SWITCHES Program Overview

B. TECHNICAL PROGRAM OVERVIEW

This program seeks to fund transformational advances in wide bandgap (WBG) materials, device fabrication, and device architectures. The goal of this program is to enable the development of high voltage (1200V+), high current (100A) single die power semiconductor devices that, upon ultimately reaching scale, would have the potential to reach functional cost parity with silicon power transistors while also offering breakthrough relative circuit performance (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.

C. BACKGROUND

Electricity accounted for 40% of primary energy consumption in the United States in 2011.[1] Power electronics are projected to play a significant and growing role in the delivery of this electricity. It has been estimated that as much as 80% of electricity could pass through power electronics between generation and consumption by 2030.[2] (30% of electrical energy passes through power electronics converters today.) Technical advances in power electronics promise enormous energy efficiency gains throughout the United States economy.[3] Examples of these potential benefits include:

> **Motor Drives:** Electric motors account for over 38% of U.S. electricity consumption.[4] Replacing on/off control or throttling valves with variable frequency drives in industrial pumps and HVAC systems would result in energy savings of up to 65%.[5] Their widespread adoption, enabled by low cost high performance power electronics could yield up to a 20% reduction in U.S. electricity consumption.[6,7]
>
> **Automotive:** The electrification of vehicles could substantially increase transportation energy efficiency, reduce U.S. oil imports, and mitigate greenhouse gas (GHG) emissions.[8] High costs have thus far prevented these vehicles from gaining widespread adoption. While batteries are the dominant factor in powertrain cost, the limitations of current power electronic systems for both battery charging and traction drive inverters also play an important role. Advances in power electronics promise to substantially reduce the weight and additional cost of the electrification of vehicles.[9]
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> **Electric Power Generation:** Power converters are required to connect solar photovoltaics and wind turbines to the electric grid.[10] Advances in power electronics have potential to reduce inverter losses by over 50% while also

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[1] U.S. Energy Information Administration, *Annual Energy Review 2011* (Washington, DC: U.S. Department of Energy, 2012), http://www.eia.gov/totalenergy/data/annual/index.cfm
[2] 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)
[3] "SiC and GaN electronics: Where, when and how big?" *Compound Semiconductor*, July 27, 2012, http://www.compoundsemiconductor.net/csc/features-details.php?cat=features&id=19735293
[4] P. Waide and C. Brunner, "Energy-Efficiency Policy Opportunities for Electric Motor-Driven Systems." (Paris, France: International Energy Agency, 2011), http://www.iea.org/publications/freepublications/publication/EE_for_ElectricSystems.pdf
[5] Consortium for Energy Efficiency, *Motor Efficiency, Selection, and Management: A Guidebook for Efficiency Programs* (Boston, MA: Consortium for Energy Efficiency, 2011), http://library.cee1.org/sites/default/files/library/9322/CEEMotorGuidebook_2.pdf
[6] M. A. Briere, "GaN on Si Based Power Devices: An Opportunity to Significantly Impact Global Energy Consumption," Paper presented at CS MANTECH Conference, Portland, OR, May 2010, http://www.csmantech.org/Digests/2010/Papers/13.1.066.pdf
[7] M. Lowe, R. Golini, and G. Gereffi, "U.S. Adoption of High-Efficiency Motors and Drives: Lessons Learned," (Center on Globalization, Governance and Competitiveness, Duke University, 2010), http://www.cggc.duke.edu/pdfs/CGGC-Motor_and_Drives_Report_Feb_25_2010.pdf
[8] Office of Energy Efficiency and Renewable Energy, Vehicle Technologies Program, *DOE Vehicle Technologies Multi-Year Program Plan 2011-2015* (Washington, DC: U.S. Department of Energy, 2010), http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/vt_mypp_2011-2015.pdf
[9] Experian Automotive, "Hybrid vehicle market share grew by 41 percent in 2012," news release, April 22, 2013, http://press.experian.com/United-States/Press-Release/experian-automotive-hybrid-vehicle-market-share-grew-by-41-percent-in-2012.aspx
[10] Office of Energy Efficiency and Renewable Energy, Sunshot Initiative, "Sunshot Vision Study," February 2012. (Washington, D.C.: U.S. Department of Energy), http://www1.eere.energy.gov/solar/pdfs/47927.pdf

enabling reductions in cost, weight, and volume.[11] These advances could accelerate the adoption of these new sources of generation, with their commensurate reductions in emissions.

Electric Power Transmission: Congestion of electric transmission networks and the challenges associated with variable power generation (wind and solar) can be mitigated with embedded power electronics-based power flow controllers.

Achieving high power conversion efficiency in these systems requires low-loss power semiconductor switches. Today's incumbent power semiconductor switch technology is silicon (Si) based MOSFETs, IGBTs and thyristors. Silicon power semiconductor devices have several important limitations:

(1) 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 thickness. The large thickness translates to devices with high resistance and associated conduction losses.
(2) 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.
(3) 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.

