Wide Bandgap Semiconductors: *Pursuing the Promise*

Wide bandgap semiconductors are poised to revolutionize the next generation of power electronics and clean energy innovations. Advanced manufacturing processes that take advantage of this innovative technology will give U.S. manufacturers a competitive edge in growing global markets. *Photo credits: iStock/19221337, 18866928, 15649881*

Superior semiconductor materials will enable greater energy efficiency in industrial-scale power electronics and clean energy technologies.

Wide bandgap (WBG) semiconductor materials allow power electronic components to be smaller, faster, more reliable, and more efficient than their silicon (Si)-based counterparts. These capabilities make it possible to reduce weight, volume, and life-cycle costs in a wide range of power applications. Harnessing these capabilities can lead to dramatic energy savings in industrial processing and consumer appliances, accelerate widespread use of electric vehicles and fuel cells, and help integrate renewable energy onto the electric grid.

Wide bandgap semiconductors (shown in green) are materials that possess bandgaps significantly greater than those of silicon.

Semiconductor Materials		
Material	**Chemical Symbol**	**Bandgap Energy (eV)**
Germanium	Ge	0.7
Silicon	Si	1.1
Gallium Arsenide	GaAs	1.4
Silicon Carbide	SiC	3.3
Zinc Oxide	ZnO	3.4
Gallium Nitride	GaN	3.4
Diamond	C	5.5

WBG semiconductors (see table below) permit devices to operate at much higher temperatures, voltages, and frequencies—making the power electronic modules using these materials significantly more powerful and energy efficient than those made from conventional semiconductor materials.

WBG materials also emit light in the visible color range, an optical property useful for applications in solid-state lighting. Gallium nitride (GaN), for example, is an enabling material behind the ultra-high efficiency of light emitting diodes (LEDs).

WBG semiconductors are expected to pave the way for exciting innovations in power electronics, solid-state lighting, and other diverse applications across multiple industrial and clean energy sectors. Realizing the energy-saving potential of WBG semiconductors will require the development of cutting-edge manufacturing processes that can produce high-quality WBG materials, devices, and modules at an affordable cost. Investing in this innovative technology will help U.S. industry maintain a competitive edge.

Smaller, Faster, and More Efficient

WBG materials have the potential to enable cutting-edge electronic and optical devices with vastly superior performance compared to current technology. Specific energy-related benefits are listed below:

Electronic devices

- *Reduced energy losses:* Eliminates up to 90% of the power losses that currently occur during AC-to-DC and DC-to-AC electricity conversion.[1]
- *Higher-voltage operation:* Handles voltages more than 10 times higher than Si-based devices, greatly enhancing performance in high-power applications.[2]
- *Higher-temperature operation:* Operates at temperatures over 300°C (twice the maximum temperature of Si-based devices). This tolerance for higher operating temperature results in better overall system reliability, enables smaller and lighter systems with reduced lifecycle energy use, and creates opportunities for new applications.[2]
- *Higher frequencies:* Operates at frequencies at least 10 times higher than Si-based devices, making possible more compact, less costly product designs and opening up a range of new applications, such as radio frequency (RF) amplifiers.[1]
- *Improved power quality:* Ensures more reliable and consistent power electronic device operation.

Optical devices

- *Greater lighting efficiency:* WBG-based LEDs produce more than 10 times more light per watt of input energy than comparable incandescent bulbs and extend service life by 30 times or more.

Applications

As manufacturing capabilities improve and market applications expand, costs are expected to decrease, making WBG-based devices competitive with less expensive Si-based devices.

Industrial Motors: WBG materials will enable higher-efficiency, variable-speed drives in motors—pumps, fans, compressors, and HVAC systems—used across manufacturing. Motor systems use 69% of the electricity consumed in U.S. manufacturing.[3]

Electronics: WBG materials are already used in large, high-efficiency data centers and show promise as compact power supplies for consumer electronics.

Grid integration: WBG-based inverters can convert the DC electricity generated from solar and wind energy into the AC electricity used in homes and businesses—while reducing losses by 50%.[2]

Utility applications: WBG have the potential to reduce transformer size by a factor of ten or more. WBG-based power electronics could also accelerate development of high-voltage DC power lines, which will operate more efficiently than existing high-voltage AC transmission lines.

Electric vehicles and plug-in hybrids: WBG materials are expected to cut electricity losses by 66% during vehicle battery recharging.[2] They also offer greater efficiency in converting AC to DC power and in operating the electric traction drive during vehicle use. The ability of these electronics to tolerate higher operating temperatures could reduce the size of an automotive cooling system by 60% or even eliminate the secondary liquid cooling system.[2]

Military: WBG semiconductors have great potential as an enabling material in high-density power applications, satellite communications, and high-frequency and high-power radar.

Geothermal: WBG-based electronic sensors can withstand the harsh, high-pressure, and high-temperature environments of geothermal wells.

Lighting: At today's energy prices, LED lighting is expected to save $250 billion in cumulative energy costs by 2030.[4]

Challenges

WBG materials and devices are rapidly gaining acceptance. However, a number of manufacturing challenges must be addressed to make WBG materials cost effective in more applications.

- *Substrate size and cost:* While the quality of GaN and silicon carbide (SiC) wafers is improving, the cost of producing larger-diameter wafers needs to be reduced.
- *Device design and cost:* Novel device designs that effectively exploit the properties of WBG materials are needed to achieve the voltage and current ratings required in certain applications. Alternative packaging materials or designs are also needed to withstand the high temperatures in WBG devices. Architectures that improve manufacturability and affordability are needed to spur commercialization.
- *Systems integration:* WBG devices are not always suitable drop-in replacements for Si-based devices. The larger, more complex systems must be redesigned to integrate the WBG devices in ways that deliver unique capabilities.

Broad Economic Impacts

WBG semiconductors are a foundational technology that promises to transform multiple industries and markets. Low-cost, high-performance power electronics are expected to become integral to everything from household appliances and consumer goods to military systems, vehicles, and a modernized grid that incorporates renewable energy. The WBG share of the global lighting market alone is projected to reach $84 billion by 2020.[5] GaN and SiC are expected to claim 22% of the $15 billion global market for discrete power electronic components by 2020 in just four industry segments (buildings and industrial, electronics and IT, renewables and grid storage, and transportation).[6]

The ability to design and manufacture innovative WBG-enabled devices cost effectively will create a strong foundation of domestic materials technology expertise and give U.S. manufacturers early entry and, therefore, a competitive edge in key global markets. Extensive use of these devices will save U.S. businesses and consumers billions of dollars in energy costs.

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1 *Power Electronics for Distributed Energy Systems and Transmission and Distribution Applications*, ORNL, 2005.

2 *Silicon Carbide: Smaller, Faster, Tougher*. IEEE Spectrum, October 2011.

3 *Manufacturing Energy and Carbon Footprints*, U.S. DOE, October 2012.

4 *Energy Savings Potential of Solid-State Lighting in General Illumination Applications*, U.S. DOE, January 2012.

5 *Lighting the Way*, McKinsey & Company, Inc., August 2012.

6 *Beyond Silicon*, Lux Research, Inc., March 2012.

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