Materials Science Forum
ISSN: 1662-9752, Vol. 858, pp 868-871
doi:10.4028/www.scientific.net/MSF.858.868
© 2016 Trans Tech Publications, Switzerland

Submitted: 2015-09-18
Revised: 2015-11-26
Accepted: 2016-01-02
Online: 2016-05-24

Gamma-ray irradiation response of the motor-driver circuit with SiC MOSFETs

Y. Kobayashi[1], T. Yokozeki[1,2], T. Matsuda[1,2], S. Mitomo[1,2], K. Murata[1,2], M. Hachisuka[1], Y. Kaneko[1], T. Makino[2], A. Takeyama[2], S. Onoda[2], T. Ohshima[2], Y. Tanaka[3], M. Kandori[3], T. Yoshie[3], Y. Hijikata[1]

[1]Saitama University, Sakura-ku, Saitama, 338-8570, Japan.

[2]Japan Atomic Energy Agency, Takasaki, 370-1292, Japan

[3]Sanken Electric, Niiza, Saitama, Japan

E-mail:kobayashi@opt.ees.saitama-u.ac.jp

Keywords : SiC MOSFET, motor-driver circuit, gamma-ray irradiation

Abstract. Gamma-ray irradiation effects on motor-driver circuits composed of 4H-SiC Metal-Oxide-Semiconductor Field Effect Transistors (MOSFETs) under motor driving with different Pulse-Width-Modulation (PWM) frequencies were investigated. In the case of PWM frequency at 10 kHz, the driving current and voltage waveforms were normal beyond the irradiation exceeded 1.1 MGy. In addition, the motor was still rotating in this total dose. We compared the radiation responses of SiC MOSFETs between the cases of driving states and no bias. The drain current – gate voltage characteristics with no bias shifted to the negative voltage side wider than the driving states. Also the leakage current in the case of driving state is fewer than that of no bias.

Introduction

It has been reported that SiC power devices have a higher radiation resistance than that of Si power devices [1,2]. Therefore, they are expected to apply to nuclear facilities and aerospace industry. Especially, they are strongly needed for the decommissioning work under high radiation in Fukushima Dai-ichi nuclear reactors. In previous studies, the radiation resistance of SiC Buried Gate Static Induction Transistors (BGSITs) was shown to be over 10 MGy [3]. However, from the viewpoint of use as a power device, a normally-off characteristic is desirable. Therefore, the development of highly radiation hardened SiC Metal-Oxide-Semiconductor Field Effect Transistors (MOSFETs) is important because MOSFETs are easily achieved to normally-off. In previous works, the radiation resistances of SiC MOSFETs have been evaluated in the case of no gate-bias, and it was reported that the threshold voltage is degraded as the total dose increases and the devices turn to normally-on characteristic at around the total dose of 100 kGy [1,2,4]. Taking the practical application into account, the gamma-ray irradiation responses of operating circuits are necessary to investigate. However, the evaluation of radiation hardness of a circuit composed of SiC MOSFETs has not yet been reported. In this study, we fabricated a motor-driver circuit with 4H-SiC MOSFETs and it was irradiated with gamma-rays under motor driving. In addition to the radiation hardness test for the circuit, we conducted the drain current (I_d) - gate voltage (V_g) measurements for the SiC MOSFETs in the circuit in order to clarify the degradation characteristic of the MOSFETs under operation.

Experiments

In this study, 4H-SiC MOSFETs with the blocking voltage of 1200 V and the rated current of 20 A, provided from Sanken electric co., ltd. were used. They were mounted in “TO3P” packages and their gate oxide thickness was 35 nm. The oxide was fabricated by dry O_2 thermal oxidation followed by N_2O post-oxidation annealing at the same temperature. Figure 1 shows the three-phase bridge circuit used as the motor driver in this study. Pulse-Width-Modulation (PWM) wave which

