Commercial Wide Bandgap RF Power Devices – Fact or Fiction?

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Abstract

Wide bandgap RF power devices, SiC SIT's, SiC MESFET's and AlGaN/GaN HFET's are described and their performance is compared with that of Si LDMOS FET's and GaAs FET's. The prospects for commercialization are discussed in light of the available market and technical challenges.

INTRODUCTION

In recent years, wide bandgap semiconductors, silicon carbide (SiC) and gallium nitride (GaN), have received increased attention because of their potential for a wide variety of high power devices [1-4]. Their unique material properties, high electric breakdown field, high saturated electron drift velocity, and, for SiC, high thermal conductivity, are what gives these materials their tremendous potential in the power device arena. The data in Table 1 allow a comparison of the basic material properties of silicon, gallium arsenide, 4H silicon carbide, and gallium nitride. The 5-6 times higher breakdown field of both SiC and GaN is what gives these materials their advantage over Si and GaAs for high voltage, RF power devices. SiC clearly has an advantage over GaN in thermal conductivity, but the AlGaN/GaN heterojunction which can be grown in the GaN material system enables lateral GaN HFET's to have superior current handling capability compared to lateral SiC devices. Moreover, GaN can be epitaxially grown on SiC, taking advantage of SiC's higher thermal conductivity. In this paper wide bandgap RF power devices will be discussed in terms of fabrication and state-of-the-art experimental performance. The experimental results will be compared with those of Si and GaAs devices. In addition, the challenges facing wide bandgap RF power devices as they move toward commercialization will be discussed.

TABLE 1
Si, GaAs, SiC, and GaN Material Properties

Property	Si	GaAs	4H-SiC	GaN
Bandgap (eV)	1.11	1.43	3.2	3.4
Relative Dielectric Constant	11.8	12.8	9.7	9.0
Breakdown Field (V/cm)	6×10^5	6.5×10^5	35×10^5	35×10^5
Saturated Velocity (cm/sec)	1×10^7	1×10^7	2×10^7	1.5×10^7
Electron Mobility (cm^2/V-sec)	1350	6000	800	1000
Hole Mobility (cm^2/V-sec)	450	330	120	300
Thermal Conductivity (W/cm-°K)	1.5	0.46	4.9	1.7

RF POWER DEVICES

A. SiC Static Induction Transistors (SIT's)

SiC SIT's, similar in design and operation to silicon SIT's [5], are a vertical device with an ohmic source contact on the top and an ohmic drain contact on the back of the wafer (Figure 1). Between these two N$^+$ regions is an N$^-$ epitaxial drift layer whose doping is one of the factors that determines the device breakdown voltage and pinch-off voltage. Trenches are etched to define the channel region and Schottky gate contacts are formed in the bottom and along the sidewalls of the trench. Majority carriers flow from the source contact to the drain contact through accumulation layers in the n-type channel region. By applying a negative voltage to the gate contact, the current flow can be modulated and even decreased to zero when the depletion regions under each gate electrode meet in the middle of the channel. Although SIT's generally have the lowest operating frequencies and lowest RF power densities compared with other wide bandgap RF power devices, they have achieved some of the highest total output powers. 4H-SiC SIT's have been demonstrated with 400 W pulsed power at 1.3 GHz, 78 W pulsed power at 2.9 GHz, and 47 W pulsed power at 4 GHz [6]. In addition, a one kilowatt, 600 MHz SiC power module containing four SIT's with a total source periphery of 94.5 cm has been demonstrated [7].

B. SiC MESFET's

Unlike the SIT, SiC RF MESFET's are lateral devices, similar to GaAs MESFET's, with both source and drain contacts on the top surface of the wafer (Fig. 2). Source and drain ohmic contacts are typically placed on top of an N$^+$ epitaxial layer and are separated by a more lightly doped N-

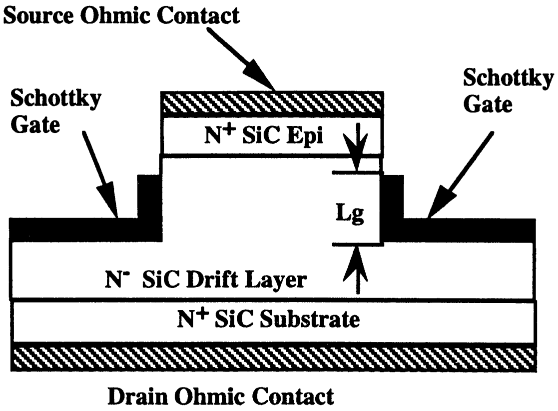

Fig. 1. Cross sectional view of a SiC static induction transistor (SIT). Current flows vertically from source to drain.

