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A Defect-Informed Phase-Field Model for Gate Oxide Breakdown in SiC MOS Structures

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Abstract—Silicon carbide (SiC) MOS structures are promising for high voltage and high temperature power electronics, but gate oxide breakdown remains a major reliability concern because of its stochastic nature and the limited accessibility of the underlying failure pathway. In this work, a defect-informed phase-field framework is developed to investigate oxide breakdown in SiC MOS structures. The model is initialized using a depth-resolved pre-existing defect profile extracted from capacitance and conductance frequency response, thereby linking electrical characterization with physics-based breakdown simulation. The results show that breakdown starts from localized nucleation at defect-rich weak points near the SiO₂/SiC interface, followed by directional growth, interaction, and coalescence of degraded regions into a through-thickness conductive path. Combined analysis of the phase-field variable and electric field distribution shows that local electric field redistribution plays a key role in guiding conductive path propagation and determining the final breakdown trajectory. Post-breakdown focused ion beam scanning electron microscopy (FIB-SEM) reveals a tortuous and spatially confined channel morphology, consistent with the defect-assisted and field-driven breakdown picture predicted by the model. The proposed framework provides a useful tool for analyzing breakdown trajectories and gate oxide reliability in SiC power devices.

Index Terms—phase-field simulation, silicon carbide, gate oxide breakdown.

I. INTRODUCTION

Silicon carbide (SiC) MOSFETs are widely regarded as key devices for high voltage and high temperature power electronics because of their wide bandgap, high critical breakdown electric field, and high thermal conductivity [1]–[3]. However, despite the rapid progress in device development and commercialization [4], gate oxide reliability remains a major obstacle to further performance enhancement and long-term stable operation [5]. The electrical and structural integrity of the SiO₂/SiC gate stack directly influences threshold voltage

stability [6], gate leakage characteristics, and device lifetime [7]–[9]. Under high electric field and elevated temperature stress, degradation of the gate oxide is further accelerated, making reliability assessment even more challenging [10]–[13]. As highlighted by recent reviews and experimental investigations, gate oxide degradation continues to be one of the most important reliability issues in SiC MOS devices [14].

Within device degradation phenomena, gate oxide breakdown is one of the most critical yet least predictable failure events because of its intrinsically stochastic nature [14], [15]. Even under nominally identical electrical stress conditions, both the breakdown time and the failure mode exhibit substantial dispersion, reflecting the strong influence of local defects, trap generation, and oxide non-uniformity [14]. To date, oxide degradation has been investigated mainly through indirect electrical observables, including leakage current evolution, threshold voltage shift, and breakdown statistics [16], [17]. Although these approaches are valuable for reliability assessment and lifetime estimation, they offer limited access to the underlying physical process of breakdown. In particular, they cannot directly reveal how a localized conductive path is initiated, propagates, and ultimately leads to catastrophic failure. Consequently, the spatiotemporal evolution of breakdown in SiC gate oxides remains insufficiently understood.

A further fundamental challenge is that the physical understanding of oxide breakdown remains incomplete, in many respects, as also evidenced by the continuing lack of agreement on lifetime extrapolation models. From a macroscopic perspective, the widely used E-model, $\ln(T_{bd}) \propto -E_{ox}$, is generally associated with thermochemical bond breakage, whereas the inverse-field (1/E) model, $\ln(T_{bd}) \propto 1/E_{ox}$, is often interpreted in terms of anode-hole injection induced damage [14]. At the microscopic scale, many studies describe breakdown as an electrically driven degradation process involving charge trapping, defect accumulation, and the gradual formation of percolation-like conductive paths [18], [19]. Although additional effects such as local current crowding and secondary heating may become relevant in severe failure stages, the electrically driven evolution of localized degradation remains

