Technology and Market Intelligence: Wide Bandgap Semiconductors:

Silicon Carbide for Automotive Applications

Prepared for the Department of Energy

Synthesis Partners, LLC

This report is intended for public release.

Please contact Steven Boyd, DOE or Synthesis Partners with questions or comments. Thank you.

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Tasking

Synthesis Partners was tasked by the Department of Energy (DOE) to undertake research to address the following specific questions regarding wide bandgap semiconductors and their application in the hybrid and electric vehicle markets.

1. Review current technology R&D activities relevant to automotive power semiconductors

2. Focus on near-military specifications at significantly lower costs

3. Focus on devices with the following characteristics:
    a. 600-1200 V
    b. 5-20 A or higher if possible, up to ~70 A
    c. 200-300°C
    d. Large wafer sizes preferred for lower cost

Sources and Methods

This research and analysis effort accessed a wide range of secondary and primary sources in a short period of time. Table 1 below provides summary information concerning the sources searched during the November 2009 – February 2010 timeframe.

We analyzed many targeted secondary sources, including 16 market research reports, 20 companies, a number of journal articles and white papers, and conducted personal interviews with researchers and industry leaders. Table 1 below presents more detailed information.

Primary research (i.e., personal and telephone interviews and email exchanges) focused on the research programs and semiconductor companies that best represent the state-of-the-art in wide bandgap semiconductor research and development, both in the US and overseas. Research focused primarily on silicon carbide (SiC) power semiconductors for the automotive market but also looked into other materials and applications when relevant.

Table 1: Research Summary

Source	**Number Researched**	**Percentage Relevant**
Market Research Reports	16	0%
Companies	20	100%
Trade/Professional Associations	2	100%
Universities	14	100%
Financial/Commodity Sites	0	0%
Companies Contacted	**Negative or No Response**	**Positive Response**
ABB	X	
American Microsemiconductor	X	
Cree		X
Delphi		X

Dow Corning		X
Fairchild	X	
Ford		X
Fuji Electric	X	
GE		X
GeneSiC Semiconductor		X
GM		X
Honda	X	
Infineon		X
Kyocera		X
Mitsubishi	X	
Powerex		X
ROHM		X
SEMIKRON		X
Toyota	X	
US Hybrid		X
Labs/Agencies Contacted		
ORNL		X
NASA		X
Universities Contacted		
Auburn University		X
Georgia Tech Research Institute	X	
MIT	X	
MS State	X	
NC State	X	
Purdue	X	
Rensselaer Polytechnic Institute	X	
Rutgers	X	
University of Arkansas		X
University of South Carolina	X	
UT Knoxville	X	

Background

Wide bandgap semiconductors (WBGS) use materials such as silicon carbide (SiC), gallium nitride (GaN), gallium arsenide (GaAs) and aluminum nitride (AlN) as the semiconductor material instead of the silicon (Si) typically used. These materials produce a semiconductor that can operate at much higher temperatures and frequencies, and handle much greater voltages than standard silicon-based semiconductors.

WBGS are used to produce wide bandgap transistors for power switching applications and RF signal processing. SiC and GaN are the two most commonly used materials for these applications. The main factor limiting their adoption for these applications is the wafer size that can be produced both technically and economically using currently-available processes. The temperature resistance that gives these devices an operational advantage also serves as a complicating factor in the manufacturing and production processes, given (among other factors) the higher temperature manufacturing methods that are needed to produce the wafers.

However, the production process for these semiconductors is significantly slower than that of silicon crystals for standard semiconductors. Producing the crystals to fabricate the wafers requires temperatures in excess of 2000° C for SiC. The material does not melt; it sublimates and the crystals must then be condensed from the vapors. The largest wafer size currently commercially available for this material is four inches (100mm). While the capability to produce six-inch wafers exists, according to John Palmour of Cree, the world's leading producer of SiC semiconductors and LEDs, market demand is currently insufficient to warrant production.

Gallium nitride (GaN) is produced by condensing the GaN vapors (usually created by combining the vapors of a gallium compound with nitrogen or ammonia vapors) into crystals or by condensing the GaN in layers directly onto the substrate (typically SiC or sapphire, though success in depositing GaN directly onto Si substrates has recently been reported in R&D projects). According to Cree, these processes are prone to producing crystals with substandard lattice structures. The crystals produced are smaller than either Si or SiC crystals, thus driving up the cost of producing bulk materials.

In terms of higher-voltage applications relevant to drive-trains, the result is that market demand for emerging WBGS modules is low because their manufacturing cost is high, in part due to the unavoidably complex manufacturing processes. Low market demand in turn leads to especially high cost-premiums given the large capital expenditures that are spread over relatively low-volume production runs.

Technologically, WBGS devices have distinct advantages over other semiconductors due to their much higher operating temperature range. Silicon-based semiconductors fail at about 150°C. Semiconductors based on GaN can operate at temperatures in excess of 200°C; tests by Toyota have shown they can withstand temperatures in excess of 300°C. NASA tests have shown some SiC devices can operate at temperatures as high as 650°C.

WBGS can operate at approximately twice the voltage of Si-based semiconductors, have higher thermal conductivity (heat is more easily transferred from the device and is thus less likely to cause heat-related problems in other devices) and can operate at higher frequencies. These semiconductors are also much lighter and smaller than Si-based devices of comparable ratings. This allows smaller and lighter devices to be built using WBGS.

We assess that GaN is less likely to be used in automotive applications prior to the adoption of SiC, primarily because GaN has a significantly higher cost of production than SiC at this time. This is based on the scarcity (according to public information) of low-cost substrates on which GaN can be easily grown for high-voltage applications. However, it is likely that new substrates are being developed by OEM suppliers to take advantage of the potential advantages provided by GaN, which include easier and lower-cost processing as compared with SiC – if it can be grown on Si or other low-cost substrates. For example, Delphi and International Rectifier began work on a $6.7m Recovery Act R&D project in March 2010 to leverage a new process developed by International Rectifier for depositing GaN-on-Si, which is compatible with standard CMOS lines utilizing 6” (150mm) wafers. Delphi will supply new packaging technologies that allow dual side cooling and higher current densities, while Oak Ridge National Laboratory will provide device and system benefit characterization, and support on sintering under this project.

Interestingly, using Si as a substrate may compromise the advantage of the higher operating temperatures GaN provides. Cree currently grows its GaN wafers on SiC. This process is expensive and is not used except for those applications which have no alternative, such as certain types of Light Emitting Diode (LED) displays.

It is notable that the use of GaN in low-voltage Schottky diode applications is increasing. These applications use sapphire as a substrate. GaN on Si substrate is also used by some manufacturers to produce FET devices. However, no information was found to show that strictly GaN MOSFETS or IGBTS are currently being produced. There are indications that research is underway in this area, however.

The use of GaN for lower voltage applications, in particular for the LED industry, is not new. Compound Semiconductor magazine reported in 2008 that GaN-on-sapphire substrates “promise to be a much cheaper alternative to SiC.” The magazine noted that while this combination of materials is reported to suffer from sapphire's low conductivity – something that ultimately leads to poor thermal resistances and hot, unreliable devices – Velox Semiconductor (Somerset, NJ) has demonstrated this not to be true with GaN-on-sapphire diodes incorporated in an insulating frame. According to Compound Semiconductor, “the compatibility with an insulating frame is a big advantage over SiC, because it reduces the cooling demands of the heat sinks employed in the SMPSs [switch-mode power supplies].”

In short, in the context of the multibillion-dollar LED industry, GaN-on-sapphire modules have been shown to deliver efficiencies comparable to SiC and manufacturing cost-savings over SiC using sapphire substrates. Further gains are realized from GaN's lower growth temperature (1,000 to 1,100°C versus 1,500 to 1,600°C for SiC) for these applications. Finally, it has been reported – though not independently validated – that reactor parts for SiC growth are very expensive, not particularly reliable, and suffer from a small supply base.

With regard to specific GaN patent activity claimed by the automotive industry, a limited search of recent (January 1, 2005 – present) patents for GaN semiconductor devices (including LEDs) or manufacturing techniques was conducted. It shows significant activity over the last five years by Japanese manufacturers, in particular:

Patent Assignee	Number of Patents
Mitsubishi*	151
Toyota (Toyoda Gosei)	74
Nissan	63
GM (Delphi)	2
Ford	0
Honda	0

*Patent assignee is a company within Mitsubishi Heavy Industries and may not necessarily be Mitsubishi Motors.

These initial numbers demonstrate an imbalance of activity, as several Japanese manufacturers lead the R&D activity in the field by a wide margin. Of course, this is only one measure of current R&D activity and it is not complete. Also, the existence of patents themselves does not indicate that GaN power module breakthroughs are pending for automotive applications. However, this limited review does suggest that GaN device R&D is an area in which some automotive companies are active, and therefore may be a source of future technology surprises.

While Synthesis assesses that SiC is more likely than GaN to be used as a WBG material by the automotive industry in the near-term, this topic bears further collection and analysis. Synthesis makes this judgment based on the following factors (in addition to those outlined in subsequent sections of this study, regarding SiC's relative merits):

- SiC power module technology has been further developed, and has been implemented by a select number of OEMs in the automotive industry, though its universal adoption is far from certain.
- While the investments being made to advance the state of the GaN-art by the LED industry are a key factor to consider with regard to potential innovative breakthroughs in GaN, it is unclear if such developments may drive the evolution of higher-voltage GaN modules for automotive applications.
- Pure GaN power modules are likely only for gigawatt and tetrawatt range devices, and not for those rated in megawatts (particularly the 2000-4000V range), which is the highest voltage range addressed in this report as of potential relevance to automotive producers.
- Other industries, including aerospace, defense, and medical, may provide the near-term market demand for higher voltage GaN-based WBGS devices. However, these applications will not create the demand needed to drive cost reductions to a point at which these devices are competitive for automotive applications.

On the other hand, in an analogy to the hybrid Si and SiC power modules discussed later in this study, Synthesis makes the preliminary assessment that a hybrid Si and GaN power module using GaN diodes and Si IGBTs is a plausible emerging technology. More research on this topic is needed.

Synthesis concludes that there is a long-shot that an OEM may surprise market watchers with a GaN WBGS device for automotive applications within the next five years. Technical and market issues will determine the when, where, how, and why of successful commercialization of WBGS devices. These issues are reviewed in this report.

NOTE: This study did not address the market and technical requirements for materials used in packaging WBGS devices, such as SiN and AlN. The focus of this study is on SiC as a wide bandgap semiconductor substrate material for WBGS devices.

Key Findings

- While the experts disagree on the SiC – Si cost differential at which SiC components will begin to be adopted by the automotive industry, they all agree that the cost of SiC and relatively limited supply of SiC are the prime reasons for the continuing use of Si.

- At current market prices, using SiC is cost-prohibitive in mass-produced vehicles. However, with improvements in manufacturing processes and increased demand leading to volume production, the cost could drop enough within the next 3 - 5 years to make SiC a viable alternative to Si. For this to come to pass, the price of SiC components would need to be reduced to only a small premium (e.g., 20-30%) over Si components. However, one key source (Friedrichs, Peter et al, eds.: *Silicon Carbide*, 2010, Chapter 1, p. 12), which is a chapter on Toyota written by Kiminori Hamada of Toyota's Electrical Engineering Division, states: "[I]t must be understood that despite these superior material properties, SiC has little chance of being used unless it can be obtained at a cost that is the same as or lower than that of Si, which currently dominates nearly all semiconductor applications for rational economic reasons."

- At the current rate of development it will be at least five years before SiC MOSFET prices are low enough to interest automakers in replacing Si devices in large volumes.

- Above 2000V, "there is no competition for SiC, and this will be its sweet-spot.", according to Abas Goodarzi of US Hybrid Corporation.

- SiC power modules will not be useful for any automotive applications below 500V.

- Japanese government agencies, automakers and associated industry partners are actively pursuing SiC technology developments.