New opportunities for higher efficiency have emerged with the development of wide bandgap (WBG) power semiconductor devices. Table 1 compares several different WBG device materials relative to Si. WBG semiconductor-based devices are capable of low-loss operation at high voltages (> 1 kV to tens of kV), high frequencies (tens of kHz to tens of GHz), and high temperatures (>150^{o}C). Power converters based on WBG devices can achieve both higher efficiency and higher gravimetric and volumetric power conversion densities. For example, in a recent demonstration, a 2kW motor driven by high frequency GaN devices resulted in an increase in efficiency of over 2% at full load and 8% at low load relative to the same motor being driven by Si IGBTs.[12]

Table 1: Power Semiconductor Material Properties[13,14,15]

		Si	4H-SiC	GaN (2 DEG)	GaN (Bulk)	Diamond
Bandgap	**Eg (eV)**	1.1	3.26	3.39	3.39	5.45
Electron Concentration	**n_i (cm^{-3})**	1.5×10^{10}	8.2×10^{-9}	1.9×10^{-10}	1.9×10^{-10}	1.6×10^{-27}
Electron Mobility (low)	**μ_n (cm^2/V s)**	1350	700	1000	500	1900
Electron Mobility (high)	**μ_n (cm^2/V s)**	1450	950	2000	1200	4000

[11] H Zhang and LM Tolbert , "Efficiency Impact of Silicon Carbide Power Electronics for Modern Wind Turbine Full Scale Frequency Converter," *IEEE Transactions on Industrial Electronics* 58, no. 1 (2011): 21-28, doi: 10.1109/TIE.2010.2048292

[12] Y-F. Wu et al., "High-Frequency, GaN Diode-Free Motor Drive Inverter with Pure Sine Wave Output," *Power Transmission Engineering*, October 2012, 40-43, http://www.powertransmission.com/issues/1012/motor_drive_inverter.pdf
[13] U.K. Mishra, L. Shen, T.E. Kazior, and Y-F. Wu, "GaN-Based RF Power Devices and Amplifiers," *Proceedings of the IEEE* 96, no. 3 (2008): 287-305, doi: 10.1109/JPROC.2007.911060
[14] F. Morancho, "State of the art and trends in power semiconductor devices for optimized power management," Presentation at 40th Anniversary Meeting of LAAS-CNRS, Toulouse, France, October 2008, http://www.laas.fr/files/LAAS/40ans_LAAS-CNRS_A5-Morancho.pdf
[15] C. Mion et al., "Accurate dependence of gallium nitride thermal conductivity on dislocation density," *Applied Physics Letters* 89, 092123 (2006), doi: 10.1063/1.2335972

Electron Saturation Velocity	**v_{sat} (10^7cm/s)**	1	2	2.5	2.5	2.7
Breakdown Electric Field	**E_{br} (MV/cm)**	0.3	3	3.3	3.3	5.6
Thermal Conductivity	**k (W/cm °K)**	1.5	4.9	1.3	2.3	20
Maximum Operating Temperature	**T_{max} (°C)**	175	500	650	650	700

Substantial technical progress has been made on WBG-based power switches over the past decade. Substantial investments from the Department of Defense[16] and several DOE offices, including the Advanced Manufacturing Office,[17] the Office of Electricity Delivery and Energy Reliability,[18] and the Vehicle Technologies Program,[19] have helped build early U.S. leadership and bring WBG devices closer to widespread adoption. ARPA-E's Agile Delivery of Electrical Power Technologies (ADEPT) program, initiated in 2010, funded several teams to develop new devices and demonstrate their efficacy in system demonstrations.[20] The ADEPT program focused on transformational power electronics advances in a wide range of high efficiency power conversion systems. These include fully-integrated, chip-scale power converters for dimmable solid state lighting drivers and computer power supplies; package integrated power converters for automotive and industrial applications; and medium voltage converters for utility grid applications. Several ADEPT projects focused on WBG devices. For example, several program teams have recently demonstrated enhancement-mode (normally off), 600V+ GaN-on-Si High Electron Mobility Transistors (HEMTs).[21] SiC diodes with 10 kV rating and IGBT's with blocking voltages exceeding 15kV have also been demonstrated.[22,23]

SiC and GaN have also made important commercial progress over the past decade with 1200 V SiC devices[24] and 600 V GaN[25] devices now qualified and commercially available. However, SiC and GaN device technology remains relatively immature relative to Si and currently carry a substantial cost premium, limiting their widespread adoption.[26] The state of technology is such that 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.[27,28,29] Cost for an equivalent functional performance remains a major barrier to the

[16] "DARPA Sets Tough Goals For The Wide-Bandgap Community," *Compound Semiconductor*, November 8, 2002, http://compoundsemiconductor.net/csc/features-details.php?id=11332

[17] 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), http://www1.eere.energy.gov/manufacturing/rd/pdfs/wbg_2012_workshop_summary_report.pdf

[18] Office of Electricity Delivery and Energy Reliability, *Power Electronics Research and Development Program Plan,* April 2011 (Washington, DC: U.S. Department of Energy), http://energy.gov/sites/prod/files/oeprod/DocumentsandMedia/OE_Power_Electronics_Program_Plan_April_2011.pdf

[19] 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), http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/vt_mypp_2011-2015.pdf

[20] "Agile Delivery of Electrical Power Technologies," ARPA-E, U.S. Department of Energy, accessed June 2, 2013, http://arpa-e.energy.gov/?q=arpa-e-programs/adept

