Effective Passivation with High-density Positive Fixed Charges for GaN MIS-HEMTs

Shih-Chien Liu, Chung-Kai Huang, Chia-Hua Chang, Yueh-Chin Lin, Bo-Yuan Chen, Szu-Ping Tsai, Burhanuddin Yeop Majlis, Chang-Fu Dee, and Edward Yi Chang, *Fellow*, *IEEE*.

***Abstract*—An effective passivation with high-density positive fixed charges was demonstrated on GaN MIS-HEMTs. The positive fixed charges at the interface between passivation and AlGaN surface can reduce the surface potential and expand the quantum well under Fermi level. Besides, to satisfy charge balance, the net charge density at the AlGaN surface must equal to the 2DEG carrier density. Thus, the positive fixed charges passivation can increase the 2DEG carrier density and improve the switching performance of GaN MIS-HEMTs. In this work, we demonstrated a high-density positive fixed charges (~2.71 × 10^{13} e/cm^{-2}) passivation using SiON for GaN MIS-HEMTs. The device with SiON passivation exhibits significant improvements in *I–V* characteristics and dynamic R_{ON} compared to the conventional SiN passivated device.**

***Index Terms*—AlGaN/GaN HEMT, passivation, accepter-like states, positive fixed charges.**

I. Introduction

GaN-based metal-insulator-semiconductor high electron mobility transistors (MIS-HEMTs) have demonstrated outstanding high-power performance making them suitable for power switching applications [1]. However, the existence of surface states at the AlGaN surface leads to current collapse when the GaN HEMTs operate under high-electric field. Therefore, the surface passivation becomes a very important issue for GaN power devices [2].

To eliminate the surface states at the AlGaN surface and improve interface quality, many groups have performed different passivation methods including different deposition techniques, materials, and surface treatments [3-5].

However, in the real case, despite the improved interface quality between the passivation layer and AlGaN, high-density interface states still exist at the interface between passivation layer and AlGaN due to the interruption of periodic crystal lattice [6]. The interface states between passivation layer and AlGaN can be divided into acceptor- and donor- like states. When the interface states are occupied by electrons, the potentials of acceptor- and donor- like states are negative and neutral, respectively. For GaN MIS-HEMTs, the 2DEG carrier

Manuscript received, 2016. This work was sponsored by the NCTU-UCB I-RiCE program, and Ministry of Science and Technology.

S. C. Liu, Y. C. Lin, C. H. Chang, C. K. Huang, S. P. Tsai, and B. Y. Chen are with the Department of Materials Science and Engineering, National Chiao Tung University, Hsinchu 30010, Taiwan.

E. Y. Chang is with the Department of Electronics Engineering and Electronic Engineering, National Chiao Tung University, Hsinchu 30010, Taiwan (e-mail: edc@mail.nctu.edu.tw).

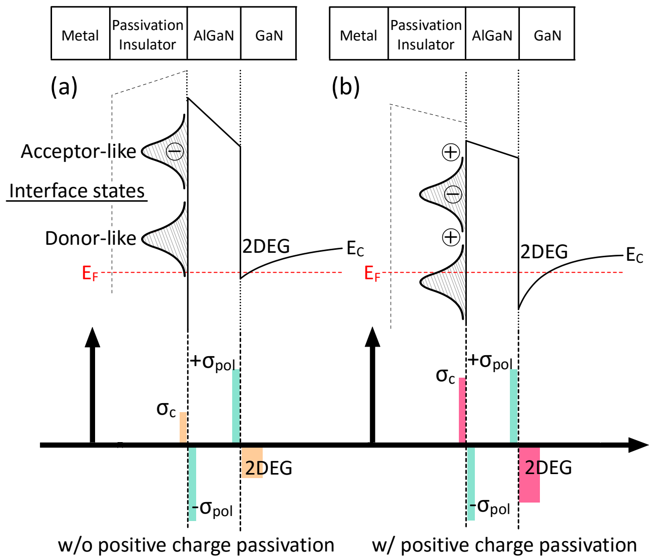

Fig. 1. Schematic of band diagram and charge distribution illustrating the behaviors of charged interface states in the GaN MIS-HEMT structure under high-electric field.

density in the access region is very sensitive to the surface potential due to the changes of the quantum well. As illustrated in Fig. 1(a), when the GaN MIS-HEMT operates under high-electric field, the electrons can be excited to fill the unoccupied acceptor-like states, leading to the AlGaN surface with a negative potential which results in the reduction of 2DEG carrier density and current collapse effect [7].

