Dual-Gate AlGaN/GaN Modulation-Doped Field-Effect Transistors with Cut-Off Frequencies $f_T > 60$ GHz

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***Abstract*—We demonstrate dual-gate AlGaN/GaN modulation-doped field-effect transistors (MODFETs) with gate-lengths of 0.16 μm and 0.35 μm for the first and second gates, respectively. The dual-gate device exhibits a current-gain cut-off frequency $f_T > 60$ GHz, and can simultaneously achieve a high breakdown voltage of $>+100$ V. In comparison to single-gate devices with the same gate length 0.16 μm, dual-gate FETs can significantly increase breakdown voltages, largely increasing the maximum allowable drain bias for high power application. The continuous wave (CW) output power is in excess of 3.5 W/mm at 8.2 GHz. The corresponding large-signal gain is 12 dB and the power added efficiency is 45%. The dual-gate device with different gate lengths shows the capability of providing simultaneous high cut-off frequencies, and high breakdown voltages for broadband power amplifiers.**

***Index Terms*—AlGaN/GaN, broadband power amplifiers, dual-gate FETs.**

I. Introduction

THE 2–20 GHz PHASED array radars, now in development, require amplifiers operating over a decade bandwidth while providing tens to hundreds of watts with high power added efficiency. GaN/AlGaN-based devices exhibit large breakdown voltages (V_{br}) that enable the use of higher drain biases than typically used in other material systems to generate larger amounts of power ($P_{\text{out}} \leq V_{br}^2/8R_L$) for high power electronics. Extensive efforts toward improving microwave performance of AlGaN/GaN modulation-doped field-effect transistors MODFETs have been made in the past years [1]–[3], focusing on extending output power and cutoff frequencies, f_T. An output power density of 9.1 W/mm at 8.2 GHz has been demonstrated on SiC substrate [4] and a higher $f_T > 110$ GHz has also been achieved with a gate-length $L_g < 0.1$ μm [5].

In broadband common-source power amplifiers, the gain bandwidth product is limited to approximately f_T. Increased f_T can be obtained by reducing the gate length L_g, however, the breakdown voltage V_{br} will be significantly reduced. In the Johnson limit [6], the product of $V_{br} f_T$ is less than $E_{\max} v_{sat}/\pi$, where $E_{\max}$ and v_{sat} are the breakdown field and the electron velocity. Increased V_{br} is obtained at the expense of decreased f_T, and high power levels are obtained at the expense of reduced amplifier bandwidth.

AlGaN/GaN dual-gate devices have the potential of simultaneously realizing a high f_T and a high breakdown voltage. Moreover, smaller feedback capacitance and higher output impedance of dual-gate devices enable flexibility for circuit application of broadband power amplifiers. A dual-gate device is electrically equivalent to a common-source (CS) / common-gate (CG) cascode pair, but occupies less die area. The current gain of the dual-gate device, $h_{21}(jf) = (f_{T1}/jf)(1 + jf/f_{T2})^{-1}$, deviates from that of the CS device $h_{21}(jf) = (f_{T1}/jf)$, only for $f > f_{T2}$, where f_{T1} and f_{T2} are the current gain cutoff frequencies of the CS and CG devices and f is the signal frequency. To provide substantial current gain, f_{T1} must be several times of the signal frequency f. In contrast, to avoid significant loss (i.e., >10%) in h_{21} in the CG stage, it is sufficient to have f_{T2} of 1.5 f to 2 f. The breakdown voltage is however determined by the CG device. Therefore, in a dual-gate device, it is advantageous to design the CS device with short L_g hence high f_T, and the CG device with long L_g hence lower f_T, but improved V_{br}. High bandwidth and high power are thus simultaneously obtained. In this paper, we report AlGaN/GaN dual-gate MODFETs with gate lengths of 0.16 μm and 0.35 μm for the first and second gate, respectively. A high $f_T > 60$ GHz and a high breakdown voltage of $>+100$ V can be simultaneously achieved for AlGaN/GaN MODFETs.

II. Device Fabrication

The epilayers of $Al_{0.3}Ga_{0.7}N$/GaN dual-gate devices were grown by metal organic chemical vapor deposition (MOCVD) on a c-plane sapphire substrate. The material structure began with a 200 Å thick GaN nucleation layer, followed by 3 μm thick insulating i–GaN as a device buffer layer. The $Al_{0.3}Ga_{0.7}N$ contains a 30 Å unintentionally doped spacer layer, a 120 Å Si-doped charge supply layer and a 50 Å thick cap layer. Sheet electron concentration and electron Hall mobility of as-grown wafer were $\sim 1.02 \times 10^{13}$ cm^{-2} and 1400 cm^2/V-s at room temperature.

