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Experimental Investigation of Single-Event Effect Mechanisms in 1200V SiC VDMOSFETs under Heavy-Ion Irradiation

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Abstract. The deployment of silicon carbide (SiC) power devices in aerospace applications is constrained by their unexpected susceptibility to single-event effects (SEEs), despite the inherent advantages of wide bandgap materials. In this work, we experimentally investigate the SEE mechanisms in in-house fabricated 1200 V SiC VDMOSFETs under heavy-ion irradiation using Ta ions with a LET of 75 MeV·cm²/mg. Real-time current monitoring, post-irradiation electrical characterization, and focused ion beam (FIB) analysis were employed to systematically examine device degradation and failure modes under various bias conditions. The results demonstrate a clear progression of damage with increasing bias voltage: no significant changes, single-event gate leakage degradation (SEGLD) at 100 V, single-event leakage current (SELC) in both I_d=I_g and I_d>I_g modes at 300–400 V, and catastrophic single-event burnout (SEB) at 500 V. Structural analyses reveal progressive deepening of gate oxide fractures, extension into the P+ source region, and eventual source metal melting, consistent with the observed electrical degradation. Notably, the threshold voltage remained stable throughout, suggesting that localized damage to limited unit cells has minimal influence on the global device threshold. These findings provide critical insights into SEE-induced degradation pathways in SiC MOSFETs and offer valuable guidelines for the design and radiation hardening of next-generation aerospace power systems.

Introduction

The rapid advancement of aerospace power systems imposes stringent requirements on power devices in terms of efficiency, reliability, and radiation tolerance. Silicon carbide (SiC) devices, owing to their wide bandgap, high breakdown field, and superior thermal conductivity, have emerged as strong candidates to replace conventional silicon-based power electronics in such environments [1].

However, recent experimental evidence indicates that SiC MOSFETs are far more vulnerable to single-event effects (SEEs) than initially expected. Phenomena such as single-event burnout (SEB), single-event leakage current (SELC), and single-event gate leakage degradation (SEGLD) have been observed at voltages significantly below the rated blocking voltage, in some cases at less than 30% [2-5]. These premature failures severely restrict the safe operating area of SiC MOSFETs in aerospace applications and highlight the urgent need for a deeper understanding of their degradation mechanisms under heavy-ion irradiation.

To date, considerable research efforts have been devoted to investigating SEE mechanisms in wide-bandgap devices. Prior studies have suggested that the onset of SEB is linked to localized thermal runaway triggered by heavy-ion tracks, while SELC and SEGLD are associated with microstructural damage in the gate oxide and channel regions. Nonetheless, the detailed evolution pathways of these failure modes, particularly under varying bias conditions, remain insufficiently explored. A systematic study that correlates bias-dependent failure behaviors with physical microstructural damage is essential to bridge this knowledge gap.

In this work, we conduct a comprehensive experimental investigation of SEE mechanisms in 1200 V SiC VDMOSFETs subjected to heavy-ion irradiation. Using Ta ions with a linear energy transfer (LET) of 75 MeV·cm²/mg, we combine real-time current monitoring, post-irradiation electrical

characterization, and focused ion beam (FIB) cross-sectional analysis to examine device degradation under multiple bias conditions. By correlating electrical signatures with microstructural evidence, we establish the progression of SEE-induced failure modes—from SEGLD to SELC and ultimately SEB—and reveal critical insights into the physical origins of these degradation pathways. The results not only deepen the understanding of SEE mechanisms in SiC MOSFETs but also provide valuable design guidelines for the development of radiation-hardened power devices for aerospace applications.

Experimental Setup

The devices under test (DUTs) were in-house fabricated 1200 V SiC vertical double-diffused MOSFETs (VDMOSFETs) packaged in TO-254. To minimize the energy loss of incident ions, the packaged devices were decapsulated prior to irradiation. Fig. 1(a) illustrates the device cross-section, while Fig. 1(b) presents the package configuration.

Heavy-ion irradiation experiments were conducted at the Institute of Modern Physics, Lanzhou, employing a tantalum (Ta) ion beam with a linear energy transfer (LET) of 75 MeV·cm²/mg. During irradiation, the drain, source, and gate terminals of the DUTs were biased externally according to the test requirements. The applied drain-to-source voltages ranged from 0 V to 500 V, thereby enabling systematic investigation of SEE phenomena under different electrical stress conditions.

