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Formation of a semi-insulating layer in n-type 4H-SiC by electron irradiation

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Electron irradiation has been applied to the formation of a semi-insulating 4H-SiC(0001) layer. The resistivity of the semi-insulating layer, which was irradiated with a fluence of 1.9×10^{18} cm^{-2} at 400 keV, exceeded 10^{10} Ωcm at room temperature. From capacitance-voltage characteristics of Schottky structure, the depth of the semi-insulating layer was estimated to be 10 μm, indicating that the whole region of lightly-doped n-type epilayer was converted to the semi-insulating layer by electron irradiation. The semi-insulating property can be ascribed to electron trapping at the $Z_{1/2}$ and $EH_{6/7}$ centers generated by electron irradiation. The threshold energy for the generation of $Z_{1/2}$ center was about 100 keV. © *2011 American Institute of Physics*. [doi:10.1063/1.3604795]

Silicon carbide (SiC) is an attractive material for realizing high-power, high-temperature, and high frequency devices.[1–4] Through recent progress in SiC technologies, high-voltage discrete devices like Schottky barrier diodes, junction field-effect transistors and metal-oxide-semiconductor FETs have been intensively developed. To promote large-scale implementation of these devices into actual electronic systems, further improvement of device processing techniques, optimization of device structure, and scale up of the devices are in progress.

Device isolation is a key technology to integrate electronic devices and has been made mainly by using pn junctions in the present-day Si, GaAs, and SiC integrated circuits (ICs). Nowadays, for Si ultra-large-scale ICs, silicon-on-insulator structures fabricated by oxygen implantation (SIMOX) (Ref. 5) or wafer bonding[6] have been developed. For future SiC ICs, however, these methods will not be good solutions. In fabrication of SiC SIMOX, an SiC layer above the oxides must be very defective, due to the severe lattice damage and oxygen incorporation caused by high-dose ($> 10^{17}$ cm^{-2}) oxygen ion implantation. On the other hand, the demerits of wafer bonding include the waste of expensive SiC substrates and the poor controllability to obtain thin SiC layers with uniform thickness.

The authors' group reported vanadium ion implantation as an attractive method to form semi-insulating SiC layers.[7] Another study showed that proton irradiation is also an effective method.[8] However, both methods have difficulty in forming a thick semi-insulating layer with a thickness of over tens of micrometers, which is especially crucial to fabricate high-frequency SiC devices. Such a thick semi-insulating layer is also useful to fabricate high-frequency GaN-based devices, which are recently used for RF and microwave applications.

The electron irradiation is an attractive candidate of the method to form tens of micrometers-thick semi-insulating layers in SiC. Electrons extracted by commercial accelerators have very large penetration power, compared with protons and vanadium ions. For example, the penetration depth of an electron accelerated at 400 keV is estimated to be about 400 μm. This means that electron irradiation has potential to form a few hundred micrometers-thick semi-insulating layers in SiC. Regarding the electron irradiation to 4H-SiC, deep levels and carrier concentration of irradiated samples have been extensively investigated.[9–14] Furthermore, control of carrier lifetimes in n-type 4H-SiC by electron irradiation has been achieved.[15] In this letter, the authors investigated the capability of electron irradiation to form thick semi-insulating 4H-SiC.

Samples used in this study were 10 μm-thick n-type 4H-SiC(0001) epilayers grown on n-type 4H-SiC(0001) substrates. The dopant was nitrogen and the doping concentrations of the epilayer and substrate were 7.2×10^{15} cm^{-3} and 1×10^{18} cm^{-3}, respectively. The typical concentration of the $Z_{1/2}$ center[9] in the as-grown samples was 9.5×10^{12} cm^{-3}, as determined from deep level transient spectroscopy (DLTS) measurements.

