Open Access

Reduction of Electron Concentration in Lightly N-Doped n-Type 4H-SiC Epilayers by 200 keV Electron Irradiation

Hideharu Matsuura[1,*], Hideki Yanagisawa[1], Kozo Nishino[1], Takunori Nojiri[1], Yoshiko Myojin[1], Yukei Matsuyama[1], Shinobu Onoda[2] and Takeshi Ohshima[2]

[1]Osaka Electro-Communication University, 18-8 Hatsu-cho, Neyagawa, Osaka 572-8530, Japan; [2]Japan Atomic Energy Agency, 1233 Watanuki, Takasaki, Gunma 370-1292, Japan

Abstract: The mechanism of the reduction in the electron concentration in lightly N-doped n-type 4H-SiC epilayers by 200 keV electron irradiation is investigated. From the temperature dependence of the electron concentration, $n(T)$, in the epilayer before and after irradiation with fluences (Φ) of 1×10^{16} and 2×10^{16} cm^{-2}, the densities and energy levels of donors and the compensating density are determined by a graphical peak analysis method. In the non-irradiated case, the density of N donors located at hexagonal C-sublattice sites ($N_{\rm NH}$) is 5.1×10^{14} cm^{-3}, and the density of N donors located at cubic C-sublattice sites ($N_{\rm NK}$) is 4.7×10^{14} cm^{-3}. $N_{\rm NH}$ decreases with increasing Φ, and it becomes less than 10^{14} cm^{-3} at $\Phi = 2\times10^{16}$ cm^{-2}, whereas $N_{\rm NK}$ decreases slightly to 4.1×10^{14} cm^{-3} at $\Phi = 2\times10^{16}$ cm^{-2}. This suggests that N donors at hexagonal C-sublattice sites are less radiation-resistant than N donors at cubic C-sublattice sites.

PACS: 71.55.Ht, 72.20.Jv.

Keywords: Electron irradiation, n-type 4H-SiC, reduction of electron concentration, reduction of donor density.

1. INTRODUCTION

SiC is a promising wide band gap semiconductor for fabricating high-power and high-frequency electronic devices capable of operating at elevated temperatures in an irradiated environment.

By comparing electron-radiation damage in p-type 4H-SiC with that in p-type Si [1-4], it was found that the reduction in the temperature-dependent hole concentration, $p(T)$, was much larger in Al-doped p-type 4H-SiC than in Al-doped p-type Si. In the analysis of lightly Al-doped p-type 4H-SiC epilayers, the density of Al acceptors with energy level $E_{\rm V}+0.22$ eV ($N_{\rm Al}$) decreased significantly with increasing total fluence (Φ) of 200 keV electrons, whereas the density of deep acceptors with energy level $E_{\rm V}+0.38$ eV ($N_{\rm DA}$) initially increased with Φ and then decreased [4, 5]. ($E_{\rm V}$ is the maximum energy of the valence band.) The 200 keV electrons can only displace substitutional C (C$_{\rm s}$) and cannot displace substitutional Si or Al in Al-doped SiC [3, 5-7]. The reduction in $p(T)$ by 200 keV electron irradiation was mainly due to the decrease in Al acceptors and not due to the increase in C vacancies (V$_{\rm C}$) created by irradiation [4, 5]. In non-irradiated epilayers, on the other hand, the relationship of $N_{\rm DA} = 0.6N_{\rm Al}$ was obtained for $8\times10^{14} \le N_{\rm Al} \le 5\times10^{16}$ cm^{-3} [3, 8], suggesting that the deep acceptors may be related to Al. From these experimental results, the following differential equations describing the fluence dependence of $N_{\rm Al}$ and $N_{\rm DA}$ were proposed [5].

