SiC and GaN Wide Bandgap Technology Commercial Status

J.W. Milligan, S. Sheppard, W. Pribble, A. Ward, S. Wood

Cree, Inc., 4600 Silicon Drive, Durham, NC 27703, (919) 313-5564, jmilligan@cree.com

Abstract

Wide bandgap (WBG) devices offer significant advantages for next generation military and commercial systems. SiC MESFETs currently achieve power densities of 4.0 W/mm with power added efficiencies in excess of 60% on a repeatable basis. GaN is also extremely promising as a next generation wide bandgap device. Cree currently offers a number of commercial products targeted at both broadband wireless and general-purpose markets. Results for two such products will be reviewed. SiC MESFETs and GaN HEMT MMICs are also offered through commercial MMIC foundry services using standard design rules and internally developed non-linear models. Using this MMIC process, results will be shown for two new commercial GaN MMIC products that have been developed for general-purpose applications in the 2.5-6.0 GHz and DC-6.0 GHz bands respectively. Additionally, preliminary results are shown for a 2-stage high efficiency S-band switch mode amplifier operating from 3.1-3.5 GHz. Significant progress has also been made in the development of 100-mm SiC substrates which is key for commercializing the technology and providing low costs. Micropipe densities as low as 2.5 cm^{-2} have been demonstrated for 100-mm HPSI substrates. With robust reliability for SiC MESFETs now established for several years, the latest results for GaN device reliability benchmarking are also shown.

INTRODUCTION

Wide bandgap (WBG) technology has matured rapidly over the last several years. SiC MESFETs have proven to be a viable alternative to traditional silicon and GaAs based power devices especially for wide band compressed power applications extending through 4 GHz [1]. Offering breakdown voltages well in excess of 100 volts, extremely low output capacitance per unit RF watt, and extremely robust reliability, the technology is currently in production and now supports a number of military and commercial applications. Cree also offers an established SiC MMIC foundry process which further broadens the scope and applicability of the technology.

In addition to SiC MESFETs, Cree has also been actively developing GaN-on-SiC as an alternative to GaAs and LDMOS devices and has been offering GaN devices for commercial sale since 2006. Like SiC MESFETS, GaN HEMTs operate at high drain voltages and provide extremely high power and wide bandwidth operation. GaN HEMTs also offer a higher f_T (e.g. >27 GHz) than SiC MESFETs and therefore may be more suitable for applications above 5 GHz.

In this paper, we review the current RF performance, commercial status and reliability for SiC MESFETs and GaN HEMTS. We also show examples of discrete devices currently available for sale and microwave circuits (hybrid and monolithic) currently in development that demonstrate the exciting advantages of wide bandgap technology for a variety applications. We also review the status of our 100-mm semi-insulating SiC substrate development.

HPSI 4H-SiC SUBSTRATES

The progression of high purity semi-insulating (HPSI) 4H-SiC substrates from 2-inch substrates just five years ago to the 100-mm (4-inch) substrates available today has been very exciting. Figure 1 shows a photograph of a 100-mm semi-insulating SiC substrate which are available for commercial purchase.

Figure 1.100-mm HPSI SiC substrates available for commercial purchase

Significant progress has been made in the reduction of all major crystal defects occurring in semi-insulating SiC bulk growth, most notably micropipes. Figure 2 shows the micropipe density of a typical 100mm SI SiC substrate.

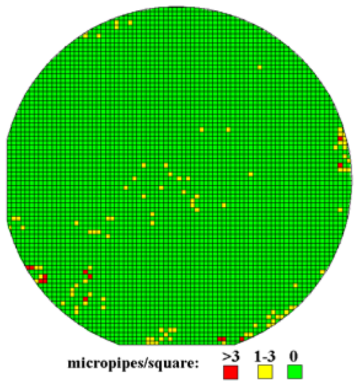

Figure 2. Micropipe map made by optical transmission microscopy showing an average micropipe density of 2.5 cm^{-2}.

As seen in the figure, the average micropipe density across a 100-mm substrate is now typically 2.5 cm^{-2}. This density is more than sufficient to provide extremely good device yield for even large periphery RF transistors. 100-mm semi-insulating SiC substrates are commercially available as bare (epi-ready) wafers or as SiC or GaN epi-wafers.

