Strengthening the Domestic Power Electronics Ecosystem

Report on the Domestic Supply Chain Gaps in the Power Electronics Industry

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Keith Evans, President, Power Electronics Industry Collaborative

Dan Radomski, Vice President, Venture & Industry Development, NextEnergy

Dave Hurst, Director, Market Analysis, NextEnergy

Swad Komanduri, Manager, Market Analysis, VFA, NextEnergy

Roland Kibler, Chief Technologist, NextEnergy

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Executive Summary

The power electronics (PE) industry is projected to double in size in the next five years. This rapid growth is being fueled by the simultaneous evolution of multiple markets and regulatory requirements. This combined push is fueling interest in understanding the gaps in the United States supply chain to better determine the best way the U.S. may be able to reduce the gaps and lead the industry. The Power Electronic Industry Collaborative (PEIC) is undertaking a two year study with grant funding from the National Institute of Standards and Technology's (NIST) Advanced Manufacturing Technology Consortia (AMTech) program to:

- Complete a study of the U.S. PE industry to identify gaps, economic impacts, and opportunities
- Engage industry, government, and universities in a dialogue to drive private & public investment, solutions, and research priorities
- Support the development of a competitive workforce that enables design and manufacturing of PE in the U.S.

This report is a first step towards achieving these objectives by understanding the gaps within the domestic supply chain for PE. This study is focused on transportation, renewable energy, and energy efficiency markets because these markets appear to be the areas where U.S. firms are likely to have the biggest influence on the overall PE market. Consequently, the applications of interest within these markets are those for which there is a competitive U.S. presence.

The supply chain for PE manufacturing can be explored from two perspectives: materials and processes. A robust domestic ecosystem for PE must necessarily be strong in both aspects. From a materials perspective, the ecosystem includes sources for raw materials to make packaged power semiconductors, sources for passive, thermal, structural, and electrical components, and end products that use PE. From a process perspective, the steps involved in developing and integrating PE can be broken down into five major steps: wafer production, die production, packaging, subassembly, and final product integration. Within these steps, the processes of wafer and die production involve the growth of crystal structures, polishing, slicing, and device fabrication all of which require significant equipment investment.

These material and process issues were explored for both Silicon (Si) technology, as well as emerging wide-bandgap (WBG) semiconductor technology, specifically Silicon Carbide (SiC) and Gallium Nitride (GaN) based systems. In the case of Si and GaN, the facilities and tools for scale manufacturing already exist to a large degree outside the U.S. and would require significant capital costs to build similar competitive facilities domestically. For SiC, this ecosystem has initial support in the US but increasing global investment is putting this advantage at risk. From a materials perspective, sources for semiconductor materials exist in the US, but high volume production of PE requires a robust supply chain for passive, thermal, electrical, and structural components. These components are largely sourced from outside the U.S. due to established supplies of raw materials for their respective production. The end result is that it is cheaper to establish PE manufacturing operations abroad, in close proximity to reliable sources of these necessary components. From a process perspective, the initial design and engineering processes often take place domestically, as well as the final applications engineering because of proximity to customers and talent availability. However, the actual manufacturing processes of die production and system assembly take place abroad, partly as a result of the materials supply issues. Of the manufacturing processes, WBG wafer production is an area of strength for the US, although it is unclear how this advantage will scale as volumes increase.

The domestic strength in design and engineering is at risk as well. The industry expresses great concern over a lack of power engineering talent in the U.S. Domestically, the number of new engineers being trained does not adequately meet the needs of the PE industry due to a combination of a lack of education programs and student interest.

