Oxide Reliability of SiC MOS Devices

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ABSTRACT

Silicon carbide possesses excellent material properties for high temperature, high frequency and high power applications. Among all the device structures, MOSFET has advantages such as low gate leakage current, easier device control etc., and therefore highly desirable. However, it has long been a common believe that the gate oxide breakdown reliability is a show-stopper, particularly at high temperature where SiC devices are expected to excel. In this paper, we report that the thermally grown gate oxide on 4H-SiC is intrinsically reliable even at temperature as high as 375°C. We further show that even with the current SiC processing technology, devices with 10 cm^2 active area can still achieve 100-year lifetime @ E<2.9MV/cm and 375°C.

INTRODUCTION

As a wide bandgap material, silicon carbide (SiC) has high breakdown electric field and high thermal conductivity, making it a good candidate for high power and high temperature applications. The fact that a natural oxide (SiO_2) can be grown on its surface gives SiC a great advantage over other wide bandgap materials for realizing power MOSFET and IGBT. However, it is widely believed that the gate oxide grown on SiC is not reliable enough, especially at high temperatures [1-3]. This conclusion was based on both theoretical as well as experimental reasons.

Theoretically, the smaller (compared to silicon) conduction band offset between SiC and SiO_2 will lead to higher leakage current and lower breakdown field. At room temperature, the conduction band offset was reported to be 2.7eV and 2.95eV for 4H-SiC and 6H-SiC respectively, while the offset between Si/SiO_2 is 3.1eV. More alarmingly, the measured effective barrier height at the SiC/SiO_2 interface decreases dramatically with temperature, making the device even less reliable at higher temperatures [2,4]. Experimentally, the reported Time Dependent Dielectric Breakdown (TDDB) measurements showed that long term operation of SiC MOS devices at temperatures higher than 250°C is not practical [3].

Surprisingly, Matocha *et al.* reported a mean time to failure longer than 100 years at 250°C and 3MV/cm recently [5]. Given such promising result, the whole breakdown reliability question for gate oxide on SiC deserved to be revisited in more details. In this paper, we show even more promising result that large area device can be operated at 375°C and 2.9 MV/cm for 100 years despite the still rather primitive processing technology.

EXPERIMENT

In this work, 4H-SiC MOS capacitors, fabricated on n-type epitaxial layers, are provided by two different vendors. The thickness of the gate oxide is in the range of 45 to 70 nm. All results shown in this paper are measured on 200 μm × 200 μm devices.

20 capacitors, all within the same die, are stressed simultaneously at the wafer level. Temperature on the wafer was directly monitored with a thermal couple. Each test device is connected through a series resistor to a constant voltage source. The voltage is monitored across each device sequentially to determine if breakdown has occurred without interrupting the applied stress. Once a failure is detected, the stress to that device is disconnected in order to ensure that thermal dissipation and current flow through the failed device does not interfere with adjacent devices under test.

RESULTS AND DISCUSSIONS

A comparison of the TDDB results (measured at 225°C) between samples provided by two different vendors is shown in Fig. 1. The basic reliability trends are quite similar. This consistency is a significant milestone. It means after years of improvements on fabrication techniques, oxides qualities are converging towards the intrinsic regime. In silicon community, such consistency was not reached until the mid 90s.

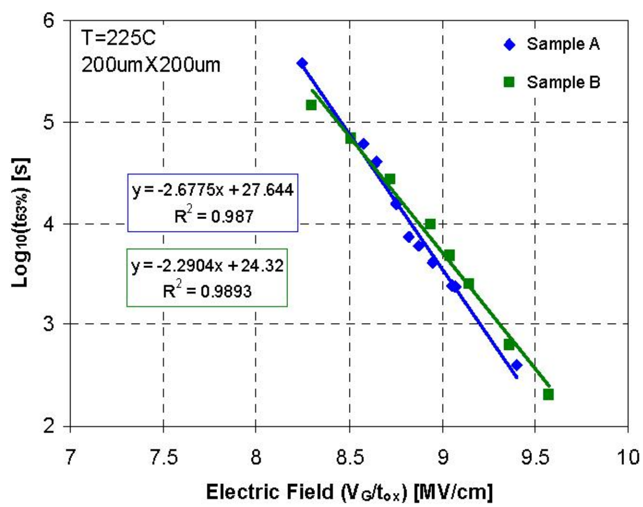

Fig. 1 Electric field acceleration results (225°C) of two sets of samples from two different vendors show the same reliability trend.

