

## Comparison of the Performance-Degrading Near-Interface Traps in Commercial SiC MOSFETs

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**Keywords:** Commercial 4H-SiC MOSFET, Characterization Technique, Device Performance, Near-Interface Traps

**Abstract.** This paper presents a comparison of the density of performance-degrading near-interface traps (NITs) in the most commonly available 1200 V commercial N-channel SiC power metal–oxide–semiconductor field-effect transistors (MOSFETs). A recently developed integrated-charge technique was used to measure the density of NITs with energy levels aligned to the conduction band, which degrade MOSFET's performance by capturing and releasing electrons from the channel biased in the strong-inversion condition. Trench MOSFETs of one manufacturer have lower densities of these NITs in comparison to MOSFETs with the planar gate structure, corresponding to observed higher channel-carrier mobility in trench MOSFETs. Different response-time distributions were also observed, corresponding to different spatial location of the measured NITs.

### Introduction

Commercialization of SiC metal–oxide–semiconductor field-effect transistors (MOSFETs) began in 2011, and since then they have become a preferred choice in the power electronics industry. In spite of technological advancements in the past decade, SiC MOSFETs are still unable to realize the full potential of SiC because of a high density of oxide defects at and near the SiC/SiO<sub>2</sub> interface [1]. These defects act as near-interface traps (NITs) for electrons, which significantly degrade the performance and adversely impacts the reliability of SiC MOSFETs [2, 3]. When the MOSFET operates at sub-threshold voltages, NITs with energy levels within the bandgap are active and capture electrons resulting in threshold voltage drift, making it a reliability issue [4]. When the applied gate voltage ( $V_G$ ) is above the threshold voltage ( $V_T$ ), the Fermi level crosses the bottom of the conduction band because of the quantum confinement effect [5]. At these gate voltages, the energy levels of NITs that are aligned to the conduction band continuously trap and release electrons from the MOSFET channel by tunneling [6]. This phenomenon degrades the performance of the device by reducing the effective channel-carrier mobility.

The standard characterization techniques can only quantify NITs in the sub-threshold region, even when the MOSFETs are biased at the operating gate voltage ranging from 15 V to 20 V [7–9]. However, we have recently developed an integrated-charge technique that can characterize the performance-degrading NITs in commercial MOSFETs at operating gate voltages [7]. In this paper, we compare the density of performance-degrading NITs in the most commonly available 1200 V commercial N channel SiC power MOSFETs by applying the integrated-charge technique.

### Experimental Details

The investigation includes 1200 V commercial N channel SiC power MOSFETs with the most popular planar and trench gate structures from various manufacturers. The on-resistance ( $R_{DS(on)}$ ) and the gate

capacitance ( $C_G$ ) at 18 V of the MOSFETs used in this study are summarized in Table 1.  $R_{DS(on)}$  was determined by standard  $I$ – $V$  measurements given in the datasheets by the manufacturers of respective devices, whereas  $C_G$  was measured using the integrated-charge technique.  $R_{DS(on)}$  and  $C_G$  were used to determine a figure of merit (FOM), which is inversely proportional to the density of performance-degrading NITs [10].

Table 1: On-resistance ( $R_{DS(on)}$ ), measured gate capacitance ( $C_G$ ) at  $V_G = 18$  V, and figure of merit,  $FOM = R_{DS(on)} \times C_G$  [10] for 1200 V commercial MOSFETs

Manufacturer	MOSFET ID	Gate Structure	$R_{DS(on)}$ [m $\Omega$ ]	$C_G$ [pF]	$FOM = R_{DS(on)} \times C_G$ [ $\times 10^{-12} \Omega F$ ]
A	A1	Trench	90	977	89
A	A2	Trench	350	280	98
B	B	Planar	281	530	149
C	C1	Planar	280	1,635	458
C	C2	Trench	105	1,424	149.5
D	D1	Planar	282	592	167
D	D2	Planar	360	583	210
E	E	Planar	192	1,295	249

