Controlling the Flow: Next-Generation Power Electronics Systems for Tomorrow's Electric Grid

GaN Initiative for Grid Applications (GIGA) Project Summary

Prepared for the U.S. Department of Energy, Office of Electricity Delivery and Energy Reliability by Energetics Incorporated in collaboration with Kerry Cheung.

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Executive Summary

Introduction

The development of next-generation power electronics (PE) systems is critical to enhance the capabilities of today's aging electric grid to adequately control, absorb, and reroute power. These advanced PE systems include solid-state transformers, inverters, fault current limiters, high-voltage direct current, and power flow controllers. Existing PE systems play a key role in our electricity delivery system, enabling electric power conversion (e.g., AC to DC, DC to AC, or DC to DC) and improved power transmission and distribution (T&D). These systems can help reduce transmission and distribution losses, optimize power delivery, protect critical assets, and enhance grid resilience. For example, over the last decade, congestion charges ranged from $1 to $2B annually at PJM, one of the largest regional transmission organizations.[2] Additionally, weather-related outages are estimated to cost the U.S. $25 to $70B annually (outages from Superstorm Sandy was estimated to cost $52B).[3] Grid enhancements through the use of next-generation PE systems can lead to significant savings among other benefits. Despite these advantages, large-scale deployment of advanced PE systems remains limited because of high costs, inadequate performance levels, and insufficient technological maturity.

Approximately 6% of U.S. electricity generated annually is lost in transmission and distribution (T&D) due to inefficiencies. This is the equivalent of powering the state of California for one year.[1]

Providing the core functionality of these systems are PE devices such as transistors, diodes, and thyristors that can comprise up to 50% of the installed costs.[4] The essential material needed to fabricate these PE devices are semiconductors that have traditionally been silicon, the bedrock material of the computer integrated circuit industry. However, advanced PE devices are now being fabricated using wide bandgap (WBG) semiconductor materials such as silicon carbide (SiC) and gallium nitride (GaN). These WBG semiconductors possess superior material properties that enable device operation at higher temperatures and voltages with faster switching speeds—resulting in smaller, more reliable, and more efficient PE systems with higher levels of control, flexibility, and performance.

While each of these three materials—silicon, SiC, and GaN—have the potential to help modernize the aging electric grid, the U.S. Department of Energy (DOE) Office of Electricity Delivery and Energy Reliability (OE) GaN Initiative for Grid Applications (GIGA) project focused on the development of PE devices based on gallium nitride on silicon (GaN-on-Si) technology. GaN-on-Si technology effectively combines the enhanced material properties of GaN with the well-established, low-cost, and high-

GaN-on-Si PE devices are a disruptive technology that offers unique opportunities to cost-effectively integrate enhanced control capabilities into the grid.

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[1] U.S. Energy Information Administration (EIA). "Frequently Asked Questions." Last updated July 10, 2015. Accessed November 29, 2015.

[2] Market Monitoring Analytics, LLC. "2012 Quarterly State of the Market Report for PJM: January through March".

[3] Congressional Research Service. "Weather-Related Power Outages and Electric System Resiliency" Aug 28, 2012.

[4] Power Electronics for Distributed Energy Systems and Transmission and Distribution Applications, Oak Ridge National Laboratory, 2005.

volume manufacturability of silicon.[5] By fabricating PE devices using GaN-on-Si technology to support the development of next-generation PE systems, WBG material performance at silicon prices is possible for a broad range of grid applications. The potential affordability and fundamental cost advantages of utilizing GaN-on-Si PE devices is a critical benefit over other WBG technologies. In addition, because GaN-on-Si PE devices are built on silicon wafers, this material option gives greater flexibility for integration with silicon based technologies, including control electronics for enhanced functionality.

GIGA Project Impacts

The GIGA project was initiated in late 2009 at a time when GaN-on-Si development efforts in the United States were still in their infancy for PE applications. Many in the industry considered it technically challenging and impractical for GaN-on-Si PE devices to operate at voltages over 600 V. The GIGA project worked to overcome this challenge. Overall, the project produced a number of important advances and valuable insights in the development of GaN-on-Si PE devices and provided critical proofs-of-concept to demonstrate what is possible with GaN-on-Si technology. Today, the power electronics industry, including many non-U.S. companies,[6] is investigating GaN-on-Si PE devices at voltages greater than 1200 V alongside production of various other GaN-on-Si devices at lower voltages. The GIGA project helped to catalyze and develop an industrial base for high powered GaN-on-Si PE devices that can be utilized across multiple sectors of the U.S. economy.

The GIGA project has helped to create a domestic GaN-on-Si industry and built the foundation to dramatically reduce the cost of key building blocks of next-generation grid components.

GIGA results have helped pique industry interest, spurring competition and investment. The GIGA project supported the maturation of the U.S. GaN-on-Si industry through its effective use of public-private collaborations to achieve significant technical milestones and proofs-of-concept. Achievements were supported and disseminated to the public through more than 75 GIGA-related publications in various technical journals and magazines. These milestones include:

- ***Materials Advancement:*** Catalyzed a low-cost domestic supply of high-quality 200 mm GaN-on-Si wafers, critical to realizing the affordability of GaN-on-Si PE devices.
- ***Device Development***: Demonstrated GaN-on-Si is a viable technology for high power applications (> 1.2 kV) and developed world record GaN-on-Si diodes and transistors (> 3 kV and > 15 A).
- ***Enhanced Manufacturability***: Demonstrated prototype manufacturing process runs that are compatible with high-volume, low-cost, integrated circuit production facilities.

More Work is Needed

While the GIGA project successfully demonstrated that GaN-on-Si technology is viable as a basis for manufacturing cost-effective high power PE devices, Figure ES-1 highlights some of the additional work

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[5] Over 180 million eight inch silicon wafers were consumed in 2013 according to SEMI, the global semiconductor industry association. By comparison, less than 900,000 eight inch equivalent SiC wafers were consumed for power in 2013 according to Yole Research.

[6] Compound Semiconductor magazine, *Commercial status of the GaN-on-silicon power industry*, March 2013. www.compoundsemiconductor.net. http://www.compoundsemiconductor.net/pdf/magazines/2013/cs-2013-volume-19-issue-2.pdf.

still needed before GaN-on-Si PE devices can be readily integrated into the PE systems critical to our nation's grid. Next steps include improving device performance, developing optimized packaging and protection circuitry, conducting reliability testing, as well as establishing high-volume production processes for GaN-on-Si wafers in existing integrated circuit foundries.

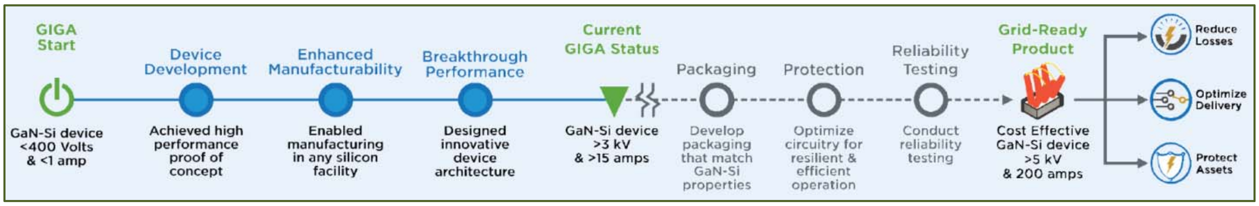


Figure ES-1: GIGA project milestones and next steps

Beyond the additional steps needed to achieve the end goal of the GIGA project, which is a packaged GaN-on-Si power module ready to integrate into PE systems, significantly more work will be needed to address the broad and diverse challenges of developing and deploying next-generation PE systems, including:

- Modeling, simulation, and testing to improve the understanding of device designs and system performance
- Applied materials research and innovation to improve fundamental properties and capabilities needed for grid applications
- Systems engineering, design, and development to improve reliability, manufacturability, and costs
- Market and power system impact analysis to assess deployment opportunities and evaluate societal benefits

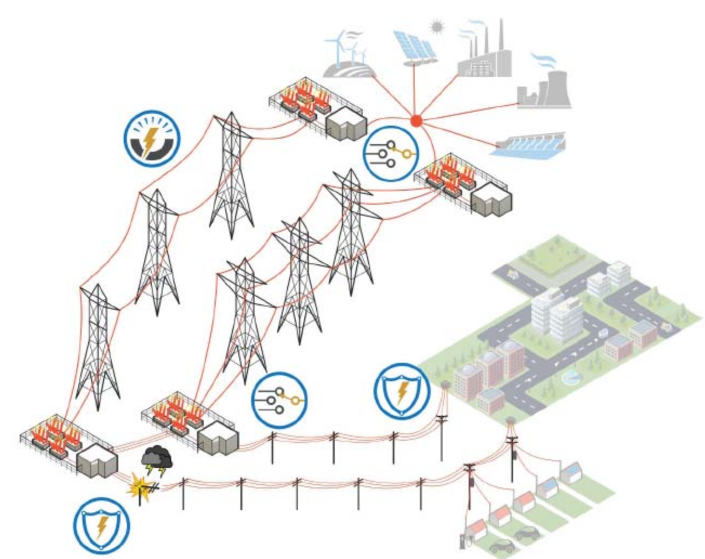
OE is pursuing a portfolio of activities to address the challenges of next-generation power electronics systems and is continually looking to engage in public-private partnerships to build on project successes, deliver grid-ready products, and demonstrate advanced applications.

