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Short Note

Annealing Behavior of Donorlike Defects Induced by High-Fluence Irradiation of High-Energy Particles in p-Type Silicon

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The high-fluence irradiation of high-energy electrons or protons converts p-type conduction of B-doped Si into n-type conduction. This type conversion results from the formation of donorlike defects. Since the donorlike defects are completely annealed out at 523 K, one of the possible origins of the donorlike defects is a complex of interstitial B and interstitial O. On the other hand, the hole concentration is reduced by irradiation less than by the fluence with which the type conversion occurs. Although this reduction is reported to arise from the creation of hole traps annealed out at >523 K, it is found that some of the defects can be annealed out at low temperatures similar to the anneal-out temperature of donorlike defects.
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KEYWORDS: donorlike defect, hole trap, electron irradiation, proton irradiation, Hall effect measurement, annealing behavior, FCCS

In space, the energy conversion efficiency of solar cells is lowered by irradiation from electrons or protons.[1)] The causes of the radiation degradation of $n^+/p/p^+$ Si solar cells are classified into three categories;[1–5)] (1) the reduction in the diffusion length of electrons in the p layer under low-fluence irradiation, (2) the reduction in the hole concentration in the p layer under intermediate-fluence irradiation, and (3) the conversion of the p layer to an n layer under high-fluence irradiation. Several types of hole traps are reported to be created by irradiation.[1–4)] Judging from Fourier-transform infrared measurements, the density (N_B) of substitutional B atoms, which act as an acceptor, decreases with fluence.[5)] These reports suggest that hole concentration should decrease with an increase in fluence. However, these causes cannot lead to the conversion of the p layer to the n layer at all. In order to convert the p layer to the n layer, the high-fluence irradiation must create donorlike defects, which supply electrons to the conduction band.

In this article, from the annealing behavior of the majority-carrier concentration, the possible origin of the donorlike defects is discussed.

The B-doped single-crystalline Si wafers used here were fabricated by the Czochralski method. The resistivity of the wafers was ~10 Ωcm, that is, the B acceptor density (N_A) was $\sim 2 \times 10^{15}$ cm^{-3}. From radioactivation analyses, the concentrations of O and C in the wafers were determined to be 8×10^{17} cm^{-3} and 1×10^{15} cm^{-3}, respectively. The thickness and area of the samples for Hall effect measurements were 220 μm and 5×5 mm^2, respectively. After the formation of good ohmic contacts at four corners of the sample, the samples were irradiated by 1 MeV electrons with 1×10^{17} cm^{-2} fluence or by 10 MeV protons with 3×10^{12}–5×10^{14} cm^{-2} fluence. Hall effect measurements were conducted by the van der Pauw method in a magnetic field of 1.4 T from low to high temperature (T), every 5 K, and it took about 15 min to obtain the data at each temperature.

The solid squares in Fig. 1 represent the temperature dependence of the electron concentration $n(T)$ in the wafer type-converted by the electron irradiation. Here, this measurement is called a first measurement. Since $n(T)$ showed a peak at approximately 390 K, high temperatures during the measurement were expected to reduce the density (N_D) of the donorlike defects. In order to confirm the decrease of N_D, a second measurement (crosses in Fig. 1) was carried out. From the figure, it is clear that the donorlike defects were reduced during the first measurement.

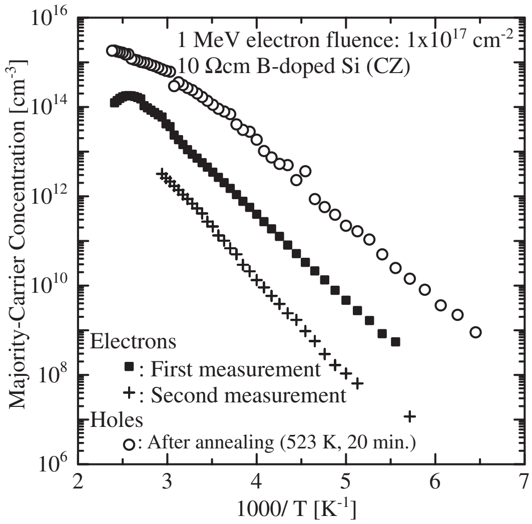

Fig. 1. Temperature dependence of electron concentrations in first and second measurements, and hole concentration after annealing. Each measurement was carried out from low T to high T.

Using $n(T)$, the values of N_D and energy levels ($E_C - E_D$) of the donorlike defects were determined by free-carrier-concentration spectroscopy (FCCS),[3,5,6)] where E_C is the conduction band minimum. One type of donorlike defect was detected, and its $E_C - E_D$ was determined to be ~0.3 eV. Although its N_D was determined to be 4×10^{14} cm^{-3} in the first measurement, its N_D was found to decrease to 5×10^{13} cm^{-3} in the second measurement. Therefore, some of the donorlike defects were annealed out during the first measurement.

