High Thermally Stable AlGaN/GaN High Electron Mobility Transistors (HEMTs) on Bulk Semi-Insulating GaN Substrates

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Abstract

In this study, a AlGaN/GaN high-electron-mobility transistor (HEMT) grown on the bulk GaN substrate was demonstrated and compared against one grown on the SiC substrate. Results of X-ray diffraction and reciprocal space mapping revealed that the bulk GaN substrate structure exhibited less lattice dislocation. The GaN substrate device demonstrated better I_{DS}–V_{GS} and gm–V_{GS} characteristics of I_{DS} = 700 mA/mm at V_{GS} = +2 V and gm_{max} = 148 mS/mm. Compared with the SiC substrate, the current density in the HEMT grown on GaN was improved. The GaN substrate also improved current collapse and dynamic ON-state resistance due to a decrease in the trapping effect. The low-frequency noise and Hooge results also indicated that the GaN substrate had lower lattice dislocation.

INTRODUCTION

AlGaN/GaN high-electron-mobility transistors (HEMTs) have demonstrated high current density and high frequency performance, and they dominate the market for high-power radio frequency (RF) technology [1]. In GaN epitaxy, the dominant substrate is SiC. However, there is a 3.5% lattice mismatch between GaN and SiC. Although this is relatively small, it remains a source of lattice defects. The use of foreign substrates for many years has led to a lack of high-quality GaN wafers [2]. In this paper, we report the growth results of AlGaN/GaN HEMT structures on the bulk GaN substrate and SiC substrate and discuss their respective characteristics.

MEASUREMENT RESULTS AND DISCUSSION

AlGaN/GaN HEMT structures were grown using metalorganic chemical vapor deposition on bulk GaN and SiC substrates, respectively. Fig. 1 shows a cross-section of the fabricated devices and the corresponding epitaxial structures. The devices had a gate length of 0.8 μm and a drain-to-source distance of 6 μm. The structure comprised an Fe-doped GaN and unintentionally doped GaN buffer, a 50-nm $Al_{0.08}GaN$ back barrier, 500 nm of UID GaN, 1 nm of AlN, an 18-nm $Al_{0.24}GaN$ barrier, and 3 nm of *in situ* SiN_x. We also grew 3 nm of Al_2O_3 to reduce the gate leakage. The same structure was grown on the bulk GaN and SiC substrates.

During device fabrication, the active region was protected by a photoresist, and the mesa isolation region was removed in a reactive ion etching chamber using BCl_3 + Cl_2 mixed-gas plasma. Ohmic contacts employed electron beam evaporation with a multilayered metal Ti/Al/Ni/Au (30 nm/125 nm/50 nm/200 nm) sequence, followed by rapid thermal annealing at 850°C for 30 s in nitrogen-rich ambient conditions. After ohmic formation, the Ni/Au (15/330 nm) gate metal was evaporated, and a 15-nm-thick SiN layer was deposited as a final passivation layer.

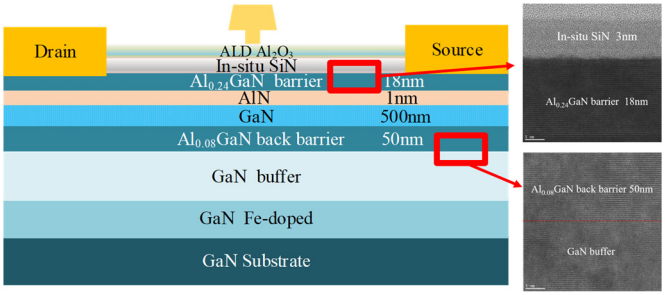

Fig. 1 Cross-section of the AlGaN/GaN HEMT on GaN substrate and cross-sectional TEM images.

Fig. 2(a) shows the X-ray diffraction (XRD) rocking curves for the identical AlGaN/GaN structures grown on bulk GaN and SiC substrates. The much narrower curves approximately 146 and 237 arcsec, respectively for the GaN peak are because of a large difference in dislocation density found for smaller magnitude GaN crystals. The shapes visible from reciprocal space mapping (RSM) are different for structures grown on different substrates, as seen in Fig. 2(b) and (c). Information regarding the relaxation level of the layers of dislocations can be obtained from the relative position of reciprocal lattice nodes. The GaN substrate RSM shape exhibits less lattice dislocation.

