Improved Dynamic ON-resistance of a Normally Off p-GaN Gate High-Electron-Mobility Transistor Using a Nongated-Region Oxidation Technique

Chia-Hao Liu [1], Hsuan-Ling Kao[1], Hsien-Chin Chiu[1], Yi-Sheng Chang[1], Hao-Yu Wang[1], Chao-Wei Chiu[1], Hsiang-Chun Wang[1], Chong Rong Haung[1], Xin-ke Liu[2]

[1] Department of Electronics Engineering, Chang Gung University, Taiwan, R.O.C.
[2]College of Materials Science and Engineering, Shenzhen University, 518060, P. R. of China
TEL: +886-3-2118800 # 3645 Email: hcchiu@mail.cgu.edu.tw

Keywords: p-GaN gate HEMT, normally off, high-resistivity GaN, O_2 plasma, low gate lag

Abstract

In this study, a device structure for a high-resistivity high-electron-mobility transistor (HR-HEMT) was developed for a normally off p-GaN gate HEMT with low gate lag and high saturation current. Instead of using a traditional etching process, oxygen plasma was adopted to compensate for holes in the p-GaN gate above the two-dimensional electron gas (2DEG) channel to release electrons in the 2DEG channel and form a high-resistivity area to protect the device. Moreover, a comparison of the traditional etching process and oxygen plasma treatment revealed that the HR-HEMT exhibited higher performance than a traditional device, with a saturation current of 111 mA/mm at V_{GS} = 6 V and a lower dynamic ON-resistance of 1.25 times at a gate bias stress of −15 V.

INTRODUCTION

GaN-based power devices are emerging as promising candidates for next-generation power switching applications due to their high mobility and wide band gap. A traditional AlGaN/GaN high-electron-mobility transistor is a normally-on device, featuring high mobility and high-density two-dimensional electron gas (2DEG) [1]. These transistors feature a quantum well beyond the Fermi level, which means that the device operates at a negative bias. However, normally off device operate at a positive bias, which are desirable for power switching devices because of simplified gate-drive topology and failsafe operation [2]. Many approaches exist for making a normally off device, such as fluoride plasma treatment [3], [4], a p-GaN gate [5]– [9], and a gate recess [10], [11]. These approaches have been used for obtaining a normally off HEMT. Structures with p-type gates have drawn increasing attention in the industry due to their low on-state resistance and a large threshold voltage. To improve the performance of p-GaN HEMTs, the etching depth uniformity of the nongated active region and the plasma-induced damage during the p-GaN removal process are particularly crucial. Traditional chlorine-based dry etching generally provides a rough surface that causes gate lag due to surface traps. Chiu *et al.* [12] demonstrated that an HEMT structure with an aluminum nitride (AlN) etching stop layer improved performance. This method can avoid over etching and protect the AlGaN barrier layer, which may improve the leakage current, drain lag, and dynamic ON-resistance (R_{on}). In [3], HR-GaN was obtained through hydrogen plasma treatment. The electric field distribution of a conventional p-GaN gate HEMT and a high-resistivity HEMT (HR-HEMT) in the off state were simulated. This indicated that passivation may occur in HR-GaN, and there were negative charges that appeared at the interface that can improve the off-state breakdown voltage [3]. Varying radio frequencies have also been used to treat p-GaN with inductively coupled plasma (ICP) [13]. However, bonds between magnesium and hydrogen are easily broken at high temperatures, which is a challenge in the alloying process. In this work, an HR-GaN cap layer was fabricated through oxygen plasma treatment with an AlN etching stop layer. The oxygen plasma treatment caused acceptors in p-GaN to be passivated by the formation of Mg–O and Ga–O, which offer high resistivity and stability as insulator materials.

EXPERIMENTAL PROCEDURES

The purpose of the oxygen plasma treatment for p-GaN HEMTs can be illustrated using a schematic band gap diagram created using 1D Poisson software, as shown in Fig. 1. After oxygen plasma treatment, Mg–GaN is oxidized and changed to MgO, Ga_2O_3, and gas N_2O. This makes p-GaN lose its p-type effect, and the p–n junction becomes invalid. Subsequently, the conduction band in the channel is pulled under the Fermi level, causing 2DEG to form in the channel. In addition, after oxygen plasma treatment, the low-resistivity p-GaN becomes HR- GaN.

