

Optimization of the a-SiC:H p-i interface layer in p-i-n a-Si:H solar cells

B. Vet, M. Zeman

Abstract—One of the approaches to improve the efficiency of hydrogenated amorphous silicon (a-Si:H) solar cells is to investigate how to enhance the open circuit voltage. In this contribution we investigate intrinsic amorphous silicon carbide (a-SiC:H) and implement it as p-i buffer layer in a-Si:H solar cells. A series of intrinsic a-SiC:H materials is deposited from different silane to methane source gas ratios, in order to tune the band gap. The solar cells with an a-SiC:H p-i buffer layer perform up till 15% better than solar cells without a p-i buffer layer. The best solar cell (10.5 %) has a-SiC:H p-i buffer layer with a band gap of 2.03 eV.

Index Terms—hydrogenated amorphous silicon, solar cell, buffer layer, optimization

I. INTRODUCTION

Hydrogenated amorphous silicon (a-Si:H) solar cell technology has the potential to substantially contribute to supplying the global demand for cheap renewable energy. Due to its high absorption in the visible range of the solar spectrum, a-Si:H allows for the design of thin film solar cells. Thin film solar cells use less raw materials and energy for their production and therefore can be manufactured at much lower price than the wafer-based silicon solar cells that currently dominate the market. The drawback of a-Si:H solar cells is the lower conversion efficiency. To enhance the performance, research effort is invested in improving the short circuit current of the a-Si:H solar cell, by designing improved light-trapping schemes [1]. Another approach is to improve the open circuit voltage (V_{oc}).

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The V_{oc} depends on the bulk properties of the absorber layer and is proportional to the mobility gap [2-4]. The V_{oc} is also sensitive to the p-i interface region [2-6]. The p-i interface is a hetero-junction with band offsets between the energy bands of a wide band-gap p-type and an intrinsic layer. The band offset in the valence band forms a barrier that impedes photo-generated holes to move from the absorber layer to the p-type layer. A lot of attention is paid to the p-i interface region in order to accommodate the band offset, to optimize the electric field profile in this region, to prevent back diffusion of photo-generated electrons into the p-type layer [4] and to reduce the density of charge carriers in order to reduce recombination [7]. Usually, a wide band gap, thin buffer layer of intrinsic or lightly doped hydrogenated amorphous silicon or hydrogenated amorphous silicon carbide is introduced at the p-i interface. The implementation of a buffer layer results in a higher V_{oc} [4].

Different types of buffer layers are studied. Tasaki et al studied graded buffer layers using computer simulations and showed that the buffer layer increases the V_{oc} and fill factor of a-Si:H solar cells [8]. Arya et al deposited a-Si:H solar cells with a graded p-i interface and obtained very high fill factors [9]. Rech et al studied a p-i buffer consisting of two layers, one lightly doped and one intrinsic [10]. They reported good stability of the solar cells implementing such a p-i buffer. Vet et al. showed with simulations that a large band gap buffer layer with appropriate electron affinity can improve the V_{oc} to more than 1 V, while retaining good fill factor and short circuit current [7].

In order to obtain high efficient a-Si:H solar cells (>10%) a good p-i buffer layer is necessary. However, not much literature about the optimization of p-i buffer layer materials is available. In this contribution we investigate the properties of the intrinsic amorphous silicon carbide material (a-SiC:H) with different band gaps by varying the source gas ratio of silane to methane. The material is implemented in a series of p-i-n solar cells on glass to investigate the effect of the buffer layer on the V_{oc} and study the relation between the material properties of the buffer and the improvement in solar cell performance.

II. METHOD

A series of intrinsic a-SiC:H layers was deposited using an

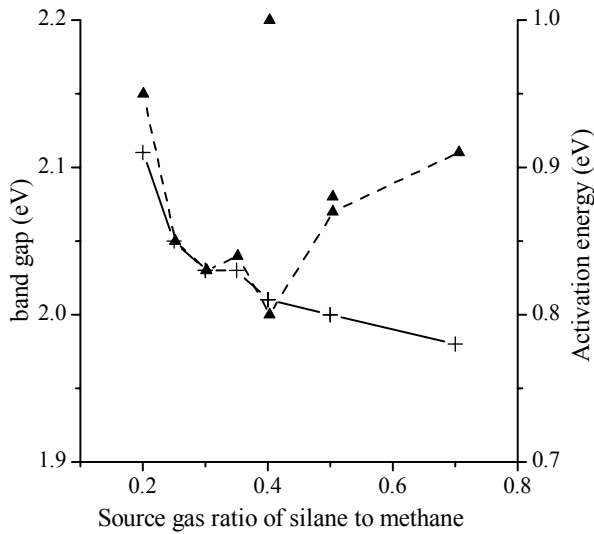


Figure 1 Optical band gap and activation energy of the a-SiC:H films as a function of the silane to methane source gas ratio