The biggest opportunities for the U.S. appear to lie within the wide band gap (WBG) materials for PE, and perhaps more specifically within SiC devices. First, non-WBG material, Silicon, is produced in high volume from Asia with a robust and established supply chain. However, the supply chain for the WBG materials is currently somewhat under-developed because the products are still relatively new to the market and undergoing extensive research and development work. This provides the U.S. with an opportunity have a significant impact on supply chain development. SiC does not yet have a specific dominant region, while many of the existing production foundries for GaN are already located in Asia. Additionally, in order to take advantage of the improved performance of WBG devices, innovation in passive components, specifically in capacitors and magnetics, is required. This presents an opportunity for the development of a robust supply chain in addition to technological leadership. With technological innovation determining market leadership for both SiC and GaN devices, the result is that both WBG materials present opportunities for the U.S. to establish die production and subassembly processes that capitalize on key advantages these PE technologies offer.

Research Methodology

The research for this report included a mix of both primary and secondary research. NextEnergy conducted twenty-six in-depth interviews with wafer manufacturers, die producers, PE assemblers, original equipment manufacturers (Tier One suppliers), final product manufacturers (or integrators), testing & equipment providers, and federal authorities in this space. These interviews consisted of one to two hour in-depth interview and manufacturing facility tour (when possible). In addition to these detailed interviews, NextEnergy has conducted more than 100 shorter form in-person interviews during PE related events with many companies at every level of the value chain. This updates and supports previous research conducted by NextEnergy on the PE market and emerging WBG technology. Secondary research for this report consists of reviewing purchased research from Yole Development, and publicly available research on the PE market from Synthesis Partners and National Renewable Energy Laboratory (NREL).

The findings were then reviewed by a committee of professionals in the PE industry. The review committee includes members from DOE Vehicle Technologies Office, DOE Advanced Manufacturing Office, National Institute of Standards & Technology (NIST), Army Research Laboratory, Tank Automotive Research, Development and Engineering Center (TARDEC), Society of Manufacturing Engineers, Argonne National Laboratory, and National Renewable Energy Laboratory. Furthermore, the results were presented to twenty-nine industry participants at the 2015 PEIC Annual Industry Summit in Charlotte, NC to incorporate their feedback. A summary of the Industry Summit is provided in Appendix A.

This analysis is the first step in assessing the US domestic PE industry. This research has been funded through a NIST Advanced Manufacturing Technology Consortia (AMTech) Program grant in 2014. The three goals of this grant include:

- Identify solutions to the fragmentation of the domestic PE industry
- Communicate the findings of the roadmapping and gap analysis, and work with stakeholders to validate findings and reach consensus on domestic opportunities and challenges
- Create new awareness of the opportunities in the power electronics industry among small and medium sized enterprises, young engineers, and scientists

The project performance period is June 2014 through May 2016.

What Are Power Electronics?

Due to the physical properties of electrons, all electronics can only function properly given a certain set of conditions. If those conditions are not met, then the system fails. Since electronic systems consist of a network of connected components, a failure of any one the components can cause the entire system to fail. PE are the systems and devices used to preserve the operating conditions for each component of the electronic system to ensure that the overall system continues to function. To accomplish this, PE systems control and convert the voltage, current, frequency, and power from one form to another to ensure that the operating conditions at each point in the circuit allow for the desired functionality. In other words, the function of PE is to transform inputted power to a different outputted form.

