Decrease in Al acceptor density in Al-doped 4H-SiC by irradiation with 4.6 MeV electrons

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From the temperature dependence of the hole concentration $p(T)$ in a lightly Al-doped 4H-SiC epilayer, an Al acceptor with ~200 meV and an unknown defect with ~370 meV are found. By irradiation with 4.6 MeV electrons, the Al acceptor density is reduced, while the unknown defect density is almost unchanged. This indicates that the substitutional Al atoms in 4H-SiC are displaced by irradiation or that the bonds between the substitutional Al atom and the nearest neighbor atom are broken by irradiation. Moreover, the reduction in $p(T)$ with irradiation arises from the decrease of the Al acceptors, not from the formation of hole traps or donor-like defects. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1634381]

Silicon carbide (SiC) is a wide bandgap semiconductor with potential for use in high power and high frequency devices capable of operating at elevated temperatures. Also for electrons with energies greater than 0.5 MeV, the damage constant for lifetime degradation in SiC has been reported to be lower than that in GaAs by more than three orders of magnitude.[1] This indicates a greatly superior resistance of SiC to displacement damage in most radiation environments.

Electron irradiation is an excellent tool for the controlled generation of intrinsic defects in silicon (Si) to be used in high power devices.[2] On the other hand, it degrades the conversion efficiency of Si solar cells used in space.[3–5] While this electron-radiation damage in Si has been investigated by many researchers, the understanding of radiation damage in SiC is far from complete.

The vacancy-related defects induced by electron irradiation were investigated mainly with the following techniques. Using electron paramagnetic resonance spectroscopy (EPR), the following defects induced by electron irradiation were reported;[6–8] a Si Frenkel pair (V_{Si}-Si), a carbon monovacancy (V_C), a divacancy (V_C-V_{Si}), and an antisite–vacancy pair (C_{Si}-V_C). In electron-irradiated B-doped 6H-SiC, a complex (B_{Si}-V_C) of B and a vacancy, which behaved as a deep acceptor,[9] was detected.[10] It was reported that electrons with energies between 1 and 3 MeV were sufficient to displace silicon atoms in 6H-SiC with one electron.[11]

Although the radiation damage has been studied mainly with EPR and deep level transient spectroscopy, the densities and energy levels of hole traps created by irradiation can also be determined accurately from the temperature dependence of the hole concentration $p(T)$.[4] In this article, we report on our investigation of the influence of electron irradiation on $p(T)$ in p-type 4H-SiC, since it is important to investigate the cause of radiation degradation of SiC power devices such as metal-oxide-semiconductor field-effect transistors and bipolar-junction transistors used in space or near nuclear reactors.

A 10 μm-thick Al-doped 4H-SiC epilayer (Al-doping density: $\sim 5\times 10^{15}$ cm^{-3}) on n-type 4H-SiC (thickness: 375.9 μm, resistivity: 0.02 Ωcm) was cut to a 1×1 cm^2 size. Ohmic metal (Al/Ti) 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 the van der Pauw method in the temperature range from 135 to 580 K and in a magnetic field of 1.4 T using a modified MMR Technologies' Hall system. After this measurement, the sample was irradiated with 4.6 MeV electrons with 2.6×10^{14} cm^{-2} fluence at room temperature. Then the $p(T)$ for the sample was measured.

The open circles and diamonds in Fig. 1 represent the measured $p(T)$ for the unirradiated and irradiated samples. It is clear from the figure that the $p(T)$ is reduced by electron irradiation. The possible origins of this reduction in $p(T)$ by irradiation are as follows: (1) a decrease in the acceptor density because substitutional acceptors are moved into the in-

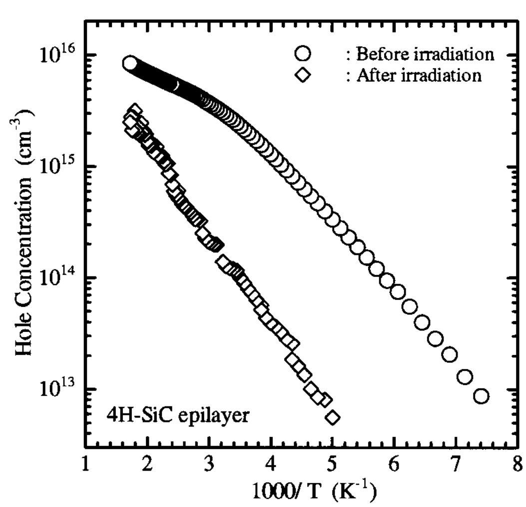

FIG. 1. Temperature dependencies of hole concentration.

