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CONTRIBUTION OF P-I INTERFACE BUFFER LAYER TO THE PERFORMANCE OF SUPERSTRATE NANOCRYSTALLINE SILICON SOLAR CELL

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Thin film nanocrystalline silicon has been widely investigated since the last decade because of its attractive opto-electronic properties. Solar cell based on this material is stable upon prolonged exposure to light and also absorbs energy of the solar spectrum up to the near infra red region. These features have led to its use in tandem with an amorphous silicon top cell for enhanced solar cell performance in the so-called micromorph solar cell. This paper investigates using advanced semiconductor analysis (ASA) simulation the use of buffer layer at the p-i interface of a superstrate nanocrystalline silicon solar cell and how this affects the solar cell performance. The p-i interface is critical to solar cell performance because it is a defect-rich region and band-gap offset is likely here. The use of buffer layers therefore reduces this band-gap offset. For this work we have tested the potential of using p-doped nanocrystalline silicon layer and a p-type amorphous silicon carbide as p-i interface buffers. Our results show that the effect of buffer layer depends on the material used, its band gap and thickness. Using a p-type nc-Si:H buffer yields no significant effect on the performance parameters of the solar cell for all the band gap and thickness ranges investigated. On the other hand, an amorphous silicon carbide buffer of suitable thickness significantly increases solar cell performance parameters.

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1. Introduction

Thin film-based solar cells have generally received a lot of attention in recent times and have been considered the most widespread alternative to bulk crystalline solar cell [1]. This interest is based on the low material consumption, the relatively low cost and large-area deposition possibilities at relatively low substrate temperature [1-3]. This low temperature deposition offers the possibility to produce flexible and light-weight solar panels which can be used to cover the roof of factory buildings for instance. Deposition at low temperature allows for the use of cost-effective substrate materials such as glass, stainless steel and plastic.

Thin film nanocrystalline silicon evolved first as thin film microcrystalline silicon, μc-Si:H and later into what is today thin film nanocrystalline silicon. First μc-Si:H layers were deposited by Veprek and Marack [4]. In 1979 Usui and Kikichi [5] doped the first microcrystalline layer using strongly hydrogen-diluted silane in a plasma induced microcrystalization at a deposition rate of less than 10^{-3} nm/s. The first substrate and superstrate-type solar cells of entirely thin film nanocrystalline layers with efficiency above 7% were made at the Université de Neuchâtel in 1996 [6]. Since then, research effort has been put into utilizing and optimizing the inherent advantages of this cell such as its stability against light-induced degradation and the extension of its spectral response to the near infrared light region. Today, thin film nanocrystalline

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solar cells are used as bottom cell in tandem and triple junction cells. In tandem cells, they are particularly used as the bottom cell to collect the less energetic photons transmitted through the top cell and to aid tunnel/recombination junctions that form the connection between individual cells. The absorption of the nc-Si:H material covers also the near infra red region of the solar spectrum (up to wavelengths of 1100 nm) and its band gap ($E_g \approx 1.1$ eV) make it a near-perfect match for amorphous silicon/nanocrystalline silicon tandem (micromorph) solar cell. Its low absorption at this spectral region (see figure 1) requires a relatively thick absorber layer and an efficient light trapping scheme for sufficient current generation to ensure current matching in the tandem cell.

The interface between the p-type and the intrinsic nc-Si:H layers have been long known as a sensitive interface which can affect solar cell performance [7]. Being an interface for two materials of different band gap, the issue of band gap offset always arises and this effect is linked to charge carrier extraction losses. Because of the different conditions under which these two layers are deposited, carrier transport through the interface can be difficult to predict. Large defect concentrations have been shown to dominate this region [8]. This paper presents a theoretical investigation into the use of buffer layers as a solution to the problems related to the p-i interface. The aim is to further understand how different buffer materials and their properties can affect nc-Si:H solar cell performance.