From deep-level-transient spectroscopy and electron spin resonance in n-type Si irradiated with low fluence, the following defects located at around $E_C - 0.3$ eV were

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reported;[7–11)] a divacancy, $(V\text{–}V)^{--/-}$ at $E_C - 0.23$ eV and $(V\text{–}V)^{-/0}$ at $E_C - 0.41$ eV, a complex ($V\text{–}O_i$) of a vacancy and an interstitial O at $E_C - 0.17$ V, and a complex ($B_i\text{–}O_i$) of an interstitial B and an interstitial O at $E_C - 0.27$ eV. The $B_i\text{–}O_i$ was reported to be annealed out at 470 K, while the V–V and $V\text{–}O_i$ were reported to be annealed out at 570 K and 620 K, respectively. Therefore, only $B_i\text{–}O_i$ is expected to be completely annealed out at 523 K.

After the second measurement, the sample was annealed at 523 K in an Ar atmosphere for 20 min. The open circles in Fig. 1 represent the temperature dependence of the hole concentration $p(T)$ after the annealing. Since the majority carriers are holes, the donorlike defects were annealed out at 523 K, indicating that the origin of the donorlike defects is neither V–V nor $V\text{–}O_i$. Therefore, the possible origin of the donorlike defects is $B_i\text{–}O_i$. This suggests that high-energy electrons forced some B atoms from the substitutional site into the interstitial site.

The energy level of the hole trap determined by FCCS using $p(T)$ in Fig. 1 is 0.3 eV above the valence band maximum (E_V). This suggests that the hole traps at $E_V + 0.3$ eV were not annealed out at <523 K.

Figure 2 shows five sets of $p(T)$ in the samples irradiated by 10 MeV protons with different fluences (open triangles: 3×10^{12}, solid inversed triangles: 1×10^{13}, open squares: 3×10^{13}, solid circles: 6×10^{13} and crosses: 1×10^{14} cm^{-2} fluences) and one $n(T)$ in Si irradiated with 5×10^{14} cm^{-2} fluence (open circles). From the experimental results, it was confirmed that in 10 MeV protons the type conversion occurs between 1×10^{14} cm^{-2} and 5×10^{14} cm^{-2} fluences. The behavior of defects induced by proton irradiation is similar to that created by electron irradiation.

Among the defects induced by the intermediate-fluence irradiation, defects annealed out at low temperatures were investigated in the same way as illustrated for the electron-irradiated sample. In fluences between 3×10^{12} and 6×10^{13} cm^{-2}, $p(T)$ in the second measurement coincided with $p(T)$ in the first measurement. This indicates that the

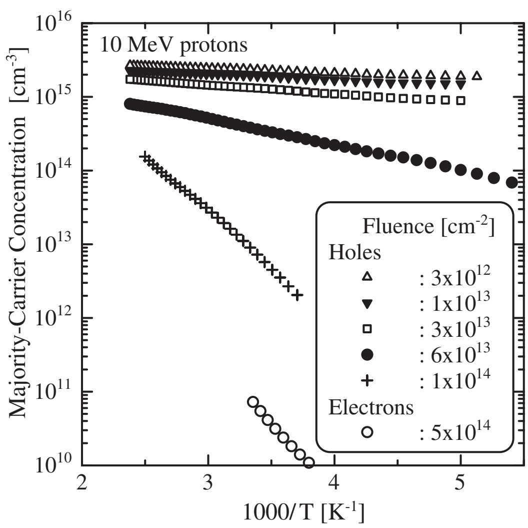

Fig. 2. Fluence dependence of hole concentration in Si irradiated by 10 MeV protons.

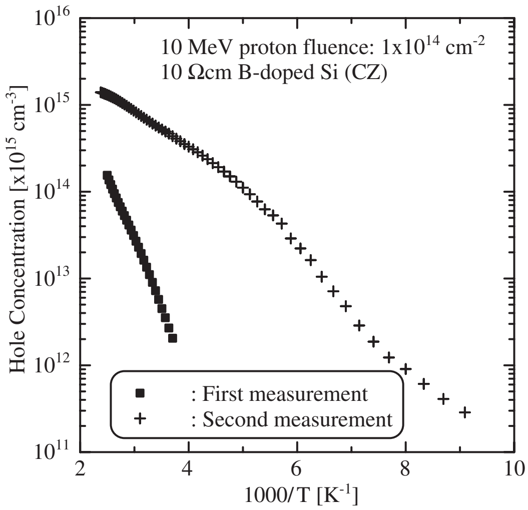

Fig. 3. Temperature dependence of hole concentrations in Si irradiated by 10 MeV protons with 1×10^{14} cm^{-2} fluence in first and second measurements. Each measurement was conducted from low T to high T.

reduction in $p(T)$ from these fluences does not mainly result from the creation of the donorlike defects. By FCCS, two types of hole traps at $E_V + 0.2$ eV and $E_V + 0.3$ eV were found in these samples.

Figure 3 depicts two sets of $p(T)$ in the sample irradiated by 10 MeV protons with 1×10^{14} cm^{-2} in the first (solid squares) and in the second (crosses) measurement. In this case, heating the sample up to 400 K in the first measurement recovered $p(T)$. This indicates that the defects with low anneal-out temperature, similar to the donorlike defects, become dominant.

In summary, B-doped p-type Si was converted into n-type Si by the high-fluence irradiation. One of the possible origins of the created donorlike defects was a complex of an interstitial B and an interstitial O, because other appropriate defects annealed out at ≤ 523 K have not been reported yet. By irradiation with the intermediate fluence close to the high fluence, the dominant defects are also considered to be defects similar in anneal-out temperature to the donorlike defects.

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