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Recovery of the Electrical Characteristics of SiC MOSFETs Irradiated with Gamma-rays by Thermal Treatments

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Abstract. Effects of gamma-ray irradiation and subsequent thermal annealing on the characteristics of vertical structure power Metal-Oxide-Semiconductor Field Effect Transistors (MOSFETs) fabricated on 4H-SiC were studied. After irradiation at 1.2 MGy, the drain current – gate voltage curves of the MOSFETs shifted to the negative voltage side and the leakage drain current at inverse voltage increased. No significant change in the degraded electrical characteristics of SiC MOSFETs was observed by room temperature annealing. The degraded characteristics of SiC MOSFETs began to recover by annealing above 120 ^{o}C, and their characteristics reached almost the initial ones by annealing at 360 ^{o}C.

Introduction

Since SiC has high radiation resistance [1,2], it is regarded as a promising candidate for electronic devices used in harsh radiation environments, such as nuclear and accelerator facilities. Especially, extremely high radiation resistant devices (MGy order) are required for decommissioning of TEPCO Fukushima Dai-ichi nuclear reactors, and SiC devices are expected to be installed to instruments for the decommission. In previous studies, Tanaka *et al*. demonstrated 10 MGy tolerance of 4H-SiC Buried Gate Static Induction Transistors (BGSITs) [1]. Onoda *et al.* also revealed 10 MGy radiation hardness of 4H-SiC Metal-Semiconductor Field Effect Transistors (MESFETs) [2]. However, from point of the view of electric circuit design, the development of radiation resistant devices based on Metal-Oxide-Semiconductor Field Effect Transistors (MOSFETs) is also important since MOSFETs can easily realize normally-off and low-loss devices. In previous studies, the radiation response of 6H-SiC MOSFETs up to 530 kGy was investigated [3]. Chen *et al.* reported that the effects of nitric oxide (NO) passivation on radiation response of 4H-SiC MOS capacitors up to 80 kGy, and MOS capacitors with NO passivation showed better radiation resistance than those without NO passivation [4]. On the other hand, it was also reported by Dixit *et al.* that 4H-SiC MOS capacitors with nitrided gate showed a larger midgap voltage shift than those without nitrided gate [5]. In addition, Zhang *et al*. studied X-ray irradiation and post irradiation effects in *p* and *n*-type 4H-SiC MOS capacitors with and without nitrided gate [6]. For power MOSFETs, commercially available 1200V 4H-SiC power MOSFETs were irradiated with gamma-rays up to 15 kGy up to 125 ^{o}C and the threshold voltage (V_T) shift to the negative voltage side was observed [7]. Those studied demonstrated the high capability of SiC MOS devices as radiation resistant devices. However, the maximum total dose was a few hundreds kGy and the highest annealing temperature was 200 ^{o}C in previous studies. For the development of electronic devices with extremely high radiation resistance for nuclear facilities, it is necessary to clarify the radiation response up to MGy order and also annealing behaviors under higher temperatures. In this study, we irradiate vertical structure power 4H-SiC MOSFETs with gamma-rays up to 1.2 MGy, and investigate the recovery of their degraded characteristics due to thermal annealing up to 360 °C.

Experimental

The samples used in this study were vertical structure power 4H-SiC MOSFETs with the blocking voltage of 1200 V. The gate oxide was fabricated using dry oxidation and subsequent treatment in N_2O. The thickness of gate oxide was 45 nm. The MOSFETs were mounted in “TO3P” packages. For comparison, vertical structure power Si MOSFETs with the same rated current as SiC MOSFETs (20 A) and blocking voltage of 250 V were also used in this study. For the Si MOSFETs, the gate oxide was fabricated using pyrogenic oxidation and the thickness of gate oxide was 150 nm. The Si MOSFETs were mounted in “TO220” packages. The MOSFETs were irradiated with gamma-rays from ^{60}Co source at a dose rate of 3.6 kGy(SiO_2)/h up to 1.2 MGy in a N_2 atmosphere at room temperature (RT). During the irradiation, no bias was applied to all electrodes of the MOSFETs. After the irradiation, the stability of their degraded characteristics was investigated for 240 h at RT. Then, the MOSFETs were annealed in the atmosphere up to 360 °C, from 40 °C with 20 °C step for 20 min. The current-voltage (*I-V*) characteristics were measured using a semiconductor parameter analyzer (Agilent 4156B) and power device analyzer (B1505A) at RT.

Results and Discussion

Figure 1 shows the typical drain current (I_D) – gate voltage (V_G) curves in the subthreshold region (subthreshold curves) for (a) a SiC MOSFET (b) a Si MOSFET before and after irradiation, and after annealing at RT and elevated temperatures. For both SiC and Si MOSFETs, the I_D – V_G curves shift to the negative voltage side and the leakage current of I_D increased by irradiation at 1.2 MGy. These behaviors can be interpreted in terms of positive charge generated in gate oxide by irradiation. For the SiC MOSFET, no significant change in the slope of I_D was observed by the irradiation. This might suggest that interface traps between SiO_2 and SiC act as fixed charge such as oxide-trapped charge because their energy level tends to be near the midgap (deep levels from the conduction band). Besides, a large hump was observed in V_G ranging between -2 and -6 V after irradiation. The origin of the hump has not yet been clarified. However, since thicker oxide leads to larger I_D–V_G shift after irradiation, thick oxide such as field oxide near the gate might affect the hump. To clarify this, we intend to carry out detailed analysis of the device structure. On the other hand, for the Si MOSFET, the slope of I_D decreased by the irradiation. This indicates that interface traps are created by irradiation.

