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Operation Properties of μc-Si:H *pin* and a-Si:H/μc-Si:H Tandem Solar Cells

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Abstract: The operation properties of a-Si:H, μc-Si:H and a-Si:H/μc-Si:H tandem solar cells are studied in this paper. The short circuit current density (jsc) of the tandem solar cells are strongly dependent on different light trapping and current matching schemes by varying front TCO, structure of back reflector and thickness of bottom cell. The ZnO front TCO and thicker i-layer of bottom cell are advantages for obtaining high jsc. The effect of intermediate ZnO layer on operation of tandem solar cells are also discussed.

Introduction

After a-Si:H/μc-Si:H tandem (or micromorph) solar cells were introduced by IMT (Institute of Microtechnique, University of Neuchatel)[1], much progress has been made in small area and large area cells[2,3]. Kaneka Corp. has achieved

14.7% and 11.6% initial efficiency in small area R&D and large area mass-produced tandem cells, respectively[2,4].

The main target is to produce high efficiency thin-film tandem solar cells at low cost. In order to accomplish these targets, a lot of research groups and production companies are devoting resources to increase solar cell efficiency by optimizing both top/bottom cells and current matching within two cells. The stability and deposition rate of tandem cells has also one of the been main research areas. Although there has been intensive work in many research groups, device physics of tandem solar cells have not been well understood until now.

In this paper the operation properties are discussed in a-Si:H/μc-Si:H tandem solar cells with different light trapping scheme and thickness of bottom cells.

Experimental

The a-Si:H, μc-Si:H and a-Si:H/μc-Si:H thin-film solar cells were fabricated with a multi-chamber cluster tool system as shown in Figure 1. The system consists of five deposition, two central and load/unload chambers. The process chambers contain 2 PECVDs, VHFCVD, HWCVD and rf sputtering systems. A robot arm is located inside the central chamber in order to transfer substrate into each process chamber without breaking the vacuum. With this system, the solar cells can be produced without any impurity contamination during deposition of pin thin-films and sample transfer. Two kinds of substrate were used for solar cell fabrication; Asahi-U(SnOz:F) and texture etched ZnO:AI. The ZnO:Al films were texture etched in 1 % HCL solution to get rough surface. [5]

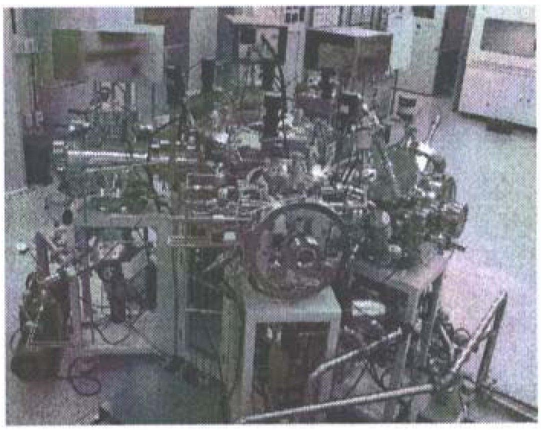

Figure 1. Photograph of multi-chamber cluster tool system used for solar cell fabrications.

The intrinsic a-Si:H and μc-Si:H thin-films were deposited by 60MHz VHFCVD. The p μc-Si:H(25nm) and n a-Si:H(30nm) layers were prepared by conventional PECVD method. The ZnO intermediate layer in a tandem cell was deposited by rf sputtering method with ZnO:Alz03 target at room temperature. The low rf power was employed to prevent surface damage by ion collisions during sputtering of intermediate ZnO film. The solar cell area was defined to be O.25cmz by shadow mask during deposition of inter-ZnO and Ag back contact.