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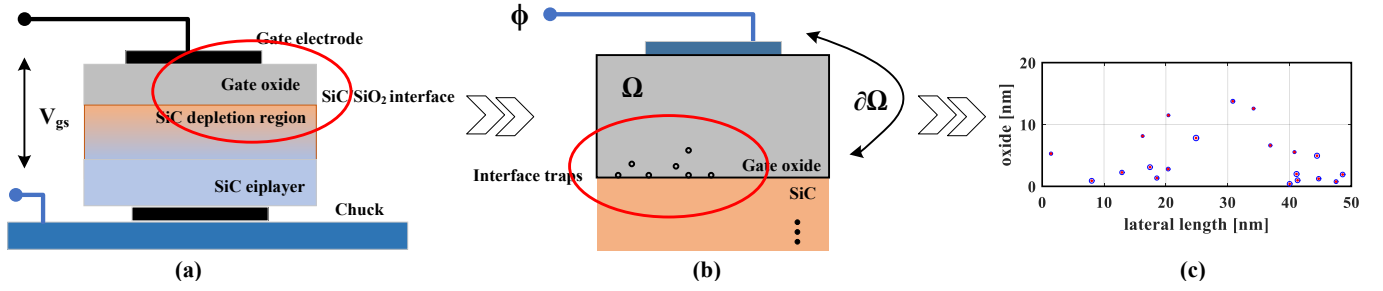


Fig. 1. Cross sectional illustration of the SiC MOS structure and defect distribution. (a) Experimental test structure used for the electrical measurement, (b) the gate-stack region, showing that oxide defects are mainly concentrated near the SiO₂/SiC interface, and (c) approximate spatial distribution of the interfacial defects, reconstructed from the measured capacitance/conductance frequency response.

the central process in the initiation and early growth of breakdown paths. This lack of a unified physical picture suggests that different stress conditions may activate different dominant degradation pathways, thereby making mechanism interpretation and lifetime prediction more difficult. These considerations highlight the need for physics-based models capable of consistently describing the evolution of defect generation, leakage conduction, and localized breakdown path formation.

To address these limitations, a physics-based framework is required to describe the nucleation and propagation of breakdown paths. In this respect, the phase-field method is particularly well suited because it represents breakdown as the continuous evolution of a damage variable, naturally captures the initiation and growth of localized conductive channels, and avoids explicit tracking of complex moving interfaces. Compared with purely statistical lifetime models or post-failure characterization, such an approach provides a more direct description of the breakdown process itself. Previous phase-field studies on dielectric materials have also shown that this method is effective in describing localized damage evolution under electrical driving forces within a unified formulation [20]. However, this type of framework has rarely been developed specifically for SiC gate oxides, where reliability remains a critical bottleneck and the breakdown pathway is still not well understood.

Therefore, this work develops a phase-field framework for oxide breakdown in SiC MOS structures to investigate the spatiotemporal evolution of the breakdown process and to clarify the role of electric field concentration in localized conductive path formation. By introducing a continuous breakdown variable and coupling the electric field with phase evolution, the proposed model provides a unified description of the degradation process from its initial stage to final catastrophic failure. This approach not only helps explain the intrinsic difficulty of predicting oxide breakdown in SiC, but also enables visualization and analysis of the otherwise inaccessible breakdown trajectory. As a result, it offers useful physical insight for gate oxide design and reliability improvement. The rest of this paper is organized as follows. Section II introduces the phase-field model for oxide breakdown in SiC MOS structures. Section III presents the simulation results and

discusses the spatiotemporal evolution of breakdown as well as the experimental validation. Section IV summarizes the main conclusions.

II. THEORETICAL MODEL

Figure 1 illustrates the overall workflow of the proposed modeling framework. Starting from the experimental SiC MOS test structure, the gate-stack region is first extracted and transformed into a simplified computational domain Ω focused on the SiO₂/SiC interface. The initial defect distribution in the oxide, which is mainly concentrated near the interface $\partial\Omega$, is then approximately reconstructed from the measured capacitance and conductance frequency response and mapped onto the transformed domain. Based on this defect-informed configuration, a phase-field description is introduced through a continuous breakdown variable to represent the nucleation and propagation of localized conductive paths, while the electric field is solved together with the phase evolution. In this way, the framework connects experimentally inferred defect information with the spatiotemporal simulation of oxide degradation and final breakdown in SiC MOS structures.

A. Physical domain and phase-field description

To model oxide breakdown in SiC MOS structures, a phase-field framework is formulated for the gate-stack system composed of a gate electrode, a SiO₂ gate oxide, and a SiC substrate. Because breakdown is highly localized and typically develops into a narrow conductive path, a continuous phase-field variable $\eta(x, t)$ is introduced to describe the local degradation state of the oxide. Here, $\eta = 1$ corresponds to the intact oxide, whereas $\eta = 0$ denotes the fully developed breakdown phase. Following the central idea of previous phase-field models for dielectric breakdown, the conductive path is represented by a continuous damage-like field instead of an explicitly tracked sharp interface. This formulation is particularly suitable for gate oxide breakdown because it enables direct description of the spatiotemporal nucleation and growth of the breakdown path.

