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Dynamic Characterizations of AlGaN-GaN HEMTs with Field-plates using a Double-gate Structure

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Abstract

A novel double gate AlGaN/GaN HEMT, in which an additional top-gate covers the adjacent regions of normal gate, was proposed and fabricated for the first time to compare the dynamic characteristics of AlGaN/GaN HEMTs with source field plate(SFP) and gate field plate(GFP). During the dynamic characterization, the device was configured in two operation modes, one is the source-field-plate mode (SFP-mode) with the top gate biased at 0V, another is the gate-field-plate mode (GFP-mode) with applying the gate pulse signal on the top gate at the same time. Compared to an AlGaN/GaN HEMT without field plates, both GFP and SFP much improve the dynamic performances. Compared to SFP, the GFP shows better dynamic performances with a ~34% reduction of switch-on delay time and ~6% reduction of dynamic on-resistance. By study of the dynamic characteristics with applying negative voltage on the top gate during off-state, the mechanism differences between GFP and SFP are discussed in detail.

Full Text

Dynamic Characterizations of AlGaN/GaN HEMTs with Field-Plates Using a Double-Gate Structure

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Abstract– A novel double-gate AlGaN/GaN HEMT, in which an additional top-gate covers the adjacent regions of the normal gate, was proposed and fabricated for the first time to compare the dynamic characteristics of AlGaN/GaN

HEMTs with source field plate (SFP) and gate field plate (GFP). During dynamic characterization, the device was configured in two operation modes: one is the source-field-plate mode (SFP-mode) with the top gate biased at 0 V, and the other is the gate-field-plate mode (GFP-mode) with the gate pulse signal applied to the top gate simultaneously. Compared to an AlGaN/GaN HEMT without field plates, both GFP and SFP significantly improve dynamic performance. Compared to SFP, GFP demonstrates superior dynamic performance with approximately 34% reduction in switch-on delay time and 6% reduction in dynamic on-resistance. The mechanism differences between GFP and SFP are discussed in detail through studies of dynamic characteristics with negative voltage applied to the top gate during the off-state.

Index Terms– AlGaN/GaN high electron mobility transistor (HEMT), dynamic performance, power device

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I. Introduction

AlGaN/GaN HEMTs have successfully demonstrated promising potential in high-frequency and power electronics applications [?][?]. However, the current collapse effect is detrimental to HEMT performance, with trap states in the bulk and/or surface of the material playing important roles due to virtual gate effects [?][?]. For high-voltage AlGaN/GaN HEMTs operating in switching mode, the current collapse effect in dynamic performance always results in degradation—specifically, longer switch-on delay time and higher dynamic ON-resistance [?][?] —which increases power consumption in electrical energy conversion systems where GaN-based power devices are considered the most promising candidates [?][?].

Field plates (FPs), including source field plate (SFP) [?][?], gate field plate (GFP), and multi-field-plate (MFP) [?][?], have demonstrated effectiveness in improving dynamic performance in AlGaN/GaN HEMTs, showing lower dynamic ON-resistance. However, no direct comparison has been made between SFP and GFP, and the mechanism differences underlying dynamic performance improvement between SFP and GFP have not been explicitly distinguished thus far.

In this study, a novel double-gate AlGaN/GaN HEMT (DG-HEMT) was proposed and fabricated for the first time to investigate the effects of SFP and GFP on dynamic characteristics. In this new device structure, an additional top-gate electrode covers the normal gate and extends toward the source and drain electrodes with overhangs, as shown in Fig. 1(a). According to their directions (pointing to source or drain), the overhang lengths are expressed as L_{TS} and L_{TD}, respectively. Thus, the gate-adjacent regions, where charging and discharging usually occur, are under the control of the top-gate. When pulse dynamic characterization is carried out, an additional pulse signal is applied to the top-gate. If this additional signal is biased constantly at 0 V, the device' s

operation mode is equivalent to that with SFP (SFP-mode). Conversely, if this additional signal is identical to that applied to the normal gate, the device' s operation mode is equivalent to that with GFP (GFP-mode). Consequently, more information regarding dynamic performance can be obtained from the same AlGaN/GaN HEMT, allowing us to directly compare the effects of SFP and GFP on dynamic characteristics and further distinguish the mechanism differences between them.

II. Device Fabrication

In this work, the AlGaN/GaN heterostructure was grown on a 2-inch (0001) sapphire substrate using metal-organic chemical vapor deposition (MOCVD). The epitaxial structure consists of a 2- m-thick GaN buffer layer, a 1.0-nm-thick AlN spacer, and a 30-nm-thick $Al_{0.3}Ga_{0.7}N$ barrier layer. Hall measurement results show a 2DEG density of 1.44×10^{13} cm^{-2} and an electron mobility of 1080 $cm^2/V \cdot s$, yielding a sheet resistance of 400 Ω/ .

The device fabrication process began with mesa isolation using Cl_2/BCl_3-plasma-based dry etching. Next, source/drain ohmic contacts were formed by depositing Ti/Al/Ni/Au (20 nm/160 nm/50 nm/100 nm) metal stacks, followed by annealing at 850 °C for 30 s in an N_2 atmosphere. The contact resistance of approximately 0.7 $\Omega \cdot mm$ was derived from measurements of linear Transmission Line Method (TLM) patterns. The gate was then formed by depositing Ni/Au (50 nm/200 nm) and lift-off. A dielectric layer of 165 nm SiN was deposited at 350 °C in a PECVD system. The top-gate electrode was formed using the same processes as the normal gate. Finally, electrode pads were opened by RIE dry etching of the SiN layer. The gate-source spacing is 5 m, the gate-drain spacing is 12 m, and the gate width and length are 100 m and 2 m, respectively. Fig. 1(b) shows the optical microscopy image of the fabricated DG-HEMT with L_{TS} of 2 m and L_{TD} of 4 m, respectively. For comparison, normal AlGaN/GaN HEMTs with identical geometries were fabricated on the same wafer simultaneously.

