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A novel multi-threshold coupling InAlN/GaN double-channel HEMT for improving transconductance flatness

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GaN-based HEMTs have significant advantages, making them a prime choice for high-frequency, high-power switching [1]. However, the inherent poor linearity of GaN HEMT has yet to be solved, which can be reflected by the nonlinearity of the transconductance ($G_{\rm m}$) profile [2]. This makes it hard to achieve high data transmission efficiency and less signal distortion in the wireless communication system [3].

It is known that the $G_{\rm m}$ profile of the DC (double channel) HEMTs owes double $G_{\rm m\text{-}max}$ features, demonstrating that it is possible to realize $G_{\rm m}$ flatter in a wide gate voltage ($V_{\rm gs}$) range [4]. However, the thickness of barriers ($T_{\rm bar}$) and channel-to-channel distance ($d_{\rm c\text{-}c}$) is too large to form a close coupling between the channels of the device, making the difference between the peaks so large that limits the transconductance flatness.

In this study, a novel multi-threshold coupling InAlN/GaN DC HEMT (MC-DC HEMT) has been proposed. The fabricated device shows the gate voltage swing (GVS) amplitude of 7.8 V and $G_{\rm m\text{-}max}$ of 216.3 mS/mm. Also, the current gain cutoff frequency ($f_{\rm T}$) and maximum oscillation frequency ($f_{\rm max}$) keep constant 34 and 72 GHz in a wider gate voltage bias, and an exceptional linearity performance with the (output third-order intercept point) $\rm OIP_3$ of 38 dBm, an improvement of 10 dBm compared with the reference device.

Experiment. The structure of the MC-DC HEMT investigated is shown in Figures 1(a)–(d). The InAlN DC structure whose $T_{\rm bar}$ is 8 nm and $d_{\rm c\text{-}c}$ is 18 nm was grown on SiC substrate. For the details of device fabrication see Appendix A.

Result and discussion. The optimal structural parameters of the MC-DC HEMT (see Appendixes B and C) are $W_{\rm R} = 0.2$ μm, $H_{\rm R} = 18$ nm, and $\alpha = 0.8$.

Figure 1(h) demonstrates that the $G_{\rm m\text{-}max}$ of the MC-DC HEMT, compared with that of planar HEMT, is reduced. But GVS reaches a maximum amplitude of 7.8 V. And the threshold voltage ($V_{\rm th}$) drifted positive to −9.3 V, and the maximum drain current density ($I_{\rm d\text{-}max}$) is 1622 mA/mm, as shown in Figure 1(i). It is known that when the power amplifier enlarges an input signal of frequency f, the base wave output signal and $G_{\rm m}$ are positively correlated, while the harmonic outputs at frequencies $2f$ and $3f$ are also positively correlated with the first and second-order derivatives of $G_{\rm m}$ [2]. Figures 1(j) and (k) show that the derivatives of $G_{\rm m}$ of the MC-DC HEMT improve slightly in the transition region from the subthreshold to the peak value. In the linear increase region, the $G_{\rm m}$ profile of the MC-DC HEMT is much flatter, thus suppressing the undesired harmonic component. The results show that the MC structure effectively improves the transconductance flatness, and Figure 1(l) shows its advantage in device-level linearization technology.

To characterize the small-signal performance of the MC-DC HEMT. As shown in Figures 1(m)–(o), the maximum $f_{\rm T}/f_{\rm max}$ for MC-DC HEMTs is 34/72 GHz, and also, $f_{\rm T}$ and $f_{\rm max}$ maintain constant over a very wide gate voltage range of GVS over 7 V.

The two-tone characteristic of the MC-DC HEMT of $\rm OIP_3$ is 38 dBm, corresponding to the input third-order intercept point ($\rm IIP_3$) of 27 dBm. This result shows a good agreement with the flatter $G_{\rm m}$ curve, and the $G'_{\rm m}$, $G''_{\rm m}$ of the MC-DC HEMT are closer to zero over a wide range of $V_{\rm gs}$, effectively suppressing harmonics and $\rm OIP_3$ degradation, making MC-DC HEMT a competitive candidate in realizing high linearity at high power conditions.

Conclusion. This work proposed an InAlN/GaN MC-DC HEMT, with a selective-etched upper barrier and a complete non-etched lower channel to improve $G_{\rm m}$ flatness. The device has excellent $G_{\rm m}$ flatness in DC performance as GVS close to 8 V, nearly constant $f_{\rm T}$ and $f_{\rm max}$ profiles, and $\rm OIP_3$ improved by 10 dBm compared with the reference device.

