Progress in SiC Materials and Microwave Devices

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ABSTRACT

Significant progress has been achieved in making larger (2 inch) 4H-SiC substrates with much lower micropipe defect densities. With the recent availability of semi-insulating 4H-SiC substrates, the demonstration of impressive microwave power results have been made possible both in SiC MESFETs and in GaN/AlGaN HEMTs grown on these substrates. SiC MESFETs have achieved RF power densities of 4.6 W/mm and 4.3 W/mm at 3.5 GHz and 10 GHz, respectively. The largest total RF output power from a single MESFET is 80 watts CW at 3.1 GHz. GaN/AlGaN HEMTs fabricated on these substrates have demonstrated a record 6.9 W/mm at 10 GHz, and a total RF output power of 9.1 watts CW at 7.4 GHz .

INTRODUCTION

Silicon carbide technology has made tremendous strides in the last several years, with a variety of encouraging device and circuit demonstrations being made on SiC substrates. The commercial availability of relatively large, high quality wafers of the 6H and 4H polytypes of SiC for device development has facilitated these exciting breakthroughs in laboratories throughout the world. These have occurred in numerous application areas, including high power devices, and high power/high frequency devices. This paper will describe progress made in increasing the quality and size of SiC wafers, the thermal conductivity of the substrates, and some of the resulting microwave device demonstrations in both SiC MESFETs and in GaN/AlGaN devices grown on SiC.

SILICON CARBIDE SUBSTRATES

To enable the commercialization of SiC, specific focus has been placed on achieving larger diameter high quality substrates. This has led to the production of 50 mm diameter 4H and 6H wafers for mass production of LEDs, and the demonstration of 75 mm wafers. Despite the growing interest in SiC, the micropipe defects that occur in the material are seen by many as preventing the commercialization of many types of SiC devices, especially high current power devices, such as MESFETs, and both p-i-n and Schottky rectifiers. However, in SiC boules grown by the seeded sublimation method, recent results show a reduction in the micropipe densities by over an order of magnitude. The continuing improvement of wafer quality and the production of wafers with micropipe densities of less than 1 cm^{-2} indicate that micropipes will be reduced to a level that makes high current devices viable, and that these defects may eventually be totally eliminated. Figure 1 shows the decrease in micropipe density for Cree's best R&D wafers over the past 5 years. During this time the diameter of the wafers measured has gone from 25 mm to 30 mm to 35 mm. The best results achieved to date was a total of 7 micropipes on a 35 mm 4H-SiC wafer, which translates to a density of 0.5 cm^{-2}. The lowest density in a 50 mm diameter wafer is less than 2 cm^{-2}.

The high thermal conductivity of SiC is a major advantage for the production of high power microwave and power switching devices. In order to take advantage of the high power densities available in this material, it is also necessary to dissipate very high power densities, making the

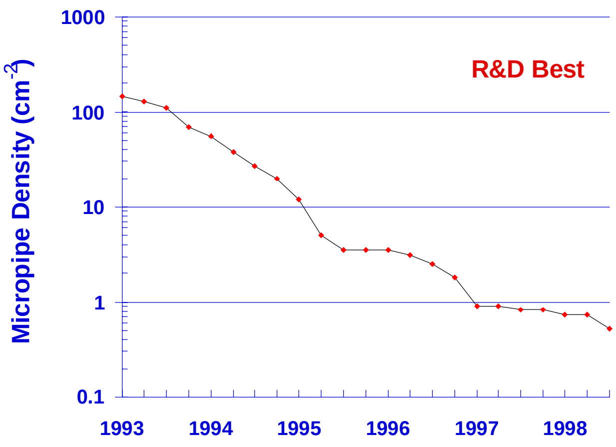

Figure 1: Plot of micropipe density vs. year for “best” SiC wafer produced at Cree Research.

TABLE I

THERMAL CONDUCTIVITY DATA FOR SiC

Sample Type	Direction	Carrier (cm^{-3})	Thermal Conductivity 298 K (W/cm-K)	373 K (W/cm-K)
4H Semi Ins.	// c	S.I.	3.3	2.6
4H n	// c	2.0e18 n	3.3	2.5
4H n	⊥ c	5e15 n	4.8	2.9
6H n	// c	1.5e18 n	3.0	2.3
6H n	// c	3.5e17 n	3.2	2.3
6H n	⊥ c	3.5e17 n	3.8	2.8
6H p	⊥ c	1.4e16 p	4.0	3.2
Slack[1]	⊥ c	~1e17	~5	~3

