Measurement of Total Ionizing Dose Effects on SiC Trench MOSFETs by Gamma-ray and Alpha-particle Irradiation

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***Abstract*—We measured total ionizing dose effect (TID) on Si, SiC planar and SiC trench power MOSFETs by using Co-60 γ-ray source and ^{241}Am α-particle source. Measurement results show that SiC power MOSFETs have higher tolerance to γ-ray irradiation. In contrast, the SiC trench MOSFET is most vulnerable to α-particle-induced TID. Threshold voltage shift, $\Delta V_{\rm th}$ of the SiC trench MOSFET is -4.8 V after 150 krad α-particle irradiation, which is 12.6% larger than that in the Si MOSFET. In this measurements, the SiC planar MOSFET has the highest tolerance for both α-particle and γ-ray irradiation. $\Delta V_{\rm th}$ of the SiC planar MOSFET is 1/20 or less than that of the Si MOSFET.**

***Index Terms*—total ionizing dose effect, SiC trench MOSFET, α particle.**

I. INTRODUCTION

A next-generation power semiconductor, SiC MOSFET can improve the performance of power conversion circuits owing to its excellent physical properties such as wide band gap, fast electron mobility and high breakdown field. Lightweight power conversion circuits with high speed switching of SiC MOSFETs are important for spacecraft electric propulsion system. However, it is essential to evaluate the total ionizing dose (TID) effect on SiC MOSFETs in the space environment [1]. Since the recommended driving voltage of SiC MOSFETs is higher than that of Si MOSFETs, the recombination rate of electron-hole pairs is lower in the oxide layers of SiC MOSFET [2], which could lead them to be susceptible to TID. In addition, it is necessary to measure how the low quality gate oxide of SiC MOSFETs impacts TID effect.

In this paper, we measure TID effects on commercial Si, SiC and SiC trench MOSFETs by γ-ray and α-particle irradiation in order to compare radiation-induced degradation on them. Irradiation tests are performed by using Co-60 source and ^{241}Am source.

II. MEASUREMENT SETUP

To compare TID effects on Si, SiC planar and SiC trench MOSFETs, we measured four commercial power MOSFETs summarized in Table I, which have similar maximum $V_{\rm DS}$ and $I_{\rm D}$. Note that all MOSFETs are manufactured by different companies. Fig. 1 shows cross-sectional views of planar and trench MOSFETs. Structurally, planar MOSFETs have higher on-resistance than trench MOSFETs due to the JFET resistance ($\rm R_{JFET}$) of $\rm N^+$ region between the $\rm P^+$ regions.

TABLE I
ELECTRICAL CHARACTERISTICS OF TARGET MOSFETS

MOSFET	Si planar	SiC planar	SiC trench	
			A	B
Maximum $V_{\rm DS}$ [V]	600	650	650	650
Maximum $I_{\rm D}$ [A]	21	22	20	21
Maximum $V_{\rm GS}$ [V]	25	19	23	22
Recommended driving $V_{\rm GS}$ [V]	10	15	18	18
$R_{\rm on}$ [mΩ]	130	120	107	120

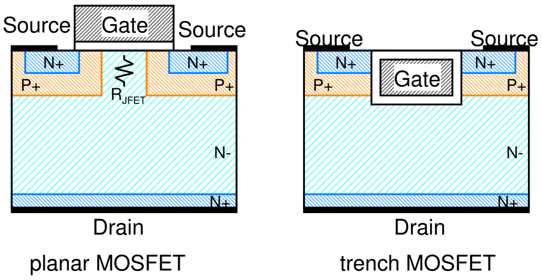

Fig. 1. Cross-sectional views of planar MOSFET and trench MOSFET.

