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The study of a new n/p tunnel recombination junction and its application in a-Si:H/μc-Si:H tandem solar cells*

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This paper reports that a double N layer (a-Si:H/μc-Si:H) is used to substitute the single microcrystalline silicon n layer (n-μc-Si:H) in n/p tunnel recombination junction between subcells in a-Si:H/μc-Si:H tandem solar cells. The electrical transport and optical properties of these tunnel recombination junctions are investigated by current–voltage measurement and transmission measurement. The new n/p tunnel recombination junction shows a better ohmic contact. In addition, the n/p interface is exposed to the air to examine the effect of oxidation on the tunnel recombination junction performance. The open circuit voltage and FF of a-Si:H/μc-Si:H tandem solar cell are all improved and the current leakage of the subcells can be effectively prevented efficiently when the new n/p junction is implemented as tunnel recombination junction.

Keywords: double N layer, tunnel recombination junction, oxidation interface, a-Si:H/μc-Si:H tandem solar cell
PACC: 8115H, 8630J, 6855

1. Introduction

The a-Si:H/μc-Si:H tandem solar cell has attracted much interest for its high conversion efficiency and better stability in comparison with amorphous based single junction solar cell.[1−4] To optimize the performance of the tandem solar cell, it is essential to design and fabricate a good n/p tunnel recombination junction (TRJ). The TRJ should be Ohmic contact to recombine electrons from top cell and holes from bottom cell. If the TRJ cannot provide enough recombination, light induced dipoles would be created, due to the extra accumulation of trapped electrons or trapped holes, which would weaken the electric field in the top cell and bottom cell, subsequently, deteriorate the performance of the tandem solar cell. It has been proposed that transport in these junctions proceeds by nonlocalized recombination of oppositely charged carriers which tunnel through mid-gap or band tail defect states.[5,6] Many approaches have evolved for improving the performance of the TRJ. Numerical modelling shows that a low mobility gap (LMG) and highly defective layer added between the n and p layer are beneficial to recombination.[7,8] Metal oxide layer such as TiO_x,[9,10] NbO_x[10] and a-SiC:H[11] were used as the recombination layer at the beginning, but the deposition was not compatible with PECVD processing of thin film solar cells. Microcrystalline silicon was also used as the recombination layer for its LMG and high defects.[12−14] A heavily doped layer[15] and interface oxidation treatment [16,17] were also introduced to obtain better TRJ. Loffler *et al*[18] found that for the formation of TRJ with two microcrystalline layers in a-Si:H/a-Si:H tandem solar cell with n/i/p configuration led to current leakage of the first deposited subcell under low light conditions. They ascribed this shunting problem to the damage during deposition of the n-μc-Si:H layer.

In this paper, we introduce a double n layer to substitute single n-μc-Si:H layer in TRJ in a-Si:H/μc-Si:H tandem solar cell with pin configuration, where an n-a-Si layer was deposited before n-μc-Si . Air break of the n/p interface is also performed to study

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the influence of the interface oxidation on the performance of tandem solar cells.

2. Experiments

P and n layers are prepared with VHF (very high frequency)-PECVD (60 MHz) and RF (radio frequency)-PECVD (13.56 MHz) respectively, in a cluster CVD system.[19] The n layer was firstly deposited on TCO (SnO_2), and then p layer is deposited on n layer to simulate the actual n/p TRJ in micromorph tandem solar cells, Al is evaporated as the electrode. The structure is glass/SnO_2/n/p/Al, as can be seen from Fig.1. Devices are characterized by resistance, I–V, $R(V)/R\ (0) - V$, transmission measurements.

The a-Si:H top cell is made by RF-PECVD before it is transferred to VHF-PECVD system to deposit μc-Si:H bottom cell, it was exposure to air to oxide the n/p interface. The tandem solar cell consisted of the following structure: Glass/SnO_2:F/p-a-SiC/i-a-Si:H/n/oxide layer/p-μc-Si:H/i-μc-Si:H/n-a-Si/ZnO/Ag. All solar cells are characterized by light IV measurements under AM 1.5, 100 mW/cm^2, 25 °C. Spectral response measurements of the a-Si:H/μc-Si:H tandem solar cells are carried with red, blue and without bias light.

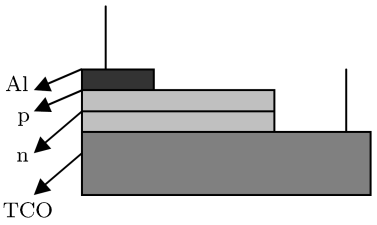


Fig.1. Schematic diagrams of n/p structure on TCO.

