

# Relationship between defects induced by irradiation and reduction of hole concentration in Al-doped 4H–SiC

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## Abstract

From the temperature dependence of the hole concentration in lightly Al-doped 4H–SiC epilayers, a shallow acceptor with  $E_V + 0.2$  eV, which is an Al atom ( $\text{Al}_{\text{Si}}$ ) at a Si sublattice site, and an unknown deep defect with  $E_V + 0.35$  eV are found, where  $E_V$  is the valence band maximum. In unirradiated epilayers, moreover, the density ( $N_{\text{Defect}}$ ) of this defect is close to the Al acceptor density ( $N_{\text{Al}}$ ). With irradiation of 0.2 MeV electrons, the  $N_{\text{Al}}$  is reduced, while the  $N_{\text{Defect}}$  is increased. Judging from the minimum electron energy required to displace a substitutional C atom ( $\text{C}_s$ ) or  $\text{Al}_{\text{Si}}$ , the bond between  $\text{Al}_{\text{Si}}$  and its nearest neighbor  $\text{C}_s$  is broken due to the displacement of the  $\text{C}_s$  by this irradiation. Moreover, the displacement of the  $\text{C}_s$  results in the creation of a complex ( $\text{Al}_{\text{Si}}-\text{V}_C$ ) of  $\text{Al}_{\text{Si}}$  and its nearest neighbor C vacancy ( $\text{V}_C$ ), indicating that the possible origin of the defect with  $E_V + 0.35$  eV is  $\text{Al}_{\text{Si}}-\text{V}_C$ .  
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**Keywords:** Al-doped 4H–SiC; Electron irradiation; Radiation damage; Reduction in hole concentration

## 1. Introduction

Silicon carbide (SiC) is a promising wide band gap semiconductor for fabricating high-power and high-frequency electronic devices capable of operating at elevated temperatures.

From the temperature dependence of the hole concentration  $p(T)$  for lightly Al-doped 4H–SiC epilayers, one acceptor species with  $\sim 200$  meV and one defect with  $\sim 350$  meV are observed [1,2], where all the energy levels are measured from the valence band maximum ( $E_V$ ). From photoluminescence (PL) [3], the acceptor species is ascribed to an Al atom ( $\text{Al}_{\text{Si}}$ ) at a Si sublattice site. However, the origin of this defect has so far not been determined.

This defect cannot be determined accurately from deep level transient spectroscopy (DLTS), since the density ( $N_{\text{Defect}}$ ) of this defect is nearly equal to the density ( $N_{\text{Al}}$ ) of the Al acceptor. This is because DLTS can determine the

energy levels and densities of defects only when the defect density is much lower than the acceptor density.

Irradiation with 4.6 MeV electrons at  $2.6 \times 10^{14} \text{ cm}^{-2}$  fluence reduced the  $N_{\text{Al}}$  by  $\sim 10$ , while reducing the  $N_{\text{Defect}}$  only slightly [2]. Therefore, the reduction in  $p(T)$  with this irradiation results from a decrease in  $N_{\text{Al}}$  due to the displacement of the  $\text{Al}_{\text{Si}}$  or the bond breaking between  $\text{Al}_{\text{Si}}$  and its nearest neighbor C.

Boron (B) in 4H–SiC was reported to form two electrical levels in the lower half of its bandgap [4]. One is located at  $\sim 300$  meV as determined by Hall-effect measurements [4], and the other is between 550 and 650 meV as determined by DLTS [5]. The shallow level is assigned to a B atom ( $\text{B}_{\text{Si}}$ ) at a Si sublattice site. The probable identification of the deep level is a complex ( $\text{B}_{\text{Si}}-\text{V}_C$ ) of  $\text{B}_{\text{Si}}$  and its nearest neighbor C vacancy ( $\text{V}_C$ ) [6,7].

By analogy with B in 4H–SiC, the deep defect in Al-doped 4H–SiC may be an  $\text{Al}_{\text{Si}}-\text{V}_C$  complex, which was detected by electron paramagnetic resonance (EPR) spectroscopy [7].

Since the atomic mass of C is smaller than that of Si, the maximum energy transferred from one electron to one

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substitutional C atom ( $C_s$ ) in SiC by elastic collision is larger than that to one substitutional Si atom ( $Si_s$ ). This indicates that the minimum electron energy necessary for displacing one  $C_s$  should be lower than that for one  $Si_s$ .

In this article, we report on our investigation of the origin of the unknown deep defect as well as the mechanism for the reduction in  $N_{Al}$  by irradiation with electrons of several energies. The densities and energy levels of acceptors and defects are determined by free carrier concentration spectroscopy (FCCS) from the  $p(T)$  without any assumptions regarding the acceptor species and the defects.

