Strategies for Wide Bandgap, Inexpensive Transistors for Controlling High-Efficiency Systems

Timothy D. Heidel[1], David Henshall[1], and Pawel Gradzki[2]
[1] Advanced Research Projects Agency – Energy (ARPA-E) U.S. Department of Energy, Washington, DC, USA – Tel. 202-287-6146, timothy.heidel@hq.doe.gov [2] Booz Allen Hamilton, Washington, DC, USA

Keywords: Power Semiconductor Devices, Gallium Nitride, Silicon Carbide, Diamond, Bulk GaN Substrates

Abstract

Wide bandgap power semiconductor devices offer enormous energy efficiency gains in a wide range of potential applications. However, today, they remain too costly relative to Si devices to gain ubiquitous adoption in many higher power applications. In 2014, ARPA-E launched a new research program entitled SWITCHES, that seeks to enable the development of high voltage (1200 V+), high current (100 A) single die power semiconductor devices that, upon ultimately reaching scale, have the potential to reach functional cost parity ($/A) with silicon power transistors while also offering breakthrough relative circuit performance (low losses, high switching frequencies, and high temperature operation).

INTRODUCTION

Technical advances in power electronics promise enormous energy efficiency gains throughout the United States economy. Some of the largest of these potential gains are found in relatively high power applications including industrial motor drives, automotive battery chargers and inverters, and in electric power generation and transmission. Achieving high power conversion efficiencies in these applications requires low-loss power semiconductor switches. Unfortunately, in these high power applications, today's incumbent power semiconductor switch technologies --- Silicon (Si) based MOSFETs, IGBTs and thyristors --- suffer from relatively high losses and are limited to operating at relatively low switching frequencies and low temperatures.

Wide bandgap (WBG) power semiconductor devices are an attractive emerging alternative for use in these applications. Power converters based on WBG devices can achieve both higher efficiency and higher gravimetric and volumetric power conversion densities. Despite recent progress, high cost remains an important barrier to the widespread adoption of WBG devices. Also, most WBG discrete devices demonstrated to date have had relatively low current ratings. In 2014, ARPA-E launched a program entitled SWITCHES (Strategies for Wide Bandgap, Inexpensive Transistors for Controlling High-Efficiency Systems) to catalyze the development of WBG devices using new fabrication innovations and/or new device architectures that, if successful, could allow WBG devices to reach cost parity with Si-based power semiconductor devices in applications that require high voltage (1200 V+) and high current (100 A). This paper gives an overview of the technical opportunities that are being pursued in the SWITCHES program.

BACKGROUND

Substantial technical progress has been made on WBG-based power switches over the past decade. Substantial investments from the U.S. Department of Defense and several U.S. Department of Energy offices helped build early U.S. leadership and bring WBG devices closer to widespread adoption. The Advanced Research Projects Agency-Energy (ARPA-E) has been investing in WBG power semiconductor device research since 2010. ARPA-E's ADEPT (Agile Delivery of Electrical Power Technologies) program, funded several research teams to develop new SiC and GaN devices and demonstrate their performance in power converters for applications including LED drivers, automotive battery chargers, and motor drives. For example, in one project, a 2kW motor driven by high frequency GaN devices resulted in an increase in efficiency of over 2% at full load and 8% at low load relative to the same motor being driven by Si IGBTs [1]. In another project, a 6.1 kW isolated on-board vehicle battery charger utilizing SiC devices was demonstrated with a peak system efficiency of 95%, a volumetric power density of 5.0 kW/L, and a gravimetric power density of 3.8 kW/kg.[2] SiC and GaN have also made important commercial progress over the past decade with up to 1700 V SiC devices and 650 V GaN devices now qualified and commercially available.

Many of the largest opportunities for increased energy efficiency and reduced energy-related emissions exist in extremely cost sensitive industries. High cost for equivalent functional performance remains a major barrier to the widespread adoption of WBG devices, despite opportunities for superior system performance (including reductions in system costs). WBG devices will have to approach functional cost parity ($/A) with Si power devices to gain ubiquitous adoption in many higher power applications. In addition to high cost, most WBG discrete devices demonstrated to date have been limited to relatively low current ratings (<50 A). Traction, industrial, and grid applications advantage devices with high current ratings (>100 A) as implementation of low current devices in parallel increases power system complexity and cost. While increased adoption of WBG devices and economies of scale are expected to contribute to cost reductions over the next few years, fundamental technical breakthroughs will likely also be required to allow high voltage, high current WBG devices to reach functional cost party ($/A) with incumbent Si-based power semiconductor devices.

