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Reduction in Majority-Carrier Concentration in Lightly-Doped 4H-SiC Epilayers by Electron Irradiation

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Abstract. The mechanisms for the reduction in the hole concentration in lightly Al-doped p-type 4H-SiC epilayers by electron irradiation as well as in the electron concentration in lightly N-doped n-type 4H-SiC epilayers by electron irradiation are investigated. In the p-type 4H-SiC epilayers, the temperature dependence of the hole concentration, $p(T)$, is not changed by 100 keV electron irradiation, while the $p(T)$ is decreased by 150 keV electron irradiation. The density of Al acceptors with energy level $E_\mathrm{V}+0.22$ eV decreases with increasing fluence of 150 keV electrons, whereas the density of deep acceptors with energy level $E_\mathrm{V}+0.38$ eV increases. In the n-type 4H-SiC epilayers, the temperature dependence of the electron concentration, $n(T)$, is decreased by 200 keV electron irradiation. The density of N donors located at hexagonal C-sublattice sites decreases significantly with increasing fluence of 200 keV electrons, whereas the density of N donors located at cubic C-sublattice site decreases slightly.

Introduction

By comparing electron-radiation damage in p-type 4H-SiC with that in p-type Si [1,2], it was found that the reduction in the temperature-dependent hole concentration, $p(T)$, in Al-doped p-type 4H-SiC by electron irradiation was much larger than in Al-doped p-type Si. In Al-doped p-type 4H-SiC epilayers, the density of Al acceptors with energy level $E_\mathrm{V}+0.22$ eV (N_Al) decreased significantly with increasing fluence (Φ) of 200 keV electrons, whereas the density of deep acceptors with energy level $E_\mathrm{V}+0.38$ eV (N_DA) initially increased with Φ and then decreased [2]. Here, E_V is the maximum energy of the valence band. From these experimental results, the following differential equations describing the fluence dependence of N_Al and N_DA have been proposed [2].

$$\frac{\mathrm{d}N_\mathrm{Al}}{\mathrm{d}\Phi}=-\kappa_\mathrm{Al200}N_\mathrm{Al} \tag{1}$$

and

$$\frac{\mathrm{d}N_\mathrm{DA}}{\mathrm{d}\Phi}=-\frac{\mathrm{d}N_\mathrm{Al}}{\mathrm{d}\Phi}-\kappa_\mathrm{DA200}N_\mathrm{DA}\ , \tag{2}$$

where κ_Al200 and κ_DA200 are the removal cross sections for 200 keV electron irradiation of the Al acceptor and the deep acceptor, respectively. By fitting the curve to the experimental data, κ_Al200 and κ_DA200 were determined to be 4.4×10^{-17} and 1.0×10^{-17} cm^2 [2].

In unirradiated epilayers, on the other hand, the relationship of $N_\mathrm{DA}=0.6N_\mathrm{Al}$ was obtained for $8\times10^{14}<N_\mathrm{Al}<5\times10^{16}$ cm^{-3} [3], suggesting that the deep acceptors may be related to Al. Furthermore, we investigated the mechanisms for the changes of $p(T)$ in Al-doped 6H-SiC by electron irradiation and annealing [4].

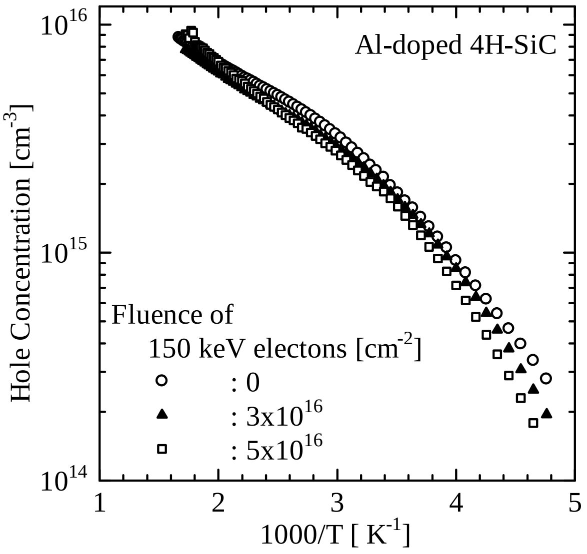

Fig. 1 Temperature dependence of hole concentration in Al-doped 4H-SiC before and after 150 keV electron irradiation.

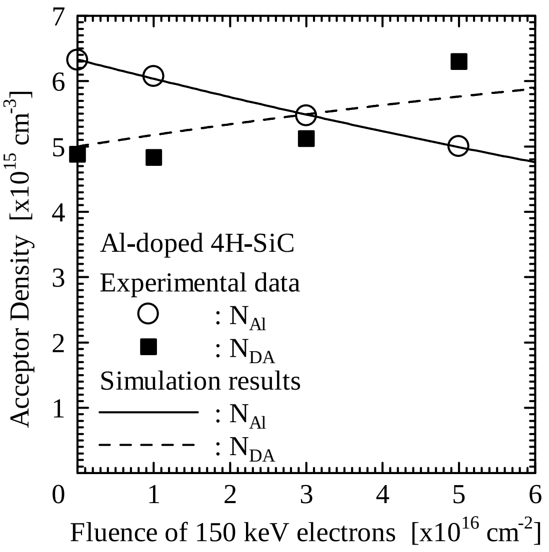

Fig. 2 Fluence dependence of densities of Al acceptor and deep acceptor.

