ABSTRACT: Resistive losses arise at the transport barriers at the interfaces between the different semiconductor materials in the TCO/a-Si/c-Si stack and limit the power output of silicon heterojunction (SHJ) solar cells. A key element is the unisotype recombination junction at the TCO/a-Si(p) interface. We identify sufficient doping on both sides of this junction to be crucial for low contact resistance ($\rho_c$). For a-Si this is achieved by using a sufficient but not too high doping gas concentration during deposition. On the TCO side high oxygen ($O_2$) gas concentration during deposition have to be avoided. To combine high transparency of $O_2$-rich TCOs with low $\rho_c$ and $R_{\text{sheet}}$ of $O_2$-poor TCOs, we utilize a TCO layer stack. We show that a low $O_2$ content in the vicinity of the TCO/a-Si(p) interface is mandatory to provide efficient tunnelling transport and to avoid resistive losses at the TCO/a-Si(p) interface.

Keywords: Silicon Heterojunction, Amorphous silicon, Doping, Contact resistance

1 INTRODUCTION

Silicon heterojunction (SHJ) solar cells hold the current world record efficiency for silicon single junction solar cells [1]. One of the remaining limitations are the significant resistive losses originating at the critical TCO/a-Si and a-Si/c-Si junctions [2, 3]. The contact resistivity ($\rho_c$) at the hole contact is one of the main contributors to the cell’s series resistance ($R_s$) [4, 5]. The unisotype recombination junction at the TCO/a-Si(p) interface relies on efficient tunnelling transport, either via direct tunnelling or facilitated via trap states within the band gap (trap-assisted tunnelling, TAT) [6–8].

Optimizing transport in SHJ is governed by the trade-off between optical and electrical properties. On the TCO side, transparency and conductivity can be tuned via the TCO oxygen ($O_2$) content [9]. While high-mobility TCOs with $\mu_{\text{TCO}} > 100$ cm²/Vs allow the reduction of charge carrier concentration ($N_{\text{TCO}}$) for higher transparency while maintaining high lateral conductivity [10], issues regarding rather high $\rho_c$ have been reported [11]. One approach to decouple optical and electrical as well as bulk and interface properties, is to utilize layer stacks [11–13].

In this contribution we present a thorough investigation of the ITO/a-Si(p) contact resistivity. First, the optimum a-Si doping regarding $\rho_c$ is determined. Second, $\rho_c$ is screened over a wide range of ITO $O_2$ contents. We show that, aside lateral transport ($R_{\text{sheet}}$), vertical transport ($\rho_c$) can also be strongly effected for highly transparent but low conductive TCOs. Finally, the beneficial effect on $\rho_c$ of an $O_2$-poor ITO interlayer combined with an $O_2$-rich “bulk” ITO is presented. For our more detailed investigation of the influence of doping on SHJ contacts including numerical device simulations and solar cell results we refer to [14].

2 EXPERIMENTAL

Fig. 1 shows sketches of the resistance test structures that were utilized to evaluate the TCO/a-Si contact resistance. The basic fabrication is described in [3]. To realize the doping variation within a-Si(p), the trimethylborane (TMB) gas concentration during plasma-enhanced chemical vapor deposition (PECVD) was varied while the total gas flow and all other deposition parameters were fixed. The ITO doping was changed via the $O_2$ content in the sputtering gas during deposition. In both cases, the deposition time was adapted to reach a comparable layer thickness for all groups. TCO layer properties for films on glass substrates were obtained from Hall effect measurements using the van der Pauw’s method. Prior to the $I$–$V$ measurements, the structures were annealed on a Präzitherm hotplate in ambient air at 180 °C for 10 min. Two-terminal $I$–$V$ measurements were performed on a WAVEABS Sinus-220 at 25 °C.

![Figure 1: Sketch of the used resistance test structures. The intrinsic a-Si layer was omitted for the ITO $O_2$ content variation to be more sensitive to the TCO/a-Si contact. The rear contact of all groups comprised only boron doped a-Si with fixed doping concentration and full area metallization.](image)

3 RESULTS

The dependence of $\rho_c$ on the TMB gas concentrations is shown in Fig. 2. An optimum was observed at a doping gas concentration of 3 % for samples with ITO (dotted lines) and without ITO (solid lines). Optimum $\rho_c$ was 150 $\Omega$cm² without and 200 $\Omega$cm² with ITO. The increase in $\rho_c$ due to ITO was lowest at 3 % (+50 $\Omega$cm²) and significantly higher at lowest...
(+200 mΩ-cm²) or highest TMB gas concentration (+500 mΩ-cm²). The optimum doping concentrations of TMB was used for the ITO O₂ content variation and the ITO stacks in the following sections.