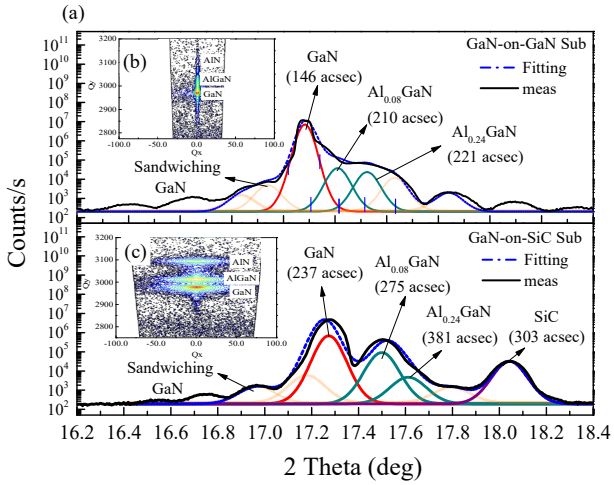

Fig. 2 (a) 2θ-ω XRD of both structures; (b) RSM shape of GaN substrate structures; and (c) RSM shape of SiC substrate structures.

Fig. 3 displays the I_{DS}–V_{GS} and gm–V_{GS} of the AlGaN/GaN HEMT on the two substrates at V_{DS} = 10 V and 300 and 400 K, respectively. For devices on the GaN and SiC substrates at 300K, the maximum drain current values at V_{GS} = 2 V were 700 and 582 mA/mm, respectively, and the peak transconductance levels at V_{DS} = −2 V and -1V were 143 and 101 mS/mm, respectively. A current and transconductance improvement was thus observed for the bulk GaN substrate AlGaN/GaN HEMT.

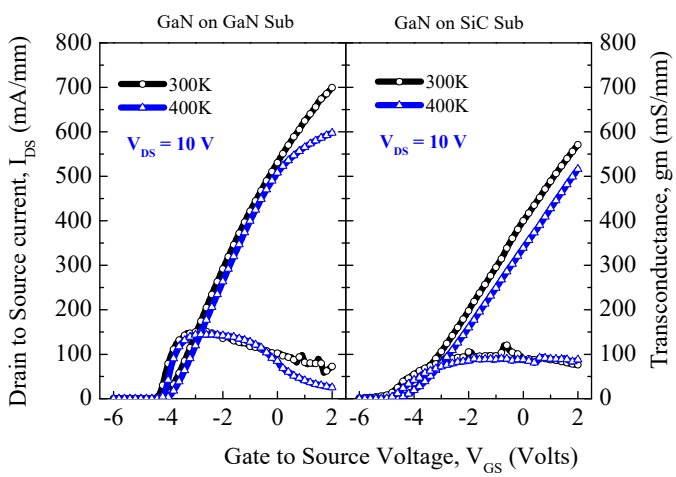

Fig. 3 Measured I_{DS}–V_{GS} and gm–V_{GS} curves at V_{DS} = 10 V for both devices.

The dynamic ON-resistance (R_{on}) was calculated from the pulse I-V measurement. Fig. 4 shows the pulse I-V measured at 300 and 400 K with pulse width = 2 μs and pulse period = 200 μs. The quiescent drain voltage during the OFF-state was from 0 to 100 V, step = 20V. The current collapse [V_Q(0,0) to V_Q(0,100)] was 12% and 24%, and the ratio of R_{on},D was 1.27 and 1.54 for GaN and SiC substrate devices, respectively. Fig. 5 displays the ratio of R_{on},D compared with the static R_{on},Q (0,0). The result shows that the GaN substrate device had a lower dynamic R_{on} ratio, indicating that the device had a low trapping effect.

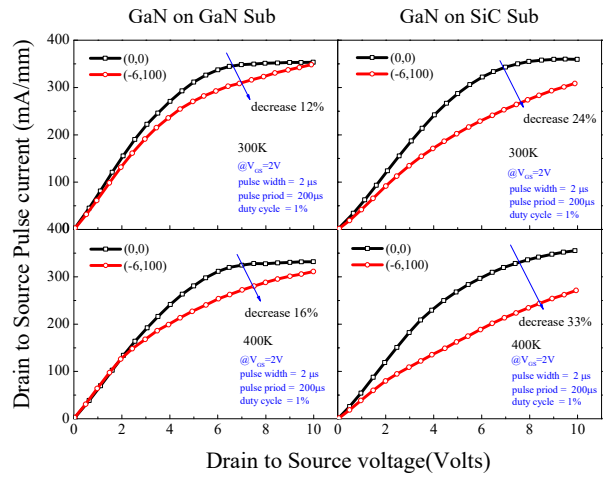

Fig. 4 Pulse I-V measurement of the two devices.

