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Overcoming Barriers to the Adoption of WBG Semiconductors for Power Electronics and a more Electric Future

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Abstract

Electricity generation currently accounts for ~38% of primary energy consumption in the U.S [1] and over the next 25 years is projected to increase more than 50% worldwide [2]. As a result, electricity continues to be the fastest growing form of end-use energy. Power electronics play a significant and growing role in the delivery of electricity as they are utilized to control and convert electrical power to provide optimal conditions for transmission, distribution, and load-side consumption. Estimates suggest that the fraction of electricity processed through some form of power electronics could be as high as 80% by 2030 (including generation and consumption), approximately a twofold increase over the current percentage [3]. Therefore, advances in power electronics have the potential for enormous energy efficiency improvements. Power semiconductor devices based on wide-bandgap materials such as SiC and GaN offer breakthrough relative circuit performance enabling low losses, high switching frequencies, and high temperature operation in a wide range of potential applications. However, even with the considerable materials advantages, a number of challenges are preventing widespread adoption of power electronics using WBG semiconductors. Significant work still remains to overcome these barriers and realize the full potential of WBG materials in power electronics, systems, and improving energy efficiency. This paper discusses the ARPA-E Programs [4] tackling these challenges.

1. Introduction

The superior electrical properties of wide-bandgap (WBG) power semiconductors, such as gallium nitride (GaN) and silicon carbide (SiC), offer an emerging attractive alternative to Si in many applications and can enable power converters with higher efficiency and higher power conversion densities. However, even with the considerable materials advantages, a number of challenges are preventing widespread adoption of power electronics using WBG semiconductors. High cost, challenging fabrication of practical devices, demonstrated reliability, and system integration remain important barriers to the widespread adoption of WBG devices. The U.S. Department of Energy's Advanced Research Project Agency has invested in WBG semiconductors to enable a new generation of power semiconductor devices that far exceed the performance of silicon-based devices. High impact opportunities exist across a variety of potential applications given below. See reference [5] and references therein for details.

Motor Drives: It is estimated that 40-60% of currently installed electric motors could benefit from variable frequency drives (VFDs), which enable efficient adaptation to speed and torque demands. However, VFDs are bulky and occupy significant space. Size, power density and efficiency should be improved, and the overall system cost reduced.

Automotive: Power electronics such as traction inverters, DC boost converters, and on-board battery chargers are critical elements in hybrid and electric vehicles (EVs). Along with efficient, lightweight, and low-cost DC fast charging infrastructure (>120 kW), they can advance the commercial viability of EVs and have the potential to reduce the greenhouse gas emissions that stem from the transportation sector.

Data Centers: Energy consumption in data centers accounts for approximately 2% of electricity use in the U.S. in 2014. The power delivery architecture of most modern data centers consists of a line frequency transformer, low voltage power distribution network, centralized backup unit, and inefficient voltage regulators. Innovative system design enabled by WBG converters can result in more efficient systems.

Aerospace: Longer, thinner, and lighter wings can reduce fuel consumption and carbon emissions by 50% relative to current commercial aircraft. Achieving this wing design requires electromechanical actuators that are small and lightweight with robust operation over a wide temperature range. Electrification of environmental controls, fuel pumps, brakes, and de-icing systems can further reduce weight and increase efficiency through elimination of bleed air controls and pneumatic/hydraulic systems. WBG-based converters, with high gravimetric/volumetric power density offer a pathway to achieve energy savings in air transport by reducing weight in electric aircraft and enabling new paradigms in body design.

Distributed Energy Resources: In grid applications, such as solar PV, wind, storage integration, MVDC distribution, HVDC and flexible alternating current transmission systems (FACTS), power conditioners are required to process and control the flow of electricity by supplying voltages and currents in a form that is optimally suited to the load. Power electronics are responsible for a loss of about 4% of all of the electricity generated in these applications and are the dominant point of failure for installed systems.

2. Overcoming Barriers

ARPA-E launched the SWITCHES Program in 2014 to address the high cost barrier of WBG devices. The SWITCHES program was aimed at the key materials and device fabrication issues that drive costs for SiC and GaN devices. The goal was to enable the development of high voltage (>1200V) and high current (100A) WBG power semiconductor devices that have the potential to reach functional cost parity with Si power transistors while also offering breakthrough relative circuit performance.