[21] B. Hughes et al., "GaN HFET switching characteristics at 350V/20A and synchronous boost converter performance at 1MHz." Paper presented at Twenty-Seventh Annual IEEE Applied Power Electronics Conference and Exposition (APEC), Orlando, FL, February 2012, doi: 10.1109/APEC.2012.6166174

[22] "High Temperature SiC Bare Die," GeneSiC Semiconductor, accessed June 6, 2013, http://www.genesicsemi.com/index.php/hit-sic/baredie

[23] S.H. Ryu et al., "15 kV IGBTs in 4H-SiC," *Materials Science Forum* 740-742 (2013): 954-957, doi: 10.4028/www.scientific.net/MSF.740-742.954

[24] Cree, "Cree Announces Volume Production of Second-Generation SiC MOSFET, Bringing Significant Cost Savings to Power-Conversion Systems," news release, March 13, 2013, http://www.cree.com/news-and-events/cree-news/press-releases/2013/march/2nd-gen-mosfet

[25] Transphorm Inc., "Transphorm Releases First JEDEC-Qualified 600 Volt GaN on Silicon Power Devices," news release, March 14, 2013, http://www.transphormusa.com/news/transphorm-releases-first-jedec-qualified-600-volt-gan-silicon-power-devices

[26] R. Eden, "Market Forecasts for Silicon Carbide & Gallium Nitride Power Semiconductors," Presentation at 2013 Applied Power Electronics Conference and Exposition, Long Beach, CA, March 2013, http://www.apec-conf.org/images/PDF/2013/Industry_Sessions/is1.4.2.pdf

[27] "Railway Inverter with Hybrid SiC Power Module," *Power Electronics Europe*, October 5, 2012

[28] M. Lowe, R. Golini, and G. Gereffi, "U.S. Adoption of High-Efficiency Motors and Drives: Lessons Learned," (Center on Globalization, Governance and Competitiveness, Duke University, 2010), http://www.cggc.duke.edu/pdfs/CGGC-Motor_and_Drives_Report_Feb_25_2010.pdf

[29] K. Boutros, R. Chu, and B. Hughes, "GaN power electronics for automotive application." Paper presented at 2012 IEEE Energytech, Cleveland, OH, May 2012, doi: 10.1109/EnergyTech.2012.6304646

widespread adoption of WBG devices, despite opportunities for superior performance (including reductions in system costs).[30] WBG devices will have to approach functional cost parity with Si power devices to gain widespread adoption.

In addition to high cost, most WBG discrete devices demonstrated to date have had relatively low current ratings. Traction, industrial, and grid applications advantage devices with high current ratings (>100 A) because implementation of low amperage devices in parallel increases power system complexity and cost.

As viable devices become commercially available and device maturity increases, WBG device costs are expected to fall over the next several years.[31,32] Device manufacturers are continuing to reduce defect densities (enabling higher device yields) and also have plans to migrate to larger substrates as demand increases. However, despite these improvements, existing WBG fabrication processes and device architectures make it difficult for the devices to achieve functional cost parity with silicon-based devices as well as achieve the high current ratings that are needed in high power applications. In particular, lateral high electron mobility transistor (HEMT) devices (the dominant GaN device architecture today) suffer from relatively low current densities relative to die size, which limits the ability to cost effectively scale lateral device topologies to high current ratings.

D. TECHNICAL PROGRAM OBJECTIVES

This program seeks to fund transformational advances in WBG materials, device fabrication and device architectures. The goal of this program is to enable the development of high voltage (1200V+), high current (100A) power semiconductor devices that, upon reaching scale, have the potential to reach functional cost parity with silicon power semiconductor devices on a $/A basis, while also offering breakthrough relative performance (low losses, high switching frequencies, and high temperature operation). These transformational technologies promise to reduce the barriers to ubiquitous deployment of low-loss wide bandgap power semiconductor devices in stationary and transportation applications.

Recent research results indicate that new materials advances, device architectures, and device fabrication processes could substantially accelerate progress towards WBG devices that achieve both higher current ratings and functional cost parity with silicon-based devices, thus gaining ubiquitous deployment.[33,34,35] These approaches have, as of yet, received relatively little attention from industry and the research community since they are perceived to be technically unproven and high risk.

Vertical device architectures for GaN power semiconductor transistors, for example, could substantially reduce cost and increase current densities (relative to die size). The dominant GaN device architecture today is the High Electron Mobility Transistor (HEMT) heterostructure depicted in Figure 1(a). For this structure, the source, drain, and gate terminals are all located on the surface of the device. Current flows laterally through a 2D Electron Gas (2DEG) that forms at the GaN/AlGaN heterojunction interface. The high electron mobility that is achieved in a 2DEG makes this device architecture appealing. GaN based HEMTs are particularly attractive as the free-carrier concentration in the 2DEG channel is formed by strain induced and spontaneous polarization, shifting the Fermi-level above the conduction band without the presence of mobility limiting extrinsic dopants. This device architecture has also received substantial attention due to the ability to be fabricated on GaN layers deposited heteroepitaxially on low cost silicon substrates.

