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Degradation of thin film nanocrystalline silicon solar cells with 1 MeV protons

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Abstract

Thin film hydrogenated nanocrystalline silicon (nc-Si:H) solar cells were deposited at a high growth rate of 5 nm/s by Very High Frequency Plasma Enhanced Chemical Vapor Deposition (VHF PECVD). A single deposition yielded 30 working cells out of 30 test cells. After characterization of J-V characteristics under AM1.5 conditions, spectral response and Fourier Transform Photocurrent Spectroscopy (FTPS) for defect density, the cells were subjected to a beam of 1 MeV protons, with different irradiation times for a series of cells, up to a maximum fluence of 1015 protons per cm2, to investigate the feasibility of using this type of solar cells in space. After degradation, the cells were characterized again. The highest fluence reduced the conversion efficiency of the solar cells by a factor of 10. These values are compared to a similar experiment in literature for thin film amorphous silicon cells. The spectral response shows that the quantum efficiency for low energy photons is drastically reduced, suggesting that the damage is mainly inflicted to the bulk of the absorber material. This is strongly supported by the FTPS results, which show a clear trend of increasing defect density with increasing fluence. The optical absorption coefficient at 0.8 eV increased by a factor of 20. After characterization, the cells were isochronally annealed, up to the deposition temperatures, to investigate if the original performance of the cell could be restored. The mid-gap absorption decreased by a factor of 5 after annealing.

1. Introduction

Space applications of thin film solar cells thus far have not drawn much attention, although they can have an exclusive advantage over conventional wafer-based solar cells due to their low weight. For solar cells to be used in space, it is rather the weight per watt-peak than the cost per watt-peak that matters, which would make thin film cells a superior choice, provided that a suitable lightweight substrate is used, such as plastic or aluminum foil. However, a second necessity for space solar cells is their radiation hardness. The radiation hardness of

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nanocrystalline solar cells is the topic of this paper. It is not possible to make definite conclusions about the lifetime of nc-Si:H solar cells in space, since the radiation conditions strongly depend on the type of space mission and the activity of the sun, which is the main source of the radiation. However, it is possible to compare the present results to similar experiments on nc-Si:H [1] and amorphous a-Si:H [2] or tandem cells consisting of both materials [3]. Thin film silicon solar cells generally show a higher radiation hardness compared to multicrystalline silicon solar cells. Crystalline silicon has an indirect band gap and a correspondingly low optical absorption coefficient, making the c-Si cells more vulnerable to radiation damage [4], since the carrier collection in these thick cells is based on diffusion rather than drift. An investigation of the proton irradiation resistance for multicrystalline silicon solar cells, although peformed at higher proton energy, can be found in [5].

2. Experiment

Superstrate type nc-Si:H solar cells were deposited on TCO coated glass substrates in the ultra high vacuum multichamber deposition system ASTER using VHF PECVD. The absorber layer, having a thickness of 1 μm, was deposited at 5 nm/s using 350 W of 60 MHz VHF power at a pressure of 9 mbar from a mixture of hydrogen and silane at a flow ratio of 300:20. A showerhead electrode was employed for the source gas distribution in a configuration parallel to the grounded substrate at a distance of 6 mm. The front TCO is texture-etched ZnO:Al [6]. The cells were about one micrometer thick. After characterization the cells were subjected to a 1-MeV proton beam. The penetration depth for protons with this energy is in the order of one millimeter into the glass. Since the film thickness is much less than that, the energy dissipation is practically homogeneous over the thickness of the film. The sample consisted of 30 test cells of 4×4 mm^2 area for each test cell, defined by evaporated silver-aluminum back-contacts. The cells were divided into six groups, each of which received a different fluence of protons, ranging from 10^{13} to 10^{15} protons per cm^2. Irradiation took place at room temperature at a constant intensity. The intensity was such that the largest fluence took 2 hours to complete. Before and after the proton degradation step, the cells were characterized using current-voltage (J-V) measurement under dark and AM1.5 light conditions, spectral response and FTPS; FTPS is used to measure the mid-gap absorption which is taken to be proportional to the defect density [7]. After the last characterization step, the cells were isochronally annealed in steps of 10°C for 10 minutes up to 180°C. After each step the mid-gap absorption was measured again for the cell that had the strongest proton-induced degradation.

