Unpassivated High Power Deeply Recessed GaN HEMTs With Fluorine-Plasma Surface Treatment

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***Abstract*—In this letter, unpassivated high power deeply recessed GaN-based high electron mobility transistors (HEMTs) are reported. The introduction of a thick graded AlGaN cap layer and a novel fluorine-plasma surface treatment reduced the gate-leakage current and increased breakdown voltage significantly, enabling the application of much higher drain biases. Due to excellent dispersion suppression achieved at an epitaxial level, an output power density of more than 17 W/mm with an associated power added efficiency (PAE) of 50% was measured at 4 GHz and $V_{DS} = 80$ V without SiN_x passivation. These results demonstrate the great potential of this novel epitaxial approach for passivation-free GaN-based HEMTs for high-power applications.**

***Index Terms*—GaN, high electron mobility transistors (HEMTs), microwave power FETs, MODFETs, passivation, RF-dispersion.**

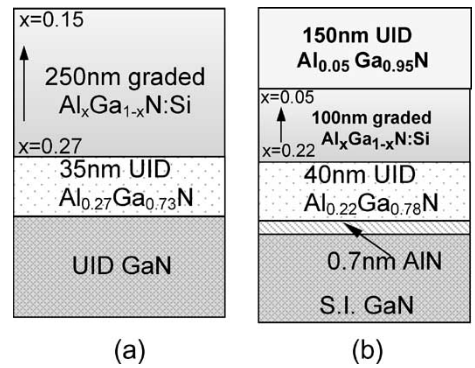

Fig. 1. Epitaxial structures of the improved deeply recessed GaN HEMTs. (a) MBE-grown HEMT, (b) MOCVD-grown HEMT.

I. Introduction

A COMBINATION of high breakdown field, high sheet charge density and high electron velocity gives AlGaN/GaN high electron mobility transistors (HEMTs) a great potential for high-power and high-frequency applications. An output-power density of more than 30 W/mm at 4 GHz and 10.5 W/mm at 40 GHz have been reported [1], [2]. Surface passivation with SiN_x is commonly used to reduce dc-to-RF dispersion, but the reproducibility of the breakdown voltage and gate leakage, and the effectiveness of dispersion elimination is undependable. Alternatively, epitaxial solutions to a dispersion control have demonstrated effective dispersion suppression without SiN_x passivation [3], [4]. One of these approaches, the deeply recessed GaN HEMTs, use a thick epitaxial cap layer to reduce the modulation from the surface to the channel, thus significantly reducing the dispersion caused by surface traps [5]. After the introduction of a thin SiO_2 layer on the sidewall of the gate recess to reduce the gate leakage current and increase the breakdown voltage, the unpassivated deeply recessed thick-GaN-capped HEMTs showed a very promising power of 12 W/mm at 4 and 10 GHz [6]. However, the introduction of the SiO_2 is undesirable for long-term stability because of electron trapping in the SiO_2 caused by the high electric field. In this paper, we propose a novel epitaxial structure and a processing technology to solve the problem. A thick AlGaN cap layer, instead of the GaN cap used previously, combined with a novel fluorine-plasma surface treatment, is shown to dramatically decreased the gate leakage current and increased the breakdown voltage. The new devices achieved excellent microwave power performance without SiN_x passivation.

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II. Device Structure and Fabrication

The new epitaxial design utilizes a thick AlGaN cap, instead of a GaN cap. The higher Shottky barrier of the gate on AlGaN as compared to GaN was expected to reduce the gate-leakage current and increase the low breakdown. Two different device structures were studied in this paper, one grown by metal–organic chemical vapor deposition (MOCVD) and one grown by an RF plasma-assisted molecular beam epitaxy (MBE) on SiC substrates. Sample A grown by MBE [Fig. 1(a)] consisted of a $\sim$ 40 nm AlN nucleation layer and a 0.7-μm thick, carbon-free GaN buffer. The structure was capped with 35 nm of unintentionally doped (UID) $Al_{0.27}Ga_{0.73}N$ followed by 250 nm of $Al_xGa_{1-x}N$, which was graded downwards from $x = 0.27$ to $x = 0.15$ and doped by Si at 3×10^{17} cm^{-3}. The MBE growth was optimized for low buffer leakage utilizing N-rich growth conditions for the AlN nucleation [7]. Sample B grown by MOCVD [Fig. 1(b)] has a slightly different epitaxial structure. It consisted of a semi-insulating Fe-doped GaN buffer layer, followed by a 0.7-nm AlN interfacial layer, a 40-nm

$Al_{0.22}Ga_{0.78}N$ layer, a 100-nm graded-downwards $Al_xGa_{1-x}N$ layer ($x = 0.22$ to 0.05) doped by Si at 8×10^{17} cm^{-3}, and finally a 150-nm UID $Al_{0.05}Ga_{0.95}N$ cap layer. The thickness of the cap layer is limited by the thermal stress, which is larger in sample B due to the higher growth temperature of MOCVD, therefore a thinner graded AlGaN layer followed by a low-Al composition bulk AlGaN layer was grown to avoid cracking upon cool-down. This structure lowers the total Al content in the cap relative to a uniformly graded cap. Both structures exhibited the root-mean-square (rms) surface roughness of about 0.8 nm measured by atomic force microscopy (AFM).

