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Radiation Effects of Protons and Electrons on Backfield Silicon Solar Cells

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The electrical properties of back field silicon solar cells were investigated after the samples were irradiated by protons and electrons with 30–180 keV and a given flux of 1.2×10^{12} cm^{-2} s^{-1} for various fluences at 77 K. The results show that the short-circuit current decreases gradually with increasing proton fluence, whereas the open-circuit voltage degrades severely under lower fluences. Radiation of electrons with energy lower than 180 keV and various fluences causes negligible change in the electrical properties of the solar cell, but a significant change appears and then a recovery effect of the electrical properties in in situ measurements during irradiation and afterward, respectively. The effect of the combined radiation of protons and electrons does not show simple additivity; the radiation effects of protons dominate the process. The damage caused by proton radiation is larger than that from combined radiation under lower electron fluences, whereas the combined radiation results in more severe damage under higher fluences. The changes in the electrical features of solar cells after radiation are explained.

I. Introduction

As key elements to provide spacecraft with electrical energy in orbit, solar cells and their properties should be stable under conditions in the space environment, such as various particle radiations and space thermal cycling. It is reported that the electrical properties of solar cells can degenerate under space radiations.[1–5] However, more investigation was done for higher-energy (>1 MeV) particle radiations; thus improved knowledge of lower-energy proton environments is required.[6,7] It is necessary to characterize the effects of charge particles with lower energy than 200 keV, because there are large numbers of low-energy particles in the Earth's radiation belts. On the other hand, the solar cells in its orbit are subjected not only to single charged particles such as protons or electrons, but also to their combined effects in the meantime. Additionally, the solar cells are under a low-temperature condition when the spacecraft passes into the Earth shadow. To evaluate the performance of solar cells in geostationary Earth orbit, it is necessary to characterize the combined effects of charged particles at low temperature (such as liquid nitrogen temperature, 77 K). The aim of this study was to investigate the combined radiation effects of protons and electrons on electrical properties of silicon solar cells, as well as the radiation damage mechanism.

II. Experimental

A. Sample Solar Cells

The backfield silicon solar cells (Si–n^+/p/p^+ monocrystal battery) are schematically shown in Fig. 1. They are 250 μm thick with a base layer (region III in Fig. 1) resistivity of 10–12 $\Omega \cdot$ cm. The size of the experimented cell unit is 20×20 mm. In the base region of the P layer the boron doping concentration is about 10^{18} cm^{-3}; the aluminum-doped p^+ layer (II region in Fig. 1) is about 0.5 μm to form a backfield with the base p region. The phosphorus-doped Si emitter n^+ (V region in Fig. 1) is at depth 0.2-μm from the surface, and the doping content of phosphorus is about 10^{20} cm^{-3} in this layer. To increase the efficiency of the solar cell, an attenuating reflection film (VI region in Fig. 1) of a 100-Å-thick SiO_2 was thermally oxidized on the cell surface. The gate electrode and back contact layer (shadow regions) are deposited silver of 5 μm. The I–V curve of the unirradiated cell is shown in Fig. 2 (curve 1) under an AM1.5 luminous source. The short-circuit current I_{sc}, open circuit voltage V_{oc}, fill factor FF, and efficiency η are measured as 136.5 mA, 557.0 mV, 0.79, and 12.5%, respectively.

B. Radiation Experiments

The ground-based simulator used in this study can simulate the radiation of solar electromagnetic rays, electrons, and protons at low temperatures in orbit, independently and simultaneously. The irradiation energy of charged particles was chosen in the range 60–180 keV, the flux 1.2×10^{12} cm^{-2} s^{-1}, and the fluence from 2×10^{13} to 2×10^{16} cm^{-2}. The homogeneity of the irradiation flux is more than 95% in the area of 100×100 mm^2 by scanning the particle beams. During the irradiation, the chamber was kept at a vacuum better than 10^{-4} Pa and various temperatures.