3. Results

Figure 1 shows normalized solar cell performance parameters, i.e., the short-circuit current (J_{sc}), the open-circuit voltage (V_{oc}), the fill factor (FF) and the conversion efficiency (N_{eff}), under AM1.5 illumination. Each point consists of the average of 4 test cells that received the same fluence. The irradiation affects all cell parameters. The N_{eff} shows the greatest decrease in performance, since it is the product of the other three numbers.
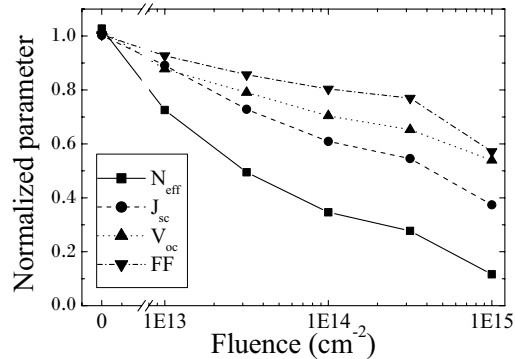
Figure 1: Effect of proton irradiation on the nc-Si:H solar cell performance

Figure 2 shows some of the results of Klaver [1] for a similar experiment on amorphous silicon cells, together with the behavior of the nc-Si solar cell described in this paper. The degradation of the nc-Si:H cell with increasing fluence shows a trend similar to that of a-Si:H cells. Moreover, the degradation appears to be dependent on thickness, regardless of the type of material used. This is understandable, since the energy deposition of the radiation is homogeneous, and proportional to the cell thickness, whereas solar cell performance is typically measured on a per-unit-area basis. In thicker solar cells, more defects are created per unit area.
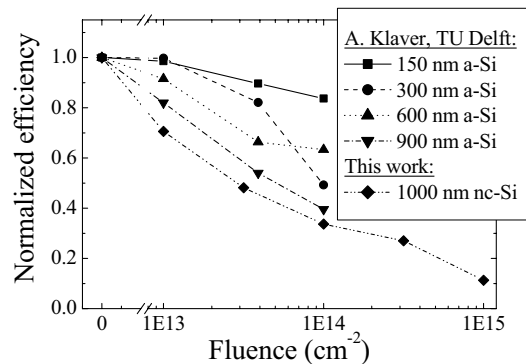

Figure 2: Effects of proton irradiation on both a-Si:H and nc-Si:H thin film solar cells

The average spectral response averaged over 4 cells in the differently irradiated groups are shown in Figure 3. The fact that the cells are relatively thin for nc-Si:H cells and that they lack a ZnO:Al-Ag back reflector construction is clearly visible in the quick decay of the quantum efficiency in the red part of the spectrum.
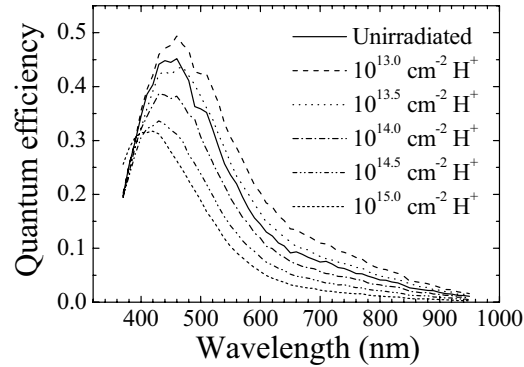
Figure 3: The spectral response of cell groups with varying proton damage

Because of the spread in results from different cells, and the limited degradation after the smallest fluences, the spectral response of two of the irradiated groups of cells is actually better than the unirradiated group in Figure 3. Therefore, a clearer presentation of the spectral response is given in Figure 4, which shows the spectral response values of groups of varying proton fluence relative to the response of the same groups before the degradation. This figure makes it very clear that the biggest setback in quantum efficiency caused by the proton irradiation occurs in the red part of the spectrum. Note that the quantum efficiency of the unirradiated sample also departs from the first measurement. This is partially attributed to the measurement error and partially to environmental and handling effects on the sample during the experiment.
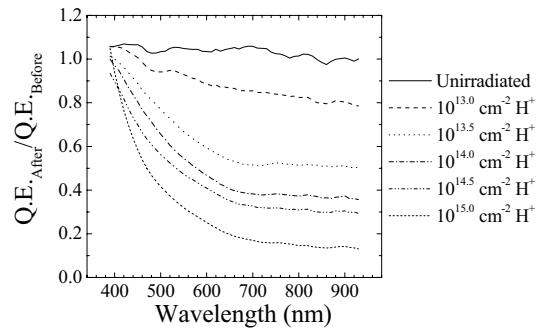

Figure 4: The ratio of the quantum efficiencies before and after the proton irradiations, for each group of cells. The data points consituting each curve are averaged for noise reduction.

