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Influence of Defect Post-deposition Treatments on poly-Si Thin-film Solar Cells on Glass grown by ECRCVD

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ABSTRACT

The epitaxial thickening of a thin polycrystalline Si (poly-Si) film (seed layer) is a promising approach to realize an absorber layer of a poly-Si thin-film solar cell on glass. Such cell concept combines the benefits of crystalline Si and the high potential for cost reduction of a thin-film technology. Here, we discuss the influence of post-deposition treatments on the properties of absorber layers grown by electron-cyclotron resonance chemical vapor deposition (ECRCVD) and the solar cell performance, respectively. Defect annealing was used to improve the structural quality of the absorber layers and to increase the doping efficiency. For this, we used rapid thermal annealing (RTA) processes. Annealing times (up to 400 s) were applied at temperatures of up to 950 °C. Defect passivation treatments were carried out at temperatures of about 350 °C to passivate the remaining defects in the films by hydrogen. The impact of both treatments on the solar cell parameter will be discussed focusing on RTA. Excellent V_{OC}'s of up to 361 mV were achieved without hydrogenation showing the high potential of ECRCVD-grown absorbers. Applying both treatments resulted so far in an increase of V_{OC} of about 400 mV. Because of the fact, that both post-treatments (particularly hydrogenation) are still not yet optimized, further improvements can be expected.

INTRODUCTION

An attractive low-temperature route to a poly-Si thin-film solar cell on a low-cost substrate like glass bases on the seed layer concept. In such a cell concept, we use a thin large-grained poly-Si seed layer on glass formed by aluminium-induced crystallisation (AIC). The absorber layer is grown on this seed layer in a subsequent epitaxial deposition process.

The epitaxial growth process is limited by the glass to temperatures of about 600°C. At these low temperatures it becomes necessary to apply deposition techniques which provide additional non-thermal energy to the surface of the growing film in order to obtain epitaxial growth. ECRCVD, as an ion-assisted deposition technique, is suitable for epitaxial growth of Si in this temperature regime [1,2]. But in contrast to conventional CVD at high temperatures (~1100 °C), at low temperatures the structural quality of epitaxial growth is mainly determined by the seed layer properties (e.g. crystal orientation). This results typically in a higher density of crystal defects in the grown films leading to a decreased carrier lifetime and therefore enhanced recombination losses in solar cells. Another feature of low-temperature Si epitaxy is a very low doping efficiency [3].

The presence of crystal defects influencing the performance of an electrical device can be reduced by post-deposition treatments of the Si films. For instance high-temperature annealing can improve the structural quality of such a film by rearranging the crystal structure (e.g. point defect removal, doping activation) [4]. The limitation to temperatures below 600°C by the glass substrate for all process steps generally does not allows such treatments. Only very short annealing treatments as in RTA processes can be applied. Enhanced RTA processes showed already the potential for significant improvements on thin-film technologies like crystalline Si thin-film solar cells on glass [5]. In this paper, we present results of solar cells with absorber layers epitaxially grown by ECRCVD on poly-Si seed layers on glass treated by different RTA procedures.

EXPERIMENT

Solar cell structure

We prepared solar cells on poly-Si seed layers on glass. The seed layers were prepared by the aluminium-induced layer exchange (ALILE) on Corning 1737F. Details of this preparation can be found in [6]. The resulting poly-Si film (about 200 nm) on glass is p^+-type due to doping with Al. It is characterised by large grains (about 20 µm) and a (100) preferential orientation (about 75% of all grains are tilted less then 20° relative to (100)) [5].

The crystalline Si absorber layers were grown in an ECRCVD system with a RR 250 PQ (Roth & Rau, Germany) plasma source decomposing silane (SiH_4) and diborane (B_2H_6) by an H_2 plasma. The thickness of the absorber layers was about 2µm. The premix gas ratio used for doping was $[B_2H_6]/[SiH_4]$ = 100 ppm with an as-grown doping efficiency of about 0.1% [3]. The substrate temperature was about 600 °C. The resulting growth rate amounted to 20 nm/min. More details can be found elsewhere [2].