Positive fixed charges at the interface between passivation and AlGaN have been reported to be effective in reducing current collapse [7, 8]. Therefore, the passivation layer with high density of positive fixed charges is desirable to reduce the negative potential on the AlGaN surface which can improve the switching performance of GaN power devices. It was reported that SiON has higher density of positive fixed charges (Q_f) compared to pure SiN or SiO due to the increased Si^+ dangling bonds ($O_2N{\equiv}Si\bullet$ and $ON_2{\equiv}Si\bullet$) [9, 10]. Theoretically, as illustrated in Fig. 1(b), the positive fixed charges at the SiON/AlGaN interface can reduce the surface potential and expand the quantum well under Fermi level. Besides, to satisfy charge balance, the net charge density (σ_c) at the AlGaN surface, which includes interface fixed charges, surface donor, and trapped surface charge, must equal to the 2DEG carrier density [11]. Thus, physically, the SiON passivation with high-density

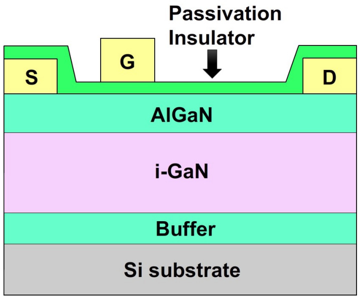

Fig. 2. (a) Schematic cross section of the GaN MIS-HEMT with 12-nm passivation and gate insulator.

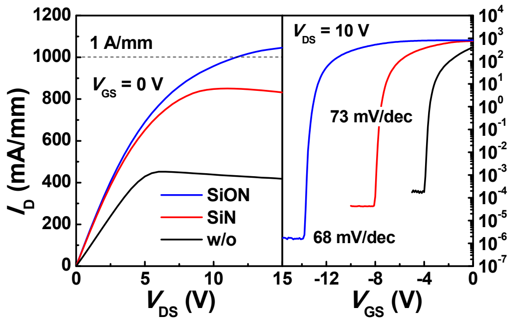

Fig. 4. I_D–V_{DS} characteristics (left) and transfer characteristics (right) of the GaN devices with different passivation and gate insulator layers.

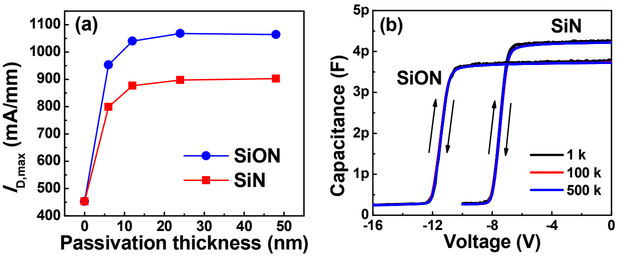

Fig. 3. (a) The $I_{D,max}$ of passivated devices versus passivation thickness. (b) Capacitance–voltage characteristics of SiON/AlGaN/GaN and SiN/AlGaN/GaN MIS capacitors.

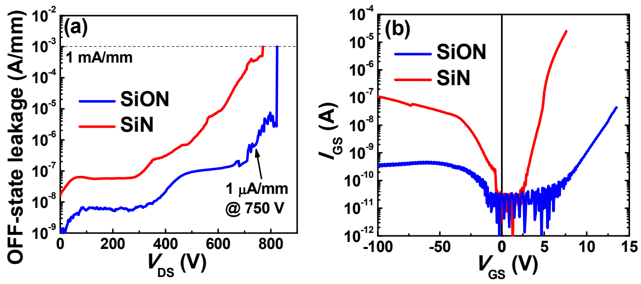

Fig. 5. (a) OFF-state drain leakage currents and (b) gate leakage currents of the GaN devices with different passivation and gate insulator layers.

positive fixed charges can effectively increase the 2DEG carrier density and improve the switching performance for GaN MIS-HEMTs.

In this work, the mechanisms of positive fixed charge passivation on GaN MIS-HEMTs were investigated in details. The results indicate that the density of positive fixed charges significantly affect the performances of GaN MIS-HEMTs.