Based on this phase-field description, the total free energy in the oxide domain Ω_{ox} is written as

$$F = \int_{\Omega_{ox}} [f_{dw}(\eta) + f_{grad}(\nabla\eta) + f_{elec}(\eta)] d\Omega \quad (1)$$

where f_{dw} is the local double-well potential, f_{grad} is the gradient energy density, and f_{elec} is the electrostatic contribution.

The local double-well potential is defined as

$$f_{dw}(\eta) = W\eta^2(1 - \eta)^2 \quad (2)$$

where W is the barrier height between the intact and breakdown states. The gradient term is given by

$$f_{grad}(\nabla\eta) = \frac{\kappa_n}{2} |\nabla\eta|^2 \quad (3)$$

where κ_n controls the width and energy of the diffuse breakdown front.

For voltage-controlled stress, the electrostatic energy density is expressed as

$$f_{elec}(\eta) = \frac{1}{2} \epsilon(\eta) |\nabla\phi|^2 \quad (4)$$

where ϕ is the electric potential and $\epsilon(\eta)$ is the effective permittivity of the degrading oxide. This form is consistent with the complementary electrostatic energy treatment commonly adopted in phase-field breakdown models [20].

To interpolate the dielectric response between the intact oxide and the breakdown phase, the effective permittivity is taken as

$$\epsilon(\eta) = \frac{\epsilon_{ox}}{h(\eta) + \alpha} \quad (5)$$

where ϵ_{ox} is the permittivity of the intact oxide, $h(\eta)$ is a smooth interpolation function, and α is a small numerical regularization parameter. In this work,

$$h(\eta) = 4\eta^3 - 3\eta^4 \quad (6)$$

is used to ensure a smooth transition between the intact and degraded states.

B. Experiment-based initialization of spatial defect distribution

The initial spatial distribution of oxide defects is constrained by the experimentally extracted depth-resolved trap profile, denoted here as $N_t(x)$. In the SiC admittance-based extraction framework, the trap capture time increases exponentially with the distance from the SiO₂/SiC interface. This relation establishes a frequency–depth mapping and enables reconstruction of a nonuniform defect profile from the measured capacitance and conductance spectra, $C(\omega)$ and $G(\omega)$. Specifically, the trap waiting time is expressed as

$$\tau_t(x) \propto \exp(2\kappa x), \quad (7)$$

where κ is the wave-decay constant in the oxide. The effective probe depth x_d is determined by the signal frequency through the condition $\tau_t(x_d) = 1/\omega_m$. Therefore, the measurement frequency selects the corresponding probing depth, providing depth-resolved information to constrain the defect field in the oxide [21].

Based on the frequency dispersion of $C(\omega)$ and $G(\omega)$, the trap distribution can be obtained as [22]

$$\frac{dG}{dx} = \frac{q^2 N_t(x)}{4kT} \frac{\omega^2 \tau_t(x)}{1 + \omega^2 \tau_t^2(x)} - \frac{2C(x, \omega)G(x, \omega)}{\epsilon_{ox}}, \quad (8)$$

$$\frac{dC}{dx} = \frac{q^2 N_t(x)}{4kT} \frac{1}{1 + \omega^2 \tau_t^2(x)} + \frac{G^2(x, \omega) - \omega^2 C^2(x, \omega)}{\omega^2 \epsilon_{ox}}, \quad (9)$$

where k is the Boltzmann constant and T is the absolute temperature. The extracted $N_t(x)$ shows a pronounced peak near the SiO₂/SiC interface and then decays rapidly with depth, indicating that the defect population is strongly concentrated in the near-interface region. In this way, the experimentally extracted trap profile serves as the spatially varying defect seed for subsequent phase-field evolution. This experimentally constrained defect profile is now used to initialize the spatial heterogeneity of the oxide in the phase-field model. The extracted profile and its physical implications are discussed in Section III.

