GaN HEMTs Grown on Sapphire Substrates for Microwave Power Amplification

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GaN based high-electron-mobility-transistors (HEMTs) have shown superior power-frequency performance to their lower band-gap counterparts. Such devices grown on sapphire substrates generated a power density of 3.3 W/mm at 18 GHz without thermal management[1], which is by a factor of 3 higher than that of GaAs-based HEMTs. Further improved power density values up to 6.8 W/mm at 10 GHz were achieved with devices grown on SiC substrates[2], by combining the excellent device properties of GaN HEMTs and the high thermal conductivity of SiC. However, GaN-HEMT-on-sapphire, when proper thermal management is done, is still a strong candidate for practical applications due to the much lower cost and the larger wafer size of sapphire substrates compared with SiC's. **In this paper, we present development of large-periphery GaN-HEMTs-on-sapphire with output power up to 7.6 W. We also present initial demonstration of GaN-based 3-9 GHz wide bandwidth amplifiers with 9~12 dB linear gain and 3.2 W output power.**

The devices under study were GaN HEMTs grown on C-plane sapphire substrates by Metal-Organic-Chemical-Deposition (MOCVD). The gate-lengths and source-drain separations were 0.7~0.85 and 2.5 μm, respectively. Small devices normally have a maximum drain current of 1~1.2 A/mm and breakdown voltages of 50~80 V. The current-gain and power-gain cutoff frequencies were 15~18 and 30~40 GHz, respectively. Flip-chip bonding to AlN substrates was employed as the thermal management scheme for large devices, where AlN has a thermal conductivity κ=1.8 W/cm°C, compared to κ=0.3 W/cm°C for sapphire.

1, 2, 4 and 6 mm devices were developed using 10 to 40 gate fingers of 100~150 μm wide. These devices showed output power levels of 2.1 W, 3.2 W, 5.5 W and 7.6 W, respectively, with PAEs of 35~53 % at 4 GHz. Devices were then analyzed and a modified design was performed to reduce the gate-feed resistance and to optimize thermal management. These resulted in a much improved output power of 3.2 W for the 1-mm wide device, which is close to the 3.9 W value from the 1-mm GaN-HEMTs-on-SiC reported in [2], showing the effectiveness of the thermal management scheme. Larger devices with the improved design are under fabrication and will be presented in the conference.

Broadband power amplifiers, in the form of Microwave-Integrated-Circuit (MIC), were also successfully designed and fabricated using AlN as the circuit substrates with devices flip-chip bonded on to it. The metal resistors were made by Ti with SiN passivation. The Metal-Insulator-Metal (MIM) capacitors were realized with Au as the metals and SiN as the insulator. An L-C-R broadband input matching was employed to achieve 3-9 GHz bandwidth. The output of the smaller amplifier, using a 1-mm device, directly connects to the 50-Ω load; while the larger amplifier with a 2-mm device uses a 25-to-50 Ω broadband impedance transformer. The measured transducer gain was 9~12 dB from 3-9 GHz, very close to simulation. The input reflection coefficient was less than –10 dB in the major part of the band. The output power was about 1.6 W and 3.2 W, respectively, from 4 to 8 GHz for these initial GaN-based amplifiers.

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[1] Y.-F. Wu, B. P. Keller, P. Fini, J. Pusl, M. Le, N.X. Nguyen, C. Nguyen, D. Widman, S. Keller, S.P. Denbaars, and U.K. Mishra, "Short-Channel $Al_{0.5}Ga_{0.5}N$/GaN MODFETs with power density > 3 W/mm at 18 GHz", *Electronics Letters, no. 20, vol. 33, pp. 1742-1743, Sept. 25, 1997.*

[2] S.T. Sheppard, K. Doverspike, W.L. Pribble, S.T. Allen and J.W. Palmour, "High Power Microwave GaN/AlGaN HEMTs on Silicon Carbide," Late News, 56th Device Research Conference, Charlottesville, VA, June 22-24, 1998.

