Si Substrate Suitable for Radiation-Resistant Space Solar Cells

Hideharu Matsuura, Shirou Kawakita[1)] Takeshi Ohshima[2)] and Hisayoshi Itoh[2)]
Osaka Electro-Communication University, 18-8 Hatsu-cho, Neyagawa,
Osaka 572-8530, Japan
1) Japan Aerospace Exploration Agency, 2-1-1 Sengen, Tsukuba,
Ibaraki 305-8505, Japan
2) Japan Atomic Energy Agency, 1233 Watanuki, Takasaki, Gunma 370-1292, Japan

Abstract

Irradiating group-III (B, Al, Ga)-doped Czochralski (CZ)-grown Si substrates as well as B-doped magnetic Czochralski (MCZ)-grown and floating-zone (FZ)-grown Si substrates with 10 MeV protons or 1 MeV electrons, we investigate both the reduction in the hole concentration and the conversion of p-type to n-type using Hall-effect measurements. In all the 10 Ωcm CZ-Si, the density of each acceptor species is reduced by irradiation, and finally the conversion occurs with $1x10^{17}$ cm^{-2} fluence of 1 MeV electrons or with $2.5x10^{14}$ cm^{-2} fluence of 10 MeV protons. In 10 Ωcm MCZ-Si and 10 Ωcm FZ-Si, on the other hand, the conversion does not occur under the same irradiation conditions. Moreover, the reduction in the concentration for the FZ-Si is much less than the others. From these results, it is elucidated that the conversion as well as the reduction in the hole concentration is strongly dependent on the concentration of oxygen in Si, not on the type of acceptor species in Si. Therefore, the p-type FZ-Si substrate is appropriate for radiation-resistant space solar cells such as $n^+/p/p^+$ Si solar cells and upcoming III-V tandem solar cells on n^+/p Si substrates.

1. Introduction

Space solar cells are exposed to a lot of protons and electrons with a high energy, and irradiation lowers conversion efficiency of solar cells. In particular, $n^+/p/p^+$ Si solar cells used in the Engineering Test Satellite-VI, which was constructed by the National Space Development Agency of Japan (NASDA) and launched in August 1994, were heavily damaged in the Van Allen radiation belts. This phenomenon is strongly related to a decrease in the hole concentration in the p substrate and the conversion of p-type to n-type with irradiation of protons and electrons [1]. Here, the acceptor species in the p-type Si substrates was B.

The origins of traps created by irradiation have usually been investigated using deep-level transient spectroscopy (DLTS) and electron paramagnetic resonance spectroscopy. Judging from those results, in B-doped p-type Si, Yamaguchi et al. [2] reported that hole traps with E_V+0.18 eV and E_V+0.36 eV and a donorlike defect with E_C-0.18 eV were mainly introduced by irradiation, which were considered to be a divacancy (V-V), a complex (C_i-O_i) of an interstitial C (C_i) and an interstitial O (O_i), and a complex (B_i-O_i) of an interstitial B (B_i) and O_i, respectively, where E_V is the valence band maximum and E_C is the conduction band minimum. In Ga-doped p-type Si, they also reported that the generation of the hole trap with E_V+0.36 eV was strongly suppressed compared with B-doped p-type Si, and the donorlike defect with E_C-0.18 eV was not detected [3].

From DLTS, however, the quantitative relationship between the hole concentration and the trap densities in p-type Si substrate is far from complete [4]. Since the densities and energy levels of traps that affect the hole concentration can be directly determined using the temperature dependence of the hole concentration p(T) obtained by Hall-effect measurements, on the other hand, the relationship between p(T) and the trap densities can be directly investigated. From free-carrier concentration spectroscopy (FCCS) [1], the donorlike defect with E_C-0.3 eV was reported in the type-converted samples [5], which was different from the donorlike defect with E_C-0.18 eV from DLTS. The result obtained from FCCS is consistent with other reports [6].

