Proton Irradiation Effects on Amorphous Silicon Triple-Junction Solar Cells

Shin-ichiro Sato[*1], Kevin Beernink[2], and Takeshi Ohshima[1]
1 Japan Atomic Energy Agency (JAEA), Japan
2 United Solar Ovonic LLC, USA
*Email: sato.shinichiro@jaea.go.jp
Keyword(s): Thin Film Si Solar Cell, Radiation Effects, Proton Irradiation

Abstract

Degradation behavior of a-Si/a-SiGe/a-SiGe triple-junction solar cells irradiated with various energy protons are investigated *in-situ*. It is clarified that the degradation due to proton irradiation is scaled by a unit of displacement damaged dose and thus the proton-induced degradation is mainly caused by the displacement damage effect. The performance recoveries immediately after irradiation are also investigated and it is clarified that all the parameters recover significantly at room temperature. In particular, the remarkable recovery is observed in the short-circuit current. This is thought to be due to recovery of the carrier lifetime, which is based on annealing of radiation defects.

1. Introduction

Amorphous silicon (a-Si) thin film solar cells are expected to be utilized as flexible space solar cells, since it is known that they have not only good radiation tolerance, but also the potential for reductions of both cost and stowage volume [1, 2]. Although radiation degradation of a-Si solar cells and their thermal recovery of post-irradiation have been investigated [3–5], systematic knowledge of the radiation degradation of a-Si solar cells has not been obtained compared to other types of solar cells, such as crystalline Si and III-V compounds.

Recently, we have reported that the temperature during irradiation strongly affects performance degradation of a-Si single-junction solar cells, and the cell performance significantly recovered immediately after irradiation even at room temperature (RT) [6]. These results indicate that thermal recovery always occurs simultaneously with radiation degradation. Thus, temperature during irradiation, irradiation rate, and the elapsed time between irradiation and measurement should be controlled in conducting radiation ground tests for a-Si solar cells.

In this paper, we report degradation behavior of a-Si/a-SiGe/a-SiGe triple-junction (TJ) solar cells irradiated with 10 keV to 10 MeV energy protons and discuss the degradation mechanism. In addition, we report the performance recovery at RT just after irradiation by using *in-situ* current-voltage (*I-V*) measurement system. High energy protons penetrate and deposit their energies uniformly in the cell, whereas low energy protons stop in the active layers (top, middle or bottom layer) of the cell and selectively degrade each layer. Thus, structural dependency on radiation tolerance can be clarified by analyzing proton energy dependency of the degradation behavior.

2. Experimental

Samples used in this study were a-Si/a-$Si_{0.8}Ge_{0.2}$/a-$Si_{0.6}Ge_{0.4}$ TJ solar cells, which were not light-soaked. The cells were fabricated at United Solar Ovonic LLC. The typical cell characteristics are listed in Table I. Proton irradiation from 10 keV to 10 MeV was performed at the Takasaki Ion Accelerators of advanced Radiation Application (TIARA), Japan Atomic Energy Agency (JAEA). *I-V* characteristics under AM-0, 1 sun conditions were measured *in-situ* in an irradiation chamber (*in-situ* measurement). Note that 20 keV H_2 ion beams were used for 10 keV proton irradiation. A control cell was prepared in order to check the light-induced degradation due to repetition of *I-V* measurement. The control cell was not irradiated and was simultaneously measured with an irradiated cell. No light induced degradation due to the *in-situ I-V* measurement was observed in the irradiation experiments.

Proton beam flux, temperature during irradiation, and elapsed time between irradiation and measurement were strictly controlled in order to compare the degradation behavior accurately. The proton beam flux and the irradiation temperature were 1.4×10^{10} $cm^{-2}\cdot s^{-1}$ and 298 K, respectively, and the *I-V* measurement was done 1 minute after irradiation was stopped. The proton irradiation was performed until the short-circuit current (Isc) decreased to around 45 %, and the recovery of the cell performance after irradiation was investigated for 60 minutes at 298 K in vacuum. The cells were kept under dark conditions

Table I. Initial electric performance of sample at AM-0, 1 sun conditions.

Isc (mA/cm^2)	8.84
Voc (V)	2.18
Pmax (mW/cm^2)	13.3
FF	0.689
Efficiency (%)	9.73
Active Area (cm²)	1.00

except when the *I-V* measurement was performed.