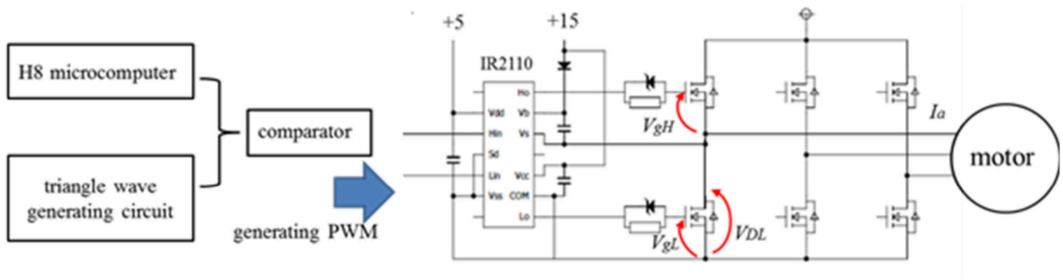
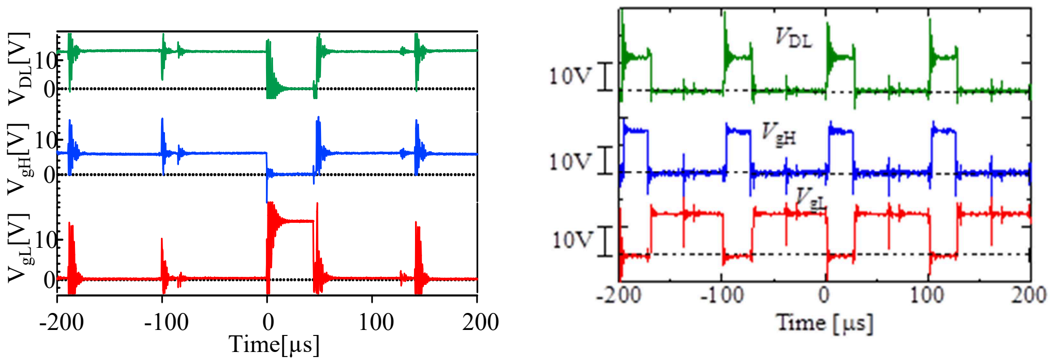


Fig. 1 Schema of motor-driver circuit used in this study. Only the six SiC MOSFETs emebedded in the three-phase bridge were irradiated with gamma-ray.

was generated by comparison between the input signal and the triangle wave using a comparator (H8 microcomputer) was introduced to a gate controller (IR2110). The used motor was the one with 26 W in output and 1.425 A in rated current. The frequencies of PWM wave were selected as 3 kHz and 10 kHz. The frequency of motor-driving current was 30 Hz. Gamma-ray irradiation was carried out using a ^{60}Co source at a dose rate of 3.61 kGy(SiO_2)/h up to 1.1 MGy at room temperature. The MOSFETs were put linearly in front of the radiation source to irradiate uniformly. However, the control circuit was located far away from the radiation source and was shielded by lead blocks, in order to investigate the radiation degradation of the SiC MOSFETs embedded in the circuit. Namely, only the SiC motor driver was exposed to the gamma-rays. The waveforms of gate voltage of high and low side transistors (V_{gH} and V_{gL}, respectively), drain voltage of low side transistor (V_{DL}) and motor-driving current (I_a) were monitored during the irradiation. After each irradiation, I_d – V_g characteristics were measured and the values of ΔV_{th} (=after irradiation – before irradiation) were obtained from I_d – V_g curves. Here, the averages of V_{th} from the six MOSFETs in the circuit were adopted.

Results and Discussion

Figure 2 shows the waveforms of voltages in the case of PWM frequency of 3 kHz (a) and 10 kHz (b) at irradiation of 62 kGy and 1.1 MGy, respectively. Voltage notations in the figure are referred in Fig. 1. The MOSFETs of high side and low side were turned-on alternately by the gate controller. In the case of 10 kHz, the waveforms were not changed at all in spite of total dose over 1 MGy. Figure 3 shows the waveform of motor-driving current in the case of 10 kHz at irradiation of 1.1MGy. The waveform shown in Fig. 3 was completely the same as that before irradiation. Furthermore, the motor kept its rotation after irradiation. Therefore, this motor-driver circuit achieved the radiation hardness up to 1.1 MGy.



