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Mechanisms of Reduction in Hole Concentration in Al-Implanted p-Type 6H-SiC by 1 MeV Electron Irradiation

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The reduction in temperature-dependent hole concentration $p(T)$ in Al-implanted p-type 6H-SiC by 1 MeV electron irradiation is investigated. By analysis of $p(T)$, the density (N_A), level position (E_A) in the bandgap and nature of the acceptor are determined, and this acceptor is assigned to an Al acceptor. E_A is independent of irradiation fluence (Φ), while N_A is strongly dependent on Φ. We derived an analytical expression for the fluence dependence of N_A and we estimated the removal coefficient (i.e., removal cross-section) of N_A to be 6.4×10^{-18} cm^2 for 1 MeV electron irradiation. The reduction in $p(T)$ by electron irradiation is found to be mainly due to the decrease in N_A, not to the increase in the density of deep-level defects in the bandgap, because the decrement in N_A is much larger than the increment in the density of deep-level defects.
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KEYWORDS: 6H-SiC, Al-doped SiC, p-type SiC, electron irradiation, reduction in hole concentration, radiation damage, decrease in acceptors, displacement damage

1. 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 was reported to be lower than that in GaAs by more than three orders of magnitude, and lower than that in Si by at least one order 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 Si used in high-power devices.[2]) On the other hand, it degrades the conversion efficiency of Si solar cells used in space.[3–6]) As a result, electron-radiation damage in Si has been intensively investigated. However, the understanding of radiation damage in SiC is far from complete.

The density and energy level of traps have usually been evaluated by deep level transient spectroscopy (DLTS). By DLTS, however, the quantitative relationship between hole concentration and trap density is not obtained. This is because DLTS can be applicable to the characterization of deep-level traps only when the density of the traps is lower by at least one order of magnitude than a dopant density (i.e., donor or acceptor density).[6–8])

If the density and energy level of traps can be determined using the temperature-dependent hole concentration $p(T)$, the relationship between $p(T)$ and trap density can be directly investigated. As for the analysis of $p(T)$, a graphical peak analysis method (FCCS: free carrier concentration spectroscopy) has been proposed and tested, by which the densities and energy levels of acceptors and hole traps can be estimated from the experimental $p(T)$ without any assumptions regarding acceptor species and hole traps.[9–13])

By comparing the radiation damage in 4H-SiC with that in Si,[6,14,15]) it was found that the reduction in $p(T)$ in Al-doped p-type 4H-SiC by electron irradiation was much larger than that in p-type Si. Since the large reduction in $p(T)$ in Al-doped 4H-SiC by electron irradiation was an unexpected result, the decrease in $p(T)$ by irradiation with different electron energies was investigated.[14–16]) Since 6H-SiC is expected to be a suitable polytype for electronic devices used in high-energy radiation environments, we report on the reduction in $p(T)$ in Al-implanted p-type 6H-SiC by 1 MeV electron irradiation.

2. Experimental Procedure

In order to form a p-type 6H-SiC layer, Al ions were implanted at 800 °C in a 4.9-μm-thick n-type 6H-SiC epilayer with a N-doping level of 6.7×10^{15} cm^{-3} on an n$^+$-type 6H-SiC substrate. To obtain a 0.5-μm-thick box profile of Al concentration, fivefold Al ion implantation was carried out using 20, 50, 110, 200, and 340 keV onto the n-type SiC epilayer surface. After the implantation, the samples of 5×5 mm^2 size were annealed at 1700 °C for 30 min in an Ar atmosphere. Ohmic metal (Al/Ti) was deposited on four corners of the surface of the sample, and the samples were annealed at 900 °C for 1 min in an Ar atmosphere to form good ohmic contacts. Before irradiation, hole concentration at 300 K was measured in the van der Pauw configuration. We left one sample unirradiated, labeled A1, while three samples were irradiated with 1 MeV electrons at fluences of 1×10^{16}, 5×10^{16}, and 1×10^{17} cm^{-2}, which are referred to as A2, A3, and A4, respectively. After the irradiation, $p(T)$ was measured in the temperature range from 210 to 720 K and at a magnetic field of 1.4 T using a modified MMR Technologies' Hall system.

3. Results and Discussion

Table I shows the hole concentrations at 300 K before and after irradiation, denoted by $p_0(300)$ and $p(300)$, respectively. Since $p_0(300)$ is slightly different among the samples, the ratios of $p_0(300)$ to $p(300)$ are also listed in Table I. The hole concentration is expected to be reduced by the increase in the density of deep-level defects and the decrease in the density of acceptors. Therefore, we evaluated these densities in order to determine the main cause of the reduction in $p(T)$.

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Table I. Hole concentrations at 300 K before and after 1 MeV electron irradiation.

Sample	Before irradiation	After irradiation		
	$p_0(300)$ ($\mathrm{cm^{-3}}$)	Fluence ($\times 10^{16}\,\mathrm{cm^{-2}}$)	$p(300)$ ($\mathrm{cm^{-3}}$)	$p(300)/p_0(300)$
A1	9.98×10^{16}	0	—	1.000
A2	8.06×10^{16}	1	7.17×10^{16}	0.889
A3	6.19×10^{16}	5	3.38×10^{16}	0.546
A4	1.00×10^{17}	10	4.58×10^{16}	0.458

Table II. Results obtained by FCCS.