Using group-III (B, Al, Ga)-doped Czochralski (CZ)-grown Si wafers as well as B-doped magnetic Czochralski (MCZ)-grown and floating zone (FZ)-grown Si wafers, we report on our investigation of the

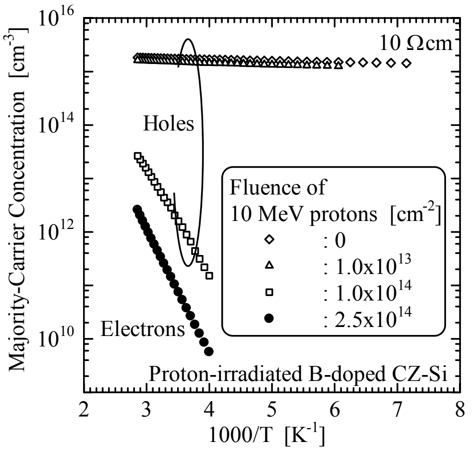

Fig. 1. Temperature dependence of majority-carrier concentration for B-doped CZ-Si.

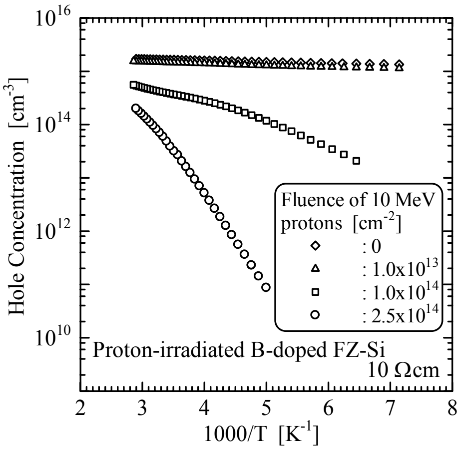

Fig. 2. Temperature dependence of hole concentration for B-doped FZ-Si.

relationship between the generation of hole traps as well as donorlike defects by irradiation and the acceptor species (i.e., B, Al and Ga) in Si, or between the generation of hole traps as well as donorlike defects and the O concentration (C_O) in Si..

2. Experimental

The samples were 10 Ωcm B-doped single-crystalline Si wafers grown by the CZ, MCZ, and FZ methods. From radioactivation analyses, C_O and the C concentration (C_C) in the wafer were determined as 8×10^{17} and 1×10^{15} cm^{-3} for the CZ-Si, 2×10^{17} and 8×10^{15} cm^{-3} for the MCZ-Si, and 1×10^{15} and 5×10^{15} cm^{-3} for the FZ-Si. 10 Ωcm Al- and Ga-doped single-crystalline CZ-Si wafers were also measured. The values of C_O and C_C were respectively 5×10^{17} and 8×10^{15} cm^{-3} for the Al-doped CZ-Si, and 8×10^{17} and 8×10^{15} cm^{-3} for the Ga-doped CZ-Si. The thickness and size of samples for Hall-effect measurements were 220 μm and 5×5 mm^2. After irradiation by 1 MeV electrons or 10 MeV protons at several fluences, Au was evaporated on the four corners of the surface of the sample. Then, the Hall-effect measurement was conducted by the van der Pauw method in a magnetic field of 1.4 T using a modified MMR Technologies' Hall system. The temperature range of the measurement was limited from 85 to 350 K, because some defects are likely to be annealed out at approximately 400 K.

3. Results

Figure 1 shows the temperature dependence of the majority-carrier concentration for the proton-irradiated 10 Ωcm B-doped CZ-Si. The diamonds, triangles, squares, and solid circles correspond to the fluences of 0, 1.0×10^{13}, 1.0×10^{14}, and 2.5×10^{14} cm^{-2}, respectively. Only the wafer irradiated with 2.5×10^{14} cm^{-2} fluence showed n-type conduction. These results are the same in 10 Ωcm Al- and Ga-doped single-crystalline CZ-Si. Therefore, the conversion is independent of the acceptor species in Si.

Figure 2 shows the p(T) for the 10 Ωcm B-doped FZ-Si irradiated with several fluences of 10 MeV protons. The ◇, △, □, and ○ symbols correspond to the fluences of 0, 1.0×10^{13}, 1.0×10^{14}, and 2.5×10^{14} cm^{-2}, respectively. With irradiation at 2.5×10^{14} cm^{-2} fluence, the type conversion did not occur, indicating that the lower C_O suppresses the formation of the donorlike defect with irradiation. Therefore, it is clear that O is related to the donorlike defect.

