The DARPA Wide Band Gap Semiconductors for RF Applications (WBGS-RF) Program: Phase II Results

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Keywords: GaN, HEMT, power amplifier, reliability

Abstract

Dramatic progress has been achieved, during Phase II of the Wide Band Gap Semiconductors for RF Applications (WBGS-RF) program, sponsored by the Defense Advanced Research Projects Agency (DARPA), in extending the lifetime of high performance gallium nitride high electron mobility transistors, operating at frequencies up to 40 GHz. This paper summarizes the significant progress made by the contractor teams participating in the Phase II portion of the program.

INTRODUCTION

GaN-on-SiC based transistors enable high power added efficiency (PAE) power amplifiers that have significantly higher output power and power density than is presently available from amplifiers based upon other materials (such as GaAs or InP). The performance improvements available from GaN-based devices result from material characteristics such as high electron sheet charge density and very high electrical breakdown fields. Thermal characteristics are enhanced by using high thermal conductivity SiC substrates. Over the past several years, the Defense Advanced Research Projects Agency's (DARPA) Microsystems Technology Office has made a sustained investment in advancing the state-of-the-art of GaN-on-SiC material, transistors and MMICs in its Wide Band Gap Semiconductors for RF Applications (WBGS-RF) program. This paper summarizes the GaN-on-SiC-based transistor results achieved at the conclusion of the WBGS-RF Phase II program, including a discussion of the key insights and technology advances that enabled these results. All three teams participating in the program met or exceeded all of their program objectives, and are participating in Phase III. The on-going Phase III effort will develop GaN-on-SiC MMICs and demonstrate their use in several important DoD system applications.

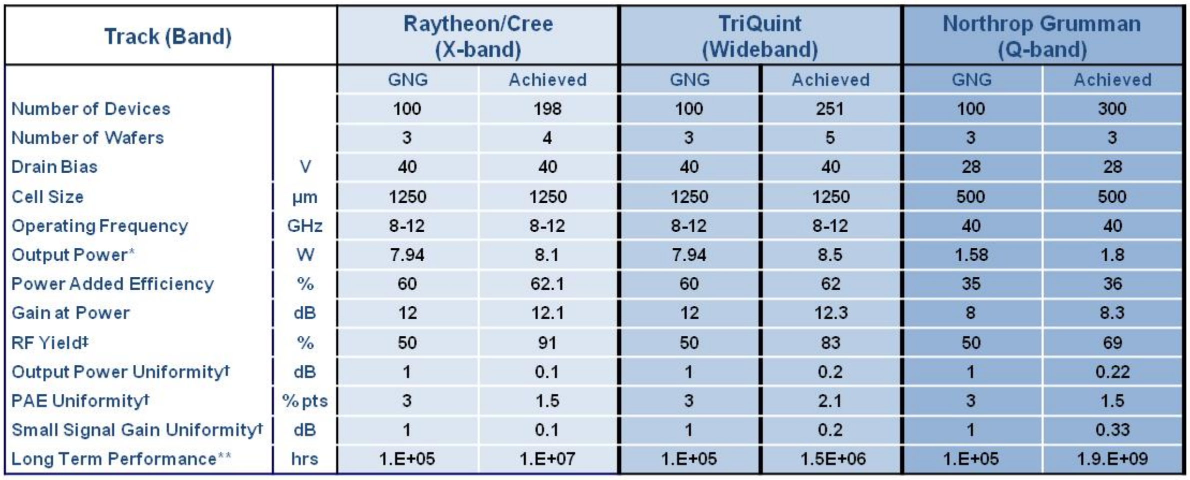
THE WBGS-RF PROGRAM

The WBGS-RF program is a multi-year, multi-phase program aimed at establishing all of the capabilities necessary to realize GaN-on-SiC based transistors and MMICs that can provide reproducible, highly reliable, high performance operation in DoD systems including radar, communication and electronic warfare systems. Phase I of the program, conducted between 2002 and 2004, resulted in improved AlGaN/GaN epitaxy and SiC material quality. The recently concluded Phase II portion of the program, which ran from 2005 until 2008, focused on increasing the lifetime and producibility of high performance GaN-on-SiC transistors. The two-year long Phase III portion of the program, currently underway, is focused on achieving long lifetime, high performance MMICs. One track will result in the first ever pilot radar sub-array using wide band gap semiconductors.

Each of the three teams participating in the WBGS-RF program has a unique set of objectives, within the program. The Raytheon/Cree team is developing X-band HEMTs, MMICs, T/R modules and a pilot radar sub-array. The TriQuint team also produced X-band HEMTs in Phase II but oriented its device designs toward its final program goal of producing wideband MMICs (operating over greater than an octave of frequencies) in Phase III. The Northrop Grumman team developed transistors operating at substantially higher frequencies, at Q-band (~40 GHz). This higher operating frequency range imposed a different set of design constraints on their HEMTs as compared to those of the two other teams.