Based on these observations, the pre-existing defect population is associated with the earliest extracted trap profile under electrical stress, denoted by $N_{pre}(x)$. Following [23], this profile is approximated by an exponentially decaying function,

$$N_{pre}(x) = N_0 \exp(-x/\lambda) \quad (10)$$

where x is the distance from the SiO₂/SiC interface, N_0 is the defect density at the interface, and λ is the fitted decay length. After normalization over the oxide thickness, the probability density of defect occurrence along the depth direction is expressed as

$$P_t(x) = \frac{\lambda^{-1} \exp(-x/\lambda)}{1 - \exp(-t_{ox}/\lambda)} \quad (11)$$

where t_{ox} is the oxide thickness. For the two-dimensional simulation domain, the lateral defect positions are assumed to be statistically uniform. The corresponding joint probability density is therefore written as

$$P_t(x, y) = \frac{1}{L_y} P_t(x) \quad (12)$$

where L_y is the lateral size of the oxide domain, which is 50 nm in this work for simplification. Based on this distribution, the initial defect seeds are sampled in the oxide domain to represent spatial heterogeneity prior to breakdown evolution.

A total of N_d defect nuclei are then generated by random sampling from the probability density in (12). To characterize the initial defect morphology, the effective defect size a_0 and the intrinsic phase-field length scale l_0 are introduced based on physically informed connections to the charge transport and phase-field literature [18], [19], [24]. In the modified charge transport model, the defect size a_0 is introduced together with the defect scattering length relation, $l_{sca} = C_{trap}^{1/3} - a_0$, and a fitted value of 0.5 nm is reported [18]. In the present work, a_0 is interpreted as the effective seed radius of a pre-existing degraded nucleus rather than as a directly measured geometrical quantity.

The phase-field length scale l_0 is defined following the dielectric breakdown phase-field formulation, in which it characterizes the width of the conductive channel and the spatial extent of the localized degraded zone around it. The value of l_0 is estimated from the effective conduction area A_{eff} reported in the charge transport model [19]. In that model, A_{eff} denotes

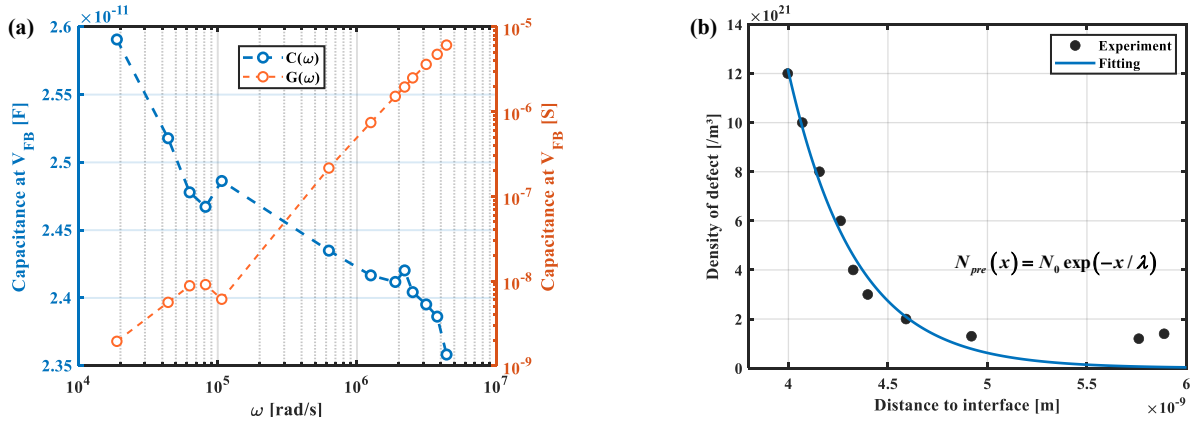


Fig. 2. Measured capacitance $C(\omega)$ and conductance $G(\omega)$ at the flatband condition at room temperature as functions of angular frequency. (b) Extracted pre-existing defect distribution and its exponential fitting.

the effective area through which electronic conduction occurs and is used to convert the predicted electron flux into the measured current in a one-dimensional formulation. At the same time, A_{eff} can be interpreted as being proportional to the fraction of the structure that participates in conduction. Assuming that breakdown conduction is dominated by a main conductive path with an approximately circular cross section, the equivalent area per path has been reported to be in the range of 10^{-18} – 10^{-20} m^2 [19], [25], [26]. The corresponding equivalent channel radius is therefore taken as 0.9 nm.

C. Governing equations

Under the quasi-static approximation, the electric potential satisfies

$$\nabla \cdot [\epsilon(\eta) \nabla \phi] = 0 \quad (13)$$

where $\epsilon(\eta)$ is the local permittivity depending on the breakdown state. This equation governs the electrostatic equilibrium in the degrading oxide and is consistent with previous phase-field models for dielectric breakdown.