Figure 5 shows the results of the FTPS measurements, given as the absorption coefficient in the infrared part of the spectrum. A large change in the absorption coefficient is observed for photons with energy around 0.8 eV.
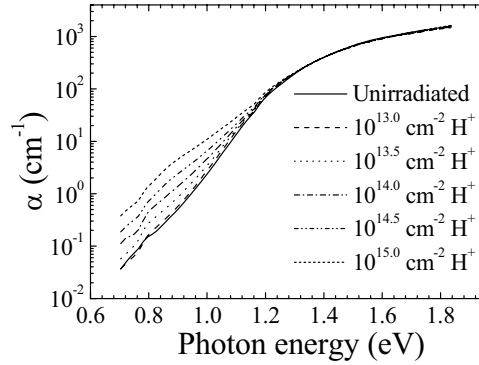
Figure 5: Cell group averaged FTPS absorption curves for nc-Si:H solar cells that received a varying proton fluence.

The absorption coefficient at 0.8 eV is commonly taken to be proportional to the dangling bond density [6]. All measured FTPS spectra have been calibrated to the c-Si absorption spectrum at 1.4 eV. At 0.8 eV, the absorption coefficient increased by a factor of 20. This is represented more clearly in Figure 6, where the ratio between the absorption curves before and after the measurements is shown. In this figure also a change of the absorption on the right side of the 1.4 eV calibration point is observed. This suggests a slight amorphization by the irradiation, however, too small to be detectable by Raman spectroscopy. Using a proportionality constant [6] between $\alpha(0.8 \text{ eV})$ and the midgap defect density of states, N_d, it is found that for the largest fluence of 10^{15} 1-MeV protons per cm^{-2}, N_d increased from 10^{16} cm^{-1} to $2 \times 10^{17} \text{ cm}^{-1}$.
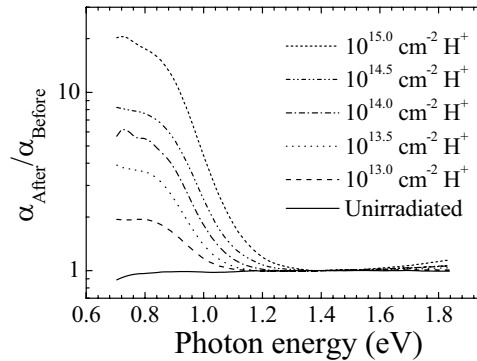

Figure 6: The ratio of the absorption coefficient before and after the proton irradiations, for each group of cells.

In order to test the reversibility of the proton-induced defect creation, the cell that received the largest fluence was annealed. After annealing this cell in a nitrogen atmosphere in consecutive steps of ten minutes at temperatures increasing by 10°C for each step up to 180°C, the absorption coefficient was observed to decrease again. Figure 7 shows the absorption coefficient of this cell after annealing relative to its as-irradiated state. To prevent the figure from becoming too cluttered, the 110°C, 130°C, 150°C, and 170°C, steps are not shown. After the 180°C step, the absorption coefficient was reduced by a factor of 5. The absorption coefficient at 0.8 eV finally reached a level very comparable to that of the samples that received a fluence of $3 \times 10^{13} \text{ cm}^{-2}$. The conversion efficiency, however, as could be inferred from Figure 1, was not restored to a level consistent with this fluence, thus indicating that the inflicted damage is not totally reversible by annealing.
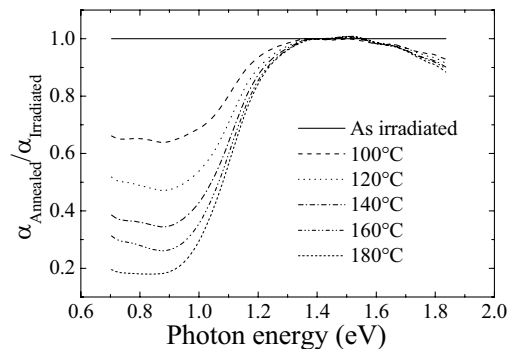
Figure 7: Isochronal annealing of the cell that received the highest fluence. The curves indicate the absorption coefficient relative to the as-irradiated condition of the cell, after the 10-minute step at the indicated temperature.

The annealing treatment was not continued above 180°C, to stay clear of the deposition temperature and rule out the possibility of concomitant structural modification.

4. Conclusions

After irradiation with 10^{15} 1-MeV protons the performance of a typical nanocrystalline silicon solar cell is decreased to 10% of its original conversion efficiency. From the quantum efficiency it can be concluded that most of the performance is lost in the low energy part of the spectrum, for which the charge carriers are created in the bulk of the cell. From the absorption coefficient in the infrared as measured from FTPS it is learned that the amount of mid gap defects is strongly increased by the degradation by protons. The strongly increased recombination causes the quantum efficiency for the red part of the spectrum to diminish. Comparison with similar experiments on thin film a Si:H solar cells from the literature suggests a relation between thickness and performance degradation for thin film cells. The negative effects of the proton degradation on the defect density can only partially be undone by thermal treatment. Together with the observed changes in the higher energy part of the absorption spectrum, this suggests that the remainder of the induced defects is caused by irreversible modification of the material.

5. Acknowledgements

6. References

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