Gallium Nitride (GaN) Microwave Transistor Technology For Radar Applications

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Abstract:

This paper reviews the relative merits of Si, GaAs, SiC, and GaN materials and describes how the attributes of each impact the operation of microwave transistors for the generation of high RF output power, on the order of hundreds to thousands of watts, as necessary for radars systems. It is shown that the superior physical attributes of GaN lead to microwave transistors that are extremely well suited for high power applications. The superior properties of GaN combined with modern high efficiency biasing techniques make GaN technology a prime candidate for use in transmitters for radar systems.

I. INTRODUCTION

Many microwave radar transmitters require active devices which can produce RF output power in the order of kilowatts to even megawatts. Routinely microwave traveling-wave tube devices are utilized for this application. However, the currently used traveling-wave tubes are inefficient, large, expensive, and have suspect reliability. While semiconductor-based amplifiers in principle can offer a more effective solution, up to recently semiconductor transistors have been limited in the DC voltage that can be applied to the device by the inherent critical breakdown field that the material can sustain. Since limited DC voltage can be applied, high RF power operation requires large DC and RF current, which in turn requires large area devices[1]. High current operation is inefficient due to series losses and due to the fact that large area devices have inherently high capacitance and very low impedance which limit operating frequency and bandwidth[1]. GaN technology now offers a solution to this dilemma.

Solid-state amplifiers are already replacing traveling-wave-tube amplifiers (TWTAs) for a variety of microwave power applications. However, the low operating voltages of Si and GaAs devices lead to a large device periphery, resulting in high device and circuit complexity and reducing production yield and reliability. Wide bandgap technologies like GaN can achieve power density five times higher than that of conventional GaAs-based Metal-Semiconductor Field Effect Transistor (MESFETs) and Heterojunction Bipolar Transistors (HBTs). This will ultimately result in reduced circuit complexity, improved gain, efficiency, and higher reliability. In particular, radar systems will benefit from the development of this technology.

II. GaN IS THE FUTURE

The development of the wide bandgap semiconductor materials, such as GaN and GaN-based alloys, offers the ability to fabricate RF active devices, specifically AlGaN/GaN power High Electron Mobility Transistors (HEMTs), with significantly improved output power performance [1]. The improved RF output power is made possible due to the much improved material properties: high electric breakdown field, high saturated electron drift velocity, and when epitaxially grown on semi-insulating SiC substrates, improved thermal conductivity. The data in Table 1 [2] allows a comparison of the most important performance metrics of silicon (Si), gallium arsenide (GaAs), silicon carbide (SiC), and gallium nitride (GaN). The larger thermal conductivity of SiC and GaN enables lower temperature rise due to self heating. The five to six times' higher breakdown field of SiC and GaN is what gives those materials the advantage over Si and GaAs for RF power devices[2]. SiC is a wide bandgap material (3.26eV), but suffers from poor electron transport properties, which hinders its use in very high frequency amplifiers. SiC has also been limited by expensive, small and low-quality substrate wafers.

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

Properties	**Si**	**GaAs**	**4H-SiC**	**GaN**
Bandgap (eV)	1.11	1.43	3.26	3.42
Relative Dielectric Constant	11.8	12.8	9.7	9.0
Breakdown Field (V/cm)	2.5e5	3.5e5	35e5	35e5
Saturated Velocity (cm/sec)	1.0e7	1.0e7	2.0e7	1.5e7
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

Even though the mobility of the carriers is significantly better for GaAs devices, the higher peak and saturation velocity for GaN HEMTs compensates for the relatively lower mobility, enabling high frequency performance. These advantages for GaN, with the high linearity and low noise of the HEMT architecture, open the application of these devices for high power Radar amplifiers.

An additional advantage of GaN HEMTs stems from the large conduction band energy offset between the GaN channel and the AlGaN barrier layer. This allows a significant increase in the channel carrier density in GaN-based HEMTs with respect to other materials (up to $10^{13}cm^{-2}$ and above). This, along with higher voltage handling, increases power density. Power Density is a very important metric for high power devices because a higher power density yields a smaller die size and more easily realized input and output matches. The rapid progress in saturated CW RF power densities versus time for GaN FETs at X band is shown in Figure 1.

