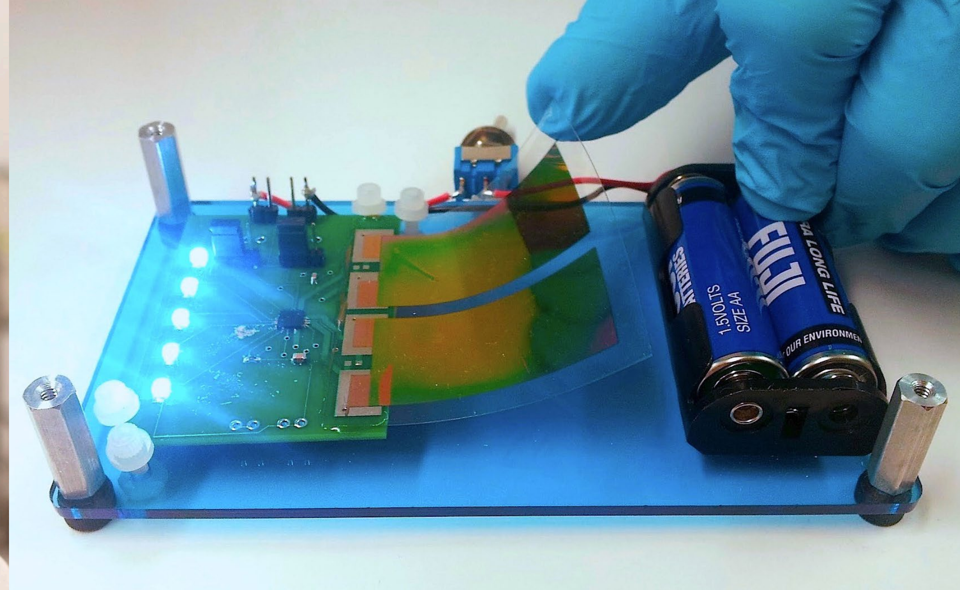

Wide Band-Gap Semiconductor Based Power Electronics for Energy Efficiency

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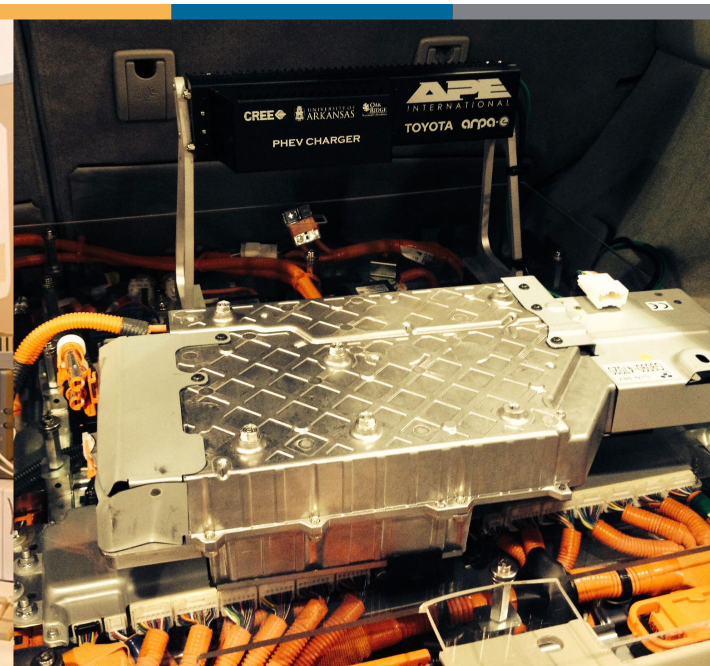

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ABSTRACT

The U.S. Department of Energy's Advanced Research Project Agency for Energy (ARPA-E) was established in 2009 to fund creative, out-of-the-box, transformational energy technologies that are too early for private-sector investment at make-or break points in their technology development cycle. Development of advanced power electronics with unprecedented functionality, efficiency, reliability, and reduced form factor are required in an increasingly electrified world economy. Fast switching power semiconductor devices are the key to increasing the efficiency and reducing the size of power electronic systems. Recent advances in wide band-gap (WBG) semiconductor materials, such as silicon carbide (SiC) and gallium nitride (GaN) are enabling a new generation of power semiconductor devices that far exceed the performance of silicon-based devices. Past ARPA-E programs (ADEPT, Solar ADEPT, and SWITCHES) have enabled innovations throughout the power electronics value chain, especially in the area of WBG semiconductors. The two recently launched programs by ARPA-E (CIRCUITS and PNDIODES) continue to investigate the use of WBG semiconductors in power electronics. From materials and devices to modules and circuits to application-ready systems integration, ARPA-E projects have demonstrated the potential of WBG semiconductors to lower the cost of high-efficiency power electronics to enable broad adoption in energy applications.

INTRODUCTION

Electricity generation currently accounts for 40% of primary energy consumption in the U.S.[1] and over the next 25 years is projected to increase more than 50% worldwide.[2] Electricity continues to be the fastest growing form of end-use energy. Power electronics are responsible for controlling and converting 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 proportion.[3] Development of advanced power electronic devices with exceptional efficiency, reliability, functionality, and form factor will provide the U.S. with a competitive advantage in deployment of advanced energy technologies. Additionally, widespread integration of innovative converters offers substantial energy saving opportunities both directly, by inherently more efficient designs, and indirectly, by facilitating higher levels of adoption for fundamentally higher performing applications and technology solutions.

Technical Opportunity

Achieving high power conversion efficiency requires low-loss power semiconductor switches. Today's incumbent power silicon (Si) based switch technology includes metal oxide field effect transistors (MOSFET), IGBTs and thyristors. Silicon power semiconductor devices have several important limitations:

- *High Losses*: The relatively low silicon bandgap (1.1 eV) and low critical electric field (30 V/µm) require high voltage devices to have substantial critical thickness. The large thickness translates to devices with high resistance and associated conduction losses.
- *Low Switching Frequency:* Silicon high voltage power MOSFETs require large die areas to keep conduction losses low. Resulting high gate capacitance and gate charge produce large peak currents and losses at high switching frequencies. Silicon IGBTs have smaller die than MOSFETs due to utilization of minority carriers and conductivity modulation, but the relatively long lifetime of minority carriers reduces the useful switching frequency range of IGBTs.

1 U.S. Energy Information Administration, Monthly Energy Review (March, 2015)

2 U.S. Energy Information Administration, International Energy Outlook 2016 (May, 2016)

3 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)

- *Poor High-Temperature Performance:* The relatively low silicon bandgap also contributes to high intrinsic carrier concentrations in silicon-based devices, resulting in high leakage current at elevated temperatures. Temperature variation of the bipolar gain in IGBTs amplifies the leakage and limits the maximum junction temperature of many IGBTs to 125°C.

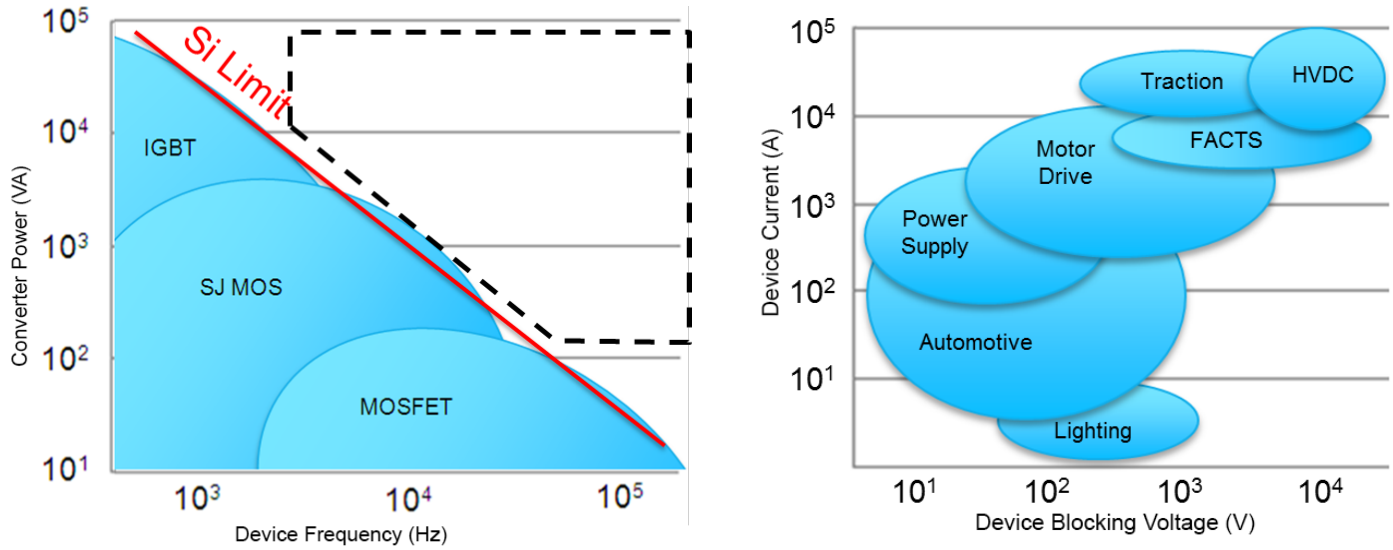

Figure 1: (Left) Relationship of converter power vs switching frequency where the red line indicates the limit of silicon operation. The dotted line area illustrates the opportunity space where WBG systems can operate and silicon devices cannot. (Right) Application areas that lie within the dotted line area include motor drives, automotive, power supplies, aerospace, and distributed energy resources.

