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Theoretical Study of Transparent Conducting Oxide and Amorphous Silicon Interface and Its Impact on the Properties of Amorphous Silicon/Crystalline Silicon Heterojunction Solar Cell

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Abstract

The physics of transparent conducting oxide (TCO) and n-type doped amorphous silicon interface has been studied with the aid of two-dimensional numerical simulations (Sentaurus TCAD, Synopsys), in order to determine the impact of the TCO work-function on the electrical performance of amorphous silicon (a-Si)/crystalline silicon (c-Si) heterojunction solar cell. Previous studies have indicated requirement of lower work-function for TCO in contact with n-type doped a-Si for higher solar cell efficiency. However due to the limitations in TCO deposition process conditions it is not possible to achieve a work-function below a certain value which limits the device efficiency. An alternate approach has been explored where the TCO in contact with n-type doped a-Si has been eliminated and a direct contact has been established with the metal. This has resulted in significant improvement in the calculated device efficiency due to the principal contribution from increased open circuit voltage and fill factor.

Keywords: Heterojunction solar cell; amorphous silicon; transparent conducting oxide; work-function

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1. Introduction

The amorphous silicon (a-Si)/crystalline silicon (c-Si) heterojunction solar cells [1] combine the superior efficiency of c-Si along with low cost advantage of a-Si. Compared to homojunction c-Si solar cells, the device exhibits lower efficiency reduction with increasing device temperature and a higher open circuit voltage potential [2]. Transparent conducting oxide (TCO) is an essential component of the heterojunction solar cell, which is needed for optical transparency, conductivity as well as work-function matching between silicon and metallic contacts. TCO is in direct contact with the emitter (a-Si). The doping of the emitter and TCO work-function together determine the band-bending and current transport across the device.

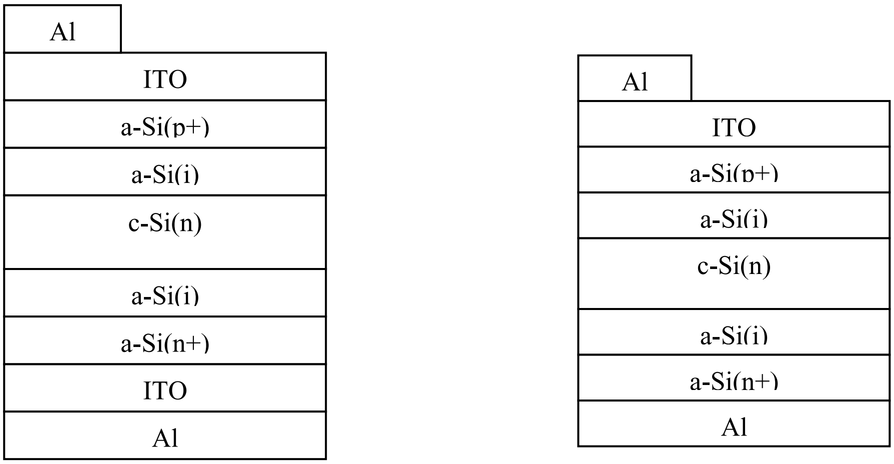
The focus of the current study is to understand the physics of TCO and n-type doped a-Si interface, in order to determine the impact of TCO work-function on the electrical performance of a-Si/c-Si (n-type) silicon heterojunction solar cell. We have considered indium tin oxide (ITO) as the TCO material. Prior studies [3, 4] have indicated that for best solar cell efficiencies, work-function of front TCO in contact with a-Si(p+) layer should be as high as possible and that of the TCO which is in contact with the rear a-Si(n+) layer should be as low as possible. This would imply the use of different type of TCO on the front and rear of the solar cell, which would be practically difficult and expensive process. Also recent experimental literature [5, 6] suggests the range of rear ITO work-function to be 4.4 eV-4.9 eV, which would limit the device efficiency. We have explored an alternative approach where we eliminate the rear TCO altogether.