Fig. 2 shows the lifetime projection based on electric field acceleration results measured on 200 μm × 200 μm MOS capacitors at 225°C and 375°C. At 225°C, a projected 100-year lifetime is achievable if the operation electric field is kept below 5.9 MV/cm, and a 10-year lifetime can be reached if the electric field is less than 6.5MV/cm. At 375°C, the operation electric field can be 3.9MV/cm and 4.6MV/cm for 100-year and 10-year lifetime respectively. The field acceleration factors are 1.84 and 1.46 decades per MV/cm for 225°C and 375°C respectively. These results are highly encouraging and remove a major concern about SiC MOSFET, namely the reliability of SiO_2 on SiC.

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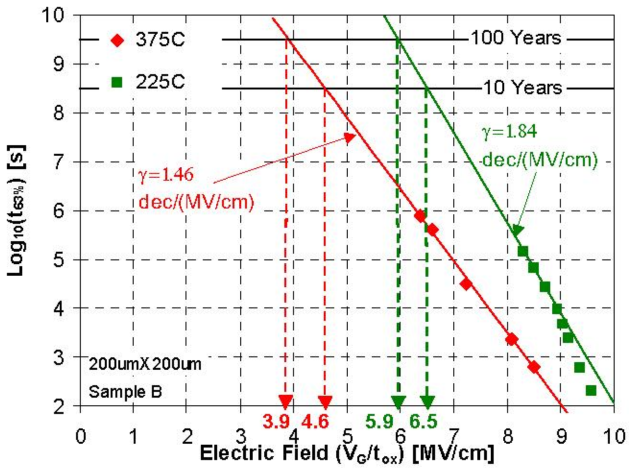

Fig. 2 Lifetime projection based on electric field acceleration results measured on 200μm×200μm MOS capacitors at 225°C and 375°C.

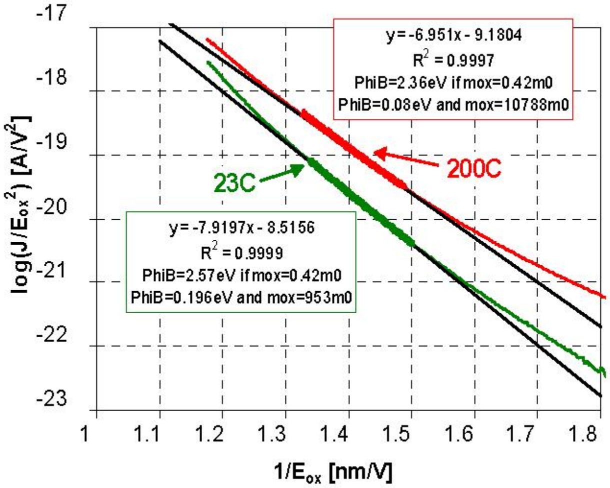

Fig. 3 FN plots of the electron tunneling current at room temperature and 200°C. Effective barrier heights are extracted using different methods.

Effective barrier height (Φ_B) at RT and high T

How to explain the good result on reliability? What happen to the extremely low barrier height at high temperature? To answer this question, we made our own barrier height measurement. In the literature, the effective barrier height (Φ_B) between SiC and SiO_2 is often extracted from the measurement of Fowler-Nordheim (FN) tunneling current [2,4]. The expressions are as follows:

$$J_{FN}(T) = A(T)E_{ox}^2 \cdot \exp\left(-\frac{B(T)}{E_{ox}}\right), \tag{1}$$

$$A(T) = \frac{q^3 m_{SiC}}{8\pi h m_{ox}\Phi_B}, \qquad B(T) = \frac{4\sqrt{2m_{ox}\Phi_B^3}}{3q\hbar}$$

where J_{FN} is the current density of the FN tunneling current. E_{ox} is the electric field across the oxide, q is the electron charge, h and ħ are the Planck constants. m_{ox} and m_{SiC} are the effective electron mass in oxide and SiC, respectively. By rearranging Eq. (1), a linear relationship can be obtained between $\log(J/E_{ox}^2)$ and $1/E_{ox}$, as in Eq. (2).

