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Relationship between absorber layer defect density and performance of a-Si:H and μc-Si:H solar cells studied over a wide range of defect densities generated by 2 MeV electron bombardment

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ABSTRACT

We summarize an extensive study on the impact of absorber layer defect density on the performance of amorphous (a-Si:H) and microcrystalline (μc-Si:H) silicon solar cells. To study the effects of the absorber layer defect density we subjected set of a-Si:H and μc-Si:H cells to a 2 MeV electron bombardment. Subsequently the cells were stepwise annealed to vary the defect density. The cells have varying thicknesses and are illuminated from either the p- or n-side. For reference we subjected i-layers to the same treatment as the cells. The procedure enabled the reversible increase of the i-layer defect density (N_S) with two orders of magnitude according to electron spin resonance measurements (ESR) performed on reference samples. The large variation of N_S induces substantial changes in the current–voltage characteristics (*J–V*) and the external quantum efficiency spectra (EQE). These changes in device characteristics provide a solid reference for analysis and device simulations. It was found that performance of a-Si:H cells degraded weakly upon N_S increase up to 10^{17} cm^{-3} and dropped steeply as defect density was increased further. In contrast, performance of μc-Si:H cells showed continuous reduction as N_S raised. By comparing p- and n-side illuminated cells we found that, for N_S above 10^{17} cm^{-3}, the p-side illuminated a-Si:H cells outperformed the n-side illuminated ones, however, the difference was barely visible at N_S below 10^{17} cm^{-3}. On the contrary, the device performance of n-side illuminated μc-Si:H cells was much more affected by the increase in defect density, as compared to the p-side illuminated cells. EQE results evidenced a significant asymmetry in collection of electrons and holes in μc-Si:H devices, where carrier collection was limited by holes as defect density was increased. Based on the experimental data we speculate that the improvement of absorber material in terms of as-deposited defect density is not of primary importance for the performance of a-Si:H cells, whereas in μc-Si:H based solar cells, the reduction of the absorber layer defect density below the state-of-the-art levels, seems to improve the cell performance.

1. Introduction

The usual design of a solar cell based on amorphous or microcrystalline hydrogenated silicon (a-Si:H, μc-Si:H respectively) is a p-i-n diode [1–3], i.e., the design consists of a layer sequence of a p-doped, an intrinsic, and an n-doped layer. In this solar cell type, the p-doped and n-doped layers serve as carrier-selective contacts and establish a potential gradient for the effective separation and collection of photogenerated carriers. These doped layers usually exhibit high defect densities leading to high recombination rates [4]. Recombination rates in these layers are so high that the p and n layers do not contribute to the photocurrent generation and thus these layers must be kept as thin as possible to reduce optical absorption losses. The absorber consists of an intrinsic layer (i-layer), which, owing to its relatively low defect density, guarantees sufficient excess carrier lifetimes for the successful collection of carriers at the p and n terminals. However, the electronic defects in this absorber layer are critical for the device performance. The dominant defect type in a-Si:H or μc-Si:H is attributed to Si dangling bonds [5] which act as trapping and recombination centers reducing the excess carrier lifetime and electric field magnitude in the bulk of the i-layer. As a result the carrier extraction is suppressed which leads to poor photovoltaic performance of a solar cell.

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Asymmetries in a-Si:H solar cell devices may lead to considerable differences in device performance depending on whether light enters the cell through the p-layer or through the n-layer. For example, a-Si:H cells designed for illumination through p-layer usually performs better than the n-side illuminated counterparts, especially after prolonged light exposure [6–9]. This feature of a-Si:H cells is commonly discussed in terms of a "limiting carrier" – the carrier type for which the $\mu\tau$ product (mobility times lifetime) is insufficient for the effective collection over the entire thickness of the i-layer [10,11]. In the case of a-Si:H cells, the holes are considered to be the limiting carrier with a band mobility of approximately 1 cm^2/Vs vs. 10 cm^2/Vs for electrons [10,11]. The presence of bandtail states in a-Si:H causes much lower values of the drift mobility of holes [11,12]. Currently, all commercially produced and the vast majority of experimental a-Si:H cells, are designed for p-side illumination. In contrast to a-Si:H cells, solar cells with μc-Si:H absorber layers can be illuminated from either p- or n-side without any significant impact on their performance [13]. It is suggested that electron and hole mobility-lifetime products in μc-Si:H absorber layer are both larger and more symmetrical than those in a-Si:H [13,14]. The possibility to illuminate cells with μc-Si:H absorbers from the n-side was successfully explored by applying highly transparent n-type alloys, such as SiC [15] or SiO_x [16] as window layers. The asymmetries in performance depending on the illumination direction are strongly linked to defect density in the absorber layers via the carrier lifetime and built in field.