2. Simulations

The numerical simulations have been carried out using Sentaurus TCAD tool [7]. It uses finite element method in which a real semiconductor device is represented as a 'virtual' device whose physical properties are discretised onto a non-uniform grid or mesh.

The device structures for simulations are depicted in Figs. 1(a) and 1(b). The first device consists of c-Si substrate of n-type doping (c-Si(n)), on either side of which intrinsic amorphous silicon (a-Si(i)) of band-gap = 1.72 eV is placed. The front layer which forms the emitter is p-type doped a-Si (a-Si(p+))and back surface is n-type doped a-Si (a-Si(n+)), both of which have band-gap = 1.74 eV. ITO of work-function = 4.7 eV is placed between a-Si and aluminium metal contacts (from literature [5, 6] it is known that ITO work-function ranges from 4.4 eV to 4.9 eV and we have used the average value). In the second device, rear ITO has been removed and direct contact is established between a-Si(n+) and aluminium metal.

For electrical modelling, we have used the drift-diffusion model as the transport model in the device regions and thermionic emission, band-to-band tunneling at the hetero-interfaces as described by Schulze *et al.* [8]. The amorphous layers have two Gaussian defects and exponential band-tails from the band edges. Defect recombination in the bulk and interfaces is modeled with Shockley-Read-Hall model; in addition, Auger recombination in c-Si is taken into account using standard values for c-Si [9]. The metal-semiconductor contact has been assumed to be of Schottky type. We have made use of Fermi Dirac statistics for carrier distribution. For optical modelling we have made use of the Transfer Matrix Method (TMM). The illumination spectrum used is air mass 1.5 (AM1.5). The device parameters for modelling have been taken from experimental data described in literature. Device level simulations have been performed on the two devices (with and without the rear ITO) and comparison has been made between energy-band diagram, electrical parameters and recombination rates.



(a) (b)

Fig. 1. (a) Device structure for simulations; (b) Device structure for simulations after removal of rear ITO

3. Results and discussion

3.1. Energy band-diagrams of the device with and without rear ITO

Shown in Fig. 2 is the simulated energy band diagram comparison of the devices with and without the rear ITO. As can be seen, the barrier for the electron transport from a-Si(n+) to the rear metal contact reduces upon removal of the rear ITO. This indicates improvement in the fill-factor due to reduction in the series resistance and an improvement in the open-circuit voltage owing to favourable band-bending. The work function of aluminium (= 4.1 eV) being less than ITO, forms a better contact to n-type a-Si.

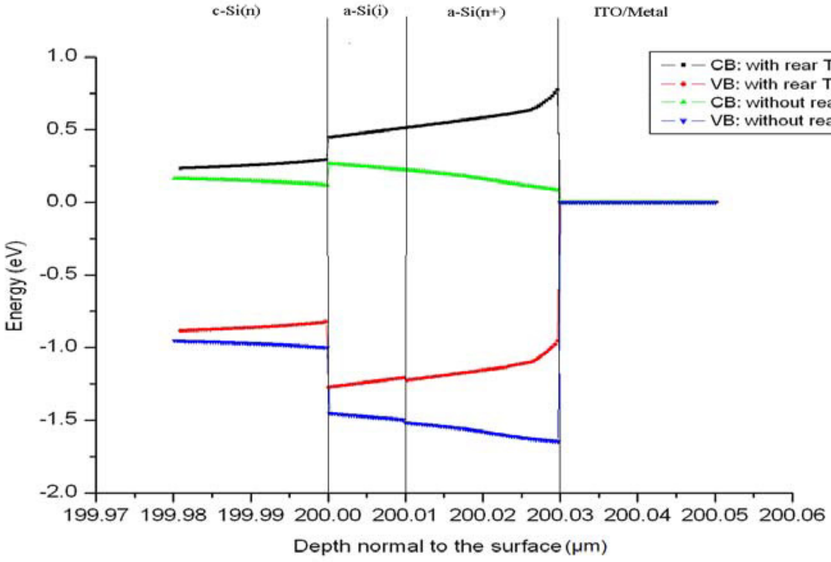


Fig. 2. Energy band-diagram comparison of the devices with and without rear ITO

3.2. Electrical parameters of the device with and without rear ITO

Shown below in Table 1 is the simulated improvement in the electrical performance of the device after removal of rear ITO.