Sample	Fluence ($\times 10^{16}\,\mathrm{cm^{-2}}$)	N_A ($\mathrm{cm^{-3}}$)	E_A (eV)	N_{comp} ($\mathrm{cm^{-3}}$)	N_A^{*} a) ($\mathrm{cm^{-3}}$)
A1	0	3.14×10^{19}	$E_V + 0.222$	1.88×10^{17}	3.14×10^{19}
A2	1	2.38×10^{19}	$E_V + 0.220$	3.72×10^{17}	2.95×10^{19}
A3	5	1.44×10^{19}	$E_V + 0.235$	2.40×10^{17}	2.32×10^{19}
A4	10	1.65×10^{19}	$E_V + 0.225$	3.88×10^{17}	1.65×10^{19}

a) $N_A^{*} = N_A \times [9.98 \times 10^{16}/p_0(300)]$

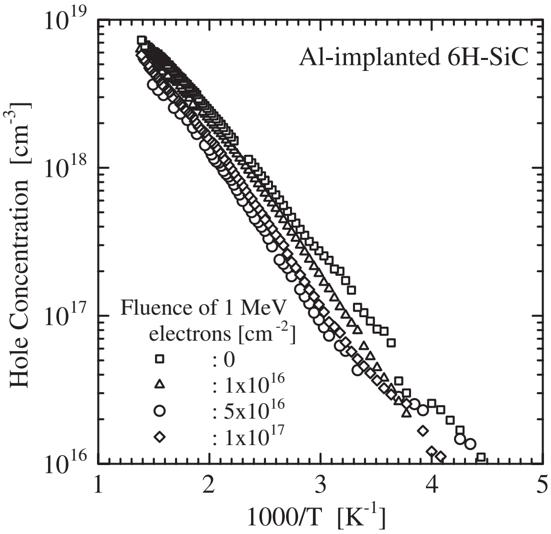

Fig. 1. Temperature dependence of hole concentration for Al-implanted 6H-SiC unirradiated or irradiated by 1 MeV electrons at three fluences.

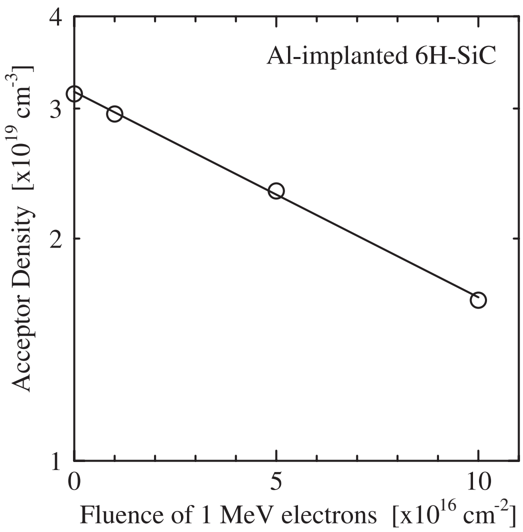

Fig. 2. Fluence dependence of corrected acceptor density.

Figure 1 shows $p(T)$ for the unirradiated and irradiated p-type 6H-SiC. Using each $p(T)$ in Fig. 1, the density (N_A) and energy level (E_A) of acceptors, and a compensating density (N_{comp}) were determined by FCCS, and are listed in Table II, where N_{comp} represents the sum of donor densities and deep-level hole-trap densities. In the analysis of $p(T)$, the excited states of acceptors were considered because the Al-doping level was high in these implanted layers.[17–20] E_A is independent of fluence, and is approximately $E_V + 0.22$ eV, indicating that the acceptor is an Al acceptor,[21,22] where E_V is the valence-band maximum.

Because $p_0(300)$ was slightly different among the samples, N_A before irradiation should be different, indicating that the acceptor density for the irradiated samples should be corrected as follows.

$$N_A^{*} = N_A \times \frac{9.98 \times 10^{16}}{p_0(300)}, \tag{1}$$

where N_A^{*} is the corrected acceptor density. The results are also listed in Table II, and are denoted by circles in Fig. 2.

The density of Al acceptors is decreased by the displacement of Al atoms or their nearest neighbor C atoms because only the Al atom bonding to four C atoms works as an Al acceptor. Since the number of collisions between incident electrons and those atoms in unit volume is proportional to N_A^{*}, the following differential equation describing the fluence dependence of the acceptor density $N_A(\Phi)$ is obtained:

$$\frac{dN_A(\Phi)}{d\Phi} = -\kappa_A N_A(\Phi), \tag{2}$$

where κ_A is the removal coefficient (or removal cross-section) of Al acceptors for 1 MeV electron irradiation and Φ is the fluence of 1 MeV electrons. Therefore,

$$N_A(\Phi) = N_A(0)\exp(-\kappa_A \Phi). \tag{3}$$

In Fig. 2, the solid line is the fit obtained by the least-square method. Because the experimental data agree quite well with the theoretical model, κ_A is determined as $6.4 \times 10^{-18}\,\mathrm{cm^2}$ from the slope.

As shown in Table II, the values of N_{comp} are of the order of $10^{17}\,\mathrm{cm^{-3}}$, which are much lower than N_A. This indicates that the reduction in $p(T)$ by the irradiation is mainly due to the decrease in N_A, not to the increase in the density of deep-level defects. Furthermore, the surroundings of Al acceptors are considered to be more easily changed by irradiation than the surroundings of the SiC matrix.

4. Conclusions

We investigated $p(T)$ in Al-implanted p-type 6H-SiC before and after 1 MeV electron irradiation as a function of the fluence. Using $p(T)$, the acceptor density and level position in the bandgap were determined by FCCS. As determined from the acceptor level, this acceptor species was assigned to Al. The reduction in $p(T)$ by electron irradiation was mainly due to the decrease in the density of Al acceptors, not to the increase in the density of deep-level defects. Therefore, the surroundings of Al acceptors were changed by electron irradiation more easily than the surroundings of the SiC matrix.

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