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Evaluation of Hole Traps in 10-MeV Proton-Irradiated p-Type Silicon from Hall-Effect Measurements

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Using the temperature dependence of the hole concentration $p(T)$ obtained from Hall-effect measurements, we attempt to uniquely determine the densities and energy levels of hole traps in 10-MeV proton-irradiated p-type silicon. Since the function $p(T)\exp(E_{\mathrm{ref}}/kT)/kT$ has a peak at the temperature corresponding to each hole trap level, the trap densities and energy levels can be determined uniquely and accurately. Here, k is the Boltzmann's constant, T is the absolute temperature and E_{ref} is a newly introduced parameter which shifts the peak temperature of the function within the measurement temperature range. Three types of hole trap levels (about 0.09 eV, 0.13 eV and 0.19 eV above the top (E_{V}) of the valence band) are observed, and these hole trap densities increase with increasing 10-MeV-proton fluence. The hole traps at $E_{\mathrm{V}} + 0.09$ eV and $E_{\mathrm{V}} + 0.19$ eV have been reported and their origins have been discussed. However, the hole trap at $E_{\mathrm{V}} + 0.13$ eV has not yet been reported. The quantitative relationship between the decrease in hole concentration and the increase in densities of certain traps due to proton irradiation has been clarified for the first time.

KEYWORDS: hole traps, proton-irradiated silicon, trap density, trap level, graphic approach, Hall-effect measurement, temperature dependence, majority-carrier concentration, unique solution

1. Introduction

In space, solar cells are exposed to protons and electrons with high energy. By irradiation, the energy conversion efficiency of solar cells is lowered. In particular, silicon solar cells used in the Engineering Test Satellite-VI (ETS-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 considered to be strongly related to a decrease in the majority-carrier concentration due to the generation of traps in silicon (Si) by high-fluence irradiation.[1)] Therefore, the relationship between the densities of traps generated by irradiation and the majority-carrier concentration must be investigated.

Traps have usually been evaluated using deep level transient spectroscopy (DLTS),[2–11)] photoluminescence[9,12–15)] and electron paramagnetic resonance.[9–11,16–20)] From those studies, the origins of these traps have been elucidated. However, the quantitative relationship between the majority-carrier concentration and trap densities is not clear, because the trap densities determined by DLTS were too low to explain the decrease in the majority-carrier concentration by irradiation.[2,21)]

Hall-effect measurements provide the temperature dependence of the majority-carrier concentration $p(T)$ as well as the temperature dependence of the mobility. If the densities and energy levels of traps can be directly determined using $p(T)$ obtained from the Hall-effect measurement, the relationship between these properties of traps and the majority-carrier concentration can be directly investigated.

One of the present authors has proposed a simple method to graphically determine the densities and energy levels of impurities in a semiconductor from $p(T)$.[22–25)] In this method, a function $p(T)\exp(E_{\mathrm{ref}}/kT)/kT$ is defined, which has a peak at the temperature corresponding to each impurity level, where k is the Boltzmann's constant, T is the absolute temperature and E_{ref} is a parameter which shifts the peak temperature of this function within the measurement temperature range.

In this paper, we apply the above method to obtain a unique solution (the densities and energy levels of hole traps) using $p(T)$, as a part of the study of the radiation damage mechanisms of silicon solar cells in space, proposed by NASDA. In order to generate hole traps in p-type Si, the wafers are irradiated with 10-MeV protons. We show that the above method can be used to determine the densities and energy levels of the hole traps uniquely and accurately. Moreover, we quantitatively discuss the relationship between the densities and energy levels of hole traps and the majority-carrier concentration.

2. Theoretical Consideration

2.1 General case

In a p-type semiconductor, we should consider l types of acceptors (density $N_{\mathrm{A}i}$ and energy level $E_{\mathrm{A}i}$ of i-th acceptor, where $1 \le i \le l$), n types of hole traps (density $N_{\mathrm{TH}i}$ and energy level $E_{\mathrm{TH}i}$ of i-th hole trap, where $1 \le i \le n$), m types of electron traps (density $N_{\mathrm{TE}i}$ and energy level $E_{\mathrm{TE}i}$ of i-th electron trap, where $1 \le i \le m$) and k types of donors (density $N_{\mathrm{D}i}$ and energy level $E_{\mathrm{D}i}$ of i-th donor, where $1 \le i \le k$), where all energy levels are measured from the top of the valence band (E_{V}), and $E_{\mathrm{A}i-1} < E_{\mathrm{A}i}$, $E_{\mathrm{TH}i-1} < E_{\mathrm{TH}i}$, $E_{\mathrm{TE}i-1} < E_{\mathrm{TE}i}$ and $E_{\mathrm{D}i-1} < E_{\mathrm{D}i}$. An acceptor is negatively charged when it emits a hole, and a donor is positively charged when it emits an electron. On the other hand, a hole trap is positively charged when it captures a hole, and an electron trap is negatively charged when it captures an electron.[26)] From the charge neutrality condition, therefore, the free hole concentration in the valence band is obtained as:

$$p(T) = \sum_{i=1}^{l} N_{\mathrm{A}i} f_{\mathrm{A}}(E_{\mathrm{A}i})$$

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$$-\sum_{i=1}^{n} N_{\mathrm{TH}i}\,[1-f_{\mathrm{A}}(E_{\mathrm{TH}i})] +\sum_{i=1}^{m} N_{\mathrm{TE}i}\,f_{\mathrm{D}}(E_{\mathrm{TE}i}) -\sum_{i=1}^{k} N_{\mathrm{D}i}\,[1-f_{\mathrm{D}}(E_{\mathrm{D}i})] +n(T), \tag{1}$$

where $n(T)$ is the free electron concentration in the conduction band, $f_{\mathrm{A}}(E)$ is the Fermi-Dirac distribution function for acceptors or hole traps, which is given by[27]

$$f_{\mathrm{A}}(E)=\frac{1}{1+g_{\mathrm{A}}\exp\left(-\dfrac{E_{\mathrm{F}}-E}{kT}\right)}, \tag{2}$$