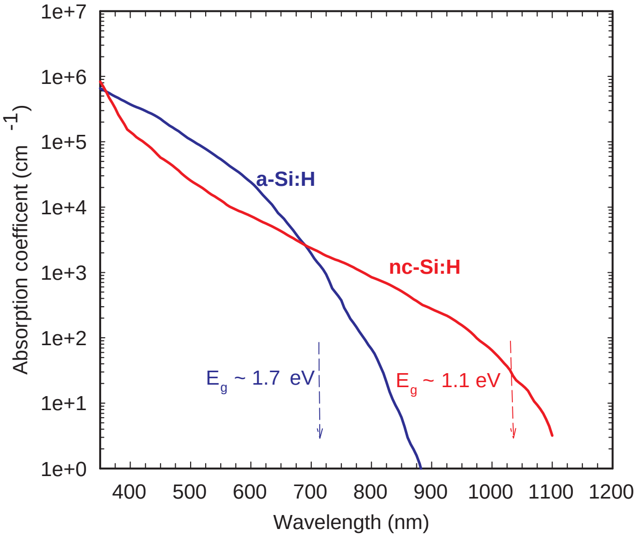


Fig. 1. The absorption as a function of wavelength of thin film nanocrystalline silicon compared to that of a-Si:H. The band gaps, E_g, of the two materials are shown.

2. Materials and method

The work reported here is based on both experimental and theoretical investigation. The experimental part involved the deposition of thin film nanocrystalline silicon layers and solar cells and the amorphous silicon carbide layer. These depositions were done in the radio frequency plasma enhanced chemical vapor deposition (rf PECVD) facility at the Delft University of Technology, Netherlands. The deposited experimental single layers and solar cells were characterized and their parameters used as input to calibrate the simulation model, ASA. Advanced Semiconductor Analysis (ASA) is a one-dimensional simulation program developed by the solar cell group of the Delft University of Technology, the Netherlands. It was originally designed for the simulation of multilayered heterojunction device e.g. a-Si:H solar cell and has recently been updated for use in single junction nanocrystalline solar cell and optical systems with multi-rough interfaces.

The calibration procedure was as follows: fabrication of the reference solar cell, measurements of the J-V curve and the spectral response of the solar cell under standard AM1.5 illumination and fitting the model parameters to reasonably agree with the measured characteristics [9]. The reference cell comprises p-, i-, and n- layers of thicknesses 25, 1100 and 20 nm respectively. The front TCO is 800 nm ZnO:Al and the back contact was a stack of 100 nm Ag layer upon which a 200nm Al layer was evaporated. In optical calibration, light scattering at the rough interfaces of the solar cell is taken into account. In the simulation, we have investigated p-type nanocrystalline silicon layer and amorphous silicon carbide buffer layers.

Fig. 2 shows the result of the optical and electrical calibration of our model. Here we see a good agreement between the measured and the simulated.

