The Operation of Microwave Power Amplifiers Fabricated from Wide Bandgap Semiconductors

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Abstract

There are a variety of RF and microwave electronic devices that can be fabricated from wide bandgap semiconductors such as SiC and GaN. These semiconductors have many properties that make them near ideal for electronic devices intended for high temperature, high frequency, high power, and radiation hard applications. Prototype SiC and GaN-based electronic devices with very good dc and RF performance have been demonstrated and devices such as diodes are commercially available, while RF and high frequency transistors are rapidly approaching the commercialization stage. In this work the performance of microwave power amplifiers fabricated using SiC and GaN-based MESFET's are discussed and investigated. It is demonstrated that these amplifiers can produce RF output power on the order of 4-6 W/mm of gate periphery with near ideal power-added efficiency.

Introduction

High frequency electronic devices fabricated from SiC and GaN are approaching the commercialization stage. High temperature SiC diodes for high power switching applications are commercially available and transistors that can operate with high RF output power and at elevated temperature are under development. A variety of diodes and transistors fabricated from these materials have the potential to be useful in microwave power amplifier and oscillator applications [1,2]. Preliminary devices with impressive dc and RF performance have 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 of gate periphery and power-added efficiency on the order of 45% at 6 GHz [3]. 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 [4,5], and 2.27 W/mm with 65.7% for a class B amplifier reported at 850 MHz [6]. A 4H-SiC MESFET with a fmax of 42 GHz has been reported [7]. This device produced 5.1 db gain at 20 GHz. Static Induction Transistors also look very promising and a 4H-SiC SIT with 38 W RF output power, 9.5 db of gain, and 45% drain efficiency at 3 GHz has been reported [8,9]. The device was operated under pulse bias and is useful for radar applications [10]. A two stage amplifier with 1 kW RF output power using these devices was reported and is a commercial product for the HDTV market [9]. 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 [2]. The hole mobility in SiC and GaN 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) [2] or less, unless techniques can be found to produce significantly reduced base resistances. It has been determined that contact resistance to the p-type base must be reduced to about $Rc \sim 10^{-6}$ Ω-cm^2 in order to obtain X-Band (i.e., 8-12 GHz) performance [11]. The p-type contact resistance must be reduced one to two orders of magnitude lower than currently obtained. Heterojunction HBT's using GaN as the emitter and SiC for the base and collector have been proposed and initial results reported [12]. DC current gain as high as

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100,000 was reported. Since SiC has very high breakdown fields, however, devices with excellent high power performance are possible at lower frequencies. Preliminary FET's fabricated from GaN, and AlGaN/GaN, in particular, also look promising for high frequency, high power applications [13-17].

Among the most promising devices for high frequency RF power applications are MESFET's fabricated from 4H-SiC and AlGaN/GaN. Since these devices can be fabricated entirely from n-type material the losses associated with use of p-type regions can be avoided. The MESFET is also relatively easy to fabricate due to a simple structure. In this work the dc and microwave performance of this device are described, and performance projections presented. It is demonstrated that microwave power amplifiers fabricated from SiC and AlGaN/GaN offer superior performance compared to comparable components fabricated from conventional GaAs MESFET's. In particular, room temperature RF output power on the order of 4-6 W/mm of gate periphery with power-added efficiency approaching the ideal values for class A and B operation is available. The improved RF output power capability of amplifiers fabricated using these devices make them attractive for use in base station transmitters for cellular telephone systems, power modules for phased-array radars, and other applications. The devices are particularly attractive for applications that require operation at elevated temperature.

Charge Transport Characteristics

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 wide bandgap semiconductors such as SiC and GaN have relatively low mobility, but very high saturation velocity. For typical device doping density (N_d~$2x10^{17}$ cm^{-3}), the electron mobilities for 6H- and 4H-SiC are about 250 cm^2/V-sec and 500 cm^2/V-sec, respectively and the mobility for GaN is in the range of 400-500 cm^2/V-sec. The AlGaN/GaN heterojunction has been shown to produce a two-dimensional electron gas with a room temperature mobility in the range of 1000-1500 cm^2/V-sec. The factor of two increase in mobility for 4H-SiC compared to 6H-SiC is one of the reasons that the 4H polytype is preferred for device applications, and most current device development effort is directed towards use of the 4H- polytype.

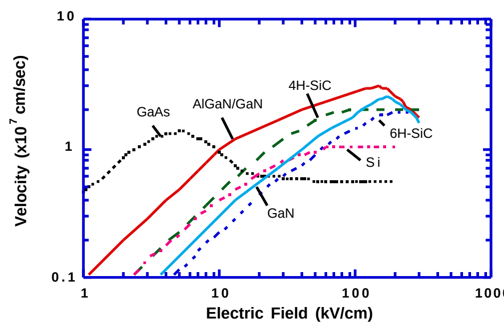

Fig. 1 Electron Velocity versus Electric Field Transport Characteristics for Several Semiconductors at Room Temperature

The electron saturation velocity in both 6H- and 4H-SiC is v_s~ $2x10^7$ cm/sec, which is a factor of two higher than for Si (v_s~$1x10^7$ cm/sec) and a factor of four higher than for GaAs (v_s~$(0.5\text{-}0.6)x10^7$ cm/sec). The saturation velocity in GaN and AlGaN/GaN is above $2.5x10^7$ cm/sec. The high electron velocity permits high dc and RF currents to be developed and should permit efficient RF operation into the microwave and mm-wave frequency bands.

