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Reduction in Al Acceptor Density by Electron Irradiation in Al-Doped 4H-SiC

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Abstract. The influence of electron irradiation on the hole concentration in Al-doped 4H-SiC epilayers is investigated with free carrier concentration spectroscopy (FCCS) using the temperature dependent hole concentration $p(T)$. By 4.6-MeV electron irradiation, $p(T)$ is reduced over the whole temperature range. Using FCCS, the densities and energy levels of acceptors or hole traps are determined. In the unirradiated and irradiated samples, ~200 meV and ~370 meV acceptor levels or hole-trap levels are detected. By irradiation, only the density of Al acceptors whose energy level is ~200 meV is reduced from 6.2×10^{15} cm^{-3} to 8.2×10^{14} cm^{-3}. This indicates that the main reduction in $p(T)$ by the electron irradiation resulted from the decrease of the Al acceptor density, not from the creation of defects.

Introduction

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].

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

Using electron spin resonance (ESR) spectroscopy, the following vacancy-related defects induced by electron irradiation were reported [6-8]; a Si Frenkel pair, a C vacancy, a divacancy, and an antisite-vacancy pair. In electron-irradiated B-doped 6H-SiC, a complex of B and a vacancy, which behaves as a deep acceptor [9], was detected [10]. It was reported that electrons with energies between 1 and 3 MeV were sufficient to displace Si atoms in 6H-SiC with one electron [11].

Although the radiation damage has been studied mainly with ESR and a 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 $p(T)$ [4,5]. In this article, we report on our investigation of the influence of electron irradiation on $p(T)$ in p-type 4H-SiC epilayers by means of free carrier concentration spectroscopy (FCCS) [5,12-14].

Experimental

10 μm-thick Al-doped 4H-SiC epilayers (Al-doping density: ~5×10^{15} cm^{-3}) on n-type 4H-SiC (thickness: 375.9 μm, resistivity: 0.02 Ωcm) were 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

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900 °C for 1 min in an Ar atmosphere to form good ohmic contact. 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, and then the $p(T)$ for the sample was measured.

Results and Discussion

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 interstitial 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.

In order to investigate acceptor densities and hole-trap density with $p(T)$, FCCS 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]

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

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, and k is the Boltzmann constant. From each peak, the density and energy level of the corresponding acceptor or hole trap can be determined accurately.

On the other hand, $H(T, E_{\mathrm{ref}})$ is theoretically expressed as [13,14]

$$H(T, E_{\mathrm{ref}}) = \sum_i \frac{N_{\mathrm{A}i}}{kT} \exp\left(-\frac{\Delta E_{\mathrm{A}i} - E_{\mathrm{ref}}}{kT}\right) I(\Delta E_{\mathrm{A}i}) - \frac{N_{\mathrm{comp}} N_{\mathrm{V0}}}{kT} \exp\left(\frac{E_{\mathrm{ref}} - \Delta E_{\mathrm{F}}}{kT}\right) \tag{2}$$

and

$$I(\Delta E_{\mathrm{A}i}) = \frac{N_{\mathrm{V0}}}{g_{\mathrm{A}} + \exp\left(\dfrac{\Delta E_{\mathrm{F}} - \Delta E_{\mathrm{A}i}}{kT}\right)}, \tag{3}$$

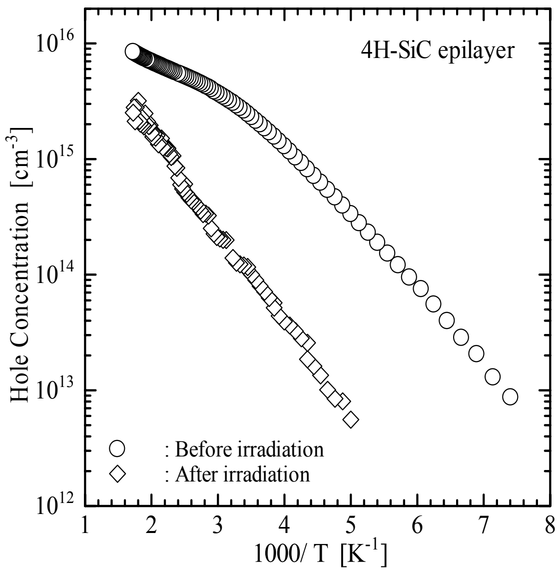

Fig. 1 Temperature dependent hole concentration.

