Review of Public Data on Costs of Wide Bandgap (WBG) Substrate Manufacturing

Prepared for the Department of Energy

By

Synthesis Partners, LLC

This information is intended for public release.

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Introduction

This report has been provided to the Vehicle Technologies Office of the Department of Energy (VTO-DOE) as a FY14 Task 3 deliverable, wherein Synthesis Partners (Synthesis) was tasked by the VTO to undertake preliminary research on publicly available cost information related to wide bandgap (WBG)-based traction drive inverters.

The type of question that motivates this research is: Can silicon carbide (SiC) or gallium nitride (GaN) insulated gate bipolar transistor (IGBT) devices be manufactured at a cost-point that will yield a device able to compete with Si power IGBT devices for use in traction drive PE and other automotive system applications in North America?

This report provides targeted results from a 2014 secondary source data scan and in-depth review of selected confidential primary source interviews (completed in 2012-2014) regarding WBG substrate manufacturing costs. The research has focused on North American (NA) and English-language sources.

This effort is intended to support follow-on analyses sponsored by VTO regarding NA WBG industrial base expansion activities. As such, this report provides a top-level view of the issues discovered regarding the cost of manufacturing WBG substrates for next-generation traction drive inverters. The range of companies that Synthesis believes are interested in WBG NA substrate manufacturing developments today are listed in Appendix 2. This list of organizations is continuously updated and, as needed, we will update our data.

This report does not analyze chargers or batteries, and does not address any particular substrate manufacturing cost model. Follow-on analyses of specific questions derived from traction drive inverter cost models may be a subject of future research.

Please contact Christopher Whaling at Synthesis Partners at cwhaling@synthesispartners.com, or via www.synthesispartners.com with any questions or comments. Thank you.

Sources and Methods

This document is based on Synthesis' integrated analysis of targeted secondary sources and primary source information. This primary research approach is not a survey and is not intended to produce statistically significant results. Multiple contacts were made to include the maximum number of different, unique perspectives. The key secondary sources used are listed in the bibliography at the end of this document. The information is English-language-based and focused exclusively on NA.

The primary source information was developed by Synthesis through confidential interviews regarding numerous topics of interest to DOE, including WBG topics, executed mainly in the 2012-2014 timeframe. It has been analyzed and filtered by several Synthesis analysts. All interviews are maintained in confidence. Each interview is written up by Synthesis, reviewed by the source and is only then used as a source of anonymized material for further analysis.

Table 1 below provides a view of the range of primary sources that Synthesis leveraged for this document. Synthesis' analyzed each of the interviews obtained, and reviewed the nature of the contacts made (as reflected in Table 1), for information on WBG substrate manufacturing costs.

Table 1: Primary Source Research Statistics

Research Statistics – Primary Sources (All sources are English language unless otherwise specified)	
Companies vetted for contact	338
OEMs	23
Tier 1	31
Tier 2	60
Tier 3	130
Tier 4	43
Multi-Tier	30
Other	21
Total contacts made (multiple contacts within many organizations)	1,275+
E-mails	725+
Phone Calls	525+
In-Person Conference Contacts	25+
Distribution of in-depth interviews	100%
OEMs	15%
Tier 1s	13%
Tier 2s	22%
Tier 3-4s	24%
Multi-Tier	15%
Others (National Lab, Government Office, Academic, Association, etc.)	11%

Interviewees, independent experts and DOE personnel were not asked to endorse the conclusions or recommendations contained herein, nor did they review the final draft of the report before its release to the DOE VTO.

Synthesis has made good faith attempts to ensure this study is accurate, up-to-date and comprehensive. Nonetheless, Synthesis looks forward to working with DOE VTO stakeholders to identify gaps and refinements so that the results of this research activity continue to be accurate and timely for DOE VTO decision-making.

Initial Estimates of WBG Substrate Manufacturing Costs

There is considerable industry interest in building lower cost, higher-temperature, more efficient and more power dense inverters. Before providing data on estimates of WBG substrate manufacturing costs, we provide two examples of this recent industry engagement.

NC State's Power America Institute shows a one-of-a-kind effort to accelerate NA manufacturing competitiveness and innovation in WBG. The Power America Institute is a $140 million DOE-partner funded advanced manufacturing institute that will focus academic, government and industry partners on an effort "to revolutionize energy efficiency across a wide range of applications, including electronic devices, power grids and electric vehicles." (See http://www.ncsu.edu/power/). The Institute's mission is to "develop advanced manufacturing processes that will enable large-scale production of wide bandgap (WBG) semiconductors, which allow electronic components to be smaller, faster and more efficient than semiconductors made from silicon." Power America can give U.S. manufacturers a boost in the emerging WBG market. Among NC State's partners are four other universities — Arizona State, Florida State, the University of California-Santa Barbara and Virginia Tech — and 18 energy industry leaders.

A second example of industry interest in accelerating WBG breakthroughs is the Google Little Box Challenge. (See www.littleboxchallenge.com). The Little Box Challenge is offering a $1M dollar prize to any team that can design and build a kW-scale inverter that is 95% efficient and capable of handling 2 kVA loads with high power density (at least 50 Watts per cubic inch). This requires shrinking an inverter "down to something smaller than a small laptop (a reduction of >10^x in volume)" and the winners will "help revolutionize electricity for the next century."

WBG semiconductor devices are one of the critical enabling technologies for the Little Box Challenge. Today's SiC JFETs and diodes can provide best in class performance in terms of efficiency and thermal performance, and GaN devices are in development to compete at higher voltages (>5,000 volts), and for very high frequency applications (generally suited to defense applications).

Synthesis' review of the secondary and primary sources as of this reporting shows a variety of estimates of current WBG substrate manufacturing costs. The information developed from primary source interviews is shown in Table 2 below. This information frames the discussion that follows regarding the range of primary and secondary views about WBG substrate manufacturing costs and what those costs may portend for future automotive applications specifically.

Table 2: Initial Estimates of WBG Substrate Manufacturing Costs

Initial Estimates of WBG Substrate Manufacturing Costs						
Product	**Details**	**Si Substrate***	**SiC-on-SiC Substrate***	**GaN-on-GaN Substrate***	**GaN-on-SiC Substrate***	**GaN-on-Si Substrate***
6" Wafer or Epiwafer (Unless otherwise specified.)	Manufacturing cost estimate	$12 for average 6" wafer. (2013) $25-$50 for a 6" Si substrate (2012)	$24-$100 At the component level, SiC costs remain about double that of Si. (2014)	$2,000 for a 2" GaN substrate. (2013) $1,900 for a 2" bulk GaN substrate. (2012)	$29-$120 GaN-on-SiC wafers cost about 20% more than their SiC-on-SiC counterparts. (2013)	Approx. $1,000. (2011, 2012, 2013, 2014)

**Source: Estimates based on Synthesis research and interviews completed in 2013 and 2014.*

Table 2 shows a range of estimates for 6" wafer substrate manufacturing costs culled from dozens of Synthesis' full-length interviews. Only those substrates for which sources provided cost data are included. Other WBG materials are addressed in Table 3, based on secondary source information on comparisons of WBG to Si on key figures of merit beyond costs.

