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On the Repeatability and Reliability of Threshold Voltage Measurements during Gate Bias Stresses in Wide Bandgap Power Devices

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***Abstract*—This paper investigates the peculiarities and challenges of accurate threshold voltage (V_{TH}) measurement after gate bias stress in SiC MOSFETs and GaN e-HEMTs. Traditional techniques historically used in silicon MOSFETs involve test sequences typically comprising preconditioning, V_{TH} measurement, gate voltage stress and V_{TH} measurement after stress. However, with Wide bandgap (WBG) devices like SiC and GaN transistors, the repeatability of V_{TH} measurement, the impact of V_{TH} measurement duration, delay between successive measurements and the role of preconditioning on the accuracy of V_{TH} are currently under study. With current industrial and academic research interest in bias temperature instability in WBG devices, this paper provides significant insight into how repeatable V_{TH} measurement is in WBG devices since measuring V_{TH} can change it. The impact of repeated measurements on the cumulative V_{TH} shift is investigated in both WBG technologies with different delay times between successive measurements with and without preconditioning. Unipolar and Bipolar preconditioning pulses are compared regarding V_{TH} measurement in SiC MOSFETs.**

Keywords*—*GaN e-HEMTs, Gate Bias stress tests, SiC MOSFETs, Threshold Voltage Shifting

I. INTRODUCTION

Qualification of power MOSFETs and IGBTs requires gate oxide reliability tests to ensure stable and reliable operation of the power device in the field. The gate leakage current and threshold voltage are critical parameters for gate reliability tests. Depending on the qualification standards, for example, AEC Q101, the rated gate voltage is applied on the gate of the power device for 1000 hours with the device at a junction temperature of 150°C or 175°C [1]. The gate leakage current should be continuously monitored, and the threshold voltage should not have changed by more than ±20% [2]. The threshold voltage can be measured as a point measurement with a forcing current or as a gate sweep measurement. The former is done by connecting the gate to the drain, forcing a small current through the drain-source and measuring the gate-source or drain-source voltage as the threshold voltage. The latter is done by sweeping the gate voltage from zero upwards until a pre-defined drain-source current is measured and the drain-source maintained at a predefined constant voltage.

Applying a gate voltage (V_{GS}) stress voltage causes charges to drift/diffuse into the gate oxide, causing a V_{TH} shift. The shift in V_{TH} can be temporary (i.e., reversible by applying a V_{GS} of opposite polarity or simply grounding the gate to allow charge recovery) or permanent (due to V_{TH} hysteresis) [3-5]. Preconditioning (a process of removing temporary charges by applying a predefined V_{GS} pulse to the device under test) is recommended before V_{TH} measurement. These tests are routine for silicon devices. However, the complex gate dielectric systems in wide bandgap (WBG) devices like Silicon Carbide (SiC) MOSFETs and Gallium Nitride (GaN) e-HEMTs require a re-evaluation of the test procedures and standards [6, 7]. The highly dynamic nature of V_{TH} in WBG devices, due to charges with a wide range of time constants, means the time between V_{GS} stress removal and V_{TH} measurement is critical. This was defined as a maximum of 24 hours for silicon devices but has been redefined as 96 hours for SiC MOSFETs [8] and largely remains unclear for GaN e-HEMTs. V_{TH} shift from V_{GS} stress has been studied extensively in SiC MOSFETs [9-11] and is increasingly being studied in GaN e-HEMTs [12, 13].

This paper addresses some more fundamental questions on the repeatability of V_{TH} measurements in WBG devices. Specifically, the impact of preconditioning, the effect of time delay between successive V_{TH} measurements and the impact of the measurement duration V_{TH} measurement repeatability are addressed. Section II of the paper details the experimental set-up; section III reports the results of the measurements, and section IV concludes the paper.