In 2017 ARPA-E launched the PNDIODES (Power Nitride Doping Innovation Offers Devices Enabling SWITCHES) program to address one of the challenging fabrication processes for vertical GaN devices, the lack of a selective area p-type doping process in GaN. The most obvious selective area p-type doping approaches are ion implantation and diffusion, had not produced p-type regions or satisfactory p-n junctions in GaN. The PNDIODES Program aims to develop transformational advances and mechanistic understanding in the process of selective area doping in GaN. The expectation is this will lead to the demonstration of arbitrarily placed, reliable, contactable, and generally useable p-n junction regions that enable high-performance vertical power semiconductor devices.

The CIRCUITS (Creating Innovative and Reliable Circuits Using Inventive Topologies and Semiconductors) program was launched in 2017 to surmount the systems integration barrier. Previous efforts by ARPA-E and others have primarily focused on WBG material and device development without consideration of the circuit topology. The circuit design is also critical to the large-scale implementation of more efficient WBG devices as a result of their ability to operate at higher voltage, higher frequency, and higher temperature. New circuit topologies and designs are needed that optimize the properties of the WBG semiconductor devices in the circuit while minimizing the size and costs of auxiliary circuit components such as cooling systems. The CIRCUITS program seeks to accelerate the development of a whole new class of efficient, lightweight, and reliable power converters based on WBG semiconductors. With an explicit focus on novel circuit topologies, advanced control and drive electronics, and innovative packaging, CIRCUITS aims to catalyze disruptive improvements for power electronics afforded by WBG semiconductors. The CIRCUITS project teams will develop efficient, lightweight, and reliable power converters for various applications including motor drives, automotive, power supplies, data centers, aerospace, distributed energy, and the grid. The circuit topologies employed by the CIRCUITS teams will be optimized for WBG semiconductors to maximize overall electrical system performance and offer significant direct and indirect energy savings. The CIRCUITS projects will establish the building blocks for WBG enabled power converters with higher efficiency, enhanced reliability, and superior total cost of ownership. In addition, a reduced form factor will drive adoption of higher performance and more efficient power converters relative to today's state-of-the-art systems. New circuit topologies and designs are needed that optimize the properties of the WBG semiconductor devices in the circuit while minimizing the size and costs of auxiliary circuit components. The CIRCUITS Program seeks to accelerate the development of a whole new class of efficient, lightweight, and reliable power converters based on WBG.

Recent advances in hardware for handling direct current (DC) electricity have created an opportunity for greater use of DC in distribution and transmission on the electric grid. There remains, however, a significant technology gap in the safety and protection mechanisms required to mitigate potentially damaging faults in these systems. This lingering risk of electrical fault scenarios (e.g., shorts and overloads) remains a primary hurdle preventing the growth of DC markets. In AC networks, electricity alternates direction periodically, naturally providing a "zero crossing" where no current flows for a brief moment, which allows electrical faults to easily be extinguished. DC networks, on the other hand, deliver power without zero crossings, which greatly increases the likelihood of electrical arcs in conventional circuit breakers, making them useless in fault scenarios. The projects that comprise ARPA-E's BREAKERS (Building Reliable Electronics to Achieve Kilovolt Effective Ratings Safely) program will develop novel technologies for medium voltage direct current (MVDC) circuit breakers, applicable to markets including electrified transportation, MVDC grid distribution, renewable interconnections, and offshore oil, gas, and wind production. Project teams will either develop transformational improvements to conventional direct current (DC) circuit breakers (i.e., mechanical, solid state, hybrid) or construct circuit breakers based on completely novel designs. These systems must achieve program goals of handling a voltage between 1 – 100 kV DC and power above 1 MW at extremely high efficiencies and fast response times.

3. Conclusions

Significant work still remains to overcome barriers to realize a more electric future. Fundamental research into materials, processing, manufacturing, along with continued development down the power electronics value chain into circuits and systems are vital.

References

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