Ti/Al/Ni/Au (200 Å/2000 Å/550 Å/450 Å) ohmic contacts were evaporated and then annealed at 880 °C for 30 s. Gate

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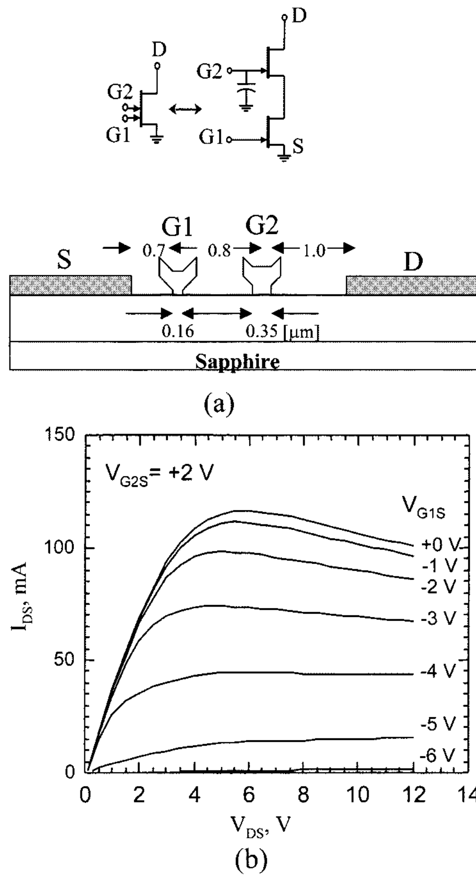

Fig. 1. (a) Schematic diagram of GaN/AlGaN dual-gate FETs (b) Drain output I–V characteristics of $0.16/0.35 \times 150$ μm dual-gate MODFET's with second gate biased at +2 V.

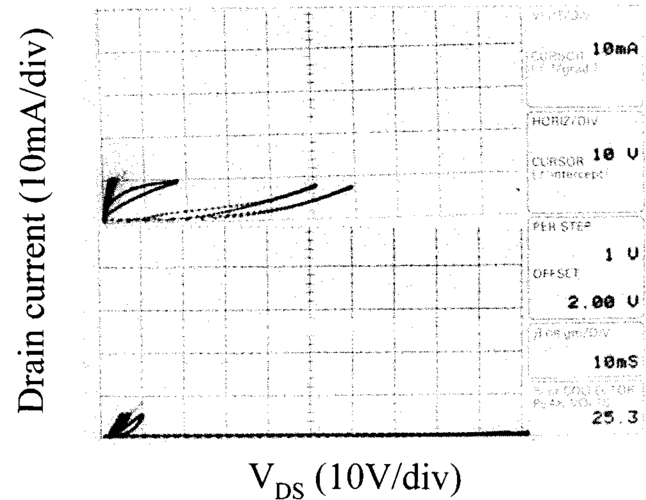

Fig. 2. Comparison of breakdown behaviors of single-gate and dual-gate GaN/AlGaN MODFETs fabricated on the same wafer. The dual-gate device increases three-terminal breakdown voltage up to +100 V.

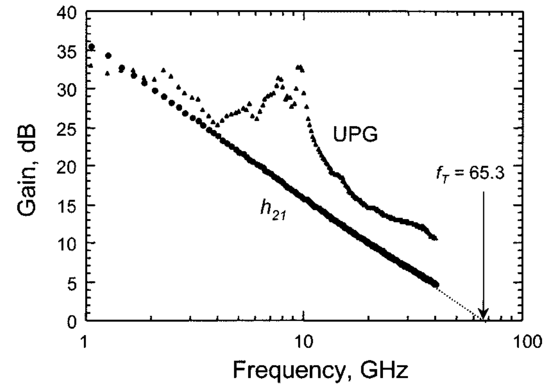

Fig. 3. Comparison of RF performance between single and dual gates devices fabricated on the same wafer: (a) S_{11}, (b) S_{22}, (c) S_{12}, and (d) S_{21}. The single-gate device was biased at $V_{DS} = +12$ V and $V_{GS} = -3$ V, and the dual-gate device was operated with bias voltages of $V_{G2S} = +2$ V, $V_{DS} = +12$ V and $V_{G1S} = -3$ V.

