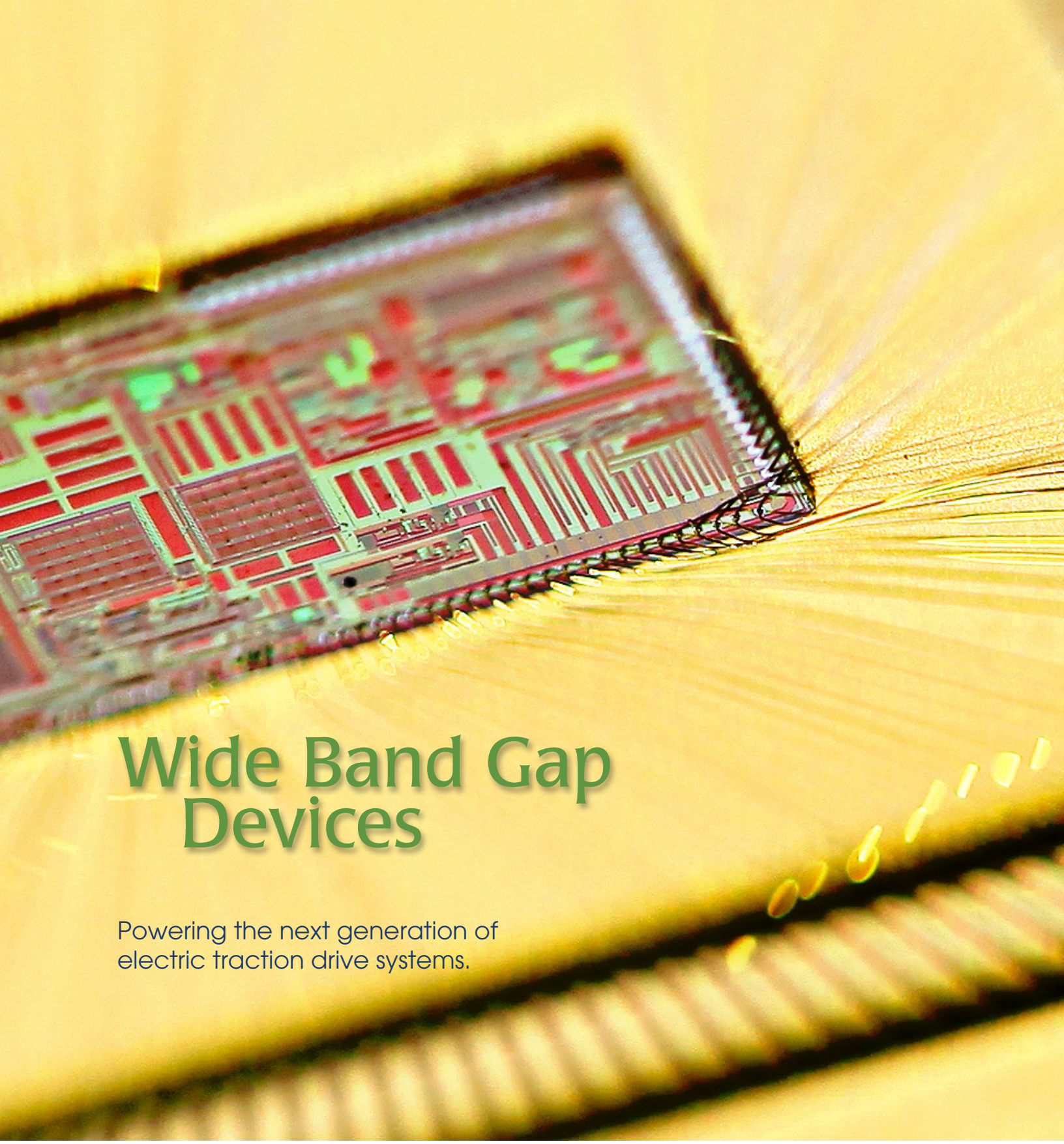


Wide Band Gap Devices

Powering the next generation of electric traction drive systems.

