N-side illuminated microcrystalline silicon solar cells

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Thin-film microcrystalline silicon solar cells illuminated through the *n* layer were studied and compared with classical *p*-layer illuminated cells. To investigate the corresponding charge carrier extraction properties, variation of the intrinsic absorber layer thickness was carried out. It was found that the $J-V$ characteristic and the quantum efficiency of the *n*- and *p*-side illuminated cells are almost identical in the thickness range investigated, up to 7 μm. No differences in the collection of photogenerated electrons or holes are observed. Hence, the illumination side of μc-Si:H single junction solar cells of conventional thickness may be randomly chosen without adverse effect on their performance. [DOI: 10.1063/1.1395518]

Microcrystalline silicon (μc-Si:H) prepared by plasma enhanced chemical vapor deposition (PECVD) has received considerable attention since its first successful application as an absorber layer in thin-film solar cells[1–3] and much improvement in the solar cell efficiencies has been obtained since. However, there is no detailed knowledge of the transport behavior, in particular with relation to the performance of the material in solar cells. As an example, deposition conditions near the transition to the amorphous growth regime yield the highest solar cell efficiency.[4,5] In this context, the question arises as to what extent solar cells with μc-Si:H absorber layers are limited in performance by the features of the amorphous silicon (a-Si:H) device physics. As is widely known, solar cells with a-Si:H absorber layers require illumination through the *p* side for optimum stabilized performance. The origin of this is the complex relationship between the carrier mobility, which is much lower for holes than for electrons, and the charging of ambipolar defects, causing electric field distortions, especially in the degraded state, where the defect density is high. This has been studied in great detail over the last two decades (see Refs. 6 and 7 for early experimental and theoretical work and Ref. 8, and references cited therein). Whether effects similar to those of collection asymmetry in thick degraded a-Si:H cells also apply to μc-Si:H devices is the topic of the present study.

The solar cells were prepared by PECVD in a multichamber system at a plasma excitation frequency of 95 MHz.[5,9] Layer deposition sequences of $p-i-n$ and $n-i-p$ were applied to glass substrates coated with textured ZnO (superstrate design) for illumination from the *p*-layer and *n*-layer sides, respectively. The deposition conditions were independently optimized for both cell types, resulting in a silane concentration (SC)($=[SiH_4]/[SiH_4+H_2]$) of 5.5% and a substrate temperature (T_S) of 250 °C for the $n-i-p$ cells, while for the $p-i-n$ cells a SC of 5.0% and a T_S of 200 °C were used.

From previous studies[4,5,9] we know that both conditions resulted in high quality materials having very similar carrier transport properties when employed in solar cells. For example, the fill factor (FF), short-circuit current density (j_{sc}) and quantum efficiencies were identical. However, the use of higher SC values had an (presently not understood) influence on the solar cell device performance, as characterized by the shift of dark $J-V$ curves and a corresponding higher open-circuit voltage V_{oc}.[4,5,9] To indicate the illumination side of the solar cells in the present study, an arrow is used to complement the deposition sequence designations of the $p-i-n$ and $n-i-p$ cases. Therefore, *p*-side illuminated $p-i-n$ cells are indicated by $\rightarrow p-i-n$, while *n*-side illuminated $n-i-p$ cells are indicated by $\rightarrow n-i-p$. It should be pointed out that, despite the reverse deposition sequence, both structures employed the same device preparation conditions, i.e., both were deposited on ZnO/glass substrates and were illuminated through glass.

Figure 1 shows a comparison of the quantum efficiency (QE) curves measured for 1 μm thick μc-Si:H$\rightarrow p-i-n$ and $\rightarrow n-i-p$ cells. These data were obtained from spectral response measurements *without* any bias illumination. It was found that identical QE curves were obtained using a differential spectral response method in which bias illumination was used. These results suggest that the collection behavior

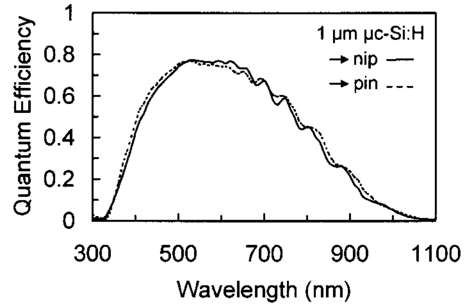

FIG. 1. Quantum efficiency of 1 μm$\rightarrow n-i-p$ and $\rightarrow p-i-n$ solar cells.

