GaN Technology for Radars

Colin S. Whelan, Nicholas J. Kolias, Steven Brierley, Chris MacDonald, Steven Bernstein

Raytheon Company, Tewksbury, Massachusetts, USA
cwhelan@raytheon.com, 978-858-4141

Keywords: GaN, gallium nitride, microwave devices, MMICs

Abstract

Microwave GaN technology is now in production and poised to revolutionize many of today's radar and communication systems. Simultaneously, mm-wave GaN processes are rapidly being matured to meet the growing needs of high power and efficiency, at higher frequencies. In this paper, we present an overview of GaN development, focusing on reliability and affordability for defense applications.

INTRODUCTION

Historically, performance improvements afforded by new microwave semiconductor technologies such as GaAs MESFETs and PHEMTs have been evolutionary, resulting in incrementally more power density, gain, or noise figure. Gallium Nitride (GaN) technology, however, is truly revolutionary, resulting in dramatic (>5X) improvements in RF power density. The revolutionary power improvements afforded by GaN are now being realized in state-of-the-art monolithic microwave integrated circuits (MMICs) assembled in Transmit/Receive (T/R) modules, enabling the next generation of radar and communication systems.

High power semiconductors play an important role in radar performance. In a phased array radar, the RF energy is distributed to each element, phase shifted and then amplified before being radiated. The final amplification of the RF signal at each element is performed by the power amplifier. Traditionally, gallium arsenide (GaAs) has been the semiconductor of choice for efficiently amplifying this signal, creating the desired output power. Throughout the 1990's, Raytheon and others pioneered the insertion of GaAs-based MMICs into phased array radars, providing enabling system capabilities. As the performance requirements of these military systems have increased to meet the ever growing threats, so too have the power and efficiency requirements for the power amplifiers. Over that time, GaAs performance was stretched from the unit gate power density of 0.5 watt per millimeter of transistor periphery to 1.5 W/mm by increasing the drain voltage from 5V to nearly 24V. GaN, however, continued to make dramatic performance and maturity improvements, quickly surpassing GaAs' capability in power, efficiency, thermal spreading, cost effectiveness and frequency coverage (Table 1).

Today, with the development of microwave GaN complete, the power, efficiency and bandwidth performance of GaN-based MMICs is unsurpassed, revolutionizing the design of radars by creating not only higher performance but also lower system cost. With over 5 W/mm of power density, GaN RF amplifiers can provide more than 5X the power per element of GaAs, in the same square millimeter area footprint. Fewer high power GaN MMICs can be used to replace many low power GaAs MMICs, or alternatively, equal power GaN chips can be made dramatically smaller than their GaAs equivalent. Both approaches reduce overall system costs while enabling size-constrained systems. The higher drain current that GaN offers makes the broadband matching of high power MMICs simpler and more efficient than GaAs, while the 7-8X improvement in the thermal conductivity provided by the high conductivity SiC substrate enables amplifier cooling. This higher efficiency, achieved at high power, combined with better thermal dissipation, is a game changer for solid state electronic warfare systems. Finally, the wide band gap intrinsic to GaN material provides large critical breakdown fields and voltages, making a more robust amplifier, which eases T/R module and system implementation.

Table 1. GaN vs. GaAs Comparison

Parameter	GaAs	GaN
Output power density	0.5 – 1.5 W/mm	4– 8 W/mm
Operating voltage	5 – 20 V	28 – 48 V
Breakdown voltage	20 – 40V	> 100V
Maximum current	~ 0.5 A/mm	~1 A/mm
Thermal conductivity (W/m-K)	47	390(z)/490 (SiC)

This paper will review the advances in GaN device development, starting in the 1990's with the first transistor to its production status today. DC Arrhenius reliability data and RF operating life measurements of Raytheon's microwave process will also be presented. Finally, sample MMIC designs will be reviewed, along with system insertion considerations, including cost and thermal constraints.

GaN Development

The development of GaN semiconductors began more than 30 years ago, driven by their unique properties seemingly ideal for high-power microwave devices based on their high theoretical breakdown field and high saturated electron velocity. But at that time, the gallium nitride material quality was insufficient to produce microwave RF transistors. This all began to change in the early 1990s, Figure 1, when researchers used gallium nitride to fabricate the world's first green, blue, violet and white light-emitting diodes (LEDs) [1,2]. This breakthrough drove forward a rapid improvement in GaN material quality. Now, these LEDs can be found in traffic lights, TVs and flashlights.