It is worth noting that  $C_G$  is different from the input capacitance,  $C_{iss}$ , provided in the datasheets.  $C_G$  is a function of  $V_G$ , however, the datasheets provide  $C_{iss}$  at  $V_G = 0$  and large drain-to-source voltages [10]. Also, the gate oxide capacitance ( $C_{ox}$ ) can be defined as the gate capacitance,  $C_G$ , measured at the manufacturer's recommended gate drive voltage and grounded drain and source terminals. At this operating gate voltage, the P-type body of MOSFETs is inverted at the semiconductor surface creating the channel, whereas the N-type drift region is accumulated. Consequently, the active area and thickness of the gate capacitor become equal to the gate area ( $A_G$ ) and gate oxide thickness ( $t_{ox}$ ), respectively. The gate oxide thickness of the device can be determined from  $I_G$ – $V_G$  characteristics using Fowler–Nordheim tunneling, which can further be utilized to find  $A_G$  [7, 11].

To perform the measurements using the integrated-charge method, the drain, and the source of the MOSFET were connected to the ground and an external resistance,  $R_{EXT}$ , was connected in series with the gate. The series connection of the gate capacitance,  $C_G$  and  $R_{EXT}$ , was biased with an input DC voltage from 20 V and slowly stepped down to -20 V. At a specific input DC voltage, a square waveform with small voltage steps ( $\Delta V_{step}$ ) and time interval of  $t_{step} = 1/(2f)$  was superimposed by a Tektronix AFG1022 function generator. The current in the  $RC$  circuit charges the gate capacitor during the interval  $t_{step}$  and then discharges it during the other half of the cycle. The voltage across the  $R_{EXT}$  was measured using Tektronix P6139B voltage probes with Tektronix DPO 7104 oscilloscope to obtain the current through the gate capacitor. The measured current was used to determine the charge  $qN_{carriers}$  in response to the applied  $\Delta V_{step}$ . This charge corresponds to an electrically active gate capacitance  $C_G = qN_{carriers} / \Delta V_{step}$ . To quantify the NITs with response times shorter than 500  $\mu s$ , 50  $\mu s$ , 5  $\mu s$ , and 500 ns, square waveforms were used with frequencies of 1 kHz, 10 kHz, 100 kHz, and 1 MHz, respectively. All the measurements were performed at room temperature.

## Results and Discussion

The capacitance–voltage ( $C$ – $V$ ) curves for different response times  $\tau_{min}$  obtained using the integrated-charge technique are shown in Fig. 1 (a) and (b) for MOSFET D2 with planar gate structure and MOSFET A1 with trench gate structure, respectively.  $C_G$  was measured as a function of  $V_G$  for the response times (capture/release times) of 500  $\mu s$ , 50  $\mu s$ , 5  $\mu s$  and 500 ns. A reduction in the gate capacitance is observed with shorter response times because the trapped charge is unable to contribute

to the measured gate current for the duration it is trapped, which reduces the electrically active gate capacitance. Hence, the total density of trapped charge per unit area can be determined by [12]:

$$\Delta N_{trapped}(\tau_{min}) = \frac{\Delta V_{step}}{qA_G} [C_{G-long} - C_{G-short}(\tau_{min})] \quad (1)$$

where  $C_{G-long}$  is the measured  $C-V$  curve with the reference  $t_{step}$  of 500  $\mu$ s, and  $C_{G-short}$  is the measured  $C-V$  curve with the shorter time steps. The total density of trapped charge was calculated for 50  $\mu$ s, 5  $\mu$ s, and 500 ns using 500  $\mu$ s as the reference.