3. Results and discussions

3.1. The n/p or 2n/p type tunnel junction

In order to understand the difference between n/p and 2n/p type TRJ, three structures are made: the first is n-a-Si/n-μc-Si/p-μc-Si without interface oxidation; the second is n-a-Si/n-μc-Si/p-μc-Si with interface oxidation; the third is n-μc-Si/p-μc-Si with interface oxidation. As shown in Table 1, all samples have the same deposition conditions for the μc-Si:H p layers.

Table 1. The n/p tunnel recombination junction with different structures.

No.	Structure	n/p interface with oxidation treatment	R/(ohmic/cm^2)
1#	n-a-Si/n-μc-Si/p-μc-Si	No	5
2#	n-a-Si/n-μc-Si/p-μc-Si	Yes	2.5
3#	n-μc-Si/p-μc-Si	Yes	2.5

Figure 2 shows the I–V curves of the TRJs. All TRJs have Ohmic behaviour in the voltage range (–0.1 V–0.1 V), but 2# and 3# show better Ohmic characteristics than 1#, which indicate that the oxidation treatment has benefit to improve the contact characteristics of the junction. The reason can be attributed to the fact that the oxidation treatment of the n/p interface creates a high defective layer to enhance the recombination in the n/p junction and improve the nucleation of the μc-Si:H p layer, which can be confirmed by the Raman spectrum measurement of the p layer (not shown here). Among the devices with oxide treatment, 2# has better Ohmic behaviour than 3#, because 2# has a grading of doped n layer (from n-a-Si to n-μc-Si) which provides the diffusion gradient necessary to drive electrons produced in the n layer towards the recombination region.

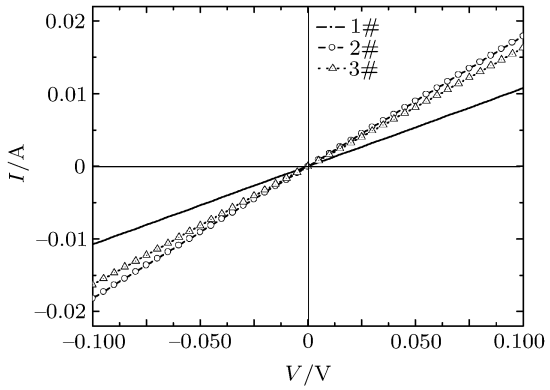


Fig.2. I–V curves of different n/p tunnel junctions.

Figures 3(a) and 3(b) show the voltage dependence of resistance (R) for three TRJs. To show the

contact behaviour more clearly we plot the $R(V)/R(0)$ versus voltage (Fig.3(b)). Three TRJs have resistance nearly symmetric about 0 V, indicating that these TRJs are not operating as n/p diodes, the dominant recombination process may be through multi-tunnelling or interface states.

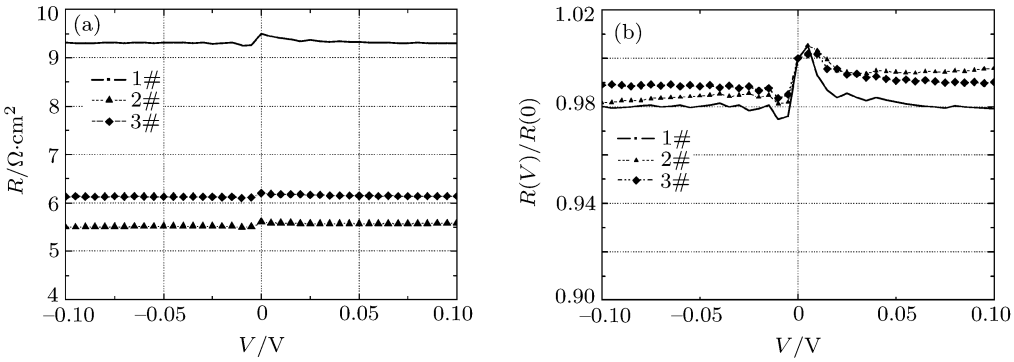


Fig.3. (a) Voltage dependence of resistance (V/I) of these p/n junctions. (b) Resistance normalized to value near 0 V.

The open circuit voltage V_{oc} of these n/p junctions are measured at AM1.5, with red filter and in dark respectively, a red filter ($\lambda > 580$ nm) is used to simulate the conditions of the TRJ in tandem solar cell. Results are shown in Table 2. The V_{oc} obtained at AM1.5 are higher than the V_{oc} obtained with red filter, in dark condition it has the lowest values. Considering that the light arriving at the TRJ is mainly long wavelength light, we find that the best device is 3# because of its lowest V_{oc} with the red filter. Transmission spectrum measurements show that there is no optical loss for 2# and 3# in comparison with 1#.

