Phys. Status Solidi A **214,** No. 4, 1600446 (2017) / **DOI** 10.1002/pssa.201600446

physica status solidi a
www.pss-a.com
applications and materials science

Impacts of gate bias and its variation on gamma-ray irradiation resistance of SiC MOSFETs

Koichi Murata[*,1,2], Satoshi Mitomo[1,2], Takuma Matsuda[1,2], Takashi Yokoseki[1,2], Takahiro Makino[2], Shinobu Onoda[2], Akinori Takeyama[2], Takeshi Ohshima[2], Shuichi Okubo[3], Yuki Tanaka[3], Mikio Kandori[3], Toru Yoshie[3], and Yasuto Hijikata[,1]**

[1] Saitama University, Sakuraku, Saitama 338-8570, Japan
[2] National Institutes for Quantum and Radiological Science and Technology (QST), Takasaki 370-1292, Japan
[3] Sanken Electric Co., Ltd., Niiza, Saitama 352-8666, Japan

Received 20 June 2016, revised 21 October 2016, accepted 21 October 2016
Published online 7 November 2016

Keywords gamma-ray irradiation, gate bias, MOSFETs, SiC

[*] Corresponding author: e-mail murata@opt.ees.saitama-u.ac.jp, Phone: +81 488 583 465, Fax: +81 488 580 940
[**] e-mail yasuto@opt.ees.saitama-u.ac.jp, Phone: +81 488 583 822, Fax: +81 488 583 822

Gamma-ray irradiation into vertical type n-channel hexagonal (4H)-silicon carbide (SiC) metal-oxide-semiconductor field effect transistors (MOSFETs) was performed under various gate biases. The threshold voltage for the MOSFETs irradiated with a constant positive gate bias showed a large negative shift, and the shift slightly recovered above 100 kGy. For MOSFETs with non- and a negative constant biases, no significant change in threshold voltage, V_{th}, was observed up to 400 kGy. By changing the gate bias from positive bias to either negative or non-bias, the V_{th} significantly recovered from the large negative voltage shift induced by 50 kGy irradiation with positive gate bias after only 10 kGy irradiation with either negative or zero bias. It indicates that the positive charges generated in the gate oxide near the oxide–SiC interface due to irradiation were removed or recombined instantly by the irradiation under zero or negative biases.

1 Introduction High radiation resistant devices are required for decommissioning of the TEPCO Fukushima Daiichi nuclear power plant. Silicon carbide (SiC) is expected as a semiconductor material applied to electronic devices used in such an extremely high radiation environment, owing to its high radiation resistance [1–12] as well as excellent characteristics as power devices [13, 14]. With respect to radiation hardness, Sellina and Vaitkus suggested that SiC and GaN are promising candidates as radiation hard semiconductor dectectors [6]. Dixit et al. reported radiation response of nitrided and non-nitrided SiO_2/4H-SiC MOS Capacitors [7]. Tanaka et al. demonstrated 10 MGy tolerance of 4H-SiC buried gate static induction transistors (BGSITs) [9]. 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 [10]. Although electronic devices with the normally-off characteristic are preferable for the power electronics applications, it is difficult to fabricate BGSITs with the normally-off characteristic. metal-oxide-semiconductor field effect transistors (MOSFETs) can easily realize the normally off and low power-loss characteristics, hence, we have investigated the radiation resistance of SiC MOSFETs [15–18]. In our previous study, the radiation response of 4H-SiC MOSFETs up to 1.2 MGy and their annealing effects up to 360 °C were reported [15, 16]. Akturk et al. reported that 4H-SiC MOSFETs irradiated with gamma-rays under gate voltage of 18 V showed the threshold voltage (V_{th}) shift of the negative voltage side, though in their experiments the total dose of gamma-ray was restricted to several tens of kGy [12].

Recently, we found that the radiation degradation of electrical characteristic of SiC-MOSFET was suppressed when SiC-MOSFETs installed in a motor-driver circuit were irradiated with gamma-rays under switching operation [18]. It suggests that the charges generated in gate oxide or/and SiC–oxide interface due to irradiation were removed or recombined under switching condition. In the previous case of Si MOS device, it is reported that the threshold voltage rebounded by applying variable bias to the gate electrode during irradiation [19]. In this study, the relation between bias condition and gamma-ray irradiation response of 4H-SiC MOSFETs was investigated by applying a constant or variable bias to gate electrode during irradiation.

