High Performance Enhancement-Mode AlGaN/GaN MOSHEMT using Bimodal-Gate-Oxide and Fluoride-Based Plasma Treatment

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Keywords: GaN HEMT, Enhancement-mode, Bimodal-gate-oxide, CF$_4$ plasma treatment

Abstract
We present high performance E-mode AlGaN/GaN MOSHEMT achieved by CF$_4$ plasma treatment and bimodal-gate-oxide scheme. ALD-Al$_2$O$_3$ is utilized to prevent deep F$^-$ ion implantation into the 2DEG channel, while sputtered-SiO$_2$ is employed to suppress the plasma induced gate leakage current and increase the gate swing. Comparing with the D-mode counterpart, thus-fabricated E-mode MOSHEMT exhibited 3 V shift in $V_{th}$, but only 8% degradation in $I_{max}$, demonstrating the promise of bimodal-gate-oxide scheme for realizing E-mode operation of GaN-based MOSHEMTs.

INTRODUCTION
As a promising candidate device for both microwave and high-power switching applications, AlGaN/GaN high electron mobility transistors (HEMTs) and metal-oxide-semiconductor (MOS)-HEMTs are attracting increasing interests. However, the polarization-induced 2-dimensional electron gas (2DEG) causes the usual depletion-mode (D-mode) operation of such devices. From the application point of view, enhancement-mode (E-mode) transistors are more desirable for circuit simplification and safety issues. Besides, the lack of high-quality GaN p-channel FETs makes the direct-coupled FET logic (DCFL) consisting monolithically integrated E/D-HEMTs the most practical circuit scheme for GaN-based digital ICs.

E-mode HEMTs have been realized using gate-recess [1] or fluoride-based plasma treatment techniques [2]. The latter is a more reliable and self-aligned approach, in which the incorporated fluorine ions (F$^-$) act as immobile negative charges that deplete the 2DEG and positively shift the threshold voltage ($V_{th}$). Nevertheless, E-mode HEMT with comparable performance as the D-mode counterpart has yet to be achieved, since the highly energetic F$^-$ ions implanted into the 2DEG channel degrade the electron mobility by impurity scattering. The maximum drain current ($I_{max}$) is further reduced by the limited gate swing, which is a consequence of plasma-induced surface damage that increases leakage current in the gate region.

In this study, an Al$_2$O$_3$ layer deposited by atomic layer deposition (ALD) was utilized as the energy barrier to prevent deep implantation of F$^-$ ions. Different experimental parameters, like the Al$_2$O$_3$ layer thickness, are carefully examined to achieve the optimized device performance. Based on our previous research on bimodal gate-oxide scheme [3], a sputtered-gate-SiO$_2$ layer was further added in a self-aligned manner to suppress the plasma-induced gate leakage current. Thus-fabricated bimodal-gate-oxide MOSHEMT demonstrated large shift in $V_{th}$ and small degradation in $I_{max}$ as comparing with the D-mode reference sample.

EXPERIMENTAL
Device isolation and recess source/drain etching were first performed on the AlGaN/GaN template. Ti/Al/Ti/Au were deposited by electron-beam evaporation as the Ohmic contacts, followed by rapid thermal annealing at 830 °C for 30 s. A thin Al$_2$O$_3$ film was then deposited on the epilayer by ALD at 300°C. After that, the gate window was opened by photolithography and CF$_4$ plasma treatment was carried out at the optimized conditions. Subsequently, the gate metals (Ni/Au) were deposited in a self-aligned manner. For some samples, before gate metal deposition, 10-nm-SiO$_2$ was deposited in the gate region by RF magnetron sputtering using conditions described in [4]. Finally, post-annealing was conducted at 450 °C for 10 min as a standard process to partially recover the plasma damage.