Table 2. The V_{oc} of the n/p junctions, measured at AM1.5, with red filter and in dark respectively.

No.	2n/p (without)	2n/p (with)	n/p (with)
V_{oc}(AM1.5)/V	1.15	1.07	0.94
V_{oc}(red filter)/V	1.0	0.95	0.92
V_{oc} in dark/V	0.96	0.90	0.88

3.2. Micromorph tandem solar cell

The above-mentioned TRJs are used in a-Si:H/μc-Si:H tandem solar cell to study their influence on the cell performance. We use the air exposure as the oxidation treatment. Table 3 lists different n layers, p layers and different interface treatments of micromorph tandem solar cells.

Table 3. Different n layers and different n/p interface treatments of micromorph tandem solar cells with p layers deposited with the same conditions.

cell series	n layer	p layer	n/p interface treatment (air exposure)
1#	25 nm a-Si:H	30 nm μc-Si:H	No
2#	26 nm μc-Si:H	30 nm μc-Si:H	No
3#	3 nm a-Si:H+23 nm μcSi:H	30 nm μc-Si:H	No
4#	6 nm a-Si:H+20 nm μc-Si:H	30 nm μc-Si:H	No
5#	6 nm a-Si:H+20 nm μc-Si:H	30 nm μc-Si:H	Yes

The quantum efficiency (QE) of micromorph tandem solar cells are measured under red bias light, blue bias light and without bias light, more details can be seen from another paper.[20] Figure 4 shows the results of measurements. As can be seen from Fig.4(a) that when pure a-Si:H n-layer is used, QE measured in dark condition (without bias light) follows the response of the sub-cell with the lowest current at each wavelength, showing nearly a triangular shape, when μc-Si:H n-layer is used, a departure of lowest spectral

response in the long wavelength range (> 600 nm) is observed, while in the short wavelength it is in accord with the response of the bottom cell. As discussed by Loffler[18] and Rubinelli,[21] this indicates that there is apparent current leakage of the top cell because of an inefficiency blocking the current generated in bottom cell by the top cell. Implementing a thin n-a-Si:H layer between the a-Si:H i-layer and μc-Si:H n-layer, decreasing the thickness of the μc-Si:H n-layer at the same time, we find that the current leakage effect becomes smaller (Figs.4(c) and 4(d)). When the thickness of the a-Si:H n-layer is increased to 6 nm while decreasing the thickness of the μc-Si:H n-layer to 20 nm, the spectral response in dark condition follows the expected curve along the lower current of the two individual cells at each wavelength perfectly, the shunting disappears.