$$\frac{{\rm d}N_{\rm Al}}{{\rm d}\Phi} = -\kappa_{\rm Al}N_{\rm Al} \quad (1)$$

and

$$\frac{{\rm d}N_{\rm DA}}{{\rm d}\Phi} = -\frac{{\rm d}N_{\rm Al}}{{\rm d}\Phi} - \kappa_{\rm DA}N_{\rm DA}, \quad (2)$$

where $\kappa_{\rm Al}$ and $\kappa_{\rm DA}$ 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 Φ dependence of $N_{\rm Al}$ or $N_{\rm DA}$, the values $\kappa_{\rm Al} = 4.4\times10^{-17}$ cm^2 and $\kappa_{\rm DA} = 1.0\times10^{-17}$ cm^2 were determined [5].

Lightly doped n-type epilayers also play an important role in the performance of power electronics semiconductor devices; for example, in order to operate a SiC power metal-oxide-semiconductor field-effect transistor (MOSFET) in a harsh radiation environment, high radiation-resistance of lightly doped n-type SiC is required. In this letter, we report on the influence of 200 keV electron irradiation on the temperature dependence of the electron concentration, $n(T)$, in lightly N-doped n-type 4H-SiC epilayers.

---

*Address correspondence to this author at the Osaka Electro-Communication University, 18-8 Hatsu-cho, Neyagawa, Osaka 572-8530, Japan; Tel: +81-72-820-9031; Fax: +81-72-820-9031;
E-mail: matsuura@isc.osakac.ac.jp

1874-1835/11 2011 Bentham Open

2. EXPERIMENTAL

A 10-μm-thick N-doped n-type 4H-SiC epilayer on p$^+$-type 4H-SiC was cut to a size of 3 mm × 3 mm. A 100-nm-thick Ohmic metal (Ni) was deposited on the four corners of the surface of the sample, and the sample was then annealed at 1000 ºC in an Ar atmosphere. $n(T)$ and the temperature-dependent electron mobility, $\mu_e(T)$, for the non-irradiated sample were obtained by Hall-effect measurements in a van der Pauw configuration. Measurements were taken over a temperature range of 85 to 300 K and in a magnetic field of 1.4 T by using a modified Hall system (MMR Technologies). Next, the sample was irradiated with 200 keV electrons with fluence of 1×10^{16} cm^{-2}, and the Hall-effect measurement was repeated. The sample was irradiated again and a third Hall-effect measurement was carried out. Consequently, $n(T)$ and $\mu_e(T)$ for samples irradiated with total fluences of 0, 1×10^{16}, and 2×10^{16} cm^{-2} were obtained. The Hall-effect measurements were carried out twice at each fluence and $n(T)$ remained unchanged, indicating that any defects affecting $n(T)$ were not annealed at temperatures up to 300 K. As judged from the magnitude of $\mu_e(T)$, band conduction of electrons was dominant in these samples within the temperature range of the measurements.

The densities and energy levels of donor species were determined from $n(T)$ by a graphical peak analysis method called free carrier concentration spectroscopy (FCCS) [9-11]. By using the experimental $n(T)$, the FCCS signal is defined to be [9-11]

$$H(T,E_{\mathrm{ref}}) \equiv \frac{n(T)^2}{(kT)^{5/2}}\exp\left(\frac{E_{\mathrm{ref}}}{kT}\right), \qquad (3)$$

where k is the Boltzmann constant and E_{ref} is a parameter that shifts the peak temperature of the FCCS signal within the temperature range of the measurement. The FCCS signal has a peak at the temperature corresponding to each donor level. From each peak, the density and energy level of the corresponding 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/).

3. RESULTS AND DISCUSSION

Fig. (**1**) 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} (□). From each experimental $n(T)$ shown in Fig. (**1**), two types of donor species were detected by FCCS, and the density of donors and the compensating density (N_{comp}) were determined. Judging from the accuracy of Hall-effect measurement and FCCS analysis, the density values have two significant figures, and values larger than 10^{13} cm^{-3} are accurate. N_{comp} is the density of electron traps deeper than the N-donor levels plus the density of acceptors.

