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

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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 $p(T)$ in Al-doped 4H-SiC epilayers irradiated with 4.6 MeV electrons, we reported that the density (N_{Al}) of a shallow acceptor with $E_{\mathrm{V}}+0.2$ eV, which is an Al atom at a Si sublattice site, was significantly reduced by the irradiation, while the density (N_{Deep}) of a deep acceptor with $E_{\mathrm{V}}+0.37$ eV was slightly decreased [1], where E_{V} is the valence band maximum. By irradiation of 200 keV electrons, on the other hand, N_{Al} decreased and N_{Deep} increased [2]. Furthermore, the sum of N_{Al} and N_{Deep} was unchanged [2]. In unirradiated epilayers, the relationship of $N_{\mathrm{Deep}}=0.6N_{\mathrm{Al}}$ was obtained in a range of N_{Al} between 8×10^{14} and 5×10^{16} cm^{-3} [3].

Since electrons with <300 keV can displace only carbon (C) atoms in SiC whereas electrons with >500 keV can displace all the atoms (i.e., C, Al and Si) in SiC [2], we investigate the changes of N_{Al} and N_{Deep} in a 10 μm-thick Al-doped 4H-SiC epilayer by irradiation of 200 keV electrons.

2. Experiment

A 10 μm-thick lightly Al-doped p-type 4H-SiC epilayer on n-type 4H-SiC (thickness: 376 μm, resistivity: 0.02 Ωcm) was cut to a 1 x 1 cm^2 size. Ohmic metal (Ti / Al) was deposited on the four corners of the surface of the sample, and

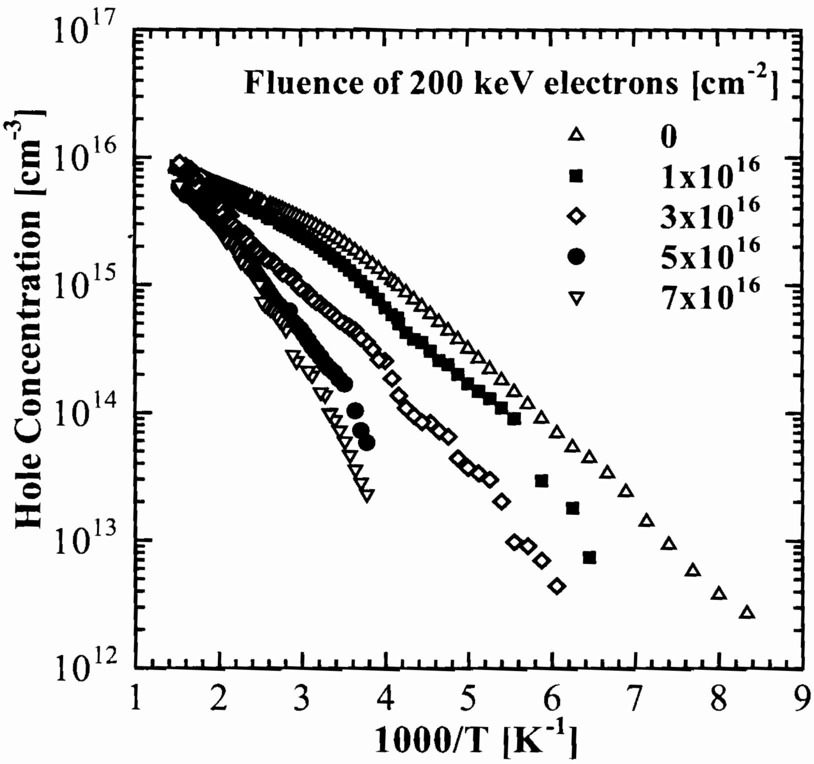

Fig. 1. Temperature dependence of hole concentration for Al-doped *p* -type 4H-SiC by irradiation of 200 keV electrons.

then the sample was annealed at 900 °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 650 K at a magnetic field of 1.4 T using a modified MMR Technologies' Hall system. After the Hall-effect measurement was carried out in the sample irradiated with 1×10^{16} cm^{-2} fluence, the sample was irradiated with 2×10^{16} cm^{-2} fluence. The irradiation and measurement were repeated. Therefore, the $p(T)$ and $\mu_p(T)$ for samples irradiated with the total fluences of 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 $p(T)$ denoted by open triangles (unirradiated), solid squares (1×10^{16} cm^{-2} fluence), open diamonds (3×10^{16} cm^{-2} fluence), solid circles (5×10^{16} cm^{-2} fluence) and open inverted triangles (7×10^{16} cm^{-2} fluence).

