High Power Hybrid and MMIC Amplifiers Using Wide-Bandgap Semiconductor Devices on Semi-insulating SiC Substrates

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Abstract

An overview of hybrid and monolithic high-power microwave amplifiers using SiC MESFET and GaN HEMT active devices is presented. High power densities of 5.2 W/mm and 63% power added efficiency (PAE) have been demonstrated for SiC MESFETs at 3.5 GHz. This performance has driven the development of wide-bandwidth MMIC amplifiers, which have yielded 37 W of pulsed power at 3.5 GHz. GaN HEMTs on SiC substrates can achieve these high performance levels at frequencies where SiC cannot operate. At 10 GHz, a 12-mm GaN HEMT hybrid amplifier achieved a CW output power level of 38 W with an associated gain of 8 dB and PAE of 29%, complementing a previous pulsed result of 50.1 W. MMIC amplifiers have also been demonstrated using GaN-on-SiC technology. At 16 GHz, a two-stage GaN HEMT MMIC wide-bandwidth amplifier was capable of a peak power level of 24.2 watts with an associated gain of 12.8 dB and PAE of 22%. Recently, a 6-mm single-stage narrow-band MMIC amplifier has produced 32 watts of pulsed power at 10 GHz with an associated gain of 8.3 dB and a PAE of 35.3%. Finally, to validate progress in scaling unit cell performance to large devices, we have demonstrated 103 W of CW power from a *single* GaN HEMT transistor at 2 GHz with an associated drain efficiency of 52%.

Introduction

The high operating voltages and high power densities that are possible with the wide-bandgap RF devices offer a number of advantages for power amplifier design, manufacture and assembly in comparison to GaAs MESFET technologies. For example, the output impedance of the total periphery required for a 40 W GaAs amplifier would be about 20 times lower than the output-impedance for a 40 W GaN HEMT, leading to much lower losses in an output matching network for the GaN example. In addition, the 5-10X power density available from a wide-bandgap device makes it possible to achieve higher total power with a single chip, whereas an equivalent-power GaAs amplifier would comprise several smaller periphery chips, requiring multi-chip modules and incurring further loss in power combining. With a single chip, high-power amplifier design and assembly becomes far simpler, and these advantages can also be utilized to improve the quality of the output matching circuit on MMIC amplifiers. We have incorporated all of the important passive components that are required to realize MMICs with SiC- and GaN-based active devices, including thin-film resistors, MIM capacitors, Au airbridges and substrate via holes. The early development of SiC substrate vias enabled the straightforward implementation of the amplifier circuits with SiC- and GaN-based RF technologies [1].

Wide-bandgap semiconductor technology for high power microwave devices has matured rapidly in the last several years, as evidenced by the encouraging device and circuit demonstrations being made with both SiC MESFETs and GaN HEMTs grown on semi-insulating 4H-SiC substrates. Reports of high total RF power from both SiC and GaN over a wide frequency range [2, 3, 4] are beginning to validate the very high power densities that have been demonstrated on small periphery devices for several years [5, 6, 7]. These high power densities in terms of W/mm also present an extreme power dissipation demand on the substrate. Fortunately, the high thermal conductivity of the SiC substrates, >3.3 W/cm-K, allows these higher power densities to be efficiently dissipated, preventing the extreme channel temperatures due to self-heating that are likely with low thermal conductivity substrates such as sapphire and silicon. High quality, 50-mm-diameter semi-insulating 4H-SiC substrates are now commercially available for use in both SiC and GaN microwave device fabrication, and 75-mm semi-insulating and 100-mm 4H-SiC n-type wafers have been demonstrated [8]. In this paper, we present previous and new achievements in the field of wide-bandgap semiconductor microwave power devices for hybrid and MMIC power amplifiers.