The two energy levels detected here correspond to the energy levels of the isolated, substitutional N donors at hexagonal and cubic C-sublattice sites [12-15]. The energy level of N donors at hexagonal C-sublattice sites was $E_{\mathrm{NH}} = E_{\mathrm{C}} - 70$ meV, where E_{C} is the conduction band minimum. The energy level of N donors at cubic C-sublattice sites was $E_{\mathrm{NK}} = E_{\mathrm{C}} - 120$ meV.

The corresponding densities were $N_{\mathrm{NH}} = 5.1\times10^{14}$ and $N_{\mathrm{NK}} = 4.7\times10^{14}$ cm^{-3}. $N_{\mathrm{NH}} \approx N_{\mathrm{NK}}$, 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.

The electron concentration was simulated numerically by using the following equations:

$$n(T) + N_{\mathrm{comp}} = N_{\mathrm{NH}}\left[1 - f_{\mathrm{FD}}(E_{\mathrm{NH}})\right] + N_{\mathrm{NK}}\left[1 - f_{\mathrm{FD}}(E_{\mathrm{NK}})\right] \qquad (4)$$

and

$$n(T) = N_{\mathrm{C}}(T)\exp\left(-\frac{E_{\mathrm{C}} - E_{\mathrm{F}}(T)}{kT}\right), \qquad (5)$$

where $f_{\mathrm{FD}}(E)$ is the Fermi-Dirac distribution function, given by

$$f_{\mathrm{FD}}(E) = \frac{1}{1 + \frac{1}{2}\exp\left(\frac{E - E_{\mathrm{F}}(T)}{kT}\right)}, \qquad (6)$$

and $N_{\mathrm{C}}(T)$ is the effective density of states in the conduction band, which is given by

$$N_{\mathrm{C}}(T) = 2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2} M_{\mathrm{C}}. \qquad (7)$$

Further, $E_{\mathrm{F}}(T)$ is the Fermi level at T, m_e^* is the electron effective mass, M_{C} is the number of equivalent minima in the conduction band, and h is Planck's constant. Each solid line in Fig. (**1**) is the result of an $n(T)$ simulation using the values of N_{NH}, E_{NH}, N_{NK}, E_{NK}, and N_{comp} for the corresponding Φ. The simulations are in good agreement with the corresponding experimental results.

Fig. (**2**) shows the fluence dependence of N_{NH} and N_{NK}, denoted by ○ and □, respectively. N_{NH} decreased substantially with increasing Φ, 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 should be the most radiation-resistant and 6H-SiC should be the least radiation-resistant of N-doped 3C-SiC, 4H-SiC, and 6H-SiC.

Let us now consider other mechanism of the reduction in $n(T)$ by 200 keV electron irradiation. 200 keV electron irradiation can only displace $\mathrm{C_S}$ in SiC [7, 16, 17]. Therefore, $\mathrm{V_C}$ and an interstitial C ($\mathrm{C_i}$) are created by the irradiation.

With the rate of displacement of C_s by collision with 200 keV electrons being denoted by κ_{CD}, the density of carbon-related defects (V_C or C_i), $N_{CD}(\Phi)$, can be expressed as [5]