Figure 1 illustrates the opportunity space associated with silicon performance limitations. As switching frequency increases, converter power is reduced. In practice, high power silicon systems operate at low frequencies (<10 kHz). This translates to larger passive components (e.g. inductors, capacitors) which increases volume and weight. Wide band-gap (WBG) systems can be operated at higher power and higher frequency within the space silicon devices cannot.

As a result, new opportunities for higher efficiency have emerged with the development of WBG power semiconductor devices, driven by the fundamental differences in material properties between Si and semiconductors such as Silicon Carbide (SiC) and Gallium Nitride (GaN). Higher critical electric fields in these WBG materials (≥ 2 MV/cm) enable thinner, more highly doped voltage-blocking layers, which can reduce on-resistance by two orders of magnitude in majority carrier architectures (e.g., Metal Oxide Field Effect Transistors, MOSFETs) relative to an equivalent Si device.[4] Moreover, high breakdown electric field and low conduction losses mean that WBG materials can achieve the same blocking voltage and on-resistance with a smaller form factor. This reduced capacitance allows higher frequency operation compared with a Si device. The low intrinsic carrier concentration of WBG materials enables reduced leakage currents and robust high-temperature performance. WBG semiconductors therefore provide a pathway to more efficient, lighter, high temperature capable (reduced cooling requirements), and smaller form factor power converters. However, to unlock the potential of WBG based devices, intensive and systematic R&D efforts need to take place at every stage of the power electronics value chain, as depicted in Figure 2.

4 Heffner, A. et al. Recent Advances in High-Voltage, High-Frequency Silicon-Carbide Power Devices. Industry Applications Conference, 41st IAS Annual Meeting (2006)

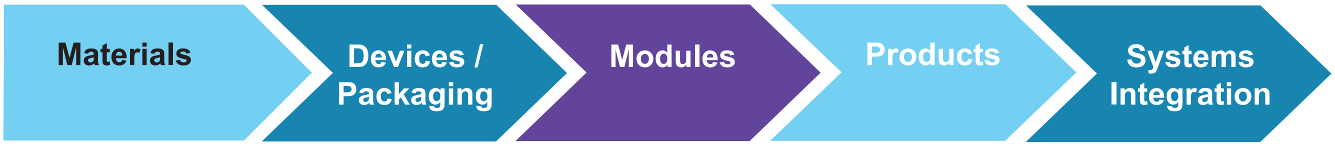

Figure 2: Power Electronics Value Chain.

Application Space

High impact opportunities exist across a variety of applications, including:

Motor Drives: Across all sectors, electric motors account for approximately 40% of total U.S. electricity demand.[5] It is estimated that 40-60% of currently installed electric motors could benefit from variable frequency drives (VFDs),[6] which enable efficient adaptation to speed and torque demands. Depending on the application, incorporation of VFDs can reduce energy consumption by 10-30%.[7] Conventional VFDs for high power applications are bulky and occupy significant space. Size, power density and efficiency can be improved, and the overall system cost reduced, by using WBG-based VFDs.

Automotive: Power electronics such as traction inverters, DC boost converters, and on-board battery chargers are critical elements in hybrid and electric vehicles (EVs). They affect energy efficiency in two ways: directly through switching and other losses, and indirectly by adding volume and weight to the vehicle. WBG inverters can reduce both direct and indirect losses by operating at higher switching frequencies, efficiencies, and temperatures.[8] As a result, 15% improvement in energy efficiency has been predicted for representative hybrid EVs employing SiC traction inverters, with even larger energy savings possible given greater degrees of drivetrain electrification.[9] Assuming aggressive market adoption of EVs in the U.S., use of WBG vehicle power electronics could save as much as 1 quadrillion Btu of energy per year by 2050 relative to conventional Si-based systems.[10] Additionally, efficient, lightweight, and low-cost DC fast charging infrastructure (≥120 kW) enabled by WBG converters will advance the commercial viability and adoption rate of EVs. In conjunction with a cleaner electricity generation portfolio, this has the potential to significantly reduce the one quarter of total U.S. greenhouse gas emissions that stem from the transportation sector.[11]

Data Centers: Energy consumption in data centers accounted for approximately 2% of total electricity use in the U.S. in 2014.[12] 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.[13] Strategies to improve energy efficiency range from integration of lower loss power converters to complete redesign of the power delivery network.[14] The latter approach often involves converting higher voltages at the rack level, where space is limited and proper thermal management is imperative. High power density converters based on

5 Waide, P.; Brunner, C. U. Energy-Efficiency Policy Opportunities for Electric Motor-Driven Systems. IEA (2011)

6 Energy Efficiency Roadmap for Electric Motors and Motor Systems. *Energy Efficient End-use Equipment*, IEA (2015)

7 Energy Efficiency and Power Electronics. Danfoss, ATV Seminar, March 1, 2012

8 Hamada, K. et al. SiC-Emerging Power Device Technology for Next-Generation Electrically Powered Environmentally Friendly Vehicles. *IEEE Transactions On Electron Devices* (2015)

9 Zhang, H. et al. Impact of SiC Devices on Hybrid Electric and Plug-In Hybrid Electric Vehicles. *IEEE Transactions on Industry Applications* (2011)

10 U.S. Department of Energy. Quadrennial Technology Review (2015)

11 Williams, J.H. et al. Pathways to Deep Decarbonization in the United States (2014)

12 Shehabi, A. et al. United States Data Center Energy Usage Report. Berkeley, CA: Lawrence Berkeley National Laboratory (2016)

13 Zhabeloval, G. et al. Data center energy efficiency and power quality: an alternative approach with solid state transformer. *41st Annual conference of the IEEE Industrial Electronics Society* (2015)

14 Candan, E. et al. A Series-Stacked Power Delivery Architecture with Isolated Differential Power Conversion for Data Centers. *IEEE Transactions On Power Electronics* (2016)

WBG devices can be key enablers for more efficient systems, as higher temperature tolerance can reduce cooling loads and further boost data center grid-to-chip efficiency.

Aerospace: Longer, thinner, and lighter wings can reduce fuel consumption and carbon emissions by 50% relative to current commercial aircraft.[15] Such a reduction would save approximately 1 quadrillion Btu of energy per year across the U.S. fleet at current demand.[16] Achieving this transformative wing design requires electromechanical actuators that are small and lightweight with robust operation over a wide temperature range.[17] Moreover, 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.[18] WBG-based converters, with high gravimetric and volumetric power density plus high temperature operation, offer a pathway to achieving significant energy savings in air transport. These key attributes will contribute to weight reduction, enabling new paradigms in body design.

Distributed Energy Resources: In grid applications, such as solar photovoltaic (PV) and wind, as well as the emerging fields of high voltage direct current (HVDC) and flexible alternating current transmission systems (FACTS), power conditioners are required to control the flow of electricity. This is achieved by supplying voltages and currents in a form that is optimally suited to the load. Traditional Si power electronics are responsible for a loss of approximately 4% of all of the electricity generated in these applications and are the dominant point of failure for installed systems. For instance, a typical maximum conversion efficiency for a silicon-based PV inverter is approximately 96% (AC output/DC input)[19] including transformer losses, which drops significantly at operating temperatures above 50 °C. Novel WBG electronic circuits present a route to lower system-level costs by operating at higher switching frequencies that reduce the size of passive components and lower the overall system footprint. In addition, WBG circuits will increase system-level efficiency by allowing PV arrays to operate at higher voltages (e.g. > 1,500V_{DC}). This will enable DC systems with fewer voltage conversions/transformers, replacing traditional combiner boxes with DC/DC converter. The need for on-site AC transmission lines will ultimately allow for easier integration of energy storage solutions in the central substation. Together with a higher semiconductor operating temperature, the advantages of WBG electronics offer a pathway to more robust power converters with mean time to failure (MTTF) comparable to the PV and wind system lifetime (typically 25 years or longer). This will lower the equipment replacement cost and total plant Operation & Maintenance and can have a significant impact on the levelized cost of electricity in distributed resource applications.

15 Slimmed Down Aircraft Wing Expected to Reduce Fuel and Emissions by 50%. NASA, accessed November 29, 2016, https://www.nasa.gov/image-feature/ames/slimmed-down-aircraft-wing-expected-to-reduce-fuel-and-emissions-by-50

16 Transportation Energy Data Book. Oak Ridge National Laboratory, 35th edition (2016)

17 Thin-Wing Electromechanical Actuation (EMA) Demonstration. Department of Defense Air Force Research Lab.

18 Wheeler, P. The More Electric Aircraft: Why Aerospace Needs Power Electronics. Accessed November 29, 2016, http://www.lboro.ac.uk/microsites/research/iemrc/Events%20write%20up/Power%20Electronics%2014.05.09/More_Electric_Aircraft_000.pdf

19 SMA Technical Information, Efficiency and Derating, WKG-Derating-US-TI-en-15, Version 1.5, 2016

EVOLUTION OF ARPA-E'S FOCUSED PROGRAMS IN POWER ELECTRONICS

ARPA-E has catalyzed innovations in power electronics ever since its inception in 2009. The exploration began with OPEN 2009 projects in GaN materials as well as packaging for automotive and LED applications. In 2010, ARPA-E launched its first focused program in power electronics, Agile Delivery of Electric Power Technology (ADEPT), which cast a broad net for innovations in power conversion. ADEPT sought breakthrough technologies in magnetic materials with high operating flux densities, advanced solid-state switch technologies, advanced circuit topologies and converter architectures, and advanced charge storage devices. A year later, Solar ADEPT was launched to bring the general approach of ADEPT to PV power electronics. The successes in ADEPT and Solar ADEPT, along with four WBG related projects in OPEN 2012, showed that WBG semiconductor devices held exceptional potential in dramatically improving energy efficiency, broadening the application space of power electronics. Therefore, ARPA-E initiated the Strategies for Wide-Bandgap, Inexpensive Transistors for Controlling High-Efficiency Systems (SWITCHES) program with a focus on material- (e.g. GaN substrates) and device-level technologies (diodes and transistors). The experience and lessons learned from SWITCHES have revealed the need for further exploration both further up and down the value chain. Down the value chain, the major obstacle experienced by many SWITCHES project teams was selective area p-type doping of GaN. This initiated the Power Nitride Doping Innovation Offers Devices Enabling SWITCHES (PNDIODES) program, a supplementary program that would seek the fundamental understanding of material properties and processing technologies for selective area doping of GaN. Up the value chain, ARPA-E recognized the opportunities that harness recent advancements at the component level for transformational developments at the circuit and system levels. Hence the launch of Creating Innovative and Reliable Circuits Using Inventive Topologies and Semiconductors (CIRCUITS) Program. The time evolution of ARPA-E power electronics programs is depicted in Figure 3.