From the results in Table 2, and the context of the full-length interviews on which it is based, Synthesis concludes: 1) the range of wafer-based cost substrate manufacturing costs reported in Table 2 is significant; 2) the context through which one interprets these cost data is critical, because absolute, wafer-based cost differentials do not begin to address the system-wide benefits that WBG materials for traction drive inverters may produce and which need to be addressed, and; 3) these estimates are just a start, and need further refinement, extension and definition with VTO stakeholders.

Comparison of WBG Substrate Materials with Si on Key Figures of Merit

Table 3 below shows a comparison of Si to WBG semiconductor materials, including the functional material gallium oxide Ga_2O_3, along key figures of merit. The functional material Ga_2O_3 is included due to its highly stable crystal structure, which makes it valuable for dielectric coatings and for insulating barriers in tight junctions.

Table 3: Comparison of Semiconductor Materials to Gallium Oxide (Ga_2O_3)

Characteristic	Si	GaAs	4H-SiC	GaN	β-Ga_2O_3
Bandgap (eV)	1.1	1.4	3.3	3.4	4.8-4.9
Electron Mobility (cm^2/Vs)	1400	8000	1000	1200	300
Breakdown Field (MV/cm)	0.3	0.4	2.5	3.3	8
Relative dielectric constant	11.8	12.9	9.7	9.0	10
Baliga's FOM (to Si)	1	15	340	870	3444

Source: www.compoundsemiconductor.net

Manufacturers are looking to new, highly efficient, high-temperature and power-dense power module designs to take advantage of relative advantages of WBG materials.

For a technical comparison of WBG materials and the electrical engineering reasons for moving beyond Si, please see B. Ozpineci and L. M. Tolbert's report, entitled "Comparison of Wide-Bandgap Semiconductors for Power Electronics Applications," (December 12, 2003) (See http://web.ornl.gov/~webworks/cppr/y2001/rpt/118817.pdf). That technical viewpoint provides important background to any discussion on the role of costs in WBG manufacturing.

In terms of cost (our focus in this report), experts estimate a high-quality, 6-inch substrate wafer of Ga_2O_3 could be mass-produced for approximately $120/wafer. This compares to $12 for an average 6" Si wafer (based on 2013 sources), and $25-$50 for a 6" Si wafer (based on 2012 sources), as reported in Table 2. This does not mean to suggest that automotive PE should prefer one or another substrate based on wafer-based costs alone. Indeed, a technical assessment of the system-wide costs and benefits of a WBG-based PE traction drive system is needed. That system-wide assessment is outside the scope of this document.

A top-level, non-technical analysis and review of the relative benefits of WBG substrates, focused on silicon carbide vs. Si for automotive traction drive applications, is available in the Synthesis report entitled "Technology and Market Intelligence: Wide Bandgap Semiconductors: Silicon Carbide for Automotive Applications," (June 2010). It is recommended for background data on WBG issues and for information on the application of WBG in automotive traction drive in particular.

Overview of Wide Bandgap Material and Production Processes

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. Use of these materials produce a semiconductor that can operate at much higher temperatures and handle much greater voltages than standard semiconductors for use in power electronic (PE) devices. This is desirable because vehicle electrification demands increased power density (greater power in smaller volumes) and higher temperature-capable systems (due to the fact that increase power density and higher operating temperature ranges can reduce the need for expensive cooling systems, and thus can reduce system costs).

Automotive applications of Insulated-Gate Bipolar Transistors (IGBTs) include ignition systems and inverters/motor controllers in hybrid and electric vehicles. These applications are ideal for IGBT devices because they require high-voltage switching capabilities and can withstand the harsh environmental factors associated with an automotive drive train. However, they do not use WBGs to-date due to cost.

A listing of terms with non-technical definitions related to WBG materials and devices used in this document is listed in Table 4 for reference.

Table 4: Glossary of Terms With Non-Technical Definitions

Term	**Non-Technical Definitions**
Baliga's FOM (to Si)	Defines performance of WBG devices compared to Si (Si = 1), based on material parameters to minimize the conduction loss in low-frequency unipolar transistors. Parameters include the static dielectric constant, electron mobility and the bandgap of the material.
Bandgap (eV)	The term "band gap" refers to the energy difference between the top of the valence band to the bottom of the conduction band. In order for an electron to jump from a valence band to a conduction band, it requires a specific minimum amount of energy for the transition, the band gap energy. Band gap energy is measured in terms of the electronvolt (eV). The eV is the amount of energy gained (or lost) by the charge of a single electron moved across an electric potential difference of one volt.
Breakdown field (MV/cm)	Measurement of the field strength at which electrical field breakdown (electric field frees bound electrons) occurs in the named dielectric material. It depends on dielectric strength of the material, which depends on the configuration of the material or the electrodes with which the field is applied. It is measured in terms of MV/cm or 10^6 Volts/cm.
Electron mobility (cm^2/Vs)	Electron mobility characterizes how quickly an electron can move through a metal or semiconductor, when pulled by an electric field. Almost always, higher mobility leads to better device performance, with other things equal. It is measured in terms of cm^2/(Vs), where Vs = volts per second.
Embedded software design and engineering	The development and coding of device drivers (using, e.g., memory-mapped I/O, struct overlays, bitmasks and bitfields) to control hardware peripherals, such as circuits, valves, sensors and other electrical and electro-mechanical systems.
Epitaxy	The deposition of a crystalline overlayer on a crystalline substrate. Epitaxy is used in the production of silicon wafers for semiconductor fabrication.
Fabrication	The process of creating the integrated circuit chips used in power electronic devices from wafers of silicon or other semiconductor materials.
FET	Field-effect transistor; a transistor commonly used for amplifying weak signals.
Foundry	The separation of a semiconductor fabrication plant operation (foundry) from a