Figure 1 shows the complete process sequence of the solar cell test structures under investigation. The solar cells were prepared using a slightly boron-doped absorber layer grown on the poly-Si seed layer. A highly phosphorous doped hydrogenated a-Si layer was deposited as standard emitter (thickness: 20 nm) by plasma-enhanced CVD (PECVD). ZnO:Al was used as transparent conducting oxide. The 80 nm thick ZnO:Al film was grown by reactive DC

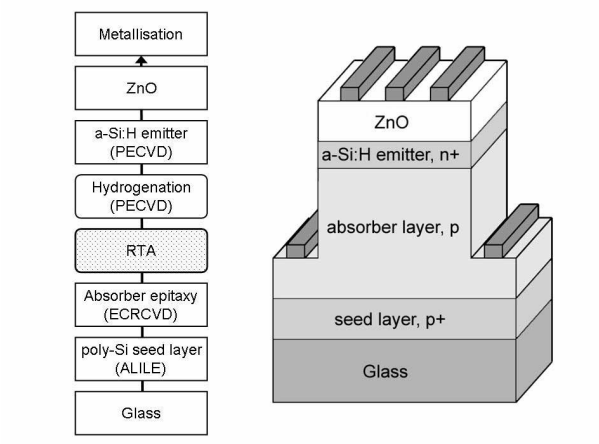

Figure 1. Process sequence and schematic design of a Si thin-film solar cell on a poly-Si seed layer on glass.

magnetron sputtering at a substrate temperature of 180°C. Device separation (mesa-etching) and metal grid definition (Al lift-off) were realised by photolithography. The cells had a non-interdigitating grid and a cell area of about 4 ×4 mm². No light trapping was applied to this solar cell structures.

Post-deposition treatments

Two kinds of absorber layer post-deposition treatments were used. RTA processing was carried out under nitrogen atmosphere in a rapid thermal processing (RTP) system (Heatpulse 210T from AG Associates) consisting of a quartz chamber, two banks of tungsten-halogen lamps, a graphite-coated Si wafer as sample carrier and a microcontroller unit. As annealing procedures simple temperature profiles were used. The annealing started in the pre-heated chamber (around 280°C after sample loading), immediately followed by a mid-temperature annealing phase (400°C, 40s) and the final annealing step with different temperatures (850°C-950°C) and duration (200s-400s). To reach the final plateau temperature we used a ramp up rate of about 120 K/s. The unloading process took place in about 200s.

In addition to RTA, we applied a hydrogenation procedure on most of our samples in order to reduce electrically active defects in the absorber layers by passivating them by atomic hydrogen. This treatment was carried out in a parallel-plate PECVD system at 350°C for 15 min. The process pressure and the power density amounted to 0.75 to 1 mbar and 15 mW/cm², respectively. The hydrogenation was finished by a rapid unloading from the chamber. The samples were kept in vacuum. After cooling down the PECVD system, the samples were transferred into the same chamber in order to proceed with emitter deposition. Note: the hydrogenation of our layers is still a non-optimized process. Future work on a specially designed hydrogenation system will be carried out in order to exhaust the potential of cell improvement by this treatment.

DISCUSSION

In order to compare the influence of different post-deposition treatments on the absorber layer the open-circuit voltage is a good parameter to characterize the quality of this layer in a solar cell. The results are not dependent on additional cell design related parameters like contacts and series resistance. Therefore the use of the so called "Suns-V_{OC}" technique is an excellent tool to measure the effect of absorber treatments [7]. Nevertheless, in order to receive a more complete information on our samples, we analysed complete solar cell structures in a sun-simulator under standard test conditions (AM1.5). Thus, also possible effects on the short-circuit current density (J_{SC}) can be made visible. In figure 2, the influence of post-deposition treatments of the absorber on the solar cell performance is shown as an example. The samples were processed always in the same runs of deposition/treatment. The as-grown V_{OC} is about 215 mV. Due to a 900°C anneal for 300s, the V_{OC} increased to 315 mV. By the additional application of a hydrogenation process the V_{OC} increased further up to 354 mV in this particular example. This shows not only the strong improvement of the absorber layer by an annealing treatment but also the positive effect of hydrogenation on the V_{OC}. In addition, a large increase of J_{SC} was observed due to the hydrogenation.

