Stability and Temperature Dependence of Dynamic R_{ON} in AlN-Passivated AlGaN/GaN HEMT on Si Substrate

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Abstract

We carried out detailed characterization and evaluation of dynamic performance of high-voltage AlGaN/GaN high electron mobility transistors (HEMTs) with AlN/SiN$_x$ passivation by means of pulsed I-V measurements. Transient OFF-to-ON switching tests verify the effectiveness of surface passivation by PE-ALD grown AlN epitaxial layer. The dynamic ON-resistance (R_{ON}) measured 350 ns after the switching event (500 ns) remains as low as only 1.08 times the static R_{ON} with an OFF-state drain bias of 60 V. Less than 10% degradation in dynamic R_{ON} is achieved under 40-V switching at various frequencies of 1-133 kHz within a wide temperature range of –50–200 °C. The stability of dynamic R_{ON} is also confirmed with a simple approach by monitoring the pulsed current at a drain bias of ~1 V for 100 consecutive switching cycles.

INTRODUCTION

Power switches built on III-nitride (e.g., AlGaN/GaN) HEMT structures have shown great promise as the key elements for achieving an energy-efficient power conversion system in recent years [1]. The unique and outstanding material properties (e.g., high critical breakdown electric field) of gallium nitride and the availability of high-quality heterojunctions (with high 2DEG density and mobility) enable AlGaN/GaN high-voltage power HEMTs to deliver enhanced device performance that could break the theoretical limit of silicon power MOSFETs [2]. In reality, however, the intrinsic capability of GaN lateral power devices still remains out of reach due to several challenging technical issues, one of which is the higher dynamic ON-resistance (R_{ON}), or reduced transient ON-state drain current obtained during high-voltage drain bias switching [3].

Aimed at addressing the surface-state-relevant issue, we have recently developed an effective and robust surface passivation technology employing epitaxial AlN thin film grown in a PE-ALD system as the passivation dielectric [4]–[6]. Owing to the strong polarization effect in the AlN passivation layer, a large amount (~3.2 × 10^{13} cm^{-2}) of positive polarization charges are introduced, compensating any slow-response surface/interface traps that would cause current collapse. The effectiveness of surface passivation has been verified by high-voltage OFF-to-ON switching measurements [4], [6]. However, only slow trapping effects have been investigated because the switching intervals are relatively long in the range of 0.1–2.7 s. In addition, it is crucial to evaluate current collapse at elevated temperatures because a power switching transistor usually operates at a relatively high junction temperature. To date, however, only a few works on this important topic have been reported, with more severe degradation in dynamic R_{ON} observed at higher temperatures [7], [8].

In this work, we carried out detailed pulsed *I-V* characterization in a wide temperature range (–50–200 °C) to evaluate the PE-ALD AlN passivation technique for high-voltage AlGaN/GaN HEMTs.

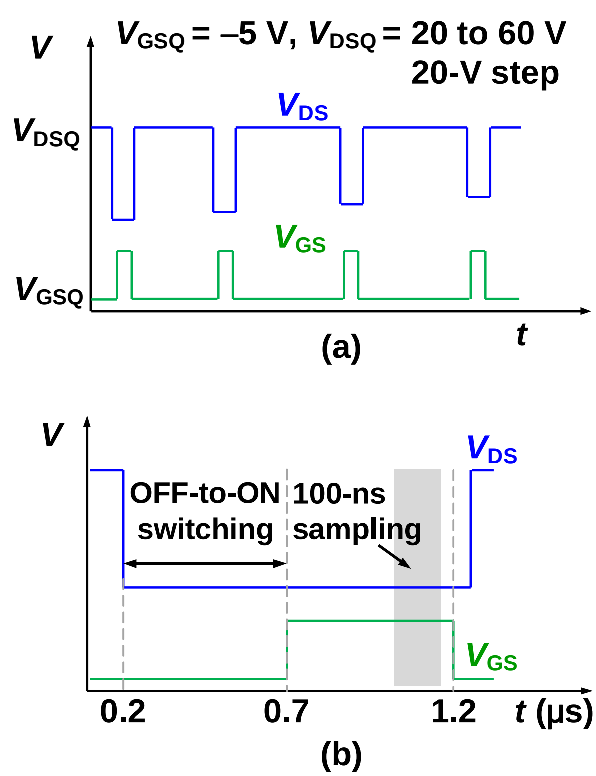

Fig. 1: Pulsed *I-V* characterization: (a) waveforms of V_{GS} and V_{DS}; (b) timing diagrams of V_{GS} and V_{DS} during OFF-to-ON switching (500 ns) and ON-state sampling (100 ns).