Model	vertically integrated design and build operation, into separate companies or business units based on different processes and components of the semiconductor.
GaN	Gallium Nitride; a compound used to make light-emitting diodes and high-voltage and high-frequency semiconductor devices capable of operating at high temperatures,
HEMT	High-Electron-Mobility Transistor; a field-effect transistor incorporating a junction between two materials with different bandgaps.
IGBT	Insulated Gate Bipolar Transistor; a power semiconductor device that combines high efficiency and fast switching. It combines an isolated gate FET for the control unit with a bipolar power transistor as a switch into a single device.
JFET	A junction field-effect transistor, which is a type of field-effect transistor in which the semiconductor gate region or regions form one or more p-n junctions with the conduction channel.
MOSFET	Metal oxide semiconductor field-effect transistor; a type of transistor used for amplifying for switching electronic signals.
On-resistance	Lower on-resistance translates into lower conduction losses and reduced power consumption for energy-saving solutions. Electrical resistance is equal to the voltage across the conductor divided by the current flowing in the conductor: usually measured in ohms.
PCB Assemblies	Printed circuit board assemblies.
Packaging	The final stage of printed circuit manufacturing, in which the integrated circuit chip is encased to prevent physical damage.
Power Silicon	Another word for silicon transistor.
Relative dielectric constant	The dielectric constant is the ratio of the permittivity of a substance to the permittivity of free space. It is an expression of the extent to which a material concentrates electric flux, and is the electrical equivalent of relative magnetic permeability.
SiC	Silicon Carbide; a compound used as an abrasive and to make ceramics and high-voltage, high-temperature electronic semiconductors.
Substrate	A substance to which a layer of another substance is applied, such as sapphire over which GaN is layered in producing light-emitting diodes.
WBG	Wide Bandgap; refers to material such as SiC or GaN used to replace silicon in semiconductor devices, allowing them to operate at higher voltages, frequencies, and temperatures than standard silicon-based semiconductor devices. Also refers to devices made using WBG materials. (Note: There are WBG materials other than SiC and GaN. However, these materials are getting the most attention in the production of IGBTs and other power electronic devices used in traction drive inverters.)

Source: Synthesis Partners, LLC (2014)

<u>Advantages</u>

WBG materials share several advantages over the Si traditionally used in semiconductor devices, including smaller size and higher operating temperatures and frequencies.

SiC's thermal conductivity is more than three times that of either Si or GaN. While standard silicon-based transistors have an upper operating limit of around 125°C, SiC devices can easily operate at 300°C.

However, GaN has an advantage over SiC because it can be grown on standard silicon wafers, while SiC requires somewhat more esoteric and expensive substrates. Also, GaN's superior on-resistance means it can be used to build devices that are up to one-hundredth the size of comparable Si devices and about a tenth the size of similar SiC devices.

Overall, the advantages of WBG devices were best summed up in an interview with an OEM: "WBG devices themselves are unlikely to be lower cost on a $/Amp or $/kW basis in the near future, but they enable higher efficiency powertrains, more compact, and lower thermal load systems and therefore ultimately lower system capital and operating (fuel and repair) costs."

Semiconductor Manufacturing Process Details

The steps in making semiconductor products are:

1. Epitaxy growth – grow additional crystals on top of the desired substrate

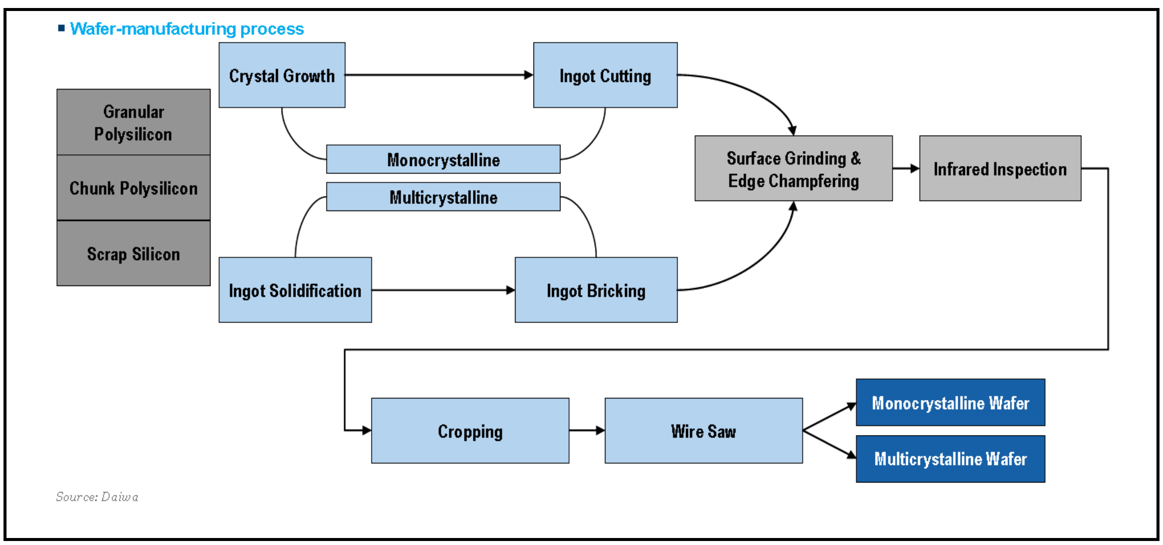
2. Device fabrication – etch the epitaxy with chemicals, blast it with ions, expose it to specialized gases, and deposit metals to create a power semiconductor switch.

3. Packaging – attach miniscule wires to the finished device and surround it with plastic to create a "brick" with 4 electrical terminals.

4. System integration – attach 2 wires for triggering the switch to the packaged brick, and 2 heavier cables for the input and output power connections.

Steps 1 and 2 are shown in greater detail in Figure 1.

Figure 1: Wafer Manufacturing Process



Source: asiaresearch.daiwacm.com

Epitaxy is the most difficult and most expensive step in the WBG fabrication process, particularly when using SiC. While Silicon can be made into well-ordered crystals after being melted into liquid form, SiC evaporates directly into gas form without going through a liquid phase when heated. Depositing crystals from the gas form requires delicate temperature control under seal. It is very difficult to deposit an even layer of SiC without producing irregular (and therefore useless) crystal lattice structures. A great deal of expertise is needed to produce viable SiC wafers.

GaN has its own set of problems with epitaxy; currently the process for GaN is much more expensive than that for silicon. GaN and silicon have different crystal structures, and when growing GaN on silicon these differences produce stress that usually results in one layer splitting off from the other. To prevent this, buffer layers and careful control over the deposition process are used to prevent the stress cracks and splitting.

What We Know From Primary and Secondary Sources Regarding WBG Costs

The price-point difference between Si-based devices and WBG devices is due to the manufacturing process, not the material. As stated above, the most expensive portion of WBG fabrication is the epitaxy step in the manufacturing process.

A Tier 1 manufacturer stated the main cost driver in SiC is the cost of the wafer (which includes the manufacturing process to produce it) because of the length of time it takes to grow, which results in fewer SiC wafers produced and smaller wafers in relation to Si. Smaller wafer sizes limit the number of devices that can be made, increasing per-unit costs. Producing larger wafers enables the production of more devices per wafer and lower device costs.

Current information suggests that there is only one firm producing SiC wafers in the U.S., though sources also indicate there may be two other firms interested in beginning production.

Globally, most producers provide four-inch SiC wafers with a few producing six-inch wafers. This compares to low-defect, production-ready Si wafers at six to 12 inches.