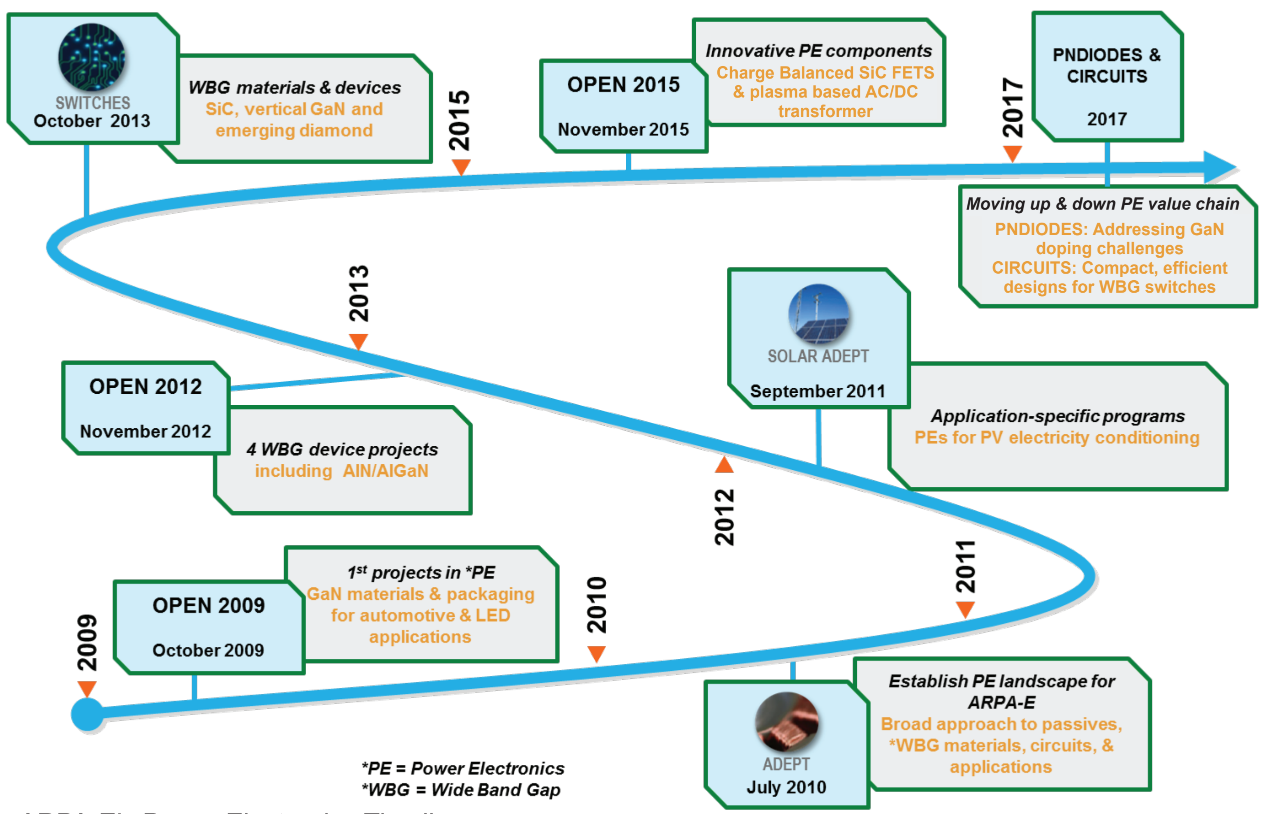

Figure 3: ARPA-E's Power Electronics Timeline.

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ADEPT

Broad Exploration of Power Electronics Landscape

BROAD EXPLORATION OF POWER ELECTRONICS LANDSCAPE - ADEPT

In 2010, the ADEPT program set out to lower the cost and improve performance of power converters and associated management systems. The program sought innovations across the entire value chain in power electronics from advanced component technologies and converter architectures, to packaging and manufacturing processes. The program aimed to address three categories of performance and integration levels: 1) fully-integrated, chip-scale power converters, 2) package-integrated power converters, and 3) lightweight, medium voltage energy conversion for high power applications. The original program areas of interest included magnetic materials with high operating flux densities, advanced solid-state switch technologies, advanced circuit topologies and converter architectures, and advanced charge storage devices. The most successful projects in the ADEPT program were those that utilized WBG components.

One example of a successful project is the development of a SiC-based EV battery charger, led by Arkansas Power Electronics International (APEI). The project was titled "10 times smaller EV charger using SiC based power transistors", and APEI later won a 2014 R&D100 award.[20] On-board battery chargers for EVs and plug-in hybrid electric vehicles (PHEV) such as the Toyota Prius offer the convenience of universal charging from any available power outlet, but this functionally adds additional volume and weight to the system. WBG power electronics based chargers can enable operation at higher switching frequencies as well as elevated temperatures, thus allowing for a more compact system size/weight via reductions in passive component sizes as well as simplification of the thermal management system.

The APEI team designed a two-stage architecture with topologies that optimized for system density and efficiency. This leveraged the benefits of SiC power devices over traditional Si power diodes into significant system level improvements. In the first stage AC-DC converter, a bridgeless boost power factor correction (PFC) topology was chosen. This capitalizes on the negligible reverse recovery current of SiC devices over Si power diodes, resulting in performance advantages especially at frequencies in excess of 100 kHz. The second stage was a DC-DC converter utilizing a phase-shifted full-bridge (PSFB) topology. This took advantage of the low output capacitance, high voltage blocking capability, and stable on-resistance at elevated temperatures of SiC devices for greater overall converter performance.[21]

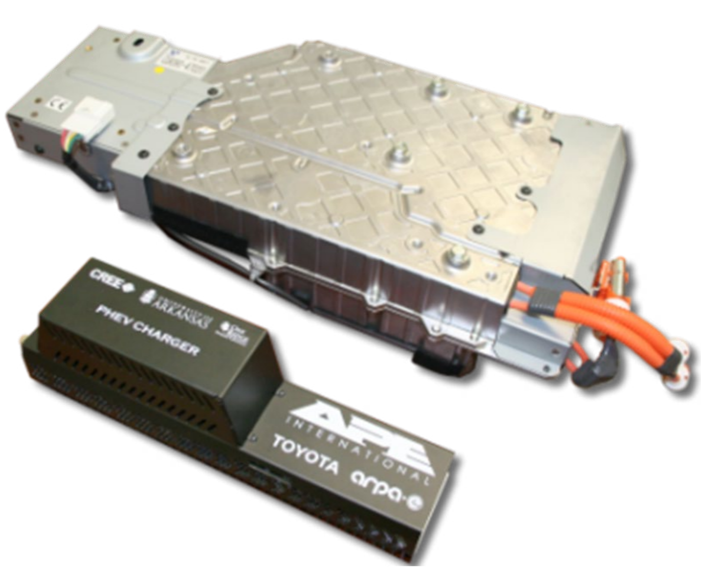

Figure 4: (bottom) APEI's prototype charger compared to (top) 2010 Toyota Prius plug-in hybrid battery charger (from ref 20).

The experimental implementation of the charger utilized commercially available 1200V/20A SiC MOSFET and Schottky Diodes from Cree packaged in a multi-chip power module designed by APEI. The full system housed three such models each with different device configurations. The SiC based charger, shown in Figure 4, operated at a switching frequency of 200 kHz with a total weight of 1.6 kg and volume of 1.2 L. This demonstrated a 10x increase in volumetric power density and 9x increase in gravimetric power density compared to

20 "2014 Awards Highlight New Trends," *R&D Magazine*, Ed. T. Studt, Vol 56, no. 5, pg. 22, October 2014

21 B. Whitaker, A. Barkley, Z. Cole, B. Passmore, D. Martin, T. R. McNutt, A. B. Lostetter, J. S. Lee, and K. Shiozaki, "A High-Density, High-Efficiency, Isolated On-Board Vehicle Battery Charger Utilizing Silicon Carbide Power Devices," *IEEE Transactions on Power Electronics*, vol. 29, no. 5, May 2014. DOI: 10.1109/TPEL.2013.2279950

the 2010, Si based Toyota Prius plug-in battery charger. At the highest tested peak power level of 6.1 kW the system efficiency was 94%, with an overall peak efficiency of 95% at an output power of 3.1 kW. This is a clear demonstration of the added value that WBG power electronics provides for automotive technologies.

Two ADEPT projects investigating the potential of GaN devices were also able to make tremendous advancements. Transphorm's project "High Performance GaN HEMT modules for Agile Power Electronics" aimed to develop kW class inverters with greater efficiency and power density than incumbent Silicon based Insulated Gate Bipolar Transistor (IGBT) motor drives. To achieve this, the team had to overcome material challenges associated with the epitaxial growth of GaN on 6-inch Si with low defect density, fabricate GaN-on-Si High Electron Mobility Transistors (HEMTs), and demonstrate improved power module performance over the state of the art Si IGBTs.