There has been concern that the low mobility of the wide bandgap semiconductors would severely limit transistor performance. This is investigated in Fig. 2, which shows the maximum power-added efficiency for a MESFET class A amplifier as a function of semiconductor mobility for three values of drain-source voltage. A critical value for mobility exists at which optimum performance is obtained. Mobility above the critical value does not result in significantly improved performance. The critical value is achieved when the conducting channel under the gate region operates in velocity saturation. The critical value is a function of gate length and drain voltage since these parameters effect the electric field magnitude under the gate. Once the field is sufficiently high to saturate the electron velocity the mobility only effects source resistance, and this effect is minimized for power devices by wide gate width.

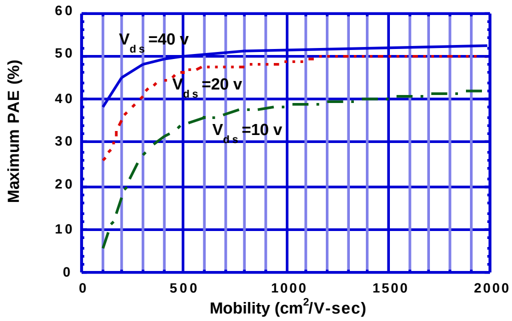

Fig. 2 Maximum PAE for a Class A MESFET Amplifier as a Function of Semiconductor Mobility

MESFET Amplifier Performance

The parameter values for a 4H-SiC MESFET designed for optimum X-band performance are listed in Table 1.

Table 1

Optimized SiC MESFET Design Parameters

Parameter	Value
Gate Length	0.5 µm
Gate Width	1 mm
Source-Drain Spacing	2 µm
Channel Doping	5x10^{17} cm^{-3}
Channel Thickness	0.15 µm

The device produces a maximum open channel current of I_{dss}~580 mA/mm and a maximum transconductance of g_m~62 mS/mm. The high frequency capability of the device is indicated by the small-signal current and power gains. The gains were calculated as a function of frequency for class A operation at Vds=40 v. The small-signal current gain yields an f_T=23 GHz and the small-signal power gain yields an f_{max}=56 GHz. When the device is operated in a class A amplifier at 10 GHz a maximum power-added efficiency of 50%, an RF output power of 4 W, and a gain at peak efficiency of 10 db are obtained. The linear gain for the amplifier is about 15 db. The RF performance of the amplifier as a function of frequency is shown in Fig. 3. The amplifier produces near ideal class A power-added efficiency through X-band, with gain above 10 db and RF output power about 4 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.

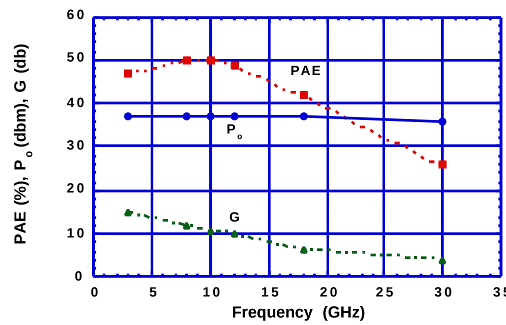

Fig. 3 RF Performance versus Frequency for a 4H-SiC MESFET Class A Amplifier (Vds=40 v)

The essentially constant RF output power obtained as a function of frequency results due to increased RF input power, and the gain is, in fact, decreasing with frequency. Performance degrades with increasing frequency due to resistive losses that result from the relatively low magnitude for the electron mobility. This effect becomes more significant as frequency increases and becomes a limiting mechanism at high frequency. These calculations indicate that 4H-SiC MESFET's have excellent high frequency RF performance potential, at least through X-Band.

Similar analysis of AlGaN/GaN HFET's indicate that due to higher channel currents increased RF output power, on the order of 6 W/mm can be obtained. The higher mobility permits high efficiency operation into the mm-wave region and PAE greater than 30 % at 30 GHz is predicted.

Conclusions

The wide bandgap semiconductors SiC and GaN can be used to fabricate high frequency electronic devices with RF power performance superior to devices fabricated from Si and GaAs. SiC and GaN-based MESFET's, in particular, are capable of high frequency operation with improved RF performance in comparison to standard Si and GaAs based devices. Optimized MESFET's fabricated from 4H-SiC and AlGaN/GaN can produce near ideal power-added efficiency for both class A and class B operation, and RF output power on the order of 4-6 W/mm, which is greater than a factor of four compared to GaAs devices. SiC devices are useful through X-band and the AlGaN/GaN devices will be useful into the mm-wave region.

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