Recent Application of Silicon Carbide to High Power Microwave

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ABSTRACT:

Silicon Carbide is an emerging semiconductor material which is now proven to be especially well suited for high power, high frequency applications. Recent results verify the superiority of silicon carbide over both silicon or gallium arsenide for fabrication of high power transistors from DC through X-Band. A silicon carbide UHF television module has demonstrated good signal fidelity at the 2000 Watt PEP level. S-Band transistors show well over 200 watts peak for radar applications, and over 6 Watts has been obtained at X-Band in a silicon carbide MESFET.

Introduction

The material supply and processing requirements of silicon carbide present various fabrication difficulties which are unique among current semiconductors, and has required new techniques for dealing with the relatively high defect levels and variability of currently available material. Northrop Grumman began applied research into silicon carbide materials, processing and device design at the Science and Technology Center in Pittsburgh PA several years ago. More recently, an additional device development capability has been added at the Advanced Technology Laboratory in Baltimore MD and a pilot production facility has been established there for UHF transistors.

High power silicon carbide transistors have been successfully assembled using matching and packaging techniques which are similar those employed in commercial silicon bipolar technology. The very high voltage of silicon carbide has been found to effectively complement the high power levels which are achieved, resulting in overall device impedance levels which are higher than with silicon technology, even though the power levels are also considerably higher.

Silicon Carbide Transistor Structures for Microwave Operation

Two types of microwave transistors have recently been developed and demonstrated at Northrop Grumman. The Static Induction Transistor (SIT) shows best performance for high peak power applications up to about 4 GHz [1][2][3][4]. The MESFET structure complements this performance for higher frequency operation up through 10 GHz, and operates well under pulse or CW conditions. Both devices have been shown capable of exceeding the historic power density limitations of silicon and gallium arsenide by over a factor of four.

UHF SIT Development and Application

Low frequency SITs were developed and produced in pilot production quantities for the UHF television band. These were second generation devices and contain many refinements to those previously reported [1][3]. The UHF television transistors were packaged in a push-pull gemini package, figure 1. Each side of the device has a capability of housing 3 SiC chips with 14 cells maximum per chip.The largest such gemini transistor would be 84 cells with output power potential of 350 Watts average (1750 Watts peak). The gemini transistor used for the experimental transmitter contained only 24 cells producing 60 Watts average (300 Watts peak) with -30 dB third order products at 9.5 dB Gain. This device was 35% efficient, operating at 60 Vdc drain and -10 Vdc gate voltages. The power levels are derated

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from their peak potential due to the linearity requirements of the broadcast application.

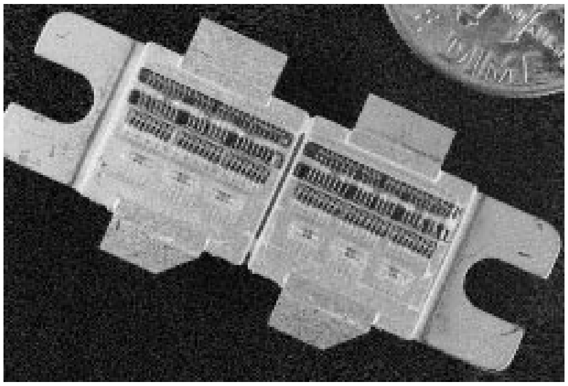

Figure 1. Push Pull Silicon Carbide SIT

A demonstration UHF Silicon Carbide power module was used at the National Association of Broadcasters Convention in 1996 for an over-the-air broadcast of High Definition Television (HDTV). Figure 2 shows the module with a one driving four transistor architecture which was used in the module to provide 200 Watts average (1 KW peak) output power out of the transmitter with better than -30 dB third order products. The linearity requirements limited the module output power for the television application, and the module is actually capable of 400 Watts average (2.0 KW peak). These performance levels are achieved from 4 gemini push-pull output transistors utilizing only 30% of the transistor package capacity.

Under class C operation, the same 24 cell gemini transistor produces over 350 Watts peak output power at efficiencies greater than 50% with greater than 10 dB Gain.

S-Band Device Scaleup

SIT cells fabricated at the Northrop Grumman Science and Technology Center have previously shown proof-of-principle for high gain and power density at S-Band [2][3][4] . The S-Band SIT process has recently been used at the Northrop Grumman Advanced Technology Laboratory pilot production silicon carbide line.

Multiple one centimeter periphery cells were fabricated on die measuring 800 by 3000 microns. Cell pitch was 250 microns, such that three die and 36 cells total could be packaged in a standard 0.4 by 0.5 inch Kyocera package pill.

