SiC for Microwave Power Applications: Present Status and Future Trends

R.J. Trew
U.S. Department of Defense
Washington, DC

Abstract

A variety of RF and microwave electronic devices can be fabricated from SiC. MESFET's and SIT's fabricated from 4H-SiC grown on 6H- or 4H-SiC substrates with very good dc and RF performance have been demonstrated. These devices are being developed for microwave power amplifiers for short pulse, high power RADAR applications at C, S, and X-bands, and for communications amplifiers for base station transmitters at L and S band. These devices have the potential to produce RF power densities in excess of that possible from Si or GaAs based devices, with power-added efficiency approaching theoretical limits for class A and B operation. SiC MESFET's can produce RF power density on the order of 4 W/mm and experimental devices are rapidly approaching the theoretical potential.

I. Introduction

There is significant interest in the use of SiC devices for applications such as microwave power amplifiers that can be used in phased-array radars, base station transmitters for mobile communications, high-efficiency and broadband radar transmitters, and other applications. RF and microwave devices that can be fabricated from SiC include MESFETs, SIT's, BJT's and HBT's. The most attractive microwave devices that can be fabricated from SiC are the MESFET and SIT. Both devices have demonstrated excellent dc and RF performance.

II. SiC Transistors

MESFETs fabricated from 6H-SiC were first reported by Muench et. al. [1] in 1977. Current saturation was observed, but the device gain was very low and limited by resistive losses. Much improved performance has been reported as improved device fabrication techniques yield lower parasitics and devices with impressive dc and RF performance have recently been reported. For example, 6H-SiC MESFET's that can operate at frequencies up to X-Band (10 GHz) have been produced with RF output power for a class A amplifier in the range of 2.5 W/mm and power-added efficiency on the order of 45% at 6 GHz [2].

MESFET's with excellent RF performance have also been fabricated from 4H-SiC with RF output power on the order of 2.8 W/mm at 1.8 GHz [3], and 2.27 W/mm with 65.7% for a class B amplifier reported at 850 MHz [4,5]. A 4H-SiC MESFET with a fmax of 42 GHz has been reported [6]. This device produced 5.1 db gain at 20 GHz. A 4H-SiC MESFET with 53 W output power and 37% power-added efficiency at 3 GHz has been reported [7]. The dc performance of the device demonstrated a maximum channel current of 520 mA/mm and a transconductance of 70 mS/mm. the transistor demonstrated an f_T of 14 GHz, and an f_{max} of 40 GHz. Static Induction Transistors also look very promising for short pulse RADAR applications and a 4H-SiC SIT unit cell with 38 W RF output power, 9.5 db of gain, and 45% drain efficiency at 3 GHz has been reported [8,9]. These cells can be combined to produce amplifiers that yield 450 W at L-Band and 150 W and S-Band. A two stage amplifier with 1 kW RF output power using these devices was reported [10] and is a commercial product for the HDTV market. Heterojunction bipolar transistors fabricated from SiC may also be possible, although the low mobility of p-type material required for the base region may limit the frequency performance of the device [11,12]. The hole mobility in SiC is very low, generally in the range of 20-50 cm^2/v-sec., and it is very difficult to produce low resistance base regions. This may limit the operation of bipolar transistors to S-band (4 GHz) [11] or less.

III. Semiconductor Material and Contact Properties

A summary of the semiconductor material properties most important to electronic device performance are listed in Table 1 for several semiconductors. Desirable material properties include a large energy gap, a low value of dielectric constant, high thermal conductivity, and high critical electric field for breakdown. SiC has more optimum values for all these parameters compared to conventional semiconductors.

The dc and RF currents that flow through a device are directly dependent upon the charge carrier velocity versus electric field transport characteristics of the semiconductor material. Generally, high charge carrier mobility and high saturation velocity are desirable. A comparison of the electron velocity-electric field (v-E) characteristics for several semiconductors is shown in Fig. 1. The v-E characteristic is described in terms of charge carrier mobility defined from the slope of the v-E characteristic at low electric field and the saturated velocity defined when the carrier velocity obtains a constant, field-independent magnitude. A primary disadvantage of fabricating transistors from SiC is the relatively low values for the charge carrier mobilities. In general, the wide bandgap semiconductors such as SiC have relatively low mobility, but very high saturation velocity.