Transphorm developed 600V normally-on HEMTs and achieved enhancement mode, or normally-off, operation by integrating a Si FET in a cascode configuration.[22] Under resistive load switching, an inverter using the 600V GaN e-mode HEMTs hard switched at 100 kHz PWM frequency and demonstrated 98.5% efficiency. When evaluated in a motor drive test lab side to side with a Si IGBT-based motor-drive inverter operating at 15 kHz PWM frequency, the GaN inverter showed 8, 4, and 2% improvement in efficiency at low, mid, and full loads (roughly 500, 1000, and 1500 W) respectively operating at 7x higher PWM frequency[23]. In 2015, Transphorm, Inc. announced that its 600V GaN transistor has been fully Joint Electron Device Engineering Council (JEDEC) qualified and is slated for mass production in an industry standard TO-247 size package.[24]

The ADEPT project led by the Massachusetts Institute of Technology took a broader approach to the challenge and addressed three areas needed to improve power conversion: switching devices, inductors, and circuit design in their work on a novel GaN device, with an application focus on power converters for driving light emitting diode (LED) loads. In the device arena, MIT pioneered a tri-gate normally off metal-insulator-semiconductor field-effect transistor and demonstrated it with a breakdown voltage of 565 V at a drain leakage current of 0.6 uA/mm[25]. In parallel, MIT also developed novel circuit topologies that leveraged wide-bandgap power electronics to break the performance constraints of commercially available systems. An LED driver employing a new power conversion architecture for single-phase AC grid interfaces was developed. The driver operated from 120 V_{AC}, while supplying a 35 V, 30 W output. Operating at a variable switching frequency of 5-10 MHz with an efficiency of >93%, the converter had a power factor of 0.89 with an overall box power density of 2.7 W/cm^3. For comparison, commercial LED drivers typically operate in the 50-100 kHz frequency range, with maximum efficiencies around 88% and power densities <1.0 W/cm^3.

The technologies and related IP developed at MIT is now being commercialized at several different start-ups. The circuit design concepts developed during ADEPT and lessons learned informed the design of a new laptop charger now being commercialized by FINsix, a MIT spin-out. The charger – named DART – is a 65 W charger that is 3 times smaller and lighter than conventional chargers. FINsix and Lenovo are currently in a partnership to make the smaller charger available for select ThinkPad models. Another MIT spinout – Cambridge Electronics – was started by students whose research was funded by ADEPT and are offering state-of-the-art GaN devices for sale. The company has received numerous awards including the Massachusetts's MassVentures Start Award as well as the 2016 Compound Semiconductor Industry Award.

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22 P. Parikh, Y-F. Wu, L. Shen, "Commercialization of High 600V GaN-on-Silicon Power Devices," ISCRM, September 2013.

23 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*, October 2012.

24 http://www.transphormusa.com/news/transphorm-announces-industrys-first-600v-gan-transistor-247-package/

25 B. Lu, E. Matioli, and T. Palacios, "Tri-Gate Normally-Off GaN Power MISFET," *IEEE Electron Device Letters*, vol. 33, no. 3, March 2012. DOI: 10.1109/LED.2011.2179971

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Solar ADEPT

Solar Photovoltaics Applications

SOLAR PHOTOVOLTAICS APPLICATIONS – SOLAR ADEPT

Solar ADEPT held similar aspirations to ADEPT but specifically focused on packaging and manufacturing processes for power converters to reduce costs for photovoltaic systems. Similar to ADEPT, Solar ADEPT aimed to address technical challenges at different performance and integration levels, from chip-scale all the way to utility-scale. Tailored for the solar PV application space, Solar ADEPT defined its technical targets into four categories: 1) fully-integrated, chip-scale power converters for sub-module applications, 2) package-integrated microinverters with reduced size and improved performance, 3) lightweight inverters for commercial roof-top and wall-mount applications, and 4) lightweight, solid-state, medium voltage energy conversion for high-power applications such as utility-scale inverters with direct grid connection.

In their "Bidirectional GaN-on-Si transistors for more compact and reliable power converters" project Transphorm aimed to develop GaN-on-silicon based four quadrant switches for residential and commercial solar micro-inverters. Most silicon based switches, with the exception of the triode for alternating current (TRIAC), block voltage only in one direction when gated off - and are thus unidirectional. Bidirectional switches – also called four quadrant switches (FQS) - that allow current flow in both directions when on would enable many new circuit topologies and applications. Building upon their expertise and experience from the ADEPT program, Transphorm demonstrated high voltage (both 600 V and 1200 V) FQSs with maximum switching frequencies > 25 MHz for a 400 V bus. The single monolithic GaN FQS, replacing four discrete Si devices, enabled a 4% improvement in converter efficiency at low power and 0.2% improvement at full power, approximately a 50% lower power device loss.

The ADEPT and Solar ADEPT program successes were significant in advancing commercial applications of SiC and GaN devices. However, SiC and GaN device technology remained immature relative to Si and carried a substantial cost premium, limiting their widespread adoption . Many of the largest opportunities for increased energy efficiency and reduced energy-related emissions exist in extremely cost conscious industries, including markets for railway traction drives, automotive applications, and industrial motors. Unit cost for equivalent functional system performance remains a major barrier to the widespread adoption of WBG devices, despite opportunities related to their superior attributes (including reductions in system costs).

CHANGING WHAT'S POSSIBLE

SWITCHES

Wide-Bandgap Materials and Devices

WIDE-BANDGAP MATERIALS AND DEVICES – SWITCHES

Analysis of market drivers showed that accelerating the commercial uptake of more efficient approaches enabled by WBG devices requires driving down the costs of the components. This led to the creation of the Strategies for Wide Bandgap, Inexpensive Transistors for Controlling High-Efficiency Systems (SWITCHES) program. The SWITCHES program was aimed at transformational advances that address key materials, device fabrication, and device architecture issues that drive costs for SiC and GaN devices, as well as to evaluate ultra-wide-bandgap (UWBG) materials such as a diamond. The goal was to enable the development of high voltage (>1,200V), high current (100A) single die power semiconductor devices that, upon ultimately reaching scale, would have the potential to reach functional cost parity with Si power transistors. Additionally, they would offer breakthrough relative circuit performance through low losses, high switching frequencies, and high temperature operation. These transformational technologies would have promise to reduce the barriers to ubiquitous deployment of low-loss WBG power semiconductor devices in stationary and transportation energy applications. From a cost basis perspective, the barrier to market entry needs to be competitive. Low current silicon switching devices (<50A) can be purchased as low as ¢5/A [26]. However, this is not the case for high current applications. The SWITCHES cost target for WBG packaged devices was ¢10/A for a <u>100A</u> device, which would make them competitive with the best silicon IGBT devices in the same class.

The SWITCHES program has made tremendous advances in SiC device fabrication. In their project "Lower cost SiC manufacturing using existing low-cost, high-volume silicon manufacturing" Monolith Semiconductor, Inc. was able to made great strides in developing large-area, high-voltage, SiC devices. Before the SWITCHES program, planar and vertical SiC MOSFET power devices were limited in availability and were typically fabricated in relatively low volume at dedicated facilities that utilized unique process steps. This resulted in high cost and prohibitively expensive devices. Monolith Semiconductor partnered with XFab Inc., an automotive qualified Si Complementary Metal-Oxide Semiconductor (CMOS) manufacturing foundry, to develop and implement an advanced SiC power MOSFET process on their 150mm diameter silicon production line. Working in an active Si foundry provides significant cost benefits. Using an existing Si manufacturing infrastructure, the overhead costs to manufacture SiC devices can be reduced. The innovation in Monolith's approach centered on adopting commercially available 150mm SiC wafers and designing SiC devices and fabrication processes that are compatible with existing, high-volume Si manufacturing facilities.[27]

This allows for highly competitive products, rapidly deployed in the market. Monolith successfully demonstrated fabrication of MOSFETs on XFab's production line with blocking voltage of 1700V and a specific on-resistance as low as 3.1 $m\Omega\text{-}cm^2$ at room temperature, increasing to 6.7 $m\Omega\text{-}cm^2$ at 175°C. Clamped inductive switching characterization of the SiC MOSFETs showed turn-off losses as low as 110 µJ. After 750 hours of gate stress at a gate bias of V_{GS}=+20V and 175°C, only a 250mV shift in the threshold voltage was observed[28]. Design changes and processes improvements increased the production line yield of the devices to commercially acceptable levels which illustrated the promise for high-volume production of reliable SiC MOSFETs on 150mm wafers. The company anticipates to reach ¢10/A for their devices in the near future.

