GaN-based FETs for Microwave High-Power Applications

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Abstract — **The present status of GaN-based FETs has been described with a focus on microwave high-power performance. Our latest developments of the devices are presented, and the device and amplifier performance is reported. This includes the demonstration of a 230-W CW output power at 2 GHz, a 156-W pulsed output power at 4 GHz, and a 5.8-W CW output power at 30 GHz. The results confirmed excellent potential of the GaN-based FETs especially for high-voltage, high-power applications at microwave and millimeter-wave frequencies.**

I. INTRODUCTION

GaN-based FETs have been receiving increased interest as promising candidates especially for microwave high-power applications, such as wireless base station amplifiers which require excellent power performance even at backed-off power levels [1]-[3]. Their competitive advantages resulting from III-V wide bandgap materials include high breakdown voltages, extremely high power densities, and high gain at microwave frequencies, due to high drift velocity at high electric fields, as well as temperature tolerance. Although basic investigations and the improvement on material quality are still necessary, impressive results have been reported on high-power GaN-based FETs [4]-[6], and technical progress has steadily been made toward their commercialization.

In this paper we describe AlGaN/GaN heterojunction FETs with field-modulating plates (FPs) [7]. With reduced impact of surface/interface traps, this structure effectively suppresses current collapse and increases breakdown characteristics, resulting in high-voltage and high-power operation. Design and some of our latest power performance of the FP-FETs at various frequencies from L- to Ka-bands are presented together with amplifier performance.

II. DEVICE STRUCTURE

The structure of a recessed-gate AlGaN/GaN FET with a field-modulating plate (FP) is illustrated in Fig. 1. The AlGaN/GaN heterostructure was grown on a semi-insulating SiC substrate using MOCVD. SiN film was used for surface passivation to reduce current slump. Details of the fabrication process have been reported previously [3], [5]. The gate length was 1.0 µm for L-band FP-FETs and 0.5 µm for C-band FP-FETs. The gate FP in conjunction with the recessed-gate structure enabled collapse-free, high-voltage operation, providing high output power with insignificant power slump and increased gain characteristics. The substrate was thinned to 50 µm for power performance evaluation to ensure low thermal resistance.

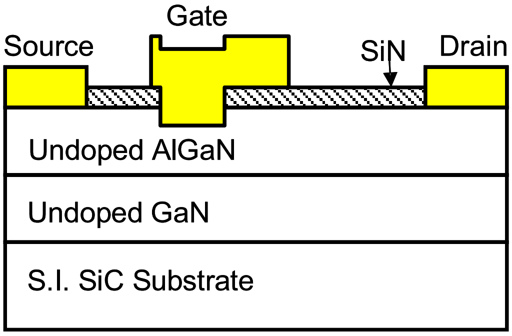


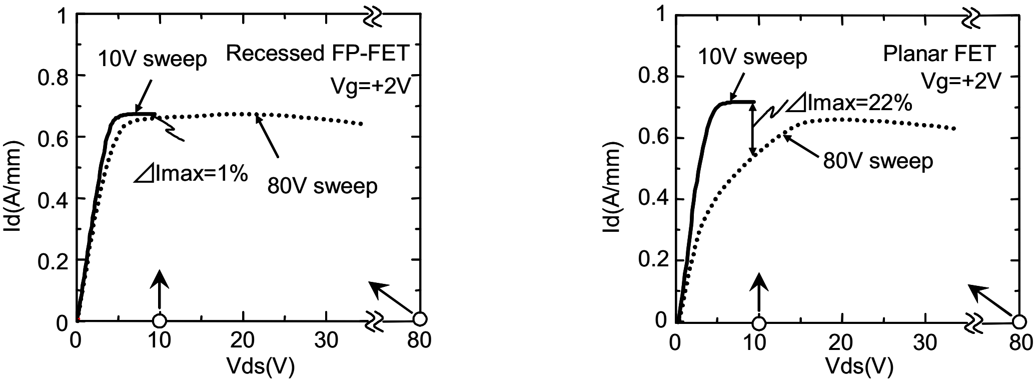
Fig. 1. Schematic cross section of the AlGaN/GaN FP-FET with a recessed-gate structure.

