SILICON CARBIDE MESFET's
FOR HIGH-POWER S-BAND APPLICATIONS

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Abstract

Silicon carbide MESFET's with 0.7 µm gates and 18 mm of total periphery had a P_{1db} of 15 watts CW at 2.1 GHz with a power-added efficiency of 54%. These FET's were optimized for S-band power and had an f_T of 8.5 GHz and an f_{max} of 25 GHz. Similar devices with 0.45 µm gate lengths had an f_T of 22 GHz and an f_{max} as high as 50 GHz, demonstrating the potential of this technology to extend to much higher frequencies.

Introduction

Silicon carbide (SiC) MESFET's are emerging as a promising technology for high-power microwave applications due to a combination of superior 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 that had a CW output power of 15 W at 2.1 GHz with an associated power-added efficiency (PAE) of 54% when operated at a drain bias of 30 V. In another recent advancement, similar SiC MESFETs were fabricated with 0.45 µm gate lengths, and these devices had an f_T of 22 GHz and an f_{max} as high as 50 GHz. Modeling indicates that scaling the FET's further to a 0.35 µm gate technology will result in excellent devices for X-band power.

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 or Si. This is illustrated in Figure 1, which shows the measured breakdown voltage of 4H-SiC p-n junction diodes as well as the theoretical curves for Si and GaAs. This high breakdown field has been exploited to fabricate sub-micron SiC MESFET's with gate-to-drain breakdown voltages as high as 170 V [1].

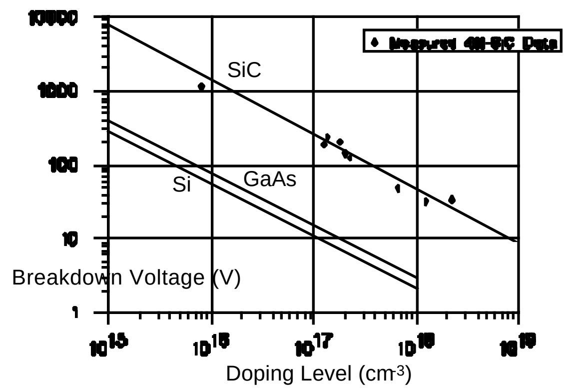

Figure 1: Measured breakdown voltage of p-n junction diodes as a function of doping, and the theoretical maximums for Si and GaAs.

The one drawback to SiC for use in microwave devices is its poor low-field electron mobility, which is in the range of 300 - 500 cm^2/V-sec. for doping levels of interest for MESFET's, i.e., 1×10^{17} $cm^{-3} < N_D < 5\times10^{17}$ cm^{-3}. 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

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operate the SiC devices under extremely high electric fields. The saturated electron velocity in 6H-SiC is 2×10^7 cm/s and has been predicted by Monte Carlo simulations to be 2.7×10^7 cm/s in 4H-SiC [2], 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, typically around 300 mA/mm for 0.7 µm gate length devices, due to the high saturated velocity. When combined with the high breakdown voltage, this results in the large RF power density of 3 W/mm that has been measured for SiC MESFET's [3].

The other property of SiC that gives it a significant advantage over other semiconductors is its very high thermal conductivity, which has been measured to be as high as 4.9 W/K-cm in undoped material, more than 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 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 has been modeled to be at least 5 times that of devices made from GaAs [4].

Recent Advances in SiC Substrates

The development of SiC electronic devices has been limited in the past by the lack of 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 has made advancements in crystal growth technology that resulted in producing 4H-SiC wafers with a micropipe density of < 1 cm^{-2}, which is more than two orders of magnitude less than it was three years ago. Because the active area of microwave MESFET's is very small, limited to the source-drain separation of 3 µm, a micropipe density of < 10 cm^{-2} has a negligible contribution to yield. Therefore, with these recent reductions in micropipe defect densities, SiC crystal quality has improved to the point where it would be viable to fabricate SiC MESFET's in production quantities.

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-diameter substrates, and since that time, all R&D work at Cree has moved to 35-mm-diameter wafers. Last year, Cree shifted its high volume production of blue LED's (GaN epitaxial layers on SiC substrates) to 40-mm wafers and plans to transition to 50-mm wafers (standard SEMI 2-inch) in the near future.