type channel region. The majority carriers flow in the channel from source to drain and are controlled by a Schottky gate contact. Device isolation can be achieved either with a P$^-$ buffer layer on a conducting substrate or with a high resistivity substrate to achieve higher cut-off frequency devices [8]. The highest SiC MESFET power density achieved using a conducting substrate is 3.3 W/mm with V_d = 50 V at a frequency of 850 MHz [9] and using a semi-insulating substrate is 5.6 W/mm with V_d = 60 V at a frequency of 3.5 GHz [10]. These two results illustrate the significant increase in frequency performance that can be achieved by using a semi-insulating, rather than a conducting substrate. The highest total power reported for a single SiC MESFET (48 mm) is 80 W at 3.1 GHz with V_d = 58 V[10]. Under pulsed conditions this same 48 mm MESFET achieved 120 W at 3.1 GHz. Under pulsed test conditions another SiC MESFET achieved 6.3 W at 10 GHz [11].

C. AlGaN/GaN HFET

AlGaN HFET's (Fig. 3) are also lateral devices, but contain a more complex material structure than the SiC MESFET. First, because GaN substrates are not readily available, the GaN epitaxial channel layer is grown with an interposed nucleation layer on a sapphire or on a high resistivity SiC substrate [12-14]. Sapphire has been a good substrate for device development and for demonstration of high frequency performance, but it has a very low thermal conductivity (0.42 W/cm-°K) compared to that of SiC (Table 1). Wider bandgap $Al_xGa_{1-x}N$ is grown on the channel layer forming a quantum well at the interface. The very high sheet carrier density 1×10^{13} cm^{-2} in the quantum well gives the AlGaN HFET very high current carrying capability and high transconductance, both of which are very attractive for high frequency power devices. AlGaN HFET's have achieved the highest f_T's and f_{max}'s of any wide bandgap semiconductor RF device. AlGaN HFET's have been demonstrated with f_T's and f_{max}'s greater than 28 GHz and 82 GHz, respectively. Recently an AlGaN HFET on a 4H-SiC substrate has achieved the highest RF power density ever reported for a wide bandgap semiconductor device, 9.1 W/mm at 10 GHz [15]. A flip-chip mounted, 2 mm AlGaN HFET achieved 9.8 W at 8.2 GHz.

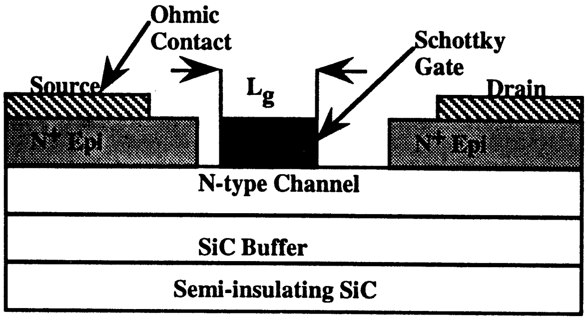

Fig. 2. Cross section of an RF SiC MESFET. Current flows from source to drain in N-type channel layer.

PERFORMANCE COMPARISON

Three important parameters for comparing RF device performance are operating frequency, power density, and total output power. The relative operating frequency of these three wide bandgap devices can be compared by plotting f_{max} versus transconductance, because device transconductance is an important factor in determining f_{max} (Figure 4). The SiC SIT's have the lowest reported transconductance and therefore, the lowest f_{max}'s. Because the maximum useful operating frequency of a device is about one order of magnitude below f_{max}, SIT's are relegated to applications with operating frequencies below 1 GHz. On the otherhand, AlGaN/GaN HFET's have the highest transconductances and the highest f_{max}'s, and therefore are suitable for applications above 10 GHz. SiC MESFET's have f_{max}'s between these two extremes. The data for SiC MESFET's clearly show the advantage of using semi-insulating substrates to achieve higher frequency performance. Even though the MESFET's on conducting and semi-insulating substrates have comparable transconductances, those on semi-insulating substrates have 2-3 times higher f_{max} because of the lower parasitic gate capacitance, another important factor in determining f_{max}.