(a)3 kHz at 62 kGy (b)10 kHz at 1.1 MGy

Fig. 2 Waveforms of voltages (notations are referred in Fig.1) in the case of PWM frequency of 3 kHz (a) and 10 kHz (b).

Figure 4 shows $I_d - V_g$ characteristics of SiC MOSFETs irradiated under the driving state with the frequency of 10 kHz. Figure 4(a) and (b) are drawn by linear and logarithm scales as the vertical axis, respectively. As shown in Fig. 4(a), with increasing the total dose, the characteristics shifted to negative voltage side. However, even at the total dose of 1.1 MGy, the MOSFETs did not show normally-on characteristic and forward current reduction. As shown in Fig. 4(b), it is found that the I_d in the reverse voltage region (i.e. leakage current) increased with increasing total dose. Although the reason for this leakage current has not been clarified yet, our recent investigation from SiC MOSFETs with the same structure but without the package revealed that the leak-path came from the packaging process or/and materials used in the package.

Next, we compare the characteristics of the SiC MOSFETs shown in Fig.4 with discrete SiC MOSFETs irradiated with gamma-rays under no bias (gate and drain were left open). Figure 5 shows the change in $I_d - V_g$ characteristics of SiC MOSFET by irradiation under driving state (solid lines) and discrete MOSFETs (dashed lines) by irradiation under no bias condition. The shift of the characteristics to the negative voltage side for MOSFETs with no bias was larger than that for MOSFETs with driving state. Furthermore, the leakage current in the case of driving state was much smaller than that in the case of no bias. Figure 6 shows the relative threshold voltage ΔV_{th} as a function of total amount of irradiation. In the case of no bias, the V_{th} decreased significantly after irradiation at 50 kGy. On the other hand, in the case of driving state at 10 kHz, although the V_{th} slightly decreased after the irradiation at 60 kGy, it hardly decreased even after the total dose at 1.1MGy. Also in the case of driving state at 3 kHz, the change of V_{th} shows almost the same tendency as that in the case of 10 kHz. Therefore, we can conclude that the characteristic degradation of SiC MOSFETs themselves

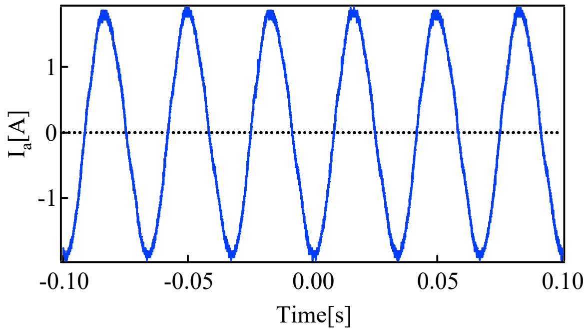


Fig. 3 Waveforms of motor-driving current when the total dose at 1.1 MGy.

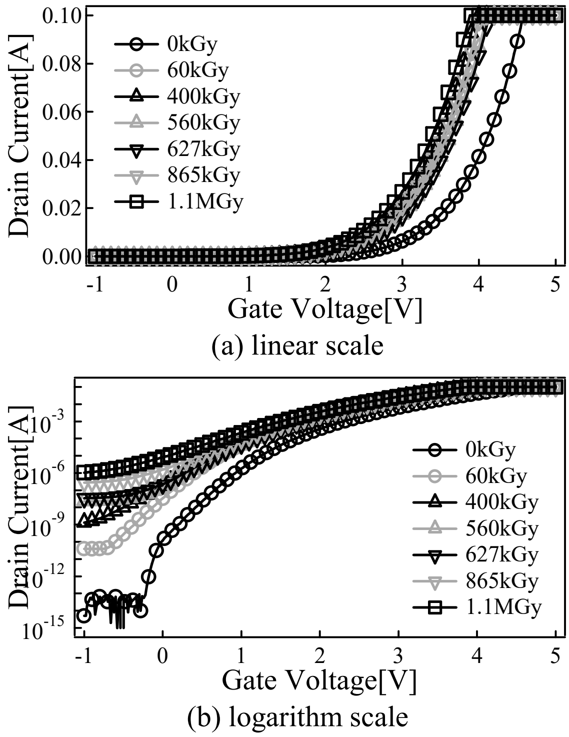


Fig. 4 I_d-V_g characteristics of motor-driving states of 10 kHz.

