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Temperature dependence of electron concentration in type-converted silicon by $1\times10^{17}\,\mathrm{cm}^{-2}$ fluence irradiation of 1 MeV electrons

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The conduction type of boron (B)-doped silicon (Si) changes from p type into n type by the $1\times10^{17}\,\mathrm{cm}^{-2}$ fluence irradiation (high-fluence irradiation) of 1 MeV electrons. The temperature dependence of the electron concentration $n(T)$ obtained from Hall-effect measurements is reported. From the analysis of $n(T)$, the density and energy level of the defects created by the high-fluence irradiation are determined to be $1.5\times10^{14}\,\mathrm{cm}^{-3}$ and $E_C-0.30\,\mathrm{eV}$, respectively, where E_C is the energy level at the bottom of the conduction band. Moreover, the compensated density is $9.5\times10^{13}\,\mathrm{cm}^{-3}$, which is in agreement with the density of B that acts as an acceptor, determined by Fourier-transform infrared spectroscopy. © *2000 American Institute of Physics.* [S0003-6951(00)03415-X]

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 $n^+/p/p^+$ silicon (Si) solar cells, which are usually used in space, are classified into three categories:[2–10] (1) the reduction in the diffusion length of the minority carriers (i.e., electrons) for low-fluence irradiation, (2) the reduction in the concentration of the majority carriers (i.e., holes) for intermediate-fluence irradiation, and (3) the conversion of p type to n type for high-fluence irradiation. By the low-fluence and intermediate-fluence irradiation, several types of hole traps were reported to be generated.[5,7,9] However, the conversion mechanism of p-type Si by the high-fluence irradiation has not been clarified yet.[6,8,10]

One of the authors has proposed and experimentally tested a simple method for graphically determining the densities and energy levels of impurities or defects from the temperature dependence of the majority-carrier concentration $n(T)$.[9,11–14] From Hall-effect measurements of p-type Si irradiated by the intermediate fluence, the densities and energy levels of three types of hole traps could be determined accurately.[9]

In this method, the following function is defined:[14]

$$H(T,E_{\mathrm{ref}})\equiv\frac{n(T)^2}{(kT)^{2.5}}\exp\left(\frac{E_{\mathrm{ref}}}{kT}\right), \tag{1}$$

which has a peak at the temperature corresponding to each energy level, where k is the Boltzmann constant, T is the absolute temperature, and E_{ref} is a parameter which can shift the peak temperature of $H(T,E_{\mathrm{ref}})$ within the measurement temperature range. From the number of the peaks of $H(T,E_{\mathrm{ref}})$, we can know how many types of impurities or defects are included. Then, from each peak value and peak temperature, we can determine the density and energy level of the corresponding impurity or defect accurately.

In this letter, we report $n(T)$ in type-converted Si, and determine the density (N_D) and energy level (E_D) of the defect created by the high-fluence irradiation using $H(T,E_{\mathrm{ref}})$. Moreover, the reduction in the density (N_{B}) of boron (B) that acts as an acceptor is investigated by means of Fourier-transform infrared spectroscopy (FTIR).

B-doped single-crystalline Si wafers were made by the Czochralski method. The resistivity of the wafers was approximately 10 Ω cm. From radioactivation analyses, the oxygen (O) and carbon (C) concentrations in the wafers were determined to be 8.4×10^{17} and $1.4\times10^{15}\,\mathrm{cm}^{-3}$, respectively. The thickness of samples for the FTIR measurement was 550 μm. The thickness and size of samples for the Hall-effect measurement were 220 μm and 5 mm×5 mm, respectively. In order to form ohmic contacts at the four corners of the sample, Ti, Pd, and Ag were evaporated on the corners in sequence. Then, the samples were irradiated with 1 MeV electrons. The highest fluence was $1\times10^{17}\,\mathrm{cm}^{-2}$. The electron irradiation was performed at room temperature using a Cockcraft–Walton type accelerator at the Takasaki division of the Japan Atomic Energy Research Institute (JAERI). The Hall-effect measurement was carried out using Toyo Technica ResiTest 8310, and the FTIR measurement was performed at 8 K using Bruker IFS-120HR. Baber[15] and Nagai *et al.*[16] described how to determine N_{B}.