$$\frac{dN_{CD}(\Phi)}{d\Phi} = \kappa_{CD}\,. \tag{8}$$

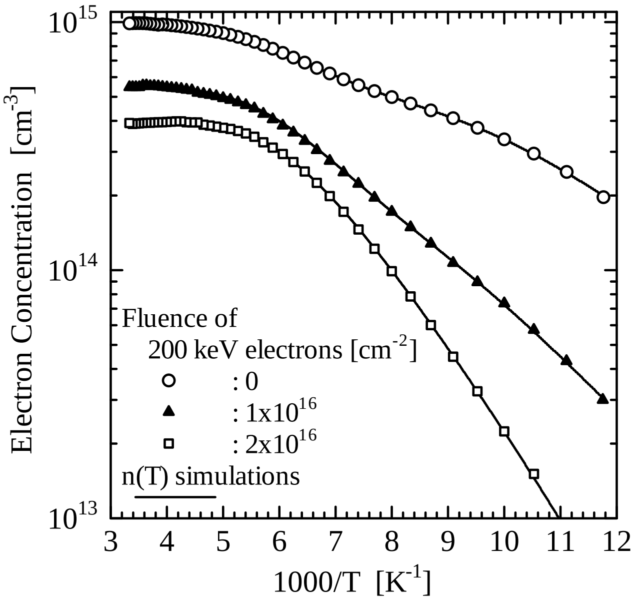

Fig. (1). Temperature dependence of electron concentration before and after 200 keV electron irradiation. Solid lines represent the $n(T)$ simulation using the values determined by FCCS.

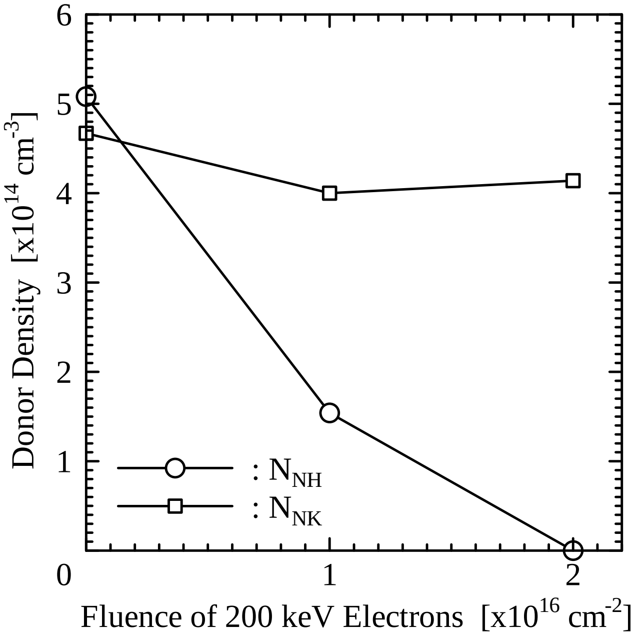

Fig. (2). Fluence dependence of the density of N donors at hexagonal and cubic C-sublattice sites.

Therefore,

$$N_{CD}(\Phi) = \kappa_{CD}\Phi + N_{CD}(0)\ . \tag{9}$$

In other words, κ_{CD} is the generation rate of carbon-related defects. The density of defects related to C_s displacement (i.e., $Z_{1/2}$ centers with $E_C - 0.65$ eV and $EH_{6/7}$ centers with $E_C - 1.55$ eV) has been reported to be nearly proportional to Φ [18], as expected from Eq. (9). The HK4 center with E_V+1.44 eV has been reported to be a complex including defects induced by C_s displacement [7, 16-18]. According to studies of intrinsic defects in SiC [19], the (0/+) level of V_C is at $E_V + 1.4$ eV and its (+/++) level is at $E_V + 1.68$ eV. Since the defects induced by C_s displacement are located around the middle of the band gap in SiC, they should act as electron traps in n-type SiC.

We now turn to the influence of $N_{CD}(\Phi)$ on $n(T)$. In order to simulate $n(T)$ for irradiated cases, the following assumptions are made: (1) the 200 keV electron irradiation does not change N_{NH}, E_{NH}, N_{NK}, and E_{NK} from their values at $\Phi = 0$ cm^{-2}, and (2) the irradiation only increases N_{comp} (that is, N_{comp} for an irradiated sample is the sum of N_{comp} for the non-irradiated case and the increase in $N_{CD}(\Phi)$ due to the irradiation). Fig. (**3**) shows $n(T)$ simulations with N_{comp} of 0, 4.3×10^{14}, and 5.8×10^{14} cm^{-3}, which are used in order for the values of $n(T)$ simulated at higher temperatures to be close to the experimental $n(T)$, denoted by solid, broken, and dot-dashed curves, respec-