γ-ray irradiation tests are performed using a Co-60 source at National Institutes for Quantum Science and Technology, Japan. α-particle irradiation tests are performed using a 3 MBq ^{241}Am source. In α-particle irradiation tests, molded resin of target power MOSFETs is removed since all α particles from ^{241}Am are completely blocked by molded resin. Dose rates of the Co-60 and ^{241}Am sources are 110 rad/s and 11 rad/s, respectively [3]. The dose rate of α particles is calculated from flux and linear energy transfer [3]. Since the flux of α particles is attenuated by air, so it depends on the distance between the ^{241}Am source and target dies [4].

During irradiation, $V_{\rm GS}$ is fixed to 10V or 18V which is recommended driving voltages for the target Si MOSFET or SiC trench MOSFET, respectively. $I_{\rm D}$-$V_{\rm GS}$ characteristic of target MOSFETs is measured every 100 seconds. $I_{\rm D}$ is measured by a DC power module, N6761A (Keysight) with 200 μA measurement range option, whose accuracy is 0.5% + 100 nA.

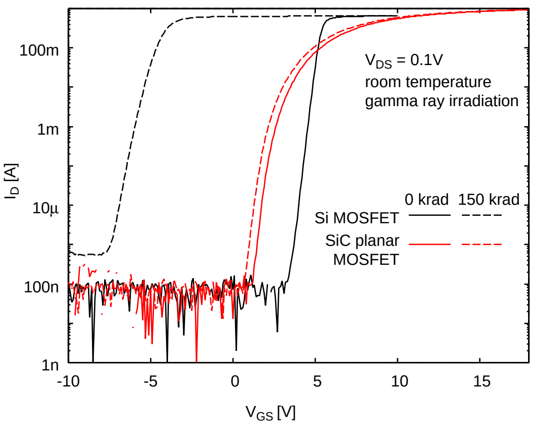

Fig. 2. I_D-V_{GS} curves of the Si and SiC planar MOSFETs before and after 150 krad γ-ray irradiation.

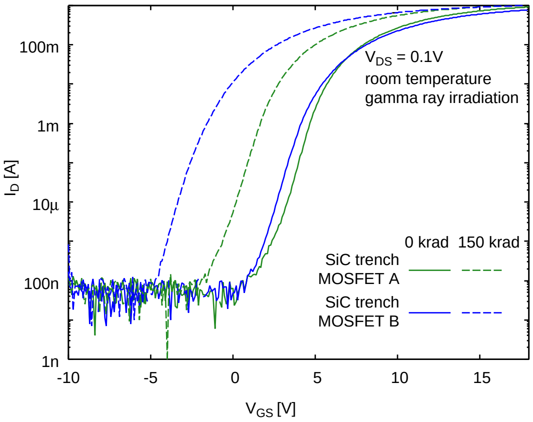

Fig. 3. I_D-V_{GS} curves of the two SiC trench MOSFETs before and after 150 krad γ-ray irradiation.

III. MEASUREMENT RESULTS

A. γ-ray irradiation

Figs. 2 and 3 show I_D-V_{GS} curves at V_{DS} = 0.1 V before and after 150 krad γ-ray irradiation. Note that the constant current of 100 nA in I_D-V_{GS} curves is due to the minimum resolution of the current source. The magnitude of TID effects is clearly different for each power MOSFET, and the SiC MOSFET has the highest tolerance to γ-ray radiation. The two SiC trench MOSFETs also have higher radiation tolerances than the Si MOSFET. However, the V_{th} shift in the SiC trench MOSFET B is roughly twice in the SiC trench MOSFET A. From Ref. [5], gate oxide of trench MOSFETs tend to trap more positive charge than Si planar MOSFETs due to the process differences. In addition to those process differences, the planes (si-face, a-plane and m-plane) used for the channel layer could be different in SiC planar and SiC trench MOSFETs due to the hexagonal prismatic crystal structure of 4H-SiC [6], [7]. These differences lead to the large difference of TID tolerance in the SiC MOSFETs.