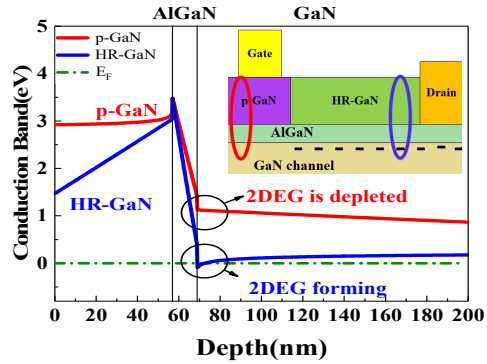

Fig.1 Band gap diagram of p-GaN/AlGaN/GaN with HR-GaN.

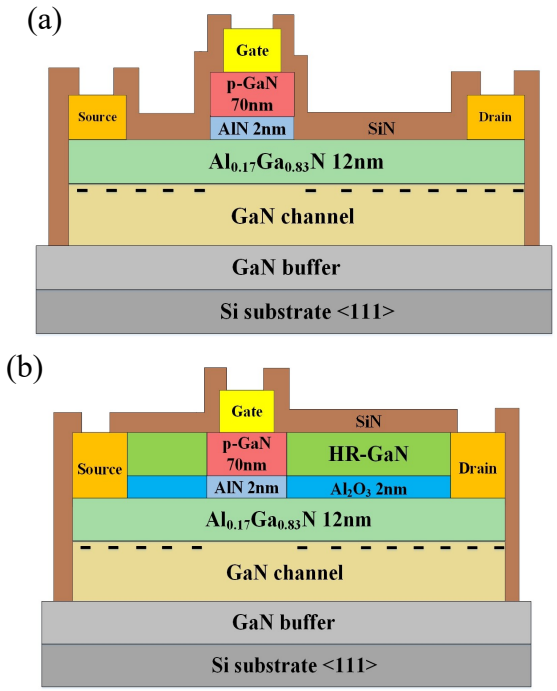

Fig.2. Diagram of devices (a) and (b), which respectively used dry etching and O_2 plasma treatment to create the p-GaN layer.

Fig. 2 presents diagrams of epistructures used in this study. The p-GaN/AlGaN/GaN HEMT was grown on 6-inch Si (111) substrates through metal organic chemical vapor deposition. A 300-nm-thick undoped GaN channel was grown on top of a 4-µm-thick undoped AlGaN/GaN buffer transition layer. Then, a 12-nm-thick $Al_{0.17}Ga_{0.83}N$ layer, 2-nm-thick AlN layer, and 70-nm-thick p-type GaN top layer were composited. The Mg concentration was 3×10^{19} cm^{-3}, which was thermally annealed through MOCVD at 720°C for 10 min in N_2 ambient, and the activation of Mg concentration was 1×10^{18} cm^{-3} according to the Hall measurement.

For the HEMT device fabrication, the mesa region was etched with a combination of Cl_2, BCl_3, and Ar gases through reactive ion etching (RIE). Subsequently, the p-GaN nongated regions were etched using different methods. As shown in Fig. 2, device A, a standard HEMT (ST-HEMT), was etched through RIE with $Cl_2/BCl_3/Ar$. However, device B, an HR-HEMT, was fabricated through oxygen plasma treatment. High-density oxygen plasma was produced by the ICP over 18 min with an RF power of 300 W and a DC power of 100 W at room temperature. The ohmic contact region was etched by CF_4 and Ar, and Ti/Al/Ni/Au metal film was deposited as a source and drained by electron beam evaporation. It was then annealed at 875°C for 35 s in a N_2 atmosphere using an RTA system, and Ti/Au was deposited as the gate metal. Ti/Au was subsequently deposited as the pad for interconnection. Eventually, two devices were passivated with Si_3N_4 through plasma-enhanced chemical vapor deposition. The fabricated devices had a gate width of 100 µm, a gate length of 2 µm, a source-gate distance of 3 µm, and a gate–drain distance of 6 µm.