2 Experimental Vertical type n-channel 4H-SiC MOSFETs with the blocking voltage of 1200 V and the rated current of 20 A were used in this study. The gate oxides with the thickness of 45 nm were grown by dry oxidation and subsequent nitridation treatment. The MOSFETs were mounted in "TO3P" packages. Gamma-ray irradiation were performed using ^{60}Co sources at dose rates of 1–10 kGy(SiO_2)h^{-1} up to 2.5 MGy at room temperature (RT) in a N_2 atmosphere at Takasaki Advanced Radiation Research Institute, QST [20]. Constant bias of +4.5 V (i.e., 1.0 MV cm^{-1}), 0 V, or −4.5 V was applied to the gate electrode of each MOSFET (the source and drain were grounded). The drain current (I_D)–gate voltage (V_G) characteristics of the MOSFETs were measured before and after gamma-ray irradiation using a semiconductor parameter analyzer (Agilent 4156B) and a power device analyzer (Agilent B1505A) at RT. The value of V_{th} was estimated from the value at the intersection between the V_G axis and the line extrapolated from the square root of I_D in the saturation region.

Next, gamma-ray irradiation in the cases of variable gate bias was also carried out. The MOSFETs initially biased with +4.5 V were irradiated at a dose rate of 10 kGy(SiO_2) h^{-1} up to 50 kGy at RT in a N_2 atmosphere. After that, the samples were aged at RT for 470 h under non-biased condition to observe stability of the electrical characteristics. Subsequently, these samples were irradiated again with no or negative bias (0 or −4.5 V, respectively). The bias conditions are summarized in Table 1.

3 Results and discussion

3.1 Constant gate bias condition Figures 1–3 show the typical I_D–V_G curves in the subthreshold region for SiC MOSFETs irradiated with constant positive gate bias (+4.5 V), non-bias (0 V), and negative gate bias (−4.5 V). It is seen from the figures that the initial (0 kGy) values of V_{th} are scattered among samples by at most 0.4 V. Although we think that this scattering within this range is allowable to investigate the radiation response of SiC MOSFETs, we adopt the increment of threshold voltage ΔV_{th} instead of V_{th} in order to minimize the uncertainty as low as possible. The value of ΔV_{th} is determined by subtracting the threshold voltage of non-irradiated sample from that of irradiated sample. As previously shown in Ref. [16], ΔV_{th} can cancel out the effect

Table 1 Gate bias conditions.

notation	gate bias voltage 0–50 kGy	W/O irradiation	50–100 kGy
+/0 bias	+4.5 V	0 V for 470 h	0 V (Ground)
±bias	+4.5 V		−4.5 V

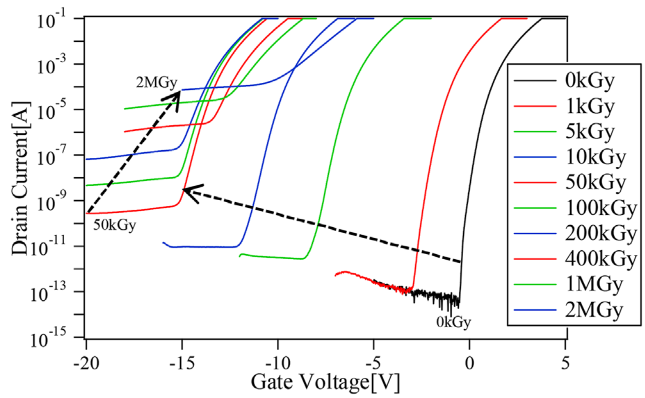

Figure 1 I_D versus V_G curves in the subthreshold region for SiC MOSFET with positive bias before and after irradiation.

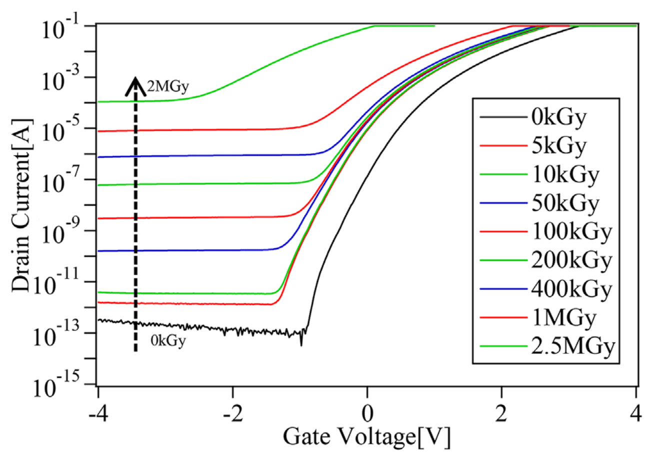

Figure 2 I_D versus V_G curves in the subthreshold region for SiC MOSFET with non-bias before and after irradiation.