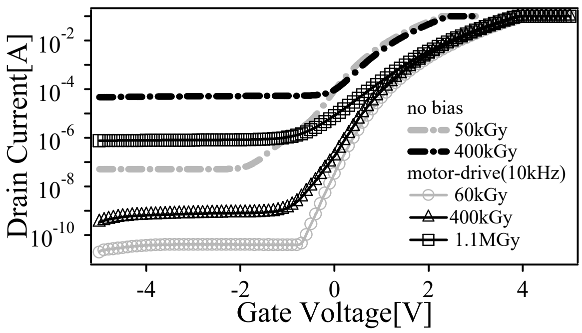


Fig. 5 Change in I_d-V_g characteristics of no bias (dashed lines), motor-driving states of 10 kHz (solid lines).

by gamma-ray irradiation is significantly suppressed in the case of driving states.

The cause of shift to the negative voltage side is thought to be the generation of positive fixed charge in the SiO_2 layer, which is attributed to the hole-trapped at intrinsic thermal oxide traps near the oxidation interface [5]. Thus, it can be considered that the heat generated by driving current anneals out the trapped holes. In our previous study, it was revealed that the V_{th} degradation by gamma-ray irradiation was restored by annealing at the temperature larger than 120 °C [2]. Therefore, the annealing effect due to driving current is probably insignificant because the device temperature should be no more than 60 °C during motor driving. Another possibility is that AC driving of gate-bias may have some effect for reducing the hole trapping. Since such an AC driving enhances electrons swing in the oxide, generated holes may be recombined with electrons before captured by the hole traps. Further investigations are needed to clarify the reason for the improvement in radiation hardness of SiC MOSFETs.

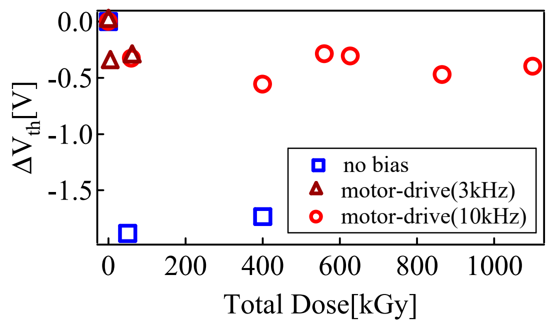


Fig. 6 Relative threshold voltage ΔV_{th} as a function of total dose for no bias (squares) and motor-driving state of 3 kHz (triangles) and 10 kHz (circles).

Summary

The motor-driver circuit composed of SiC MOSFETs was irradiated with gamma-ray up to 1.1 MGy under motor-driving, and the gamma-ray dose dependence of circuit operating characteristics and device performances with different PWM frequencies were evaluated. The motor-driving current and gate-voltages waveforms were not changed at all after irradiation of 1.1 MGy, indicating that the motor driving beyond 1 MGy was realized. In the case of driving state, the shift of $I_d - V_g$ characteristics to the negative voltage side was much less and the leakage current was fewer than those in the case of no bias condition. Furthermore, the threshold was hardly degraded in the case of driving states. Therefore, we confirmed that a continuous operation of the SiC-MOSFETs in the motor-driver circuit had an effect for suppressing their degradation due to the gamma-ray irradiation. These results suggest that SiC MOSFETs are suitable for the radiation hardened power module with over MGy class.

Acknowledgement

This study was partially supported by the Nuclear Science Research Initiative of Japan.

References

[1] T. Ohshima et al.: *Radiation response of silicon carbide diodes and transistors*. INTECH Open Access Publisher (2012).
[2] T. Yokoseki *et al.*: Mater. Sci. Forum 821-823 (2015) 705.
[3] Y. Tanaka et al.: Mater. Sci. Forum 645-648 (2010) pp941-944.
[4] K.K.Lee et al: IEEE Trans. Nucl. Sci. 50(2003) pp. 194-200.
[5] James.-R et al: IEEE. Nucl and Spa. Rad. Effect. *"Short course Notebook:Total-Dose Effects in MOS Devices"* (2011).