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Comparison of Gate Oxide Lifetime Predictions with Charge-to-Breakdown Approach and Constant-Voltage TDDB on SiC Power MOSFET

Shengnan Zhu*, Tianshi Liu*, Limeng Shi*, Michael Jin*, Hema Lata Rao Maddi*,
Marvin H. White*, and Anant K. Agarwal*
*Department of Electrical and Computer Engineering, The Ohio State University, OH, USA (zhu.2670@osu.edu)

***Abstract*—The gate oxide reliability for commercial silicon carbide (SiC) power metal-oxide-semiconductor field-effect-transistors (MOSFETs) is significant for their applications. The constant-voltage time-dependent dielectric breakdown (TDDB) measurement is commonly utilized to evaluate the dielectric failure time of the SiC power MOSFETs under normal operation. A charge-to-breakdown approach based on the oxide tunneling current behavior has been proposed recently for the projection of dielectric failure time. The method is less time-consuming but requires the oxide leakage current behavior of the devices to follow a universal envelope. This work compares the predicted failure times of commercial 1.2 kV SiC MOSFETs from the charge-to-breakdown approach and the constant-voltage TDDB method. The results show that the constant-voltage TDDB method applied under low oxide fields ($\mathrm{E_{ox}} < 9\,\mathrm{MV/cm}$) produce the most conservative prediction of the device lifetime.**

***Index Terms*—SiC power MOSFET, constant-voltage TDDB, charge-to-breakdown approach, gate oxide reliability, lifetime prediction.**

I. Introduction

Silicon carbide (SiC) power metal-oxide-semiconductor field-effect-transistors (MOSFETs) have been commercialized during the past decades and used in PV converters, power supplies, and electric vehicles. The applications require the MOSFETs to have excellent reliability and ruggedness. It is known that one of the failure mechanisms for SiC power MOSFETs is the failure of the gate oxide. Thus, investigations into the gate oxide failure modes and the prediction of oxide lifetime are of significance for SiC MOSFETs.

The charge-driven oxide breakdown and field-driven oxide breakdown are widely discussed as the two main mechanisms for oxide failure [1]. The charge-driven mechanism is based on the assumption that the degradation of the gate oxide is caused by the current flow through the dielectric where the electrons are injected via Fowler-Nordheim (F-N) tunneling through the SiC/gate oxide barrier [2]. The field-driven mechanism assumes the oxide electric field is the main reason for the weakening of the molecular bonds of the gate dielectric, resulting in smaller activation energy to break the bonds within the gate oxide [2], [3].

The constant-voltage time-dependent dielectric breakdown (TDDB) measurement is normally applied to examine the oxide lifetime based on the field-driven mechanism. Liu et al. conducted constant-voltage TDDB measurements on 1.2 kV commercial SiC MOSFETs [4] [5]. The results show that the oxide lifetime under operating oxide electric field ($\mathrm{E_{ox}} = 4\,\mathrm{MV/cm}$) is overestimated with the constant-voltage TDDB measurements under high oxide electric fields due to the hole generation induced acceleration for the gate oxide failure. Therefore, it is recommended that the constant-voltage TDDB should be conducted under low electric fields ($\mathrm{E_{ox}} < 8.5\,\mathrm{MV/cm}$) to achieve a more accurate lifetime prediction for the gate oxide. However, constant-voltage TDDB can take a long time, especially at lower oxide electric fields.

The charge-to-breakdown approach is recently proposed by Moens et al. to extract the gate oxide lifetime [6]. They observed that the gate leakage currents under different oxide fields of the SiC MOS capacitors follow a universal envelope. The behavior can be used to predict oxide lifetime with the assumption that the dielectric breakdown is caused by a critical amount of charges passing through the oxide. The charge-to-breakdown approach is less time-consuming than the constant-voltage TDDB method. To the best of the authors' knowledge, there have not been any published studies that apply this approach to commercial SiC power MOSFETs.

This work applies the charge-to-breakdown approach to 1.2 kV commercial SiC MOSFETs from different vendors. A comparison between the predicted oxide lifetimes based on charge-to-breakdown and constant-voltage TDDB methods is conducted to evaluate the different lifetime prediction methods.