The SWITCHES program also made significant advances in GaN device design and fabrication. Before the SWITCHES program, the majority of GaN power device development had been directed toward lateral architectures, such as high-electron mobility transistors (HEMTs). There were no vertical GaN devices commercially

26 ARPA-E SWITCHES FOA, https://arpa-e-foa.energy.gov/FileContent.aspx?FileID=1f3b152b-a75a-4118-a6a6-30868377dac8

27 S. Banerjee, K. Matocha, K. Chatty, J. Nowak, B. Powell, D. Guttierrez, and C. Hundley, "Manufacturable and rugged 1.2 KV SiC MOSFETs fabricated in high-volume 150mm CMOS fab." Paper presented at 2016 28th International Symposium on Power Semiconductor Devices and ICs (ISPSD), Prague, Czech Republic, June 2016, DOI: 10.1109/ISPSD.2016.7520832

28 K. Matocha, S. Banerjee, and K. Chatty, "Advanced SiC Power MOSFETs Manufactured on 150mm SiC Wafers", *Materials Science Forum*, vol. 858, pp. 803-806, 2016, DOI: 10.4028/www.scientific.net/MSF.858.803

available. The lateral devices suffered from well-known issues such as current-collapse, dynamic on-resistance, inability to support avalanche breakdown[29], and usable breakdown voltages of no greater than 650V. Vertical devices on the other hand offer the possibility to realize the potential of GaN including true avalanche-limited breakdown. Two projects in the SWITCHES program (Avogy, Inc. and Cornell University) were able to demonstrate near theoretical, high-power vertical GaN diodes exhibiting very high breakdown voltages (1700 - 4000 V) and figures-of-merit (V_B^2/R_{ON}) greater than 3 GW/cm^2.[30,31] The SWITCHES sponsored researchers demonstrated that vertical GaN devices are avalanche capable[32] indicating the ruggedness of such devices in breakdown, a critical requirement for power switching and rectifying applications. The pathway towards achieving ¢10/A for GaN devices was shown to be promising. Projects funded by SWITCHES have demonstrated 80% process yield for 100A, 1200V p-n junctions. With the current cost of 4" GaN wafers and a die size of 12-16 mm^2 for a 100A, 1200V device, vertical GaN devices should be capable of reaching the price range of ¢5/A to ¢7/A.

Normally-off vertical transistor devices have been more challenging to fabricate compared to diodes, especially at high current levels, due to the requirement of selective area doping in many vertical device architectures. Attempts at selective area doping in vertical GaN devices in the SWITCHES program resulted in devices with large junction leakage currents, lower than breakdown voltages expected, and avalanche breakdown ruggedness not demonstrated. This is the major challenge faced by the SWITCHES projects with vertical GaN architectures. To overcome the selective area doping limitation in GaN two SWITCHES projects have investigated unique vertical GaN device designs that reduce or eliminate the need for selective area doping. The University of California, Santa Barbara demonstrated one such novel vertical GaN devices to achieve both low on-resistance (R_{ON}) and enhancement mode operation in a vertical GaN device called an "in-situ oxide, GaN interlayer-based vertical trench MOSFET" or OG-FET. In the traditional trench MOSFET structure, a dielectric is deposited on an n-p-n trenched structure and the channel forms via p-GaN inversion at the dielectric/p-GaN interface. However, this results in a relatively high R_{ON} due to poor electron mobility in the channel. By changing the structure to include a metal-organic chemical vapor deposition regrown un-intentionally doped GaN interlayer followed by an in-situ, Al_2O_3 dielectric cap on the n-p-n trenched structure, a pathway (channel) for enhanced electron mobility is created, resulting in reduced resistance. The normally-on OG-FETs fabricated by UCSB demonstrated a threshold voltage of 2V, breakdown voltages of 990 V (E_{BR} ~ 1.6 MV/cm), and an R_{ON} of 2.6 mΩ-cm^2.[33]

The SWITCHES project led by Columbia University "High-performance, low-cost vertical GaN devices through smaller devices and GaN substrate re-use" demonstrated a GaN vertical fin power field-effect-transistor structure (VFET) on bulk GaN substrates that addresses the selective area doping limitation of conventional power vertical GaN transistor device structures. The VFET, shown in Figure 5, consists of fin-shaped channels etched into an 8-μm-thick n- doped GaN drift layer using a combined dry/wet etching technology to achieve smooth fin vertical sidewalls.[34] The current flows vertically from the backside drain contact to source contacts deposited on top of

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29 E. Zanoni, M. Meneghini, A. Chini, D. Marcon, and G. Meneghesso, "AlGaN/GaN-based HEMTs failure physics and reliability: Mechanisms affecting gate edge and Schottky junction," *IEEE Trans. Electron Devices*, vol. 60, no. 10, pp. 3119–3131, Nov. 2013, DOI: 10.1109/TED.2013.2271954.

30 I. C. Kizilyalli, A. P. Edwards, H. Nie, D. Disney, and D. Bour, "High voltage vertical GaN p-n diodes with avalanche capability", *IEEE Trans. Electron Devices*, vol. 60, no. 10, pp. 3067-3070, 2013, DOI: 10.1109/TED.2013.2266664

31 K. Nomoto, B.Song, Z. Hu, M. Zhu, M. Qi, N. Kaneda, T. Mishima, T. Nakamura, D. Jena, and H.G. Xing, "1.7-kV and 0.55- mΩ·cm^2 GaN p-n Diodes on Bulk GaN Substrates With Avalanche Capability", *IEEE Electron Device Letters*, vol. 37, no. 2, pp 161-164, 2016, DOI: 10.1109/LED.2015.2506638

32 O.Aktas, and I. Kizilyalli, "Avalanche capability of vertical GaN pn junctions on bulk GaN substrates." *IEEE Electron Device Letters*, vol. 36, no. 9, pp 890-892, 2015, DOI: 10.1109/LED.2015.2456914

33 C. Gupta, C. Lund, S. Chan, A. Agarwal, J. Liu, Y. Enatsu, S. Keller, and U. Mishra, "In Situ Oxide, GaN Interlayer-Based Vertical Trench MOSFET (OG-FET) on Bulk GaN substrates" *IEEE Electron Device Letters*, vol: 38, no. 3, pp. 353-355, 2017, DOI: 10.1109/LED.2017.2649599

34 M. Sun, Y. Zhang, S. Bedell, J. Barth, D. Sadana, K. Shepard, X. Gao and T. Palacios, "Vertical GaN Power Transistors Using Controlled Spalling for Substrate Heterogeneity" Presented at 3rd Annual SWITCHES Review Meeting, Philadelphia, PA, March 2017

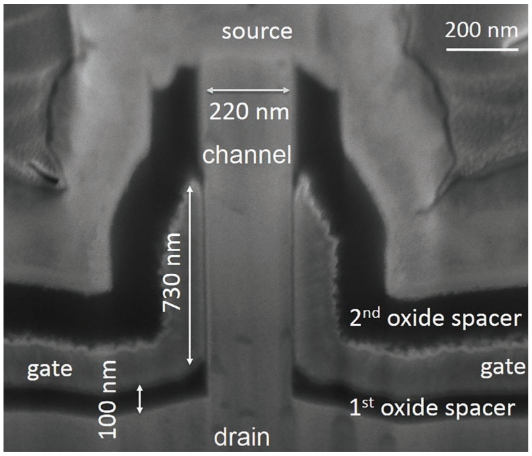


Figure 5: Scanning electron microscope cross sectional view of a fabricated GaN VFET (from ref 34).

the fins. The sub-micron fin channels are surrounded by metal gate pads which, below the threshold voltage, pinch-off the channel. In this vertical transistor design only n-GaN layers are needed, no material regrowth or p-GaN layer is required.[35] Fabricated VFETs demonstrated specific on-resistance of 0.2 mΩ-cm^2, threshold voltage of 1 V, and a breakdown voltage >1200 V with high ON current (>25 kA/cm^2) and low OFF current at 1200 V (<10^{-4} A/cm^2). This amounts to a figure-of-merit (V_B^2/R_{ON}) of ~7.2 GW/cm^2. Large devices demonstrated high current up to 10 A and breakdown voltage >800 V.[36, 37]

Additionally, the SWITCHES program has made advances in the area of epitaxial lift-off of GaN materials. Two SWITCHES projects by the MicroLink Devices and Columbia University teams focused on GaN substrate re-use and thinning. These projects demonstrated large area (>2") layers released from bulk GaN wafers by epitaxial liftoff and spalling without damage to the lifted off layer. The MicroLink Devices project "High-performance, low-cost vertical GaN devices through smaller devices and GaN substrate re-use" demonstrated wafer-scale epitaxial lift-off (ELO) using an InGaN release layer and a bandgap-selective photo-enhanced wet etching to fully released a GaN foil from 2-inch bulk GaN substrate as shown in Figure 6.[38] Perforations spaced at 1mm apart were used to allow for the wet chemical etch access to the InGaN release layer. The leakage current in both reverse and low-forward-bias regimes for thin-film Schottky diodes was reduced after ELO processing. This is potentially due to the elimination of leakage paths through the underlying n+ buffer layer that is removed in the ELO process.[39]

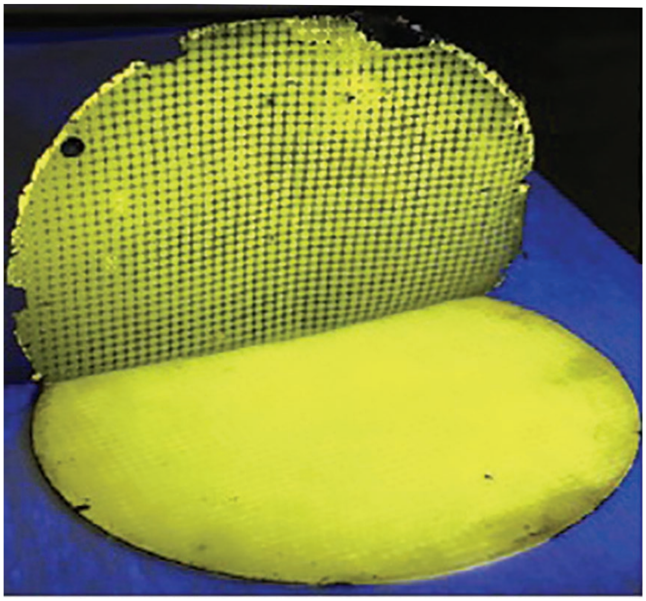


Figure 6: A 5-micron-thick GaN epitaxial film released from a 4-inch sapphire substrate using perforations on a 1-mm pitch. The yellow luminescence of the nitrogen face of the released film is visible under ultraviolet illumination (from ref 39).

