Micromorph tandem solar cells: optimization of the microcrystalline silicon bottom cell in a single chamber system*

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We report on the development of single chamber deposition of microcrystalline and micromorph tandem solar cells directly onto low-cost glass substrates. The cells have pin single-junction or pin/pin double-junction structures on glass substrates coated with a transparent conductive oxide layer such as SnO_2 or ZnO. By controlling boron and phosphorus contaminations, a single-junction microcrystalline silicon cell with a conversion efficiency of 7.47% is achieved with an *i*-layer thickness of 1.2 μm. In tandem devices, by thickness optimization of the microcrystalline silicon bottom solar cell, we obtained an initial conversion efficiency of 9.91% with an aluminum (Al) back reflector without a dielectric layer. In order to enhance the performance of the tandem solar cells, an improved light trapping structure with a ZnO/Al back reflector is used. As a result, a tandem solar cell with 11.04% of initial conversion efficiency has been obtained.

Keywords: amorphous and microcrystalline silicon, single chamber, solar cells

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1. Introduction

Hydrogenated microcrystalline silicon (μc-Si:H) has attracted a great deal of attention for use as a long wavelength absorbing material for the bottom cell in double-junction thin film solar cells, where the top cell is normally hydrogenated amorphous silicon (*a*-Si:H). This cell structure is normally called a 'micromorph' tandem solar cell and was introduced by Meier *et al.*[1] At present, very encouraging results using μc-Si:H solar cells efficiencies have been achieved in different laboratories,[2–4] but most of them are deposited in a multi-chamber reactor. Plasma-enhanced chemical vapour deposition (PECVD) of pin type solar cells in a single plasma reactor offers advantages of reduced time and cost as compared to multi-chamber processes.[5]

In this paper, based on our previous research,[6,7] we report on our latest results of μc-Si:H pin solar cells and 'micromorph' tandem solar cells deposited in a single chamber system. The thickness of the bottom solar cells and the back reflector were selected to optimize the performance of the tandem solar cells.

2. Experimental

Single junction μc-Si:H solar cells and the bottom cell in tandem solar cells were prepared in a single chamber PECVD deposition system with parallel plate electrodes with a very high frequency (VHF) of 75 MHz. For the depositions of μc-Si:H single-junction solar cells and μc-Si:H bottom cells in a-Si:H/μc-Si:H double-junction solar cells, the substrate temperature was fixed at 180 °C and the deposition pressure was 1.8 Torr (1 Torr=1.33322×10^2 Pa). The reactive gases for the deposition of the solar cells included silane (SiH_4), hydrogen (H_2), diborane (B_2H_6) and phosphine (PH_3). The silane concentration (SC=$[SiH_4]/[SiH_4+H_2]$) in the feed gases for the undoped layer was 5.85%. A discharge power density of 95 mW/cm^2 was used, under which the deposition

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rate was about 0.5 nm/s for the intrinsic μc-Si:H layer deposition.

Solar cells with pin deposition sequences were prepared on TCO coated glass substrates. For μc-Si:H pin single-junction solar cells, ZnO-coated glasses were used. SnO_2 coated glasses (Asahi U) were used for the a-Si:H/μc-Si:H tandem solar cells and the a-Si:H solar cell. The ZnO/Al or Al back reflectors were deposited on the back of the devices and defined the solar cell area of 1.0 cm^2. A schematic diagram of the solar cell structure is shown in Fig. 1. The a-Si:H top cell had a thickness of 250 nm. Solar cell characterization was performed under an AM1.5G illumination at 25 °C. The thickness of all the solar cells was measured by using a step profiler. The structural properties were characterized with Raman spectroscopy (LabRAM UV, including 325-nm, 488-nm, and 632.8-nm wavelength lasers).

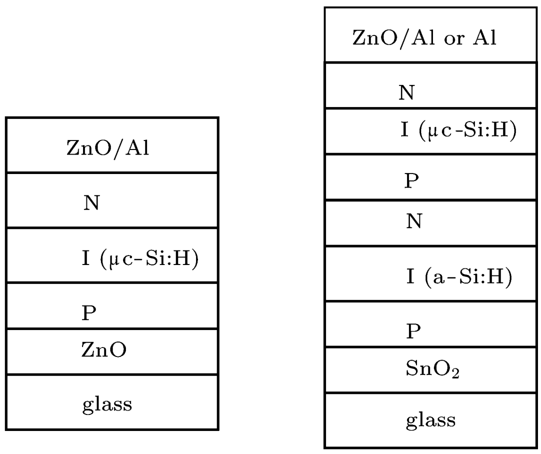

Fig. 1. Schematic diagram of the single junction microcrystalline silicon solar cell (a) and the amorphous and microcrystalline silicon tandem solar cell (b).

