Characteristics in AlN/AlGaN/GaN Multilayer-Structured High-Electron-Mobility Transistors

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A new multilayer-structured AlN/AlGaN/GaN heterostructure high-electron-mobility transistor (HEMT) is demonstrated. The AlN/AlGaN/GaN HEMT exhibits the maximum drain current density of 800 mA/mm and the maximum extrinsic transconductance of 170 mS/mm. Due to the increase of the distance between the gate and the two-dimensional electron-gas channel, the threshold voltage shifts slightly to the negative. The reduced drain current collapse and higher breakdown voltage are observed on this AlN/AlGaN/GaN HEMT. The current gain cut-off frequency and the maximum frequency of oscillation are 18.5 GHz and 29.0 GHz, respectively.


The AlGaN/GaN heterostructure high-electron-mobility transistors (HEMTs) have great potential for high voltage, current, and power device applications due to its inherent wide band-gaps, high electron saturation velocity, and piezoelectric field-induced high two-dimensional electron-gas (2DEG) density at hetero-interface.[1–8] Many studies have been carried out to improve the power and high frequency characteristics of the nitride-based HEMTs.[9] However, many GaN-based power HEMTs suffer from current collapse during a large signal operation at high frequency, usually referred to as the “dc-to-rf dispersion”. The slow response of surface traps is believed to be one of the major contributing factors.[4] Recently, solutions to the dispersion problem have been addressed at epitaxial level.[2,3] The development of GaN/AlGaN/GaN HEMTs is one of these efforts, whereas the maximum drain bias that could be applied to these devices during power measurements was limited by high gate leakage and low breakdown voltage. A reduction in gate leakage and an increase in breakdown voltage are needed to obtain higher power. In this Letter, we propose a new structured AlN/AlGaN/GaN HEMT, which is able to solve the dispersion problem well and to increase the breakdown voltage obviously.

In this work, a multilayer AlN/AlGaN/GaN material was grown by metal organic chemical vapor deposition (MOCVD) on a sapphire substrate. The respective Ga, N, and Al precursors were trimethylgallium (TMG), ammonia (NH3), and trimethylaluminum (TMAI). Hydrogen (H2) was used as the carrier gas. The thicknesses of unintentional doped AlGaN and GaN were 25 nm and 1.2 µm respectively, and the Al composition of the AlGaN layer was 30%. The structure is finished with a 2-nm unintentionally doped AlN cap layer. For comparison, a separate structure was grown without the 2 nm i-AlN cap layer and subjected to the HEMT device processing simultaneously.

The AlN/AlGaN/GaN (device A) and the AlGaN/GaN (device B) HEMTs were fabricated by depositing a Ti/Al/Ni/Au metal stack for the ohmic contacts followed by annealing at 860°C for 30 s in an N2 atmosphere. Then, Cl2/BCl3 plasma was used for the mesa isolation. Subsequently, the Ni/Al/Ni Schottky contacts were defined in the transistors (0.5 µm gate length). The devices were passivated by Si3N4 lastly and all the measurements were performed at room temperature (295 K).

Figure 1(a) shows the distribution of carrier concentration, and we find the 2DEG concentrations of devices A and B are $1.02 \times 10^{13} \text{cm}^{-2}$ and $1.05 \times 10^{13} \text{cm}^{-2}$, respectively. This indicates that an ultra-thin AlN cap does not affect the concentration of the 2DEG. However, we find the location of channel drift 1.2 nm toward the barrier side in the AlN/AlGaN/GaN HEMT compared with the AlGaN/GaN HEMT. Although the centroid of the 2DEG is in the binary material GaN, there is a penetration of the wavefunction into the ternary AlGaN barrier. The shift of wavefunction towards to the interface can partially explain the decrease of mobility. The deeper penetration implies more alloy disorder scattering. Hall measurement results also show that the mobility in device A is 900 cm2/Vs and the mobility of device B is 1400 cm2/Vs. Therefore, the product of mobility and concentrations of 2DEG in device A is slightly higher than that of device B. Figure 1(b) shows the $I_D-S-V_D$ curves with gate bias from $V_G = -6 \text{V}$ to $V_G = 0 \text{V}$ with step of 2 V. The knee voltage $V_{\text{knee}}$ of device A is slightly higher than device B, two reasons attribute to the higher $V_{\text{knee}}$. On the one hand,
the AlN cap layer under the ohmic contact increases the ohmic contact resistance. On the other hand, the sheet resistance of device A is higher than device B due to the lower mobility.[4]

![Image](image_url)

**Fig. 1.** (a) Apparent carrier concentration vs penetration depth of the AlN/AlGaN/GaN HEMT and the AlGaN/GaN HEMT measured by \( C − V \) profiling technique. (b) Direct-current characteristics for the AlN/AlGaN/GaN HEMTs and AlGaN/GaN HEMTs.

