

# 1–8-GHz GaN-Based Power Amplifier Using Flip-Chip Bonding

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**Abstract**— We report the first gallium nitride (GaN)-based broad-band power amplifier. The circuit was fabricated on an AlN substrate using AlGaIn/GaN power high-electron mobility transistors (HEMT's), grown on sapphire substrates, which were flip-chip bonded for thermal management. The amplifier employed a modified traveling-wave power amplifier (TWPA) topology that eliminated the backward wave of conventional TWPA's. Using four HEMT's each with 0.75- $\mu\text{m}$  gate length and 0.75-mm gate periphery, a small-signal gain of  $\sim 7$  dB was obtained with a bandwidth of 1–8 GHz. At mid-band, an output power of 3.6 W was obtained when biased at  $V_{ds} = 18$  V and 4.5 W when biased at  $V_{ds} = 22$  V.

**Index Terms**— Flip-chip, GaN, power amplifier.

## I. INTRODUCTION

COMPARED to gallium arsenide (GaAs) p-HEMT's and other conventional III-V devices [1]–[3], GaN HEMT's have demonstrated superior microwave power performance. In terms of power density, GaN HEMT's on sapphire substrates have achieved 3.3 W/mm at 18 GHz [2], whereas GaN HEMT's on SiC have demonstrated 6.9 W/mm at 10 GHz [3]. The major difference of the two substrates lies in thermal conductivity, which is 0.3 W/cm  $^{\circ}\text{C}$  for sapphire and about 4 W/cm  $^{\circ}\text{C}$  for SiC. However, SiC substrates are ten times more expensive than sapphire substrates, constituting a disadvantage in an amplifier technology. In this study, we used GaN HEMT's grown on sapphire with thermal management through flip-chip bonding onto AlN substrates having a much higher thermal conductivity (1.8 W/cm  $^{\circ}\text{C}$ ) than sapphire [4], [5]. With this approach, GaN HEMT's with gate widths in the millimeter range are able to produce useful amounts of total microwave output power. These latest developments in the GaN HEMT device technology enable the fabrication of GaN broad-band amplifiers with superior power levels.

## II. AMPLIFIER DESIGN AND FABRICATION

The modified capacitive-division traveling-wave power amplifier (TWPA) [6] is shown in Fig. 1. It employs the conventional TWA's artificial input transmission line to realize

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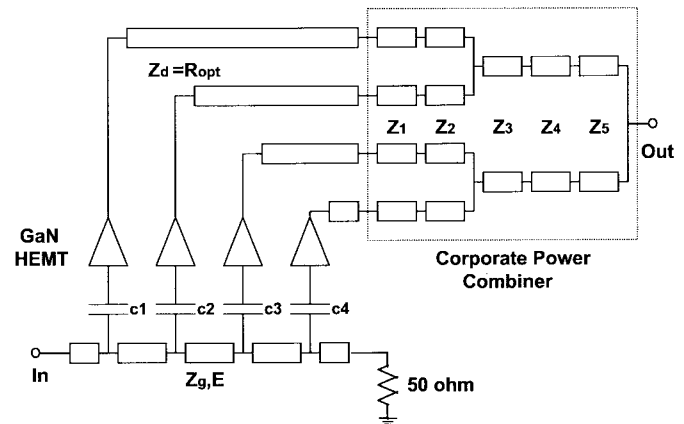


Fig. 1. Schematic of the GaN modified TWPA with corporate power combiner.

the input broad-band matching condition. The artificial output line is replaced by delay lines for phase equalization followed by a broad-band corporate combiner. The corporate combiner was designed to present the optimum load to each device for maximum power. Compared with the conventional TWA, this modified TWA topology eliminates the backward wave, thus theoretically increase the efficiency by a factor of two. Furthermore, the combiner structure can avoid the problems associated with realizing very-high impedance lines. These advantages make the modified TWA topology an excellent candidate for broad-band high-efficiency power amplifiers.

In order to achieve high output power, large gate periphery devices are needed which introduce large gate capacitances ( $C_{gs}$ ). Capacitive division [7] was employed to increase the bandwidth. Also, to obtain equal input drive for each device, the capacitances were varied ( $C_4 > C_3 > C_2 > C_1$ , in Fig. 1) to compensate for the loss along the input line. Since such a loss is frequency dependent, a perfect compensation can only be realized at one frequency, which was chosen at the mid-band in our design.

