Analysis of the effects of Gamma-ray irradiation on SiC MOSFETs

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Abstract

The TID effect generated in the MOS structure under the influence of radiation induces unreliability of the power system. To analyze this, we irradiated gamma-ray to SiC MOSFET and SiC n-type MOSCAP and extracted electrical characteristics. As a result of the analysis, g_m, R_{on}, and BV decreased by the TID effect and increased due to hole traps generated in the oxide. In addition, the degradation mechanism was verified by substituting actual experimental values into the TCAD simulation. In this study, the mechanism of electrical property degradation of SiC MOSFETs by gamma-ray irradiation was investigated.

INTRODUCTION

SiC has high reliability in extreme environments and low Ron is advantageous for radiation-resistant design, drawing attention as a power semiconductor for space environments [1]. However, in the space environment, the characteristics of power semiconductors can be destroyed by radiation and high temperature environments [2]-[4]. In the MOS structure, the threshold voltage and on-resistance decrease due to the positive charge inside the oxide caused by the TID effect. As a result, leakage current increases, power consumption becomes serious, and it is greatly affected by noise. In particular, thick field oxide is located in the edge termination area, it is necessary to verify the occurrence of the TID effect by analyzing the yield characteristics and extracting the oxide characteristics.

In this paper, SiC MOSFETs were irradiated with gamma-ray at doses of 1 and 3 Mrad, and I-V and C-V characteristics were analyzed to extract g_m, R_{on}, and BV variations and oxide film characteristics. The oxidation characteristics reduced through measurement are substituted into TCAD simulation to verify the degradation mechanism of SiC MOSFETs by gamma-ray irradiation.

EXPERIMENT AND DISCUSSION

The devices investigated in this study are a 1.2 kV, 189 mΩ n-channel SiC MOSFET from STMicro electronic and an n-type SiC MOS capacitor fabricated by us. The device was investigated and characterized with a radiation source of 1.33 MeV Co-60 gamma-ray at the Advanced Radiation Technology Institute (ARTI). Cross-sectional construction of a typical SiC vertical MOSFET is shown in Fig. 1.

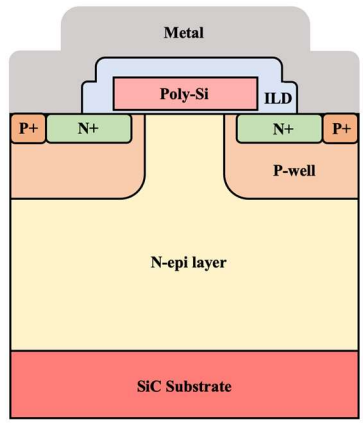

Fig. 1. The cross-section construction of SiC vertical MOSFET

The gamma-ray dose was 1 ,3 Mrad for each device. After gamma-ray irradiation, the I-V characteristics of the SiC MOSFET were compared with g_m, R_{on}, and BV, and the oxide characteristics were evaluated by analyzing the C-V characteristics of the n-type SiC MOS capacitor. The I-V characteristics of SiC MOSFETs according to the amount of gamma-ray irradiation were measured using Keysight's B1505A, and the C-V characteristics of SiC MOS capacitors were measured using Keysight's B1500A for comparison and analysis.

From the transconductance curve in Fig. 2, we can see that a higher drain current flows at the same voltage due to the effect of positive charge, and the off-state current in the lower threshold region is larger after gamma-ray irradiation. Transconductance was extracted. Transconductance was extracted using Equation. 1 [5].

$$g_m = \frac{\Delta I_{DS}}{\Delta V_{GS}} \quad (1)$$

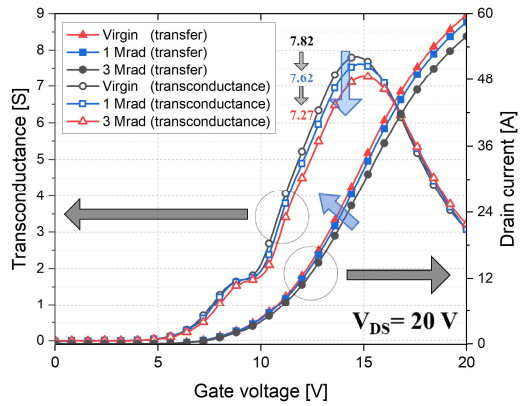

Fig. 2. Transfer curve (right-axis) and transconductance curve (left-axis) according to the dose of gamma-ray irradiation.

The g_m was 7.82 S (Virgin), 7.62 S (1 Mrad), and 7.27 S (3 Mrad), which decreased with gamma-ray irradiation dose. When the MOS structure is irradiated with gamma-ray, EHP is generated in the oxide, and holes are left and accumulated due to the difference in carrier mobility. These accumulated holes act as traps and affect the operation of the MOSFET.