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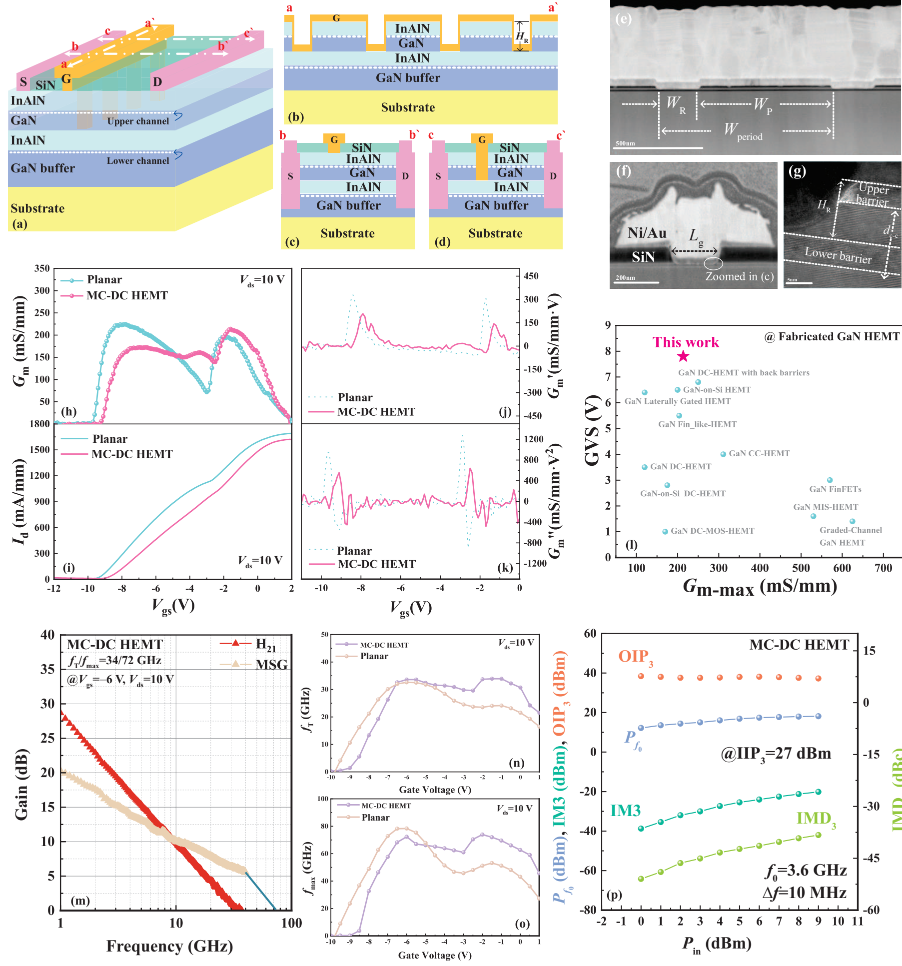

Figure 1 (Color online) (a) Structure diagram of the novel InAlN/GaN MC-DC HEMT cross-sectional views of the MC-DC HEMT (b) along the gate width, (c) planar region and (d) recess region along the source-drain direction; (e) SEM view of the cross-section along the gate width, the width of the recess region (W_R), and the proportion of the width of the planar region (W_P) to a period width (W_period) called the etching ratio (α), where W_period = 1 μm, W_P = 800 nm, W_R = 200 nm, $\alpha = W_\mathrm{P}/W_\mathrm{period}$ = 0.8; (f) SEM view of the cross section at recess region along the gate length; SEM view of the oval-shaped in (f) zoomed in (g); the etching recess depth (H_R) is defined as the downward etching distance of the upper barrier surface, where H_R = 18 nm; the MC-DC HEMT at W_R = 200 nm, H_R = 18 nm, α = 0.8 comparison of (h) G_m profile and (i) transfer characteristics; (j) the first- and (k) second-order derivatives of G_m profiles of HEMT; (l) benchmark of reported GaN-based HEMTs in terms of GVS versus $G_\text{m-max}$; (m) small-signal characteristics of MC-DC HEMTs, (n) f_T and (o) f_max versus V_gs; (p) two-tone power linearity measurements at 3.6 GHz with tone spacing of 10 MHz for MC-DC HEMT.

This impressive improvement in G_m, small- and large-signal linearity indicates that the novel MC-DC HEMT provides an approach to be used in high-linearity RF applications.

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Supporting information Appendixes A–E. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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