$f_{\mathrm{D}}(E)$ is the Fermi-Dirac distribution function for donors or electron traps, which is given by[27]

$$f_{\mathrm{D}}(E)=\frac{1}{1+\dfrac{1}{g_{\mathrm{D}}}\exp\left(-\dfrac{E_{\mathrm{F}}-E}{kT}\right)}, \tag{3}$$

E_{F} is the Fermi level measured from E_{V}, g_{A} is the degeneracy factor of acceptors or hole traps, and g_{D} is the degeneracy factor of donors or electron traps.

As proposed in the previous papers,[22–25] a function $S(T, E_{\mathrm{ref}})$ is defined as

$$S(T, E_{\mathrm{ref}}) \equiv \frac{p(T)}{kT}\exp\left(\frac{E_{\mathrm{ref}}}{kT}\right). \tag{4}$$

Therefore, the function $S(T, E_{\mathrm{ref}})$ is expressed as

$$\begin{aligned} S(T, E_{\mathrm{ref}}) =& \sum_{i=1}^{l}\frac{N_{\mathrm{A}i}}{kT}\exp\left(-\frac{E_{\mathrm{A}i}-E_{\mathrm{ref}}}{kT}\right)F_{\mathrm{A}}(E_{\mathrm{A}i}) \\ &+\sum_{i=1}^{n}\frac{N_{\mathrm{TH}i}}{kT}\exp\left(-\frac{E_{\mathrm{TH}i}-E_{\mathrm{ref}}}{kT}\right)F_{\mathrm{A}}(E_{\mathrm{TH}i}) \\ &+\sum_{i=1}^{m}\frac{N_{\mathrm{TE}i}}{kT}\exp\left(-\frac{E_{\mathrm{TE}i}-E_{\mathrm{ref}}}{kT}\right)F_{\mathrm{D}}(E_{\mathrm{TE}i}) \\ &+\sum_{i=1}^{k}\frac{N_{\mathrm{D}i}}{kT}\exp\left(-\frac{E_{\mathrm{D}i}-E_{\mathrm{ref}}}{kT}\right)F_{\mathrm{D}}(E_{\mathrm{D}i}) \\ &-\left(\sum_{i=1}^{n}N_{\mathrm{TH}i}+\sum_{i=1}^{k}N_{\mathrm{D}i}\right)\frac{1}{kT}\exp\left(\frac{E_{\mathrm{ref}}}{kT}\right) \\ &+\frac{n(T)}{kT}\exp\left(\frac{E_{\mathrm{ref}}}{kT}\right), \end{aligned} \tag{5}$$

where

$$F_{\mathrm{A}}(E)=\frac{\exp\left(\dfrac{E_{\mathrm{F}}}{kT}\right)}{g_{\mathrm{A}}+\exp\left(\dfrac{E_{\mathrm{F}}-E}{kT}\right)}, \tag{6}$$

and

$$F_{\mathrm{D}}(E)=\frac{g_{\mathrm{D}}\exp\left(\dfrac{E_{\mathrm{F}}}{kT}\right)}{1+g_{\mathrm{D}}\exp\left(\dfrac{E_{\mathrm{F}}-E}{kT}\right)}. \tag{7}$$

The fifth term on the right-hand side of eq. (5) decreases monotonically with an increase in T. The sixth term is negligible, because $n(T)$ is very small in a p-type semiconductor. However, the function

$$\frac{N_i}{kT}\exp\left(-\frac{E_i-E_{\mathrm{ref}}}{kT}\right) \tag{8}$$

in the other terms has a peak value of $N_i\exp(-1)/kT_{\mathrm{peak}i}$ at $T_{\mathrm{peak}i}=(E_i-E_{\mathrm{ref}})/k$, indicating that the peak value and temperature provide N_i and E_i, where N_i represents $N_{\mathrm{A}i}$, $N_{\mathrm{TH}i}$, $N_{\mathrm{TE}i}$ or $N_{\mathrm{D}i}$, and E_i represents $E_{\mathrm{A}i}$, $E_{\mathrm{TH}i}$, $E_{\mathrm{TE}i}$ or $E_{\mathrm{D}i}$. Even when none of the peaks of $S(T, 0)$ appear within the measurement temperature range, the peak of $S(T, E_{\mathrm{ref}})$ can be shifted to the measurement temperature by changing E_{ref}. Although each peak temperature of $S(T, E_{\mathrm{ref}})$ is shifted from $(E_i-E_{\mathrm{ref}})/k$ to the lower temperature due to the temperature dependence of $F_{\mathrm{A}}(E_i)$ or $F_{\mathrm{D}}(E_i)$, we can easily determine the accurate values of N_i and E_i from each peak value and temperature of $S(T, E_{\mathrm{ref}})$ using a personal computer, as mentioned below and as done in previous papers.[22–25] Although p-type semiconductors have been discussed here, n-type semiconductors can be discussed in the same manner.[28]

