ULTRA FAST SWITCHING TECHNOLOGY FOR MOTOR DRIVES AND DC/AC INVERTERS

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PROJECT TITLE: High Performance GaN HEMT Modules for Agile Power Electronics
PROGRAM: ADEPT
AWARD: $2,950,000
PROJECT TEAM: *Transphorm Inc. (Lead)*, UC Santa Barbara, Virginia Tech
PROJECT TERM: September 2010 – February 2013

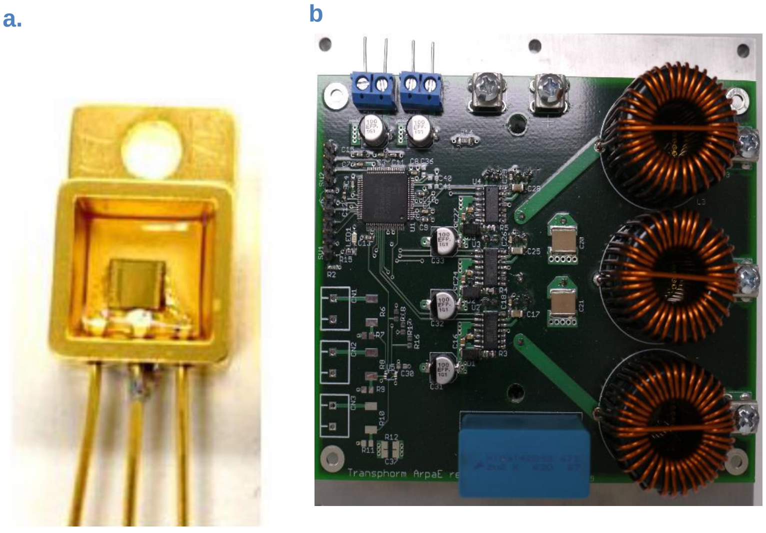
TECHNICAL CHALLENGE

Electricity generation from renewable sources and energy conservation through its efficient use are cornerstones of energy security and lower carbon dioxide emissions. Reducing energy loss during power conversion, such as when the DC output from a solar array has to be converted to AC for delivery to the power grid, is important for energy conservation. In addition, providing power that is optimized for driving electric motors, which presently account for nearly one half of U.S. industrial electricity consumption[1], and over one third of U.S. electricity use overall[2], can greatly improve their energy efficiency. The compact size of power conversion modules is also important – compactness allows retrofitting or embedding in machines.

TECHNICAL OPPORTUNITY

Achieving higher energy efficiency and performance requires low-loss power semiconductor switches. Wide Bandgap (WBG) semiconductor devices can operate at far higher frequencies and with significantly lower losses than incumbent Si-based transistors and thyristors. WBG devices have demonstrated half the losses and ten-times smaller size and weight compared with conventional power converters in a wide range of applications. In the years before this project began, substantial technical progress had been made on gallium nitride (GaN) based high electron mobility transistors (HEMTs). Devices with the potential to operate at high-power density and significantly higher frequencies relative to silicon-based transistors had been demonstrated for radio frequency (RF) and microwave applications. However, most GaN power transistors at the time were fabricated on expensive silicon carbide (SiC) substrates and were normally-on devices (many safety critical applications require normally-off devices). The research community had started to show the feasibility of fabricating GaN devices on low cost Si substrates, and several approaches to achieving manufacturable normally-off devices had been proposed. Furthermore, a variety of new circuit concepts had been proposed that could take advantage of the higher (> 1 MHz) switching frequencies potentially enabled by GaN devices.

a. b



a) Transphorm's GaN e-mode switch in metal package
b) Inverter on a card with low-pass filters giving true sinewaves

INNOVATION DEMONSTRATION

Under ARPA-E support, Transphorm's goal was to advance the state-of-the-art in compact high efficiency power conversion by developing high performance GaN HEMT switches on low cost silicon substrates. Specifically the project team aimed to demonstrate high voltage (600V and 900V) GaN-on-silicon normally-off power switches that could be manufactured at competitive costs. To do so required Transphorm to overcome challenges of growing high quality GaN layers on Si substrates. This task was particularly challenging due to the mismatch of both crystal lattice structure and coefficients of thermal expansion mismatch between GaN and Si. The team addressed this issue by developing unique buffer layer structures between the GaN and Si, and

[1]https://www.eia.gov/todayinenergy/detail.cfm?id=18151
[2]Energy-Efficiency Policy Opportunities for Electric Motor-Driven Systems, Table 14 (IEA 2011)

developed normally-on devices. The team also demonstrated normally-off devices by developing a new gate region etch process combined with a modified process for growing a new stable gate dielectric.

Transphorm's GaN switches demonstrated significant advantages over silicon Si MOSFETs with lower gate charge and faster switching speeds in excess of 150 V/ns. This can be compared to current silicon technology with switching rates less than 50V/ns.

Under ADEPT support, Transphorm packaged the ultra-fast GaN normally-on switches as cascodes in a 3-phase bridge and demonstrated a 3 kW motor drive operating at >100 kHz with <1.5% loss, with aspirations to expand the power level to >20 kW in the future. Transphorm's GaN based system resulted in a six times size reduction over the silicon incumbent technology (a Si IGBT motor drive operating at 10-20 kHz with approx. <5% loss). The drive also incorporates on-board filters that enable generation of smooth 3-phase AC waveforms (sine waves) at 60 Hz. This drive with low distortion improves electric motor efficiency by reducing loss of energy in harmonics, reduces insulation failure by eliminating voltage spikes (which can occur in unfiltered drives), lessens mechanical vibration and bearing wear, and thereby extends motor life. These features enable speed control of cheaper non-inverter grade motors thus expanding the application space and overall energy savings. The development of this demo system facilitated Transphorm's efforts to partner with customers in their efforts to evaluate GaN devices and design GaN-based systems.

