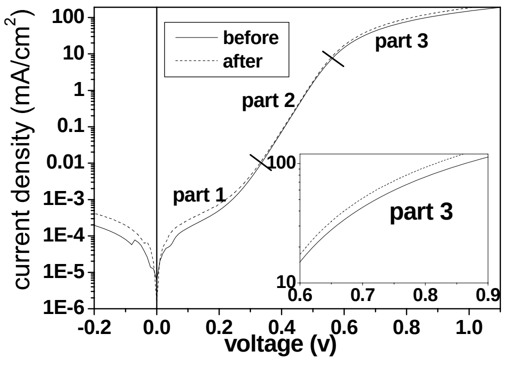

Fig. 4. Dark J-V curves of a μc-Si:H single junction cell, before and after annealing treatment.

The dark J-V curves of cell number 4 for the annealing are illustrated in Fig.4. In part 1, the curve moves up after annealing treatment; this correlates to the reduced Rp upon annealing. The perfect overlap of part 2 means that the diode quality does not change much, therefore, the Voc stays roughly the same. The high forward bias region of the curve (part 3) after annealing (also see the inset) demonstrates a clear improvement of the device contacts. All dark J-V data are consistent with the J-V data under illumination.

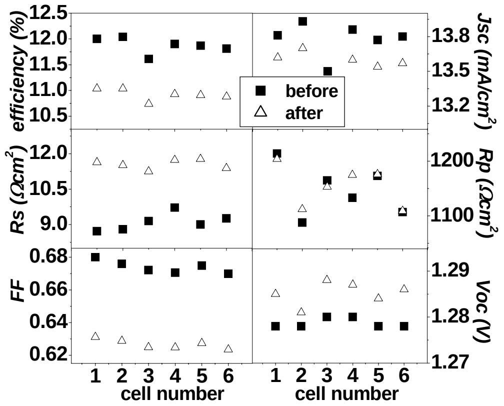

Fig. 5. Characteristics of a micromorph cell before and after light soaking(best cells, top cell limited).

Based on these data, we infer that during light soaking, exposure to light for long time has no effect on Rs. We presume that there is a decrease in the defect density in the i-layer of μc-Si:H single junction cells, and this gives rise to higher Voc values. Annealing, on the contrary, does not influence the quality of the diode, but high temperature does generate a better contact, resulting in a smaller Rs, and thus the current is enhanced. In addition, Raman spectroscopy indicates no significant crystallinity change before and after the annealing experiment. Thus, we propose that the thermal effect during annealing can improve the contacts and have better carrier collection in a μc-Si:H single junction cell.

Because of the fact that our best tandem cells (1st series) (η>12%) are top cell limited, they degrade (though by only 5%) under light soaking. To obtain more stabilized cells, bottom cell limited tandem cells (2nd series) were deposited. The a-Si:H top cell (i-layer thickness ~250nm) is deposited according to our standard a-Si:H single junction cell procedure (i-layer thickness ~400nm, efficiency>10% for FF >0.7, Jsc >16mA/cm² and Voc >0.85V). The micromorph tandem cell was deposited based on the above top cell and a μc-Si:H single junction bottom cell. An initial efficiency of 10.3% (FF=0.69, Jsc=11.32 mA/cm², Voc=1.32V) was achieved. The highest efficiency was achieved by another cell after annealing treatment, with an efficiency of 10.5% (FF=0.67, Jsc=11.58mA/cm², Voc=1.35V). For these cells, only the annealing experiments were performed.

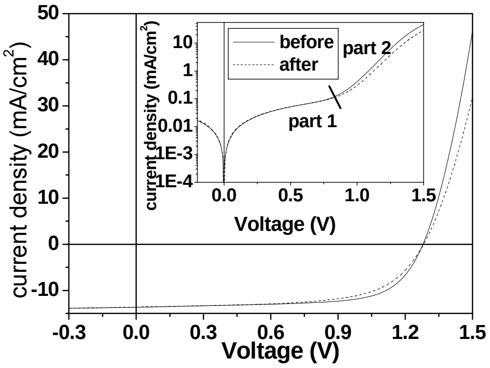

Fig. 6. Light and dark (inset) J-V curves of a micromorph cell before and after light soaking.