In this study, we have investigated the change of $p(T)$ in lightly Al-doped 4H-SiC epilayers by 100 or 150 keV electron irradiation. Moreover, we have studied the decrease in the temperature-dependent electron concentration, $n(T)$, in lightly N-doped n-type 4H-SiC epilayers by 200 keV electron irradiation.

Experimental

A 10 μm-thick Al-doped p-type 4H-SiC epilayer on n$^+$-type 4H-SiC was cut to a size of 1×1 cm^2, while a 10 μm-thick N-doped n-type 4H-SiC epilayer on p$^+$-type 4H-SiC was cut to a size of 3×3 mm^2. The $p(T)$ or $n(T)$ was measured in a van der Pauw arrangement in a magnetic field of 1.4 T using a modified MMR Technologies' Hall system. At room temperature, the p-type sample was irradiated by 100 or 150 keV electrons, and the n-type sample was irradiated by 200 keV electrons.

The densities and energy levels of acceptors or donors were determined from $p(T)$ or $n(T)$ by a graphical peak analysis method called free carrier concentration spectroscopy (FCCS) [1-3], whose signal has a peak at the temperature corresponding to each acceptor or donor level. From each peak, the density and energy level of the corresponding acceptor or donor can be accurately determined. Software for FCCS (for the Windows operating system) can be downloaded for free at our web-site (http://www.osakac.ac.jp/labs/matsuura/).

Results and Discussion

In the Al-doped p-type SiC epilayer, the $p(T)$ was not changed by 100 keV electron irradiation at fluences less than 7×10^{16} cm^{-2}, indicating that C atoms located at substitutional sites cannot be replaced by 100 keV electron irradiation. From the analyses of $p(T)$, it was found that both of N_{Al} and N_{DA} were unchanged by the irradiation.

The $p(T)$, on the other hand, was decreased by 150 keV electron irradiation. Figure 1 shows the $p(T)$ before irradiation (○) and after irradiation with 150 keV electrons at $\Phi = 3\times10^{16}$ cm^{-2} (▲) and $\Phi = 5\times10^{16}$ cm^{-2} (□).

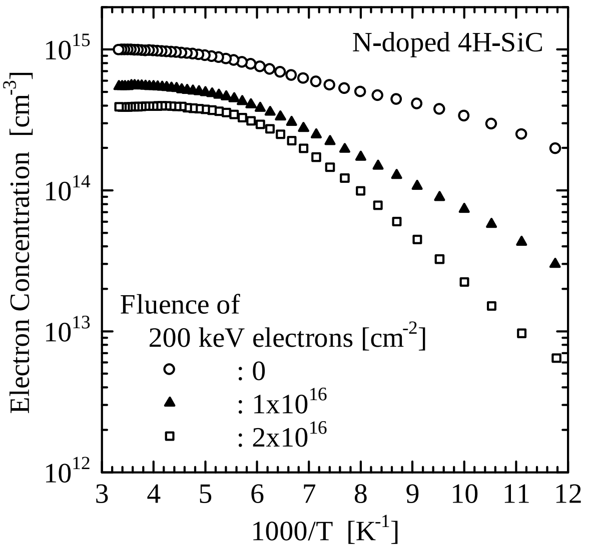

Fig. 3 Temperature dependence of electron concentration in N-doped 4H-SiC before and after 200 keV electron irradiation.

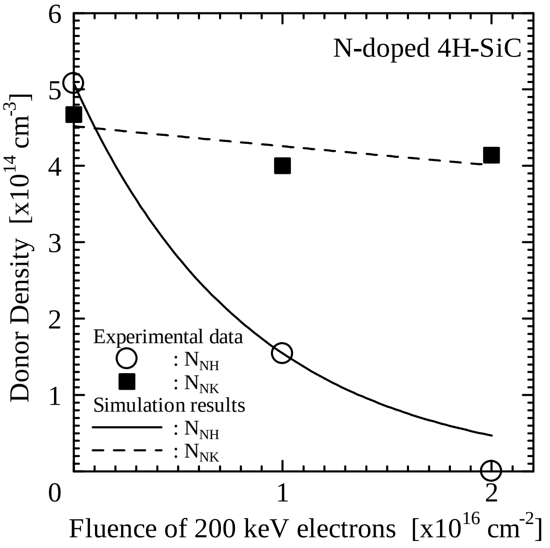

Fig. 4 Fluence dependence of densities of N donors at hexagonal and cubic C-sublattice sites.

From each $p(T)$, two types of acceptor species were detected and evaluated using FCCS. The fluence dependence of N_{Al} (○) and N_{DA} (■) are shown in Fig. 2. The N_{Al} decreased with increasing Φ of 150 keV electrons, from which the removal cross section (κ_{Al150}) for 150 keV electron irradiation of the Al acceptor was determined to be 4.8×10^{-18} cm^2, using an equation similar to Eq. 1. The solid curve in Fig. 2 represents the simulated fluence-dependent N_{Al}, which is in good agreement with the experimental results shown by ○.