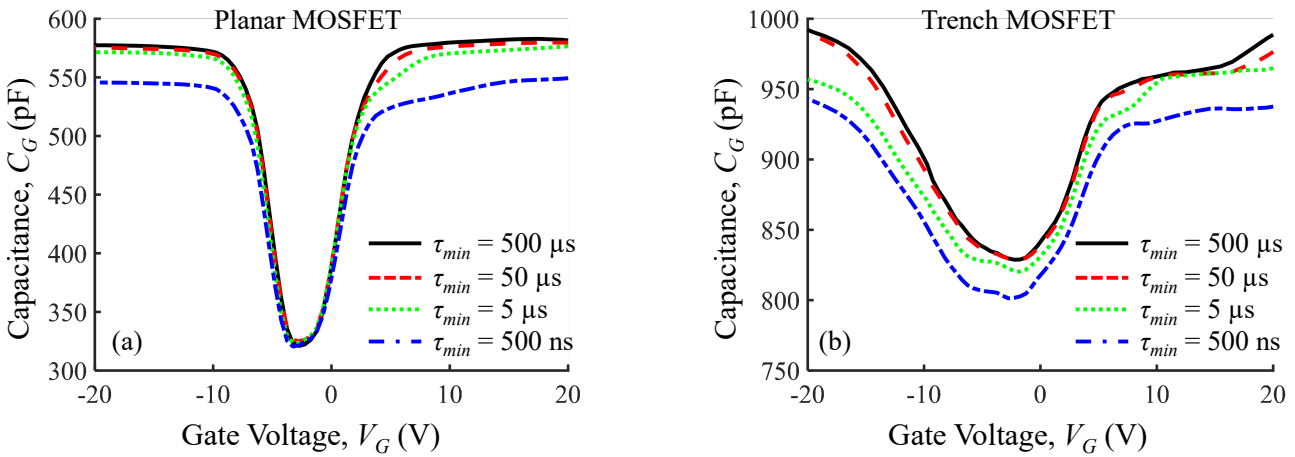


Fig. 1: Capacitance–voltage curves of 1200 V commercial N-channel SiC Power MOSFETs for MOSFET D2 with planar gate structure (a) and MOSFET A1 with trench gate structure (b).

The focus of this paper is to characterize the NITs that can trap electrons from the channel and consequently degrade the performance of the device. These NITs can trap electrons only at above-threshold gate voltages. Hence, it is important to compare the fraction of trapped electrons at above-threshold gate voltages. At a given voltage, the fraction of electrons that are trapped for a period longer than  $\tau_{min}$ , in response to applied voltage step ( $\Delta V_{step}$ ), can be given by [12]:

$$\gamma(\tau_{min}) = \frac{\Delta N_{trapped}(\tau_{min})}{C_{ox} \Delta V_{step} / qA_G} = \frac{C_{G-long} - C_{G-short}(\tau_{min})}{C_{ox}}. \quad (2)$$

Figure 2 shows the fraction of trapped electrons for various capture/release times ( $\tau_{min}$ ) in the above-threshold region. The results show that more electrons are trapped for shorter response times, irrespective of the manufacturer or the type of gate structure. It is important to note that most devices exhibit no significant change in the density of NITs with increased gate voltage, which indicates fairly uniform distribution of NIT's energy levels. However, referring to Fig. 2 (a) and Fig. 2 (b), we observe that MOSFET C1 (planar) and MOSFET C2 (trench) show a higher density of NITs at low voltages compared to higher voltages. This indicates that MOSFET C1 and MOSFET C2 have a higher density of NITs with low energy levels and capture/release times between 5  $\mu$ s and 50  $\mu$ s.

The fraction of the total density of electrons trapped for longer than  $\tau_{min}$  at the operating gate voltage,  $V_G$ , can be determined by [12]:

$$\gamma_{TOT}(\tau_{min}) = \frac{\Delta V_{step}}{V_G - V_T} \sum_0^{V_G} \gamma(\tau_{min}). \quad (3)$$

Figure 3 compares  $\gamma_{TOT}(\tau_{min})$  for different capture/release times and for all measured MOSFETs at  $V_G = 18$  V. It can be seen that MOSFET E and MOSFET B have higher slope compared to other devices. These means that the density of NITs in these devices is higher near the SiC/ SiO<sub>2</sub> interface and lower further from the interface. It can also be observed from Fig. 3 that, for manufacturer C, the trench