I. Power Electronics Systems for the Grid

Greater deployment of power electronics systems is critical to realizing the future electric grid.

For more than a century, the nation's electric grid has powered our economy, sustained our industrial and individual needs, and raised our quality of life. However, the electric grid is being challenged to address the requirements of our digitalizing economy, more decentralized generation and controls, and accelerated progress towards an environmentally responsible future. These profound changes affecting the electric power sector offer an unprecedented opportunity to transform the grid. Increasing needs for flexibility, reliability, and resilience in the transmission and distribution (T&D) system require technologies and techniques not conceived of when much of the current infrastructure was deployed. During this period of transition, the deployment of new technologies will play a critical role in shaping the future grid.

Next-generation power electronics (PE) systems are one of the key solutions to modernize the electric grid among other technological improvements needed. These advanced technologies—including solid-state transformers, fault current limiters, high-voltage direct current, and power flow controllers—can reduce T&D losses, optimize power delivery, protect critical assets, and enhance resilience. Figure 1 highlights the potential benefits of advanced PE systems deployed in the electric grid.



Reduce Losses: high voltage direct current systems act as an express lane for delivering electricity. These systems carry large amounts of power over long distances more efficiently, including clean electricity produced at wind and solar facilities that are located far from major load centers.

Optimize Delivery: power flow control systems act as routers to smartly direct where electricity goes. These systems relieve grid congestion, deferring expensive investments, and can reroute power to serve critical loads during an outage.

Protect Assets: fault current limiter systems act as surge protectors for the electric grid. These systems absorb excess power caused by lightning strikes or abnormal events that can damage expensive assets, minimizing the risk of failure, and accelerating power restoration to homes and businesses.

Figure 1: Applications and benefits of power electronics systems in the electric grid[7]

PE systems already play a critical role in today's electricity grid. Among other functions, they perform power conversion, improve power T&D, and integrate and stabilize adjacent power grids. As various institutions and research entities work on improving the electric grid, it is becoming increasingly clear that next-generation PE systems will be critical to realize the envisioned capabilities and efficiencies of the

[7] U.S. Department of Energy, Office of Electricity Delivery & Energy Reliability, Power Electronics Systems for the Electric Grid Factsheet, March 2015.

future grid. Greater deployment of next-generation PE systems can more effectively handle the projected changes in the electric grid, diminish losses during power conversions, and reduce the need for auxiliary components.

Wide bandgap (WBG) PE devices can enhance PE systems.

Despite the advantages offered by PE systems, large-scale deployment of these systems remains limited because of high costs, inadequate performance levels, and insufficient technological maturity. In today's systems, silicon PE devices (such as transistors, diodes, and thyristors) are the most widely used technology. However, silicon-based PE systems will be increasingly challenged to cost-effectively meet the new capabilities and growing performance demands of future grid applications. Next-generation PE systems based on advanced materials, such as wide bandgap (WBG) semiconductors (e.g., silicon carbide (SiC), gallium nitride (GaN)), allow for new designs and capabilities that can dramatically shift the cost-performance curves. While silicon PE devices are rapidly approaching their maximum performance limits for high power applications, advances in WBG PE devices show the potential for operation at higher voltages, higher temperatures, and higher frequencies by virtue of their material properties (see Table 1 below). The limitations of silicon PE devices directly impact the performance and cost of grid PE systems that utilize them including:

- **Voltage Limits:** Grid applications typically require systems that can operate at tens to hundreds of thousand volts. This requirement means that multiple silicon-based devices are typically connected together in series or "stacked" to achieve the desired voltage rating. Stacked structures are more expensive (proportional to the number stacked) and often require complicated triggering and control circuitry to maintain voltage-sharing between devices in the stack.[8]
- **Temperature Limits:** Grid applications typically involve the control of hundreds to thousands of amps of electrical current, leading to high temperatures due to resistive heating. Silicon-based devices must be operated below 150°C to preserve functionality and integrated cooling systems are often used to meet this requirement. These systems of pumps, radiators, and fans adds to total system costs, increases volume and weight, and increases maintenance costs.
- **Frequency Limits:** The size of supporting PE circuit elements, such as capacitors and inductors, and PE system components, such as transformers, are directly related to the device operating frequency. Silicon-based devices typically do not operate at frequencies greater than 5 kHz in grid applications, resulting in large PE modules and system components with greater associated costs for materials.

[8] L.M. Tolbert, B. Ozpineci, S.K. Islam, and M.S. Chinthavalli "Wide Bandgap Semiconductors for Utility Applications" *Proceeding* (379) Power and Energy Systems - 2003 http://power.eecs.utk.edu/pubs/iasted_2003_wide_bandgap.pdf.

*Table 1: Physical characteristics of silicon (Si), silicon carbide (SiC-4H), and gallium nitride (GaN) and impact on power electronics device operating limits. Property values shown in **bold** denote higher performance material properties.*[9, 10]

Materials Property	***Power Electronic Device Impact***	***Si***	***SiC***	***GaN***
Band Gap (eV)	Max. Operating Voltage	*1.1*	***3.2***	***3.4***
Electric Breakdown Field (kV/cm)	Max. Operating Voltage	*300*	***3000***	***3500***
Thermal Conductivity (Watts/cm-K)	Max. Operating Temperature	*1.5*	***5***	*1.3*
Intrinsic Carrier Concentration (cm^{-3} @ 300°C)	Max. Operating Temperature	*> 10^{15}*	***1 x 10^4***	***2 x 10^2***
Electron Mobility (cm^2/V-sec)	Max. Operating Frequency	*1450*	*900*	***2000***
Electron Saturation Velocity (10^6 cm/sec)	Max. Operating Frequency	*10*	***22***	**25**

The capabilities of high powered WBG PE devices can be leveraged to enhance grid PE systems, addressing many of the limitations imposed by the use of silicon-based devices. For a comparable device geometry, a WBG PE device can operate at voltages that are at least 10 times larger, at temperatures over 200°C, and at frequencies greater than 100 kHz.[11,12] These advantages can lead to PE system designs that are more compact with fewer components, leading to cost saving opportunities and increased reliability. Next-generation PE system designs based on WBG materials will need to balance the reduction or elimination of auxiliary components with the increased cost of WBG PE devices. Reducing the cost of WBG PE devices will enable the broader use of these advanced technologies.

GaN-on-Si technology has the potential to realize low-cost WBG PE devices.

GaN-on-Si technology is a material system that consists of thin-film gallium nitride (GaN) grown on silicon (Si) substrates (see Figure 2). GaN-on-Si technology capitalizes on the advantages of both materials, benefiting from the superior material properties of the GaN active layer, while utilizing commercially available, low-cost silicon substrates - the bedrock material of the computer integrated circuit industry. Additionally, GaN-on-Si technology can leverage the well-established

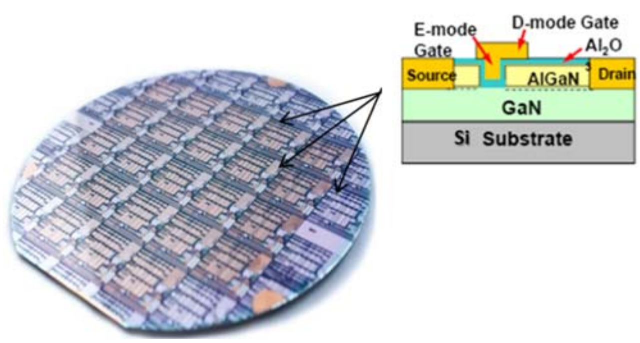


Figure 2: Schematic of GaN-on-Si devices on a silicon wafer

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[9] Digikey, *Gallium Nitride (GaN) versus Silicon Carbide (SiC) in the High Frequency (RF) and Power Switching Applications*. Available at: https://www.digikey.com/Web%20Export/Supplier%20Content/Microsemi_278/PDF/Microsemi_GalliumNitride_VS_SiliconCarbide.pdf?redirected=1.