The influence of the O₂ content on ρ_h is depicted in Fig. 3. ρ_h was rather constant in the range of 0-1.6 % O₂ content. Lowest ρ_h values were obtained for ITO deposited with a medium O₂ content of 1.6 %, but no clear optimum could be resolved due to wafer to wafer scattering. For highly transparent ITO with high O₂ content ρ_h increased significantly. ITO sheet resistances displayed at the top x-axis were measured on glass in the as deposited state. Similarly to ρ_h, R_sheet increased with rising ITO O₂ content.

Fig. 4 shows again the increased ρ_h of O₂-rich ITO (3.5 %, group 2) compared to medium-O₂ ITO (1.6 %, group 1). By inserting a 20 nm-thick O₂-poor ITO (1.0 % O₂) interlayer between a-Si(p) and the O₂-rich ITO, the ρ_h was reduced by about 60 mΩ-cm² (group 3) to nearly the same value as for the single layer medium-O₂ ITO (1.6 %, group 1). When the 20 nm-thick O₂-poor ITO (1.0 % O₂) interlayer was inserted at the metal/ITO interface, the ρ_h was also reduced to a value of 100 mΩ-cm² (group 4)).

**DISCUSSION**

In case of the a-Si doping variation in Fig. 2, ρ_h is expected to be lowest for a-Si with the highest active dopant concentration. For too low TMB concentration not enough dopants are incorporated in the a-Si layer. For too high TMB concentrations the increased defect density drastically lowers the doping efficiency [15–17]. In both cases, the active dopant concentration is insufficient to provide proper hole conductivity via induced c-Si band bending in the contact region [8, 18]. Additionally, the TCO/a-Si(p) contact suffers from insufficient a-Si doping. This contact relies heavily on tunnelling transport. As the charge carrier concentration N_{a-Si(p)} decreases with non-optimal doping, the depletion width and therefore the barrier width increases. This reduces the tunnel probability, hence ρ_h of the TCO/a-Si(p) contact increases.

On the TCO side, in principle, exists a trade-off for hole contact transport between high N_{TCO} at low O₂ content and better work function matching to a-Si(p) at high O₂ content. In [13, 19] it was shown, that the ITO work function could indeed be tailored by varying the O₂ content to either facilitate hole or electron extraction. However, on device level, transport was not improved with higher O₂ content. Similarly, in Fig. 3 ρ_h increased with rising O₂ content. Thus, it seems that the less efficient tunnelling at high O₂ content is more relevant for the contact resistance, as the better work function matching at the TCO/a-Si(p). In addition to reduced tunnel probability due to reduced N_{TCO}, the formation of a resistive interlayer might also impede transport [19]. Considering the negative Gibbs formation energy for the silicon oxidation reaction at the ITO/a-Si interface [20, 21], the formation of a silicon oxide layer upon TCO...
growth is feasible [13, 19, 22, 23]. During the annealing step this silicon oxide might thicken or densify further.

To combine high transparency and low resistance for solar cell application, an ITO stack was utilized (Fig. 4). During the annealing step the O₂ content in the ITO stack might balance and result in an ITO with overall lower O₂ content compared to the reference without interlayer, explaining the lower overall ρ despite such an interlayer. However, the comparison between groups 3 and 4 in Fig. 4 shows that in particular at the ITO/a-Si interface the O₂ content has to be low respectively N_{TCO} has to be high for low ρ. Moreover, similar results were obtained with twice the O₂-rich ITO thickness and even thinner O₂-poor ITO interlayers down to 4 nm [14]. Thus, ρ is rather governed by properties in the vicinity of the TCO/a-Si interface than ITO “bulk” properties. The reason for the improved ITO/a-Si(p) contact with such an O₂ poor interlayer could be (i) enhanced tunnel probability due to higher N_{TCO} at the interface, (ii) the avoidance or the less pronounced formation of a resistive layer at the interface due to the lower oxygen content or (iii) a combination of (i) and (ii).

5 CONCLUSION

The hole contact resistivity of SHJ stacks was studied with respect to doping on both sides of the ITO/a-Si(p) junction. On the a-Si(p) side, an optimum regarding ρ was found when sufficient but not too high doping gas concentration during deposition was used. On the ITO side, increasing O₂ content lead to increased ρ due to reduced N_{TCO} and/or the formation of a resistive interlayer. It could be shown that the use of a thin layer of low-O₂ ITO at the ITO/a-Si(p) interface decreases ρ and relaxes the trade-off between optical and electrical TCO properties. The use of such a TCO stack can lead to improved power conversion efficiency on cell level.

6 ACKNOWLEDGMENT

The authors would like to thank A. Leimenstoll, F. Schätzle, K. Zimmermann for sample preparation and D. Kurt and Z. Newcomb-Hall for sample preparation and dark J-V measurements.

This work was funded by the German Federal Ministry for Economic Affairs and Energy under contract No. 03EE1032 (CUSTCO) within the SOLAR-ERA.NET program.

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