3. Results

Degradation curves of Isc, open-circuit voltage (Voc), and maximum output (Pmax) of the cells irradiated with 10 keV, 20 keV, 40 keV, 65 keV, 80 keV, 100 keV, 200 keV, 2 MeV and 10 MeV protons are shown in Figs. 1 (a), (b), and (c), respectively. The degradation of Isc was larger as the proton energy was lower, except the results of 10 keV and 20 keV proton irradiations. Whereas the remaining factors of Isc intensively decreased in the high fluence regime, the Voc gradually decreased and kept the relatively higher value. Here, remaining factor is defined as the ratio of the values after irradiation to before irradiation. The remaining factor of Voc was around 80 % independent of incident proton energy when the Isc decreased to around 45 %. With respect to the proton energy dependence of degradation behavior, similar results were obtained in the degradation of Isc and Voc. As for Pmax, similar degradation curves were obtained in all cases. The degradation of Pmax is mainly attributed to the degradation of fill factor (FF) rather than that of Isc and Voc.

The cell performance recovery after 80 keV proton irradiation at the fluence of 2.0×10^{13} cm^{-2} is shown in Fig. 2. All the parameters (Isc, Voc, FF, and Pmax) significantly recovered immediately after the irradiation was stopped. In particular, the Isc values prominently recovered in all cases. This indicates that radiation defects in the active layers were annealed and the minority carrier lifetime recovered (RT annealing) [6].

Figure 3 shows the comparison of the Isc recovery after irradiation. In this figure, recovery amount is defined as the amount of increase one hour later after irradiation (all the values are normalized so that the values before irradiation are 100 %). It is shown in Fig. 3 that the recovery amount of Isc had a tendency to be large in low energy proton irradiation.

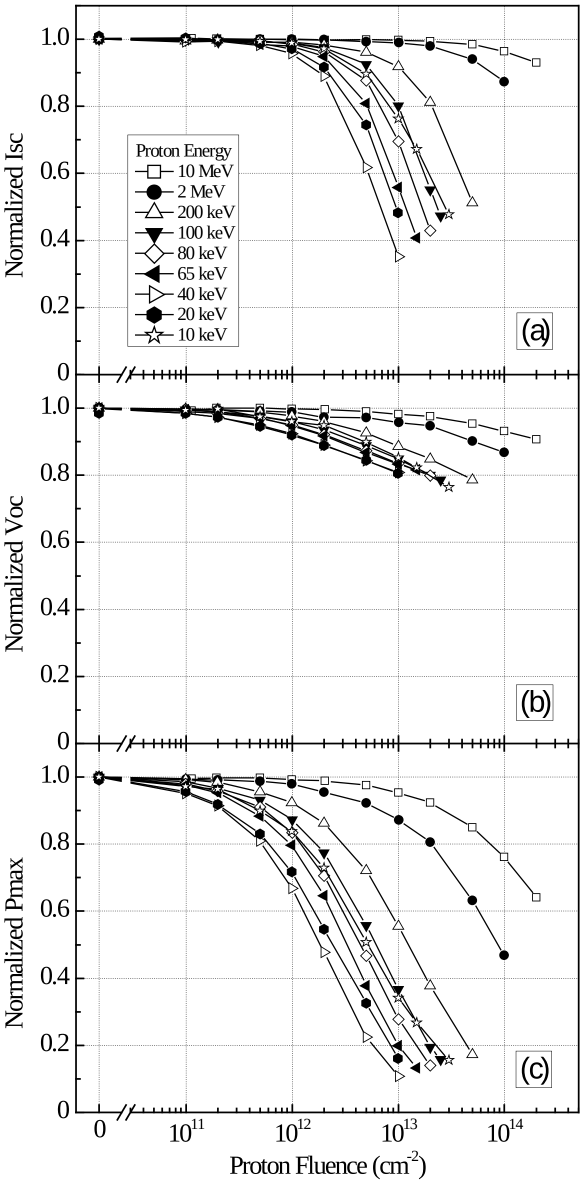

Fig. 1. Degradation curves of (a) Isc, (b) Voc, and (c) Pmax of the cells as a function of proton fluence. All the values are normalized by the values before irradiation.

