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Decrease in Hole Concentration in Al-doped 4H-SiC by Irradiation of 200 keV Electrons

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Abstract

From the temperature dependence of the hole concentration $p(T)$ in a lightly Al-doped 4H-SiC epilayer irradiated with several fluences of 200 keV electrons, the density of Al acceptors with $E_V + 0.2$ eV decreases significantly with increasing fluence, whereas the density of unknown defects with $E_V + 0.37$ eV increases with fluence and then decreases slightly. Although only C vacancies increase with fluence because 200 keV electrons can displace only C atoms, only the increase in the density of C monovacancies cannot explain the changes of $p(T)$ by 200 keV electron irradiation. It may be necessary to consider the relationship between C vacancies and Al acceptors.

1. Introduction

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 it is considered to exhibit a greatly superior resistance to displacement damage in most radiation environments. The understanding of radiation damage in SiC, however, is far from complete, compared with in Si.

Using electron paramagnetic resonance spectroscopy (EPR), the following vacancy-related defects induced by electron irradiation were reported [1,2]; a Si Frenkel pair (V_{Si}-Si), a C 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, furthermore, B_{Si}-V_C complexes, which behaved as an acceptor deeper than B acceptors, were detected [3].

Besides EPR and deep level transient spectroscopy, the radiation changes of the densities and energy levels of acceptors and hole traps that affect the hole concentration can be determined accurately from the temperature dependence of the hole concentration $p(T)$ [4]. From $p(T)$ for lightly Al-doped 4H-SiC epilayers irradiated with 4.6 MeV electrons, we reported that the density (N_{Al}) of a shallow acceptor with $E_V + 0.2$ eV, which is an Al atom at a Si sublattice site, was significantly decreased, whereas the density (N_{Defect}) of an unknown deep acceptor with $E_V + 0.37$ eV was slightly decreased [5], where E_V is the valence band maximum. By irradiation of 200 keV electrons, on the other hand, N_{Al} decreased and N_{Defect} increased [6]. However, the sum of N_{Al} and N_{Defect} was unchanged [6]. In unirradiated epilayers, furthermore, the relationship of $N_{Defect} = 0.6 N_{Al}$ was obtained in a range of N_{Al} between 8×10^{14} and 5×10^{16} cm^{-3} [7], suggesting that this defect may be related to Al.

Since electrons with <300 keV can displace only C atoms in SiC whereas electrons with >500 keV can displace all the atoms (i.e., C, Al, Si) [6], we investigate the changes of N_{Al} and N_{Defect} in a lightly Al-doped 4H-SiC epilayer by irradiation with several fluences of 200 keV electrons.

2. Experimental

A 10 μm-thick lightly Al-doped 4H-SiC epilayer on n-type 4H-SiC (thickness: 376 μm, resistivity: 0.02 Ωcm) was cut to a 1×1 cm^2 size. The $p(T)$ and the temperature dependence of the hole mobility $\mu_p(T)$ were measured by the van der Pauw configuration in the temperature range from 120 to 650 K at a magnetic field of 1.4 T. The $p(T)$ and $\mu_p(T)$ for the unirradiated epilayer were measured, and then the sample was irradiated with 1×10^{16} cm^{-2} fluence of 200 keV electrons. After

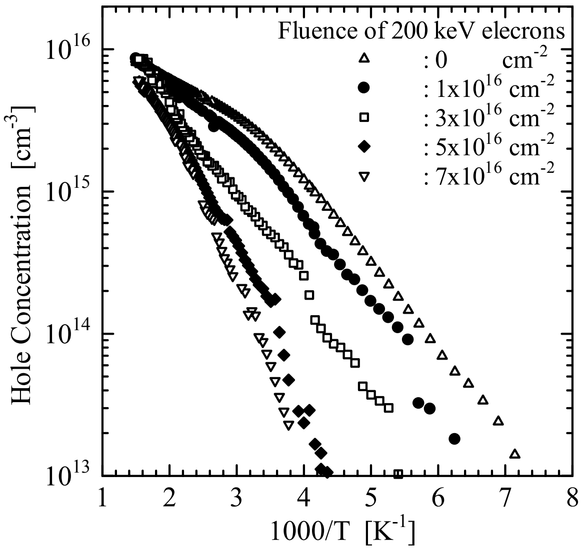

Fig. 1. Temperature dependence of hole concentration.

