Developing GaN HEMTs for Ka-Band with 20W

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Abstract — AlGaN/GaN High Electron Mobility Transistors(HEMTs) were developed for Ka-band. The developed device showed 138 GHz of fmax, which depended on the thickness of the AlGaN barrier layer and the gate length. It had a 6.4 mm gate periphery on a metal carrier plate. The output power achieved 20 W with impedance matching circuits.

Index Terms — AlGaN, GaN, HEMT, Ka-band.

I. Introduction

As a promising candidate for the next generation of microwave power devices, AlGaN/GaN HEMTs have attracted much research interest due to the inherent advantages of their high breakdown field and high current density. In X-band and Ku-band, AlGaN/GaN HEMTs have been reported [1, 2] and products using this technology have been released.

In Ku-band, Satellite Communications, SATCOM, has been adopting Solid State Amplifiers, SSPA. In Ka-band, Traveling Wave Tube Amplifiers, TWTA, have been adopted because the output power of GaAs pHEMT is not enough [3, 4].

AlGaN/GaN HEMTs at millimeter-wave frequencies have drawn a great deal of interest. AlGaN/GaN HEMTs on-wafer load-pull systems were reported for 5.8 W/mm (5.8 W) at 30GHz with 10 × 100 µm of the gate width [6], 6.9 W/mm (1.04 W) at 30 GHz with 2 × 75 µm [10], and 5.4 W/mm (8.05 W) at 30 GHz with 1.5 mm [9]. AlGaN/GaN HEMTs with impedance matching circuits exhibited 3.3 W/mm (20.7 W) at 26 GHz [15]. AlGaN/GaN HEMT MMICs were also reported for 3.1 W/mm (5.0 W) at 26.5 GHz with 1.6 mm of the gate width in the final stage, and 3.3 W/mm (4.0 W) at 35 GHz with 1.2 mm of the gate width in the final stage [13, 14].

In this paper, we demonstrate the RF performance of the AlGaN/GaN HEMTs with impedance matching circuits by comparing the thickness of the AlGaN barrier layer.

II. Device Structure and Fabrication

An undoped AlGaN/GaN HEMT structure was grown on a SiC substrate by MOCVD. As the gate length becomes shorter, the AlGaN barrier layer thickness should become thinner. Two types of AlGaN barrier layers were compared. One had a thickness of 20µm with a 25% Aluminum content. The other one had a 15µm thickness with a 30% Aluminum content. To reduce the short channel current, a GaN buffer layer was important. Three types of GaN buffers were compared. A square shaped Schottky gate electrode was formed with E-beam evaporation. We used SiN film deposited by a conventional PE-CVD for surface passivation. The interconnection, air-bridges and pads were formed with a standard Au-plating process. To know the dependency of the gate length, it was fabricated from 0.25µm to 0.05µm.

III. Device Characteristics

Fig. 1 shows the DC characteristics for the small gate width of the 100µm periphery device. The HEMTs fabricated on the AlGaN with a thickness of 15µm and a 30% Aluminum content exhibited around 125mA/mm of saturation drain current at Vds=5V. The pinch-off voltage of all the devices was -3 V. Maximum transconductance (gm) of 400mS/mm was obtained at Vds=5V. The HEMT fabricated on the AlGaN with 20µm of thickness and a 25% Aluminum content exhibited 115mA/mm of saturation drain current at Vds=5V. The pinch-off voltage was -4 V. A maximum transconductance (gm) of 350mS/mm was obtained at Vds=5V.

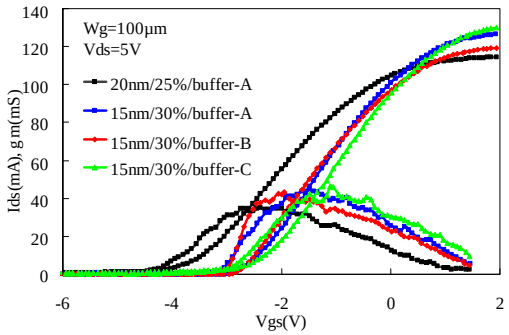

Fig. 1 Measured 100µm AlGaN/GaN HEMT drain current curves and transfer curves at Vds=5V.

Fig. 2 (a) shows the fmax for two fingers of 50µm at Vds=24V and Ids=16mA. All of the HEMTs, except on buffer-C, increased their fmax along with narrowing the gate length from 0.25µm to 0.15µm and exhibited over 100 GHz of fmax. The HEMT of 15nm/30%/buffer-B showed 138GHz of fmax at 0.15µm of the gate length. At 0.05µm of the gate length, the fmax was smaller than that at 0.15µm of the gate length. The HEMTs on buffer-C decreased the fmax along with narrowing the gate length from 0.25µm to 0.05µm.