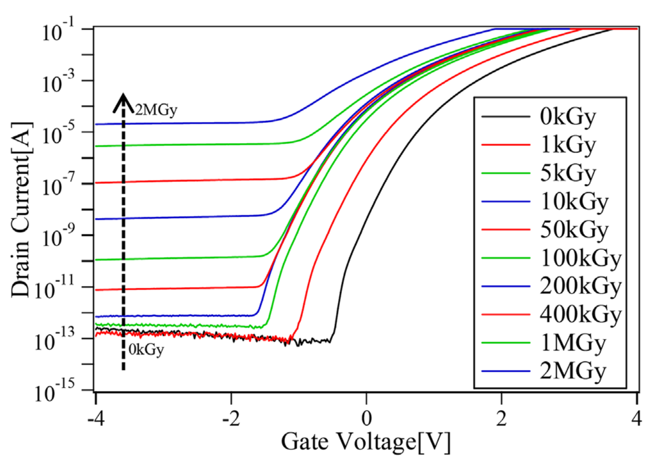

Figure 3 I_D versus V_G curves in the subthreshold region for SiC MOSFET with negative bias before and after irradiation.

of the initial V_{th} value. In addition, since applied biases of $\pm$4.5 V were quite larger than the scattering of initial V_{th}, it is considered that the gate voltage V_G was applied by the same manner to these samples.

The I_D–V_G curves for MOSFETs with positive bias largely shifted to negative voltage side with total dose of gamma-rays. Increases in leakage current with increasing doses were also observed for all the samples. In addition to these experiments, we measured I_D–V_G curves for an un-irradiated sample biased with the same positive gate voltage without irradiation (not shown here). The curve hardly shifted to negative voltage side even after biasing of 24 h. Therefore, the large negative shift of I_D–V_G curve is induced only by the irradiation under positively biased condition.

Figure 4 shows the shift of V_{th} from the non-irradiated value (ΔV_{th}) as a function of absorbed dose. The circles, squares, and triangle symbols indicate the observed values obtained from the MOSFETs with positive, non-, and negative biases, respectively. A large negative shift due to irradiation was seen in the case of positive bias, and the shift recovered at above 100 kGy. For irradiation with non- and negative gate biases, no significant change in V_{th} was observed up to 800 kGy. However, at above 800 kGy, the ΔV_{th} for irradiation with non-bias decreased although that for negative bias showed a little reduction. In previous studies on gamma-ray irradiation effects for Si MOSFETs [21–23], it is reported that holes of electron-hole pairs generated by gamma-ray irradiation in the gate oxide are trapped at intrinsic defects of the oxide near the Si/SiO_2 interface, leading to the negative shift of I_D–V_G characteristic of MOSFET [24]. If holes are pushed to the Si/SiO_2 interface side by positive bias, a large V_{th} shift is observed. On the other hand, the V_{th} shift is suppressed by negative bias since holes are swept away from the interface [25]. The results obtained for SiC MOSFETs in this study can be interpreted in terms of the same manner although defects located near the SiC–SiO_2 interface might be different from that near the Si–SiO_2 interface.

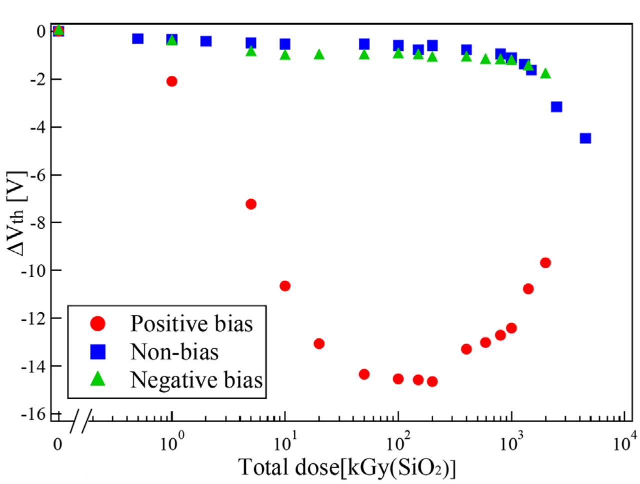

Figure 4 Dependence of ΔV_{th} on absorbed dose for SiC MOSFETs with positive, non-, and negative biases.

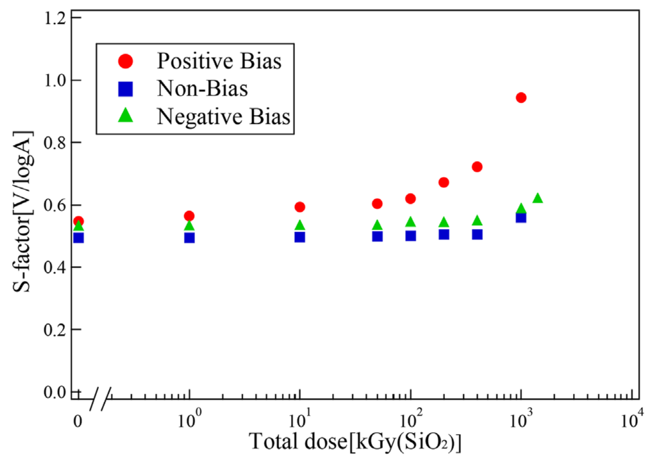

Figure 5 Dependence of *S*-factor on absorbed dose for SiC MOSFETs with positive, non-, and negative biases. The values of subthreshold swing were estimated from the changes of V_G in I_D between 10^{-4} and 10^{-3} A.