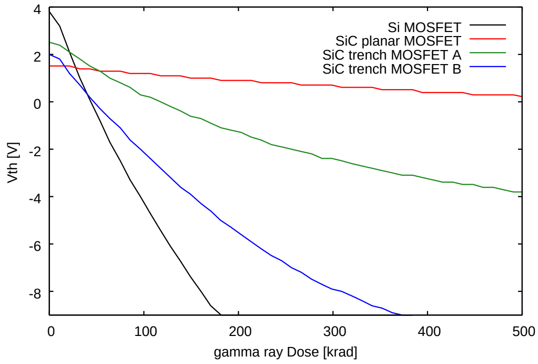

Fig. 4. TID-induced V_{th} shift with respect to irradiation γ-ray dose.

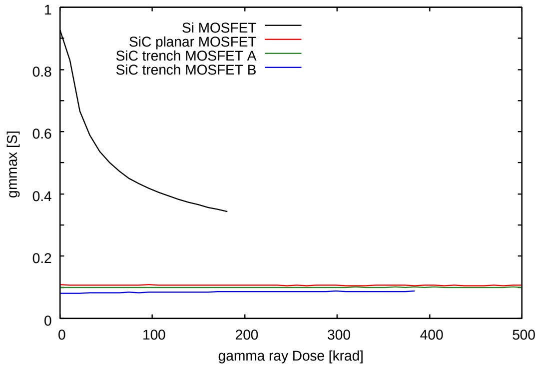

Fig. 5. TID-induced g_{mmax} change with respect to irradiation γ-ray dose.

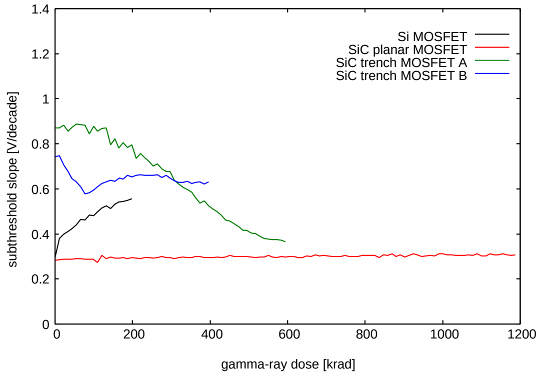

Fig. 6. TID-induced subthreshold slope curve respect to irradiated γ-ray dose.

A constant value of leakage current that does not depend on gate voltage exists only in the Si MOSFET after 150 krad γ-ray irradiation. During irradiation, leakage current does not change regardless of irradiated γ-ray, and leak current became so small that it could not be observed after irradiation. Therefore, this leakage current is caused by the photoelectric effect by the γ rays irradiated during the measurement of I_D-V_{GS} curve. It was detected only in the Si MOSFET because of its narrow band gap and wide depletion region.

Figs. 4 and 5 show the measurement results of V_{th} and maximum transconductance (g_{mmax}) with respect to γ-ray irradiation dose, respectively. The threshold voltage, V_{th} is defined as the value of V_{GS} when I_D is 1 μA at V_{DS} = 0.1 V. g_{mmax} of the Si MOSFET is drastically decreased by the TID,

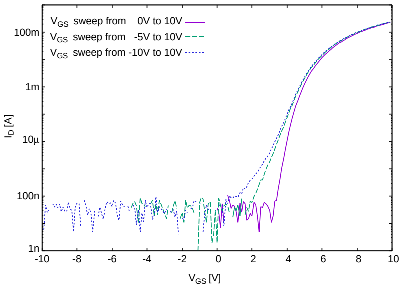

Fig. 7. I_D-V_{GS} curves with different initial V_{GS} value in non-irradiated SiC trench MOSFET A.

