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 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_{2}N≡Si^{+} and O_{2}N≡Si^{+}) [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 (\sigma_{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...
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 AlGaN 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 metal deposition, 1-nm GaN cap layer and with a post deposition annealing at 500°C. The AlGaN/GaN HEMT heterostructure was grown by plasma-enhanced chemical vapor deposition system at 300°C and with a post deposition annealing at 500°C. The silane (2% SiH₄/N₂) was kept constant at 40 sccm and the flow ratios of NH₃:N₂O 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 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, Capacitance–voltage characteristics 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.
were calculated to be $8.7 \times 10^{12}$ F and $11.8 \times 10^{12}$ F, respectively. The density of positive fixed charges, extracted from the formula, were $-2.71 \times 10^{13}$ and $-1.54 \times 10^{13}$ 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 $I_{D,\text{max}}$ 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 $I_{D,\text{max}}$ 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 $B^F$ for the device with SiON compared to the device with SiN. For the device with SiON, the $B^F$ 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 SiN 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 ($V_{DS}$) 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 NI267A fast switch module. For the $V_{DS}$ 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.

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 Δ$V_{th}$ 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