$$\log_{10}\left(\frac{J}{E_{ox}^2}\right) = \log_{10} A(T) - \frac{1}{\ln 10}\cdot\frac{B(T)}{E_{ox}} \tag{2}$$

By fitting the FN plot, Φ_B and m_{ox} can be extracted if m_{SiC} is a constant. In the literature, m_{ox} is commonly treated as a constant ($0.42m_0$) [2,4] and extract Φ_B from the slope of the FN plot using only the expression for *B(T)*.

In Fig. 3, we followed the commonly used method to extract Φ_B at room temperature and 200°C. The data used for fitting is taken when the E_{ox} is between 6.7 to 7.4MV/cm to avoid the distortion from system leakage at low field and the distortion due to charge trapping at high field. As can be seen, this choice is somewhat arbitrary. However, as long as we keep the range constant, the comparison of the extracted barrier height from different temperature is still valid. The extracted effective barrier height is 2.57eV at room temperature and 2.36eV at 200°C. The Φ_B change is clearly not as extreme as reported.

Note that we are following the common practice of using only the equation for *B(T)* to extract barrier height. If we let m_{ox} be a variable, and extract Φ_B and m_{ox} simultaneously using both expressions for A(T) and B(T) in Eq. (1), we get rather strange result like Φ_B=0.196eV m_{ox}=953m_0 for T=23°C and Φ_B=0.08eV m_{ox}=10788m_0 for T=200°C (m_{SiC}=0.37m_0 is used). This consistency issue raise serious question on the validity of Φ_B extracted using FN method.

Weibull slope and Area scaling

In many applications of power devices, e.g. DC/DC converter power module that handles as much as 1000 A of current, the required total active area of the power device can be quite large. For a current density of 100 A/cm^2 (current state-of-the-art), the total device area needed is 10 cm^2. Will such a large area be a problem for reliability? To answer that question, we need to know the Weibull distribution, particularly the slope β.

The expression for Weibull distribution is given by

$$F(T_{BD}) = 1 - \exp\left[-\left(\frac{T_{BD}}{\alpha}\right)^{\beta}\right], \tag{3}$$

where F is the cumulative failure factor, α is the characteristic time (63% failed), β is the Weibull slope. It can be shown that area scaling is given by

$$T_{BD}(A_1) = T_{BD}(A_2)\left[\frac{A_2}{A_1}\right]^{1/\beta} \tag{4}$$

A_1 and A_2 are the two scaling areas. If β equals to infinity, Eq. (4) shows that the time-to-breakdown is independent of area. Larger β means breakdown lifetime is less sensitive to area.

If there is only one breakdown mechanism, β should be the same for different areas. Thus if the oxides are truly of intrinsic quality, there should only be one β value for each oxide thickness and area scaling is simple. However, β value measured from one sample population (same thickness) varies from 3 to 10 as shown in Fig. 4. While there is no model to predict what the β value should be for thick oxide, the fact that value as high as 10 was observed suggest that the intrinsic value is at least 10 or larger. It also suggest that the good result obtained so far is still not the best that can be achieved.