TECHNICAL OPPORTUNITIES

Recent research results indicate that new materials advances, device architectures, and device fabrication processes could substantially accelerate progress towards the demonstration of WBG devices that achieve both higher current ratings and functional cost parity with silicon-based devices. Some of these approaches have, as of yet, received relatively little attention from industry and the research community since they are perceived to be technically unproven and high risk.

In the context of SiC, wafer manufacturers are continuing to improve growth performance and reduce defect densities (enabling higher device yields) and also have roadmaps to migrate to larger 150mm diameter substrates as demand increases. However, SiC devices currently operate far from the theoretical limits for SiC. This is primarily due to a high density of interface states close to the conduction band edge introduced by the silicon dioxide gate in these devices. These interface states lead to degradation of channel mobility by an order of magnitude [3] and decreased switching speed. Also, in some SiC MOSFETs, the high electric field near the gate has prevented the devices from taking full advantage of the breakdown field strength of SiC. Numerous research groups are pursuing new materials and device innovations that promise to enable SiC devices with higher channel carrier mobilities and higher breakdown field strengths.

While most commercial SiC devices today are majority carrier devices, minority carrier SiC devices could offer higher performance/cost, particularly in high voltage applications. In the past, high current density operation in minority carrier devices has been hindered by forward voltage degradation due to stacking fault defects,[4] which reduce the useful area of a die and may result in non-uniform current flow, localized overheating, and premature failures.

Finally, SiC devices today are typically fabricated in relatively low volume, dedicated facilities and utilize unique process steps and/or equipment such as a high temperature anneal during implant activation. Device designs compatible entirely with silicon fabrication facilities (except epitaxial growth) could be an important pathway to lower costs. Migrating SiC device manufacturing to legacy (silicon),

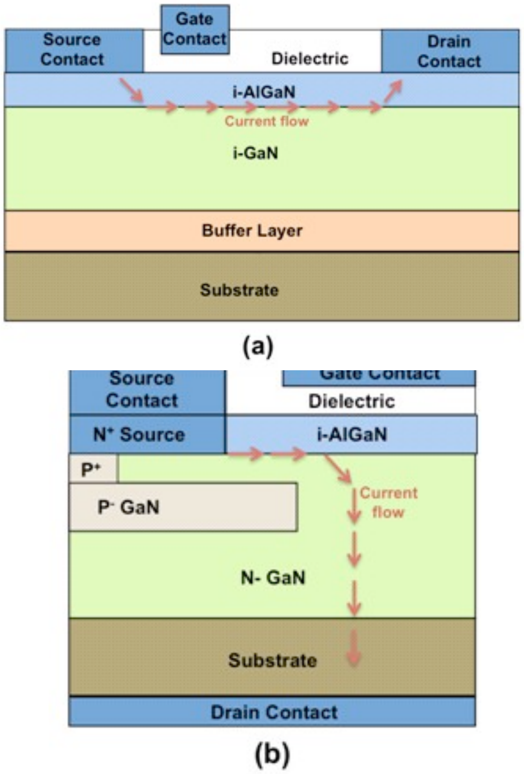

Figure 1: (a) Generalized device structure for AlGaN/GaN High Electron Mobility Transistor (HEMT) (b) Generalized device structure for vertical GaN transistor.

TABLE I
SWITCHES PROGRAM TECHNICAL TARGETS

Category	Value
Discrete Device Price (Packaged)	<= $0.10 /A
Drain--Source Breakdown	>= 1200 V (V_{DSS} @ T_C = 25°C and V_{GS} = 0)
Continuous Drain Current	>= 100 A (I_D @ T_C = 25°C and V_{GS} <= 20 V)
Operating Junction Temperature	-55 °C to 150 °C
I_{off}/ I_{on} Ratio	$> 10^6$
V_{th} (not applicable to diodes)	> 2 V @ I_D = 5 mA
Dynamic Performance	Project must demonstrate device driving a hard switched boost (PFC) converter at f >= 40 kHz, Vout = 800 V, Imax = 50 A.
Specific R_{DSON}	$<3\ m\Omega\cdot cm^2$ @ V_{GS} = 15 V
Switching Loss E_{ON}+E_{OFF}	< .5 mJ @ 800 V and 50 A