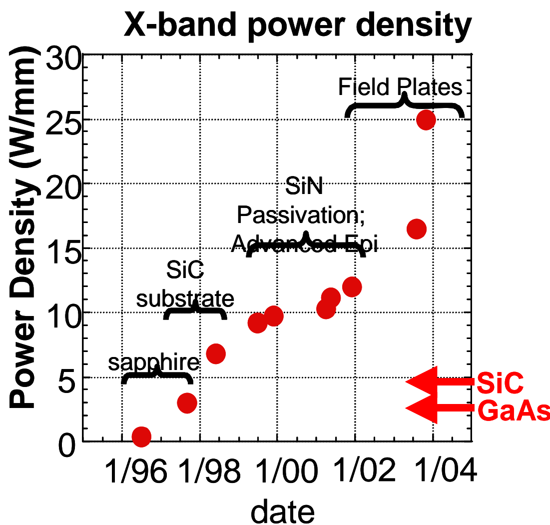

Figure 1. Power density for GaN FETs at X band as function of year. Best values for GaAs and SiC FETs are also shown.

The high operating voltages and high power densities that are possible with the wide bandgap RF devices offer a number of advantages for power amplifier design, manufacture and assembly in comparison to Si LDMOS and GaAs MESFET technologies. GaN HEMT technology offers high power per unit channel width that translates into smaller less expensive devices for the same output power, which are not only easier to fabricate but also increase the impedance of the devices. This enables lower complexity and lower cost impedance matching in amplifiers. The high voltage operation possible with GaN helps in eliminating the need for voltage converters, further reducing system cost.

III. THE PATH IS CLEAR

The present day state-of-the-art output power vs frequency for microwave solid state devices and microwave tubes is shown in Figure 2 [1]. Historically, tube amplifiers, such as grid controlled tubes, magnetrons, klystrons, traveling-wave tubes (TWTs), and crossed field amplifiers (CFAs) have been used as power amplifiers for radar transmitters. These amplifiers generate high power, but usually operate with low duty cycle. The klystron amplifier offers higher power than the magnetron at microwave frequencies, and also allows the use of more complex waveforms. The TWT is similar to the klystron, but with wider bandwidth. CFAs are characterized by wide bandwidth, modest gain, and compactness. Solid State Power Amplifiers (SSPAs) support long pulses and high duty cycle waveforms. Individual SSPA elements can be combined to produce sufficient amplification, despite the fact that individual SSPA elements have low power amplification. Silicon bipolar transistors, and gallium arsenide MESFETs, and GaAs PHEMTs are some of the solid state elements used in SSPAs. GaN HEMTs however, can be combined to create a SSPA with a significant improvement in mean output power resulting in an improvement of the radar detection range.

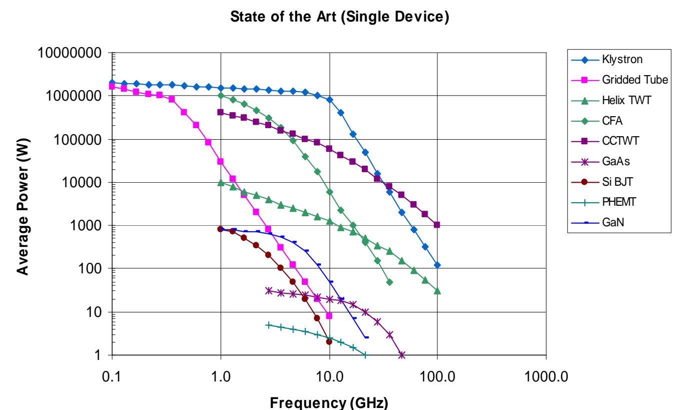

Figure 2. Present Day State of the Art Microwave Tubes and Solid State Devices

As shown, solid state transistors produce RF power levels less than about 100 watts at S-band frequencies and below, and their output continuously decreases with increasing frequency[1]. The RF output power capability of GaAs FETs approaches 50 watts at S-band and at Ka band is limited to about one watt[1]. The GaAs FETs are limited in RF output power capability primarily due to the low drain bias breakdown voltage[1]. Semiconductor devices fabricated from wide bandgap material, such as GaN, offer significantly improved RF performance.