4. Discussion

By analyzing the degradation curves of Isc and Voc shown in Figs. 1 (a) and (b), clarification is given as to which energy deposition process of incident protons is dominant in the degradation of the cell performance. The radiation degradation of a-Si solar cells is expected to be affected by both the electronic excitation effect and the displacement damage effect, although it is unclear which effect is the main cause of the electrical degradation. Srour *et al.* have investigated radiation degradation of a-Si solar cells using protons, electrons and X-rays, and have concluded that the electrical degradation correlated with ‘ionizing dose’ of radiations, which reflected the amount of excited electrons [4]. On the contrary, Shimazaki *et al*. have also reported proton irradiation effects on a-Si solar cells and have concluded that the electrical degradation did not correlate with the ionizing dose, but rather correlated with ‘displacement damage dose (DDD)’, which reflected the amount of displacement damage [5]. This discrepancy might be caused by an uncertainty of the degradation data they used. Since *in-situ* measurement techniques were not used in both studies, radiation degradation of the cells was expected to recover substantially and substantial error might be introduced in the data. On the other hand, fluctuation of the data based on the annealing effect was minimized in this study by not only using the *in-situ* measurement technique, but also by strictly controlling the irradiation conditions. Therefore, a definite conclusion could be obtained from the results of this study.

Figure 4 shows the degradation curves of Isc and Voc of the cells which are scaled using the ionizing dose

(J/kg) and the DDD (MeV/g). Although the data shown in Figs. 4 (a) and (b) are the same as Fig. 1 (a), the abscissa axes in Figs. 4 (a) and (b) are converted from a unit of fluence to ionizing dose and DDD, respectively. The same is true of Fig. 4 (c) and (d). The ionizing dose is defined as the product of the electronic energy depositions (eV/cm, or J/cm), the mass density (g/cm^3), and the proton fluence (cm^{-2}). The electronic energy deposition was derived from the TRIM code [7]. The DDD is defined as the product of the NIEL value (Non-Ionizing Energy Loss, MeV·cm^2/g) and the proton fluence. The NIEL value was derived from Ref. [8] by considering the mass density and the elemental composition of the cell. In order to consider the deposited energy distribution in the depth direction, both the electronic energy deposition and the NIEL value per unit depth were calculated using the TRIM code and their average values in the whole region of the cells were used.

The results clearly showed that a universal curve was drawn by the DDD scaling, while not being drawn by the ionizing dose scaling. This indicates that the degradation in Isc and Voc is mainly attributed to the displacement damage effect, and the degradation due to proton irradiation is different from the light-induced degradation [9]. However, the degradation curve of 10 keV proton irradiation slightly deviated from the universal curve (open star symbols in Fig. 4 (b)). In principle, the Voc of triple-junction solar cells is represented as the sum of the Voc's of the three sub-cells, and the Isc value is equal to the minimum Isc among them (current-limiting cell). Thus, it seems reasonable that the degradation in Voc is correlated with the average DDD value in the whole region of the cell, whereas the degradation in Isc should be correlated with the average DDD value in the current-limiting cell. Since the current matching between sub-cells was achieved in the cells before irradiation, the most degraded sub-cell was expected to become the current limiting cell. According to the calculation using TRIM and NIEL, the current-limiting cell was expected to be the top cell in the case of 10 keV proton irradiation, the middle cell in 20 keV proton irradiation, and the bottom cell in 40 keV to 80 keV proton irradiation. However, universality of the degradation curves scaled by the DDD was not improved when the DDD values in the 'expected' current-limiting cell were used. This is thought to be due to the differences of radiation tolerance and RT annealing rate between the sub-cells. As shown in Fig. 3, the more remarkable recovery of Isc at RT was observed in 10 keV and 20 keV proton irradiations. This strongly indicates that the recovery of the top cell is more remarkable than that of middle and bottom cells.