Figure 3 shows the dependence of the majority-carrier concentration at 300 K on the fluence of 1 MeV electrons for the 10 Ωcm B-doped CZ-, MCZ-, and FZ-Si. The p(T) in the 10 Ωcm CZ-, MCZ-, and FZ-Si are denoted by ◇, △, and □, respectively, whereas the n(T) for the 10 Ωcm CZ-Si is denoted by ●. The large decrease in p(T) or the type conversion with irradiation is found to occur at above 1.0×10^{16} cm^{-2} fluence in the 10 Ωcm CZ- and MCZ-Si, while the p(T) is reduced slightly in the 10 Ωcm FZ-Si.

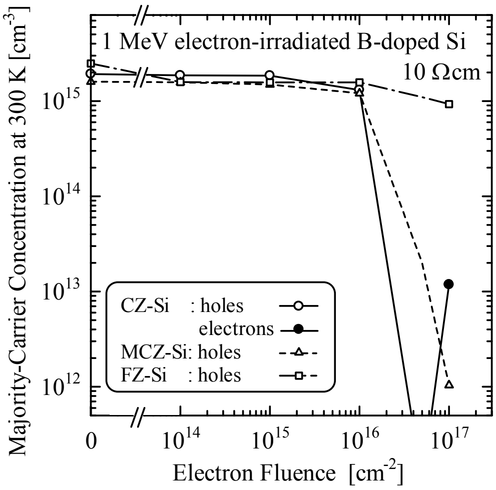

Fig. 3. Dependence of majority-carrier concentration at 300 K on fluence of 1MeV electrons.

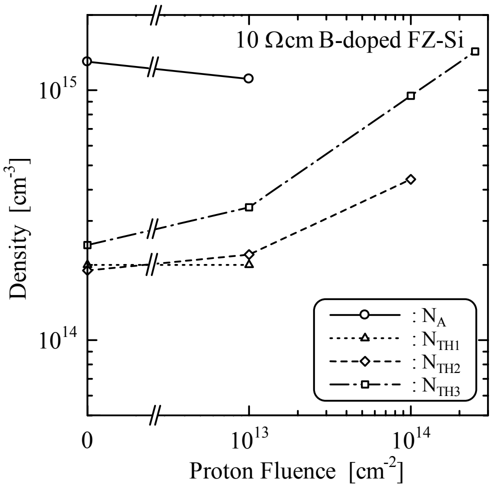

Fig. 4. Dependence of N_A or N_{THi} for B-doped FZ-Si.

Similar to the proton irradiation, the type conversion occurred in the 10 Ωcm Al- or Ga-doped CZ-Si with irradiation by 1 MeV electrons at 1.0×10^{17} cm^{-2} fluence. Therefore, the 10 Ωcm FZ-Si is found to be more radiation resistant than the other samples.

4. Discussion

The densities and energy levels of hole traps for the 10 cm B-doped FZ-Si with 10 MeV protons were determined by FCCS using p(T) shown in Fig. 2. Three hole traps with E_V+ ~0.1eV, E_V+ ~0.16 eV, and E_V+ ~0.30 eV were observed, whose energy levels are assigned to ΔE_{TH1}, ΔE_{TH2}, and ΔE_{TH3}, respectively. These densities are denoted by N_{TH1}, N_{TH2}, and N_{TH3}, respectively.

Figure 4 shows the dependencies of acceptor density (N_A) and hole-trap densities on proton fluence. The values of N_{TH2} and N_{TH3} increase clearly. Moreover, the N_{TH3} of the sample irradiated with 2.5×10^{14} cm^{-2} exceeds the N_A of the unirradiated sample. Because the density and energy level of the hole trap with a density higher than the acceptor density can be determined from FCCS [4], FCCS is superior to DLTS from the viewpoint of the evaluation of traps with high densities.

Irradiation introduces a vacancy (V), an interstitial Si (Si_i), and B_i in B-doped Si. From Fourier-transform infrared spectroscopy at low temperatures, the density of a substitutional B (B_s), which acts as an acceptor, is reported to decrease with increasing fluence [5], indicating that B_i is created by irradiation. In Fig. 4, furthermore, the values of N_{TH2} and N_{TH3} increase with fluence. Finally, N_{TH3} becomes larger than N_A at 1.0×10^{14} and 2.5×10^{14} cm^{-2} fluences.