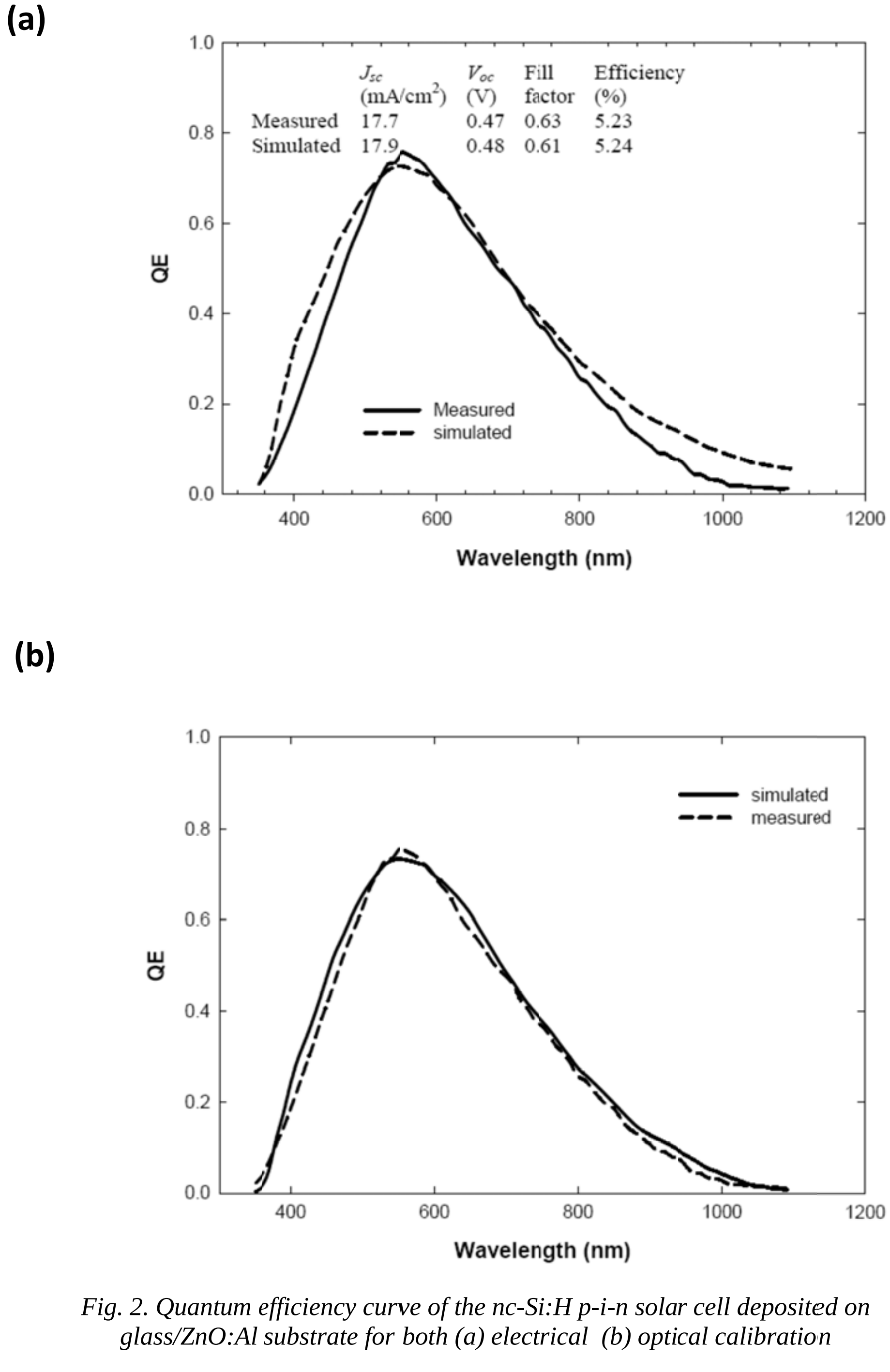


Fig. 2. Quantum efficiency curve of the nc-Si:H p-i-n solar cell deposited on glass/ZnO:Al substrate for both (a) electrical (b) optical calibration

3. Results and discussions

3.1 Effects of defect-rich p-i interface on nc-Si:H solar cell performance

To show the quality of the p-i interface of solar cell, we use the short wavelength (blue) response as an index [10]. Here, the blue response indicates how good or bad charge carriers are extracted through this interface. For a defect-rich interface, the blue response shows a drop. To further investigate this, we have deposited a nc-Si:H solar cell on a flat substrate and measured its quantum efficiency. Using our calibrated ASA model, we simulate a similar solar cell but with a defect-rich 3nm layer between the p- and the i-layers. As shown in figure 3, the deviation between the measured and the simulated cell at the short wavelength region is linked to limitations in charge carrier extraction due to the defect-rich p-i interface.

