Preliminary Results from Phase II of the Wide Bandgap Semiconductor for RF Applications (WBGS-RF) Program

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***Abstract* – This paper details the latest progress in the Wide Bandgap Semiconductors for RF Applications (WBGS-RF) program sponsored by the Microsystems Technology Office of the Defense Advanced Research Projects Agency (DARPA/MTO). While the first phase of WBGS-RF focused on semi-insulating substrates and epitaxial growth, this phase pushes new RF capabilities in wide bandgap device fabrication, showing improvements in power-added efficiency, gain, bandwidth, power density and reliability of wide bandgap RF power devices. Although this report gives initial DC and RF test results from sample devices, further improvement is expected as this phase of the program progresses.**

Keywords: GaN, SiC, substrate, power amplifier, HEMT

I. INTRODUCTION

The DARPA Microsystem Technology Office (MTO) has a long history of supporting III-V semiconductor material development for novel electronic devices. The Wide Bandgap Semiconductor for RF Applications (WBGS-RF) program explores semiconductors with bandgaps significantly greater than silicon; specifically, GaN, SiC, and AlN. While many circuits could benefit, driving RF power amplifier performance is the focus of WBGS-RF, improving the power added efficiency, bandwidth, and power density of these devices. Improving the features of these new devices will fill a variety of military roles. X-Band T/R modules are used in radar assemblies, wide-band high power amplifiers for electronic warfare and Q-band high power amplifiers for satellite communications.

II. WBGS-RF - PHASE II

Phase II of the DARPA WBGS-RF is a comprehensive effort to establish capabilities to design, fabricate and demonstrate wide bandgap devices with high performance and reliability at an affordable cost. Specific program objectives include:

- Demonstrating manufacturable and reproducible WBGS device and MMIC fabrication processes,
- Demonstrating WBGS devices and MMICs that, while maintaining high levels of producibility and reliability, also achieve substantially higher levels of performance compared to GaAs-based microwave and millimeter-wave devices and MMICs,
- Understanding the degradation mechanisms of WBGS devices, leading to robust, highly reliable devices and MMICs,
- Developing and using physics-based models to accurately predict device RF performance,
- Demonstrating superior thermal management strategies through heat spreading and cooling.

To demonstrate the widespread applicability of the resultant devices and MMICs, a three-track demonstration portion of the program was established. Three contractor teams have been selected to fabricate and demonstrate devices that address each of these tracks. A summary of each track now follows.

A. Wideband High Power Amplifier (HPA)

In this track, the TriQuint team will demonstrate power amplifier devices and MMICs that operate over an instantaneous bandwidth in excess of one decade (e.g, from 2 GHz to 20 GHz), inclusive of X-band. The specific key technical requirements for this track are shown in Table I. As is the case for all current DARPA efforts, contractors are expected to meet or exceed specific go/no-go (GNG) milestones as the program progresses.

TABLE I
EARLY BENCHMARKS TOWARDS PHASE II WIDEBAND HPA GOALS

Type	Q1 Status	M10 Status	Milestone	GNG
Integration Level	Device	Device	Device	Device
Track (Band)	X	X	X	X
Drain Bias (V)	35	30	28	40
Cell Size (µm)	300	400	400	1250
Operating Frequency	10	10	10	10
Output Power (W)	2.4	3	2.63	8
Power Density (W/mm)	8	7.5	6.6	6.4
Power Added Eff. (%)	66	56	60	60
Gain at Power (dB)	12.7	10.9	10	12
RF Yield (%)	n/a	n/a	50	50
Pout Uniformity (dBm)	n/a	33.6/0.23std	1.5	1
PAE Uniformity (%)	n/a	51.3/3.6std	6	3
SS Gain Uniformity (dB)	n/a	12.6/0.2std	1.5	1
Long Term Performance (hrs)	-0.48dB @1Khr.	-0.48dB @1Khr.	1E5	1E5

Recent improvements achieved by the TriQuint team are:

- Demonstrated 6.5 W/mm, 58% PAE, 11.7 dB gain on 400-µm unit cell at 35V bias,
- Increased V_{ds} from 30V to 40V, PAE > 60%, Gain > 12dB and Power density > 7W/mm,
- Improved reliability by reducing gate leakage, increasing the voltage breakdown and further reducing defect density, all made possible by intimate understanding of the physics of failure,
- Demonstrated RF uniformity of 0.9 dB in maximum stable gain (MSG) at 10 GHz across nine 3-inch wafers.