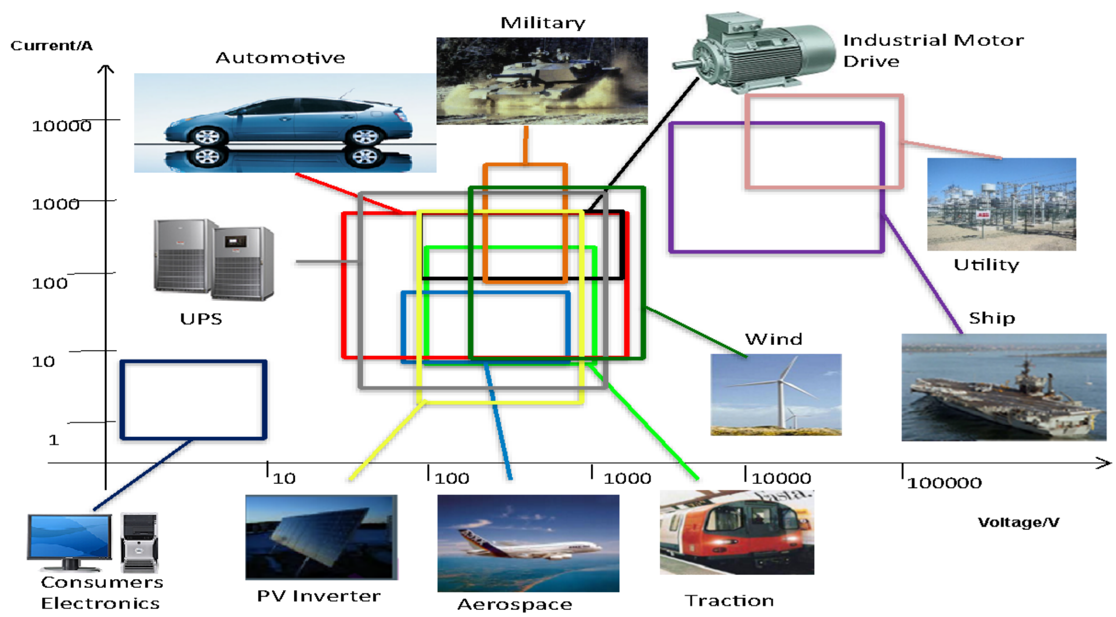
One of the most common function of PE is to convert direct current (DC) to alternating current (AC). This is because the primary source of energy in many systems is a battery, which uses direct current. However, many motors, actuators, and devices use alternating current. Therefore, a system is needed within the circuit to ensure that the DC from the battery can be converted to AC that can be used by these devices. This device that converts DC to AC is an inverter. Similarly, a device that converts AC to DC is a rectifier. This is often used for consumer electronics, since the power grid uses AC, but many consumer electronics operate on a battery.

Another common use of PE is to change the voltage or frequency level to ensure that neighboring components or devices within the circuit can coexist on the same circuit. To change the voltages and frequencies to make these systems compatible with one another while using the same power source of the car battery, power electronic systems are needed. These devices that change one form of AC to another form of AC are known as AC/AC converters, and their DC counterparts are known as DC/DC converters, colloquially known as buck/boost converters. Together, these four systems are the primary categories of PE used today: inverters, rectifiers, DC/DC converters, and AC/AC converters.

Market Definition

As a result of the vital need for PE in all electronic systems, PE are used in a broad range of applications. As shown by Figure 1, the power levels between 50 V and 10 kV support a wide range of market applications of PE. Most PEIC members are focused on these power levels, and many of the firms interested in these power levels are already U.S. headquartered firms. Therefore, these power levels are an area of interest because the U.S. market has the ability to pull forward advanced and next generation PE into their products.

Figure 1: Broad application base for power electronics



Source: PEIC

This project explores this segment of the overall PE industry. For the purposes of this project, PEIC members are focused on three primary application areas: transportation, renewable energy (renewables), and energy efficiency. The industry for lower voltage consumer electronics applications is largely located outside the U.S. making the U.S. influence market driven, as opposed to innovation driven. PE are particularly vital for transportation applications because multiple PE systems are needed within each vehicle. A typical automobile uses at least an inverter and a DC/DC converter, therefore given the volume and size of the automobile market, this market is a key driver for PE. Secondly, with the global regulatory push to increase adoption of renewables into the power infrastructure, renewables are projected to be a key growing market for PE. Outside of renewables and transportation, U.S. PE products are also used in wide range of products, including appliances, building tech, data centers, industrial tech, and grid and energy storage. Specific applications that have been discussed during primary interviews include uninterrupted power supplies (UPS), data centers, and industrial motor drives applications; however, these applications are not projected to grow as rapidly as transportation and renewables, according to a report by Yole Development.