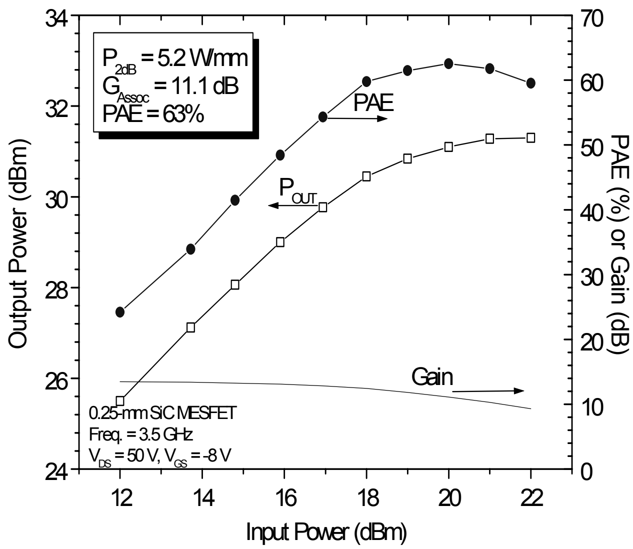

Figure 1: A 3.5 GHz CW power sweep of a 0.25-mm SiC MESFET tuned in class AB operation. V_{DS} = 50 V.

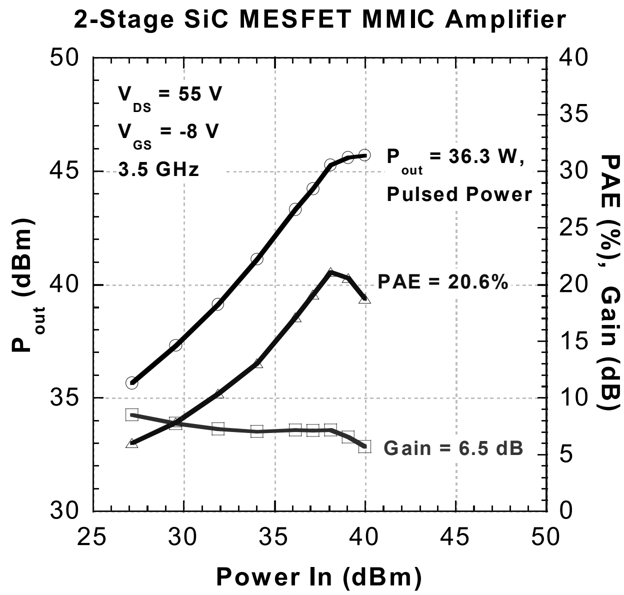

Figure 2: A 3.5 GHz pulsed power sweep of a SiC MESFET wideband MMIC amplifier tuned in class AB operation. V_{DS} = 55 V, 1 kHz PRF, 16 µs pulse width.

Silicon Carbide MESFETs

For operating frequencies from 1-10 GHz, we have focused on the development of SiC MESFET technology because of its higher level of maturity. The processes for growing and fabricating SiC MESFET devices are well established. The optimized S-band power MESFETs at Cree have a nominal gate length of 0.7 µm and employ a channel doping of about 3×10^{17} cm^{-3}. These devices are capable of very high power levels due to their high breakdown voltage of 150 V.

In our work on SiC MESFETs, we have addressed trapping issues by improving the surface passivation as well as developing substrates that are free of deep level impurities. Semi-insulating SiC substrates with resistivities greater than 10^{10} Ω-cm have recently been demonstrated using a high purity growth process that utilizes an intrinsic deep level state instead of vanadium to obtain the semi-insulating properties [9]. These efforts have resulted in the best combination of power density and efficiency reported to date for these devices of 5.2 W/mm and 63% power added efficiency (PAE) at 3.5 GHz, as shown in the RF power sweep of Figure 1.

These SiC MESFETs can also be used to realize high-power, very wide bandwidth MMIC amplifiers in the lower microwave frequency regime. Two-stage, reactively matched amplifiers were designed and fabricated with a 6-mm input driving a 12-mm output transistor and both RF ports matched to 50 Ω. On-wafer testing under pulsed mode conditions at 3.5 GHz was then performed with a supply voltage of 55 V and a class AB bias. The RF power sweep in Figure 2 shows a high power level of 36.3 W with an associated gain of 6.5 dB. The MMIC PAE was measured to be 20.6%, while the MMIC drain efficiency was 26.5%. The output stage drain efficiency was 35.7%. The gain was limited due to poor matching at the amplifier input. This was demonstrated by improved gain measured at higher frequencies, where the small signal gain was over 10 dB and the associated power gain was 8 dB.