Improving reliability is a crucial goal in this phase of the WBGS-RF program, requiring a fundamental understanding of failure mechanisms. Identifying the process and device design changes which improve the DC and RF life-test reliability results is essential to meeting the program goals. Figure 1 shows one example of RF reliability testing which meets the 6-month Go/No-Go goal milestones.

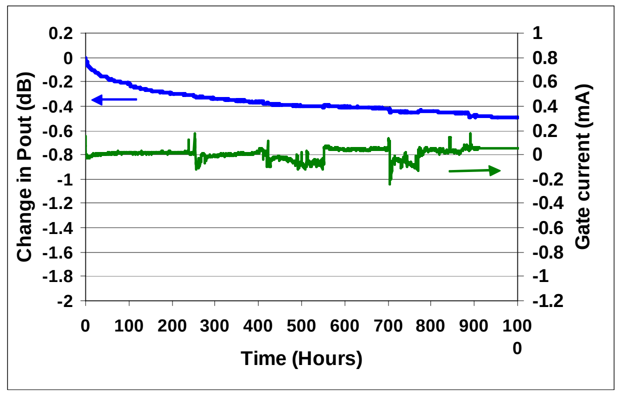

FIGURE 1
SHORT-TERM RF STABILITY PLOT SHOWING 0.5dB POWER VARIATION OVER 1000 HOURS AT Vds = 30V.

B. X-band Transmit and Receive (T/R) Module

In general, WBGS-RF module characteristics are expected to be equivalent to or better than those of current T/R modules capable of delivering 10 watts of CW output power over the same frequency range. Led by the Raytheon-Cree team, this WBGS-RF module works towards a power amplifier MMIC which meets the specific performance requirements laid out in Table II. Similar to the previous track, reliability tasks include reducing the gate leakage by optimizing the GaN cap and AlGaN Schottky layers through the growth of the AlGaN composition as well as its thickness and doping. Fe-doped GaN minimizes buffer leakage while epitaxial material swaps and improved growth conditions have lowered the dislocation density on 3" wafers. Recent device topology and process optimization has yielded improvements in RF performance (see Figure 2).

TABLE II
EARLY BENCHMARKS TOWARDS PHASE II X-BAND DEVICE GOALS

	Month ARC					
Parameter	***6***	***10***	***16/(18)***	***22***	***28 (GNG)***	***34***
Drain Bias (V)	28	28	28/40	28/40	40	48
Pout (dBm)	36	37	38/39	38/39	39	39
Pout (W/mm)	3.2	4.0	5.0/6.4	5.0/6.4	6.4	6.4
Pout Uniformity (dB)		1.5	1.5/2	1/1.5	1	1
Gain (dB)	10	10	10/10	11/11	12	12
Gain Uniformity (dB)		1.5	1.5/1.5	1.5/1.5	1	1
PAE (%)	50	55	55/50	65/55	60	60
PAE Uniformity (%)		6	6/6	3/4	3	3
150°C Life time (hrs.)	1E3	1E4	1E5/1E3	1E6/1E4	1E5	1E5

TABLE III
EARLY BENCHMARKS TOWARDS PHASE II Q-BAND GOALS

	Phase II		
	Today (11 months)	18 months	36 months
Type	Status	Milestone	GNG
Integration Level	Device	Device	Device
Track (Band)	Q	Q	Q
Drain Bias (V)	25	25	28
Cell Size (µm)	500	500	500
Operating Frequency	40	>40	>40
Output Power (W)	1.55	1.26	1.58
Power Density (W/mm)	3.1	2.5	3.2
PAE (%)	29.6	27	35
Gain at Power (dB)	6.5	7	8
RF Yield (%)		20	50
Output Power		1.5	1
PAE Uniformity (%pts)		6	3
SS Gain Uniformity (dB)		1.5	1
LNA Survivability (W)	N/A	N/A	N/A
Long Term Performance	>1E4	1E4	1E5