Even if the same amount of gate voltage is applied, the higher the fixed charge of the gate oxide, the better the electron accumulation. Moreover, V_T decreased to 4.63 V (Virgin), 4.25 V (1 Mrad), and 3.98 V (3 Mrad) according to the gamma ray dose. However, as the V_T decreases, leakage current and power consumption increase [6]-[8].

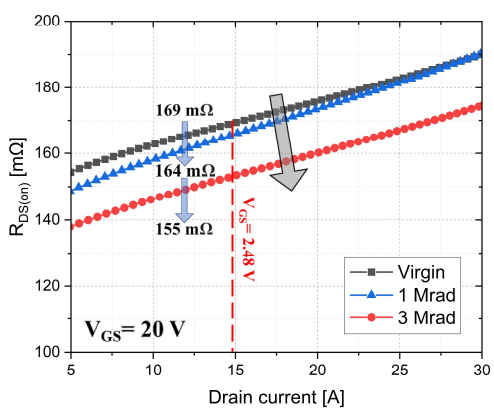

Fig. 3. On-resistance curve according to gamma-ray irradiation dose.

Fig. 3 is the R_{on}-I_{DS} curve when the gate voltage is in the operating range of 20V. The R_{on} was 169 mΩ (Virgin), 164 mΩ (1 Mrad), 155 mΩ (3 Mrad), which decreased as the amount of gamma-ray irradiation increased. Therefore, current flows better overall after gamma-ray irradiation. It can be assumed that the smaller R_{on} is, the larger the capacitance value between the gate electrode and the drain electrode is, and the deterioration of switching characteristics after gamma-ray irradiation.

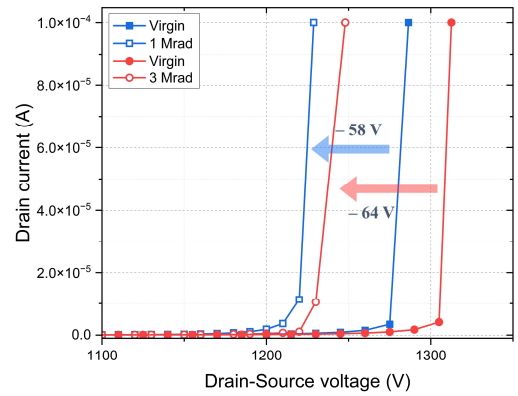

Fig. 4. Breakdown characteristic curve according to gamma-ray irradiation dose.

In Fig. 4, it realized that the BV characteristics before and after gamma-ray irradiation decreased according to the dose. As a result of the extraction, the BV reduced by 58 V (1 Mrad), 64 V (3 Mrad).

Due to the TID effect by gamma-ray irradiation, hole trap is generated even in edge termination where thick field oxide or ILD is located. This hole trap affects the formation of a depletion region between the P-well and N-drift region. As the Q_F oxide increases, a depletion region with a larger curvature is formed, and as the electric field is concentrated in this region, the breakdown characteristic is lowered [9, 10].

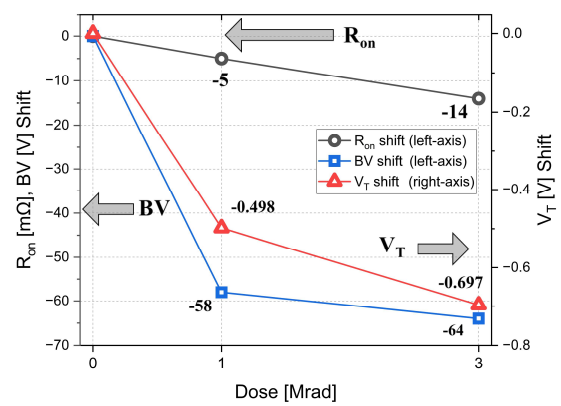

Fig. 5. Output characteristic curve according to gamma-ray irradiation dose.

Fig. 5 shows the amount of parameter change extracted from the characteristics before and after gamma-ray irradiation, which changes according to the trend.

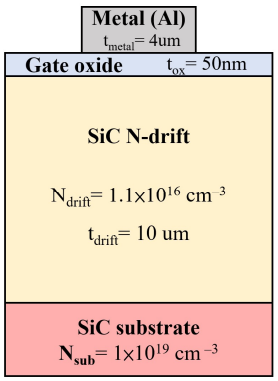

Fig. 6. The cross-section construction of SiC n-type MOSCAP.

We designed and fabricated the MOS capacitor shown in Fig. 6 to confirm the change in oxide properties according to gamma ray irradiation. Then, the corresponding MOS capacitors were irradiated with gamma-ray at doses of 1, 3 Mrad.

