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A NEW APPROACH TO THE ANALYSIS OF FORWARD BIAS DARK CURRENT-VOLTAGE CHARACTERISTICS OF A-SI:H SOLAR CELLS

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ABSTRACT

Generally the dark forward bias current voltage (J_D -V) characteristics of a-Si:H solar cells are analyzed without clearly separating their contributions due to carrier recombination in the bulk from that at the p/i interface regions nor those imposed by carrier injection from the p and n contacts. Furthermore their exponential regimes are interpreted and fitted with constant diode quality factor n with modeling which is based on many fitting parameters that have not been reliably established. A new approach has been developed for the analysis of J_D -V characteristics for the entire voltage range relevant to the operation of solar cells, which has allowed the three contributions to be identified and characterized. It is based on the analysis of their bias dependent differential diode quality factors, $n(V)$, from which important information on the energy distribution of the defect states in the i-layers has been obtained. Results are presented and discussed here for p-i-n a-Si:H solar cells having sufficiently low p/i interface recombination so that the limitations by the bulk recombination on open circuit voltage, V_{oc} , can be identified. These results are then correlated with the defect state distributions previously obtained from the analysis on differential diode quality factor $n(V)$ characteristics for hydrogen diluted and undiluted intrinsic layers both in the annealed state as well as after introducing light induced defects.

INTRODUCTION

A good understanding of the defect states in the intrinsic layers of a-Si:H solar cells and the limitations imposed by different device loss mechanisms on their performance and stability is critical in the optimization of constituent materials as well as cell structures for the further improvement of the already high performance of these solar cells. The conventional measurement techniques and analysis used in such investigations are primarily based on the analysis of light current-voltage (I-V) parameters such as fill factor (FF), open circuit voltage (V_{oc}), and short circuit current (J_{sc}), measured under 1 sun illumination. These parameters are inherently complicated, being affected by the contributions from different parts of the cells such as bulk i-layer, p/i interface as well as n and p contacts, which are difficult to separate and thus to quantify. In order to overcome these limitations new approaches are being developed. They include the

systematic analysis on carefully designed cell structures of forward bias dark current (J_D -V) characteristics which are extensively used in characterizing crystalline solar cells. In the past, little attention was given to J_D -V characteristics of a-Si:H based solar cells because of reported lack of correlation between light and dark I-V's and the predictions of the defect pool model for the presence of very high densities near the n and p contacts and non-uniform distributions of defect states across the i-layer [1]. Recently however, equivalence between the carrier recombination in the J_D -V and light I-V characteristics has been established from the superposition between J_{sc} - V_{oc} and J_D -V characteristics over a wide range of illumination intensities [2, 3]. It has also been shown that in solar cells with high quality materials and optimized cell structures the defect state densities are approximately uniform across the entire bulk i-layer [4]. Consequently, it has been possible through the new approaches to the analysis of J_D -V characteristics to obtain valuable information about the contributions of p/i interface recombination and potential barriers at the p and n contacts, as well as bulk recombination. A key factor of the new approach is the analysis of differential diode quality factors, $n(V)$, characteristics whose presence has not been previously recognized and allow direct information to be obtained about the nature and densities of the defect states in the i-layers [5]. The advantages of this new approach are illustrated here with successful application of the results on J_D -V characteristics to the results on V_{oc} 's under various illumination intensities in the cells where the p/i interface recombination is minimized and the carrier transport is dominated by the recombination in the bulk i-layers. Excellent correlation is found between the J_D -V characteristics and V_{oc} 's for cells with different bulk i-layers in their annealed states as well as after light induced degradation. In addition, the distinct differences observed in the degradation kinetics of 1 sun V_{oc} between the cells having hydrogen diluted (protocrystalline) and undiluted i-layers are correlated with the differences in their defect state distributions between these two materials as indicated by the analysis carried out previously on the differential diode quality factors $n(V)$ [5].

EXPERIMENTAL DETAILS

The p (a-SiC:H)/ i (a-Si:H)/ n (μ c-Si) (superstrate) a-Si:H solar cells used in this study were fabricated by RF plasma enhanced chemical vapor deposition at a

substrate temperature of 200°C under conditions described previously [6]. The bulk i-layers in the cell structures were deposited using SiH₄ diluted with H₂, with $R = [H_2]/[SiH_4]$ of either 10 (diluted) or 0 (undiluted). To minimize the contributions of shunts, cell structure areas of 0.02 cm² were used, which were defined by removing the uncovered top n μc-Si:H layers with reactive ion etching. The J_D-V characteristics measurements were carried out at temperatures that were controlled to within ±0.1°C and a three-probe technique was used to eliminate any effects of extraneous series resistance. Care was also taken to ensure that the steady-state currents were measured at low biases and that no defects were introduced by double injection in the high forward bias regions. The annealed states were achieved by heating the cells for 4 hours at 170°C and the light induced defects were introduced using illumination generated by ELH lamp which has light intensity equivalent to that of 1 sun illumination. The illumination intensities lower than that of 1 sun was obtained with various combinations of neutral density filters.