II. EXPERIMENTAL SET-UP

The experimental setup is shown in Fig. 1. It comprises the Device Under Test (DUT), a gate driver, a Source Measurement Unit (SMU) from Keithley model 2602B, a circuit with relays for changing the set-up between preconditioning mode and measurement mode and a National Instruments board for controlling relays. Fig. 2(a) shows a

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circuit schematic of Fig. 1 while it is in V_{TH} measurement mode (with the gate and drain connected by the relay and the SMU forcing 1 mA through the drain-source). In contrast, Fig. 2(b) shows the circuit schematic of Fig. 1 while it is in preconditioning mode (the drain-source is shorted while the gate driver applies a pre-programmed V_{GS} pulse to the DUT). The selected DUTs are a 650 V silicon MOSFET from IXYS with datasheet reference IXFX20N120, a 650 V SiC MOSFET from ST with datasheet reference SCT10N120AG and a 650 V GaN e-HEMT from GaN Systems with datasheet reference GS66508T. The following section details the experiments and the results.

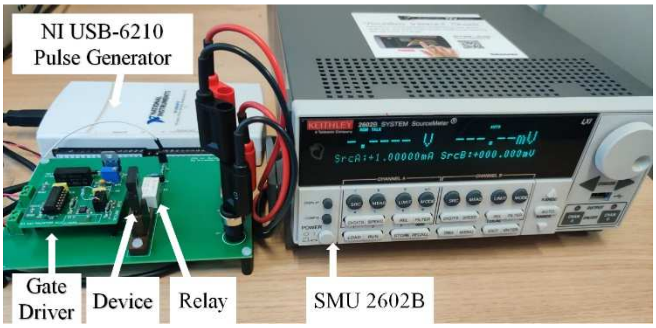


Fig. 1. Experimental set-up for V_{TH} measurements in Power devices

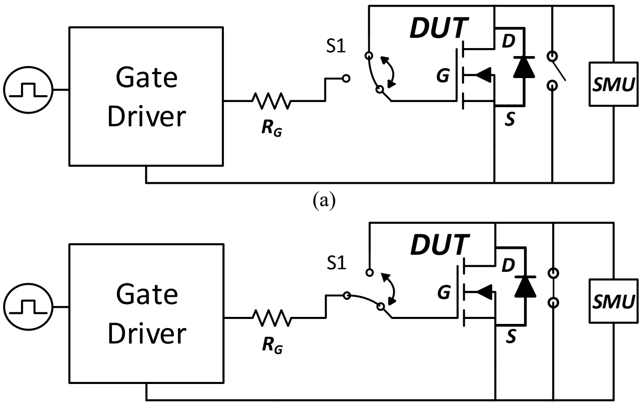


Fig. 2. (a) Circuit schematic in V_{TH} Measurement mode.
(b) Circuit schematic while it is in gate preconditioning mode.

III. THRESHOLD VOLTAGE MEASUREMENT REPEATABILITY

Four experiments have been performed to investigate the repeatability of V_{TH} measurements.

A. *Experiment 1: Repeatability of V_{TH} Measurement with Unipolar Preconditioning.*

In this experiment, V_{TH} is measured 5 consecutive times, with a unipolar preconditioning pulse between each measurement. The pulse is at the rated gate voltage and is 100 milliseconds long. Fig. 3 shows the gate pulse sequence for this test.

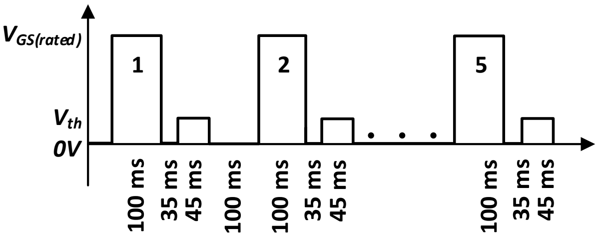


Fig. 3. Gate pulse sequence for V_{TH} repeatability measurements with unipolar preconditioning.

An essential parameter in this test is the time delay between the successive measurements. This time delay has been set at 100 milliseconds and 100 seconds to investigate its impact on V_{TH} repeatability. The results are shown for the silicon MOSFET, SiC MOSFET and GaN e-HEMT in Fig. 4(a) for 100 milliseconds time delay and Fig. 4(b) for 100 seconds time delay.