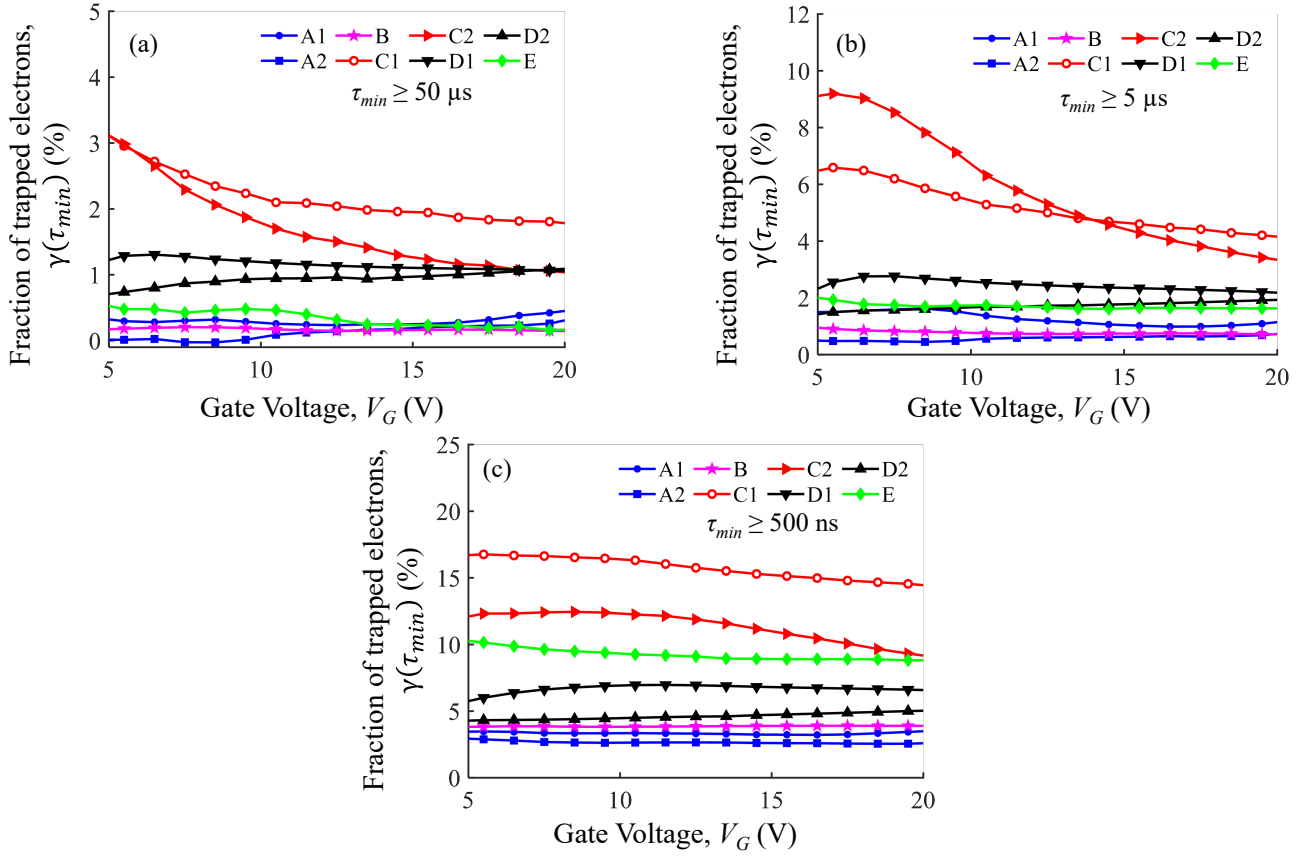


Fig. 2: The fraction of channel electrons trapped for longer than  $\tau_{min} = 50 \mu s$  (a), longer than  $\tau_{min} = 5 \mu s$  (b), and longer than  $\tau_{min} = 500 ns$  (c).

MOSFET C2 has a lower density of NITs compared to the planar MOSFET C1. Overall, the density of the performance-degrading NITs in trench MOSFETs by manufacturer A correspond to improved performance in comparison with planar MOSFETs. These results also confirm that lower values of the figure of merit proposed in [10] correspond to lower densities of NITs and, hence, correspond to higher-quality MOSFETs.