thermal conductivity an extremely important parameter. Thermal conductivity data is plotted in Table I for low doped n- and p-type, doped n-type and semi-insulating material. The thermal conductivity was measured by creating a temperature difference across a piece of SiC. Thermocouples were inserted into holes drilled 1 cm apart and ΔT and applied power were used to calculate the thermal conductivity at 25°C and 100°C. Copper and Al were used as calibration standards. Thermal conductivity is the product of a material's density, heat capacity and its thermal diffusivity: the latter being dependent on the doping and quality of a material. The very low doped material exhibits a-axis thermal conductivity roughly the same as that reported by Slack [1] for pure Lely platelets. The doped materials and c-axis direction have significantly lower thermal conductivity values.

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SiC MICROWAVE MESFETS

The development of high quality semi-insulating (SI) 4H-SiC substrates has enabled very significant advances in high power microwave devices. Cree’s optimized S-band power FETs have a gate length of 0.7 µm and employ a channel doping of 3×10^{17} cm^{-3}. These FETs are designed to have a threshold voltage of V_{gs} = -10 V, resulting in an I_{dss} of 300 mA/mm at V_{ds} = 10 V and a peak transconductance of 45 mS/mm. With this device structure, 1-mm FETs typically have a three-terminal breakdown voltage V_{ds} > 150 V, defined at the 1 mA/mm point. As determined from small-signal S-parameter measurements, average values for frequency response are f_T = 9 GHz and f_{max} = 20 GHz.

From these devices a maximum power density of 4.6 W/mm at 3.5 GHz has been measured using an on-wafer load pull system. As shown in Figure 2, a 0.25-mm FET operating at a drain bias of 60 V had a peak power of 1.15 W, a Class A PAE of 39% and an associated power gain of 12.5 dB. A similar device operating at 800 MHz had a power density of 3.0 W/mm and an improved PAE of 60%, as shown in Figure 3, demonstrating that the intrinsic efficiency of SiC MESFETs can be high. Both the high power density and the high efficiency are derived from the ability of the devices to be biased at very high operating voltages.

A single SiC MESFET chip with 48-mm of gate periphery was packaged in a hybrid circuit with input and output matching networks fabricated from alumina, and produced 80 watts CW at 3.1 GHz with 37% PAE, as shown in Figure 4. This is the highest CW power level ever reported for a single device operating at this frequency, and demonstrates the potential of SiC to have a substantial impact on solid state microwave power amplifiers.

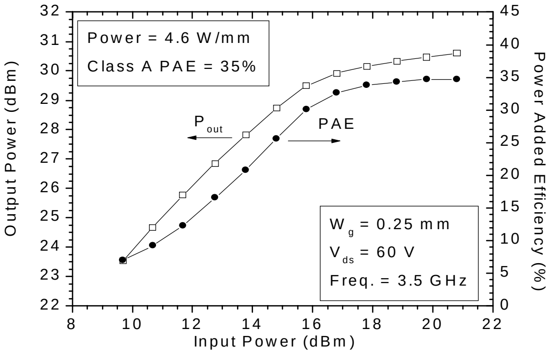

Figure 2: 0.25-mm SiC MESFET with a peak power density of 4.6 W/mm at 3.5 GHz with a drain bias of 60 V.

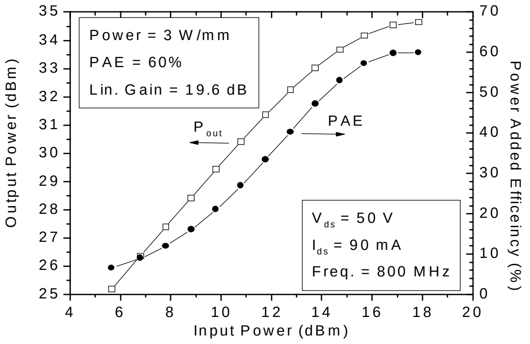

Figure 3: 0.84-mm SiC MESFET with a peak PAE of 60% and 3.0 W/mm from on-wafer load pull at 800 MHz.

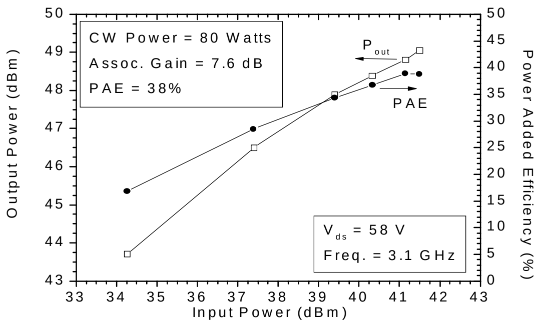

Figure 4: Power sweep of a 48-mm SiC MESFET at 3.1 GHz showing a CW power level of 80 W.