RESULTS

It has been shown that in the cells where bulk recombination dominates the current and the defect state distribution is essentially uniform across the bulk i-layer, there is a dependence of the J_D-V characteristics on the bulk i-layer thickness as a result of the scaling of the electric fields [4]. One natural extension to this is that because of the higher recombination in the thicker cells there should also be a corresponding reduction in their 1 sun V_{oc}'s. This requires that the bulk recombination dominates the carrier transport not only at relatively low biases but also at high biases up to 1 sun V_{oc}. That this is indeed the case is illustrated in Fig. 1 which shows the results on the thickness dependence of 1 sun V_{oc} as well as J_D-V characteristics for p-i-n cells having the same structure but different thickness of R=0 bulk i-layers. In these cells the recombination at the p/i interfaces is minimized by having a 200Å of R=40 protocrystalline i-layer in the p/i region. It can be seen in the insert of Fig. 1 that the 1 sun V_{oc} decreases systematically with the increasing thickness of the bulk i-layer where a decrease of ~30mV (from about 0.89 to 0.86V) occurs in V_{oc} for an increase of a factor of 2 in the dark currents at low biases. This 30mV decrease in V_{oc} is consistent with the increase in the dark currents whose increase for this change in voltage corresponds to the "effective" diode quality factor of ~1.6 present in these cells [5]. It is important to note here that these V_{oc}'s were measured not with fixed illumination intensities but instead with a fixed J_{sc} of 10 mA/cm² (equivalent to 1 sun J_{sc} for the cells with 0.4μm thick i-layer) to eliminate the effect from the changes in light absorption due to the differences in the i-layer thickness. In thicker cells the increases in the dark current at voltages corresponding to 1 sun V_{oc} cannot be directly observed because they become limited by carrier injection over the potential barriers in the i-layers adjacent to the p and n contacts [4].

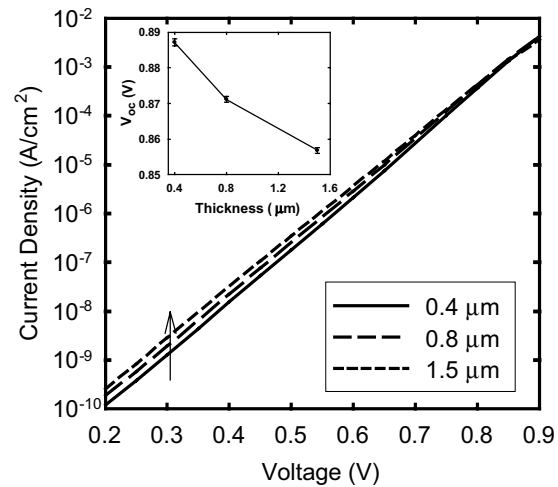


Fig. 1: Thickness dependence of 1 sun V_{oc} and J_D-V characteristics for p-i-n cells having the same structure but different thickness of R=0 bulk i-layers.

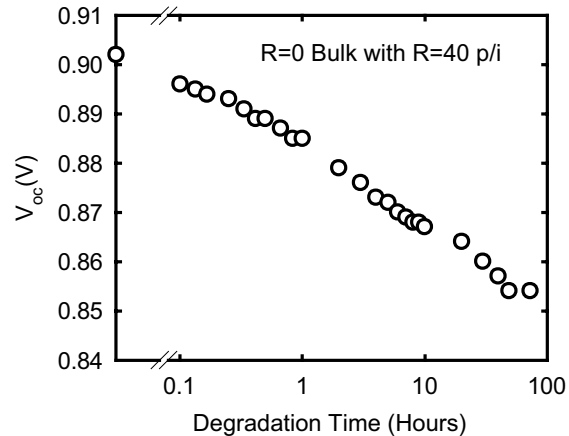


Fig. 2: Degradation of 1 sun V_{oc} under 1 sun illumination at 25°C for the cell in Fig. 1 with the 0.4μm thick i-layer.