2.2 *The case of proton-irradiated p-type Si*

Since only B is doped in p-type Si used here, one type of acceptor is considered. Since E_{F} is located near and above E_{V} as mentioned later, $f_{\mathrm{D}}(E_{\mathrm{TE}i})\simeq 0$ and $f_{\mathrm{D}}(E_{\mathrm{D}i})\simeq 0$, indicating that electron traps are not electrically charged and all donors are positively charged. Also, $n(T)$ is negligible below room temperature in p-type Si. Thus, eq. (1) can be approximately expressed as

$$p(T)\simeq N_{\mathrm{A1}}f_{\mathrm{A}}(E_{\mathrm{A1}})-\sum_{i=1}^{n}N_{\mathrm{TH}i}\,[1-f_{\mathrm{A}}(E_{\mathrm{TH}i})]-N_{\mathrm{D}}, \tag{9}$$

where

$$N_{\mathrm{D}}=\sum_{i=1}^{k}N_{\mathrm{D}i}. \tag{10}$$

Then, the function $S(T, E_{\mathrm{ref}})$ can be expressed as

$$\begin{aligned} S(T, E_{\mathrm{ref}}) \simeq& \frac{N_{\mathrm{A1}}}{kT}\exp\left(-\frac{E_{\mathrm{A1}}-E_{\mathrm{ref}}}{kT}\right)F_{\mathrm{A}}(E_{\mathrm{A1}}) \\ &+\sum_{i=1}^{n}\frac{N_{\mathrm{TH}i}}{kT}\exp\left(-\frac{E_{\mathrm{TH}i}-E_{\mathrm{ref}}}{kT}\right)F_{\mathrm{A}}(E_{\mathrm{TH}i}) \\ &-\left(\sum_{i=1}^{n}N_{\mathrm{TH}i}+N_{\mathrm{D}}\right)\frac{1}{kT}\exp\left(\frac{E_{\mathrm{ref}}}{kT}\right). \end{aligned} \tag{11}$$

3. Experimental

Samples for Hall-effect measurements were made of a B-doped single crystalline Si wafer grown by the Czochralski method. The thicknesses and sizes of the samples were

220 μm and 5 mm × 5 mm, respectively. The resistivity of the wafer was around 10 Ω·cm and the value of N_A was 2.19×10^{15} cm^{-3}. In order to form ohmic contacts at the four corners of the sample, Ti, Pd and Ag were evaporated on the corners in sequence and then the sample was kept at 673 K for 20 min. After that, the sample was irradiated with 10-MeV protons of 3×10^{13}-cm^{-2} or 6×10^{13}-cm^{-2} fluence at the fluence rate of 2.5×10^{10} cm^{-2}·s^{-1}. Then, the sample was kept at 333 K for 24 h for an annealing treatment. The proton irradiation was performed at room temperature using the Azimuthally Varying Field (AVF) cyclotron at the Takasaki division of the Japan Atomic Energy Research Institute (JAERI). The Hall-effect measurement was performed using Toyo Technica ResiTest 8310.

4. Results and Discussion

4.1 3×10^{13}-cm^{-2}-proton-fluence irradiated Si

Figure 1 shows $p(T)$ for the sample irradiated with 10-MeV protons of 3×10^{13} cm^{-2}. Solid circles represent the experimental data and the solid line represents the spline function calculated using the experimental data. The broken line represents E_F calculated using the solid line and

$$E_F = kT \ln\left[\frac{N_V(T)}{p(T)}\right], \tag{12}$$

where $N_V(T)$ is the effective density of states in the valence band for Si, which is given by[27)]

$$N_V(T) = 2.00 \times 10^{15} T^{3/2}\ \text{cm}^{-3}. \tag{13}$$

Figure 2 shows $S(T, 0)$ calculated using the solid line in Fig. 1. Two peaks are seen in the figure, indicating that at least two types of hole traps exist. Let us consider $S(T, 0)$ at the low peak temperature ($T_{\text{peak}j} = 166$ K) in Fig. 2. All B atoms in Si are negatively ionized at around 166 K, because E_F at around 166 K is much higher than the ionization energy (45 meV) of B. Thus, $f_A(E_{A1}) \simeq 1$. Since it is considered

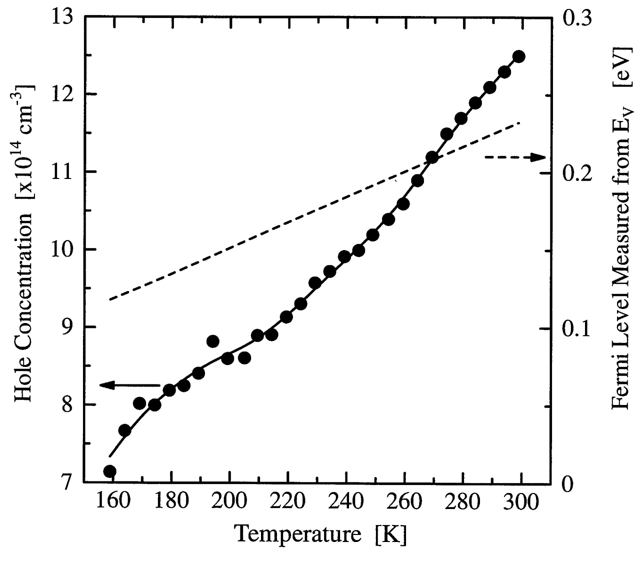

Fig. 1. Temperature dependence of majority-carrier concentration for a 3×10^{13}-cm^{-2}-proton irradiated sample. Solid circles represent the experimental data, and the solid line represents the spline function calculated using the experimental data. The broken line represents the temperature dependence of the Fermi level.

