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Mechanisms of reduction in hole concentration in Al-doped 4H-SiC by electron irradiation

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Abstract

From the temperature dependence of the hole concentration in unirradiated lightly Al-doped 4H-SiC epilayers, an Al acceptor with $E_V + 0.2$ eV, which is an Al atom (Al_{Si}) at a Si sublattice site, and an unknown deep acceptor with $E_V + 0.35$ eV are found, where E_V is the top of the valence band. Both the densities are similar. With irradiation of 0.2 MeV electrons the Al acceptor density is reduced, while the unknown deep acceptor density is increased. Judging from the minimum electron energy required to displace a substitutional C atom (C_s) or the Al_{Si}, the bond between the Al_{Si} and its nearest neighbor C_s is broken due to the displacement of the C_s by this irradiation. Moreover, the displacement of the C_s results in the creation of a complex (Al_{Si}–V_C) of Al_{Si} and a carbon vacancy (V_C), indicating that the possible origin of the deep acceptor with $E_V + 0.35$ eV is Al_{Si}–V_C.

Keywords: Al-doped 4H-SiC; Electron irradiation; Deep acceptor; 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 ~200 meV and another acceptor species with ~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 shallow acceptor species is ascribed to an Al atom (Al_{Si}) at a Si sublattice site. The origin of the deep acceptor (i.e., defect) has so far not been determined. The density (N_{Defect}) of this defect is a little lower than the density (N_{Al}) of the Al acceptor, with the N_{Defect} proportional to the Al-doping density [1]. This indicates that the deep defect may be related to Al.

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

Since the atomic mass of C is smaller than that of Si, the minimum electron energy necessary for displacing one substitutional C atom (C_s) should be lower than that for one substitutional Si atom (Si_s).

In this article, we report on our investigation of the origin of the deep defect as well as the mechanism for the reduction in N_{Al} by irradiation with electrons of different energies. Free carrier concentration spectroscopy (FCCS) is applied to determine the densities and energy levels from the $p(T)$ without any assumptions regarding the acceptor species and the defects.

2. Experiment

A 10 μm-thick Al-doped p-type 4H-SiC epilayer (Al-doping density: ~5×10^{15} cm^{-3}) on n-type 4H-SiC (thickness:

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376 μm, resistivity: 0.02 Ω cm) was cut to a 1×1 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 °C for 1 min in an Ar atmosphere. The $p(T)$ was measured by van der Pauw configuration in the temperature range from 120 to 600 K in a magnetic field of 1.4 T. The sample was irradiated with 1.0×10^{16} cm^{-2} fluence of 0.2 MeV electrons at room temperature. After the irradiation, the $p(T)$ was measured.

3. Results and discussion

Fig. 1 shows the experimental $p(T)$ for the unirradiated sample (○) and the sample (Δ) irradiated with the 1.0×10^{16} cm^{-2} fluence of 0.2 MeV electrons. The $p(T)$ for the sample irradiated with the 2.6×10^{14} cm^{-2} fluence of 4.6 MeV electrons is also shown by ◇, which was reported previously [2].

The reduction in $p(T)$ by irradiation with 0.2 MeV electrons is less than that due to irradiation with 4.6 MeV electrons, although the larger amount of electrons was delivered to the sample in the case of the 0.2 MeV electron irradiation. This suggests that the mechanism for the reduction in $p(T)$ by irradiation depends on the electron energy.

The densities and energy levels of the Al acceptor and the defect in the samples before and after irradiation can be determined by the FCCS. Using the experimental $p(T)$, the FCCS signal is defined by [1,2]

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

where k is the Boltzmann constant and E_{ref} is the parameter that can shift the peak temperature of $H(T, E_{\mathrm{ref}})$ 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.