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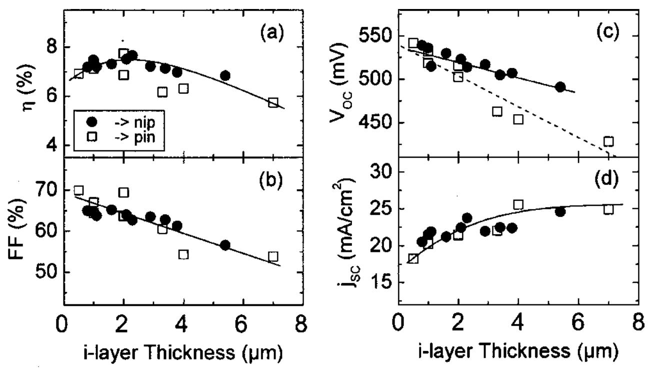

FIG. 2. Solar cell parameters obtained from $J-V$ measurements under AM 1.5 illumination for $\rightarrow p-i-n$ (□) and $\rightarrow n-i-p$ (●) cells with different active layer thicknesses. The lines are a guide to the eye.

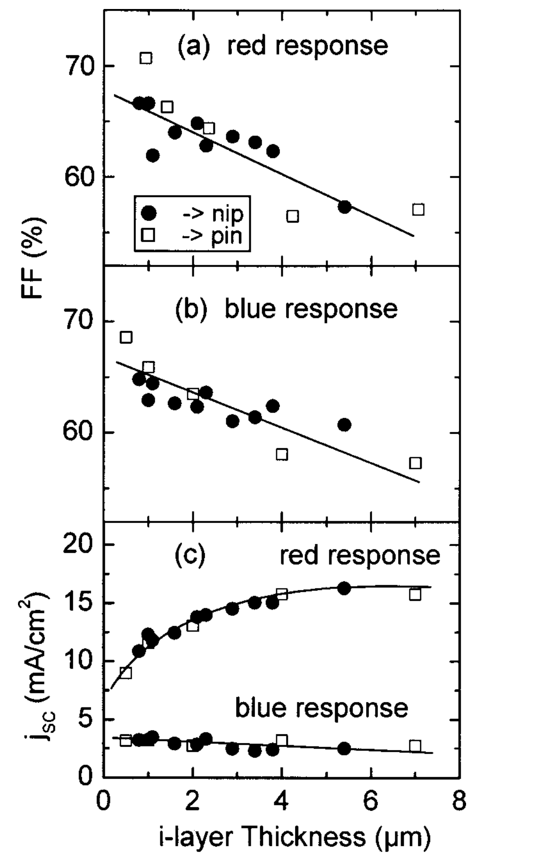

FIG. 3. Fill factor (a), (b) and the short-circuit current density j_{sc} (c) obtained from $J-V$ measurements under AM1.5+red and blue filter illumination for $\rightarrow p-i-n$ (□) and $\rightarrow p-i-n$ (●) solar cells with different active layer thicknesses. The lines are a guide to the eye.

is injection level independent and no effects such as electric field redistribution under illumination occur. Both QE curves shown in Fig. 1 were nearly identical over the entire wavelength range (300–1100 nm), i.e., no difference related to the *p*- and *n*-side illumination occurs.

Next, the absorber layer thickness was varied and solar cell characteristics such as $J-V$ measurements under blue and red illumination were studied. With increasing absorber layer thickness, the distance necessary for a charge carrier to travel in order to be collected increases, while the average electric field is reduced. For this reason, possible differences in the collection efficiency of electrons and holes are more pronounced for the thicker solar cell cases. Since light with long wavelength is absorbed uniformly within the active layer, the $J-V$ parameter values obtained under red light illumination should not depend on the illumination side. In contrast, short wavelength light generates electron-hole pairs near the n/i or the p/i interface for the $\rightarrow n-i-p$ and the $\rightarrow p-i-n$ cells, respectively. Consequently, in $\rightarrow n-i-p$ cells, holes have to propagate across the entire intrinsic layer in order to be collected (in contrast to electrons, which only have to travel a short distance to the n layer), while in $\rightarrow p-i-n$ devices electrons travel a longer distance. Recombination losses of one carrier species can be characterized by a pronounced voltage dependence of photo current under short wavelength illumination from the corresponding side, which in turn is characterized by a drop in the fill factor.