- In May 2010, the Japanese Ministry of Economy, Trade and Industry (METI) announced the start of the "New Material Power Semiconductor Device Project Toward Achieving a Low-Carbon Society" (budget for FY 2010: 2 billion yen, or approx. $22.6 million). The project includes the expansion of the R&D Partnership for Future Power Electronics Technology (FUPET) and the establishment of the SiC Alliance. FUPET and the SiC Alliance "will play important roles in promoting SiC research and development and introducing SiC to society," according to reports. METI is clearly actively supporting research towards practical applications of SiC.

- Japanese automakers are currently using a variety of substrate materials, including SiC, to work on power modules in the 1200V range and may be pushing beyond it. For example, Nissan claimed to have developed the world's first inverter using SiC diodes for vehicle use in September 2008, and implemented it in the XTRAIL FCV (Fuel Cell Vehicle). Mitsubishi is actively pursuing SiC technology R&D for their HEV/EVs, and Honda/ROHM appears poised to bring a SiC power module to the market.

- Bridgestone Corporation of Tokyo (the world's largest tire and rubber company), commenced production of silicon carbide wafers in 2010. It is reported that the PureBeta™ SiC Single Crystal Wafer being produced by Bridgestone extends the company's experience in using polymer technology and nanotechnology in developing tires.

- As currently implemented, Si power modules perform effectively due to a dedicated cooling system. There are no indications that eliminating this cooling loop will increase efficiency or reduce weight of <u>current</u> designs. However, as manufacturers design <u>future</u> automobiles, SiC provides an alternative to employing these dedicated cooling systems and will allow greater weight reduction with more efficient packaging and placement of components.

- While a Si-only solution could provide an approach to handling increased operating temperatures, the penalties of increased size and weight do not make it an optimum solution. In the long-run, alternative technology approaches, including SiC, are anticipated.

- At current market prices, eliminating the secondary cooling loop does not compensate for the increased cost of SiC. Realizing the full benefits of SiC, including higher operating temperatures and weight savings, will involve redesigning the vehicle to take advantage of the characteristics of SiC components. A detailed assessment of the implications of these changes at the system level has not been identified in the public domain.

- Using a hybrid Si MOSFET/IGBT-SiC diode device may provide an entry point for SiC, allowing increased production which should lead to lower costs. However, there is debate regarding the technical merits of transitioning from Si-SiC devices to an all-SiC device.

- While the American automakers do not appear to be interested in using voltages above the 600V-700V range, the Japanese manufacturers are working in that direction. This is one of the primary reasons they are interested in wide bandgap materials.

- Most indicators point to SiC as the best wide bandgap material for use in hybrid vehicle power electronics. However, Toyota is pursuing GaN as an alternative to Si. It is possible, though no evidence was found to confirm, that Toyota is developing a breakthrough technology which would allow cost-competitive production of GaN devices.

- US HEV sales are not sufficient to drive automotive OEMs to transition to SiC at this time. Thus, it appears that OEMs will need to consider the both HEV and non-HEV vehicle sales to achieve the necessary economies-of-scale to drive SiC costs to a competitive premium over the costs of Si.

- The current state of demand for SiC MOSFETS is a chicken-and-egg challenge: Dramatic reductions in the cost of SiC MOSFETS for automotive applications depend on large-volume production runs. However, without the high volumes, producers can't achieve the price-points required by automotive users. Automotive applications are particularly demanding, with a low-to-zero tolerance for price premiums.

- Non-automotive industries (e.g., wind, solar, and civilian/military aerospace applications) will drive SiC production growth over the next several years.

- SiC's adoption in the automotive sector will also be affected by other factors outside the automakers' control, such as efficiency and emission mandates.

1. Current technology R&D activities relevant to automotive power semiconductors

The following sections address the three questions outlined in the tasking by assessing the technical and market opportunities and challenges for SiC:

- Reviewing current technology R&D activities relevant to automotive power semiconductors
  - Addressed in our discussion of the supply curve
- Focusing on near-military specifications at significantly lower costs
  - Addressed in our discussion of the demand curve
- Focusing on devices that are 600-1200 V; 5-20 A or higher, if possible up to ~70 A; operating temperature ranges of 200-300°C; and large wafer sizes preferred for lower cost
  - Addressed through a review of developments relevant to the automotive market

We addressed the following issues to assess the applicability of wide bandgap materials for automotive power electronics from both technical and market perspectives:

- Technical feasibility and timeframe, or the supply curve. Specifically, the current state and rate of change in performance/cost trade-offs along the SiC technology development path. The issue of specific applications and industries is difficult to assess, because the technology development includes distinct challenges and opportunities at multiple levels, including the materials science, wafer-, diode/transistor, IC/ power module, packaging, and systems design and engineering levels.

- Market demand and timeframe, or the demand curve. Specifically, the current state and near-term expectations for demand, given specific power ratings and SiC performance/cost trade-offs. This depends on the nature of the applications that are most likely to benefit in the near-term from SiC breakthroughs, which are those applications in which SiC technical performance gains are needed (vis a vis current Si-only state-of-the-art) and are possible at a price point that markets will pay.

Synthesis has worked to produce original analysis during the course of this brief project to better define the state of play of SiC technology for current and future automotive applications. Synthesis' research efforts discovered no existing detailed analysis in public sources of the key elements affecting the supply and demand curves for WBGS. Further, integration of such findings into an assessment that would address the point at which the supply and demand curves might intersect, especially in the context of automotive sector needs, was also not found.

2. Supply and Demand Curve Assessments

The following section addresses technical feasibility and associated timeframes, as well as the issues of market demand, volume, and timeframes. It concludes with an assessment of the potential application of SiC technology to mass-produced hybrid vehicles.

a. Supply Curve Assessment

US Hybrid's Abas Goodarzi states that people who engineer and build cars are in general agreement that SiC has a way to go before it can be applied to mass-market vehicle applications. Nonetheless it has developed a reputation as the "next big thing." Academia in particular appears to possibly overemphasize the benefits of SiC. From a technical standpoint, Synthesis nonetheless finds that while SiC has a specific role to play in automotive design, its contribution will be narrow in the sense that it will likely only be in niche applications in the near term (approximately five years).

Research revealed that there are three separate but overlapping sources of research and development activities for WBGS for automotive power semiconductors:

- Academic institutions,
- National laboratories and
- Private industry.

However, most of the research consists of collaborative efforts between various organizations in each of these categories.

1. Academic institutions

Almost every school with an engineering or materials sciences department is doing or has performed research projects involving silicon carbide or other WBGS materials. However, schools with active research *programs* concerning wide bandgap semiconductor devices (primarily SiC devices) and/or their application in hybrid/electric vehicles are much fewer in number. Table 2 shows schools in the US at which these programs were found to be active. Table 3 contains information on similar programs discovered in schools outside of the US. The points of contact for all of these programs are noted in Appendix A. Unless otherwise noted, the Technology Readiness Levels (TRLs) listed were provided by the source indicated.

Table 2: Academic SiC Research Programs in the US

School	Program	Summary of Research Efforts	TRL
Auburn University	WBG Semiconductor Research Group	Auburn's WBGS research is focused on optimizing the oxide/SiC interface in power MOSFETS. Their research has underway for over 12 years. They' have reported limited successes. They are involved in pure scientific research on the devices and do not address cost/benefit or other aspects related to business or production issues. Auburn partners with Cree and GE. GE uses their research findings in their "internal business units" while Cree is applying it to production of SiC MOSFETS. The channel mobility/channel resistance problem Auburn is researching appears in mostly in devices in up to the 3kV range. The university's primary focus is on the 600V - 2kV range so while they are not specifically researching automotive applications, their research certainly is applicable to those applications. *Source: Interview with Dr. John R. Williams*	8 (see Note 1)
Georgia Tech	Microelectronics and Nanotechnologies Group	"Electro-Optical Systems Laboratory (EOSL) performs state-of-the- art research in the development and application of wide bandgap semiconductors for electronic and opto-electronic applications. Silicon carbide (SiC) and gallium nitride (GaN) have wide energy bandgaps that provide the potential for revolutionary performance improvement over silicon and gallium arsenide devices. We are growing epitaxial layers of GaN on various substrates using molecular beam epitaxy. EOSL has two molecular beam epitaxy systems that permit both solid and gas source growth processes." *Source: http://eosl.gtri.gatech.edu/Default.aspx?tabid=109*	3 (See Note 2)

Mississippi State University	Center for Advanced Vehicular Systems (CAVS)	"The goal of the Alternative Power Systems thrust is to achieve higher fuel efficiency and reduce pollution using advanced controls and renewable energy. This is accomplished through modeling and simulations of power train and bio-diesel hybrid technologies, including electric motor propulsion, power electronic switching and electronic control systems. This research is funded by the Air Force Research Laboratories and the United States Army Space and Missile Defense Command." "Engineers involved in vehicle system integration are developing power electronics that use the latest advances in silicon-carbide semiconductors developed at MSU and throughout the industry. This hardware, a working example of the practical-minded research conducted by CAVS, is then integrated into military vehicles such as the popular High Mobility Multi-Wheeled Vehicle ('HMMWV' or 'hummer.')" *Source: http://www.cavs.msstate.edu/*	3 (See Note 2)
MIT	Wide Bandgap Semiconductor Materials and Devices	"Since 1998, we have been involved with various micro- and opto-electronic devices fabricated in different semiconductor material systems. Out of all of these systems, nitride-based semiconductors have a unique combination of properties that make them especially suitable for many of the new challenges and applications of the 21st century. This material system is characterized by a wide range of very interesting properties, which make it the most complete semiconductor family. Some of these properties are: a direct bandgap tunable from 6.2 eV (AlN) down to 0.6 eV (InN), piezoelectricity, polarization, large breakdown voltage, biocompatibility, high chemical and thermal stability, etc. Moreover, even superconductivity and ferromagnetism have been proposed by some researchers. This vast array of properties makes these semiconductors ideal for many applications, including LEDs and lasers, photodetectors, transistors, piezoelectric filters, biosensors, etc." *Source: http://web.mit.edu/tpalacios/Research.htm*	3-4 (See Note 2)

Purdue University	Wide Band Gap Semiconductor Device Research Program	"We are a world leader in characterizing and improving the MOS interface between SiO2 and SiC, and we have developed several novel devices in SiC for the first time. To our knowledge, we are the second university group to build MOS transistors in SiC and the first university group to build bipolar transistors. We originated the concept for the nonvolatile RAM in SiC, and worked with Cree Research to demonstrate storage times of >100 years with no power applied to the device. Our group also built the first monolithic digital integrated circuits in SiC (1993), the first charge-coupled devices (CCDs) in SiC (1995), the first planar double-implanted MOS (DMOS) power transistors in SiC (1996), the first p-well CMOS integrated circuits in SiC (1996), and the first lateral DMOS power transistors (1997) with blocking voltages of 2.6 kV." *Source: http://www.ecn.purdue.edu/WBG/Introduction/*	5-6 (See Note 2)
Rensselaer Polytechnic Institute	Advanced Power Device Research Laboratory (APDRL)	"Power devices are the primary focus of laboratory research. The group studies both Silicon and wide bandgap based devices, such as Silicon Carbide and Gallium Nitride. Some device applications of interest include power MOSFETs, BJTs, Thyristors, GTOs, IGBTs and power rectifiers. The specific research interests of each student member are presented on the student profile page. "APDRL facilities support all phases of device development including design, fabrication and characterization. The laboratory is equipped with both PC and workstation machines, which contain the necessary device simulation and layout tools. Fabrication is done in Rensselaer's Class 100 Clean Room, also located in the Center for Industrial Innovation. Characterization takes place in the APDRL's Room 4108 facility. Here, the group uses both automated and standalone test fixtures including a microelectronic probe station, curve tracer, device parameter analyzer and an oscilloscope." *Source: http://www.rpi.edu/dept/cie/cpes/NF_HOME.htm*	3-6 (See Note 2)

