Wide Bandgap Semiconductor Devices and MMICs: A DARPA Perspective

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Abstract

This paper reports on the recent successful completion of Phase I of DARPA's Wide Bandgap Semiconductor Technology Initiative (WBGSTI). Phase I results are given for semi-insulating substrates and epitaxial growth, and a description and expectations for the upcoming Phases II and III are also provided.

INTRODUCTION

Wide bandgap devices and MMICs with high power density, high power added efficiency (PAE), high gain and wide bandwidth of operation have been demonstrated by a number of manufacturers. Excellent performance has been reported for devices operating at frequencies ranging from below 1GHz to approximately 40GHz [1]. Although many promising microwave frequency results have been achieved, beginning more than 10 years ago from SiC devices [2], fabrication yield of high performance WBG devices has historically been very low. A principal reason for this was the lack of SiC substrates with sufficiently high resistivity to provide semi-insulating properties and a low enough number of serious defects such as micropipes to assure that most of the devices on a wafer would operate properly. In addition, and partly as a result of the lack of high quality substrates, homo- and hetero-epitaxial growth of wide bandgap materials, such as GaN, had not been routinely achieved with high uniformity across large diameter wafers with high enough electron mobility to be useful in making microwave and mm-wave devices.

During the past three years, rapid progress has been made in the development of SiC substrates, with increasingly larger diameter, that exhibit a low enough number of defects and high enough resistivity to serve as excellent platforms upon which to produce high yields of large area devices and MMICs with excellent performance characteristics. In addition, WBG epitaxial structures have been demonstrated that result, for example, in GaN HEMTs capable of saturated power outputs of 174 watts at 2.1 GHz and with a maximum PAE of 54% and linear gain of 12.9 dB with a power output of 150 watts at the same frequency. [3]

WBGSTI PHASE I RESULTS

Although many efforts throughout the world, funded by both commercial and government organizations, have contributed to the rapid advances in wide bandgap technology during the past few years, Phase I of the DARPA Wide Bandgap Semiconductor Technology Initiative (WBGSTI) has served as a significant catalyst for accelerating improvements in the characteristics of several types of wide bandgap materials including SiC, GaN and AlN. During the course of the program, the diameter of commercially available SiC substrates has increased from 2" to 3" with 4" diameter material being developed by several vendors and expected to become commercially available within the next year. At least one vendor, Cree, has also established a SiC device and MMIC foundry and is offering high power SiC devices for sale. Table I shows the rapid progress that has been made in improving both the absolute values of key substrate parameters and in improving the uniformity of those parameters during the course of Phase I. Results have been particularly impressive for SiC substrates with most of the program's goals for this type of substrate already achieved or exceeded. Significant progress has also been made toward improving the characteristics of GaN and AlN substrates. Table II shows the improvements of GaN epitaxial layers grown by both MBE and MOCVD techniques during the course of the DARPA WBGSTI program. Again, impressive progress has been made both in achieving reproducible high mobility active layers and in uniformity of material characteristics across wafers.

Recently, high power, high efficiency, X-band devices, fabricated on GaN substrates produced by ATMI (recently acquired by Cree), have been demonstrated by BAE Systems. In addition to the achievement of impressive performance at microwave frequencies, the ability to make millimeter-wave devices capable of producing 3.5 W of output power with PAE of 22% at 35 GHz has also been demonstrated [4].

Another technique being used successfully to enhance device performance is the incorporation of field-plates. Their use has led to the realization of devices with extremely high breakdown voltage, high power outputs and impressive power added efficiencies. One example is a GaN HEMT which yielded an output power density of 32.2 watts/mm with a power added efficiency of 54.8% at 4 GHz when biased at 120 volts [5].