rf-PECVD process. The samples were deposited from a mixture of the source gasses silane (SiH_4), methane (CH_4) and hydrogen (H_2). The ratio of SiH_4 to CH_4 , $R = [\text{SiH}_4]/[\text{SiH}_4 + \text{CH}_4]$ was varied from 0.2 to 0.7 while keeping the total flow of $\text{SiH}_4 + \text{CH}_4$ constant at 5.3 sccm. The source gas mixture is diluted by 200 sccm of H_2 so that the dilution ratio $D = [\text{SiH}_4 + \text{CH}_4]/[\text{H}_2 + \text{SiH}_4 + \text{CH}_4] = 1/40$. The deposition pressure was 2.6 mbar. The layers were grown to a thickness of 200 nm.

Single junction p-i-n solar cells were deposited on Asahi U-type substrates using the above described films as buffer layer at the p-i interface. The solar cells have the following structure: p-type a-SiC:H layer (10 nm) / a-SiC:H buffer layer (5 nm) / intrinsic absorber layer (300 nm) / n-type a-Si:H layer (20 nm). The back contact consists of 150 nm of silver and 300 nm of aluminum. For statistical reasons, 30 back contacts squares with an area of 0.16 cm^2 , hereafter called „(solar cell) dots“, were deposited on each sample. Another series of p-i-n solar cells was deposited in which the thickness of the a-SiC:H buffer layer was varied from 3 nm to 20 nm. R was kept constant at 40%. Additionally a reference solar cell was deposited which has similar structure, except for the fact that the buffer layer was omitted.

The thickness of the films and the E04 optical band gap, were determined from reflection transmission measurements on the film. The activation energy of the films was measured. The solar cells on glass were characterized with an Oriel solar simulator. The results of the measurements on the solar cells on glass given in this article are the statistical averages over the three most efficient solar cell dots of a given sample, unless otherwise mentioned. The quantum efficiency of the solar cells of the best solar cell dot was measured.

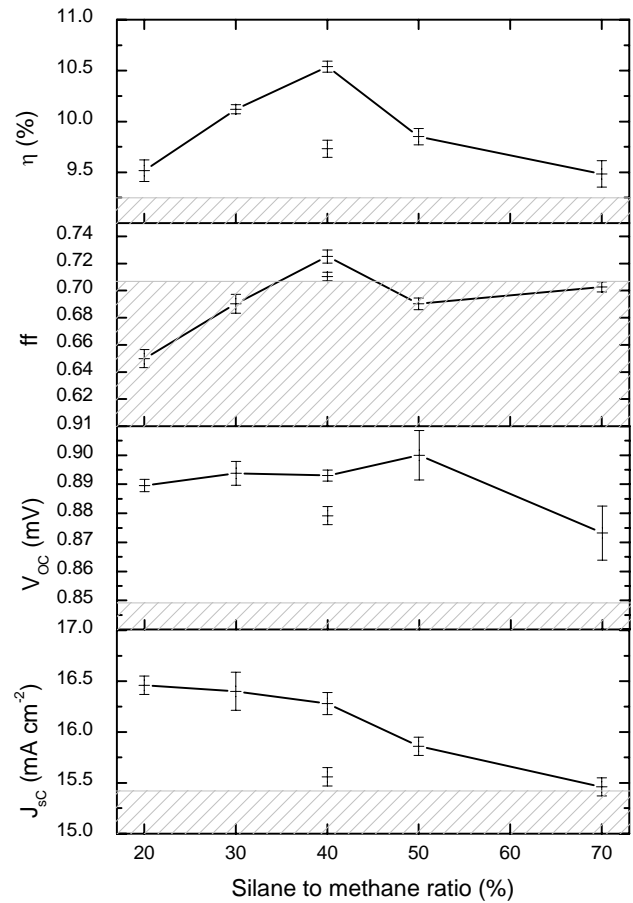


Figure 2 External parameters of the solar cells as a function of the silane to methane ratio of the p-i buffer layers.

III. RESULTS AND DISCUSSION

Figure 2 shows the results of the reflection / transmission measurements and the activation energy measurements. The figure shows a decreasing trend of the band gap as function of the silane to methane source gas ratio. The band gap is as high as 2.10 eV for the ratio of $R=0.2$ and decreases to 1.98 eV for $R=0.7$. The activation energy follows the same trend as the band gap for $R=0.2$ to 0.4, but then the correlation ends and the activation energy increases while the band gap decreases. The activation energy is very high, 0.8 eV to 0.9 eV, only slightly less than half of the band gap, which indicates that the a-Si:H layers are highly intrinsic. The high activation energy also indicates a low defect density because defect states have an asymmetric distribution in the band gap and cause a shift of the Fermi level with respect to mid gap. This would result in a reduction of the activation energy. Also, the activation energy gives a lower bound for the mobility gap, which is at least twice the activation energy.