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

Wide Band Gap Devices for the Next Generation of Electric Traction Drive Systems

Wide Band Gap materials, such as silicon carbide and gallium nitride, enable the development of smaller semiconductor devices that demonstrate significantly higher performance while demanding less power than more commonly used silicon semiconductor devices. With properties suitable for conducting electricity in extreme environments, they are ideal devices for applications that are subject to high voltages and temperatures found in electric vehicles.

Despite the benefits, commercial viability of wide band gap materials and devices is limited with pricing 3 to 5 times higher than silicon semiconductor devices. Wide band gap materials contribute about 40% of the total device cost depending on availability, quality, and performance. Device design, fabrication, and packaging are also key factors to higher costs.

Significant DOE investments in materials and power electronics research and development capabilities at Oak Ridge National Laboratory and with supplier and university collaborations are accelerating production of wide band gap materials and devices for future electric vehicles. A vertically integrated approach, ORNL efforts range from fundamental science to technology development and maturation strategies with a focus on materials research, device design, packaging, manufacturing processes, system design and development, and reliability.

Why wide band gap materials and devices?

Energy Independence

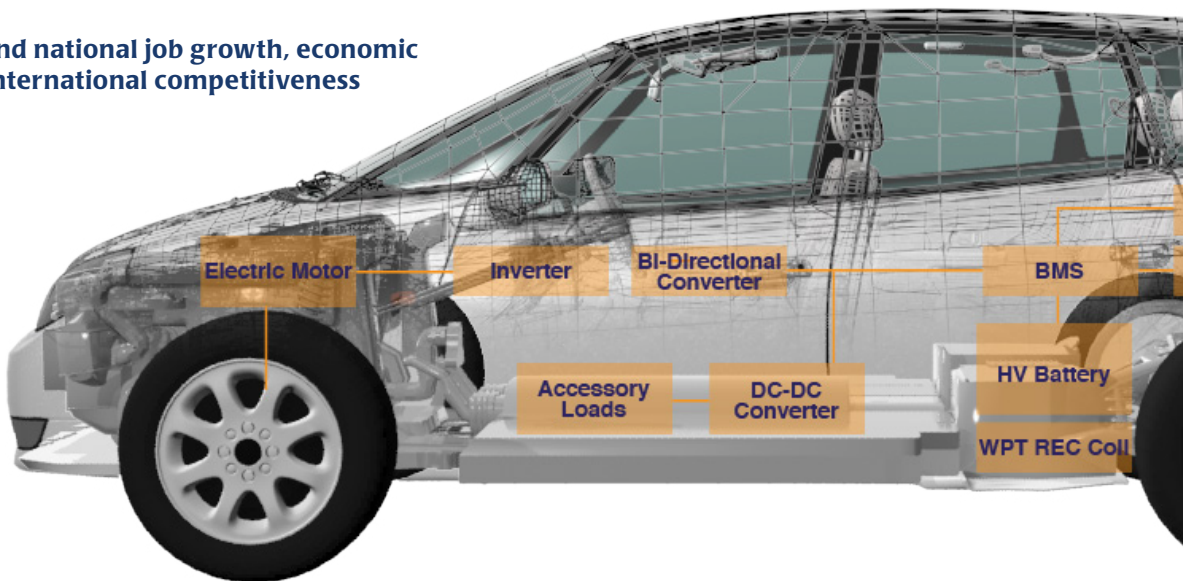
Enable a more sustainable energy future through electric vehicle strategies that improve drivetrain performance and efficiency

US Manufacturing

Boost the development and growth of existing and new wide band gap materials producers, device manufacturers, and automotive manufacturers

Job Growth

Cultivate regional and national job growth, economic development, and international competitiveness



Cover photo: Silicon-on-insulator (SOI) universal gate drive chip developed by ORNL for wide band gap devices capable of operating -55°C to 200°C

Today's Research

Innovations leading to new power electronics

Materials

A world-leader in materials research, ORNL is applying vast expertise in single crystal growth, epitaxial film deposition, and buffer development to improve the quality of wide band gap semiconductors by reducing internal defects and stresses. Researchers are also exploring continuous manufacturing of flexible single crystal wide band gap semiconductors and substrates as well as solution precursors for low-cost single crystal buffers and wide band gap films.