[10] Philip Zuk, *High-Voltage Silicon MOSFETs, GaN, and SiC: All have a place*, June 12 2012. Available at: http://www.edn.com/design/components-and-packaging/4375812/3/High-Voltage-Silicon-MOSFETs-still-hold-lead-over-SiC-and-GaN.

[11] D.A. Marckx, *Breakthrough in Power Electronics from SiC*. National Renewable Energy Laboratory subcontract report, March 2006. http://www.nrel.gov/docs/fy06osti/38515.pdf.

[12] B. Ozpineci and L.M. Tolbert. Comparison of Wide Bandgap Semiconductors for Power Electronics Applications. Oak Ridge National Laboratory. http://web.ornl.gov/~webworks/cppr/y2001/rpt/118817.pdf.

integrated circuit processing facilities for low-cost PE device production. In short, GaN-on-Si technology enables WBG material performance at silicon prices for a broad range of power applications.

The potential affordability and fundamental cost structure advantage of GaN-on-Si lateral PE devices (where current flows across the surface of the wafer) is a critical advantage over other WBG technologies. While GaN can be grown on various substrates (e.g., Si, SiC, GaN, sapphire) with modest incremental costs, the cost of these material systems are dominated by the substrate. The production of Si substrates is much less expensive and consumes less energy than SiC substrates, as the latter is grown at much higher temperatures and much slower rates (~1-2 mm/hr for SiC vs. 100 mm/hr for Si).[13,14,15,16] Currently, there are no suppliers of large diameter GaN substrates and sapphire substrates remains very expensive. Vertical PE devices (where current flows through the wafer) have the capability for inherently higher power densities than lateral devices, but face affordability issues due to the high cost of WBG substrates.

II. GIGA Project Overview

The U.S. Department of Energy (DOE) Office of Electricity Delivery and Energy Reliability (OE) GaN Initiative for Grid Applications (GIGA) project focused on the development of high power PE devices based on GaN-on-Si technology. A basic driver for GIGA is that WBG PE devices should be closer in cost structure to conventional silicon-based alternatives in order to enable broad deployment. GIGA led the way in the development of lateral PE devices on a material system with significant cost advantages for grid PE systems application. While SiC is currently at a more advanced stage compared to GaN-on-Si for the development of high power PE devices, this came about after more than a decade of Department of Defense investments. Several DOE programs initiated after GIGA continue to address cost challenges associated with WBG PE devices (e.g., Power America, SWITCHES).[17]

More than 75 GIGA related publications provided industry and other stakeholders with the results of GaN-on-Si studies

GaN-on-Si lateral devices take advantage of the very high electron mobility at the AlGaN/GaN interface (~2000 cm^2/V-sec) leading to lower conduction losses and higher efficiencies. Additionally, lateral devices make the fabrication process much easier and more cost-effective than vertical devices. While there has been significant commercial interest in developing GaN-on-Si PE devices for low voltage (< 1 kV) applications, limited attention was given to higher voltages. Many in the industry considered it technically challenging and impractical for GaN-on-Si PE devices to operate at voltages over 600 V when GIGA started. The GIGA project focused on developing materials and devices capable of operating at voltages > 1 kV. Since GaN-on-Si PE devices are built on silicon substrates, integration with silicon-based technologies such

13 Carl-Mikael Zetterling, Process Technology for Silicon Carbide Devices, 2002.
14 Wai-Kai Chen, The VLSI Handbook, Chapter 5: Silicon Carbide Technology, 2007.
15 S. E. Saddow and A. Agarwal. Advances in Silicon Carbide Processing and Applications. 2004.
16 Tsunenobu Kimoto and James A. Cooper. Fundamentals of Silicon Carbide Technology: Growth, Characterization, Devices and Applications. 2014.
17 ARPA-E SWITCHES Program: http://arpa-e.energy.gov/?q=arpa-e-programs/switches.

as control electronics is readily possible. New hybrid circuits optimized for high voltage applications can lead to enhanced capabilities at reduced costs.[18]

Silicon-based PE devices with low to midrange power ratings are widely utilized at high production volumes in the consumer and transportation sectors. However, high power versions for the utility sector lack the production volumes needed to help drive down costs.[19] As commercial WBG PE devices gain market share in industry segments such as electric vehicles, solar PV inverters,[20] lighting, and consumer electronics, cost challenges from production volumes will persist for high power versions. As illustrated in Figure 3, the technology developed through GIGA would alter this paradigm. High power GaN-on-Si PE devices that leverage the manufacturing processes and cost advantages of low power products (i.e., high volumes) can be used in the utility sector with new designs for grid PE systems.

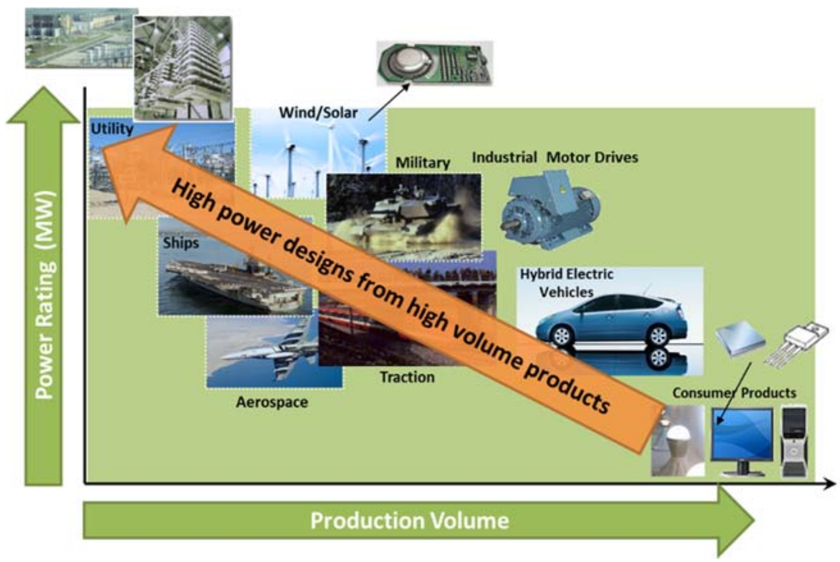

Figure 3: Power electronics devices span across many applications with different power ratings and production volumes. Utility applications can benefit from high power devices that leverage high volume manufacturing.

The GIGA team began work in October 2009 to advance GaN-on-Si materials and device technology for cost-effective, WBG PE devices suitable for grid PE systems application. The initial team, formed via competitive R&D research subcontracts in August 2009, was led by MIT Lincoln Laboratory (MIT/LL) and included the MIT campus Advanced Semiconductor Materials and Devices research group (MIT) and MACOM Technology Solutions (MTS). Oak Ridge National Laboratory and Sandia National Laboratories were also part of the team, providing key advanced packaging reliability testing and device reliability testing, respectively. By December 2012, the fourth core member, IQE (Kopin Corp. at the time[21]), joined

[18] Jinwook W. Chung, "Millimeter-wave GaN high electron mobility transistors and their integration with silicon electronics," MIT (2011), http://dspace.mit.edu/handle/1721.1/63065#files-area.
[19] B. Ozpineci, M.S. Chintavali, and L. M. Tolbert, *Enhancing Power Electronic Devices with Wide Bandgap Semiconductors*, (Oak Ridge, TN: Oak Ridge National Laboratory, 2007).
[20] H. Zhang, L. Tolbert, B. Ozpineci, "Impact of SiC devices on Hybrid Electric and Plug-in Hybrid Electric Vehicles," *Industry Applications Society Annual Meeting,* October 2008, pp. 1-5.
[21] IQE acquired Kopin Wireless in January 2013.

the team to provide a domestic supply of commercial-grade GaN epitaxial materials. The project period of performance ended in September 2014.

