3–9-GHz GaN-Based Microwave Power Amplifiers with L-C-R Broad-Band Matching

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Abstract—**We present an initial demonstration of GaN-based broad-band power amplifiers in the form of a flip-chip integrated circuit (FC-IC) with AlN as the circuit substrates. The input matching consists of a high-to-low impedance transformer and an L-C-R broad-band network. Using 0.7-μm gate-length GaN high-electron-mobility transistors (HEMT's) with current-gain and power-gain cutoff frequencies of 18 and 35 GHz, excellent transducer gain up to 11.5 dB at 8 GHz, along with a bandwidth of 3–9 GHz, was achieved. The saturation power levels were about 32 and 35 dBm, respectively, for these two amplifiers using 1- and 2-mm-wide devices, which are about twice as high as achievable with GaAs-based counterparts of the same sizes.**

Index Terms—**Amplifier, field-effect transistors, gallium-nitride (GaN), microwave power.**

I. INTRODUCTION

GaN-BASED high-electron-mobility transistors (HEMT's) have shown superior power-frequency performance to their lower band-gap counterparts due to the high breakdown field and high electron saturation velocity, as well as the high carrier density and mobility through the AlGaN/GaN heterostructures. These devices can be grown on either sapphire or SiC substrates with the former a more popular choice because of the much lower cost of sapphire than SiC. GaN HEMT's on sapphire have generated a power density of 3.3 W/mm at 18 GHz without thermal management [1], which is by a factor of three higher than that of GaAs-based HEMT's. 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 HEMT's and the high thermal conductivity of SiC. However, GaN-HEMT-on-sapphire, with proper thermal management, is still a strong candidate for practical applications considering the much lower cost and the larger available wafer size of the sapphire substrates. Although not yet mature, output power up to 7.6 W at 4 GHz was demonstrated with GaN-HEMT-on-sapphire, where thermal management was achieved by flip-chip bonding onto AlN substrates [3]. In this letter, we present an initial demonstration of GaN-based broad-band amplifiers using the above technology. The design emphasis was on high gain and flat output power across the bandwidth.

II. AMPLIFIER DESIGN AND CONSTRUCTION

The traveling-wave amplifier (TWA) is a popular broad-band amplifier design having numerous advantages [4]. However, when it and its variations are used as power amplifiers, the input drive of each transistor is difficult to be equalized over the whole bandwidth, due to the frequency-dependent nature of input-line loss. As the input drive increases, usually the first transistor reaches saturation much earlier than the others do. By the time all the transistors are saturated, the first one is already over-driven, leading to poor efficiency and reliability. The L-C-R input network in this study uses the same broad-banding mechanism of a TWA: to absorb the input capacitance of the transistor in a synthetic transmission line, as shown in Fig. 1(a). However, only one transistor is used to eliminate uneven input drive. Also the synthetic line impedance is lowered to about 10 Ω instead of 50 Ω to achieve the desired bandwidth. This necessitates a 50–10 Ω impedance transformation, which is realized using a few sections of quarter-wave lines with decreasing impedance. The actual design is shown in Fig. 1(b), where each component at the input was optimized for high gain and low input reflection over the 3–9-GHz bandwidth. This resulted in component values slightly different from the simple synthetic line theory. The output uses an L-C network to compensate the output capacitance (C_{ds} and C_{gd}) of the transistor, such that the intrinsic device sees approximately a real load within the bandwidth.

The circuit model of the GaN HEMT was developed from previous devices [5]. Major small-signal parameters of a 1-mm-width 0.7-μm-gatelength device at normal bias include: gate–source capacitance $C_{gs} = 3$ pF, gate–drain capacitance $C_{gd} = 0.13$ pF, drain–source capacitance $C_{ds} = 0.3$ pF (after flip-chip bonding), intrinsic transconductance $g_{m0} = 330$ mS, source resistance $R_s = 1.7\,\Omega$, drain resistance $R_d = 2.5\,\Omega$, gate and channel resistance $R_g = R_i = 1\,\Omega$, and output resistance $R_{ds} = 150\,\Omega$. The current-gain and power-gain cutoff frequencies are about 18 and 35 GHz, respectively. The gate turn-on voltage is $V_{\rm on} = 1.5$ V and pinch-off voltage $V_p = -4$ V. The maximum dc drain current and gate–drain breakdown are 1 A and 60–70 V, respectively. The parameters were fit to the Raytheon Statz87 III-V FET model for large-signal harmonic-balance simulation. Note that traps in the semiconductor, due to the immature material technology, limit the ac current and voltage swings to about 0.7 A and 40–50 V, respectively, which account for the discrepancy between the actual and the simulated large-signal performances presented below.