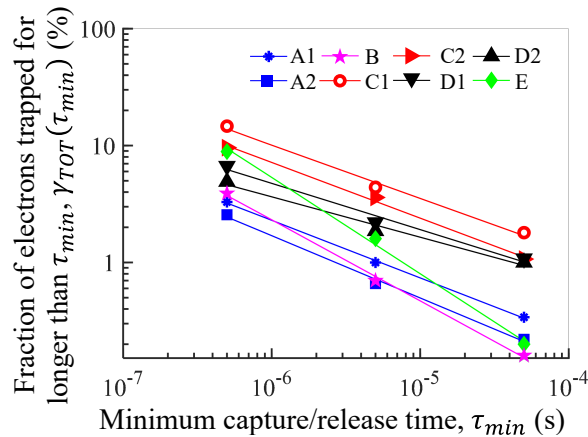


Fig. 3: The fraction of the total density of trapped channel electrons for longer than  $\tau_{min}$  at  $V_G = 18V$ .

## Summary

A comparative analysis of the most commonly available 1200 V commercial SiC power MOSFETs in terms of the density of performance-degrading NITs is presented in this paper. The quantification

of the NITs is performed with a recently developed integrated-charge method which is capable of characterizing NITs in the above-threshold region. The results present comparative trap-distribution profiles of the NITs in various commercial devices, which contributes to better understanding of their energy and spatial positions. The results show that up to 15% of channel electrons were trapped at the operating gate voltage for longer than 500 ns, and this fraction is expected to be higher for the shorter response times.

## Acknowledgement

This work was performed at the Australia National Fabrication Facility (ANFF), Queensland node, QLD, Australia, a company established under the National Collaboration Research Infrastructure Strategy to provide nano- and microfabrication facilities to Australia's researchers.

## References

- [1] H. Yoshioka, T. Nakamura, and T. Kimoto, Accurate evaluation of interface state density in SiC metal-oxide-semiconductor structures using surface potential based on depletion capacitance, *J. Appl. Phys.* 111(1) (2012) 014502.
- [2] T. Kimoto, and H. Watanabe, Defect engineering in SiC technology for high-voltage power devices, *Appl. Phys. Express* 13 (2020) 120101.
- [3] P. Fiorenza, F. Giannazzo, and F. Roccaforte, Characterization of SiO<sub>2</sub>/4H-SiC Interfaces in 4H SiC MOSFETs: A Review, *Energies* 12 (2019) 2310.
- [4] A.J. Lelis, R. Green, and D.B. Habersat, SiC MOSFET threshold-stability issues, *Mater. Sci. Semicond. Process* 78 (2018) 32–37.
- [5] D. Haasmann, and S. Dimitrijević, Energy position of the active near-interface traps in metal–oxide–semiconductor field-effect transistors on 4H–SiC, *Appl. Phys. Lett.* 103 (2013) 113506.
- [6] R. Y. Khosa, and E. Ö. Sveinbjörnsson, Conductance signal from near-interface traps in n-type 4H-SiC MOS capacitors under strong accumulation, *Mater. Sci. Forum* 897 (2017) 147-150.
- [7] M. Chaturvedi, S. Dimitrijević, D. Haasmann, H.A. Moghadam, P. Pande, and U. Jadli, Quantified density of performance-degrading near-interface traps in SiC MOSFETs, *Sci. Rep.* 12 (2022) 4076.
- [8] F. Triendl, G. Fleckl, M. Schneider, G. Pfusterschmied, and U. Schmid, Evaluation of interface trap characterization methods in 4H-SiC metal oxide semiconductor structures over a wide temperature range, *J. Vac. Sci. Tech. B* 37 (2019) 032903.
- [9] P. Pande, D. Haasmann, J. Han, H.A. Moghadam, P. Tanner, and S. Dimitrijević, Electrical characterization of SiC MOS capacitors: A critical review, *Microelectron. Reliab.* 112 (2020) 113790.
- [10] M. Chaturvedi, S. Dimitrijević, D. Haasmann, H.A. Moghadam, P. Pande, and U. Jadli, A figure of merit for selection of the best family of SiC power MOSFETs, *Electronics* 11 (2022) 1433.
- [11] B. J. Baliga, *Fundamentals of power semiconductor devices*, Springer-Verlag, New York, NY, USA, 2010.
- [12] M. Chaturvedi, S. Dimitrijević, D. Haasmann, H.A. Moghadam, P. Pande, and U. Jadli, Comparison of commercial planar and trench SiC MOSFETs by electrical characterization of performance-degrading near-interface traps, *IEEE Trans. Electron Devices* 69 (2022) 6225–6230.