Figure 5 shows the subthreshold swing (*S*-factor) as a function of absorbed dose. In this study, the values of *S*-factor were estimated from the changes of V_G in I_D between 10^{-4} and 10^{-3} A, because the subthreshold current below 10^{-4} A was significantly increased by gamma-ray irradiation. The large increase in *S*-factor for MOSFETs with positive bias is observed at above 100 kGy. For MOSFETs with non- and negative gate biases, no significant increase in *S*-factor was observed. Since the *S*-factor is presumably proportional to the density of interface traps, this result suggests that interface traps increases due to irradiation from 100 kGy and the electron trapping is remarkably enhanced by the irradiation with positive bias.

Figure 6 shows increase of trap density in oxide against the non-irradiated value (ΔN) as a function of absorbed dose. We calculated oxide and interface trapped charges by the following formulae [4, 26]:

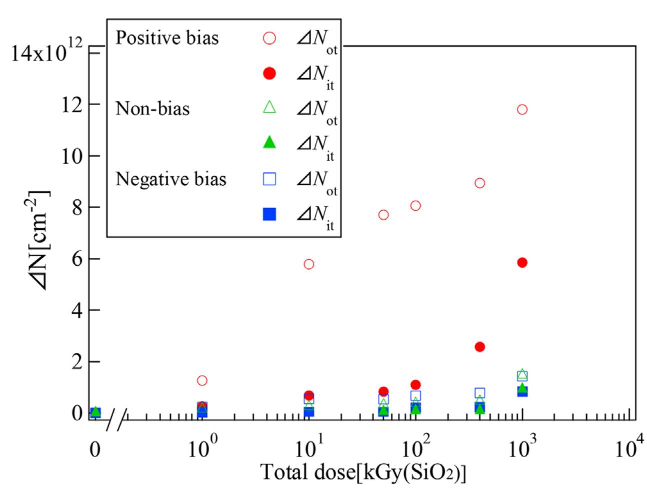

Figure 6 Dose dependence of trap densities in oxide and at interface for SiC MOSFETs irradiated with positive, non-, and negative biases.

$$I_D = \sqrt{2}C_m\left(qN_A\frac{L_b}{\beta}\right)\left(\frac{n_i}{N_A}\right)^2 \exp(\beta\phi_s)/\sqrt{\beta\varphi_s}, \quad (1)$$

$$\Delta V_{th} = \Delta V_{ox} + \Delta V_{it}, \quad (2)$$

$$\Delta N_{OX} = \Delta V_{ox} C_{OX}/q, \quad (3)$$

$$\Delta N_{it} = \Delta V_{it} C_{OX}/q, \quad (4)$$

where, C_m, is $\mu(W/2L)$, N_A is the channel doping, L_b is Debye length given by $[\varepsilon_s/(\beta q N_A)]^{1/2}$, ϕ_s the band bending at the surface, n_i is the intrinsic carrier concentration and β is equal to q/k_BT, where q and k_B are the electron charge and the Boltzmann constant, respectively, and C_{OX} is oxide capacitance per area equal to ε_{OX}/t_{OX}, and ε_{OX}, and t_{OX} are the dielectric constant and the thickness of gate oxide, respectively, and the subscripts "ox" and "it" mean the corresponding values for oxide and interface, respectively.

For MOSFETs with no and negative gate biases, no significant increase was aroused. For the positive-biased sample, the amount of trapped holes in oxide increased with increasing dose. The positive charge of holes shifted threshold voltage to negative voltage side. Whereas, interface trapped charge increased above 100 kGy. We consider that the negative charge trapped at the interface compensates the positive charge trapped in oxide, and, as a result, the recovery of threshold voltage V_{th} above 100 kGy appears.

Figure 7 shows normalized channel mobilities of SiC MOSFETs as a function of absorbed dose. The values of normalized channel mobility are the ratios of channel mobility (μ_{ch}) to the initial (non-irradiated) value (μ_{ch0}), where the values of μ_{ch} were obtained from the maximum in the range of $V_G > V_{th}$. In general, channel mobility depends on V_G and is estimated from the following equation:

$$\frac{\delta I_D}{\delta V_D} = \frac{Z}{L}\mu_{CH} C_{OX}(V_G - V_{th}), \quad (5)$$