Results and Discussion

1. a-Si:H and μC-Si:H solar cells

Figure 2 shows the I-V curves of IlC-Si:H, a-Si:H and aSi:H/μc-Si:H tandem *pin* solar cells. The μc-Si:H solar cells (a & b) prepared on textured ZnO:Al TCO have different thickness of intrinsic layer. The solar cells with thick i-layer give higher jsc as the expense of reduced Voc and FF. The deterioration of Voc and FF in a thick solar cell is assumed to be caused by higher deposition rate, since the thick i-layer was prepared at increased VHF power, by which material quality should be reduced. Figure 2 (c) also shows the I-V curve of a-Si:H solar cell used in aSi:H/μc-Si:H tandem solar cells. The a-SiC:H p-Iayer was used for a-Si:H and a-Si:H/μc-Si:H tandem solar cells.

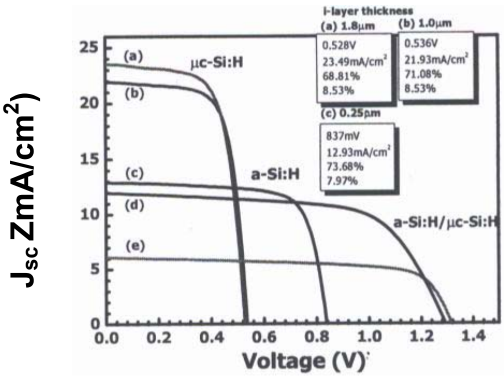

Figure 2. I-V curves of the μc-Si:H, a-Si:H and a-Si:H/μc-Si:H tandem pin solar cells. The thickness of intrinsic layer in μcSi:H and a-Si:H solar cells is varied. The I-layer thickness in tandem solar cells is 1.0 μm and O.251lm for a-Si:H and μc-Si:H, respectively. The μC-Si:H solar cells are prepared on wet etched ZnO:Al TCO and have ZnO/Ag back reflector. The a-Si:H and tandem solar cells are deposited on Asahi-U glass and have Ag back contact.

2. a-Si:H/μC-Si:H tandem solar cells

This section deals with operation properties of a-Si:H/μC-Si:H tandem cells. In order to optimize current matching between top and bottom cells, we varied front TCO, thickness of bottom cell and back reflector as shown in Table 1. At first, tandem cells are deposited on Asahi-U (SnO_2:F) substrate, in which thickness of bottom cells varied from 1.0 to 1.8Ilm, but thickness a-Si:H was fixed at 250nm. The increase of bottom cell thickness gives higher jsc in a tandem cell but lower Voc and FF. The decrease of V_{oc} and FF in a thick cell may result from the same cause observed in a thick μC-Si:H cell since the bottom i-layer was deposited at the same conditions with Figure 2 (a).

Table 1. Operation parameters of a-Si:H/μC-Si:H tandem solar cells with different current matching scheme.

Cell-ID	Structure	Parameters
Tandem-A (Fig. 2 e)	Asahi-U (Sn02:F) Thick. of bottom cell = 1.0μm Back contact: Ag	1.32V 6.17mA/m2 67.5% 5.5%
Tandem-B	Asahi-U (Sn02:F) Thick. of bottom cell = 1.8μm Back contact: Ag	1.22V 8.64mNm2 66.6% 7.0%
Tandem-C	Textured ZnO:AI Thick. of bottom cell = 1.8μm Back contact: Ag	1.33V 9.74mA/m2 62.5% 8.1%
Tandem-D (Fig. 2 d)	Textured ZnO:Al Thick. of bottom cell = 1.8μm Back contact: *ZnOIAg*	1.29V 11.97mA/m2 63.7% 9.8%

Tandem-B and C in a Table 1 show the effect of light scattering at the TCO front contact on current matching in a tandem cell. The solar cells (Tandem-C) prepared on textured ZnO:A1 films give higher performances in $j_{sc,}$ V_{oc} and efficiency except FF by enhanced light scattering at ZnO surface compared to Asahi-U. Low FF of solar cell on ZnO:AI may result from poor contact with a-SiC:H p-Iayer and ZnO. The back reflector plays an important role in a tandem cell for increasing jsc like μC-Si:H cell. The insertion of ZnO thin-film between n a-Si:H and Ag metal gives a jsc increase of more than *2mA/cm2* in a tandem cell, which is deduced from increased absorption of incident (or reflected) light in a μC-Si:H bottom cell.