The domination of these V_{oc}'s by bulk recombination currents at biases corresponding to 1 sun V_{oc} in the cells studied could be further confirmed with the degradation kinetics of the 1 sun V_{oc}. Shown in Fig. 2 is the degradation of the 1 sun V_{oc} under 1 sun illumination at 25°C for the cell in Fig. 1 having the 0.4μm thick i-layer. It can be seen that there is an immediate decrease in the 1 sun V_{oc} which is a clear indication that there are no significant contributions from p/i interface recombination. After 100 hours of degradation there is a decrease in V_{oc} of around 50 mV that is consistent with the changes in the J_D-V characteristics of the same cell as shown in Fig. 3. In Fig. 3 there is an increase in the recombination current of a factor of ~3 at a bias that corresponds to the 1 sun V_{oc}.

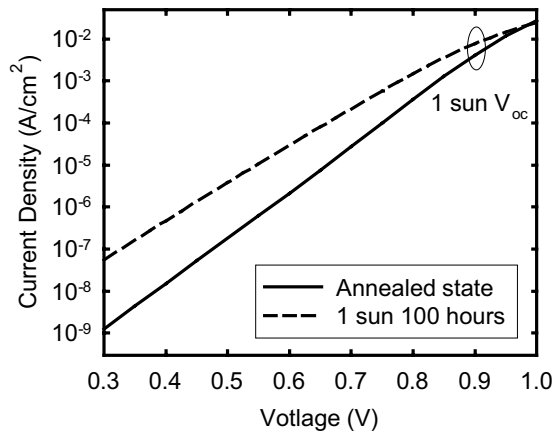


Fig. 3: J_D - V characteristics of the cell in Fig. 2 in the annealed state and after 100 hours of 1 sun illumination.

Similar correlations between the degradation of V_{oc} 's and J_D - V characteristics are also obtained for the cells with $R=10$ protocrystalline i-layers. This is illustrated in Figs. 4 and 5 with results on a p-i-n cell with $0.4\mu\text{m}$ thick $R=10$ bulk i-layer and 200\AA thick $R=40$ p/i interface. In Fig. 4 the decreases in V_{oc} 's measured under light intensities from 1 to 10^{-4} sun, are shown as a function of the degradation time under 1 sun illumination. It can be seen that as the light intensity and V_{oc} are lowered there are corresponding changes in both the rate and magnitude of the voltage decreases in reaching a degraded steady state after ~ 100 hours of illumination. For the illumination intensity of 10^{-4} sun, corresponding to an initial V_{oc} of 0.62V, there is a decrease of ~ 70 mV in V_{oc} . For 1 sun illumination the degradation is less than 10 mV, a value that is also significantly smaller than the 50 mV degradation of the 1sun V_{oc} for the cell with $R=0$ i-layer after the same degradation. This small degradation at such a high illumination level cannot be due to the limitations imposed by p/i interface recombination since a similar dependence of 1 sun V_{oc} on thickness was also found for the cells with $R=10$ i-layers. The degradation in V_{oc} 's in Fig. 4 can be directly correlated with the changes in J_D - V characteristics shown in Fig. 5. In Fig. 5 there are systematic increases in the dark currents with illumination time just as in the corresponding V_{oc} 's. The changes in the currents which are larger at the lower biases correspond to the higher decreases in V_{oc} 's measured at the lower illumination intensities. Unlike the large change in the cell with the $R=0$ i-layer, there is hardly any discernable changes in the dark current at the levels equivalent to 1 sun J_{sc} . This cannot be completely due to the carrier injection limitations imposed by the potential barriers since these limitations occur at similar current levels for both types of the cells. The difference in the 1 sun V_{oc} degradation between the cells with the $R=10$ and $R=0$ i-layer thus clearly points to a distinct difference in their gap state distributions upon light induced degradation.

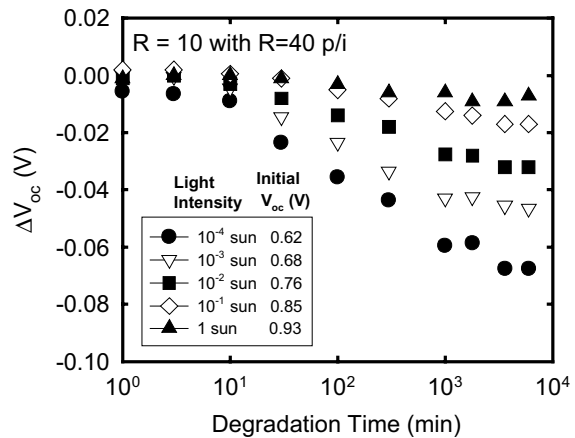


Fig. 4: Degradation of V_{oc} 's for a p-i-n cell with $0.4\mu\text{m}$ thick $R=10$ bulk i-layer and 200\AA thick $R=40$ p/i interface measured under light intensities from 10^{-4} to 1 sun.

