SCIENCE CHINA
Information Sciences

• LETTER •

June 2024, Vol. 67, Iss. 6, 169402:1–169402:2
https://doi.org/10.1007/s11432-024-3998-2

High-Al-composition AlGaN/GaN MISHEMT on Si with f_T of 320 GHz

Hanghai DU[1,2†], Lu HAO[1†], Zhihong LIU[1,2*], Zeyu SONG[1], Yachao ZHANG[1], Kui DANG[1], Jin ZHOU[2], Jing NING[1], Zan LI[3], Jincheng ZHANG[1,2*] & Yue HAO[1,2]

[1]*State Key Laboratory of Wide Bandgap Semiconductor Devices and Integrated Technology, School of Microelectronics, Xidian University, Xi'an* 710071*, China;*
[2]*Guangzhou Wide Bandgap Semiconductor Innovation Center, Guangzhou Institute of Technology, Xidian University, Guangzhou* 510555*, China;*
[3]*State Key Laboratory of Integrated Services Networks, School of Communication Engineering, Xidian University, Xi'an* 710071*, China*

Received 13 January 2024/Revised 26 March 2024/Accepted 1 April 2024/Published online 23 May 2024

GaN-based metal-insulator-semiconductor high-electron-mobility-transistors (MISHEMTs) have many excellent performances compared with the Si and GaAs counterparts, and are prime candidates for applications in communication base stations, radars, and satellites. Most of the current GaN RF transistors for the below Ka-band applications adopt a conventional AlGaN/GaN heterostructure with a typical Al-composition from 0.25 to 0.3 for the barrier layer. For higher frequency applications, the thin barrier AlN/GaN heterojunction or InAlN/GaN heterojunction is preferred [1].

The AlN/GaN heterojunction can provide a relatively high breakdown electric field compared with that of the InAlN/GaN heterojunction, which is restricted by its narrow bandgap and the quality of its epitaxy. However, the existing major issue in the former is the large ohmic contact resistance (R_c) due to the wider bandgap of the AlN barrier, especially in deep submicrometer AlN/GaN transistors. Although the regrowth n^{++} GaN ohmic technique can yield a low R_c [2], this method is more complicated for deep-submicrometer devices.

In this study, a high-Al-composition $Al_{0.65}Ga_{0.35}N$/GaN MISHEMT on Si with *in-situ* SiN_x enhanced ohmic contacts has been demonstrated. Several outstanding DC and RF performances were experimentally realized.

Experiment. The details of the epitaxial structure were described in [3]. The device fabrication started from the planar isolation implemented by ion implantation, followed by deposition of patterned Ti/Al/Ni/Au stack metals on the 8-nm thick *in-situ* SiN_x surface, and rapid thermal annealing at 850°C for 30 s in N_2 atmosphere to form ohmic contacts. After that, ultra-short gate electrode windows were opened by electron beam lithography process and followed by F-based RIE to remove partial *in-situ* SiN_x. There is a 2-nm thick residual *in-situ* SiN_x layer as gate dielectrics to suppress gate leakage current. Finally, 40-nm thick Ni metal located at the center of the source and drain was defined as the gate electrode. The device in this work has a 45-nm rectangular gate (L_G) for source-to-drain distance (L_{SD}) of 650 nm.

Results and discussion. Figures 1(a) and (b) clarify the cross-section schematic of the fabricated device and the cross-sectional TEM (transmission electron microscope) image of the 45-nm MIS-type gate respectively, where the source and drain ohmic alloys have contacted with the $Al_{0.65}Ga_{0.35}N$ barrier layer after the high-temperature annealing process. The ohmic contact performance was evaluated using the transmission line method (TLM) as shown in Figure 1(c). The R_c was extracted to be 0.18 Ω·mm, while that without *in-situ* SiN_x layer is about 0.32 Ω·mm (not shown). Such low R_c is mainly due to low-work function metal silicides and more TiN alloys were formed by the solid-phase reaction of the metal stacks and the thin layer *in-situ* SiN_x during the high-temperature annealing process [3]. Figure 1(d) depicts the DC output curves of the device with L_{SD} = 650 nm. A gratifying I_D of 2.63 A/mm was obtained. Meanwhile, an ultralow on-resistance (R_{on}) of 0.68 Ω·mm was achieved without the use of other complex techniques. Figures 1(e) and (f) plot the linear scale and semi-log scale DC transfer curves. The high peak extrinsic transconductances (g_m) were determined to be 704 and 560 mS/mm at V_{DS} = 5 V and V_{DS} = 2 V, respectively. The ultra-high I_D ON/OFF ratio of 10^9 was achieved at V_{DS} = 2 V for the 45-nm gate device, which benefits from the high gate-to-channel aspect ratio and the low gate leakage current (I_G) suppressed by the 2-nm amorphous *in-situ* SiN_x gate dielectrics. The drain induced barrier lower (DIBL) and minimum sub-threshold swing (SS) were extracted to be ultra-low values of 42 mV/V and around 100 mV/dec, respectively. These results indicate that our transistor has minimized short-channel effects (SCEs).

Figure 1(g) shows the de-embedding RF small-signal

* Corresponding author (email: liuzhihong@ieee.org, jchzhang@xidian.edu.cn)
† Du H H and Hao L have the same contribution to this work.