Fig. 2 (b) shows the fmax for two fingers of 50µm at Vds=10V and Ids=16mA. When comparing Vds=24V and 10V, the decline at 0.05µm of the gate length at Vds=10V was smaller than that at Vds=24V. That meant that the decline at Vds=24V was caused by the short channel effect. The buffer-C did not make enough potential to prevent the short channel effect. Comparing 20nm/30%/buffer-A and 15nm/30%/buffer-A, the decline also depended on the thickness of the AlGaN barrier layer.

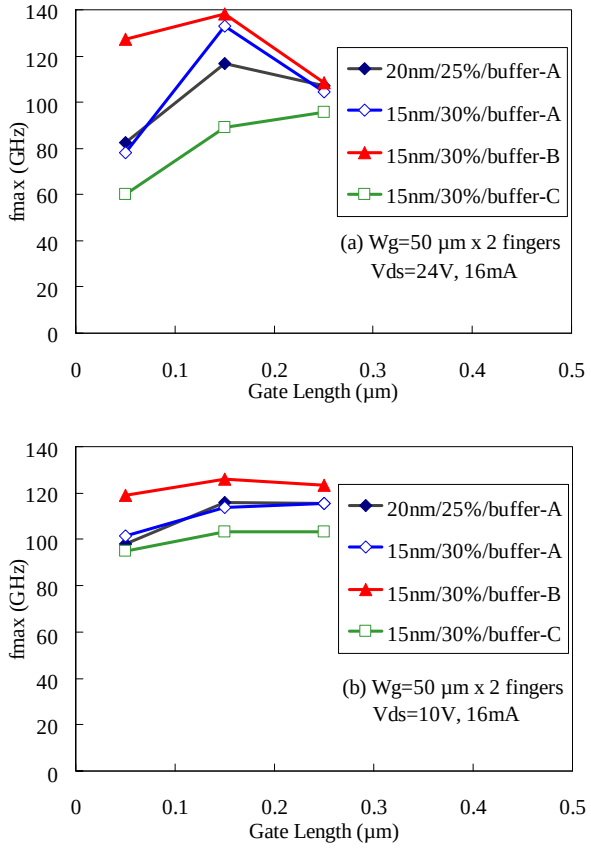

Fig. 2 fmax as a function of the gate length for 50µm x 2 devices.
(a) Vds=24V, 16mA , (b) Vds=10V, 16mA

IV. Output Power Performance of the Unit Cells

Output power densities were measured on a load-pull system to estimate the capability of each structure. The frequency was set at 14 GHz, which was the frequency at which the tuners in our system could make the optimum impedance for the devices with 4×100 µm of the gate width.

The 15nm/30%/buffer-B showed the best fmax of the four, but the power density was the smallest because of current collapse.

Fig.3 shows the operating drain voltage (Vds) dependence of 3dB compression output power (P3dB) and the power-added efficiency (PAE) of a device which had a gate width of four 100µm-fingers on the 15nm/30%/buffer-A at 14GHz. The gate length was 0.15µm. These results were measured on a wafer with the source and load conditions tuned to the maximum efficiency for each operating drain voltage. It was noted that the output power increased linearly and the PAE remained constant. These results showed that the structure had a capability of 2.9 W/mm for output power at Vds=24V, and 4.8 W/mm for output power at Vds=40V.

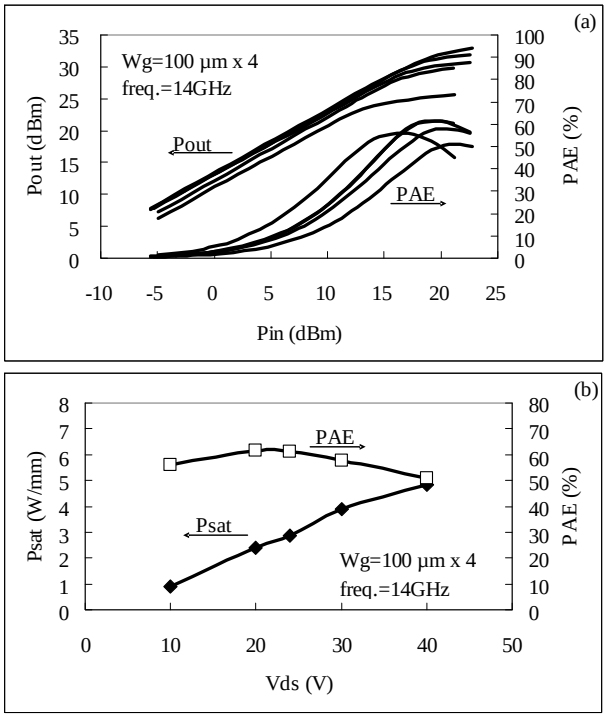

Fig. 3 (a) Output power and power-added efficiency of HEMT on 15nm/30%/buffer-A as a function of input power under CW operating conditions at 14GHz. Wg=100µm x 4, (b) Operating voltage dependence of saturated output power and power-added efficiency under CW operating conditions at 14GHz. Wg=100µm x 4.