## 2. Experiment

A 10  $\mu\text{m}$ -thick lightly Al-doped p-type 4H-SiC epilayer on n-type 4H-SiC (thickness: 376  $\mu\text{m}$ , resistivity: 0.02  $\Omega\text{cm}$ ) was cut to a  $1 \times 1 \text{ cm}^2$  size. Ohmic metal (Ti/Al) was deposited on the four corners of the surface of the sample, and then the sample was annealed at 900  $^\circ\text{C}$  for 1 min in an Ar atmosphere. The  $p(T)$  and the temperature dependence of the hole mobility  $\mu_p(T)$  were measured by van der Pauw configuration in the temperature range from 120 to 600 K in a magnetic field of 1.4 T using a modified MMR Technologies' Hall system. The sample was irradiated with  $1.0 \times 10^{16} \text{ cm}^{-2}$  fluence of 0.2 MeV electrons,  $5.0 \times 10^{15}$  or  $1.0 \times 10^{16} \text{ cm}^{-2}$  fluence of 0.5 MeV electrons, or  $1.0 \times 10^{16} \text{ cm}^{-2}$  fluence of 1 MeV electrons at room temperature. After the irradiation, the  $p(T)$  and the  $\mu_p(T)$  were measured.

## 3. Results and discussion

Fig. 1 shows the experimental  $p(T)$  for the sample ( $\circ$ ) before irradiation and the samples irradiated with the  $1.0 \times 10^{16} \text{ cm}^{-2}$  fluence of 0.2 MeV electrons ( $\Delta$ ) and the  $5.0 \times 10^{15} \text{ cm}^{-2}$  fluence of 0.5 MeV electrons ( $\times$ ). The  $p(T)$  for the sample irradiated with the  $2.6 \times 10^{14} \text{ cm}^{-2}$  fluence of 4.6 MeV electrons is also shown by  $\diamond$ , which was reported previously [2]. Each  $\mu_p(T)$  seemed unchanged by the irradiation, indicating that the band conduction of holes is dominant in the temperature range of the measurement.

The  $p(T)$  for the sample irradiated with the  $1.0 \times 10^{16} \text{ cm}^{-2}$  fluence of 0.5 or 1 MeV electrons could not be measured, because of much higher resistivity of the sample. Since the  $p(T)$  for 10- $\Omega\text{cm}$  B-doped Si (B-doping density:  $2 \times 10^{15} \text{ cm}^{-3}$ ) is reported to be reduced slightly by irradiation with  $1.0 \times 10^{16} \text{ cm}^{-2}$  fluence of 1 MeV electrons [8], the Al-doped p-type 4H-SiC is found to be less radiation resistant compared with B-doped Si, although it is generally accepted that SiC has a very high resistance to displacement damage due to radiation because the lattice constant of SiC is smaller than that of Si.

The reduction in  $p(T)$  by irradiation with 0.2 MeV electrons is less than that due to irradiation with 0.5 or 4.6 MeV electrons, although the larger amount of electrons was delivered to the sample in the case of the 0.2 MeV

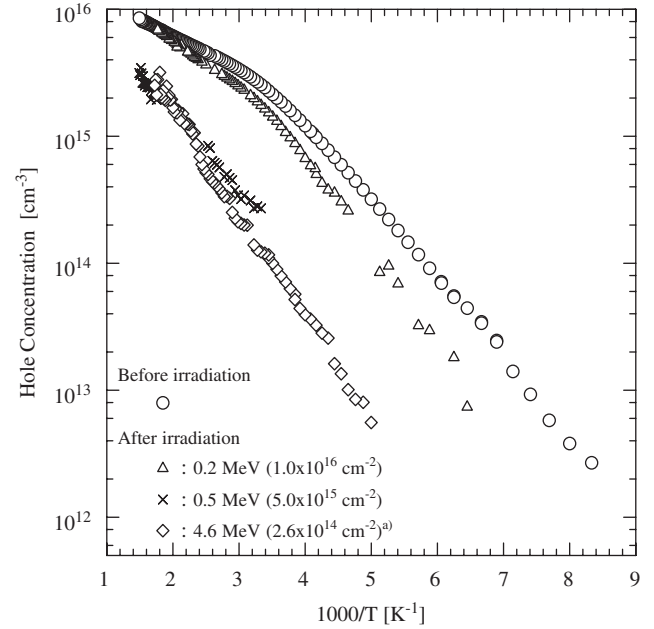


Fig. 1. Temperature dependence of hole concentration for Al-doped p-type 4H-SiC before and after irradiation with electrons at three difference energies. (a) After Ref. [2].

electron irradiation. This suggests that the mechanism for the reduction in  $p(T)$  by irradiation depends on the irradiated electron energy.

