SiC MESFET and MMIC Technology Transition to Production

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Abstract

Significant progress has been made in the development of SiC MESFETs and MMIC power amplifiers manufactured on 3-inch high purity semi-insulating (HPSI) 4H-SiC substrates. MESFETs operating over 5000 at a T_J =140 °C with no degradation are presented. Over two thousand high power SiC MMIC amplifiers have been fabricated with excellent yield and repeatability using our released second generation MMIC foundry process.

INTRODUCTION

SiC MESFETs offer significant advantages for next generation commercial and military systems. Increased power density and higher operating voltage enable higher performance, lighter weight, and wider bandwidth systems. With the transition of our commercial SiC discrete and MMIC foundry operations to a stable 3-inch HPSI substrate platform in mid 2003 [1], continued improvement in reliability, performance, yield, and cost of SiC MESFETs and complex MMIC has been realized. The ability to fabricate SiC MMICs allows another degree of freedom for systems engineers in the development of next generation radar, electronic warfare (EW), and communication systems.

SiC MESFET DEVICE PERFORMANCE

SiC MESFETs have matured in performance and manufacturing process stability. These devices now achieve a power density of approximately 4.0 W/mm and power added efficiencies greater of 60% at T_J of 25ºC on a regular basis. As an example, Figure 1 shows a 1.0 mm gate periphery MESFET operating at 50V producing 3.8 watts of output power at 68% drain efficiency at 3.5 GHz.

In addition to our standard 10 watt commercial MESFET released in 2003, earlier this year we introduced a 60 watt product (CRF-24060) based on the same second generation MESFET process (see Figure 2).

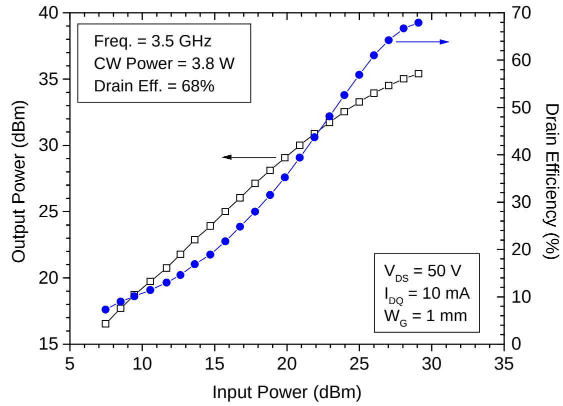

Figure 1: On-wafer CW load pull measurement of SiC MESFET with 3.8 W/mm and 68% drain efficiency.

This part is available as a packaged part or as a bare die to support wide band hybrid applications. The higher output impedance of SiC MESFETs facilitates matching over much wider bandwidths than possible with silicon or GaAs transistors. As shown in Figure 3, over 80 watts of RF output power was achieved from 900 MHz to 1600 MHz with a typical gain of greater than 12 dB using the packaged version of the commercially available part. Power added efficiency (PAE) for the circuit is typically 40% over the entire band with PAE over 50% at 1 GHz. There has been a large amount of interest in this part for both communications and EW applications. An amplifier very similar to the one shown in Figure 4 is also sold as a standard evaluation circuit.

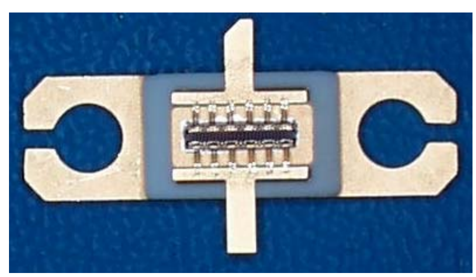

Figure 2: Cree CRF-24060 commercial 60 watt transistor shown without the lid.

