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Change of Majority-Carrier Concentration in p-Type Silicon by 10 MeV Proton Irradiation

H. Iwata, S. Kagamihara, H. Matsuura, S. Kawakita[1)], T. Oshima[2)], T. Kamiya[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 Research Institute, 1233 Watanuki-cho, Takasaki, Gunma 370-1292, Japan

Abstract

The hole concentrations in B-, Al- and Ga-doped p-type Si wafers produced by the Czochralski (CZ) method are reduced by the 1×10^{13} cm^{-2} fluence irradiation of 10 MeV protons, which is found to arise from the creation of hole traps as well as the decrease of acceptors by the irradiation. Although all the B-, Al-, Ga-doped p-type CZ Si wafers are converted to n-type by the 2.5×10^{14} cm^{-2} fluence irradiation of 10 MeV protons, B-doped p-type Si fabricated by the floating-zone (FZ) method is not converted by the same fluence irradiation. Since the concentration of O atoms in FZ Si is much lower than that in CZ Si, the cause of the type–conversion of p-type Si is considered to be the creation of donor-like defects related with O. Therefore, FZ Si is found to be excellent in radiation resistance.

1. Introduction

In space, solar cells are exposed to a lot of protons and electrons with high energy. By irradiation, the energy conversion efficiency of solar cells is lowered [1]. The causes of the radiation degradation of n/p silicon (Si) solar cells are reported to be (1) the reduction in the diffusion length of electrons in the p layer for low fluence irradiation, (2) the reduction in the hole concentration in the p layer for intermediate-fluence irradiation, and (3) the conversion of the p layer to an n layer for high-fluence irradiation [1-5]. Moreover, the cause of the type-conversion was reported to be a donor-like defect, which may be a complex (B_i-O_i) of an interstitial boron (B) atom and an interstitial oxygen (O) atom [6]. Therefore, it is anticipated that the type-conversion will not occur in p-type Si without B or O atoms.

In this article, we measure the temperature dependence of the majority-carrier concentration in irradiated B-, aluminum (Al)- and gallium (Ga)-doped p-type Si fabricated by the Czochralski (CZ) method. Using these experimental results, we investigate the relationship between the donor-like defect and B, and discuss the relationship between radiation resistance and the acceptor species (B, Al, Ga). Furthermore, we measure the temperature dependence of the majority-carrier concentration in irradiated B-doped Si produced by the floating-zone (FZ) method. That is because the concentration (C_{O}) of O in FZ Si is much lower than that in CZ Si.

2. Free Carrier Concentration Spectroscopy

Free carrier concentration spectroscopy (FCCS) can accurately determine the densities and energy levels of impurities and traps from the temperature dependence of the majority-carrier concentration obtained by Hall-effect measurements. Using an experimental temperature-dependent majority-carrier concentration (i.e., hole concentration $p(T)$ or electron concentration $n(T)$), the FCCS signal is defined as [7,8]

$$H(T, E_{\mathrm{ref}}) \equiv \frac{p(T)^2}{(kT)^{5/2}} \exp\left(\frac{E_{\mathrm{ref}}}{kT}\right) \quad \text{or} \quad H(T, E_{\mathrm{ref}}) \equiv \frac{n(T)^2}{(kT)^{5/2}} \exp\left(\frac{E_{\mathrm{ref}}}{kT}\right) . \tag{1}$$

The FCCS signal has a peak at the temperature corresponding to each impurity level or trap level, where E_{ref} is the parameter that can shift the peak temperature of $H(T, E_{\mathrm{ref}})$ within the temperature range of the measurement, k is the Boltzmann constant, and T is the measurement temperature. From each peak value and peak temperature, the density and energy level of the corresponding impurity or trap can be accurately determined.