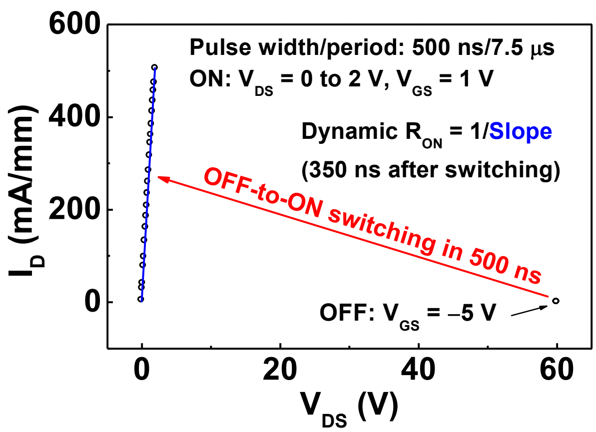

Fig. 2: Dynamic R_{ON} extraction from a pulsed output curve in the linear regime. The applied pulse width and period are 500 ns and 7.5 μs, respectively. The measurement data were recorded 350 ns after the OFF-to-ON switching event.

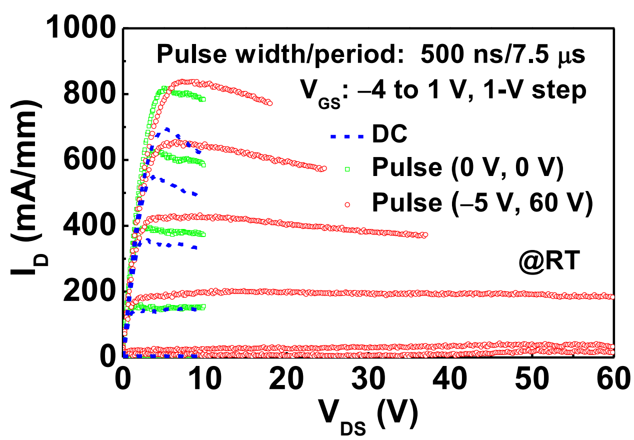

Fig. 3: Pulsed I_D-V_{DS} characteristics (with the dc reference) from two quiescent bias points of (V_{GSQ}, V_{DSQ}) = (0 V, 0 V) and (–5 V, 60 V) with pulse width/period of 500 ns/7.5 μs at room temperature.

PULSED I-V METHOD AND DYNAMIC R_{ON} EXTRACTION

The AlN-passivated HEMTs used in this study were fabricated on an $Al_{0.25}Ga_{0.75}N$/GaN-on-Si sample described in our previous work [6]. The device features a gate-source distance of 1 μm, a gate length of 1.5 μm, a total gate periphery of 2 × 50 μm, and a gate-drain distance of 5 μm. In order to evaluate current collapse quantitatively, on-wafer transient OFF-to-ON switching characterization of the device is performed with an AMCAD pulsed *I-V* system. As shown in Fig. 1, the applied pulse width and period are 500 ns and 7.5 μs, respectively. The device is switched from the OFF state with a quiescent gate bias of –5 V and a quiescent drain