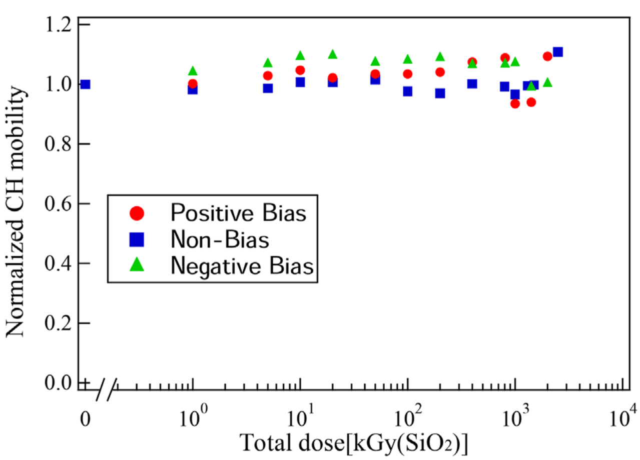

Figure 7 Dependence of the μ_{CH}/μ_{CH0} for SiC MOSFETs irradiated with positive, non-, and negative biases.

where Z and L are gate width and gate length, respectively. No significant change in the normalized mobility is observed with increasing dose for all the cases of biases. In contrast, the S-factor in the case of positive bias increased from 100 kGy, which corresponds to the reduction of channel mobility in general. Since channel mobility is deteriorated complexly by interface state density near the conduction band edge [27], the value of V_{th} and so on, the negative effect due to the irradiation on channel mobility (e.g., increase in interface state density) might be compensated by some positive effect.

3.2 Variable gate bias condition Figures 8 shows the I_D–V_G curves in the subthreshold region for SiC MOSFETs irradiated with variable biases from +4.5 to 0 V and from +4.5 to −4.5 V, respectively (hereafter, +/0 bias and ±bias, respectively). Here, the duration of +bias was the irradiation time corresponding to total dose of 50 kGy. For both bias cases, the I_D–V_G curves of MOSFETs with initial gate bias of +4.5 V significantly shifted to negative voltage side as mentioned above. On the contrary, after changing the bias to zero or negative, the I_D–V_G curves immediately recovered to positive voltage side though the leakage current slightly increased.

Figure 9 shows ΔV_{th} for SiC MOSFETs with +/0 bias and ±bias as a function of dose up to 100 kGy. As observed in Fig. 4 (constant bias condition), the ΔV_{th} during positive bias applied shifts extremely to the negative voltage side. Figure 10 shows ΔV_{th} as a function of aging time at RT after 50 kGy irradiation with positive bias. As shown in Fig. 10,

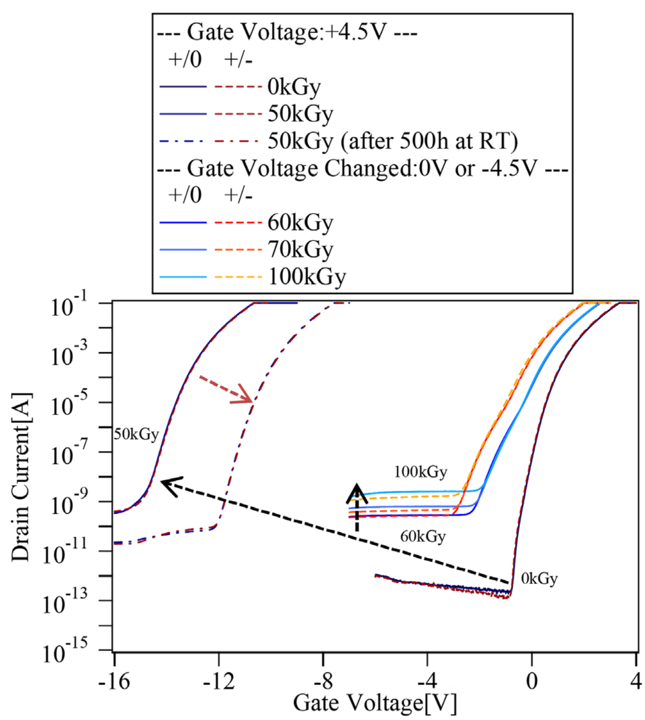

Figure 8 ID versus VG curves in the subthreshold region for SiC MOSFET with +/0 and ± bias before and after irradiation.

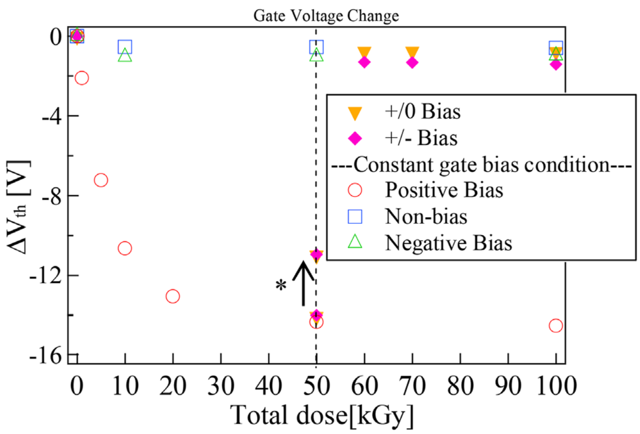

Figure 9 Dependence of ΔV_{th} on absorbed dose for SiC MOSFETs with +/0 bias, ± bias, and results of Section 3.1. (*The detail is shown in Fig. 10.)