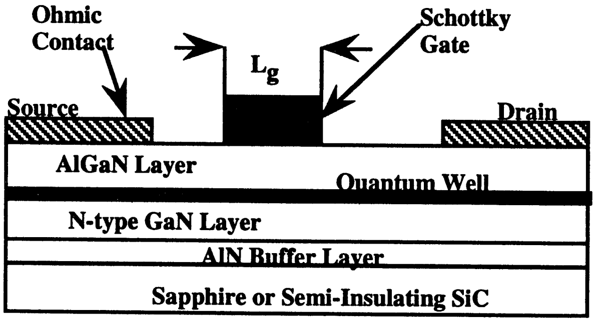

Fig. 3. Cross section of AlGaN heterojunction FET (HFET). Current flows in quantum well from source to drain.

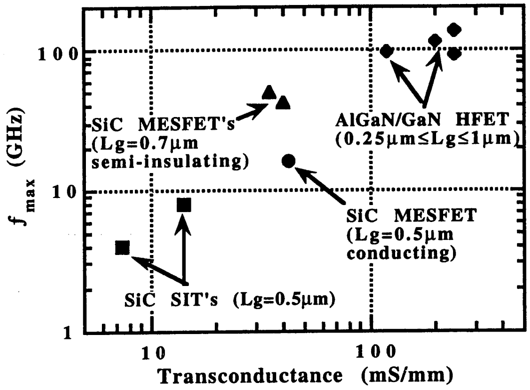

Fig. 4. Maximum frequency of oscillation (f_{max}) versus device transconductance for SiC SIT's, SiC MESFET's, and AlGaN/GaN HFET's.

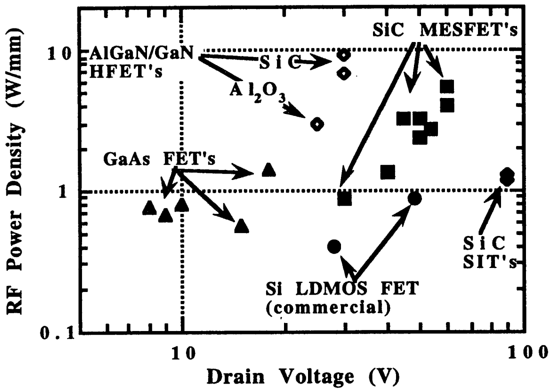

Fig. 5. RF power density (W/mm) as a function of operating voltage (V) for SiC SIT's, SiC MESFET's, and AlGaN/GaN HFET's.

The high breakdown field of wide bandgap semiconductors, SiC and GaN, enables devices with higher RF power densities than the narrower bandgap materials, Si and GaAs. The power densities of SiC and GaN devices, as well as Si and GaAs devices, are plotted versus operating voltage in Figure 5 for comparison. In general, Si and GaAs FET's have power densities near and below 1 W/mm, but the wide bandgap devices have power densities above 1 W/mm for comparable operating voltages. The highest power densities reported for SiC SIT's, SiC MESFET's, and AlGaN/GaN HFET's are 1.3 W/mm, 5.6 W/mm, and 9.1 W/mm, respectively. When comparing the power density of different devices, it is important to also know the total power capability of the device, because larger devices generally have lower power densities than smaller devices. This is clearly illustrated in the GaAs data, because the lowest power density device (0.56 W/mm at 15 V) has a significantly higher total power capability (200W) than the other GaAs devices [16]. The AlGaN/GaN HFET data on SiC and Al_2O_3 substrates clearly illustrates the importance of low thermal resistance in achieving high power density. The highest reported power densities using Al_2O_3 and SiC substrates are 3.1 W/mm and 9.1 W/mm, respectively. The thermal conductivity of Al_2O_3 is approximately an order of magnitude lower than that of SiC.

Another basis for comparing RF power devices is the total power handling capability that each technology has demonstrated. The highest total RF powers that have been achieved using each of the wide bandgap power devices are plotted in Fig. 6 versus the frequency of operation. The power axis of this graph spans 3 orders of magnitude indicating the wide range of RF powers that has been achieved. The highest RF powers, greater than 400 W, have been achieved with SiC RF SIT's, as was mentioned previously [6,7]. However, these very high power levels have been achieved at frequencies equal to or less than 2 GHz with the devices operated in the pulsed-mode. A 4H-SiC MESFET's operated in the pulsed-mode has achieved 120 W at 3.1 GHz [10] and 6.35 W at 10 GHz [11]. The highest CW-mode (continuous wave) RF power level achieved with a single SiC MESFET is 85 W at 3 GHz [10]. Initially, RF power levels of AlGaN HFET's were severely limited by the use of sapphire substrates, but recently AlGaN/GaN HFET's fabricated using a semi-insulating SiC substrate have achieved total output powers of 9.1 W, 9.8 W, and 4 W at 7.4 GHz, 8.2 GHz, and 10 GHz, respectively [10, 14-15]. Recently GaAs HFET's have achieved 200 W at 2.16 GHz [16] and 15.8 W at 12 GHz [17]. The RF power performance of commercially available Si LDMOS FET's is included for comparison [18].