On the bulk (free standing) GaN substrate development side, Soraa Inc. developed, in their OPEN 2009 and SWITCHES projects, a large diameter ammonothermal reactor capable of more than 600ºC operation and a pressure greater than

35 M. Sun, M. Pan, X. Gao, and T. Palacios, "Vertical GaN power FET on bulk GaN substrate" Paper presented at 2016 74th Device Research Conference (DRC), Newark, DE, June 2016, DOI: 10.1109/DRC.2016.7548467

36 M. Sun, Y. Zhang, X. Gao, and T. Palacios, "High-Performance GaN Vertical Fin Power Transistors on Bulk GaN Substrates" *IEEE Electron Device Letters*, vol: 38, no. 4, pp509-512, 2017, DOI: 10.1109/LED.2017.2670925

37 Y. Zhang, M. Sun, D. Piedra, J. Hu, Z. Liu, Y. Lin, X. Gao, K. Shepard, and T. Palacios, "1200 V GaN Vertical Fin Power Field-Effect Transistors" Presented at IEEE International Electron Device Meeting, San Francisco, CA, December 2017

38 C. Youtsey, R. McCarthy, R. Reddy, K. Forghani, A. Xie, E. Beam, J. Wang, P. Fay, T. Ciarkowski, E. Carlson, and L. Guido, "Wafer-scale epitaxial lift-off of GaN using bandgap-selective photoenhanced wet etching" *Phys. Status Solidi B*, vol: 254, no. 8, pp 1600774, 2017, DOI 10.1002/pssb.201600774

39 J. Wang, C. Youtsey, R. McCarthy, R. Reddy, N. Allen, L. Guido, J. Xie, E. Beam, and P. Fay, "Thin-film GaN Schottky diodes formed by epitaxial lift-off" *Applied Physics Letters*, vol: 110, pp 173503, 2017, DOI: 10.1063/1.4982250

3,000 atmospheres in order to grow bulk GaN crystals.[40] The ammonothermal GaN crystal growth method is adapted from the hydrothermal method used to grow quartz crystals, which are very inexpensive and represent the second-largest market for single crystals for electronic applications (after silicon). Soraa successfully demonstrated growth of GaN crystals that are over two inches in diameter at a rate of at least 10 microns per hour, and the fabrication of 2 inch GaN wafers from the crystals (Figure 7).[41] The wafers met Soraa's target specifications for LED crystal quality, dopant levels, dislocation density, miscut, and surface roughness. Soraa has also shown that with additional processing steps, they have the ability to make wafers with a dislocation density less than $1\text{x}10^4$ cm^{-2}, a breakthrough that will enable higher-performing power electronics devices with a breakdown field greater than 3 MV/cm for GaN.

In the SWITCHES program advances were similarly achieved in the UWBG material diamond. SWITCHES projects focusing on diamond by Arizona State University and Michigan State University have demonstrated thick (>1mm) diamond growth by CVD and doping of diamond with $>10^{20}$ cm^{-3} boron and phosphorous for p+ and n+ layers, respectively. Using the advances in diamond growth Schottky and p-n didoes with >1000V blocking and 100-500 A/cm^2 forward current were demonstrated.[42,43] These achievements have yet to reach program targets, but are nonetheless foundational in the pursuit of ultra-wide-bandgap semiconductor devices.

The projects in the SWITCHES program have made tremendous advances in materials development, vertical device architecture, and low cost device fabrication. The SWITCHES program set out to achieve three key aggressive targets: 1200V breakdown, 100A single-die current, and cost of packaged discrete device of no more than ¢10/A. The program is drawing to a close by the end of 2017 and while no project has yet to achieve all the targets of the program, the portfolio of projects are well underway to achieving these targets communally.

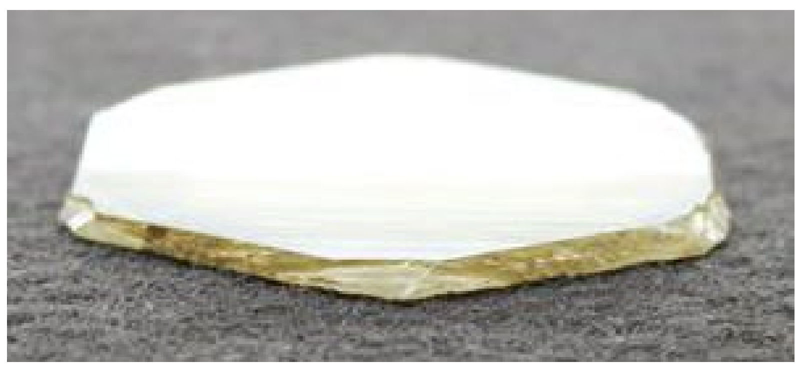


Figure 7: 2 inch GaN crystal and wafer fabricated by Soraa's process (from ref 40).

40 R. McCarthy, "High-Power Vertical-Junction Field-Effect Transistors Fabricated on Low-Dislocation Dislocation GaN by Epitaxial Lift-Off" Presented at 3rd Annual SWITCHES Review Meeting, Philadelphia, PA, March 2017

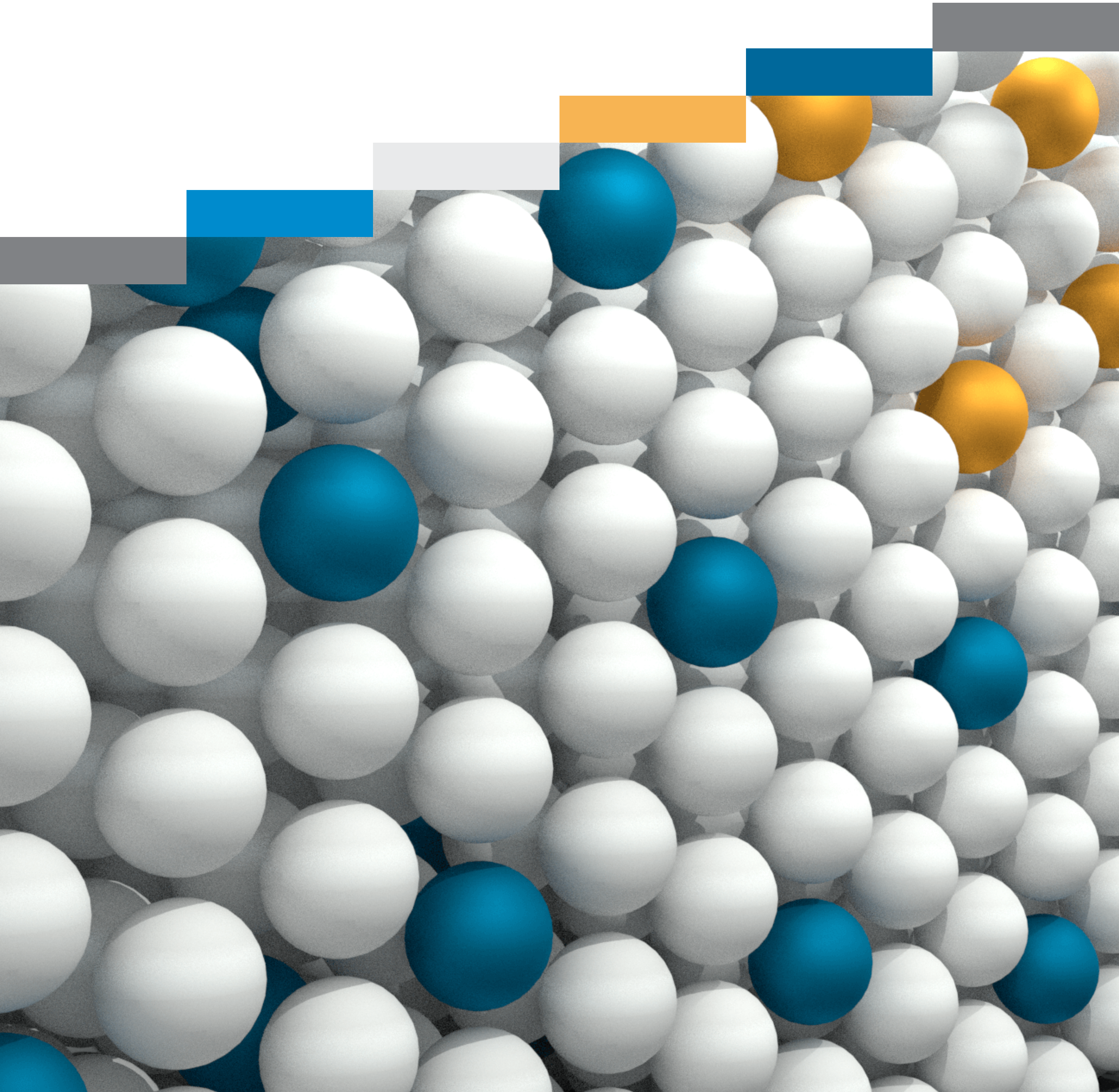
41 "Lower Cost GaN for Lighting and Electronics Efficiency" Advanced Research Projects Agency – Energy Project Impact Sheet, (March 2016) https://arpa-e.energy.gov/sites/default/files/documents/files/Soraa_Open2009_ExternalImpactSheet_FINAL.pdf

42 M. Dutta, F. Koeck, W. Li, R. Nemanich, and S. Chowdhury, "High Voltage Diodes in Diamond Using (100)- and (111)- Substrates", *IEEE Electron Device Letters*, vol. 38, no. 5, pp. 600-603, 2017, DOI: 10.1109/LED.2017.2681058

43 S. Nicley, S. Zajac, R. Rechenberg, M. Becker, A. Hardy, T. Schuelke, and T. Grotjohn, "Fabrication and characterization of a corner architecture Schottky barrier diode structure" *Phys. Status Solidi A*, vol: 212, no. 11, pp 2410-2417, 2057, DOI 10.1002/pssa.201532220

PNDIODES

Addressing Material Challenges



ADDRESSING MATERIAL CHALLENGES - PNDIODES

Many SWITCHES project teams experienced a major obstacle in fabricating vertical GaN power electronic devices specifically the lack of viable GaN selective area doping or selective area epitaxial regrowth processes that yields material of sufficiently high quality to enable defect-free p-n junctions on patterned GaN surfaces. An example is shown in Figure 8. In GaN selective area p-type doping has proved elusive, because the most obvious approaches, such as laterally patterned ion implantation with activation or selective area diffusion of p-type dopants (e.g. Mg, Be, Zn), have not produced p-type regions or satisfactory p-n junctions. Furthermore, selective area etch and regrowth approaches have resulted in poor electrical performance not sufficient to be useful in power electronic applications. A breakthrough is needed to enable high performance vertical GaN transistors. This specific remaining challenge to the SWITCHES program prompted the announcement in late 2016 of the Power Nitride Doping Innovation Offers Devices Enabling SWITCHES (PNDIODES) program. The PNDIODES program aims to develop transformational advances and mechanistic understanding in the process of selective area doping in the III-Nitride wide-bandgap semiconductor material system. The expectation is this will lead to the demonstration of arbitrarily placed, reliable, contactable, and generally usable p-n junction regions that enable high-performance and reliable vertical power semiconductor devices.