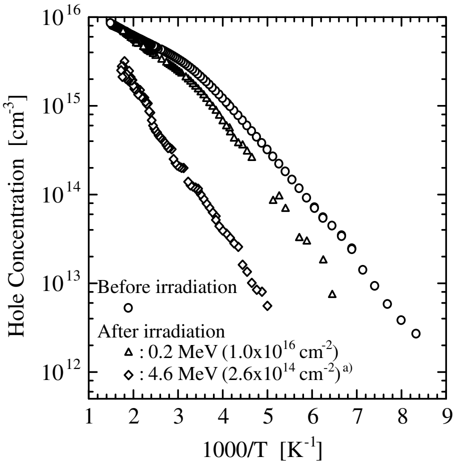

Fig. 1. Temperature dependence of hole concentration for Al-doped p-type 4H-SiC before and after irradiation with electrons. (a) After [2].

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

Although one of the possible origins of the deep acceptor is B with which 4H-SiC is sometimes contaminated [4], the concentration of B in this epilayer, which was determined by secondary ion mass spectroscopy, was $<4 \times 10^{14}$ cm^{-3}, indicating that B is not related to the deep acceptor. It may be closely linked with the D_1 line observed by PL [5] or with a complex ($\mathrm{Al_{Si}}$–$\mathrm{V_C}$) of $\mathrm{Al_{Si}}$ and a carbon vacancy ($\mathrm{V_C}$) observed by electron paramagnetic resonance [6].

The maximum energy $E_{\max}$ transferred from the electron energy E_{e} to a nucleus is given by [7]

$$E_{\max} = \frac{2E_{\mathrm{e}}(E_{\mathrm{e}} + 2m_{\mathrm{e}}c^2)}{Mc^2}, \tag{2}$$

where 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 ~40 eV [8], 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 irradiated electron when $E_{\max} \geqslant E_{\mathrm{d}}$. Therefore, one electron with 0.19–0.36 MeV can displace only $\mathrm{C_s}$.

With irradiation by 0.2 MeV electrons at 1.0×10^{16} 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 the $\mathrm{Al_{Si}}$ and its nearest neighbor $\mathrm{C_s}$ is broken due to the displacement of $\mathrm{C_s}$ by this electron irradiation, the Al acceptor density is decreased and the density of the $\mathrm{Al_{Si}}$–$\mathrm{V_C}$ complex is increased, which is consistent with the experimental finding. Therefore, the origin of the deep acceptor is most likely $\mathrm{Al_{Si}}$–$\mathrm{V_C}$.

With irradiation by electrons at $\geqslant 0.5$ MeV, the N_{Al} should decrease due to the displacement of both $\mathrm{C_s}$ and $\mathrm{Al_{Si}}$. If the deep acceptor is $\mathrm{Al_{Si}}$–$\mathrm{V_C}$, the N_{Defect} should decrease due to the displacement of $\mathrm{Al_{Si}}$, and should increase due to the displacement of Al's nearest neighbor $\mathrm{C_s}$. Therefore, the N_{Al} is reduced significantly, whereas the N_{Defect} is decreased slightly, which is in good agreement with the experimental results [2].

Table 1
Results obtained by the FCCS for Al-doped p-type 4H-SiC epilayers before and after 0.2 MeV electron irradiation with 1.0×10^{16} cm^{-2} fluence

	Before	After
ΔE_{Al} (meV)	203	217
N_{Al} (cm^{-3})	5.2×10^{15}	4.3×10^{15}
$\Delta E_{\mathrm{Defect}}$ (meV)	357	363
N_{Defect} (cm^{-3})	3.5×10^{15}	5.2×10^{15}
N_{comp} (cm^{-3})	4.7×10^{13}	2.1×10^{14}

4. Conclusion

We have investigated the reduction in $p(T)$ for Al-doped p-type 4H-SiC epilayers irradiated with electrons of different energies, and have determined the densities and energy levels of shallow and deep acceptors using the FCCS. With irradiation by 0.2 MeV electrons, the shallow Al acceptor density was decreased, while the unknown deep acceptor 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 its nearest neighbor C_s, which resulted in an increase of Al_{Si}–V_C. This suggests that the deep acceptor is Al_{Si}–V_C.

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