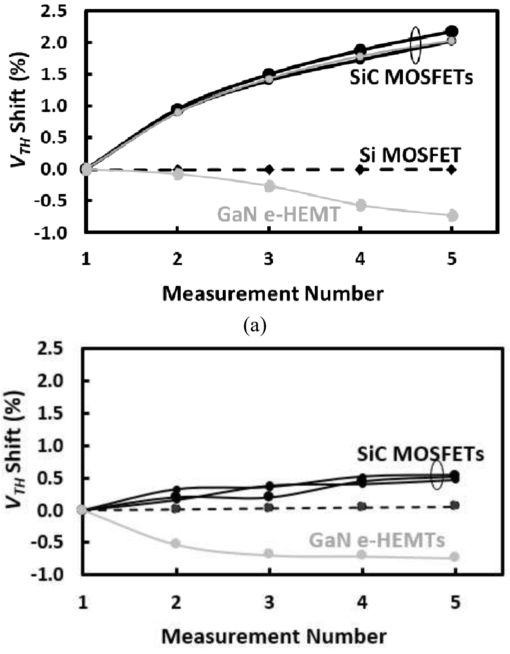
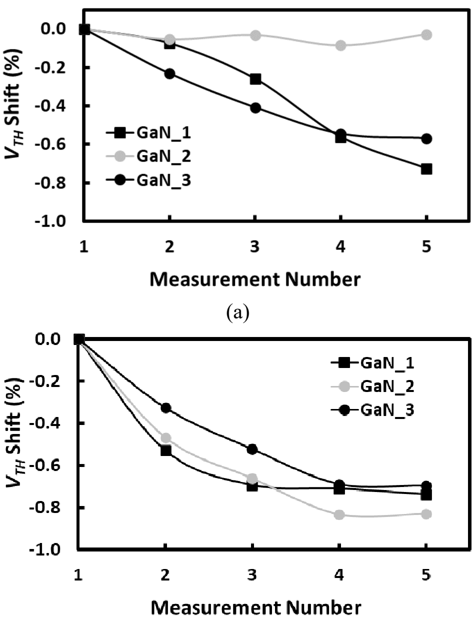


Fig. 4. V_{TH} shift as a function of measurement number (a) 100 milliseconds time delay between measurements (b) 100 seconds time delay between measurements.

For the Silicon MOSFETs, V_{TH} is measurement invariant. It remains constant regardless of measurement number and time delay between successive measurements, as shown in Fig. 4(a) for 100 milliseconds and Fig. 4(b) for 100 seconds. These measurements were repeated for three different devices, and the trends were identical. For the SiC MOSFETs, positive preconditioning shifts V_{TH} positively. A 100-millisecond positive preconditioning pulse shifted V_{TH} by +2% over 5 successive measurements with a 100-millisecond delay between measurements. When the delay is increased to 100 seconds, as shown in Fig. 4(b), the cumulative V_{TH} shift reduces to less than 0.5%. This indicates that more than 100 seconds is required to allow the release of the majority of the trapped negative charge for V_{TH} to be repeatable. These experiments were repeated for 3 devices, and all showed the same trends.

For the GaN e-HEMTs, positive preconditioning shifts V_{TH} negatively. A positive preconditioning pulse shifted V_{TH} by non-repeatable and random negative magnitudes when the delay between successive measurements is 100 milliseconds, as shown in Fig. 5(a). The range of V_{TH} shift was between -0.02% to -0.8%. When the delay between measurements was increased to 100 seconds, the variability in V_{TH} shift reduced, and all devices turned by approximately -0.7 to -0.8%, as shown in Fig. 5(b). There is evidence of a cumulative V_{TH} shift due to preconditioning and V_{TH} measurements in the GaN e-HEMTs for both short and long delay times.