RESULTS AND DISCUSSION

Fig. 3(a) and (b) show the output characteristic and the transfer characteristic of the ST-HEMT (with dry etching) and HR-HEMT (oxygen plasma treatment) with $L_{GS}/L_G/L_{GD}/W_G$ = 3/2/6/100 µm, respectively. From Fig. 3(a), the drain leakage currents for the HR-HEMT and ST-HEMT were 4.4 $\times 10^{-7}$ and 1.03 $\times 10^{-6}$ mA/mm, respectively, at VGS = 0 V. These results indicate that O_2 plasma passivated p-GaN, resulting in extremely low damage to the device. By contrast, conventional etching of p-GaN with corrosion gases resulted in many dangling bonds. These bonds were traps that blocked electrons' path from the drain to source by hopping conduction. Additionally, the threshold voltage (V_{TH}) value was 1.3 V in both devices. The drain ON/OFF current ratio (I_{ON}/I_{OFF}) values of the HR-HEMT and ST-HEMT were 3.9 $\times 10^9$ and 1.8 $\times 10^7$, respectively, and the subthreshold swing was improved from 118 to 104 mV/dec in the HR-HEMT. In Fig. 2(b), the I_{DS}–V_{DS} curves of the HEMTs are shown by varying gate bias. The maximum output current density was 88 mA/mm at a gate bias of 6 V, and the ON-resistance was 31.8 Ω·mm for the ST-HEMT. By contrast, these results were respectively 159 mA/mm and 17.1 Ω·mm for the HR-GaN HEMT. The greater output current performance of the HR-HEMT may be increased due to Al_2O_3 stop layer which can protect AlGaN barrier layer. This may have had the same effect as an etching stop layer that was shown previously [12]. In the present study, Al_2O_3 was formed through an etching process and could protect the AlGaN barrier layer. However, the O_2 plasma treatment passivated p-GaN, which raised the performance of the device. Compared with a conventional etching process, the HR-HEMT had a favorable current density and low leakage current.

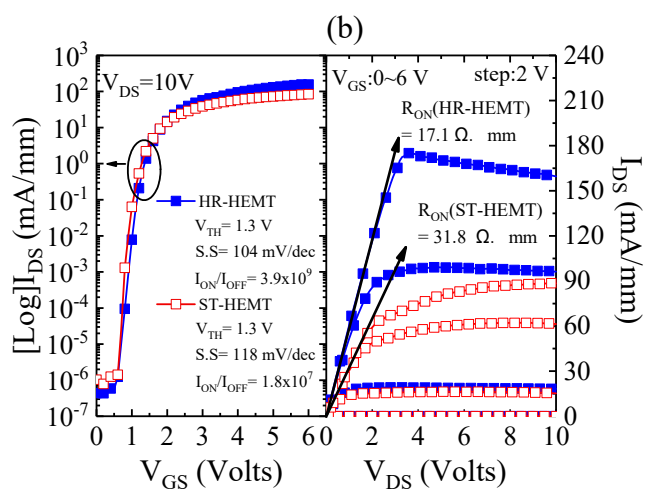

Fig. 3. I–V characteristics of the HR-HEMT and ST-HEMT. (a) Transfer characteristics (b) output characteristics.

To analyze the surface trapping/detrapping from dry etching and oxygen plasma treatment in the p-GaN HEMT, low frequency noise spectra were taken five conditions at 100 Hz in different bias. The $1/f$ noise measurement system was performed using an HP-4142 power supply, a 35670A dynamic signal, and an Agilent E3611a control unit. In this work, the frequency range was measured from 10 to 1000 Hz. If the slope of S_{ID}/I_{DS}^2 is close to −2, the spectral fluctuation will be dominated by surface traps [14]. The slopes for HR-GaN and ST-GaN were −1.52 and −1.73, respectively. Moreover, the noise of HR-HEMT was lower than that for ST-HEMT by approximately one order of magnitude.

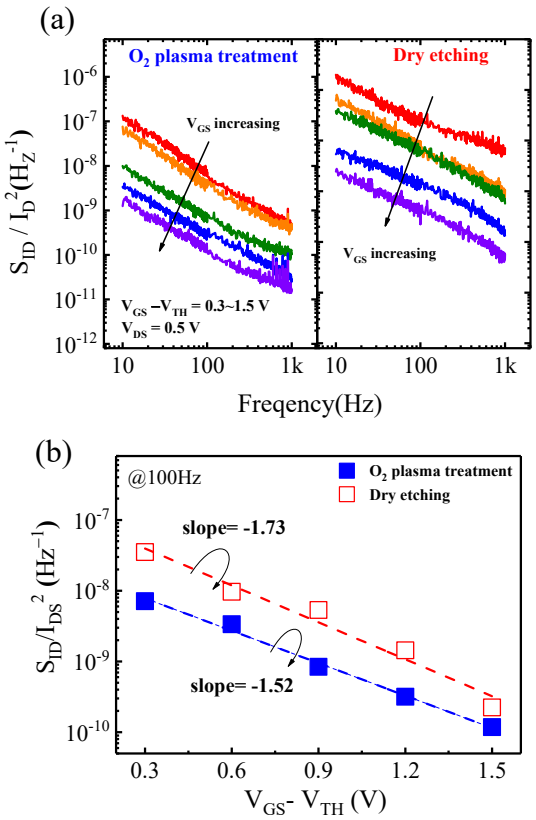

Fig. 4. (a) LFN spectra and (b) S_{ID}/I_{DS}^2 slope as a function of gate voltage overdrive for the HR-HEMT and ST-HEMT.