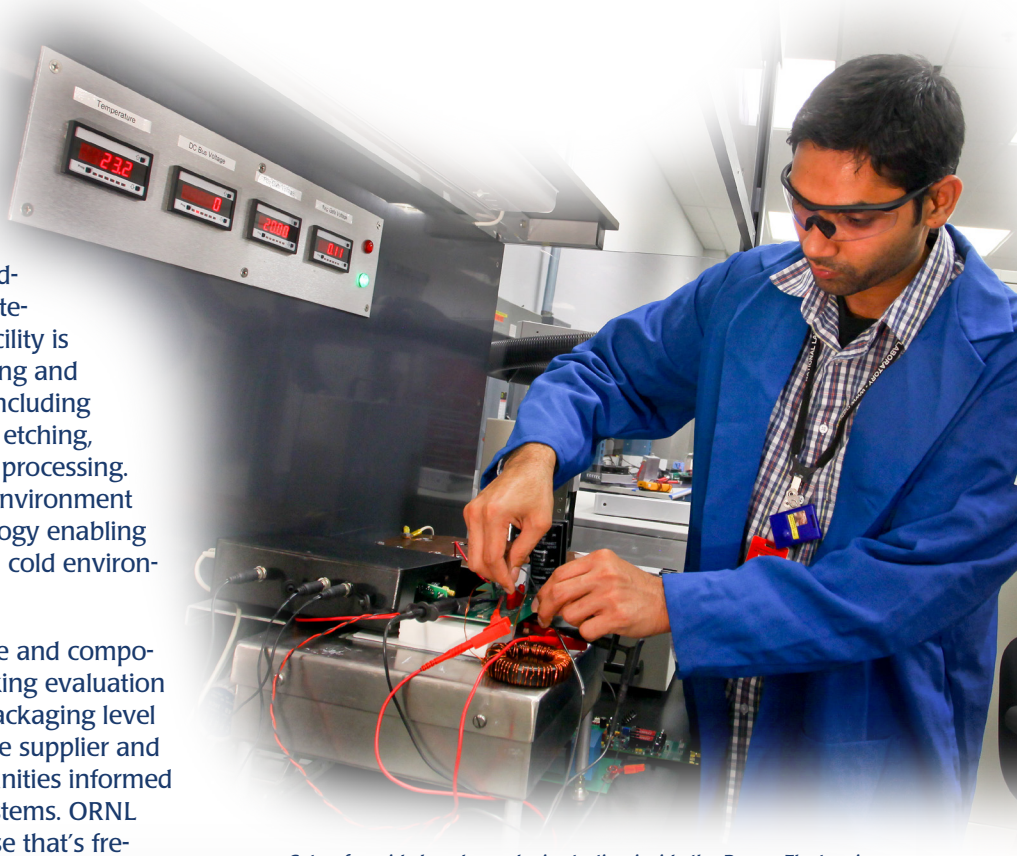
With the advent of wide band gap based devices operating at higher temperatures and in harsh environments compared to silicon-based devices, new packaging materials are required that can withstand these same operating conditions. ORNL scientists are actively engaged in understanding the inadequacies in current packages and developing alternate materials capable of providing the performance advantages feasible from wide band gap devices without sacrificing reliability. This alternative materials research explores new adhesion techniques (including sintered die attach) that are capable of withstanding harsh environments and high cyclic stresses. Substrate activities focus on raising thermal conductivity, enhancing thermal cycling characteristics, and metallization. Other materials research includes development of insulating materials for high voltage and high temperature operations. The Lab maintains close relationships with wide band gap fabricators, device fabricators, materials suppliers and end-users to facilitate vertically integrated teams that can develop, evaluate, and rapidly bring these new technologies to the marketplace.