All of the Phase II teams succeeded in significantly increasing the lifetime of their transistors (i.e., operation with no or minimal performance degradation) to thousands of hours at a device junction temperature of 150 °C. High performance X-band GaN HEMTs have now been shown to be capable of achieving reliability levels approaching or equaling those of GaAs and InP HEMTs. When the Phase II program began in 2005, there were already numerous examples of high performance microwave frequency GaN HEMTs reported in the literature from organizations around

TABLE 1
SUMMARY OF WBGS-RF PHASE II RF PERFORMANCE, UNIFORMITY AND LIFETIME



Track (Band)		Raytheon/Cree (X-band)		TriQuint (Wideband)		Northrop Grumman (Q-band)	
		GNG	Achieved	GNG	Achieved	GNG	Achieved
Number of Devices		100	198	100	251	100	300
Number of Wafers		3	4	3	5	3	3
Drain Bias	V	40	40	40	40	28	28
Cell Size	µm	1250	1250	1250	1250	500	500
Operating Frequency	GHz	8-12	8-12	8-12	8-12	40	40
Output Power*	W	7.94	8.1	7.94	8.5	1.58	1.8
Power Added Efficiency	%	60	62.1	60	62	35	36
Gain at Power	dB	12	12.1	12	12.3	8	8.3
RF Yield‡	%	50	91	50	83	50	69
Output Power Uniformity†	dB	1	0.1	1	0.2	1	0.22
PAE Uniformity†	% pts	3	1.5	3	2.1	3	1.5
Small Signal Gain Uniformity†	dB	1	0.1	1	0.2	1	0.33
Long Term Performance**	hrs	1.E+05	1.E+07	1.E+05	1.5E+06	1.E+05	1.9.E+09

* Measured at compression corresponding to maximum PAE
† Uniformity defined as the standard deviation from ≥100 devices/MMICs on all validation wafers
‡ The fraction of devices from all validation wafers meeting or exceeding all relevant GNG requirements
** Failure is defined as a 1 dB decrease in output power

the world. Unfortunately, many of these devices, particularly those operating at very high power densities, suffered from rapid performance degradation as a function of time. Output power and gain often decreased dramatically within the first hours of operation [1]. Yield of these high performance devices was, typically, also quite low. Recognizing the necessity of achieving stable levels of high performance as function of time, Phase II of the WBGS-RF program established a principal objective of increasing the fundamental understanding of design and fabrication characteristics of GaN-based transistors so that the factors causing degraded performance could be identified and eliminated. The systematic experimentation and physics-based performance modeling that focused on understanding the causes of degradation resulted in each team demonstrating stable, high power density HEMTs. For example, X-band HEMTs demonstrated power density exceeding 6.4 W/mm with estimated MTTF over 10^6 hours, at 150°C junction temperature.

Throughout the program, contractors' reported experimental data were routinely corroborated by DoD scientists and engineers who were part of the Government's Tri-Service team of evaluators. This validation was a critical element of enhancing cross-team communication, and ensuring the Government's understanding of the contractor data. The Tri-Service team, composed of personnel from the Air Force Research Laboratory, the Naval Research Laboratory, and the Army Research Laboratory, provided independent analysis and evaluation of devices from over 500 wafers delivered to the Government. Each delivered wafer had a standard set of process control monitors that allowed the Tri-Service team to track process developments and compare its findings with the contractor's data over time. Standard evaluation circuits were tested for both DC and RF parameters. The Tri-Service team also corroborated device reliability and performed failure analysis.

WBGS-RF PHASE II RESULTS SUMMARIZED

All of the goals, in all three tracks, were met or exceeded by the teams in Phase II. Table 1 summarizes the Go/No Go criteria (goals) for each track and the results achieved by each of the teams. The RF performance represents averages achieved over multiple devices and across several wafers (hundreds of devices over at least 3 wafers). The contractors' reported results in Table 1 were corroborated by the Tri-Services evaluation team. The final baseline designs developed in the program simultaneously provide high performance and projected long life with excellent uniformity, all necessary for manufacturable designs.

