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Low-Resistance TCO n-p Tunnel Recombination Junction for Multi-Cell Interface Layers in Thin-Film Solar Cells

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1. Introduction

Multi-junction thin-film solar cells are promising devices which realize highly efficient and low cost electricity production. The combination of these cells with a low concentration of sunlight is an effective scheme for a further increase in conversion efficiency.[1] Under concentrated illumination with a multiplied photo current, the energy loss by series resistance becomes more significant. Series resistance is the sum of the resistances of the silicon layers, electrodes, contacts and inter-cell junctions, etc.[2] Of these, the resistance of the inter-cell junctions is dominant. Moreover, it is multiplied by the number of junctions. Therefore low resistance inter-cell junctions are indispensable for multi-junction thin-film solar cells.

Two types of inter-cell junctions with Si based tandem cells have been reported.[3] Type 1 is tunnel recombination junctions[3] (TRJ) consist of highly doped p/n homo junctions, or hetero junctions, or inserted p/n junction layers. Type 2 is interlayers[4,5] which consist of highly doped degenerated transparent conductive oxides (TCOs). Combining these two, we proposed[6] a TCO tunnel recombination junction (TCO-TRJ) consisting of TCO-p/n junction layers inserted between sub-cells. We expect to obtain low resistance inter-cell junctions with enhanced tunneling without energy loss by utilizing degenerated TCO-p/n junction.

To realize the ideal TCO-TRJ, we found that the careful control of oxygen deficiency (or excess) at the p/n interface is necessary to exclude carrier depletion as shown in Fig. 1. In this paper, we report the successful fabrication of low resistance TCO-TRJs by controlling the gas supply during the sputtering deposition, and by introducing a new stack configuration. Furthermore, the applicability of these TCO-TRJs to amorphous-Si/microcrystalline-Si (a-Si/μc-Si) tandem cells is demonstrated by showing their effectiveness in the operation under concentrated illumination.

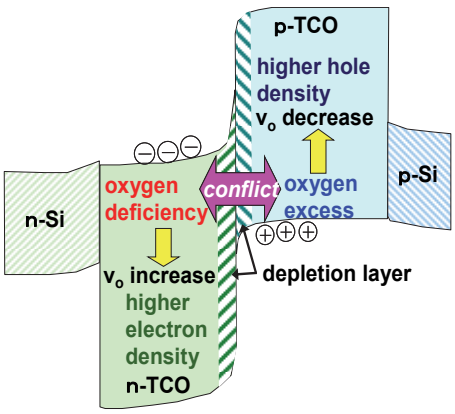

Fig. 1. Schematic illustration of the band diagram of the TCO n-p junction layer inserted in the sub-cell n-p tunnel junction.

2. Experimental

The TCO layers were deposited by radio frequency (RF) magnetron sputtering using Ar and O_2 as sputtering gases, and additionally N_2 was introduced. We studied ZnO:Al and InZnO as n-type TCOs and NiO:Li as p-type one. The substrate temperature was set at 200 ºC, and the pressure of the chamber during depositions was 0.3-0.5 Pa. The RF power for the sputtering was 100 W.

We developed two model device structures. One was for measuring the contact resistances of the TCO-TRJ (Model I). The other was for measuring the total contact resistances of the junction of n- and p-type Si layers interposed by TCO-TRJ in between (Model II). Model I devices were fabricated on n-Si substrates. The TCO-TRJ structure and Au contact electrode were deposited with the same metal mask. Finally Ti/Al was deposited for the back contact. Model II devices were fabricated on glass substrates with an n-TCO. The TCO-TRJ structure was sandwiched between n and p-type μc-Si layers formed by chemical vapor deposition. After the deposition of a ZnO/Ag contact electrode, the devices were isolated by a laser scribing method. Differential contact resistances were obtained from current density vs. applied voltage (J-V) measurements.

Amorphous-Si/(TCO-TRJ)/μc-Si tandem cells were fabricated on textured substrates with the TCO contact layer. The basic characteristics under 1 sun and 5 suns illumination were investigated.

3. Results and Discussion

Figure 2 shows the electrical characteristics of TCO-TRJs using Model device I. The J-V curve for a ZnO/NiO-TRJ with process conditions before improvements is shown in Fig. 2a. The obtained differential resistance as a function of current density is shown as curve #1 in Fig. 2b. It can be seen that the rectifying and non-Ohmic characteristics are both large, and the estimated contact resistance at zero current is about 10 Ωcm^2.