COMMERCIALIZATION

No one questions the commercial value of wide bandgap, GaN based blue LED's and lasers. Many companies worldwide are pursuing short wavelength lasers for increased data storage density. The commercial value of wide bandgap switch-mode and RF power devices is less clear. The biggest difference in these two applications is that the wide bandgap photonics devices face little competition from alternative technologies that perform the same function. However, in both the switch-mode and RF power markets wide bandgap power devices face stiff competition from well entrenched, mature semiconductor technologies, silicon and gallium arsenide. For a new technology to gain a foothold in the market place it must offer all of the attributes of the mature technologies that customers have come to expect, such as proven reliability, multiple dependable sources, accurate device models, and low cost. In addition the new technology must offer a significant performance improvement at a reasonable cost. This cost requirement is less stringent for military systems and therefore, expensive, new technologies often are first utilized here. In contrast, the commercial market wants devices with improved performance at preferably lower cost.

The experimental results in Fig. 5 clearly show that wide bandgap power devices offer higher power density than Si and GaAs power devices. This higher power density offers

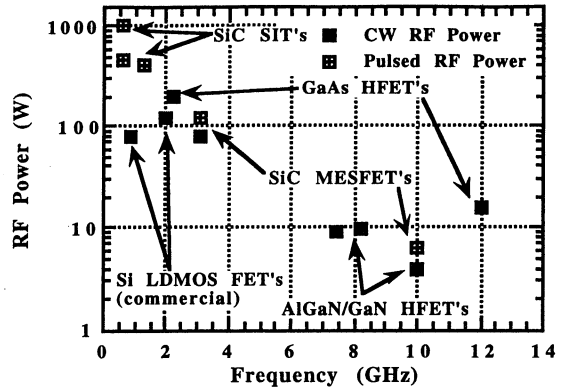

Fig. 6. Total RF output power (W) as a function of operating frequency (GHz) RF for SiC SIT's, SiC MESFET's, and AlGaN/GaN HFET's.

physically smaller power devices that are easier to match and require less power combining, both of these reduce system loss. The wide bandgap devices should also be more tolerant of high operating temperatures, an advantage especially to military systems. However these advantages are achieved only at operating voltages above about 10-20 V. This fact relegates wide bandgap RF power devices to base-station and infrastructure applications. The RF semiconductor content in these applications is approximately \$600M/year which at present is mostly Si LDMOS.

Given the performance advantages of wide bandgap devices and the availability of a large market, what are the technical challenges facing the technologies? Many of these challenges are not very different from those facing other semiconductor technologies. In order to achieve high device yield the starting material and fabrication processes must be controlled sufficiently to ensure reproducibility of device specifications. In addition starting material and packaging costs must be kept as low as possible. The wide bandgap technologies offer some interesting challenges and possibilities in these areas. Assuming that the high thermal conductivity of the SiC substrate is required, only 50 mm semi-insulating and conducting wafers are currently available. Larger diameter 75 mm and 100 mm wafers have been demonstrated in R&D. SiC substrates have a unique defect called a “micropipe” which is a small hole (0.5-2 μm dia.) that extends through the wafer. If present in or near device channel regions, micropipes are a “killer” defect. The lowest micropipe density reported to date is 0.5 cm^{-2} in R&D material. Production grade substrates have micropipe densities 1-2 orders of magnitude higher. Also commercially available SiC epitaxy has very wide specifications on thickness uniformity (± 25%) and on doping density (± 50%). The cost per unit area of a semi-insulating SiC starting wafer with epitaxy is 25 times that of a GaAs wafer. Clearly the quality and cost of SiC substrates and epitaxy will have to be improved significantly in order to achieve low die cost. Finally, high power density, wide bandgap devices may benefit from lower package costs, because smaller packages will be required for equivalent RF output power.

CONCLUSIONS

Wide bandgap devices offer higher RF power densities than Si and GaAs devices, and the total available market for such devices is approximately \$600M per year. The amount of this market that wide bandgap power devices will capture is totally dependent on their cost for performance as compared to that of Si and GaAs devices.

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