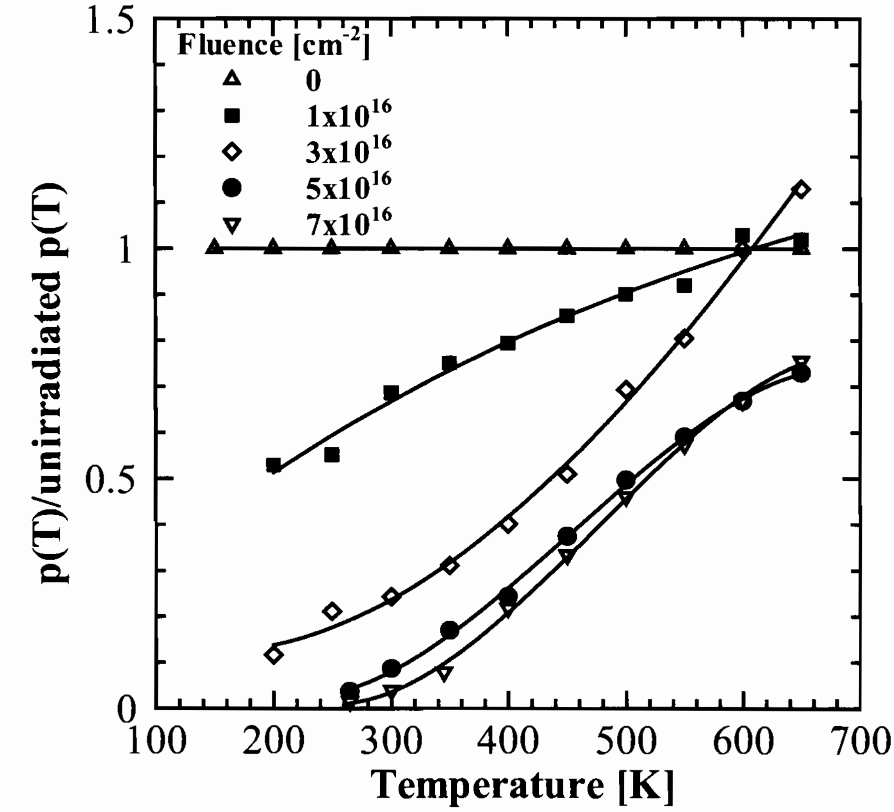

Fig. 2. $p(T)$ normalized by $p(T)$ for unirradiated sample

As is clear from Fig. 1, the $p(T)$ at low temperatures decreased significantly with increasing fluence. The $p(T)$ at high temperatures, on the other hand, was slightly changed by the irradiation.

Figure 2 shows the $p(T)$ normalized by the $p(T)$ for the unirradiated sample, where symbols are the same as in Fig. 1. It is clear from Fig. 2 that the $p(T)$ at low temperatures decreased with increasing fluence, suggesting that N_{Al} is decreased. When the epilayer was irradiated with 5.0 x 10^{16} cm^{-2} and 7.0 x 10^{16} cm^{-2} fluences, furthermore, almost all of Al atoms did not function as acceptors. By irradiation with 1×10^{16} and 3×10^{16} cm^{-2} fluences $p(T)$ at high temperatures increased a little, whereas by irradiation of 5×10^{16} and 7×10^{16} cm^{-2} fluences $p(T)$ decreased. These suggest that N_{Deep} may be increased at low fluences and be decreased at high fluences.

