Applications of SiC MESFETs and GaN HEMTs in Power Amplifier Design

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Abstract — **Very high power densities have been shown for both SiC MESFET and GaN HEMT devices. Both of these active devices benefit from the high breakdown voltages afforded by their wide-bandgap semiconductor properties. The GaN device also benefits from current densities as high as 1 A/mm. This high power density, along with good efficiency and linearity, provide an excellent base for future military and commercial power amplifier applications. High power densities are possible using narrow band power-matching networks. Although the gain-bandwidth limitation is exacerbated due to the high-impedance load lines required, high power design is possible even over multi-octave bandwidths.**

I. INTRODUCTION

Wide bandgap semiconductor technology for high power microwave devices has matured rapidly in the last several years, as evidenced by the impressive device and circuit demonstrations being made with both SiC MESFETs and GaN HEMTs grown on SiC substrates. Small periphery devices in both SiC and GaN have been reported to have very high power densities in terms of W/mm for several years [1,2]. There are now demonstrations of large periphery devices exhibiting similar power densities [3,4,5]. These results exceed total power levels with established technologies above 2 GHz and realize the advantage of much higher input and output impedance levels available with wide bandgap semiconductors.

To demonstrate the utility of wide bandgap semiconductors in microwave power applications, a simple comparison is made between GaN and several of the established technologies. Typical values for F_t, peak current, and operating drain voltage are used, along with an assumed output capacitance of 0.2 pF/mm which applies approximately to all, to calculate an optimum ideal-element power match in the 6-18 GHz band for each device. The results are shown in Table 1. Assuming a match of at 15 dB to the optimum load is required for best power-pae operation, the real output (Z_{out}) termination left after resonating Cds is calculated and normalized to the 6 W/mm output of GaN. It shows that, in order to deliver the power similar to GaN, each of the other competing technologies would require significant impedance transformation. So, although the calculated gain-bandwidth is somewhat limited by the higher load-line impedance required by GaN devices, circuit design for high power is greatly simplified by removal of many levels of impedance transformation. A similar analysis will show this result holds for the input match as well.

In order to advance SiC- and GaN-based RF technologies to the next level, we have now also incorporated all of the important passive components that are required to realize MMICs. Air bridges that are a

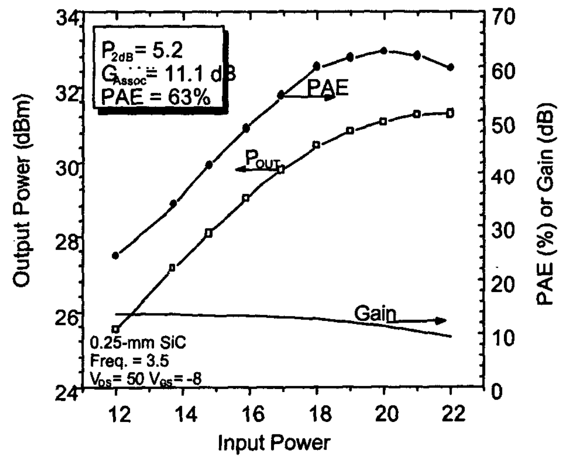

Figure 1. A 3.5 GHz CW power sweep of a 0.25-mm SiC MESFET tuned in class AB operation. V_{DS} = 50 V.

standard feature of multi-finger discrete FETs are also employed as the top plate connection for metal-insulator-metal (MIM) capacitors. Capacitors for the high power MMICs must handle much higher voltages as compared to GaAs technology, so high-yield MIM insulators have been developed to support peak voltages over 150 V. Precision bias resistors are used with a typical sheet resistance of about 22 Ω/□. I-line steppers are employed to fabricate 0.40 μm gates on the large-area circuits. The development of SiC through-wafer vias has allowed the

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TABLE I

COMPARISON OF TYPICAL MICROWAVE POWER DEVICES

Technology	F_t (GHz)	I_{pk} (mA)	Max V_{ds}	Z_{opt} (Ω)	P_{max} (mW)	Z_{out} (Ω)
GaAs MESFET	20	330	10	55	750	5.2
GaAs pHEMT	30	550	8	25	960	3.8
InP pHEMT	60-100	800	6	13	1000	1.7
GaN HEMT	35	800	35	75	6000	49

straightforward implementation of these amplifier circuits without the need for cumbersome co-planar waveguide grounding schemes. Results are presented from MMIC amplifiers in both technologies to validate their potential for military and commercial RF systems.