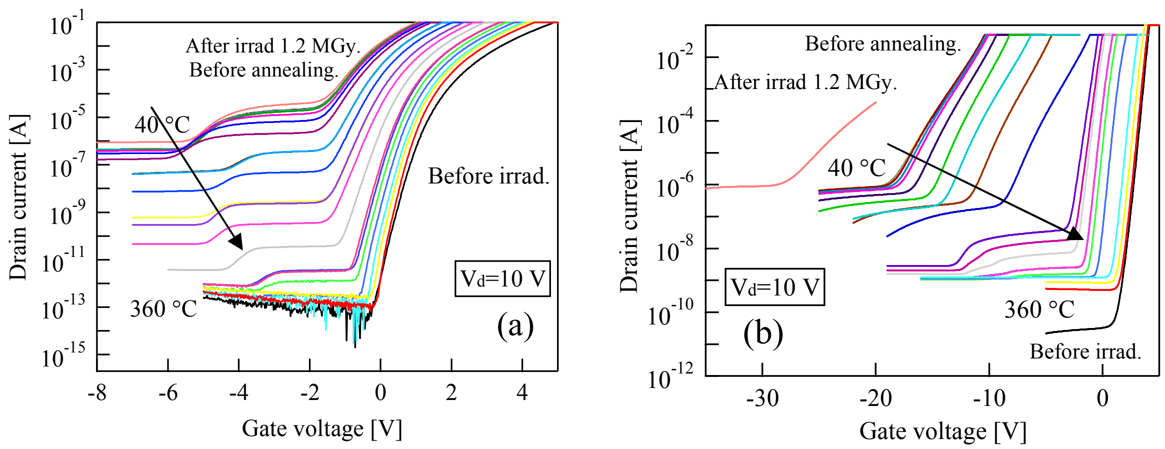

Fig. 1 Typical I_D vs V_G curves in the subthreshold region for (a) a SiC MOSFET (b) a SiMOSFET before and after irradiation, and after annealing at RT and elevated temperature.

After the irradiation, the MOSFETs were kept at RT for 240 h (RT-annealing). After the RT-annealing, no significant change in the degraded electrical characteristics of SiC MOSFETs was observed although the obvious recovery of the electrical characteristics was observed for Si MOSFETs. This indicates that charge-trapped in SiO_2 on SiC and/or interface traps between SiO_2 and SiC are more stable than that for Si.

By annealing at elevated temperature, the I_D - V_G curves for the irradiated SiC MOSFET shifted to the positive voltage side and the I_D decreased with increasing annealing temperature above 120 °C. In addition, the hump became smaller with increasing annealing temperature above 120 °C. For the Si MOSFET, although the tendency of the recovery of the I_D - V_G curves is the same as that of the SiC MOSFET, the larger recovery including the slope of I_D was obtained.

Figure 2 shows the annealing temperature dependence of the shift in V_T from the initial value (ΔV_{th}) for SiC and Si MOSFETs. The V_{th} were determined from the value at the intersection between the V_G-axis and the line extrapolated from the curve of the square root of I_D vs. V_G in the saturation region. The values of V_{th} for SiC and Si MOSFETs before irradiation were 2.89 and 3.76 V, respectively. As shown in Fig. 2, the recovery of ΔV_{th} starts around 120 °C for the SiC MOSFET and around 100 °C for the Si MOSFET. By the annealing at 360 °C, the value of V_{th} was recovered up to 91% and 97% of the initial values for SiC and Si MOSFETs, respectively. These results indicate that annealing at 360 °C can remove both interface traps and oxide-trapped charges generated by gamma-ray irradiation.

Figure 3 shows the annealing temperature dependence of subthreshold voltage swing (S) for SiC and Si MOSFETs. In this study, the value of S was estimated from $dV/d\log I_D$ between 10^{-3} and 10^{-4} A because the hump appeared after irradiation and the value of S cannot be evaluated from $dV/d\log I_D$ below 10^{-4} A. As shown in Fig. 3, no significant change in the value of S for SiC MOSFETs by the irradiation as well as annealing was observed. For the Si MOSFET, the value of S increased to approximately seven times larger than the initial value by the irradiation at 1.2 MGy. Then, by the annealing, the S for Si MOSFETs decreased with increasing annealing temperature and completely recovered to the initial value after the annealing at 360 °C. These results indicate that interface traps between SiO_2 and SiC are more stable