II. Experimental

The commercial 1.2 kV 4H-SiC power MOSFETs (packaged in TO-247) from two vendors have been tested in this work. General information of the measured commercial MOSFETs is listed in Table I. The threshold voltages of the devices

TABLE I
General information for commercial SiC MOSFETs

Properties	Vendor E	Vendor H
MOSFET type	planar	planar
Voltage rating (V)	1200	1200
Current rating (A)	10	40
Threshold voltage (V)	6.1∼6.2	4.6∼4.8
Gate oxide BV (V)	50	43
Est. oxide thickness (nm)	47	40

are extracted the using linear extrapolation method [7]. Devices with similar threshold voltages are selected to be tested in this work. The breakdown voltages for different vendors are measured with ramped-voltage breakdown measurement. The gate oxide thickness of these MOSFETs is estimated from the breakdown voltages by assuming the gate oxide breakdown field as 11 MV/cm. Gate leakage current vs. time under different gate voltage (V_G) have been measured on MOSFETs using the method described in [8]. A source/measurement unit (Keysight B2901A) is used to applied the gate voltages and monitor current for the measurements.

III. Results and Discussion

The constant-voltage TDDB and charge-to-breakdown approaches are introduced in this section. The comparison of predicted failure times with the constant-voltage TDDB method and the charge-to-breakdown approach are reported for vendors E and H.

A. Constant-Voltage TDDB

The constant-voltage TDDB measurement is conducted by applying a constant voltage to the gate terminals of SiC power MOSFETs until the devices break down. The breakdown times of the devices under test (DUTs) are recorded. The Weibull distribution and E-model are used to analyze the constant-voltage TDDB data and predict the failure time for the SiC power MOSFETs under normal operation gate voltages [2] [9]. The details for the measurement and analysis have been explained in our previous studies [4]. The lifetime prediction in the constant-voltage TDDB method is based on the field-driven theory. The oxide breaks down because the applied field weakens the chemical bond in the dielectric.

The constant-voltage TDDB method has been applied to vendors E and H in our previous work. The results for vendor E are reconstructed in Fig. 1. Two sets of oxide lifetime predictions are made from the constant-voltage TDDB results at $E_{ox} < 9\,MV/cm$ and $E_{ox} > 9\,MV/cm$. It has been demonstrated that under $E_{ox} > 9\,MV/cm$, hole trapping accelerates the dielectric failure [8]. Thus, the constant-voltage TDDB results at $E_{ox} > 9\,MV/cm$ overestimate the oxide lifetime at lower V_G and should be avoided.

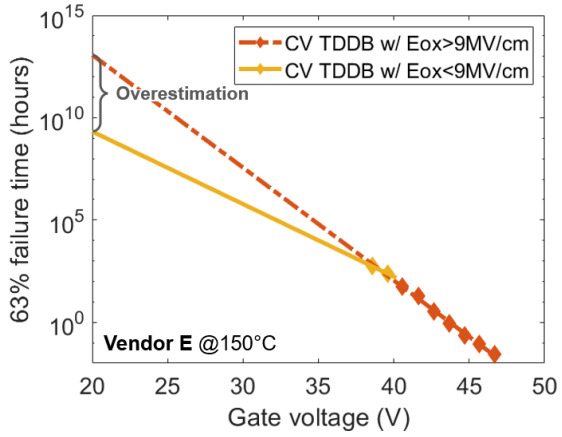

Fig. 1. 63% failure time vs. V_G for vendor E. Reconstructed from [4]

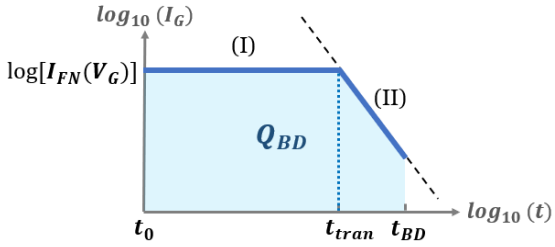

Fig. 2. Gate leakage current profile in charge-to-breakdown approach.