Rutgers	SiCLAB	"SiCLAB is a world leading university-based SiC device research lab in the United States. SiCLAB started working on SiC devices in 1992 and reported the world's first near 1000V SiC Schottky diode in 1993. SiCLAB's mission is to develop the knowledge base and power electronic technologies for energy efficient systems with special focus on (i) enabling the revolution of the nation's inefficient electrical energy infrastructure and allowing market-driven integration of green energy into biomimetically controlled electricity network, and (ii) providing super-efficient and compact power electronics (power ICs, high-temperature power modules and converters/inverters) for the ultimate ecovehicles. Other research efforts include SiC UV and EUV detectors, linear and 2D arrays and SiC single photon detectors. SiCLAB's research has been supported by funding of over $1M/yr in the past ten years from DARPA, Army TARDEC, ONR, NRL, Air Force, NASA, NSF, DOT, United Silicon Carbide, Inc., and Sensors Unlimited, Inc." *Source: http://www.ece.rutgers.edu/~jzhao/*	3-6 (See Note 2)

University of Arkansas	Semiconductor Devices Group	The program at U of Arkansas does "practically everything but build the SiC devices." They work with Cree, Semisouth, ROHM and other manufactures to develop power modules and other devices from their existing semiconductors. Their services include design, modeling and integration. Design: The program starts with the devices then design modules utilizing other materials to optimize electronic packaging and thermal mitigation. Modeling: The university has a WBG modeling group that uses computer simulations to gain insight into the details of the operation of designs. In addition to nominal operating conditions, the designer analyzes the robustness of the design through a number of studies such as dynamic thermal analysis, worst case analysis, and statistical variations in circuit performance due manufacturing tolerances on parts, and failure modes and effects to determine the safe operating area of the circuit. Integration: Existing chips are integrated into power modules with an eye toward maximum power density, reducing weight, and maximum thermal mitigation. A 1200v power module has been developed which is 3x5" in size and operates at 250°C. It is "minimally rated" at 150A, but can handle up to 600A. It has been running continuously for "several months" with no degradation in efficiency. *Source: Interview with Dr. Alan Mantooth*	5
University of North Carolina	Power Semiconductor Research Center (PSRC)	PSRC's mission statement: "To serve as an international forum for the exploration of ideas that enable improvements in power semiconductor devices." "Since its inception, the center has received strong support by the worldwide power semiconductor industry. Twenty companies from around the globe have participated in PSRC providing not only monetary support but intellectual support as well in the form of Industrial Scholars who have performed research at PSRC in collaboration with Faculty and Graduate Students." (The web site does not identify these twenty companies.) *Source: http://www.psrc.ncsu.edu/index.html*	2-4 (See Note 2)

University of South Carolina	Silicon Carbide Lab	"USC's Silicon Carbide Laboratory maintains an impressive technological infrastructure for Silicon Carbide Research. The lab has in-house capabilities that stretch from bulk and epi growth to device fabrication and characterization. The infrastructure is composed of both purchased commercial equipment as well as purpose built systems designed and built by researchers here at USC. The lab has three operational bulk growth furnaces, two CVD reactors (one capable of HTCVD temperatures above 2000°C), a fully stocked clean room facility for device fabrication, and characterization capabilities including SEM (including electron beam induced current mode SEM), polarized light microscopy, Raman spectral analysis, and atomic force microscopy. These capabilities ensure productive research without dependence on external sources for testing, substrates, etc. Use the links in the navigation bar to take a tour of the lab and meet the researchers in order to learn more about our work and the capabilities of the lab." *Source: http://www.ee.sc.edu/research/SiC_Research/*	3-6 (See Note 2)
University of Tennessee, Knoxville	Power Engineering Laboratory	"The University of Tennessee Power Engineering Laboratory is known for its high quality research contributions in power system analysis, power system reliability, power quality, power electronic converters, control of motor drives, and silicon carbide based power electronic systems." *Source: http://power.eecs.utk.edu/*	3-6 (See Note 2)

Notes

Note 1. TRL assessed by Synthesis based on statement from Dr. Williams: "Cree and GE are now offering specification sheets for SiC MOSFETs fabricated with our NO passivation process."

Note 2. TRL assessed by Synthesis from best available information.

Table 3: Academic SiC Research Programs outside the US

School	Program	Country	Summary of Research Efforts
Technische Universität München	Walter Schottky Institut	Germany	"The work of the second semiconductor physics group at the Walter Schottky Institut deals with various aspects of new and non conventional semiconductor materials and material combinations: semiconductors with a wide bandgap (GaN, InGaN, AlGaN, diamond, SiC) disordered semiconductors (amorphous, nanocrystalline, and polycrystalline) advanced thin film systems (silicon-based luminescent layers, thin film solar cells, organic/anorganic heterosystems, biofunctionalized semiconductors). Most of these material systems are prepared in our group by suitable deposition techniques (MBE, MOCVD, Plasma-enhanced CVD, e-beam evaporation, sputtering). Their efficient optimization is based on the large pool of structural, optical, and electrical characterization techniques available in our Institute. Complementary to the usual spectroscopic techniques we have developed and employ a variety of highly sensitive methods which enable us to study in particular the influence of defects on the electronic performance of materials and devices. Such techniques include subgap absorption spectroscopy, optically induced capacitance spectroscopy and, in particular, modern spin resonance techniques which are applied to various materials systems and devices for spintronics. "In addition to the preparation and characterization of new semiconductor materials we also work on the modification and processing of semiconductors with pulsed high power laser systems (laser-crystallization, holographic nano structuring, laser-induced etching) and investigate the potential of new material systems for novel device structures. Recent examples include nano structured thin film solar cells, high electron mobility transistors based on AlGaN/GaN hetero structures, as well as UV-detectors, sensors and biosensors." *Source: http://www.wsi.tum.de/Research/tabid/56/Default.aspx*

Griffith University	Queensland Microtechnology Facility	Australia	"A unique processing focus on developing SiC films on Si wafers that is aimed at integrating the benefits of the standard Si technology with the superior electrical, thermal, optical, and mechanical properties of crystalline SiC. "The unique equipment for epitaxial growth of SiC films on Si wafers and the standard semiconductor processes are used as a platform technology for research and development of a broad range of superior semiconductor devices, including a nonvolatile memory cell, power switches, solar cells, devices for micro-electro-mechanical systems, and optoelectronic devices." *Source:* *http://www.griffith.edu.au/engineering-information-technology/queensland-microtechnology-facility*
KTH Royal Institute of Technology	Silicon Carbide Electronics Program	Sweden	"The Silicon Carbide Electronics Program (SiCEP) is the largest single research program and is carried out in collaboration with Linköping University and Chalmers. Central in this program is the study of defects and impurities following ion implantation, but also the role of hydrogen in dopant passivation and diffusion. A strategic part of the program is improved computer simulation tools for predictions of device performance in SiC where physical modeling and experimental verification is a major issue. Device related research involves a high voltage diode (aiming for > 10 kV blocking) and optical characterization to reveal internal device properties." *Source:* *http://www.imit.kth.se/FTE/*

2. National laboratories

   i. Oak Ridge National Laboratory (ORNL)

The Power Electronics and Electrical Power Systems Research Center at the Energy and Transportation Science Division at ORNL is researching the application of SiC-based power devices in hybrid vehicles and the fabrication of SiC MOSFETS for use in high-power commercial applications.

One study of interest compared the performance of SiC and Si technology, using a full-system simulation based on a vehicle with "Camry-like characteristics." The model consisted of a propulsion model, and electric motor/generator model and an inverter loss model. The goal was "to assess the cost-benefit of replacing Si devices with WBG devices." The study simulated the US06 drive cycle, the so-called "aggressive" cycle used by the EPA for emission and fuel economy certification.

As shown in Table 4, silicon carbide devices showed efficiency gains across all testing scenarios. Although SiC showed efficiency gains over Si devices at all stages of the test, the greatest gains came when operating at higher frequencies and higher temperatures. The study, however, did not factor in the cost differential between SiC and Si devices, nor did it compute any ROI associated with the use of SiC devices.

Table 4: Performance Comparison Study of SiC and Si Technology

Comparison of Si and SiC system performance for US06						
Temperature	**10 kHz**			**20 kHz**		
	Overall Vehicle Efficiency [%]					
	Si	SiC	Gain	Si	SiC	Gain
70°C	83.9	85.2	1.3	80.2	82.7	2.5
105°C	83	85.2	2.2	78.4	82.6	4.2
	Inverter Efficiency [%]					
	Si	SiC	Gain	Si	SiC	Gain
70°C	96.3	97.4	1.1	93.1	95.3	2.2
105°C	95.5	97.3	1.8	91.6	95.2	3.6
	Inverter Energy Loss [kJ]					
	Si	SiC	Gain	Si	SiC	Gain
70°C	519.9	359.4	160.5	986.3	666.7	319.6
105°C	625.5	369	256.5	1234.3	682.3	552

Source: "Performance Comparison Study of SiC and Si Technology for an IPM Motor Drive System," ORNL, October 2009

ii. Other National Laboratories

Other national laboratories are working with various aspects of silicon carbide. However, research did not indicate that any are currently researching its semiconductor properties. There were some dated references to work done at Argonne on WBGS, but nothing in the recent past. Researchers there are developing hybrid vehicle technology, but this work is not focused on power electronics, as is the case at ORNL. Argonne has a modeling center, though, that has the ability to run simulations like the ones outlined in the ORNL project above.

3. Manufacturers and Key Technology Developers

i. Cree

Cree is the world's leading producer of SiC semiconductors and LEDs. According to president John Palmour, Cree produces 85-90 percent of the world's supply of SiC, and manufactures 60 percent of the SiC power semiconductors (the other 40 percent is manufactured by Infineon in Germany). Currently Cree produces SiC in

4” wafers and builds SiC-based inverters for solar power stations and power supplies for servers.

Cree shipped six million SiC diodes in 2008. As of the second quarter of FY2010, Cree had already shipped more than six million SiC diodes. They expect this increased production level to continue. The majority of SiC diodes are being used in LCD backlighting in televisions.

In terms of production capacity, Cree believes it has sufficient capacity to meet demand for the next three to five years. “We have empty floor space and empty clean room space,” according to Dr. Anant Agarwal, Crees’ Manager of SiC Power Devices.

Cree states that it can meet demand at market-competitive price points (see supply curve section below) for SiC devices and modules in a three to five year timeframe.

On May 17, 2010 Cree announced that it has introduced the industry’s first “commercially available Z-Rec™ 1700-V Junction Barrier Schottky (JBS) diode products intended for high-voltage power-conversion applications in motor-drive, wind-energy and traction systems.” The SiC power device leverages silicon carbide’s advantages vis a vis silicon by virtually eliminating diode switching losses. It reportedly increases efficiency, reliability and longevity of power systems while reducing the overall system size, weight and cost. According to Cengiz Balkas, Cree vice president and general manager, "The 1700-V diodes extend our leadership in energy-efficient power systems for data-center and solar-power markets to new markets such as wind-energy, train, tram and electric-vehicle power converters. … The advantages of silicon carbide are clear, and for high-voltage, high-frequency systems, you can't afford not to use SiC."

In late 2009 Cree acquired a SiC and power device patent portfolio from Daimler AG. The portfolio consists of approximately 20 patent families, including patents issued in the United States, Germany, Japan, and China. For example, US Patent No. 5,856,231 ('231) titled "Process for Producing High-Resistance Silicon Carbide" is an important piece of the portfolio that relates to the manufacturing of semi-insulating SiC using vanadium doping.

Dr. Cengiz Balkas, Cree vice president and general manager stated: "We had licensed this impressive group of patents for many years and the full acquisition is a valuable addition to our already extensive intellectual property position." Dr. Vijay Balakrishna, a Cree product line manager, materials, added, "Cree is already the leader in high purity semi-insulating SiC and acquiring the '231 patent further bolsters our IP position, especially in semi-insulating SiC achieved through vanadium doping."

ii. Dow Corning

Dow Corning manufactures three- and four-inch 4H wafers. The 4H refers to the polytype or lattice structure of the SiC. There are over 250 polymorphs of SiC, but the three most common polytypes used for semiconductors are the hexagonal 2H, 4H and 6H. Dow also supplies epitaxy for device makers, but does not manufacture semiconductor devices themselves.

iii. General Electric

General Electric's research into wide bandgap semiconductors is conducted in conjunction with their research into high-voltage power electronics for wind turbines, aircraft, and electric railroad locomotives. Much of their research has focused on the 2000-4000V range. As there are indications that automotive applications could be nearing the 2000V range in the next three to five years, increased production in this voltage range could affect the cost for automotive applications as well.