The Synthesis report “Technology and Market Intelligence: Hybrid Vehicle Power Inverters Cost Analysis” (July 2011) included an analysis of cost drivers for two traction drive inverters, one in current production and one scheduled for production in 2016. The two top cost drivers for both inverters are PCB assemblies/components and Si-based power silicon (each comprise of about 25 percent of the total inverter cost). With the current higher production costs of WBG devices, these cost drivers would only increase in impact if WBGs were used in place of Si.

But the outstanding question remains: How should the cost of a WBG-based traction drive inverter system be compared to the cost of a Si-based system? What is an appropriate approach, and how can it be validated? These questions have yet to be addressed in the public literature in a non-technical, broadly accessible, but rigorous way.

<u>Cost of Si vs. WBG-Based Devices</u>

As noted, both GaN and SiC can be used to produce smaller devices than possible with Si. Since GaN can be grown on standard silicon wafers, it has a cost advantage over SiC, which needs more expensive substrates. However, many experts believe that improvements in SiC crystal growth will negate this advantage, eventually giving SiC a cost advantage in higher-voltage devices (1200 V and up). On page 43 of the prior Synthesis report, entitled “Wide Bandgap Semiconductors: Silicon Carbide for Automotive Applications,” there is a figure showing the range of significant applications available for SiC, at varying voltage levels, and an accompanying discussion of the relative merits of WBG vs. Si.

One Tier 3 supplier stated:

> "Right now, the SiC: Si wafer cost ratio is at least 20. As time goes on, this ratio will likely become smaller as the cost of silicon will remain constant and the cost of SiC will come down. However, it is likely that the relatively higher price of SiC will relegate SiC's application to higher value areas where economics are not a major consideration (vis a vis SiC's performance attributes). In the near term, due to SiC's very thick boules and its expensive substrates, applications are likely to be targeted to below 1-2KV. GaN will be applied to the medium-range and silicon will continue to be used at the higher range."

The only cost disadvantage when comparing GaN transistors with MOSFETs is the epitaxial growth of the GaN on the silicon wafer. However, advances in epitaxial technology are expected to ameliorate this over the next few years, giving GaN a cost advantage over MOSFETs.

As it stands now, WBG devices remain expensive because of the difficult manufacturing process, which has led to low demand and small production runs, and as a result WBG costs have yet to benefit from economies of scale. Synthesis asserts that a strategic assessment addressing options on reduce the cost of WBG manufacturing in NA is needed.

Some individuals in DOE are more optimistic about the future cost of WBG devices than some of the suppliers interviewed. DOE sources predicted that "production on 6-inch will reduce chip cost by 50% every two years and performance will be improved. WBG devices will replace Si in mainstream applications at 600V to 1700V in the next 5 years." They also predicted that "the overall market for WBG devices will double every 2 years from the current $100M to $3B in 10 years and new systems enabled by WBG will create $20B in new markets in the US and worldwide." (Source: Argarwal, "WBG Revolution in Power Electronics").

The industry believes that a SiC cost of 1.5 - 4x cost of Si is needed to achieve wide replacement of Si with SiC. To achieve this, it will be necessary to reduce all of the WBG cost drivers simultaneously. A benchmark data-point is that as of September 2013, SiC was approximately 3 - 6x the cost of Si. More collection is needed to develop a more precise, current estimate.

<u>Drill-Down on Cost Drivers for WBG Traction Drive Inverters</u>
There are at least five cost-drivers to consider when analyzing the cost of semiconductors in general and WBG semiconductors in particular. These five cost drivers are prime considerations for future cost modeling efforts:

- *Substrate Costs:* Substrate cost is driven by the size of the wafer and the substrate material used. This in turn is driven by the type, size, and complexity of chip being produced. While smaller wafers are cheaper to produce, the chip yield from each is less than from a larger wafer, and thus the cost per chip at scale is higher on smaller wafers.

  As device size (chip size) increases, the yield of chips per wafers decreases. According to Sheng and Colino, "the cost of die (per device) increases exponentially as the device size is increased due to reduced yield and a decrease in the number of devices that can fit on a wafer. As an example, a 100A silicon chip costs 2.5 times that of a 50A chip and a 200A chip cost 5.5 times that of a 100A chip."

However, a SiC chip requires one-fifth the area as a Si chip to achieve the same power, due to SiC's greater conductivity/resistivity. Thus, ideally, five times more devices could be produced from a six-inch SiC wafer than a comparable-sized Si wafer.

Table 5 below shows the advantages and disadvantages of various substrates used to produce light-emitting diodes and illustrates the cost factors at play. This analysis is also relevant to automotive PE.

Table 5: LED Substrate Choices

LED Substrate Choices		
Substrate	**Advantages**	**Disadvantages**
Sapphire	Globally dominate; Relatively low cost	Difficult to scale size
SiC	Lattice match closer than sapphire; Unique device structures possible	Not widely available at low cost
GaN	Lattice matched; Reduced droop	Cost; Large diameters not available
Silicon	Takes advantage of low-cost semiconductor manufacturing infrastructure	Epi growth difficult to master

Source: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/lester_substrate-pkg_tampa2014.pdf

- *Processing Costs:* Currently, WBG semiconductors are produced in such low volumes that fixed costs dominate the processing cost. As stated in a previous Synthesis report ("Technology Intelligence: Wide Bandgap Semiconductors"), "The overarching driver for lowering prices is volume production. If the demand for SiC MOSFETS reached the 20 million annually, the price could drop to within 2x that of Si MOSFETS, which may be a breakthrough price-point for automotive customers, given potential system-level savings driven by SiC." The question of what it is needed to make NA a global hub of WBG manufacturing remains insufficiently researched and answered.

- *Yield Costs:* WBG wafers are more prone to flaws such as micro pipes or other lattice defects during epitaxy than Si wafers, leading to lower yields and a higher cost per device. The associated packaging, assembly and test costs exacerbate the issue.

- *Material Costs:* As previously noted, the raw materials used in WBG are not a large factor in overall cost. In February 2013, "silicon carbide with around 80% silicon content costs $1,000-1,100/metric tonnes on a delivered basis… In comparison, the spot import price of Chinese-origin ferrosilicon this week stood at $1,400-1,420/metric tonnes." (Source: Watanabe, "Global Metals Outlook") This means raw SiC is 20% cheaper than ferrosilicon (the raw material used to produce Si) with 75% Si content.

- *System-Level Efficiency and Overall System-Level Costs:* System-level (defined as some combination of the entire traction drive inverter, a cooling system and integration with a motor in a packaged, traction drive assembly) efficiency and cost are key factors, and yet are poorly understood. Many of the sources providing insight to Synthesis about WBG costs of manufacturing and adoption have underscored the significance of the need for a more specific, quantified understanding of the system-costs of WBG in traction drive inverters.