that $f_A(E_{THi}) \simeq 1$ $(i \le j-1)$ and $f_A(E_{THi}) \simeq 0$ $(i \ge j+1)$ at around 166 K, eq. (9) can be approximately expressed as

$$p(T) \simeq \Delta p_{j-1} + N_{THj} f_A(E_{THj}), \tag{14}$$

where

$$\Delta p_{j-1} = N_{A1} - \sum_{i=j}^{n} N_{THi} - N_D \tag{15}$$

and Δp_{j-1} means the density of holes captured by the acceptor or the hole traps shallower than the j-th hole trap at 0 K. Therefore, the approximate $S(T, E_{\text{ref}})$ is expressed as

$$S1_j(T, E_{\text{ref}}) = \frac{N_{THj}}{kT}\exp\left(-\frac{E_{THj}-E_{\text{ref}}}{kT}\right)F_A(E_{THj}) + \frac{\Delta p_{j-1}}{kT}\exp\left(\frac{E_{\text{ref}}}{kT}\right). \tag{16}$$

In order to reduce the number of unknowns to two, that is, E_{THj} and $\Delta p_{j-1}/N_{THj}$, the following function is introduced as

$$Y1_j(T, E_{\text{ref}}) \equiv \frac{S(T, E_{\text{ref}})}{N_{THj}} \tag{17}$$

$$\simeq \frac{S1_j(T, E_{\text{ref}})}{N_{THj}} \tag{18}$$

$$= \frac{1}{kT}\exp\left(-\frac{E_{THj}-E_{\text{ref}}}{kT}\right)F_A(E_{THj}) + \frac{\Delta p_{j-1}}{N_{THj}}\cdot\frac{1}{kT}\exp\left(\frac{E_{\text{ref}}}{kT}\right). \tag{19}$$

In order to determine E_{THj} and $\Delta p_{j-1}/N_{THj}$, the value of T_{Rj} is introduced as the lower one of temperatures at which the ratio $S(T, E_{\text{ref}})/S(T_{\text{peak}j}, E_{\text{ref}})$ has a value of R (i.e., $0 < R < 1$), where $S(T, E_{\text{ref}})/S(T_{\text{peak}j}, E_{\text{ref}}) = Y1_j(T, E_{\text{ref}})/Y1_j(T_{\text{peak}j}, E_{\text{ref}})$. When $T_{Rj} = 160$ K, $R = 0.997$. Using a personal computer, we determine the values of E_{THj} and $\Delta p_{j-1}/N_{THj}$ which maximize $Y1_j(T, 0)$ at 166 K and make $Y1_j(T, 0)$ 99.7% of the maximum value at 160 K. The values of E_{THj} and $\Delta p_{j-1}/N_{THj}$ are 0.0949 eV and 0.975, respectively.

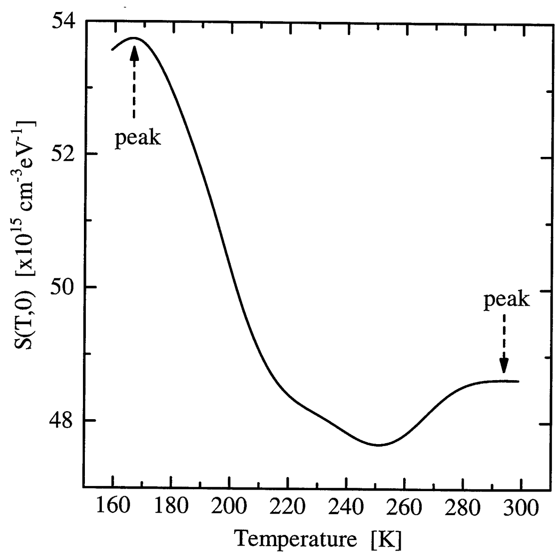

Fig. 2. $S(T, 0)$ signal which is given by $p(T)/kT$.

As is clear from eq. (17), N_{THj} is given by

$$N_{THj} = \frac{S(T_{peakj}, E_{ref})}{Y1_j(T_{peakj}, E_{ref})}. \quad (20)$$

Since $Y1_j(166, 0)$ is calculated to be $1.13 \times 10^2\,eV^{-1}$ using eq. (19) from the obtained values of E_{THj}, $\Delta p_{j-1}/N_{THj}$ and $S(T_{peakj}, 0) = 5.37 \times 10^{16}\,cm^{-3}\cdot eV^{-1}$, the value of N_{THj} is estimated to be $4.75 \times 10^{14}\,cm^{-3}$. Then, Δp_{j-1} is estimated to be $4.62 \times 10^{14}\,cm^{-3}$.

In order to evaluate the deep hole trap (l-th hole trap), a function, which is not influenced by the shallow hole traps and the acceptor, is introduced as

$$S2_l(T, E_{ref}) \equiv S(T, E_{ref}) - \frac{N_{THj}}{kT}\exp\left(-\frac{E_{THj} - E_{ref}}{kT}\right) F_A(E_{THj}) - \frac{\Delta p_{j-1}}{kT}\exp\left(\frac{E_{ref}}{kT}\right) \quad (21)$$

$$\simeq \frac{N_{THl}}{kT}\exp\left(-\frac{E_{THl} - E_{ref}}{kT}\right) F_A(E_{THl}). \quad (22)$$

Figure 3 shows $S2_l(T, 0)$ and $S2_l(T, 0.08)$ calculated using eqs. (4) and (21) and the obtained values of E_{THj}, N_{THj} and Δp_{j-1}. Since $S2_l(T, 0)$ has no peak within the measurement temperature range, the peak of $S2_l(T, E_{ref})$ is shifted to the left by using $E_{ref} = 0.08\,eV$. The values of T_{peakl} and $S2_k(T_{peakl}, 0.08)$ obtained from the solid line are 288 K and $2.84 \times 10^{17}\,cm^{-3}\cdot eV^{-1}$, respectively.