A short-channel AlGaN/GaN FET was fabricated for high-power operation at higher frequencies. A 0.25-µm T-shaped gate provides affordable gain even in the Ka-band. The layer structure and the fabrication process were almost the same as that of the L-band FP-FETs except for the short gate fabrication [8].

III. DC CHARACTERISTICS

A recessed-gate FP-FET with a gate width W_g of 50 µm was used for DC characterization. The maximum drain current I_{max} and the maximum transconductance were 0.8 A/mm and 270 mS/mm, respectively. The gate-drain breakdown voltage, which is given at −1 mA/mm, was 200 V.

Figures 2 (a) and (b) compare the I_{max} between the recessed-gate FP-FET and the planar FET without the FP [3]. In these measurements, the drain *I-V* characteristics were taken with the drain bias voltage being swept from 0 to 10 V and from 0 to 80 V. As shown in Fig. 2, the recessed-gate FP-FET showed negligible current collapse while the planar FET exhibited a significant decrease in I_{max} under high voltage operation. Through comparison between various gate structures, we have found that using the FP is primarily important to suppress the current collapse and the gate recess further minimizes the residual current collapse [5].



(a) (b)

Fig. 2. Drain *I-V* characteristics of (a) the recessed-gate FP-FET and (b) the planar FET without the FP [3]. The drain bias voltage was swept from 0 to 10 V and from 0 to 80 V. The ΔI_{max} represents the relative variation in I_{max}, described by $\Delta I_{max} = (I_{max}(10\text{ V}) - I_{max}(80\text{ V}))/I_{max}(10\text{ V})$.

IV. RF PERFORMANCE

A. L-band Power Performance

An FP-FET with a gate width W_g of 1 mm was mounted on a ceramic package, and its power performance was evaluated at 2 GHz with an unmodulated single-tone input. Figure 3 compares the continuous wave (CW) saturated output power as a function of the drain bias voltage V_{dd} between a recessed-gate FP-FET and a planar FP-FET [9]. The saturated output power for the recessed-gate FP-FET increases almost linearly with an increase in V_{dd}, while the planar FP-FET evidently suffers from power slump at V_{dd} of higher than 40 V. The output power density of the recessed FP-FET reached 12 W/mm at a V_{dd} of 66 V.

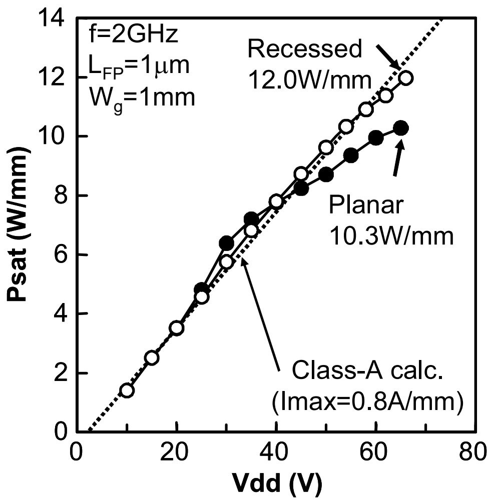


Fig. 3. Dependence of CW saturated output power on drain bias voltage, obtained for the recessed-gate FP-FET and the planar FP-FET with a gate width of 1 mm [9].

Figure 4 shows the photograph of a multi-cell recessed-gate FP-FET chip. The total gate width is 48 mm. Using this chip, high-power performance of the recessed-gate FP-FET was evaluated. In Fig. 5 we show the output power, the gain, and the power-added efficiency (PAE) as a function of the input power, obtained for the single-chip FP-FET at a V_{dd} of 53 V [5]. A CW output power of 230 W (4.8 W/mm) was obtained with a linear gain of 9.5 dB and a PAE of 67%. This output power is the highest ever achieved for any single-chip device.

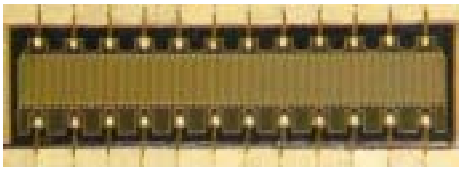


Fig. 4. Photograph of the multi-cell recessed-gate AlGaN/GaN FP-FET chip with a total gate width of 48 mm.