Overall, the project produced a number of important advances and valuable insights in the development of GaN-on-Si PE devices and provided critical proofs-of-concept to demonstrate what is possible with GaN-on-Si technology. Today, the power electronics industry, including many non-U.S. companies,[22] is investigating GaN-on-Si PE devices at voltages greater than 1200 V alongside production of various other GaN-on-Si devices at lower voltages. The GIGA project helped to catalyze and develop an industrial base for high powered GaN-on-Si PE devices that can be utilized across multiple sectors of the U.S. economy.

A key factor in enabling the advancements made throughout the GIGA project was the integrated team approach that brought together device experts, materials experts, and companies with the ability to commercialize and manufacture devices. This well-structured team included distinct, complementary roles for each performer, as illustrated in Figure 4.

MIT Lincoln Laboratory	MIT Massachusetts Institute of Technology	Sandia National Laboratories
Team lead: Materials growth and device technology	Device design and processing	Device reliability testing
IQE	MACOM Technology Solutions	Oak Ridge National Laboratory
Commercial epitaxial material supplier	Commercial device foundry – advanced device	Materials & advanced packaging reliability testing

Figure 4: The GIGA Team: MIT Lincoln Laboratory, MIT, MACOM, and IQE, ORNL and SNL.

III. Project Accomplishments and Technical Advances

An important contribution of the GIGA project was analyzing the performance trade-offs between lateral and vertical GaN-based power transistors.[23] The conventional wisdom from traditional silicon device development is that thermal dissipation issues would render lateral devices inappropriate at high power. GIGA results and simulations suggest that under certain scaling conditions (up to 5 kV), lateral GaN-on-Si power transistors have similar thermal performance as vertical GaN power transistors. Since vertical devices are much more expensive to fabricate, GaN-on-Si devices would be the preferable option. While vertical devices have the capability for inherently higher power densities than lateral devices, this PE device attribute is not as critical for grid PE systems application which is much more sensitive to costs.

[22] Compound Semiconductor magazine, *Commercial status of the GaN-on-silicon power industry*, March 2013. www.compoundsemiconductor.net. Available at: http://www.compoundsemiconductor.net/pdf/magazines/2013/cs-2013-volume-19-issue-2.pdf.

[23] Yuhao Zhang, "Simulation and Fabrication of GaN-Based Vertical and Lateral Normally-off Power Transistors", 2013. Available at: http://dspace.mit.edu/bitstream/handle/1721.1/82179/861974857-MIT.pdf?sequence=2.

The GIGA project advanced the performance landscape of GaN-on-Si PE devices, addressing concerns within the research community of the viability of lateral devices at high power levels. While GIGA focused on power applications, project results has helped advance other applications and sectors. For example, the advances in material and device processing also support radio frequency (RF) applications. Full details of these accomplishments and technical advances are available in the GIGA Final Technical Report and include:

- ***Materials Advancement:*** Catalyzed a low-cost domestic supply of high-quality 200 mm GaN-on-Si wafers, critical to realizing the affordability of GaN-on-Si PE devices.
- ***Device Development***: Demonstrated GaN-on-Si is a viable technology for high power applications (>1.2 kV) and developed world record GaN-on-Si diodes and transistors (>3 kV and >15 A).
- ***Enhanced Manufacturability***: Demonstrated prototype manufacturing process runs that are compatible with high-volume, low-cost, integrated circuit production facilities.

Materials Advancement for High Quality Wafers

Achievements: Materials Advancement

- ✓ Catalyzed the development of domestic commercial suppliers of GaN-on-Si wafers with sizes from 100 mm to 200 mm
- ✓ Improved understanding of epitaxial materials growth and characterization
- ✓ Demonstrated the growth of a virtually flat, crack-free GaN HEMT structure on Si substrate up to 5 µm in thickness

At the project onset, the domestic production of GaN-on-Si wafers were not of sufficient quality to support development of high power GaN-on-Si PE devices. The GIGA team had to rely on a high-priced Japanese supplier, limiting the affordability of GaN-on-Si PE devices. To address this foundational challenge, the GIGA team developed techniques to produce low cost wafer materials. R&D efforts advanced progress from exploratory material growth techniques in a laboratory setting to the point where high quality GaN-on-Si wafers could be produced at 8-inch (200 mm) silicon wafer manufacturing facilities. Due in part to GIGA achievements, there are now at least three companies that have been able to develop commercial GaN-on-Si epitaxial capabilities. The result is a robust domestic supply of affordable, high-quality commercial GaN-on-Si wafers that did not exist before.

The GIGA project also made multiple material growth and characterization advances. One major technical challenge was the post-growth wafer bow due to stress between the materials needed to form the GaN High Electron Mobility Transistor (HEMT) structure and the silicon substrate. Managing the buildup of stress in the epitaxial growth process becomes more challenging as the GaN HEMT structure becomes thicker which is required for high voltage devices. The GIGA team developed in-situ monitoring techniques and improved growth processes to address this challenge. By the end of the project, the GIGA team demonstrated the growth of 5 µm thick GaN HEMT structures that were crack-free with good uniformity (see Figure 5). These GaN-on-Si wafers showed < 50 µm wafer bow, which is virtually flat and necessary for PE device fabrication.

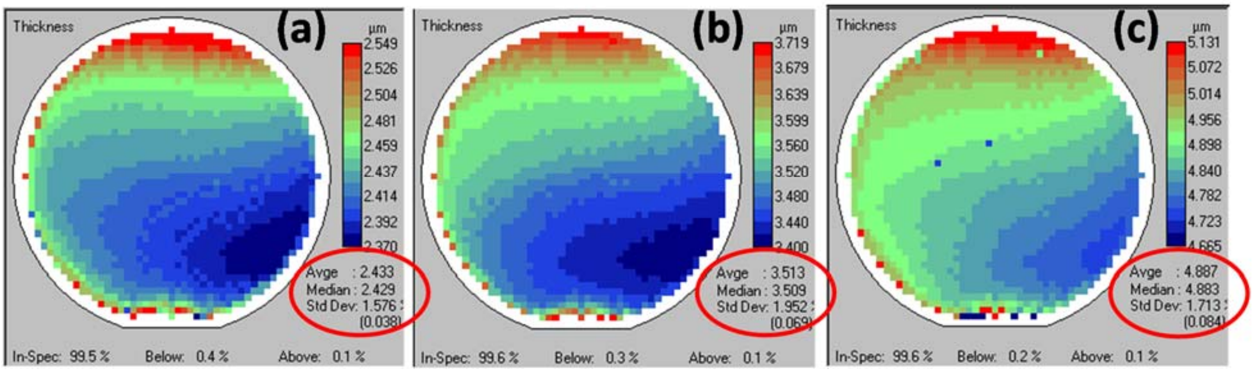

Figure 5: Thickness maps of 2.5 µm (a), 3.5 µm (b) and 5 µm (c) thick GaN HEMT structure on (111) Si showing good uniformity

Device Development of Advanced Electronics

At the project onset, commercial GaN-on-Si R&D efforts were focused on developing PE devices at voltages below 600 V with limited work at 1200 V. Many in the industry considered it technically challenging and impractical for GaN-on-Si PE devices to operate at voltages greater than 600 V. Through coordinated electronic device design and fabrication R&D, the GIGA team was able to produce GaN-on-Si PE devices operating at world record performance. The voltages levels achieved are more than 15 times greater than what was commercially available for GaN-on-Si PE devices at the start of GIGA. The GIGA team has been a leader in developing high power GaN-on-Si PE devices, demonstrating diodes and transistors operating at voltages > 3000 V and currents > 15 A.

Achievements: Device Development

- ✓ Established GaN-on-Si technology as a viable option for high power PE devices
- ✓ Demonstrated GaN-on-Si diodes and transistors with >3 kV and >15 A
- ✓ Developed advanced fabrication processes and device architectures including silicon removal techniques and field plate technology
- ✓ Investigated and fully characterized breakdown mechanisms in GaN-on-Si device structures
- ✓ Improved understanding of power device design and optimization, especially electric field control

To increase the operating voltage of GaN-on-Si PE devices, the GIGA team experimented with several device fabrication techniques. Silicon substrate removal and device transfer processes were developed to minimize parasitic leakage currents. By utilizing these technique, diode breakdown voltages > 3000 V were observed (see Figure 6), which was limited by the test equipment. Additionally, experiments with local substrate removal (i.e., removing the silicon only under the gate) also showed excellent results, offering an approach that is more amenable to cost-effective manufacturing. Experiences with high-volume LED manufacturing processes give an indication that substrate removal could be scalable and cost-effective with GaN-on-Si PE devices. With further development of these device fabrication techniques, the GIGA team was able to demonstrate ~3000V HEMT devices (i.e., transistors), as shown in Figure 7.