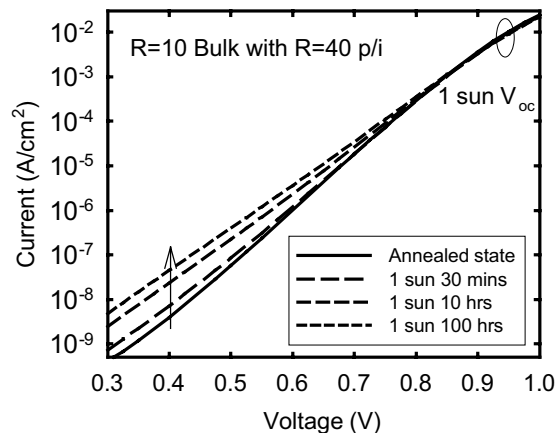


Fig. 5: J_D - V characteristics of the cell in Fig. 4 in the annealed state and after light induced degradation.

DISCUSSION

Several conclusions can be drawn from the above experimental results. First, in these cells the currents are dominated by bulk recombination up to bias levels equivalent to 1 sun V_{oc} . This is significant since then the results obtained on the J_D - V characteristics can be directly applied to the analysis of solar cell performance. Second, there are large light induced changes in the densities and distributions of the defect states in both the undiluted and diluted protocrystalline i-layers associated with Staebler-Wronski Effect (SWE). Thirdly, the distributions of gap states in the two i-layers are distinctly different, thus leading to the differences in the corresponding solar cell performance and stability.

In order to understand the relation between solar cell parameters such as V_{oc} and the distribution of gap states in the i-layers it is necessary to identify the differences present in the two i-layer materials. The essential features of the distributions for both the undiluted and diluted i-

layers have been obtained from the analysis on the $n(V)$ characteristics [5]. In both cases they are consistent with a Gaussian-like distribution around midgap followed by an exponentially rising distribution away from the midgap which could also be regarded as the rising edge of a second Gaussian-like distribution. Similar Gaussian-like distributions have been proposed in several previous studies [7-10]. There is however a major difference between the undiluted and diluted i-layer where in the former case the rising edge of the second Gaussian-like distributions are much less steep. Furthermore, after the introduction of light induced defects, the distributions in both i-layers broaden with a much smaller broadening occurring in the case of the protocrystalline i-layer. For both cases there is also a large increase in the density of states around midgap which causes the large increases in the dark currents under low forward biases and the large decreases in the V_{oc} 's under illumination intensities much smaller than 1 sun. On the other hand, in the case of the dark currents under high forward bias and V_{oc} under sufficiently high illumination intensity, the splitting between the two quasi-Fermi levels are sufficiently large as to include as recombination centers not only the gap states around midgap but also those located further away from the midgap. For the cell with protocrystalline i-layer, due to the narrower Gaussian-like distributions in the annealed and degraded states, the positions of quasi-Fermi levels at 1 sun V_{oc} are in a region where the native defects away from midgap play a dominant role in the recombination. This then explains the very small degradation of 1 sun V_{oc} while there is significant degradation for the V_{oc} 's under the lower intensities of illuminations. On the other hand, for the cell with undiluted i-layer, due to the broad distribution away from midgap the contribution from the light induced defects increases the recombination over that of the native defect states alone and accounts for the significant degradation in 1 sun V_{oc} . It is very important to note here that for cells having both undiluted and protocrystalline i-layers the degradation in the 1 sun V_{oc} 's are much smaller than that expected if these V_{oc} 's were limited purely by the recombination through the neutral dangling bonds, with states located around midgap and detected by electron-spin resonance. This is a further indication for the gap states other than the neutral dangling bonds determining cell performance [11, 12] and the key role of the Gaussian-like distributions away from midgap identified from the analysis of the $n(V)$ characteristics.

CONCLUSIONS

It has been shown from the J_D - V characteristics it is possible to identify and quantify the limitation imposed on 1 sun V_{oc} by bulk recombination. As a consequence, it has been possible to relate the light induced changes in J_D - V characteristics to those in 1 sun V_{oc} for cells with undiluted and protocrystalline i-layers. In addition, the new approach in the analysis of J_D - V characteristics in terms of differential diode quality factor $n(V)$ has allowed these differences to be directly related to those in the distributions of gap states in the corresponding i-layers. The results also demonstrate that J_D - V characteristics

offer a *new and powerful probe* for characterizing mechanisms limiting the performance and stability of a-Si:H solar cells as well obtaining direct information about the distribution of gap states in the intrinsic layers. They also point out the key reason why it is not possible to obtain correlation between solar cell characteristics and neutral dangling bond densities. It is therefore important to take advantage of this powerful probe in guiding systematic approach to further improving performance of a-Si:H based solar cells as well as obtaining new insights into SWE.

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