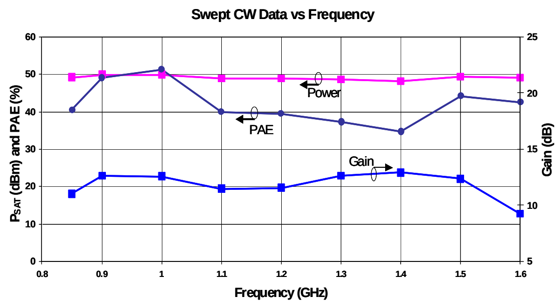

Figure 3: Measured broadband power performance of a Cree CRF-24060 commercial 60 watt transistor

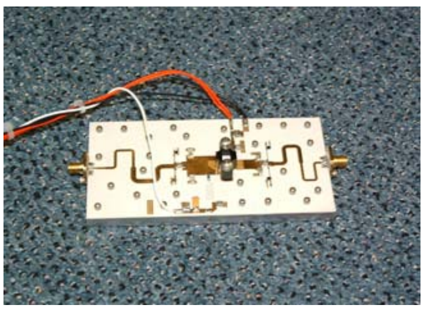

Figure 4: CRF-24060 60 watt transistor evaluation circuit

SiC MESFET RELIABILITY

Reliability studies conducted on second generation 10-watt SiC MESFETs fabricated on HPSI substrates demonstrate robust device characteristics. Figure 5 shows data from a RF-driven operating life test on fifteen 10-Watt SiC MESFETs operating at a T_J = 140°C. The parts under test were driven in 2 dB of compression at 2.6 GHz. After 5000 hours, there was no measurable change in RF output power or other electrical device characteristics. Accelerated life testing has validated that this device process supports a mean time to failure (MTTF) of $2x10^6$ hours at a junction temperature of 175ºC.

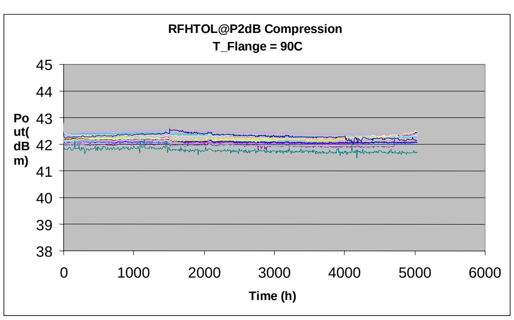

Figure 5: RF Operating Life data on fifteen 10 Watt SiC MESFETs operating at T_J = 140°C showing no degradation after 5,000 hours.

SiC MMIC FOUNDRY PROCESS

Given the rapid progress in the technical performance and reliability of SiC device technology, the focus during the last several years has been process stability, yield improvement, and higher levels of integration (i.e. SiC MMIC development) with the goal of becoming a high volume, low cost supplier of the technology.

With cooperative funding from the US Navy, the Missile Defense Agency, and the Department of Defense's Title III program, Cree has developed a fully qualified 3-inch MMIC foundry process. Demonstrating the same excellent reliability as our line of commercial discrete MESFETs, the SiC MMIC process has started supporting advanced development programs across a wide variety of DoD applications. Table I summarizes the typical performance of the unit cell transistor available in the process.

TABLE I
Typical FET unit cell performance for the foundry process at T_J=25ºC

Drain Voltage	50 V
Gate length	0.5 µm
P_{3dB} Power Density	4 W/mm
PAE at P_{3dB}	60%
Linear Gain at 3.5 GHz	12 dB

The MMIC process is very similar to existing GaAs MMIC processes in that it offers thinned substrates, thin-film resistors, high voltage MIM capacitors, spiral inductors, and through-wafer vias to accommodate FET source grounding and grounding for MMIC microstrip circuit elements. Un-thinned coplanar designs can also be fabricated. The process supports MMIC amplifier performance up to 6 GHz depending on bandwidth and gain requirements. Standard foundry layout design rules and fully scalable non-linear models are available in most of the commonly used commercial circuit simulators for parties interested in designing into the foundry. Alternatively, custom MMIC design services are offered.

Table II shows an example of small signal device parameters for 8 mm unit cells from a recent SiC MMIC foundry lot. As seen, all of the major intrinsic device parameters of interest are well controlled and close to their target values for the process.