TABLE II
SWITCHES PROGRAM PROJECTS

	Project Title	Project Team	ARPA-E Award (USD)
SiC	Advanced Manufacturing and Performance Enhancements for Reduced Cost Silicon Carbide MOSFETS	Monolith Semiconductor (Lead), Rensselaer Polytechnic Institute, United Technologies Research Center, University of Arkansas, X-Fab Texas	$3.2 M
GaN	Vertical GaN Transistors on Bulk GaN Substrates	Avogy (Lead), ABB, North Carolina State University, Oak Ridge National Laboratory, Soraa	$3.2 M
GaN	Vertical GaN Power Transistors Using Controlled Spalling for Substrate Heterogeneity	Columbia University (Lead), IBM T. J. Watson Research Center, Massachusetts Institute of Technology, Veeco	$3 M
GaN	High-Quality, Low-Cost GaN Single Crystal Substrates for High-Power Devices	Fairfield Crystal Technology (Lead), Stony Brook University	$1.4 M
GaN	Low-Cost Gallium Nitride Vertical Transistor	HRL Laboratories (Lead), Kyma Technologies, Malibu IQ, Virginia Polytechnic Institute and State University	$2.9 M
GaN	Epitaxial GaN on Flexible Metal Tapes for Low-Cost Transistor Devices	iBeam Materials (Lead), Sandia National Laboratory	$0.79 M
GaN	Transformational GaN Substrate Technology	Kyma Technologies (Lead), Avogy, Pennsylvania State University, Soraa	$3.2 M
GaN	Vertical-Junction Field-Effect Transistors Fabricated on Low-Dislocation-Density GaN by Epitaxial Lift-Off	MicroLink Devices (Lead), Ammono, Qorvo, University of Notre Dame, Virginia Polytechnic Institute and State University	$3.2 M
GaN	GaN Homoepitaxial Wafers by Vapor Phase Epitaxy on Low-Cost, High-Quality Ammonothermal GaN Substrates	SixPoint Materials (Lead), University of Notre Dame	$1.7 M
GaN	Large-Area, Low-Cost Bulk GaN Substrates for Power Electronics	Soraa (Lead)	$0.2 M
GaN	Current Aperture Vertical Electron Transistor Device Architectures for Efficient Power Switching	University of California Santa Barbara (Lead), Arizona State University, Transphorm, US Naval Research Laboratory	$2.6 M
GaN	PolarJFET Novel Vertical GaN Power Transistor	University of Notre Dame (Lead), Cornell University IQE, Qorvo, United Technologies Research Center	$2.5 M
Diamond	Diamond Diode and Transistor Devices	Michigan State University (Lead), Fraunhofer USA Center for Coatings and Laser Applications	$0.56 M
Diamond	Diamond Power Transistors Enabled by Phosphorus Doped Diamond	Arizona State University (Lead)	$0.42 M

high-volume device fabrication facilities could be a particularly attractive route to the manufacturing of lower cost SiC devices. Enabling silicon fabrication facilities to process SiC wafers will require new device designs and new process development.

In the context of GaN, the dominant power transistor device structure used today is the lateral High Electron Mobility Transistor (HEMT) structure depicted in Figure 1(a). GaN based HEMTs are particularly attractive as current flows predominantly in a 2D Electron Gas (2DEG) that forms at the GaN/AlGaN heterojunction interface. The free-carrier concentration in the 2DEG channel is formed by strain induced and spontaneous polarization, shifting the Fermi-level above the conduction band without the presence of mobility limiting extrinsic dopants. This enables extremely fast switching speeds and low device resistance. This device architecture has also received substantial attention due to the ability for devices to be fabricated on GaN layers deposited heteroepitaxially on low cost silicon substrates.

However, GaN HEMTs suffer from relatively low current densities relative to die size, which limit the ability to cost effectively scale lateral device topologies to high current ratings and high voltages. The substantial gate/drain lateral spacing that must be maintained to allow for high breakdown voltages reduces the effective current density (relative to die size), increasing device cost per Ampere substantially for high voltage devices. Thermal management is also complicated by the fact that all current flow is confined to a relatively thin portion of the device near the top surface. Joule heating related to device losses must be dissipated across the thickness of the substrate, motivating research into advanced wafer thinning or novel thermal spreading approaches to device assembly.

Vertical GaN device architectures as illustrated in Figure 1(b), could overcome these limitations. Vertical device structures for GaN have, thus far, received relatively little attention in the research community but have been recognized as a necessary eventual device architecture for use in high power automotive applications.[5][6] As with vertical FET and IGBT technologies in Si and SiC, it is expected that vertical devices will be able to achieve higher effective current densities and will enable improved thermal management. Recent demonstrations of high-voltage vertical structure GaN devices appear very promising.[7][8] Advances in the growth of high quality bulk GaN substrates will also be critical to the development of vertical power semiconductor devices in GaN.[9] Low defect density bulk GaN substrates are expected to be required for many vertical device concepts. Today, GaN substrates are limited to small sizes and are very costly to produce. Many existing commercially available substrates have small domain structure unsuitable for high current (large area) power devices.