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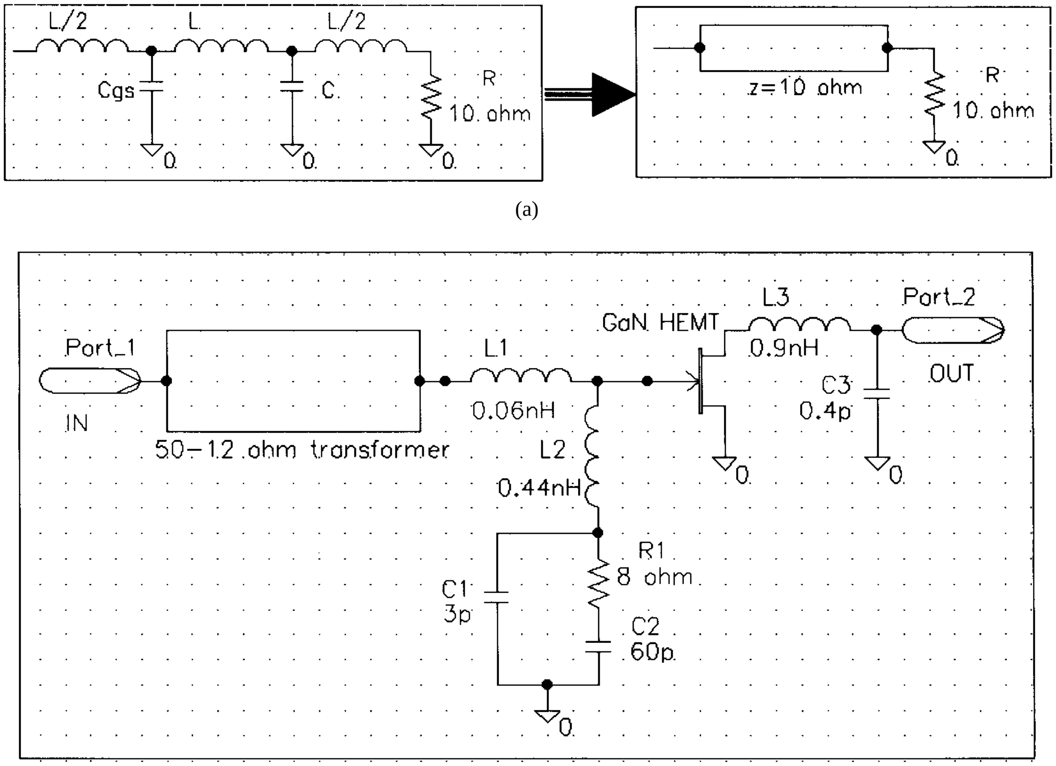

(a)

(b)

Fig. 1. Schematics of (a) the L-C-R input broad-banding mechanism: absorbing C_{gs} in a low-impedance synthetic transmission line. (b) The 3–9-GHz broad-band amplifier using a 1-mm-wide GaN HEMT (amplifier-1).

Two amplifiers were designed and fabricated. The schematic of amplifier-1 is shown in Fig. 1(b), which uses a 1-mm-wide GaN HEMT. The optimum load for this 1-mm device is about 50 Ω, hence no output impedance transformation is needed. Amplifier-2 uses a 2-mm-wide device with a similar schematic except additional impedance transformations at both the input and output.