The evolution of the breakdown phase is described by a modified Allen–Cahn equation [20],

$$\frac{\partial \eta}{\partial t} = -L_\eta H(f_{elec} - f_{th}) \left[\frac{\partial f_{dw}}{\partial \eta} - \kappa_\eta \nabla^2 \eta + \frac{\partial f_{elec}}{\partial \eta} \right] \quad (14)$$

where L_η is the phase-field mobility and $H(\cdot)$ is the Heaviside step function. The threshold form ensures that phase evolution occurs only when the local electrical driving force exceeds the endurance threshold f_{th} .

For the electrical boundary conditions, the gate electrode is subjected to the applied gate bias, $\phi = V_{gs}(t)$ on $\partial\Omega_{gate}$, while the SiC side boundary is assigned the substrate potential. The lateral boundaries are electrically insulated.

III. RESULTS AND DISCUSSION

This section first presents the extraction of the depth-resolved defect distribution from the measured frequency-dependent capacitance and conductance characteristics. The experimentally inferred defect profile is then used to initialize

the phase-field simulation, and the time-resolved evolution of the localized conductive path is analyzed. Finally, the simulated breakdown morphology is compared with SEM observations to discuss the physical consistency between the defect-informed breakdown evolution and the observed failure pattern.

A. Defect-informed simulation of conductive path evolution

Figure 2(a) presents the measured capacitance $C(\omega)$ and conductance $G(\omega)$ at the flatband condition as functions of angular frequency. The evident frequency dispersion indicates that oxide traps located at different depths contribute differently to the admittance response. Based on the frequency–depth mapping described in Section II, the corresponding depth-resolved defect profile is extracted, as shown in Fig. 2(b). The extracted profile exhibits a pronounced defect density N_0 peak near the SiO_2/SiC interface, followed by a rapid decay toward the oxide bulk.

To initialize the phase-field simulation, the pre-existing defect profile is fitted by the exponential form in (10), yielding $N_0 = 5.993 \times 10^{20} \text{ m}^{-3}$ and $\lambda = 2.767 \text{ nm}$. The fitted distribution is then used as the depth-dependent probability basis for stochastic generation of the initial defect field in the oxide domain. In this way, the experimentally identified defect nonuniformity is incorporated directly into the model initialization.

Based on the extracted defect distribution, phase-field simulations were performed to track the temporal evolution of oxide breakdown, while the corresponding electric field distribution was analyzed simultaneously to clarify the driving mechanism of conductive path formation. In the present model, the phase field variable η describes the local degradation state of the oxide, where $\eta = 1$ denotes the intact oxide and $\eta = 0$ denotes the degraded phase. At the same time, η determines the local permittivity and therefore affects the electric field distribution, whereas the redistributed electric field enters the electrostatic driving term and governs the subsequent phase evolution. As a result, the breakdown process is controlled by

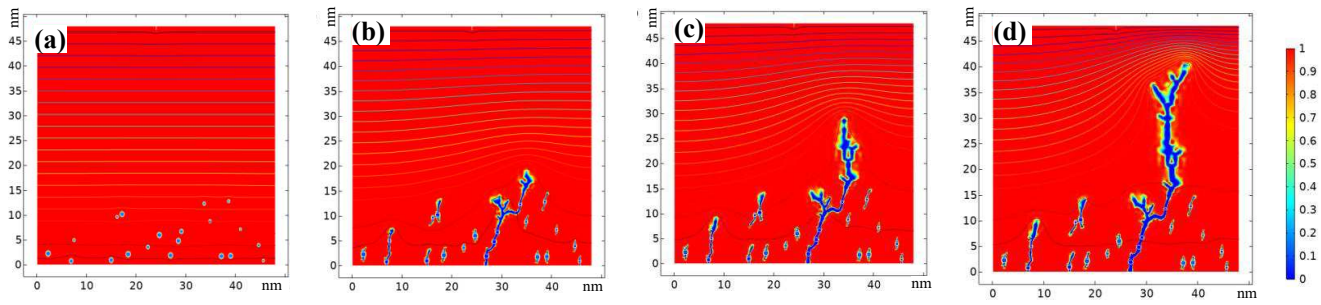


Fig. 3. Representative phase-field of breakdown-path evolution at different stress stages: (a) Stage I, nucleation of isolated degraded regions at pre-existing weak points near the SiO₂/SiC interface; (b) Stage II, directional growth of the degraded regions along the electric field direction; (c) Stage III, interaction and coalescence of neighboring degraded zones; and (d) Stage IV, formation of a continuous through-thickness conductive path, corresponding to catastrophic oxide breakdown.