Seven projects were selected for funding as part of the PNDIODES program. The project teams will work to develop transformational advances and mechanistic understanding in the process of selective area doping for GaN using innovative technologies. Projects led by Arizona State University, Sandia National Laboratories, and Yale University, will focus on selective area doping using patterned etch and regrowth technology. They will attempt to obtain a deep understanding of the process, including various etching methods, interface impurity control, and the effect of crystal growth direction. Projects led by Adroit Materials, JR2J, and State University of New York Polytechnic Institute, will focus on selective area doping using ion implantation and innovative annealing, or heat treatment. This will include processes such as laser spike and Gyrotron annealing to remove implantation damage and activate the dopants. The remaining project led by the University of Missouri will focus on the development of neutron transmutation doping, exposing GaN wafers to neutron radiation to create a stable network of dopants within, to fabricate a uniformly doped n-type GaN wafer to achieve low resistance substrates.

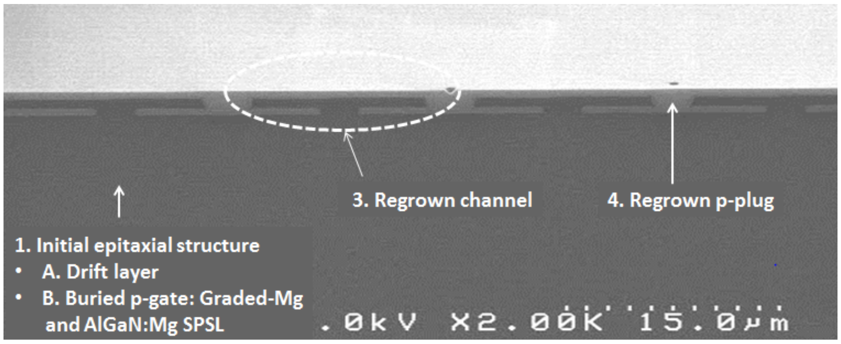


Figure 8: GaN Selective Area Doping example.

The Department of Energy and Department of Defense have identified power electronics based on wide-bandgap semiconductors as a major area of concern for energy efficiency and the reduction in size and weight, as well as improvement in the reliability of power conversion systems. Success in the PNDIODES program would offer innovative options to help drive research, development, and commercialization of vertical GaN power electronic devices.

CIRCUITS

System-Level Advances

SYSTEM-LEVEL ADVANCES - CIRCUITS

Previous efforts by ARPA-E have primarily focused on WBG material and device development without focused consideration and redesign of the circuit topology. Such solutions do not fully exploit the potential performance improvements enabled by this new class of power semiconductor devices. The circuit design is critical to the large-scale implementation of more efficient WBG power systems as a result of their ability to operate at high voltage, high frequency, and high temperature. For WBG power electronics devices, their benefits will not be fully realized if they are treated as drop-in replacements for Si devices. Instead, new circuit topologies and designs are needed that take full advantage of the attributes of the WBG semiconductor devices, resulting in minimization of form factor, cooling systems, and auxiliary circuit components. The Creating Innovative and Reliable Circuits Using Inventive Topologies and Semiconductors (CIRCUITS) funding opportunity announcement released in early 2017 seeks to accelerate the development and deployment of a whole new class of efficient, lightweight, and reliable power converters based on WBG semiconductors. The program will drive transformational system-level advances that enable effective operation at high switching frequency, high temperature, and low loss. With an explicit focus on novel circuit topologies, advanced control and drive electronics, as well as innovative packaging, CIRCUITS aims to catalyze disruptive improvements for power electronics afforded by cutting edge materials such as WBG semiconductors. Such technological breakthroughs would catalyze the adoption of higher performance power converters in various critical applications such as motor drives, automotive, power supplies, data centers, aerospace, ship propulsion, rail, distributed energy, and the grid. This will enable significant direct and indirect energy savings and emissions reductions across electricity generation, transmission and distribution, and load-side consumption.

Twenty-one innovative projects were selected for funding as part of the CIRCUITS program. The project teams will accelerate the development and deployment of a new class of circuit topologies optimally designed for WBG semiconductors to maximize system performance that will save energy and give the United States a critical technological advantage in an increasingly electrified economy. CIRCUITS projects will establish the building blocks of this class of power converter by advancing higher efficiency designs that exhibit enhanced reliability and superior total cost of ownership. In addition, a reduced form factor (size and weight) will drive adoption of higher performance and more efficient power converters relative to today's state-of-the-art systems. Some examples of the projects include:

The Eaton Corporation will develop and validate a wireless-power-based computer server supply that enables distribution of medium voltage (AC or DC) throughout a data center and converts it to the 48 VDC used by computer servers. The Eaton team has targeted the data center sector, as it is quickly becoming a major consumer of electricity in the United States. If successful, project developments will reduce U.S. data center energy consumption and operating cost while creating a high-volume commercial market for SiC-based power converters.

Marquette University will develop a small, compact, lightweight, and efficient 1 MW battery charger for electric vehicles with a switching frequency of 1Mhz. The team aims to use state-of-the-art MOSFET switches based on SiC to ensure the device runs efficiently while handling very large amounts of power in a small package. This project endeavors to triple the current state-of-the-art in power density and double specific power of chargers today. If successful, such a device could help to dramatically reduce charging times for big batteries, like those in electric vehicles, to a matter of minutes.

University of Arkansas will develop a 2 by 250 kW power inverter system for use in the electrification of heavy equipment and other higher volume transportation applications (e.g., trucks, buses, cars). The team will leverage SiC power electronics devices to achieve high levels of efficiency while greatly increasing the volumetric and gravimetric power density of its system over existing ones. If successful, the team will achieve an improvement of four times the power density and reduce converter cost by 50% compared to today's technology.

IMPACTS

ARPA-E's sustained exploration in WBG-based power electronics has helped foster a vibrant ecosystem in WBG R&D. Prior to ARPA-E PE programs, the Department of Defense[44] spearheaded R&D efforts in WBG semiconductors for defense applications. For civilian applications, several DOE offices, including the Energy Efficiency and Renewable Energy (EERE), Advanced Manufacturing Office[45] (AMO), the Office of Electricity Delivery and Energy Reliability[46], and the Vehicle Technologies Program[47], are now also working to bring WBG devices closer to widespread adoption. As of February 2017, ARPA-E has awarded 57 projects related to power electronics, totaling almost $155 million in federal funding. Together, ARPA-E power electronics projects have published 141 peer reviewed technical papers that have been cited 2,204 times, and have been awarded 26 patents. Nine teams have cumulatively raised almost $386 million in publicly reported funding from the private sector to bring their technologies into commercial applications.

ARPA-E's focus is for transformational change within technology to bridge the gap between the laboratory and follow on funding from private investment companies. Often, follow on funding will come from other DOE Program Offices when the next phase of development still has some risk associated with it. For example, two programs associated with the EERE SunShot Initiative that include PV power electronics development to enhance energy efficiency are the 2011 program Solar Energy Grid Integration Systems - Advanced Concepts, $25.9M, and the 2015 program, Sustainable and Holistic Integration of Energy Storage and Solar PV (SHINES), $15M. Both program FOAs reference ARPA-E and its associated projects in the field of power electronics as influencing the aim and scope of the activities.

In 2014, the AMO set up Power America as a manufacturing innovation institute to accelerate the development of next generation of energy-efficient, high-power electronic devices using wide-bandgap semiconductor technologies. One of the active members Power America was X-FAB Inc. X-FAB has established a 150mm Silicon Carbide foundry line in Lubbock, Texas with the support from the PowerAmerica Institute. X-FAB's goal is to accelerate the commercialization of SiC power devices by leveraging the economies of scale that have been established in its silicon wafer fabrication line. In parallel, Monolith Semiconductors Inc., of Round Rock, Texas received funding from ARPA-E through the SWITCHES program to design their next generation SiC diodes and MOSFETs. By partnering with X-Fab Inc., they were able to establish a pathway to manufacture their devices adopting a "fab-less" production model. In March 2017, Littelfuse Inc., a leading manufacturer of electrical circuit protection equipment based in the USA, made an incremental $15M investment in Monolith Semiconductors Inc., which gave it a majority ownership position in the company.