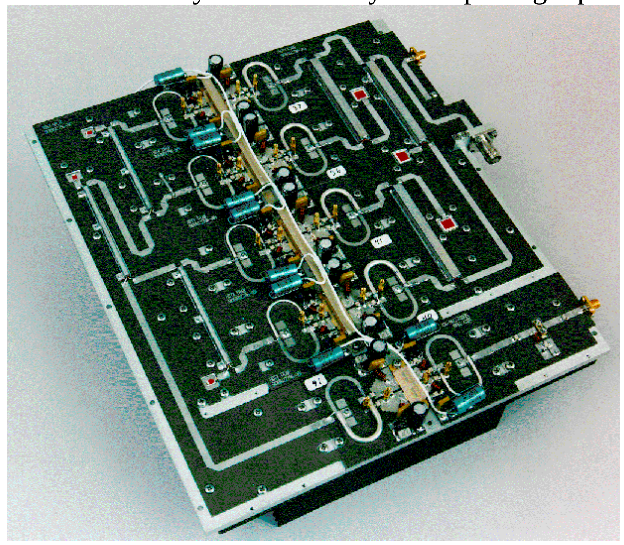

Figure 2. Silicon Carbide UHF TV Module

An initial package was assembled with 19 cells wired in parallel. A single step LC matching circuit was included on the input side using bondwire inductance and a silicon MOS film capacitor. The parallel summed output capacitance was measured at 13.3 pf and was resonated in the package using a parallel inductance consisting of multiple bondwires and a MOS DC blocking capacitor. The input impedance level was measured as 3.0+j6.55 ohms at 2.9 GHz. The impedance of the optimum large signal load, referenced to the package interface, was measured at 6.6+j0.3 ohms at 2.9 GHz. Figure 3 shows the packaged device assembly.

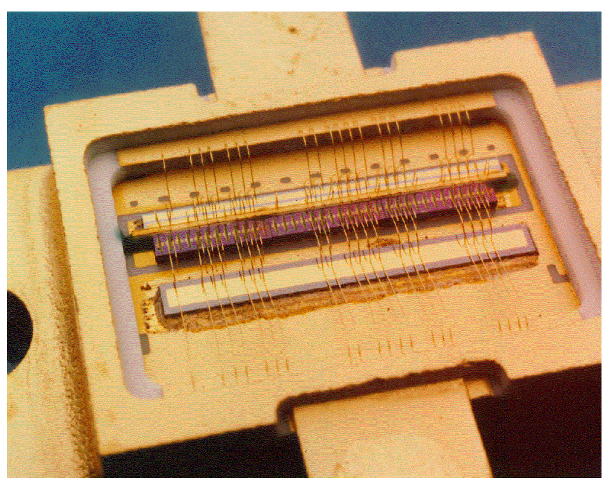

Figure 3. 19 cell, 200 Watt S-Band SIT

The transistor was operated in a Class AB pulse mode with 90 volt drain voltage, and 500 mA quiescent current. Data was taken at both 25 microseconds and 250 microseconds pulse length with performance summarized in figures 4 and 5. Very linear operation was obtained over a wide dynamic range, and a soft saturation characteristic was obtained, similar to that found in the UHF devices. Heating effects in the long pulse case produced an 0.8 dB drop in gain as compared to the shorter pulse. This gain drop correlates with the calculated cell transient temperature and a gain sensitivity of 0.013 dB per degree C. This is a similar temperature vs. gain sensitivity to that observed in silicon and gallium arsenide devices. No equivalent degradation was observed in the device drain efficiency.

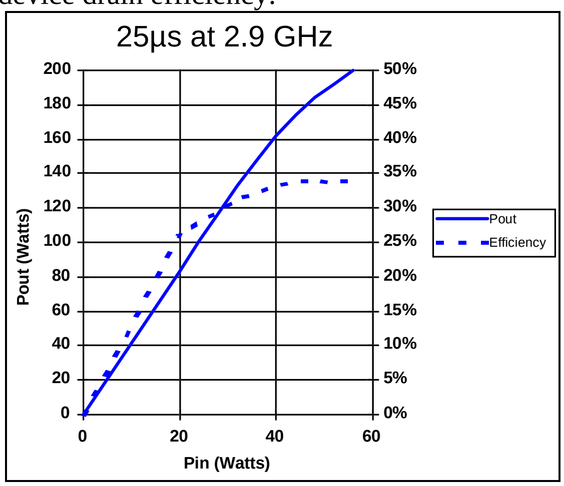

Figure 4. Short Pulse Operation of 19 Cell SIT

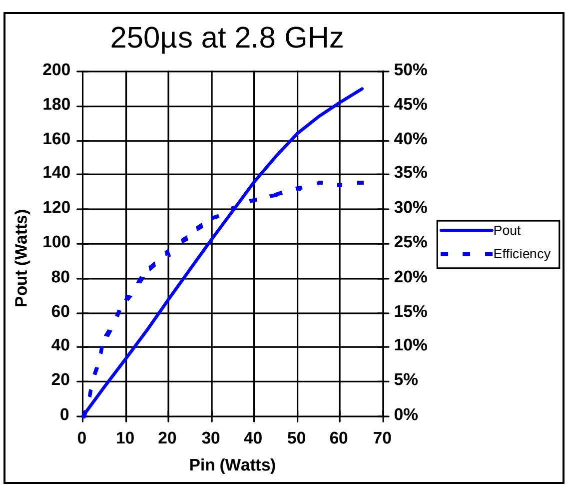

Figure 5. Long Pulse Operation of 19 Cell SIT

Silicon Carbide MESFET Development

MESFETs were fabricated on high resistivity 6H-SiC substrates by electron beam direct write processing. The gate length in these devices was 0.5 µm and the gate-source and gate-drain spacings were 0.5 µm and 1 µm, respectively. Air-bridges were used to interconnect the source fingers of multi-finger devices, and devices up to 6.4 mm periphery have been fabricated using this process.