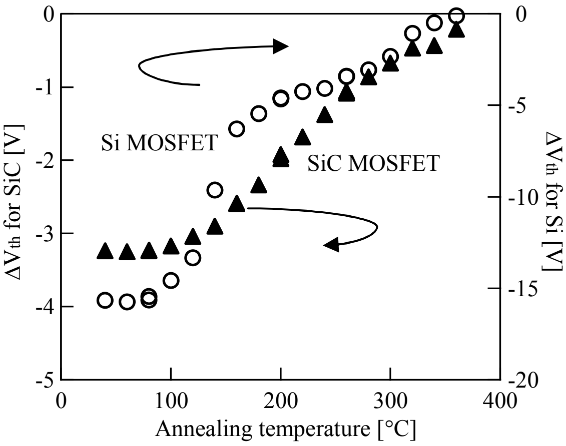

Fig. 2 Annealing temperature dependence of the ΔV_{th} for SiC MOSFET (Triangles) and Si MOSFET (Circles).

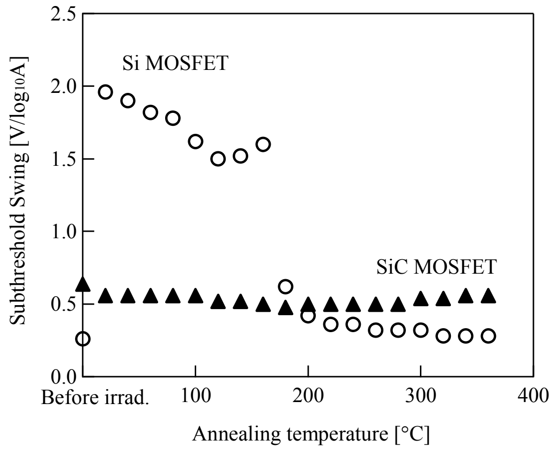

Fig. 3 Annealing temperature dependence of the Subthreshold Swing for SiC MOSFET (Triangles) and Si MOSFET (Circles).

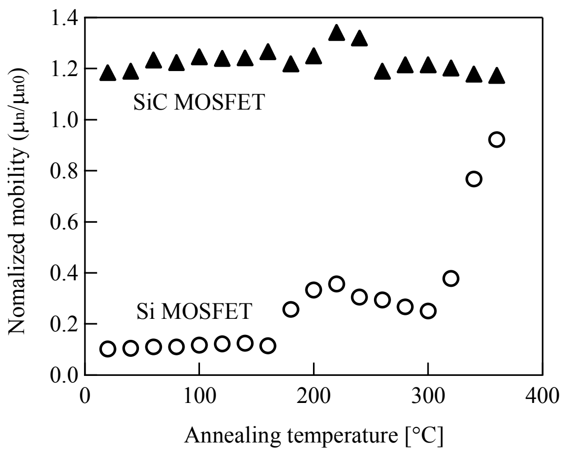

Fig. 4 Annealing temperature dependence of the μ_n/μ_{n0} for SiC MOSFET (Triangles) and Si MOSFET (Circles).

than that between SiO_2 and Si. Thus, the result is consistent with that obtained from RT-annealing effect.

Figure 4 shows the annealing temperature dependence of channel mobility. The values of the channel mobility (μ_n) normalized by the initial value (μ_{n0}) are plotted in the figure. Although the MOSFETs in this study have a vertical structure, the channel mobility for MOSFETs was simply estimated using a following formula in this study,

$$\frac{\partial I_d}{\partial V_g} = \frac{Z}{L}\mu_n C_{ox} V_d \ , \qquad (1),$$

where C_{ox}, Z and L are the oxide capacitance, the gate width and the gate length, respectively. Here, it is assumed that the electrical characteristics in bulk SiC does not change in this dose range and that the mobility is mainly affected by interface traps generated by irradiation. As shown in Fig. 4, no significant change in the μ_n/μ_{n0} for the SiC MOSFET by the irradiation and subsequent annealing was observed. On the other hand, the μ_n/μ_{n0} for the Si MOSFET was remarkably decreased by the irradiation at 1.2 MGy. By the annealing, the significant recovery of μ_n/μ_{n0} was observed by the annealing above 180 ^{o}C. Then, after the annealing at 360 ^{o}C, the value of μ_n/μ_{n0} was recovered up to 92 % of the initial value. Those results are consistent with the results obtained from the subthreshold voltage swing (shown in Fig. 3).

Conclusions

Vertical structure power 4H-SiC MOSFETs were irradiated with gamma-rays up to 1.2 MGy, and the effect of thermal annealing up to 360^{o}C on the degraded characteristics was investigated. Charge-trapped in oxide and interface traps, which are generated in SiC MOSFETs by irradiation, are more stable than those in Si MOSFETs. The degraded $I_D - V_G$ curves and threshold voltage shifts (ΔV_{th}) for SiC MOSFETs start to recover by the annealing above 120^{o}C, and their characteristics become almost the initial ones by annealing at 360 ^{o}C. Although subthreshold voltage swing and channel mobility for Si MOSFET are significantly changed by irradiation and annealing, those for SiC MOSFETs are hardly changed, which evidences the possibility of SiC MOSFETs as high radiation resistant devices.

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