DEVELOPING POWERFUL AND EFFICIENT ELECTRIC POWER CONVERTERS

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PROJECT TITLE: Low-Cost, Highly Integrated, Silicon Carbide Multi-Chip Power Modules for Plug-in Hybrid Electric Vehicles

PROGRAM: ADEPT

AWARD: $3,914,527

PROJECT TEAM: *Arkansas Power Electronics International (APEI) (Lead),* Cree Power and RF (now Wolfspeed); Oak Ridge National Laboratory; Toyota Motor Engineering & Manufacturing North America; University of Arkansas

PROJECT TERM: September 2010 – March 2014

TECHNICAL CHALLENGE

Thirty percent of U.S. electric power flows through power converters to support electric motors, HVAC, battery chargers, data centers and electric power generation and distribution. Unfortunately, incumbent power electronics technologies, which are based on silicon (Si) devices, are susceptible to breakdown under high voltage, limited to low switching frequencies, and perform poorly at high-temperatures. As a result, Si-based devices waste as much as 10% of the power that passes through them, which prevents Si-based systems from operating at improved efficiencies. One recent estimate predicted that within the next 20 years, 80% of the electricity used in the United States will flow through power electronics systems – which underlines the critical need to improve their efficiency, which would result in billions of dollars in energy savings.[1] Power electronics systems and devices based on new materials and improved circuit design techniques are the key to achieving substantially higher electrical power conversion efficiency and performance across the broad array of power electronics applications.

TECHNICAL OPPORTUNITY

Achieving higher energy efficiency and performance requires low-loss power semiconductor switches with significantly better performance than incumbent Si-based transistors and thyristors. Wide bandgap (WBG) semiconductor devices provide system designers with new opportunities to create systems with higher efficiency, higher temperature, and higher frequency than previously achievable. Substantial technical progress has been made on WBG-based power switches over the past decade creating the potential for new high-performance, high-efficiency power electronic systems from qualified, commercial devices.

Engineers used SiC MOSFETs to create a charger (black) six to seven times faster than the current on-board charger (silver) of a 2010 Toyota Prius Hybrid. The device can also charge the vehicle in one-third of the time required by the standard charger.

INNOVATION DEMONSTRATION

The APEI team (now the Wolfspeed team, a new team comprised of the former APEI team and Cree's Power & RF division) aimed to revolutionize WBG power electronics systems by developing a high-performance Silicon Carbide (SiC) based power module and associated gate driver that would improve overall performance through the reduction of electrical parasitics, enabling higher frequency operation and higher power density. To accomplish this, the team incorporated an advanced SiC multichip power module (MCPM) power packaging concept with a tightly integrated, high temperature gate driver board. The development of the new module was based on coupling Wolfspeed's SiC transistor

[1] L.M. Tolbert, et al., "Power Electronics for Distributed Energy Systems and Transmission and Distribution Applications: Assessing the Technical Needs for Utility Applications. " (Oak Ridge, TN: Oak Ridge National Laboratory, 2005).

(MOSFET) design with packaging technology specifically optimized to maximize the performance of the SiC chip for low inductance, higher temperature capability, and a small gate loop through high-level gate driver integration.

The new module was integrated into a Toyota 2010 Prius Plug-In Hybrid Electric Vehicle Platform to demonstrate the performance of the module and Wolfspeed's SiC-based system design philosophy. The project team developed and demonstrated a 6.2 kW Plug-In Hybrid Electric Vehicle (PHEV) onboard battery charger that is more than ten times smaller and lighter than existing state-of-the-art 1 kW Si-based chargers. The SiC-based charger cut system losses nearly in half, increasing operational efficiency to greater than 96%—and greatly reduced the time needed to charge an EV battery.

PATHWAY TO ECONOMIC IMPACT

The module developed in this work is now represented in an active product line, the HT-4000 series of power modules and an associated evaluation gate driver board (http://www.apei.net).

Wolfspeed's demonstration of the plug-in vehicle charger technology was recognized with an R&D 100 award in 2014, distinguishing it as one of the top technological breakthrough products released in 2013. This recognition has resulted in follow on funding from the Department of Energy's Vehicle Technology Office (VTO) for the development of a traction drive for the Toyota Prius platform and for a traction inverter targeted at the Ford EV platform using Wolfspeed's existing high-performance module lines.

The SiC charger technology was part of the portfolio that contributed to APEI's acquisition by its project partner, Cree, in July of 2015. Cree's Power and RF business, now known as Wolfspeed, seeks to accelerate the market for high-performance, best-in-class SiC power modules.

