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

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Abstract

We present high performance E-mode AlGaN/GaN MOSHEMT achieved by Fluoride-based 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 2.56 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 HEMTs and MOSHEMTs are attracting increasing interests. However, the polarization-induced 2DEG causes the usual D-mode operation of such devices. From the application point of view, E-mode transistors are more desirable for circuit simplification, safety issues and low standby power dissipation. Besides, the lack of high-quality GaN *p*-channel FETs makes 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 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 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 ALD was utilized as the energy barrier to prevent deep implantation of F^- ions. Different experimental parameters, like the plasma pressure and 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

AlGaN / GaN HEMT epitaxial structure [16 nm $Al_{0.23}Ga_{0.77}N$ / 2 μm semi-insulating GaN / 30 nm low-temperature GaN buffer on (0001) Al_2O_3 substrate] was used as the starting material. The theoretical V_{th} was calculated to be -1.6 V by using [4]

$$V_{th} = \phi_B - \Delta E_C / e - dP_{total} / \varepsilon \quad (1)$$

where ϕ_B is the Schottky barrier height, ΔE_C is the conduction band discontinuity at the heterojunction, *e* is the elementary charge, P_{total} is the total polarization charge, ε is the dielectric constant, and *d* is the barrier layer thickness. The following parameters are used in the calculation: $\phi_B = 1.24$ eV [5], $\Delta E_C = 0.2$ eV [6], d = 16 nm, and $P_{total} = 8.8 \times 10^{12}$ cm^{-2}. The dielectric constant can be expressed as [7]

$$\varepsilon_{Al_xGa_{1-x}N} = x\varepsilon_{AlN} + (1-x)\varepsilon_{GaN} \quad (2)$$

where $\varepsilon_{AlN} = 8.5$ and $\varepsilon_{GaN} = 10$ [8]. Therefore, for Al content of 23%, the dielectric constant of the barrier is determined to be 9.65.

Device isolation and recessed source/drain etching were first performed on the epi-structure. 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 °C. TMA was used as a source of aluminum, and H_2O vapor was used as a source of oxidant. After that, the gate window was opened by photolithography and CF_4

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plasma treatment was carried out in a RIE chamber. Because of the photoresist protection, F^- ions were only implanted under the gate, which is very important in order to reduce the access resistance. Subsequently, the gate metals (Ni/Au) were deposited in a self-aligned manner. For some samples, before the gate metal deposition, 10-nm-SiO_2 was deposited in the gate region by RF magnetron sputtering using conditions described in [9]. Finally, post-annealing was conducted at 450 ℃ for 10 min to recover the plasma damage. The temperature was chosen as the upper limit at which Ni-Au Schottky metals are compatible with, in order to maximize the damage recovery effect.

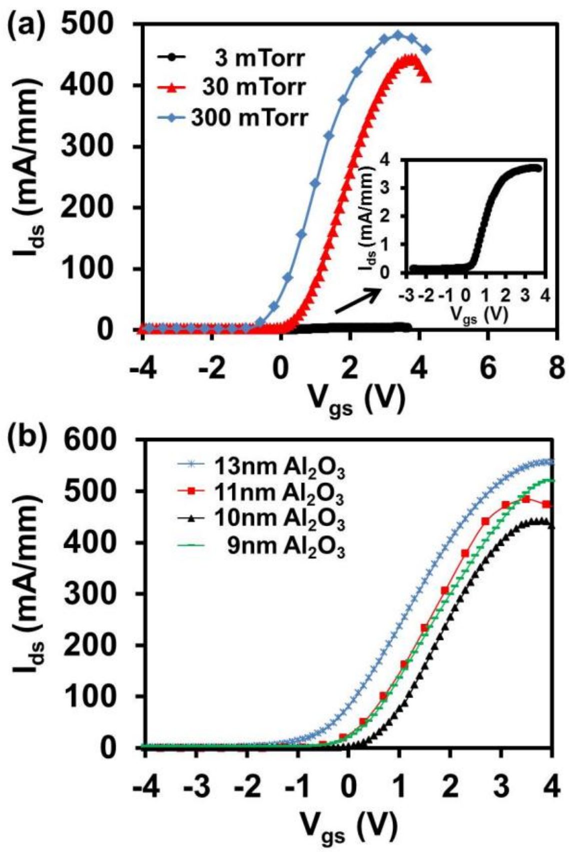

Fig. 1. Transfer characteristics of Al_2O_3/AlGaN/GaN MOSHEMTs with (a) different plasma pressures and (b) different Al_2O_3 thicknesses.