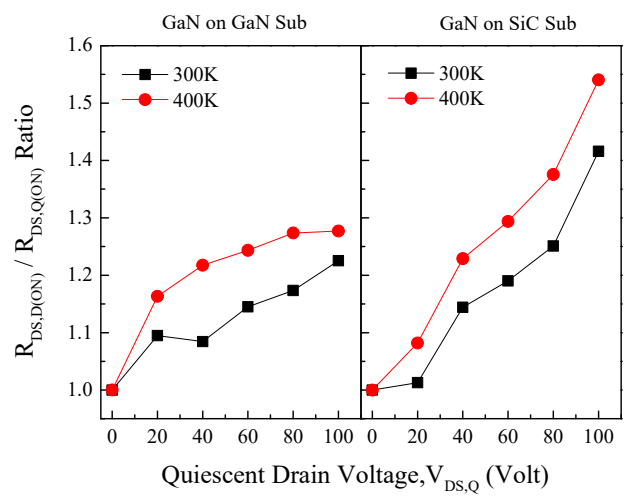

Fig. 5 Dynamic R_{on} measurement for the two devices.

To examine traps in the GaN buffer layers of both devices, low-frequency noise (LFN) spectra were measured at various gate overdrive voltages. The drain current power spectral density S_{ID} was measured and normalized to the square of the drain current versus frequency at a frequency of 100 Hz. If the slope of S_{ID}/I_D^2 is close to −1, the spectral fluctuation is dominated by the mobility fluctuation model, but if it approaches −2, it is dominated by fluctuation in the carrier numbers [3]. A value between −1 and −2 indicates that the noise is attributable to the correlation between the number of carriers and mobility fluctuation. As shown in Fig. 6, slopes at 300 K for the AlGaN/GaN HEMT on the GaN and SiC substrates are −1.91 and −1.66, respectively. The two devices were also measured at 400 K under the same conditions. The results for GaN and SiC substrates were −2.24 and −2.75,

respectively. As V_{GS}-V_{th} increased, the sheet carrier concentration increased, trapping and detraping process reduces fast and mobility flucuation dominates in this region. It shows a sharp decrease in the result [4].

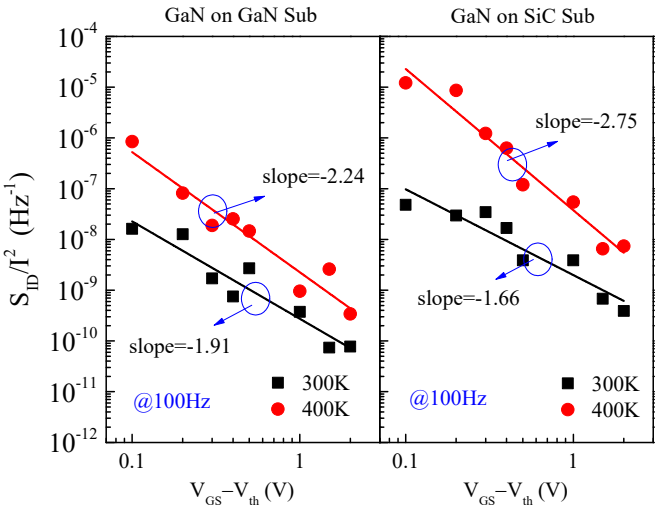

Fig. 6 LFN spectra of the two devices.

Mobility fluctuation theory considers that 1/f noise is a result of the fluctuation in mobility based on Hooge's empirical relation for S_{ID}/I_D^2, as follows [5]:

$$\alpha_H = \frac{S_{ID} f W L C_b (V_{GS} - V_{th})}{q I^2}$$

where α_H is the Hooge parameter. As illustrated in Fig. 7, the average α_H values at 300 and 400 K were 1.15×10^{-5} and 5.02×10^{-5}, respectively, for the AlGaN/GaN HEMTs on the GaN substrate. The results for the AlGaN/GaN HEMTs on the SiC substrate were 6.55×10^{-5} and 2.89×10^{-4}, indicating the superior properties of the AlGaN/GaN HEMTs on the GaN substrate.