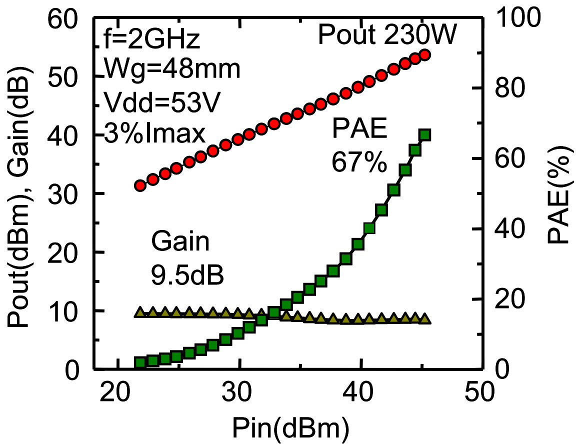


Fig. 5. CW output power, gain, and PAE vs. input power characteristics of the single-chip recessed-gate FP-FET at a drain bias voltage of 53 V [5].

B. C-band Power Performance

The power performance at 4.0 GHz was characterized for the FP-FET with a W_g of 24 mm. Figure 6 shows the dependence of the saturated output power on the V_{dd}, obtained under pulsed and CW operations [10]. A CW output power of 62 W and a pulsed output power of 156 W were obtained at V_{dd} of 37 V and 50 V, respectively. These output power values are the highest ever achieved for GaN-based FETs in the C-band to our knowledge. The output power for the pulsed operation is twice as high as that for the CW operation, suggesting significant thermal effects.

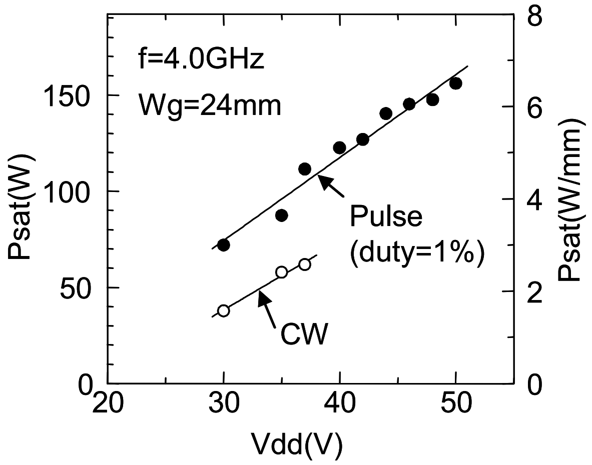


Fig. 6. Dependence of saturated output power on the drain bias voltage, obtained for the recessed-gate FP-FET with a W_g of 24 mm under pulsed and CW operations at 4 GHz [10]. The pulse width and the duty cycle were 10 µs and 1%, respectively.

A C-band compact power amplifier was designed using the 24-mm single-chip FP-FET. Figures 7 and 8 show an equivalent circuit and a photograph of the internally-matched amplifier [10]. The input matching circuit, composed of a power divider and 2-stage LC low-pass filters, and the output matching circuit, compose of a power combiner and impedance transformers, were formed on alumina substrates. The package size is 12.7 mm x 12.9 mm, which is less than 1/2 in area of that for our conventional GaAs-based power amplifiers with a comparable output power.

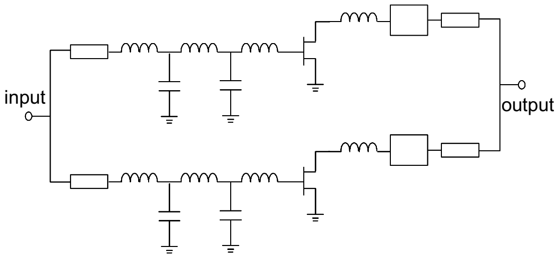


Fig. 7. Equivalent circuit for the C-band single-ended power amplifier [10].

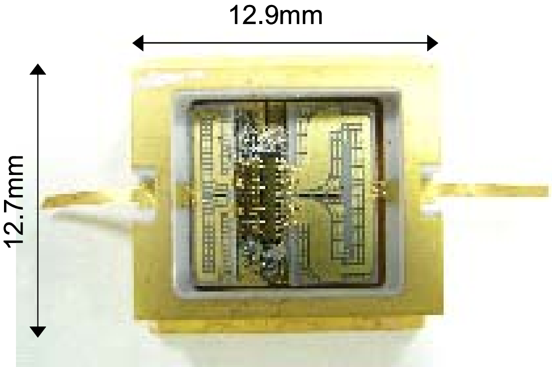


Fig. 8. Top view of the C-band internally-matched power amplifier, using the single-chip recessed-gate FP-FET with a W_g of 24 mm [10].