In Fig. 5, the light soaking results of the cells of the first series are given. The efficiency and FF drops by approximately 8.7% and 7.5% respectively. Rp remains almost the same. Rs is increased; this is a fingerprint of a degraded contact, which leads to a lower Jsc. Voc also increased after light soaking. The corresponding J-V curves of a cell of this series are given in Fig.6. The change in the light J-V curves, indicate that more recombination takes place after light soaking, giving rise to an increased dark current. In addition, it is well known that the dark J-V curve of a light soaked a-Si:H cell moves up with light soaking, indicating a bigger dark current, due to the increase in defect density. On the other hand, in Fig.3 for our μc-Si cells, the dark current was reduced after light soaking. Considering the results from a μc-Si:H single junction cell, the Staebler-Wronski effect in an a-Si:H top cell and the fact that Rp does not play any role, we can conclude that in spite of the increased Voc of our micromorph tandem cell, the light soaking process degrades the tandem cell as a result of the dominant degradation of the top cell i-layer.

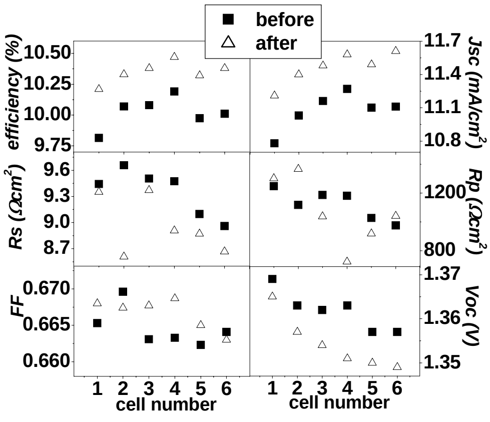

Fig. 7. Characteristics of a micromorph cell before and after annealing (bottom cell limited).

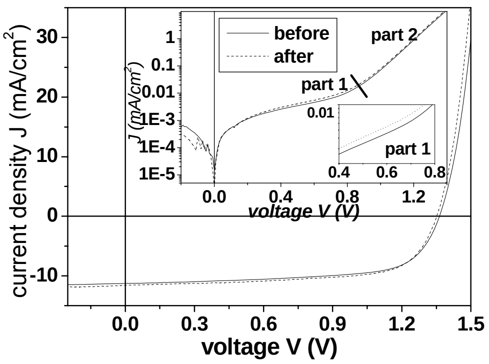

Fig. 8. Light and dark(inset) J-V curves of a micromorph cell before and after annealing.

The J-V characteristic of a tandem cell of series 2 before and after annealing is given in Fig. 7. It is seen that in spite of the Voc drop and ambiguous Rp trend after annealing, the cell efficiency and FF increase relatively by 4% and 0.5% respectively. Rs is reduced after annealing, leading to an increase in Jsc. The J-V curve of cell number 4 is plotted in Fig. 8. In part 2 of the inset dark J-V curve, there is again a perfect overlap, indicating that annealing does not change the quality of the diodes. The improvement in tandem cell performance can be explained partly by the reason that the heat during the annealing process improved the contacts and conductivity in the tandem cell.

4. Conclusions

In general, the light induced effect during light soaking does not increase the recombination rate in the i-layer and even may reduce the defect density in the μc-Si:H i-layer, and the thermal effect during the annealing treatment can improve the contacts in solar cells.

For μc-Si:H single junction solar cells, both light soaking and annealing treatment improve the cell performance. On the other hand, in mircromorph tandem cells, light soaking leads to degradation, because the improvement of the bottom cell can not compensate for the deterioration in the top cell, especially in the top cell limited condition. Annealing treatment can improve the tandem cell performance, because a lower defect density in top cell and better contacts throughout the entire tandem cell are achieved.

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[*] Corresponding author: J.K.Rath@phys.uu.nl