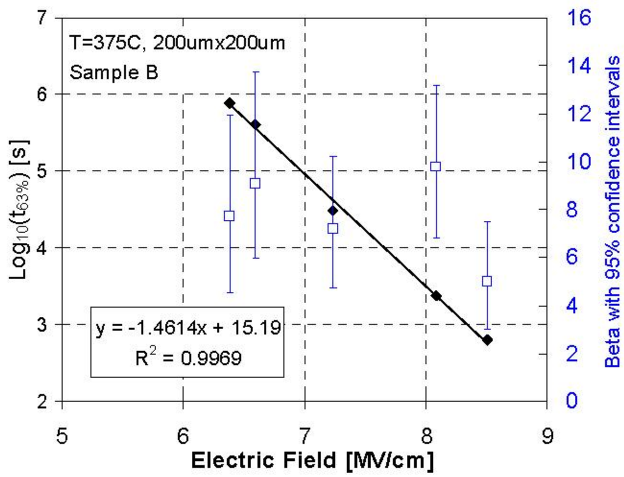

Fig. 4 Weibull slope (β) varies randomly in a large range for Weibull distributions at different electric fields. Error bars indicate the 95% confidence intervals of β.

If β value is 10 or larger, then there is no need to worry about the area scaling effect on reliability because the impact will be negligible. However, when the β value is 3, area scaling must be taken into account. Clearly, while the oxide growth process has come a long way, much of the breakdown distribution is affected by extrinsic failure. Since SiC power module is ready to put into real system for test, we need to answer the question of reliability for the SiC MOSFET with the current technology.

Fig. 5 plots the worst-case scenario of area scaling, where $\beta = 3$ is used to scale the area to 10 cm^2. It can be seen that even at the worst-case, and T = 375°C, the oxide on devices with total area of 10 cm^2 is still reliable enough to have a 100-year and 10-year lifetime at operation electric field of 2.9 MV/cm and 3.6 MV/cm respectively.

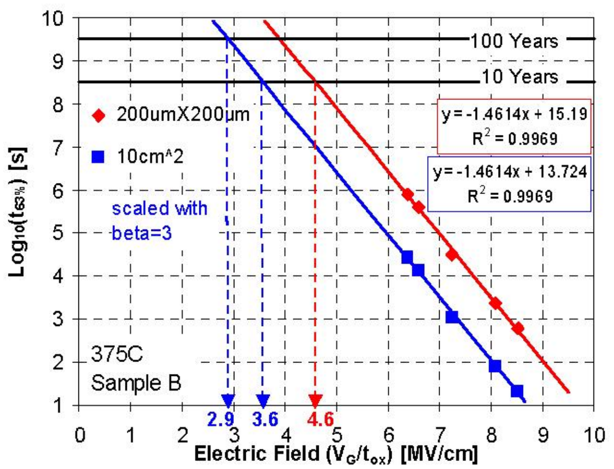

Fig. 5 Area scaling to 10 cm^2 in the worst-case scenario with β = 3. At 375°C, 100-year lifetime for a power module with total device area of 10 cm^2 can be reached when the operation electric field is kept below 2.9MV/cm.

It should be noted that the reliability performance reported here is after screening off the early failures. Indeed, exactly how to screen the early failures affect the extracted β value.

Factors which affect β determination

For non-intrinsic breakdown populations, there are a few factors that affect the determination of β. We will discuss these factors to identify the most important one for improvement.

1. Sample size of breakdown data: It is known that β is difficult to measure to a satisfactory accuracy if the sample size is not sufficiently large. In this work, β is extracted from a sample size of 20. It is limited by the test setup, availability of test devices as well as the test time required especially for low electric field stresses. Fortunately, β is not as sensitive to sample size for thick oxides as it would be for ultra thin oxides.

2. Multiple breakdown mechanisms: For non-intrinsic population, the Weibull distribution is a mixture of breakdown mechanisms. For the determination of characteristic time and β, we remove the extrinsic part from the distribution, and then recalculate the Weibull distribution. However, it is often not very clear where to put the cutoff line for removal. This can lead to a β variation. An example is shown in Fig. 6. β = 9.79 if only two data points in the tail are considered to be extrinsic failures, while β = 10.87 if four points are treated as extrinsic failures. This $\Delta\beta$ = 1 can be translated into a 10% difference in lifetime projection when the device is scaled up to 10 cm^2.

