GaN-based Components for Transmit/Receive Modules in Active Electronically Scanned Arrays

Mike Harris, Robert Howard and Tracy Wallace

Georgia Tech Research Institute, 925 Dalney Street, Atlanta, GA 30332
Email: mike.harris@gtri.gatech.edu Tel: 404-407-6015

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Abstract

This paper presents an analysis of the benefits and challenges of using gallium nitride (GaN) based components in next generation transmit/receive (T/R) modules for active electronically scanned arrays (AESAs). GaN is particularly well-suited for high power amplifiers (HPAs) in transmit and may be considered for limiters and low noise amplifiers (LNAs) in the receive path. Higher radiated power per element increases the range while the cost per radiated watt can be lower. Higher radiated power per element can also reduce antenna size (area/module count) for fixed range performance. GaN's higher drain voltage results in improved efficiencies at the next higher level assembly in the array by reducing the amount of copper conductors in the assembly. Higher voltage operation also reduces current requirements on dc/dc converters that are used throughout the array. Challenges in using GaN include its perceived lack of maturity and cost.

INTRODUCTION

Figure 1 is a block diagram of the RF components typically used in a T/R module. The phase shifter and attenuator may be combined into one MMIC. When integrated at this level, the MMIC is called a multi-function circuit (MFC) or a common leg circuit (CLC) since they are in both the transmit and receive paths.

Today's AESAs predominantly use gallium arsenide (GaAs) pseudomorphic high electron mobility transistor (PHEMT) technology for the RF components in both transmit and receive paths [1]. Multi-function self-aligned gate (MSAG) chip sets have also been produced for these applications [2]. It is well known that GaN has the potential to be the technology of choice for high power amplifiers [3]. Power densities of greater than 25 watts per mm of gate periphery have been demonstrated on GaN HEMTs and optimized devices have unity current gain frequencies greater than 40 GHz [4].

This paper presents a comparison of the technologies available for T/R modules and discusses system level factors that make it compelling to consider GaN-based MMIC components for future AESAs.

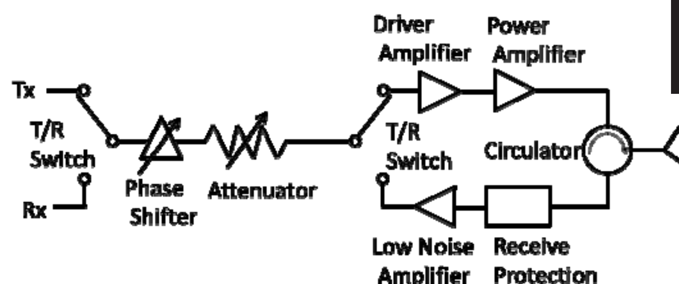

Figure 1. Block Diagram of the RF Components in a T/R Module.

TECHNOLOGY COMPARISON FOR POWER AMPLIFIERS

Semiconductor technologies that are available for an AESA application depend primarily on the frequency of operation. At UHF frequencies, silicon bipolar and silicon lateral double-diffused metal oxide semiconductor (LDMOS) technologies are available and are cost effective. However, in CW or long pulse width applications, these technologies may be challenged thermally and at higher frequencies are not suitable.

Ground-based, airborne, and shipboard AESAs being developed today are L-band, S-band or X-band. In these frequency bands, technologies that can be considered are silicon carbide (SiC), GaAs, GaN and indium phosphide (InP). Silicon germanium (SiGe) operates in these bands but is a low power technology (<1W at X-band).

From a T/R module designer's perspective, the key parameters for comparing technologies for amplifier applications are the output power density, operating voltage, dc supply current, energy storage to support the RF pulse, chip area, and cost. Table 1 compares the leading HPA technologies with respect to these key parameters. These comparisons are based on an HPA delivering ~20W of RF output power.

TABLE 1.
Technology Comparison for Power Amplifier MMICs.

Process	Voltage (V)	Power Density (W/mm)	Peak Current (A)	Chip Area $(mm)^2$	Therm. Cond. (W/mK)	Cost ($/W)
GaN HEMT	24-48	>5	2.5	17	390	12-14
HV GaAs	15-24	2	5	25	44	15-20
LV GaAs	8-10	0.7	6	40	44	18-20

Based on the key parameters in Table 1, it is clear that GaN on SiC excels in all of these parameters. Even though it is an emerging technology, its cost on a dollars/W basis is better than competing technologies. SiC MESFET MMICs were not included in the table since they have been overtaken by GaN on SiC in a manner that PHEMT succeeded GaAs MESFET.

GaN - A Natural for Class-E MMIC Amplifiers

Traditional MMIC power amplifiers, used in T/R modules, are biased in a class AB configuration. The theoretical maximum power added efficiency (PAE) for class AB amplifiers is in the range of 50-78.5%, but in practice the efficiency is at best in the range of 35-45% for GaAs-based amplifiers and 50-60% for large periphery GaN-based amplifiers.

GaN, with its high breakdown voltage, opens up a new range of bias conditions, termed "switch-mode," wherein the transistor amplifier is operated as a switch. This mode of operation results in much higher efficiencies and allows systems trades that may result in using air-cooled higher level assemblies rather than liquid cooled assemblies.