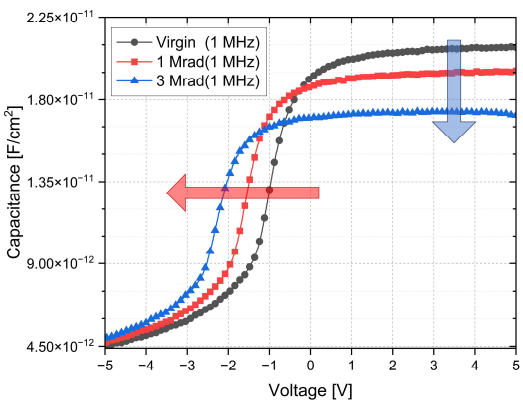

Fig. 7. C-V characteristic curve according to gamma-ray irradiation dose.

Fig. 7 shows the C-V curve of the n-type MOS capacitor according to the dose of gamma-ray irradiation, and is a curve extracted through C-V sweep measurement at a frequency of 1 MHz. We realized that the gamma-ray irradiation dose had a tendency shift to the left. For the analysis of the TID effect, the shifts of ΔV_{FB} and Q_F according to the gamma-ray irradiation dose were extracted in Fig. 7. C_{ox} is extracted as oxide capacitance in Fig. 7 and q has a charge of 1.6×10^{-19} C [11]. C_{ox} is 6.65×10^{-8} F/cm (virgin), 6.24×10^{-8} F/cm (1 Mrad), 5.49×10^{-8} F/cm (3 Mrad) depending on gamma-ray irradiation dose. As a result, Q_F was 3.39×10^{12} cm^{-2} (1 Mrad), 3.94×10^{12} cm^{-2} (3 Mrad), and it increases according to the gamma-ray dose.

These results prove that the TID effect was caused by gamma-ray irradiation, resulting in hole trapping in the oxide. We also noticed that ε_{ox} was affected as C_{ox} decreased with the irradiated gamma-ray dose. ε_0 is the dielectric constant of air, ε_{ox} is the dielectric constant of the oxide to be extracted, and t_{ox} is the thickness of the oxide. The t_{ox} of the fabricated MOS capacitor is 50 nm. ε_{ox} decreased to 3.83 ε_0 (virgin), 3.52 ε_0 (1 Mrad), 3.10 ε_0 (3 Mrad). This degradation is influenced TID effects and Maxwell Wagner interfacial polarization [12]. Since ε_{ox} decreases as the dose increases, it was verified that gamma-ray also affect the material properties of SiC MOSFETs. Table 1 shows ΔV_{FB}, Q_F, and ε_{ox} according to gamma-ray irradiation dose.

TABLE I
SUMMARY OF OXIDE CHARACTERISTIC CHANGES ACCORDING TO GAMMA-RAY DOSE

Dose (Mrad)	ΔV_{FB} (V)	Q_F (cm^{-2})	ε_{ox} (ε_0)
Virgin	1.346	2.98×10^{12}	3.83
1	1.916	3.39×10^{12}	3.52
3	2.616	3.94×10^{12}	3.10

In summary, the TID effect is demonstrated by confirming that the Q_F increases with the dose of gamma-ray irradiation. We also prove that the high energy of gamma-ray affects material properties by reducing ε_{ox} depending on the dose of gamma-ray.

We demonstrated the TID effect of the oxide properties Q_F and ε_{ox}. To prove the BV deterioration mechanism identified above, the Q_F inside the edge termination area field oxide, the value measured in the experiment, was substituted into the Sentaurus' TCAD simulation. The structure of the simulation used SZ-JTE, and the design parameters were designed by reflecting the parameters summarized in Table 2 [13].

TABLE II
SZ JTE DESIGN PARAMETER IN TCAD SIMULATION

N-drift layer		JTE		Substrate	Field oxide
N_{drift} (cm^{-3})	t_{drift} (μm)	N_{JTE} (cm^{-3})	L_{JTE} (μm)	N_{sub} (cm^{-3})	t_{ox} (μm)
8.0×10^{15}	11	1.2×10^{17}	50	1.0×10^{18}	0.865

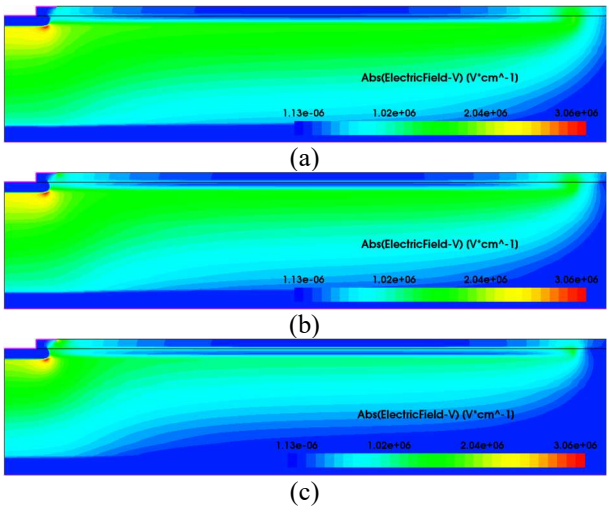

Fig. 7. Electric field distribution of SZ-JTE structure according to gamma-ray irradiation Q_F.
(a) Q_F= 2.98×10^{12} cm^{-2} (b) Q_F= 3.39×10^{12} cm^{-2} (c) Q_F= 3.94×10^{12} cm^{-2}