GE has stated that they plan to have silicon carbide power semiconductors "coming to market in the next 1 - 3 years" for use in aircraft. These SiC systems "will dramatically reduce inefficiencies and the size and weight of electric components" which they estimate as "a $1 billion market opportunity." To date, GE has not released any specifications on these components.

Chief Engineer Ljubisa Stevanovic stated that early adopters of the higher voltage SiC semiconductors will pay 5-10x the price of Si semiconductors. He cited aerospace, medical devices (e.g., MRIs and other scanners), data centers, and military vehicles as the most likely initial markets. He believes that it is unlikely that the price premium of SiC vis a vis Si MOSFETs will be less than 30 percent for the foreseeable future.

For automotive applications, Stevanovic sees SiC coming into use when battery cells reach the 600V level, which the Japanese (he did not specify which of the hybrid and/or electric vehicle companies) are currently pursuing. Stacking the 600V packs puts them into the 1200V range, a range at which the SiC devices are more efficient than Si. An added benefit of eliminating cooling loops through the use of SiC will be to simplify the design and help achieve cost-competitiveness with Si devices.

iv. Honeywell International, Inc. (Phoenix, Ariz.) (working with Cree, Inc.)

On April 9, 2010, Honeywell was awarded a $12,150,000 cost-plus-fixed-fee contract from the U.S. Department of Defense to develop technologies to improve and enable SiC power devices and component technologies. Cree is performing a significant portion of this work. These technologies will enable military and commercial systems to be more efficient while operating at higher temperatures and small footprints. These technologies are critical to meeting performance requirements for advanced military and U.S. energy platforms. Work is to be performed in Phoenix, Ariz. (0.98 percent); Durham, N.C. (48.65 percent); Niskayuna, N.Y. (9.87 percent); Fayetteville, Ark. (9.57 percent); East Butler, Pa. (15.16 percent); Longwood, Fla. (6.69 percent); and Midland, Mich.; (8.09 percent), with an estimated completion date of May 29, 2011. One bid was solicited with one bid received for this contract. The Army Research Development and Engineering Command Contracting Center, Research Triangle Park, Durham, N.C., is the contracting activity (DAAD19-01-C-0067).

v. Arkansas Power Electronics International Inc. (APEI):

APEI continues transition work on its high-temperature SiC power module. The module was initially designed for Sandia National Laboratories in response to a request for electronics that could withstand higher temperatures. APEI received $3 million in Congressional funding in late 2009 to support transfer of the power module to the F-35 Joint Strike Fighter.

APEI was co-founded by the dean of Valparaiso University's College of Engineering and was part of a team that won a 2009 R&D 100 award for a silicon carbide-based power module that could improve the performance of hybrid electric vehicles and renewable energy generation systems. The high-temperature silicon carbide power module was developed jointly by Arkansas Power Electronics International Inc., the University of Arkansas, Rohm Semiconductor and Sandia National Laboratories. Dr. Kraig Olejniczak, dean of the Valparaiso College of Engineering, launched APEI in 1997. The company is working on further improvements in high-temperature electronics that would be able operate at over 400 degrees Celsius.

vi. C9 Corporation

C9 (Saratoga County, NY) currently has a contract with the U.S. Department of Defense to develop silicon carbide-type semiconductors for the military to use with solar and LED applications. C9 and Precision Flow Technologies are collaborating with The Solar Energy Consortium (TSEC) (Lake Katrine in Hudson Valley, NY), which is made up of the C9 Corporation, L-3 Communications, Precision Flow Technologies, and NanoDynamics-88 and serves as a link between the consortium and the federal government for future partnerships. Over the past three years, TSEC has successfully secured $8.4 million in funding for C9 and its partners. In late 2009, TSEC received $2.8 million from Congress to continue their development of high-tech solar and LED products for the U.S. military.

The Defense Department supports silicon carbide-based semiconductor solar and LED development for its use in powering hand-held and backpack devices for troops, the recharging of unmanned ground and aerial reconnaissance platforms, and for Hybrid Electric Combat Vehicle drive trains.

vii. Kyocera

Kyocera works with the semiconductor companies to package semiconductors and systems, but the company does not manufacture semiconductors. “Package” can mean either designing and manufacturing the housing which contains the system, or the printed circuit board on which the components are mounted. Kyocera designs and manufactures both types of packages, primarily for high temperature, high voltage, or rough usage applications.

In the hybrid vehicle market, the company works with semiconductor manufacturers in packaging inverter modules consisting of high-voltage IGBTs. The most common materials Kyocera deals with there are AlN and SiN. As noted in the Background section, this research did not focus on packaging materials.

Packaging materials vary based on the operating temperature, power requirements and thermal conductivity of the type of semiconductor used. Kyocera’s work in the automotive market is typically not directly with the automakers or semiconductor manufacturers. Instead, the company tends to work more with the assembly houses who in turn work with the OEMs.

According to Senior Applications Engineer Adam Schubring, Kyocera foresees no material challenges for packaging. The most common materials they work with are aluminas and silicas, which are “pretty standard stuff.” He said their “worst case” is in working with alumina ceramic products which require specialized production techniques While these materials are commonly available, he does not predict any production or supply issues with these materials.

The only manufacturing bottlenecks Mr. Schubring foresees would be if the OEMs wanted to use “nonstandard materials and processes”, though he would not elaborate on what these might be. He stated that 90-99 percent of the assembly houses did not know what to do with these materials, which could limit manufacturing capability.

viii. Powerex

Like Kyocera, Powerex does not do chip or wafer work; only packaging. Their primary semiconductor supplier is Cree. The company works for GE (which owns half of the company), Semisouth, Infineon, Mitsubishi (another co-owner), and ROHM. Powerex expects Mitsubishi Electric Corp. to announce their own SiC chip in 2011 or 2012 but could not provide any further information.

ix. Mitsubishi

In January 2010, Mitsubishi announced that they will begin volume production of SiC semiconductors "for cars and industrial machinery" in 2011 at its Power Device Works in Fukuoka. The company has invested 3.5 billion yen (approximately $37M) in a facility which is expected to start producing power semiconductors in March 2011. According to Nikkei, Mitsubishi Electric is "working to develop a mass production system in which the [SiC] chip packages will be less then a fourth the volume and weight of existing silicon-based power semiconductors. Mitsubishi Electric expects to enter into volume production in 2011 and plans to invest a total of 13.5 billion yen ($145 million) by March 2013 to gradually expand its production scale."

x. Honda Motor Co.:

On March 11, 2010, Kenichi Nonaka of Japan received international patent (WO/2010/024240) covering a bipolar silicon carbide semiconductor device and method for manufacturing same. The patent was assigned to Honda Motor Co. Ltd., Tokyo. The original patent was filed in Japan under application No. PCT/JP2009/064770 on Aug. 25, 2009.

According to an abstract posted by the World Intellectual Property Organization (WIPO): "Disclosed is a bipolar silicon carbide semiconductor device which is a BJT having a four-layered structure and achieves an improved current amplification factor and a small and stable base resistance by reducing the probability of re-combination of electrons and holes and thereby suppressing recombination between a main current and a control current. The semiconductor device comprises a recombination suppression region having the same conductivity type as and a higher resistivity than a base region or a recombination suppression region having the same conductivity type as and a higher resistivity than an emitter region, which is formed near the surface between a base contact region and the emitter region."

xi. ROHM

ROHM, in a partnership with Honda, has produced what is claimed to be the world's first high-power module driven entirely by SiC devices. The article in which this development was reported does not specify whether it is for automotive use or otherwise. The module incorporates a 1-phase converter circuit and a 3-phase inverter circuit in a single package using SiC Schottky barrier diodes and MOSFETs. It is rated at 1200 V and 230 A (289-kVA equivalent). These performance attributes indicate it could be used in HEVs and EVs.

ROHM has also partnered with Sandia National Laboratories, Arkansas Power Electronics, and the University of Arkansas to develop a SiC power module for hybrid vehicles. According to Sandia, ROHM will begin manufacturing this module in 2010 for Honda to use in their "next-generation" hybrid and electric vehicles. It is unclear whether this is the same module described above.

In a partnership with Kyoto University Graduate School of Engineering, ROHM has also developed a "large surface area trench gate vertical-type MOSFET" composed of SiC, which is rated at 300A. Previously, crystal defects limited SiC devices to around 100A, requiring the use of Si devices in parallel to handle the 600A of current required by electric vehicles and other applications. ROHM refined their epitaxial process and "successfully reduce[s] the effects of crystal defects, making it possible to expand chip area by 2.5 times, from 3mm×3mm to 4.8mm×4.8mm." This allows a 20 percent reduction in ON resistance (which is the resistance value of a power element during operation and influences the performance of a power MOSFET. The lower the value, the better the performance), increasing current capacity to 300A.

xii. Bridgestone Corporation (Tokyo, Japan)

Bridgestone Corporation (the world's largest tire and rubber company) commenced production of SiC wafers in 2010. It is reported that the company is pursuing this expansion step to offset decline in its mainstay tire business. Bridgestone has developed two to three inch diameter wafers for use in power chips by using technologies used in tire production processes. These chips are likely to be used in electric vehicles. The firm produces the wafers at a facility in Kodaira, Tokyo, with a starting volume of approximately 500 units per month. Sample exports to device manufacturers occurred in late 2009 or early 2010.

The PureBeta™ SiC Single Crystal Wafer is based on Bridgestone's experience in using polymer technology and nanotechnology in developing tires. The technology incorporates high-purity SiC powder particle development, single crystal growth and processing capabilities. Bridgestone's goal is to apply the SiC single crystal wafers as substrates in optical devices, high-frequency devices, power devices, heat-resistant vehicle devices and other devices. Bridgestone has produced silicon carbide sintered products in use in a broad range of practical applications by the world's leading semiconductor device and tool manufacturers.

xiii. METI (Japan)

In May 2010, the Japanese Ministry of Economy, Trade and Industry (METI) announced the start of the "New Material Power Semiconductor Device Project Toward Achieving a Low-Carbon Society", with an FY 2010 budget of 2 billion yen, or approximately $22.6 million). The project includes the expansion of the "R&D Partnership for Future Power Electronics Technology" (FUPET) and the establishment of an "SiC Alliance." FUPET and the SiC Alliance "will play important roles in promoting SiC research and development and introducing SiC to society," and METI will continue to actively support these frameworks toward practical applications of SiC.

The following additional information was released by MEITI regarding this development:

• The structure of the FUPET consisted of nine entities that are mainly device manufacturers. FUPET has been expanded to include those enterprises that jointly made the proposal. It is now a partnership consisting of enterprises, universities and public research institutes comprising of a broad swath of the supply chain in the industry – a total of 25 entities.

• The SiC Alliance is made up of a broad range of SiC-related enterprises, including universities and government ministries. The alliance's objective is to oversee all SiC research and development activities performed in Japan and to promote mutual collaboration among participants. Specific activities include a project developing high voltage SiC devices under the "World-Leading Innovative RandD on Science and Technology program," which is promoted at the Cabinet-level in Tokyo, and the "SiC and Related Wide-Band-Gap Semiconductors" activity, which is led by a group of researchers from the Japan Society of Applied Physics.

b. Demand Curve Assessment

The biggest hurdle to the use of SiC devices in automotive applications is their cost.

There are two prime factors that account for the cost disparity between Si and SiC devices: the material costs and the size of the wafer. While Si wafers are commonly produced in six- or eight-inch sizes, SiC wafers are currently four inches in diameter. The wafer size determines the number of devices which can be produced from a single wafer, and thus the cost of the devices, all other factors remaining equal. While six-inch silicon carbide wafers are possible, Dow Corning's Mark Loboda estimates it will be at least two to five years (2012 to 2015) before the industry starts demanding them in that size. In other words, the timing depends first on the market demand for a sufficient volume of the larger six-inch wafers, which then will drive the timing of SiC manufacturers' ability to produce six-inch wafers at a competitive cost. The optimal demand-supply scenario is still at least two to five years off, according to Mr. Loboda.