II. Device Fabrication

The AlGaN/GaN HEMT heterostructure was grown by metal-organic chemical vapor deposition (MOCVD) on silicon substrate. The epitaxial structure consisted of 1-nm GaN cap layer, 25-nm $Al_{0.2}Ga_{0.8}N$ barrier layer, 1.3-µm i-GaN layer and a buffer layer consisted of GaN/AlGaN/AlN with total thickness of 4-µm. The device fabrication process features Ti/Al/Ni/Au ohmic contact metal and Ni/Au gate metal. The wafer was separated into two samples after mesa etch and ohmic contact formation to ensure the same starting characteristics for the devices. The gate-to-drain spacing L_{GD}, gate-to-source spacing L_{GS}, and gate length L_G were 10-µm, 3-µm, and 2-µm, respectively. Both SiON and SiN films were adopted as the passivation and gate insulator for GaN MIS-HEMTs. Before ohmic metal and passivation deposition, 1-nm GaN cap layer was removed by wet etching. The schematic cross section of the AlGaN/GaN HEMT with passivation and gate insulator is shown in Fig. 2. The passivation layers were prepared by plasma-enhanced chemical vapor deposition system at 300°C and with a post deposition annealing at 500°C. The silane (2% SiH_4/N_2) was kept constant at 40 sccm and the flow ratios of NH_3:N_2O were 1:5 and 1:0 for SiON and SiN, respectively. The refractive index of SiON and SiN were ~1.75 and ~1.96, respectively. The SiON with refractive index of ~1.75 was optimized to form highest density of positive fixed charges. The $I_{D,max}$ of passivated devices versus passivation thickness are shown in Fig. 3(a). Saturated $I_{D,max}$ are observed when the passivation thicknesses are about 12 nm.

III. Results and Discussion

To obtain the high quality interface with different passivation materials, the N-passivation (nitridation) technique was adopted prior to SiON and SiN passivation [3, 5]. After passivation, the capacitance–voltage curves were measured with various frequencies from 1 to 500 kHz. As shown in Fig. 3(b), with N-passivation technique, the capacitance–voltage curves of SiON/AlGaN/GaN and SiN/AlGaN/GaN MIS capacitors exhibit a steep slope without hysteresis and dispersion, indicating the similar interface quality with low interface trap density using N-passivation (nitridation) technique.

The correlation of the ΔV_{th} and the interface fixed charges have been reported [12], which can be expressed by

$$\Delta V_{th} = V_{th}\,(\text{MIS} - \text{HEMT}) - V_{th}\,(\text{HEMT}) = \frac{-Q_f}{C_{ox}}$$

where, Q_f is the interface fixed charge at the interface between passivation layer and AlGaN and C_{ox} is the capacitance of the SiON and SiN.

For the transfer characteristics shown in Fig. 4, a large ΔV_{th} which was observed for the device with SiON gate insulator, indicating the existence of high-density positive fixed charges at the SiON/AlGaN interface. The C_{ox} value of SiON and SiN

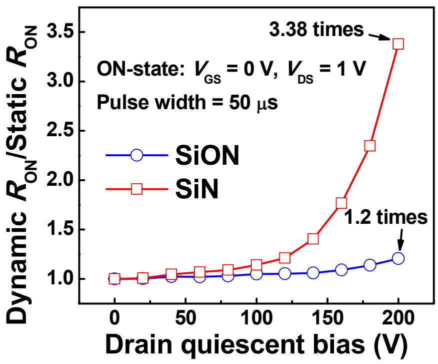

Fig. 6. Dynamic R_{ON} / static R_{ON} extracted from various OFF-state quiescent bias.

were calculated to be 8.7 × 10^{12} F and 11.8 × 10^{12} F, respectively. The density of positive fixed charges, extracted from the formula, were ~2.71 × 10^{13} and ~1.54 × 10^{13} e/cm^{-2} for SiON and SiN, respectively.

The basic DC *I*–*V* characteristics of the devices are shown in Fig. 4. For the device with SiON passivation, a higher $I_{D,max}$ of >1 A/mm, lower specific R_{ON} of 0.94 mΩ • cm^2, and lower subthreshold slope (*SS*) of 68 mV/dec were observed. In contrast, the device with SiN passivation exhibits a lower $I_{D,max}$ of 896 mA/mm, higher specific R_{ON} of 0.99 mΩ • cm^2, and *SS* of 73 mV/dec. These results reveal that the device passivated with the higher density of positive fixed charges has a higher 2DEG carrier density which is consistent with the physical phenomena as illustrated in Fig. 1.

The leakage current characteristics of the devices are shown in Fig. 5. The OFF-state breakdown characteristics, shown in Fig. 5(a), exhibit an improved *BV* for the device with SiON compared to the device with SiN. For the device with SiON, the *BV* of 750 V at a low leakage current of 1 μA/mm was achieved, yielding a high-power figure of merit of ~620 MW/cm^2. Furthermore, the device with SiON exhibits a lower gate leakage current compared to the device with SiN, as shown in Fig. 5(b). The results indicate that SiON with higher bandgap and dielectric strength effectively suppresses leakage current compared to pure SiN [13].