Another obstacle to the development of GaN transistors was the lack of an inexpensive substrate material. Traditionally, the substrate material of the transistor is the same material as the transistor itself, but, to date, researchers have been unable to grow large area, high quality GaN substrates. Researchers first turned to growing GaN transistors on sapphire substrates, and in 1996 demonstrated the first microwave GaN power transistors. The sapphire substrates are low cost and widely available; however, their poor thermal conductivity and non-ideal lattice match to GaN limited the performance of the transistors. Semi-insulating silicon carbide (SiC) substrate proved a better choice with a good lattice match to GaN and an excellent thermal conductivity. The only drawback was that silicon carbide substrates were only available in small sizes (50 mm diameter) and were very expensive (100 times the price of GaAs) in the late 1990s. The last 10 years have seen a rapid improvement in the size, quality and cost of the silicon carbide substrates. Today, Raytheon's production GaN process uses 100 mm (4-inch) diameter SiC substrates [3,4].

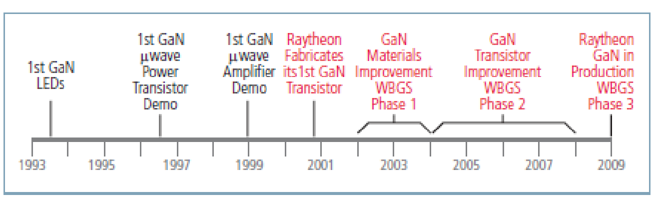

Figure 1. Timeline of GaN development

Reliability

Over the last six years, through the testing of hundreds of transistors and MMICs, Raytheon's 4" microwave GaN processes has demonstrated the required reliability for military systems. Figure 2 shows the DC Arrhenius results of a population of ~70 devices tested at five highly accelerated temperatures and 28V bias. The activation energy is ~1.7eV with a median time to failure (MTTF) at 150C of ~10^8 hours [5], exceeding the 10^6 hr standard. Figure 3 shows no change in output power of twelve X-band MMICs operating ~3-4 dB compressed at 28V for more than 1,000 hours. Channel temperatures are estimated to be ~150C-200C during this RF operating test. Additional testing for more than 15,000 hours on X-band MMICs has yielded similar results.

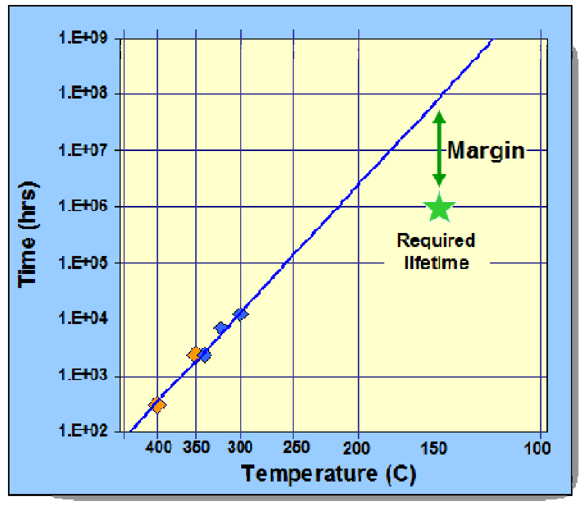

Figure 2. DC Arrhenius results of accelerated testing of 10x125um GaN transistors operating at 28V.

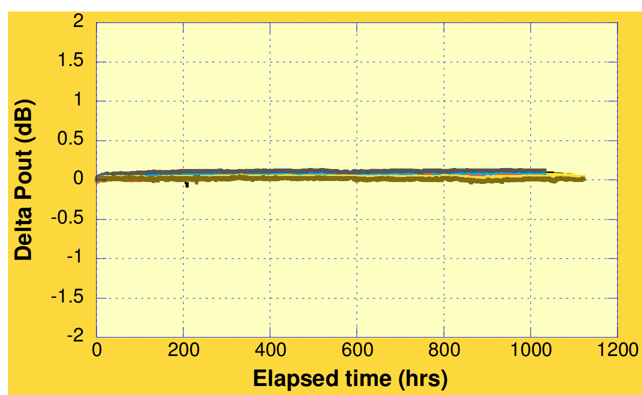

Figure 3. A dozen X-band MMICs demonstrating no change in output power over 1,000 hrs of RF operation at 28V.

MMICs

Raytheon has developed MMICs using both microstrip and coplanar waveguide (CPW) circuit design techniques, each of which offers advantages. Figure 4 shows two low frequency MMICs designed and fabricated using both topologies, and which demonstrated similar performance and size. The CPW process is lower in cost and higher yielding since it eliminates the backside grinding and via process, but at higher frequencies the output matching network becomes higher loss using this technique. In a face-up module implementation, the CPW design also offers a superior conduction path due the heat spreading of the thick SiC material. The microstrip MMIC offers slightly lower loss and is easier to design, allowing for faster design iterations.