II. DEVICE RESULTS

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 total defect densities in SiC (10^4 cm^{-2}) are 4-5 orders of magnitude lower

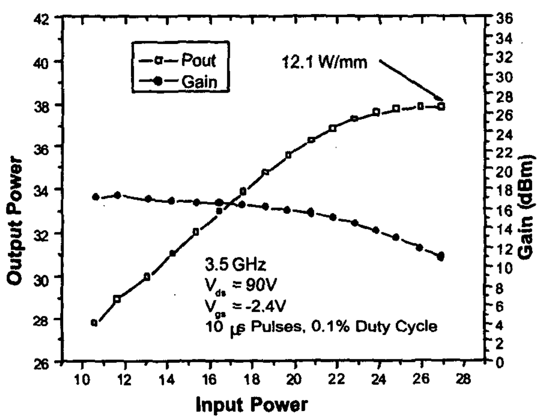
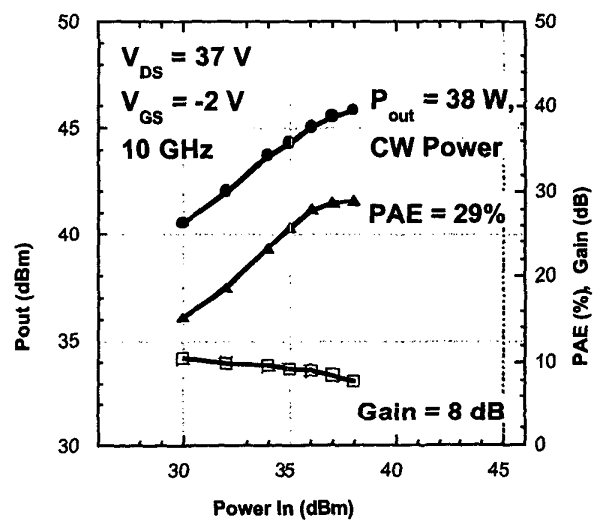


Figure 2. A 3.5 GHz pulsed power sweep of a 0.25-mm GaN HEMT tuned in class A operation with V_{DS} = 90 V. The PAE at peak power was 34%. L_g = 0.4 μm.

than can be typically obtained for GaN material grown on either sapphire or SiC substrates, which should result in higher device reliability. Also, the processes for growing and fabricating SiC MESFET devices are more 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.

Process improvement efforts have focused on reduction of both surface and substrate trapping effects for epitaxial SiC grown on SiC subatrates. The result is 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 load-pull measurement of Fig. 1.

Although AlGaN/GaN HEMTs are less technologically mature than SiC MESFETs, the performance benefits Figure



3: 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 microns.

demonstrated for these devices in both power density and frequency response is remarkable. The two factors most cited as limiting for GaN HEMT power densities are surface trapping, which causes frequency dispersion in current, and low breakdown voltage caused by material defects and processing. We have recently made great strides in the latter by optimizing the material growth and processing, and have been able to measure power densities with bias voltages as high as 90 V. This resulted in an extremely high power density of 12 W/mm in an on-wafer pulsed load-pull measurement of a small, 0.25 mm gate width GaN HEMT on a semi-insulating SiC substrate, as shown in Fig. 2. The PAE at peak power under these conditions was 34%. Since the power dissipation was also extremely high for this demonstration, there was significant channel heating even for such a small device, as evidenced by the drop in power density to 9.3 W/mm under CW operation.

III. HYBRID AMPLIFIER RESULTS

While high W/mm demonstrations provide insight into the potential for GaN devices, the most important demonstration is that of total power from a large periphery

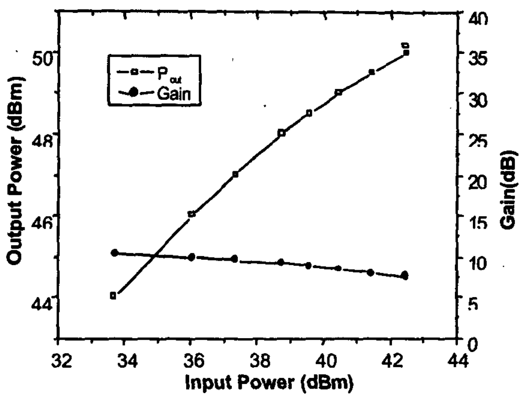


Figure 4: A 2 GHz CW power sweep of a 24-mm GaN HEMT hybrid amplifier.

device, where the effects of device yield and thermal design begin to limit the ultimate performance of the technology. We have grown discrete GaN HEMTs on semi-insulating SiC substrates with a 2 µm thick layer of undoped insulating GaN, followed by a 5 nm thick spacer layer of undoped AlGaN, a 12 nm thick layer of Si-doped AlGaN, and another 10 nm thick undoped AlGaN cap layer. The Al percentage in all of the AlGaN layers was 17%, as measured by photo-luminescence. The devices were fabricated with a total periphery of 12 mm and a gate length of 0.4 µm. Backside vias were etched through the SiC substrate and gold plated to facilitate a low inductance connection to the source pads. Using the discrete 12-mm HEMTs, hybrid amplifiers were designed and assembled to demonstrate high power capability. Parallel-plate capacitors provided a narrow-band reactive match at 10 GHz, and quarter-wave transformers were fabricated on alumina substrates to raise the impedance of the input and output ports to 50Ω. The plot in Fig. 3 shows a power output of 38 W at 10 GHz, with a PAE of 29%. The pulsed power for this device was only marginally higher, 42 Watts, demonstrating excellent die attach and thermal dissipation.