The dynamic R_{ON} has been commonly used to examine the trapping effects caused by the interface states in the GaN device structure [14]. Thus, the dynamic R_{ON} can be used to evaluate the effectiveness of the passivation. As shown in Fig. 6, the dynamic R_{ON} were extracted from various OFF-state drain quiescent voltage (V_{DSQ}) from 0 V to 200 V within 5 ms and ON-state with V_{GS} = 0 V, V_{DS} = 1 V. The ON-state pulse width was 50 μs using Agilent B1505A with N1267A fast switch module. For the V_{DSQ} stress at 200 V, the dynamic R_{ON} increases slightly to 1.2 times for the device with SiON passivation. In contrast, the dynamic R_{ON} increases 3.38 times for the device with SiN passivation. As illustrated in Fig. 1, the increase of dynamic R_{ON} can be understood as that the quantum well was raised by the negative potential attributed to the negatively charged acceptor-like interface states, resulting in a reduction of 2DEG carrier density [2, 7]. The results indicate that the quantum well of SiON passivated device is more stable than the SiN passivated device under high-voltage switching. It proves that the negative potential at AlGaN surface is effectively reduced by SiON passivation with high-density positive fixed charges. The SiON passivation is therefore preferable for GaN power device applications.

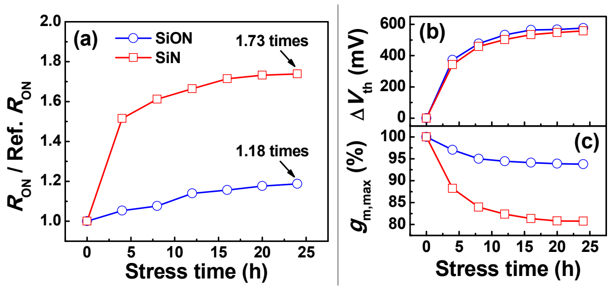

Fig. 7. Time evolutions of (a) R_{ON}, (b) ΔV_{th}, and (c) $g_{m,max}$ during OFF-state stress on the GaN MIS-HEMT with SiN and SiON passivation.

The stability of the GaN MIS-HEMT with SiON is also investigated in this study. The OFF-state (V_{DS} = 100 V) stress conditions were adopted to observe the stability of the devices under high-electric field [15]. The changes of R_{ON}, V_{th}, and $g_{m,max}$ during stress for the SiON and SiN passivated devices are shown in Fig. 7. The SiON passivated device exhibits a slight degradation in R_{ON} and $g_{m,max}$ after 24 hours stress. In contrast, a severe degradation in R_{ON} and $g_{m,max}$ were observed for the SiN passivated devices after 24 hours stress. For both SiON and SiN passivated devices, a ΔV_{th} of ~560 mV were observed. Both SiON and SiN passivated devices show saturated *I-V* characteristics after 20 hours stress. The results indicate that SiON passivation with higher density of positive fixed charges can improve the stability of GaN MIS-HEMTs under high-electric field.

IV. Conclusion

The high-density positive fixed charges passivation is proved to be effective in improving switching performance and increasing 2DEG carrier density for GaN MIS-HEMTs. The device with SiON passivation, which has higher-density positive fixed charges than SiN passivation, demonstrates significant improvements in *I*–*V* characteristics and dynamic R_{ON} compared to the conventional SiN passivated device. Overall, the high-density positive fixed charges passivation is desirable for GaN power device applications.

References

[1] K.-Y. Roy. Wong, M.-H. Kwan, F.-W. Yao, M.-W. Tsai, Y.-S. Lin, Y.-C. Chang, P.-C. Chen, R.-Y. Su, J.-L. Yu, F.-J. Yang, G. P. Lansbergen, C.-W. Hsiung, Y.-A. Lai, K.-L. Chiu, C.F. Chen, M.-C. Lin, H.-Y. Wu, C.-H. Chiang, S.-D. Liu, H. -C. Chiu, P.-C. Liu, C.-M. Chen, C.-Y. Yu, C.-S. Tsai, C.-B. Wu, B. Lin, M.-H. Chang, J.-S. You, S.-P. Wang, L.-C. Chen, Y.-Y. Liao, L.Y. Tsai, Tom Tsai, H.C. Tuan & Alex Kalnitsky, "A Next Generation CMOS-Compatible GaN-on-Si Transistors for High Efficiency Energy Systems," *IEEE IEDM,* pp. 229-232, 2015.