B. Charge-to-breakdown Approach

The charge-to-breakdown approach is based on the assumption that the gate leakage current profile under constant gate biases follows a universal envelope. The gate leakage current vs. stress time under a constant gate voltage (V_G) in the loglog scale is illustrated in Fig.2. The profile has two phases. In phase I (t_0 to t_{tran}), the gate leakage current stays constant with a value of $I_{FN}(V_G)$. In phase II (t_{tran} to t_{BD}), the current linearly decreases with the stress time. This decreasing trend can be fitted with a straight line as described by:

$$\log(I_G) = p_1 \log(t) + p_2, \tag{1}$$

where I_G is the gate leakage current, t is stress time, p_1 is the slope of the line, and p_2 is the intercept of the fitted line. Plug $t = t_{tran}$ into (1), we have:

$$\log(I_{FN}(V_G)) = p_1 \log(t_{tran}) + p_2. \tag{2}$$

Therefore, the t_{tran} can be calculated from (2) if $I_{FN}(V_G)$, p_1, and p_2 are known.

In the charge-to-breakdown approach, it is assumed that the oxide breakdown is caused by a critical amount of charge (Q_{BD}) passing through the dielectric. The charges that pass through the dielectric can be calculated by integrating the gate leakage I_G current to the stress time t. Therefore, when the device breaks down, the integrated charges are equal to Q_{BD}, and the stress time is defined as t_{BD}. The integration of Q_{BD} is expressed as:

$$\begin{aligned} Q_{BD} &= \int_0^{t_{BD}} I_G dt \\ &= \int_0^{t_{tran}} I_{FN}(V_G)\, dt + \int_{t_{tran}}^{t_{BD}} I_G dt \\ &= I_{FN}(V_G) \cdot t_{tran} + 10^{p_2} \cdot \frac{{t_{BD}}^{p_1+1} - t_{tran}\, p_1 + 1}{p_1 + 1} \end{aligned} \tag{3}$$

Therefore, if the Q_{BD}, t_{tran}, $I_{FN}(V_G)$, p_1 and p_2 are known, the device failure time t_{BD} can be calculated from (3).

C. Experimental Extractions of the Key Parameters

The charge-to-breakdown approach is applied to SiC commercial power MOSFETs from vendor E to extract the failure times under different gate voltages. The initial FN current ($I_{FN}(V_G)$) is obtained from the FN tunneling current. The ramped-voltage measurement result for vendor E is shown in Fig. 3 (blue curve). At lower V_G, the FN tunneling current is below the noise level. Thus, the FN tunneling theory is

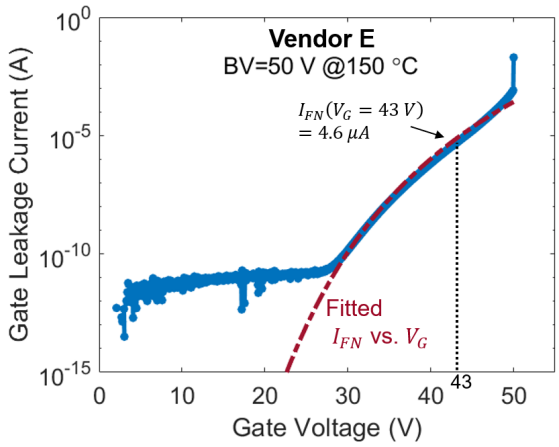

Fig. 3. Ramped-voltage breakdown measurement on vendor E (blue solid line), and fitted FN tunneling current (red dash line).

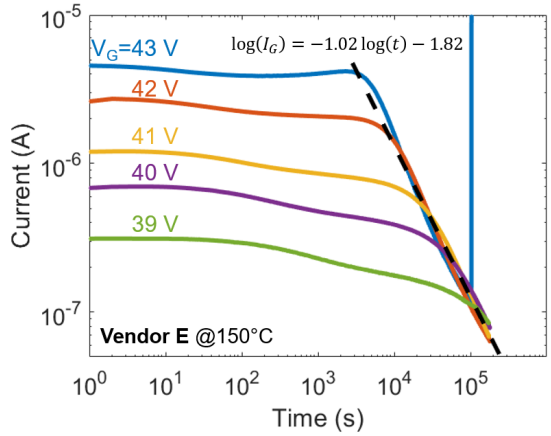

Fig. 4. Gate leakage currents under $V_G = 43\,V$ to $39\,V$ for vendor E and the fitted line for universal envelope (black dash line).