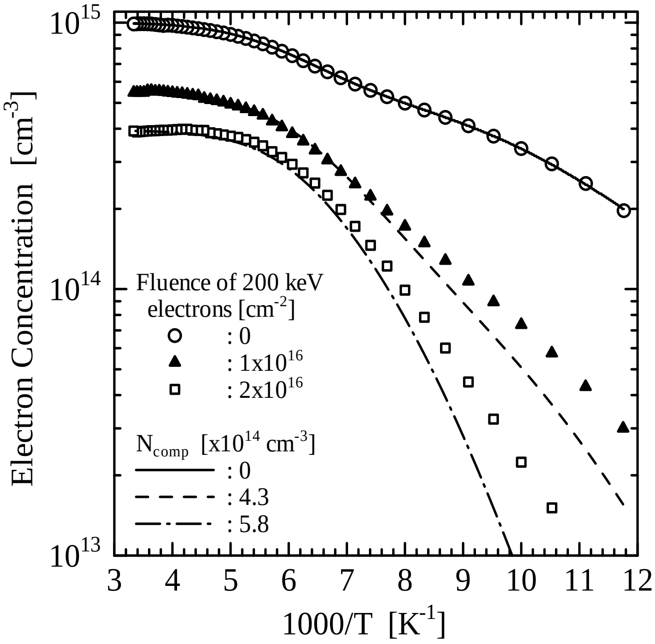

Fig. (3). $n(T)$ simulations using three values of N_{comp}, along with N_{NH}, N_{NK}, E_{NH}, and E_{NK} for a non-irradiated sample.

tively. Also shown for comparison are the measurements of $n(T)$ for total fluences of 0, 1×10^{16} and 2×10^{16} cm^{-2}, denoted by ○, ▲, and □, respectively. In the irradiated samples, at lower temperatures, the $n(T)$ simulation is much lower than the experimental $n(T)$.

In a comparison between Figs. (**1** and **3**), the deviation of the simulation curve from the experimental data is much larger in Fig. (**3**) than in Fig. (**1**). Therefore, it is clear that, although $n(T)$ does decrease with increasing N_{comp}, the reduction in $n(T)$ by electron irradiation cannot be explained by only an increase in the density of deep-level defects.

Irradiation-induced defects in N-doped n-type 4H-SiC have been intensively studied by deep level transient spectroscopy (DLTS) [16-18]. By DLTS, deep-level defects with density much lower than the total density of N donors can be investigated [5]. On the other hand, changes in N-donor density due to irradiation can be investigated by FCCS. In this study, therefore, it is found that N donors are less radiation-resistant at hexagonal C-sublattice sites than at cubic C-sublattice sites.

4. CONCLUSION

The electron concentration in lightly N-doped n-type 4H-SiC epilayers was decreased by 200 keV electron irradiation. The influence of the increase in the deep-level defects' density and the decrease in donor density on the decrease in the electron concentration by irradiation was investigated by using simulation results. Finally, this decrease in the electron concentration arose because the electron irradiation reduced the density of N donors. Moreover, the density of N donors at hexagonal C-sublattice sites was reduced much more than the density of N donors at cubic C-sublattice sites. This finding suggests that 3C-SiC should be the most radiation-resistant and 6H-SiC should be the least radiation-resistant of N-doped 3C-SiC, 4H-SiC, and 6H-SiC.

REFERENCES

[1] Matsuura H, Iwata H, Kagamihara S, *et al.* Si substrate suitable for radiation-resistant space solar cells. Jpn J Appl Phys 2006; 45: 2648-55.