[2] R. Vetury, N. Q. Zhang, S. Keller, and U. K. Mishra, "The impact of surface states on the DC and RF characteristics of AlGaN/GaN HFETs," *IEEE Trans. Electron Devices,* vol. 48, no. 3, pp. 560-566, Mar. 2001.

[3] S. Yang, Z. Tang, K.-Y. Wong, Y.-S. Lin, C. Liu, Y. Lu, S. Huang, and K. J.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JEDS.2017.2669100, IEEE Journal of the Electron Devices Society

Chen, "High-Quality Interface in MIS Structures With In Situ Pre-Gate Plasma Nitridation," *IEEE Electron Device Lett.,* vol. 34, no. 12, pp. 1497-1499, Dec. 2013.

[4] S. Huang, Q. Jiang, S. Yang, C. Zhou, and K. J. Chen, "Effective passivation of AlGaN/GaN HEMTs by ALD-grown AlN thin film," *IEEE Electron Device Lett.,* vol. 33, no. 4, pp. 516-518, Apr. 2012.

[5] S.-C. Liu, B.-Y. Chen, Y.-C. Lin, T.-E. Hsieh, H.-C. Wang, and E. Y. Chang, "GaN MIS-HEMTs With Nitrogen Passivation for Power Device Applications," *IEEE Electron Device Lett.,* vol. 35, no. 10, pp. 1001-1003, Oct. 2014.

[6] H. Lüth, *Solid surfaces, interfaces and thin films* vol. 4: Springer, 2001.

[7] G. Koley, V. Tilak, L. F. Eastman, and M. G. Spencer, "Slow Transients Observed in AlGaN/GaN HFETs: Effects of SiNx Passivation and UV Illumination," *IEEE Transactions Electron Device Lett.,* vol. 50, no. 4, pp. 886-893, Apr. 2003.

[8] Y. S. Lin, K. Y. Wong, G. P. Lansbergen, J. L. Yu, C. J. Yu, C. W. Hsiung, H. C. Chiu, S. D. Liu, P. C. Chen, F. W. Yao, R. Y. Su, C. Y. Chou, C. Y. Tsai, F. J. Yang, C. L. Tsai, C. S. Tsai, X. Chen, H. C. Tuan and Alex Kalnitsky, " Improved Trap-Related Characteristics on SiNx/AlGaN/GaN MISHEMTs With Surface Treatment," *Proceedings of the 26th International Symposium on Power Semiconductor Devices & IC's,* Jun., 2014.

[9] Z. Zhuo, Y. Sannomiya, Y. Kanetani, T. Yamada, H. Ohmi, H. Kakiuchi, and K. Yasutake, "Interface properties of SiO_xN_y layer on Si prepared by atmospheric-pressure plasma oxidation-nitridation," *Nanoscale research letters,* vol. 8, pp. 1-6, Dec. 2013.

[10] A. G. Aberle, "Overview on SiN surface passivation of crystalline silicon solar cells," *Solar Energy materials and solar cells,* vol. 65, pp. 239-248, Jan. 2001.

[11] J. P. Ibbetson, P. T. Fini, K. D. Ness, S. P. DenBaars, J. S. Speck, and U. K. Mishra, " Polarization effects, surface states, and the source of electrons in AlGaN/GaN heterostructure field effect transistors," *Applied Physics Lett.,* vol. 77, no. 2, pp. 250-252, Nov. 2000.

[12] G. Dutta, S. Turuvekere, N. Karumuri, N. DasGupta, and A. Dasgupta, "Positive shift in threshold voltage for reactive-ion-sputtered Al_2O_3/ AlInN/GaN MIS-HEMT," *IEEE Electron Device Lett.,* vol. 35, no. 11, pp. 1085-1087, Nov. 2014.

[13] V. Nguyen, W. Lanford, and A. Rieger, "Variation of Hydrogen Bonding, Depth Profiles, and Spin Density in Plasma- Deposited Silicon Nitride and Oxynitride Film with Deposition Mechanism," *Journal of The Electrochemical Society*, vol. 133, pp. 970-974, May 1986.

[14] D. Jin and J. A. Del Alamo, "Methodology for the study of dynamic ON-resistance in high-voltage GaN field-effect transistors," *IEEE Trans. Electron Devices,* vol. 60, no. 10, pp. 3190-3196, Oct. 2013.

[15] G. Meneghesso, G. Verzellesi, F. Danesin, F. Rampazzo, F. Zanon, A. Tazzoli, M. Meneghini, and E. Zanoni, "Stability of GaN high-electron-mobility transistors: state of the art and perspectives," *IEEE Trans. on Device and Materials Stability,* vol. 8, no. 2, pp. 332-343, Jun. 2008.