Chemical vapor deposition system used in the fundamental study of wide band gap semiconductor films

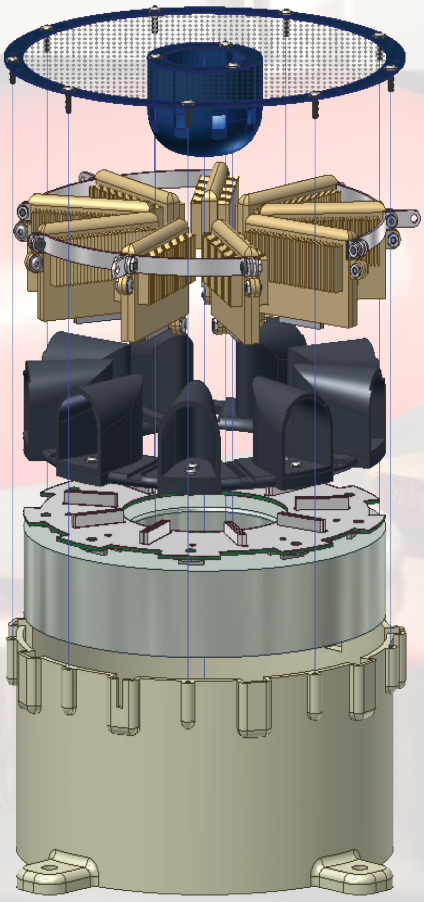
Devices

Within its Nanoscale Science and Technology Laboratory (NSTL), ORNL houses semiconductor-based device fabrication equipment to support a wide variety of thin-film and solid-state electronic research projects. With state-of-the-art technology and expertise, the facility is a key industry resource for hands-on training and consultation in fabrication and processes including photolithography, thin-film deposition and etching, metrology and imaging, and wet chemical processing. Complementary to NSTL is ORNL's Harsh Environment Electronics Laboratory that houses technology enabling custom circuit design for extreme heat and cold environments.

The Lab's automated wide band gap device and component testing capabilities enable benchmarking evaluation and characterization at the bare die and packaging level as well as device modeling to help keep the supplier and Federal research and development communities informed on the state of the art for traction drive systems. ORNL maintains a wide band gap device database that's frequently accessed by the research community.



Setup for wide band gap device testing inside the Power Electronics and Electrical Power Systems Research Center



Systems

Wide band gap research at ORNL is focused on the development of high efficiency, high temperature wide band gap-based inverters for automotive and power system applications. Research involves work on high temperature packaging (>200°C), high temperature gate drive electronics, inverter/converter design and prototype development, efficiency estimation with device and system simulation, and experiments.

The Power Electronics and Electrical Power Systems Research Center works closely with industry partners to conduct high-level system modeling of power converters for motor drives showing the impact of using wide band gap devices.

The device level development of wide band gap material has progressed from designing discrete level low amperage devices to building modules with scalable devices and higher power ratings. This growth has enabled researchers to test modules for efficiency comparison with silicon devices and also build several converter and inverter prototypes.