LONG-TERM IMPACTS

The onboard vehicle battery charger demonstrated during this project has been widely discussed in industry since its introduction into the technical marketplace. This project demonstrated one of the first commercial-facing high power systems incorporating SiC MOSFETs, showing that SiC device technology enables higher efficiency systems and a potential for 10-fold increase in both gravimetric and volumetric power density. This project also demonstrated that the system-level savings achieved using SiC devices can be large enough to justify their widespread adoption, despite the present higher cost of the component SiC devices relative to the Si devices they can replace.

With greater than 30% of all electricity generated today processed by power electronics systems, reducing the energy losses in Si-based devices would significantly reduce U.S. energy use, and even more in the future. By developing more effective power conversion systems, that are used in applications from battery chargers and traction drives in electric vehicles to connecting photovoltaics and wind turbines to the electric grid, it is possible to drive down the costs associated with these clean energy applications, making them more marketable and viable for consumer and industry adoption. In particular, this project's demonstration that overall system costs can be reduced despite using more expensive components is extremely important for continuing the adoption of commercially available, more efficient, WBG semiconductor power devices.

INTELLECTUAL PROPERTY AND PUBLICATIONS

As of February 2016, the APEI/Wolfspeed team's project has generated three invention disclosures to ARPA-E and one U.S. Patent and Trademark Office (PTO) patent:

Patents

"Vertical power transistor with built-in gate buffer," (11/10/2015), Patent No 9184237, Washington, DC: U.S. Patent and Trademark Office.

The APEI/Wolfspeed team has also published the scientific underpinnings of this technology extensively in the open literature. A list of publications resulting from this project is provided below:

Publications

Cole, Z., Passmore, B., Whitaker, B., Barkley, A., McNutt, T., & Lostetter, A. (2013). A High Temperature, Fast Switching SiC Multi-chip Power Module (MCPM) for High Frequency (> 500 kHz) Power Conversion Applications. *High Temperature Electronics Network (HiTEN)* 2013, Oxford, UK, July 8 - 10, 2013.

Lamichhane, R., Ericsson, N., Frank, S., Britton, C., Marlino, L., Mantooth, A., Francis, M., Shepherd, P., Glover, M., Perez, S., Mcnutt, T., Whitaker, B., & Zach Cole, Z. (2014). A wide bandgap silicon carbide (SiC) gate driver for high-temperature and high-voltage applications. *2014 IEEE 26th International Symposium on Power Semiconductor Devices & IC's (ISPSD)*. 414-417.

Mudholkar, M., Ahmed, S., Ericson, M., Frank, S., Britton, C., & Mantooth, H. (2014). Datasheet Driven Silicon Carbide Power MOSFET Model. *IEEE Transactions on Power Electronics IEEE Trans. Power Electron.,* 2220-2228.

Nance, E., Frank, S., Britton, C., Marlino, L., Ryu, S., Grider, D., Mantooth, A., Francis, M., Lamichhane, R., Mudholkar, M., Shepherd, P., Glover, M., Valle-Mayorga, J., Mcnutt, T., Barkley, A., Whitaker, B., Cole, Z., Passmore, B., & Lostetter, A. (2014). A 4H silicon carbide gate buffer for integrated power systems. *Power Electronics, IEEE Transactions, Volume 29 (2):* 539-542.

Shepherd, P., et al. (2014). Integrated Protection Circuits for an NMOS Silicon Carbide Gate Driver IC. *IMAPS High Temperature Electronics Conference (HiTEC)* 2014, Albuquerque, NM, May 2014.

Whitaker, B., Barkley, A., Cole, Z., Passmore, B., Martin, D., Mcnutt, T., Lostetter, A., Seung Lee, J., Shiozaki, K. (2014). A High-Density, High-Efficiency, Isolated On-Board Vehicle Battery Charger Utilizing Silicon Carbide Power Devices. *IEEE Transactions on Power Electronics IEEE Trans. Power Electron.,* 2606-2617.

Whitaker, B., Barkley, A., Cole, Z., Passmore, B., Mcnutt, T., & Lostetter, A. (2013). A high-frequency, high-efficiency silicon carbide based phase-shifted full-bridge converter as a core component for a high-density on-board vehicle battery charging system. *2013 IEEE ECCE Asia Downunder*. 1233-1239.

Whitaker, B., Barkley, A., Cole, Z., Passmore, B., Mcnutt, T., & Lostetter, A. (2013). High-frequency AC-DC conversion with a silicon carbide power module to achieve high-efficiency and greatly improved power density. *2013 4th IEEE International Symposium on Power Electronics for Distributed Generation Systems (PEDG*). 1-5.

Valle-Mayorga, J., Rahman, A., & Mantooth, H. (2012). Back to the Future: An All-NMOS SiC Linear Voltage Regulator for High Temperature Applications. *2012 IEEE Compound Semiconductor Integrated Circuit Symposium (CSICS)*. 1-4.