RESULTS AND DISCUSSIONS

The MOSHEMT characteristics like I_{max} and V_{th} strongly depend on different processing parameters. As shown by the transfer characteristics in Fig. 1(a), as the plasma pressure decreased from 300 mTorr to 3 mTorr, higher bombardment energy of F^- ions led to a larger implantation depth. Therefore, the stronger depletion effect positively shifted V_{th}. On the other hand, gradual degradation in I_{max} was also observed as a consequence of more impurity scattering. The influence of Al_2O_3 film thickness on the transfer characteristics is shown in Fig. 1(b). As the film thickness decreased from 13 nm to 10 nm, the F^- ions were closer to the 2DEG, which positively shifted V_{th} by stronger depletion. However, a back shift in V_{th} occurred when further reducing the film thickness to 9 nm. It has been reported that MOSHEMT structures experience an increase in 2DEG concentration with thinner Al_2O_3 layer, which is mainly attributable to the reduction of fixed negative charges inside the oxide [10,11].Therefore, a more negative gate bias is required to completely deplete the 2DEG. The trade-offs of device performance with respect to different experimental conditions were thoroughly investigated until a recipe for optimization was established.

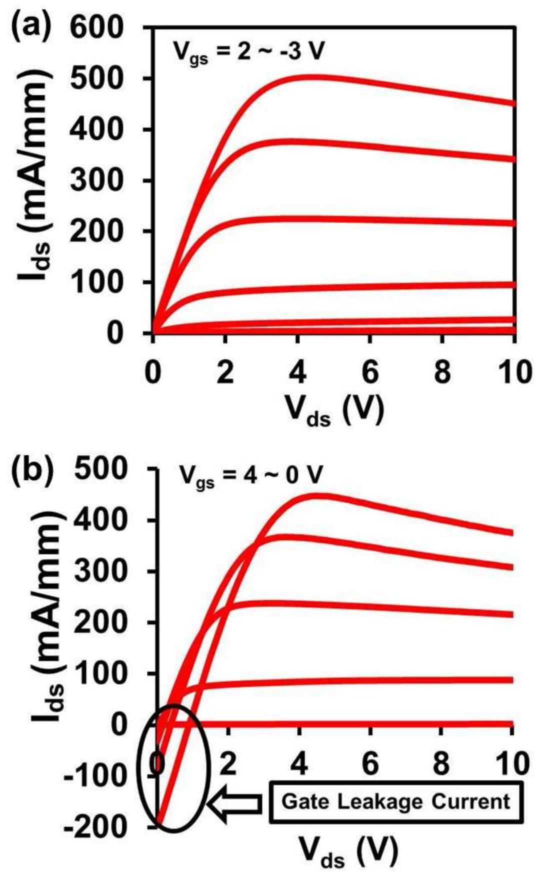

Fig. 2. The I_{ds}-V_{ds} curves of (a) conventional D-mode HEMT, and (b) E-mode MOSHEMT with ALD-Al_2O_3 layer and F^- ions incorporation.

Fig. 2 shows the I_{ds}-V_{ds} curves of the conventional D-mode HEMT and the E-mode MOSHEMT with Al_2O_3 layer. The pinch-off voltage 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. The small degradation in the drain current verifies the efficacy of Al_2O_3 layer as the energy barrier to preserve the 2DEG electron mobility. SIMS was conducted to provide direct evidence of the F^- ion distribution. The samples were subjected to post-annealing at different temperatures for 10 min. Fig. 3 confirms that the F^- ions were mainly accumulated in the top 5 nm of the Al_2O_3 layer. As a consequence, the concentration was dramatically reduced from 10^5 counts at the surface to 10^3 counts at the 2DEG. By comparison, previous results showed that when no Al_2O_3 buffer layer was used, the F^- ion concentration remained as high as 10^4 counts when reaching the 2DEG [12]. The one order of magnitude lower F^- ion density results in much less impurity scattering hence improving the 2DEG properties. Besides, the implanted F^- ions demonstrated good thermal stability up to 700 ℃, rendering the efficacy of thus-fabricated E-mode MOSHEMTs for high-temperature applications.