(a)

(b)

Fig. 5. V_{TH} shift in 3 GaN e-HEMTs as a function of measurement number (a) 100 milliseconds time delay. (b) 100 seconds time delay

An essential difference between SiC MOSFETs and GaN e-HEMTs is that positive V_{TH} shift in SiC MOSFETs results from positive V_{GS} stress, whereas in GaN e-HEMTs, negative V_{TH} shift can result from positive V_{GS} stress. Previous studies of bias-temperature-instability in GaN e-HEMTs have shown that at low V_{GS} stress, the V_{TH} shift is positive due to electron trapping in the gate p-GaN layer [14,15]. In contrast, at high V_{GS} stress, the V_{TH} shift is negative due to hole trapping at the AlGaN/GaN interface [14,15]. Since the preconditioning pulse imposes the rated V_{GS} stress on the GaN e-HEMT gate, the negative V_{TH} shift reported here is in agreement with the previous studies.

B. *Experiment 2: Repeatability of V_{TH} Measurement with Bipolar Preconditioning.*

In this experiment, V_{TH} is measured 5 consecutive times, with a bipolar preconditioning pulse between each measurement. Fig. 6 below shows the gate pulse sequence for this test including pulse durations.

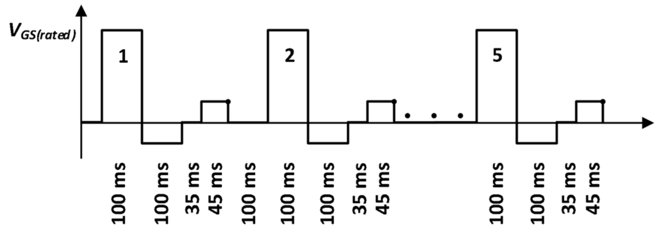
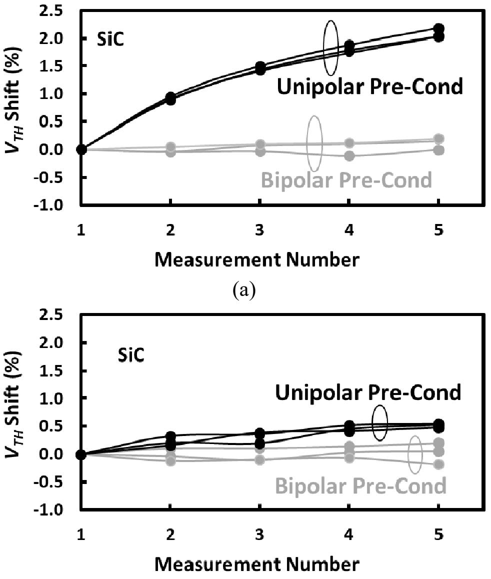


Fig. 6. Gate pulse sequence for V_{TH} repeatability measurements with Bipolar preconditioning.

The results for the bipolar preconditioning experiments on the SiC MOSFETs are shown in Fig. 7(a) for V_{TH} measured after 100 milliseconds and Fig. 7(b) for V_{TH} measured after 100 seconds. In Fig. 7, the V_{TH} drift as a function of measurement number is compared for unipolar and bipolar preconditioning. In the case of SiC MOSFETs, as shown in Fig. 7(a) and 7(b), the bipolar preconditioning pulse yields less variation in V_{TH} compared to the unipolar preconditioning pulse. While the drift in V_{TH} for the unipolar preconditioning pulse is as high as 2% for 100 millisecond time delay for the bipolar pulse, it is below 0.5%. As the time delay between V_{TH} measurement is increased to 100 seconds, the measured ΔV_{TH} as a function of measurement number reduces to 0.5% for unipolar pulse and 0.05% for the bipolar pulse. It is clear that the bipolar preconditioning pulse is more effective in ensuring minimum variability in the measured V_{TH}.