[2] Matsuura H, Aso K, Kagamihara S, Iwata H, Ishida T, Nishikawa K. Decrease in Al acceptor density in Al-doped 4H-SiC by irradiation with 4.6 MeV electrons. Appl Phys Lett 2003; 83: 4981-3.

[3] Matsuura H, Kagamihara S, Itoh Y, Ohshima T, Itoh H. Relationship between defects induced by irradiation and reduction of hole concentration in Al-doped 4H-SiC. Physica B 2006; 376-377: 342-5.

[4] Matsuura H, Minohara N, Inagawa Y, Takahashi M, Ohshima T, Itoh H. Mechanisms of decrease in hole concentration in Al-doped 4H-SiC by irradiation of 200 keV electrons. Mater Sci Forum 2007; 556-557: 379-82.

[5] Matsuura H, Minohara N, Ohshima T. Mechanisms of unexpected reduction in hole concentration in Al-doped 4H-SiC by 200 keV electron irradiation. J Appl Phys 2008; 104: 043702 1-6.

[6] von Bardeleben HJ, Cantin JL, Henry L, Barthe MF. Vacancy defects in p-type 6H-SiC created by low-energy electron irradiation. Phys Rev 2000; 62: 10841-6.

[7] Steeds JW, Carosella F, Evans GA, Ismail MM, Danks LR, Voegeli W. Differentiation between C and Si related damage centres in 4H and 6H SiC by the use of 90-300 kV electron irradiation followed by low temperature photoluminescence microscopy. Mater Sci Forum 2001; 353-35: 381-4.

[8] Matsuura H, Komeda M, Kagamihara S, *et al.* Dependence of acceptor levels and hole mobility on acceptor density and temperature in Al-doped p-type 4H-SiC epilayers. J Appl Phys 2004; 96: 2708-15.

[9] Matsuura H, Masuda Y, Chen Y, Nishino S. Determination of donor densities and donor levels in 3C-SiC grown from Si_2 $(CH_3)_6$ using Hall-effect measurements. Jpn J Appl Phys 2000; 39: 5069-75.

[10] Kagamihara S, Matsuura H, Hatakeyama T, *et al.* Parameters required simulating electric characteristics of SiC devices for n-type 4H-SiC. J Appl Phys 2004; 96: 5601-6.

[11] Matsuura H, Nagasawa H, Yagi K, Kawahara T. Determination of densities and energy levels of donors in free-standing undoped 3C-SiC epilayers with thicknesses of 80 μm. J Appl Phys 2004; 96: 7346-51.

[12] Ikeda M, Matsunami H, Tanaka T. Site effect on the impurity levels in 4H, 6H, and 15R SiC. Phys Rev 1980; B 22: 2842-54.

[13] Götz W, Schöner A, Pensl G, *et al.* Nitrogen donors in 4H-silicon carbide. J Appl Phys 1993; 73: 3332-8.

[14] Harris GL, editor. Properties of Silicon Carbide. INSPEC: London; 1995.

[15] Pernot J, Zawadzki W, Contreras S, Robert JL, Neyret E, Cioccio L-Di. Electrical transport in n-type 4H silicon carbide. J Appl Phys 2001; 90: 1869-78.

[16] Storasta L, Bergman JP, Janzén E, Henry A, Lu J. Deep levels created by low energy electron irradiation in 4H-SiC. J Appl Phys 2004; 96: 4909-15.

[17] Danno K, Kimoto T. Investigation of deep levels in n-type 4H-SiC epilayers irradiated with low-energy electrons. J Appl Phys 2006; 100: 113728 1-6.

[18] Danno K, Kimoto T. Deep levels in electron-irradiated n- and p-type 4H-SiC investigated by deep level transient spectroscopy. Mater Sci Forum 2007; 556-557: 331-4.

[19] Choyke WJ, Matsunami H, Pensl G, editors. Silicon Carbide. Springer: Berlin 2004.

Received: June 01, 2010 Revised: March 08, 2011 Accepted: March 28, 2011