ΔV_{th} recovered by about 3 V after RT aging. While, further irradiation of SiC MOSFETs with changing the bias to zero or negative, the ΔV_{th} drastically recovered only by 10 kGy irradiation for 1 h. For the +/0 and ±bias conditions, each the recovery of ΔV_{th} is comparable to the value in the case of constant bias condition. Namely, the recovery of ΔV_{th} in the case of ±bias was slightly smaller than in the case of +/0 bias by 0.6 V. No further significant change in ΔV_{th} was observed for either +/0 or ±bias until 100 kGy.

We carried out additional irradiation of 10 kGy (total dose: 110 kGy) under zero bias with respect to the MOSFETs irradiated with ±bias condition (denotes +/−/0). Similarly, the +/0 biased sample was also irradiated for comparison (denoted +/0/0). Figure 11 shows ΔV_{th} for SiC MOSFET as a function of dose between 50 and 110 kGy. At 110 kGy, ΔV_{th} for the +/−/0 biased sample is the same as that for +/0/0 biased sample, which is beyond the value in case of constant negative bias and is close to that in the case of constant non-bias. These results suggest that

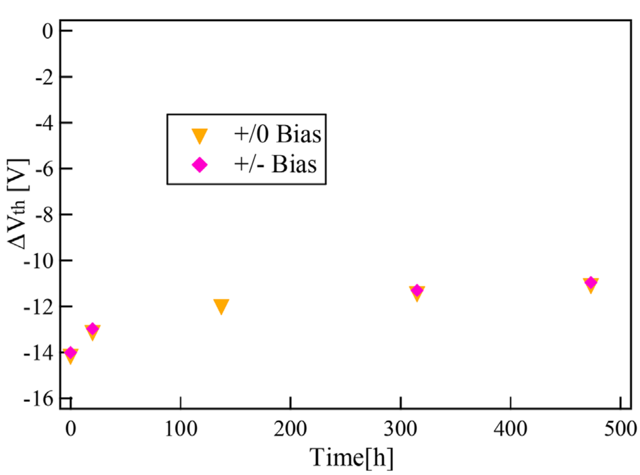

Figure 10 The recovery of V_{th} by 470 h of room temperature aging.

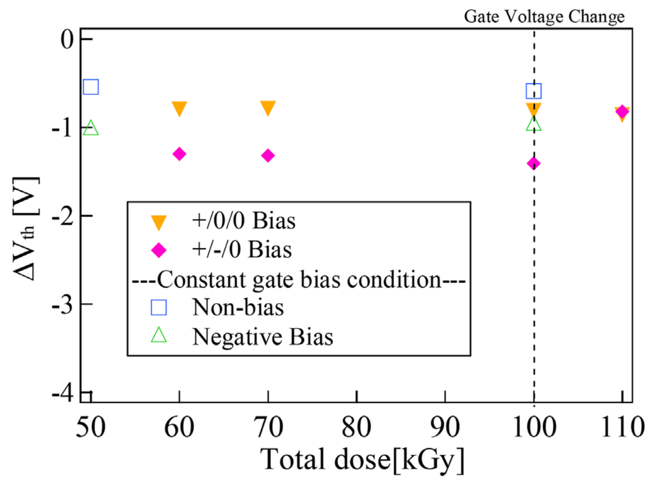

Figure 11 Dependence of ΔV_{th} for SiC MOSFET irradiated additional irradiation 10 kGy.

irradiation under zero bias is more efficient than that under negative bias in order to recover the V_{th}.

Figure 12 shows the *S*-factor as a function of absorbed dose between 0 and 110 kGy. As shown in the figure, the *S*-factors instantly decreased after the bias is switched from positive to non-/negative bias. This means that electrons trapped at the interface states were smoothly detrapped by the irradiation with non-/negative bias, similarly to V_{th}. The figure also shows that the values of *S*-factor both for the +/0/0 and +/−/0 biased samples were almost the same values with each other and were larger than that for constant non-biased samples over all the total dose region measured. This suggests that the degree of recovery due to the irradiation is not different regardless of negative bias or non-bias, although that of ΔV_{th} is slightly different.