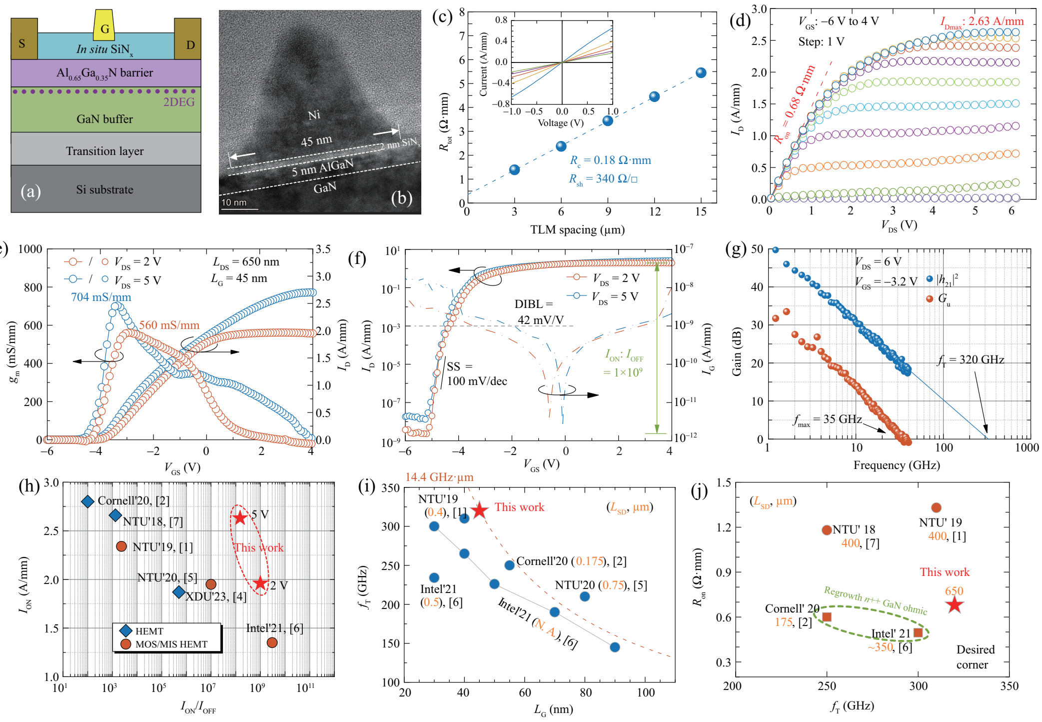

Figure 1 (Color online) (a) Cross-section schematic of the fabricated transistor; (b) TEM image of the MIS-gate structure; (c) extraction of ohmic contact resistance by using TLM; the inset is *I-V* characteristics of TLM resistances; (d) output characteristics of the 45-nm gate device with $L_{\rm SD}$ = 650 nm; (e) linear and (f) log-scale transfer characteristics of the 45-nm gate device under varying bias voltages; (g) RF small-signal characteristics of the transistor; (h) benchmarking the maximum current and ON-OFF current ratio; (i) benchmarking the $f_{\rm T}$ and $L_{\rm G}$; (j) benchmarking the $R_{\rm on}$ and $f_{\rm T}$.

characteristics of the transistor. A cut-off frequency ($f_{\rm T}$) of 320 GHz was achieved by extrapolating $|h_{21}|^2$ with a slope of −20 dB/dec. To the best of our knowledge, the value of $f_{\rm T}$ is the highest among the reported GaN-on-Si transistors [1]. A value of $f_{\rm T} \times L_{\rm G}$ was yielded to be 14.4 GHz·μm, with a gate-to-channel aspect ratio of 6.4. The low maximum oscillation frequency ($f_{\rm max}$) value of 35 GHz is due to the high gate resistance. Figure 1(h) illustrates advantages of the transistor in terms of $I_{\rm Dmax}$ and $I_{\rm D}$ ON/OFF ratio [1, 2, 4–7]. Figure 1(i) compares the $f_{\rm T}$ in this work with those reported state-of-the-art results in [1, 2, 5, 6] for GaN-on-Si. Figure 1(j) depicts the plot of $R_{\rm on}$ versus $f_{\rm T}$ that benchmarks the performances of the fabricated device against some state-of-the-art GaN-on-Si and GaN-on-SiC transistors [1, 2, 6, 7]. Compared with these complex-process transistors, our transistor shows competitive performances.

Conclusion. We demonstrated a novel high-Al-composition-AlGaN/GaN MISHEMT on Si with *in-situ* SiN_x enhanced ohmic contacts. The fabricated 45-nm gate AlGaN/GaN MISHEMT on Si exhibits a low $R_{\rm on}$ of 0.68 Ω·mm, a high $I_{\rm D}$ of 2.63 A/mm, a high $g_{\rm m}$ of 704 mS/mm, and a record $f_{\rm T}$ of 320 GHz. These results imply that this ohmic scheme has a significant potential to facilitate the development of high-performance GaN-based RF devices.

Acknowledgements This work was supported in part by National Key R&D Program (Grant No. 2020YFB1807300), National Science Fund for Distinguished Young Scholars (Grant No. 2020YFB1807300), Fundamental Research Funds for the Central Universities (Grant No. ZYTS24060), Shaanxi Key Industry Innovation Project (Grant No. 2020ZDLGY03-04), and Guangdong Key Area R&D Program (Grant No. 2020B010171002).

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