In order to determine E_{THl}, the following function is introduced as

$$Y2_l(T, E_{THl}) \equiv \frac{S2_l(T, E_{ref})}{N_{THl}} \quad (23)$$

$$\simeq \frac{1}{kT}\exp\left(-\frac{E_{THl} - E_{ref}}{kT}\right) F_A(E_{THl}). \quad (24)$$

Then, the value of E_{THl}, which maximizes $Y2_l(T, E_{THl})$ in eq. (24) at 288 K, is 0.191 eV. Since $Y2_l(288, 0.08)$ is calculated to be $4.84 \times 10^2\,eV^{-1}$ using eq. (24) and $E_{THl} = 0.191\,eV$, the value of N_{THl} is $5.87 \times 10^{14}\,cm^{-3}$.

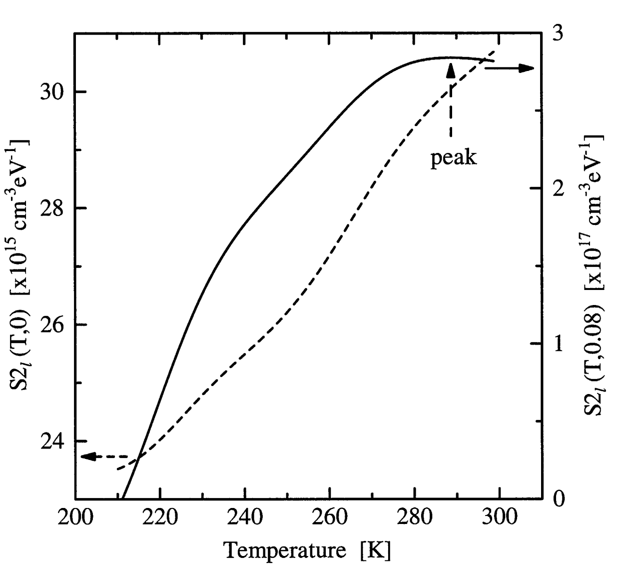

Fig. 3. $S2_l(T, E_{ref})$ signals for two E_{ref} values of 0 eV and 0.08 eV.

The density of holes, which are partially captured by the acceptors or which are captured by the hole traps shallower than 0.0949 eV, is $4.62 \times 10^{14}\,cm^{-3}$ at 0 K. The densities of the hole traps at 0.0949 eV and 0.191 eV above E_V are $4.75 \times 10^{14}\,cm^{-3}$ and $5.87 \times 10^{14}\,cm^{-3}$, respectively, and all these traps are fully filled with holes at 0 K. Because the total density of holes (i.e., the acceptor density) is $2.19 \times 10^{15}\,cm^{-3}$, the sum ($\Delta N_{l+1}$) of the densities of hole traps deeper than 0.191 eV is $6.63 \times 10^{14}\,cm^{-3}$,[29] and all these hole traps are fully filled with holes at 0 K.

4.2 6×10^{13}-cm^{-2}-proton-fluence irradiated Si

Figure 4 shows $p(T)$ and E_F for the sample irradiated with 10-MeV protons of $6 \times 10^{13}\,cm^{-2}$. Solid circles represent the experimental data and the solid line represents the spline function calculated using the experimental data. The broken line represents E_F calculated using the solid line.

Figure 5 shows $S(T, 0)$ and $S(T, 0.015)$. The broken line does not show a peak. First, let us determine the density and energy level of the deep hole trap (i.e., l-th hole trap) in this case, since the l-th hole trap is considered to have the most influence on the curve. In order that the peak appears within the measurement temperature range, the peak is shifted to the left by using $E_{ref} = 0.015\,eV$. The values of T_{peakl} and $S(T_{peakl}, 0.015)$ given by the solid line are 287 K and $6.29 \times 10^{16}\,cm^{-3}\cdot eV^{-1}$, respectively. Since the approximate $S(T, E_{ref})$ can be expressed as

$$S1_l(T, E_{ref}) = \frac{N_{THl}}{kT}\exp\left(-\frac{E_{THl} - E_{ref}}{kT}\right) F_A(E_{THl}) + \frac{\Delta p_{l-1}}{kT}\exp\left(\frac{E_{ref}}{kT}\right) \quad (25)$$

where

$$\Delta p_{l-1} = N_{A1} - \sum_{i=l}^{n} N_{THi} - N_D, \quad (26)$$

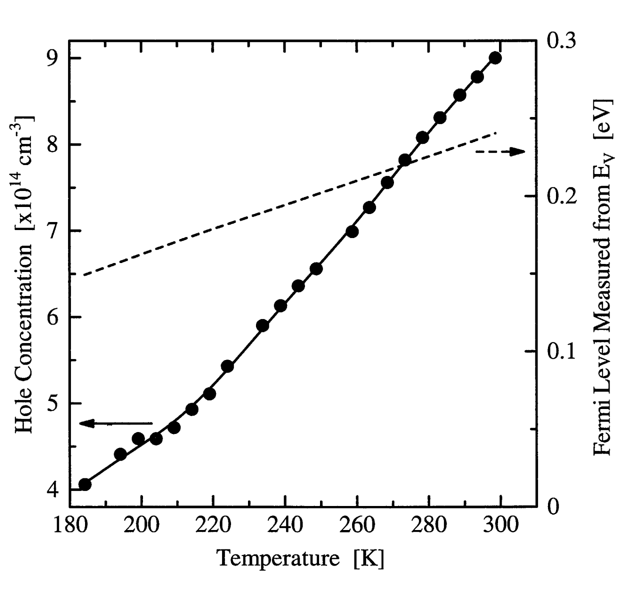

Fig. 4. Temperature dependence of majority-carrier concentration for a 6×10^{13}-cm^{-2}-proton irradiated sample. Solid circles represent the experimental data, and the solid line represents the spline function calculated using the experimental data. The broken line represents the temperature dependence of the Fermi level.