In Fig. 1, the  $p(T)$  for the sample with irradiation of 0.2 MeV electrons is decreased at low temperatures, indicating that the  $N_{Al}$  was reduced with irradiation of 0.2 MeV electrons. On the other hand, the  $p(T)$  for this sample seems unchanged at high temperatures, suggesting that the sum of  $N_{Al}$  and  $N_{\text{Defect}}$  did not change by this irradiation. Therefore, with irradiation of 0.2 MeV electrons, the  $N_{Al}$  was decreased, while the  $N_{\text{Defect}}$  was increased.

The densities and energy levels of acceptors and defects can be determined by the FCCS. Using an experimental  $p(T)$ , the FCCS signal is defined by [1,2]

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

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

In the samples before and after irradiation, the values of an Al acceptor level ( $\Delta E_{Al}$ ),  $N_{Al}$ , a defect level ( $\Delta E_{\text{Defect}}$ ),  $N_{\text{Defect}}$ , and a compensating density ( $N_{\text{comp}}$ ) were determined by the FCCS, and are listed in Table 1. In the

Table 1  
Results obtained by the FCCS for Al-doped p-type 4H-SiC epilayers before and after electron irradiation

Conditions	Before	After	Before	After	Before	After <sup>a</sup>
Energy (MeV)		0.2		0.5		4.6
Fluence (cm <sup>-2</sup> )		1.0 × 10 <sup>16</sup>		5.0 × 10 <sup>15</sup>		2.6 × 10 <sup>14</sup>
ΔE <sub>Al</sub> (meV)	203	217	204	—	203	206
N <sub>Al</sub> (cm <sup>-3</sup> )	5.2 × 10 <sup>15</sup>	4.3 × 10 <sup>15</sup>	4.8 × 10 <sup>15</sup>	~2.6 × 10 <sup>14</sup>	6.2 × 10 <sup>15</sup>	8.2 × 10 <sup>14</sup>
ΔE <sub>Defect</sub> (meV)	357	363	319	356	365	383
N <sub>Defect</sub> (cm <sup>-3</sup> )	3.5 × 10 <sup>15</sup>	5.2 × 10 <sup>15</sup>	2.3 × 10 <sup>15</sup>	1.4 × 10 <sup>15</sup>	4.2 × 10 <sup>15</sup>	3.4 × 10 <sup>15</sup>
N <sub>comp</sub> (cm <sup>-3</sup> )	4.7 × 10 <sup>13</sup>	2.1 × 10 <sup>14</sup>	1.9 × 10 <sup>13</sup>	—	3.4 × 10 <sup>13</sup>	7.4 × 10 <sup>14</sup>

<sup>a</sup>After Ref. [2].

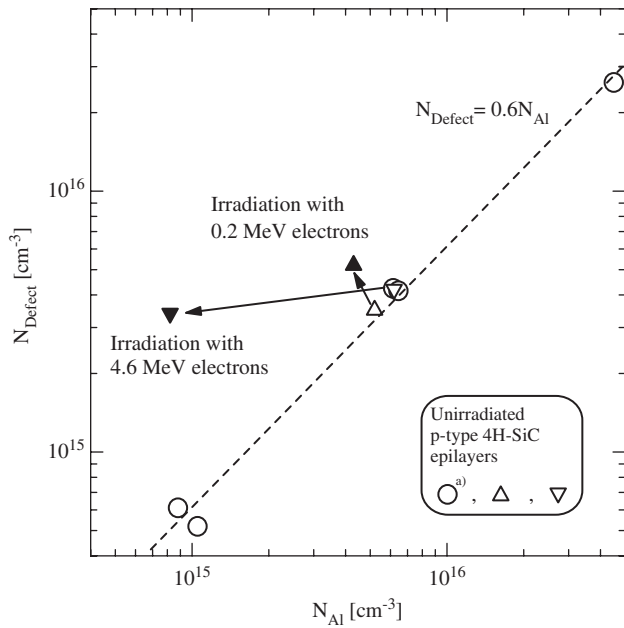


Fig. 2. Relationship between  $N_{Al}$  and  $N_{Defect}$ . (a) After Ref. [1].

sample irradiated with  $5.0 \times 10^{15} \text{ cm}^{-2}$  fluence of 0.5 MeV electrons, the values of  $\Delta E_{Al}$  and  $N_{comp}$  could not be determined, because a reliable  $p(T)$  could not be measured at low temperatures. Each  $p(T)$  simulated with the values shown in Table 1 is in good agreement with the corresponding experimental  $p(T)$ , indicating that the values determined by the FCCS are reliable.

Fig. 2 depicts the relationship between  $N_{Al}$  and  $N_{Defect}$  in each sample. The symbols of  $\triangle$  and  $\blacktriangle$  represent the relationships before and after irradiation with 0.2 MeV electrons, while the symbols of  $\nabla$  and  $\blacktriangledown$  are the relationships before and after irradiation with 4.6 MeV electrons. The relationships in unirradiated epilayers with several doping densities are denoted by  $\circ$ , which were reported previously [1].