Figure 9 shows the output power and efficiency vs. input power characteristics of the developed C-band power amplifier under CW operation at 4.0 GHz [10]. The amplifier exhibited an output power of 61 W (2.5 W/mm) with a linear gain of 10.2 dB and a PAE of 42% at a V_{dd} of 36 V. It should be noted that the output power obtained for the amplifier agrees well with that for the FP-FET characterized in a test fixture.

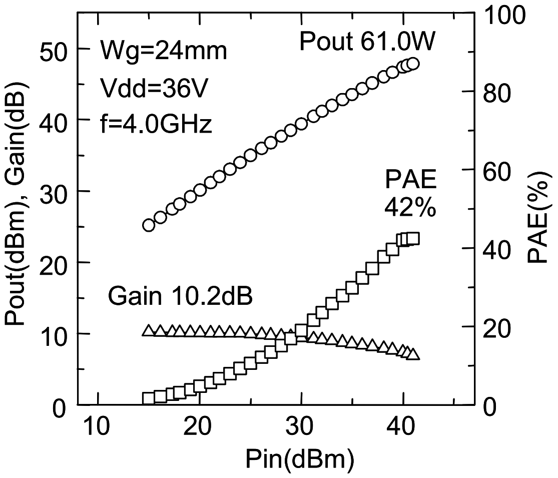


Fig. 9. Output power, linear gain and PAE for the C-band internally-matched power amplifier as a function of input power [10].

C. Ka-band Power Performance

Further investigation on the power performance in the higher frequency band was carried out, using a 0.25-µm-gate AlGaN/GaN FET. Figure 10 shows the output power, the gain, and the PAE as a function of the input power, obtained for a unit-cell FET with a W_g of 1 mm [8]. Through on-wafer load-pull measurements, we confirmed its excellent high-power performance even in the Ka-band. A CW output power of 5.8 W (5.8 W/mm), a PAE of 43%, and a linear gain of 9.2 dB were obtained at 30 GHz under 30-V operation.

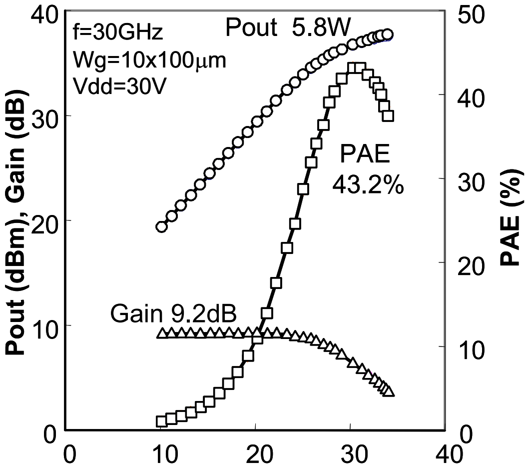


Fig. 10. CW output power, gain, and PAE vs. input power for the unit-cell AlGaN/GaN FET with a W_g of 1 mm, obtained by on-wafer load-pull measurements at 30 GHz [8].

V. CONCLUSION

We described the present status of GaN-based FETs with a focus on microwave high-power performance. The recessed-gate FP-FETs enabled collapse-free, high-voltage operation, exhibiting a CW output power of 230 W at 2 GHz and a pulsed output power of 156 W at 4 GHz. A CW output power of 5.8 W was also obtained for a 0.25-μm-gate FET at 30 GHz. These results indicate excellent potential of the GaN-based FETs for high-voltage, high-power applications at microwave and millimeter-wave frequencies.

ACKNOWLEDGEMENT

The authors thank the research colleagues at NEC Corporation for their technical contributions and discussions. They also wish to thank N. Shibata and his group members for the MOCVD growth of FET wafers. Continuous support from Y. Nanishi, H. Okumura, A. Suzuki, and Y. Sato are also appreciated. This work was supported by the High-Power, High-Frequency Gallium Nitride Device Project of NEDO.

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