SiC COMMERCIAL DEVICE STATUS

Cree has been manufacturing and shipping SiC MESFET products in a 3-inch manufacturing process for the last several years and has plans to migrate to a 100mm (4-inch) manufacturing line during calendar 2008. At present, commercial products include 10-watt and 60-watt transistors that are available in a variety of packaged formats, including bare die. Figure 3 shows our 10-watt packaged MESFET along with a typical example of the wideband performance that can be achieved using it. This part has found wide use in many applications requiring extremely wideband operation and is currently shipping in volume production. At 48 volts, our production SiC transistor unit cells typically produce 4 W/mm and greater than 60% power added efficiency at 3.5 GHz.

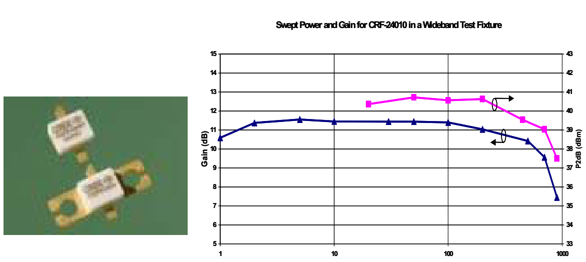

Figure 3. Excellent RF performance from 1-900 MHz using Cree's CRF-24010 standard 10 W SiC MESFET

GaN DEVICE STATUS

Cree GaN HEMTs are fabricated with ohmic and Schottky contacts that are formed directly on the top AlGaN layer. The high-resistivity of the underlying insulating GaN layer provides excellent device isolation. Ohmic contacts are very repeatable with contact resistivity below <0.5 Ω-mm. An offset gate configuration is used to reduce source resistance and increase gate-drain breakdown voltage to accommodate high peak voltages. Gate electrodes are formed by recessing through dielectric to the AlGaN surface and then depositing gate metal. The unit-cell devices exhibit CW on-wafer output power levels of 5.0 W/mm when measured on a load-pull bench at 28 V and 3.5 GHz. At 28 V, the measured unity gain cutoff frequency (f_T) of the technology is approximately 27 GHz for a 0.45 μm optical gate.

Cree continues to add to a growing line of GaN power transistors that are commercially available. An example is shown in Figure 4 which shows the typical performance of our CGH27060F 60-watt part in a circuit optimized for commercial broadband wireless applications (BWA) between 2.5 and 2.7 GHz. The device in this application circuit provides >13 dB of gain, 2.5% EVM, and 25% drain efficiency with 10 watts of average RF output power.

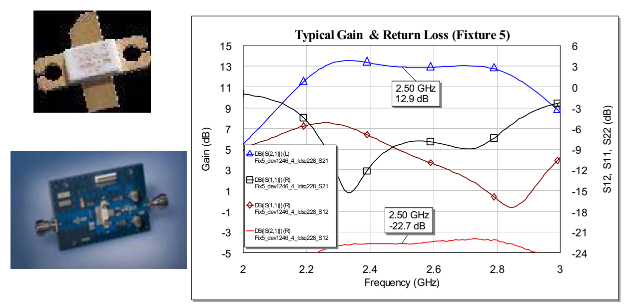

Figure 4. Cree GH27060F in a broadband application circuit designed for BWA applications

Cree's GaN products are also being used to produce very efficient wideband amplifiers for a host of general-purpose applications. An example of one such amplifier is shown in Figure 5 which shows the typical performance our CGH40045F 45-watt power transistor in a wideband circuit covering 800 MHz to 2 GHz. The device in this demonstration circuit exhibits >15 dB of gain and P_{SAT} >50 watts with drain efficiencies between 47 and 56%.

Cree's commercial discrete GaN HEMT products are built upon four die engine with increasing power and periphery (15, 30, 60, and 120 watt die). These discrete die are packaged (with internal matching if required) for both commercial wireless and general-purpose applications. Bare die are also available for customers possessing their own hybrid die-attach capability.