Finally, other WBG materials also hold significant potential for use in high power applications. In particular, the diamond semiconductor device community has made substantial progress over the past decade. The combination of recent advances in diamond substrates, p-type and n-type doping, and high quality contacts provide a strong foundation for the demonstration of high performance power semiconductor devices in diamond.

ARPA-E SWITCHES PROGRAM

In 2014, ARPA-E launched the SWITCHES (Strategies for Wide Bandgap, Inexpensive Transistors for Controlling High-Efficiency Systems) program, which is focused on the development of high voltage (1200 V+), high current (100 A) single die power semiconductor devices that, upon ultimately reaching scale, could have the potential to reach functional cost parity ($/A) with silicon power transistors. The SWITCHES program is focused on the technical targets listed in Table 1. The program targets are aimed at enabling high performance and widespread market adoption. The cost target in particular was set based on an analysis of high voltage silicon power device prices at the start of the program. In total, the program includes 14 individual research and development projects, comprising a total ARPA-E investment of approximately $27M USD over three years. Project titles and team members are detailed in Table II.

The program has a single SiC project. Monolith Semiconductor is developing advanced device designs that promise to reduce on resistance and switching energies in SiC MOSFETs. The team is also working to leverage a low-cost, high-volume, 150mm manufacturing facility.

SWITCHES program GaN projects are focused in two technical areas: (1) low cost, high quality, freestanding GaN substrates and (2) vertical GaN diodes and transistors. Several teams are using ammonothermal growth and/or hydride vapor phase epitaxy (HVPE) to demonstrate high quality GaN boules with increasing diameters. Several projects are seeking to combine these two growth techniques in order to simultaneously achieve low defect densities and high effective growth rates. Teams are also attempting to demonstrate large area, reliable epitaxial liftoff and GaN substrate reuse either by photoelectrochemical etching or spalling. Teams in the program are also exploring a variety of vertical GaN transistor structures. Many of these new device structures require improved approaches to fabricating buried p-type layers or improvements in the growth of dielectrics on GaN. Finally, high voltage devices require high quality, relatively thick epitaxial GaN films. All of the device-focused projects are expected to culminate in boost converter demonstrations that demonstrate devices switching at 40kHz or higher (Vout = 800 V, Imax = 50 A).

Finally, the SWITCHES program includes two projects that are focusing on the demonstration of diamond power semiconductor devices.

CONCLUSIONS

ARPA-E's SWITCHES program is aiming to catalyze technical breakthroughs in SiC, GaN and Diamond power semiconductor devices that will allow high voltage and high current WBG transistors to rapidly reach functional cost parity with high voltage silicon power transistors while also offering breakthrough relative circuit performance (low losses, high switching frequencies, and high temperature operation).

REFERENCES

[1] Y-F. Wu et al., *High-Frequency, GaN Diode-Free Motor Drive Inverter with Pure Sine Wave Output*, Power Transmission Engineering, October 2012, pp. 40-43.

[2] B. Whitaker et al., *A High-Density, High-Efficiency, Isolated On-Board Vehicle Battery Charger Utilizing Silicon Carbide Power Devices*, IEEE Trans. on Power Elec. **29** (5), pp. 2606-2617 (2013).

[3] A.F. Frazzetto et al., *Limiting mechanism of inversion channel mobility in Al-implanted lateral 4H-SiC metal-oxide semiconductor field-effect transistors*, Applied Physics Letters **99**, 072117 (2011).

[3] R.E. Stahlbush et al., *Effect of Stacking Faults Originating from Half Loop Arrays on Electrical Behavior of 10 kV 4H-SiC PiN Diodes*, Materials Science Forum **387**, pp. 717-720 (2012).

[4] M. Su et al., *Challenges in the Automotive Application of GaN Power Switching Devices*, 2012 CS MANTECH Technical Digest, April 2012.

[5] T. Uesugi and T. Kachi, *Which are the Future GaN Power Devices for Automotive Applications, Lateral Structures or Vertical Structures?*, 2011 CS MANTECH Technical Digest, May 2011.

[6] D. Disney et al., *Vertical power diodes in bulk GaN*, 25th International Symposium on Power Semiconductor Devices, Kanazawa, Japan, May 2013.

[7] R.P. Tompkins et al., *GaN Power Schottky Diodes*, 2012 Electrochemical Society Meeting, Seattle, WA, May 2012.

[8] D. Ehrentraut et al., *High Quality, Low Cost Ammonothermal Bulk GaN Substrates*, Jpn. J. Appl. Phys. **52,** 08JA01 (2013).

ACRONYMS

ARPA-E	Advanced Research Projects Agency - Energy
GaN	Gallium Nitride
SiC	Silicon Carbide