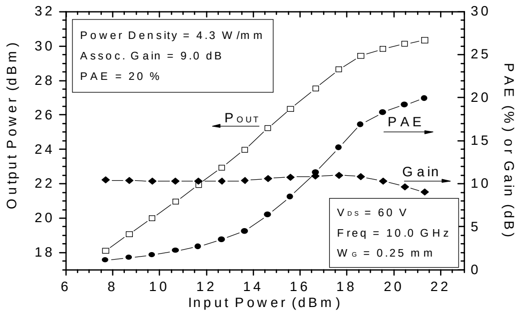

Figure 5: On-wafer load pull sweep of a SiC MESFET with a 0.45 µm gate length showing 4.3 W/mm at 10 GHz.

With an increase in the channel doping and a reduction of the gate length to 0.45 µm, SiC MESFETs have shown excellent power performance up to 10 GHz. As illustrated by the power sweep in Figure 5, a power density of 4.3 W/mm was measured from a 0.25-mm MESFET at 10 GHz, with a peak power of 1.1 W, a Class A PAE of 20% and an associated gain of 9 dB.

GaN/AlGaN HEMTS ON SiC SUBSTRATES

Yet another demonstration of the advantages of semi-insulating SiC is its impressive benefit recently demonstrated as a substrate for GaN/AlGaN High Electron Mobility Transistors (HEMTs). The close lattice match between SiC and GaN results in a lower defect density epilayer than typically obtained with growth of GaN on sapphire substrates. Additionally, the much high thermal conductivity of the SiC substrate is critical for dissipating the very high power densities possible with the GaN system. GaN devices fabricated on sapphire substrates have achieved relatively high power densities, but the junction temperatures at which these levels are achieved are typically in excess of 300°C due to the very high thermal impedance of the substrate[2]. The structure of the GaN/AlGaN HEMT devices fabricated on SiC substrates is shown in Fig. 6. The structure contains an AlN buffer layer, 2 µm of undoped GaN and approximately 27 nm of $Al_{0.14}Ga_{0.86}N$. The AlGaN cap layer comprises a 5 nm undoped spacer layer, a 12 nm, $2x10^{18}/cm^3$ Si-doped donor layer and a 10 nm undoped barrier layer. Device isolation is achieved with shallow mesas dry etched in a chlorine-based plasma.

Typical dc output characteristics of a 1-mm-wide HEMT with L_G = 0.45, L_{GS} = 1.0 and L_{GD} = 1.5 µm show a peak current of 680 mA/mm at V_{GS} = +2 V and a maximum extrinsic transconductance near V_{GS} = -0.5 V of 200 mS/mm. Typical three-terminal gate-drain breakdown voltages range between 60-70 V. Small-signal gain measurements at V_{DS} = 20 V and V_{GS} = -1 V show an extrapolated unity gain frequency f_T of 28 GHz [3]. The maximum available gain (MAG) remained high up to the maximum frequency of the network analyzer, so the f_{MAX} of this device is estimated to be 114 GHz by modeling the power gain above 35 GHz. The effective channel electron velocity, as determined from the slope of the f_T vs. $1/L_G$ data from many devices, lies in the range 6-8x10^6 cm/s.

On-wafer measurements were performed on a Maury load-pull system at 10 GHz and a drain bias of 30 V. A power sweep for a 0.125 mm HEMT (L_G = 0.45, L_{GS} = 0.5, and L_{GD} = 1.0 µm) is plotted in Fig. 7. The most significant result was a record RF power density of

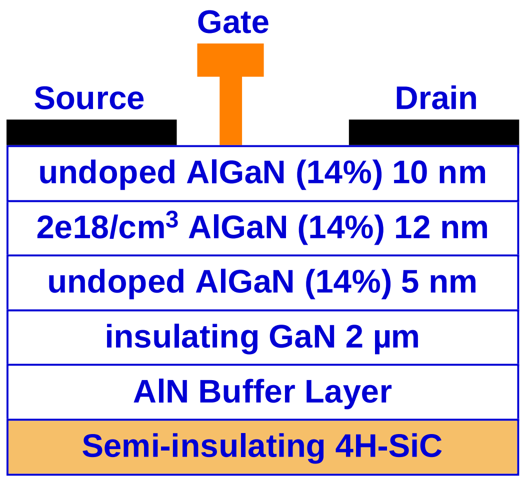

Figure 6: Cross-sectional view of the GaN/AlGaN HEMT structure grown on a semi-insulating 4H-SiC substrate.