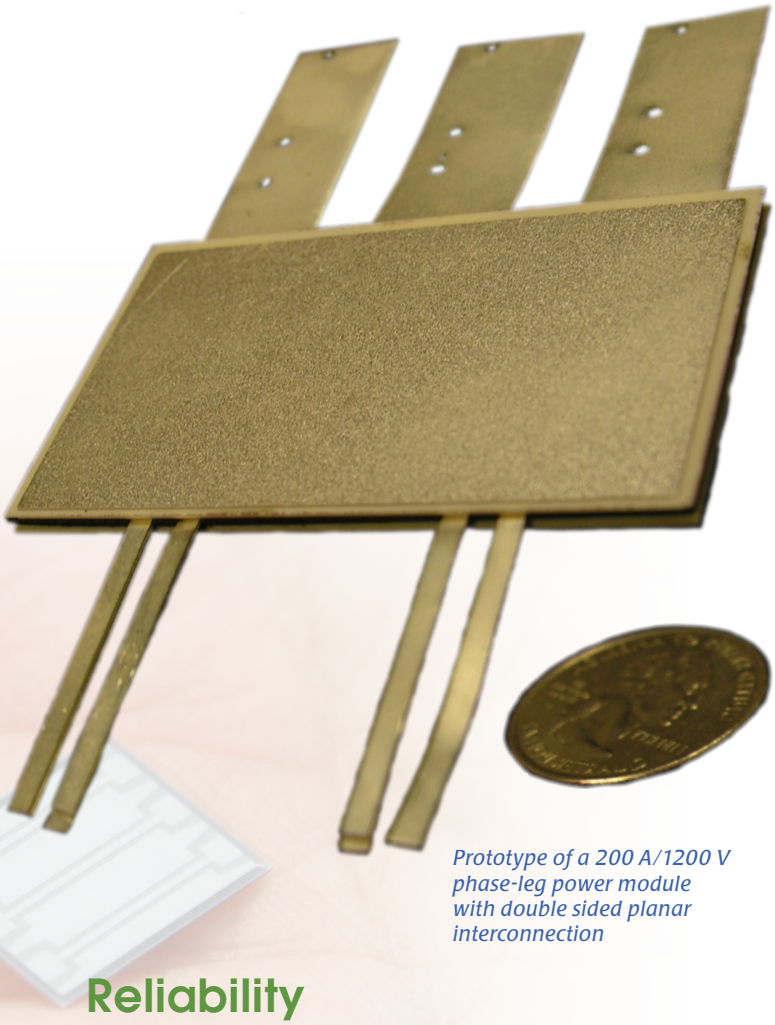
ORNL collaborated with partners to build industry's first silicon insulated-gate bipolar transistor–silcon carbonide Schottky diode hybrid 55kW inverter. The 55-kW automotive inverter built under the FreedomCAR Program demonstrated up to 30% improvement is efficiency compared to a similar all-silcon module. Recently, ORNL has developed all-silicon carbide air cooled inverter designs with innovative high temperature module and heat sink designs.

55-kW air cooled all silicon carbide traction drive inverter

Packaging

The Power Electronics and Electrical Power Systems Research Center houses a full suite of state-of-the art technologies and real-world simulation capabilities inside its packaging laboratory. This specialized laboratory enables greater exploration of the power electronics module that is composed primarily of wide band gap semiconductor devices and plays a large role in the operation of an electric vehicle.

ORNL researchers have prototyped a variety of wide band gap-based inverters, dc-dc converters, and power modules. For example, the Planar_Bond_All power module benefits the automotive industry with properties for improving efficiency, power density, and cost while simplifying the packaging process.



Prototype of a 200 A/1200 V phase-leg power module with double sided planar interconnection

Manufacturing

Multiple ORNL facilities are available to support wide band gap device fabrication including the new Manufacturing Demonstration Facility (MDF), which offers industry access to unique additive manufacturing and material characterization tools and expertise for facilitating pathways to revolutionary processes and technologies. For example, the MDF's additive manufacturing capabilities enable product customization and improved performance, function and costs – desired attributes for future wide band gap devices.