the Hall-effect measurement was carried out in the irradiated epilayer, the sample was irradiated with 2×10^{16} cm^{-2} fluence. The measurement and irradiation with 2×10^{16} cm^{-2} fluence of 200 keV electrons were repeated. In consequence, the $p(T)$ and $\mu_p(T)$ for the samples irradiated with the total fluences of 0, 1×10^{16}, 3×10^{16}, 5×10^{16} and 7×10^{16} cm^{-2} were obtained.

3. Results and Discussion

Figure 1 shows the experimental $p(T)$ for fluences of 0, 1×10^{16}, 3×10^{16}, 5×10^{16} and 7×10^{16} cm^{-2}, denoted by open triangles, solid circles, open squares, solid diamonds and open inversed triangles, respectively. Judging from the magnitude of $\mu_p(T)$, the band conduction of holes was dominant in these samples within the measurement temperature range. The $p(T)$ at low temperatures decreased significantly with increasing fluence, whereas the $p(T)$ at high temperatures was slightly changed by the irradiation, which is clear from Fig. 2. Figure 2 depicts the fluence dependence of $p(T)$ at 270, 390 and 650 K, denoted by open circles, solid triangles and open squares, respectively.

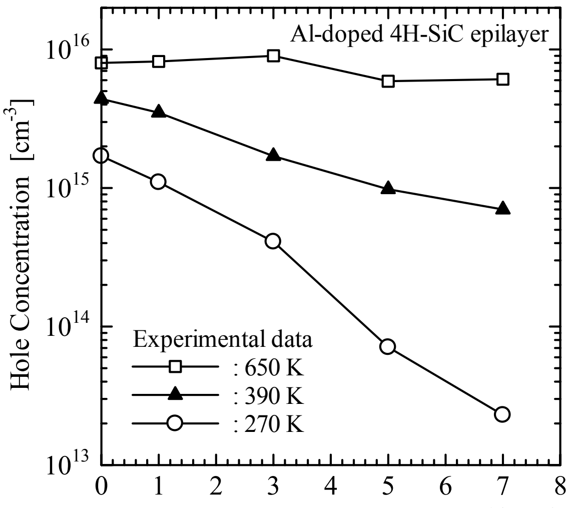

Fig. 2. Fluence dependence of hole concentration at three temperatures.

Table I. Results obtained by FCCS in Al-doped 4H-SiC irradiated by 200 keV electrons

Fluence [x10^{16} cm^{-2}]	0	1	3	5	7
N_{Al} [x10^{15} cm^{-3}]	5.33	4.25	1.49	0.50	<0.01
E_{Al} [meV]	$E_{\mathrm{V}}+204$	$E_{\mathrm{V}}+219$	$E_{\mathrm{V}}+221$	$E_{\mathrm{V}}+230$	-------
N_{Defect} [x10^{15} cm^{-3}]	3.74	5.39	11.4	6.88	7.87
E_{Defect} [meV]	$E_{\mathrm{V}}+370$	$E_{\mathrm{V}}+374$	$E_{\mathrm{V}}+376$	$E_{\mathrm{V}}+379$	$E_{\mathrm{V}}+388$

To quantitatively discuss the changes of N_{Al} and N_{Defect} by the irradiation, free carrier concentration spectroscopy (FCCS) [4,7] was applied to the determination of an Al acceptor level (E_{Al}), N_{Al}, a defect level (E_{Defect}) and N_{Defect} from $p(T)$. The FCCS signal has a peak at the temperature corresponding to each acceptor level or defect level. From each peak, therefore, the density and energy level of the corresponding acceptor or defect can be accurately determined. Using $p(T)$ in Fig. 1, the densities and energy levels were determined, and are listed in Table I.