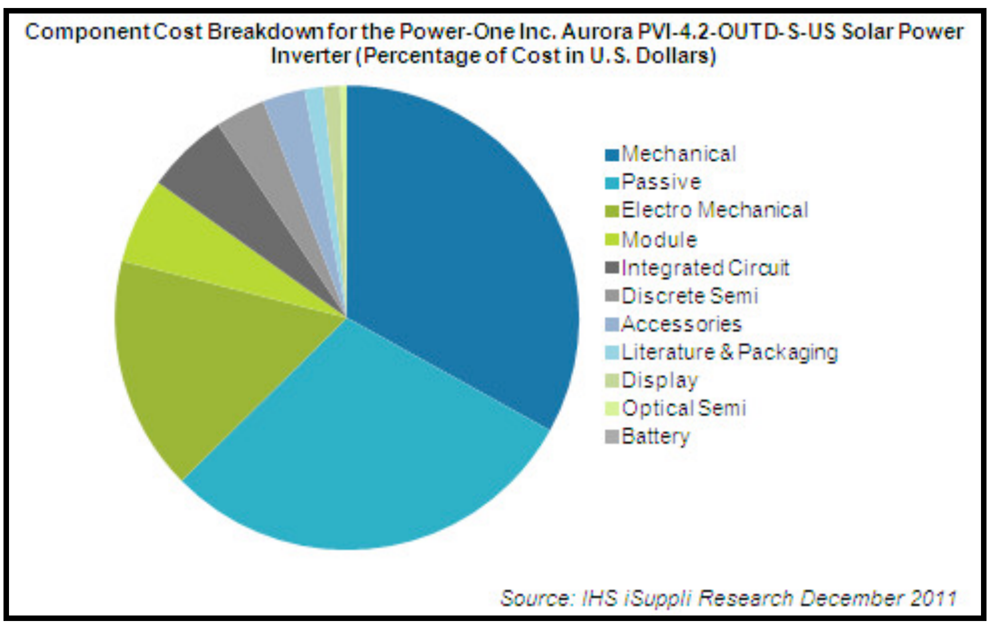
Review of the Most Detailed Inverter Cost of Production Diagrams

In December 2011, IHS released the results of a teardown of the Aurora PVI-4.2-OUTD-S-US, a silicone-based residential photovoltaic inverter from Power-One Inc. Their results are shown below. To compare, also below is the Synthesis pie-chart assessment from 2011 regarding the ranking of cost-drivers in a Si-based traction drive inverter.

The two charts below demonstrate that the greatest costs are not material-based. This points again to the significance of assessing WBGs from a system-level efficiency and cost view, rather than an individual inverter cost of manufacturing view. In particular, a system-level efficiency argument for WBG needs to be better specified than it has been to-date in order to calibrate the WBG vs. Si in the context of an automotive, NA-manufacturing discussion.

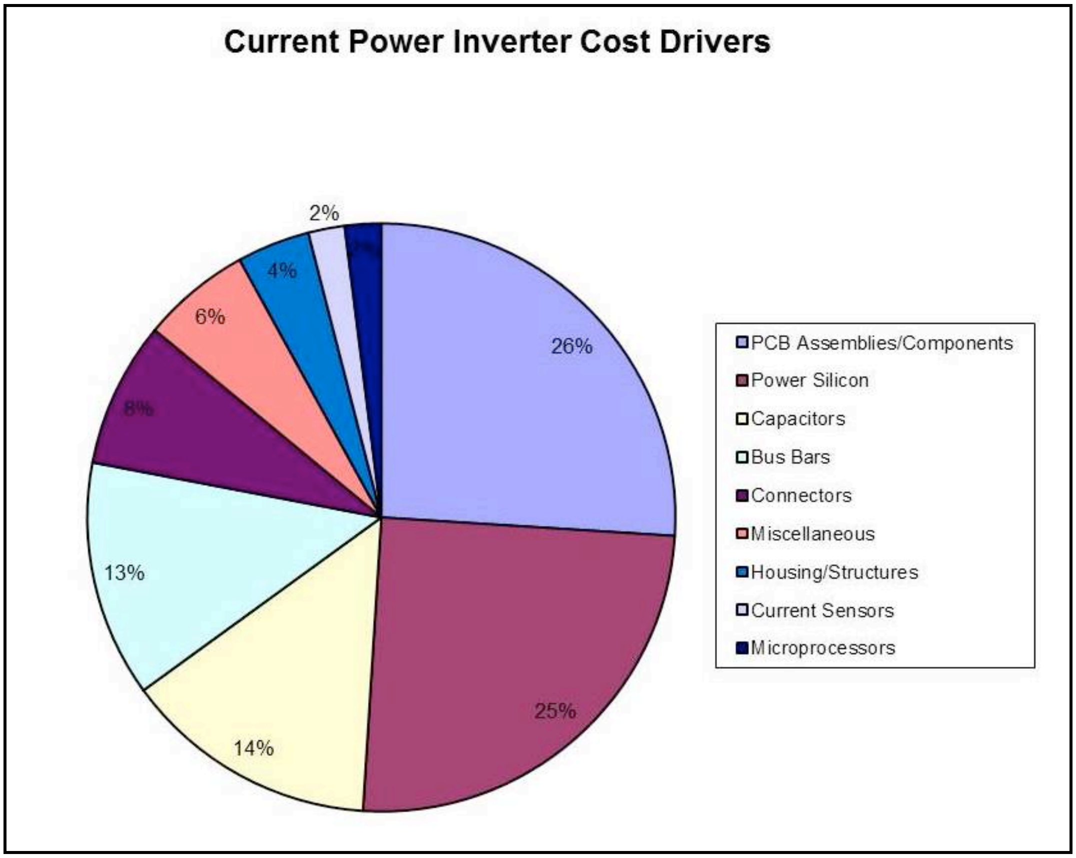
IHS estimated a production cost of $689.35 for the photovoltaic inverter. Surprisingly, the semiconductors are not the greatest expense in manufacturing the photovoltaic inverter. IHS estimates the greatest expense (33.1% of the inverters total BOM) (Bill of Materials) is in the mechanical components (see Chart 1 below), including the heat sinks, which use commodity metals. Much of these mechanical components are used to keep the semiconductors cool.

Chart 1: IHS Findings from Teardown of Aurora PVI-4.2-OUTD-S-US



The IHS chart compares with Synthesis' estimate of the factory cost of a Prius-type traction drive inverter at $536 - $693 (from Synthesis report "Technology and Market Intelligence: Hybrid Vehicle Power Inverters Cost Analysis," July 2011). The Synthesis report performed both top-down and bottom-up analyses of the factory cost of traction drive inverters to arrive at this estimate. The breakdown of the cost drivers used in this analysis is shown in Chart 2.