Mr. Loboda estimates that the material costs for SiC substrate wafers are about 15-20x the price of Si wafers. He does not see this cost differential dropping drastically over the next 5-10 years unless the demand for SiC devices increases considerably and manufacturers begin to use SiC to replace Si. However, the OEMs seem to be focusing on the relative costs of the components, in that new items must be available at the comparable or lower cost to existing items, according to Mr. Loboda and other sources. This focus may cause the OEMs to overlook other cost savings which using SiC components could produce – such as reduced cooling requirements.

Scott Leslie from Powerex estimates SiC MOSFETs cost about $11/amp and SiC Schottky diodes are about $1.25/amp. He states SiC MOSFETs are about 100x more expensive than comparable voltage Si IGBTs and SiC diodes are 62x more expensive than Si diodes. While Cree has developed a SiC MOSFET that is priced at 10-15x that of Si, it is currently an engineering prototype and is not yet in production.

Dr. Phil Neudeck from NASA's Glenn Research Center stated that "on a system-to-system basis (such as hybrid and electric vehicle drive and power management), I do believe that systems/circuits enabled by wide bandgap semiconductors in the future will be cost-competitive compared to their silicon-enabled counterparts." However, he qualifies his assertion by stating "the overall improvement in critical system metrics (such as watts/pound, watts/cubic meter or cost/horsepower) will in the future justify paying more for a wide bandgap power device as it will cut need for (and size and cost of) other components in the overall system."

Dr. Neudeck sees the current uses of WBGS as "niche" applications. He states "to turn those niches into the game-changing dominance that power semiconductor physics suggests should theoretically happen requires substantial improvements in manufacturing cost and material quality. Present SiC and GaN crystal manufacturing techniques will not get us 'there' very soon."

Mr. Palmour of Cree disagrees with Dr. Neudeck's assessment concerning current manufacturing techniques and crystal-growth technology. He stated that Cree consistently produces high-quality crystals and can produce up to six-inch wafers if needed. Cree has done away with the micropipe defect that plagued crystals several years ago and is currently working on eliminating dislocation defects.

Mr. Palmour's opinion regarding the cost of SiC components compared to conventional Si power semiconductors is that the overall system cost must be considered, not simply the component cost. As SiC devices can operate at higher frequencies, voltages and temperatures than Si, this enables the production of smaller, lighter systems which operate more efficiently than a comparable Si-based system. He believes that the increased efficiencies should offset the increased cost of the devices.

Ljubisa Stevanovic from GE agrees that system cost and performance will be the driving factor to the more widespread use of SiC devices. He believes that while the cost of 10 percent of a system (the chip) may be 5x greater, the remaining 90 percent of the system cost (packaging, cooling, etc.) could experience a cost reduction of 50 percent, thus providing an overall system benefit. Such an approach also provides a pathway to improved performance, and a long-term platform to meet power control needs as voltages and other demands increase.

c. Combined Assessment of the Supply and Demand Curves

The rationale for hybrid vehicles is improved fuel efficiency, given increased gas prices and pressure to reduce dependence on carbon-based fuels and their associated emissions. Auto manufacturers have been encouraged by governments and market forces to achieve these objectives by improving vehicle operating efficiencies and reducing weights.

Silicon carbide represents a technological advance in power module substrate material that can deliver significant efficiency and weight improvements over existing Si-based power systems. However, as discussed, currently SiC is only available at a premium price.

The debate surrounding the timing of the widespread use of SiC in mass-market hybrid automobiles is a lively one, involving when, where, why, and how SiC may supplant Si as the power module substrate of choice in automotive applications. The debate is complex, and involves both supply and demand curve interactions. This issue needs to be deconstructed in order to shed light on the prospect for SiC for mass-market hybrid automotive applications.

This section attempts to clarify the plausible impact of SiC in mass-market hybrid automobiles by identifying and characterizing key technical and market assumptions. These assumptions are presented with supporting and detracting information uncovered in the course of this research. Of course, as new information becomes available, the attendant conclusions should also be reviewed. Additional information on the sources listed is provided in the bibliography.

Assumption #1: SiC power modules displacing Si power modules is a cost issue – not technological.

Evidence in Favor

- The primary reason given by a number of sources for staying with Si instead of using SiC is the cost. [Infineon, Semikron, GM, Cree]
- The development of a SiC MOSFET is a solved problem. [Semikron, Infineon]
- Cree consistently produces high-quality crystals and can produce up to six-inch wafers if needed. Cree has done away with the micropipe defect that plagued crystals a few years ago and is working on eliminating dislocation defects. [Palmour]
- Larger SiC wafer sizes (6-inch) are possible from a technical standpoint, however there is insufficient demand to justify their production at the present time. [Loboda].
    - Silicon wafers are commonly produced in six- or eight-inch sizes while silicon carbide wafers are four inches. This limits the number of devices which can be produced from a wafer.
- “I would be willing to pay two times the price of Si-based power devices for 2000V, 300A [non-automotive] applications today…. I already know it performs as well as Si IGBTs … so if it comes in at within 200 percent of the IGBT price, I will buy it today.” [Goodarzi].
- “[I]t must be understood that despite these superior material properties, SiC has little chance of being used unless it can be obtained at a cost that is the same as or lower than that of Si, which currently dominates nearly all semiconductor applications for rational economic reasons." (Mr. Kiminori Hamada of Toyota's Electrical Engineering Division, writing in Friedrichs, Peter et al, eds.: Silicon Carbide, 2010, Chapter 1, p. 12).

Evidence Against

- One suggestion was identified that indicates technological hurdles are key to the slow adoption of SiC in the near-term.

  Specifically, Mr. Neudeck stated: “To turn those niches into the game-changing dominance that power semiconductor physics suggests should theoretically happen requires substantial improvements in manufacturing cost and material quality. Present SiC and GaN crystal manufacturing techniques will not get us 'there' very soon." [Neudeck]

Summary Assessment

The debate about SiC is a debate about costs and benefits more than technological capability or manufacturability. While experts disagree on the SiC price needed for widespread adoption (in comparison to Si), they all agree that SiC cost and relatively limited supply are the primary reasons for continuing to use Si. We assess that the adoption issue is a matter of price-sensitivity, because the engineers who are potential users of SiC are aware of the system-level benefits of SiC. The basic question is; at what price-point does the purported benefits of SiC power electronics make mass market use cost-effective?

Assumption #2: SiC technology is needed in mass-market hybrid automotive applications to enable power electronics to operate at higher operating temperatures and power ratings, increase efficiency, reduce weight (e.g., with less packaging and electronics placed closer to the engine or battery).

Background Data: The normal operating temperature for the coolant in an internal combustion engine is 90-105°C (195-220°F), which provides the standard temperature for proper engine operation and emissions control. It is notable that any changes that would result in running the engine cooler than 90-105°C may require significant changes in the design of the emission controls. The normal ambient underhood temperature of an automobile is in the neighborhood of 175°C [ORNL].

Evidence in Favor

- Si-based power converters have a maximum operating temperature of 125°C (with maximum junction temperature of 150°C). Even at lower temperatures, system performance degrades as the temperature increases. [ORNL]
- While Si-based power components can operate at the 105°C range, this allows only a 20° leeway before system performance begins to degrade. [Cree] Under severe operating conditions such as prolonged stop-and-go driving in hot weather, the coolant temperature in an automobile may, in extreme situations, exceed the 125°C level for short-periods.
- "Raising the operating temperature is one of the best ways of simultaneously reducing energy loss when using WBGS (raising the temperature allows the WBGS device to work at a higher frequency), and reducing the volume, weight and cost of the entire power electronics system, including the heat-sink apparatus. For application to future electric vehicles (EVs) and hybrid electric vehicles (HEVs), power devices will be expected to function reliably at a Tj = 200-300°." [Silicon Carbide/Nissan]
- "The performance of Si-IGBTs is, however, thought to be reaching their theoretical limit. As a consequence, wide-bandgap semiconductor SiC devices

are expected to be post-silicon IGBT devices as power-converter components for future electric-powered vehicles." [Silicon Carbide/Honda]

- While coolant temperature is not an issue for the electronics in conventional automobiles, it is in hybrid vehicles. This is because traditional vehicle electronics operate at a much lower voltage and lower frequency than those in a hybrid vehicle and thus produce less heat to dissipate. By contrast, conventional Si applications in hybrid vehicles cannot operate sufficiently with air cooling and need a dedicated cooling loop to enable them to remain in the optimum operating temperature in hybrid vehicles. This argues in favor of SiC components in hybrid vehicle applications. [SP]
- Presently, hybrid vehicles use a secondary 70°C cooling loop to protect the power electronics. The secondary system includes an electric pump, heat exchanger, ethylene glycol coolant, and overflow reservoir tank, all of which add weight and cost to the vehicle. The heat-sink for a Si-based power module typically occupies one-third of the total volume of a power converter and usually weighs more than the converter itself, suggesting the value of a smaller, lighter SiC power module. [ORNL]
- The increase in continuous power found in a PHEV leads to an increase in the thermal demands on the electric traction drive components. [NREL]

<u>Evidence Against</u>

- Hybrid vehicles currently use Si-based power modules which have heatsinks and dedicated cooling loops to dissipate heat. These vehicles are satisfying current market needs at competitive prices and performance levels. [SP]
- The secondary coolant loop permits Si-based power modules to operate at lower temperatures than the engine coolant system (70°C). [ORNL]
- The current gains in fuel efficiency are below the limits of what is possible using silicon-based technology. The major barrier to producing 65mpg cars is not technological, but rather the fact that consumers apparently have not been willing to pay a premium for the EV/HEV technology when the price of gasoline is below a certain point. The following data points from The DOE Vehicle Technologies Program, Electrical and Electronics Technical Team Roadmap (EE Roadmap) (082909 draft) are instructive:
  - The FreedomCAR 2015 target of $12/kW motor peak power output would be compatible* with a gasoline price of about $4 per gallon. [EE Roadmap 082909draft, p. 21]
  - A study by Energy and Environmental Associates (EEA) in 2006 indicated that Toyota's ultimate cost target for the electric propulsion system in the Prius is $17 per kW peak, which is compatible* with a gasoline price in excess of $6 per gallon. [p. 21]

    *"Compatible" is defined as the price-point necessary to provide consumer payback of the extra cost of the hybrid automobile in three years through fuel savings (assuming that the fuel efficiency doubles from 27 mpg to 54 mpg, and a vehicle that travels 12,000 miles per year). [p 21].

    - We may conclude from the above two points that gasoline prices of $4 to $6 per gallon are necessary to present a compelling cost-benefit case to consumers for the purchase of EVs or HEVs, assuming the best possible (or, lowest cost) scenario, which is that by 2015 (according to FreedomCAR 2015 targets) the EVs or HEVs will be based on $12/kW power electronics technology. [SP]
- SiC technology must achieve significant cost reductions to attain the 2015 target of $12/kW peak. It appears likely that auto makers will pursue other, less expensive approaches to achieving efficiency gains before turning to less technologically mature and more costly SiC technology. [SP]

<u>Summary Assessment</u>

As currently implemented, Si power modules perform effectively due to a dedicated cooling system. However, as manufacturers design future automobiles, SiC provides an alternative to using these dedicated cooling systems and will allow greater weight reduction with more efficient packaging and placement of components. However, a detailed assessment of the system-level benefits of SiC will need to be completed before OEMs make the switch.

Assumption #3: SiC power modules eliminate the need for a secondary cooling loop, along with other potential efficiencies. Thus, SiC could lead to cost-savings that are sufficient to justify its adoption by automotive producers.