Figure 13 shows trap density in oxide and at interface for SiC MOSFETs irradiated with +/0/0 and +/−/0 bias

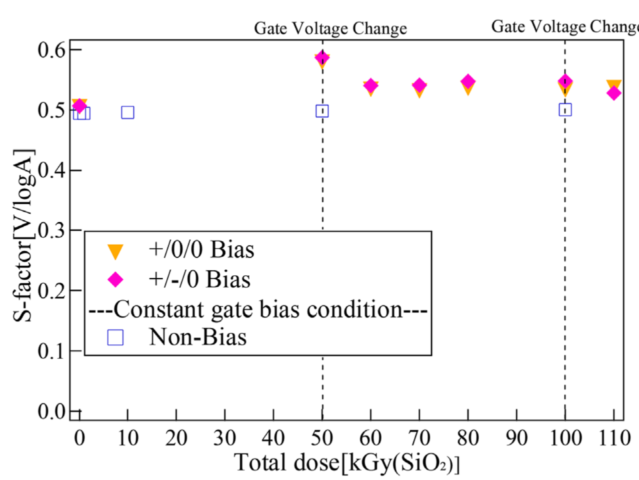

Figure 12 Dependence of *S*-factor on absorbed doses for SiC MOSFETs with +/0/0, +/−/0, and non-bias conditions. The values of *S*-factor were estimated from the changes of V_G in I_D between 10^{-4} and 10^{-3} A.

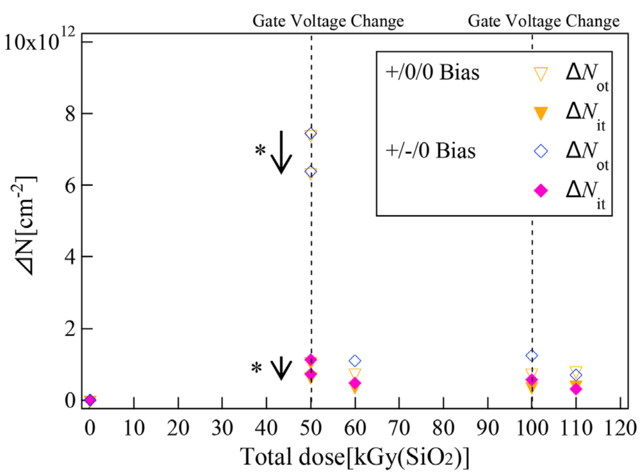

Figure 13 Dose dependence of trap densities in oxide and at interface for SiC MOSFETs irradiated with +/0/0 and +/−/0 bias conditions. (*The recovery of ΔN by 470 h of room temperature aging.)

conditions. It is observed that ΔN_{ot} of both samples remarkably decreases after changing the bias from positive to zero or negative. In contrast, decrement of ΔN_{it} is relatively small. This indicates significant recovery of ΔV_{th} when switching the bias is originated from annihilation of trapped holes in oxide.

4 Conclusions

Vertical type 4H-SiC MOSFETs were irradiated with gamma-rays under various gate bias conditions. The threshold voltage V_{th} for the MOSFETs irradiated with constant positive gate bias showed a large negative shift, and the shift recovered above 100 kGy, which is probably due to the electron traps at the interface states formed by the irradiation. In addition, it was found that RT aging has a small effect for the recovery from the large V_{th} shift due to the irradiation with positive bias. For MOSFETs with constant non- and negative gate biases, no significant change in ΔV_{th} was observed up to 800 kGy. Based on the results, the reason for the negative shift due to irradiation is interpreted as the accumulation of holes near the SiC/SiO_2 interface as in the analogy for Si MOSFET. On the other hand, the subthreshold swings (S-factors) for the MOSFET with positive bias showed a large increase from 100 kGy although that for negative or non-bias showed a small increase from 800 kGy. Therefore, the irradiation with positive bias also has an effect for enhancing the electron trapping at the interface state.

Under variable gate bias condition, the ΔV_{th} remarkably shifted toward positive voltage side due to only 10 kGy irradiation after varying the gate bias from positive to either negative or zero. This indicates that holes generated by the irradiation are removed or recombined under zero/negative bias condition. In addition, the S-factor and interface trapped charge also recovered by further irradiation with positive/non-bias, similarly with V_{th}. This suggests that the electrons trapped at the SiC–oxide interface were smoothly detrapped by the irradiation with positive/non-bias. In conclusion, the remarkable degradation of electrical characteristics due to irradiation with positive gate bias can be instantly improved when the gate bias is switched to negative/zero, indicating the high radiation resistance of SiC MOSFETs if they are operated in switching bias condition such as an inverter application.

Acknowledgement This study was carried out under the Nuclear Science Research Initiative of Japan.