C. Electrical Property Measurement and Deep-Level Transient Spectra

The electrical properties of the samples were characterized by I–V curves in a solar cell measurement system. AM1.5 was used as a luminous source to measure electrical properties and spectral response of the solar battery. To analyze the radiation-induced defects, deep-level transient spectroscopy (DLTS) was measured at the temperature range from 77 to 450 K in a DLTS measurement system produced by Innovance Comp.

III. Results and Discussion

A. Changes in Electric Properties of Solar Cell Under Proton Irradiation

Figures 2a and 2b show the I–V curves for the samples irradiated with 60- and 170-keV protons, respectively. The changes in the normalized short-circuit current I_{sc}/I_0 and the normalized open-circuit

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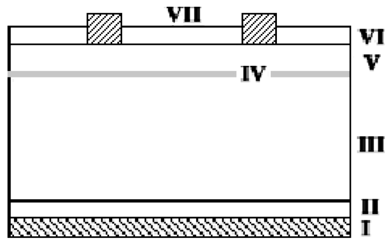

Fig. 1 Schematic diagram of the solar cell.

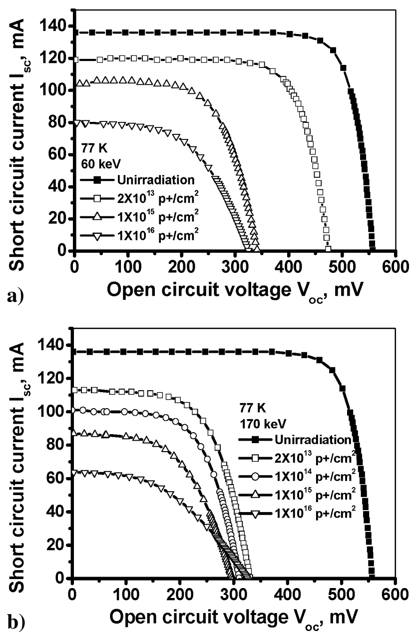

Fig. 2 *I–V* curves for samples irradiated with a) 60- and b) 170-keV protons.

Table 1 Variation of the samples before and after proton irradiation (AM 1.5)

Characteristics	V_{oc}, mV	I_{sc}, mA	FF	EFF	R_s[a] (Ω)
Nonirradiation	557.0	136.5	0.79	12.5%	0.42
60 keV, 1×10^{16} cm^{-2}	325.5	80.0	0.57	3.5%	3.40
170 keV, 1×10^{16} cm^{-2}	326.0	63.5	0.45	2.0%	4.30

[a] R_s, internal resistance in series.

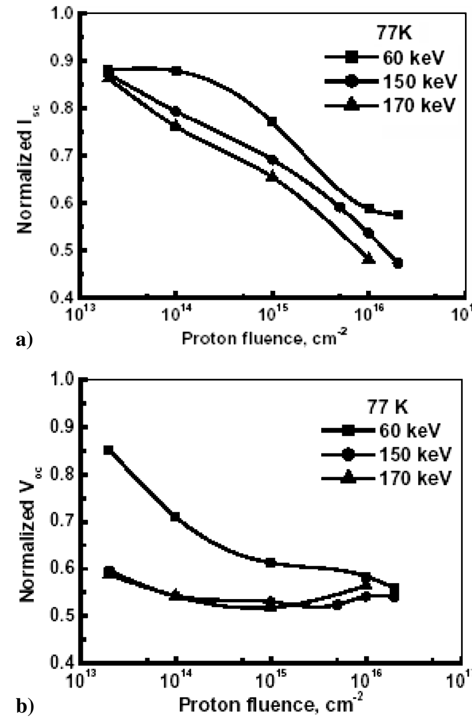

Fig. 3 Changes in a) normalized I_{sc} and b) normalized V_{oc} with fluence for the samples irradiated with 60-, 150-, and 170-keV protons.