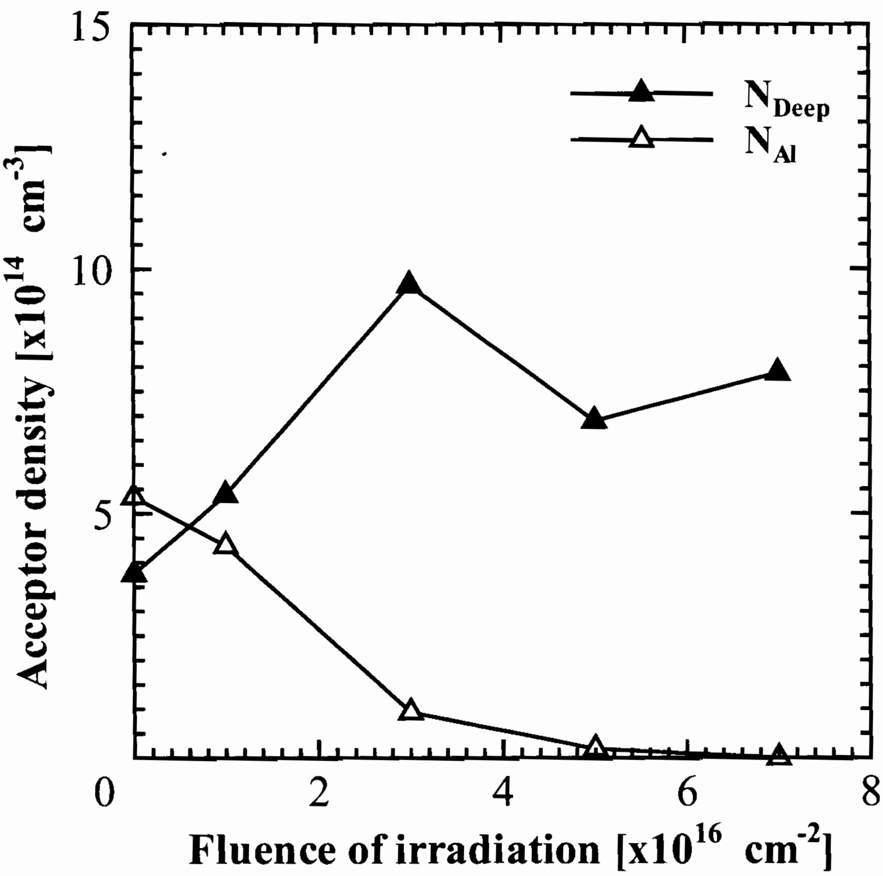

Fig. 3. Fluence dependence of N_{Al} and N_{Deep}

Table 1. Results obtained by FCCS

Fluence [cm^{-2}]	0	1×10^{16}	3×10^{16}	5×10^{16}	7×10^{16}
N_{Al} [cm^{-3}]	5.34×10^{15}	4.34×10^{15}	9.33×10^{14}	1.87×10^{14}	———
E_{Al} [meV]	205	218	226	———	———
N_{Deep} [cm^{-3}]	3.77×10^{15}	5.38×10^{15}	9.67×10^{15}	6.89×10^{15}	7.87×10^{15}
E_{Deep} [meV]	371	374	366	376	388

To quantitatively discuss the changes of N_{Al} and N_{Deep} by irradiation, the free carrier concentration spectroscopy (FCCS) was applied to the determination of these densities from $p(T)$. Using an experimental $p(T)$, the FCCS signal is defined by [1]

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

where k is the Boltzmann constant, T is the absolute temperature, 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. Table 1 shows the result obtained by FCCS.

Figure 3 depicts the fluence dependence of N_{Al} and N_{Deep}. N_{Al} decreases with increasing fluence. On the other hand, N_{Deep} increases with fluence, and then decreases.

When one of four C atoms bonded to an Al atom may be displaced by the irradiation of 200 keV electrons, the Al atom does not function as an acceptor, which makes N_{Al} low.

By the displacement of one of the four C bonded to the Al atom, a complex (Al-V_C) of the Al atom and its neighbor C vacancy (V_C) is formed. In this case, the density of Al-V_C should increase with fluence. When one of three C atoms bonded to the Al atom of Al-V_C is displaced by irradiation of 200 keV electrons, the Al-V_C complex changes into a V_C-Al-V_C complex. In this case, the density of Al-V_C should decrease with fluence. Therefore, the density of Al-V_C increases when there are abundant Al acceptors, whereas it decreases when there are little Al acceptors. This fluence dependence of the Al-V_C density is similar to that of N_{Deep} by irradiation of 200 keV electrons, suggesting that Al-V_C may be the deep acceptor observed here. Further research in this area is in progress.

4. Conclusion

We have investigated the reduction in $p(T)$ for a lightly Al-doped 4H-SiC epilayer with irradiation by several fluence of 200 keV electrons, and have determined the densities and energy levels of a shallow acceptor and a deep defect using FCCS. $p(T)$ at low temperatures decreased with increasing fluence, whereas $p(T)$ at high temperatures increased slightly and then decreased slightly. The density of Al acceptors with $E_V + 0.2$ eV decreased with increasing fluence, the density of deep acceptors with $E_V + 0.37$ eV increased slightly and then decreased slightly. The fluence dependence of the deep acceptor density can be explained by the formation and annihilation of Al-V_C complexes by irradiation because 200 keV electrons can displace only C atoms. To assign the deep acceptor to the Al-V_C complex, however, further research is required.

Acknowledgements

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References

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

[2] H. Matsuura, S. Kagamihara, Y Itoh, T. Ohshima, and H. Itoh, Physica B 376-377 (2006) 342.

[3] H. Matsuura, M. Komeda, S. Kagamihara, H. Iwata, and R. Ishihara, J.Appl. Phys. 96 (2004) 2708.

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