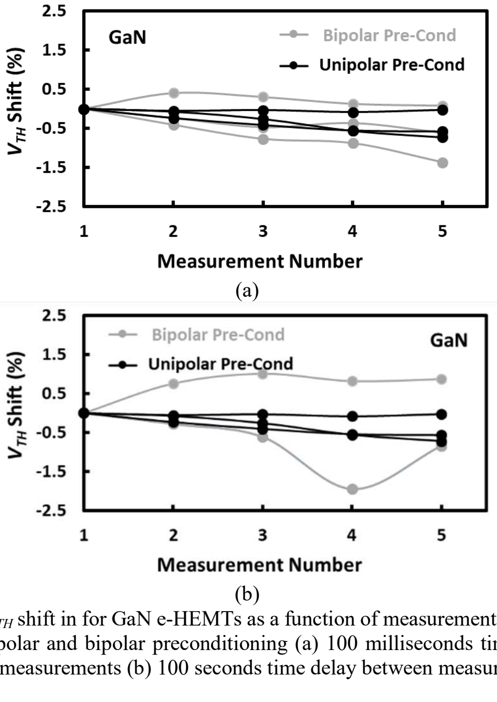


(a)

(b)

Fig. 7. V_{TH} shift in SiC MOSFETs as a function of measurement number, with unipolar and bipolar preconditioning (a) 100 milliseconds time delay between measurements (b) 100 seconds time delay between measurements.

Fig. 8(a) and 8(b) show the results of V_{TH} shifts from repeated measurements in the GaN e-HEMTs for 100-millisecond and 100 second delay times. The results for the GaN e-HEMTs are random and do not show any trends when comparing the unipolar and bipolar preconditioning pulses. This is both due to the complexity of charge trapping and release in GaN e-HEMTs (as discussed earlier) and limitations of the V_{TH} measurement system, since microsecond level resolution is required to measure the dynamic V_{TH}.



(a)

(b)

Fig. 8. V_{TH} shift in for GaN e-HEMTs as a function of measurement number, with unipolar and bipolar preconditioning (a) 100 milliseconds time delay between measurements (b) 100 seconds time delay between measurements

C. Experiment 3: Repeatability of Threshold Voltage Measurement without Preconditioning.

In this experiment, V_{TH} is measured repeatedly on the same DUT. However, the preconditioning pulse is removed. This has been done with a time delay between successive measurements set at 100 milliseconds and 100 seconds to investigate the impact of recovery time on threshold voltage repeatability. Fig. 9 shows the gate pulses applied on the DUT.

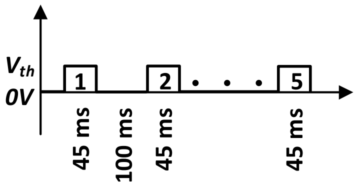
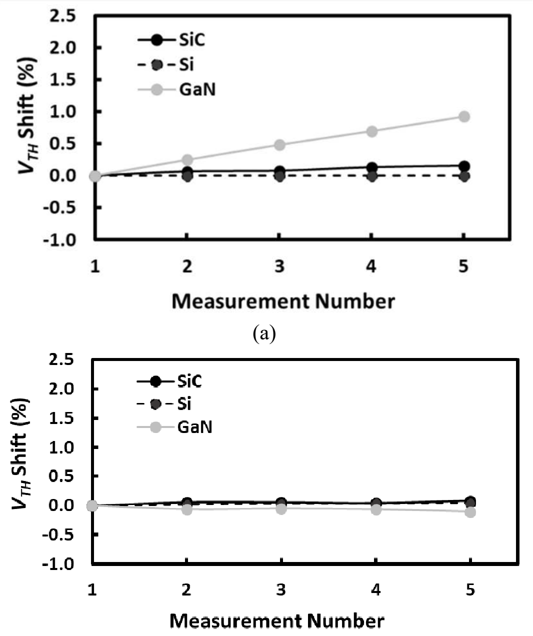


Fig. 9. Gate pulse sequence for V_{TH} repeatability measurements without preconditioning.

The results of the experiment are shown in Fig. 10(a) for 100 milliseconds time delays between successive V_{TH} measurements and Fig. 10(b) for 100 seconds time delay.



(a)

(b)

Fig. 10. V_{TH} measurement repeatability without preconditioning (a) 100 milliseconds delay (b) 100 seconds delay.