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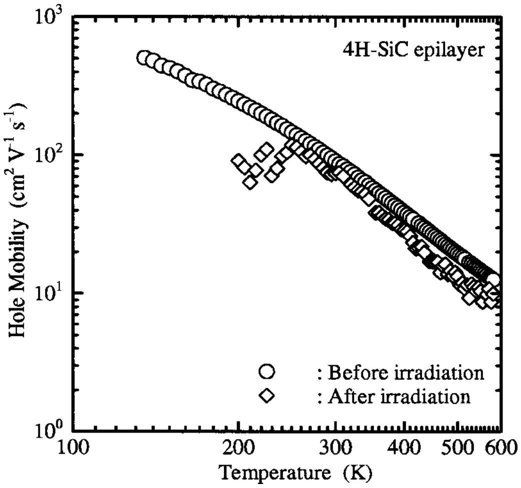

FIG. 2. Temperature dependencies of electron mobility.

TABLE I. Results obtained by FCCS.

	Before irradiation	After irradiation
ΔE_{A1} (meV)	203	206
N_{A1} (cm^{-3})	6.2×10^{15}	8.2×10^{14}
ΔE_{A2} (meV)	365	383
N_{A2} (cm^{-3})	4.2×10^{15}	3.4×10^{15}
N_{comp} (cm^{-3})	3.4×10^{13}	7.4×10^{14}

terstitial sites or because the bonds between the substitutional acceptor and the nearest neighbor atom are broken, or (2) the creation of hole traps or donor-like defects, which capture holes emitted from the acceptors.

The open circles and diamonds in Fig. 2 represent the experimental temperature dependence of electron mobility $\mu_n(T)$ for the unirradiated and irradiated samples. The reduction in $\mu_n(T)$ by irradiation is small above 250 K, but it is large below 250 K. This large reduction below 250 K may result from ion scattering.

In order to investigate acceptor densities and hole-trap densities with $p(T)$, free carrier concentration spectroscopy (FCCS)[5,12–14] is used. The FCCS is a graphical peak analysis method for determining the densities and energy levels of acceptor species and hole traps using $p(T)$ without any assumptions regarding acceptor species and hole traps. Using an experimental $p(T)$, the FCCS signal is defined as[4,5,13,14]

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

The FCCS signal has a peak at the temperature corresponding to each acceptor level or hole-trap level, where E_{ref} is the parameter that can shift the peak temperature of the FCCS signal within the temperature range of the measurement. From each peak, the density and energy level of the corresponding acceptor or hole trap can be determined accurately.

The solid line in Fig. 3 represents the FCCS signal of $H(T,E_{\mathrm{ref}})$ with $E_{\mathrm{ref}}=1.27\times10^{-3}$ eV for the unirradiated sample. Here the FCCS signal is calculated by interpolating $p(T)$ with a cubic smoothing natural spline function at intervals of 0.1 K. From the peak at 464.2 K, the corresponding density (N_{A2}) and energy level (ΔE_{A2}) measured from the valence band (E_V) are determined as 4.2×10^{15} cm^{-3} and 365 meV.

The FCCS signal of $H2(T,E_{\mathrm{ref}})$, in which the influence of ΔE_{A2} is removed, is calculated and denoted by the broken line in Fig. 3. Here, $E_{\mathrm{ref}}=0.145$ eV. From this peak at 266.7 K, the corresponding density (N_{A1}) and energy level (ΔE_{A1}), and the compensating density (N_{comp}) are determined as 6.2×10^{15} cm^{-3}, 203 meV and 3.4×10^{13} cm^{-3}, respectively.

In the same way as illustrated for the unirradiated sample, the densities and energy levels for the irradiated sample are determined and listed in Table I. The value of N_{A1} is reduced by electron irradiation, while N_{A2} appears unchanged.