3. Results and discussion

3.1. Amorphous and microcrystalline silicon single-junction solar cell

This section presents some results for the single-junction a-Si:H and μc-Si:H solar cells. The basic structure of the cell is glass/SnO_2/p/i/n/Al and glass/ZnO/p/i/n/ZnO/Al. Figure 2 presents the initial J–V performance of an a-Si:H solar cell with an i-layer thickness of 250 nm, which yields a short-circuit current density (J_{sc}) of 12.92 mA/cm^2 and an open-circuit voltage (V_{oc}) of 0.909 V. This kind of thin a-Si:H top cell is suitable for the fabrication of micromorph tandem solar cells. The development of micromorph tandem solar cells is mostly concerned with establishing a robust and reproducible process for μc-Si:H bottom cells. As for the single chamber depositions of the μc-Si:H solar cells, the cross contaminations of boron and phosphorus are very serious. For p–i–n type solar cell fabrications, the boron contamination in the subsequent i-layer should not exceed 10^{17} at.cm^{-3}. In our previous paper,[8] an interface layer with a suitable high crystalline volume fraction inserted between the p and sequentially deposited i layer was proposed to reduce the contaminations and then improve the performance of the μc-Si:H solar cells prepared in a single chamber system. As for phosphorus contamination, we have also proposed several techniques, including an intrinsic μc-Si:H covering layer, a p layer deposition covering layer and hydrogen plasma treatment, to reduce the contamination.[9] A combination of the above methods was used to reduce the cross contaminations, and a single-junction μc-Si:H solar cell (shown in Fig. 3) with 7.47% initial conversion efficiency has been obtained.

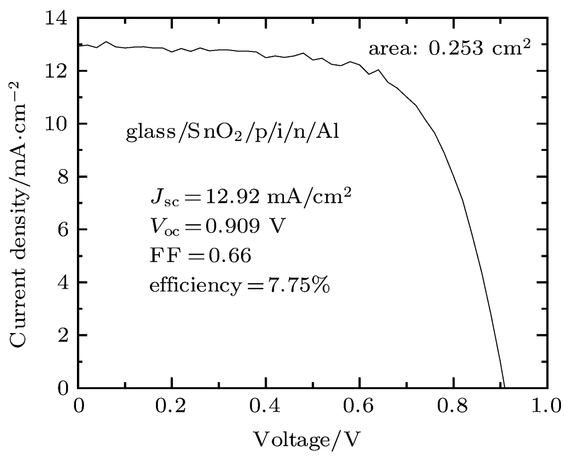

Fig. 2. Initial I–V curve (AM1.5G) of the a-Si:H pin single-junction solar cell.

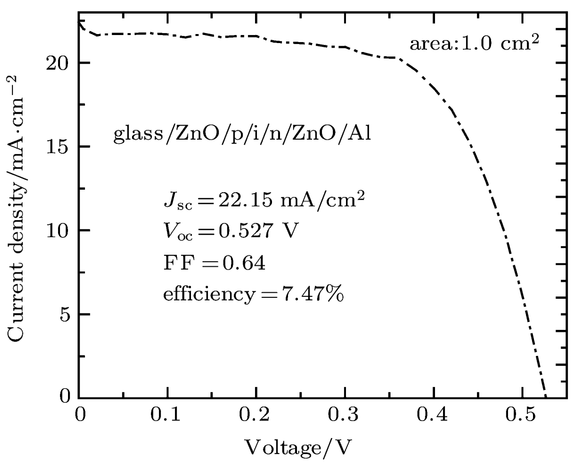

Fig. 3. Initial I–V curve (AM1.5G) of the μc-Si:H pin single-junction solar cell.

3.2. Micromorph tandem solar cells

Table 1 shows the data for the initial I–V parameters under an AM1.5G illumination and figure 4 shows the performance parameters of tandem solar cells prepared with different deposition times, which correspond to the change of cell thicknesses. The cells, prepared at a fixed silane concentration (SC) of 5.85%, show that the J_{sc} increases with the increase of thickness, which can be attributed to an enhanced absorption of the incident light. The V_{oc} slightly decreases from maximum values of 1.396 V down to 1.355 V. The fill factor (FF) decreases too, starting at a maximum value of 0.69 at 60 min of deposition time. The variation of V_{oc} and FF suggests a limitation in the built-in electric field, which comes from the fixed p and n layer deposition conditions. The decrease of V_{oc} and FF is partly compensated by the increase of J_{sc}. T0he highest efficiency is 9.91% in this set of solar cells. From the above results, it can be concluded that the thickness of the bottom cell is very important for the total current of tandem solar cells, which will largely affect the performance of the cell.

Table 1. Initial solar cell parameters of micromorph pin tandem cells deposited in a single chamber system on glass substrate coated with SnO_2 transparent conductive oxide. The thickness is about μc-Si:H bottom solar cell.