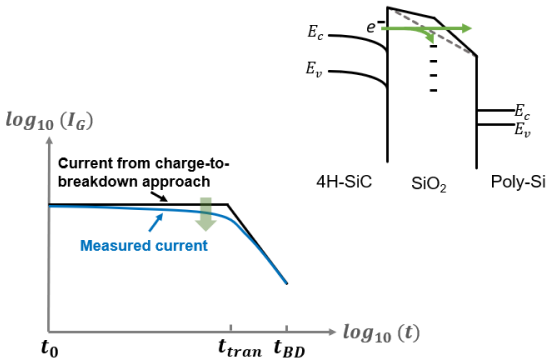

Fig. 5. Gate current deviation between the profile in charge-to-breakdown approach and the measured results (left); band diagram for electron trapping (right).

applied to fit the experimental data (red dash line) and obtain the tunneling current value (I_{FN}) at lower V_G [10].

The p_1 and p_2 are from the fitted line, which is acquired from the gate leakage currents under different values of V_G, as shown in Fig. 4. The measured gate leakage currents under $V_G = 43\,V$ to $39\,V$ for vendor E is shown in Fig. 4. The fitted line is plotted as a black dash line, and the p_1 and p_2 are extracted to be -1.02 and -1.82, respectively.

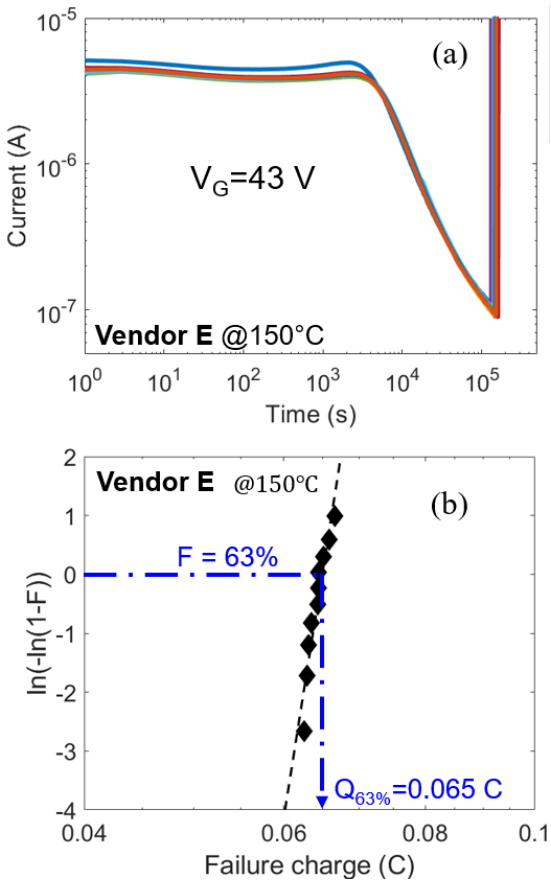

Fig. 6. (a) Gate leakage currents for ten devices under $V_G = 43\,V$; (b) Weibull plot for the Q_{BD}s of ten DUTs.

Under low gate voltages ($V_G = 41\,V$ to $39\,V$), the gate leakage currents show a noticeable decrease in the initial phase. The reason can be explained by the electron trapping process illustrated in Fig. 5. Under low V_G, electron trapping dominates in the gate oxide. The trapped electrons relax the oxide field, increase the tunneling barrier width, and reduce the gate leakage current. As a result, the measured gate leakage current gradually decreases instead of staying constant, as assumed by the charge-to-breakdown approach. Therefore, the charge-to-breakdown approach inaccurately estimates the failure times when there is significant electron trapping for the DUTs. This approach needs to be further modified for MOSFETs with a higher density of oxide traps.

Ten SiC power MOSFETs from vendor E are stressed under $V_G = 43\,V$ until breakdown. The gate leakage currents are monitored and shown in Fig. 6 (a). The Q_{BD} for each DUT is calculated by integrating the gate current w.r.t the stress time until breakdown. Ten Q_{BD} values are obtained and analyzed using Weibull distribution as plotted in Fig. 6 (b).