The circuit was designed to operate over a 1–9-GHz frequency range, with a flat transducer gain ( $S_{21}$ ) of 8 dB, based on HPEEsof simulation using a small-signal model developed in [8]. Since GaN-based HEMT technology is still at a relatively immature stage, an accurate large signal model was unavailable. Direct current  $I$ - $V$  characteristics were employed to predict the optimum load for maxim output power of the devices used. The optimum load seen by the device was

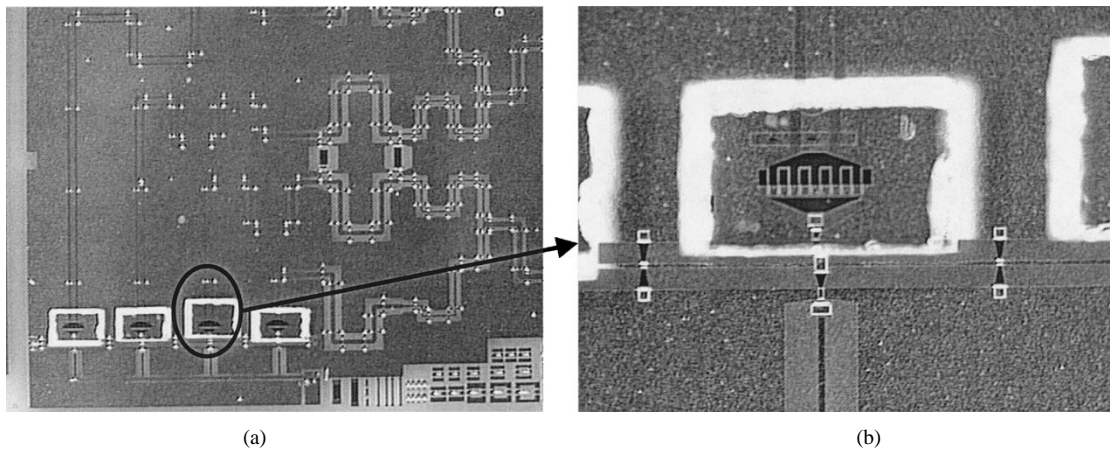


Fig. 2. Photographs of the fabricated GaN-modified TWPA and close-up view of the flip-chip bonded GaN HEMT. (The device is visible through the transparent sapphire substrate.)

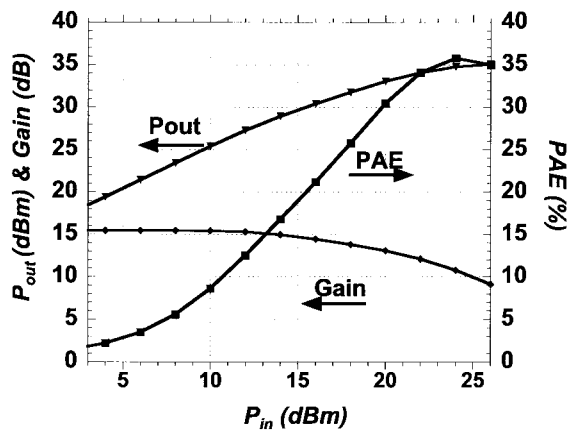


Fig. 3. Power performance of a 1-mm-wide GaN HEMT grown on sapphire. ( $L_g = 0.75 \mu\text{m}$ ,  $f = 4 \text{ GHz}$ , biased at  $V_{ds} = 25 \text{ V}$ , class AB).

chosen to maximize the product of current and voltage swing available from the device. GaN HEMT's with 0.75-mm gate periphery were utilized which have a  $50\text{-}\Omega$  optimum load with the assumption that  $I_{\text{max}} = 600 \text{ mA}$ ,  $V_{\text{knee}} = 5 \text{ V}$ , and a bias point of  $V_{ds} = 20 \text{ V}$ . The corporate power combiner, comprised of five sections of quarter-wavelength CPW transmission lines, was designed to transform  $NZ_0$  ( $N$  is the number of the devices,  $Z_0 (= 50 \Omega)$  is the amplifier load) to the optimum load to be seen by the device ( $50 \Omega$ ). The  $NZ_0$  term results from  $N$  devices output signals sharing the  $Z_0$  under even-mode excitation of the combiner. The number  $N = 4$  was chosen for optimum power-combining efficiency and to avoid extremely high-impedance transmission lines. The CPW transmission lines were meandered to reduce the circuit size.

Fig. 2 shows the finished amplifier and a close-up view of the flip-chip bonded GaN HEMT. The circuit was fabricated on a 10-mil-thick polished AlN substrate ( $\epsilon = 8.5$ ). The board dimensions were  $17 \text{ mm} \times 12 \text{ mm}$ . The gate bias and termination resistors were made of NiCr, and the gate capacitors were MIM capacitors with  $0.3\text{-}\mu\text{m}$ -thick  $\text{Si}_3\text{N}_4$  as the insulating dielectric medium. Air-bridges were used for the CPW grounding and crossover connections. Thick gold bumps were evaporated for bonding the flipped GaN HEMT's.

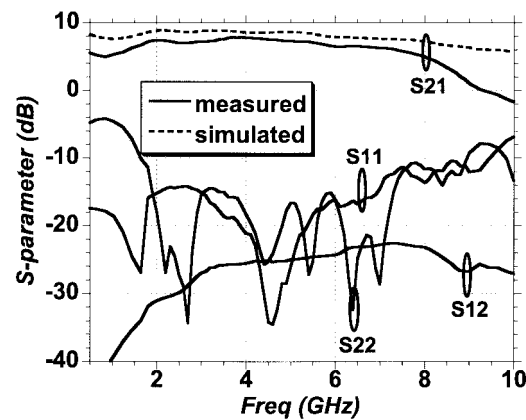


Fig. 4. Small-signal performance of the amplifier (with simulated  $S_{21}$  for comparison).