Small signal RF gain measurements [5] show excellent 8.5 dB gain at 10 GHz with an f_{max} of 25 GHz and an f_t of 10 GHz. Power measurements made at 40V drain bias for a 2 mm periphery 6H-SiC MESFET at 6 GHz yield 3.5 W, with 45.5% power added efficiency and 6dB of associated gain.[6] The power output corresponds to 1.75 W/mm and is nearly three times larger than that normally obtained with GaAs MESFETs. The power performance and the operating frequency reported here are the highest yet reported for 6H-SiC devices.

4H-SiC offers higher performance potential than 6H devices due to the higher mobility and the shallower donor ionization energies in 4H-SiC. We have fabricated similar MESFET structures in 4H-SiC which produce channel currents greater than 500 mA/mm which is nearly a factor of two higher than that obtained with 6H-SiC. The dc transconductance, g_m, is also higher in these devices and shows a maximum value of 40 mS/mm. These MESFETs also exhibit high gate-drain breakdown voltages of about 100 V (at 0.5 mA/mm).

Small-signal RF performance of 4H-SiC MESFETs are shown in figure 6. [7] It may be seen that these devices show a maximum available gain (MAG) of 5.1 dB at 20 GHz. Extrapolation of Mason's unilateral gain at 6 dB/octave yields a f_{max} value of 42 GHz which is the highest reported to date for SiC devices.

More recently, we have demonstrated high power operation of 4H-SiC MESFETs at X-band. We have obtained power output of 6 Watts at 10 GHz using a 1.92 mm periphery MESFET with 0.5 µm gate length. (Figure 7). The associated gain, drain efficiency, and power added efficiency were 5.1 dB, 50%, and 34.6% respectively.

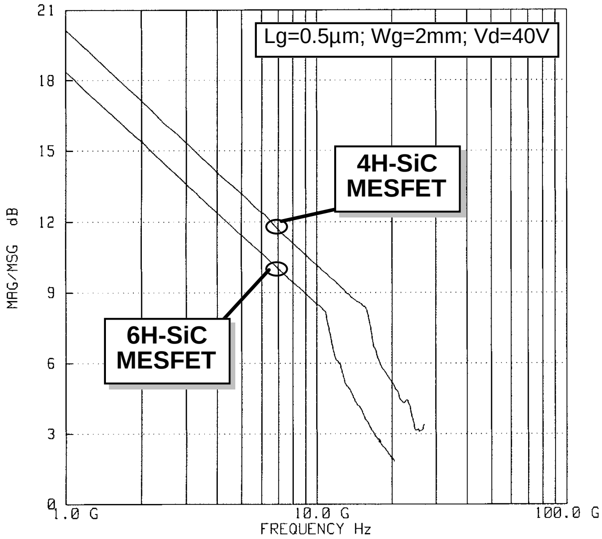

Figure 6. Small signal characteristics of 6H and 4H MESFETs

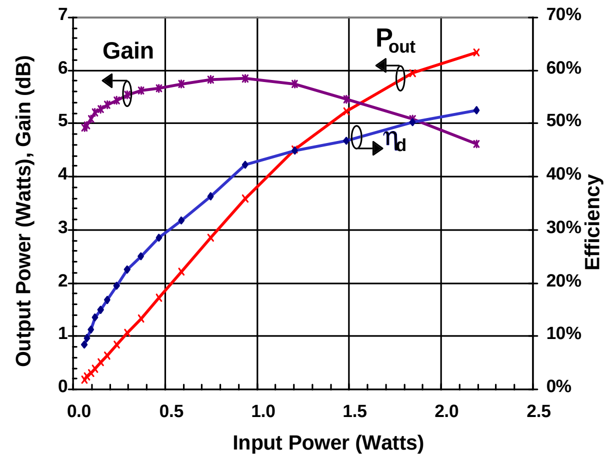

Figure 7. Performance of SiC MESFET at 10 GHz

These results were obtained under Class AB conditions with the gate biased at 10% I_{DSS}. A higher power output of 6.35 W (3.3 W/mm) was obtained at higher input drive level with 4.6 db gain, and 52% drain efficiency. These power results were obtained under pulsed conditions with 100 µs wide pulses at 10% duty cycle and a drain bias voltage of 45 V. To our knowledge, the present results represent the highest power output obtained at X-band using wide bandgap semiconductors. The power density at X-band is also the highest reported to date. Further improvements in performance can be expected by optimizing the device structure.

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