Table 1
Material Properties for Several Semiconductors

Material	E_g (eV)	ε_r	κ $(W/^oK\text{-}cm)$	E_c (V/cm)
Si	1.12	11.9	1.5	$3\text{x}10^5$
GaAs	1.43	12.5	0.54	$4\text{x}10^5$
InP	1.34	12.4	0.67	$4.5\text{x}10^5$
4H-SiC	3.2	10.0	4	$3.5\text{x}10^6$
6H-SiC	2.86	10.0	4	$3.8\text{x}10^6$
GaN	3.4	9.5	1.3	$2\text{x}10^6$
Diamond	5.6	5.5	20-30	$5\text{x}10^6$

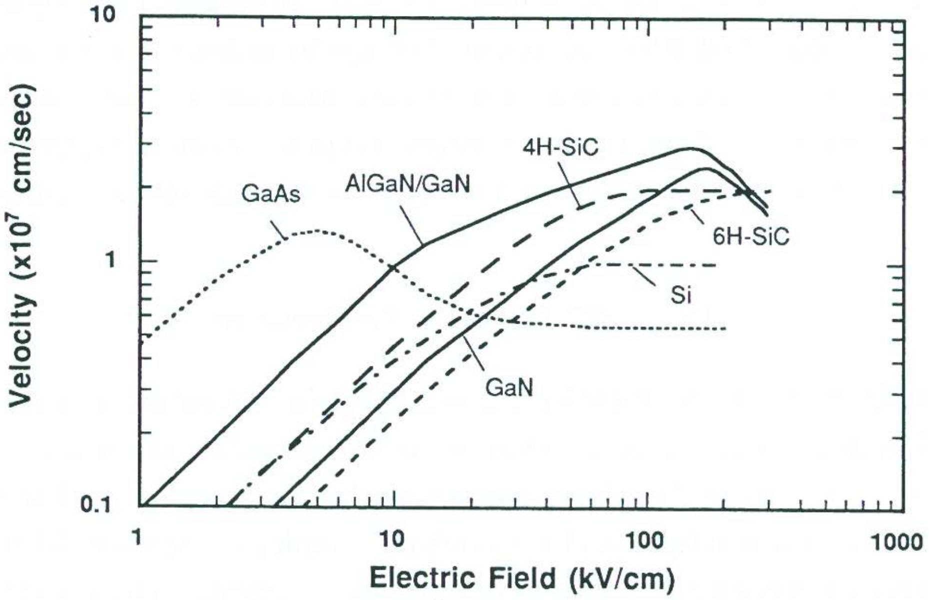

Fig. 1 Electron Velocity vs. Electric Field Characteristics for Several Semiconductors at 10^{17} cm^{-3} Impurity Concentration

For typical device doping density (N_d~$2\text{x}10^{17}$ cm^{-3}), the electron mobility for 6H- and 4H-SiC are about 250 cm^2/V-sec and 500 cm^2/V-sec, respectively. The factor of two increase in mobility for 4H-SiC compared to 6H-SiC is one of the major reasons that the 4H polytype is preferred for device applications. The electron saturation velocity in both 6H- and 4H-SiC is $v_s \sim 2x10^7$ cm/sec, which is a factor of two higher than for Si ($v_s \sim 1x10^7$ cm/sec) and a factor of four higher than for GaAs ($v_s \sim (0.5\text{-}0.6)x10^7$ cm/sec). The magnitude of electric field that produces saturated charge carrier velocity is also important since the device must be able to develop the saturation field to obtain maximum RF performance and high frequency operation.

The saturation fields for 4H-and 6H-SiC are about $E_s \sim 60$ kV/cm and $E_s \sim 200$ kV/cm, respectively, which are high compared to the comparable values of $E_s \sim 3$ kV/cm and $E_s \sim 35$ kV/cm for GaAs and Si. The hole mobility in SiC is very low, and on the order of 20-50 cm^2/V-sec, and it is very difficult to observe saturation effects. The extremely low mobility requires very high saturation fields, which approach the critical field for avalanche breakdown. The low hole mobility presents serious problems for use of p-type material in devices. The wide bandgap of SiC results in high critical electric field for breakdown, which is on the order of 3-4 MV/cm, and almost an order of magnitude greater than for Si and GaAs. High breakdown voltage permits high drain bias voltages to be applied, which is necessary to obtain high RF output power. The high breakdown field also permits the electric field internal to the device to achieve the value necessary to produce charge carrier velocity saturation. This latter factor is fundamental to successful development of SiC electronic devices since the charge carrier mobility is low and high velocity saturation fields result.