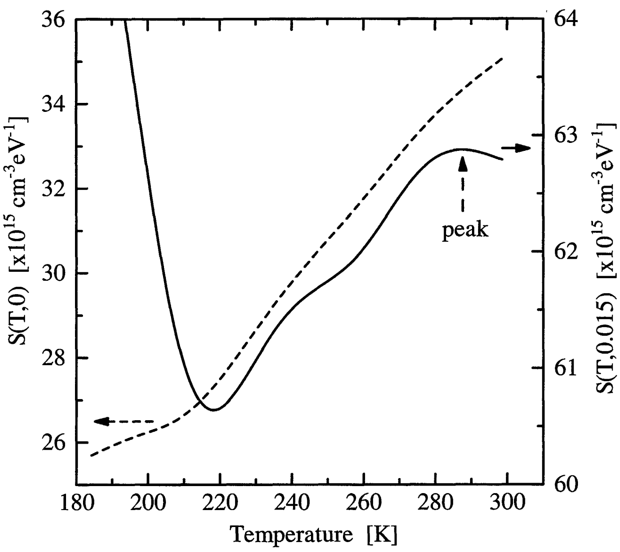

Fig. 5. $S(T, E_{\rm ref})$ signals for two $E_{\rm ref}$ values of 0 eV and 0.015 eV.

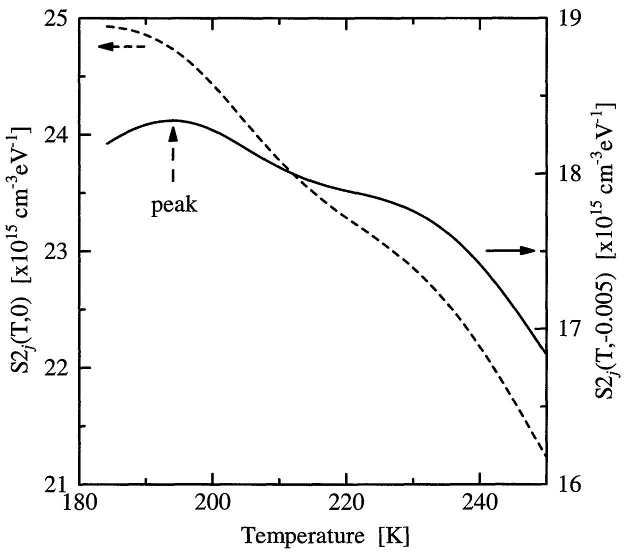

Fig. 6. $S2_j(T, E_{\rm ref})$ signals for two $E_{\rm ref}$ values of 0 eV and −0.005 eV.

the values of $E_{{\rm TH}l}$, $N_{{\rm TH}l}$ and Δp_{l-1} are determined to be 0.192 eV, $7.20 \times 10^{14}\,{\rm cm}^{-3}$ and $4.53 \times 10^{14}\,{\rm cm}^{-3}$, respectively, using $T_{{\rm peak}l} = 287\,{\rm K}$, $S(T_{{\rm peak}l}, 0.015) = 6.29 \times 10^{16}\,{\rm cm}^{-3}{\cdot}{\rm eV}^{-1}$, $T_{{\rm R}l} = 270\,{\rm K}$ and $R = 0.994$ in the same manner as in §4.1.

In order to evaluate the shallow hole trap (i.e., j-th hole trap), a function which is not influenced by the l-th hole trap is introduced as

$$\begin{aligned} S2_j(T, E_{\rm ref}) \equiv\ & S(T, E_{\rm ref}) \\ & - \frac{N_{{\rm TH}l}}{kT}\exp\left(-\frac{E_{{\rm TH}l} - E_{\rm ref}}{kT}\right) F_{\rm A}(E_{{\rm TH}l}) \quad (27) \\ \simeq\ & \frac{N_{{\rm TH}j}}{kT}\exp\left(-\frac{E_{{\rm TH}j} - E_{\rm ref}}{kT}\right) F_{\rm A}(E_{{\rm TH}j}) \\ & + \frac{\Delta p_{j-1}}{kT}\exp\left(\frac{E_{\rm ref}}{kT}\right). \quad (28) \end{aligned}$$

Figure 6 shows $S2_j(T, 0)$ and $S2_j(T, -0.005)$ calculated using eqs. (4) and (27) and the obtained values ($E_{{\rm TH}l} = 0.192\,{\rm eV}$, $N_{{\rm TH}l} = 7.20 \times 10^{14}\,{\rm cm}^{-3}$). Since $S2_j(T, 0)$ has no peak within the measurement temperature range, the peak is shifted to the right by using $E_{\rm ref} = -0.005\,{\rm eV}$. The values of $T_{{\rm peak}j}$ and $S2_j(T_{{\rm peak}j}, -0.005)$ obtained from the solid line are 194 K and $1.83 \times 10^{16}\,{\rm cm}^{-3}{\cdot}{\rm eV}^{-1}$, respectively. Using $T_{{\rm R}j} = 185$ and $R = 0.993$, the values of $E_{{\rm TH}j}$, $N_{{\rm TH}j}$ and Δp_{j-1} are obtained to be 0.0922 eV, $7.31 \times 10^{14}\,{\rm cm}^{-3}$ and $-2.63 \times 10^{14}\,{\rm cm}^{-3}$, respectively, in the same manner as in §4.1. The negative value ($\Delta p_{j-1} = -2.63 \times 10^{14}\,{\rm cm}^{-3}$) implies that only 64% of the j-th hole trap with a value of $7.31 \times 10^{14}\,{\rm cm}^{-3}$ is filled with holes at 0 K.