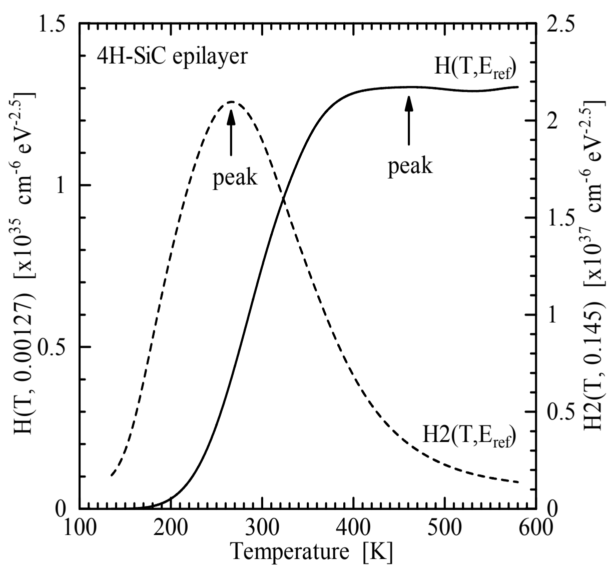

Fig. 2 FCCS signals.

where N_{Ai} and ΔE_{Ai} are the density and energy level of the i th acceptor or hole trap, N_{comp} is the compensating density, ΔE_F is the Fermi level, g_A is the degeneracy factor for acceptors or hole traps, $N_{V0} = 2(2\pi m_h^* / h^2)^{3/2}$, m_h^* is the hole effective mass, and h is Planck's constant. Here, all energy levels are measured from the valence band maximum.

The solid line in Fig. 2 represents the FCCS signal with E_{ref} =1.27×10^{-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}) are determined as 4.2×10^{15} cm^{-3} and 365 meV.

The FCCS signal of $H2(T, E_{ref})$, in which the influence of ΔE_{A2} is removed [14], is calculated using

$$H2(T, E_{ref}) = \frac{p(T)^2}{(kT)^{5/2}} \exp\left(\frac{E_{ref}}{kT}\right) - \frac{N_{A2}}{kT} \exp\left(-\frac{\Delta E_{A2} - E_{ref}}{kT}\right) I(\Delta E_{A2}), \quad (4)$$

and is denoted by the broken line in Fig. 2. Here, E_{ref} =0.145 eV. From this peak at 266.7 K, the corresponding density (N_{A1}) and energy level (ΔE_{A1}), and 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 1. The value of N_{A1} is clearly reduced by electron irradiation, while N_{A2} appears unchanged.

To verify the values obtained by FCCS, the $p(T)$ is simulated with the values shown in Table 1. The open circles and diamonds in Fig. 3 represent the experimental $p(T)$ for the unirradiated and irradiated samples, and the solid and broke 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 measurements [15] and Hall-effect measurements [16], the energy level of ~200 meV is ascribed to Al acceptors in 4H-SiC. Moreover, N_{A1} is close to the Al-doping density, suggesting that the origin of ΔE_{A1} is the Al acceptor. Although the possible origin of ΔE_{A2} is B with which 4H-SiC is sometimes contaminated, on the other hand, the concentration of B in this epilayer, which was determined by secondary ion mass spectroscopy, was <4×10^{14} cm^{-3}, and ΔE_A of B was reported to be 285 meV [16]. Therefore, the origin of ΔE_{A2} is unfortunately unknown.