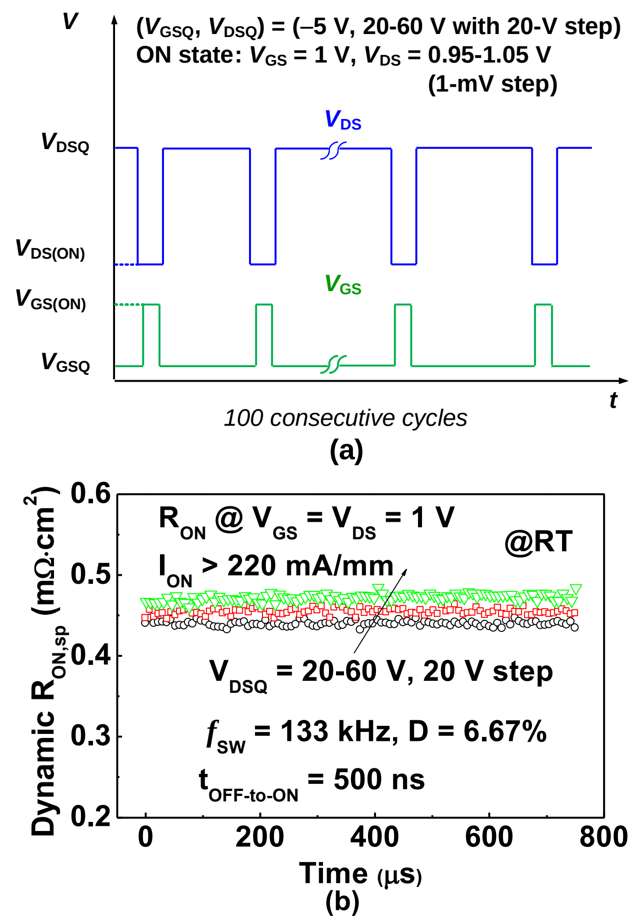

Fig. 4: (a) Pulsed I-V measurement setup of continuous switching tests for evaluation of dynamic R_{ON} stability. (b) Time evolution of dynamic R_{ON} during 100 consecutive switching cycles at a switching frequency of 133 kHz and with a duty cycle of 6.67% with an OFF-state drain bias of 20–60 V at RT.

bias of 20–60 V (20 V step) to the ON state in 500 ns. Transient ON-state drain current I_D and drain-source voltage V_{DS} are sampled simultaneously 350 ns after the OFF-to-ON switching event. Within the 100-ns measurement window, 100 data points are sampled and averaged to obtain accurate results. Dynamic R_{ON} is then extracted from the linear regime (V_{DS}: 0 to 2 V) of the pulsed output curve at a gate bias of 1 V, as shown in Fig. 2. The testing sample is placed on the thermal chuck, for which the temperature is varied from –50 to 200 °C in a 25 °C step.

RESULTS AND DISCUSSION

The pulsed I_D-V_{DS} characteristics are plotted in Fig. 3. Low current collapse at room temperature (RT) can be implied from the subtle difference observed in the pulsed I_D-V_{DS} curves measured from two quiescent bias

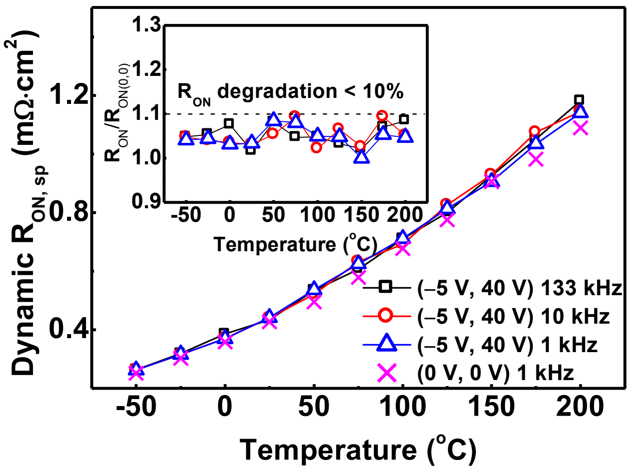

Fig. 5: Temperature dependence of specific dynamic R_{ON} and (inset) normalized dynamic R_{ON} at various frequencies of 1-133 kHz. Temperature of the base plate is set to be from –50 to 200 °C in a 25-°C step. R_{ON} extrapolated from the pulsed I_D-V_{DS} curve at V_{GS} = 1 V from (0 V, 0 V) is used as reference.

conditions of (V_{GSQ}, V_{DSQ}) = (0 V, 0 V) and (–5 V, 60 V) in the linear regime. The larger saturation current after stress is due to the field-assisted electron de-trapping from the traps at the drain-side gate edge.