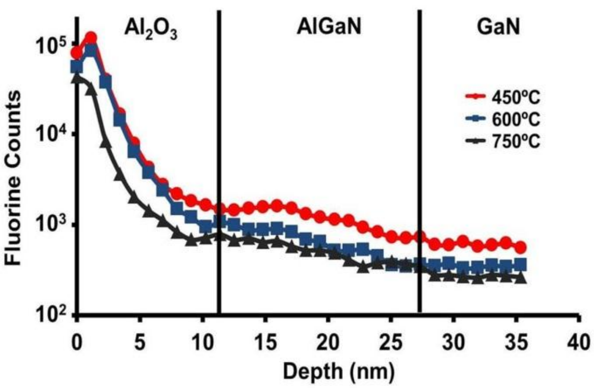

Fig. 3. SIMS measurements of the Fluorine ion distributions after CF_4 plasma treatment and post-annealing at different temperatures for 10 min.

However, when V_{gs} was increased beyond 2 V, significant gate leakage current was observed [(Fig. 2(b)], which was 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. 4). Our previous study has proved that the highly condensed sputtered-SiO_2 is very effective in blocking the gate leakage current [3, 9]. 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_{ds}-V_{ds} curves of the new bimodal-MOSHEMT, the device swung from V_{gs} of +5 V to 0 V, and was completely pinched-off at 0 V.

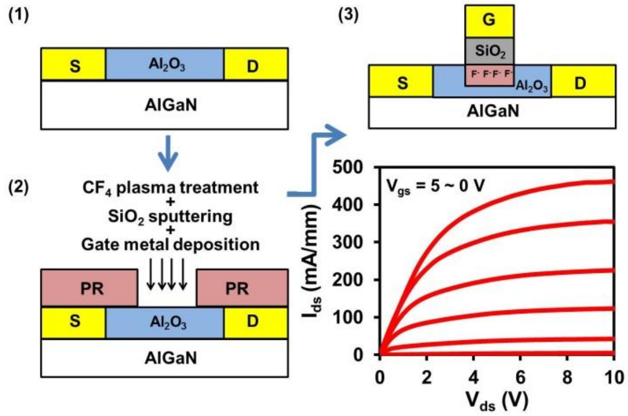

Fig. 4. Schematic illustration of fabricating bimodal-MOSHEMT in a self-aligned manner, with the last picture showing the I_{ds}-V_{ds} curves of thus-fabricated bimodal-MOSHEMT.

No leakage current was observed when V_{gs} was increased up to 5 V. Defining V_{th} as the gate voltage at which the linear extrapolation of I_{DS} intercepts with the V_{GS} axis, the values were extracted to be -1.67 V for D-mode HEMT and 0.89 V for E-mode MOSHEMT. Despite of the large V_{th} shift of 2.56 V, I_{max} was only decreased by 8% when converting from D-mode (503 mA/mm) to E-mode (462 mA/mm), which is a better result than what people previously reported in literature [13-16]. However, one must note that by adding the gate-oxides, there will be degradation in the transistor switching speed due to smaller g_m. The transfer characteristic measurement shows that g_m was reduced from 150 mS / mm of the conventional HEMT to 113 mS / mm of the bimodal-MOSHEMT.

CONCLUSIONS

By combining fluoride-based plasma treatment with bimodal-gate-oxide scheme, high-performance GaN-based E-mode MOSHEMTs have been demonstrated. The 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.

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ACRONYMS

HEMT: high electron mobility transistor
MOS: metal-oxide-semiconductor
2DEG: 2-dimensional electron gas
D/E mode: depletion/enhancement-mode
DCFL: direct-coupled FET logic
V_{th}: threshold voltage
I_{max}: maximum drain current
ALD: atomic layer deposition
TMA: Trimethylaluminum
SIMS: secondary ion mass spectrometry
g_m: transconductance