The output power density of 2.9 W/mm at 24V needed 5.2 mm of gate width, which was more than 104 50µm-fingers.

Fig. 4 (a) shows MSG/MAG and Mason's U. The number of 50µm-fingers (N) was 2, 4, 8 and 12. Fig. 4 (b) showed fmax and maximum gain at 26 and 30GHz as a function of the number of 50µm-fingers (N). The number of 50µm-fingers for

the unit-cell was determined at twelve by the RF gain and the chip width.

The wafer was thinned to 50µm to reduce the thermal resistance and diced into unit-cells. The unit-cell of Wg=0.6mm which had twelve 50µm-fingers, was mounted on a metal carrier plate with input and output matching circuits. The matching circuits were tuned at 28GHz for Vds=24V. Fig. 5 (a) shows the input-output characteristics for Vds=24V, 30V and 35V. All of the output powers and gains were almost the same. Fig. 5 (b) shows the output power and PAE as a function of Vds. Because the matching circuits were fixed, the output power didn't increase with the drain voltage as it had done when the measurement was set at 14GHz on a wafer with sourcepull and loadpull tuners. The saturated output power was 3.6W/mm for Vds=24V at 28GHz. The PAE was 28.6%.

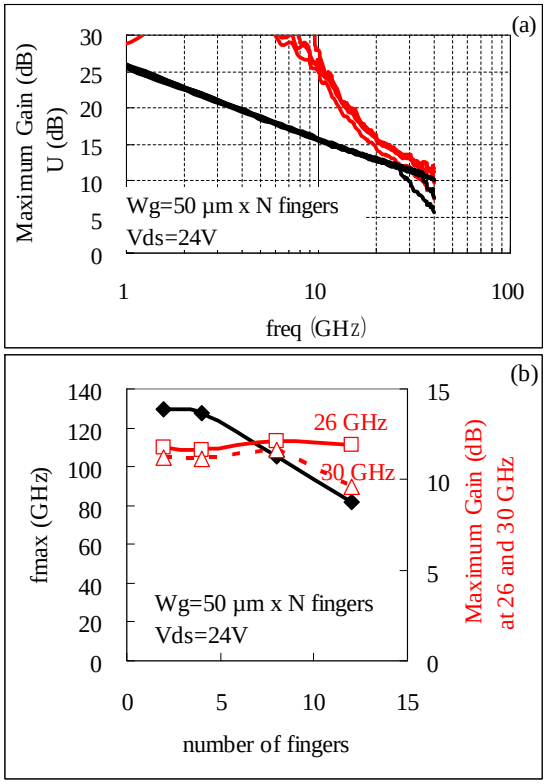

Fig. 4 (a) MSG/MAG and Mason's U. The number of 50µm-fingers (N) were 2, 4, 8 and 12, (b) fmax and maximum gain at 26 and 30GHz as a function of the number of 50µm-fingers (N).

V. Output Power Performance of a 6.4-mm-wide device

Fig. 6 shows the input-output characteristics of a 16-cell HEMT on a metal carrier plate with input and output matching circuits for Vds=24V at 26GHz. The measured output power reached 15W (41.7dBm) at a drain voltage of 24V. The maximum PAE was 13.3% with 9W of output power.