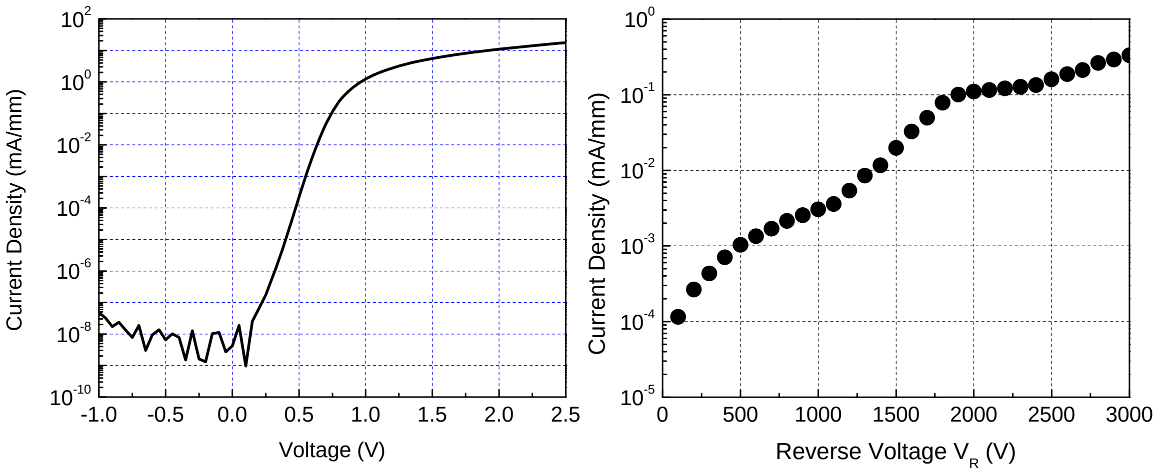

Figure 6: Forward and reverse characteristics for a GaN-on-Si Schottky diode with spacing of 40 µm.

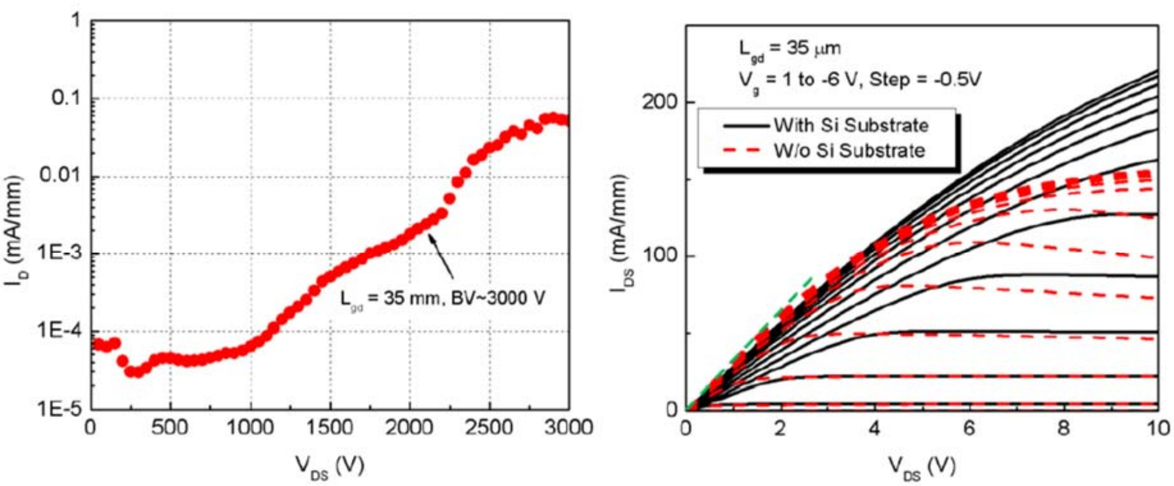

Figure 7: Off state (left) and on state (right) characteristic of GaN HEMT device with L_{gd} = 35 µm after removing the substrate.

While the substrate removal technique was shown to be effective at increasing breakdown voltages, the GIGA team also developed more standard device design and processing techniques to address concerns with ease of manufacturing and scale-up. Through the use of anode connected field plates to control electric fields, excellent wafer-level results (i.e., consistent breakdown voltages > 2000V) were obtained for diodes processed in a standard fabrication facility. Figure 8 shows the maximum forward current of these enhanced diodes demonstrating a current carrying capability of ~10 A. The fact that these measurements were taken for devices without a package (i.e., soldered heat sink) is a good indicator of the survivability and ruggedness of GaN-on-Si PE devices.

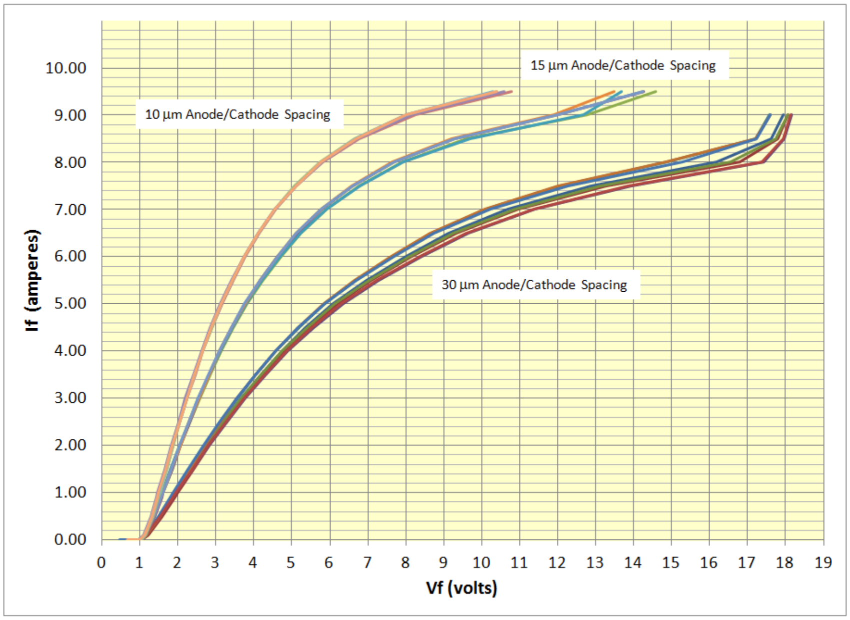

Figure 8: Linear Plot of the Forward Characteristic of Lateral GaN-on-Si Schottky Diodes having a total Anode Periphery of 20.0 mm and 10 µm to 30 µm Anode-to-Cathode Spacings

The GIGA team also explored the use of multi-level field plates (see Figure 9) to properly control high electrical fields present in GaN HEMT devices, as well as leveraging multi-finger device designs to increase current carrying capabilities. Effective electric field engineering was recognized as critical for achieving even higher voltage operation. By utilizing advanced field plate structures, the GIGA team demonstrated GaN-on-Si transistor breakdown voltages of ~2000 V. Another important benefit of the advanced field plate structures is suppression of the gate-to-drain leakage currents (up to 10,000X observed). These enhanced GaN HEMT devices demonstrated a maximum normalized current of ~0.7 A/mm when soldered in a RF package (as there was no suitable power package), a > 40% improvement over unpackaged devices. If these GaN-on-Si transistors were produced with a 30 mm gate periphery and proper packaging, > 20 A of current handling capability could be readily achieved.