Fig. 1. Transfer characteristics of Al$_2$O$_3$/AlGaN/GaN MOSHEMTs with different Al$_2$O$_3$ thicknesses but same plasma treatment condition.
RESULTS AND DISCUSSIONS

The MOSHEMT characteristics like $I_{\text{max}}$ and $V_{th}$ strongly depend on different processing parameters, including CF$_2$ plasma treatment condition and Al$_2$O$_3$ film thickness. A series of experiments were conducted for recipe optimization. For example, Fig. 1 shows the influence of Al$_2$O$_3$ film thickness on the $I_d$-$V_{gs}$ curves. As the film thickness decreased from 13 nm to 9 nm, the F ions were closer to the 2DEG, which positively shifted $V_{th}$ due to stronger depletion effect. On the other hand, thinner Al$_2$O$_3$ film generated larger stress-induced-polarization in the AlGaN/GaN epilayer, which increased the 2DEG density and negatively shifted $V_{th}$. The trade-off of device performances with respect to different experimental conditions were thoroughly investigated until an optimization was established.

![Fig. 2. $I_d$-$V_{gs}$ curves of (a) the conventional D-mode HEMT, and (b) the E-mode Al$_2$O$_3$-MOSHEMT.](image1)

Fig. 2 shows the $I_d$-$V_{gs}$ curves of the conventional D-mode HEMT and the E-mode MOSHEMT with Al$_2$O$_3$ layer. $V_{th}$ of the former was -3 V, while that of the latter was 0 V. Meanwhile, $I_{\text{max}}$ was only reduced from 503 mA/mm to 460 mA/mm, verifying the efficacy of Al$_2$O$_3$ layer as the energy barrier to preserve the 2DEG electron mobility. Secondary ion mass spectrometry measurements confirmed that the F ions were mainly accumulated in the top 5 nm of Al$_2$O$_3$. As a consequence, the concentration in the 2DEG was dropped by an order of magnitude compared to the sample without the Al$_2$O$_3$ buffer [5].

![Fig. 3. Schematic illustration of fabricating bimodal-MOSHEMT in a self-aligned manner, with the last picture showing the $I_d$-$V_{ds}$ curves of thus-fabricated bimodal-MOSHEMT.](image2)

However, when $V_{gs}$ was increased beyond 2 V, significant gate leakage current occurred due to the defects in Al$_2$O$_3$ created by plasma bombardment. To solve this problem, a sputtered-SiO$_2$ layer was added before gate metal deposition, thus creating a bimodal-gate-oxide scheme (Fig. 3). Our previous study has proved that the highly condensed sputtered-SiO$_2$ is very effective in blocking the gate leakage current [3, 4]. And since the SiO$_2$ layer is deposited after plasma treatment, it is not subject to plasma damage. Besides, since we are able to sputter SiO$_2$ at room temperature, the same photolithography step for plasma treatment can be used to pattern SiO$_2$, fulfilling the goal of a self-aligned process. From the $I_d$-$V_{ds}$ curves of the new bimodal-MOSHEMT (Fig. 3), the device swung from $V_{gs}$ of +5 V to 0 V, and was completely pinched-off at 0 V. No leakage current was observed when $V_{gs}$ was increased up to 5 V. Despite of the large $V_{th}$ shift of 3 V, $I_{\text{max}}$ was only decreased by 8% when converting from D-mode (503 mA/mm) to E-mode (462 mA/mm), a better result than what people previously reported in literature [6-9].

CONCLUSIONS

By combining fluoride-based plasma treatment with bimodal-gate-oxide scheme, high-performance GaN-based E-mode MOSHEMTs have been demonstrated. ALD-Al$_2$O$_3$ acted as the energy barrier to prevent deep F ion implantation during subsequent CF$_2$ plasma treatment, therefore preserving the electron mobility in the 2DEG. The gate leakage problem caused by plasma-induced damage to the Al$_2$O$_3$ layer was solved by further adding the highly condensed sputtered-gate-SiO$_2$ in a self-aligned manner. Thus-obtained MOSHEMTs exhibited $V_{th}$ of 0 V, gate swing of 5 V, and $I_{\text{max}}$ of 462 mA/mm, showing that the bimodal-gate-oxide scheme is ideally suited to fabricate GaN-based MOSHEMTs for E-mode operation.

ACKNOWLEDGEMENTS

The MOCVD AlGaN/GaN templates used in this work were provided by Kyungpook National University, Korea for which we are grateful to Prof. Jung-Hee Lee and Mr. Dong-Seok Kim.

REFERENCES