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Change in Characteristics of SiC MOSFETs by Gamma-ray Irradiation at High Temperature

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Abstract. Radiation response of 4H-SiC vertical power Metal-Oxide-Semiconductor Field Effect Transistors (MOSFETs) was investigated at 150°C up to 10.4 MGy. Until irradiation at 1.2 MGy, the drain current – gate voltage curves of the SiC MOSFETs shifted to the negative voltage side, and the leakage of drain current at gate voltages below threshold voltage increased with increasing absorbed dose. However, no significant change in the electrical characteristics of SiC MOSFETs was observed at doses above 1.2 MGy. For blocking characteristics, there were no degradations of the SiC MOSFETs irradiated at 150°C even after irradiated at 10.4 MGy.

Introduction

In order to decommission TEPCO Fukushima Daiichi nuclear reactors, the development of electronic devices used in harsh radiation environments, especially extremely high dose regions such as MGy order is demanded. Silicon Carbide (SiC) is expected to apply to electronic devices used in harsh radiation environments as well as high power devices because of its excellent physical, chemical and mechanical properties [1- 14]. In a previous study, 10 MGy tolerance of 4H-SiC Buried Gate Static Induction Transistors (BGSITs) was demonstrated [6]. For designing electronic circuits with various functions, the development of radiation resistant devices based on Metal-Oxide-Semiconductor Field Effect Transistors (MOSFETs) is one of the key issues since MOSFETs can easily realize normally-off characteristics. The radiation response of 6H-SiC MOSFETs was previously investigated up to 530 kGy [9]. Besides, commercially available 4H-SiC power MOSFETs mounted in the packages with the blocking voltage of 1200 V were irradiated with gamma-rays up to 15kGy up to 125°C, and as a result, threshold voltage (V_{th}) shifted to the negative voltage side [12]. Recently, we also reported that the degraded characteristics of 4H-SiC power MOSFETs (blocking voltage of 1200 V) due to gamma-ray irradiation at 1.2 MGy were recovered by annealing above 120°C, and their characteristics became almost the initial ones by annealing at 360°C [14]. The reported result suggests that the charge trapped in oxide and/or interface traps generated by irradiation are annealed above 120°C. Thus, the degradation of SiC MOSFETs might depend on irradiation temperature, especially above 120°C. In addition, for the development of electronic devices with extremely high radiation resistance for nuclear facilities, it is necessary to clarify the radiation response of SiC MOSFETs in the high temperature and high dose conditions. In this study, we reveal changes in the characteristics of vertical 4H-SiC power MOSFETs by gamma-ray irradiation at 150°C up to 10 MGy.

Experimental

The samples used in this study were vertical structure 4H-SiC power MOSFETs with the blocking voltage of 1200 V and the rated current of 20 A. The gate oxide was fabricated using dry oxidation and subsequent treatment in N_2O. The thickness of gate oxide was 45 nm. The SiC MOSFETs were mounted in "TO3P" packages. The MOSFETs were irradiated with gamma-rays from ^{60}Co source at a dose late of 3.6 kGy(SiO_2)/h up to 10.4 MGy at either room temperature (RT) or 150°C in a N_2 atmosphere. During the irradiation, no bias was applied to all electrodes of the MOSFETs. Before and after irradiation, the current-voltage ($I - V$) characteristics were measured in the air at RT.

Results and Discussion

Fig. 1 shows the typical drain current (I_D) – gate voltage (V_G) curves in the subthreshold region (subthreshold curves) for SiC MOSFETs, before and after (up to 10.4 MGy) irradiation at (a) 150°C and (b) RT. For both SiC MOSFETs irradiated at 150 °C and RT, the $I_D - V_G$ curves shift to negative voltage side and the leakage current of I_D increases until irradiated at 1.2 MGy. However, slight recovery of the $I_D - V_G$ curves for MOSFETs irradiated at 150 °C is observed at doses above 1.2 MGy although $I_D - V_G$ curves for MOSFETs irradiated at RT keep shifting to negative voltage side. In addition, the increase of leakage current of I_D for MOSFETs is obviously reduced by irradiation at 150°C. This suggests that the positive charges generated in gate oxide due to irradiation are partially annealed during irradiation at elevated temperature [14,15]. On the other hand, no significant change in the slope of I_D for SiC MOSFETs irradiated at 150 °C is observed although we cannot say the slope of I_D for SiC MOSFETs irradiated at RT because of high leakage current. This might suggest that interface traps generated between SiO_2 and SiC by irradiation act as fixed charge such as oxide-trapped charge because their energy levels are located near the midgap (deep levels from the conduction band) [9]. Fig. 2 shows the total dose dependence of the V_{th} for SiC MOSFETs irradiated at 150°C (filled) and RT (unfilled). The values of V_{th} were estimated 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. As shown in Fig. 2, the V_{th} for SiC MOSFETs shifts to negative voltage side due to irradiation. However, the V_{th} is almost a constant value at dose above 1.2 MGy in the case of irradiation at 150°C although the value of V_{th} irradiated at RT decreases with increasing dose. This result indicates that the amount of oxide-trapped charges generated by irradiation and that dissociated