IV. SiC MESFET Performance

A promising transistor for microwave power amplifier applications is the 4H-SiC MESFET. A design optimization investigation reveals that such a device with the design parameters listed in Table 2 produces a maximum channel current of I_{dss}=490 mA and a maximum device transconductance of g_m=50 mS/mm. Heating the device to 500 °C reduces the maximum channel current to I_{dss}=135 mA/mm and the maximum transconductance to g_m=18 mS/mm. When the 4H-SiC MESFET is operated in a class A amplifier the RF performance shown in Fig. 2 results. The amplifier performance is good through X-band, with gain above 10 db and RF output power about 4-5 W/mm. Amplifier performance degrades at frequencies above X-band, but is still good as high as 30 GHz, where the amplifier produces 4 W/mm RF output power, 26% PAE, and 4 db gain. Performance degrades with increasing frequency due to resistive losses that result from the relatively low magnitude for the electron mobility.

Table 2

4H-SiC MESFET Design Parameters

Parameter	Value
Gate Length, L_g	0.5 μm
Gate Width, W	1 mm
Channel Doping, N_d	$5x10^{17}$ cm^{-3}
Channel Thickness, a	0.15 μm
Electron Mobility, μ_n	350 cm^2/V-sec
Saturated Velocity, v_s	$2x10^7$ cm/sec

When operated in a class B amplifier at 8 GHz the amplifier produces P_o~36 dbm (4 W), 60 % PAE, and about 15 db linear gain. At 500 °C the amplifier produces about P_o=30 dbm (1 W), PAE=32 %, and a linear gain of 8.5 dB. These results indicate that 4H-SiC MESFET's have excellent microwave RF performance potential up to X-band, and are capable of producing good RF performance as high as 30 GHz.

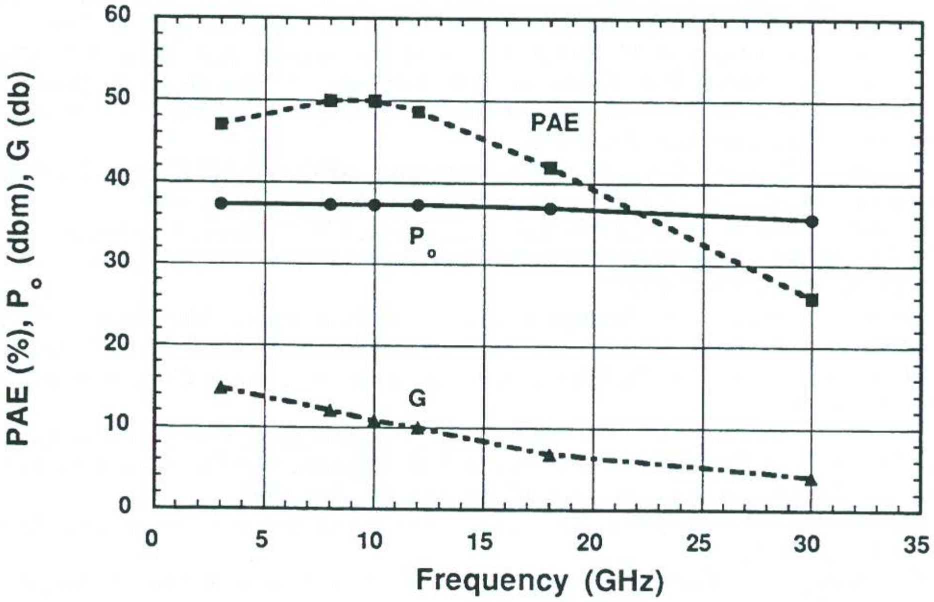

Fig. 2 RF Performance for a Class A 4H-SiC MESFET Amplifier (Vds=40v)