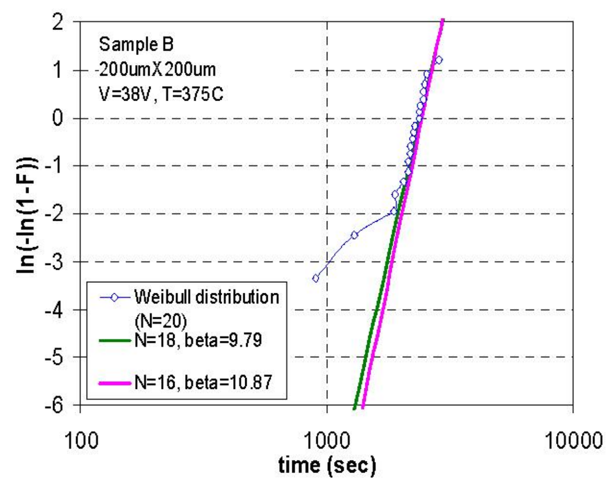

Fig. 6 Example of β variation due to different removal of extrinsic failures. β=9.79 if two data points are considered to be extrinsic, while β=10.87 if four data points are considered to be extrinsic.

3. V_{FB} non-uniformity: Flat-band voltage variation across the devices under test can reduce β dramatically. Fig. 7 shows the C-V measurements on 12 devices selected uniformly across the die. The measured V_{FB} varies from –1.4V to +0.2V. It means that the set of devices under the same constant voltage stress actually have different electric field across the oxide. Take V_{stress} = 60 V, t_{ox} = 66 nm for example, E_{ox} varies from 9.06 MV/cm to 9.30 MV/cm. With a field acceleration factor of 2.7 decades/(MV/cm), this ΔE_{ox} can cause the lifetime to change by 4.5 times.

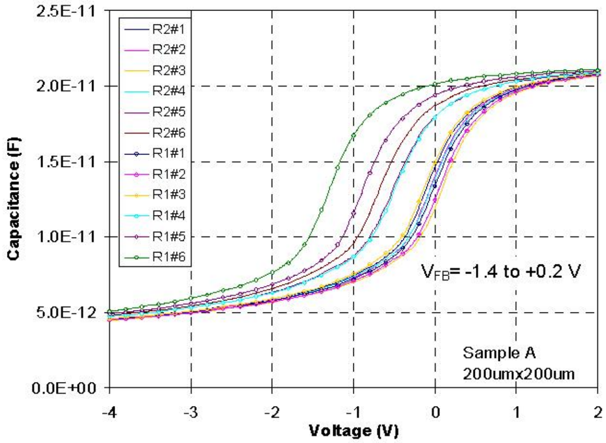

Fig. 7 Variation of flat-band voltage on 12 devices uniformly selected across the die. V_{FB} ranges from –1.4V to +0.2V.

Fig. 8 demonstrated the influence of ΔE_{ox}=0.24 MV/cm on β. 20 characteristic times are selected from 20 Weibull distributions with a ΔE_{step} = 0.24/20 = 0.012 MV/cm. Each of these Weibull distributions has a beta of 9. The curve with solid-square symbols is the new distribution with ΔE_{ox} = 0.24 MV/cm. It can be seen that β degraded drastically from 9 to 2.4.

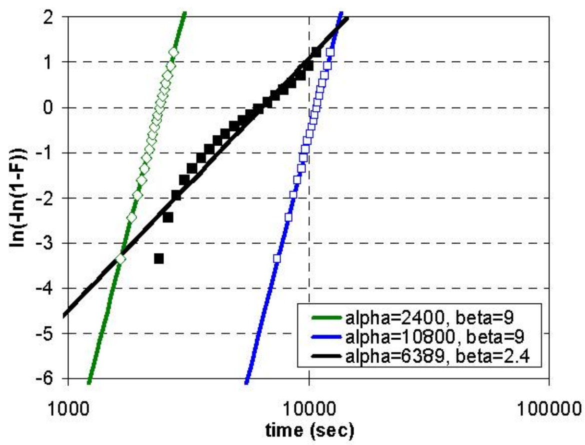

Fig. 8 Simulated Weibull distribution of 20 devices with a ΔE_{step}=0.012MV/cm. Total ΔE_{ox} across the devices is 0.24MV/cm. β degraded from 9 to 2.4.