When the y-axis equals zero, the cumulative percentage of failure (F) is 63%. It means that 63% of the samples have failed. The corresponding failure charge is extracted to be $Q_{63\%}$, and the value is 0.065 C for vendor E. We use $Q_{BD} = Q_{63\%}$ to calculate the t_{BD} in the charge-to-breakdown approach using eqn. (3). The produced t_{BD} is referred to as

63% failure time.

D. Comparison of the Two Methods

The 63% failure times for vendor E under $V_G = 20\,V$ to $43\,V$ are calculated with the charge-to-breakdown approach and compared with constant-voltage TDDB results (Fig. 7). The charge-to-breakdown approach produces the highest failure time at $V_G = 20\,V$. The constant-voltage TDDB under low gate voltages ($E_{ox} < 9\,MV/cm$) produces the most conservative lifetime prediction.

The same measurements are repeated on vendor H, and the results (Fig. 8) reflecting a similar tendency as vendor E. Considering the safety-critical nature of the automotive industry, the constant-voltage TDDB under $E_{ox} < 9\,MV/cm$ is recommended to achieve a conservative oxide lifetime estimation. Although, with the most conservative method, both vendors achieve over 100-year oxide lifetime at $V_G = 20\,V$, reflecting promising oxide reliability of the commercial SiC power MOSFETs.

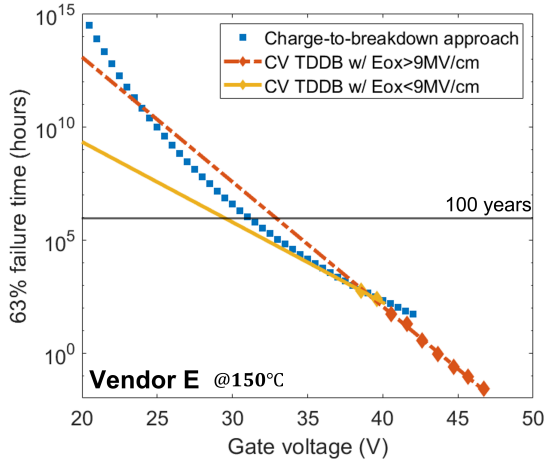

Fig. 7. Comparison of the 63% failure time vs. gate voltage between charge-to-breakdown and constant-voltage TDDB methods for vendor E.

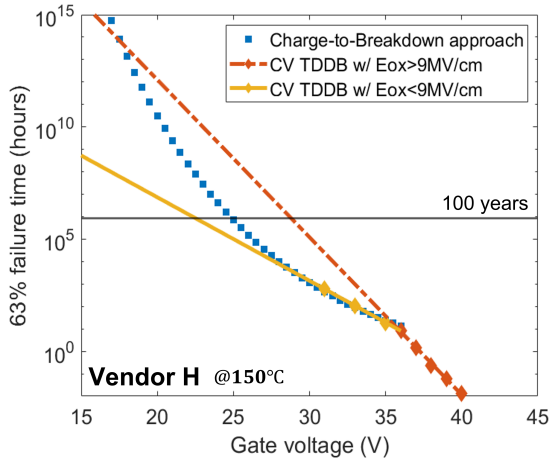

Fig. 8. Comparison of the 63% failure time vs. gate voltage between charge-to-breakdown and constant-voltage TDDB methods for vendor H.

IV. Conclusion

The charge-to-breakdown approach indicates a higher failure time than the constant-voltage TDDB method for SiC power MOSFETs under normal operation. The constant-voltage TDDB measurement conducted under low oxide fields ($E_{ox} < 9\,MV/cm$) yields the most conservative failure time prediction.

The charge-to-breakdown approach is less time-consuming, but it requires that the gate leakage current behavior of the devices follows a universal envelope. Additionally, the current model used in the charge-to-breakdown approach does not take into account the effect of electron trapping on the gate leakage current during the initial phase. Further investigation of the approach needs to be conducted to achieve a more accurate dielectric failure time prediction.

Acknowledgments

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