III. Device Characteristics and Discussion

The two device types—normal HEMT and DG-HEMT—exhibit almost identical DC characteristics. Typical DC characteristics are shown in Fig. 2, measured in the DG-HEMT with the top-gate floating. The threshold voltage (V_{th}) is approximately -3.4 V, and the drain current is approximately 34 mA at $V_G = 1$ V, $V_D = 10$ V.

On-wafer dynamic tests were conducted using a DC probe station. The testing circuit is schematically shown in Fig. 3. The load resistor (R_d) of 20 kΩ was chosen such that the drain current at switch-on state (~10 mA) is approximately

one-third of the maximum output current (~34 mA at $V_G = 1$ V). The power supply was set at 200 V. The circuit parasitic capacitance C_L of 106 pF was extracted from the rising edge of the drain output voltage waveform. The drain output voltage (V_o), gate input signal (V_G), and top-gate input signal (V_{TG}) were recorded by an oscilloscope. During dynamic testing, two operation modes –SFP-mode and GFP-mode–were characterized. To explicitly understand the effects of GFP on dynamic performance, the dynamic performance of the device driven in another mode where the top-gate was applied with different negative voltages during the off-state was also investigated.

[Figure 3: see original paper] Schematic diagram of the dynamic testing system.

In Fig. 4, the drain output voltage (V_o) waveforms of a DG-HEMT operating in SFP-mode and GFP-mode are compared with that of a normal HEMT. The falling delay time (τ_{fd}) is defined as the interval from the beginning of gate switch-on (t_0) to t_d when V_o drops to 90% of the V_o peak-to-peak value. The dynamic ON-resistance (R_{on_D}) is defined as the average resistance from t_d to the next switch-off time (t_1). The normal HEMT without FPs exhibits serious dynamic performance degradation with a longer τ_{fd} (2.75 s) and a higher R_{on_D} (2916 Ω). In contrast, τ_{fd} and R_{on_D} are 1.6 s and 500 Ω for SFP-mode, and 1.05 s and 470 Ω for GFP-mode, indicating that field plates significantly improve the dynamic performance of AlGaN/GaN HEMTs. Moreover, the dynamic performance of GFP-mode is superior to that of SFP-mode, with approximately 34% reduction in τ_{fd} and 6% reduction in R_{on_D}.

[Figure 1: see original paper] (a) Schematic cross-sectional diagram of a double-gate AlGaN/GaN HEMT (DG-HEMT), (b) The optical image of the DG-HEMT.

In AlGaN/GaN HEMTs, the peak electric field usually locates under the drain-side gate edge; the higher the peak electric field, the more charges are trapped in the regions adjacent to the gate electrode during the off-state. Field plates, both SFP and GFP, can effectively suppress the peak electric field by leveling the electric-field distribution underneath the gate electrodes [?][?], thereby reducing the amount of trapped charges. As a result, dynamic performance can be significantly improved.

It can be observed that for the device operating in GFP-mode, when the device is switched on by applying a positive pulse voltage (+1 V) to the gate, the GFP is also positively biased. Although the trapped negative charges cannot be released rapidly, more electrons can be induced immediately by the positive voltage at the GFP, which partly compensates for the 2DEG loss caused by negative charges trapped at the interface or in the barrier layer, thus improving device dynamic performance.

Is this positive-voltage-induced 2DEG compensation sufficient to account for the total improvement in dynamic performance? To clarify this, another dynamic test was conducted in which the top-gate was applied with different negative

voltages (from -5 V to -15 V) during the off-state while being maintained at 0 V during the on-state.

[Figure 4: see original paper] Input pulse signals and drain output voltage (V_o) waveforms of a DG-HEMT working at SFP-mode, GFP-mode and a normal-HEMT.

Table 1 lists the τ_{fd} and R_{on_D} measured at different off-state top-gate voltages. It can be observed that dynamic performance improves as the off-state top-gate voltage decreases (becomes more negative). During the off-state, a negative voltage applied to the top-gate induces an upward electric field that blocks electrons from moving upward to the barrier layer and interface. Consequently, fewer negative charges are trapped in those regions during the off-state, resulting in shorter τ_{fd} and lower R_{on_D}. This mechanism also accounts for the superior dynamic characteristics of GFP since the GFP is negatively biased during the off-state.

Table 1. τ_{fd} and R_{on_D} vs. Off-state top-gate voltage $V_{TG-off-state}$

$V_{TG-off-state}$ (V)	τ_{fd} (s)	R_{on_D} (Ω)

IV. Conclusion

A novel AlGaN/GaN DG-HEMT was used to investigate the dynamic performance of devices with SFP and GFP. Devices with field plates exhibit superior dynamic performance compared to those without field plates. Furthermore, GFP improves dynamic performance more than SFP does, which is explained by two mechanisms: one is 2DEG compensation during the on-state, and the other is reduced negative charge trapping during the off-state.

V. Acknowledgment

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