In the Silicon MOSFETs, V_{TH} measurement is invariant. It remains constant regardless of measurement number for 100 milliseconds and 100-second delay between V_{TH} measurements. In SiC MOSFETs, the V_{TH} shift is lower without preconditioning compared to with preconditioning. It reduces to 0.2% from the 2% shift due to preconditioning. There is no evidence of stress accumulation, and the measurements are repeatable as the V_{TH} shift is low.

In the GaN e-HEMTs, the V_{TH} shift becomes positive without preconditioning (recalling that it was negative with preconditioning). There is some cumulative effect of successive measurements as the V_{TH} increases with the measurement number. As the time delay between the measurements is increased to 100 seconds, the overall V_{TH} repeatability is improved.

D. Experiment 4: Impact of V_{TH} Measurement duration

In this experiment, the V_{TH} pulse duration's impact on the V_{TH} measurement's repeatability is assessed. Since measuring V_{TH} in WBG devices changes V_{TH}, it is essential to ascertain the optimal measurement duration to ensure that V_{TH} measurement is repeatable. The circuit is in measurement mode, as shown in Fig. 2(a), where the gate-drain are shorted and a current of 1mA is forced by the SMU. The test sequence is shown in Fig. 11 and consists in determining the V_{TH} using measurement windows of different duration, with the measurement point at the instant identified by a ●. Fig. 12 shows the results of V_{TH} measurement performed with different durations, ranging from 50 milliseconds to 500 milliseconds. The results show that the measured V_{TH} is stable and repeatable for the WBG devices within the range considered.

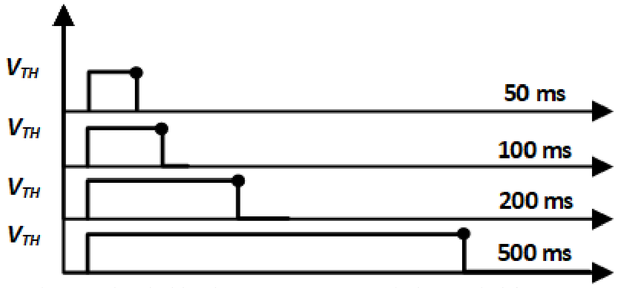


Fig. 11. Threshold voltage measurement window varied from 50 milliseconds to 500 milliseconds.

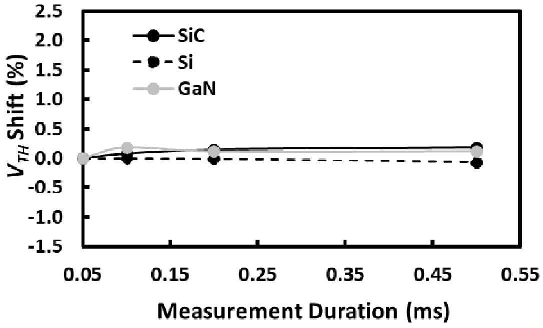


Fig. 12. V_{TH} shift as a function of V_{TH} measurement duration

IV. ROLE OF PRE-CONDITIONING IN V_{TH} MEASUREMENT AFTER GATE STRESS IN SIC MOSFETS

In this section, a series of gate stresses (up to 1000 seconds) are performed on SiC MOSFETs. The V_{TH} is measured before and after each stress at duration (1, 10, 100 and 1000 seconds). The objective of this investigation is to evaluate the effectiveness of the type of preconditioning for measuring the V_{TH} shift after a gate stress. The sequence used is (i) precondition with either unipolar or bipolar pulse (ii) measure V_{TH} to determine pre-stress values (iii) apply V_{GS} stress for the pre-defined time (iv) measure V_{TH} to determine post-stress peak value. This sequence is repeated for each stress duration. Here, three different conditions are assessed to investigate the impact of preconditioning on the measured V_{TH} shift. First, a unipolar preconditioning pulse is used (by applying the rated +20 V for 100 milliseconds). Second, a bipolar preconditioning pulse is used (by applying a +20 V pulse for 100 milliseconds followed by a -5 V pulse for another 100 milliseconds). Third, no preconditioning is applied. The overall pulse sequence for this experiment is shown in Fig. 13.