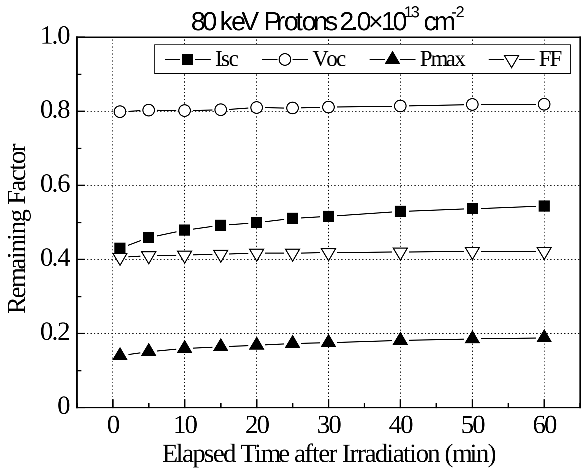

Fig. 2. Performance recoveries after 80 keV proton irradiation at the fluence of 2.0×10^{13} cm^{-2}. Isc: closed squares, Voc: open circles, Pmax: closed triangles, and FF: open inverted triangles. All the values were normalized by the values before irradiation.

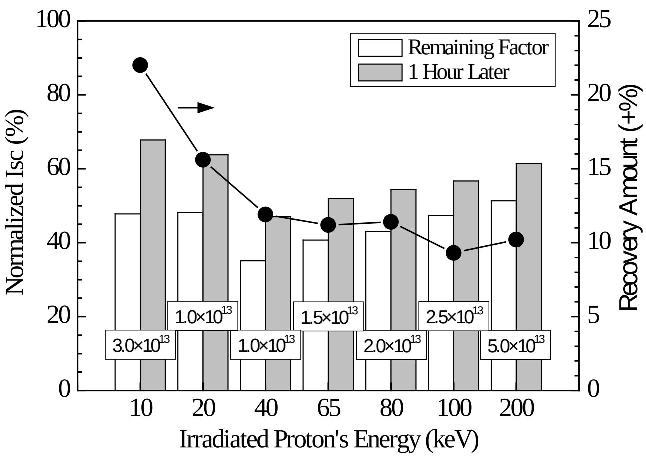

Fig. 3. Comparison of recovery of Isc after irradiation. The abscissa represents the irradiated proton's energy and the irradiation fluence (cm^{-2}) is shown in the boxes. White and shaded bars represent the normalized Isc values 1 minute and 1 hour later after irradiation, respectively. Recovery amount is defined as a difference of them.

5. Summary

The degradation behavior of a-Si/a-SiGe/a-SiGe TJ solar cells irradiated with 10 keV to 10 MeV protons and the performance recoveries after irradiation were investigated using the *in-situ I-V* measurement system. The irradiation conditions were strictly controlled to clarify the annealing behavior at RT, and the following findings were obtained.

The degradation in Pmax is mainly due to the degradation in FF independent of irradiated proton's energy, and both the Isc and Voc degradations are relatively smaller. Significant recovery of all the parameters appears