Market Drivers

The PE industry is projected to double in size in the next five years according to market research firm, Yole Development. This rapid growth is being fueled by the simultaneous evolution of multiple markets and regulatory requirements. The primary driver for the growth of the PE industry is the global regulatory push towards reduced emissions, integration of renewables, and higher energy efficiency. The United States, the European Union, Japan, India, and China have all enacted strict Carbon emission reduction targets over the course of the next decade. Combined with rising fuel costs, increasing populations, a growing middle class, and an increasing demand for vehicles, these regulations most significantly affect the passenger vehicles market. Additionally, emission reduction laws specifically target pollutants that are released by motor vehicles. Consequently, the auto industry is responding by focusing the bulk of R&D efforts on electrifying vehicles. The hybrid and electric vehicles market is projected to be the largest application of PE by 2020.

The hybrid and electric vehicle application of PE is particularly significant because it requires the use and integration of multiple power electronic systems in the final product. As a result of using inverters, DC/DC converters, and battery chargers, the technological innovations in the EV/HEV space span many other applications. Furthermore, because the automobile industry is globalized and highly competitive, automotive OEMs are leading the charge for PE innovations. Since automobiles are expected to be a long term investment for the consumers and are highly regulated for safety purposes, one of the primary drivers for technological adoption is reliability. Given that PE often limit the lifetime of various systems in a vehicle, ensuring reliability of PE for over 10 years is a key driver in the EV/HEV application space. Furthermore, as cars are expected to provide better fuel efficiency and performance, reducing weight, volume, and cost, while improving performance puts a lot of focus on PE systems in automobiles. Since PE are responsible for a large portion of efficiency losses, innovation to improve efficiencies are a key driver for the PE industry.

As a result of the critical need for PE innovation, companies in this space are taking a more active role in understanding the full value chain of the industry. Consequently, industry players are attempting to vertically integrate, either through R&D efforts, through acquisitions, or some combination. Wafer producers are expanding into packaging in an effort to get the ideal solution for specific applications. Module manufacturers are acquiring foundries in an effort to reduce supply chain risk and improve process efficiencies. Subassembly manufacturers are focusing on packaging innovation in an effort to have the ideal integration with their systems. OEMs are designing their own subassemblies in an effort to have the performance and cost meet their needs.

In addition to the electrification of passenger vehicles, regulatory pushes are also driving the electrification of other forms of transportation. One of the most immediate markets affected by these regulations is the marine vehicle market. In 2010 the International Maritime Organization designated emission control areas in the English Channel and the American Coast. This is driving the marine industry to transition from mechanical to electric drive. Furthermore, all of the other drivers that are driving the auto industry are also driving the marine industry. Electric drive offers higher efficiency, reducing the need for fuel that is growing more expensive by the day. Additionally, electric drive offers reduced operation costs and allows for larger electric loads to share propulsion power sources. While all of the drivers are the same, the technological challenges are unique, as power demands for marine applications can be immense, on the order of 100 MW, which is not the case for automobiles.

Regulations also affect many other industries outside of transportation. One of the key such industries is renewables. With the global regulations to increase renewable integration into the grid, the renewable energy industry is poised for rapid growth over the next decade. In the U.S., twenty-nine states have adopted Renewable Portfolio Standards (RPS) that require a percentage mix of the energy generation be from a renewable source, and seven more have renewable generation goals. This could include biofuels, but for the majority of these states, the focus is on solar and wind energy generation. The result is a regional market for renewables in the U.S.

Since renewable energy is intermittent while the grid has a specific frequency and voltage, all renewable electricity must pass through PE systems to match the requirements of the grid. Additionally, this intermittency introduces the potential need for energy storage for the grid, commercial buildings, or residential homes. Since all renewable energy must be transformed in some way to match the grid whether being stored first or not, there are efficiency losses associated with this process. As a result, the renewable requirement is another component encouraging growth of the PE industry. These trends are also being matched on a consumer level. With added incentives and energy conscious consumers, residential solar installations are accelerating, thereby driving the market for solar inverters. As a result, competitive market forces are driving innovation to increase efficiencies at the system level and reduce cost to take advantage of this opportunity.