voltage V_{oc}/V_0 are given as functions of fluence of protons with various energies, as shown in Figs. 3a and 3b. With both the fluence and energy of the proton beam increasing, the short-circuit current I_{sc} decreases gradually. The irradiation of protons also leads to a significant decrease of the open-circuit voltage V_{oc}, but the degradation extent depends on the fluence and energy of the protons. After the irradiation of protons with 150–170 keV, the V_{oc} is noticeably degraded at lower fluences, and then stays almost unchangeable with an increase in fluence. Table 1 shows that after the irradiation of protons with 60 and 170 keV for the fluence of 1×10^{16} cm^{-2}, all the characteristics including the V_{oc}, I_{sc}, FF, and EFF decrease, whereas the internal resistance in series increases remarkably (almost 10 times higher than that of the as-received). This implies that the concentration of effective carriers inside the samples is obviously reduced due to the proton irradiation. On the other hand, much more degradation of the open-circuit voltage V_{oc} takes place than of the short-circuit current I_{sc} of the beginning of proton radiation. This should be due to lower-energy proton radiation (than 1.5 MeV) producing nonuniform damage in the Si solar cell.[6] In our case the proton energy is less than 170 keV; thus the irradiation results in more severe damage in the junction region of the cells, causing more and faster degradation in the V_{oc}, as we have seen in Figs. 2 and 3. From Table 1, we can also see that, in the case of radiation fluence of 1×10^{16} cm^{-2}, the irradiated cells have a similar V_{oc}, but higher proton energy (170 keV) causes more decrease in the corresponding I_{sc}, FF, and EFF, indicating that more radiation-induced defects form in the cells under higher proton energy. However, the defects formed in the junction region are similarly dependent on the proton fluence but not on the energy in this study.

B. Changes in Electric Properties Under Electron Irradiation

The $I–V$ curves were measured ex situ for the samples before and after the irradiations of 60 and 180 keV electrons. The results (not shown here) indicate negligible change in the $I–V$ curves after the electron radiation. However, the situation is quite different if the $I–V$ curves are examined in situ during the exposure. With increasing electron fluence, the normalized V_{oc} gradually decreases, whereas the normalized I_{sc} increases up to a fluence of around 1×10^{16} cm^{-2} and then decreases gradually (see Fig. 4a). Figure 4b shows the changes in the V_{oc} and I_{sc} with time in vacuum after electron irradiation. It indicates that with increasing time, the V_{oc} rises and the corresponding I_{sc} drops. Both the V_{oc} and I_{sc} tend to return gradually to the pristine levels of the unirradiated samples. This phenomenon implies that recovery must be considered in evaluating the electron radiation effect for the back-field Si solar cells in orbit.

C. Changes in Electric Properties Under the Combined Irradiation of Protons and Electrons

Figure 5 shows the normalized $I–V$ curves for the samples under the proton, the electron, and the combined irradiations at 170 keV, respectively. It implies that damage effect of electrons is negligible but protons radiation causes severe damage in the solar cells (see curves 1, 2, and 4). The effect of the combined radiation of protons and electrons does not show simple additivity, but it should be noted that the proton effects dominate the radiation process. The degradation extent due to the proton radiation is larger than that of the combined radiation under the same proton fluence and lower electron fluence (see curves 3 and 4). In contrast, the combined radiation results in more severe damage under the same proton fluence and higher electron fluence (see curves 4 and 5).