Chart 2: Synthesis Analysis of Traction Drive Inverter Cost Drivers (July 2011)



Source: Synthesis report "Technology and Market Intelligence: Hybrid Vehicle Power Inverters Cost Analysis" (July 2011)

The Chart 2 findings held true for both current generation inverters and an inverter in the planning phases. In Synthesis' 2015 report on the NA traction drive PE supply chain, information is provided showing that the NA traction drive inverter supply base appears poised to head in the direction of commoditization. This means there is great interest in manufacturing and design approaches that deliver significant cost and parts reduction, especially regarding the largest cost-drivers.

Based on the above charts, as well as the results from WBG supply chain interviews completed by Synthesis in 2014, it could be argued that the system cost and size could be reduced by utilizing WBG semiconductors, resulting in lower mechanical costs and more efficient packing.

Questions Raised by the Research

<u>Does It Make Sense to Evaluate WBG-Si Costs at the Device Level?</u>
One issue with WBGs is how their cost comparison with Si-based devices should be determined; at the device-level or at the system (up to and including the full inverter, with associated cooling system and, possibly, integration with the traction drive motor) level?

As a Tier 2 supplier pointed out during an interview, "the real cost issue is at the system level -- this is where the real payoff of SiC can be demonstrated. Way too much focus is being given to bring a SiC wafer's cost in line with a Silicon wafer and similarly, a SiC device with a Silicon device.” The issue is how to define, characterize and make the business case regarding a WBG system based on quantified figures of merit at a system level.

Another Tier 3 supplier identified system cost as the primary issue with WBGs:

> “Many WBG-related questions address manufacturing cost issues and while these are important, the real cost issue is at the system level -- this is where the real payoff of SiC can be demonstrated. Way too much focus is being given to bring a SiC wafer's cost in line with a Silicon wafer and similarly, a SiC device with a Silicon device.”
>
> “If you try and equalize the cost of SiC with Silicon at each stage of the wafer or device manufacturing, you will find that SiC is and will more than likely continue to be more expensive, at the substrate level and at the device level. You may approach roughly comparable costs at the module level, but it's not until you get to the system level that SiC clearly demonstrates a payoff.”
>
> “Unfortunately, the focus on making cost comparisons at each stage of the manufacturing process has resulted in OEMs and suppliers repeating the same thing -- that we can't use/sell WBG until it's the same price as Silicon.”
>
> “This mindset has brought us to a situation where the best devices are not being produced here, not because there is a technological/capability issue, but rather a systematic attitude to wait until SiC is cost-competitive with Silicon at every stage in the manufacturing process rather than taking into account its clear benefits at the systems level.”

Another Tier 2 stated, “there is an on-going debate as to whether cost parity should be calculated at the device or system level… Although I believe both SiC and GaN can/will be proven to be reliable semiconductor technologies for WBG power electronics, there are still some reliability challenges, assessments, and demonstrations to be addressed. In addition, there are certainly cost considerations for the various end-use applications of interest."

Accurately computing total manufacturing cost is also an issue. A third Tier 2 stated: “...total manufacturing cost must include yield -- not taking yield into account would be a glaring omission.”

<u>What Types of Collaboration Can Catalyze Maximum WBG Cost Reduction?</u>
Another issue that will affect cost is the type and level of collaborative efforts in NA, and how these collaborations are managed to achieve cost reduction. Some sources – and these are not representative of a majority opinion – have raised questions regarding expectations for the Power America (Next Generation Power Electronics Manufacturing Innovation Institute) initiative:

A Tier 2 supplier stated:

> “The Next Generation Power Electronics Manufacturing Innovation Institute was expected to be based on the Foundry Model, but industry has been very disappointed in the lack of progress to date within the Institute, mainly due to the apparent inability of North Carolina State and DOE to resolve the basic formative issues that are required before the Institute can get up and running. Meanwhile, initiatives such as the New York Power Electronics Manufacturing Consortium (NY-PEMC) have been announced which

> represent a possible fragmentation of what was intended to be a collaborative approach."

A Tier 3 supplier added:

> "Current programs such as the Next Generation Power Electronics Innovation Institute and the National Network for Manufacturing Innovation (NNMI) are providing WBG support, but the goals are too broad and these programs are generally not supportive of commercial companies and commercializing technology."

These are only two views. More research is needed to determine the true impact – today and in the mid-term – of activities like the NNMI and NGPEI. A comparative analysis of the results of similar activities in Japan and Germany may be needed, to include identification of approaches to addressing gaps and constraints in the R&D-to-commercial product value chain in NA. The details on gaps identified in the NA supply chain in Synthesis' 2014 NA PE and motors supply chain research may be useful in this regard.

<u>What Role Can the Foundry Model Play in Reducing WBG Costs?</u>

As mentioned above, the industry had high hopes for the foundry model, which have yet to be realized. The Department of Defense and DOE have researched the foundry model and a recent update on these efforts is reported in "WBG Revolution in Power Electronics," Dr. Anant Agarwal, EERE/DOE, WiPDA 2012, October 14, 2014.

According to Dr. Agarwal, DoD has invested $500M in WBG over the past 20 years, resulting in improved wafer quality and an increase in the wafer diameter from 1 to 6 inches. Several dedicated foundries have also been created. Since then some of the foundries have gone out of business and some are on the verge of doing so. According to Dr. Agarwal, this would indicate the dedicated model is good only for big companies with adequate resources to maintain high-volume production and dedicated foundry investments over time.

DOE estimates that 90% of the manufacturing processes for a 6-inch wafer Si foundry are similar to the processes needed for SiC. The other 10% of the processes would require a $10M investment in equipment industry-wide (to support all SiC foundries, at current low volume market assumptions), but new companies may need only an additional $1-2M investment to bring the WBGs to market. Table 6 illustrates that aggregating demand for 6" SiC wafers can reduce manufacturing costs. The question is when this might occur, why and by what sustainable market drivers?

Table 6: Commercial Foundry Costs for 122V, 20 A SiC MOSFET

	Today's WBG Dedicated Foundry Cost	**Commercial Si Foundry Cost**		
Production Volume	Low	Medium	Medium	High
Wafer Size (mm)	100	100	150	150
Cost of Substrate + Epi	$1200	$1200	$3000	$800
Cost of processing	$1800	$700	$700	$500
Chip Size (mm)	2.5 x 2.5	2.5 x 2.5	2.5 x 2.5	2.5 x 2.5
Number of Chips 80% Yield, 5mm Exclusion Zone, 90% Packing Factor	549	732	1772	1772

Cost Per Chip	$5.46	$2.60	$2.09	73¢
Cost Per Amp	27¢	13¢	10.5¢	3.7¢
Cost Per Amp at 50% Gross Margin	54¢ - 5x of Silicon	26¢	21¢	7.4¢

Source: "WBG Revolution in Power Electronics," Dr. Anant Agarwal, EERE/DOE, WiPDA 2012, October 14, 2014.