One of the other major regulatory drivers of PE innovation is the increased focus on energy efficiency. Similar to the RPS, many states have enacted energy efficiency requirements. The most direct effect is that of increasing innovation in making power electronic systems more efficient. This is leading to industry investing in developing new technology to make existing systems more efficient. Outside of this direct effect, these regulations have corollary effects as well. Industrial motor systems (including those within heating ventilation and air conditioning systems) are the largest energy consumers in manufacturing facilities and therefore a key target for improved efficiency. These improvements will often include reduced energy losses from PE.

Outside of regulatory pushes, there are market pulls that are driving PE innovation. The largest market for PE is in industrial applications. This includes PE for servers, work stations, data centers, telecommunications processing, and motor drives. Because these applications are so vital and often involve human interactions in close proximity, safety and reliability are primary drivers for innovation. Often times, the operating expenses for these machines are significant, therefore making the PE more efficient can translate to significant savings over time. Data centers alone constitute up to 2% of all energy used in the United States, a number that is projected to grow rapidly by 2020. Consequently, there is a lot of focus on increasing efficiency for PE in these applications.

Technology Overview

This study explores the power electronics supply chain from two perspectives: materials and processes. In order to do so, this section provides a technical overview of both materials and processes required for power electronics manufacturing.

Materials

Power electronics systems require the following materials:

- Power semiconductor (including packaging)
- Passive components
- Electrical components
- Structural components
- Thermal components

While all of the materials listed are necessary, they are not equal in cost, potential for developing IP, domestic focus, and global investment.

Table 2: Summary of PE Cost Drivers & Global Activity

	Cost	IP Potential	US Activity (R&D)	Global Investment
Power semiconductor	**High**	**High**	**High**	**High**
Passive components	Medium	Medium	Low	High (Asia) Low (Europe)
Electrical components	Low	Low	Low	Low
Structural components	Low	Low	Low	Low
Thermal management	Medium	Medium	Medium	Medium

Source: NextEnergy

As demonstrated by Table 1, the power semiconductor is the primary cost and R&D driver in developing a PE system. A key aspect of power semiconductor functionality is determined by the crystal material it uses.

Semiconductor Materials

To achieve functionality, PE primarily depend on semiconductor devices. Semiconductors are solid-state devices that allow for control of electricity without the need for mechanical switches. A semiconductor is a material, whose crystal structure allows for the material to selectively conduct electrons. By changing the conditions of the semiconductor, it can act as either a conductor or an insulator, thereby becoming a switch controlled by changing current in the circuit. As a result of this property being dependent on the crystalline properties of the semiconductor material, the material must be deliberately chosen and processed to create the ideal crystal structure for a given application. There are certain key characteristics that determine its utility for specific applications:

- *Band Gap (eV)*: this is the amount of energy required to excite an electron from the valence band to the conduction band. Since semiconductors are naturally insulators, energy is required to make the material act as a conductor.
- *Electron Mobility*: How quickly an electron travels through a given material in a given electric field. If electrons move faster, the semiconductor can switch between being a conductor and insulator faster, thereby enabling higher switching speeds and operating frequencies.
- *Breakdown Field*: Key to the functionality of a semiconductor is that the material conducts only under certain specific conditions such as when a biasing voltage is applied. However, it is possible to permanently ionize and change the semiconductor to a full conductor by applying too much voltage. The breakdown voltage is the voltage at which a semiconductor's crystal structure collapses and it becomes a full conductor.
- *Thermal Conductivity*: How well the material conducts heat. This is important since as power gets dissipated, it gets transformed into heat. The heat must be conducted through the material in quickly enough to prevent the system from overheating.
- *Coefficient of thermal expansion:* How the materials expands with higher temperatures. This is particularly important when the substrate joins another material as different coefficients of thermal expansion could cause warping and cracks at high temperatures

Table 2 below shows the comparison of properties for the three most common semiconductor materials of Si, SiC, and GaN. As the table shows, the band gap for SiC and GaN is significantly larger than for Si. As a result, SiC and GaN are considered wide band gap (WBG) materials. The characteristics of these materials allow for devices to operate at higher voltages, higher current densities, higher frequencies and higher temperatures than conventional semiconductor materials allowing for more powerful and more efficient electronic devices, which can in turn lead to more cost effective systems. In power conversion applications for example, higher frequency switching can allow for smaller passive devices (capacitors and inductors) which allows significantly smaller packaging. The improved thermal conductivity allows for faster heat dissipation within the devices, thereby allowing the device to operate at higher power levels.