Sample	Deposition time/min	Thickness/μm	Area/cm^2	J_{sc}/mA·cm^{-2}	V_{oc}/V	FF	Efficiency/%
A	60	1.8	1.0	7.75	1.396	0.69	7.47
B	75	2.5	1.0	9.61	1.379	0.682	9.04
C	90	3.0	1.0	10.19	1.377	0.654	9.18
D	105	3.5	1.0	11.43	1.355	0.64	9.91

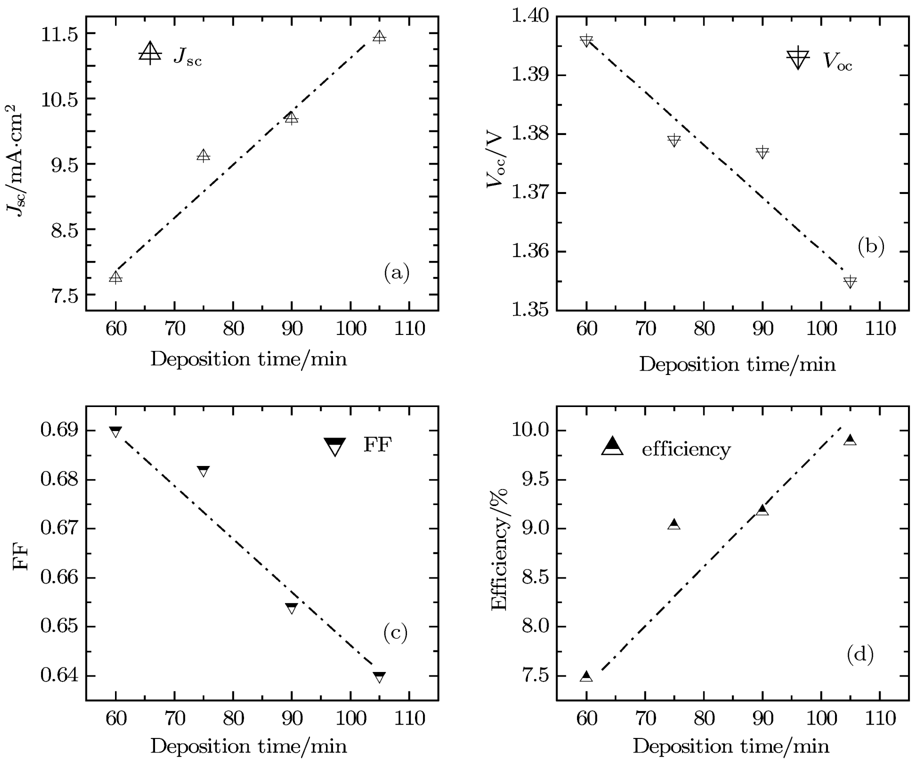

Fig. 4. Performance parameters of micromorph pinpin tandem solar cells with different deposition times for the bottom cells: (a) short-circuit current density J_{sc}, (b) open-circuit voltage V_{oc}, (c) fill factor FF; (d) efficiency η.

Raman spectra for the above sample are shown in Fig. 5, it is noted that the crystalline volume fraction slightly increases with increasing deposition time from 632.8-nm wavelength laser measurement results, which will enhance the current density of the cell. However, the crystalline volume fraction changes slightly for deposition times longer than 75 min, which means that the homogeneity along the growth direction was well controlled, which is very important for effectively collecting photo-generated carriers. As a result, more light will be converted into electricity and the cell efficiency increases. In addition, from the 325-nm wavelength laser we can deduce more information about the tandem solar cells. From the 325-nm wavelength laser, we can make sure that the n-layer of the bottom cell is amorphous, which is important to prevent current cross collection.