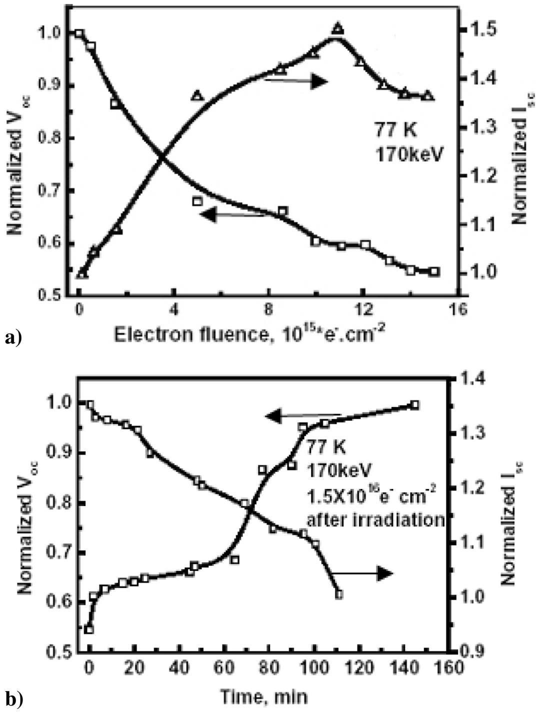

Fig. 4 Normalized V_{oc} and normalized I_{sc} measured in situ a) as a function of fluence for the samples during irradiation with 170-keV electrons and b) as a function of time in vacuum after irradiation with 170-keV electrons.

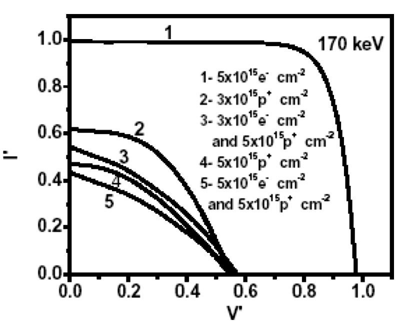

Fig. 5 Normalized *I–V* curves for samples under the proton, electron, and combined irradiation with 170 keV.

IV. Analysis of Radiation-Induced Defects and Damage Mechanisms

A. Defects Induced by Proton Radiation

Figure 6 shows the DLTS spectra of the samples after irradiation by protons with different energy and fluence. With lower proton energy (curve 1) or lower radiated fluence (curve 3), the DLTS signals show symmetrical distributions, but radiation with higher proton energy (even though the fluence is relatively lower) results in more intense DLTS peak compared curve 1 with curve 3 in Fig. 6. According to the DLTS analysis results, the primary defects induced by the protons are believed to be of the H1 type with energy level +0.45 eV (Refs. 8, 9), which contributes to the DLTS peak at a temperature of 240 K. The H1-type defects are generally referred to as the combination of radiation-induced vacancies with boron atoms, namely the [V+B] defects. Thus, under the <180-keV proton irradiation, a large number of vacancies could be formed in the base region close to the p–n junction of the backfield Si cells, and the vacancies would interact with the boron atoms nearby in the silicon, forming [V+B] type defects. It should be noted that these defects can trap the carriers in the cells, reducing the lifetime of the carriers, consequently decreasing the short-circuit current of the cells (Figs. 2, 3, and 5). The interaction of the radiation-induced vacancies with boron atoms can provide the thermodynamic driving force for the segregation of boron atoms in the base region close to

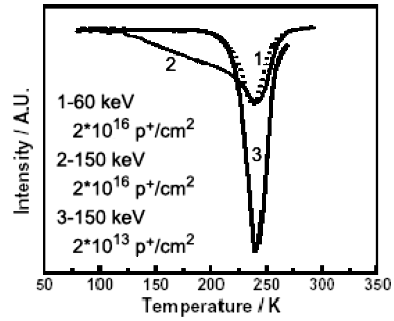

Fig. 6 DLTS spectra for cells irradiated by proton beams with different energy and fluences.

the p–n junction. As a result, a higher series resistance due to higher concentration of the [V+B] defects near the p–n junction could be formed after the proton radiation. The appearance of a deep level and the formation of such a resistance layer can contribute to the decrease in electric properties (decrease of I_{sc} and V_{oc}) for the backfield Si solar cells irradiated with <200-keV protons.