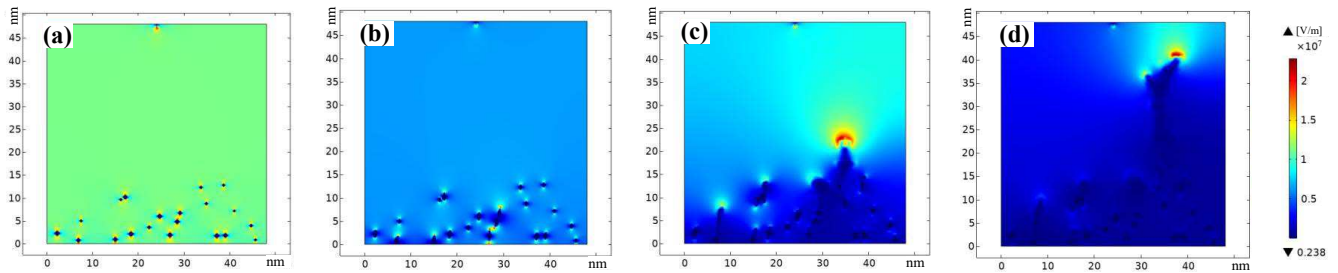


Fig. 4. Electric field distribution corresponding to the representative phase-field at different breakdown stages: (a) Stage I, weak local field enhancement near isolated defect nuclei close to the SiO₂/SiC interface; (b) Stage II, electric field concentration at the tips of the degraded regions; (c) Stage III, interaction and partial overlap of neighboring high field zones during path coalescence; and (d) Stage IV, strong field amplification near the advancing tip and constricted region of the through-thickness conductive path immediately before complete breakdown.

a coupled interaction between phase degradation and electric field redistribution.

Figure 3 shows representative snapshots of the phase-field variable, and Fig. 4 shows the corresponding electric field distribution at different stress stages. At Stage I, most of the oxide remains intact, and the electric field is still nearly uniform in the bulk oxide. Only at a few pre-existing weak points near the SiO₂/SiC interface does the local electrical driving force become sufficiently high to overcome the defect formation barrier, leading to local phase degradation and the formation of isolated nuclei. At this stage, the field enhancement is weak and remains confined to the vicinity of these nuclei.

At Stage II, once degraded nuclei appear, the electric field is redistributed and becomes concentrated at the tips of the low- η regions. This tip enhancement makes further phase degradation energetically favorable along the field direction, so that the degraded zones preferentially grow directionally rather than spread laterally. Therefore, the phase-field snapshots show the emergence of slit-like conductive features, while the electric field distribution reveals the physical origin of their directional growth. At Stage III, as neighboring degraded regions continue to extend, their associated high field zones begin to interact and overlap. Under this condition, coalescence becomes increasingly favorable because the additional electrostatic energy release exceeds the extra energetic cost of defect formation and interfacial expansion. Correspondingly, the phase-field result shows merging of neighboring degraded zones, and

the electric field map exhibits an increasingly localized high field pathway. At Stage IV, a continuous conductive path is established across the oxide thickness. Inside the main path, η approaches 0, indicating a fully degraded phase, while the strongest field concentration appears near the advancing tip and narrow constricted region of the through-thickness path. This result indicates that catastrophic breakdown is not caused by uniform degradation of the whole oxide, but by progressive localization driven by defect-triggered nucleation and subsequent electric field focusing.

Taken together, the combined phase-field and electric field results show that the experimentally extracted interfacial defect nonuniformity determines not only the initial nucleation sites of degradation, but also the subsequent field redistribution pathway that controls conductive path propagation and final breakdown morphology. In this sense, oxide breakdown in SiC MOS structures can be understood as a defect-triggered and field-driven localization process.

