# SILICON CARBIDE MESFET's WITH 2 W/mm AND 50% P.A.E. AT 1.8 GHz

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## Abstract

Silicon carbide MESFET's with 0.7 μm × 332 μm gates under Class B bias at 1.8 GHz had $P_{1dB}$ = 28.3 dBm (2 W/mm CW) and 50.4% PAE. At the same power density, these FET's had 66% PAE at 0.85 GHz. This high power density combined with the extremely high thermal conductivity of SiC makes it a promising technology for high power microwave applications.

## Introduction

Silicon carbide (SiC) MESFET's are emerging as a promising technology for high power microwave applications due to several unique properties of SiC, including a high breakdown electric field, high saturated electron velocity and high thermal conductivity. In this paper we report on SiC MESFET's with 0.7 μm × 332 μm gates that were measured under Class B bias at 1.8 GHz to have $P_{1dB}$ = 28.3 dBm (2 W/mm) and 50.4% power added efficiency (PAE). This is the highest combination of power density and efficiency reported to date for SiC devices at this frequency. This same device had 2 W/mm and 66% PAE when measured at 850 MHz, indicating that SiC MESFET's are capable of simultaneously delivering very high power densities and high drain efficiencies.

The rolloff in PAE with frequency was due to the fact that these FET's had an $f_{max}$ of only 16 GHz. With the advent of semi-insulating SiC substrates [1] [2], the $f_{max}$ of SiC MESFET's has more than doubled, as evidenced by recent reports of 32 GHz [3] and 42 GHz [4] devices. With this substantial increase in the frequency response, combined with recent improvements in substrate size and quality [2], SiC MESFET's should rapidly become an important technology in the microwave power arena.

## Advantageous Properties of Silicon Carbide

SiC occurs in over 200 different crystal structures, or polytypes, but for semiconductor applications the 6H and 4H polytypes have received the most attention due to the availability of high quality single crystalline substrates. For microwave MESFET's the 4H-SiC polytype is preferable because it has a larger bandgap and higher electron mobility than 6H-SiC. It is the wide bandgap of 3.2 eV, as compared to 1.1 eV for Si and 1.4 eV for GaAs, that gives SiC its primary advantage for high power microwave devices. This wide bandgap gives rise to a breakdown electric field that is 10 times higher than in GaAs, and this has been exploited to make SiC MESFET's with breakdown voltages exceeding 100 V.

The one drawback to SiC for use in microwave devices is its poor low-field electron mobility, which is in the range of 300 - 600 $cm^2$/V-sec. for doping levels of interest for MESFET's, i.e., $1\times10^{17}$ $cm^{-3}$ < $N_d$ < $5\times10^{17}$ $cm^{-3}$ [5]. This results in a larger source resistance and lower transconductance than is typical of GaAs MESFET's, but is partially offset by the ability to operate the SiC devices under extremely high electric fields. The saturated electron velocity in 6H-SiC is $2\times10^7$ cm/s and has been predicted to be $2.7\times10^7$ cm/s in 4H-SiC [6], almost 3 times higher than in GaAs at high fields. Although the knee voltage of SiC MESFET's is relatively high (typically ≈ 10 V), the drain efficiency of the devices is still high because the breakdown voltage is over 100 V. The channel current density is reasonably large, over 300 mA/mm for 0.7 μm gate length devices [7], due to the high saturated velocity. When combined with the high breakdown voltage, this results in the large power density observed for SiC MESFET's.

The other property of SiC that gives it a significant advantage over other semiconductors is its thermal conductivity of 4.9 W/K-cm, which is 3.3 times higher than in Si and 10 times higher than in GaAs. This means that not only is the power density of SiC high in

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terms of W/mm of gate periphery but SiC also has extremely high power handling capability in terms of $W/mm^2$ of die area. For high power, high frequency applications, this is the more important figure of merit since die size becomes constrained by wavelength. Because of the excellent thermal properties of SiC, the ultimate power level attainable from a SiC MESFET at any given frequency should be at least 5 times that of devices made from GaAs [8].