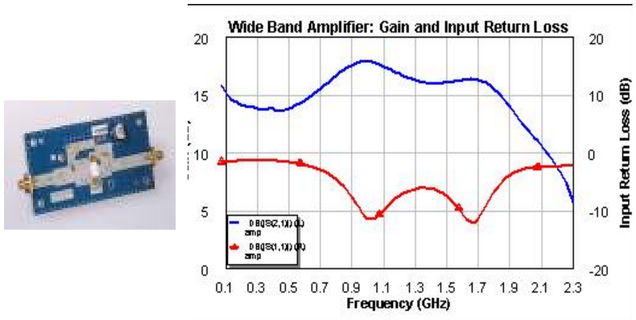

Figure 5. Cree CGH40045FF in a wideband application circuit designed for general purpose applications

DEVICE RELIABILITY

SiC MESFETs

Reliability for Cree SiC MESFETs is now well established. As seen in Figure 6, the activation energy for the dominant failure mechanism is 1.2 eV. This corresponds to a device MTTF of 2.2E6 hours when operated at a junction temperature of 225 °C. As a result, SiC MESFETs are extremely temperature robust and well suited for applications requiring high operating temperatures.

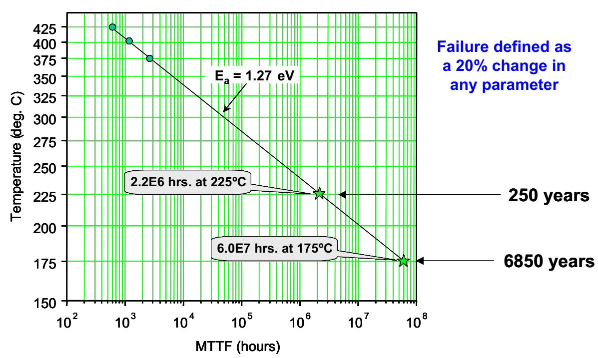

Figure 6. SiC MESFET reliability showing 2.2E6 MTTF at 225 °C junction temperature

GaN HEMTs

Cree is currently benchmarking its baseline 28 volt GaN HEMT commercial process. Preliminary data suggests the process will be capable of supporting a MTTF of approximately 1E6 hours when operated at a junction temperature of 175°C. Figure 7 shows a graph of RF output power versus time for ten packaged 3.6mm HEMTs driven to 2dB compression. As seen, there is very little change in performance over one thousand hours of RF driven operation when operated at 28 volts. The corresponding device junction temperature was ~150° C.

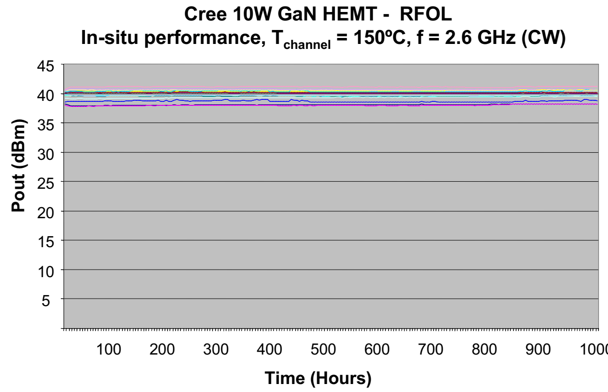

Figure 7. GaN device output power versus time showing no degradation over 1,000 hours when operated 2 dB compressed at 28 volt drain and a junction temperature of 140 °C.

SiC / GaN MMIC FOUNDRY PROCESS

Cree offers both SiC MESFET and GaN HEMT MMIC foundry processes. To support this business, large signal, non-linear models are provided to external designers, along with layout design rules in a process very similar to a traditional GaAs foundry development activity. To aid in this process, process design kits (PDKs) are now available in popular RF simulator platforms.

Cree's MMIC process provides for all of the standard passive components necessary to develop traditional microstrip MMIC designs using wide bandgap transistors. These passive components include airbridges, MIM capacitors, thin film resistors and through-wafer slot vias. The MIM capacitors have been developed to support peak voltages over 100 V. Thru-substrate slot vias are implemented in the 4-mil SiC substrate for each device source contact and for passive element grounding to provide increased gain and a cleaner circuit layout.

Our manufacturing process uses i-line optical steppers for gate lithography that can resolve device gate lengths down to 0.35µm. This gate length is sufficient to produce SiC MMIC amplifiers with useful operational frequencies through 5 GHz and GaN MMICs with operational frequencies through approximately 20 GHz. E-beam processes are also offered to support mm-wave circuit prototyping.

WBG MODULE / MMIC PERFORMANCE

Cree is actively developing high power MMIC and module products to service a variety of commercial and DoD applications. For many applications, high power over wide bandwidths is needed while maintaining high efficiency. Figure 8 shows a GaN MMIC amplifier under development to support general-purpose applications. As seen in the figure, the 2-stage MMIC operates from 2.5-6.0 GHz with 18 dB of small signal gain. The MMIC is conveniently packaged in a 0.5"X0.5" flange mount and is matched to 50 ohms on the input and output. The part provides 25 watts with efficiencies ranging from 30-50% at 28 volts.