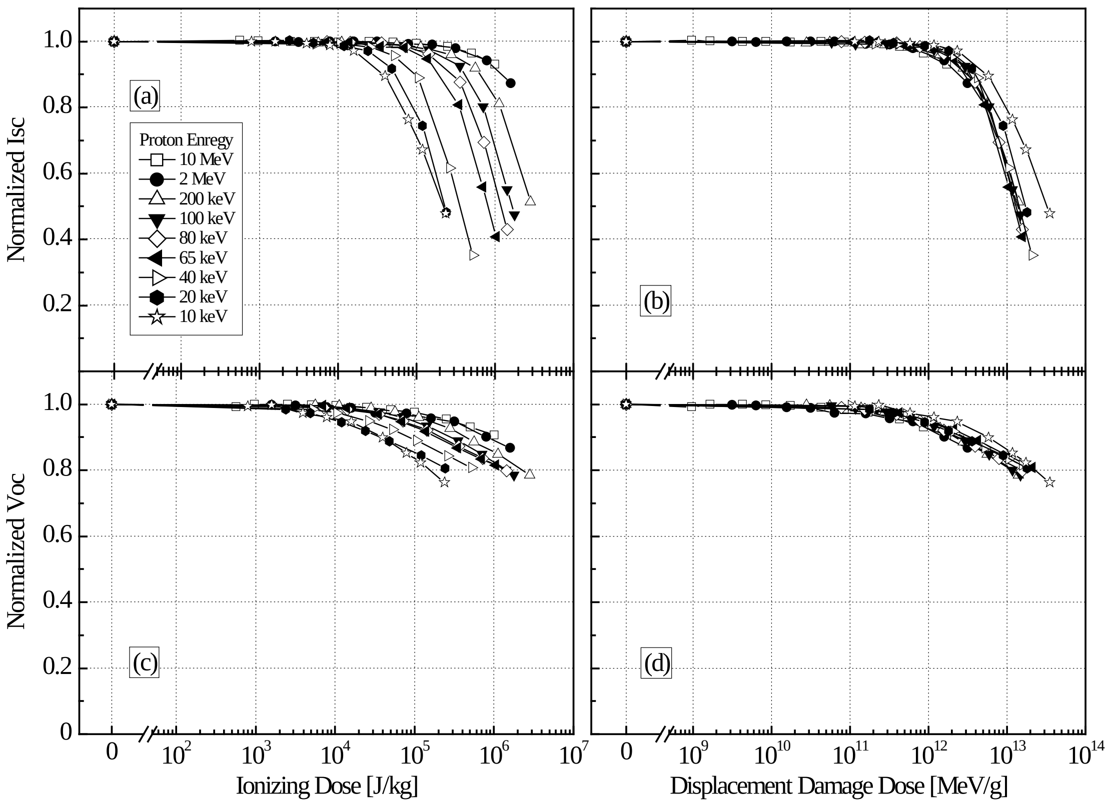

Fig. 4. Ionizing dose scaling and displacement damage dose (DDD) scaling for the degradation curves of Isc and Voc. The abscissa axes are converted from fluence (cm^{-2}) to ionizing dose (J/kg) in (a) and (c), DDD (MeV/g) in (b) and (d). The ordinate axes are the remaining factors of Isc in (a) and (b), Voc in (c) and (d).

immediately after proton irradiation and the Isc value remarkably recovers in particular. This is due to recovery of the carrier lifetime, which is based on RT annealing of radiation defects. The recovery of top (a-Si) cell at RT is more remarkable than the other sub-cells. The degradation due to proton irradiation is scaled by a unit of displacement damage dose. Therefore, the proton-induced degradation is mainly caused by the displacement damage effect, although the electronic excitation effect, which is the cause of light-induced degradation, may partly contribute.

Acknowledgments

Work at United Solar was funded by Air Force Research Laboratory, Space Vehicles Directorate under contract FA9453-06-C-0339.

References

[1] S. G. Bailey *et al.*, "The Future of Space Photovoltaics," in *Proceedings of 34th PVSC*, Philadelphia, PA, pp. 001909-001913 (2009).
[2] A. Banerjee *et al.*, "Advances in Cell Efficiency of a-Si:H and nc-Si:H-Based Multi Junction Solar Cells for Space and Near-Space Applications," in *Proceedings of 35th PVSC*, Philadelphia, PA, pp. 002651-002655 (2009).
[3] R. A. C. M. M. van Swaaij *et al.*, "Comparison of Amorphous Silicon Solar Cell Performance Following Light and High-Energy Electron-Beam Induced Degradation," *J. Non-Cryst. Sol.*, vol. 354, pp. 2464-2467 (2008).
[4] J. R. Srour *et al.*, "Radiation Effects and Annealing Studies on Amorphous Silicon Solar Cells," *IEEE Trans. Nucl. Sci.*, vol. 56, pp. 3300-3306 (2009).
[5] K. Shimazaki *et al.*, "Analysis of Radiation Response and Recovery Characteristics of Amorphous Silicon Solar Cells," in *Proceedings of 4th WCPEC*, Hawaii, HI, pp. 1797-1800 (2006).
[6] S. Sato *et al.*, "Electron and Proton Irradiation Effects on Substrate-Type Amorphous Silicon Solar Cells," in *Proceedings of 37th PVSC*, Seattle, WA (2011) *in Press*.
[7] Available: http://www.srim.org/
[8] I. Jun *et al.*, "Proton Nonionizing Energy Loss (NIEL) for Device Application," *IEEE Trans. Nucl. Sci.*, vol. 50, pp. 1924-1928 (2003).
[9] D. L. Staebler *et al.*, "Reversible Conductivity Changes in Discharge-Produced Amorphous Si," *Appl. Phys. Lett.*, vol. 31, pp. 292-294 (1977).