Over the last decade, ORNL researchers have worked closely with industry partners on the roll-to-roll manufacturing of epitaxial thin film products that routinely exceed five hundred meters in piece length. They have gained substantial expertise in manufacturing challenges such as uniformity, throughput, and yield. These insights are being applied to our manufacturing efforts in order to accelerate the product-to-market cycle. ORNL is developing a high throughput process for manufacturing high performance ultraviolet light emitting diode (LED) semiconductor light sources with efforts extending roll-to-roll metal organic chemical vapor deposition processing to wide band gap materials. The quantitative impacts of the new process include improved luminescence and ultraviolet absorption capabilities with low-cost and scalable methods of film preparation. ORNL is also working with device providers to incorporate the next level of circuit integration capabilities in gallium nitride and gallium nitride-on-silicon processes.

Reliability

Next generation, high performance power electronic packages and systems must utilize wide band gap devices operating at high temperatures to obtain their optimum benefit in automotive applications. Such devices, their associated packages, and the systems they are designed for are subject to temperatures up to 175°C, temperature cycles due to the shut-downs, start-ups, and fluctuations in power demand. Understanding the effect of these prolonged operating conditions is critical.

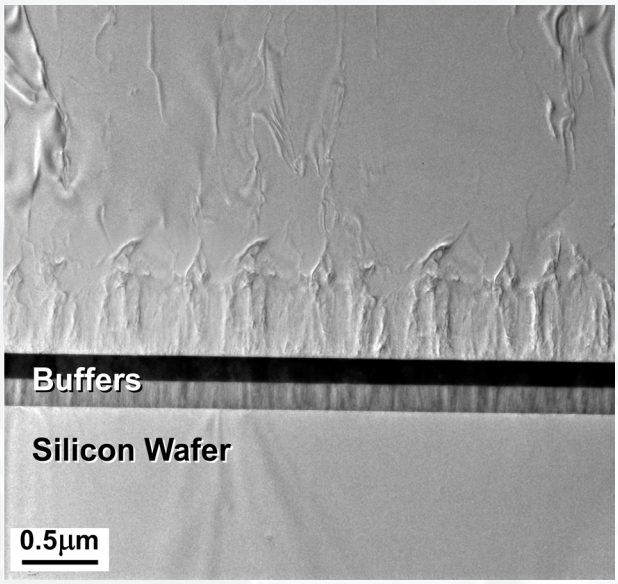
Among research efforts, ORNL is focused on understanding the damage evolution and failure of die attaches (one of the likely weak links in high temperature packages). Recent work focused on studying the behavior of die attachments when cycling between 5°C and 200°C using high resolution X-ray radiography and finite element analysis with a particular emphasis on understanding the role of materials properties and temperature cycling as damage evolves within the solder joints. Understanding these materials relationships provides ORNL with the capability to better predict for device manufacturers the reliability of joints under field conditions while also providing feedback for the development of new materials in order to improve their lifetime and reliability for electric drivetrain applications.

Tomorrow's Research

Wide band gap devices as packaged power modules represent a key pillar in future traction drive systems along with non-rare earth motors and higher level integration, collectively leading to affordable and higher efficiency electrified vehicles. Power inverters benefit from the higher voltage capability of wide band gap devices facilitating system cost reductions. Converters and onboard chargers benefit most from high frequency switching capability of wide band gap devices that directly address the 60% cost of passive and power device content. At the traction drive system level, the transition from silicon to wide band gap technologies will enable a single coolant loop or potentially a blend of coolant loop and air cooling for overall mass, volume, and cost reductions. Advances in wide band gap material and device manufacturing will further enhance traction drive system efficiency and reliability.

In addition to silicon carbide and gallium nitride, ORNL scientists are exploring the growth mechanism and potential impact of other wide band gap materials. For example, very thick epitaxial films have been deposited on buffered silicon substrates using plasma-assisted metal organic chemical vapor deposition process. Efforts to introduce various dopants into these films are being pursued.

ORNL researchers are exploring the feasibility of a very high throughput fabrication process that can potentially result in near-net-shape single crystalline materials with pristine surfaces that are ready for further processing. If successful, this process promises to produce high quality materials at very low cost.