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

Table 1 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}

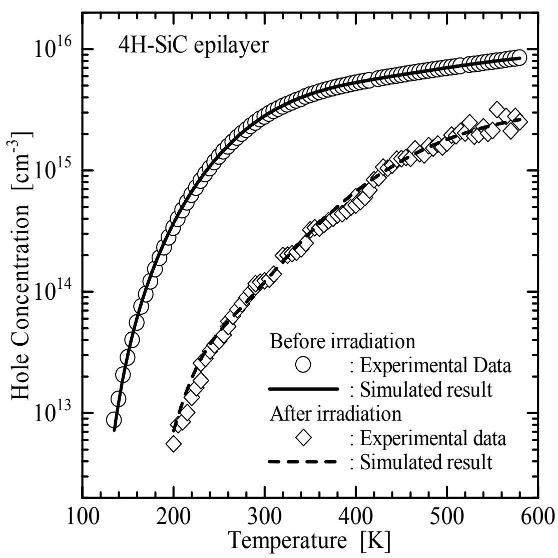

Fig. 3 Comparison between experimental and simulated $p(T)$.

B-doped Si was reduced by 10-MeV proton irradiation because of the decrease in the B acceptor density in Si [5].

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.

Summary

The effect of electron irradiation on Al-doped 4H-SiC epilayers was investigated with Hall-effect measurements. The hole concentration in the p-type 4H-SiC epilayer was reduced by 4.6-MeV electron irradiation, and using 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 main reduction in $p(T)$ by irradiation resulted from the decrease of Al acceptor, not from the creation of hole traps or donor-like defects.

References

[1] A.L. Barry, B. Lehman, D. Fritsch and D. Bräuning: IEEE Trans. Nucl. Sci. Vol. 38 (1991), p. 1111.

[2] S.M. Sze: *Physics of Semiconductor Devices* (Wiley, New York, 1981) 2nd.

[3] T. Hisamatsu, O. Kawasaki, S. Masuda, T. Nakao and Y. Wakow: Solar Energy Mater. Solar Cells Vol. 50 (1998), p. 331.

[4] H. Matsuura, Y. Uchida, T. Hisamatsu and S. Matsuda: Jpn. J. Appl. Phys. Vol. 37 (1998), p. 6034.

[5] H. Matsuura, Y. Uchida, N. Nagai, T. Hisamatsu, T. Aburaya and S. Matsuda: Appl. Phys. Lett. Vol. 76 (2000), p. 2092.

[6] H.J. von Bardeleben and J.L. Cantin: Mater. Sci. Forum Vol. 353-356 (2001), p. 513.

[7] H.J. von Bardeleben, J.L. Cantin, P. Baranov and E.N. Mokhov: Mater. Sci. Forum Vol. 353-356 (2001), p. 509.

[8] Th. Lingner, S. Greulich-Weber and J.-M. Speath: Mater. Sci. Forum Vol. 353-356 (2001), p. 505.

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

[10] V.Ya. Bratus, I.N. Makeeva, S.M. Okulov, T.L. Petrenko, T.T. Petrenko and H.J. von Bardeleben: Mater. Sci. Forum Vol. 353-356 (2001), p. 517.

[11] A.A. Rempel, K. Blaurock, K.J. Reichle, W. Sprengel and H.-E. Schaefer: Mater. Sci. Forum Vol. 389-393 (2002), p. 485.

[12] H. Matsuura and K. Sonoi: Jpn. J. Appl. Phys. Vol. 35 (1996), p. L555.

[13] H. Matsuura, Y. Masuda, Yi Chen and S. Nishino: Jpn. J. Appl. Phys. Vol. 39 (2000), p. 5069.

[14] H. Matsuura, K. Morita, K. Nishikawa, T. Mizukoshi, M. Segawa and W Susaki: Jpn. J. Appl. Phys. Vol. 41 (2002), p. 496.

[15] M. Ikeda, H. Matsunami and T. Tanaka: Phys. Rev. B Vol. 22 (1980), p. 2842.

[16] T. Troffer, M. Schadt, T. Frank, H. Itho, G. Pensl, J. Heindl, H.P. Strunk and M. Maier: Phys. Status Solidi A Vol. 162 (1997), p. 277.