RF PERFORMANCE

All three teams achieved all of the aggressive RF performance goals while still meeting the uniformity and long term performance goals. While the ultimate goal for the Raytheon and TriQuint teams differed, during Phase II, they both demonstrated X-band devices operating at a 40 V bias level. The Raytheon team (along with Cree) demonstrated 4-wafer averaged PAE of 62.1%, 8.1 W output power and 12.1 dB gain in devices with 1.25 mm gate periphery. TriQuint produced devices with slightly higher power and comparable efficiency, 5-wafer averaged output power of 8.5 W, 62% PAE and 12.3 dB gain. While each the teams had unique designs, the designs shared the key design features such as a source-connected field plate, thus increasing the uniformity of the electric field profile across the gate region. The devices produced by Northrop

Grumman for Q-band operation operated at lower bias voltage, 28 V. Its 500 μm gate periphery HEMTs averaged 1.8 W output power with 36% PAE and 8.3 dB gain over 5 wafers. At this higher operating frequency, field plates were not used because of the resulting increase in capacitance would have degraded the performance. Other methods were used to achieve reliable high performance.

Key to achieving Phase II's goals and surpassing what had been previously achieved for stable devices was the systematic investigation of the role of the device epi-layer design and device fabrication methods on performance and reliability. New analytical models developed in the program assist with understanding device stability [2]. Improvements in PAE and gain were achieved through careful design of the buffer layer and reduction of gate current leakage. The role of buffer layer doping and the barrier strain and thickness were carefully investigated to balance the requirements for high power density and stable operation. In addition, the teams investigated various back barriers to increase carrier confinement. This design feature is expected to contribute to advances in Phase III performance.

STABILITY AND DEGRADATION

The most challenging aspect of the Phase II effort was advancing the understanding of the physical mechanisms that cause degradation, and producing designs to either eliminate these mechanisms or substantially mitigate their effects. Demonstrating stability and projected long life was recognized as a key stepping stone to achieving acceptance of GaN for use in military applications, which typically have reliability and performance requirements that exceed those of commercial applications.

Prior to the Phase II program, high frequency GaN HEMTs designs often had a lifetime of only a few hours. All three teams made remarkable advances in actual transistor tested life. Today, many device designs have demonstrated operation at X-band and higher for more than 1,000 hours with some demonstrations of 10,000 hours with output power degradation of less than 1 dB. Lifetime estimates were determined using single failure mode Arrhenius method elevated temperature testing. All three teams had estimated lifetimes in excess of 10^6 hours at 150°C junction temperature. TriQuint's lifetime data is shown in Figure 1. The figure shows the MTTF projection of > 10^6 hours where both DC and RF lifetime data are included. Figure 2 shows the MTTF reported by the Raytheon team. A challenge encountered in generating Arrhenius lifetime estimation was the extremely high junction temperatures needed to induce failures on a time scale practical for lifetime testing. More testing and analysis at less stressed conditions is required to assure the single mode assumption is correct for operational conditions.

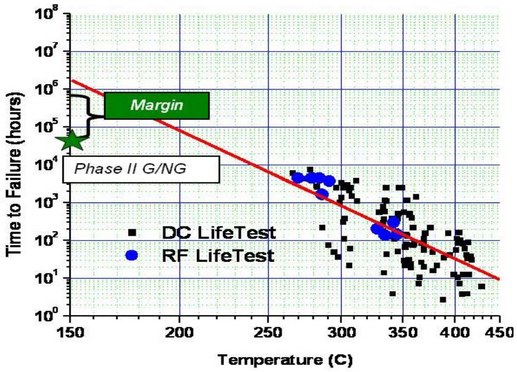


Figure 1. MTTF projection for TriQuint devices at the end of Phase II. Note that results exceed the program objectives, with a MTTF of > 10^6 hours at a junction temperature of 150°C.

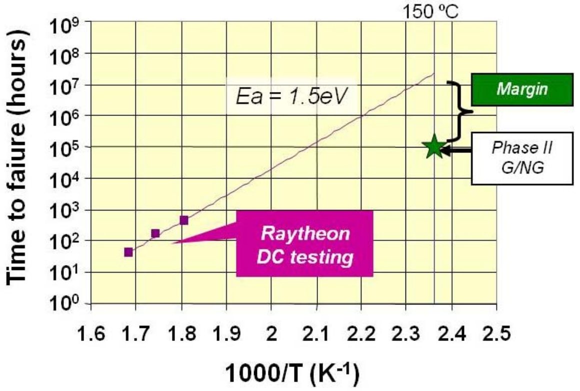


Figure 2. MTTF projection for Raytheon devices at the end of Phase II, with a MTTF of > 10^6 hours at a junction temperature of 150°C based upon tests at 280, 300 and 320°C.