### Recent Advances in SiC Substrates

The development of SiC electronic devices has been limited in the past due to the availability of large, high quality SiC substrates. The primary defects in bulk SiC are micropipes, which are superscrew dislocations in the crystal that have open cores, resulting in pinholes in the wafer. Recently Cree reported advances in crystal growth technology that resulted in producing 4H-SiC wafers with a micropipe density of 3.5 $cm^{-2}$ [2], which is 2 orders of magnitude smaller than it was 3 years ago. Because the active area of microwave MESFET's is very small, limited to the source drain separation of 3 to 5 μm, a micropipe density of < 10 $cm^{-2}$ has a negligible contribution to yield.

Wafer size has been increasingly steadily over the past several years, and this rate is accelerating in order to keep pace with the world wide demand for SiC substrates. The devices reported here were fabricated on 30 mm substrates. Cree has recently shifted its high volume production of blue LED's (GaN epi layers on SiC substrates) to 40 mm wafers and plans to transition to 50 mm wafers (standard 2-inch) in the near future.

The availability of bulk grown semi-insulating SiC removes the final impediment for using SiC as a substrate for high frequency devices. Most of the SiC MESFET's fabricated to date have had limited frequency responses due to the conductive substrate, just as Si bipolar transistors are limited by the substrate. Figure 1 shows the measured resistivity of one of these recently developed 4H-SiC substrates. The resistivity of these wafers was so high that it could not be measured with a conventional Hall effect technique. Instead, the resistivity shown in Figure 1 was determined from I-V measurements that were made using a picoammeter with the substrate at high temperatures. By extracting an activation energy for the deep level dopants that are used to create the semi-insulating material, a room temperature resistivity in the range of $10^{13}$-$10^{15}$ Ω-cm is determined. Semi-insulating 6H-SiC has also been reported to have room temperature resistivities in the $10^{15}$ Ω-cm range [9].

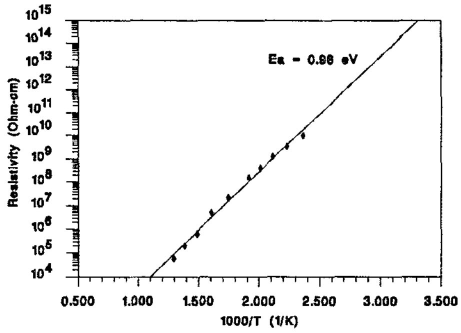


Figure 1: Resistivity of semi-insulating 4H-SiC substrates as determined using high temperature I-V measurements.

### SiC Power MESFET's

A cross section of the SiC MESFET is shown in Figure 2. The FET's on which the power data were obtained were fabricated on conducting 4H-SiC substrates, and thus required the thick p- buffer layer to provide isolation. Due to the substrate parasitics, the frequency response of these devices was limited to $f_T$=7 GHz and $f_{max}$=16 GHz. Similar FET's have recently been fabricated on semi-insulating 4H-SiC substrates [3], and the frequency response of these devices was improved to $f_T$=14 GHz and $f_{max}$=32 GHz, as shown in Figure 3.

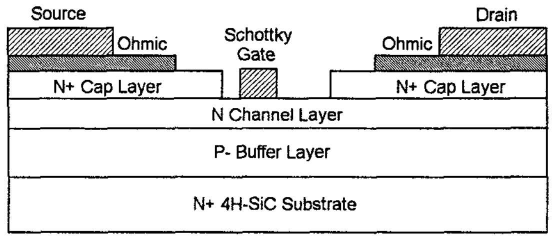


Figure 2: Cross section of a SiC MESFET. An epitaxially-grown p- buffer layer was required to provide isolation from the conductive substrate.