In this study, electron irradiation was performed onto the samples by using commercial electron irradiation systems (NHVC EBC-300 and EPS-800) without intentional heating. A part of samples were irradiated at an energy of 400 keV, while the fluence was changed from 6.0×10^{15} to 1.9×10^{18} cm^{-2}, to investigate the relation between the resistivity and the fluence. Other samples were irradiated at different energies of 200–746 keV with a fixed fluence of 4×10^{15} cm^{-2} to investigate the relation between the concentration of $Z_{1/2}$ center generated by electron irradiation and the energy of electrons. After the irradiation, thermal treatment was not performed.

For electrical measurements, Ni/SiC Schottky structures were formed on samples. The Schottky metal was thermally evaporated onto the surface of the samples, and ohmic contacts were formed with Ag paste on the back side. The diameter of Schottky contacts was 300–1500 μm. The resistivity of each sample was estimated by current–voltage (I-V) measurements. Capacitance–voltage (C-V) measurements were performed to estimate the doping concentration or the depth of semi-insulating region. The concentration of the $Z_{1/2}$ center

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in each sample was determined by DLTS measurements performed in the temperature range from 100 to 350 K. In DLTS measurements, the capacitance was measured periodically in a period width, in which the transient is to be measured, and then developed into Fourier series.[16] The reverse bias voltage and pulse voltage were -3 V and 0 V, respectively, during the measurements. Danno and Kimoto reported that the $Z_{1/2}$ and $EH_{6/7}$ (Ref. 10) concentrations generated by electron irradiation exhibit a close one-to-one relationship.[12] This means that the concentration of $Z_{1/2}$ center is a good indicator of the concentration of deep levels, which affect the resistivity of irradiated samples.

Figure 1 shows the semilogarithmic plots of forward current density-voltage characteristics for the samples irradiated at 400 keV with various fluences. The characteristics of an as-grown (unirradiated) sample are also shown. As the fluence increases, the forward current density significantly decreased. By assuming that the series resistances of irradiated samples are mainly attributed to the resistance of 10 μm-thick epilayers, the resistivities of irradiated samples were estimated from the slope of linear region in the linear plots of current density-voltage characteristics in the range from 1.5 to 2.0V. Figure 2 depicts the dependence of resistivity for irradiated epilayers on the electron fluence. The resistivity of epilayers irradiated with a fluence of 1.9×10^{18} cm^{-2} was as high as 5×10^{10} Ω cm, indicating that the epilayer becomes semi-insulating.

To confirm the assumption that the series resistance of irradiated samples is mainly attributed to the resistance of the 10 μm-thick epilayer, the thickness of the semi-insulating region was estimated from C-V characteristics. Figure 3 shows the $1/C^2$-V characteristics for the as-grown sample and the semi-insulating sample formed by irradiation at 400 keV with a fluence of 1.9×10^{18} cm^{-2}. The capacitances were normalized by the area of Schottky contacts. The capacitance of the semi-insulating sample is very small and exhibits very little dependency on the bias voltage. This suggests that, regardless of the bias voltage, a depletion layer with a constant thickness exists under the Schottky contact for the semi-insulating sample. The capacitance of semi-insulating sample is 0.89 nF/cm^2, by which the thickness of the depletion layer is estimated as 10.0 μm. This result indicates that the whole region of the 10 μm-thick epilayer is semi-insulating, keeping the substrate conductive.

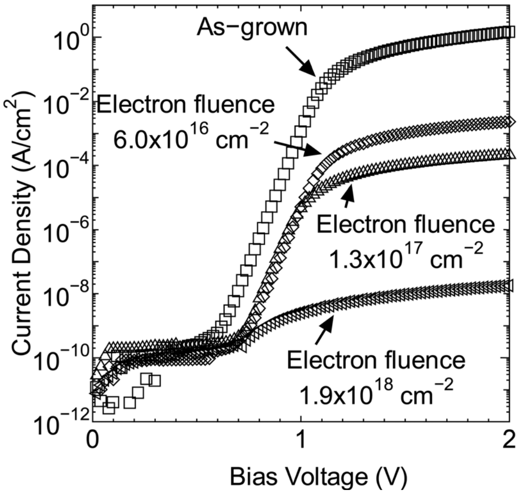

FIG. 1. Current density-voltage characteristics for Ni/n-type 4H-SiC Schottky structures electron-irradiated at 400 keV with the fluences from 6.0×10^{15} to 1.9×10^{18} cm^{-2}. The characteristics of the as-grown sample are also shown for comparison.