In Fig. 6, the hole trap corresponding to $T_{{\rm peak}k} = 240\,{\rm K}$ seems to exist. In order to determine $E_{{\rm TH}k}$ and $N_{{\rm TH}k}$ of this hole trap, a function which is not influenced by the hole traps shallower and deeper than the k-th hole trap is introduced as

$$\begin{aligned} S3_k(T, E_{\rm ref}) \equiv\ & S(T, E_{\rm ref}) \\ & - \frac{N_{{\rm TH}j}}{kT}\exp\left(-\frac{E_{{\rm TH}j} - E_{\rm ref}}{kT}\right) F_{\rm A}(E_{{\rm TH}j}) \\ & - \frac{N_{{\rm TH}l}}{kT}\exp\left(-\frac{E_{{\rm TH}l} - E_{\rm ref}}{kT}\right) F_{\rm A}(E_{{\rm TH}l}) \\ & - \frac{\Delta p_{j-1}}{kT}\exp\left(\frac{E_{\rm ref}}{kT}\right) \quad (29) \\ \simeq\ & \frac{N_{{\rm TH}k}}{kT}\exp\left(-\frac{E_{{\rm TH}k} - E_{\rm ref}}{kT}\right) F_{\rm A}(E_{{\rm TH}k}). \quad (30) \end{aligned}$$

In the curve of $S3_k(T, 0)$ calculated using eq. (29) and the obtained values of $N_{{\rm TH}j}$, $E_{{\rm TH}j}$, $N_{{\rm TH}l}$, $E_{{\rm TH}l}$ and Δp_{j-1}, the peak temperature and peak value are 237 K and $5.60 \times 10^{14}\,{\rm cm}^{-3}{\cdot}{\rm eV}^{-1}$, respectively. Therefore, $E_{{\rm TH}k}$ and $N_{{\rm TH}k}$ are obtained to be 0.131 eV and $1.37 \times 10^{13}\,{\rm cm}^{-3}$, respectively, in the same manner as in §4.1.

The acceptor and hole traps shallower than 0.0922 eV are completely empty at 0 K. The densities of hole traps at 0.0922 eV, 0.131 eV and 0.192 eV above $E_{\rm V}$ are $7.31 \times 10^{14}\,{\rm cm}^{-3}$, $1.37 \times 10^{13}\,{\rm cm}^{-3}$ and $7.20 \times 10^{14}\,{\rm cm}^{-3}$, respectively. Two deep hole traps are fully filled with holes at 0 K, while only 64% of the shallow hole trap is filled with holes at 0 K. Then, the sum (ΔN_{l+1}) of the densities of hole traps deeper than 0.192 eV is $9.88 \times 10^{14}\,{\rm cm}^{-3}$, and all these hole traps are fully filled with holes at 0 K.

4.3 *Verification of the results*

Let us verify the obtained values (Δp_{j-1}, $E_{{\rm TH}j}$, $N_{{\rm TH}j}$, $E_{{\rm TH}k}$, $N_{{\rm TH}k}$, $E_{{\rm TH}l}$, $N_{{\rm TH}l}$) shown in Table I. The temperature dependence of $E_{\rm F}$ is calculated using the obtained values (Δp_{j-1}, $N_{{\rm TH}j}$, $E_{{\rm TH}j}$, $N_{{\rm TH}k}$, $E_{{\rm TH}k}$, $N_{{\rm TH}l}$, $E_{{\rm TH}l}$) and the following two equations:

$$\begin{aligned} p(T) = \Delta p_{j-1} & + N_{{\rm TH}j} f_{\rm A}(E_{{\rm TH}j}) + N_{{\rm TH}k} f_{\rm A}(E_{{\rm TH}k}) \\ & + N_{{\rm TH}l} f_{\rm A}(E_{{\rm TH}l}) \quad (31) \end{aligned}$$

and

$$p(T) = N_{\rm V}(T)\exp\left(-\frac{E_{\rm F}}{kT}\right). \quad (32)$$

Then, $p(T)$ is calculated using eq. (32), which is shown by the solid lines in Fig. 7. In the figure, the solid circles represent the experimental data. As is clear from the figure, the

Table I. The densities and energy levels of hole traps generated by 10-MeV-proton irradiation.

fluence (cm^{-2})	3×10^{13}	6×10^{13}
Δp_{j-1} (cm^{-3})	4.62×10^{14}	-2.63×10^{14}
E_{THj} (eV)	0.0949	0.0922
N_{THj} (cm^{-3})	4.75×10^{14}	7.31×10^{14}
E_{THk} (eV)	—[a]	0.131
N_{THk} (cm^{-3})	—[a]	1.37×10^{13}
E_{THl} (eV)	0.191	0.192
N_{THl} (cm^{-3})	5.87×10^{14}	7.20×10^{14}
ΔN_{l+1} (cm^{-3})	6.63×10^{14}	9.88×10^{14}

a) The dash indicates that the trap density is too low to be estimated by our method.

b) All energy levels are measured from E_V.