Since the empirical relationship in the unirradiated epilayers is obtained from Fig. 2 as

$$N_{Defect} = 0.6 \times N_{Al}, \quad (2)$$

this defect is most likely related to Al. The irradiation with 0.2 MeV electrons resulted in a decrease in  $N_{Al}$  and an

increase in  $N_{Defect}$ , while the irradiation with 4.6 MeV electrons led to the decreases in both  $N_{Al}$  and  $N_{Defect}$ .

Although one of the possible origins of the unknown defect is B with which 4H-SiC is sometimes contaminated [4–6], the concentration of B in these epilayers, which was determined by secondary ion mass spectroscopy, was  $< 4 \times 10^{14} \text{ cm}^{-3}$ , indicating that B is not related to this defect. It may be closely linked with the  $D_1$  line observed by PL [9] or with  $Al_{Si}-V_C$  observed by EPR [7].

The maximum energy ( $E_{max}$ ) transferred from an electron to a nucleus is given by [10]

$$E_{max} = \frac{2E_e(E_e + 2m_e c^2)}{Mc^2}, \quad (3)$$

where  $E_e$  is the incident electron energy,  $M$  is the atomic mass,  $m_e$  is the electron mass, and  $c$  is the velocity of light. In SiC, the threshold displacement energy ( $E_d$ ) was reported as  $\sim 40 \text{ eV}$  [11–13], which might depend to some extent on the conduction type, the growth techniques, and so on. This indicates that the atom at the substitutional site is displaced by the incident electron when  $E_{max} \geq E_d$ .

Fig. 3 shows the atomic-mass-unit dependence of the minimum electron energy ( $E_{min}$ ) required for the displacement of the substitutional atom. Judging from the figure, one electron with 0.19–0.36 MeV can displace only  $C_s$ .

With irradiation by 0.2 MeV electrons at  $1.0 \times 10^{16} \text{ cm}^{-2}$  fluence, the decrement of  $N_{Al}$  is nearly equal to the increment of  $N_{Defect}$ , as shown in Table 1. If the bond between  $Al_{Si}$  and its nearest neighbor  $C_s$  is broken due to the displacement of the  $C_s$  by this electron irradiation, the Al acceptor density is decreased and the density of the  $Al_{Si}-V_C$  complex is increased, which is consistent with our experimental finding. Therefore, the origin of the unknown defect is most likely  $Al_{Si}-V_C$ .

With irradiation by electrons at  $\geq 0.5 \text{ MeV}$ , the  $N_{Al}$  should decrease due to the displacement of both  $C_s$  and  $Al_{Si}$ . When the unknown defect is  $Al_{Si}-V_C$ , the  $N_{Defect}$  should decrease due to the displacement of  $Al_{Si}$ , while it should increase due to the displacement of the  $C_s$  closest to Al. Therefore, the  $N_{Al}$  is reduced significantly, whereas the  $N_{Defect}$  is decreased slightly, which is in good agreement with our experimental results.

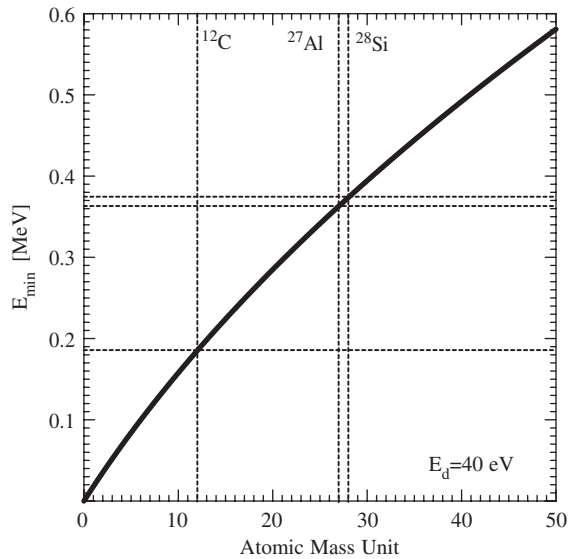


Fig. 3. Atomic-mass-unit dependence of minimum electron energy required for displacement of substitutional atom in SiC.

#### 4. Conclusion

We have investigated the reduction in  $p(T)$  for Al-doped p-type 4H-SiC epilayers with irradiation by electrons of several energies, and have determined the densities and energy levels of a shallow acceptor and a deep defect using FCCS. With irradiation by 0.2 MeV electrons, the shallow Al acceptor density was decreased, while the unknown deep defect density was increased. Since one 0.2 MeV electron could displace only  $C_s$  into an interstitial site, the Al acceptor density was decreased due to the displacement of the  $C_s$  closest to Al, which resulted in an increase in the density of  $Al_{Si}-V_C$ . Therefore, the deep defect is most likely  $Al_{Si}-V_C$ .

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