Figure 3 shows the fluence dependence of N_{Al} and N_{Defect}. N_{Al} decreased with increasing fluence, and finally with 7×10^{16} cm^{-2} fluence Al acceptors run out. On the other hand, N_{Defect} increased with fluence, and then decreased.

Because 200 keV electrons can displace only C atoms, one of four C atoms bonded to an Al atom is displaced by the irradiation, and then the Al atom cannot act as an acceptor with $E_{\mathrm{V}}+0.2$ eV. Therefore, N_{Al} decreases with fluence. In this case, a complex ($\mathrm{Al_{Si}}$-$\mathrm{V_C}$) of the Al atom and its neighbor $\mathrm{V_C}$ is formed, suggesting that the density of $\mathrm{Al_{Si}}$-$\mathrm{V_C}$ increases with fluence. When one of three C atoms bonded to the Al atom of $\mathrm{Al_{Si}}$-$\mathrm{V_C}$ is displaced by the irradiation, on the other hand, the $\mathrm{Al_{Si}}$-$\mathrm{V_C}$ density decreases with fluence. Therefore, the $\mathrm{Al_{Si}}$-$\mathrm{V_C}$ density is increased by 200 keV electron irradiation when Al acceptors are abundant in SiC, whereas it is decreased when Al acceptors are running short. This fluence dependence of the $\mathrm{Al_{Si}}$-$\mathrm{V_C}$ density is similar to that of N_{Defect} by irradiation of 200 keV electrons, suggesting that $\mathrm{Al_{Si}}$-$\mathrm{V_C}$ may be the deep acceptor with $E_{\mathrm{V}}+0.37$ eV. However, there remains a question of how much $\mathrm{Al_{Si}}$-$\mathrm{V_C}$ complexes are created with these fluences.

Next, we attempt to explain the fluence dependence of $p(T)$ in Fig. 1 using the following

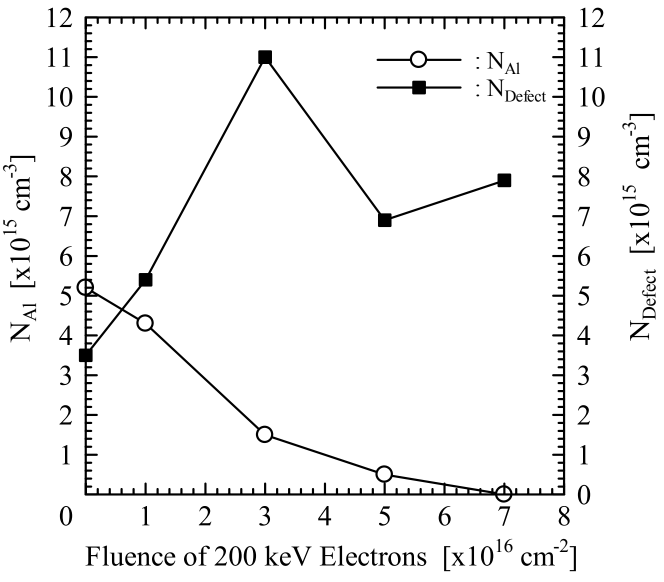

Fig. 3. Fluence dependence of acceptor density and defect density.