3. Experimental

Single-crystalline Si wafers used here are B-, Al- and Ga-doped CZ Si wafers, and B-doped FZ Si wafers. The value of C_{O} is 8×10^{17} cm^{-3} and 1×10^{15} cm^{-3} for CZ Si and FZ Si, respectively, while the concentration of carbon atoms is in the order of 10^{15} cm^{-3} for both of CZ Si and FZ Si. The resistivity of the wafers was approximately $10\,\Omega\mathrm{cm}$. The thickness and size of the samples for Hall-effect measurements were 300 μm and 1 cm×1 cm, respectively. The samples were irradiated with 10 MeV protons. The fluence of protons were 1×10^{13} cm^{-2}, and 1×10^{14} cm^{-2}, which corresponds to the intermediate fluence, and 2.5×10^{14} cm^{-2}, which corresponds to the high fluence. Then, in order to form good ohmic contacts at four corners of the sample, Au was evaporated on the corners. The Hall-effect measurements were carried out by the van der Pauw method in a magnetic field of 1.4 T in a temperature range from 85 K to 350 K.

4. Results and Discussion

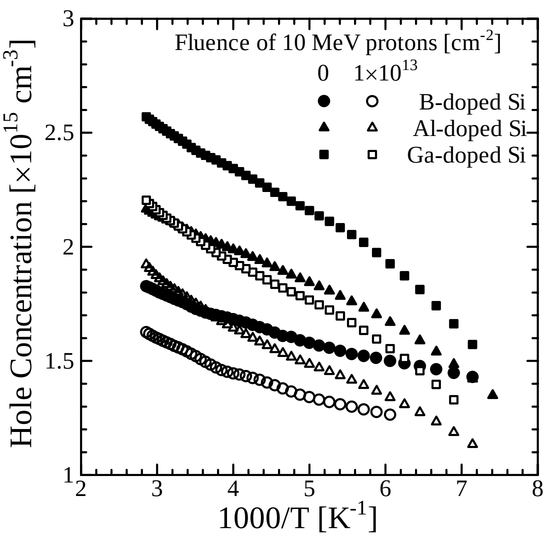

Fig.1. Change of hole concentration in Si by 1×10^{13} cm^{-2} fluence irradiation of 10 MeV protons.

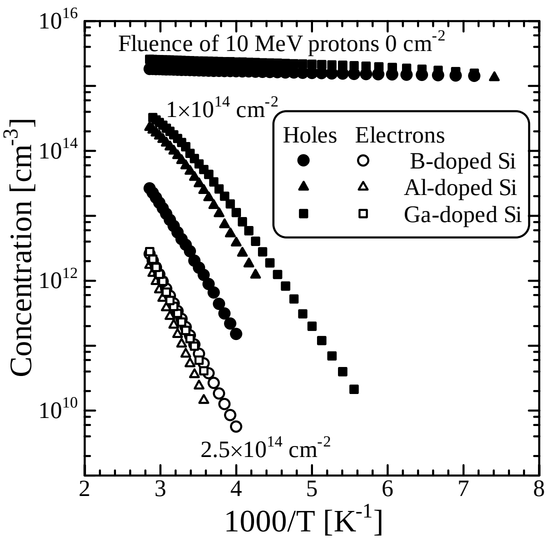

Fig.2. Relationship between acceptor species and change of majority-carrier concentration by irradiation.

Figure 1 shows $p(T)$ for the B-, Al- and Ga-doped CZ Si wafers, which are denoted by circles, triangles and squares, respectively. Solid marks represent the data for unirradiated samples, while open marks represent the data for samples irradiated by 10 MeV protons with the 1×10^{13} cm^{-2} fluence. As is clear from the figure, all the hole concentrations in B-, Al- and Ga-doped CZ Si wafers are reduced by this irradiation. Using $p(T)$ in Fig. 1, the densities and energy levels of acceptors and hole traps are determined by FCCS, and listed in Table I. Here, N_A and ΔE_A are the density and energy level of doped acceptors (B, Al or Ga), N_{TH1} and ΔE_{TH1} are those of hole traps that are not assigned [3], and N_{TH2} and ΔE_{TH2} are those of hole traps assigned to divacancy (V-V) [9,10]. In Table Ⅰ, the acceptor densities in the B-, Al- and Ga-doped CZ Si wafers are decreased by irradiation, while the density of V-V is increased by irradiation, suggesting that substitutional dopants (B, Al, Ga) and substitutional Si atoms are displaced by the 10 MeV proton irradiation. This is why interstitial dopants (B, Al, Ga) and V-V are created by irradiation of 10 MeV protons.