Over time, various Figures Of Merit (FOM), for evaluating semiconductors for high power and high frequency potential have emerged. These FOM for high performance RF semiconductors attempt to combine the most relevant material properties into a number that provides

an estimation of the comparative strengths of the associated materials. The Johnson FOM ($JFOM=E_{CR}\, v_{sat}/\pi$) takes into account the breakdown electric field E_{CR} and the saturated electron velocity v_{sat} and corresponds approximately to the product of device cutoff frequency f_t times the corresponding breakdown voltage. As can be observed from Figure 3[3], the Johnson FOM for GaN is larger by at least x15 than that for GaAs.

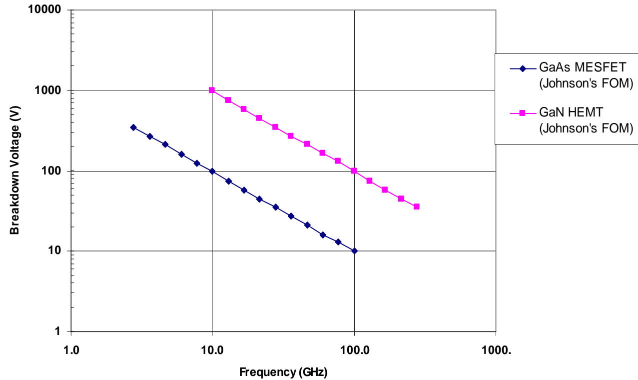

Figure 3. Johnson's Figure of Merit

Aethercomm believes that if the trends in GaN advancement are maintained at their current rate, the predicted performance of GaN HEMT's in the year 2010 will be as depicted in Figure 4. As shown in the figure, GaN will soon overtake all of its competitors in every category.

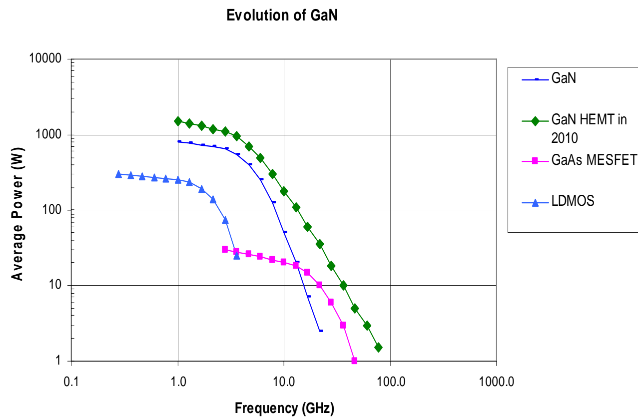

Figure 4. Evolution of GaN FET performance

IV. EFFICIENCY IS THE KEY

Modern radar systems for military applications place new requirements on RF power amplifiers due to the desire to reduce system size, weight, and cost. A major shift in amplifier specifications focuses more on amplifier efficiency to reduce DC power requirements and improve system reliability through lower component power dissipation. Furthermore, wide bandgap, broadband high efficiency microwave devices will enable enhanced system capability.

The low parasitic capacitance and high breakdown voltage of GaN HEMTs makes them ideal for realizing the Class E and Class F high efficiency amplifier modes. Both modes have theoretical efficiencies of 100%. Recently, several GaN transistor vendors have implemented Class E amplifiers in hybrid form. Typical results are ten watts output power at L-band with efficiencies from 80% to 90%.

Aethercomm recently delivered a Class F high efficiency amplifier module operating at L-band to a major defense contractor. The desired output power was to exceed 50W with an efficiency of 60% for the entire amplifier. Due to the tight delivery schedule, it was necessary to use off the shelf packaged transistors rather than developing a custom hybrid solution.

The power amplifier final stage was implemented using a balanced pair of packaged GaN HEMTs operating in Class F. Matching networks supplying the harmonic terminations necessary for Class F operation were designed by starting with an idealized model of the transistor. The parasitic capacitance and inductance of the transistor package was then added and the matching networks were modified appropriately to maintain the required harmonic terminations at the transistor die. The amplifier was then simulated using a nonlinear model of the transistor and the matching networks were modified to optimize efficiency and power.