There has also been recent progress on the development of high-quality semi-insulting 4H-SiC for use as a substrate for the fabrication of microwave MESFET's. Preliminary measurements indicate that the micropipe density of the semi-insulating wafers is similar to that of the n-type wafers, and the wafer diameter has been increased to 35 mm. This material has been characterized extensively by W.C. Mitchell and R. Perrin at the Air Force Wright Patterson Laboratory. Figure 2 is an Arrhenius plot of the high temperature resistivity of one of these wafers determined from Hall-effect measurements. The extracted activation energy of 1.7 eV is consistent with deep-level compensation in SiC with a bandgap of 3.2 eV and leads to an extrapolated room temperature resistivity of 10^{20} Ω-cm.

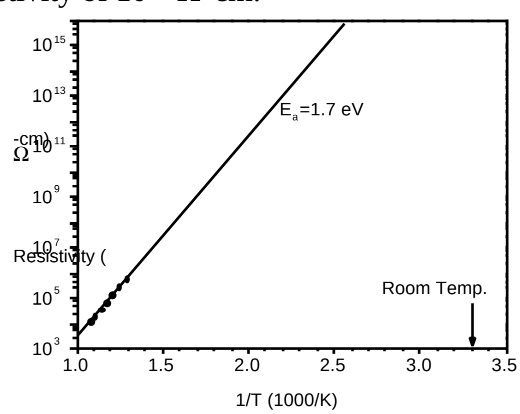

Figure 2: Plot of resistivity vs. 1/T for semi-insulating 4H-SiC as determined with Hall-effect measurements.

SiC Power MESFET's

A cross section of the SiC MESFET is shown in Figure 3. The epitaxial layers were grown on a semi-insulating 4H-SiC substrate and included a *p*- buffer layer, a channel layer doped $N_D = 3\times10^{17}$ cm^{-3} and a heavily doped *n*+ cap layer. The FET's consisted of 0.7 µm × 500 µm T-gate fingers with a nominal gate-source spacing of 0.5 µm.

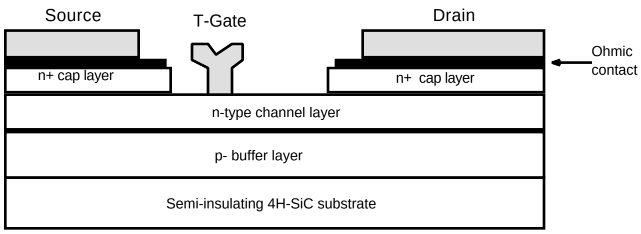

Figure 3: Cross section of a SiC MESFET (not to scale.) The epitaxial layers were grown on a semi-insulating 4H-SiC substrate and included a *p*- buffer layer, a channel layer doped $N_D = 3\times10^{17}$ cm^{-3} and a heavily doped *n*+ cap layer.

Figure 4 shows a measured family of dc I-V curves for a 2-finger FET. At V_{ds} = 10 V, I_{dss} = 275 mA/mm and the peak transconductance was 35 mS/mm. This same FET had a 3-terminal breakdown voltage as defined at the 1 mA/mm point of 125 V. The relatively high pinch-off voltage of V_{gs} = -10 V is necessary to obtain adequate current for the FET to be used as a power device, since the current is limited by the low electron mobility.

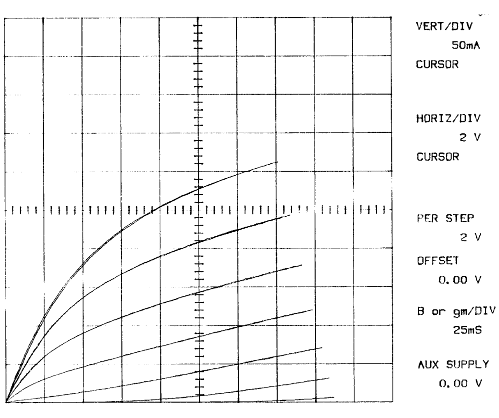

Figure 4: Family of I-V curves of a 0.7 µm × 1 mm SiC MESFET with 275 mA/mm and 35 mS/mm and a breakdown voltage > 100 V.

Small-signal S-parameter measurements taken on two-finger FET's at V_{ds} = 30 V and V_{gs} = -3 V were used to determine that the devices had f_T = 9 GHz and f_{max} = 25 GHz. Modeling indicates that this is sufficient frequency response to obtain high efficiency operation at S-band under power match conditions. In order to increase the frequency performance to make X-band power FET's, the gate length will have to be scaled to deep sub-micron dimensions. Figure 5 shows the measured frequency response of a SiC MESFET with a gate length of 0.45 µm and 250 µm finger-widths, from which an f_T of 18 GHz and an f_{max} of 50 GHz was determined. Figure 6 shows the frequency response of another FET from the same wafer that had a shorter gate-to-drain spacing, which increased f_T to 22 GHz, but had finger widths of 500 µm, which reduced the f_{max} / f_T ratio.