Fig. 14 shows the measured permanent V_{TH} shift (after preconditioning) as a function of stress time while Fig. 15 shows the measured peak V_{TH} shift (after stress) as a function of stress time.

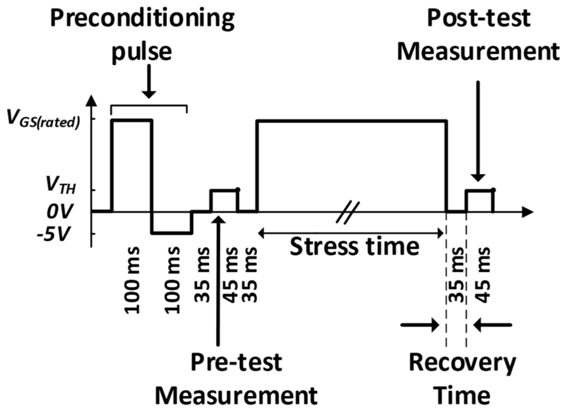


Fig. 13. Pulse train for gate stress experiments with different preconditioning

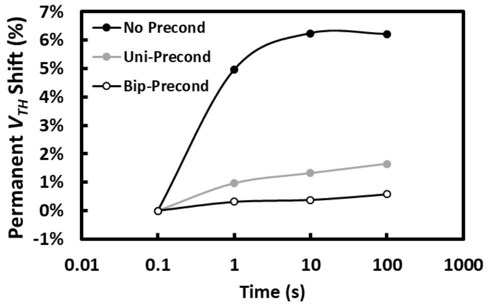


Fig. 14. Permanent V_{TH} shift as a function of V_{GS} stress time with unipolar preconditioning, bipolar preconditioning and no preconditioning

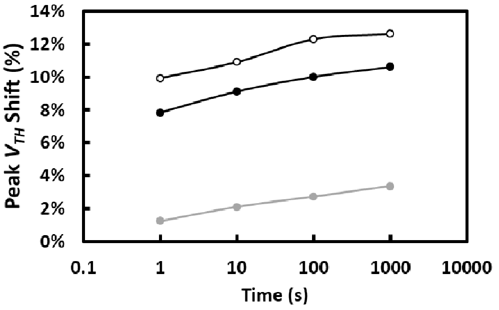
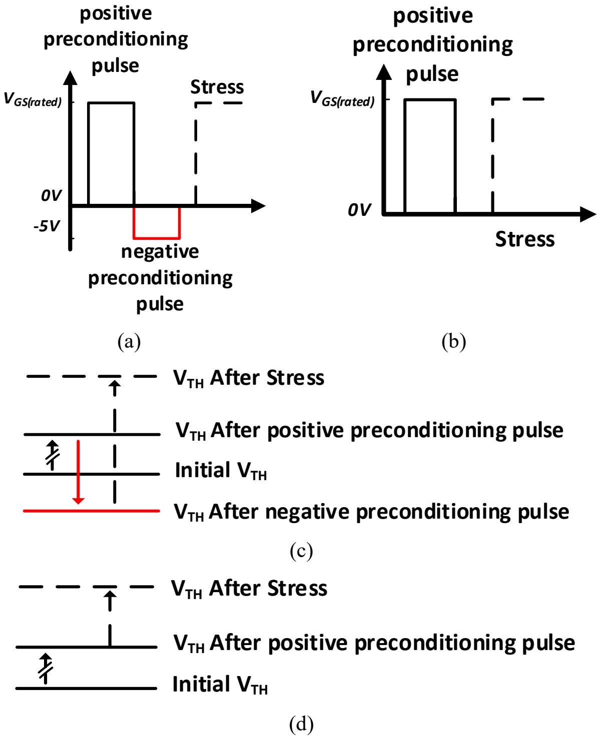


Fig. 15. Peak V_{TH} shift as a function of V_{GS} stress time with unipolar preconditioning, bipolar preconditioning, and no preconditioning