The MESFET's consisted of two 0.7 μm × 166 μm gate fingers for a total gate periphery of 332 μm. The source-gate and gate-drain spacings were 0.3 μm and 0.8 μm, respectively. The epitaxially-grown layers consisted of a 6 μm p-type isolation layer with a doping of $N_a=1.4\times10^{15}$ $cm^{-3}$, a 0.26 μm channel layer with an n-type doping of $N_d=1.7\times10^{17}$ $cm^{-3}$, and an 0.15 μm n+ cap layer doped $N_d>2\times10^{19}$ $cm^{-3}$. The FET's were fabricated using six lithography steps, including two electron-beam direct writes using a Cambridge EBML-300 system.

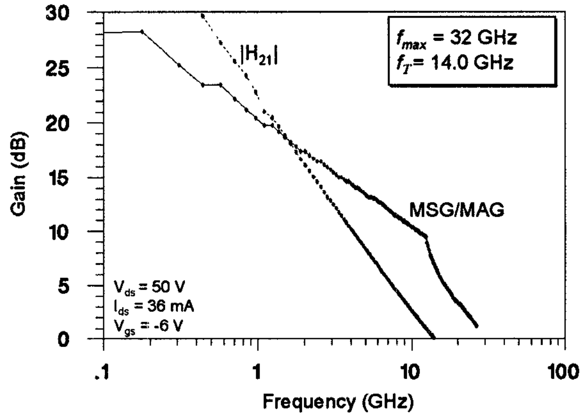


Figure 3: Measured frequency response of a 0.5 μm × 330 μm 4H-SiC MESFET fabricated on a recently developed 4H-SiC semi-insulating substrate.

Figure 4 shows the measured power data taken on a Maury load-pull system in a high-Q test fixture at 1.8 GHz for a SiC MESFET biased with $V_{ds}$ =40 V and a quiescent drain current of 5% of $I_{dss}$. The FET had 12.4 dB linear gain under power match conditions and a PAE of 50% with an associated power of 28.2 dBm at the 1 dB compression point. At 850 MHz, the frequency of interest for cellular phone applications, the peak efficiency for this FET was 65.7% PAE (Figure 5) under Class B bias with $V_{ds}$ = 40 V and a quiescent $I_{ds}$ of 4 mA (5% $I_{dss}$). At this bias point, the FET had 28.8 dBm maximum output power (2.27 W/mm) and 28.5 dBm output power (2.12 W/mm) at the 3 dB compression point. This demonstrates the ability of SiC MESFET's to simultaneously attain high efficiencies and power densities much higher than in GaAs FET's or HEMT's. By using semi-insulating substrates and scaling down the gate length, the PAE of SiC MESFET's should be competitive with GaAs devices through X-band.

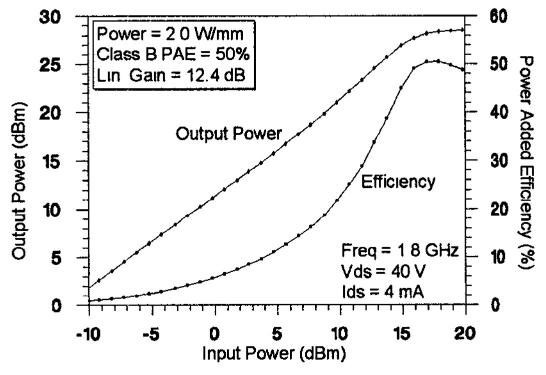


Figure 4: Measured rf power of a 0.7 μm × 330 μm 4H-SiC MESFET showing a peak PAE of 50% at 1.8 GHz with a power density of 2 W/mm.