On the other hand, the spectra becomes asymmetric with increasing energy and fluence of radiation protons, as shown in Fig. 6 (curve 2), indicating formation of some new trapping centers with relatively lower level than that of H1. Analysis indicates that there exist three possible deep levels: V+V type 0.25 eV and V+O+C type 0.33 eV, besides H1 (V+B) type 0.45 eV (Refs. 8–10). These results imply that proton radiation with higher energy and larger fluence produces defects that are more complicated. Two possible reasons lead to this change: combination of single defects such as two vacancies combining into a V+V defect, direct formation of some complicated defects under stronger radiation. When the irradiation energy and fluence increase, the decrease in the DLTS peak height (Fig. 6) indicates that the number of single defects (vacancy+B) decreases but some more complicated defects form, implying that the main mechanism for the formation of complicated defects is combination of single defects.

B. Electron-Induced Changes of the Properties of the Solar Cell

After irradiation by electrons, no obvious change in the electrical properties of solar cells was detected in ex situ measurements, implying that no deep-level defect formed during the radiation. Nevertheless, significant change in short-circuit current and open-circuit voltage is detected through in situ measurements (Fig. 5, curve 1), and the changes recover after radiation. These features are due to electrons with energy less than 180 keV not being able to kick out the lattice atoms to form vacancies or interstitial atoms, which are origins of the deep-level states. Seitz and Koehler had estimated that the threshold energy is around 145 keV for electron irradiation to form displacement atoms,[11] which is roughly in agreement with our results. Nevertheless, the electron radiation can excite valence electrons (even the inner valence electrons) to high-level states and then produce large numbers of electron–hole pairs, consequently increasing the concentration of minority carriers and the short-circuit current in the solar cells. Additionally, the process of electron radiation is an implantation of carriers (electrons) into the p–n junction. Both of the two factors lead to a decrease in the inner field potential of the p–n junction; thus the open-circuit voltage decreases during the electron radiation. As the electron radiation stops, the radiation-induced electron–hole pairs recombine, and the carrier concentration decreases to the unirradiated level. The inner field of the cell recovers to normal neutral states, as seen in Fig. 4.

C. Combined Radiation Effects

The combined radiation effects of protons and electrons are not clear. Because electrons with energy less than 180 keV cannot produce deep-level defects directly, it is understandable that effects of combined radiation on the solar cell are dominated by the proton-induced process, as shown in Fig. 5. However, due to the charge of the electron being opposite to that of the proton, the neutralized effect may change the process of interaction of protons in the Si lattice.

On the other hand, the large number of electron–hole pairs excited by implanted electrons change the electronic states of lattice atoms, consequently modifying the interactions of protons within the solar cell. Additionally, combination radiation of protons and electrons implies more particle energy deposited in the radiation region, resulting in an induced thermal effect. All these factors may cause a difference of the combined radiations from that of the protons. Further investigation should be done to clear the damage mechanism after the combined radiations.

V. Summary

Proton radiation with energy less than 200 keV decreases the electrical properties of the backfield Si solar cells. The change feature depends on the radiation energy and fluence. The degradation of the properties is attributed to proton radiation producing large numbers of deep-level defects in the backfield solar cells. The defects include simple vacancies, interstitial atoms, and some complicated defect complexes such as V+V and V+C+O. These defects become the trap centers of carriers in Si, decreasing the lifetime of the carriers. Electron radiation with energy less than 180 keV cannot produce these deep-level defects; thus no permanent degradation was observed in the solar cells. However, implantation of electrons can excite the valence electrons to the conductive band and then form large numbers of electron–hole pairs. This results in an increase in the short-circuit current and a decrease in the open-circuit voltage as measured in situ during radiation. This effect recovers automatically due to the recombination of the electron–hole pairs after radiation. The process of combined radiation of protons and electrons (particle energy less than 180 keV) is dominated by the effect of proton radiation, but the fluence of electron radiation exerts an influence on the damage extent. Further investigation should be done to expose the real mechanism of the combined radiation.

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