lithography was performed with a JEOL JBX-5DII (U) electron beam system. Both T-shaped gates with 0.16 and 0.35 μm footprints separated by 0.8 μm were produced with a PMMA/P(MMA-MAA)/PMMA tri-layer resist to reduce the resistance of submicrometer gates. Ni/Au/Ni (200 Å/3700 Å/300 Å) were then evaporated as gate metals. The gate of CG device was connected to the source of the CS device using MIM capacitors with 1600 Å SiO_2, providing RF grounding, and then a thick Ni/Au layer (~4500 Å) was evaporated on the top of the SiO_2 capacitors as the second gate pads. The final step in the process was to form a device mesa with Cl_2 reactive ion beam etching. The first gate was separated by 0.7 μm from the source, and the second gate was 1 μm away from the drain contact. A schematic diagram of the finished dual-gate device is shown in Fig. 1(a).

III. Device Characteristics and Discussion

The common source dc characteristics of the dual-gate device with the second gate biased at +2 V are shown in Fig. 1(b). The saturation current, I_{DSS}, is about 0.8 A/mm and pinch-off voltage is −6 V. The peak value of extrinsic transconductance, g_m, is about 220 mS/mm at V_{G2S} of +2 V. The average values of contact resistance and sheet resistance are 0.9 Ω-mm and 500 $\Omega/\Box$, respectively. As seen in Fig. 2, the breakdown voltages of 0.16 μm single-gate FETs were less than +50 V, which is typical of such short-channel GaN/AlGaN MODFETs [8]. The 0.16/0.35 μm dual-gate FETs had larger breakdown voltages of over +100 V. The reason for the increased breakdown voltage is the drain voltage is supported by the longer gate, which has a higher breakdown voltage because of electric field alleviation as discussed in [7]. Since the drain voltage swing of CS device is limited to the pinch-off voltage of CG device, leakage associated with large drain voltage excursions in short-channel devices is eliminated. Therefore, the maximum allowable drain bias is increased for high frequency and high power amplifiers.

DC to 40 GHz device S-parameters were measured at a V_{DS} of +13.5 V, I_{DS} of 240 mA/mm, and a V_{G2S} of +2 V. Both CS and CG devices, we biased in the saturation region. Fig. 3 shows the h_{21} and unilateral power gain (UPG) of dual-gate devices. The dual-gate device exhibits $f_T > 65$ GHz and $f_{\max} >$ 100 GHz. Since the current gain of dual-gate devices follows $h_{21}(jf) = (f_{T1}/jf)(1+jf/f_{T2})^{-1}$, h_{21} of the dual-gate FETs is within roughly 10 to 20% of that of the single-gate device at the frequencies measured. Fig. 4 shows a comparison of RF performance between single-gate and dual-gate devices. Due to the presence of the second gate, the dual-gate device substantially

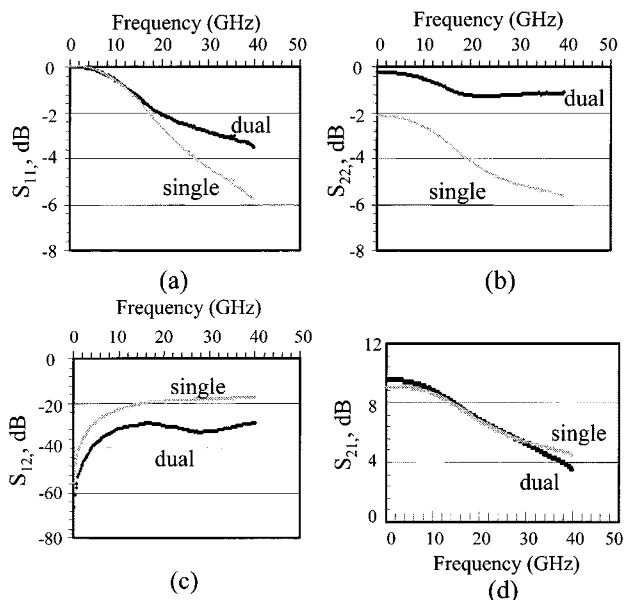

Fig. 4. Gain-frequency characteristics of dual-gate AlGaN/GaN MODFETs.