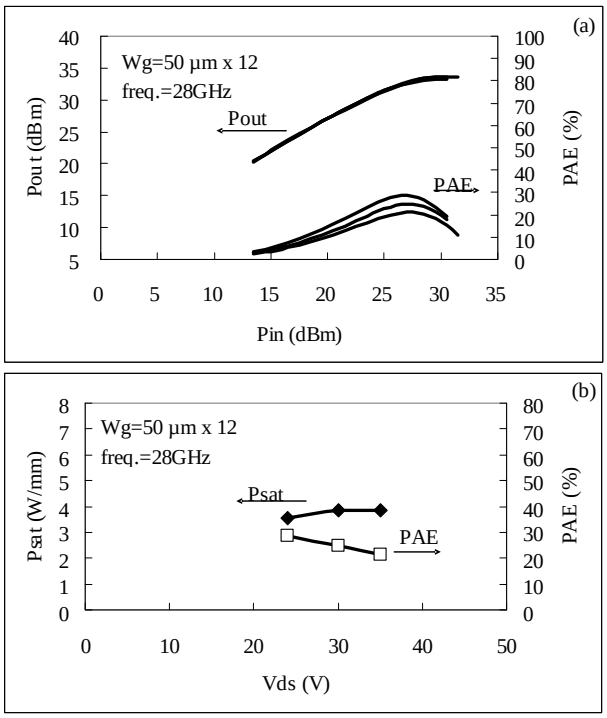

Fig. 5 (a) Input-output characteristics of a unit-cell HEMT on a metal carrier plate with input and output matching circuits for Vds=24V, 30V and 35V at 28GHz. (b) Output power and PAE as a function of Vds.

Fig. 7(a) shows the saturated output power for AlGaN/GaN HEMT reported as a function of the operating frequency. To the best of our knowledge, the saturated output power of over 20W under CW operation in Ka-band is the top level. Fig.7 (b) shows the power added efficiency for AlGaN/GaN HEMT reported in Ka-band as a function of the saturated output power. To the best of our knowledge, the power added efficiency of 18.5% with the saturated output power of 20W in Ka-band is the top level.

VI. Conclusion

In this study, we developed AlGaN/GaN HEMTs for Ka-band by optimizing the AlGaN thickness and aluminum content. We showed the gate length dependency of fmax for some AlGaN barrier layers. The output power density and output power of the unit-cell on the AlGaN with a thickness of 15µm and a 30% Aluminum content were 3.6 W/mm and 2.1W. The HEMT with a gate width of 6.4mm demonstrated a saturated output power of 20W under CW operating conditions at 26GHz. This is our first step in developing GaN MMIC for Ka-band.

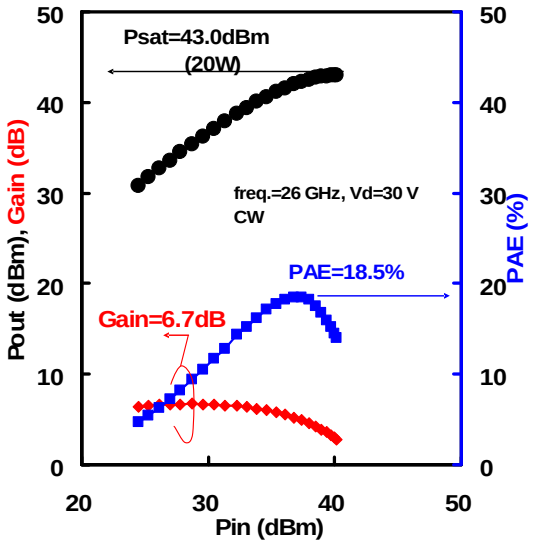

Fig. 6 Input-output characteristics of a 16-cell HEMT on a metal carrier plate with input and output matching circuits for Vds=24V at 26GHz.

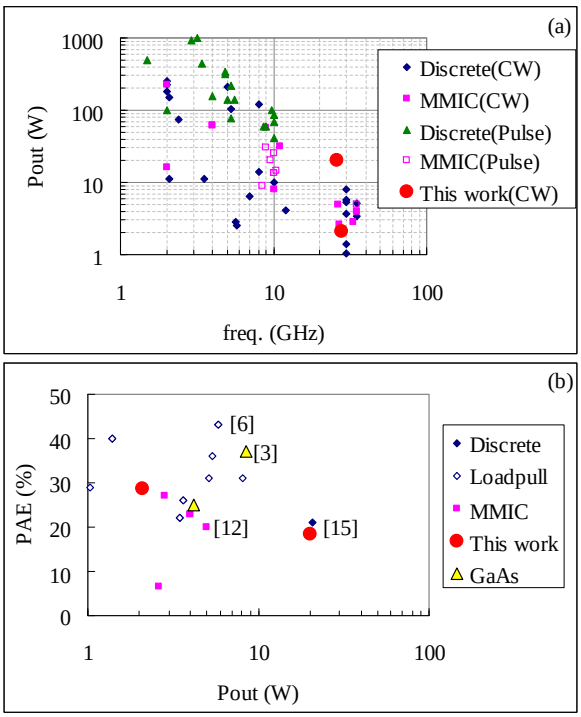

Fig. 7 (a) Power performance of AlGaN/GaN HEMT developed in this work and the works previously reported. (b) PAE performance of AlGaN/GaN HEMT developed in this work and the works previously reported at Ka-band.

