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Radiation response of silicon carbide metal–oxide–semiconductor transistors in high dose region

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Radiation response of vertical structure hexagonal (4H) silicon carbide (SiC) power metal–oxide–semiconductor field effect transistors (MOSFETs) was investigated up to 5.8 MGy. The drain current–gate voltage curves for the MOSFETs shifted from positive to negative voltages due to irradiation. However, the drain current–gate voltage curve shifts for the MOSFETs irradiated at 150 °C was smaller than those irradiated at room temperature. Thus, the shift of threshold voltage due to irradiation was suppressed by irradiation at 150 °C. No significant change or slight decrease in subthreshold voltage swing for the MOSFETs irradiated at 150 °C was observed. The value of channel mobility increased due to irradiation, and the increase was enhanced by irradiation at 150 °C comparing to irradiation at RT.

1. Introduction

The importance of the development of electronic devices used in harsh radiation environments, such as nuclear and accelerator facilities, has increased. Electronic devices with extremely high radiation resistance (MGy order) are required for the decommissioning of Tokyo Electric Power Company (TEPCO) Fukushima Dai-ichi nuclear reactors. Silicon carbide (SiC) is regarded as a promising candidate material for power devices with outstanding characteristics including extremely low switching loss and on-state resistance.[1–11] In addition, SiC is expected to enable highly radiation resistant electronics.[12–25] Tanaka et al. reported that 4H-SiC buried gate static induction transistors (BGSITs) were able to be operated at doses up to 10 MGy.[17] It is also demonstrated by Onoda et al. that 4H-SiC metal–semiconductor field effect transistors (MESFETs) showed the radiation hardness of 10 MGy.[16] For metal–oxide–semiconductor field effect transistors (MOSFETs) which easily realize normally-off (enhancement-mode) and low-switching loss characteristics, 6H-SiC MOSFETs were reported to have higher radiation resistance than Si MOSFETs.[13] Furthermore, Chen et al. demonstrated that the effects of nitric oxide (NO) passivation on radiation response of 4H-SiC MOS capacitors increases exposure tolerances up to 80 kGy, demonstrating that MOS capacitors with NO passivation had better radiation resistance than those without NO passivation.[14] However, Dixit et al. reported that a larger midgap voltage shift for 4H-SiC MOS capacitors with nitrided gate was observed compared to those without nitrided gate.[15] In addition, Zhang et al. reported that the effect of X-ray irradiation and post irradiation annealing on p- and n-type 4H-SiC MOS capacitors depended on values of bias applied to gate during irradiation.[18] For power MOSFETs, commercially available 1200 V 4H-SiC power MOSFETs were irradiated with gamma-rays up to 15 kGy up to 125 °C, and as a result, the shift of the threshold voltage (V_T) to the negative voltage side was observed.[19] Recently, Yokoseki et al. revealed that 4H-SiC power MOSFETs degraded by gamma-ray irradiation at 1.2 MGy recovered by annealing above 120 °C, and their characteristics recovered almost completely by annealing at 360 °C.[25] Those results suggest that the charge trapped in oxide and/or interface traps generated by irradiation are released by thermal treatment above 120 °C. Thus, the degradation of SiC MOSFETs might be reduced by high-temperature irradiation, especially at temperature above 120 °C. However, to our knowledge, the radiation response of SiC MOSFETs under elevated temperature and up to high dose regions, such as MGy order, has not yet been investigated. Furthermore, 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 under elevated temperature up to MGy order. In this study, we investigated the radiation response of vertical structure power 4H-SiC MOSFETs irradiated with gamma-rays under 150 °C up to a dose of 5.8 MGy.

2. Experimental methods

Vertical structure power 4H-SiC MOSFETs with a blocking voltage of 1200 V and a rated current of 20 A were used in this study. The gate oxide thickness of 45 nm was formed via dry oxidation and subsequent annealing in N_2O atmosphere. The SiC MOSFETs were mounted in TO3P packages. For comparison, vertical structure power Si MOSFETs, of which the blocking voltage and the rated current are 250 V and 20 A (the same rated current as that of SiC MOSFETs) respectively, in TO220 packages were also used in this study. Since gamma-rays penetrate whole samples (package and MOSFET), the difference between TO3P and TO220 packages might not affect the radiation response of MOSFETs. For the Si MOSFETs, a gate oxide at a thickness of 150 nm was formed using pyrogenic oxidation. These MOSFETs were irradiated with gamma-rays up to 5.8 MGy(SiO_2) at a dose rate of 3.6 kGy(SiO_2)/h in N_2 atmosphere at 150 °C. During the irradiation, no bias was applied to each electrode of the MOSFETs. The current–voltage (I–V) characteristics of the MOSFETs were measured in air at room temperature (RT).