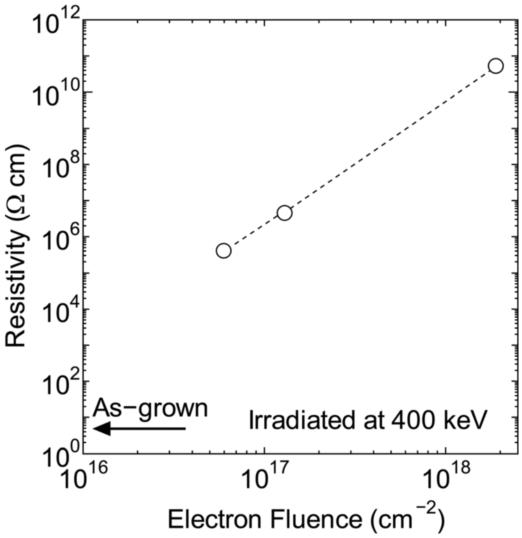

FIG. 2. Dependence of the resistivity for electron-irradiated n-type 4H-SiC layers on the electron fluence.

The dependence of the $Z_{1/2}$ concentration in irradiated samples on the irradiation energy is shown in Fig. 4. We have measured the $EH_{6/7}$ concentration in irradiated samples,[12,17] which is also shown in Fig. 4. In this figure, the $Z_{1/2}$ and $EH_{6/7}$ concentrations are normalized by the electron fluence. From DLTS measurements, the $Z_{1/2}$ and $EH_{6/7}$ centers were determined as major deep levels in each as-irradiated sample. This suggests that the $Z_{1/2}$ and/or $EH_{6/7}$ center are responsible for the semi-insulating property by electron irradiation. From Fig. 4, the threshold energy to generate the $Z_{1/2}$ and $EH_{6/7}$ centers by electron irradiation can be estimated as about 100 keV, and the generation rates of the both

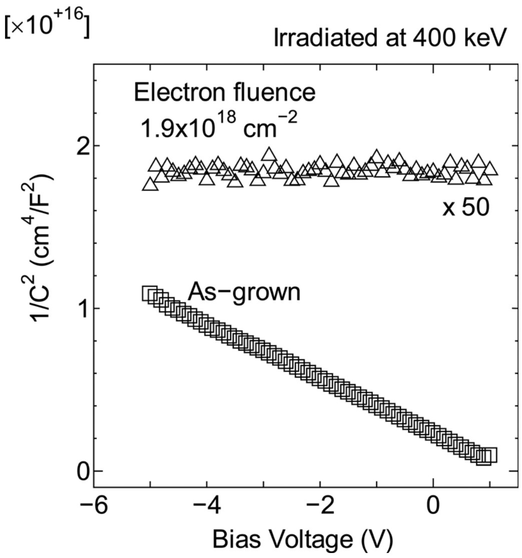

FIG. 3. $1/C^2$–V characteristics for Ni/4H-SiC Schottky structure electron-irradiated at 400 keV, with a fluence of 1.9×10^{18} cm^{-2}. The irradiated sample exhibits a semi-insulating property. The characteristics of the as-grown sample are also shown for comparison.

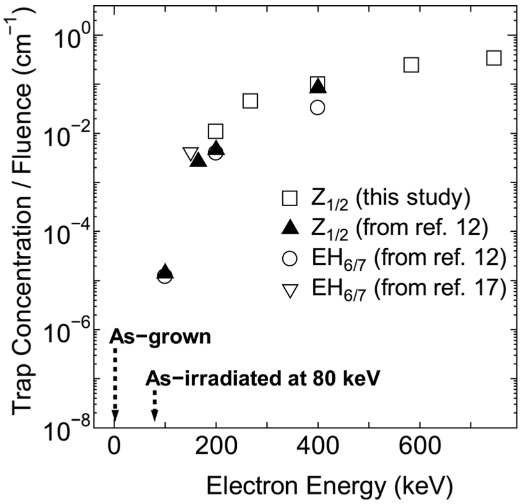

FIG. 4. Semilogarithmic plot of the $Z_{1/2}$ and $EH_{6/7}$ concentrations in as-irradiated 4H-SiC samples vs the electron energy. The $Z_{1/2}$ and $EH_{6/7}$ concentrations are normalized by the electron fluence.