Defects in amorphous and microcrystalline silicon (a-Si:H and μc-Si:H) thin films and their role in devices such as solar cells have been investigated since 1970s. These studies have been performed in view of light induced creation of metastable defects in a-Si:H (Staebler–Wronski effect [17,18]), creation of defects in a-Si:H or μc-Si:H by ionizing radiation e.g. in space [19], and in view of the high defect densities of a-Si:H or μc-Si:H absorber layers which were deposited at high deposition rates [20,21]. However, among a large number of studies on degradation of a-Si:H cells under illumination [6,9,10,22–24] the dependencies of solar cell parameters on the defect density in the i-layer were obtained mostly with device simulations [25–29]. In addition, light induced increase of defect density in a-Si:H absorber layer is usually limited by 10^{16}–10^{17} cm^{-3} [30] and often is inhomogeneously distributed within the i-layer, which hampers the analysis. A number of studies on the radiation hardness of a-Si:H and μc-Si:H solar cells [19,31–38] performed in the past focused on flux or dose dependence of solar cell performance, which is not sufficient to draw conclusions on how the defect density affects one or another solar cell parameter. In the case of deposition rate variations, factors such as the absorber layer structure (e.g. increased porosity) and interface properties will change together with bulk defect density and mask the effects of the changes in defect density in the i-layer. Using a high energy electron bombardment at low temperature with successive stepwise annealing the defect density in solar cells can be varied over many orders of magnitude, providing a unique means to study the influence of the defect density on solar cell device operation. This experiment has been successfully applied to investigate the impact of defect density on the electronic properties of a-Si:H and μc-Si:H films [39,40], the structure of these defects [41–44], and their impact on the solar cell parameters [45–47].

Extending upon the results of our previous work, we present a comprehensive study on the impact of i-layer defect density on the performance of a-Si:H and μc-Si:H solar cells. A key feature of the study is the evaluation of the defect density with electron spin resonance (ESR) measurements on intrinsic material which is virtually identical to the material used as absorber layers in the solar cells. The solar cells and the intrinsic material are subjected to the same electron bombardment and annealing procedure. The current–voltage (*J–V*) parameters and external quantum efficiency (EQE) were measured in a-Si:H and μc-Si:H solar cells, where the i-layer defect density was varied over two orders of magnitude. Our previously published data on p-side illuminated 0.3-μm thick a-Si:H and 1-μm thick μc-Si:H cells [45,46] together with the data on n-side illuminated 1-μm thick μc-Si:H cells [47], are summarized and extended with new data on p-side illuminated 1-μm thick a-Si:H, p-side illuminated 3-μm thick μc-Si:H, and n-side illuminated 0.3-μm thick a-Si:H solar cells. On the basis of this extended dataset we can analyze the relevance of bulk defect density for the photovoltaic performance of state-of-the-art thin film silicon solar cells in three different dimensions: absorber material (a-Si:H or μc-Si:H), absorber layer thickness, and illumination side (n- or p-side illuminated).

Analysis of the data reveals several key differences in carrier collection properties between a-Si:H and μc-Si:H solar cells. For example, the difference in performance between p-side and n-side illuminated a-Si:H cells is small, even at high defect densities, whereas at high defect densities a remarkable difference was observed between p-side and n-side illuminated μc-Si:H cells. We carried out device simulations of μc-Si:H solar cells to analyze this strong asymmetric behavior in carrier collection. Our results suggest that there is still room for improvement of state-of-the-art μc-Si:H solar cells, if the defect density in the intrinsic layer is reduced. The dataset we obtained for cells with varying defect densities is meant as a reference for further development of device operation models.

2. Experimental

The schematic structure for all cells used in the study is presented in Fig. 1. Single junction a-Si:H and μc-Si:H solar cells were prepared in substrate configuration (illuminated from the cell side) [48] using a n-i-p or p-i-n deposition sequence. The cell configurations and absorber layer thicknesses are summarized in Table 1. For the p-side illuminated cells we prepared cells with an absorber layer thickness of 0.3 μm and 1 μm in the case of a-Si:H and of 1 μm and 3 μm in case of μc-Si:H cells. The n-side illuminated cells we prepared with an absorber layer thickness of 0.3 μm and 1 μm for a-Si:H and μc-Si:H, respectively (i.e. only once thickness each).

Doped and intrinsic thin film silicon layers were prepared by PECVD using optimized standard deposition conditions and deposited directly on glass/textured substrates [49] with no metal back reflector. The crystallinity of μc-Si:H absorber layers, evaluated from Raman measurements, was approximately 70%. The performance of the cells has been investigated by current/voltage (*J–V*) measurements under AM 1.5 illumination and external quantum efficiency (EQE) measurements.

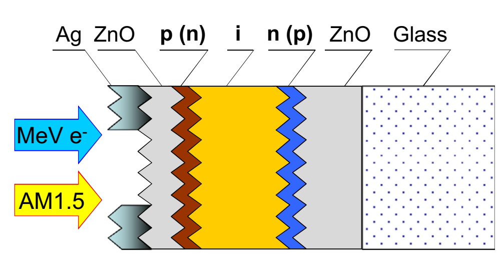

Fig. 1. Schematic structure of solar cells used for the electron bombardment experiment. Both a-Si:H and μc-Si:H cells had substrate configuration with illumination from the cell side. Cells of n-i-p and p-i-n deposition sequences were illuminated through p- and n-layers respectively.