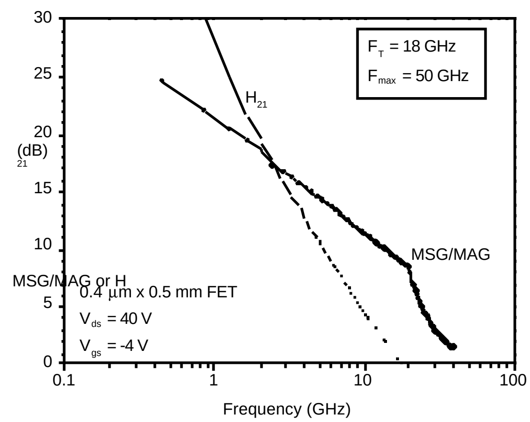

Figure 5: SiC MESFET with 0.45 µm × 250 µm gates; f_T = 18 GHz, f_{max} = 50 GHz.

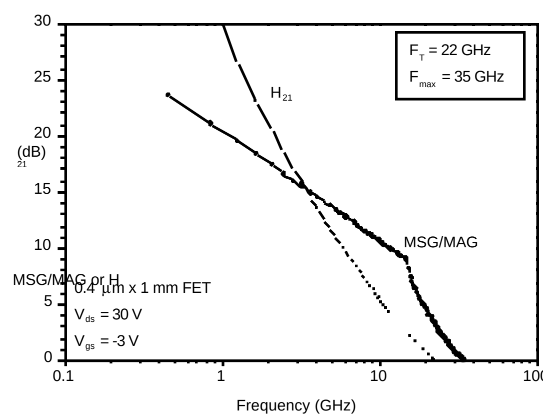

Figure 6: SiC MESFET with 0.45 µm × 250 µm gates; f_T = 22 GHz, f_{max} = 35 GHz.

Figure 7 is a plot showing f_T and f_{max} as a function of drain current and illustrates one of the properties of the SiC MESFET's that enables them to operate with very high efficiency under large signal drive conditions. At only 5% of Idss, f_T has only dropped 30% from its peak value and f_{max} is down only 10%, enabling the device to have good power gain even when operated in Class B bias.

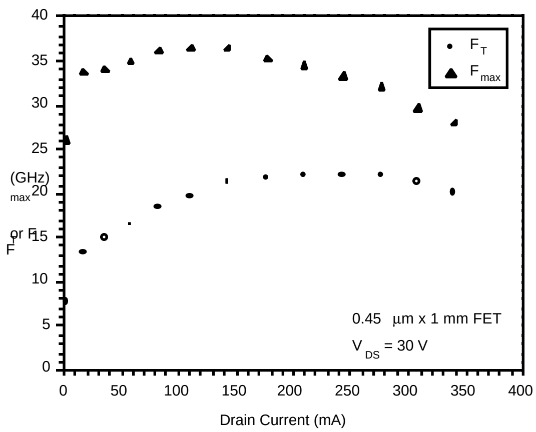

Figure 7: Frequency response as a function of drain current, showing that the SiC MESFET has excellent gain at only 5% of *Idss*.

Power Measurements

Power measurements were taken on 0.7 µm gate-length devices with gate peripheries ranging from 3 mm to 18 mm. In all cases, the power density was between 0.8 and 1.0 W/mm, significantly lower than the 3 W/mm expected based on the dc curves. Previous SiC MESFETs had shown good agreement between dc load-line predictions and RF power density [3]; the cause of the discrepancy on the recent devices is still under investigation. Nevertheless, 15 watts CW was measured at 2.1 GHz from an 18 mm FET biased at V_{ds} = 30 V, and the associated drain efficiency and PAE were 60% and 54%, respectively. This is the highest CW power level reported to date for any SiC transistor, and the fact that the die area was < 1 mm^2 demonstrates the extremely high power handling capability of this technology.

Conclusion

The high power density in W/mm^2 and the excellent power-added efficiency demonstrated by these SiC MESFET's show the potential for this technology for S-band power applications. The greatly improved frequency response of the shorter gate-length MESFET's also indicates that SiC should become an important technology for solid state microwave power through X-band frequencies. With the recent progress in increasing substrate diameter and reducing bulk crystal defects, Cree intends to rapidly develop SiC MESFET's for both military and commercial applications.

Acknowledgments

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