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 testing verifies 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 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 (high 2DEG density and mobility) enable AlGaN/GaN high-voltage power HEMTs to deliver enhanced device performance that could break the 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 (~3×10^{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 0.1-1 s. In addition, it is crucial to evaluate current collapse at elevated temperatures because a power switching transistor usually operates at a 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.

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 gate width of 2 × 50 µm, and a gate-drain distance of 5 µm. In order to evaluate current collapse quantitatively, on-wafer transient 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 OFF state to ON

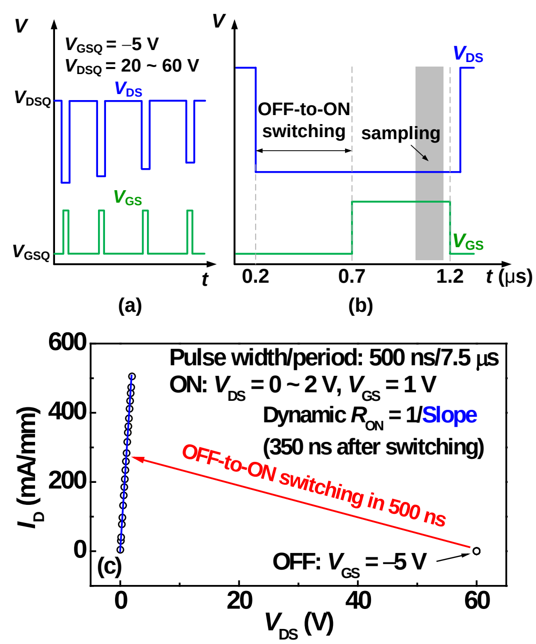

Fig. 1: Pulsed I-V characterizations: (a) waveforms of V_{GS} and V_{DS}; (b) timing diagrams of V_{GS} and V_{DS} during OFF-to-ON switching (500 ns) and ON-state sampling (100 ns); and (c) dynamic R_{ON} extracted from a pulsed output curve in the linear regime. The pulse width and period are 500 ns and 7.5 µs, respectively. The data were recorded 350 ns after switching.

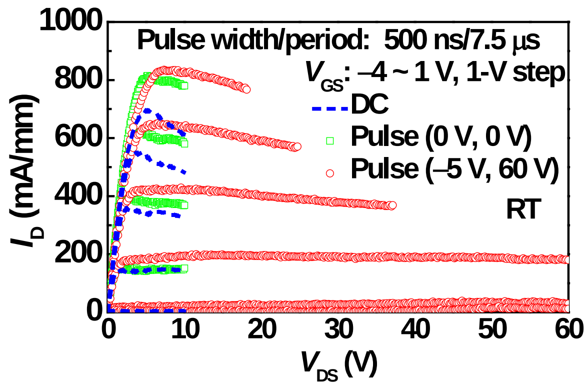

Fig. 2: Pulsed I_D-V_{DS} characteristics (with the dc reference) from two quiescent bias points of (V_{GSQ}, V_{DSQ}) = (0 V, 0 V) and (–5 V, 60 V) with pulse width/period of 500 ns/7.5 µs at RT.

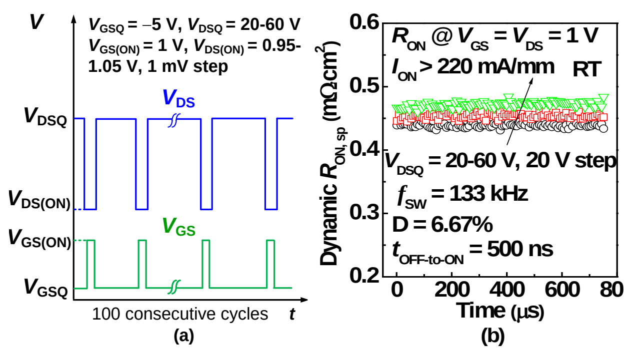

Fig. 3: (a) Pulsed I-V measurement setup of continuous switching test for evaluation of dynamic R_{ON} stability. (b) Time evolution of dynamic R_{ON} during 100 consecutive switching cycles at a switching frequency of 133 kHz and a duty cycle of 6.67% with an OFF-state drain bias of 20 ~ 60 V at RT.

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 ~ 2 V) of the pulsed output curve at a gate bias of 1 V. The testing sample is placed on the thermal chuck, for which the temperature varies from –50 °C to 200 °C.

Results and Discussion

The pulsed I_D-V_{DS} characteristics are plotted in Fig. 2. 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 conditions of (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 test for 100 consecutive cycles at a switching frequency of 133 kHz at RT is 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 (Fig. 3(a)). In the ON state, V_{GS} is kept at 1 V while 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. 3(b), the dynamic R_{ON} increases slightly with higher OFF-state drain bias due to enhanced electron trapping at AlN/GaN (passivation/cap)

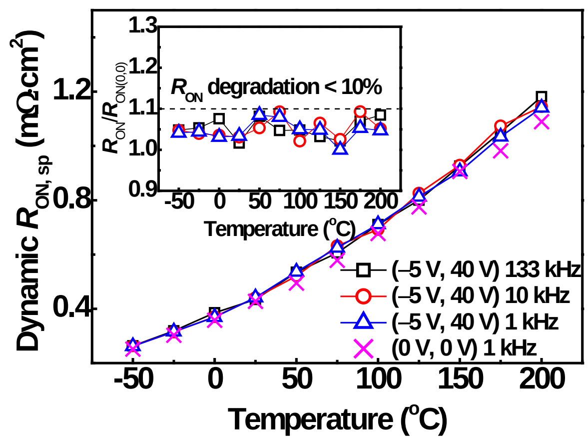

Fig. 4: Temperature dependence of specific dynamic R_{ON} and (inset) normalized dynamic R_{ON} at various frequencies of 1-133 kHz. Temperature of the base plate is set to be from –50 °C to 200 °C in a 25-°C step. R_{ON} extrapolated from the pulsed I_D-V_{DS} curve at V_{GS} = 1 V from (0 V, 0 V) is used as reference.

interface, and yet remains low (8.3% 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 1-133 kHz, as illustrated in Fig. 4. 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.

Conclusions

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

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Acronyms

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