Fig. 14 shows that when bipolar preconditioning is used, the measured permanent ΔV_{TH} is lowest (0.5%) compared with unipolar preconditioning (1.6%) and no preconditioning (6%). During positive gate bias stress, electron trapping occurs in the gate dielectric/semiconductor interface. Since charge trapping with different time constants causes temporary and permanent shifts, the preconditioning pulse is designed to remove the temporary shifts so that the permanent shifts can be measured. These results show that bipolar preconditioning is more effective at resetting the V_{TH} by removing temporary charge compared to unipolar preconditioning. No preconditioning results in the highest permanent V_{TH} shift because temporary charges are not removed and keep accumulating with subsequent measurements. Fig. 15 shows that peak V_{TH} shift is highest for the measurements done with bipolar preconditioning (13%) followed by no preconditioning (11%) and the lowest peak V_{TH} is exhibited by measurements done with unipolar preconditioning (3.5%).

Applying a bipolar preconditioning pulse dislodges the temporary charges (induced by V_{GS} stress) by changing the polarity of the electric field across the gate oxide therefore accelerating temporary charge removal. When the unipolar preconditioning pulse is used, a defined state of charge is set in the gate oxide rather than removing temporary/fast charges i.e. unipolar preconditioning charges the fast traps while bipolar preconditioning removes fast traps.

Fig. 16 illustrates this diagrammatically, where the V_{TH} shift is shown conceptually for unipolar and bipolar preconditioning.



(a) (b)

(c)

(d)

Fig. 16. (a) Bipolar preconditioning pulse (b) Unipolar preconditioning pulse (c) Conceptual diagram of V_{TH} shifts with bipolar preconditioning and V_{GS} stress and (d) Conceptual diagram of V_{TH} shifts with unipolar preconditioning and V_{GS} stress.

The measured V_{TH} shift after bipolar preconditioning is higher because the application of the negative pulse sets a lower initial V_{TH} by discharging the negative traps with fast time constants. Hence, bipolar preconditioning results in higher peak post stress V_{TH} shift because it has the lowest pre-stress V_{TH}.

V. CONCLUSIONS

Threshold voltage measurement in WBG devices is essential for reliability assessment and qualification. In this paper, the repeatability of the threshold voltage measurement is assessed and compared for commercially available SiC MOSFETs and GaN e-HEMTs. The impact of the preconditioning type (unipolar and bipolar) on V_{TH} measurement repeatability is also assessed. Since no V_{GS} stress was applied in this instance, the V_{TH} shift is solely due to preconditioning. It is shown that positive unipolar preconditioning impacts the consistency of the V_{TH} measurement for SiC MOSFETs and GaN e-HEMTs. V_{TH} shifts upwards by 2% for SiC MOSFETs and downwards by up to 1% for GaN e-HEMTs. The shifts in SiC MOSFETs are cumulative over the measurement sequence. Bipolar preconditioning is better in ensuring V_{TH} repeatability in SiC MOSFETs since the V_{TH} variability reduces to below 0.5%. In the case of GaN e-HEMTs, there is more variability in the V_{TH} shift between different devices and there is no discernable correlation between V_{TH} repeatability and the preconditioning type. A time delay of about 100 seconds between measurements is sufficient for reducing the cumulative shifts in the V_{TH} due to successive measurements in SiC MOSFETs. In GaN e-HEMTs, V_{TH} variability is not improved by delay times. Without preconditioning, the V_{TH} shifts reduce for SiC MOSFETs and GaN e-HEMTs. The V_{TH} measurement window was varied from 50 milliseconds to 500 milliseconds and shown to have a negligible impact on V_{TH} consistency. Gate bias stress tests were performed on SiC MOSFETs with unipolar, bipolar and no preconditioning. The impact of preconditioning on the peak and permanent V_{TH} shift was assessed. The measured peak V_{TH} shift was highest with bipolar preconditioning and lowest in unipolar preconditioning. For the permanent V_{TH} shift, the lowest was measured in the bipolar preconditioning and the highest was measured with no preconditioning.

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