3. Results and discussion

Figures 1(a) and 1(b) show the typical drain current–gate voltage (I_D–V_G) curves in the subthreshold region (sub-

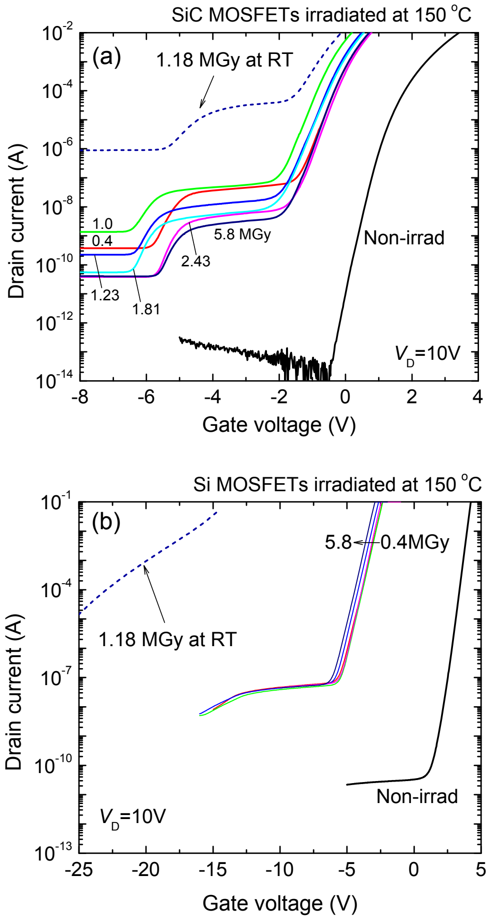

Fig. 1. (Color online) I_D–V_G curves in the subthreshold region (subthreshold curves) for (a) SiC and (b) Si MOSFETs before and after (up to 5.8 MGy) irradiation of gamma-rays at 150 °C. The V_D of 10 V was applied during the measurements. For comparison, I_D–V_G curves for MOSFETs irradiated with gamma-rays at 1.18 MGy at RT were plotted as dotted lines in the figures.

threshold curves) for SiC and Si MOSFETs, respectively before and after (up to 5.8 MGy) irradiation of gamma-rays at 150 °C. The drain voltage (V_D) of 10 V was applied during the I_D–V_G measurements. For comparison, I_D–V_G curves for MOSFETs irradiated with gamma-rays at 1.18 MGy at RT were plotted as dotted lines in the figures. For both SiC and Si MOSFETs, the I_D–V_G curves shift to negative voltage side and leakage current (i.e., I_D at $V_G < V_T$) increases due to irradiation. However, the shift of I_D–V_G curves and the increase in leakage currents for both SiC and Si MOSFETs are clearly suppressed by irradiation at 150 °C. Yokoseki et al. reported that the degraded characteristics of SiC MOSFETs due to gamma-ray irradiation were recovered by annealing above 120 °C.[25] The result obtained in this study can be explained in terms that positive charge generated in gate oxide due to irradiation is partially annealed by elevated temperature during irradiation since the shift of I_D–V_G curves to negative voltage side occurs due to positive charge generated in the gate oxide. For the slope of I_D–V_G curves, no significant change is observed for SiC MOSFETs irradiated at RT as well as 150 °C. On the other hand, the slope of I_D–V_G curves for Si MOSFETs decreases from irradiation at RT, while the change in slope is suppressed by irradiation at 150 °C. Since the slope of I_D–V_G curves becomes shallow from the generation of interface traps, the obtained results indicate that the number of interface traps generated between SiC and SiO_2 is lower than that between Si and SiO_2, and that interface traps between Si/SiO_2 are less thermally stable than those between SiC/SiO_2.[26,27] For the large increase in leakage current, charge generated in thick oxide such as field oxide might act as the surface potential applied to the MOSFETs. As a result, the leakage path might be generated at the surface of the samples. However, the detailed origin of the leakage current has not yet been clarified. Further investigation is necessary to understand the origin of this large increase in leakage current due to irradiation.