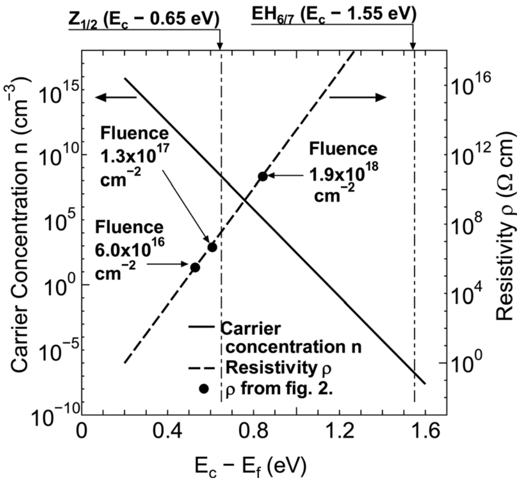

FIG. 5. Calculated carrier concentration and the resistivity as a function of the Fermi level for n-type 4H-SiC, where a fixed electron mobility of 800 cm^2/Vs was assumed.

centers become significant when the electron energy exceeds 200 keV. These results are consistent with previous reports that the both centers may be related to a carbon vacancy[11,12] and that the carbon-atom displacement by electron irradiation is pronounced at electron energies above 100 keV.[11,12,18]

From Fig. 4, the concentration of generated $Z_{1/2}$ center can be estimated as 6×10^{15}, 1×10^{16}, and 2×10^{17} cm^{-3} for irradiated samples with fluences of 6.0×10^{16}, 1.3×10^{17}, and 1.9×10^{18} cm^{-2}, respectively. The resulting resistivities of irradiated epilayers are 4×10^5, 4×10^6, and 5×10^{10} Ω cm, respectively. Since the initial carrier concentration is about 7×10^{15} cm^{-3}, all of the carriers will be captured by the $Z_{1/2}$ or $EH_{6/7}$ centers, taking account of the fact that the $EH_{6/7}$ center with a similar concentration to the $Z_{1/2}$ center is generated.[12] This is why the resistivities of these three samples are very high. Fig. 5 shows the calculated carrier concentration and the resistivity as a function of the Fermi level for n-type 4H-SiC, where a fixed electron mobility of 800 cm^2/Vs was assumed. The generation current and carrier injection from the n-type substrate during I-V measurements were neglected for simplicity. If the $Z_{1/2}$ center is the major compensating defect, the Fermi level may be pinned near the energy level of the $Z_{1/2}$ center and the resistivity should be about 10^7 Ω cm, as shown in Fig. 5. The resistivity of the third sample (5×10^{10} Ω cm) is much larger than 10^7 Ω cm, which suggests that the $EH_{6/7}$ center also worked as a major compensating defect and the Fermi level will be located in between the $Z_{1/2}$ and $EH_{6/7}$ centers.

In summary, the capability of electron irradiation to form semi-insulating n-type SiC was investigated. The resistivity of the as-irradiated samples increased as the electron fluence at an energy of 400 keV. The sample irradiated with a fluence of 1.9×10^{18} cm^{-2} was semi-insulating, which exhibited a high resistivity of 5×10^{10} Ω cm. The thickness of the semi-insulating layer estimated from C-V measurements was 10.0 μm, indicating that the whole region of 10 μm-thick epilayer could be converted to semi-insulating property. The generation of $Z_{1/2}$ and $EH_{6/7}$ centers by electron irradiation started at the electron energy of about 100 keV.

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