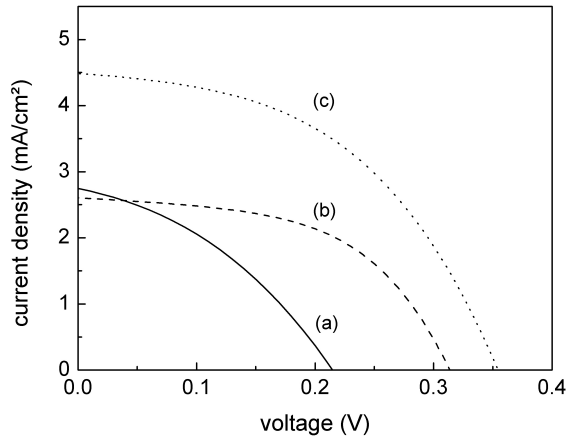

Figure 2. Current-voltage characteristic of solar cells with different absorber layer treatments. (a) as grown, (b) RTA treatment (900°C, 300s), (c) RTA treatment and hydrogenation.

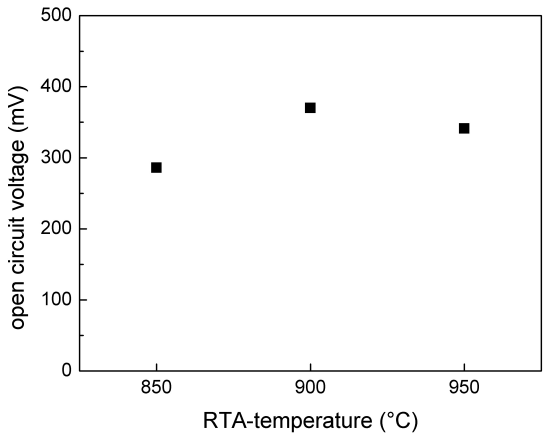

Figure 3. Open-circuit voltage V_{OC} of solar cells with different RTA plateau temperatures.

Influence of annealing temperature and time

We investigated the influence of the plateau temperature on the cell performance. For this, we applied 850°C, 900°C or 950°C as constant annealing temperature for 300s to a series of samples. All samples were hydrogenated in the same experiment afterwards. The results are shown in figure 3. We observed a significant increase of V_{OC} from 286 mV to 370 mV by increasing the temperature from 850°C to 900°C. In agreement with Terry et al. [5] a slight decrease of V_{OC} using higher temperatures was seen. In our case, this could be explained by a possible doping smearing from seed layer into absorber layer (Al diffusion) and an accompanying reduction of the p^- region. This has to be proven by secondary ion mass spectroscopy. Also a (visible) deformation of the glass and the Si layers and a resulting increase of stress by the increased thermal budget could be a possible explanation. Further investigations with a larger number of temperature values and RTA plateau times will be carried out in the next future in order to find the optimum RTA process. The focus will be the development of an enhanced RTA profile, e.g. taking into account the glass transformation temperature, will be a focus.

We analysed the influence of the plateau time on the solar cell performance. Samples were annealed at 900°C for 200s, 300s, and 400s, respectively. No hydrogenation was applied. We observed only a slight increase of V_{OC} from 344 mV to 361 mV with increasing plateau time. This is in fair agreement with the detailed study of Terry et al. [5]. They also reported about only a small change in V_{OC} in this plateau time region.

Best solar cell results

The above mentioned V_{OC} of 361 mV for an non-hydrogenated, 2 µm thick poly-Si film on glass is a remarkable result and as far as we know the highest reported value for a polycrystalline film on glass without hydrogenation.