Another recent hybrid result utilizing GaN device packaged for 2 GHz commercial applications appears in Figure 4. This shows CW output power of 102 Watts at 2 GHz with 54% drain efficiency. The fixture used for the measurement has not been optimized for gain. Power gain of 25 dB is typical of GaN HEMTs at this freqeuncy.

IV. MMIC AMPLIFIER RESULTS

The preceding sections have shown amplifiers utilizing simple circuits to provide narrow-band matching optimized for best power and power added efficiency.

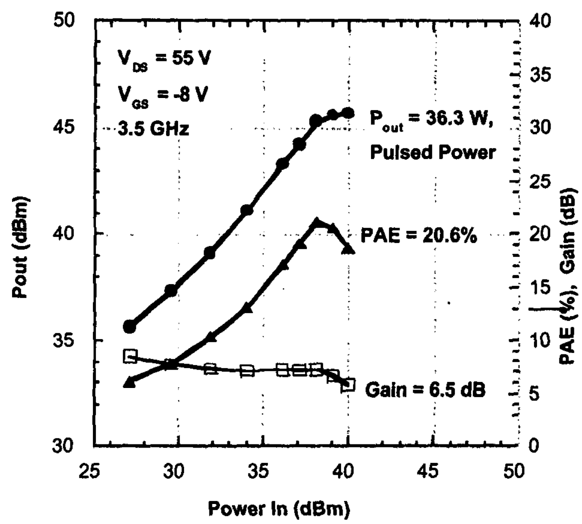


Figure 5: A 3.5 GHz pulsed power sweep of a SiC MESFET wideband MMIC amplifier tuned in class AB operation. V_{DS} = 55 V, 1 kHz PRF, 16 µs pulse width.

Given the comparatively high bias voltage required, approximately 50 V as opposed to the 10 V to 12 V for GaAs, the load-line impedance for optimum wide-bandgap device performance creates a more difficult broad-band design problem. However, for very high total power, significantly less impedance transformation is required for wide bandgap devices to work in a 50Ω system. We have two MMIC results to demonstrate the usefulness of wide-bandgap devices in broadband MMIC applications. We report here on first-pass designs, both of which have been built and tested. Second iteration designs of both are presently being fabricated.

SiC MESFETs can be used to realize high-power, very wide bandwidth MMIC amplifiers in the lower microwave frequency regime, when the basic cell design is combined with through-wafer etched source vias. 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 50Ω. On-wafer testing under pulsed mode conditions at 3.5 GHz was then

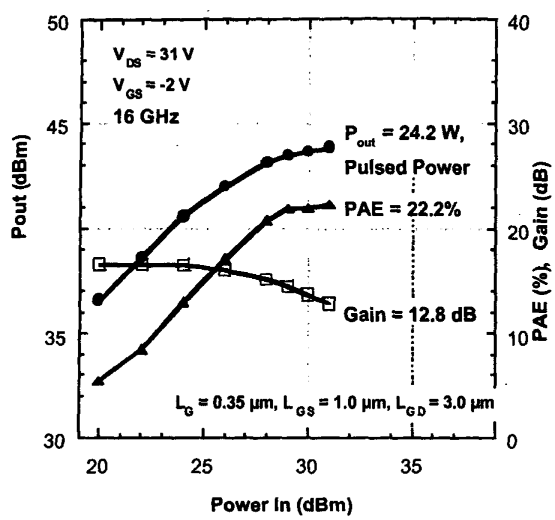


Figure 6: A 16 GHz pulsed power sweep of a GaN HEMT wideband MMIC amplifier tuned in class AB operation. V_{DS} = 31 V, 2 kHz PRF, 20 μs pulse width.

performed with a supply voltage of 55 V and a class AB bias. The RF power sweep in Fig. 5 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.

As with the SiC devices, this GaN technology has also been incorporated into a very wide bandwidth MMIC amplifier design. With our HEMT large-signal models, a two-stage, reactively-matched amplifier was designed with a 3-mm input driving a 6-mm output. All bias circuitry was on chip and the RF ports were matched to 50Ω and 25Ω at the input and output, respectively. Completed amplifiers were tested on-wafer at 16 GHz with a supply voltage of 31V and class AB bias. The RF power sweep in Fig. 6 shows a peak power level of 24.2 watts with an associated gain of 12.8 dB and PAE of 22%. This represents an impressive power-gain combination from a MMIC amplifier operating at 16 GHz.

V. CONCLUSION

Large high power-density amplifiers based on two types of wide bandgap semiconductor devices have been demonstrated. The CW measurements shown for GaN at 2 GHz show that, with proper packaging, high power density devices fabricated on SiC substrates can provide very high levels of power. The MMIC results show the usefulness of these devices for wide-band operation up to 20 GHz.

ACKNOWLEDGEMENT

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