B. Post-breakdown characterization

To further examine the post-breakdown morphology, focused ion beam scanning electron microscopy (FIB-SEM) was performed after sequential milling of the gate region. During the electrical stress test, the gate was biased while the drain and source were shorted. Figure 5 summarizes the structural features revealed during the layer-by-layer cross-sectioning process after electrical stress. Figure 5(a) shows the original

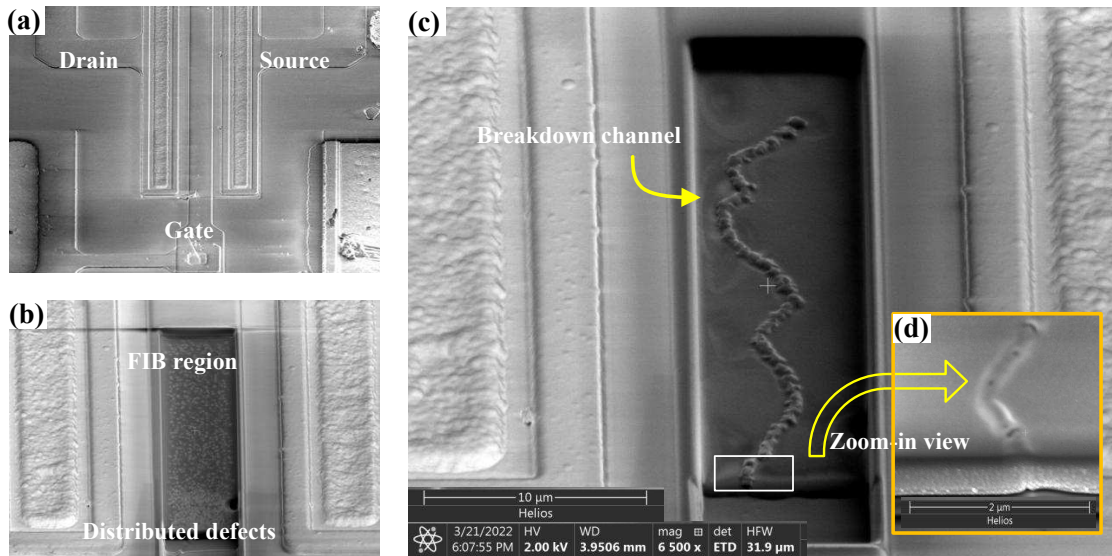


Fig. 5. FIB-SEM characterization of the post-breakdown gate region by sequential milling. (a) Top-view image of the device, indicating the gate region. (b) Shallow cross section after FIB milling, showing distributed defects inside the gate area. (c) Deeper cross section revealing a localized tortuous breakdown channel. (d) Zoom-in view of the breakdown channel, highlighting its pipe-like morphology.

top-view image before sectioning. After shallow FIB milling [Fig. 5(b)], a nonuniform distribution of localized defective regions becomes visible inside the gate area. These features are not uniformly distributed across the entire oxide region, but instead appear as spatially discrete weak points, indicating that the degradation is highly localized even at the early stage of structural exposure.

With further milling, as shown in Fig. 5(c), a continuous breakdown channel is revealed inside the oxide region. The channel follows a tortuous, pipe-like path with noticeable curvature and local width variation. This morphology suggests that breakdown does not proceed through homogeneous degradation of the entire oxide, but rather through progressive connection and coalescence of localized defect-rich regions into a confined conductive path. The enlarged image in Fig. 5(d) further highlights the detailed geometry of the breakdown channel. The channel appears narrow, bent, and locally widened, which is consistent with the defect-assisted conductive path formation predicted by the phase-field simulation. In particular, the observed curved and nonuniform channel shape supports the interpretation that the final breakdown trajectory is governed by local weak points and subsequent electric field redistribution.

IV. CONCLUSION

In this work, a defect-informed phase-field framework was developed to investigate oxide breakdown in SiC MOS structures. The model was initialized using an experimentally extracted depth-resolved defect profile obtained from capacitance and conductance frequency response, thereby linking electrical characterization with physics-based breakdown simulation. The simulation results show that oxide breakdown evolves through localized nucleation at defect-rich weak points near

the SiO₂/SiC interface, followed by field-driven coalescence, and eventual formation of a through-thickness conductive path. The coupled analysis of the phase-field variable and electric field distribution further indicates that electric field redistribution plays a decisive role in determining the propagation direction and final morphology of the breakdown path. Post-breakdown FIB-SEM observations reveal a tortuous and spatially confined channel, which is physically consistent with the defect-assisted and field-driven breakdown picture predicted by the model. These results suggest that oxide breakdown in SiC MOS structures is governed by a defect-triggered localization process rather than by homogeneous degradation of the entire oxide. The proposed framework provides a useful tool for visualizing otherwise inaccessible breakdown trajectories and offers physical insight for gate oxide reliability assessment and design optimization in SiC power devices.

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