However, the lateral GaN HEMT device architecture has two key limitations. First, since all three contacts are located on the top surface of the devices, high-voltage devices require careful management of electric field profiles in the lateral dimension between contacts, particularly in high voltage applications. Substantial gate/drain lateral spacing must be

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[30] R. Eden, "Market Forecasts for Silicon Carbide & Gallium Nitride Power Semiconductors," Presentation at 2013 Applied Power Electronics Conference and Exposition, Long Beach, CA, March 2013, http://www.apec-conf.org/images/PDF/2013/Industry_Sessions/is1.4.2.pdf

[31] R. Eden, "Market Forecasts for Silicon Carbide & Gallium Nitride Power Semiconductors," Presentation at 2013 Applied Power Electronics Conference and Exposition, Long Beach, CA, March 2013, http://www.apec-conf.org/images/PDF/2013/Industry_Sessions/is1.4.2.pdf

[32] "GaN power electronics market may top $1bn in a few years," *Semiconductor Today*, March 8, 2012, http://www.semiconductor-today.com/news_items/2012/MAR/YOLE_080312.html

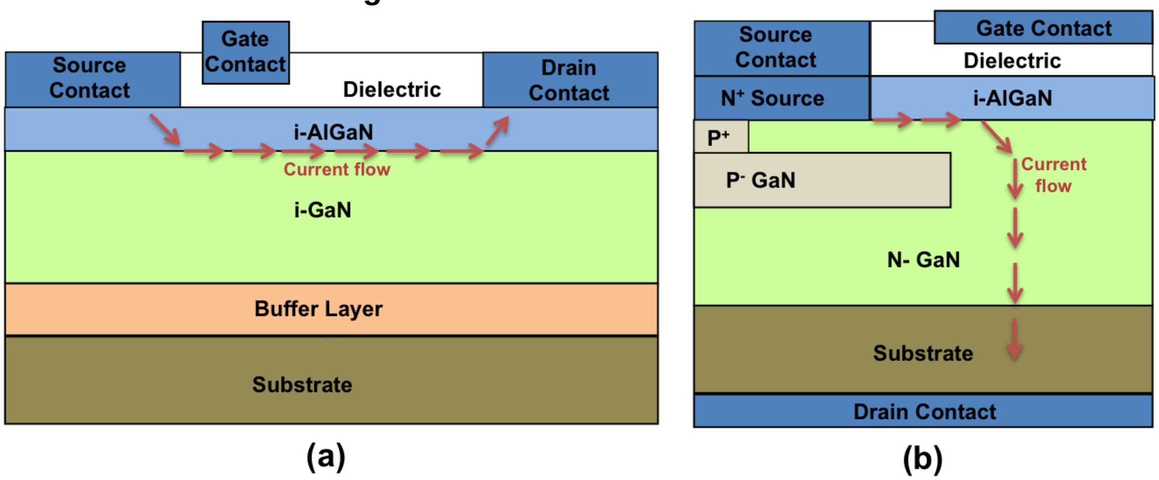
[33] S. Chowdhury et al., "CAVET on Bulk GaN Substrates Achieved With MBE-Regrown AlGaN/GaN Layers to Suppress Dispersion," *IEEE Electron Device Letters* 33, no. 1 (2012): 41-43, doi: 10.1109/LED.2011.2173456

[34] R. Yeluri et al., "Demonstration of Low ON-Resistance CAVETS with Ammonia MBE Grown Active p-GaN Layer as the Current Blocking Layer for High Power Applications." Paper presented at The Pacific Rim Meeting on Electrochemical and Solid-State Science, Honolulu, HI, October 2012, http://ma.ecsdl.org/content/MA2012-02/30/2531.short

[35] I.C. Kizilyalli et al. "Vertical Devices In Bulk GaN Drive Diode Performance To Near-Theoretical Limits," *How2Power Today*, March 2013, http://www.how2power.com/newsletters/1303/articles/H2PToday1303_design_Avogy.pdf

maintained to allow for high breakdown voltages. This requirement substantially reduces the effective current density (relative to die size) that can be achieved in these devices and also leads to a reduction in effective current density as breakdown voltage is increased. Low current densities drive down the number of die that can be fabricated on each wafer as voltage ratings increase, thus increasing the cost for a given amperage rating. Second, thermal management is complicated by the fact that all current flow is confined to a relatively thin portion of the device near the top surface. Joule heating related to device losses must be dissipated across the thickness of the substrate, motivating research into advanced wafer thinning or complicated thermal spreading approaches to device assembly.

Figure 1: GaN Device Structures



In contrast, vertical GaN device architectures as illustrated in Figure 1(b), could overcome these limitations.[36] Vertical device structures for GaN have, thus far, received relatively little attention in the research community but have been recognized as a necessary eventual device architecture for use in high power automotive applications.[37,38,39,40,41,42,43] In these devices, high electric fields occur between contacts on the bottom and top of the structure in the vertical dimension only. As with vertical FET and IGBT technologies in silicon, it is expected that vertical devices will be able to achieve higher effective current densities and will enable improved thermal management.[44] Recent demonstrations of high-voltage vertical structure GaN devices appear very promising.[45,46,47]