The main origin of the carrier depletion which forms the high resistance region at the interface was attributed to be the excess oxidation of the ZnO surface during the NiO deposition with an oxygen plasma environment. To diminish the influence of the oxygen plasma the NiO sputtering conditions were optimized: shortening the pre-sputtering time and minimizing the oxygen supply. Curve #2 in Fig.2b

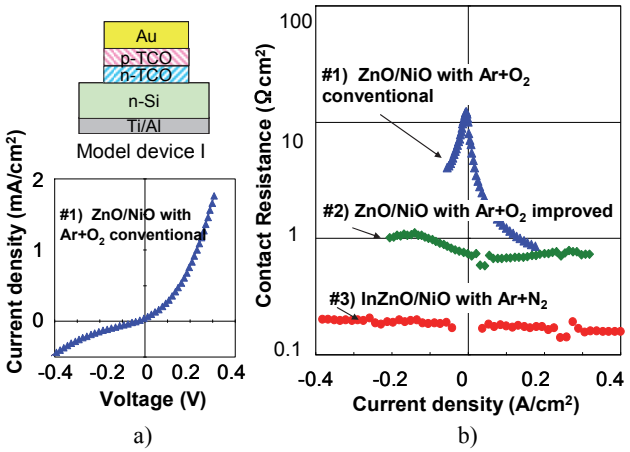

Fig. 2. Electrical characterization of TCO-TRJ using Model device I: a) current density as a function of voltage for the conventional deposition process #1 and b) contact resistance as a function of current density for three processes.

shows the results for ZnO/NiO-TRJ with the improved condition.

Further improvement was made by changing the n-type TCO from ZnO to InZnO and introducing N_2 in addition to Ar during the deposition. Curve #3 in the Fig. 2b shows the R-J data for the InZnO/NiO-TRJ with Ar+N_2 condition. From the figure, the ohmic (i.e. voltage independent) characteristic and the low contact resistance of about 200 mΩ cm^2 can be confirmed.

The total junction resistance of the n-Si/ TCO-TRJ/p-Si structure was investigated by using Model device II with glass substrate as shown in Fig. 3. When the InZnO/NiO-TRJ was formed by the improved sputtering condition mentioned above, the bottleneck of the resistance (shown as curve #5) was found to shift to the p-TCO/p-μc-Si interface, and the origin of the high resistance is presumed to be the chemical reduction of the NiO surface by hydrogen plasma during the p-μc-Si deposition and/or the potential barrier in the p/p isotype junction.

To overcome this problem, we introduced an n-μc-Si/(p-NiO/n-InZnO)/p-μc-Si configuration where the TRJ has the p-TCO under the n-TCO (reversed order) and the three

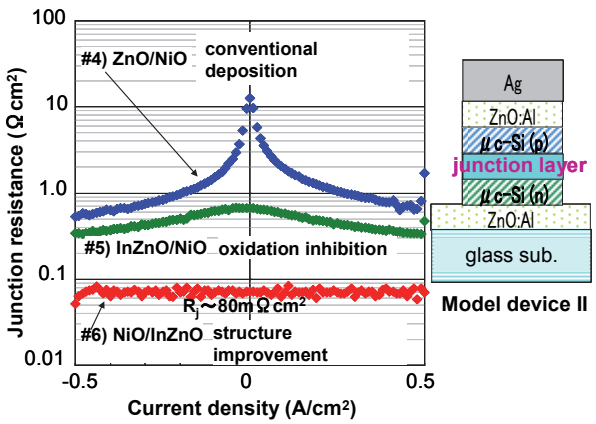

Fig. 3. Junction resistance of n-μc-Si /TCO-TRJ/p-μc-Si structures as a function of current measured by using Model device II.

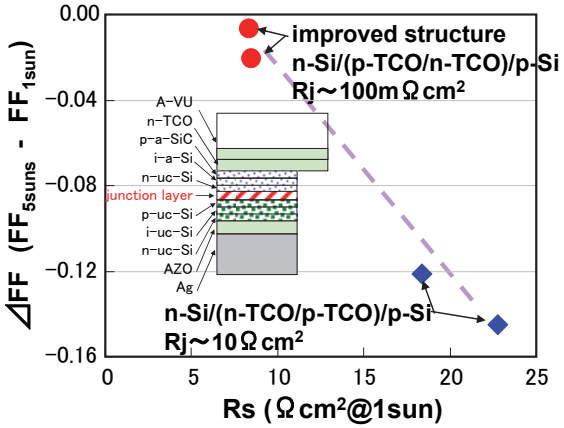

Fig. 4. Relationship between the fill factor deterioration by 5 suns illumination and the series resistance observed in the a-Si/(TCO-TRJ)/μc-Si tandem cells with conventional and improved junction layers.

junctions are all anisotype TRJs. The R-J curve of this model device is shown as curve #6 in Fig.3. By using this NiO/InZnO junction layer a junction resistance as low as 80 mΩcm^2 was achieved.

The applicability of these TCO-TRJs to a-Si/μc-Si tandem cells under concentrated operation was investigated. Figure 4 shows the relationship between the fill factor deterioration by 5 suns illumination and the series resistance observed in the tandem cells with conventional and improved junction layers. By improving the junction layer from the 10 Ωcm^2 grade conventional type to the 100 mΩcm^2 grade low resistance one, the FF deterioration was suppressed to as low as -1%.

To our knowledge, this is the first report to demonstrate the systematic suppression of FF deterioration in connection with the inter-cell junctions of Si-based tandem cells under concentrated illumination.

4. Conclusions

The sub-cell junction resistance for the TCO-TRJ of a model device was successfully decreased by diminishing the effect of oxygen plasma by choosing InZnO as an n-TCO and using N_2 gas during deposition. Finally, a junction resistance of 80 mΩcm^2 was achieved by using a NiO/InZnO reversed order junction layer. The effectiveness under 5 suns concentrated operation of the TCO-TRJs applied to a-Si/μc-Si tandem cells was demonstrated.

Acknowledgements

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