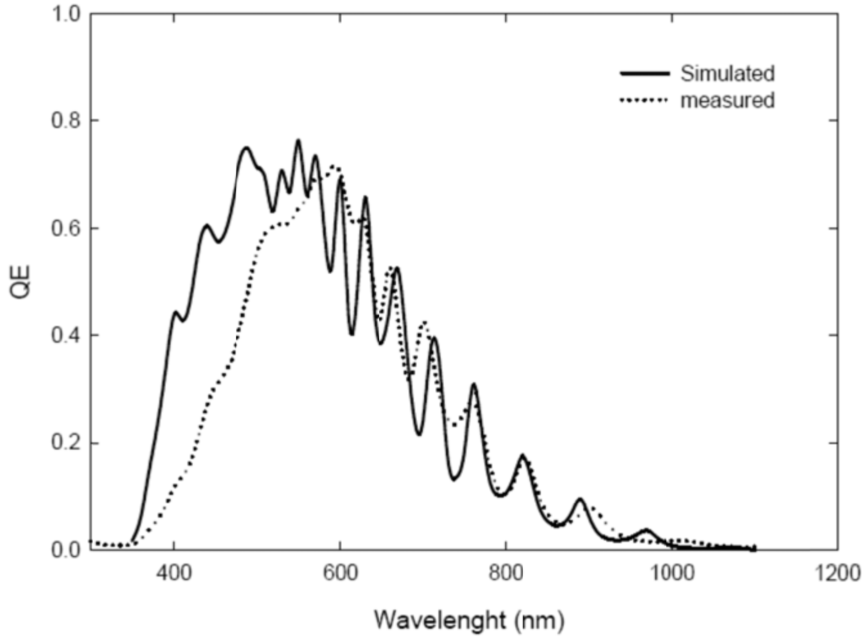


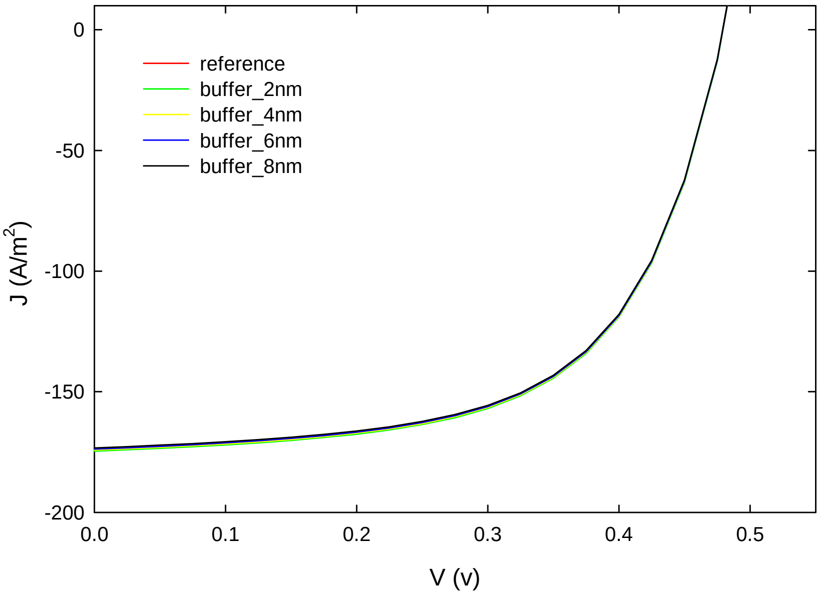
Fig. 3. Quantum efficiency curve of the nc-Si:H p-i-n solar cell deposited on glass/ZnO:Al substrate for experimental cell (measured) and simulated defect-rich cell

3.2 Effects of using p-i interface buffer layers on nc-Si:H solar cell performance

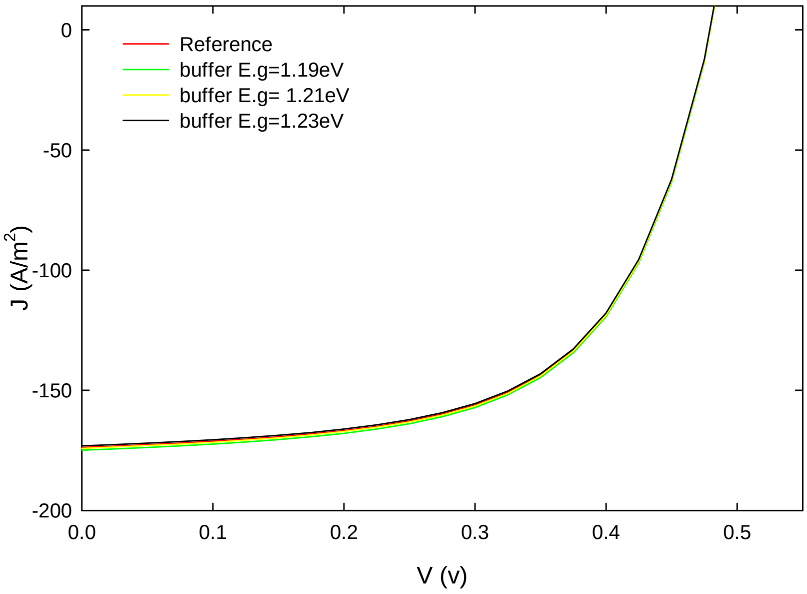
A p-type buffer layer was inserted at the p-i interface. It is believed that having a buffer layer with a higher mobility gap than the mobility gap of the i-layer in the p-i interface will improve the Voc of the solar cell as the Voc is proportional to the mobility gap [7]. In the case of a large difference between the mobility gap of the p-layer and the absorber layer, there occurs a band offset. This band offset in the valence band prevents photo generated carriers (holes) from moving to the p-layer from the absorber layer.