The processing flow was similar to that in [2] with the exception of an additional fluorine-plasma treatment of the sample surface between the gate recess and gate metallization. Recently, it was reported that a fluorine-based plasma treatment could be used to change the sheet charge density to form enhancement-mode GaN HEMTs [8], [9]. Further experiments showed that the depletion of the two-dimensional electron gas (2DEG) decreased with the reduced plasma power [10], which made this technology also useful for depletion-mode devices. In this paper, the fluorine plasma conditions employed were optimized to reduce gate leakage current and increase breakdown voltage with a minimal change of the 2DEG density, i.e., the threshold-voltage shift is negligible. A systematic study of the fluorine-based plasma treatment on AlGaN/GaN HEMTs will be published separately [10]. The fluorine-plasma surface treatment was done in a reactive ion etch (RIE) machine. A CF_4/O_2 (20 and 2 sccm, respectively) chemistry at low chamber pressure of 3 mT was used for the plasma. The relatively low dc voltage of 100 V was chosen so that the depletion of the 2DEGs was minimal. The plasma surface treatment time is 10 min. The devices had gate length of 0.6 μm and gate width of 150 μm (2×75 μm). Gate-source and gate-drain spacing were 0.7 and 3 μm, respectively.

III. Device Performance

The typical maximum current ($I_{\max}$) at $V_{GS} = 1$ V was about 1.2 A/mm for sample A and pinchoff voltage was approximately -6 V. The $I_{\max}$ of sample B was lower, about 1 A/mm, due to a slightly lower 2DEG density. These values were comparable to those of devices without fluorine-plasma surface treatment, indicating the depletion of the 2DEGs by the low-power plasma treatment was negligible.

The improvement of the gate leakage current and breakdown voltage in structures with an improved epitaxial design and processing technology was substantial. The two-terminal gate-drain leakage currents of different structures are shown in Fig. 2. With the graded AlGaN cap without fluorine exposure, the gate leakage was reduced more than one order of the magnitude as compared to the GaN cap sample, from about 20 to about 1.4 mA/mm at 30 V for both samples A and B, reflecting the higher Schottky barrier height on AlGaN. The two-terminal gate–drain destructive breakdown voltage also increased from 35 V to more than 120 V. The performance was further improved after the fluorine-plasma surface treatment. The two-terminal gate leakage currents at 30 V were reduced to 50 and 5 μA/mm for samples A and B, respectively. The destructive breakdown voltage in both structures also increased to about 200 V. The improved breakdown voltage allows much higher drain bias, thus much higher output power density. The low gate leakage current is also critical for a long-term reliability.

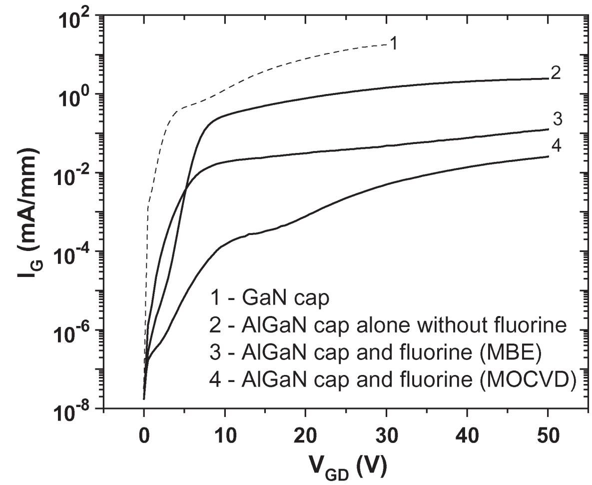

Fig. 2. Comparison of two-terminal gate-drain leakage currents of different epitaxial structures and surface treatment.