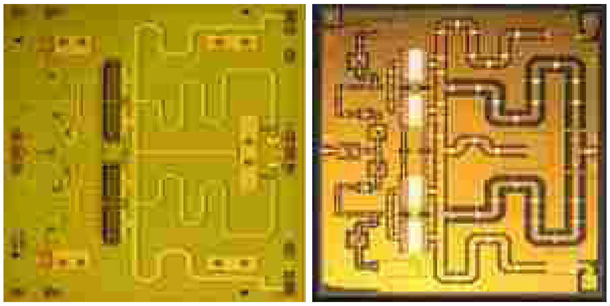

Figure 4. Fabricated low frequency Microstrip (left) and CPW (right) GaN MMICs

With the maturation of GaN in the lower RF frequency operating range, development focus has now shifted to GaN at mm-wave frequencies. At the extreme of the mm-wave RF frequency band, we have fabricated a 3-stage W-band GaN MMIC using a 2mil thick, microstrip topology operating at 17V [6]. This compact MMIC is less than $2.5mm^2$ and has 16 dB of small signal gain at 91 GHz. Under large signal compressed operation, the MMIC delivered 1.2W of output power and 20% PAE. These results compare favorably to the best efficiency demonstrated at this frequency using high gain, lower power InP technology, but at many multiples of output power.

SYSTEM INSERTIONS

GaN offers a number of advantages for next generation radars and jammers, as well as upgrades to existing GaAs or tube-based systems. Fewer high power GaN MMICs can be used to replace either many low power GaAs MMICs/modules or a single, often unreliable, high power tube, reducing overall cost while improving system reliability. For a fixed power level, a GaN MMIC can be 1/3-1/4 the size of an equivalent power GaAs MMIC due to the higher power density transistors. While the GaN starting material (GaN on SiC) is considerably more expensive than GaAs, the reduced area to generate similar power allows the GaN solution to be less expensive. For example, 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. A GaN-based system also provides additional benefits over GaAs at the system level by reducing overall module count, a major system cost driver, and the higher operating voltage improves the DC to RF conversion efficiency, reducing prime power and life cycle costs. For systems where maximum power per unit cell is desired, GaN offers ~5X power improvement in the same mm^2 as GaAs, enabling many space-constrained systems.

CONCLUSIONS

GaN material, processing, MMIC design and system insertion has matured greatly over the last decade, driven by its ability to increase the capability of RF systems, while reducing their cost. Today, GaN is quickly becoming the power amplification standard for all RF systems and is being assembled into modules and radars (Figure 5).

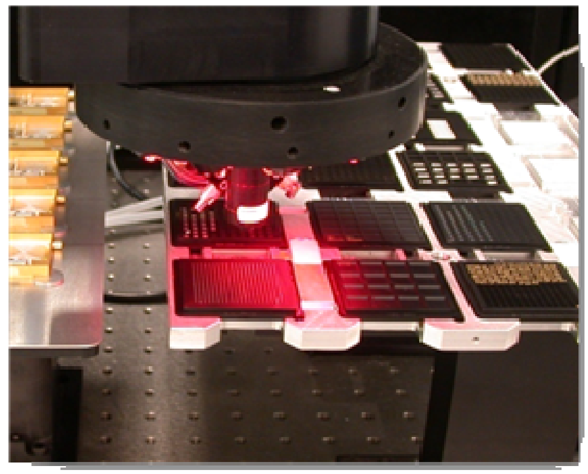

Figure 5. GaN MMICs being robotically assembled into modules.

ACKNOWLEDGEMENTS

The authors would like to thank KC Hwang, Kurt Smith, Tom Kazior, Joe Smolko, Mike Borkowski and John Zolper for their contributions to this work.

REFERENCES

[1] J. C. Zolper, “Wide Bandgap Semiconductor Microwave Technologies: From promise to practice,” *1999 IEDM Tech. Dig.*, pp. 289-392, Dec 1999.

[2] L. F. Eastman and U. K. Mishra, “The Tourghest Transistor Yet”, IEEE Spectrum, vol. 39, no 5, pp. 28-33, May 2002.

[3] C. Whelan and N. Kolias, “GaN Microwave Amplifiers Come of Age,” Raytheon Technology Today, 2010.

[4] N. Kolias, C. Whelan, T. Kazior, K. Smith, “GaN Technology for Microwave and Millimeter Wave Applications,” Microwave Theory and Techniques 2010.

[5] K. Smith, A. Kochalko, A. Hooven, C. Gil, M. Benedek, P. Phalon, R. Mcanulty, S. Brierley, “GaN Reliability,” Electrochemical Society, 2010.

[6] A. Brown, K. Brown, J. Chen, KC Hwang, N. Kolias, R. Scott, “W-band GaN Power Amplifier MMICs,” Microwave Theory and Techniques 2011.

Acronyms

GaN: Gallium Nitride
GaAs: Gallium Arsenide
SiC: Silicon Carbide
MMIC: Microwave Monolithic Integrated Circuit
CPW: Coplanar Waveguide
MTTF: Mean Time to Failure
LED: Light Emitting Diodes
T/R: Transmit/Receive