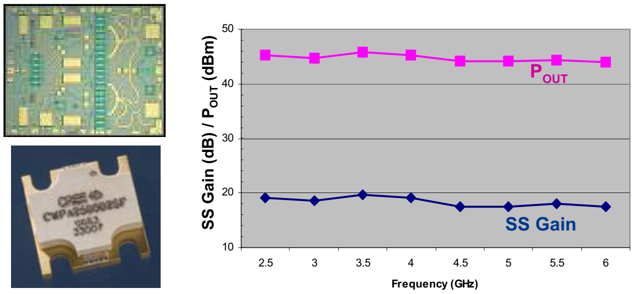

Figure 8. 2-stage GaN HEMT MMIC provides 25 watts of RF output power from 2.5-6GHz with 18 dB of small signal gain at 28 volts.

Cree is also developing a lower power wideband MMIC power amp that could be used as a driver for the part shown in Figure 8 or as a stand-alone general-purpose wideband PA. The amplifier, as shown in Figure 9, operates from 20 MHz to 6.0 GHz with 17 dB of gain. The MMIC is also conveniently packaged is a 0.5"X0.5" flange mount and is matched to 50 ohms on the input and output. The part typically provides three (3) watts of RF output power.

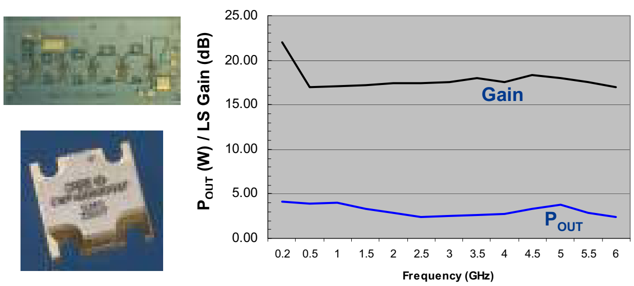

Figure 9. 3-watt packaged GaN HEMT MMIC amplifier with >17 dB of gain from 20 MHz to 6.0 GHz

For the last 3-4 years, Cree has been actively developing high efficiency switch-mode amplifiers. Although amplifiers of this type (e.g. class E, F, S, etc) have shown high power and PAE at VHF [2], conventional III-V power FET technologies have not enabled both high power (>5-10 watts) and high efficiency at microwave frequencies. The unique combination of high breakdown voltage, high peak current, and high f_T provided by GaN HEMTs, however, allow amplifiers of this type to be realized at useful powers through X-band.

Figure 10 shows measured on-wafer performance for a 2-stage, switch-mode, S-band GaN MMIC fabricated using Cree's GaN HEMT MMIC process. The MMIC measures 4.0 mm x 3.0 mm and provides 40 watts of RF output power with 25 dB of associated gain at a PAE of 60% when operated at 28 volts.

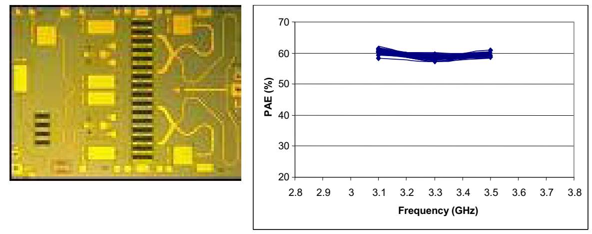

Figure 10. 40-watt 2-stage S-band GaN MMIC with 25 dB of associated gain with 60% PAE from 3.1 GHz to 3.5 GHz

CONCLUSION

Wide bandgap (WBG) devices offer significant advantages for next generation military and commercial systems. SiC MESFET devices currently achieve power densities of 4.0 W/mm with power added efficiencies in excess of 60% on a repeatable basis and are commercially available. GaN is also extremely promising as a next generation wide bandgap device. Both technologies are now also offered through commercial MMIC foundry services and a number of high performance catalog MMIC products are in development. Significant progress has also been made in the development of 100-mm SiC substrates which is key in commercializing the technology and providing low costs. With robust reliability for SiC MESFETs now established for several years, work is on-going to benchmark GaN device reliability with very promising initial results achieved.

ACKNOWLEDGEMENTS

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