Table I shows the densities and energy levels determined by FCCS for the 10 MeV proton-irradiated 10 Ωcm B-, Al-, and Ga-doped CZ-Si. N_A clearly decreases due to irradiation, whereas N_{TH2} increases with irradiation in all the CZ-Si wafers. Since the hole trap with ΔE_{TH1} was not detected in the Al- and

Table I. Densities and energy levels determined by FCCS for proton-irradiated B-, Al-, and Ga-doped CZ-Si.

Dopant	B		Al		Ga	
Fluence [cm^{-2}]	0	1x10^{13}	0	1x10^{13}	0	1x10^{13}
ΔE_A [meV]	----	----	67	69	71	74
N_A [x10^{15} cm^{-3}]	1.44	1.24	1.98	1.58	2.39	1.95
ΔE_{TH1} [meV]	112	121	---	---	---	---
N_{TH1} [x10^{15} cm^{-3}]	0.26	0.22	---	---	---	---
ΔE_{TH2} [meV]	201	198	180	180	201	203
N_{TH2} [x10^{15} cm^{-3}]	0.20	0.23	0.26	0.41	0.33	0.41

Ga-doped CZ-Si, it might be related to B.

From DLTS, the energy level of V-V was reported to be E_V+0.18 eV by Yamaguchi et al. [2], and E_V+0.23 eV by Mooney [7], which is in good agreement with the hole trap with the ΔE_{TH2} observed here. Furthermore, the V-V density was reported to increase with fluence, which is consistent with the finding that N_{TH2} increases with proton fluence. Therefore, the origin of the hole trap with ΔE_{TH2} is assigned to V-V.

The energy level of the dominant defect introduced with irradiation was reported to be E_V+0.33~ 0.36 eV. Trauwaert et al. [8] reported that those defects were considered to be C_i-O_i for a high C_O, and C_i-C_s for a low C_O. Since it is clear from Fig. 4 that the hole trap with ΔE_{TH3} is the dominant defect induced with irradiation, the possible origin of the hole trap with ΔE_{TH3} is C_i-C_s or C_i-O_i.

Song et al. [9] reported that the hole trap with E_V+0.09 eV was not observed in irradiated samples while it appeared after annealing above 340 K, suggesting that it is not the hole trap with ΔE_{TH1}. N_{TH1} is unchanged or slightly decreased with fluence, which is quite different from the fluence dependence of N_{TH2} or N_{TH3}. The hole trap with ΔE_{TH1} is observed only in the B-doped Si. The ratio of N_{TH1} to N_A of the unirradiated B-doped Si is approximately 15 %. These findings may suggest that this hole trap is a complex of B_s and some contaminated impurity or a complex of B_s and some defect. According to the literature [10], one of the possible origins of the hole trap with ΔE_{TH1} is a complex (Fe_i-B_s) of B_s and an interstitial Fe (Fe_i) whose energy level is approximately 100 meV.

5. Conclusions

With irradiation by 10 MeV protons at 2.5×10^{14} cm^{-2} fluence or by 1 MeV electrons at 1.0×10^{17} cm^{-2} fluence, the conduction of 10 Ωcm B-, Al-, and Ga-doped CZ-Si changed from the p-type to the n-type. Under the same irradiation conditions, on the other hand, the conduction of 10 Ωcm B-doped MCZ- and FZ-Si remained the p type, and the decrease in the p(T) of the FZ-Si was considerably lower, suggesting that the donorlike defect is related to O.

From FCCS, the densities of the hole traps with E_V+ ~0.2 eV and E_V+ ~0.3 eV were found to increase with increasing fluence of 10 MeV protons or 1 MeV electrons. Compared with the results from DLTS, the hole trap with E_V+ ~0.2 eV was assigned to V-V and the hole trap with E_V+ ~0.3 eV was considered to be C_i-C_s or C_i-O_i. The hole trap with E_V+ ~0.1 eV was detected only in B-doped Si, and unchanged or slightly decreased with irradiation. This may be Fe_i-B_s. Moreover, FCCS could determine the density and energy level of the hole trap with a higher density than the acceptor density, different from DLTS.

The density of the acceptor species (substitutional B, Al, or Ga) has been found to decrease with increasing fluence. Finally, FZ-Si was elucidated to be the most radiation-resistant Si substrate from the viewpoint of the preservation of p(T).

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