Table 1. Simulated improvement in the electrical performance of the device after removal of rear ITO

Parameter	% improvement after removal of rear ITO
Jsc	4
V_{oc}	18
Fill Factor	71
Efficiency	110

From the above results, we note a significant increase in fill-factor and V_{oc} upon removal of the rear ITO, which leads to more than doubling of the device efficiency. There is also a slight improvement in the short circuit current density (Jsc). This could be due to better carrier-carrier separation and improved a-Si/c-Si interface giving reduced interface recombination. Bivour *et al* in Ref. [10] through experiments have also observed increase in the device fill factor upon removal of rear ITO, which they have attributed to the increase in series resistance upon addition of ITO.

3.3. Recombination rates of the device with and without rear ITO

Shown below in Fig. 3 is the simulated comparison plot of Shockley-Read-Hall (SRH) recombination rates for the devices with and without rear ITO. These plots indicate reduction in the SRH recombination upon removal of the rear ITO. This in turn indicates better separation of the generated carriers due to favourable band-bending, hence improvement in open circuit voltage (V_{oc}).

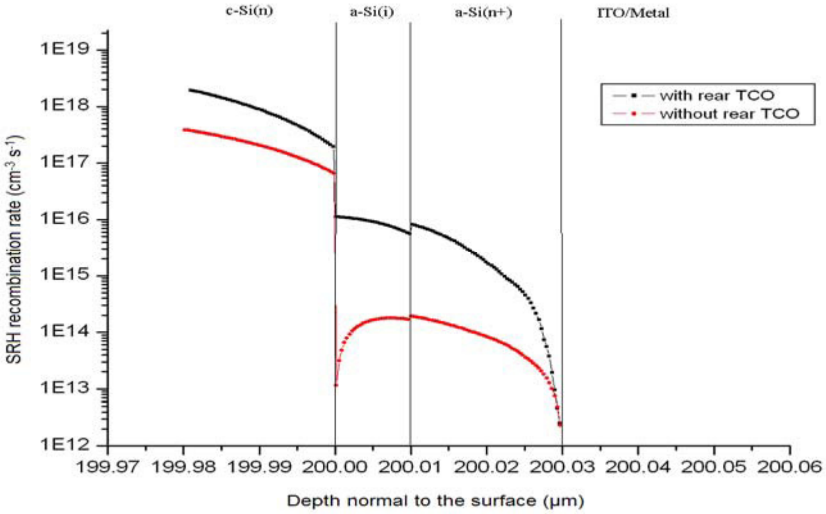


Fig. 3. Simulated Shockley-Read-Hall recombination rates for devices with and without rear ITO

4. Conclusions

With the aid of numerical simulations we have studied the physics of the interface of transparent conducting oxide (TCO) and n+ a-Si, with the objective of maximising the efficiency of a-Si/c-Si heterojunction solar cell. We have considered indium tin oxide as the TCO material. Prior studies [3, 4] indicated requirement of low work-function for TCO which is in contact with n-type doped amorphous silicon. The relatively higher work-function of ITO (4.4 eV-4.9 eV) [5, 6] limits the device efficiency. We have explored an alternate approach of eliminating the rear ITO altogether which is in contact with n+ a-Si. With the aid of simulations we have compared the structures with and without rear ITO and observed significant increase in device electrical performance upon removal of the rear ITO. The increase in fill-factor is due to the reduction in barrier for electron transport from the amorphous layer to the rear metal contact as seen from simulated energy band diagrams. The increase in open-circuit voltage is due to reduction in recombination as seen from simulated Shockley-Read-Hall (SRH) recombination plots.

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