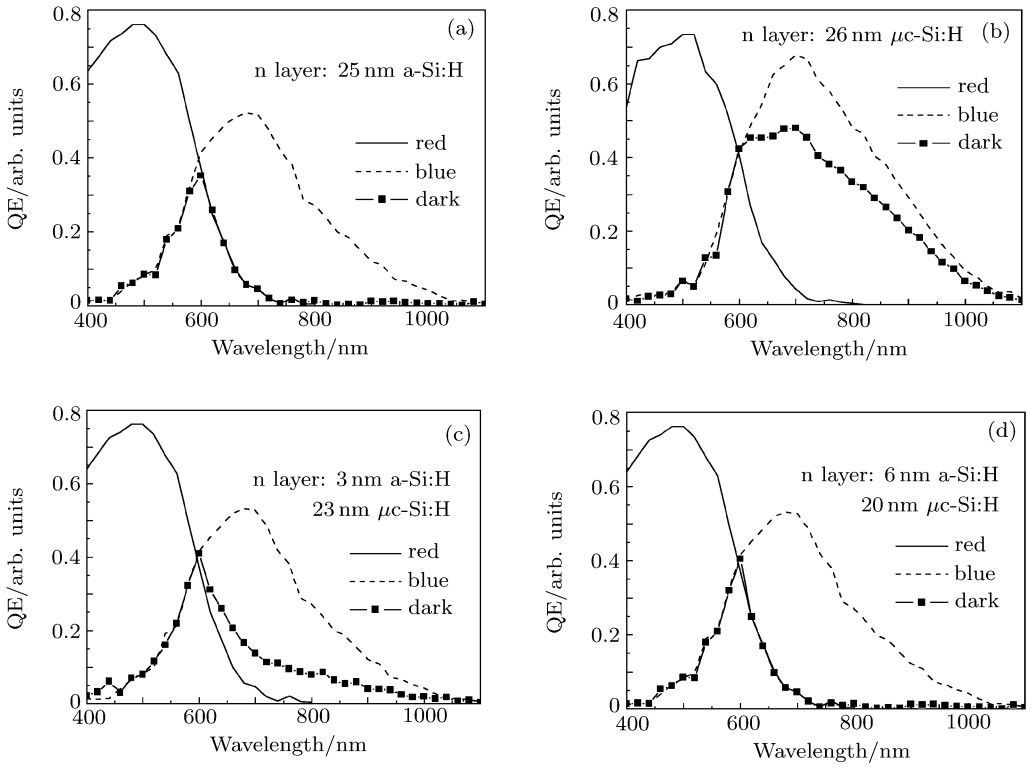


Fig.4. Quantum efficiency (QE) of micromorph tandem solar cells with different n layers in TRJ. The dashed line represents the measurement with blue bias light, the solid line represents the measurement with red bias light, the square shows the measurement in the dark (without bias light).

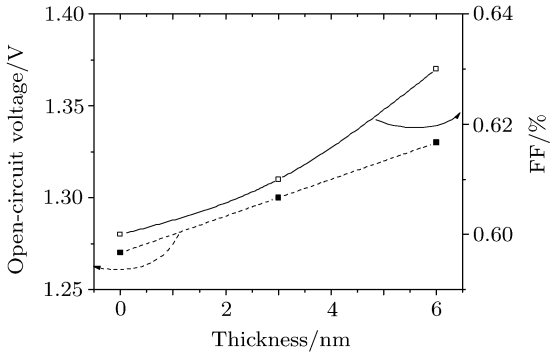


Fig.5. V_{oc} and FF as a function of the thickness amorphous n-layer.

Introduction of a thin a-Si:H n-layer solves the problem of the current leakage of the top cell, thus leads to an increasing of V_{oc} and FF of micromorph tandem solar cells, as described in Fig.5. When increasing the a-Si:H n layer thickness from 0 nm to 6 nm, the V_{oc} is increased from 1.27 V to 1.33 V and the FF is increased from 0.6 to 0.63. The other reason for the V_{oc} improvement can be attributed to the fact that the implementing of a thin n-a-Si layer also solves, at least partly, the existence of a band discontinuity between a-Si:H i-layer and μc-Si:H n-layer. A similar explanation was given by Pellaton Vaucher.[22] The improvement of FF can be attributed to better

Omhic contact, which has been discussed in Section 3.1.

The role of the interface oxidation is also studied. The I–V curves are shown in Fig.6. There is a slight improvement of the V_{oc} (from 1.33 V to 1.35 V) and FF (from 0.63 to 0.65) after interface oxidation, spectral responses of the top and bottom cells are similar for two cases. From Section 3.1 we can see that oxidation of the n/p interface creates a defective layer and thus enhance the recombination in tunnel junction between the top and bottom cell, leading to an improvement of the cell performance.

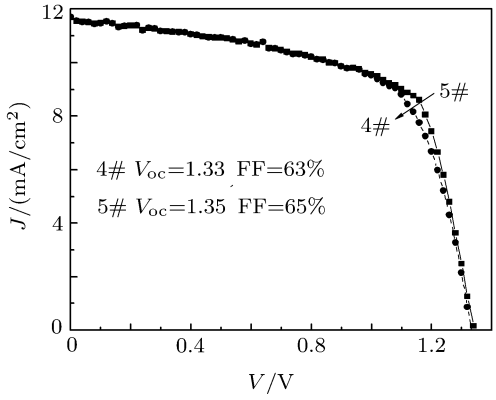


Fig.6. The $J-V$ curve of the tandem solar cell with (5#) and without (4#) oxide treatment of the n/p interface.

4. Conclusions

We introduce a double n layer (a-Si/μc-Si) to substitute the single μc-Si:H n-layer in TRJ. We find that this new structure shows a better Ohmic behaviour since it provides a diffusion gradient necessary to drive electrons produced in n layer toward the recombination layer. When oxidation treatment is performed in TRJ, a defective layer is created and thus enhances recombination in tunnel junction. As a result, the n/p junction shows a better contact characteristic.

The TRJ containing a thin a-Si:H n-layer and a μc-Si:H n-layer is implemented in the micromorph tandem solar cell. An a-Si:H n-layer with thickness of 6 nm can effectively block the current leakage of the top cell. The absence of the current leakage leads to an improvement of the V_{oc} and FF of micromorph tandem solar cell. Interface oxidation of TRJ can improve the V_{oc} and FF further.

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