GaN/AlGaN-on-SiC High Electron Mobility Transistors

The GaN/AlGaN-on-SiC HEMT is being pursued as an RF power device that is viable for commercial and military commercial applications at frequencies where SiC cannot operate. Although AlGaN/GaN HEMTs are less technologically mature than SiC MESFETs, the performance benefits demonstrated for these devices are remarkable, due to the ability to make heterostructures in the AlGaN/GaN system and strain- and polarization-induced charge which enable very high sheet carrier densities in the $1x10^{13}/cm^2$ range. The epitaxial layer structure and processing conditions presented here are similar to our previous work [5, 1] with 15-17% mole fraction AlGaN cap layers.

Previous efforts to demonstrate high total power from GaN HEMTs at X-band yielded peak pulsed output power levels of over 50 W from flip-chip IC technology [3] or hybrid ceramic matching [4], outpacing power levels of GaAs technology by 3 times at this frequency. However, these amplifiers were either unable to operate under CW conditions, or performed significantly worse due to extreme device heating. For instance, the 50-W hybrid amplifier had a much lower power and efficiency, in the range of 12 W and 10%, due to inferior device attach. Subsequent improvements to our Au/Sn die attach processes, however, have enabled us to demonstrate record CW performance at 10 GHz. The power sweep in Figure 3 shows a CW power output of 38 W at 10 GHz, with a PAE of 29% and associated gain of 8 dB. The pulsed power for this device was only marginally higher, 42 W, indicating that the much improved die attach was successful. The total CW power could have been even higher, but this device was not able to block the higher 50 V bias used for the previous device. The high gain achieved at this frequency is attributed, in-part, to the use of vias for source ground connections.

To demonstrate progress in scaling unit cell performance to large devices, we fabricated large, 24-mm transistors appropriate for frequencies of <4 GHz, assembled hybrid amplifiers, and tested them at 2 GHz. To date, this is the largest known GaN HEMT periphery fabricated on a SiC substrate. Device yields of over 50% for 18- and 24-mm devices demonstrate the ability to achieve high-quality epitaxial material with excellent uniformity. The gate fingers on the 24-mm GaN HEMTs had an L_{GS} of 0.7 µm and a gate width of 500 µm. No vias were used, since source inductance is not too large at these lower frequencies. The 24-mm chips were attached to high-thermal conductivity Cu/Mo/Cu carriers using Au/Sn solder, and tuning was provided off-chip. The best CW RF power achieved is illustrated in Figure 4, showing a peak output power level of 103 W CW with 7.6 dB of associated gain and 53% drain efficiency (DE). The gain is low because of the intentional loss in the input matching that was required to prevent oscillations. While the wafers were not stable at these high power levels, we observed stable operation with less than 1 dB lower power (>90 W). On-wafer load-pull measurements of 0.5-mm devices produced over 5 W/mm of CW saturated power and 51% DE at V_{DS} = 30 V.

As with the SiC devices, this GaN technology has also been integrated into monolithic circuits. Previous demonstrations of two-stage GaN MMIC amplifiers include over 20 W of pulsed power at 9 GHz [1] and 24.2 W of pulsed power at 16 GHz [4], both having 6-mm output stages. To complement the

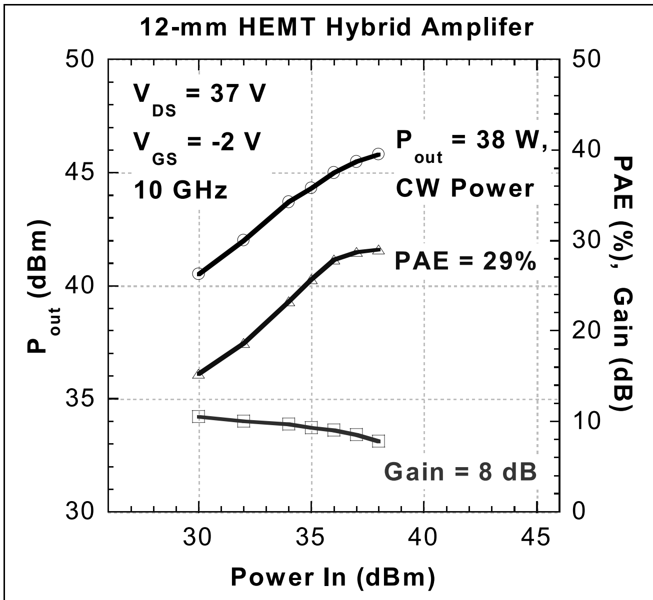

Figure 3: A 10 GHz CW power sweep of a 12-mm GaN HEMT hybrid amplifier with improved die attach, tuned in class AB operation. V_{DS} = 37 V. L_g = 0.4 µm.