Proof of the off-state breakdown voltage through simulation of HRCL-HEMT and conventional p-GaN HEMT has been published previously [15]. Hao *et al.* demonstrated that negative charges appear at the interface of HR-GaN/AlN/AlGaN because of negative polarization [16]. This effect may disperse the electric field and thereby improve the off-state breakdown voltage. Fig. 5 presents a breakdown of each device defined as the V_{DS} at which the I_{DS} reaches 1 mA/mm at V_{GS} = −2 V using an Agilent 1505. The off-state breakdown voltages of the HR-HEMT and ST-HEMT were 530 and 350 V, respectively.

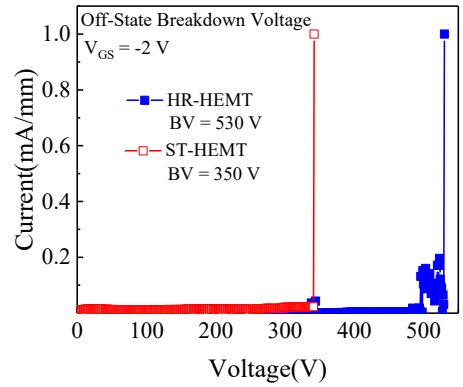

Fig. 5. Off-state breakdown characteristic for the HR-HEMT and ST-HEMT.

The dynamic R_{on} was investigated through pulse measurements of both devices and also from different quiescent bias points at V_{GS} = 4 V. The pulse width and period time were 2 and 200 μs, respectively. The quiescent gate bias (V_{GSQ}) was swept from 0 V to −15 V with −5 V increments. However, traps from surface, bulk, or interface trap states can limit device performance. Surface traps are considered to be causes of gate lag, and buffer traps are considered to be causes of drain lag [17]. As shown in Fig. 6, by comparison, the dynamic R_{on} ratio of the HR-HEMT was only 1.46 times at a gate bias stress of −15 V, much lower than the dynamic R_{on} of the ST-HEMT, which was 2.52 times. Therefore, using oxygen plasma treatment for p-GaN can more effectively reduce surface traps than dry etching.

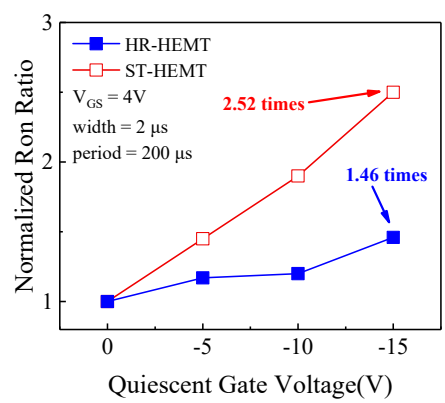

Fig. 6. With the quiescent gate bias stress voltage of the dynamic R_{on} ratio.

CONCLUSIONS

In this study, an HR-HEMT was fabricated through oxygen plasma treatment. The HR-HEMT exhibited low drain leakage current of 4.4×10^{-7} and a higher output current (159 mA/mm) than an ST-HEMT (88 mA/mm). Furthermore, the off-state breakdown voltage rose to 530 V at V_{GS} = 0 V in the HR-HEMT. The dynamic R_{on} ratios were measured, which were 1.46 times for the HR-HEMT and 2.52 times for the ST-HEMT, meaning that the HR-HEMT caused lower

gate lag. These characteristics of the HR-HEMT were a result of the oxygen plasma treatment causing very low damage to the surface, effectively reducing surface traps. However, controlling the oxidation depth of oxygen plasma treatment for p-GaN remains a challenge because of the edge effect.

REFERENCES

[1] Ambacher et al., "Two dimensional electron gases induced by spontaneous and piezoelectric polarization in undoped and doped AlGaN/GaN heterostructures," J. Appl. Phys., vol. 87, no. 1, pp. 334–344, 2000, doi:10.1063/1.371866.

[2] M. A. Khan et al., "Enhancement and depletion mode GaN/AlGaN heterostructure field effect transistors," Appl. Phys. Lett., vol. 68, no. 4, pp. 514–516, 1996, doi: 10.1063/1.116384.

[3] Y. Cai, Y. Zhou, K. J. Chen, and K. M. Lau, "High-performance enhancement-mode AlGaN/GaN HEMTs using fluoride-based plasma treatment," IEEE Electron Device Lett., vol. 26, no. 7, pp. 435–437, Jul. 2005, doi: 10.1109/LED.2005.851122.