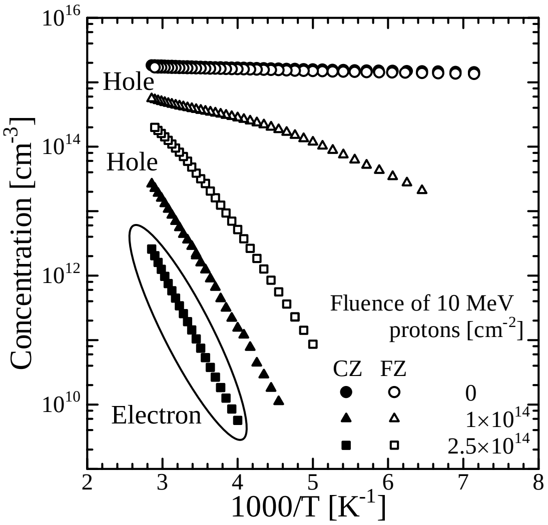

Fig.3. Temperature dependence of majority-carrier concentration in Si irradiated by 10 MeV protons for CZ and FZ Si.

Figure 2 shows $p(T)$ for the B-, Al- and Ga-doped CZ Si wafers irradiated by 10 MeV protons with three fluences (0, 1×10^{14}, 2.5×10^{14} cm^{-2}). The data for B-, Al- and Ga-doped samples are denoted by circles, triangles and squares, respectively. Solid marks mean that the majority carriers are holes, while open marks signify that the majority carriers change from holes to electrons. In the figure, the type-conversion occurs in all the B-, Al- and Ga-doped CZ Si by irradiation of 10 MeV protons with the 2.5×10^{14} cm^{-2} fluence, indicating that the donor-like defects are not always the B_i-O_i defect. This suggests that the possible origin is a complex of an interstitial dopant (B, Al, Ga) and an interstitial O atom.

Figure 3 shows the temperature dependencies of the majority-carrier concentrations in the B-doped CZ and FZ Si wafers, which are denoted by solid and open marks, respectively. Circles, triangles and squares represent the 0,

Table Ⅰ. Results for CZ p-type Si wafers.

Dopant	B		Al		Ga	
Fluence [cm^{-2}]	0	1×10^{13}	0	1×10^{13}	0	1×10^{13}
ΔE_A [meV]	40	45	67	69	71	74
N_A [cm^{-3}]	1.44×10^{15}	1.24×10^{15}	1.98×10^{15}	1.58×10^{15}	2.39×10^{15}	1.95×10^{15}
ΔE_{TH1} [meV]	112	121	—	—	—	—
N_{TH1} [cm^{-3}]	2.55×10^{14}	2.23×10^{14}	—	—	—	—
ΔE_{TH2} [meV]	201	198	180	180	201	203
N_{TH2} [cm^{-3}]	2.00×10^{14}	2.30×10^{14}	2.60×10^{14}	4.14×10^{14}	3.25×10^{14}	4.14×10^{14}

1×10^{14} and 2.5×10^{14} cm^{-2} fluence irradiation of 10 MeV protons, respectively. In the case of the 2.5×10^{14} cm^{-2} fluence irradiation of 10 MeV protons, the type-conversion does not occur in the B-doped p-type FZ Si, while it occurs in the p-type CZ Si. Since $C_{\rm O}$ in FZ Si is much lower than $C_{\rm O}$ in CZ Si, O atoms should be related with the donor-like defect that converts p-type to n-type. Therefore, it is found that p-type Si used in space should be FZ Si wafers.

5. Conclusion

All the hole concentrations in B-, Al- and Ga-doped p-type Si wafers were reduced by the 1×10^{13} cm^{-2} fluence irradiation of 10 MeV protons. This reduction was found to arise from the creation of divacancy as well as the decrease of acceptors by the irradiation. Moreover, this reduction was not related with acceptor species in p-type Si.

The created donor-like defects, which caused p-type Si to change to n-type by irradiation, were found to be related to oxygen in Si. Therefore, Si wafers suitable for radiation-proof solar cells were FZ Si wafers, with which the concentration of O in FZ Si is much lower than that in CZ Si.

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