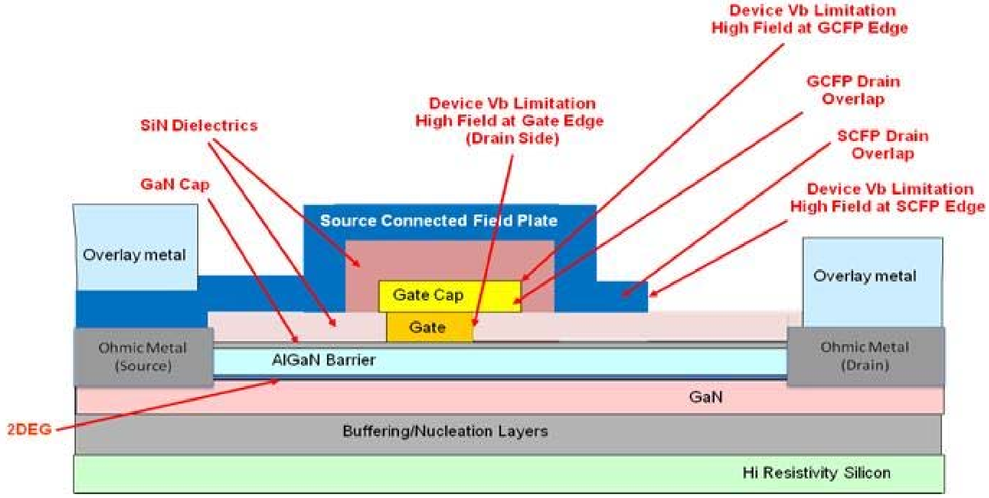

Figure 9: Conceptual Cross section of GaN HEMT device with Gate Connected and Source Connected Field Plates

Enhanced Manufacturability for End-Use Product

In addition to improving foundational wafer materials and demonstrating critical proofs-of-concept, the project made significant advances to enhance manufacturability so that GaN-on-Si PE devices can be integrated into products that would be broadly adopted by industry. The GIGA team developed technologies and processes to form gold-free, low resistance Ohmic contacts with low annealing temperatures in GaN-on-Si PE device. This key breakthrough allowed GaN-on-Si devices to be manufactured on standard high-throughput silicon integrated circuit fabrication lines without risking contamination. Additionally, the GIGA team demonstrated the fabrication and operation of enhancement mode (i.e., normally off) transistors using an innovative dual-gate technology. Availability of GaN-on-Si enhancement mode transistors ensures safe switching operations and is required for broad acceptance and use of GaN-on Si PE devices in products sold by the power electronics industry.

Achievements: Enhanced Manufacturability

- ✓ First gold-free GaN-on-Si process technology
- ✓ Prototype production runs of GaN-on-Si PE devices in a 100 mm fabrication facility with good performance and yield
- ✓ All technologies have been licensed to start-ups and other companies
- ✓ Demonstrated "normally off" device architectures for safer switching operations
- ✓ Conducted dynamic testing of packaged devices to extract switching losses
- ✓ Demonstrated operation of GaN-on-Si transistors with GaN-on-Si diodes for improved performance

The GIGA team also conducted dynamic testing of packaged GaN-on-Si transistors to extract switching losses, an important product specification, and to understand drive circuit design requirements. Transistor turn-on times of 15 nanosecond and turn-off times of 20 nanoseconds were recorded, demonstrating very fast switching operations (see Figure 10). However, unavailability of optimized packaging for GaN-on-Si PE devices presents challenges for adoption in real-world applications and will need to be addressed. Packaged GaN-on-Si diodes were also operated with the GaN-on-Si transistors in a test circuit showing improved performance compared to the use of a SiC diode. The data shows a decrease in total switching energy losses of approximately 5% with the GaN-on-Si diode. This result suggests there can be great synergy from integrating transistors and diodes in the same fabrication process, which is much more amenable with GaN-on-Si lateral device geometries.

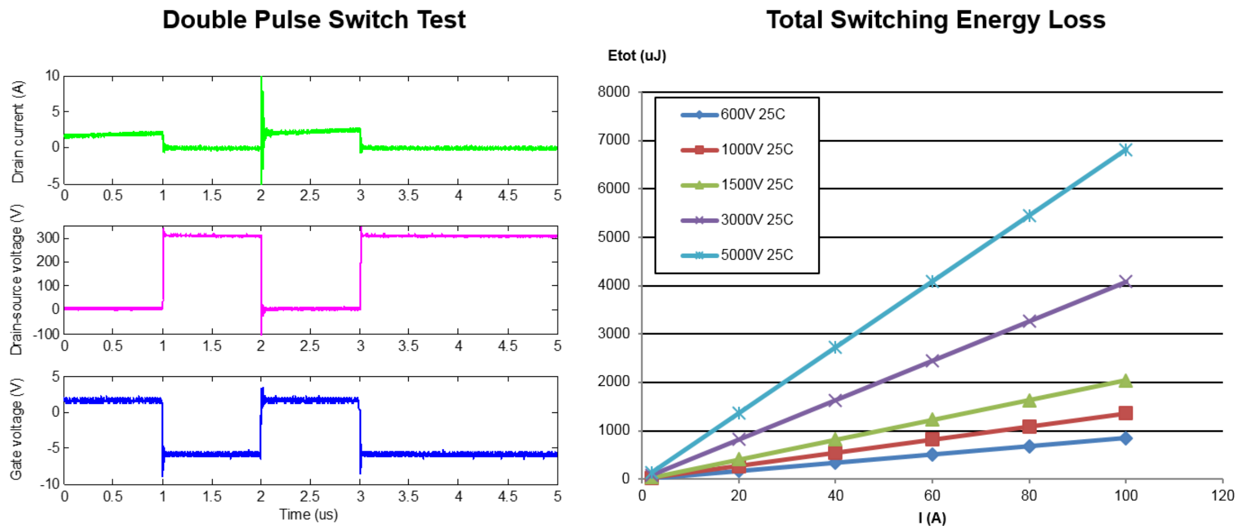

Figure 10: (left) Results of the double pulse switch test showing fast device operation; (right) Extrapolated total switching energy losses for the packaged GaN-on-Si transistor with a GaN-on-Si diode based on test data (ORNL)

IV. Remaining Gaps and Challenges

The GIGA team has made significant technical progress throughout this project but further levels of performance improvements for GaN-on-Si technology remain untapped. A number of additional steps are needed to achieve the GIGA project end goal, a packaged GaN-on-Si power module (see Appendix B) suitable for integration into grid PE systems application, as illustrated in Figure 11. Remaining gaps and challenges that must be addressed before GaN-on-Si PE devices can be integrated into grid-ready products include:

- **Breakdown Voltage**: While enhancement mode (i.e., normally off) transistors were demonstrated using an innovative dual-gate technology, these transistors must be capable of operating at higher voltages such as 3.3 kV or 5 kV which is more appropriate for grid PE systems application.
- **Threshold Voltage**: Transistor threshold voltages needs to be improved substantially, from 0.5 V to > 2 V (commercial products are typically around ~3 V), to ensure safe and reliable switching operations (i.e., avoid disruption under high electromagnetic interference).
- **Current Capacity:** More current needs to be extracted from the GaN-on-Si PE devices, escalating from ~20 A to 50 A or 100 A which is more appropriate for grid PE systems application. This level of current extraction has already been demonstrated in literature for GaN-on-Si devices.[24]
- **Material Growth:** To increase breakdown voltages and enhance device performance, the GaN HEMT structure and crystal quality can be optimized and improved.
- **Device Manufacturing:** While a prototype fabrication run has been demonstrated at a high-volume integrated circuit manufacturing facility, these processes need to be expanded and optimized for the larger 200 mm foundries to ensure low cost GaN-on-Si PE devices.

[24] Ikeda, N., Y. Niiyama, et al. (2010). "GaN Power Transistors on Si Substrates for Switching Applications." Proceedings of the IEEE 98(7): 1151-1161.

- **Packaging and Integration:** To take full advantage of the superior material properties offered by GaN-on-Si, new packaging designs and materials must be developed that are optimized for the GaN-on-Si PE devices including thermal management, protection, and drive circuitry.
- **Reliability Testing and Demonstration:** The power electronics industry must be assured of the reliability and performance of high power GaN-on-Si PE devices in real-world applications. Lifetime failure testing and demonstrations are needed before widespread adoption can take place.