Fully and partially-matched L- and S-band GaN Class-E MMIC amplifiers have been demonstrated by the Georgia Tech Research Institute using a commercial GaN foundry. L-band MMICs produced nearly 100W of output power at 80% efficiency. S-band MMICs were equally impressive delivering up to 75W at over 65% efficiency. These results demonstrate the advantages provided by GaN MMIC technology.

GaN for Receive Components

GaN-based components are also being developed for receive applications. A 0.2-8 GHz high dynamic range GaN MMIC LNA-PA that achieves 0.5dB noise figure has been reported by Northrop Grumman Space and Technology [5]. This GaN MMIC utilizes a 0.2µm AlGaN/GaN-SiC HEMT technology and has high linearity with an OIP3 of 43.2-46.5dBm. Noise figure and OIP3 results are benchmarks for GaN LNAs over this multi-octave bandwidth.

HRL Laboratories reported a robust GaN MMIC LNA operating over 4-16 GHz frequency range [6]. Measured noise figure of the MMIC is less than 2 dB and the gain is more than 10 dB. HRL's LNA survived 5.4 W of incident RF power without front-end protection. In comparison, X-band GaAs PHEMT LNAs have absolute maximum RF input power limits of ~0.1W.

GaN Challenges

The previous sections present evidence that GaN-based MMICs can provide significant performance advantages at the T/R module level resulting in an overall improvement at the system level. GaN's higher operating voltage will make it easier to produce dc/dc converters that are lower cost and likely more reliable than current low voltage converters. So the challenges for widespread acceptance of GaN MMICs for radars are maturity, reliability and perceived high cost.

Cost in terms of dollars per RF watt generated is shown in Table 1 to be favorable for GaN in HPA applications. For a fixed power level, a GaN MMIC can be 1/3-1/4 the size of an equivalent power GaAs MMIC. While the GaN starting material is considerably more expensive than GaAs, the reduced area to generate similar power allows the GaN solution to be less expensive. Raytheon has found that, if the finished GaN wafer (including material) costs 2X that of GaAs, but yet the GaN MMIC is 1/3-1/4 the size of the GaAs MMIC, the resulting GaN solution is only 50-66% the dollars per RF watt generated [6].

Accelerated testing of GaN devices at 28V by multiple suppliers and users has resulted in a calculated activation energy of 1.7ev and a predicted MTTF at 150°C of $>10^7$ hours [7].

GaN-based HEMTs were first available commercially in 2004. DARPA's Wide Bandgap Semiconductor (WBGS) program has rapidly advanced the state of maturity of GaN and resulted the establishment of multiple commercial foundries and captive foundries that have released processes back by process design kits (PDKs) allowing the design of GaN-based MMICs using electronic design automation EDA software.

The real measure of maturity and acceptance of GaN is when major defense acquisition programs (MDAPs) state that their RF front-end hardware will be based on GaN. The Three-dimensional Expeditionary Long-range Radar (3DELRR) program stipulated in their request for proposals (RFP) that the T/R modules will be GaN-based [8].

GaN in Next Generation T/R Modules

Based on GaN's RF output power performance and efficiency on transmit and its impressive noise figure on receive, it is apparent that GaN-based MMICs will be leading contenders on future AESAs. Widespread use is likely if the cost of GaN on SiC wafers continues to drop. Development of enhancement mode devices to complement current depletion mode devices will open up opportunities to build multifunctional circuits (analog and digital on the same chip). Higher levels of integration may lead to single chip GaN-based T/R MMICs [9].

CONCLUSIONS

GaN-based MMICs, applicable to T/R modules, are available off-the-shelf or can be designed and produced in several GaN MMIC foundries. Performance advantages over competing technologies make it compelling that GaN be considered. If Class-E GaN-based amplifiers can meet spectral purity requirements, it is possible to have equal range performance, equal prime power/cooling, with a 20% smaller array having similar cost.

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ACRONYMS

3DELRR: Three-Dimensional Expeditionary Long-Range Radar
AESA: Active Electronically Scanned Array
AlGaN: Aluminum Gallium Nitride
CLC: Common Leg Circuit
CW: Continuous Wave
DARPA: Defense Advanced Research Projects Agency
GaN: Gallium Nitride
GaAs: Gallium Arsenide
HEMT: High Electron Mobility Transistor
HPA: High Power Amplifier
HV: High Voltage
InP: Indium Phosphide
LDMOS: Lateral Double-diffused Metal Oxide Semiconductor
LNA: Low Noise Amplifier
LV: Low Voltage
MESFET: Metal Semiconductor Field Effect Transistor
MDAP: Major Defense Acquisition Program
MFC: Multi-function Circuit
MMIC: Monolithic Microwave Integrated Circuit
MSAG: Multi-function Self-Aligned Gate
OIP3: Output Intercept Point 3rd order
PA: Power Amplifier
PAE: Power-Added-Efficiency
PHEMT: Pseudomorphic High Electron Mobility Transistor
RF: Radio Frequency
RFP: Request for Proposal
SiC: Silicon Carbide
T/R: Transmit/Receive
UHF: Ultra-High Frequency
WBGS: Wide BandGap Semiconductor