REFERENCES

[1] K. Takagi, S. Takatsuka, Y. Kashiwabara, S. Teramoto,K. Matsushita, H. Sakurai, K. Onodera, H. Kawasaki, Y. Takada, K. Tsuda, "Ku-Band AlGaN/GaN-HEMT with over 30% of PAE", 2009 IEEE MTT-S Int. Microwave Symp., Dig., pp. 457-460, June 2009.

[2] H. Shigematsu, Y. Inoue, A. Akasegawa, M. Yamada, S. Masuda, Y. Kamada, A. Yamada, M. Kanamura, T. Ohki, K. Makiyama, N. Okamoto, K. Imanishi, T. Kikkawa, K. Joshin, and N. Hara,"C-band 340-W and X-band 100-W GaN Power Amplifiers with Over 50-% PAE", 2009

[3] M. R. Lyons, C. D. Grondahl and S. M. Daoud, "Design of Low-Cost 4W & 6W MMIC High Power Amplifiers for Ka-Band Modules", 2004 IEEE MTT-S Dig., 2004, pp.1673-1676.

[4] Kris (Keon-Shik) Kong, Bruce Nguyen, Sabyasachi Nayak, and Ming-Yih Kao, "Ka-Band MMIC High Power Amplifier (4W at 30 GHz) with Record Compact Size", 2005 IEEE CSIC Symp. Digest, pp232-235

[5] Y.-F. Wu, M. Moore, et.al., "3.5-Watt AlGaN/GaN HEMTs and Amplifiers at 35 GHz", 2003 IEEE Int. Electron Device Meeting. Dig., pp. 579-581, December 2003.

[6] T. Inoue, Y. Ando, H. Miyamoto, and Y. Okamoto, et.al., "30GHz-band 5.8W High-Power AlGaN/GaN Heterojunction-FET", 2004 IEEE MTT-S Int. Microwave Symp. Dig., pp.1649-1652, June 2004.

[7] M. Micovic, et.al., "Ka-band MMIC Power Amplifier in GaN HFET Technology", 2004 IEEE MTT-S Int. Microwave Symp., Dig., pp. 1653-1656, June 2004.

[8] M. Micovic, A. Kurdoghlian, H. P. Moyer, P. Hashimoto, A. Schmitz, I. Milosavljevic, P. J. Willadsen, W.-S. Wong, J. Duvall, M. Hu, M. Wetzel , D. H. Chow , "GaN MMIC Technology for Microwave and Millimeter-wave Applications",2005 IEEE CSIC Symp. Digest, pp173-176

[9] Y. –F. Wu, M. Moor, A. Saxler, T. Wisleder, U. K. Mishra and P. Parikh, "8-Watt GaN HEMTs at Millimeter-Wave Frequencies", 2005 IEEE IEDM Tech. Dig., December 2005, pp. 593-595.

[10] J. S. Moon, Shihchang Wu, D. Wong, I. Milosavljevic, A. Conway, P. Hashimoto, M. Hu, M. Antcliffe, and M. Micovic, "Gate-Recessed AlGaN-GaN HEMTs for High-Performance Millimeter-Wave Applications", IEEE Electron Device Lett., 2005, 26, No.6, pp. 348-350.

[11] M. van Heijningen, and F. van Raay, et.al., “Ka-Band AlGaN/GaN HEMT High Power and Driver Amplifier MMICs”, 13th GAAS Symp. Proceedings, Paris, France, October 2005, pp237-240

[12] K. S. Boutros, et.al., "5W GaN MMIC for Millimeter-Wave Applications", 2006 IEEE CSIC Symp., pp93-95, Nov. 2006.

[13] A. M. Darwish, et.al., "4-Watt Ka-Band AlGaN/GaN Power Amplifier MMIC", 2006 IEEE MTT-S Int. Microwave Symp., Dig., pp. 726-729, June 2006.

[14] A. M. Darwish, K. Boutros, B. Luo, B. D. Huebschman, E. Viveiros, and H. A. Hung, "AlGaN/GaN Ka-Band 5-W MMIC Amplifier", IEEE Trans. Microw. Theory Tech., 54, no. 12, pp.4456-4463, Dec. 2006.

[15] Y. Murase, A. Wakejima, et.al., "CW 20-W AlGaN/GaN FET Power Amplifier for Quasi-Millimeter Wave Applications", 2007 IEEE CSIC Symp., pp36-39, Oct. 2007.