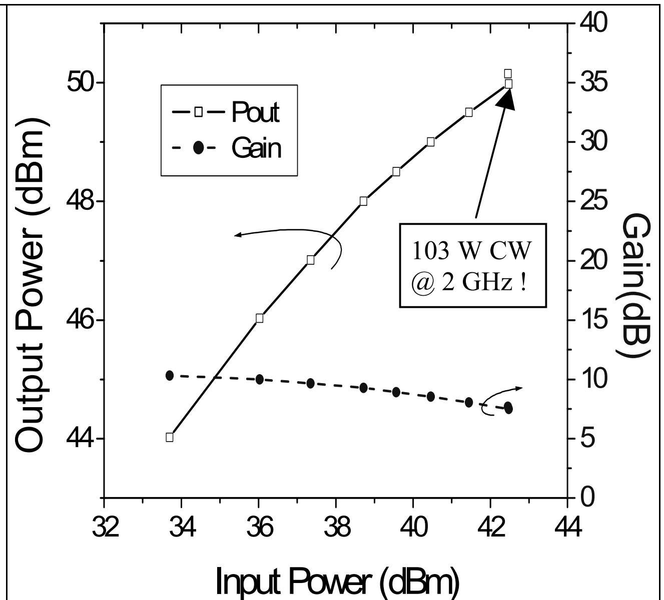

Figure 4: Output power and gain vs. input power for a 24-mm GaN HEMT at 2 GHz. The associated drain efficiency was 53%. V_{DS} = 50 V.

hybrid amplifier results, we have also investigated the benefits of on-chip partial matching for single-stage amplifier designs. A single-stage HEMT amplifier was designed with matching to 50 Ω at each port and fabricated using our standard HEMT structure of 17% AlGaN mole fraction. The typical dc characteristics comprised a max. current of 900 mA/mm and 1 mA/mm breakdown voltages around 90 V. Completed amplifiers were tested on-wafer with a supply voltage of 40 V and class AB bias. As shown in Figure 5, a 6-mm, single-stage, narrow-band MMIC amplifier has produced 32 watts of pulsed power at 10 GHz with an associated gain of 8.3 dB and a PAE of 35.3%. On-wafer CW loadpull of 1.5-mm unit cells exhibited also 5.1 W/mm of output power and 17 dB of associated gain at 3.5 GHz, showing that these devices maintain power density over a range of device peripheries.

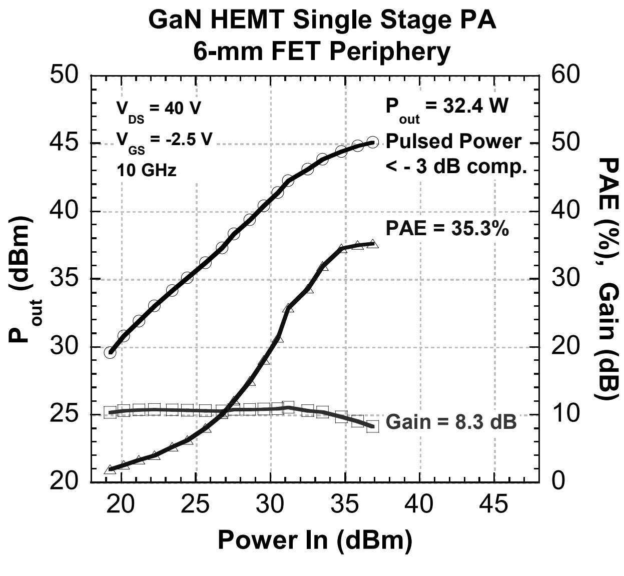

Figure 5: An on-wafer, 10-GHz, pulsed-power sweep of a GaN HEMT single-stage MMIC amplifier in class AB operation. V_{DS} = 40 V, 1 kHz PRF, 10 µs PW.

Acknowledgements

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