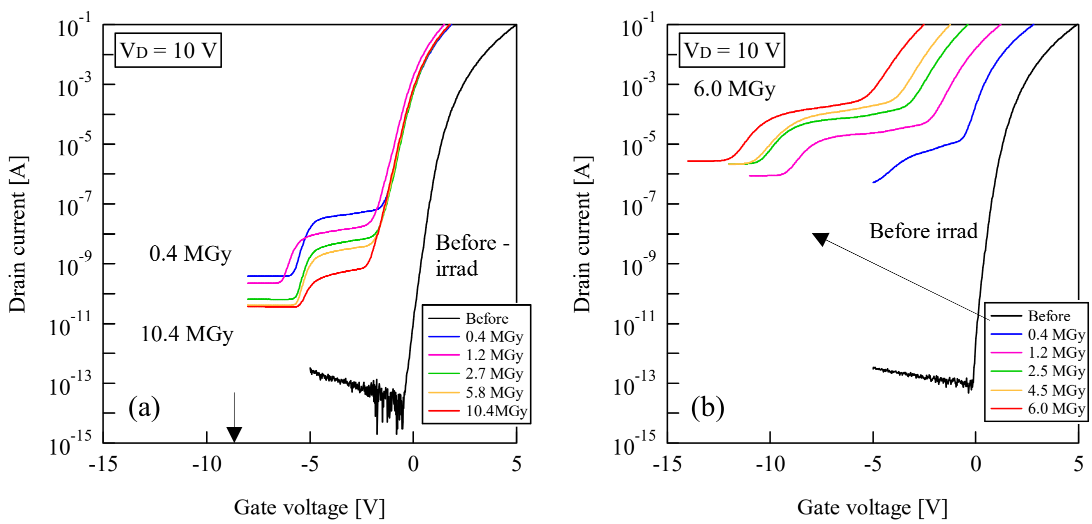

Fig. 1 I_D vs V_G curves in the subthreshold region for SiC MOSFET before and after irradiation at (a) 150°C and (b) RT.

by elevated temperature keep balanced and, as a result, the value of V_{th} is almost constant up to 10.4 MGy.

Fig. 3 shows the total dose dependence of channel mobility for SiC MOSFETs irradiated at 150°C (filled) and RT (unfilled). The values of the channel mobility (μ_{ch}) normalized by the initial value (μ_{ch0}) are plotted in the figure. Although the MOSFETs in this study have a vertical structure, we 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. Therefore, the channel mobility for MOSFETs was simply estimated using a following formula in this study,

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

where C_{ox}, Z and L are the oxide capacitance, the gate width and the gate length, respectively. As shown in Fig. 3, the values of μ_{ch}/μ_{ch0} for both MOSFETs increase up to 1.2 MGy and then, the values is almost constant above 1.2 MGy. Comparing 150°C irradiation with RT irradiation, the increase in μ_{ch}/μ_{ch0} for MOSFETs irradiated at 150°C is larger than that irradiated at RT. Although of the mechanism on the increase in the channel mobility due to irradiation has not yet been clarified, the obtained result might indicates that irradiation at high temperature is more useful for improving the channel mobility for SiC MOSFETs.

Fig. 4 shows the blocking characteristics of SiC MOSFETs before and after (up to 10.4 MGy) irradiation at 150°C when V_G is applied to 3V below V_T. As shown in Fig. 4, the value of I_D at V_D below 1200 V is around 10^{-6} A or lower even after irradiation at 10.4 MGy. Also, no significant change in the breakdown voltage (V_{BR}) is observed after 10.4 MGy. Fig. 5 shows the total dose dependence of V_{BR} for SiC MOSFETs irradiated at 150°C (filled) and RT (unfilled). The values of V_{BR} were estimated from the value of V_D at I_D = 1 mA when V_G is applied to 3V below V_T. For both SiC MOSFETs, no significant decrease in V_{BR} is observed, as shown in Fig. 5. The obtained result indicates that the blocking characteristics of SiC MOSFETs are not affected by irradiation up to 10.4MGy.