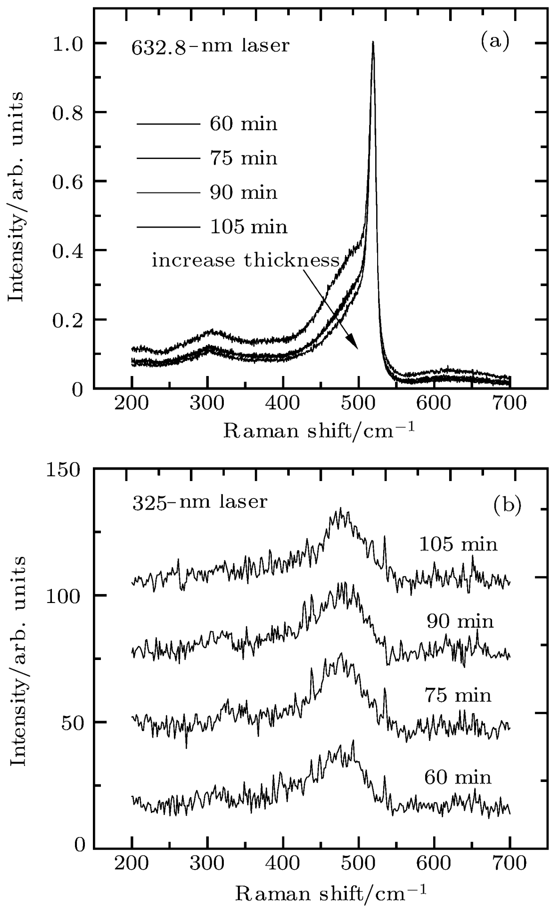

Fig. 5. Raman spectra of micromorph pinpin tandem solar cells with different absorber thicknesses for the bottom solar cells: (a) 632.8-nm wavelength laser and (b) 325-nm wavelength laser.

To further enhance the performance of the tandem solar cell, we also used a ZnO/Al back reflector, which has been proved to increase the performance in single-junction microcrystalline silicon solar cells.[10] Usually, an 80 nm–90-nm thick layer of doped zinc oxide is used for this purpose because ZnO is a well-established material in solar cell processing as the front electrode. Figure 6 shows that the tandem solar cell has a high current density with the ZnO/Al back reflector even though the thickness of the tandem solar cell is thinner than the cell having a lower current density with an only Al back reflector. As a result, it can be concluded that this layer is capable of improving the photocurrent of the tandem solar cell, where the bottom cell limits the current density in the tandem device. It is also evident that the $V_{\rm oc}$ was also enhanced by the ZnO/Al back reflector, which means that the n-type ZnO layer causes an enhanced built-in electrical field. There may be two reasons for this: one is that ZnO prevents from the Al metal electrode diffusing into the n-type silicon layer. The second is the effect of the n-a-Si:H/n-ZnO double layer. Finally, by optimizing the bottom cell thickness and other deposition parameters, a micromorph tandem solar cell with 11.04% initial conversion efficiency has been made with a ZnO/Al back reflector. The J–V curve is shown in Fig. 7, where, $J_{\rm sc}$, $V_{\rm oc}$, and FF are 11.78 mA/cm^2, 1.39 V, and 0.674, respectively.

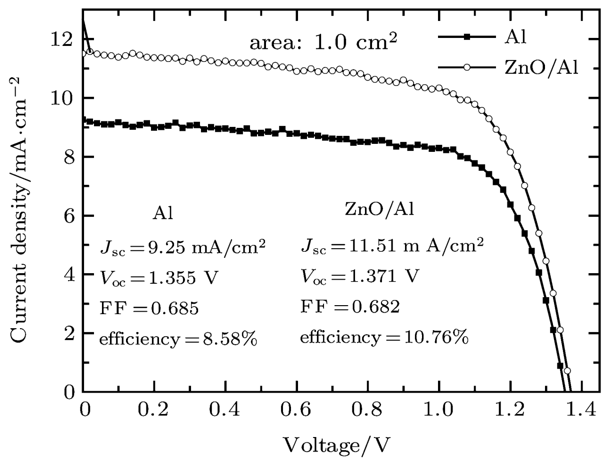

Fig. 6. Initial I–V curves (AM1.5G) of micromorph tandem solar cells prepared with an Al or a ZnO/Al back reflector.

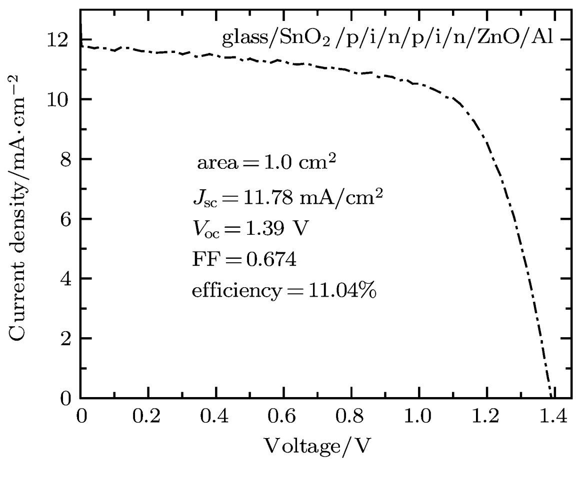

Fig. 7. Initial I–V curve (AM1.5G) of the best performing micromroph tandem solar cell deposited in a single chamber system on glass substrate coated with SnO_2 transparent conductive oxide.

4. Conclusion

We have presented our progress in the single chamber deposition of μc-Si:H single-junction p–i–n solar cells and tandem solar cells on glass substrate. In particular, we optimized the interface layer for reducing contamination and the bottom cell thickness for current matching. The highest initial efficiency is 9.91%. By using a ZnO/Al back reflector in tandem solar cells, we find that the optimized a-Si:H/μc-Si:H tandem solar cell has an initial efficiency of 11.04%.

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