TABLE II
Small signal parameters for 8 mm unit cells from a recent SiC MMIC foundry lot showing excellent process control to the target parameters

	Cgs	Cds	Rds	Cdg	gm	to
	(pF/mm)	(pF/mm)	(ohm-mm)	(fF/mm)	(mS/mm)	(ps)
Target	490	180	565	102	30.3	6.03
Foundry Lot	504	180	564	97	29.2	6.08
Offset	2.8%	0.0%	-0.2%	-5.5%	-3.5%	0.8%

Using this second generation released MMIC process, a large number SiC MMIC foundry designs (and thousands of high performance MMICs) have been successfully fabricated for multiple customers over the last 18 months. Figure 6 shows a small signal gain overlay of seventy high power SiC MMICs from a single 3-inch HPSI SiC wafers. The frequency and power information have been removed from the graph for classification reasons. It can be clearly seen, however, that the gain shape and part repeatability are indicative of a very uniform process.

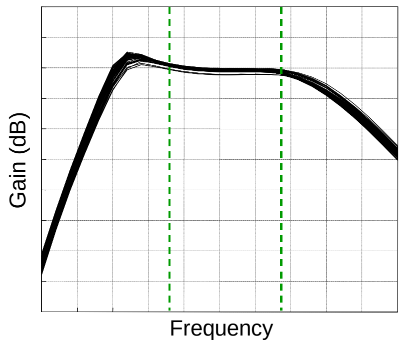

Figure 6: Small signal gain overlay for 70 high power MMICs on a single SiC wafer.

The foundry process also exhibits excellent wafer-to-wafer and lot-to-lot repeatability. An example of this is shown in Figure 7, which shows the small signal gain distribution for over 2,400 high power MMICs. These devices were manufactured across more than thirty SiC wafers and six fabrication lots. As seen, the resulting performance was tightly grouped and well controlled. These parts were subsequently on-wafer load pulled and characterized for large signal output power. Over 83% of the parts passing small signal gain requirements, also passed large signal output power requirements. This data demonstrates that the process is extremely capable of producing large numbers of high performing MMIC power amplifiers with high yield.

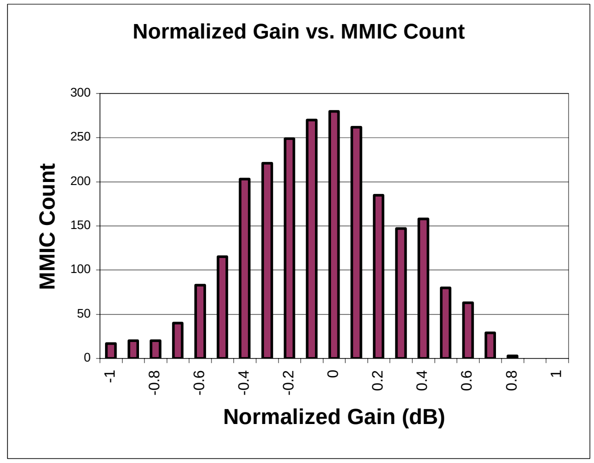

Figure 7: Distribution of small signal gain for over 2,400 high power SiC MMICs produced across six 3-inch wafers lots

CONCLUSIONS

Our 3-inch second generation SiC MESFET process has been released and running for over 18 months. Commercial 10 watt and 60 watt products have been released with reliability that meets or exceeds competing (silicon and GaAs) device technologies. These parts are actively being designed into a wide variety of communication, EW, and radar systems. Our MMIC foundry business is increasing rapidly and has been very successful in demonstrating that large, complex SiC MMICs can be reliably designed and produced.

ACKNOWLEDGEMENTS

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REFERENCES

[1] J.W. Milligan, et al, “Transition of SiC MESFET Technology from Discrete Transistors to High Performance MMIC Technology”, GaAs MANTECH Conference Digest of Papers, Miami, FL (2004).

ACRONYMS

SiC: Silicon Carbide
HPSI: High Purity Semi-insulating
MESFET: Metal Semiconductor Field Effect Transistor
MTTF: Mean Time to Failure
Electronic Warfare: EW