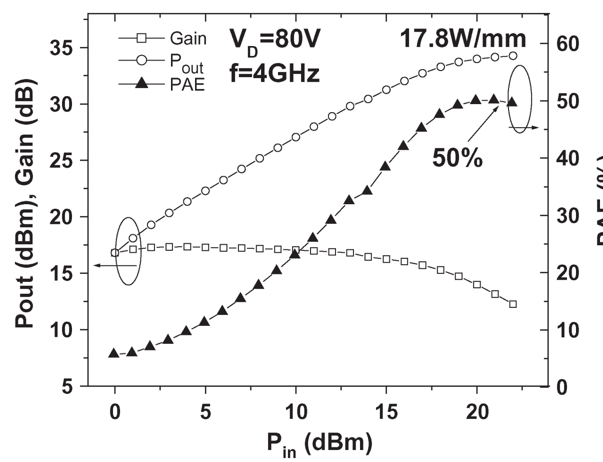

Fig. 3. Power performance of MOCVD-grown unpassivated 0.7 μm $\times$ 150 μm deeply recessed GaN HEMTs on SiC substrate at 4 GHz. An output-power density of 17.8 W/mm with an associated PAE of 50.5% at $V_D = 80$ V and $I_D = 60$ mA/mm.

Uncooled continuous-wave (CW) power measurements were performed using a Maury loadpull system. Both samples demonstrated excellent power performance without any surface passivation. The dispersion suppression by the thick AlGaN cap was successful, as indicated by the good output power density and power-added efficiency (PAE). At 4 GHz, an output power density of 5.5W/mm with a very high PAE of 74% was obtained from sample B when biased at $V_{DS} = 30$ V and $I_{DS} =$ 60 mA/mm. Sample A exhibited 5.5 W/mm with a PAE of 68% at the same bias conditions. The significant improvement in breakdown voltage due to both the thick AlGaN cap and the fluorine-plasma surface treatment enabled the devices to operate at much higher drain biases. Fig. 3 shows the 4-GHz power performance of the MOCVD-grown HEMT at $V_{DS} = 80$ V. An output power density as high as 17.8 W/mm with a PAE

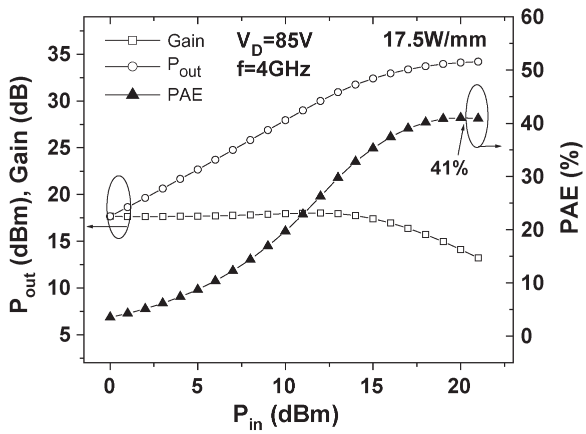

Fig. 4. Power performance of MBE-grown unpassivated $0.7\ \mu\text{m} \times 150\ \mu\text{m}$ deeply recessed GaN HEMTs on SiC substrate at 4 GHz. An output-power density of 17.5 W/mm with an associated PAE of 41% at $V_D = 85$ V and $I_D = 60$ mA/mm.

of 50% was achieved. The MBE-grown HEMT had an output power density of 17.5 W/mm with a PAE of 41% at $V_{\rm DS} = 85$ V, as shown in Fig. 4. The lower PAEs at higher biases for both samples is due to both the limited matching range of the loadpull system and some current dispersion due to the limited thickness of the cap layer. A thicker cap layer is expected to have better dispersion control at higher bias conditions due to the smaller modulation from the surface to the channel. The devices reported here achieved record output power density in unpassivated MOCVD and MBE-grown GaN HEMTs. Moreover, the power performance was also superior to that of the SiN_x-passivated GaN HEMTs without field plates. Power performance was also measured at 10 GHz. Both samples A and B delivered about 11 W/mm with a PAE of more than 50% at $V_{\rm DS} = 48$ V.

A preliminary study of RF stability was also done on the unpassivated MOCVD-grown HEMT (sample B). The device was biased at $V_{\rm DS} = 28$ V and an RF stress of 2 dB compression was applied for 20 h at 200 °C. No power degradation was observed. In addition, no drop of drain current was observed, while the gate-leakage current only slightly increased.

IV. Conclusion

Excellent power performance was demonstrated in deeply recessed GaN HEMTs with the improved epitaxial design and processing technology. The combination of a novel fluorine-plasma surface treatment and a thick graded AlGaN cap yielded a decrease in the gate leakage current by two to three orders of the magnitude and an increase in destructive breakdown voltage to about 200 V. An output power density of 17.8 W/mm with a PAE of 50% was achieved without SiN_x passivation in an MOCVD-grown deeply recessed HEMT. A similar structure grown by MBE exhibited and output power density of 17.5 W/mm with a PAE of 41%. These devices exhibited record power performance among unpassivated GaN HEMTs and demonstrated the great potential of this novel epitaxial technique as a controllable and reproducible solution for dispersion suppression with no surface passivation.

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