The experimental platform is shown in Fig. 1(c). Real-time monitoring of both drain current (I_d) and gate current (I_g) was performed using high-precision current measurement equipment to capture transient single-event responses. After irradiation, comprehensive electrical characterizations，including transfer characteristics, output characteristics, gate leakage tests, and blocking capability were conducted to evaluate device degradation using a Keysight B1505A semiconductor power analyzer, as shown in Fig. 1(d).

In order to directly examine the physical damage induced by heavy-ion strikes, focused ion beam (FIB) analysis was employed. A total of 15 devices were tested across all bias conditions, with at least three DUTs assigned to each irradiation voltage level to ensure statistical consistency. Representative DUTs that exhibited distinct SEE behaviors—such as single-event gate leakage degradation (SEGLD), single-event leakage current (SELC), and single-event burnout (SEB)—were selected for structural analysis. The corresponding microstructural evidence was correlated with electrical characteristics to establish the progression of SEE failure mechanisms, as summarized in Fig. 1(e).

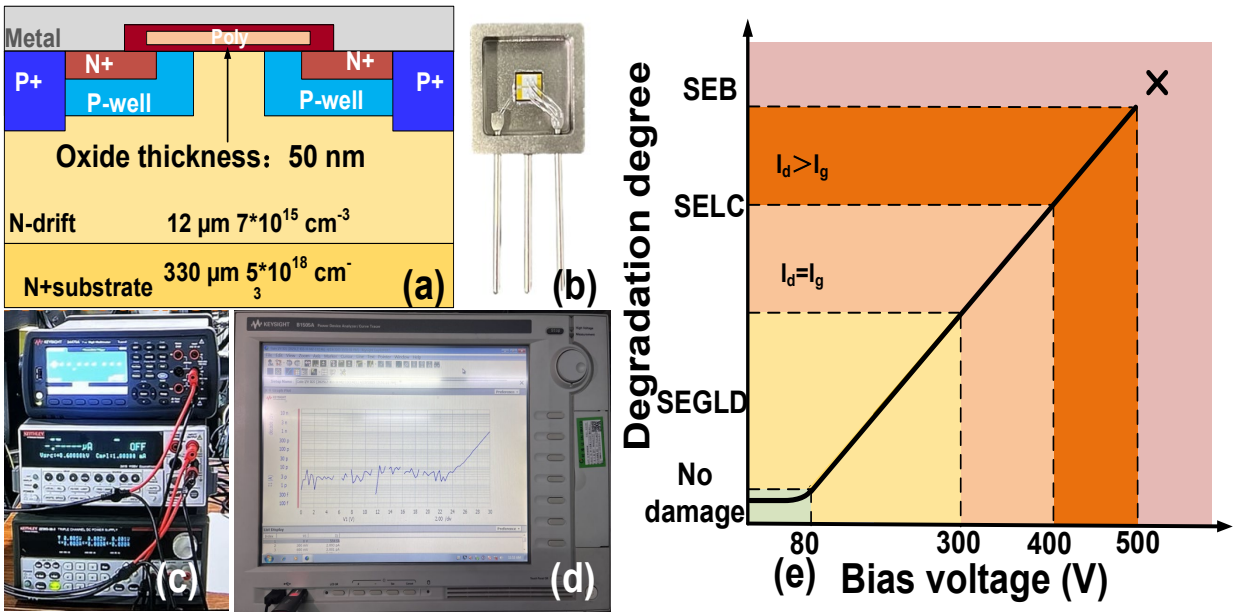

Fig. 1. (a) Device cross-section diagram. (b) Packaging schematic diagram. (c) On-site test setup. (d) Post-irradiation test setup. (e) SEE characteristic of SiC MOSFET.

Results and Discussion

The irradiation experiments reveal a distinct evolution of SEE failure modes as the applied drain bias increases. The progression follows a sequence from negligible degradation, to SEGLD, then to SELC with two distinct modes, and finally to catastrophic SEB. For each bias condition (100 V, 300 V, 400 V, and 500 V), a minimum of three devices were irradiated, and all reported behaviors were consistently observed across repeated samples.