The device epilayers were grown on sapphire substrates as published earlier [1]. Since the thermal conductivity of sapphire is poor ($\kappa = 0.3\,\mathrm{W/cm^{\circ}C}$), thermal management was achieved by flip-chip bonding onto the AlN circuit substrates having a much higher thermal conductivity ($\kappa = 1.8\,\mathrm{W/cm^{\circ}C}$). The amplifiers were constructed in the form of a flip-chip integrated circuit (FC-IC) using the coplaner-wave (CPW) transmission-line system. The metal–insulator–metal (MIM) capacitors were fabricated with Au as the metals and Si_3N_4 as the insulator, while the metal resistors were made of Ti with Si_3N_4 passivation to ensure reliability. Inductors were realized with high-impedance lines. Interconnects were achieved with air bridges. A photograph of the active region for amplifier-1 is shown in Fig. 2. The inset depicts the GaN HEMT flip-chip bonded on the AlN circuit substrate, whose photo was taken from top through the transparent sapphire on which the GaN HEMT was grown.

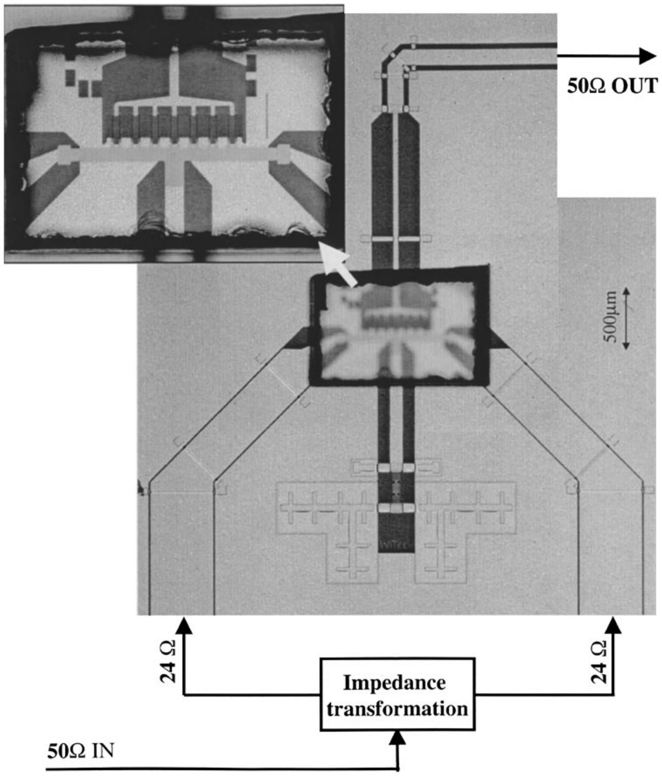

Fig. 2. Photograph of the active region of amplifier-1. Inset: the GaN HEMT flip-chip bonded on the AlN circuit substrate (seen through the transparent sapphire on which the device epilayers were grown).

III. AMPLIFIER PERFORMANCE

Fig. 3 shows the small-signal parameters of amplifer-1 with the simulated transducer gain (S_{21}) for comparison. The measured S_{21} is 8.7–11.5 dB from 3 to 9 GHz, quite close to the simulation result. The gain-frequency product at the higher band edge (8–9 GHz) is 25–31 GHz, approaching

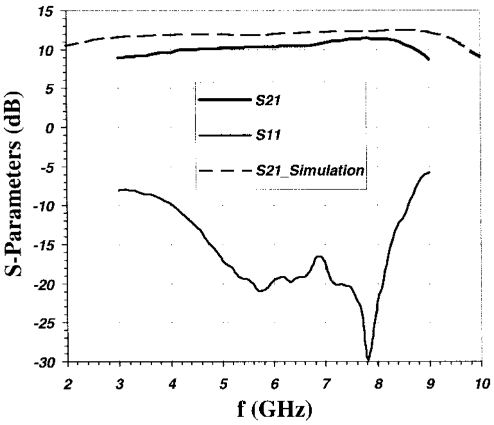

Fig. 3. Transducer gain and input refection coefficient of amplifer-1, showing excellent transducer gain of 8.7–11.5 dB across the band.