TABLE I
WBGSTI PHASE I SUBSTRATE RESULTS

Substrate Material[a]	Metric	Units	Program Start	End of Phase I
SiC	Wafer Diameter	mm	50	75
	Defect Density	MP/cm^2 [b]	>80	5
	Resistivity	Ω-cm	$<10^5$	$>10^{11}$
GaN	Wafer Diameter	mm	15×15	50
	Defect Density	defects/cm^2	$>10^9$	7×10^6
	Resistivity	Ω-cm	$<10^2$	$>10^9$
AlN	Wafer Diameter	mm	27	25
	Defect Density	defects/cm^2	$<10^4$	$<10^3$
	Resistivity	Ω-cm	$>10^{12}$	$>10^{12}$

[a]All substrates are semi-insulating [b]MP = micropipes

TABLE II
WBGSTI PHASE I EPITAXIAL GROWTH RESULTS

	Metric		Units	Program Start	End of Phase I
MBE	Material Control and Uniformity	Sheet Resistance Variation	%	±5	±2.16
		Wafer Diameter[a]	mm	50	75
	Electrical Properties	Hall Mobility	cm^2/V-s	<1000	1443
		Uniformity	%	poor	±2
		Wafer Diameter[a]	mm	50	75
MOCVD	Material Control and Uniformity	Sheet Resistance Variation	%	>±10	±1.72
		Wafer Diameter[a]	mm	50	75
	Electrical Properties	Hall Mobility	cm^2/V-s	1500	1719
		Uniformity	%	poor	±2.8
		Wafer Diameter[a]	mm	50	75

[a]90% usable area

WBGSTI PHASES II AND III

All of the above successes as well as many others have provided a solid framework for DARPA to continue its Wide Bandgap Semiconductor Technology Initiative. Phase II of the Initiative, which will be conducted between 2005 and 2007, will aim to realize a high yield of reliable, high performance GaN-based microwave and millimeter wave devices. Following Phase II, Phase III will attain high yields of reliable, high performance GaN-based MMICs and will demonstrate their use in several types of modules, as described below. This portion of the program will be conducted between 2008 and 2009. As wide bandgap devices and MMICs with outstanding performance characteristics become readily available, with demonstrated high reliability and at increasingly lower prices, they will lead to a very significant enhancement of the performance of numerous DoD and commercial systems including radars, smart weapons, electronic countermeasures systems and communication systems. Significant non-DoD commercial applications are also expected to make use of these devices and MMICs, which will help to sustain production capabilities.

Phase II and III of the DARPA WBGSTI will be comprehensive efforts to establish capabilities to design, produce, package and demonstrate the desirability of wide bandgap devices and MMICs with high performance, high reliability and produced at an affordable cost. Specific Program objectives include the following:

- Great improvement of the understanding of the physics of failure of WBGS devices, leading to realization of robust, highly reliable devices and MMICs
- Development and utilization of physics-based models that accurately predict device performance
- Demonstration of reproducible WBGS device and MMIC fabrication processes
- Demonstration of 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
- Demonstration of superior thermal management and packaging strategies.

Table III shows the quantitative goals of Phases II and III of the DARPA WBGSTI.

Work will also continue toward the optimization of wide bandgap materials. Specific material improvement objectives will include:

- The demonstration of substrates and epitaxial structures with increasingly fewer defects, (undesirable) impurities and dislocation densities
- Efforts to quantitatively determine the effects of various epitaxial designs on devices (and MMIC) performance
- The development and implementation of methods for accurately screening substrate and epitaxial materials to determine which of their characteristics are critical for achieving high yields of high performance devices and MMICs.

In order to demonstrate the widespread applicability of the resultant devices and MMICs, a three-track demonstration portion of the program has been established. Each contractor team that has been selected to participate in the program will fabricate and demonstrate devices and modules that address the requirements shown in Table III for at least one of these tracks. A summary of the contents of the modules to be developed for these tracks is as follows:

- *Track 1: X-band Transmit and Receive (T/R) Module*. This module will contain both a Wide Bandgap Power Amplifier (PA) and a Wide Bandgap Low Noise Amplifier (LNA) MMIC. The specific key technical requirements for these MMICs are shown in Table III.

Other module characteristics, including size and overall receiver noise figure performance 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.

- *Track 2: Q-band High Power Amplifier Module*. This module will contain Wide Bandgap Power Amplifier MMICs that meet specific performance requirements (see Table III) at a frequency of at least 40 GHz.
- *Track 3: Wideband High Power Amplifier Module*. This module will contain Wide Bandgap Power Amplifier MMICs that operate over an instantaneous bandwidth in excess of one decade (e.g, from 2 GHz to 20 GHz), inclusive of X-band. Specific technical milestones are listed in Table III.

