Normally-off operation AlGaN/GaN MOS-HEMT with high threshold voltage

C.-T. Chang, T.-H. Hsu, E.Y. Chang, Y.-C. Chen,
H.-D. Trinh and K.J. Chen

Normally-off operation AlGaN/GaN high electron mobility transistors have been developed utilising a fluorine-based treatment technique combined with a metal-oxide-semiconductor gate architecture. Threshold voltage as high as 5.1 V was achieved by using an 16 nm-thick Al_2O_3 gate oxide film. Additionally, the device performed a drain current density of 500 mA/mm and a peak transconductance of 100 mS/mm, which are comparable to the conventional normally-on devices.

Introduction: AlGAN/GaN-based high electron mobility transistors are promising candidates for power electronic applications owing to their attractive properties, such as high breakdown field, high electron mobility, and capability of high temperature operation. For power switching applications, devices with normally-off operation are necessary because they can not only help simplify the complexity of the circuit but also reduce standby power consumption. In addition, they provide a fail-safe function because a noise higher than 3 V may occur on the gate electrode during the device operation [1]. Several approaches towards such requirements based on an AlGaN/GaN heterostructure have been investigated, such as the recessed gate [2], fluoride-based treatment [3], and the band diagram engineered approach [4, 5]. However, these approaches still encounter an issue which is either lower current density or insufficient threshold voltage for the gate noise blocking. In this Letter, we combined the fluorine-based treatment technique and an Al_2O_3 film as the gate oxide layer to demonstrate normally-off operation AlGaN/GaN MOS-HEMTs with high threshold voltage, and with comparable current density to conventional normally-on HEMTs

Device fabrication: An AlGaN/GaN heterojunction was grown on a 2-inch c-plane sapphire substrate using metal-organic chemical vapour deposition (MOCVD). The epitaxial structure consisted of a nucleation layer, a 2 μm-thick GaN buffer layer, a 1 nm-thick AlN interlayer, and a 13 nm-thick $Al_{0.25}Ga_{0.75}N$ barrier layer. The room-temperature Hall mobility and sheet electron concentration of the sample were $1900\ cm^2/Vs$ and $8.8 \times 10^{12}\ cm^{-2}$, respectively.

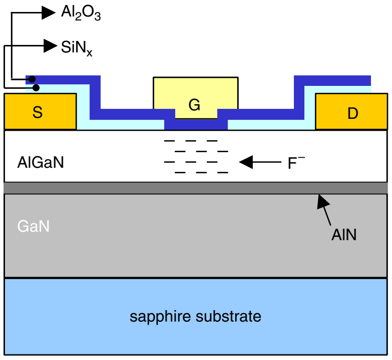

Fig. 1 *Schematic cross-section of fabricated normally-off MOS-HEMT*

Fabrication of the MOS-HEMTs started with ohmic-contact formation with 7 μm drain-source spacing. Ti/Al/Ni/Au metal stacks (20/120/25/100 nm) were evaporated as ohmic metals and subsequently annealed in N_2 ambient at 800°C for 1 min. Mesa isolation was formed utilising an inductively coupled plasma (ICP) etcher with Cl_2-based gas. A 100 nm-thick SiNx layer was deposited using plasma-enhanced chemical vapour deposition (PECVD) and was then patterned by lithography with a 1 μm-width etching window in the centre of the 7 μm drain-source gap. Before removal of the photoresist, the SiNx was etched by a reactive-ion etcher (RIE) with CF_4/O_2 gas mixture, and the device was then treated with CF_4 plasma, of which the condition was similar with that reported in [6]. Afterwards, a 16 nm-thick Al_2O_3 oxide layer was deposited using atomic-layer deposition (ALD) and the devices were subsequently annealed at 400 °C for 10 min in N_2 ambient. The thermal annealing was not only for damage recovery [*] but also for post-oxide-deposition annealing. Before gate metallisation, electrode pads were patterned by lithography and the oxide layer was removed by wet etching with HF solution. Finally, a 3 μm-length gate was evaporated with Ni/Au (20/300 nm) to cover the F ion treatment region, as illustrated in Fig. 1. The gate width of the devices in this work was 2 × 50 μm.

Device characterisation: DC performances of the devices were measured by an Agilent E5270B. Fig. 2 compares I_G-V_G characteristics of normally-off operation HEMTs using the F-based treatment technique with and without an Al_2O_3 layer. In reverse and forward performances, the MOS-HEMT appeared to have lower gate leakage current than the HEMT without the oxide layer. The gate of the conventional device started to turn on at $V_G = 2$ V, as defined by 1 mA/mm leakage current; however, the 16 nm-thick Al_2O_3 layer prevented the other device from not only Schottky gate leakage but also tunnelling leakage current up to VG = 12.7 V. Fig. 3 compares I_D-V_G characteristics of the devices with and without the oxide layer. Although the conventional device performed higher drain current and higher peak transconductance at $V_G = 5$ and 2.5 V, respectively, such performances suffered from huge gate forward leakage current, which can be seen in Fig. 2. On the contrary, the MOS device showed a peak transconductance of 100 mS/mm, and a drain current of approximately 500 mA/mm while the gate still maintained off at 11 V. This was higher than the drain current of 250 mA/mm obtained at V_G turn-on voltage ($V_{on} = 2$ V) from the device without the oxide layer. Additionally, the threshold voltage was increased from 0.7 to 5.1 V owing to the insertion of the Al_2O_3 gate oxide layer.