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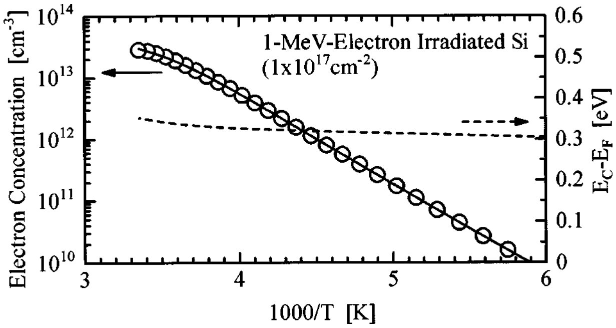

FIG. 1. Temperature dependence of the majority-carrier concentration for the $1\times10^{17}\,\mathrm{cm}^{-2}$ electron irradiated p-type Si. The open circles represent the experimental $n(T)$, and the solid line represents $n(T)$ interpolated by the spline function. The broken line represents the temperature dependence of the Fermi level.

The $1\times10^{17}\,\mathrm{cm}^{-2}$ fluence irradiation of 1 MeV electrons was found to convert the p-type Si to n type. Figure 1 shows $n(T)$ for the sample irradiated with the $1\times10^{17}\,\mathrm{cm}^{-2}$ fluence. The open circles represent the experimental $n(T)$ and the solid line represents $n(T)$ interpolated by the spline function. The broken line represents the Fermi level (E_F) calculated using[17]

$$E_C - E_F = kT\ln\left[\frac{N_C(T)}{n(T)}\right], \tag{2}$$

where $N_C(T)$ is the effective density of states in the conduction band for Si, which is given by[17]

$$N_C(T) = 5.39\times10^{15}\,T^{3/2}\,\mathrm{cm}^{-3}, \tag{3}$$

where E_C is the energy level at the bottom of the conduction band. Since E_F is located between $E_C - 0.30\,\mathrm{eV}$ and $E_C - 0.35\,\mathrm{eV}$, this sample is completely converted to n type.

Let us determine the values of N_D and E_D. In the freeze-out region, $n(T)$ is expressed as[17]

$$n(T) \simeq \sqrt{\frac{N_D N_C(T)}{2}}\exp\left(-\frac{E_C - E_D}{2kT}\right). \tag{4}$$

Using Eq. (3), therefore, the following relationship is obtained:

$$\frac{n(T)}{T^{0.75}} \simeq 5.19\times10^{7}\sqrt{N_D}\exp\left(-\frac{E_C - E_D}{2kT}\right). \tag{5}$$

From the $n(T)/T^{0.75} - 1/T$ characteristics, the values of E_D and N_D are determined to be $E_C - 0.55\,\mathrm{eV}$ and $3.8\times10^{17}\,\mathrm{cm}^{-3}$, respectively. In Fig. 1, however, the saturated value of $n(T)$ is about $3\times10^{13}\,\mathrm{cm}^{-3}$, insisting that N_D should be approximately $3\times10^{13}\,\mathrm{cm}^{-3}$ on the assumption of only one type of donor and no acceptors.[17] As a consequence, the values of $E_C - 0.55\,\mathrm{eV}$ and $3.8\times10^{17}\,\mathrm{cm}^{-3}$ are not reliable at all.

Defects (i.e., hole traps) located below the midgap, which were reported in p-type Si irradiated with the intermediate fluence, do not affect $n(T)$ in n-type Si, because E_F is located above the midgap.[9] Therefore, besides acceptors, defects (i.e., electron traps or donors) located above the midgap mainly influence $n(T)$.

Without any assumption of the number of types of donors, traps and acceptors, let us determine the reliable values from $n(T)$. Figure 2 shows $H(T,0.3)$ obtained using Eq. (1). Because only one peak appears in the figure, one type of defect mainly influence $n(T)$. The values of T_{peak} and $H(T_{\mathrm{peak}},\ 0.3)$ are 285 K and $1.1\times10^{36}\,\mathrm{cm}^{-6}\,\mathrm{eV}^{-2.5}$, respectively, from which the values of N_D, E_D and the compensated density (N_A) are determined to be $1.5\times10^{14}\,\mathrm{cm}^{-3}$, $E_C - 0.30\,\mathrm{eV}$ and $9.5\times10^{13}\,\mathrm{cm}^{-3}$, respectively.