What Do We Not Know Regarding WBG Costs?

Synthesis' interviews to-date have turned up several knowledge gaps, particularly regarding WBG production. These areas include:

- Manufacturing process
- Wafer design
- Packaging
- Supply Chain
- Software engineering

In each of these areas, we find that sources seek better technical information, especially on costs and competitive manufacturing process benchmarks

Discussion

One Tier 2 supplier raised the question "which is the best model for manufacturing process – foundry (separate businesses produce different parts of the final chip, from design to fully integrated circuits) or vertical (one business produces all parts of the final chip, from design to fully integrated circuits)?"

A Tier 1 manufacturer brought up a concern with packaging:

> "The main focus here is devising the means to get the heat out. There is a lot of work being done here as to how to package the new device to get the full benefit out of the WBG material."
>
> "Currently, at least one firm does packaging in the U.S. However, beyond this and small R&D projects where cutting edge work is being done, most packaging is done overseas. Specific reasons for this have not been identified as of yet."
>
> "With smaller die size, you have more energy per unit area. The more energy dense, the more heat you must get off/cool from the devices. Most traditional packages usually use high series inductance with the terminals. But that inductance limits the available frequency you can use. This is a design-of-device limit, not a materials limit."

When asked the number of dies that can be attached on a SiC wafer at highest, consistent quality, an OEM stated "cannot answer." Other suppliers, including the same OEM, could not identify the primary manufacturability-quality benchmarks that must be met by a device fabrication process to be sufficient to use the entire 150-mm wafer surface.

A Tier 1 expressed concern over a lack of embedded software engineers to work on WBG design:

> "Software is a major part of PE as for every new PE device, fifty percent is electrical engineering and fifty percent is software. However, I'm not seeing embedded software engineering expertise coming out of universities. This is a problem and poses a

detriment to PE development. The type of software engineer that is needed is an embedded software engineer, not a computer engineer and currently, I'm not aware of a university that trains this type of engineer. Most of the universities are focused on higher-level software languages. The low-level coding expertise that is required with embedded software is even more applicable with WBG."

Other questions raised include:

- "What are the projected lifetimes of components for different operation conditions focused on specific applications? Detailed reliability studies of packaged wide bandgap devices will need to be conducted and compared to existing Si components." (Tier 2)

- "How do you prove that packaged wide bandgap components are more reliable than existing Si components?" (Tier 2)

- "How do you speed up the design cycle for products to create a strategic advantage over competitors?" (Tier 2)

- "How do we setup a materials supply chain in the US that is cost competitive with other countries?" (Tier 2)

- "What is the practical near-term limit in terms of $/Amp? There seems to be lots of confusion about the secondary benefits of WBG vs. people mistakenly assuming they are going to be near-term cheaper on a device basis than Si devices. I'm not sure that is proven or well summarized and it should be to clear up confusion, and focus instead on the more complex benefits. And furthermore, once we have an assessment of the realistic WBG to Si cost differences, then we can determine how much value improvement is needed elsewhere to justify them." (OEM)

- "A system-level benefits analysis of using WBG in inverters that addresses price-points of specific component and system level products is not sufficiently understood and would be beneficial. However, in US and Europe, we have found that OEMs are not always good at systems-level assessments."   (Tier 1)

- "OEM purchasing personnel are not talking with technical personnel and they don't really understand each other (or have the time to share information as much as is needed)." (Tier 1)

A Look Ahead at Selected Future Developments

Research is underway into new substrates and WBG materials.   Nanomaterials are always of interest given the pace of technological innovation nanomaterials-based manufacturing and development.

Graphene is highly conductive and can be bonded to SiC or Si. Initially, graphene-based semiconductors could only be made on smaller wafers, but researchers have demonstrated that SiC can be converted to graphene, allowing graphene-based semiconductors on larger wafers. These semiconductors are still in the lab, and their potential effect on the WBG market is unclear.

Transistors built from Ga_2O_3 have a far higher electric field strength than those made from GaN and SiC, and they can be formed from native substrates produced with simple, low-cost methods, according to Masataka Higashiwaki from the Japan's National Institute of Information and Communications Technology (NICT).

GT Advanced Technologies has developed a machine, called Hyperion, which can create Si wafers that are 20 microns thick, compared with the usual 200 microns. Producing more chips from the same amount of Si could reduce the capital equipment expenditure for a vertically integrated company.

Queensland Micro and Nanotechnology Facility (QMF) and SPTS Technologies researchers joined forces to develop a production reactor targeted at producing SiC coated Si wafers for LEDs. The vertical reactor - dubbed EpiFlx - is designed for high temperature vacuum processing of large batches of wafers sized from 50mm-300mm. The company has plans to extend the epitaxial growth process to commercial scale production of SiC wafers on silicon.

Initial estimates suggest the SiC on silicon coating process, in volume production, will add no more than $35 to the cost of a silicon wafer.

Preliminary Findings

Much research remains to be addressed, particularly modeling the WBG manufacturing process and quantifying cost drivers.

Most of the components used on printed circuit boards in traction drive inverters are widely available and are considered commodities by the manufacturers. Therefore there is limited potential for significant cost reduction of the PCB Assemblies/Components, assuming the same numbers are used per device.

Just as in the case of Si-based switches, in which power silicon is the number one candidate for cost reduction, the same is true in WBG – cost reduction must address the process to produce the necessary materials and the manufacture of devices in a consistent manner at the necessary quality and price-point.

SiC and GaN are considered as good substitutes for or can be used in combination with silicon for power electronics. Still, much information remains to be discovered, particularly as it relates to consistent analyses and accurate modeling of WBG costs and manufacturing processes. This is especially true in the context of automotive applications for WBG in traction drive PE.

Cost analyses need to be automotive case-specific in order to be useful to automotive OEMs. Improved understanding of WBG cost-of-manufacture models relevant to automotive traction drive applications will drive engagement by participants and very likely accelerate the needed advances for state-of-the-art, competitively priced WBG devices.

A pragmatic, cost optimization model is needed. This would include a WBG traction drive inverter cost-of-manufacturing and manufacturing process review and accompanying cost reduction optimization analysis. The available public information on WBG costs makes clear that such an assessment would have an immediate positive impact on the on-going discussions in industry, academia and government about challenges and opportunities for WBG adoption in traction drive PE.

Discussion
The following are sample quotes underlying Synthesis' findings:

From a Tier 1 manufacturer:

"What are the projected lifetimes of components for different operation conditions focused on specific applications? Detailed reliability studies of packaged wide bandgap devices will need to be conducted and compared to existing Si components."

"How do you prove that packaged wide bandgap components are more reliable than existing Si components?"

"How do you speed up the design cycle for products to create a strategic advantage over competitors?"

"How do we setup a materials supply chain in the US that is cost competitive with other countries?"