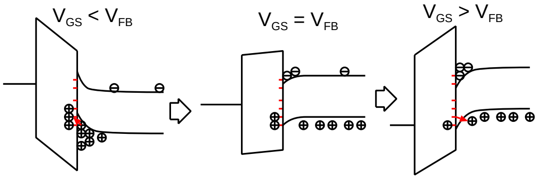

Fig. 8. Capture and emission process starting from $V_{GS} < V_{FB}$.

while that of the SiC MOSFETs is almost constant. The gate oxide of the SiC MOSFETs is low in quality and has many interface traps, so that interface traps formed by the TID does not become dominant. Thus low quality gate oxide of the SiC MOSFETs does not accelerate the TID-induced degradation.

Figs. 6 shows subthreshold slope (SS) at $I_D = 1\ \mu$A with respect to irradiated γ-ray dose. For Si MOSFET, interface traps are formed by γ ray and SS is increased by TID, which is consistent with previous researches [8], [5]. In contrast, values of SS in SiC trench MOSFETs are decreased by TID. These results are due to the measurement method of I_D-V_{GS} curves. In the γ-ray irradiation test, I_D-V_{GS} curves were measured by sweeping V_{GS} from -10 V to 18 V to obtain negative V_{th}. However, I_D-V_{GS} characteristics of SiC trench MOSFETs depend on the initial V_{GS} value at the I_D-V_{GS} measurement. Fig. 7 shows I_D-V_{GS} curves with different initial V_{GS} value in non-irradiated SiC trench MOSFET A. This dependence is caused by temporary capture of holes by the interface traps. When V_{GS} is smaller than flat band voltage (V_{FB}), holes in the channel region are attracted to the SiC/SiO$_2$ interface and they are captured by the interface traps and V_{th} is reduced by the captured holes as shown in Fig. 8. When V_{GS} increases larger than V_{FB}, the captured holes are gradually released and V_{th} returns to the original value. I_D-V_{GS} characteristics in the subthreshold region depends on the initial V_{GS} value since the number of the captured holes depends on potential difference between V_{GS} and V_{FB}. In our γ-ray irradiation test, the number of the captured holes was reduced according to irradiated dose and values of SS in the SiC trench MOSFETs decreased. It is because V_{FB} was shifted by TID and potential difference between the initial V_{GS} (-10 V) and V_{FB} decreased.

B. α-particle irradiation

Figs. 9 and 10 show I_D-V_{GS} curves at $V_{DS} = 0.1$ V before and after 150 krad α-particle irradiation. Note that I_D-V_{GS} curves in the α-particle irradiation tests are obtained by changing V_{GS} from recommended driving voltage (10 V or 18 V) to -10 V in order to remove the effect of temporary captured holes. Table II shows ΔV_{th} and Δg_{mmax} of the MOSFETs after 150 krad α-particle and γ-ray irradiation.

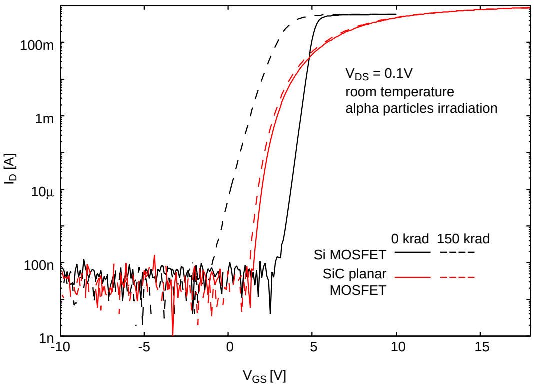

Fig. 9. I_D-V_{GS} curves of the Si and SiC planar MOSFETs before and after 150 krad α-particles irradiation.