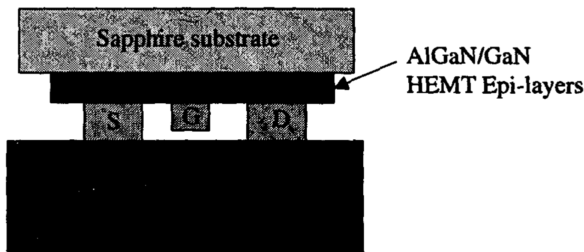
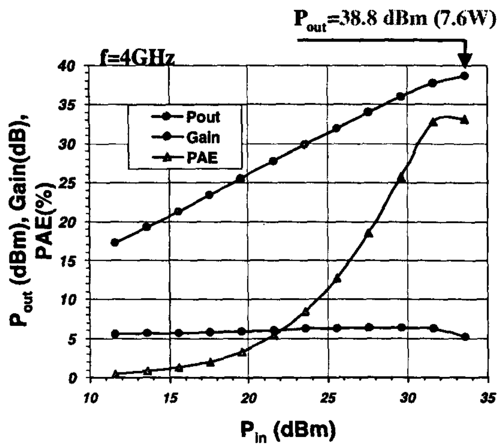


Fig.1 The schematic of a GaN-HEMT-on-sapphire flip-chip bonded to AlN for thermal management.



Bias: Class AB, V_{ds}=26V, I_{d0}=300mA

Fig.2 Power performance of an initial 6-mm wide device, showing 7.6 W output power, the highest for a GaN-HEMT-on-sapphire.

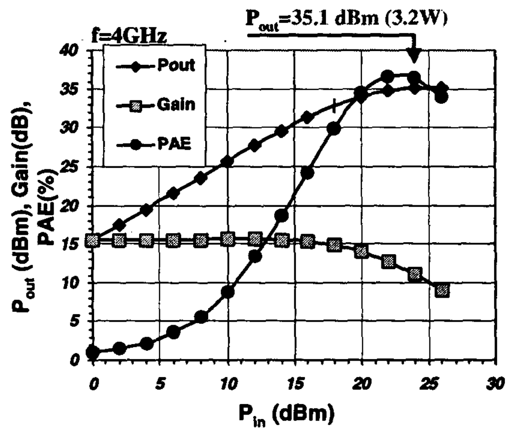


Fig.3 Power performance of an improved 1-mm wide device, showing 3.2 W output power.

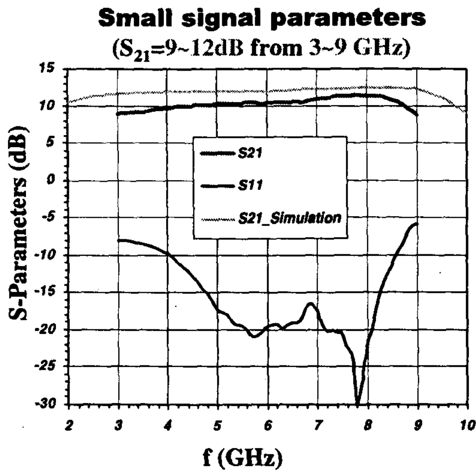


Fig.4 Transducer gain (S_{21}) and input reflection coefficient (S_{11}) of the wide-band amplifiers.

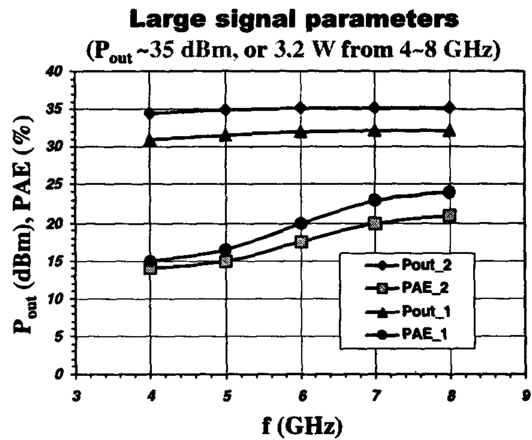


Fig.5 Saturation power and PAE of the wide-band amplifiers (1: with a 1-mm device; 2: with a 2-mm device).