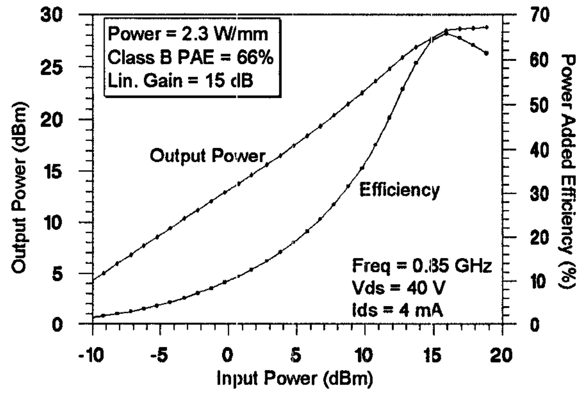


Figure 5: Measured rf power of a 0.7 μm × 330 μm 4H-SiC MESFET showing a peak PAE of 66% at 850 MHz with a power density of 2.2 W/mm.

The maximum output power point for this device at 850 MHz was under Class A operation. At a quiescent drain bias of $V_{ds}$ = 50 V and a $I_{ds}$ = 40 mA (50% $I_{dss}$), the device had a peak output power of 30.5 dBm (3.37 W/mm) and a 3 dB compression output power of 30.2 dBm (3.1 W/mm), as shown in Figure 6. At this power level, the FET had a power added efficiency (PAE) of 38.9%. This is a further demonstration of the extremely high power densities that are attainable with SiC. We have previously reported similar power densities from on-wafer measurements at 1.8 GHz [7]. Figure 7 shows the linearity of this device under Class A bias conditions with a two tone measurement at 850 ± 5 MHz. The third order intermodulation product (IM3) was -23 dBc at the 1 dB compression point.

SiC FET's with much larger gate peripheries have recently been fabricated. While these devices have not yet been thoroughly characterized, the dc data shows that the channel current scales linearly with gate width and the gate-drain breakdown voltage remains high.

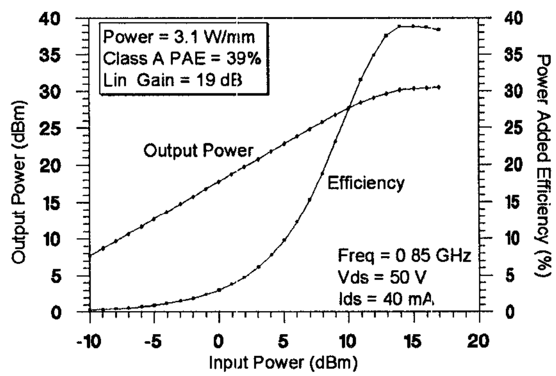


Figure 6: An rf power density of 3.1 W/mm was measured on a 0.7 μm × 330 μm 4H-SiC MESFET under Class A bias at 850 MHz.

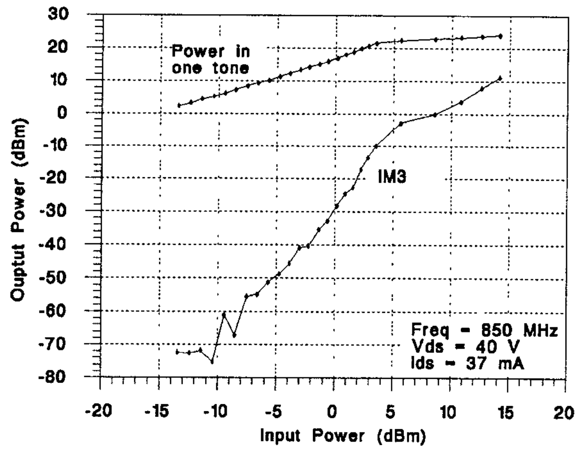


Figure 7: Linearity data for a 4H-SiC MESFET under Class A bias at 850 ± 5 MHz showing the third order intermodulation product (IM3) to be -23 dBc at the 1 dB compression point.

## Conclusion

The extremely high power density and excellent power added efficiency demonstrated by these SiC MESFET's show the potential for this technology. With the recent availability of semi-insulating 4H-SiC substrates, these power densities and efficiencies should extend into the X-band frequency range. The excellent thermal handling capability of SiC will permit scaling these devices to large power levels, and SiC is expected to rapidly become an important technology for solid state microwave power.

## Acknowledgments

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