At a drain bias of 100 V, the DUTs exhibited SEGLD. A marked increase in gate leakage current was observed post-irradiation, while the threshold voltage and transfer characteristics remained nearly unchanged. This indicates localized damage to the gate oxide rather than significant alteration of channel conduction. No noticeable post-irradiation recovery or annealing behavior was observed during room-temperature monitoring over several hours, indicating that the induced damage is largely permanent without high-temperature annealing. Focused Ion Beam (FIB) analysis confirmed that there is an approximately 1 μm deep crack in the gate oxide at the center of the JFET region in only one cell [6]. These micro-cracks serve as leakage paths, explaining the increase in gate current without notable threshold voltage shifts.

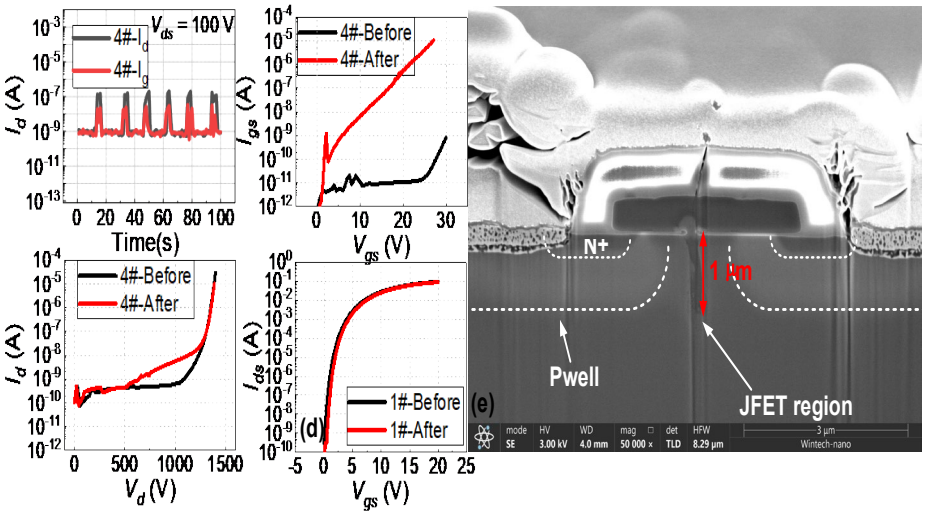

Fig. 2. (a)-(d) Test results (e) FIB cross-section image of the SEGLD DUTs, where the ILD layer corresponds to the interlayer dielectric between the metallization and gate oxide.

When the bias was raised to 300 V, DUTs transitioned into the I_d=I_g mode of SELC. In this condition, both drain current and gate current increased simultaneously, suggesting charge transport through extended oxide damage regions. FIB cross-sections revealed oxide fractures reaching a depth of about 2 μm, accompanied by partial degradation of blocking voltage to about 500 V.

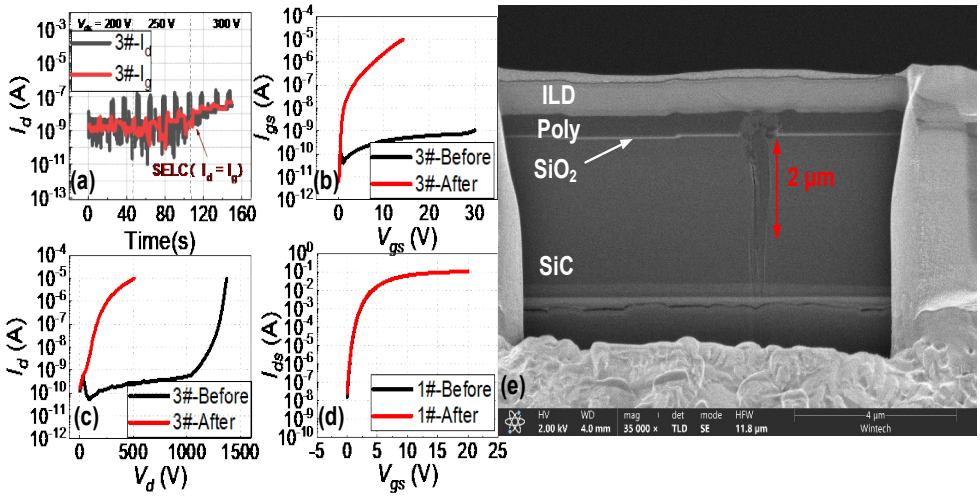

Fig. 3. (a)-(d) Test results (e) FIB cross-section image of the SELC(I_d=I_g) DUTs.