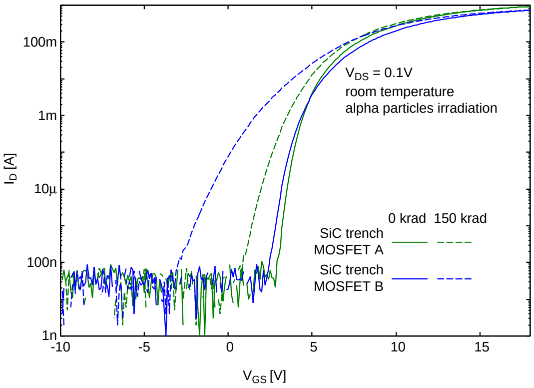

Fig. 10. I_D-V_{GS} curves of the two SiC trench MOSFETs before and after 150 krad α-particles irradiation.

TABLE II
ΔV_{th} AND Δg_{mmax} OF THE MOSFETS AFTER 150 KRAD α-PARTICLE AND γ-RAY IRRADIATION.

		Si planar	SiC planar	SiC trench	
				A	B
γ ray	ΔV_{th} [V]	-11.2	-0.5	-3.0	-5.9
	Δg_{mmax} [S]	-0.56	0.00	0.00	0.00
	ΔSS [V/decade]	0.55	0.01	-0.07	-0.10
α particles	ΔV_{th} [V]	-3.8	-0.2	-1.8	-4.8
	Δg_{mmax} [S]	-0.48	0.00	0.00	0.00
	ΔSS [V/decade]	0.22	0.02	0.26	0.62

Δg_{mmax} due to α particles is consistent with the Δg_{mmax} change due to γ rays. However, α-particle results do not show the same trend as γ-ray results. α particles induce smaller V_{th} shift in the Si MOSFET than that at the γ ray. α particles have a high linear energy transfer (LET) and generate many electron-hole pairs at once. Therefore, generated holes will recombine with electrons and oxide traps in gate oxide are less likely to capture holes [2]. Since hole recombination rate depends on electric field in gate oxide and SiC MOSFETs have

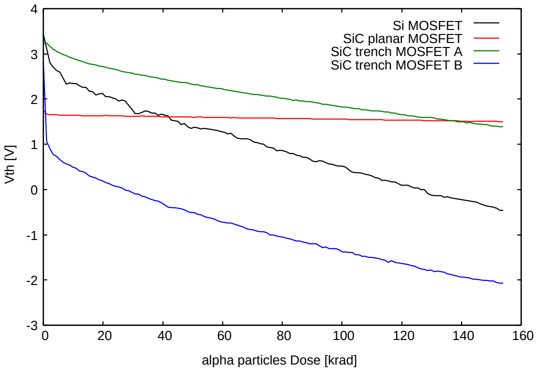

Fig. 11. TID-induced V_{th} shift with respect to irradiation α-particles dose.

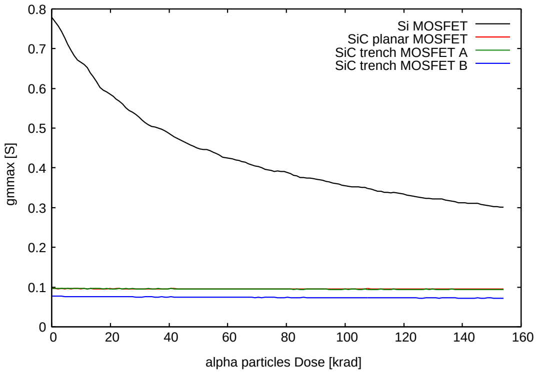

Fig. 12. TID-induced g_{mmax} change with respect to irradiation α-particles dose.