The N_{DA}, on the other hand, increased experimentally with increasing Φ. The broken curve in Fig. 2 represents the fluence-dependent N_{DA} simulated with $\kappa_{\mathrm{DA150}} = 1\times10^{-18}$ cm^2 using an equation similar to Eq. 2, which coincides qualitatively with the experimental fluence dependence of N_{DA} by 150 keV electron irradiation denoted by ■.

The values of κ_{Al150} and κ_{DA150} are lower by one order than those of κ_{Al200} and κ_{DA200}. Judging from incident electron energies, the findings are quite reasonable.

Figure 3 shows the experimental $n(T)$ before irradiation (○) and after irradiation with 200 keV electrons at $\Phi = 1\times10^{16}$ cm^{-2} (▲) and $\Phi = 2\times10^{16}$ cm^{-2} (□). The $n(T)$ in N-doped n-type 4H-SiC was decreased by the electron irradiation at the whole temperature range of the measurements, which is quite different from the case of Al-doped p-type 4H-SiC in which the $p(T)$ was decreased only at low temperatures by 200 keV electron irradiation [2].

From each $n(T)$, two types of donor species were detected and evaluated using FCCS. The two energy levels detected here correspond to the energy levels of the isolated, substitutional N donors at hexagonal and cubic C-sublattice sites [5,6]. The energy level of N donors at hexagonal C-sublattice sites (E_{NH}) was $E_{\mathrm{C}} - 70$ meV, where E_{C} is the conduction band minimum. The energy level of N donors at cubic C-sublattice sites (E_{NK}) was $E_{\mathrm{C}} - 120$ meV. The densities of N donors at hexagonal and cubic C-sublattice sites (N_{NH} and N_{NK}) were 5.1×10^{14} and 4.7×10^{14} cm^{-3}, respectively. Consequently, N_{NH} is nearly equal to N_{NK}, which coincides with the expectation that N atoms equally occupy hexagonal and cubic C-sublattice sites because the number of hexagonal sites is equal to the number of cubic sites in 4H-SiC.

Figure 4 shows the fluence dependence of N_{NH} (○) and N_{NK} (■). The N_{NH} decreased substantially with increasing Φ of 200 keV electrons, whereas N_{NK} decreased only slightly, indicating that N donors at hexagonal C-sublattice sites are less radiation-resistant than N donors at cubic C-sublattice sites. This finding suggests that 3C-SiC might be the most and 6H-SiC should be the least radiation-resistant of N-doped 3C-SiC, 4H-SiC, and 6H-SiC. By irradiation with $\Phi = 2\times10^{16}\ \text{cm}^{-2}$, the compensating density was increased by $1\times10^{13}\ \text{cm}^{-3}$, which is much less than the decrement of N-donor densities.

By analogy with Eq. 1, the fluence dependence of N_{NH} and N_{NK} are expected to be derived from the following differential equations:

$$\frac{\mathrm{d}N_{\text{NH}}}{\mathrm{d}\Phi} = -\kappa_{\text{NH}200} N_{\text{NH}} \tag{3}$$

and

$$\frac{\mathrm{d}N_{\text{NK}}}{\mathrm{d}\Phi} = -\kappa_{\text{NK}200} N_{\text{NK}}\ , \tag{4}$$

where $\kappa_{\text{NH}200}$ and $\kappa_{\text{NK}200}$ are the removal cross sections for 200 keV electron irradiation of the N donors at hexagonal and cubic C-sublattice sites, respectively. By fitting the curve to the experimental data, the values of $\kappa_{\text{NH}200}$ and $\kappa_{\text{NK}200}$ were determined to be 1.2×10^{-16} and $6.0\times10^{-18}\ \text{cm}^2$, respectively. The solid and broken curves in Fig. 4 represent the simulated fluence dependence of N_{NH} and N_{NK}, respectively.

Summary

We have investigated the changes of the hole concentration in lightly Al-doped p-type 4H-SiC epilayers by 100 or 150 keV electron irradiation as well as the changes of the electron concentration in lightly N-doped n-type 4H-SiC epilayers by 200 keV electron irradiation.

The $p(T)$ was not changed by 100 keV electron irradiation, while the $p(T)$ was decreased by 150 keV electron irradiation, indicating that 100 keV electrons could not replace the substitutional C atoms while 150 keV electrons could. The density of Al acceptors with energy level $E_{\text{V}} + 0.22$ eV decreased with increasing fluence of 150 keV electrons, and the density of deep acceptors with energy level $E_{\text{V}} + 0.38$ eV increased. This suggests that 150 keV electron irradiation can convert the Al acceptor into the deep acceptor.

The $n(T)$ is decreased by 200 keV electron irradiation. From the analyses of $n(T)$, the density of N donors located at hexagonal C-sublattice sites decreased significantly with increasing fluence of 200 keV electrons, whereas the density of N donors located at cubic C-sublattice site decreased slightly.

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