From a Tier 2:

"What is really needed is a focused effort along the lines of what we see taking place in Japan and Europe -- government-industrial collaboration on an agreed-upon strategic approach to advancing WBG capabilities that can be commercialized. If DOE VTO determines that WBG is a strategic capability requirement, then DOE VTO should consider what steps it might take to achieve that capability."

"There are examples in the U.S. where government and industry has worked together to devise and implement a WBG strategy that works. One example is the LED industry. The roadmap effort led by DOE has had a significant impact on technological and market advancement and even resulted in the phasing out of the incandescent light bulb. Can you imagine what would happen in the automotive industry if a similar approach were to be taken regarding target technologies such as WBG to implement and other target technologies to phase out?"

"WBG materials are not a solved issue. Substrates and EPI are a critical part of the WBG supply chain and improvements have to continue to be made in order for us to maintain leadership in this area. The lesson is that DOE VTO and industry need to recognize that ALL levels of the supply chain need to be continually addressed and we can't afford to take current leadership for granted."

From a Tier 1:

"USG-supported R&D helps offset corporate investment in R&D, which in turn enables the companies who otherwise would have invested funds in R&D, to spend those same funds on capital investment, to grow and speed up the time-to-market (should demand exist) for the product. The product is made (partly) feasible through the USG-funded R&D."

"Companies need to be left to make their CAPEXs … and there are many variables to manage to support the decision to do so. E.g., Fab is a very important investment. Very capital intensive. So everyone has to hedge their bets. USG funding helps companies to offset R&D costs, put more money into capital as they bring product to market, and scale to mass market."

"USG R&D funding helps to accelerate the advancement of tech. This generates time-to-market benefits."

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Selected Interviews – Proprietary, Not for Public Distribution.

Please contact Mr. Christopher Whaling, Synthesis Partners at cwhaling@synthesispartners.com for further information.

Appendix 2: Organizations of Interest to NA WBG Developments, by Tier Classification

Company	Tier	City	State	Country	URL
Denso	1	Kariya	Aichi Pref.	Japan	http://www.globaldenso.com/en
Raytheon	1	Tuscon	AZ	U.S.	http://www.raytheon.com
US Hybrid	1	Torrance	CA	U.S.	http://www.ushybrid.com
Vacon Plc. (part of Danfoss Group)	1	Raleigh	NC	U.S.	http://www.vacon.com/
Deere & Company	1	Moline	IL	U.S.	www.deere.com
Delphi Automotive LLP	1	Troy	MI	U.S.	www.delphi.com
Toshiba	1	Tokyo	Tokyo Pref.	Japan	http://www.toshiba.com
Hitachi	1	Tokyo	Tokyo Pref.	Japan	http://www.hitachi.com
Avogy, Inc.	2	San Jose	CA	U.S.	http://avogy.com
Efficient Power Conversion Corporation (EPC)	2	El Segundo	CA	U.S.	http://epc-co.com
GaN Systems, Inc.	2	Ottawa	Ontario Prov.	Canada	http://www.gansystems.com
GeneSiC Semiconductor	2	Dulles	VA	U.S.	http://www.genesicsemi.com
HRL Laboratories, LLC	2	Malibu	CA	U.S.	http://www.hrl.com
Infineon	2	Milpitas	CA	U.S.	http://www.infineon.com
Microsemi Corp.	2	Aliso Viejo	CA	U.S.	http://www.microsemi.com
Mitsubishi Electric	2	Tokyo	Tokyo Pref.	Japan	http://www.mitsubishielectric.com
Nissan Motor Co.	2	Yokohama	Kanagawa Pref.	Japan	http://www.nissan-global.com
ON Semiconductor	2	Phoenix	AZ	U.S.	http://www.onsemi.com
Philips Lumileds	2	San Jose	CA	U.S.	http://www.philipslumileds.com
Powerex	2	Youngwood	PA	U.S.	http://www.pwrx.com
Rohm	2	Kyoto	Kyoto Pref.	Japan	http://www.rohm.com
Semikron	2	Nuremberg	Bavaria	Germany	http://www.semikron.com

Company	Tier	City	State	Country	URL
STMicroelectronics	2	Geneva	Canton Geneva	Switzerland	http://www.st.com
Arkansas Power Electronics Institute	2	Fayetteville	AR	U.S.	www.apei.net
Global Power Technologies Group	3	Lake Forest	CA	U.S.	http://gptechgroup.com
II-VI Wide Bandgap Group	3	Pine Brook	NJ	U.S.	http://www.iiviwbg.com
IQE	3	Taunton	MA	U.S.	http://www.iqep.com
RF Micro Devices (RFMD)	3	Greensboro	NC	U.S.	http://www.rfmd.com
Soraa Americas	3	Fremont	CA	U.S.	http://www.soraa.com
DfR Solutions	3	Beltsville	MD	U.S.	www.dfrsolutions.com
Agnitron Technology, Inc.	4	Eden Prairie	MN	U.S.	http://agnitron.com
GT Advanced Technologies	4	Merrimack	NH	U.S.	http://www.gtat.com
Fuji Electric	1, 2, 3	Tokyo	Tokyo Pref.	Japan	http://www.fujielectric.com
General Electric	1, 2, 3	Niskayuna	NY	U.S.	http://www.ge.com
ABB Ltd.	1, 2, 3	Zurich	Canton Zurich	Switzerland	www.abb.com
Delta Products Corp.	1, 2, 3	Fremont	CA	U.S.	www.delta-americas.com
United Silicon Carbide, Inc.	2, 3	Monmouth Junction	NJ	U.S.	http://www.unitedsic.com
Kyma Technologies, Inc.	2, 3	Raleigh	NC	U.S.	http://www.kymatech.com
Transphorm Inc.	2, 3	Goleta	CA	U.S.	http://www.transphormusa.com
Monolith Semiconductor Inc.	2, 3	Ithaca	NY	U.S.	www.monolithsemi.com
United Si Carbide Inc.	2, 3	Monmouth Junction	NJ	U.S.	www.unitedsic.com
Cree, Inc.	2,3	Durham	NC	U.S.	http://www.cree.com
Dow Corning Electronic Solutions	2,3	Midland	MI	U.S.	http://www.dowcorning.com
Kyocera	2,3	Kyoto	Kyoto Pref.	Japan	http://globalkyocera.com
Hesse Mechatronics Inc.	3, 4	Paderborn	North Rhine-Westphalia	Germany	www.hesse-mechatronics.com

Company	Tier	City	State	Country	URL
Toyota	OEM, 1, 2, 3	Tokyo	Tokyo Pref.	Japan	http://www.toyota.com
New York Power Electronics Manufacturing Consortium (NY-PEMC)	Other-Assoc.	Albany	NY	U.S.	TBD
Power America	Other-Assoc.	Raleigh	NC	U.S.	www.ncsu.edu/power