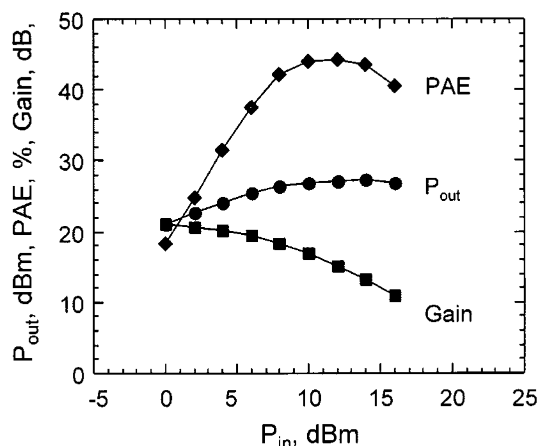

Fig. 5. Microwave power performance of dual-gate device at 8.2 GHz, with bias voltages of $V_{G2S} = +2$ V and $V_{DS} = +20$ V. The output power is greater than 3.5 W/mm, and the small signal gain, PAE, and large signal gain are 21.5 dB, 45% and 12 dB, respectively.

reduces signal feedback (S_{12}) more than 10 dB and increases output impedance (S_{22}) by 4 dB, leading to increased device power gain [9], [10]. It was noted that the maximum stable gain (MSG) and maximum available gain (MAG) of dual-gate devices were increased by 6 dB below 17 GHz, in comparison with single-gate devices. RF continuous wave (CW) power measurements were performed on uncooled devices on a sapphire substrate at 8.2 GHz. Fig. 5 shows the power performance of dual-gate devices biased at a V_{DS} of +20 V, with the second gate bias voltage of +2 V. The drain current at peak output power was 48 mA (320 mA/mm). The output power density is higher than 3.5 W/mm. The small-signal gain, power-added efficiency (PAE), and large-signal gain are 21.5 dB, 45% and 12 dB, respectively. Unfortunately, the higher breakdown voltage afforded by this scheme could not be effectively utilized because of substrate heating effects beyond a bias of +25 V.

IV. Conclusions

In conclusion, we have demonstrated dual-gate AlGaN/GaN MODFETs with T-shaped gates of 0.16 and 0.35 μm footprints on a c-plane sapphire substrate. A CW output power in excess of 3.5 W/mm was achieved at 8.2 GHz, with power-added efficiency >45%. The dual-gate device shows a capability of providing the desired characteristics of a high f_T (>60 GHz), while still maintaining a large breakdown (>+100 V) for broadband power amplifiers.

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References

[1] Y.-F. Wu *et al.*, "GaN-based FET's for microwave power amplification," *IEICE Trans. Electron.*, vol. E82-C, pp. 1895–905, 1999.

[2] A. T. Ping *et al.*, "DC and microwave performance of high- current AlGaN/GaN heterostructure field effect transistors grown on p-type SiC substrates," *IEEE Electron Device Lett.*, vol. 19, pp. 54–56, 1998.

[3] S. T. Sheppard *et al.*, "High-power microwave GaN/AlGaN HEMT's on semi-insulating silicon carbide substrate," *IEEE Electron. Device Lett.*, vol. 20, pp. 161–163, 1999.

[4] Y. F. Wu *et al.*, "High Al-content AlGaN/GaN HEMT's on SiC substrates with very-high power performance," in *IEDM Tech. Dig.*, 1999, IEDM 99–925.

[5] N. X. Nguyen, "Private communication," unpublished, 1999.

[6] E. O. Johnson, "Physical limitations on frequency and power parameters of transistors," *RCA Rev.*, pp. 163–177, 1965.

[7] T. M. Barton and P. H. Ladbrooke, "The role of the device surface in the high voltage behavior of the GaAs MESFET," *Solid-State Electron.*, vol. 29, pp. 807–813, 1986.

[8] K. K. Chu, J. A. Smart, J. R. Shealy, and L. F. Eastman, "AlGaN-GaN piezoelectric HEMT's with submicron gates on sapphire," in *Proc. Conf. Compound Semiconductor Power Transistors and State-of-the-Art Program on Compound Semiconductors (SOTAPOCS XXIX)*, Boston, MA, Nov. 1998.

[9] S. Asai, F. Murai, and H. Kodera, "GaAs dual-gate Schottky-barrier FET's for microwave frequencies," *IEEE Trans. Electron Devices*, vol. ED-22, pp. 897–904, Oct. 1975.

[10] Y. K. Chen, G. W. Wang, D. C. Radulescu, and L. F. Eastman, "Comparison of microwave performance between single-gate and dual-gate MODFETs," *IEEE Electron. Device Lett.*, vol. 9, pp. 59–61, Feb. 1988.