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[36] M. Su et al., "Challenges in the Automotive Application of GaN Power Switching Devices," Paper presented at CS MANTECH Conference, Boston, MA, April 2012, http://gaasmantech.com/Digests/2012/papers/10a.3.077.pdf
[37] T. Uesugi and T. Kachi, "Which are the Future GaN Power Devices for Automotive Applications, Lateral Structures or Vertical Structures?," Paper presented at CS MANTECH Conference, Palm Springs, CA, May 2011, http://gaasmantech.com/Digests/2011/papers/12b.2.pdf
[38] Tsutomu Uesugi and Tetsu Kachi, "GaN Power Switching Devices for Automotive Applications," Paper presented at CS MANTECH Conference, Tampa, FL, May 2009, http://mantech.org/Digests/2009/2009 Papers/2.1.pdf
[39] M.Kanechika et al., "A Vertical Insulated Gate AlGaN/GaN Heterojunction Field-Effect Transistor," *Japanese Journal of Applied Physics* 46, no. 21 (2007): L503-L505, doi: 10.1143/JJAP.46.L503
[40] M. Sugimoto et al., Nitride semiconductor device and method of manufacturing the same. U.S. Patent Application 20110316049, filed March 2, 2009, published December 29, 2011
[41] H. Ueda et al., "Wide-Bandgap Semiconductor Devices for Automobile Applications," Paper presented at CS MANTECH Conference, Vancouver, BC, Canada, April 2006, http://csmantech.pairserver.com/Digests/2006/2006 Digests/3A.pdf
[42] T. Kachi, D. Kikuta, and T. Uesugi, "GaN power device and reliability for automotive applications," Paper presented at 2012 IEEE International Reliability Physics Symposium (IRPS), Anaheim, CA, April 2012, doi: 10.1109/IRPS.2012.6241815
[43] M. Su et al., "Challenges in the Automotive Application of GaN Power Switching Devices," Paper presented at the CS MANTECH Conference, Boston, MA, April 2012, http://gaasmantech.com/Digests/2012/papers/10a.3.077.pdf
[44] S. Sze, *Physics of Semiconductor Devices* (Wiley-Interscience, 1981)
[45] I.C. Kizilyalli et al. "Vertical Devices In Bulk GaN Drive Diode Performance To Near-Theoretical Limits," *How2Power Today*, March 2013, http://www.how2power.com/newsletters/1303/articles/H2PToday1303_design_Avogy.pdf
[46] A. Bindra "As Applications Emerge, SiC Technology Charts A Growth Path," *How2Power Today*, May 2013, http://www.how2power.com/newsletters/1305/H2PowerToday1305_Semiconductors.pdf
[47] R.P. Tompkins et al., "GaN Power Schottky Diodes," Paper presented at the 2012 Electrochemical Society Meeting, Seattle, WA, May 2012, http://ma.ecsdl.org/content/MA2012-01/22/909.full.pdf

Among wide bandgap semiconductors, SiC devices today already demonstrate[48] a vertical device structure, and dies with >100A current ratings are now commercially available.[49] However, SiC device design remains challenging, die sizes are relatively large, and prices remain high. Most commercial devices today are majority carrier devices. While these devices switch substantially faster than silicon-based devices and are starting to gain commercial traction, they currently operate far from the theoretical limits for SiC. This is primarily due to a high density of interface states close to the conduction band edge introduced by the silicon dioxide gate in these devices.[50] These interface states lead to degradation of channel mobility by an order of magnitude[51] and decreased device switching speed. Also, the high electric field near the gate oxide in SiC MOSFETs prevents the devices from taking full advantage of the breakdown field strength of SiC.[52]

There have also been efforts on minority carrier SiC devices. While few minority carrier devices with insulated gates have been attempted, they would also likely suffer from degraded mobility due to interface states. Some silicon carbide minority carrier devices avoid using an insulated gate, but still require large charge injection[53] at turn-on and suffer from reduced current gain at elevated temperatures.[54] High current density operation in minority carrier devices can also be hindered by forward voltage degradation due to stacking fault defects,[55] which reduce the useful area of a die and may result in non-uniform current flow, localized overheating, and premature failures.

Finally, SiC device designs today typically require a high temperature anneal during implant activation.[56] This process step requires fabrication equipment that is not generally available in legacy (silicon) device fabrication facilities, increasing device fabrication costs. Device designs compatible entirely with silicon fabrication facilities (except epitaxial growth) could be an important pathway to lower costs.

There are several classes of unmet technological and scientific challenges that need to be solved in order to achieve high voltage, high current WBG devices, on a pathway to widespread adoption in power switches:

(1) Device Structures and Fabrication Processes: New WBG device structures that are compatible with higher current ratings and low cost are needed. Device architectures that allow higher current densities such as vertical GaN devices appear promising. Fabrication process improvements are also needed. Improved approaches to fabricating buried p-type layers or improvements in metal-semiconductor contact formation on N-polar or semi-polar GaN crystal orientations are also needed. Device designs that are compatible with lower cost fabrications processes, such as those that allow the use of legacy silicon device fabrication facilities could also be transformational and disruptive. Device structures minimizing mask count could also reduce costs. Device structures that reduce thermal management challenges could also be important. Finally, high voltage devices require relatively thick films of high quality (low defect) WBG materials. New approaches to growing WBG materials at higher speeds are needed.[57,58]

(2) Substrates: In support of the device architectures above, new substrate crystal growth, wafering and fabrication processes may be needed. Bulk GaN substrates with high quality material, required for many vertical device concepts, are currently limited to small sizes and are very costly to produce. High quality bulk GaN substrates with low defect densities are critical, as it has been shown that thermal conductivity of GaN is strongly