the 35-GHz $f_{\max}$ of the active device. This indicates a very successful high-gain design, considering the output matching was optimized for power. The actual GaN HEMT used has a V_p of -5 V instead of the design value of -4 V, which reduces the g_m and hence decreases the gain at low frequencies. However, with the same gate-length, this higher V_p also leads to a smaller C_{gs}, resulting in relatively unaltered device cutoff frequencies. Therefore, the gain at higher frequencies is recovered. The input reflection coefficient was less than -10 dB in the major part of the band. Amplifier-2 has a similar trend in transducer gain except for about 1-dB reduction in value, which may be due to the extra impedance transformations. Fig. 4 shows the saturation output power, which was measured at about 4-dB compression with a drain bias of 20 V using a 4–8 GHz bandwidth traveling-wave tube amplifier as the source. The output power was about 1.6 and 3.2 W, respectively, in the major part of the band for amplifier-1 and amplifier-2. These power levels correspond to a power density of 1.6 W/mm for the output device (which is the only gain element in our case). Although lower than the simulated value of 3–4 W/mm at the same bias due to the early stage of the technology, this power density is nonetheless by a factor of two–three higher than what is generally achieved with GaAs-based microwave amplifiers [6]. The power-added efficiencies (PAE's) ranges from 14% to 24%, also lower than the simulation results of 36%–46%. These initial circuits are under further analysis and will be improved as the technology matures.

IV. CONCLUSION

We have successfully completed an initial demonstration of GaN-based broad-band power amplifiers in the form of an FC-IC using AlN as the circuit substrates. Utilized were 0.7-μm gate-length GaN HEMT's with thermal management through flip-chip bonding. Excellent transducer gain up to 11.5 dB at 8 GHz along with a bandwidth of 3–9 GHz was achieved. The gain-frequency product of 25–31 GHz at the higher band edge was close to the 35-GHz $f_{\max}$ of the transistor. The amplifiers, using 1- and 2-mm-wide devices, generated output power about 32 and 35 dBm (or 1.6 and 3.2 W), respectively, in the major part of the band. These are about twice as high as achievable with GaAs-based counterparts of the same sizes. Much better performances are expected as the new technology matures.

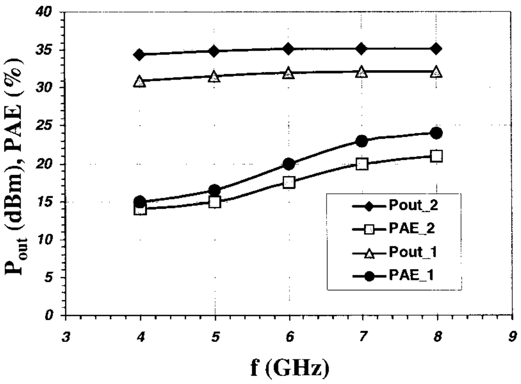

Fig. 4. Output power and PAE of the amplifiers (1: amplifier-1 using 1-mm device width; 2: amplifier-2 using 2-mm device width).

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REFERENCES

[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 MODFET's with power density >3 W/mm at 18 GHz," *Electron. Lett.*, vol. 33, no. 20, 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 HEMT's on silicon carbide," in *Late News, 56th Device Research Conf.*, Charlottesville, VA, June 22–24, 1998.

[3] Y.-F. Wu, B. J. Thibeault, J. J. Xu, R. A. York, S. Keller, B. P. Keller, and U. K. Mishra, "GaN HEMT's grown on sapphire substrates for microwave power amplification," presented at the 57th IEEE Device Research Conf., Univ. California, Santa Barbara, June 28–30, 1999.

[4] E. L. Ginzton, W. R. Hewlett, J. H. Jasberg, and J. D. Noe, "Distributed amplification," *Proc. IRE*, vol. 36, pp. 956–969, 1948.

[5] Y.-F. Wu, "Microwave power AlGaN/GaN high-mobility-transistors (HEMT's)," Ph.D. dissertation, Tech. Rep. 97-21, Dept. Elect. Comput. Eng., Univ. California, Santa Barbara, Aug. 1, 1997.

[6] J. L. B. Walker, *High-Power GaAs Amplifiers*. Norwood, MA: Artech House, 1993, pp. 43–143.