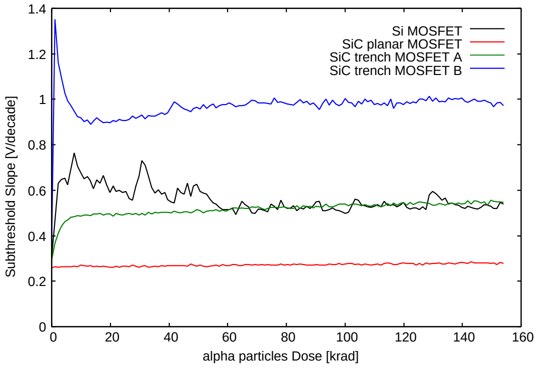

Fig. 13. TID-induced subthreshold slope curve with respect to irradiated α-particles dose.

a higher recommended driving voltage than Si MOSFETs, SiC MOSFETs are more susceptible to α-particle-induced TID. As a result, our measurement results show that SiC trench MOSFETs have a larger V_{th} shift due to α-particles-induced TID. ΔV_{th} of the SiC trench MOSFET is -4.8 V after 150 krad α-particle irradiation, which is 12.6% larger than that in a Si MOSFET.

Figs. 11, 12 and 13 show the measurement results of V_{th}, g_{mmax} and subthreshold slope at 1 μA with respect to the amount of α-particle irradiation dose, respectively. In the Si MOSFET and the SiC trench MOSFET B, there are similar sharp reductions of V_{th} and SS in the early period. These sharp reductions are not observed in γ-ray irradiation results. Fig. 14 show I_{D}-V_{GS} curves at 0, 2.2, 11 and 44 krad α-particle irradiation. At the low dose of 2.2 krad, TID by α-particle irradiation degrades I_{D}-V_{GS} characteristic in the current range of less than 100 μA and SS at 1 μA drastically increases. However, this degradation is mitigated by increasing the TID effect. The above degradation was observed only in the Si MOSFET and the SiC trench MOSFET B. But it was not observed by γ-ray irradiation tests.

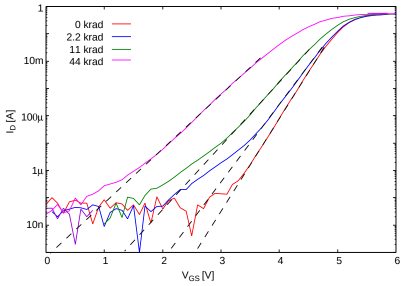

Fig. 14. I_{D}-V_{GS} curves of Si MOSFET with 0, 2,2, 11 and 44 krad α-particles.

Because of the similar response against α-particles irradiation of Si MOSFET and the SiC trench MOSFET B, we assume that the gate oxide of them was annealed with hydrogen to improve the quality of the interface in SiO_2/Si and SiO_2/SiC. We also assume that the gate oxide of the SiC planar MOSFET and the SiC trench MOSFET A was annealed with nitrogen oxide (NO), which is more effective to improve the interface quality for SiO_2/SiC interface [9]. Therefore, the difference in the TID resistance of the SiC trench MOSFETs comes from the interface states.

IV. CONCLUSION

We measured total ionizing dose effect (TID) on Si, SiC planar and SiC trench power MOSFETs by using Co-60 γ-ray and ^{241}Am α-particle sources in order to compare radiation tolerance among Si MOSFET and SiC MOSFETs.

Measurement results show that SiC power MOSFETs have higher tolerance to γ-ray irradiation. In contrast, the SiC trench MOSFET is most vulnerable to α-particle-induced TID. ΔV_{th} of the SiC trench MOSFET is -4.8 V after 150 krad α-particle irradiation, which is 12.6% larger than that in a Si MOSFET. The different results from the γ and α sources are caused by difference in recombination rates due to the recommended driving voltage. SiC MOSFET could be more vulnerable to charged particles with higher LET.

In this measurements, the SiC planar MOSFET has the highest tolerance for both α-particle and γ-ray irradiation. ΔV_{th} of the SiC planar MOSFET is 1/20 or less than that of the Si MOSFET. Although each SiC MOSFET has different TID resistance, it is possible to improve the lifetime of the satellite by selecting one with higher TID resistance.

ACKNOWLEDGMENT

The authors would like to thank to QST (National Institutes for Quantum and Radiological Science and Technology) for γ ray experiments. This work is partly supported by JSPS KAKENHI Grant Number JP20K19769.

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