In 2015, AMO launched the Next Generation Electric Machines: Megawatt Class Motors programs, and awarded $22M to five projects aimed at emerging WBG technologies focused on advancements in large-scale motor control to increase efficiency in high-energy consuming industries. Previous ARPA-E awardee GE is one of the award recipients in this program. To build capability in the field of WBG power electronics, AMO also launched a $6M program in 2015 to improve capability in the US workforce, the DOE Traineeship in Power Engineering; Leveraging Wide-Bandgap Power Electronics[48].

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44 "DARPA Sets Tough Goals For The Wide-Bandgap Community," *Compound Semiconductor*, November 8, 2002

45 Office of Energy Efficiency and Renewable Energy, Advanced Manufacturing Office, "Wide Bandgap Semiconductor for Clean Energy Workshop: Summary Report," (Washington, DC: U.S. Department of Energy, 2012)

46 Office of Energy Efficiency and Renewable Energy, Advanced Manufacturing Office, "Wide Bandgap Semiconductor for Clean Energy Workshop: Summary Report," (Washington, DC: U.S. Department of Energy, 2012)

47 Office of Energy Efficiency and Renewable Energy, Vehicle Technologies Program, *Multi-Year Program Plan 2011-2015,* December 2010 (Washington, DC: U.S. Department of Energy)

48 Conversations with P Gradzki of AMO and EERE website

CONCLUSIONS

Despite the remarkable advancements in WBG semiconductors, significant work still remains to realize the full potential of WBG materials in improving energy efficiency. As mentioned above, fundamental research into material properties and processing, and continued development up the power electronics value chain into circuits and systems, are vital steps in ensuring that America can maintain its technological lead in these promising materials, and reap the energy benefits through wide-ranging applications.

CHANGING WHAT'S POSSIBLE

APPENDIX: ARPA-E POWER ELECTRONICS PROJECTS

Table 1: ARPA-E Power Electronics Projects and Their Innovation Approaches

Program	Organization	Concept	Material	Device / Packaging	Module / System
Open 2009	Delphi Automotive Systems, LLC	Power converters using GaN-on-Si power transistor and double side cooling modules.	x	x	
Open 2009	Soraa, Inc.	2-inch GaN substrates wafers by ammonothermal for high quality, low cost.	x		
Open 2009	FastCAP Systems Corp.	Aligned carbon nanotubes ultracapacitors for increased efficiency and energy density	x		
ADEPT	Virginia Polytechnic Institute and State University	Small 3D chip integrating GaN-on-Si and high-frequency soft magnetic material for power conversion.		x	x
ADEPT	General Electric	Lower cost and size, vapor deposited magnetic films.	x		
ADEPT	HRL Laboratories, LLC	Low cost, lighter weight bidirectional EV charger using GaN based power transistors		x	x
ADEPT	Cree, Inc.	High voltage (15kV) SiC power transistors that are 50% more energy efficient.		x	
ADEPT	Teledyne Scientific & Imaging, LLC	Integrated single chip power converter for LEDs using iron magnetic alloys and GaN-on-Si devices.	x	x	x
ADEPT	Virginia Polytechnic Institute and State University	Efficient power converter integrating high-density capacitors, new magnetic materials, high-frequency integrated circuits, and a constant-flux transformer.	x	x	x
ADEPT	Georgia Tech Research Corporation	Utility-scale power router that uses an enhanced transformer to more efficiently direct power on the grid			x
ADEPT	GeneSiC Semiconductor	Unique SiC device structure for better performance		x	
ADEPT	Arkansas Power Electronics International, Inc.	10 times smaller EV charger using SiC based power transistors.		x	x
ADEPT	Massachusetts Institute of Technology	More efficient power circuits for LEDs using GaN-on-Si, new magnetic materials, and new circuit designs.	x	x	x
ADEPT	Georgia Tech Research Corporation	Compact power converters using low-cost stacked iron alloys as magnetic cores.	x		
ADEPT	Transphorm, Inc.	GaN-on-Si transistors for power converters		x	

Program	Organization	Concept	Material	Device / Packaging	Module / System
ADEPT	Case Western Reserve University	Smaller and lighter capacitors using titanium that can store 300% more energy.	x		
ADEPT	City University of New York (CUNY)	Lower cost, smaller, and more efficient power converters for LED lights using nanoscale material capacitors.	x	x	x
Solar ADEPT	Carnegie Mellon University	New nanoscale magnetic material for lower size, weight, and cost power conversion.	x		
Solar ADEPT	Cree, Inc.	Transformer-less power conversion device to directly connect solar power to the grid.			x
Solar ADEPT	University of Colorado, Boulder	Microconverters that can be integrated into individual solar panels.			x
Solar ADEPT	Transphorm, Inc.	Bidirectional GaN-on-Si transistors for more compact and reliable power converters.		x	
Solar ADEPT	SiCLAB, Rutgers University, NJ	Unique high voltage (15kV) SiC power transistors for better performance.		x	
Solar ADEPT	SolarBridge Technologies, Inc.	New power conversion technique to efficiently and cost-effectively improve the energy output of PV power plants.			x
Solar ADEPT	Ideal Power, Inc.	Bi-directional silicon power switches for reduced size, weight, and cost PV inverter.		x	x
Open 2012	Silicon Power Corporation	High-power and high-voltage optically triggered bi-directional SiC transistor switch.		x	
Open 2012	Rensselaer Polytechnic Institute	High-Voltage, Bi-Directional MOS-Grated SiC Power Switches for Smart Grid Utility Applications.		x	
Open 2012	RamGoss, Inc.	Innovative GaN device design for utility-scale electronic switches.	x	x	
Open 2012	Hexatech Inc.	High-voltage AlN devices for use in high-power electronics.	x	x	
Open 2012	Georgia Tech Research Corporation	Graphene based supercapacitor for increased energy density.	x		
Open 2012	General Electric	High Voltage, High Power Gas Tube Technology and Impact Assessment for HVDC Transmission.			x
SWITCHES	Columbia University	High-performance, low-cost vertical GaN devices thru smaller devices and GaN substrate re-use.	x	x	
SWITCHES	SixPoint Materials, Inc.	High-quality, low-cost GaN substrates produced via ammonothermal growth.	x		

Program	Organization	Concept	Material	Device / Packaging	Module / System
SWITCHES	Monolith Semiconductor, Inc.	Lower cost SiC manufacturing using existing low-cost, high-volume silicon manufacturing.		x	
SWITCHES	MicroLink Devices	High-performance, low-cost vertical GaN devices thru smaller devices and GaN substrate re-use.	x		
SWITCHES	Cornell University	Unique GaN device structure for significantly smaller size and higher performance.		x	
SWITCHES	Kyma Technologies, Inc.	High-rate large area GaN substrate growth	x		
SWITCHES	Michigan State University	High-voltage diamond devices for use in high-power electronics.	x	x	
SWITCHES	Avogy, Inc.	High yielding vertical GaN transistor for lower cost.		x	
SWITCHES	Arizona State University	Low-cost, vertical, diamond bipolar device for use in high-power electronics.	x	x	
SWITCHES	iBeam Materials, Inc.	Low-cost GaN LEDs on flexible metal foils.	x	x	
SWITCHES	Soraa, Inc.	Follow-on to OPEN2009 project. Large-area, high-quality, low cost GaN substrates	x		
SWITCHES	HRL Laboratories, LLC	High-performance, low-cost vertical GaN devices at higher power levels than lateral devices.		x	
SWITCHES	Fairfield Crystal Technology, LLC	Unique high-rate GaN boule growth for lower cost GaN wafers.	x		
SWITCHES	University of California, Santa Barbara	High-performance, low-cost vertical GaN devices at higher power levels than lateral devices.		x	
Open 2015	General Electric	High-voltage, solid-state SiC field-effect transistor charge-balanced device.		x	
Open 2015	Tibbar Technologies	Plasma-based 3-phase AC to DC converter.			x
IDEAS	GeneSiC Semiconductor	High-power and voltage vertical GaN bipolar junction transistor.		x	
IDEAS	University of Nebraska, Lincoln	Electromagnetic induction-based static power converter for efficient low cost AC to AC electrical conversions.			x
IDEAS	Northeastern University	Innovative universal power converter using SiC based devices for decreased size.			x
IDEAS	Quora Technology, Inc.	Reliable, high-power and voltage, innovative lateral GaN transistor.		x	

Program	Organization	Concept	Material	Device / Packaging	Module / System
IDEAS	Sandia National Laboratory	High-voltage, high-power density, hybrid switched-capacitor DC-DC power converter using SiC and vertical GaN devices.			x
IDEAS	University of Colorado, Boulder	Capacitive wireless power transfer architecture to dynamically charge EVs.			x
IDEAS	Sandia National Laboratory	MVDC/HVDC Power Conversion with Optically-Controlled GaN Switches.		x	x
IDEAS	Harvard University	Transistor-less Power Supply Technology Based on UWBG Nonlinear Transmission Line.			x
PNDIODES	Adriot Materals Inc.	Selective Area Doping for Nitride Power Devices.	x		
PNDIODES	Arizona State University	Effectuve selective area doping for GaN Vertical Power Transistors Enabled by Innovative Materials Engineering.	x		
PNDIODES	JR2J	Laser spike anneal technology for the activation of implanted dopants in Gallium Nitride.	x		
PNDIODES	Sandia National Laboratory	High voltage re-grown GaN P-N Diodes enabled by defect and doping control.	x		
PNDIODES	The Research Foundation for State University of New York	Demonstration of PN-junctions by implant and growth techniques for GaN.	x		
PNDIODES	University of Missouri	High quality GaN FETs through transmutation doping and low temperature processing.	x		
PNDIODES	Yale University	Regrwoth and selective area growth of GaN for vertical power electronics.	x		

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