<u>Evidence in Favor</u>

- A SiC power module could allow the possibility of eliminating the liquid cooling loop completely, thus simplifying the design. [ORNL]
- In 2006, the cost of the Si-based power module secondary cooling loop was estimated at $175 ($187, adjusted for inflation). [ORNL] Eliminating the secondary cooling loop would thus provide a cost-savings.
- Augmenting the Si to withstand increased operating temperatures would require increasing the space needed for the components by 30%. [Goodarzi]
- SiC would permit designing a smaller module. The diode mounting footprint would be reduced by 70% and total inverter size would be reduced by 15-20%. [Nissan]
- Using SiC power components would have a “snowball” effect on the design of the HEV. Higher operating frequencies would allow decreasing the size of other components in the system, including the motor. [ORNL, Cree]

<u>Evidence Against</u>

- No automotive manufacturer has yet gone on the record and agreed with this assumption or produced a car in high volumes which demonstrates the system-level efficiencies and savings. [SP]
- Si components can be adapted to operate at the higher temperatures through several approaches. Either of these would eliminate the need for the secondary cooling loop at a much lower cost than employing SiC. These include:

  - Modifying the packaging to improve the heat insulation or increase the size and number of the heat sinks. [NREL]
  - Adding up to 30% more silicon. [Goodarzi]
- If the secondary cooling loop is eliminated through the use of SiC, it would also require redesigning the non-SiC-based power modules, as well as their packaging and placement to handle higher temperatures – a potentially significant cost. This aspect is often not considered in systems-cost analyses. [Goodarzi]
- The wide bandgap semiconductors are currently used in niche applications. In order to turn those niches into large scale game-changers, substantial improvements in manufacturing cost and material quality are needed. Present SiC and GaN crystal manufacturing techniques will not get us 'there' very soon. [Neudeck]
- It is uncertain that the use of SiC would lead to cost savings greater than the increased cost of the components. It is unclear what effect higher volume production would have on the price of SiC and cooling components. Research did not reveal published studies which provide a systematic assessment of the component-by-component cost savings and collateral effects of using SiC in automobiles. [SP]

<u>Summary Assessment</u>

At current SiC market prices, eliminating the secondary cooling loop would not outweigh the increased cost of SiC. Realizing the full benefits of SiC, including higher operating temperatures and weight savings, will involve redesigning the vehicle to take advantage of the characteristics of SiC components. A detailed assessment of the implications of these changes does not appear to have been completed.

Assumption #4: Combining a SiC-diode and Si-IGBT/MOSFET is a plausible solution to increase the performance of automotive power electronics.

<u>Evidence in Favor</u>

- A hybrid Si MOSFET and SiC diode approach increases performance and minimizes increased cost (vis a vis Si), and is feasible in less than three years (approximately 2013). [Cree]
- The Schottky diodes represent approximately 10-15 percent of the overall cost of the power module. Although SiC is more than two times the price of Si today, the relatively small share of overall cost accounted for by the SiC diodes in any hybrid system indicates that SiC diodes could be competitive in a highly cost-conscious markets today. [Cree]
- The current prices for SiC Schottky diodes according to Cree are "only" about 3-5x silicon. [Cree]
- While some of the temperature advantage of a SiC-only power module is lost with the combination approach, the Si-IGBT can be run cooler in combination with SiC diodes, because of the reduced heat transfer using SiC diodes. Specifically, there is an added "temperature margin" when employing the hybrid power modules. [Cree]

- Existing Si IGBTs are rated to approximately 125° C, and most are operating at their maximum temperature thresholds. Using SiC diodes along with a Si IGBT a 25% reduction in cooling losses is achieved, which translates into a 1-1.5% gain in efficiency. [Cree]

Evidence Against

- "There is really no reason to use SiC diodes in automotive applications because it is not the diodes that are responsible for the majority of the losses in power switching, it is the Si-IGBTs. Therefore, to make the switch to SiC diodes does not make a lot of sense: by adding to cost by transitioning to SiC diodes, and leaving in the Si-IGBTs, one does not address the key source of efficiency losses in power modules (the Si-IGBTs), and one does not fully address the technology needed to operate at higher temperatures." [Semikron, Infineon]

Summary Assessment

Hybrid Si-SiC devices may provide a "foot in the door" for SiC, as additional applications enable increased production, which in turn should lead to lower costs, thus enabling more widespread adoption. However, there is debate concerning the technical merits of such an approach.

Assumption #5: A Si-only solution is possible, in which adding more Si will enable Si power modules to dissipate more heat and operate at higher temperatures, thus obviating the need to switch over to SiC power modules in the near-term.

Evidence in Favor

- The apparent lack of interest by the majority of automotive OEMs in SiC at this time (though several Japanese OEMs represent an interesting, possibly growing exception to this). [SP]
- Si could match the temperature characteristics of SiC within the operating temperature ranges found in hybrid vehicles by adding 30 percent more Si to existing designs, at a much lower cost than switching to SiC. [Goodarzi]
- Additional heat protection could be attained through the use of larger heat sinks and/or better insulation in the packaging. [Goodarzi]

Evidence Against

- Augmenting the Si to withstand the increased operating temperature would require increasing the space needed for the components by 30%. [Goodarzi]
- Increasing the number of heat sinks or amount of insulation would also increase the weight of the components. [SP]
- Increasing the size and weight of the power module decreases packaging efficiency vis a vis SiC components.
  - Employing the larger Si-only components constrain the design of more efficient vehicles. [SP]
  - The Department of Energy estimates one hundred pounds of vehicle weight reduces fuel economy by two percent [www.fueleconomy.gov].

    - A Toyota graphic shows the relationship between vehicle weight and fuel consumption and indicates that the fuel economy improvement from reducing vehicle weight produces a greater impact for a hybrid vehicle than for conventional vehicles of similar weight. [*Silicon Carbide*/Toyota]
    - Reducing weight in HEVs and PHEVs is imperative to achieving the highest fuel efficiency possible.
- A Si-only solution would still require a connection into the vehicle's primary coolant loop to maintain a manageable operating temperature, which would limit the placement of the module within the vehicle. [ORNL]
- SiC would permit designing an even smaller module. Its inherent temperature resistance would allow engineers freedom to place the electronics modules wherever there was space without having to consider proximity to the engine or other heat-generating components, resulting in more efficient space utilization [ORNL]

<u>Summary Assessment</u>

While a Si-only solution could provide a short-term fix for increased operating temperatures, the penalties of increased size and weight do not make it an optimum solution. In the long-run, alternative technology approaches, including SiC, are anticipated.

Assumption #6: SiC is cost-prohibitive for automotive OEMs when compared to Si, and projections regarding future cost reductions in SiC are insufficient for automotive OEMs to make the decision to transition to SiC in the near-term.

<u>Evidence in Favor:</u>

- With notable exceptions by Japanese OEMs and their industry partners thus far (see Evidence Against, below), the world's automakers have not announced any moves from Si to SiC technology at this time. [SP]
- A SiC market breakthrough for most automotive applications (below 1200V) will require the cost of SiC to be within no more than 20-30 percent of existing silicon-based devices. This is because it is possible – for most automotive applications – to simply use 30 percent more silicon material in a MOSFET to achieve the same performance results that SiC provides. Goodarzi/US Hybrid]
- A 30% price premium for SiC MOSFETs over silicon is not achievable in the next five years. [Cree]
- The following estimates of SiC price-points compared to Si demonstrate the premium expected for the foreseeable future:
    - SiC MOSFETs are estimated to cost about $11/amp, which is about 100x more expensive than comparable voltage Si IGBTs. [Scott Leslie/Powerex]
    - 1200 V SiC MOSFETS (in pre-production), are approximately 30x the cost of Si. [Cree]
    - Cree's current prototype SiC MOSFET is priced at 10-15x that of Si. It is an engineering prototype and not yet in production. [Cree]

    - SiC Schottky diodes are about $1.25/amp, which is about 62x more expensive than Si diodes. [Scott Leslie/Powerex]
    - Cree states it will be able to produce SiC MOSFETs for 2000V applications at 2x Si prices within three years (by 2013). However, these devices are not intended for automotive applications. The 2000V cost projection indicates that wind, solar, military vehicles, military/civilian aerospace, and radar applications are expected to demand increasing quantities of SiC MOSFETS within three years. [Cree]
    - For 1200 V MOSFETs, one can reasonably expect 2x Si prices over the next five years. [Cree]
- While six-inch silicon carbide wafers are possible, it will be at least two to five years (2012 to 2015) before the industry begins to demand them in that size, which will reduce SiC costs significantly. [Dow Corning/Loboda].
- "...the substrate technologies required are large-size high-quality wafers of 5-inch diameter or larger, and a technology that is capable of extending the length of the crystal in order to reduce cost." [*Silicon Carbide*/Toyota]
- "SiC has little chance of being used unless it can be obtained at a cost that is the same as or lower than that of Si... [A]t the point when the cost becomes almost the same as Si, small-scale use of SiC will begin, and will be followed by full-scale use when it becomes less expensive than Si." [*Silicon Carbide*/Toyota]

<u>Evidence Against:</u>

- It appears that Honda will move into the realm of SiC power electronics. They have partnered with ROHM and developed an all-SiC power inverter for hybrid vehicles. [ROHM]
- ROHM also partnered with Sandia Lab, Arkansas Power Electronics, and the University of Arkansas to develop a SiC power module for hybrid vehicles. ROHM will begin manufacturing this module beginning this year for Honda to use in their "next-generation" hybrid and electric vehicles. [Sandia Labs]
- In January 2010, Mitsubishi Electric Corp. announced that it expects to begin volume production of next-generation silicon carbide power semiconductors for cars and industrial machinery in the first quarter of 2011.
- Nissan is investigating SiC for use in HEVs or EVs. [Leslie, Nezu]
- Bridgestone Corporation of Tokyo began production of silicon carbide wafers in 2010.
- In May 2010, the Japanese Ministry of Economy, Trade and Industry (METI) announced the start of the "New Material Power Semiconductor Device Project Toward Achieving a Low-Carbon Society" (budget for FY 2010 of approximately $22.6 million). The project includes the expansion of the "R&D Partnership for Future Power Electronics Technology" (FUPET) and the establishment of the "SiC Alliance."
- In contrast to Powerex's view, Cree states that the current prices for SiC Schottky diodes are only about 3-5 X silicon. [Cree]
- The overarching driver for lowering prices is volume production. If the demand for SiC MOSFETS reached 20 million annually, the price could drop to within 2x

that of Si MOSFETS, which may be a price-point at which automotive customers would begin increased use of SiC, given the potential system-level savings. [Cree]

- Improved performance and the decrease in the number of components needed would result in a competitive price at the system level when compared with similar Si systems, according to some R&D sources and SiC providers. [Palmour, Agarwal]
- Factors outside of OEM control, such as stringent emissions and fuel economy standards, may force the OEMs to compel adoption of SiC earlier than warranted by solely market forces. [SP]

<u>Summary Assessment</u>

Based on current market prices, SiC appears cost-prohibitive for mass-produced vehicles. However, with improvements in manufacturing and increased demand leading to volume production, particularly from emerging Japanese OEM efforts, the price could drop enough within the next 3-5 years to possibly make SiC a viable alternative to Si. The critical assumption is that SiC must be available at only a small premium over Si. However, one key source (*Silicon Carbide*/Toyota) disagrees with this statement, claiming that SiC will have to be equivalent, or lower in price than Si to be saleable to automotive OEMs.

Assumption #7: The case for SiC is limited because automotive power modules have no reason to exceed the current 600V-700V ranges for almost all HEV/EV applications – while the performance gains of SiC occur at voltages above 2000V.