At a higher bias of 400 V, the DUTs entered the I_d>I_g mode of SELC. In this regime, the drain current has created a new drain-source current leakage path, indicating that damage has occurred at the device's source. Structural analysis showed cracks propagating 3.5 µm deep into the P+ source region, together with localized melting of the source metal. Correspondingly, the blocking voltage further degraded to ~250 V. These observations confirm that SELC represents a progressive damage state, with I_d>I_g being more destructive than I_d=I_g.

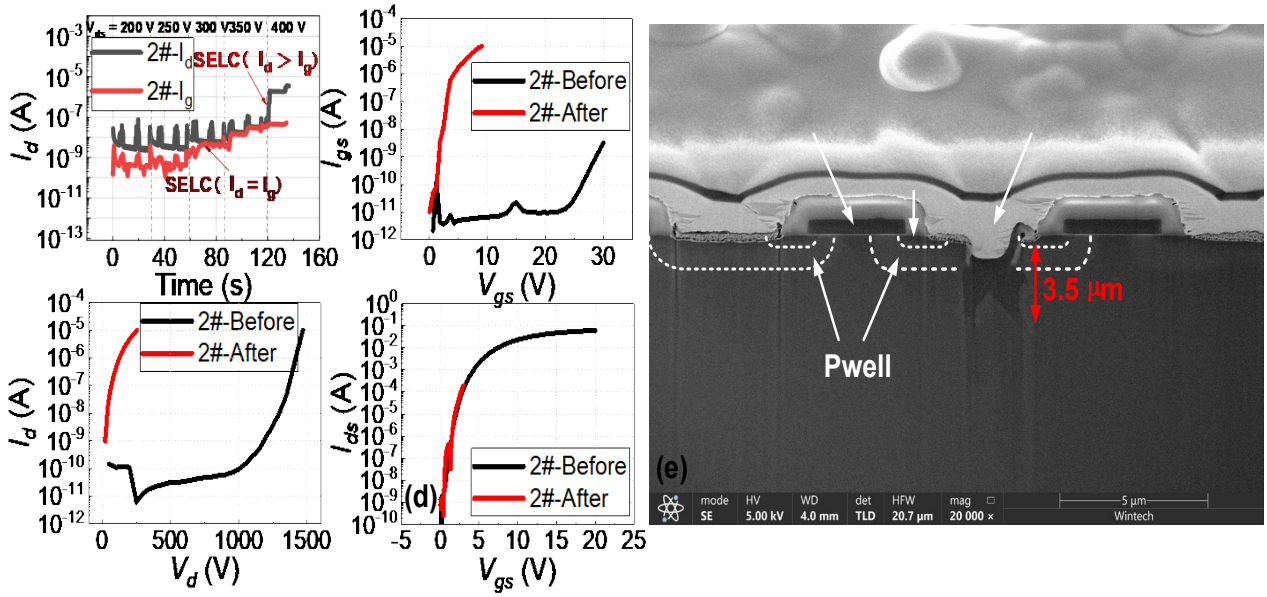

Fig. 4. (a)-(d) Test results (e) FIB cross-section image of the SELC(I_d>I_g) DUTs.

At 500 V bias, catastrophic SEB was triggered. The devices exhibited uncontrollable current surges followed by permanent failure. FIB images revealed massive damage extending over 14 µm into the device structure, with complete oxide rupture and severe metallization destruction. This is consistent with a thermal runaway process initiated by heavy-ion energy deposition, leading to irreversible device breakdown [2]. It is worth noting that the identification of SELC and SEB mechanisms was based primarily on real-time transient current monitoring, while the extent of physical damage was confirmed through post-irradiation static electrical measurements and FIB cross-sectional analysis.