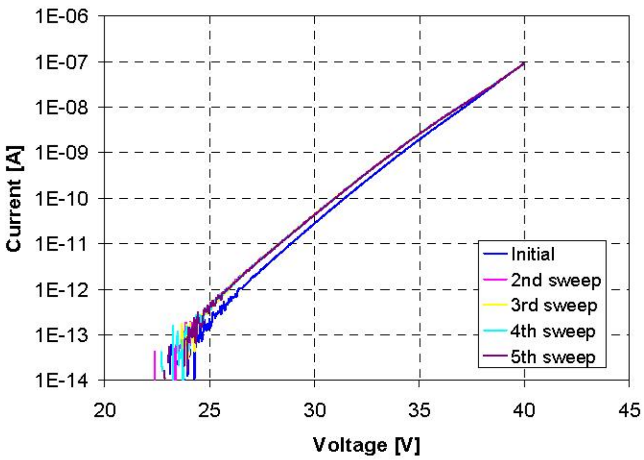

Fig. 9 Charge trapping due to pre-existing traps in the oxide shown by five consecutive I-V sweeps.

Pre-existing traps may be the main reason for the large V_{FB} non-uniformity. In Fig. 9 five consecutive I-V sweeps on the same device are shown. The initial sweep is smaller than the subsequent sweeps, except at very high voltage. All subsequent sweeps fall on top of each other. The interpretation of this set of I-V curve is that the initial sweep leads to charge trapping when the field is high enough, and this charge trapping saturates quickly. At high voltage, the fact that all the five sweeps merge together clearly indicates that charge trapping only occurs in the first sweep. Therefore, those traps must be pre-existing in the oxide. Pre-existing oxide traps are a processing issue that requires optimization.

4. Oxide thickness non-uniformity: Variation of oxide thickness (Δt_{ox}) also causes the E_{ox} to vary, hence a smaller β and shorter predicted lifetime. C-V measurements show a 4 nm oxide thickness variation across the 4-inch wafer, and 0.4 nm across a single die. This translates to a ΔE_{ox} = 0.05 MV/cm across the die. It is relatively small compared with the influence of V_{FB} non-uniformity.

Above all, the flat band voltage non-uniformity has the biggest impact on β. Since it is related to pre-existing traps in the oxide, it is a process optimization issue. Interestingly, this suggests that β is a sensitive parameter for process optimization.

SUMMARY

TDDB results are reported on the state-of-the-art 4H-SiC MOS capacitors at 225°C and 375°C. It predicts 100-year lifetime for devices with area 200µm×200µm is achievable with operation electric field less than 3.9 MV/cm at 375°C. Area scaling and Weibull slope variation are discussed. Even in worst-case scenario, for a device size of 10 cm^2, a 10-year lifetime is achievable with E<3.6MV/cm and a 100-year lifetime with E<2.9MV/cm at T=375°C. These results suggest that the oxide on 4H-SiC is sufficiently reliable even if the process is not yet optimized. This makes it hopeful for 4H-SiC MOSFET to be used at higher temperatures.

ACKNOWLEDGEMENT

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REFERENCES

[1] R. Singh et al, "Reliability of SiC MOS devices", Solid State Electronics, 48, pp.1717-1720 (2004)

[2] A. K. Agarwal et al, "Temperature Dependence of Fowler–Nordheim Current in 6H- and 4H-SiC MOS Capacitors" IEEE Electron Device Lett., 18(12): 592-594 (1997)

[3] M. M. Maranowski et al, "Time-Dependent-Dielectric-Breakdown Measurements of Thermal Oxides on N-Type 6H-SiC", IEEE Trans. Electron Devices, 46(3): 520-524 (1999)

[4] R. Waters et al, "Temperature-dependent tunneling through thermally grown SiO_2 on n-type 4H- and 6H-SiC" Applied Physics Letters 76(8): 1039-1041 (2000)

[5] K. Matocha et al, "Time-Dependent Dielectric Breakdown of Thermal Oxides on 4H-SiC", Materials Science Forum Vols. 556-557: 675-678 (2007)