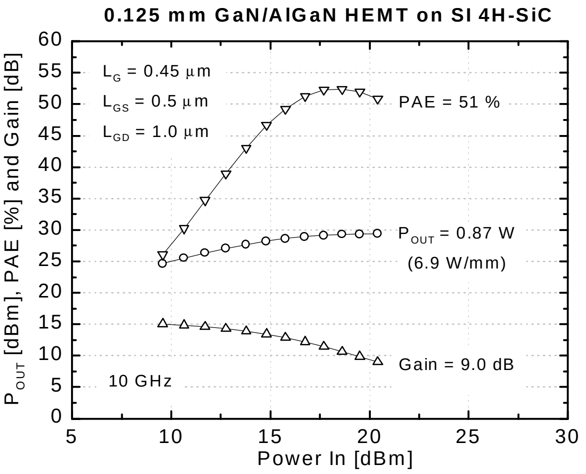

Figure 7: A 10 GHz CW power sweep for a 0.125-mm GaN/AlGaN HEMT on SI 4H-SiC (performed at the Air Force Research Laboratory, SNDM) that shows a record power density of 6.9 W/mm. The device was biased at V_{DS} = 30 V and V_{GS} = -2.25 V.

6.9 watts/mm with a PAE of 51 % and an associated gain of 9 dB, that was achieved at -6.0 dB of compression (~4.3 W/mm at -1 dB compression). This power density is about 8 times higher than typical GaAs devices, and is more than twice as high as any other GaN HEMT grown on a sapphire substrate, affirming the potential for AlGaN/GaN HEMTs on SI 4H-SiC substrates for use in high power amplifiers at X-band. When tested at 16 GHz, this device showed a CW power density of 4.4 W/mm with a PAE of 27% and an associated gain of 6.9 dB at the -3 dB compression point, which also demonstrates their advantage for high-power Ku-band operation.

In order to measure total RF power on larger parts, HEMTs with 3 mm of gate width were packaged with ceramic input and output matching networks. After thinning the SI 4H-SiC substrate to approximately 4 mils, the HEMT was packaged into a hybrid matching network on a carrier that was maintained at 18°C. The power sweep shown in Fig. 8 represents a single 3-mm device tested at 7.4 GHz. During the part of the sweep up to 30 dBm input power, the device was biased at V_{DS} = 28.4 V and V_{GS} = -1.8 V. The drain bias was changed to 31 V for the last three data points to achieve a maximum output power of 9.1 watts, a PAE of 29.6 % and an associated gain of 7.1 dB (~2.1 W/mm at -1 dB compression). The high parasitic source inductance introduced into the hybrid circuit by the Au ribbon bonds reduced the gain and frequency response, and the characterization of the 3-mm HEMT at 10 GHz was unwarranted. When source via holes are incorporated in the GaN-on-SiC HEMT process, the total RF power is expected to improve, even at 10 GHz. The 9.1 watts achieved on this device is the highest total RF power ever achieved in a GaN HEMT

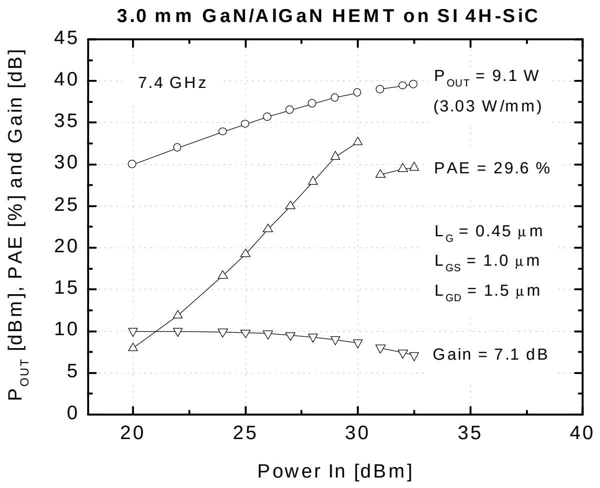

Figure 8: A 7.4 GHz CW power sweep for a 3-mm GaN/AlGaN HEMT on SI 4H-SiC in a hybrid matching circuit. For the initial part of the sweep, the device was biased at V_{DS} = 28.4 V and V_{GS} = -1.8 V. The drain bias was changed to 31 V for the last three data points to achieve a maximum output power of 9.1 watts.

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