Stepper lithography was used to fabricate the GaN HEMT's with a  $0.75\text{-}\mu\text{m}$  gate length and  $750\text{-}\mu\text{m}$  total gate width. Each gate finger is  $75 \mu\text{m}$  long;  $L_{gs} = 0.7 \mu\text{m}$  and  $L_{gd} = 1 \mu\text{m}$ . The device process was as described in [4]. The wafer was subsequently diced into  $1.2 \text{ mm} \times 1 \text{ mm}$  discrete devices. Then a flip-chip bonder was used to align and bond four devices onto the AlN circuit board with all the passive circuit components prefabricated. With this approach, we have achieved 3.2-W output power from a 1-mm-wide GaN HEMT, which is close to the best reported power density for large-gate-width devices on SiC substrates. Fig. 3 shows the power performance of this 1-mm-wide AlGaIn/GaN HEMT using ATN load-pull system (fundamental tuning only).

### III. AMPLIFIER PERFORMANCE

Fig. 4 shows the measured  $S$ -parameters of the amplifier with the simulated  $S_{21}$  for comparison. The gain is around 7 dB with a 3-dB bandwidth of 1–8 GHz. The input and output return losses ( $S_{11}$  and  $S_{22}$ ) were less than 15 dB. Fig. 5(a) shows the output power versus frequency. The amplifier was biased in class AB mode with a drain voltage of 18 V, and output power was measured at about 4-dB gain compression point. The mid-band output power was 3.6 W. Because of the power limitation of the driver, measurements at 1 and 2 GHz

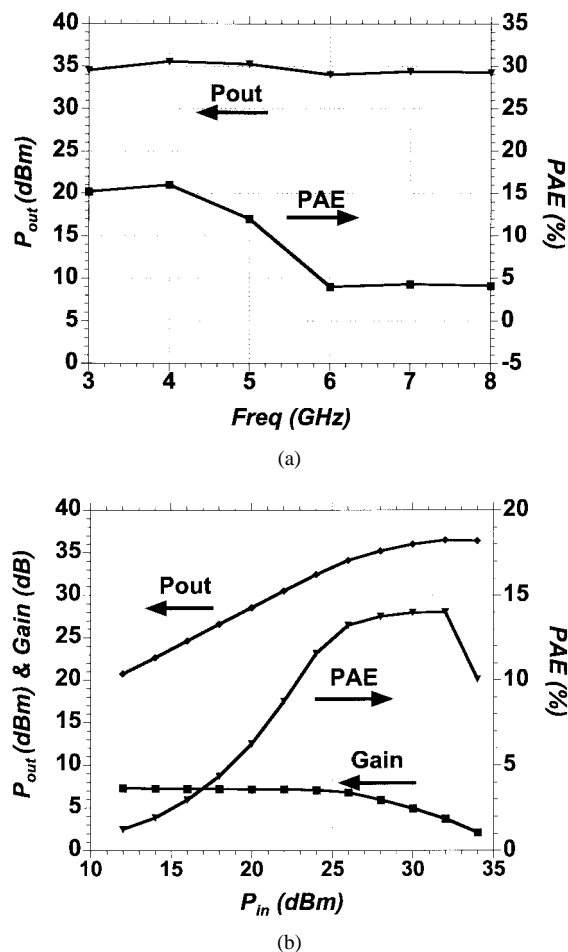


Fig. 5. Power performance of the amplifier. (a)  $P_{out}$  versus Frequency when biased at  $V_{ds} = 18$  V. (b) Power sweep at 4 GHz when biased at  $V_{ds} = 22$  V.

were not performed. The power-added efficiency (PAE) was less than 16%, which was about half of the expected value. The reasons for the low PAE include the nonuniformity of the four devices, the dc resistive loss in signal lines, and radio frequency (RF) loss at the corners of the meandering CPW lines. Fig. 5(b) shows the power measurement at 4 GHz, biased at 22 V. Output power increased to 4.5 W. Due to the relatively immature device technology, such as poor uniformity, the circuit could not be reliably biased above 20 V, hence the power performance over the entire bandwidth at 22-V drain bias was not available.

#### IV. CONCLUSION

The first GaN broad-band power amplifier was successfully designed and fabricated using the modified TWPA circuit topology. The amplifier had about 7-dB small-signal gain and very low return loss at both input and output. An output power of 3.6 W when biased at 18 V and 4.5 W when biased at 22 V was obtained at mid-band (4 GHz). Thermal management of the GaN HEMT's grown on sapphire substrates was achieved through flip-chip bonding onto an AlN circuit board. The latest developments in GaN material and device technology have been the key factors to the implementation of the GaN power amplifier.

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