<u>Evidence in Favor:</u>

- The performance benefits of SiC occur at voltages above approximately 2000V. Below 2000V the benefits of SiC are not optimized. [Goodarzi, Infineon, Semikron]
- There are no compelling reasons for mass market automotive applications to exceed 700V. [DoE, Infineon, Semikron].
- The benefits of SiC are greatest at above 1200-2000V. Below 1200V, it is easier and cheaper to simply use more Si. [Cree]
- 1500V+ power modules require specialized safety, repair, and machine shop certification for repair and replacement. This is a major hurdle for mass market automotive applications. [Infineon, Semikron]
- Research did not reveal any performance constraints that SiC can exclusively address (vis a vis Si) in current and future automobiles. [SP]

<u>Evidence Against:</u>

- Honda/ROHM announcement
- Mitsubishi Electric Corp. announcement
- Toyota currently uses IGBTs with a breakdown voltage rating of 1200V in its Lexus hybrids and is likely to increase that in the future for improved protection against surge voltage. [Frank, Ueda]
- Higher power demands and increased electric drive voltage suggest that increased voltage battery cells are likely. Specifically, stacked 600V battery cells plays to

the advantages of 1200V+ SiC power converters and inverters. This is the direction of the future, and likely where automotive design will go. [Stevanovic]

- The voltage used in the device "depends on which side of the Pacific you're on." The Japanese manufacturers are shooting at 1200-1500V, and 2000V "would be easy to do." The US manufacturers are "hanging onto 600V" and do not seem interested in going any higher. [Loboda]

Summary Assessment

While the American automakers do not seem to be interested in pushing voltages beyond the 600V-700V range, the Japanese manufacturers are working in that direction. This is one of the primary reasons they are interested in wide bandgap materials (see Assumption #8, below).

Assumption #8: SiC is the wide bandgap material of choice for replacing Si-based power electronics. GaN and other materials are too difficult to produce and too expensive to consider.

Evidence in Favor:

- Honda/ROHM announcement
- Mitsubishi Electric Corp. announcement
- Japanese auto makers are "totally focused" on getting SiC into production in their cars. Every manufacturer is working on optimizing the device elements in the inverter. [Loboda] (Note: Loboda's point that Japanese OEMs are intently focused on optimizing the inverter electronics using SiC suggests additional announcements are to be expected – with two in place to-date. [SP]
- GaN is likely only for giga and tetra devices, not for "mega-devices" (2000-4000V range). [Goodarzi]
- GaN "does not make sense" for power module application. [Cree]
- GaN is not easy to produce in quantities necessary for mass production of semiconductor devices because there is no natural substrate on which to grow it. [Cree]

Evidence Against:

- Toyota is investing significant sums into GaN R&D:
    - "As for the properties of GaN... We think it is a material with even more potential than SiC to play a leading role in the next generation of power electronics." [*Silicon Carbide*/Hamada]
    - "We have defined SiC and GaN as core materials for breakthroughs in power electronics technologies for the future." [*Silicon Carbide*/Hamada]
    - "GaN power devices are excellent candidates for automobile applications." [Ueda]

Summary Assessment

Most indicators point to SiC as the best wide bandgap material for use in hybrid vehicle power electronics. The Honda and Mitsubishi announcements are significant developments in support of this case. The fact that Toyota, as the world's leader in hybrid technology, is pursuing GaN as an alternative to Si is interesting. It is possible that they are developing a breakthrough technology which will allow cost-competitive production of GaN devices, which would be a significant technology surprise.

d. Concluding Remarks

At present, SiC exceeds the cost of Si by a margin that exceeds the premium that automotive OEMs are willing to pay. It appears that this will remain the case for at least the next five years (~2015). There are, however, intensive R&D and product development efforts on-going among Japanese OEMs which may lead SiC power modules to be brought to market in this timeframe.

The specific arguments for employing SiC to reduce the cooling requirements, as well as increase efficiency and performance in vehicle applications, according to the best available data at the time of this report. These appear insufficient to persuade US automakers to adopt the technology at this time. Si-based power modules have a very strong market-hold and may even prevent SiC from gaining widespread market acceptance by enabling larger power modules at a fraction of the SiC cost through the use of additional Si substrate content and novel packaging systems.

It is notable that the case for SiC's widespread adoption in mass market automotive applications will depend on factors outside the control of OEMs, including:

- Gas prices – probably in the range of approximately $4-$6 per gallon
- Fuel economy standards
- Tax credits and other incentives for the purchase of hybrid automobiles
- The volume of SiC sales in non-automotive applications. (High volume (20m+ annually) would likely drive SiC modules cost reductions to the level mass-market automotive OEMs require.)

The case for SiC's widespread adoption in mass-market automotive applications also depends on factors within the control of OEMs, including:

- Performance gains only possible through the use of SiC power modules
- Development of new electronics designs that deliver significant efficiency and performance gains through the use of SiC

The near-term markets for SiC are in non-automotive applications, such as medical imaging, aerospace, radar and defense electronics, railroad locomotives, heavy trucks, and hybrid military vehicles. These markets are expected to pay the premium price-point in return for the performance, reliability and efficiency gains that SiC will provide in high voltage applications (1500V+).

This is not the case for mass-market automotive applications at this time. However, it is possibly the case that should an automotive OEM require a new 1500V+ power module for a new engine and power electronics design, SiC technology would present clear advantages over Si and may transition at a competitive price in the long term.

3. Estimated Number of US Car Sales Required to Achieve Lower SiC MOSFET Prices in the Near-Term

The overarching driver for lowering SiC prices is volume production. Reducing costs is largely a matter of increasing the utilization rates of facility space and materials. Dr. Agarwal states Cree can guarantee SiC at 2x the cost of Si devices if production levels of 20 million units annually are achieved. "When Cree produces 20 million MOSFET units (not integrated power modules), at any voltage rating, it will reach the increased utilization rates to deliver the benchmark two times the cost of Si."

Assessing the automotive industry alone – which is viewed as least likely to be the early adopter of SiC because of its cost-sensitivity – it is clear that market penetration is required to achieve 20 million MOSFET units per year. Working from Cree's estimate of an average of 60 MOSFETs per vehicle, sales of 334,000 vehicles with SiC MOSFETs per year would be needed to reach the 20 million MOSFET unit benchmark. This is equivalent to 7.1 percent of the total automobile and light truck sales by the "Detroit 3" in North America in 2009 or 3.2 percent of all light vehicles sold in the US in 2009 (see Table 5 below).

Table 5: MOSFETS Required For 2009 Automobile Production

2009 Sales	Car	Light Truck	Total	Silicon MOSFETS Used	Percentage of sales required to use 20M MOSFETS
GM	945,112	1,126,637	2,071,749	124,304,940	16.1
Ford	637,087	1,040,147	1,677,234	100,634,040	19.9
Chrysler	246,624	684,778	931,402	55,884,120	35.9
Total US Manufacturers	1,828,823	2,851,562	4,680,385	280,823,100	7.1
Total US Sales (all manufacturers)	5,692,432	4,739,077	10,431,509	625,890,540	3.2

Source: Synthesis analysis of Automotive News Data Center and Cree data

It is feasible that decisions by the US automakers to use SiC MOSFETS for one or two vehicle models could achieve the benchmark 20 million MOSFET units per year – and thus drive SiC costs to two times the cost of Si.

By comparison, in terms of HEVs, the total number of HEVs sold in the US in 2009 was 290,271, which is equivalent to approximately three percent of the total US car and light truck sales in 2009. According to DOE's Alternative Fuels and Advanced Vehicle Data Center information, some 48 percent of these were Priuses, followed by Camry HEV (nearly 8 percent), Insight (7 percent), Ford Fusion (5.4 percent), Honda Civic HEV (5.2 percent), followed by smaller shares by all other brands.

Based on this data, and assuming the 60 MOSFETs per vehicle, OEMs have yet to achieve the sales volume of HEVs in the US needed to achieve the 334,000 vehicles per year benchmark necessary to achieve a 2x SiC – Si cost differential. Toyota alone (assuming Prius, Highlander and Camry HEV US sales only) reaches approximately 50% of this benchmark.

This analysis indicates that US HEV and EV markets are not of sufficient volume to drive automotive OEMs to transition to SiC at this time. Thus, it appears that OEMs will need to consider the both HEV and non-HEV vehicle sales to achieve the necessary economies-of-scale to drive SiC costs to a competitive premium over the costs of Si.

When this volume level is attained, SiC MOSFETS may have a credible path to achieving a wider-scale transition into the market. At that point, other automotive producers would have economic reasons to evaluate the benefits of SiC.

The current state of demand for SiC MOSFETS is a chicken-and-egg challenge: Dramatic reductions in the cost of SiC MOSFETS for automotive applications depend on large-volume production runs. However, without the high volumes, producers can't achieve the price-points required by automotive users. Automotive applications are particularly demanding, with a low-to-zero tolerance for price premiums.

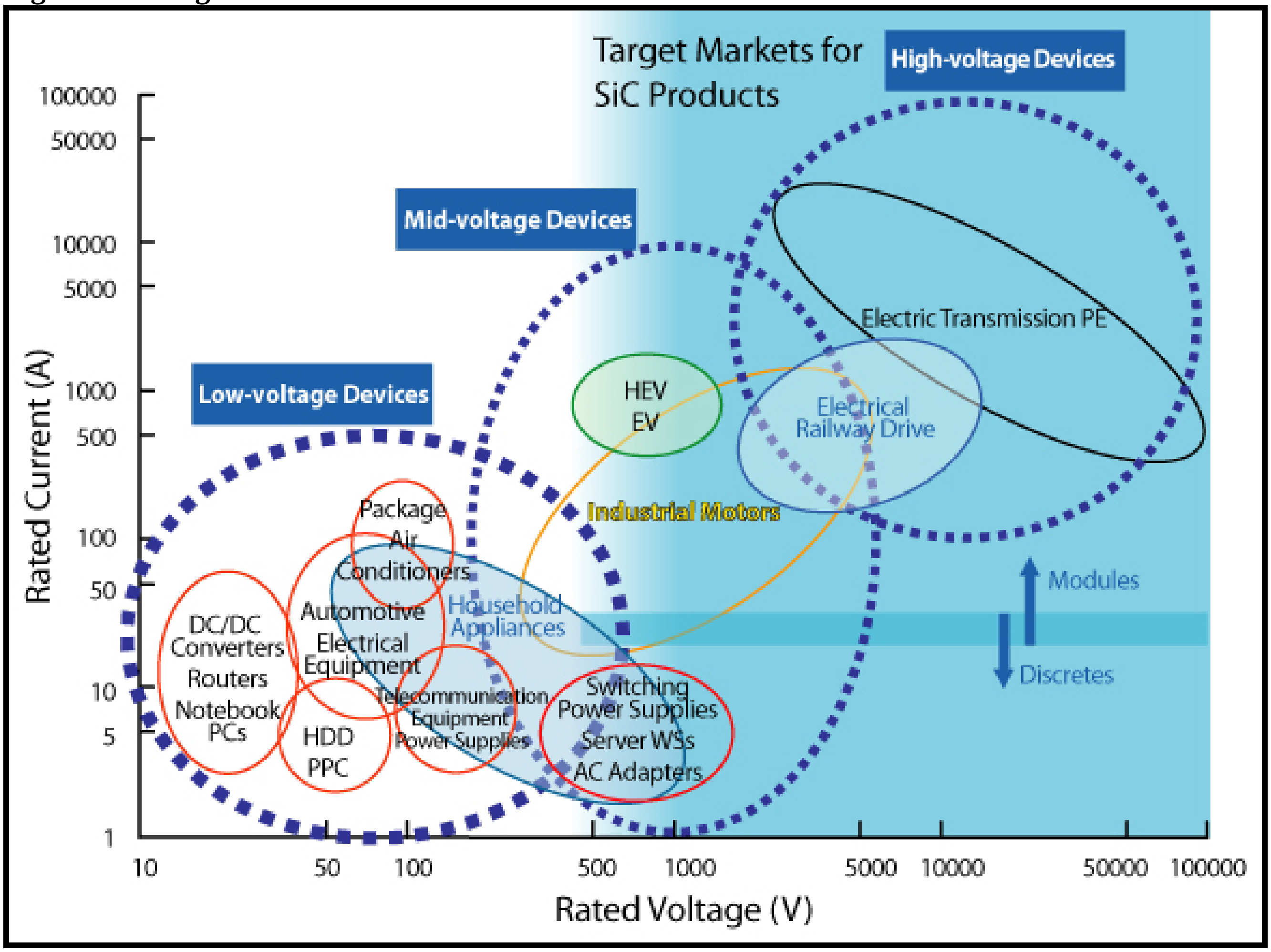
Accordingly, Synthesis assesses that non-automotive industries will drive SiC production growth over the next several years. This report does not take into account the growing impact of wind, solar, and civilian/military aerospace applications on demand for high-voltage SiC. These applications, because of their higher voltage ratings at which SiC has unique cost-performance benefits, are more likely to drive demand for SiC over the next three years. It is unclear at what point demand from these non-automotive sectors will reach 20 million MOSFET units annually.