Phases II and III of the Wide Bandgap Semiconductor Technology Initiative will also include a very substantial amount of reliability testing and assessment of failures. The objective is to assure long term reliable and stable performance of the devices and MMICs that are produced. In addition, emphasis will be placed upon the achievement of validated fabrication processes that can be used to produce a wide range of devices and MMICs. Affordable packages, or enclosures, will also be developed during the program to house MMICs or combinations of them. These packages will allow the MMICs to achieve their full performance capabilities and operate with high reliability under stressing environmental conditions. Emphasis will be placed on producing these packages and assembling modules with a minimum of hand labor and at high rates of production. In concert with the packaging fabrication efforts, thermo-electro-magnetic simulations of module characteristics will be carried out.

As is the case for all current DARPA efforts, contractors will be expected to meet or exceed specific go/no-go milestones as the program progresses.

Conclusions

In summary, it is expected that the DARPA Wide Bandgap Semiconductor Technology Initiative will result in the establishment of a number of fabrication facilities that will be capable of producing wide bandgap materials, devices, MMICs and T/R modules that provide significant performance improvements for many military and commercial systems at an affordable cost and with high reliability and stability of operating characteristics.

TABLE III

TECHNICAL GOALS OF THE WBGSTI, PHASES II AND III

	Metric	Unit	Phase II		Phase III	
			18 mo.	36 mo.	48 mo.	60 mo.
	Integration Level		Device	Device	MMIC	Module
Track 1: X-band T/R Module	Drain Bias	V	28	40	48	48
	Cell Size	µm	1250	1250	N/A	N/A
	Operating Frequency	GHz	8-12	8-12	8-12	8-12
	Output Power[a]	W	7.94	7.94	15	60
	PAE	%	60	60	55	35
	Gain at Power	dB	12	12	16	18-20
	RF Yield[b]	%	50	50	50	N/A
	Output Power Uniformity[c]	dB	1.5	1	1	N/A
	PAE Uniformity[c]	% pts	6	3	3	N/A
	Small Signal Gain Uniformity[c]	dB	1.5	1	1	N/A
	LNA Survivability	W	N/A	N/A	N/A	50
	Long Term Performance[d]	hrs	10^5	10^5	10^5	10^6
Track 2: Q-Band PA	Drain Bias	V	25	28	28	28
	Cell Size	µm	500	500	N/A	N/A
	Operating Frequency	GHz	>40	>40	>40	>40
	Output Power[a]	W	1.26	1.58	4	20
	PAE	%	27	35	37	30
	Gain at Power	dB	7	8	7.5	13
	RF Yield[b]	%	20	50	50	N/A
	Output Power Uniformity[c]	dB	1.5	1	1.5	N/A
	PAE Uniformity[c]	% pts	6	3	6	N/A
	Small Signal Gain Uniformity[c]	dB	1.5	1	1.5	N/A
	Long Term Performance[d]	hrs	10^4	10^5	10^5	10^6
Track 3: Wideband PA	Drain Bias	V	40	40	48	48
	Cell Size	µm	400	1250	1250	1250
	Operating Frequency	GHz	8-12	8-12	2-20	2-20
	Output Power[a]	W	2.63	7.94	15	100
	PAE	%	60	60	30	20
	Gain at Power	dB	10	12	9	30
	RF Yield[b]	%	50	50	50	N/A
	Output Power Uniformity[c]	dB	1.5	1	1	N/A
	PAE Uniformity[c]	% pts	6	3	3	N/A
	Small Signal Gain Uniformity[c]	dB	1.5	1	1	N/A
	Long Term Performance[d]	hrs	10^5	10^5	10^5	10^6

[a]Measured at 2 dB compression

[b]The fraction of devices from all validation wafers meeting or exceeding all relevant goals

[c]Uniformity defined as the standard deviation in measured values from 100 devices/MMICs on all validation wafers

[d]Failure is defined as a 1 dB decrease in output power compared with its level at the time that testing commences

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ACRONYMS

CW: Continuous wave
DARPA: Defense Advanced Research Projects Agency
DoD: Department of Defense
HEMT: High Electron Mobility Transistor
LNA: Low Noise Amplifier
MBE: Molecular Beam Epitaxy
MMIC: Microwave/Millimeter-Wave Monolithic Integrated Circuit
MOCVD: Metal-Organic Chemical Vapor Deposition
MP: micropipes
PA: Power Amplifier
PAE: Power-Added Efficiency
WBGS: Wide Bandgap Semiconductor
WBGSTI: Wide Bandgap Semiconductor Technology Initiative