PATHWAY TO ECONOMIC IMPACT

In February 2013, Transphorm Inc. announced that its novel 600V GaN module has enabled the world's first GaN-based high power solar converter. Transphorm and its customer-partner Yaskawa Electric built the inverter, achieving several industry firsts including the first high power (4.5 kW) converter product in the world utilizing GaN technology, the first efficient PV power conditioner to operate at 50 kHz as well as a 40% reduction in inverter size with passive cooling and 98% efficiency. This was a significant demonstration of the size reduction and high efficiency that are form and function benefits attributed to the GaN module technology.

Transphorm's 600V GaN HEMT (TPH3006PS) was named 2013 Product of the Year by Electronic Products Magazine in the "Discrete Semiconductor" category.[3] Electronics Products Magazine highlighted the ability for Transphorm's product to enable compact, lower-cost power conversion systems in a wide range of applications including power supplies and adapters, PV Inverters for solar panels, motor drives, and chargers for electric vehicles.

ARPA-E's support of Transphorm's GaN HEMT technology development has led to significant interest and subsequent funding by many private investment groups. Following earlier rounds of funding from entities such as Kleiner Perkins Caufield and Byers, Google Ventures, Soros Quantum Strategic Partners, and Fujitsu, KKR led a $70 million round of investment in Transphorm in 2015.

Transphorm has continued to expand its GaN transistor product portfolio since the conclusion of their ARPA-E project. Today, the company has more than 15 GaN/Si transistor products at various power levels on the market. The company offers a range of demo boards that can assist companies in their efforts to design power converters utilizing GaN devices.

LONG-TERM IMPACTS

Transphorm's work has significantly advanced the realization of energy efficiencies based on the use of GaN, and continues to do so through its ongoing investment in advanced GaN based product and resource development. GaN/Si-based transistors offer a pathway to lower cost WBG devices in the 600-1200V device range. Combined with the potential for substantial system size reductions, it is expected that these devices can enable lower total power converter costs relative to systems based on Si transistors. The high frequency capability of GaN devices also enable new circuit topologies and/or system performance standards.

The continuing development of GaN/Si devices will take place in the competitive power electronics market. In 2014, GaN based power devices accounted for about $10M market size with PV inverters, consumer and automotive applications. Compared to a total global power electronics market size of >$15B (2014), the GaN market portion is very small. However, the market is predicted to grow over the next 5 years as costs continue to come down making GaN devices more competitive with silicon and

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[3] http://www.electronicproducts.com/Discrete_Semiconductors/Transistors_Diodes/First_qualified_GaN_HEMT_features_very_low_energy_losses.aspx

emerging SiC technologies. It has been predicted that by 2020, the total GaN power electronics market will reach approximately $0.55B with the automotive market making up almost 30% of the total.[4]

INTELLECTUAL PROPERTY

The Transphorm team's project has generated two patents issued by the U.S. Patent and Trademark Office (PTO).

Patents

"Electronic Components with Reactive Filters". (2014) *US Patent No. 8,786,327*. Washington, DC: U.S. Patent and Trademark Office.

"Method of forming electronic components with reactive filters" (2015) *US Patent No. 9,041,435*. Washington, DC: U.S. Patent and Trademark Office.

The Transphorm team has published the scientific underpinnings of this technology in the open literature and through conference presentations. A list of publications and presentations resulting from this project is provided below:

Publications

J.Honea, J. Kang, "High-Speed GaN Switches for Motor Drives", Power Electronics Europe, Vol. 3, pp. 38-41, 2012.

J.Honea, D. Kebort, Y. Wu, R. Welch, J. Kang, and K. Shirabe, "Using GaN Devices to Improve the Power Efficiency in a Motor-Inverter Drive System", Motor, Drive, and Automation Systems Conf. 2012, Orlando, FL, March 2012.

K. Shirabe, M. Swamy , J. K. Kang, M. Hisatsune, Y. Wu, D. Kebort, and J. Honea, "Advantages of high frequency PWM in AC motor drive applications," Proceedings of the 2012 IEEE Energy Conversion Congress and Exposition (ECCE), Raleigh, NC, September 2012.

P. Parikh, Y. F. Wu, L. K. Shen, "Commercialization of High 600V GaN-on-Silicon Power Devices", Materials Science Forum, Vols. 778-780, pp. 1174-1179, October 2014.

R. Mitova, A. Dentella, M. X. Wang, R. Ghosh, U. Mhaskar, and D. Klikic, "Half Bridge Inverter with 600V GaN Power Switches" Proceedings of the PCIM Europe 2013 conference, Nuremberg, May 2013.

Y-F. Wu, D. Kebort, J. Guerrero, S. Yea, J. Honea, K. Shirabe and J. Kang, "High-Frequency, GaN Diode-Free Motor Drive Inverter with Pure Sine Wave Output" Power Transmission Engineering, Vol. 6 (5), pp. 40-43, 2012.

[4]Yole Développement report "GaN and SiC Devices for Power Electronics Applications" Jul.2015