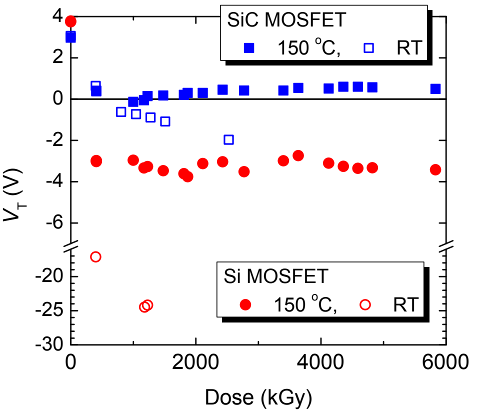

Fig. 2. (Color online) Values of V_T as a function of gamma-ray dose. Squares and circles symbols indicate results obtained from SiC and Si MOSFETs, respectively. Closed and open symbols indicate results obtained by irradiation at 150 °C and RT, respectively.

The values of V_T are 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. The values of V_T as a function of gamma-ray absorbed dose are plotted in Fig. 2. The squares and circles indicate results obtained from SiC and Si MOSFETs, respectively. The closed and open symbols indicate results obtained from samples irradiated at 150 °C and RT, respectively. The V_T for all MOSFETs decreases with increasing absorbed dose. However, the decrease in V_T for both SiC and Si MOSFETs saturates at doses above 1 MGy in the case of 150 °C irradiation (actually, for SiC, a slight recovery is observed up to 2 MGy, and then the value saturates) although V_T for SiC and Si MOSFETs irradiated at RT decreases with increasing absorbed dose. This suggests that the operation at elevated temperature is useful for extending lifetime of SiC MOSFETs in radiation environments.

Figure 3 shows absorbed dose dependence of subthreshold voltage swing (S) for SiC and Si MOSFETs. The values of S normalized by the initial value are plotted in Fig. 3. In this study, the S values for MOSFETs irradiated at 150 °C and RT were estimated from $dV_G/d\log I_D$ between 10^{-6} and 10^{-4} A, and between 10^{-4} and 10^{-3} A, respectively. Because the hump appeared after irradiation, the S values could not be evaluated from $dV_G/d\log I_D$ below 10^{-6} A for samples irradiated at 150 °C and 10^{-4} A for samples irradiated at RT. The initial values of S for SiC and Si MOSFETs irradiated at 150 °C were 0.38 and 0.29 V/log(A), respectively. As shown in Fig. 3, no significant change or slight decrease in normalized S values for SiC MOSFETs irradiated

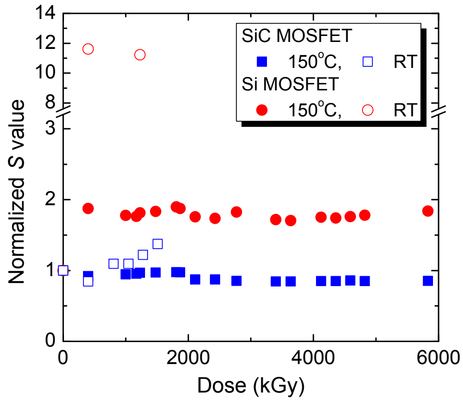

Fig. 3. (Color online) Absorbed dose dependence of subthreshold voltage swing (S) non-irradiated for SiC (squares) and Si MOSFETs (circles). The normalized values of S by the initial value are plotted in the figure. In this study, the values of S for MOSFETs irradiated at 150 °C (closed) and RT (open) were estimated from $dV_G/d\log I_D$ between 10^{-6} and 10^{-4} A, and between 10^{-4} and 10^{-3} A, respectively.

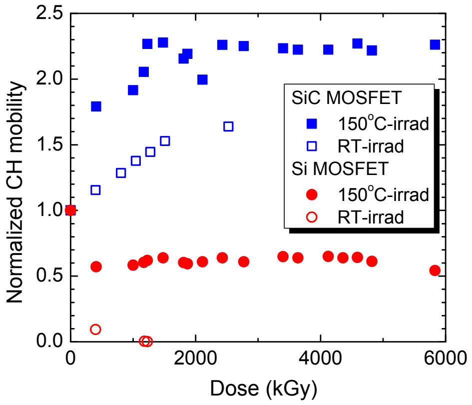

Fig. 4. (Color online) Absorbed dose dependence of channel mobility normalized by the non-irradiated value for SiC (squares) and Si MOSFETs (circles). The results obtained for 150 °C and RT irradiation are plotted as closed and open symbols, respectively.