[4] Z. Tang et al., "600-V normally off SiNx /AlGaN/GaN MIS-HEMT with large gate swing and low current collapse," IEEE Electron Device Lett., vol. 34, no. 11, pp. 1373–1375, Nov. 2013, doi:10.1109/LED.2013.2279846.

[5] X. Hu, G. Simin, J. Yang, M. A. Khan, R. Gaska, and M. S. Shur, "Enhancement mode AlGaN/GaN HFET with selectively grown pn junction gate," Electron. Lett., vol. 36, no. 8, pp. 753–754, 2000, doi:10.1049/el:20000557.

[6] Y. Uemoto et al., "Gate injection transistor (GIT)—A normally-off AlGaN/GaN power transistor using conductivity modulation," IEEE Trans. Electron Devices, vol. 54, no. 12, pp. 3393–3399, Dec. 2007, doi: 10.1109/TED.2007.908601.

[7] O. Hilt, A. Knauer, F. Brunner, E. Bahat-Treidel, and J. Würfl, "Normally-off AlGaN/GaN HFET with p-type Ga gate and AlGaN buffer," in Proc. ISPSD, Jun. 2010, pp. 347–350

[8] T.-L. Wu et al., "Forward bias gate breakdown mechanism in enhancement-mode p-GaN gate AlGaN/GaN high-electron mobility transistors," IEEE Electron Device Lett., vol. 36, no. 10, pp. 1001–1003, Aug. 2015, doi: 10.1109/LED.2015.2465137.

[9] I. Hwang et al., "1.6 kV, 2.9 mcm2 normally-off p-GaN HEMT device," in Proc. 24th Int. Symp. Power Semicond. Devices ICs, Jun. 2012, pp. 41–44, doi: 10.1109/ISPSD.2012.6229018.

[10] W. Saito, Y. Takada, M. Kuraguchi, K. Tsuda, and I. Omura, "Recessed gate structure approach toward normally off high-voltage AlGaN/GaN HEMT for power electronics applications," IEEE Trans. Electron Devices, vol. 53, no. 2, pp. 356–362, Feb. 2006, doi: 10.1109/TED.2005.862708.

[11] W. Li et al., "Design and simulation of a novel E-mode GaN MISHEMT based on a cascode connection for suppression of electric field under gate and improvement of reliability," J. Semicond., vol. 38, no. 7, p. 074001, 2017, doi: 10.1088/1674-4926/38/7/074001.

[12] H.-C, Chiu, "High-performance normally-off p-GaN Gate HEMT with composite $AlN/Al_{0.17}Ga_{0.83}N/Al_{0.3}Ga_{0.7}N$ barrier layers design", IEEE Electron Devices Society, 5 Jan. 2018.

[13] R. Hao et al., "Studies on Fabrication and Reliability of GaN High-Resistivity-Cap-Layer HEMT", IEE Trans. Electron Devices, vol. 65, no. 4, April 2018

[14] H.-C, Chiu, "High uniformity normally-off p-GaN gate HEMT using self-terminated digital etching technique" IEE Trans. Electron Devices, vol. 65, no. 11, Nov 2018.

[15] R. Hao et al., "Breakdown enhancement and current collapse suppression by high-resistivity GaN cap layer in normally-off AlGaN/GaN HEMTs," IEEE Electron Device Lett., vol. 38, no. 11, pp. 1567–1570, Nov. 2017, doi: 10.1109/LED.2017.2749678.

[16] H. Ishida, D. Shibata, M. Yanagihara, Y. Uemoto, H. Matsuo, T. Ueda, T. Tanaka, and D. Ueda, "Unlimited high breakdown voltage by natural super junction of polarized semiconductor," IEEE Electron Device Lett., vol. 29, no. 10, pp. 1087–1089, Oct. 2008, doi: 10.1109/ LED.2008.2002753.

[17] X. Y. Zhou, Z. Feng, Y. Wang, G. Gu, X. Song, S. Cai, IEEE International Conference on Solid-State and Integrated Circuit Technology, IEEE, Guilin, China 2014, pp. 1–3.

ACRONYMS

GaN: Gallium nitride
AlN: Aluminum Nitride
HR-HEMT: High Resistivity High Electron Mobility Transistor
2DEG: Two Dimensional Electron Gas
ICP: Inductively Coupled Plasma
ST-HEMT: Standard High Electron Mobility Transistor
RIE: Reactive Ion Etching