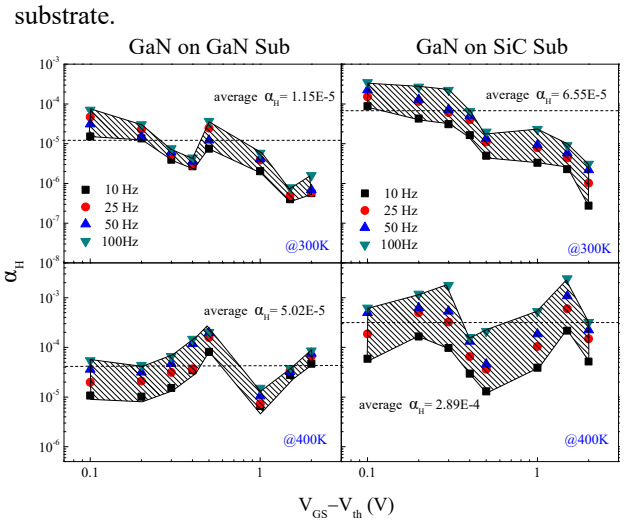

Fig. 7 Hooge parameters of the two devices.

To determine the effect of substrate isolation of both devices on RF performance, the high frequency performances of transistors were evaluated by measuring on-wafer the S-matrix parameters from 100 MHz to 28 GHz frequency range at operating condition V_{DS}=10V and V_{GS}= −2.8V and −2V for GaN substrate and SiC substrate device, using MPI T26A probe with HP4142B pulsed SMU and Agilent 8364C network analyzer. The small-signal parameters are extracted from the de-embedded S-parameters at V_{GS} of −2.8 V, −2 V and V_{DS} of 12 V at 300 K. As Fig. 8 shows the cutoff frequency (f_T) is 13GHz and 8.7GHz, the maximum oscillation frequency (f_{max}) is 24GHz and 19.8GHz for the GaN substrate and SiC substrate devices, respectively. The two values are important indexes to evaluate the RF bandwidth of a transistor. Generally, following well-known equations are shown [6]:

$$f_T = \frac{f_C}{\left(1+\frac{C_{gd}}{C_{gs}}\right) + (R_S + R_d)\left[\frac{C_{gd}}{C_{gs}}(g_m + g_{dS}) + g_{dS}\right]}$$

$$f_{MAX} = \frac{f_C}{2\left(1+\frac{C_{gd}}{C_{gs}}\right)\sqrt{g_{dS}(R_S + R_d) + \frac{1}{2}\frac{C_{gd}}{C_{gs}}\left(R_S g_m + \frac{C_{gd}}{C_{gs}}\right)}}$$

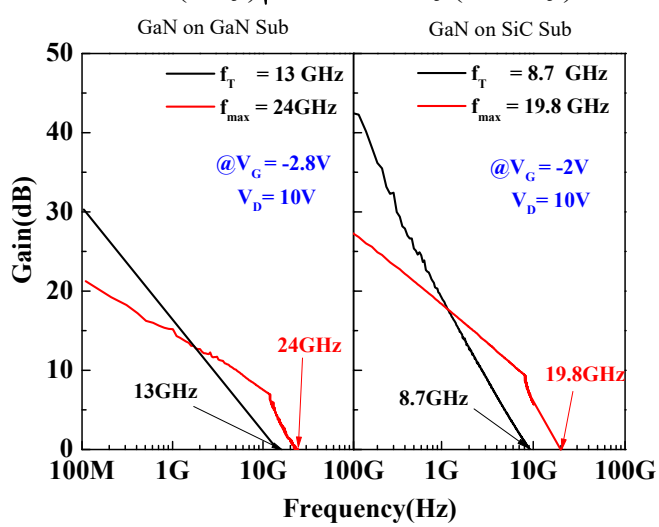

Fig.8 f_T and f_{max} for both devices.

CONCLUSIONS

This study compared AlGaN/GaN HEMTs grown on bulk GaN and SiC substrates. XRD and RSM results revealed that there was less lattice dislocation in the GaN substrate. The GaN substrate device also improved I_{DS}–V_{GS} and gm–V_{GS} output characteristics and dynamic R_{on} due to a reduced trapping effect. The LFN slope spectra for AlGaN/GaN HEMTs on the GaN and SiC substrates were −1.91 and −1.66, respectively. The Hooge parameter results revealed that the

GaN substrate had lower average α_H values. the high frequency performances of transistors, cutoff frequency (f_T) is 13GHz and 8.7GHz, the maximum oscillation frequency (f_{max}) is 24GHz and 19.8GHz for the GaN substrate and SiC substrate devices, respectively. It is shows the GaN substrate device has a better performance than the SiC substrate device.

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ACRONYMS

GaN: Gallium nitride
SiC: Silicon Carbide
HEMT: high electron mobility transistor
XRD: X-ray diffraction
RSM: reciprocal space mapping
LFN: low-frequency noise