at 150 °C was observed although the S values slightly increased with increasing absorbed dose for SiC MOSFETs irradiated at RT. For Si MOSFETs, although the S values increase by irradiation, the increase is obviously suppressed by irradiation at 150 °C, and no significant further increase in the S values is observed above 400 kGy in the case of irradiation at 150 °C. Those results indicate that the generation of interface traps is suppressed by irradiation at 150 °C. Comparing SiC with Si, the increase in normalized S values for SiC MOSFETs is smaller than that for Si MOSFETs. This result suggests that the generation of interface traps for SiC MOS structures is lower than that for Si MOS structures because S value increases with increasing interface trap density. It also should be mentioned that interface traps near the midgap of SiC (deep levels from the conduction band) might act as fixed charge since interface traps with deep levels in wide bandgap semiconductors need quite a long time to release captured-charge. Thus, S value is not affected by the generation of such deep interface traps. Since such deep interface traps cannot be separated from charge trapped in oxide, deep interface traps are counted as charge trapped in oxide, and only interface traps responding to gate bias are defined as interface traps in this study. In any case, the generation of such deep interface traps is also suppressed by 150 °C irradiation since V_T as well as S are less affected by irradiation at 150 °C than by irradiation at RT.

Because interface traps are known to degrade transport properties in channel,[26,27] the change in channel mobility from irradiation was evaluated. Figure 4 shows the absorbed dose dependence of channel mobility for MOSFETs. The values of the channel mobility (μ_n) normalized by the initial value (μ_{n0}) are plotted in this figure. Although the MOSFETs in this study have a vertical structure, the channel mobility for MOSFETs was simply estimated using the formula:

$$\frac{\partial I_d}{\partial V_g} = \frac{Z}{L}\mu_n C_{OX} V_d, \tag{1}$$

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 region (epitaxial layer and substrate) do not change in this dose range and that the mobility is mainly affected by interface traps generated by irradiation. The values of μ_n/μ_{n0} for SiC MOSFETs increase with increasing absorbed dose and saturate around 1 MGy. In addition, the values of μ_n/μ_{n0} for SiC MOSFETs irradiated at 150 °C are larger than those irradiated at RT. On the other hand, the values of μ_n/μ_{n0} for Si MOSFETs irradiated at 150 °C decrease with increasing absorbed dose and the decrease saturates around 400 kGy, although the decrease in μ_n/μ_{n0} with increasing absorbed dose is observed for Si MOSFETs irradiated at RT. As shown in Fig. 3, S value for Si MOSFETs irradiated at 150 °C increases and saturates around 400 kGy. Also, Si MOSFETs irradiated at RT have a larger S value than those irradiated at 150 °C. Since S value increases with increasing interface traps, the radiation response of μ_n/μ_{n0} for Si MOSFETs can be explained by the generation of interface traps. On the other hand, for SiC MOSFETs, the radiation response of μ_n/μ_{n0} cannot be understood in terms of interface traps because S value for SiC MOSFET irradiated at RT increases in spite of the increase in μ_n/μ_{n0}. Although the mechanism of radiation response of channel mobility for SiC MOSFETs has not yet fully revealed, it can be mentioned that irradiation at elevated temperature is effective from the point of view of the improvement of transport properties in channel region of SiC MOSFETs.

The density of effective charge (ΔN_{eff}) which gives rise to the shift of V_T (ΔV_T) is estimated by a following equation:

$$\Delta N_{\mathrm{eff}} = \frac{\varepsilon_{OX}\varepsilon_0}{qd}\Delta V_T, \tag{2}$$

where ε_{OX}, ε_0, q, and d are static permittivity of SiO_2, vacuum permittivity, electron charge, and gate oxide thickness, respectively. First, it should be mentioned that the ΔV_T is affected by both charge trapped in gate oxide and interface traps. The relationships are expressed by following equations:

$$\Delta V_T = \Delta V_{OX} + \Delta V_{IT}, \tag{3}$$

$$\Delta V_{OX} = \Delta V_{\mathrm{mid}}, \tag{4}$$

$$\Delta V_{IT} = (V_T - V_{\mathrm{mid}})_{\mathrm{post}} - (V_T - V_{\mathrm{mid}})_{\mathrm{pre}}, \tag{5}$$

where ΔV_{OX} and ΔV_{IT} are the voltage shifts due to the generation of oxide-trapped charges and interface traps, respectively. ΔV_{mid} is the shift of the midgap voltage due to