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[48] L. Cheng, et al., "High Performance, Large-Area, 1600 V / 150 A, 4H-SiC DMOSFET for Robust High-Power and High-Temperature Applications," Paper presented at the 25th International Symposium on Power Semiconductor Devices and ICs (ISPSD 2013) Kanazawa, Japan, May 2013.
[49] Cree, "Cree Announces Volume Production of Second-Generation SiC MOSFET, Bringing Significant Cost Savings to Power-Conversion Systems," news release, March 13, 2013, http://www.cree.com/news-and-events/cree-news/press-releases/2013/march/2nd-gen-mosfet
[50] R. Singh, "High Power SiC Pin Rectifiers" in *SiC Materials And Devices,* eds. M.Shur et al. (Singapore: World Scientific Publishing, 2006).
[51] A.F. Frazzetto et al., "Limiting mechanism of inversion channel mobility in Al-implanted lateral 4H-SiC metal-oxide semiconductor field-effect transistors," *Applied Physics Letters* 99, 072117 (2011). doi: 10.1063/1.3627186
[52] A. Agarwal,et al., "Temperature dependence of Fowler-Nordheim current in 6H-and 4H-SiC MOS capacitors," *IEEE Electron Device Letters* 18, no. 12 (1997): 592-594, doi: 10.1109/55.644081
[53] GeneSiC Semiconductor, GA06JT12-247 Datasheet, accessed June 6, 2013, http://www.genesicsemi.com/images/products_sic/sjt/GA06JT12-247.pdf
[54] R. Singh, et al., "1200 V-class 4H-SiC "Super" Junction Transistors with Current Gains of 88 and Ultra-fast Switching capability," *Materials Science Forum* 717 (2012): 1127-1130
[55] R.E. Stahlbush et al., "Effect of Stacking Faults Originating from Half Loop Arrays on Electrical Behavior of 10 kV 4H-SiC PiN Diodes," *Materials Science Forum* 387, (2012): 717-720, http://www.scientific.net/MSF.717-720.387
[56] S. Haney et al., "The effects of implant activation anneal on the effective inversion layer mobility of 4H-SiC MOSFETs," *Journal of Electronic Materials* 37, no. 5 (2008): 666-671, http://link.springer.com/article/10.1007/s11664-007-0310-6
[57] T. Rana, "Elimination of silicon gas phase nucleation using tetrafluorosilane (SiF4) precursor for high quality thick silicon carbide (SiC) homoepitaxy." *physica status solidi* (a) 209, no. 12 (2012): 2455-2462. http://onlinelibrary.wiley.com/doi/10.1002/pssa.201228319/full
[58] D. Miller, "Gallium Nitride Epitaxy by a Novel Hybrid VPE Technique,"(PhD diss., Stanford University, 2011)

dependent on material quality.[59] New chemistries for epitaxial growth or substrate refining techniques appear to have substantial potential.[60] Many substrates have small domain structure unsuitable for large area power devices. New approaches to fabricating bulk substrates could be an important pathway to achieving high current low cost devices.[61,62,63,64] The III-V photovoltaics community has also recently demonstrated how epitaxial liftoff and substrate reuse can be used to achieve substantially lower cost devices despite high substrate costs.[65] These same concepts could find application in wide bandgap power semiconductor devices.

E. TECHNICAL AREAS OF INTEREST

This program is focused on supporting the development of breakthrough solutions in WBG power electronics that enable high single die current ratings and the potential to reach functional cost parity with silicon-based power semiconductor devices. Research and development projects that address the Primary and Secondary Technical Targets described in Section I.F of the FOA are encouraged. ARPA-E is most interested in applications that provide a well-justified, realistic potential of meeting or exceeding all of the Primary and Secondary Technical Targets.

The following technical areas are of particular interest to this FOA:

- Wide bandgap power semiconductor devices utilizing novel fabrication processes or device structures not previously supported by ARPA-E, other governmental agencies or previously developed for commercial application; such technologies might include vertical GaN device structures, approaches to device fabrication that are compatible with substrate re-use (i.e. device liftoff), and novel structures compatible with far lower cost fabrication processes and high die current ratings. New approaches to fast, high quality thick film epitaxial growth that enables rapid fabrication of high voltage devices are also of interest.

- Investigation of technologies with the potential to enable extremely low cost and highly scalable free standing wide bandgap substrate fabrication. Such technologies might include, but are not limited to, new GaN, ZnO, SnO_2, sapphire, or other wide bandgap substrate growth techniques. Approaches that enable larger substrate sizes and substantially reduced defect densities are required. These may include advances in new chemistries for epitaxial growth or substrate refining techniques.

Researchers who might be working on sub-system materials or component level innovations are highly encouraged to partner with device designers and manufacturers as a means of evaluating device level functionality resulting from breakthroughs in the proposed effort.

F. TECHNICAL PERFORMANCE TARGETS

This FOA focuses on devices with high voltage and current ratings based on WBG semiconductor materials, device fabrication processes, and device architectures that could enable functional cost parity with conventional Si-based switches. The vision for ubiquitous wide bandgap power semiconductor device deployment is based on these devices reaching functional cost parity with today's dominant power semiconductor switch technology in high power applications: Silicon IGBTs. Table 2 lists the Primary Technical Targets for this FOA while Table 3 lists Secondary Technical Targets.