While it is difficult to foresee the timing of SiC's widescale market penetration into the automotive sector, we assess that SiC's adoption in the automotive sector will depend largely on non-automotive sectors and other factors outside the automakers' control.

4. Characteristics of SiC devices

Silicon carbide semiconductors cover a wide range of voltages and amperage as indicated by Figure 2. Current automotive applications such as HEVs and EVs fall into the "mid-voltage" range, at 600-1200V.

Figure 2: Target Markets for SiC Products



Source: ROHM Co. Ltd (http://www.rohm.com) (Used with permission of the publisher.)

a. Voltage - 600-1200 V

The key advantage of silicon carbide is its higher break-down voltage compared to silicon. More silicon is needed to achieve the equivalent voltage rating as SiC. Therefore, SiC is a natural fit for higher voltage applications. SiC becomes less attractive as voltage declines.

In the 2000V plus range, SiC is clearly superior. Si is unlikely to compete in this range in the near-future. Nonetheless, there are few current product offerings that take advantage of the SiC dielectric constant advantage at these higher voltage ranges. In the medium 1000V range, SiC devices compete with Si-based IGBTs and MOSFETs. Below 500V, Si-based MOSFETs and transistors will dominate. Dr. Goodarzi of US Hybrid Corporation does not consider SiC competitive for any applications below 500V.

We assess that SiC will be competitive for niche power applications in higher voltage ranges. With SiC power modules, a smaller device can achieve the same result as a 30 percent larger Si power module may be able to achieve. The automotive engineer and designer will make a trade-off as to the relative value of the size of the power module as compared to its cost. If there is no difference in vehicle performance the end-user will not necessarily differentiate between cars that have SiC or Si-based power devices.

There seems to be disagreement in the industry on the rationale of pushing beyond 600V with power electronics. Dow Corning's Mark Loboda stated that the voltage used in power modules "depends on which side of the Pacific you're on." He said Japanese manufacturers are shooting at 1200-1500V, and 2000V "would be easy to do." The US manufacturers are "hanging onto 600V" and do not seem interested in going any higher.

The voltage rating of the power modules is a direct function of the voltage of the battery pack found in the vehicle. Current HEVs use battery packs in the 200-300V range. The standard is for the power module to be rated at approximately 3x the battery rating. Unless there is a move to higher voltage battery packs, 600V power modules will be sufficient. Dr. Mantooth from the University of Arkansas stated "there is talk of a higher voltage battery pack [however] I can't give the numbers out from my sources". He also stated that operating at higher voltages could provide "improved efficiencies even if the battery voltage remains the same."

According to Dr. Grider of Cree, the most likely path over the next several years is to move from the 600V hybrid power modules to 800V hybrid modules, followed by 1200V hybrid modules in 2013-2014. It is not clear whether significant automotive markets will open to hybrid Si-SiC power modules in several years time. The critical dependency is the cost-competitiveness of the modules, and by extension whether Cree has sufficient production volume in the next several years to deliver the necessary price decreases by 2013/2014.

Pushing beyond the 1200V range would not be difficult, according to Dr. Agarwal of Cree. He stated that production of a 2000V SiC power module to compete with current Si-based IGBTs, is "very possible in less than five years, and in three years minimum." In fact, Cree noted that they would put this potential opportunity on their roadmap, and said, "Since we are working 1700V for solar and wind applications, to get to 2000V from a technical point of view, is a very small thing for us."

While Cree does not currently offer a 2000V device, Dr. Agarwal stated: "if we were to start today, it would take 12-18 months to develop such a device … and another 18 months to qualify it for commercial production … so approximately three years minimum."

Cree's assertion that it could satisfy a market need for 2000V SiC power modules "in less than five years" is based on the assumption that the practical market entry-price of such a SiC device is two times the price of Si-IGBTs, or approximately $5,800.

b. Amperage - 5-20 A or higher if possible, up to ~70 A

Synthesis focused on amperage ranges of interest to automotive customers in this study. Whereas sources did not specifically design responses to individual ampere-ratings, our research did not reveal information or sources suggesting that SiC producers could not meet the amperage ratings of 5-20 A and higher, up to ~70 A.

c. Operating temperature - 200-300°C (392 – 572°F)

Silicon devices are heat-sensitive; the maximum junction temperature for most Si electronics is 150-175°C. Maintaining this temperature range requires the use of either air- or liquid-cooled heatsinks. For lower power converters, bulky air-cooled heatsinks are sufficient. Higher voltage converters use liquid-cooled heatsinks which require a cooling system complete with coolant pump, fan, and radiator. This cooling system can occupy more space and weigh more than the power module itself.

Devices with higher operating temperatures are more efficient because they operate at higher frequencies with reduced switching losses. Silicon carbide can operate at much higher temperatures and dissipate heat much more efficiently than silicon. This allows for more efficient packaging due to smaller heatsinks and reduction in size or elimination of liquid cooling systems.

Some experts disagree on the advantages of higher operating temperatures. Dr. Goodarzi states that, while frequently promoted as a critical advantage for automotive applications, a higher temperature operating range is not necessary to design automotive power control applications. He notes that all the advantages of SiC occur well above the temperature range at which automobiles currently operate. In most automotive applications, the use of SiC translates to a gain of about 20-30˚C compared to Si. He believes that this can be useful in some instances, but not all.

The higher operating temperature benefits of SiC modules are lost when using the hybrid Si plus SiC approach. However, according to Dr. Agarwal, while the temperature advantage of a SiC-only IGBT is lost, the Si IGBT can be run cooler in combination with SiC diodes, because the heat transfer is reduced using SiC diodes. Specifically, there is an added “temperature margin” when employing the hybrid power modules. According to Dr. Agarwal, the Si IGBTs “run now at 110°C, and …and you don’t want them to go above 130°C … which leaves you a 20° margin.”

By comparison, with SiC diodes, Dr. Agarwal notes: “you can run with a 40°C margin. That is, with SiC diodes, the Si IGBT can run at 90°C with approximately 30 percent lower losses at that lower temperature, and with the added benefit of a significant, 40° C margin available from a power module design point of view.”

d. Wafer size - Large wafer sizes preferred for lower cost

As noted above, the standard size for SiC wafers is currently four inches. Industry experts agree that a six-inch wafer is possible if the market demands it. According to Cree’s John Palmour, the barrier to producing a six inch wafer is the lack of demand.

Six inch wafers would drive volumes higher and reduce manufacturing costs. He states fabricating larger wafers is not so much a technical issue as it is a manufacturing and marketing issue.

Dow’s Mark Loboda also does not see a lot of push to go beyond four-inch wafers for the near future, as this technology is only several years old. However, he did note that six-inch wafers are “starting to get attention.” “How long it'll take” for the industry to start demanding six-inch wafers he “can't tell”, but he thinks a good ballpark estimate is two to five years. An eight-inch wafer is "real tough" and he does not see any demand for it, as the six-inch wafer is the current wafer of choice even in the Si market. He sees the primary roadblock to overcome in producing wafers greater than four inches is the crystal growth or epitaxial growth process.

Appendix A

University Research Programs

US Programs

School	Program	Department	POC	Email	Telephone	URL
University of South Carolina	Silicon Carbide Lab	Electrical Engineering	T.S. Sudarshan	sudarsha@engr.sc.edu	(803) 777-5174	http://www.ee.sc.edu/research/SiC_Research/
Mississippi State University	Center for Advanced Vehicular Systems	Electrical and Computer Engineering	Marshall Molen	molen@cavs.msstate.edu	(662) 325-5577	http://www.cavs.msstate.edu/
University of Arkansas	Semiconductor Devices Group	Mixed Signal Computer Aided Design Laboratory	Alan Mantooth	mantooth@engr.uark.edu	(479) 575-4838	http://mixedsignal.eleg.uark.edu/sic/index.html
Purdue University	Wide Band Gap Semiconductor Device Research Program	Electrical and Computer Engineering	Michael A. Capano	capano@ecn.purdue.edu	(765) 494-3563	http://www.ecn.purdue.edu/WBG/
Auburn University	WBG Semiconductor Research Group	Physics	John R. Williams	williams@physics.auburn.edu	(334) 844-4678	http://wbgs.physics.auburn.edu/
Georgia Tech	Microelectronics and Nanotechnologies Group	Electro-Optical Systems Laboratory	Mike Harris	mike.harris@gtri.gatech.edu	404-407-6015	http://eosl.gtri.gatech.edu/Default.aspx?tabid=109
University of North Carolina	Power Semiconductor Research Center	Electrical Engineering	Jayant Baliga	bjbaliga@unity.ncsu.edu	919-515-6169	http://www.psrc.ncsu.edu/index.html
MIT	Wide Bandgap Semiconductor Materials and Devices	Electrical Engineering and Computer Science	Tomás Palacios	tpalacios@mit.edu	(617) 324-2395	http://web.mit.edu/tpalacios/index.html
Rensselaer	Advanced Power	Center for	Paul Chow	chowt@rpi.edu	(518) 276-	http://www.rpi.edu/dept/cie/c

School	Program	Department	POC	Email	Telephone	URL
Polytechnic Institute	Device Research Laboratory	Industrial Innovation.			6044	pes/NF_HOME.htm
Rutgers	SiCLAB	Electrical and Computer Engineering	Jian H. Zhao	jzhao@ece.rutgers.edu	(732)445-5240	http://www.ece.rutgers.edu/~jzhao/
University of Tennessee, Knoxville	Power Engineering Laboratory	Electrical Engineering and Computer Science	Jack Lawler	jsl@utk.edu	865-974-9886	http://power.eecs.utk.edu/

<u>Other Countries</u>

School	Program	Department	Country	POC	Email	Telephone	URL
Griffith University	Queensland Microtechnology Facility	Engineering and Information Technology	Australia	Barry Harrison	barry.harrison@griffith.edu.au	+61 7 3735 6431	http://www.griffith.edu.au/engineering-information-technology/queensland-microtechnology-facility
KTH Royal Institute of Technology	Silicon Carbide Electronics Program	Microelectronics and IT	Sweden	Jan Linnros	jan.linnros@ele.kth.se	+46 (0) 8 75 2 1422	http://www.imit.kth.se/FTE/
Technische Universität München	Walter Schottky Institut	Physics / Electrical Engineering / IT	Germany	Martin Stutzmann	stutz@wsi.tum.de	49-(0)89-289-12761	http://www.wsi.tum.de/Home/tabid/36/Default.aspx

Appendix B

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Appendix C

Research Statistics

Research Statistics	
Number market research reports reviewed (TOC review)	16
Percentage found to be relevant of those reviewed	0
Number reviewed in depth	0
Number corporate web sites reviewed	25
Percentage relevance	78
Number of pages reviewed in depth	7000+
Percentage academic	<2
Percentage market research reports	
Percentage association	
Percentage press releases	
Percentage other (company, consultant, news articles, etc.)	
Companies Contacted Directly	20
Emails sent	20
Number replied	14
Positive reply	13
Negative reply	1
No reply	6
Telephone contacts	11
Positive response	100
Negative response or no answer	0
Specific Sources/Types of Information	
Nexis	
Number of listings	138
Number of listings scanned	138
Number of listings reviewed	73
Percentage found to be potentially relevant	13
Types of listing (some categories may overlap)	
Corporate reports	8
Market Research Reports	0
Press releases	44
Country information	6
Company information	5
Journal/News articles	113
Other	17
Profound	
Number of reports found	16
Percentage found to be relevant	0
Number reviewed (TOC reviewed)	16
Number reviewed in depth (contents reviewed)	0

Other Sources Reviewed	
Professional Associations	
Number reviewed	2
Percentage found to be relevant	100
Financial/commodity sites	
Number reviewed	0
Percentage found to be relevant	0
Corporate sites	
Number reviewed	27
Percentage found to be relevant	37
Conferences attended	2
Contacts generated	17