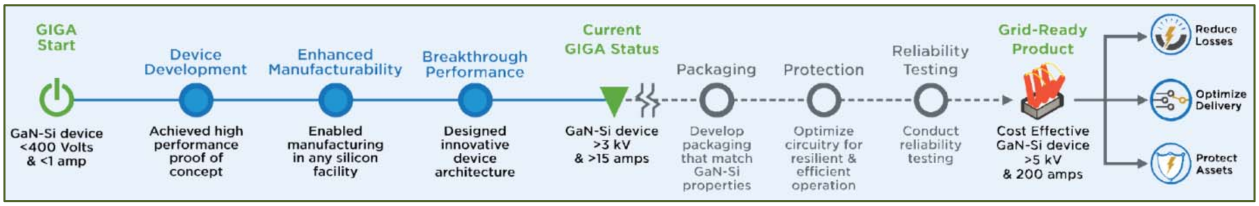

Figure 11: GIGA project milestones and next steps

Overcoming these challenges will open up the market for high power GaN-on-Si PE devices in systems and applications requiring greater than 1200 V operation. Opportunities include advanced PE systems such as solid-state circuit breakers, fault current limiters, solid-state transformers, high-voltage direct current (HVDC) systems, flexible AC transmission systems (FACTS), and other power flow controllers. Packaged GaN-on-Si power modules can also be utilized in energy storage, distributed energy, and renewable power applications (i.e., inverters). To take the next steps toward producing these grid-ready products, collaboration with grid PE systems manufacturers and integrators is critical to ensure that the products being developed will meet the specific needs and requirements of the grid hardware community.

In addition to the goals and objective of GIGA, significantly more work will be needed to address the broad and diverse challenges of developing and deploying next-generation PE systems, including:

- Modeling, simulation, and testing to improve the understanding of device designs and system performance
- Applied materials research and innovation to improve fundamental properties and capabilities needed for grid applications
- Systems engineering, design, and development to improve reliability, manufacturability, and costs
- Market and power system impact analysis to assess deployment opportunities and evaluate societal benefits

OE is pursuing a portfolio of activities to address the challenges of next-generation power electronics systems and is continually looking to engage in public-private partnerships to build on project successes, deliver grid-ready products, and demonstrate advanced applications.

Appendix A: Full GIGA Publications List

[1] B. Lu, E. L. Piner, and T. Palacios, "Breakdown mechanism in AlGaN/GaN HEMTs on Si substrate," Proc. Of the 68th Device Research Conference, Notre Dame, IN, June 21-23, 2010.

[2] Timothy Boles, Costas Varmazis, Douglas Carlson, Tomas Palacios, "Effect of Isolation Techniques on GaN on Silicon Breakdown Voltage", International Workshop on Nitrides, September, 2010

[3] B. Lu, E. L. Piner, and T. Palacios, "High Performance Dual-Gate AlGaN/GaN Enhancement-Mode Transistor," Proc. Of the International Symposium on Compound Semiconductors (ISCS-2010), Takamatsu, Japan, May 31st-June 4th, 2010.

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[5] B. Lu and T. Palacios, "High Breakdown (>1500 V) AlGaN/GaN HEMTs by Substrate Transfer Technology", IEEE Elec. Dev. Lett., vol. 31, no. 9, p. 951, September 2010

[6] Lu, B., E. L. Piner, and T. Palacios, "Schottky Drain Technology for High Voltage AlGaN/GaN HEMTs on Si Substrates," IEEE Electron Dev. Letts., vol. 31, 302-304, 2010.

[7] B. Lu, D. Piedra, and T. Palacios, "GaN power electronics," in 18th International Conference on Advanced Semiconductor Devices and Microsystems, ASDAM 2010, October 25, 2010 - October 27, 2010, Smolenice, Slovakia, 2010, pp. 105-110.

[8] M. Sun, H.S. Lee, B. Lu, D. Piedra, E. Matioli, and T. Palacios, "1.8kV-breakdown AlGaN/GaN HEMT on Si substrate with Ron=2.4mΩcm2", in the 9th International Conference on Nitride Semiconductors (ICNS-9), July, 2011, Glasgow, UK, 2011.

[9] H.-S. Lee, D. Lee, and T. Palacios, "AlGaN/GaN High-Electron-Mobility Transistors Fabricated Through a Au-free Technology," IEEE Electron Device Letters, v 32, 623-625, May 2011.

[10] M. Sun, H.S. Lee, B. Lu, D. Piedra, and T. Palacios, "1.8 kV-Breakdown AlGaN/GaN HEMT on Si Substrate with Ion Implantation Isolation", submitted to IEEE Electron Device Letters.

[11] D. Piedra, T. G. Desai, R. Bonner, J. Pascaul-Guiterrez, M. Sun, and T. Palacios, "Integration of a Phase Change Material for Junction Level Cooling in GaN Devices", submitted to the 28th Annual Thermal Measurement, Modeling and Management Symposium (SEMI-THERM 28), 2012.

[12] H. S. Lee, D. Piedra, M. Sun, X. Gao, S. P. Guo, T. Palacios, "3000 V 4.3 Ωcm2 InAlN/GaN MOSHEMTs with AlGaN Back Barrier," *IEEE Electron Dev. Letts.*, vol. 33, pp. 982-984, 2012.

[13] S. Atcitty, R. Kaplar, S. Das Gupta, M. Marinella, A. Armstrong, L. Biederman, M. Sun, T. Palacios, and M. Smith, "GaN-Based Wide-Bandgap Power Switching Devices: From Atoms to the Grid" ECS Transactions, 50, (3) , 2012

[14] D. Piedra, T. G. Desai, R. Bonner, J. Pascaul-Guiterrez, M. Sun, and T. Palacios, “Integration of a Phase Change Material for Junction Level Cooling in GaN Devices”, to be published in the 28th Annual Thermal Measurement, Modeling and Management Symposium (SEMI-THERM 28)

[15] T. Boles, C. Varmazis, D. Carlson, T. Palacios, G. Turner, and R. Molnar, ˝High Voltage GaN on Silicon HEMT”, accepted as a poster presentation at ISCS 2012.

[16] T. Boles, C. Varmazis, D. Carlson, T. Palacios, G. Turner, and R. Molnar,”>1200 volt GaN on Silicon Schottky Diode”, accepted as an oral presentation at ISCS 2012..

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[21] T. Boles, C. Varmazis, D. Carlson, T. Palacios, G. W. Turner, R. J. Molnar, “>1200 volt GaN-on-Silicon Schottky Diode”, International Symposium on Compound Semiconductors 2012, August, 2012.

[22] T. Boles, C. Varmazis, D. Carlson, T. Palacios, G. W. Turner, R. J. Molnar, “High Voltage GaN-on-Silicon HEMT”, International Symposium on Compound Semiconductors 2012, August, 2012.

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[28] T. Boles, C. Varmazis, D. Carlson, L. Xia, D. Jin, T. Palacios, G. W. Turner, R. J. Molnar, “High Voltage GaN-on-Silicon HEMT’s”, CSMANTECH, May, 2013

[29] Y. Zhang, M. Sun, T. Fujishima, Z. Liu, K. Bagnall, D. Piedra, E. Wang, and T. Palacios, "Electro-thermal Modeling and Thermal Performance Study of GaN Vertical and Lateral Power Transistors," IEEE Trans. Electron Dev., vol. 63, 2224-2230, July 2013.

[30] S. DasGupta, R.J. Kaplar, M. Sun, M.J. Marinella, S. Atcitty, and T. Palacios "Effect of Interaction of Deep Level Defects with Quantum Well States on Detrapping Transients in High-Voltage AlGaN/GaN HEMTs" Abstract #1943 224th ECS Meeting, 2013.

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[43] Palacios, T., "GaN-on-Si Technology, A New Approach for Advanced Devices in Energy and Communications," 40th European Solid-State Device Research Conference (ESSDERC), Seville, Spain, 13-17 September 2010. (Invited)

[44] Palacios, T., "GaN Power Electronics," 8th International Conference on Advanced Semiconductor Devices and Microsystems (ASDAM 2010), Smolenice, Slovakia, 25-27 October 2010. (Invited)

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[50] Palacios, T., "GaN Transistors: Revolutionizing Energy Processing," 4th International Symposium on Advanced Plasma Science and its Applications to Nitrides and Nanomaterials, Aichi, Japan, March 4-8, 2012. (Invited).

[51] T. Palacios, "Fundamentals of GaN-based High Frequency Power Electronics," Tutorial at the International Electron Device Meeting, San Francisco, December, 2012.

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Appendix B: GaN HEMT Notional Datasheet

This “notional” datasheet of a 5kV, 50A module was created by the GIGA team to better describe how the accomplishments of the GIGA project can be best leveraged into a product that would be of interest to system integrators.