References

[1] M. Bhatnagar and B. J. Baliga, in: Proc. 3rd Int. Symposium on Power Semiconductor Devices & ICs, ISPSD **91**, (1991) pp. 176–180.
[2] C. E. Weitzel, J. W. Palmour, C. H. Carter, K. Moore, K. K. Nordquist, S. Allen, C. Thero, and M. Bhatnagar, IEEE Trans. Electron Devices **43**, 1732–1741 (1996).
[3] J. B. Casady and R. W. Johnson, Solid-State Electron. **39**, 1409–1422 (1996).
[4] T. Ohshima, M. Yoshikawa, H. Itoh, Y. Aoki, and I. Nashiyama, Mater. Sci. Eng. **61**, 480–484 (1999).
[5] A. Elasser and T. P. Chow, IEEE Proc. **90**, 969–986 (2002).
[6] P. J. Sellina and J. Vaitkus, Nucl. Instrum. Methods Phys. Res. A **557**, 479–489 (2006).
[7] S. K. Dixit, S. Dhar, J. Rozen, S. Wang, R. D. Schrimpf, D. M. Fleetwood, S. T. Pantelides, J. R. Williams, and L. C. Feldman, IEEE Trans. Nucl. Sci. **53**, 3687 (2006).
[8] T. R. McNutt, A. R. Hefner, H. A. Mantooth, D. Berning, and S.-H. Ryu, IEEE Power Electron. **22**, 353–363 (2007).
[9] Y. Tanaka, S. Onoda, A. Takatsuka, T. Ohshima, and T. Yatsuo, Mater. Sci. Forum **645–648**, 941–944 (2010).
[10] C. Zhang, E. Zhang, D. M. Fleetwood, R. D. Schrimpf, S. Dhar, S. Ryu, X. Shen, and S. T. Pantelides, IEEE Trans. Nucl. Sci. **58**, 2925 (2011).
[11] Y. Katoh, L. Snead, I Szlufarska, and W. Weber, Curr. Opin. Solid State Mater. Sci. **16**, 143–152 (2012).
[12] A. Akturk, J. M. McGarrity, S. Potbhare, and N. Goldsman, IEEE Trans. Nucl. Sci. **59**, 3258–3264 (2012).
[13] H. Matsunami, Jpn. J. Appl. Phys. **43**, 6835–6847 (2004).
[14] T. Kimoto, Jpn. J. Appl. Phys. **54**, 040103 (2015).
[15] T. Yokoseki, H. Abe, T. Makino, S. Onoda, Y. Tanaka, M. Kandori, T. Yoshie, Y. Hijikata, and T. Ohshima, Mater. Sci. Forum **821–823**, 705–708 (2015).
[16] T. Ohshima, T. Yokoseki, K. Murata, T. Matsuda, S. Mitomo, H. Abe, T. Makino, S. Onoda, Y. Hijikata, Y. Tanaka, M. Kandori, S. Okubo, and T. Yoshie, Jpn. J. Appl. Phys. **55**, 01AD01 (2016).
[17] T. Matsuda, T. Yokoseki, S. Mitomo, K. Murata, T. Makino, H. Abe, A. Takeyama, S. Onoda, Y. Tanaka, M. Kandori, T. Yoshie, Y. Hijikata, and T. Ohshima, Mater. Sci. Form **858**, 860–863 (2016).
[18] Y. Kobayashi, T. Yokozeki, T. Matsuda, S. Mitomo, K. Murata, M. Hachisuka, Y. Kaneko, T. Makino, A. Takeyama, S. Onoda, T. Ohshima, Y. Tanaka, M. Kandori, T. Yoshie, and Y. Hijikata, Mater. Sci. Forum **858**, 868–871 (2016).
[19] A. Faigón, M. GarcíaInza, J. Lipovetzky, E. Redin, S. Carbonetto, L. Sambuco Salomone, and F. Berbeglia, Radiat. Phys. Chem. **95**, 44–46 (2014).

[20] Takasaki Advanced Radiation Research Institute, QST, www.taka.qst.go.jp/index_e.html

[21] G. C. Messenger, E. J. Steele, and M. Neustadt, IEEE Nucl. Sci **12**, 78–82 (1965).

[22] G. S. Anant, IEEE Nucl. Sci. **30**, 4094–4099 (1983).

[23] R. W. Tallon, M. R. Ackermann, W. T. Kemp, M. H. Owen, and D. P. Saunders, IEEE Nucl. Sci. Trans. **32**, 4393 (1985).

[24] E. H. Nicollian and J. R. Brews, MOS Physics and Technology (Wiley Interscience, New York, 2003), p. 549.

[25] J. M. McGarrity, IEEE Nucl. Sci.Trans. **27**, 1739–1744 (1985).

[26] P. J. McWhorter and P. S. Winokur, Appl. Phys. Lett. **48**, 133–135 (1986).

[27] S. Suzuki, S. Harada, R. Kosugi, J. Senzaki, W. Cho, and K. Fukuda, J. Appl. Phys. **92**, 6230–6234 (2002).