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[59] C. Mion et al., "Accurate dependence of gallium nitride thermal conductivity on dislocation density," *Applied Physics Letters* 89, 092123 (2006), doi: 10.1063/1.2335972

[60] T. Rana, et al.,"Comparison of 4H Silicon Carbide Epitaxial Growths at Various Growth Pressures Using Dicholorosilane and Silane Gases." *Materials Science Forum* 717 (2012): 117-120, http://www.scientific.net/MSF.717-720.117.

[61] T.J. Baker et al. "Technique for the Growth of Planar Semi-Polar Gallium Nitride." U.S. Patent 8,128,756, filed February 1, 2010, and issued March 6, 2012

[62] J. Bai et al. "Efficient Reduction of Defects in (1120) Non-Polar and (1122) Semi-polar GaN Grown on Nanorod Templates," *Applied Physics Letters* 102 (2013): 101906, doi: 10.1063/1.4795619

[63] D. Ehrentraut, E. Meissner, and M. Bockowski. eds., *Technology of Gallium Nitride Crystal Growth* (Springer-Verlag Berlin Heidelberg, 2010)

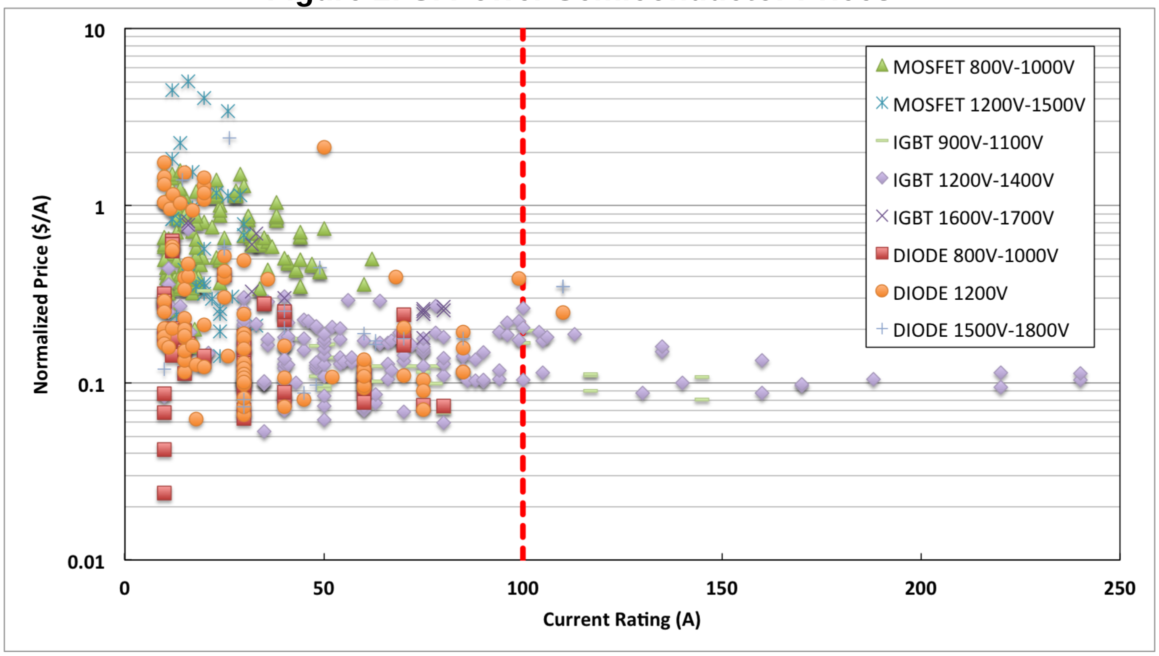
[64] Q. Sun and J. Han, "Heteroepitaxy of Nonpolar and Semipolar GaN." In *GaN and ZnO-based Materials and Devices*, ed. S. Pearton (Springer-Verlag Berlin Heidelberg, 2012), 1-27, http://www.springer.com/cda/content/document/cda_downloaddocument/9783642235207-c1.pdf?SGWID=0-0-45-1268759-p174192762

[65] K. Lee et al, "Reuse of GaAs Substrates for Epitaxial Lift-off by Employing Protection Layers," *Journal of Applied Physics* 111 (2012): 033527, doi: 10.1063/1.3684555

Figure 2 plots the price ($/A) of existing high-voltage silicon power semiconductor devices using data from the electronic components distributor Digi-Key (http://www.digikey.com/).[66] All in stock devices with relevant ratings and pricing information readily available on the Digi-Key website as of late May 2013 are included in the figure. Variability in this plot is associated primarily with different package technologies and the different applications that are targeted by each particular device. This plot indicates that 1200V, 100A devices are typically priced between $0.10/A and $0.20/A today. Si device costs are expected to continue to fall incrementally over the next decade. Based on these data, it is expected that WBG devices achieving costs of below $0.10/A (Primary Technical Target 1.1) would represent a functionally cost equivalent technology, with potential advantages of WBG devices.

The superior performance of WBG devices, relative to the Si switches they are replacing, will allow them to gain adoption in many applications before reaching functional cost parity. However, truly widespread adoption in high power, conservative, cost conscious applications such as industrial motors and automotive applications may require functional cost parity for the devices themselves.