In order to verify the values obtained, the $p(T)$ is simulated with the values shown in Table I. The open circles and diamonds in Fig. 4 represent the experimental $p(T)$ for the unirradiated and irradiated samples, and the solid and broken lines represent the simulated $p(T)$ for the unirradiated and irradiated samples. Each line is in good agreement with the corresponding experimental $p(T)$, indicating that the values determined by FCCS are reliable.

From photoluminescence (PL) measurements[15] and Hall-effect measurements,[16] the energy level of ~200 meV is ascribed to the Al acceptor in 4H-SiC. Moreover, N_{A1} is close

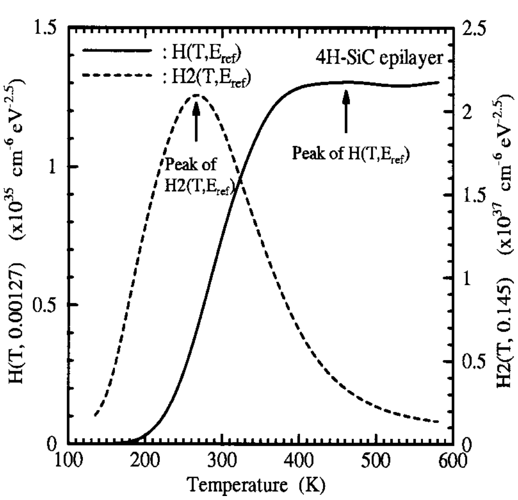

FIG. 3. FCCS signals.

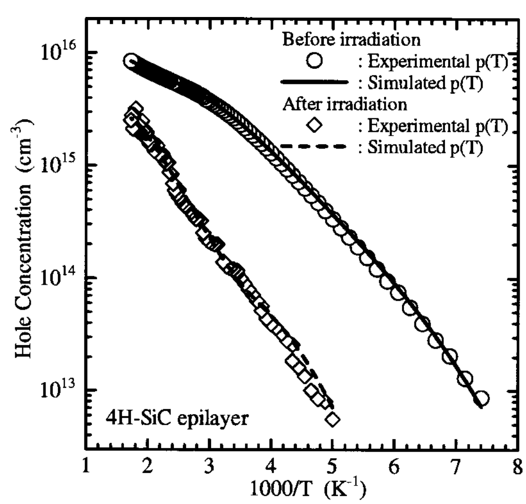

FIG. 4. A comparison between experimental and simulated $p(T)$.

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to the Al-doping density, suggesting that the origin of the shallower energy level is the Al acceptor. On the other hand, although the possible origin of the deeper energy level is B with which 4H-SiC is sometimes contaminated, the concentration of B in this epilayer, which was determined by secondary ion mass spectroscopy, was $<4\times10^{14}$ cm^{-3}, and ΔE_A of B was reported to be 285 meV.[16] Although it may be closely linked with the D_1-line observed by PL,[17] the origin of the deeper energy level is unfortunately unknown to date.

The density of substitutional Al atoms, which act as acceptors, is found to be reduced by 4.6 MeV electron irradiation. This is why the $p(T)$ is decreased by the irradiation. Similar phenomena have been reported in p-type Si: the $p(T)$ in B-doped Si was reduced by 10 MeV proton irradiation because of the decrease in the B acceptor density in Si.[5] Moreover, ion implantation has been reported to cause donor-density reduction in nitrogen (N)-doped 4H-SiC, because vacancies created by ion implantation reacted with N donors.[18,19]

The decrease in the Al acceptor density by irradiation is assumed to arise from the movement of the substitutional Al atoms into the interstitial sites, or from the bond-breaking between the substitutional Al atom and the nearest neighbor atom. Further research in this area is in progress.

In summary, the effect of electron irradiation on Al-doped 4H-SiC was investigated with Hall-effect measurements. The hole concentration in p-type 4H-SiC was reduced by 4.6 MeV electron irradiation, and by FCCS the ~200 meV Al acceptor density was found to be clearly decreased by the irradiation. On the other hand, the unknown ~370 meV defect density was unchanged. Therefore, the reduction in $p(T)$ by irradiation resulted from the decrease of Al acceptors, not from the creation of hole traps or donor-like defects.

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