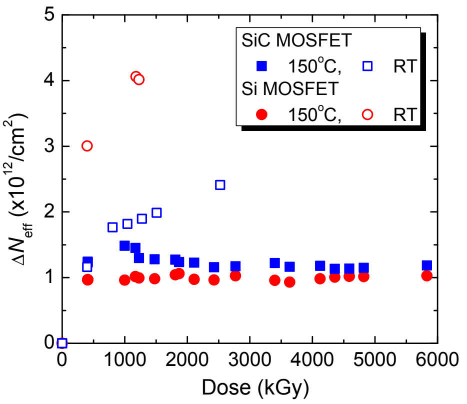

Fig. 5. (Color online) Absorbed dose dependence of ΔN_{eff} for SiC (squares) and Si MOSFETs (circles). The results obtained for 150 °C and RT irradiation are plotted as closed and open symbols, respectively.

irradiation. "post" and "pre" denote after and before irradiation, respectively. To distinguish the voltage shift due to the generation of trapped-charge from that due to the generation of interface traps, it is necessary to know the value of I_D at midgap (V_{mid}).[23] However, it is difficult to estimate accurate value of I_D at V_{mid} for SiC MOSFETs in this study because hump appeared due to irradiation, as shown in Fig. 1. Since the S values (thus, the slope of I_D–V_G curves) for SiC MOSFET irradiated at 150 °C hardly changes due to irradiation, it can be assumed that the shift of V_T for SiC MOSFET irradiated at 150 °C mainly occurs by the generation of charge trapped in gate oxide. For Si and SiC MOSFETs irradiated at RT, interface traps must be generated by irradiation because the increase in S value is observed after irradiation. The value of V_T shifts towards increasing positive voltages from the generation of interface trap. Thus, the shift of V_T due to the generation of charge trapped in oxide is cancelled out by the generation of interface traps. Therefore, the values of ΔN_{eff} obtained for Si and SiC MOSFETs irradiated at RT are smaller than the actual density of charge trapped in the gate oxide. Figure 5 shows the absorbed dose dependence of ΔN_{eff} for SiC and Si MOSFETs in the cases of irradiation at RT and 150 °C. The values of ΔN_{eff} for SiC MOSFETs irradiated at 150 °C show a small increase to $1.5 \times 10^{12}/\text{cm}^2$ around 1 MGy and slightly decrease to $1.2 \times 10^{12}/\text{cm}^2$ up to 2 MGy. Above 2 MGy, the saturation of ΔN_{eff} is observed. For SiC MOSFETs irradiated at RT, the ΔN_{eff} increases with increasing dose and reaches $2.4 \times 10^{12}/\text{cm}^2$ at 2.5 MGy. On the other hand, the values of ΔN_{eff} for Si MOSFETs irradiated at 150 °C stays around $1.0 \times 10^{12}/\text{cm}^2$ up to 5.8 MGy although the value of ΔN_{eff} for Si MOSFETs irradiated at RT increases with increasing absorbed dose and has a value of $4.0 \times 10^{12}/\text{cm}^2$ around 1 MGy. As mentioned above, since the value of ΔN_{eff} for Si MOSFETs might be underestimated, we cannot compare the results obtained from SiC MOSFETs to those from Si MOSFETs. However, at least, we can say that irradiation at elevated temperature suppresses the generation of N_{eff}, i.e., the V_T shift.

4. Summary

Vertical structure 4H-SiC power MOSFETs were irradiated with gamma-rays at 150 °C up to 5.8 MGy. Although their I_D–V_G curves shifted to negative voltages and the leakage of I_D increased due to gamma-ray irradiation, the degradation of their characteristics was suppressed by irradiation at 150 °C, compared to the results obtained from RT-irradiation. For S values, no significant change or slight decrease for SiC MOSFETs irradiated at 150 °C was observed although the values slightly increased with increasing dose for samples irradiated at RT. The channel mobility of SiC MOSFETs increased with increasing dose and the value did not change above 1 MGy, and the increase for SiC MOSFETs irradiated at 150 °C was larger than those irradiated at RT.

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