**Fig. 2.** Transfer curve for devices A and B.

Figure 2 shows the transconductance \( g_m \) versus the gate voltage \( V_G \) with \( V_D = 10 \) V. The max \( g_m \) of device A (170 ms/mm) is lightly lower than device B (197 ms/mm). The threshold voltage of device A (−5.0 V) is higher than device B (−3.2 V), because the AlN/AlGaN/GaN structure can increase the distance between the gate and the 2DEG channel, which reduces the ability of gate control to the 2DEG channel.[4] The saturation drain currents at \( V_G = 2 \) V are typically 730 mA/mm and 800 mA/mm for devices B and A, respectively. There is about 9.6% drain current increase, which indicates an effective passivation of traps by the AlN cap layer between the source and the drain. For device A, it increases the distance between the channel and the gate electrode by adding the AlN layer. Therefore, it reduces the control of gate to the 2DEG, leading to an increase of \( V_{knee} \) and decrease of \( g_m \).

In Fig. 3, we give the two terminal gate-drain \( I − V \) characteristics of devices A and B. When the same gate-drain voltage \( V_{GD} \) is applied in devices A and B, the breakdown voltage of drain voltage \( V_{BDS} \) and the breakdown drain-gate voltage \( V_{BDG} \) of device A are 84.4 V and 94.4 V. However, the breakdown voltages \( V_{BDS} \) and \( V_{BDG} \) of device B are 61.3 V and 71.3 V. This indicates that the AlN cap, which can decrease the strength of electric field,[6] can effectively improve the breakdown voltage.

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**Fig. 3.** Illustration of drain-current injection technique on (a) the AlN/AlGaN/GaN HEMT (b) the AlGaN/GaN HEMT.

For the evaluation of drain current \( I_D \) collapse behavior, pulsed \( I_{DS} − V_{DS} \) measurements (pulse width 500 ms, pulse period 1 ms) were carried out with different quiescent voltages.[7] First, the pulse voltages were applied by varying gate quiescent voltages (\( V_{GS0} = −22.5 \text{ V}, V_{STEP} = −4.5 \text{ V} \)) for a fixed drain quiescent voltage (\( V_{DS0} = 0 \text{ V} \)), then by varying drain quiescent voltages (\( V_{DS0} = 0 \sim 15 \text{ V}, V_{STEP} = 5 \text{ V} \)) for a fixed gate quiescent voltage (\( V_{GS0} = 0 \text{ V} \)).

When varying gate quiescent voltages for a fixed...
drain quiescent voltage, the surface states in device B act as electron traps located in the access regions between the gate and the drain. The trapped electrons deplete the 2DEG in the access regions of the device,\[8] thereby limiting the current. However, in device A the surface states are obviously reduced by the passivation of the AlN cap layer, therefore the impact of dispersion effects would be effectively reduced by screening the channel 2DEG from surface states. When varying drain quiescent voltages for a fixed gate quiescent voltage, the deep related traps (in bulk/buffer) are responsible for the depletion of 2DEG followed by \(I_D\) collapse. Figure 4 shows normalized \(I_D\) of devices A and B. It is clear that device B suffers severely from \(I_D\) collapse due to the surface and bulk related traps. Compared to device B, about 15% and 12% of \(I_D\) collapse suppression in device A are observed when voltages (\(V_{\text{GSO}} = -22.5\) V, \(V_{\text{DS0}} = 0\) V) and (\(V_{\text{GSO}} = 15\) V, \(V_{\text{GSS0}} = 0\) V) are applied. Thence, the \(I_D\) collapse related surface traps are effectively reduced by the AlN cap layer, the remaining \(I_D\) collapse of 30% may have influenced by bulk/buffer related traps.

The S-parameter measurements were performed for devices A and B. In Fig. 5, the corresponding current gain (\(|h21|\)), the maximum stable gain (MSG), and the maximum available gain (MAG) are given from the S-parameter measurements as a function of frequency\[9] for device A. The current gain cut-off frequency \(f_t\) and maximum frequency of oscillation \(f_{\text{max}}\) in device A are 18.5 and 29 GHz, however, in device B they are 19.6 and 37 GHz, as shown in Fig. 5. Here \(f_t = \nu_{\text{eff}}/2\pi L_g\) with \(\nu_{\text{eff}}\) being an effective velocity and \(L_g\) being the gate length. The AlN cap layer does not make the effective velocity reduce. Therefore, the \(f_t\) value of devices A and B are nearly the same. Here

\[
f_{\text{max}} = f_t/2((R_g + R_s + R_{gs})/R_{ds} + 2\pi f_t R_g C_{gd})^{0.5}
\]

with \(R_g\) and \(R_s\) being the gate resistance and the source resistance, \(R_{gs}\) and \(R_{ds}\) the gate-source resistance and drain-source resistance, and \(C_{gd}\) the gate-drain capacitance. The increase of resistance causes a sharp reduction of \(f_{\text{max}}\) in the AlN/AlGaN/GaN HEMT.

In summary, effects of an AlN cap layer in dc and ac Characteristics have been studied. In device A (with the AlN cap layer), the maximum drain current density \(I_{\text{Dmax}}\) at \(V_{\text{GS}} = 2\) V and the breakdown voltage are obviously higher than device B (without the AlN cap layer), but the maximum \(f_{\text{max}}\) is slightly lower than device B due to the increasing distance between the gate and the 2DEG channel. The \(I_D\) collapse suppression in device A is observed because the AlN cap layer can reduce the density of surface traps and screen the channel 2DEG from surface states. The \(f_t\) and \(f_{\text{max}}\) values in the AlN/AlGaN/GaN HEMT are 18.5 GHz and 29.0 GHz, respectively.

References