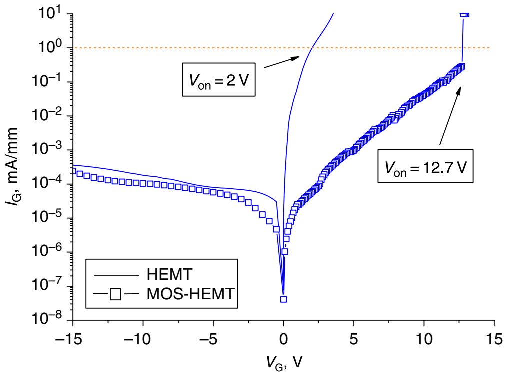

Fig. 2 *I_G-V_G characteristics of normally-off HEMT with and without gate oxide layer*

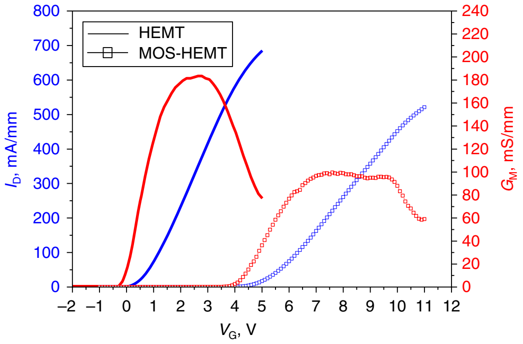

Fig. 3 *I_D-V_G characteristics of normally-off HEMT with and without oxide layer*

Conclusion: A normally-off operation AlGaN/GaN MOS-HEMT with high threshold voltage was demonstrated successfully. Lower gate leakage current and higher gate turn-on voltage, compared with the conventional CF_4-treated normally-off device, was achieved by using the Al_2O_3 gate oxide layer. As a result, a high drain current density of 500 mA/mm was obtained at a gate voltage of 11 V without huge gate leakage current, and the threshold voltage as high as 5.1 V was achieved. Such a device should be used for power electronic applications.

Acknowledgment: This work is partly supported by the National Science Council under a contract NSC98-2120-M009-010 and NSC98-2923-E009-002-MY3. The authors thank NTT Basic Research Laboratories, Japan, for their support.

13 July 2010
doi: 10.1049/el.2010.1939
One or more of the Figures in this Letter are available in colour online.

C.-T. Chang, T.-H. Hsu, E.Y. Chang, Y.-C. Chen and H.-D. Trinh (*Department of Materials Science and Engineering, National Chiao-Tung University, Hsinchu 300, Taiwan*)

E-mail: edc@mail.nctu.edu.tw

K.J. Chen (*Department of Electronic and Computer Engineering, Hong Kong University of Science and Technology, Kowloon, Hong Kong*)

References

1 Kodama, M., Sugimoto, M., Hayashi, E., Soejima, N., Ishiguro, O., Kanechika, M., Itoh, K., Ueda, H., Uesugi, T., and Kachi, T.: 'GaN-based trench gate metal oxide semiconductor field-effect transistor fabricated with novel wet etching', *Appl. Phys. Express*, 2008, **1**, (2), p. 021104

2 Palacios, T., Suh, C., Chakraborty, A., Keller, S., DenBaars, S., and Mishra, U.: 'High-performance E-mode AlGaN/GaN HEMTs', *IEEE Electron Device Lett.*, 2006, **27**, (6), pp. 428–430

3 Cai, Y., Zhou, Y., Chen, K.J., and Lau, K.: 'High-performance enhancement-mode AlGaN/GaN HEMTs using fluoride-based plasma treatment', *IEEE Electron Device Lett.*, 2005, **26**, (7), pp. 435–437

4 Mizutani, T., Ito, M., Kishimoto, S., and Nakamura, F.: 'AlGaN/GaN HEMTs with thin InGaN cap layer for normally off operation', *IEEE Electron Device Lett.*, 2007, **28**, (7), pp. 549–551

5 Ohki, T., Kikkawa, T., Kanamura, M., Imanishi, K., Makiyama, K., Okamoto, N., Joshin, K., and Hara, N.: 'An over 100W AlGaN/GaN enhancement-mode HEMT power amplifier with piezoelectric-induced cap structure', *Phys. Status Solidi C*, 2009, **6**, (6), pp. 1365–1368

6 Cai, Y., Zhou, Y., Lau, K.M., and Chen, K.J.: 'Control of threshold voltage of AlGaN/GaN HEMTs by fluoride-based plasma treatment: from depletion mode to enhancement mode', *IEEE Trans. Electron Devices*, 2006, **53**, (9), pp. 2207–2215