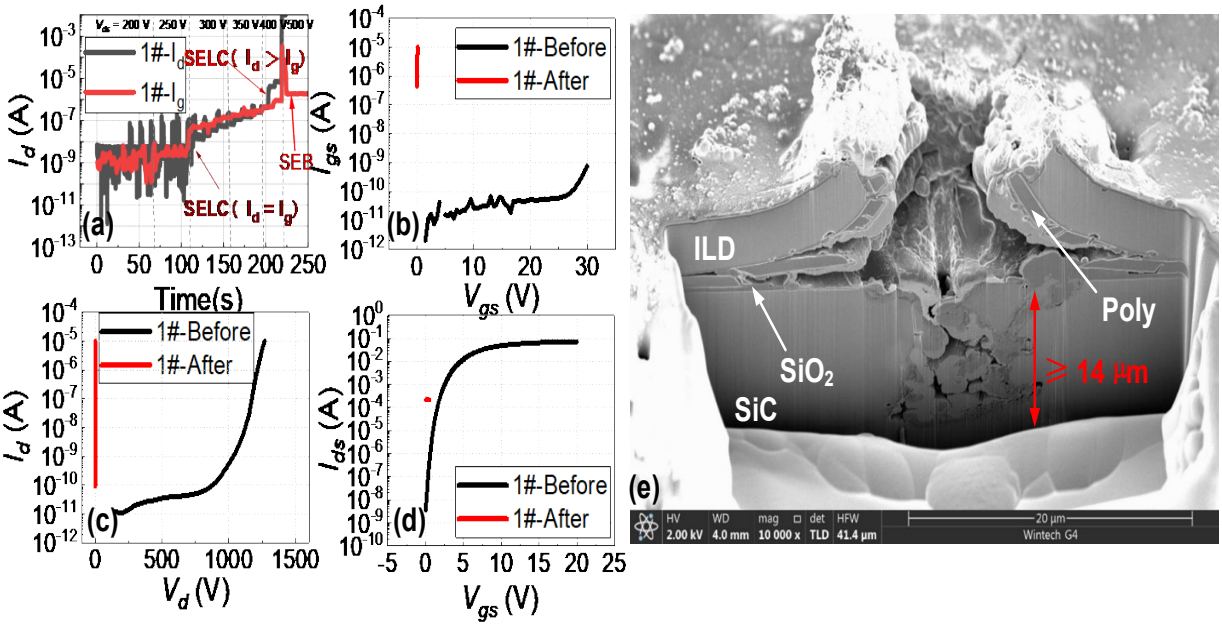

Fig. 5. (a)-(d)Test results (e) FIB cross-section image of the SEB DUTs.

An important observation is that the device threshold voltage remained stable throughout all degradation stages (except for SEB), despite substantial deterioration in gate leakage and breakdown characteristics [7]. This indicates that SEE-induced damage tends to be highly localized, affecting only a limited number of unit cells, which has little impact on the averaged threshold behavior of the entire device.

A concise summary of degradation levels at each failure mode is as follows:

SEGLD (100 V): Gate leakage increased from $<10^{-8}$ A to $\sim10^{-5}$ A, with no change in threshold voltage.

SELC (Id = Ig mode, 300 V): Both Id and Ig increased to the 100 nA level; blocking voltage reduced to ~500 V.

SELC (Id > Ig mode, 400 V): Drain leakage exceeded tens of μA; blocking capability dropped to ~250 V.

SEB (500 V): Catastrophic current surge (>1 mA) and permanent breakdown.

Summary

This work experimentally investigated single-event effect mechanisms in 1200 V SiC VDMOSFETs under heavy-ion irradiation. The results revealed a clear bias-dependent evolution of failure modes, progressing from SEGLD to SELC and finally to catastrophic SEB. FIB analyses confirmed the progressive deepening of oxide fractures and structural damage, while the device threshold voltage remained stable, indicating localized damage. The correlation between electrical degradation and microstructural damage provides crucial insight into the physical origins of SEEs in SiC MOSFETs. These results suggest that improving the robustness of the gate oxide and mitigating source-side current crowding are key strategies for radiation hardening. The observed degradation sequence provides direct guidance for optimizing oxide thickness, cell topology, and terminal design in next-generation radiation-tolerant SiC MOSFETs.

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