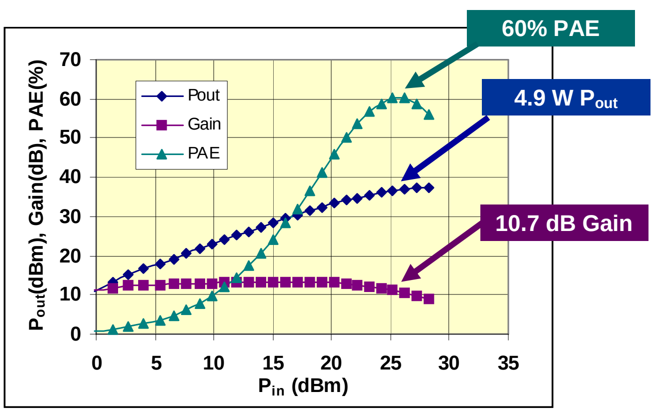

FIGURE 2
RF PERFORMANCE PLOT OF SAMPLE X-BAND DEVICE.

Accurately finding the junction temperature and dealing with impedance mismatches due to GaN thermal expansion are two thermal management challenges that have yet to be overcome.

C. Q-band High Power Amplifier

This effort of this track is to develop high performance, highly reliable Q-band devices (see Table III). For the Phase II effort, Q-band power amplifier devices will be fabricated through materials optimization beyond those performed in Phase I (e.g., defect and impurity control, defect screening, understanding the physics of failure and device design through careful modeling). Basing the process on established X-band techniques but substituting devices with shorter gates has yielded excellent millimeter-wave results (see Figure 3).

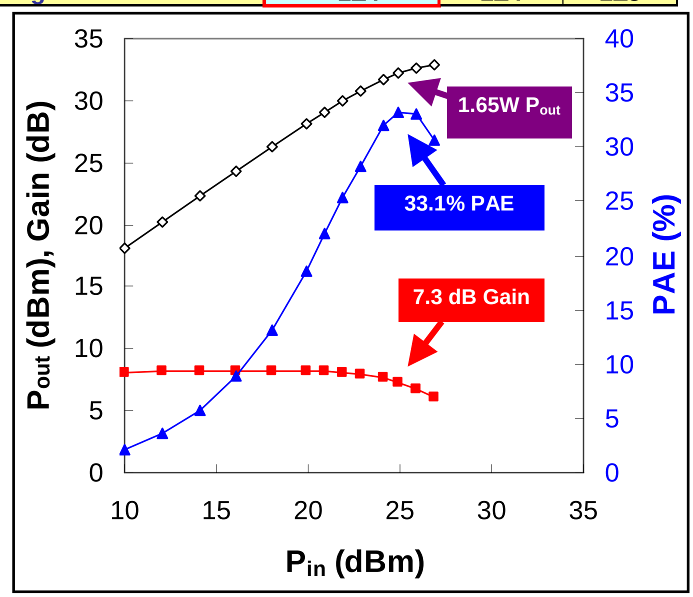

FIGURE 3
RF PERFORMANCE PLOT OF SAMPLE Q-BAND DEVICE.

Activities common to all three modules include updating the baseline material sets, establishing initial activation energies, correlating DC-to-RF lifetime tests and selecting baseline gate structures.

III. SUMMARY

In summary, it is expected that DARPA's Wide Bandgap Semiconductor Technology Initiative will result in the establishment of a number of fabrication facilities capable of producing wide bandgap materials, devices, MMICs and T/R modules. This will provide significant performance improvements for both military and commercial systems at an affordable cost