From the above results, it is concluded that the effective current matching in a a-Si:H/μC-Si:H tandem solar cell can be realized by controlling light trapping (scattering and reflection at front TCO and back contact) and thickness of bottom cells. The low Voc in a Tandem-D cell may result from low Voc of aSi:H top cell that is about 0.83V as shown in Figure 2 (c). Since μC-Si:H bottom cell has 0.53V of Voc, the Voc of a-Si:H cell should be increased to 0.9V for tandem cells to have more than IAV of V_{oc}. It has been reported that Voc of a-Si:H cell can be increased by controlling p-layers[6]. Therefore, optimization of p-Iayers of a-Si:H cells is quite important both for higher Voc and for improving FF of tandem cells.

3. The effect of ZnO intermediate layer

The ZnO intermediate layer has been reported to be effective for obtaining high jsc in thin-top cell at the cost of a reduction in the photocurrent of the μC-Si:H bottom cell[2,7].

However, in our study, the operation properties of tandem solar cells are quite different by inserting ZnO intermediate layer. Figure 3 shows the effect of ZnO intermediate layer on operation properties of a-Si:H/μc-Si:H tandem cells. The I-V curve of a tandem solar cell without ZnO inter-layer has kink from 0.6V when illuminated. On the other hand, by inserting a very thin ZnO layer (about 5nm), this kink effect of I-V curve was totally removed. Since the solar cell structure is glass/Asahi-U/p_1 a-SiC:H/I a-Si:H/n_l a-Si:H/p_2 μc-Si:H/i μc-Si:H/n_2 a-Si:H/Ag, n_1 /p_2 junction between top and bottom cells may act as reverse diode instead of tunnel junction when solar cells are illuminated. However, the insertion of a thin ZnO layer between n_1 and P_2 junction may prevent the formation of diode since carrier diffusion in a n_1 p_2 junction is protected by thin ZnO film. If the tandem solar cells can operate without ZnO intermediate layer, n_1 and p_2 layers should be optimized in their structure and doping concentration in order to make tunnel recombination junction.

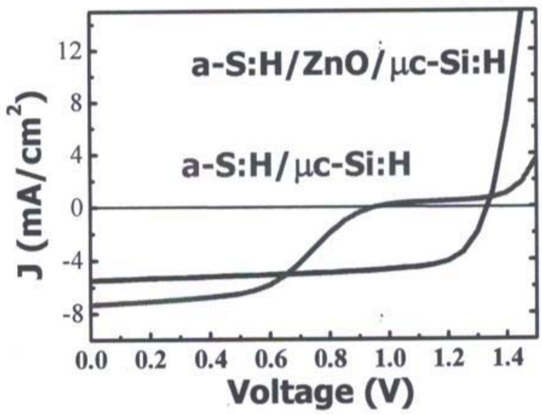

Figure 3. The effect of ZnO intermediate layer on operation properties of a-Si:H/μc-Si:H tandem cells. The top and bottom cells are prepared under the same deposition conditions on Asahi-U glass with Ag back contact.

Conclusion

The μc-Si:H and a-Si:H/μc-Si:H tandem cells were fabricated with multi-chamber cluster tool system. The μc-Si:H cells with increased i-layer thickness give higher jsc but lower Voc and FF, which supposedly resulted from degraded film quality by increased deposition rate in a thicker cell. The jsc of a-Si:H/μcSi:H tandem solar cells can be increased by enhancing both light trapping and current matching. The current matching in a tandem cell was performed by increasing thickness of the bottom cell. The insertion of thin ZnO intermediate layer between top and bottom cells were very effective to increasing solar cell performance by preventing the formation of reverse diode.

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