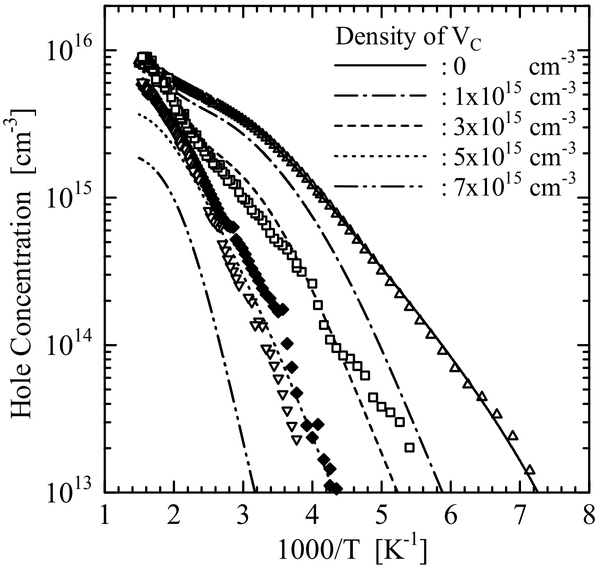

Fig. 4. $p(T)$ simulations with several densities of C vacancy.

assumption. Only the density (N_{VC}) of V_C increases with fluence, while N_{Al} and N_{Defect} are unchanged by the irradiation. Because V_C was reported to be located at the midgap in SiC, V_C captures a hole from the valence band, and never re-emits it into the valence band in the measurement temperature range. Figure 4 shows the $p(T)$ simulations with N_{VC} of 0, 1×10^{15}, 3×10^{15}, 5×10^{15} and 7×10^{15} cm^{-3}, denoted by solid, dot-dashed, broken, dotted and dot-dot-dashed lines, respectively. In the simulation, E_{Al}, N_{Al}, E_{Defect} and N_{Defect} of the unirradiated sample were used. The $p(T)$ simulations decrease with increasing N_{VC} in the whole measurement temperature range. However, the experimental $p(T)$ at low temperatures decreased with increasing fluence, whereas the experimental $p(T)$ at high temperatures did not decrease. Further research in this area is in progress.

4. Conclusion

We investigated the reduction in $p(T)$ for a lightly Al-doped 4H-SiC epilayer by irradiation with several fluences of 200 keV electrons. The $p(T)$ at low temperatures decreased significantly with increasing fluence, whereas the $p(T)$ at high temperatures seemed almost unchanged. To quantitatively discuss the changes of acceptor and defect densities by the irradiation, these densities were determined with FCCS from $p(T)$. The density of Al acceptors with $E_V+0.2$ eV decreased significantly with increasing fluence, while the density of defects with $E_V+0.37$ eV increased with fluence and then decreased slightly. Because 200 keV electrons can displace only C atoms, C monovacancies located at the midgap in SiC are created. However, it was difficult to explain the changes of $p(T)$ by the irradiation only from a viewpoint of the increase of V_C.

References

[1] H.J. von Bardeleben and J.L. Cantin, Mater. Sci. Forum **353-356**, 513 (2001)

[2] Th. Lingner, S. Greulich-Weber and J.-M. Spaeth, Mater. Sci. Forum **353-356**, 509 (2001)

[3] I.V. Ilyin, E.N. Mokhov and P.G. Baranov, Mater. Sci. Forum **353-356**, 521 (2001)

[4] H. Matsuura, H. Iwata, S. Kagamihara, R. Ishihara, M. Komeda, H. Imai, M. Kikuta, Y. Inoue, T. Hisamatsu, S. Kawakita, T. Ohshima and H. Itoh, Jpn. J. Appl. Phys. **45**, 2648 (2006)

[5] H. Matsuura, K. Aso, S. Kagamihara, H. Iwata, T. Ishida and K. Nishikawa, Appl. Phys. Lett. **83**, 4981 (2003)

[6] H. Matsuura, S. Kagamihara, Y. Itoh, T. Ohshima and H. Itoh, Physica B **376-377**, 376 (2006)

[7] H. Matsuura, M. Komeda, S. Kagamihara, H. Iwata, R. Ishihara, T. Hatakeyama, T. Watanabe, K. Kojima, T. Shinohe and K. Arai, J. Appl. Phys. **96**, 2708 (2004)