The $J-V$ parameters obtained under AM 1.5 illumination (white light) for $\rightarrow p-i-n$ and $\rightarrow n-i-p$ cells are illustrated in Fig. 2. In the thickness range investigated the results for both cell types are very similar and obey behavior typical of that already reported.[9] Regarding the question of differences in the carrier collection efficiency of both device types, the decrease of FF shown in Fig. 2(b) is of special importance. Remarkably, this decrease, reflecting the increasing amount of recombination losses, is very similar in both cases. For this reason, the enhanced light utilization of thicker solar cells leads to nearly identical short-circuit current densities, j_{sc} [Fig. 2(d)]. For both device types, the open-circuit voltage (V_{oc}) decreases upon increasing absorber layer thickness [Fig. 2(c)]. This is related to a shift of the dark $J-V$ curves to higher current densities, which can be described in terms of simple crystalline silicon diode physics by assuming dominating bulk recombination in thick devices (having diode quality factors, n, of about 2) and the corresponding increase of the saturation current density j_0.[9] It was verified that the dark $J-V$ curves of the *n*-side illuminated cells investigated here show the same behavior.[10] The minor V_{oc} difference, corresponding to an offset of the dark $J-V$ curves of $\rightarrow p-i-p$ and $\rightarrow n-i-p$ devices with the same thickness, is related to the *i*-layer preparation conditions as already discussed above. In summary, under AM 1.5 light, no illumination side dependence of the carrier collection behavior was observed. This is also reflected in the efficiency of the solar cells [Fig. 2(a)], which show a broad maximum for both device types, with a weak thickness dependence between 1 and 4 μm with peak values of up to 7.7%.

To obtain different carrier excitation profiles the AM 1.5 spectrum was modified with a red cut-on filter ($\lambda > 590$ nm) and a blue band filter (λ of around 480 nm). The corresponding thickness dependence of the FF and the short-circuit current density, j_{sc} for red and blue light illumination for both the $\rightarrow p-i-n$ and the $\rightarrow n-i-p$ cells is shown in Fig. 3.

As expected, the red response results are independent of the illumination side and are similar to the unfiltered AM 1.5 illumination results (namely, $J-V$ characteristics). With increasing *i*-layer thickness, the FF decreases [Fig. 3(a)] due to recombination losses, particularly at forward bias, while the j_{sc} increases and then saturates [Fig. 3(c)] with increasing *i*-layer thickness. Remarkably, the blue illumination $J-V$ characteristics were also independent of the illumination side even though in $\rightarrow p-i-n$ and $\rightarrow n-i-p$ devices a longer distance must be traveled by the electrons and the holes, respectively. A corresponding FF decrease [Fig. 3(b)] and a corresponding reduction in j_{sc} was observed [Fig. 3(c)]. These changes can be attributed to similar amounts of photocarrier recombination losses in both $\rightarrow p-i-n$ and $\rightarrow n-i-p$ solar cells, thus indicating that transport is not strongly limited by one carrier species.

In conclusion, μc-Si:H solar cells were prepared in $\rightarrow p-i-n$ and $\rightarrow n-i-p$ deposition sequences and illuminated through the *p* and *n* sides, respectively. Nearly identical QE curves were obtained after optimization of both device configurations. Studies in which the *i*-layer thickness was varied showed similar behavior for both cell types under AM 1.5 as well as under blue and red illuminations, indicating symmetrical collection behavior in the thickness range investigated, up to 7 μm. No asymmetric limitation of the photocurrent by either electron or hole recombination was observed. The results show that μc-Si:H solar cells can be illuminated from either side without any significant impact on their performance. Furthermore, the similar amounts of recombination losses for blue light illumination from either illumination side suggest that the electric field distributions were not dependent on the deposition sequence. These results indicate that the electron and hole mobility-lifetime products are both longer and more symmetrical than those found in amorphous silicon materials.

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