A single-ended prototype of the Class F output stage was constructed. Drain efficiency of 75%, output power of 40W, and gain of 16dB were obtained with only minor bench tuning. The results tracked the simulation closely. Low power GaN devices suitable for the driver stage were not available. The three stage driver was designed using GaAs MESFETs, which were operated in Class A. Initially, it was believed that the driver stages would have to be operated in a high efficiency mode in order to achieve the required PAE; however, analysis indicated that with proper sizing of the transistors, Class A operation was permissible. The driver had 40dB gain and 10W power consumption.

The final configuration of the power amplifier exhibited a peak PAE of 63% at an output power of 75W. At P2dB, the amplifier had an output power of 65W and 61% PAE. Table 2 gives the characteristics of the power amplifier under different drive levels. Since the Class F final stage is biased at threshold, with no quiescent current, the amplifier has gain expansion at low drive levels. The amplifier gain peaks, then compresses as the maximum output power is approached. Table 2 demonstrates the efficiency of this design.

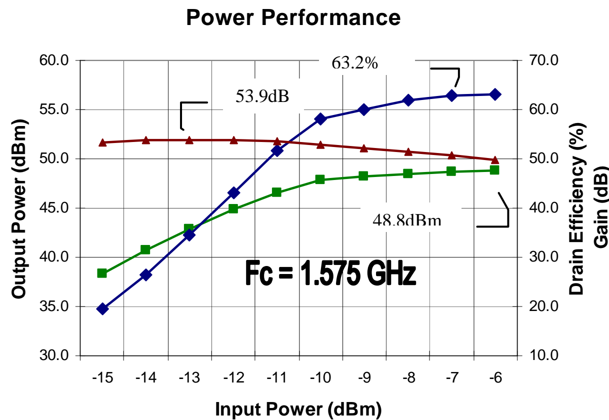

Figure 5. L-Band Class-F High Efficiency Amplifier

Aethercomm has also tested a 200W GaN HEMT device on SiC substrate designed to maximize power added efficiency while maintaining a high output power for an operating frequency of 1215MHz to 1390MHz and has observed efficiencies greater than 56% while maintaining output power levels in excess of 205 Watts at P3dB.

Many SSPAs intended for radar applications are designed with semiconductor RF devices configured for Class-C operation. This form of bias yields very efficient operation for a single transistor stage, however the Class-C transistor has such low gain, typically 6dB, that the efficiency advantage is lost due to the fact that many additional stages of gain are required to achieve the desired output power.

V. CONCLUSION

Future radar systems such as the active phased array radar (APAR) will require increasingly smaller, more highly efficient SSPAs. The desire for extremely fast scanning rates, much higher range, the ability to follow a tremendous number of targets being tracked and engaged, low probability of intercept, and the ability to function as a radio/jammer will require an innovative and cost effective transistor technology. Recent developments in the GaN HEMT have made it possible to realize highly efficient amplifiers at microwave frequencies. GaN HEMT devices provide a very high ratio of peak current to output capacitance, as well as an extremely high breakdown voltage and power density capability. This unique combination of characteristics allows designers freedom to achieve higher overall amplifier performance compared to competing devices.

REFERENCES

[1] R.J. Trew, “Wide Bandgap Transistor Amplifiers for Improved Performance Microwave Power and Radar Applications,” *15th International Conference on Microwaves, Radar and Wireless Communications, 2004 MIKON 2004,* Volume 1, 17-19 May 2004 Page(s):18 - 23 Vol.1

[2] C.E. Weitzel, “RF Power Devices for Wireless Communications,” *IEEE MTT-s Digest*, Volume 1, 2-7 June 2002 Page(s):285 – 288

[3] T. Kikkawa, K. Imanishi, M. Kanamura, and K. Joshin, “Recent Progress of Highly Reliable GaN-HEMT for Mass Production,” *CS MANTECH Conference, April 24-27, 2006* Page(s):171-174