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_2O_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-induce surface damage that increases leakage current in the gate region.

In this study, an Al_2O_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_2O_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 recessed 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_2O_3 film was then deposited on the epilayer by ALD at 300 ℃. 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 ℃ for 10 min as a standard process to partially recover the plasma damage.

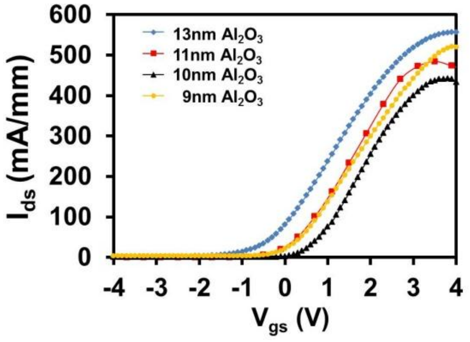

Fig. 1. Transfer characteristics of Al_2O_3/AlGaN/GaN MOSHEMTs with different Al_2O_3 thicknesses but same plasma treatment condition.

RESULTS AND DISCUSSIONS

The MOSHEMT characteristics like I_{max} and V_{th} strongly depend on different processing parameters, including CF_4 plasma treatment condition and Al_2O_3 film thickness. A series of experiments were conducted for recipe optimization. For example, Fig. 1 shows the influence of Al_2O_3 film thickness on the I_d-V_g 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_2O_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.

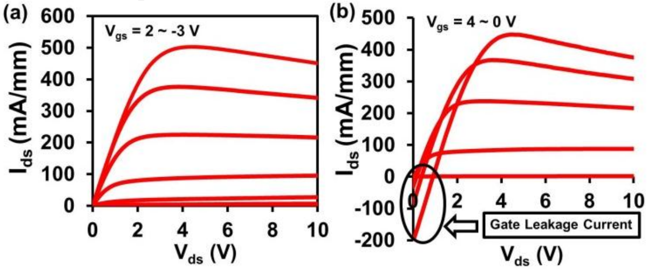

Fig. 2. I_d-V_d curves of (a) the conventional D-mode HEMT, and (b) the E-mode Al_2O_3-MOSHEMT.

Fig. 2 shows the I_d-V_d curves of the conventional D-mode HEMT and the E-mode MOSHEMT with Al_2O_3 layer. V_{th} of the former was -3 V, while that of the latter was 0 V. Meanwhile, I_{max} was only reduced from 503 mA/mm to 460mA/mm, verifying the efficacy of Al_2O_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_2O_3. As a consequence, the concentration in the 2DEG was dropped by an order of magnitude compared to the sample without the Al_2O_3 buffer [5].

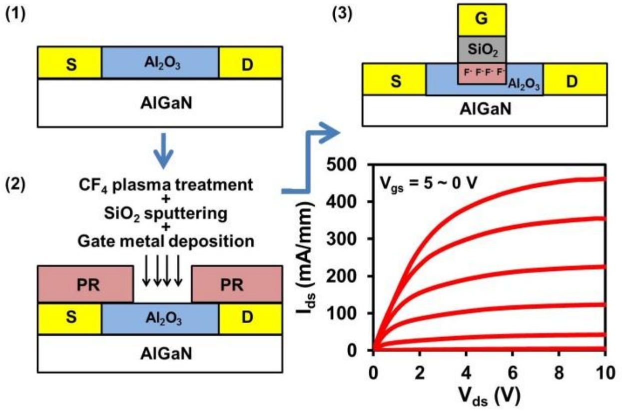

Fig. 3. Schematic illustration of fabricating bimodal-MOSHEMT in a self-aligned manner, with the last picture showing the I_d-V_d curves of thus-fabricated bimodal-MOSHEMT.

However, when V_{gs} was increased beyond 2 V, significant gate leakage current occurred due to the defects in Al_2O_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_d 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_{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_2O_3 acted as the energy barrier to prevent deep F^- ion implantation during subsequent CF_4 plasma treatment, therefore preserving the electron mobility in the 2DEG. The gate leakage problem caused by plasma-induced damage to the Al_2O_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_{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.

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