Figure 3 shows the experimental $n(T)$ and the $n(T)$ simulated with the obtained values. Since the simulated $n(T)$ is in agreement with the experimental $n(T)$, the obtained values are considered to be reliable.

Figure 4 shows the fluence dependence of N_{B} measured by FTIR. As is clear from the figure, N_{B} decreases linearly from 1.5×10^{15} to $1.4\times10^{14}\,\mathrm{cm}^{-3}$ with an increase in the fluence. This is why N_A of the high-fluence irradiated Si is much lower than N_A of the unirradiated p-type Si.

From deep level transient spectroscopy (DLTS) and electron spin resonance (ESR) measurements in the low-fluence irradiation, the following defects located at around $E_C - 0.3\,\mathrm{eV}$ were reported: a complex ($\mathrm{B}_i - \mathrm{B}_s$) of an interstitial B and a substitutional B with $E_C - 0.26\,\mathrm{eV}$,[18] a com-

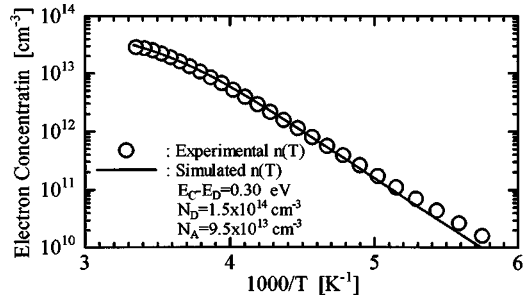

FIG. 3. Temperature dependence of the electron concentration. The open circles represent the experimental $n(T)$ and the solid line represents the $n(T)$ simulated with the obtained values.

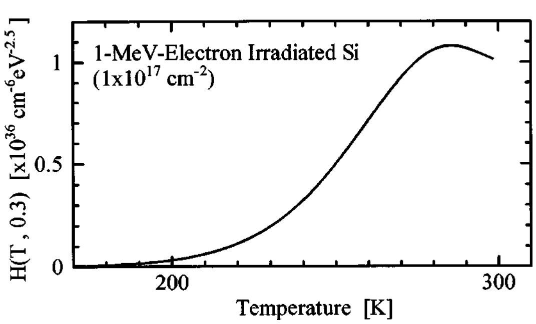

FIG. 2. $H(T,E_{\mathrm{ref}})$ signal with $E_{\mathrm{ref}} = 0.3\,\mathrm{eV}$.

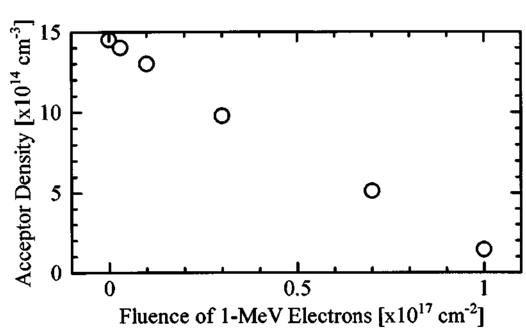

FIG. 4. Dependence of N_{B} determined by FTIR on the fluence of 1 MeV electrons.

plex (O_i–B_i) of an interstitial O and an interstitial B with $E_C-0.27$ eV,[19] and a complex (C_i–H) of an interstitial C and a hydrogen (H) with $E_C-0.31$ eV.[20] We are now investigating the origin of the defect that we determined from $n(T)$.

In conclusion, by the $1\times10^{17}\,\mathrm{cm}^{-2}$ fluence of 1 MeV electrons, the conduction type of B-doped Si changed from *p* type to *n* type. From our method, the energy level and density of the defects created by this high-fluence irradiation were determined to be $E_C-0.30$ eV and $1.5\times10^{14}\,\mathrm{cm}^{-3}$, respectively. The $n(T)$ simulated with the obtained values was quantitatively in agreement with the experimental $n(T)$, indicating that the values obtained by our method were reliable. From FTIR, the density of B that acts as an acceptor decreased linearly with an increase in the fluence of 1 MeV electrons, and it was $1.5\times10^{15}\,\mathrm{cm}^{-3}$ for unirradiation and $1.4\times10^{14}\,\mathrm{cm}^{-3}$ for the $1\times10^{17}\,\mathrm{cm}^{-2}$ fluence irradiation, which was in agreement with the acceptor density determined from $n(T)$ in the type-converted Si.

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