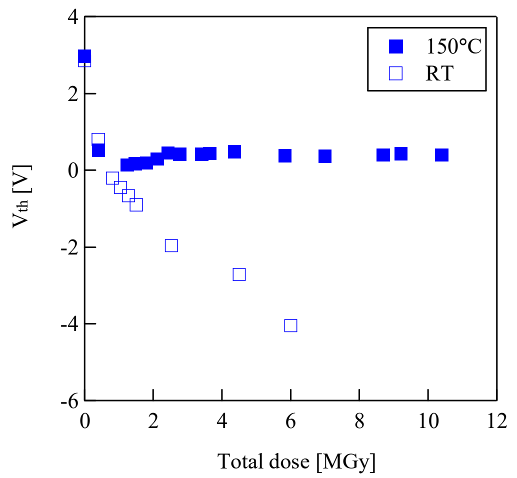

Fig. 2 Total dose dependence of the V_{th} for SiC MOSFET irradiated at 150 °C (filled) and RT (unfilled).

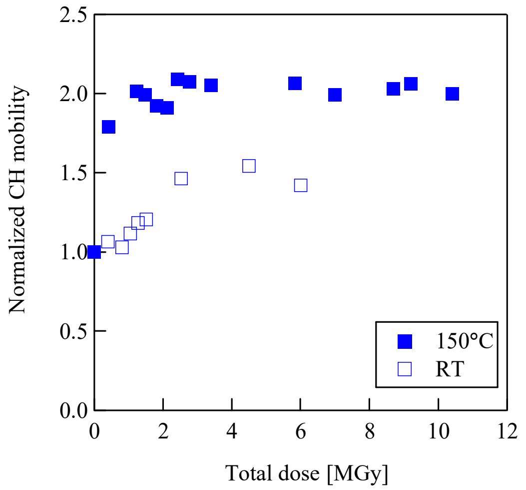

Fig. 3 Total dose dependence of the μ_n/μ_{n0} for SiC MOSFET irradiated at 150 °C (filled) and RT (unfilled).

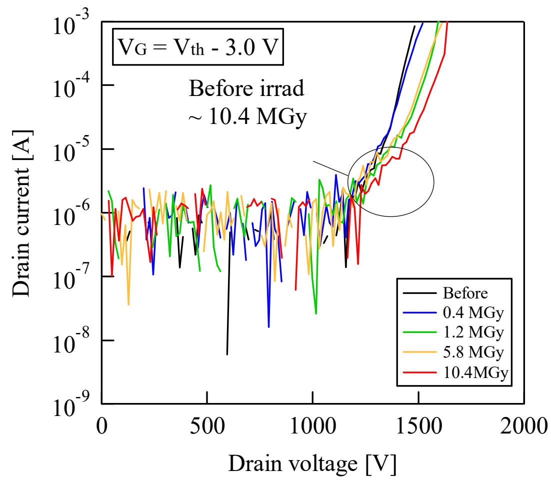

Fig. 4 Blocking characteristics of SiC MOSFET before and after irradiation at 150°C.

Conclusions

Vertical 4H-SiC power MOSFETs were irradiated with gamma-rays at 150°C up to 10.4 MGy. Their I_D – V_G curves shift to negative voltage side and the leakage current of I_D increases due to irradiation. However, the degradation of their characteristics was suppressed by irradiation at 150°C as compared to that obtained by irradiation at RT. In addition, the degraded characteristics were recovered at doses above 1.2 MGy when SiC MOSFETs were irradiated at 150°C. The blocking characteristics for both MOSFETs irradiated at 150°C and RT did not change by irradiation at 10.4 MGy.

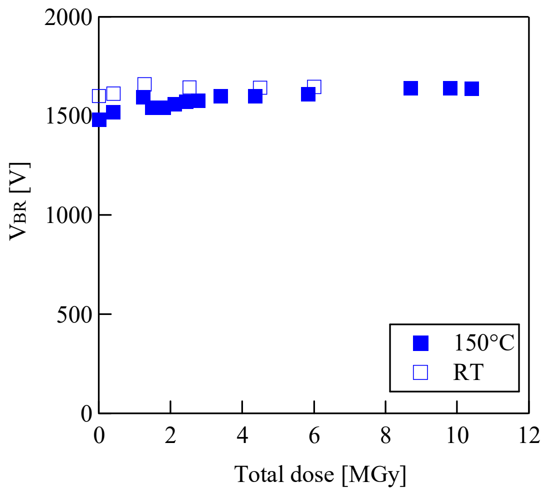

Fig. 5 Total dose dependence of the V_{BR} for SiC MOSFET irradiated at 150°C and RT.

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