The estimated long life now projected is the result of the significant investment made in understanding the degradation mechanisms. As an example, greatly reduced drain current collapse has followed as sources of traps are mitigated in the buffer, the barrier, and at the surface interfaces. The teams have observed failures with different time scales. Failures that occur in the first few minutes of operation appear to be highly dependent upon processing conditions, and are believed to be caused either by gate leakage through the surface or by Schottky barrier degradation. The degradation modes that dominate over the first few hours of operation are not well understood. Analysis of devices tested to long-term failure revealed failure modes that were previously unidentified. Although the impact of the electric field profile peaking under the gate was understood previously, evidence of crystal modifications in the AlGaN layer under the drain edge of the gate region led to new understanding of a potential long-term failure mode. Models of the lattice defect formation from the excessive stress resulting from the inverse piezoelectric effect in the barrier match experimental evidence from failed devices [3]. These models support the importance of keeping the peak electric field strength below its critical value in order to mitigate this degradation mechanism.

Uniformity

The third set of program goals were aimed at assuring that these high performance, long lifetime device designs were compatible with high yield manufacturing processes. The program's definition of uniformity was based upon the RF yield (devices meeting or exceeding the RF performance goals) including the output power uniformity, the PAE uniformity and small signal gain uniformity. All three teams were able to exceed the program's uniformity objectives, as shown by the achieved RF yield values in Table 1.

Each of the teams delivered several wafers per quarter to the Tri-Service evaluations team for DC and RF testing. The deliverables were predominantly fabricated on 3" diameter wafers. The large volume of total wafer starts in the program made it possible to collect a large amount of data for wafer-to-wafer uniformity in addition to same wafer uniformity. The large number of wafers also facilitated identifying the critical issues with the epi-layer design that led to improving uniformity. Notably, identical epi-layer designs could be fabricated in different foundries and achieve comparable RF performance and uniformity. Runs where identical epi-layer structures were processed in different foundries assisted with separating out the influence of the epi from other fabrication issues.

Steady progress in uniformity and yield was made over the course of the three year program. Figure 3 show the mean and standard deviation of the key RF performance parameters across 1,400 devices on 14 wafers. Initial results on 100-mm diameter wafers have shown epitaxial uniformity and RF device performance comparable to that achieved on 3" diameter wafers. The use of larger substrates coupled with greatly improved device yield is expected to result in significantly reduced costs in the future.

Future MMIC Development

With the successful completion of the Phase II development of reliable GaN-on-SiC transistors, the program is continuing with emphasis on development of high performance, manufacturable and reliable MMICs. Phase III of the program is a two-year development effort to achieve reliable MMICs meeting challenging performance goals. The program is on-track to demonstrate these MMICs by the end of 2010. The MMICs presently under development are expected to substantially outperform today's GaAs-based MMICs, and should provide a higher power, higher efficiency alternative to today's technology.

Conclusions

The WBGS-RF Phase II program resulted in significant advances in the state-of-the-art performance and lifetime of GaN-on-SiC HEMTs operating at X-band and higher and an operating bias of 40 V. Estimates of transistor lifetime using single failure mode Arrhenius elevated temperature testing across all three teams in the program exceeded the 100,000 hour goal at a junction temperature of 150°C. This represents as much as a five order of magnitude increase in transistor lifetime over the course of the program, taking GaN technology from a laboratory novelty to being able to vie with more mature technologies.

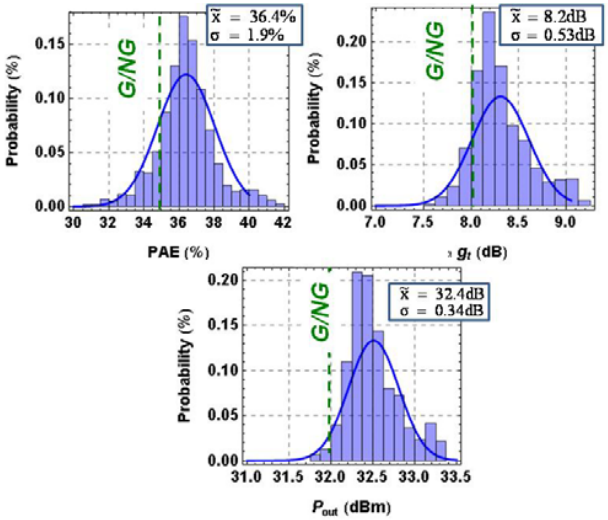


Figure 3. Phase II Northrop Grumman final deliverables uniformity data from 1400 devices over 14 wafers. The RF yield was greater than 68% for these 40 GHz devices, exceeding the program objective of 50% yield.

Acknowledgements

The authors acknowledge the support of the Government's Tri-Service evaluation team and the outstanding achievements of the performer teams participating in the WBGS-RF program, led by Joe Smolko (Raytheon), Mike Wojtowicz (Northrop Grumman) and Tony Balistreri (TriQuint).

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Acronyms

DOD: Department of Defense (US)
HEMT: High Electron Mobility Transistor
MMIC: Microwave Monolithic Integrated Circuit
MTTF: Mean Time To Failure