Cross-sectional micrograph of a heteroepitaxial single crystal thick film deposited on buffered silicon by molecular jet-assisted metalorganic chemical vapor deposition

Wide band gap materials and devices enable reduced electric traction drive costs

Wide band gap devices excel at high voltages, enabling lower-cost traction drives from a higher operating voltage

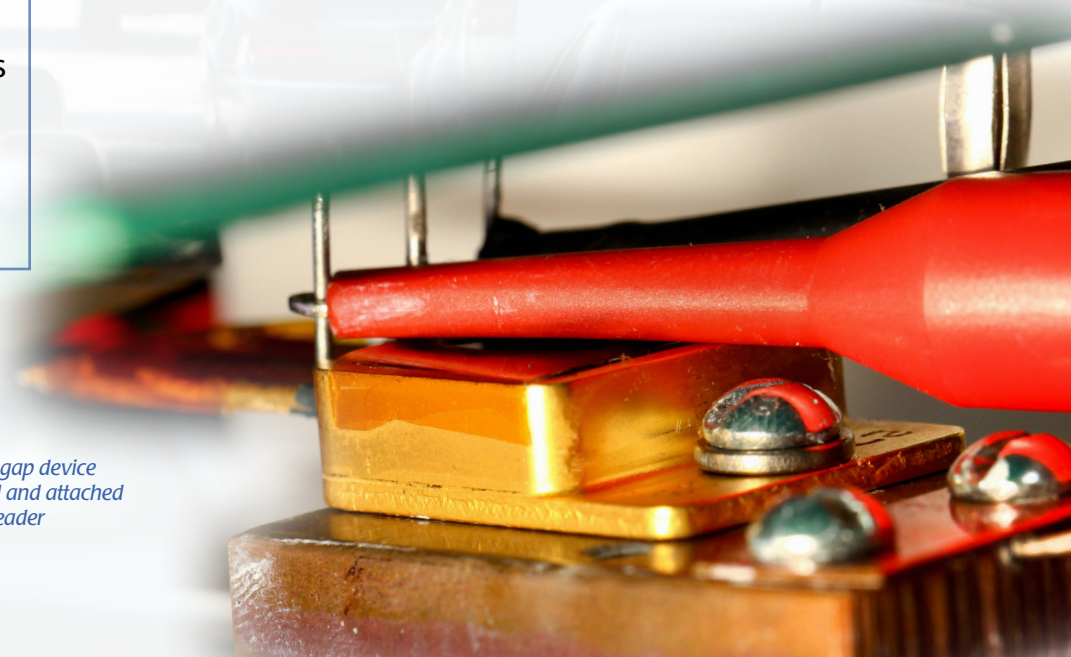
Wide band gap devices excel at electrical efficiency, enabling lower-cost heat removal designs for the traction drive system

Wide band gap devices excel at high temperature operation, enabling lower-cost heat removal designs