Continuous switching tests for 100 consecutive cycles at a switching frequency of 133 kHz at RT are conducted with various OFF-state drain biases of 20–60 V to assess the stability of dynamic R_{ON}, based on a simple pulsed *I-V* measurement setup, as illustrated in Fig. 4(a). In the ON state, V_{GS} is kept at 1 V whereas V_{DS} is swept from 0.95 V to 1.05 V with 1 mV steps. The time intervals for the ON state and the OFF-to-ON switching are both 500 ns. In Fig. 4(b), the dynamic R_{ON} increases slightly with higher OFF-state drain bias due to enhanced electron trapping at AlN/GaN (passivation/cap) interface and/or bulk trap states, and yet remains low (8% increase) and stable (2.5% variation) under 60-V drain bias switching.

Dynamic R_{ON} under 40-V switching operation at various temperatures is measured at different switching frequencies of 1, 10, and 133 kHz, as illustrated in Fig. 5. The dynamic R_{ON} exhibits an increase of less than 10% in the wide temperature range of –50–200 °C, which differs from previous results reported in [7] and [8]. In addition, almost no frequency dispersion of dynamic R_{ON} is noticed, which indicates that the electron capture process is very fast and highly suppressed owing to the effective compensation of slow-response interface traps by positive fixed charges introduced by the surface passivation dielectric layer— the polarized AlN thin film [5].

CONCLUSIONS

Temperature dependence and stability of dynamic ON-resistance of GaN HEMTs with AlN passivation have been investigated in detail with pulsed I-V measurements. The PE-ALD AlN passivation technique enables effectively suppressed current collapse phenomena, resulting in less than 10% dynamic R_{ON} increase in a wide temperature range of –50–200 °C. By measuring the dynamic R_{ON} during 100 consecutive switching cycles at a switching frequency of 133 kHz, its variation is shown to be less than 2.5%.

REFERENCES

[1] T. Morita, S. Tamura, Y. Anda, M. Ishida, Y. Uemoto, T. Ueda, T. Tanaka, and D. Ueda, "99.3% efficiency of three-phase inverter for motor drive using GaN-based gate injection transistors," in Proc. 26th IEEE APEC, Mar. 2011, pp. 481–484.

W. Saito, I. Omura, T. Ogura, and H. Ohashi, "Theoretical limit estimation of lateral wide band-gap semiconductor power-switching device," Solid-State Electron., vol. 48, no. 9, 1555–1562, Sep. 2004.

[3] R. Chu, A. Corrion, M. Chen, R. Li, D. Wong, D. Zehnder, B. Hughes, and K. Boutros, "1200-V normally off GaN-on-Si field-effect transistors with low dynamic on-resistance," IEEE Electron Device Lett., vol. 32, no. 5, pp. 632–634, May 2011.

[4] S. Huang, Q. Jiang, S. Yang, C. Zhou, and K. J. Chen, "Effective passivation of AlGaN/GaN HEMTs by ALD-grown AlN thin film," IEEE Electron Device Lett., vol. 33, no. 4, pp. 516–518, Apr. 2012.

[5] S. Huang, Q. Jiang, S. Yang, Z. Tang, and K. J. Chen, "Mechanism of PEALD-grown AlN passivation for AlGaN/GaN HEMTs: compensation of interface traps by polarization charges," IEEE Electron Device Lett., vol. 34, no. 2, pp. 193–195, Feb. 2013.

[6] Z. Tang, S. Huang, Q. Jiang, S. Liu, C. Liu, and K. J. Chen, "High-voltage (600-V) low-leakage low-current-collapse AlGaN/GaN HEMTs with AlN/SiN_x passivation," IEEE Electron Device Lett., vol. 34, no. 3, pp. 366–368, Mar. 2013.

[7] D. Jin and J. A. del Alamo, "Mechanisms responsible for dynamic ON-resistance in GaN high-voltage HEMTs," in 24th Int. Symp. Power Semicond. Devices ICs, Jun. 2012, pp. 333–336.

[8] K. Tanaka, M. Ishida, T. Ueda, and T. Tanaka, "Effects of deep trapping states at high temperatures on transient performance of AlGaN/GaN heterostructure field-effect transistors," Jpn. J. Appl. Phys., vol. 52, no. 4, pp. 04CF07-1–04CF07-5, Apr. 2013.

ACRONYMS

HEMT: High Electron Mobility Transistor
2DEG: Two-Dimensional Electron Gas
PE-ALD: Plasma-Enhanced Atomic Layer Deposition