GaN5KV200A

GaN HEMT Notional Data Sheet

Gallium Nitride on Silicon Lateral Transistor V_{CES} = 5000V, I_{Fmax} = 200A, I_{Fav}=50A

Features:

- 5000V GaN High Mobility Electron Transistor, Normally off,
- Included anti-parallel high speed GaN diode
- High speed switching, self-commutating, fast turn off and on
- 150 ° C operating temperature
- Robust packaging options: Single Switch Presspack, or Dual Switch Half Bridge Module
- Multichip packaging with internal parallel connections
- High isolation voltage
- Lowest in-class switching energy

Applications:

- Utility medium voltage solid state transformers
- Series connected utility DC-AC link converters
- Medical MIR gradient amplifiers
- Pulsed energy applications
- Electromagnetic launchers

Maximum ratings:

Parameter	Symbol	Conditions	Values	Unit
Repetitive peak forward voltage	V_{CES}	Tj=25C, Vg=0	5000	V
Maximum peak drain current	I_{CM}	Tj=150C, pulse	200	A
DC drain current	I_{CD}	Tj=150C, RMS or DC	50	A
Diode forward current surge	I_{FM}	Tj=150C, pulse	200	A
Diode forward current	I_F	Tj=150C, RMS or DC	50	A
I^2t for diode	I^2t	T=10 ms	100	A
Gate- source voltage	V_{GES}	V_{CE}=0	+-20	V
Isolation voltage	V_{iso}	Dual pack to plate	9000	VAC 60hz
Junction temperature	T_j	operating	-40 to 150	° C
Storage temperature	T_{stg}	storage	-40 to 150	° C
Maximum collector dissipation	P_c	Tc=25C, Tj<150C	1000	W

Electrical Characteristics, T_J=25°C unless otherwise specified:

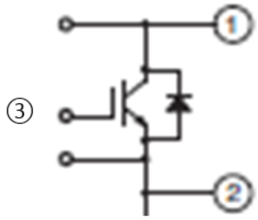
Characteristics	Symbol	Test conditions	Min	Typ	Max	Unit
Drain cutoff current	I_{CES}	V_{GE}=0, V_{CE}=V_{CES}	-	-	5	mA
Gate leakage current	I_{GES}	V_{GE}=V_{GES}, V_{CE}=0	-	-	0.5	uA
Gate-Source threshold V	$V_{GE(th)}$	I_C=10mA, V_{CE}=10V	4.0	5.0	7.0	V
D-S Saturation V	$V_{CE(sat)}$	I_C=I_{CD}, V_{GE}=15V	-	3.5	4.0	V
Input Capacitance	C_{ies}	V_{GE}=0, V_{CE}=10V	-	20	-	pF
Output Capacitance	C_{oes}	V_{GE}=0	-	300	-	pF
Reverse transfer capacitance	C_{res}	V_{GE}=0	-	100	-	pF
Inductive turn on delay	$T_{d(on)}$	V_{CC}=2500V,	-	-	100	nS
Inductive rise time	T_r	I_C=I_{CD},	-	-	30	nS
Inductive turn off delay	$T_{d(off)}$	V_{GE}=0-15V,	-	-	100	nS
Inductive fall time	T_f	R_G=30Ω,	-	-	30	nS
Turn on energy	E_{on}	L_s=200nH,	-	1875	-	uJ/P
Turn off energy	E_{off}	Inductive load	-	2000	-	uJ/P
Diode reverse recovery t	t_{rr}		-	-	100	nS
Diode reverse recovery Q	Q_{rr}		-	1000	-	nC
Diode reverse recovery E	E_{rr}		-	2500	-	uJ/P
Recommended switching f	f_{SW}	Hard switching	-	50	-	kHz
Stray inductance (D1-S2)	L_{SCE}	terminal-chip	-	60	-	nH
Lead resistance	R_{CE}	terminal-chip	-	0.8	-	m Ω

Thermal and Mechanical Characteristics, T_J=25°C unless specified

Parameter	Symbol	Test conditions	Min	Typ	Max	Unit
Thermal resistance	$R_{th(J-C)}Q$	Per HEMT(4)	-	-	0.2	° C/W
Thermal resistance	$R_{th(J-C)}D$	PerDiode(4)	-	-	0.4	° C/W
Contact resistance, case to sink	$R_{th(C-HS)}$	Per module, thermal grease applied	-	0.020		° C/W
Clearance distance in air	$d_{a(t-b)}$	Terminal to base	35	-	-	mm
Clearance distance along surface	$d_{s(t-b)}$	Terminal to base	64	-	-	mm
Clearance distance in air	$d_{a(t-t)}$	Terminal to terminal	19	-	-	mm
Clearance distance along surface	$d_{s(t-t)}$	Terminal to terminal	54	-	-	mm
Comparative tracking index	CTI		600	-	-	

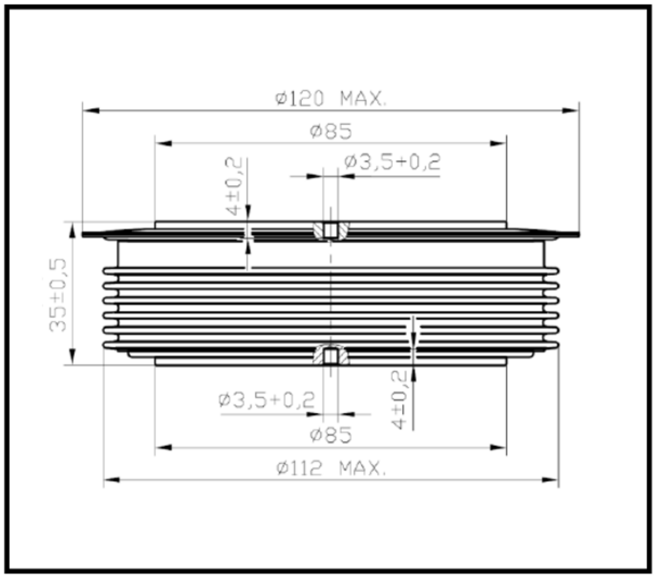
***Tc measurement point is just under the chips

Packaging Option A: Presspack, Dual sided cooling, Creepage and Clearance meet IEC 60077-1

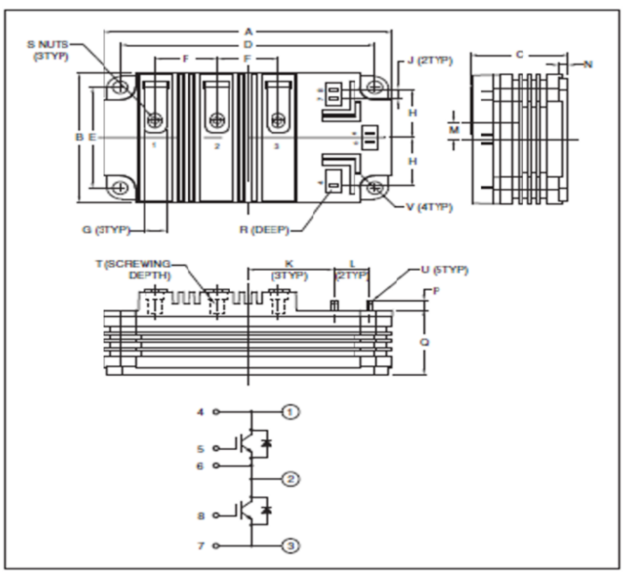


Mechanical Data

F_m	Mounting force	70 ± 7 kN
m	Weight	2.0 kg
D_S	Surface creepage distance	56 mm
D_a	Air strike distance	28 mm



Packaging Option B: Dual HV Module, Isolated Base, Creepage and Clearance meet IEC 60077-1



Outline Drawing and Circuit Diagram

Dimensions	Inches	Millimeters
A	5.51	140.0
B	2.87	73.0
C	1.89	48.0
D	4.88±0.01	124.0±0.25
E	2.24±0.01	57.0±0.25
F	1.18	30.0
G	0.43	11.0
H	1.07	27.15
J	0.20	5.0
K	1.65	42.0

Dimensions	Inches	Millimeters
L	0.69±0.01	17.5±0.25
M	0.38	9.75
N	0.20	5.0
P	0.22	5.5
Q	1.44	36.5
R	0.16	4.0
S	M6 Metric	M6
T	0.63 Min.	16.0 Min.
U	0.11 x 0.02	2.8 x 0.5
V	0.28 Dia.	7.0 Dia.