V. Summary

Microwave power amplifiers and oscillators fabricated from SiC devices offer the potential for significantly improved dc and RF performance compared to devices fabricated from traditional semiconductors such as Si and GaAs. Devices fabricated from 4H-SiC have microwave power capability at room temperature about a factor of four greater than comparable devices fabricated from GaAs or Si. The MESFET is very attractive for use in high power, high frequency amplifiers through X-Band and these devices are rapidly approaching the commercialization stage. The SIT devices also look very promising, particularly for lower frequency operation. The inherent channel current limitation of these devices will likely limit their use to C-band, although X-Band operation is possible. The SIT is capable of high RF output power and good efficiency performance and these devices are also rapidly approaching the commercialization stage.

References

[1] W.V. Muench, P. Hoeck, and E. Pettenpaul, "Silicon Carbide Field-Effect and Bipolar Transistors," *1977 IEEE International Electron Device Meeting Digest*, pp. 337-339.

[2] S. Sriram, R.R. Barron, A.W. Morse, T.J. Smith, G. Augine, A.A. Burk, R.C. Clarke, R.C. Glass, H.M. Hobgood, P.A. Orphanos, R.R. Siergiej, C.D. Brandt, M.C. Driver, and R.H. Hopkins., "High Efficiency Operation of 6H-SiC MESFET's at 6 GHz," *53rd Device Research Conference*, Charlottesville, VA, 1995.

[3] C. Weitzel, J. Palmour, C. Carter, and K. Nordquist, "4H-SiC MESFET with 2.8 W/mm Power Density at 1.8 GHz," *IEEE Electron Dev. Lett.*, vol. 15, No. 10, Oct. 1994.

[4] K.E. Moore, C.E. Weitzel, K.J. Nordquist, L.L. Pond, J.W. Palmour, S. Allen, and C.H. Carter, "4H-SiC MESFET with 65.7% Power-Added Efficiency at 850 MHz," *IEEE Electron Dev. Lett.*, vol. 18, pp. 69-70, Feb. 1997.

[5] K. Moore, C. Weitzel, K. Nordquist, L. Pond, J. Palmour, S. Allen, and C. Carter, "Bias Dependence of RF Power Characteristics of 4H-SiC MESFET's," *Proc. IEEE/Cornell Conference on Advanced Concepts in High Speed Semiconductor Devices and Circuits*, Ithaca, NY, Aug. 1995, pp. 40-46.

[6] S. Sriram, G. Augustine, A.A. Burk, R.C. Glass, H.M. Hobgood, P.A. Orphanos, L.B. Rowland, T.J. Smith, C..D. Brandt, M.C. Driver, and R.H. Hopkins, "4H-SiC MESFET's with 42 GHz fmax," *IEEE Electron Dev. Lett.*, vol. 17, pp. 369-371, July 1996.

[7] R. Sadler, C. Clarke, J. Palmour, "SiC SIT's," 1998 Device Research Conference, Charlottesville, VA, June 22-24, 1998.

[8] R.R. Siergiej, R.C. Clarke, A.K. Agarwal, C.D. Brandt, A.A. Burke, A. Morse, and P.A. Orphanos, "High Power 4H-SiC Static Induction Transistors," *IEDM Digest*, pp. 353-356, Washington, DC, Dec. 1995.

[9] R.C. Clarke, A.K. Agarwal, R.R. Siergiej, C.D. Brandt, and A.W. Morse, "The Mixed Mode 4H-SiC SIT as an S-Band Microwave Power Transistor," *Device Research Conference Digest*, pp. 62-63, Santa Barbara, CA, June 1996.

[10] A.W. Morse, P.M. Esker, R.C. Clarke, C.D. Brandt, R.R. Siergiej, and A.K. Agarwal, "Application of High Power Silicon Carbide Transistors at Radar Frequencies," *1996 IEEE MTT-S Digest*, pp. 677-680, San Francisco, CA.

[11] R.J. Trew, "SiC Microwave Devices," Chapter 6 in SiC Materials and Devices, ed. Y.S. Park, Academic Press, New York, 1998.

[12] G.-B. Gao, J. Sterner, and H. Morkoc, "High Performance of SiC Heterojunction Bipolar Transistors," *IEEE Trans. Electron Dev.*, vol. 41, pp. 1092-1097, July 1994.