Based on the previous research the samples with the high band gap ($R=0.2$ to 0.4) are the most promising p-i buffer

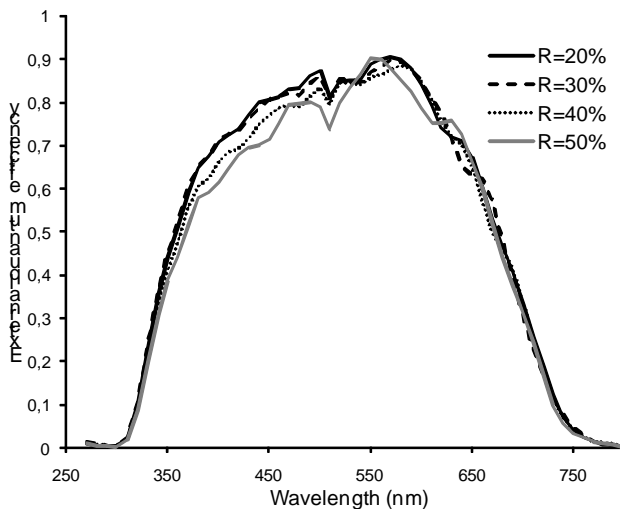


Figure 3 External quantum efficiency of solar cells with p-i buffer layers deposited at different R

layers, because simulations showed that increased band gap with appropriate electron affinity results in higher open circuit voltage.

The results of the JV measurements on solar cells with p-i buffer layers deposited at different R are depicted in Figure 2. The results of the solar cell with a p-i buffer layer deposited using a source gas ratio R=40 % falls out of the trend of the open circuit voltage and the short circuit current. The sample is repeated and the new results fit better into the trend. In fact the sample with R=40 % is the best sample of the series.

The figure shows a decreasing trend of the short circuit current with increasing R. The short circuit current drops from 16.5 mAcm^{-2} at R=20 % to 15.5 mAcm^{-2} at R=70 %. The ff has an optimum of 0.73 at R=40 %. The open circuit voltage has an optimum of 0.90 V at R=50 %. The combination of these external parameters results in a trend for the efficiency that features an optimum of 10.6 % at R=40 %. The grayed areas illustrate the external parameters of the reference sample which was deposited without a p-i buffer layer. Both the short circuit current and the open circuit voltage of the entire series of solar cells with buffer layer are well above the corresponding external parameters of the solar cell without buffer layer. Only the short circuit current of the solar cell with a buffer layer deposited at R=70 % approaches the value of the solar cell without buffer layer. The fill factor of the solar cell without buffer layer is generally better than the fill factor of the solar cells with p-i buffer layer. The only exception is the solar cell with a p-i buffer layer deposited at R=40 %. The efficiency for the best solar cell with p-i buffer layer deposited at R=40 % is about 15 % better relative to the solar cell without buffer.

The spectral origin of the current reduction of the solar cells with p-i buffer layer with a high R value is visualized in Figure 3. The figure depicts the results of the external

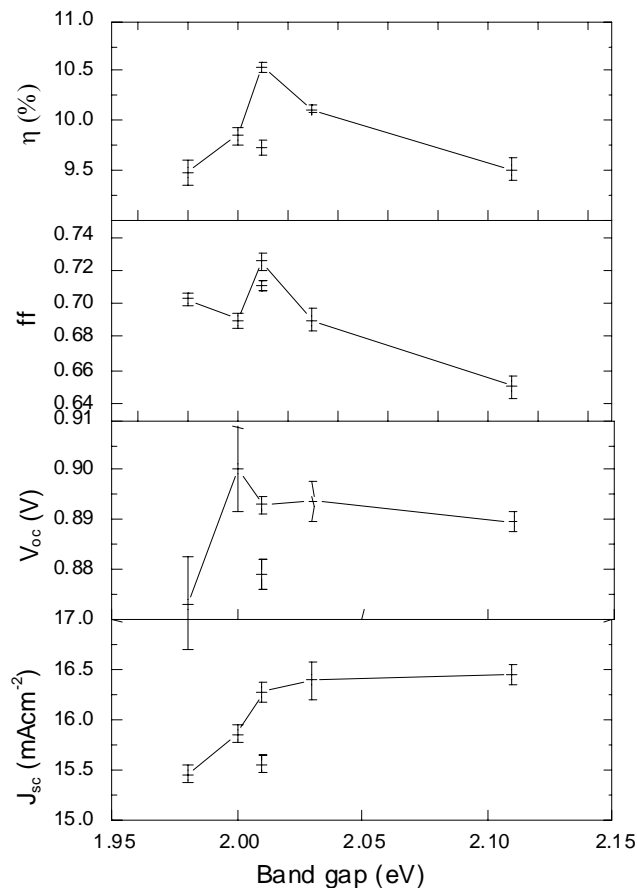


Figure 4 External parameters of the solar cells with p-i buffer layers deposited at different R as a function of the band gap of the corresponding films on glass.

quantum efficiency measurement. The external quantum efficiency decreases for higher R, especially in the short wavelength range. Since the short wavelength photons are almost completely absorbed at the front of the solar cell, this indicates that the collection of charge carriers near the p-i interface is reduced.