Figure 2: Si Power Semiconductor Prices



With regard to Primary Technical Target 1.1, all Applicants must justify how the proposed technology holds promise to meet this FOA's $0.10/A device cost target. While ARPA-E understands that some Applicants may not have access to sophisticated power semiconductor device manufacturing cost modeling tools, ARPA-E expects that all Applicants will make a strong effort to present an adequate justification. The cost target is intended to be a forward looking consideration of device costs, including packaging, assuming successful technology development and subsequent scaling of manufacturing for ubiquitous deployment. Applicants should describe all assumptions related to the scale that would be needed to achieve $0.10/A. In addition, ARPA-E expects selected applicants will revise cost-models through the course of the proposed effort, reflecting technical advances achieved during the work and demonstrating how increased scientific understanding provides a pathway to ultimately achieving cost targets in the program.

Primary Technical Targets 1.2 – 1.6 describe device characteristics that should be demonstrated experimentally in a single device by the end of the project period. These targets are consistent with the characteristics of devices that are required in high power applications, including many motor drive systems and in electric vehicles. Primary Technical Target 1.7 is a requirement to demonstrate that devices designed and fabricated under this program are suitable for high

[66] This figure is based on ARPA-E analysis of Digi-Key (http://www.digikey.com/) data. By using data provided by Digi-Key, ARPA-E does not endorse Digi-Key as a vendor, nor does it make any warranty (express or implied) or assume any liability or responsibility for the accuracy, completeness, or usefulness of the data provided by Digi-Key. Applicants may refer to similar data provided by other distributors of electronic components, including but not limited to Newark (www.newark.com) and Mouser (www.mouser.com).

frequency switching applications. Appropriate thermal management of devices will be critical to successfully meeting this technical target. Devices achieving all of the primary technical targets will be relevant for a wide range of applications.

TABLE 2: PRIMARY TECHNICAL TARGETS

ID	Category	Value
1.1	Discrete Device Cost (Packaged)	<= $0.10 /A
1.2	Drain-Source Breakdown Voltage	>= 1200 V (V_{DSS} @ T_C = 25°C and V_{GS} = 0)
1.3	Continuous Drain Current Rating (Single Die)	>= 100 A (I_D @ T_C = 25°C and V_{GS} <= 20 V)
1.4	Operating Junction Temperature	-55 °C to 150 °C
1.5	I_{off}/ I_{on} Ratio	> 10^6
1.6	V_{th} (not applicable to diodes)	> 2 V @ I_D = 5 mA
1.7	Dynamic Performance	Project must demonstrate device driving a hard switched boost (PFC) converter at f >= 40 kHz, Vout = 800 V, Imax = 50 A.

The Secondary Technical Targets listed in Table 3 are based on the desire to achieve low losses and high switching speeds. The targets are based on an assumed cooling limit of approximately 200W/cm^2 under 40kHz hard switching with a 50% duty cycle. This cooling limit is consistent with the capabilities of commonly used low cost packaging technologies.

TABLE 3: SECONDARY TECHNICAL TARGETS

ID	Category	Value
2.1	Specific R_{DSON}	< 3 mΩ·cm^2 @ V_{GS} = 15 V
2.2	Switching Loss E_{ON}+E_{OFF}	< .5 mJ @ 800 V and 50 A

Applicants proposing sub-system materials or component level innovations should specify and explain the materials and/or component level technical targets that they believe must be achieved to achieve the device-related Primary Technical Requirements specified in Tables 2 & 3.

ARPA-E will not consider selecting projects for award that do not clearly demonstrate realistic, well justified potential to meet or exceed the Primary Technical Requirements.

G. APPLICATIONS SPECIFICALLY NOT OF INTEREST

The following types of applications will be deemed nonresponsive and will not be reviewed or considered (see Section III.C.2 of the FOA):

- Applications that fall outside the technical areas and parameters specified in Sections I.E and I.F of the FOA, including but not limited to:

- Power conversion system demonstrations that are not connected to the development of new semiconductor switch technology.
    - Incremental advances to existing GaN and SiC fabrication processes and/or existing device architectures including lateral GaN HEMT structures.
    - Simulations or computer models of power semiconductor devices which do not include innovation related to any specific device design or fabrication process.

- Applications that were already submitted to pending ARPA-E FOAs.

- Applications that are not scientifically distinct from applications submitted to pending ARPA-E FOAs.

- Applications for basic research aimed at discovery and fundamental knowledge generation.

- Applications for large-scale demonstration projects of existing technologies.

- Applications for proposed technologies that represent incremental improvements to existing technologies.

- Applications for proposed technologies that are not based on sound scientific principles (e.g., violates a law of thermodynamics).

- Applications that do not address at least one of ARPA-E's Mission Areas (see Section I.A of the FOA).

- Applications for proposed technologies that are not transformational, as described in Section I.A of the FOA and as illustrated in Figure 1 in Section I.A of the FOA.

- Applications for proposed technologies that do not have the potential to become disruptive in nature, as described in Section I.A of the FOA. Technologies must be scalable such that they could be disruptive with sufficient technical progress (see Figure 1 in Section I.A of the FOA).

- Applications that are not scientifically distinct from existing funded activities supported elsewhere, including within the Department of Energy.

Applications with clear technology show stoppers that prevent reaching the Primary or Secondary Technical Targets that are not addressed clearly by the applicant.