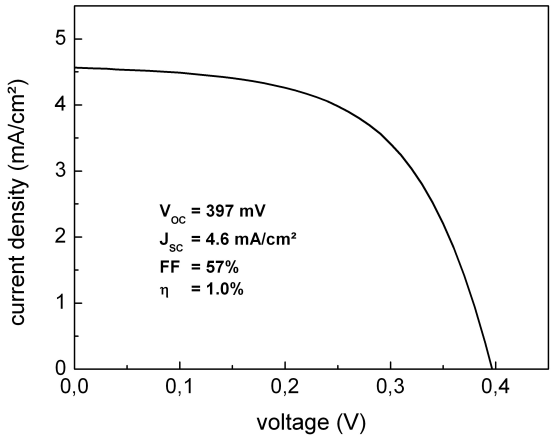

Figure 4. Current-voltage characteristic of our best solar cell in terms of V_{OC}. It consist of a 2 µm thick absorber layer grown by ECRCVD on a poly-Si seed layer on glass. The absorber was treated by defect annealing and hydrogen-passivation

The current-voltage characteristic of the same sample with hydrogenation is shown in figure 4. The cell results are V_{OC} = 397 mV, J_{SC} = 4.6 mA/cm², FF = 57%, η=1.0%. Compared to previously reported results [8], we achieved an increase of V_{OC} of about 20 mV and a strong increase of the fill factor. Unfortunately, J_{SC} is about 25% lower. The reason for this reduction is still unclear but was observed by the complete set of samples processed in the same run of cell production. The low J_{SC} itself can be explained by the used cell design. So far, no light trapping was applied to our solar cells. In addition, due to the mesa-etched structure, the cells are still characterized by a strong series resistance.

Evolution of open-circuit voltage

Good progress has been achieved in recent years of research on our solar cell concept at HMI. Figure 5 shows the evolution of V_{OC} in the last four years following the concept of the epitaxial thickening of an poly-Si seed layer by ECRCVD. The importance of absorber layer treatments like defect annealing and passivation for such kind of cell concept are clearly visible.

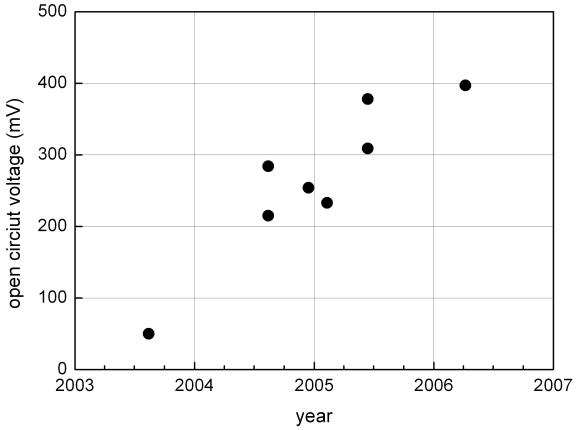

Figure 5. Evolution of open-circuit voltage of our solar cells following the concept of epitaxial thickening of an poly-Si seed layer on glass by ECRCVD.

The stepwise increase of V_{OC} was achieved by the separate introduction of doping (mid 2004), annealing and hydrogenation (beginning of 2005) and by the ongoing improvement and combination of these treatments. Further progress can be expected from the development of an efficient hydrogenation procedure, the introduction of a light trapping scheme and an optimised solar cell design.

CONCLUSIONS

By following a seed layer concept, crystalline Si thin-film solar cells were prepared in a complete low-temperature process on glass substrates. Encouraging open-circuit voltages of 361 mV without hydrogenation and 397 mV with a first hydrogenation procedure were achieved on the seed layers showing the potential of this concept. Further efforts have to be made in order to improve the solar cells. Beside the development of an efficient hydrogenation procedure as well as of a light trapping, the further optimisation of the RTA process in terms of annealing temperature, duration and profile will play an important role.

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