The introduction of a buffer layer, with a mobility gap value lower than that of the p-layer but higher than that of the i-layer supposedly improves the p-i interface thereby improving the Voc, as the Voc is not only dependent on the i-layer but on the p-i interface also [7].

In our simulations, a p-type nanocrystalline silicon buffer layer was inserted at the p-i interface. The mobility gap of the p-layer was set at 1.25 eV, the buffer layer at 1.21 eV and the i-layer at 1.18 eV. A study of the buffer layer thickness was carried out as well as a study for different values of the mobility gap of the buffer layer. The results of our simulations are shown in the figures below. For the structure we investigated, the p-type nc-Si:H buffer layer had no observable effect on the solar cell performance.



(a)



(b)

Fig. 4. IV characteristics of nc-Si:H solar cells for varying p-type nc-Si:H (a) buffer layer thickness (b) buffer layer mobility gap.

Fig. 5 shows the effect of using amorphous silicon buffer layer. Here we observe a significant effect on the external parameters of the solar cell. The open circuit voltage and the short-circuit current show 27% and 9% increase respectively with respect to the reference cell without a buffer. This significant effect of the buffer layer on the Voc relates to the fact that with the buffer, the defect concentration is reduced and the band-gap offset is controlled hence leading to increase in the open circuit voltage. The increase in current is a direct reflection of improvement in charge carrier extraction across the interface. Notice also from table 1 that the fill factor is reduced significantly but overall, the efficiency of the solar cell is increased by 5%.

Table 1. External parameters of nc-Si:H without (reference) and with a-Sic buffer layers of 2 and 4 nm thickness.

Parameter	Reference value	a-SiC_4nm	a-SiC_2nm
J_{sc} (A/m$^{2)}$	-172.7	-184.9	-188.0
V_{oc} (V)	0.4774	0.6045	0.5359
FF	0.6095	0.4108	0.5233
Efficiency (%)	5.026	4.5910	5.2720

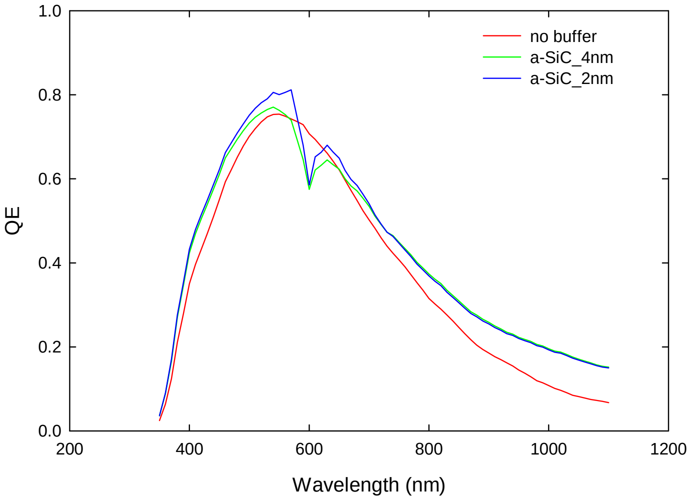


Fig. 5. Quantum efficiency of nc-Si:H solar cells without/with aSiC buffer layers of 2 and 4 nm thickness

4. Conclusions

The effect of p-i interface quality on the performance of thin film nanocrystalline silicon solar cell has been investigated. We have used both experimental and theoretical approach to show that the defect-rich p-i interface reduces the quantum efficiency of the solar cell especially at the short wavelength region. We tested the effect of inserting a buffer layer as a measure to reduce defects and band-gap offset effects at p-i interface. P-type nanocrystalline silicon and amorphous silicon carbide were implemented as buffer layers for different thicknesses and mobility gaps. Our result clearly shows that using a nanocrystalline silicon p-type buffer layer does not change the p-i interface quality. On the other hand, we have shown that the use of amorphous silicon carbide p-i interface buffer can significantly increase spectral response of nanocrystalline silicon solar cell due to increased carrier extraction. However, more theoretical and experimental work will be needed to further optimize the amorphous silicon carbide buffer layer.

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