The improvement of the open circuit voltage can be explained by the fact that the charge carrier density is reduced at the p-i interface [1]. Simultaneously the density of charge carriers in the bulk is increased. This may explain the slightly lower fill factor.

In Figure 4 the external parameters of the solar cells are plotted against the band gap measured on the films. The figure depicts the strong decrease of the current for solar cells with buffers with a band gap below 2.03 eV. The trend of the Voc is not so clear but the optimum is near the band gap of 2.01 eV. The fill factor has a linearly decreasing relation to the band gap. The optimal efficiency is at a band gap of 2.01 eV.

The optimal efficiency is not found with the cell that has the buffer layer with the highest band gap, but at a lower band gap. This behavior does not correspond to the simulation

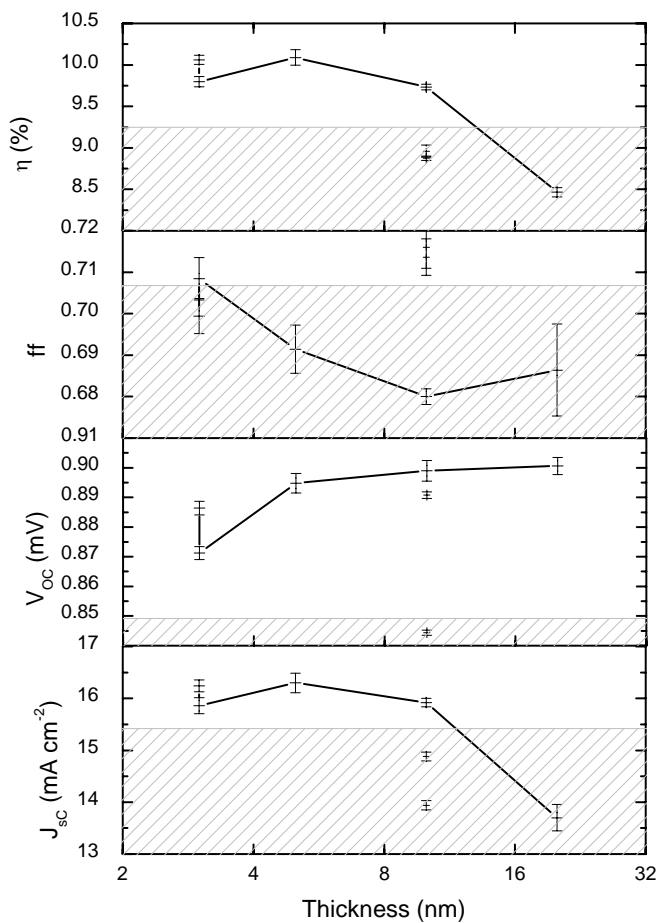


Figure 5 External parameters of the solar cells with p-i buffer layers deposited at R=40 % as a function of the thickness of the buffer layer.

study. Possible reasons for that are that the electron affinity of the high band gap buffer layers is not optimal. The buffer can form an electrical barrier, which is supported by the fact that the current reduced. Unfortunately the electron affinity cannot be measured directly, so further research and simulations are required to confirm this.

Figure 5 shows external parameters of the series of solar cells in which the thickness of the p-i buffer layer is varied. The short circuit current decreases with increasing buffer layer thickness. The open circuit voltage increases with increasing thickness of the buffer layer. At a thickness of 20 nm the Voc is 0.90 V. The fill factor shows no clear trend. The efficiency is optimal at a buffer layer thickness of 5 nm.

IV. CONCLUSIONS

We have studied the a-SiC:H material as a candidate for a p-i buffer layer in a-Si:H solar cells. The material is suitable and implementing the a-SiC:H material deposited at a silane to methane ratio of 40% as a p-i buffer layer increases the

efficiency of a-Si:H solar cells by 15 % to 10.5 %.

By changing the silane to methane ratio of the a-SiC:H material the band gap can be tuned. The band gap correlates to the fill factor, short circuit current and open circuit voltage. Increasing the band gap improves the overall efficiency of the solar cell. However, when the band gap is increase beyond 2.03 eV, the fill factor limits the efficiency.

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