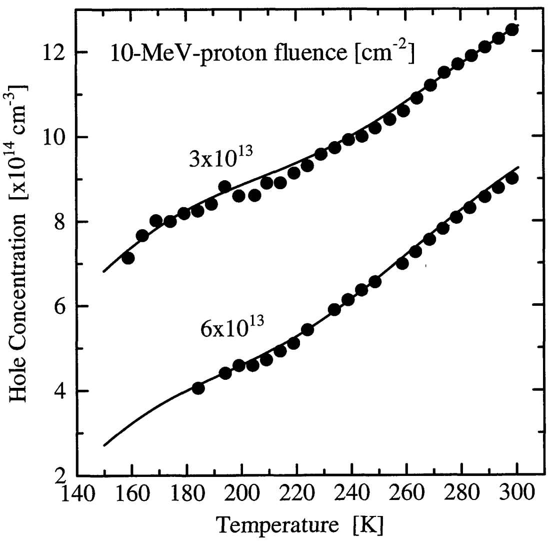

Fig. 7. The hole concentration obtained from the experimental data (solid circles) and the data (solid lines) calculated using the results shown in Table I.

solid lines show a fairly good quantitative agreement with the experimental data (solid circles).

In Si irradiated with 10-MeV protons under the same conditions as our samples, the hole trap levels obtained by DLTS were 0.1, 0.19, 0.35 and 0.48 eV above E_V.[2] The origins of the hole traps at 0.1 eV and 0.19 eV have been reported to be a carbon-related complex $(C_iC_s)^+$ and a divacancy $(VV)^+$, respectively, where C_i and C_s are the interstitial and substitutional carbon atoms, respectively, and V is the vacancy in Si.[6,9,18,19] Thus, our results show a good agreement with the reported hole trap energy levels (i.e., around 0.1 eV and 0.19 eV) generated by irradiation.

It is considered that the method proposed here is effective, since the trap levels obtained here are quite reasonable. Moreover, the quantitative relationship between the decrease in $p(T)$ and the increase in densities of certain hole traps generated by irradiation can be elucidated.

5. Summary

We have proposed a new graphical method to uniquely determine the densities and energy levels of traps in a semiconductor by means of Hall-effect measurements. Using the temperature dependence of the majority-carrier concentration $p(T)$, the function $S(T, E_{ref})$ is defined as $p(T)\exp(E_{ref}/kT)/kT$, which has a peak corresponding to each trap level. Using each peak, the density and energy level of the corresponding trap can be determined uniquely and accurately.

We have investigated hole traps generated by irradiation of 10-MeV protons in p-type Si. Three types of hole traps could be estimated by means of the method proposed here. In the hole traps generated by 3×10^{13}-cm^{-2}-proton irradiation, the density and energy level of one hole trap were 4.75×10^{14} cm^{-3} and $E_V + 0.0949$ eV, respectively, and those of another were 5.87×10^{14} cm^{-3} and $E_V + 0.191$ eV, respectively. The total density of hole traps deeper than $E_V + 0.191$ eV was 6.63×10^{14} cm^{-3}. In the hole traps generated by 6×10^{13}-cm^{-2}-proton irradiation, the density and energy level of the first hole trap were 7.31×10^{14} cm^{-3} and $E_V + 0.0922$ eV, respectively, those of the second were 1.37×10^{13} cm^{-3} and $E_V + 0.131$ eV, respectively, and those of the third were 7.20×10^{14} cm^{-3} and $E_V + 0.192$ eV, respectively. The total density of hole traps deeper than $E_V + 0.192$ eV was 9.88×10^{14} cm^{-3}.

The trap levels determined by our method coincided with those estimated by DLTS. Moreover, the trap densities determined by our method could quantitatively explain the decrease of $p(T)$ by irradiation very well, while those estimated by DLTS were too low to explain the decrease. Therefore, our method is considered to be effective for investigating traps in semiconductors.

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$$\begin{aligned} S(T, E_{ref}) &= \sum_{i=1}^{k} \frac{N_{Di}}{kT} \exp\left(-\frac{\Delta E_{Di} - E_{ref}}{kT}\right) F_D(\Delta E_{Di}) \\ &+ \sum_{i=1}^{m} \frac{N_{TEi}}{kT} \exp\left(-\frac{\Delta E_{TEi} - E_{ref}}{kT}\right) F_D(\Delta E_{TEi}) \\ &+ \sum_{i=1}^{n} \frac{N_{THi}}{kT} \exp\left(-\frac{\Delta E_{THi} - E_{ref}}{kT}\right) F_A(\Delta E_{THi}) \\ &+ \sum_{i=1}^{l} \frac{N_{Ai}}{kT} \exp\left(-\frac{\Delta E_{Ai} - E_{ref}}{kT}\right) F_A(\Delta E_{Ai}) \\ &- \left(\sum_{i=1}^{m} N_{TEi} + \sum_{i=1}^{l} N_{Ai}\right) \frac{1}{kT} \exp\left(\frac{E_{ref}}{kT}\right) \\ &+ \frac{p(T)}{kT} \exp\left(\frac{E_{ref}}{kT}\right), \end{aligned}$$

where

$$F_D(\Delta E) = \frac{\exp\left(\dfrac{\Delta E_F}{kT}\right)}{g_D + \exp\left(\dfrac{\Delta E_F - \Delta E}{kT}\right)}$$

and

$$F_A(\Delta E) = \frac{g_A \exp\left(\dfrac{\Delta E_F}{kT}\right)}{1 + g_A \exp\left(\dfrac{\Delta E_F - \Delta E}{kT}\right)}.$$

29) When the B atom combines with the vacancy created by irradiation, this no longer behaves as an acceptor in Si. Therefore, ΔN_{l+1} includes the density of B which does not behave as an acceptor.