Fig. 7 is a graph showing the electric field distribution at the SZ-JTE position after substituting ε_{ox} and Q_F according to gamma-ray irradiation into the simulation. Fig. 7 (a) shows an E_{max} of 9.92×10^5 V/cm extracted from a MOS capacitor without gamma-ray irradiation when Q_F = 2.98×10^{12} cm^{-2}. Fig. 7 (b) is after 1 Mrad gamma-ray irradiation, Q_F is 3.39 × 10^{12} cm^{-2}, and E_{max}= 1.16×10^6 V/cm. Finally, Fig. 7 (c) substitutes the Q_F of 3.94×10^{12} cm^{-2} after 3 Mrad irradiation, and E_{max} is 1.32×10^6 V/cm. As the Q_F increases, it is realized that the electric field is concentrated at the edge, and the curvature of the depletion region is formed larger. Moreover, it noticed that the electric field across the field oxide increases as ε_{ox} decreases.

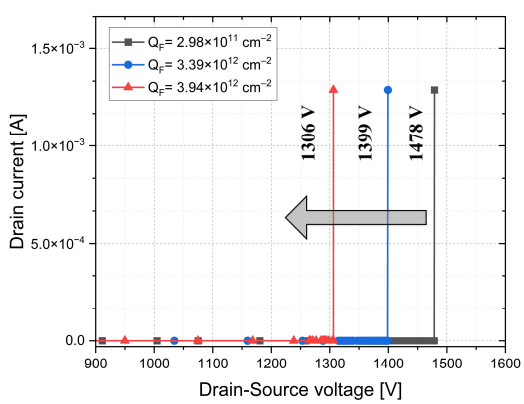

Fig. 8. Breakdown voltage according to gamma-ray irradiation Q_F

Fig.8 shows the BV according to the Q_F extracted according to the dose of gamma-ray irradiation, and the BV is 1478 V (Virgin Q_F), 1399 V (1 Mrad Q_F), 1306 V (3 Mrad Q_F, which are the same trends as those measured in the actual experiment. We notice that the electric field across the oxide increases as ε_{ox} decreases.

In conclusion, as the electric field is concentrated due to the TID effect by high-energy gamma-ray irradiation, the breakdown characteristic is degraded, and hole trap occurs in the field oxide of the edge, proving that the depletion curvature increases.

CONCLUSIONS

In this paper, I-V and C-V characteristics of 1.2 kV, 189 mΩ n-channel SiC MOSFET and n-type SiC MOS capacitor irradiated with gamma-ray was analyzed to identify the degradation mechanism for radiation effect. Because of the TID effect from gamma-ray irradiation, more electrons are accumulated by hole traps inside the oxide, resulting in 7.1 % decreased g_m and 8.2 % lower R_{on}. To verify this, the n-type SiC MOS capacitor was irradiated with gamma-ray and the oxide characteristics were extracted by C-V measurement. As a result, it was extracted that Q_F increased and ε_{ox} decreased according to the gamma-ray dose. Through this, we realized that gamma-ray irradiation not only affects the electrical operating characteristics of MOSFETs, but also affects the material properties. Finally, after gamma-ray irradiation, the BV decreased by 3%. This indicates that the TID effect is more dominant at the edge termination with thick oxide, and the depletion region between the P-well and N-drift region is formed with a large curvature due to hole trap inside the oxide. As the electric field is concentrated in this region, the breakdown characteristics deteriorate. Here, the SZ-JTE structure was designed by Sentaraus' TCAD simulation, and the Q_F and ε_{ox} obtained by measuring the actual experiment result were substituted. It was demonstrated that the curvature of the depletion region was formed large and the electric field distribution and E_{max} increased at the edge when breakdown occurred. Hence, the BV also decreased as the Q_F obtained in the experiment increased. It realized that which is consistent with the actual experimental results.

ACKNOWLEDGEMENTS

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ACRONYMS

MOSFET: Metal-Oxide-Semiconductor Field Effect Transistor
rad: radiation absorbed dose
TID: Total Ionization Dose
EHP: Electron Hole Pairs
ILD: Inter Layer Dielectrics
V_{FB}: Flat-band Voltage
Q_F: The fixed charge per unit area inside the oxide
R_{on}: On-resistance
g_m: Transconductance
BV: Breakdown Voltage
SZ-JTE: Single-Zone Junction Terminal Extension
E_{max}: the maximum electric filed