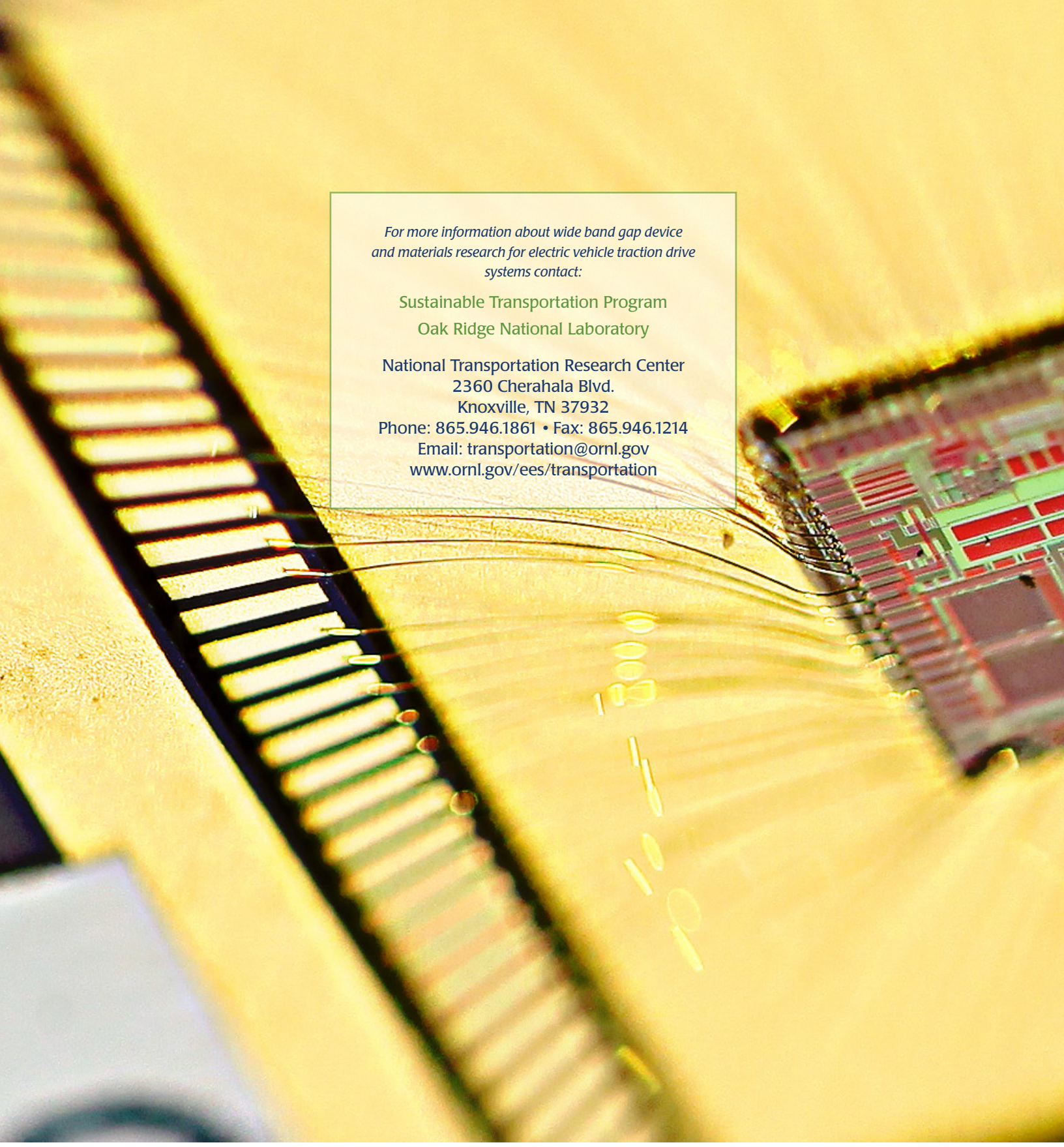
Partnerships

ORNL engages an ensemble of collaborators, capabilities, and expertise throughout the wide band gap value chain with emphasis on the creation and execution of vertically-integrated partnerships. Partners include those involved in materials research, material suppliers, device suppliers, and device manufacturers. For detailed information on ORNL partnering mechanisms, which allow for both proprietary and nonproprietary work, visit http:/www.ornl.gov/adm/partnerships.

- Academia
- Component Suppliers
- Government Agencies
- Original Equipment Manufacturers
- Consortia



A wide band gap device instrumented and attached to a heat spreader



For more information about wide band gap device and materials research for electric vehicle traction drive systems contact:

Sustainable Transportation Program

Oak Ridge National Laboratory

National Transportation Research Center
2360 Cherahala Blvd.
Knoxville, TN 37932
Phone: 865.946.1861 • Fax: 865.946.1214
Email: transportation@ornl.gov
www.ornl.gov/ees/transportation

U.S. DEPARTMENT OF ENERGY

ORNL 2012_G01058 / LAM