In addition to Si, SiC, and GaN, another potential semiconductor material for use in PE is Gallium Arsenide (GaAs). As mentioned during the PEIC Industry Summit, GaAs has some properties that make it attractive, including extremely high electron mobility (8,500 cm^2 / (V·S)) and electron saturation velocity. Furthermore, the GaAs market is several times larger than GaN and is expected to continue to grow. GaAs devices are widely used in several applications including mobile phones, satellite communications, cable TV and high frequency radar. However, GaAs has other properties that limit its utility for the applications and power levels with which this project is concerned. The breakdown field for a typical GaAs device is approximately 4 (* 10^5 V/cm), compared to 30 for SiC and 50 for GaN. Consequently, in order to use GaAs in higher power applications, multiple devices would need to be run in combination to increase the overall power capability but there is no industry push in this direction.

Table 2: Properties of semiconductor materials

Property	Si	SiC [1]	GaN
Bandgap (eV)	1.1	3.0	3.4
Electron Mobility (cm^2/Vs)	1400	400	1000[2]
Breakdown Field (10^5 V/cm)	3	30	50[3]
Thermal Conductivity (W/cmK)	1.3	4.9	0.5-2.3[4]
Coefficient of Thermal Expansion	2.6	4.2	5.6[5]
Possible Substrates	Si	SiC, Si(rarely)	Si, SiC, GaN, sapphire

Source: NextEnergy, see footnote

Once a semiconductor material is chosen, a substrate for the semiconductor is needed. A substrate serves as the physical foundation layer on which the semiconductor is added. This serves to add mechanical structure to the semiconductor so it rests on a base, and to electrically insulate the semiconductor so as to prevent outside effects from affecting the system. As shown in the table above, for Si devices, the substrate material is Si. For wide bandgap materials, GaN in particular, there are multiple substrate options available. Each substrate has different properties and costs, making some more suitable for certain applications than others. Once the substrate is determined and the semiconductor device is added to the substrate wafer, the passive, electrical, thermal, and structural components can be added to the PE system.

Passive, Electrical, Thermal, & Structural Components

The potential functional benefits of innovation in semiconductors can only be realized if the remaining components of the PE system can support those benefits. One of the biggest potential benefits of WBG semiconductors is the ability to operate at higher temperatures. However, in order to achieve these benefits, passive components, specifically capacitors, need innovation. Currently, capacitors used in PE systems are primarily film capacitors, which use polypropylene as the dielectric, which degrades at higher temperatures. Therefore, in

[1] 3H, 4H, and 6H are different polytypes of SiC used in the market. For the purposes of comparison, we are using the values for 6H-SiC

[2] Chow, T.P, Ghezzo. “SiC power devices. in III-Nitride, SiC, and Diamond Materials for Electronic Devices.” Eds. Gaskill D.K, Brandt C.D. and Nemanich R.J., *Material Research Society Symposium Proceedings*, Pittsburgh, PA. 423 (1996), 69-73

[3] Chow, T.P, Ghezzo. “SiC power devices. in III-Nitride, SiC, and Diamond Materials for Electronic Devices.” Eds. Gaskill D.K, Brandt C.D. and Nemanich R.J., *Material Research Society Symposium Proceedings*, Pittsburgh, PA. 423 (1996), 69-73

[4] Mion et al. “Thermal Conductivity, dislocation density and GaN device design” *Superlattices and Microstructures.* 2006

[5] *Gallium Nitride Epitaxy by a Novel Hybrid VPE Technique* by David J.. Miller

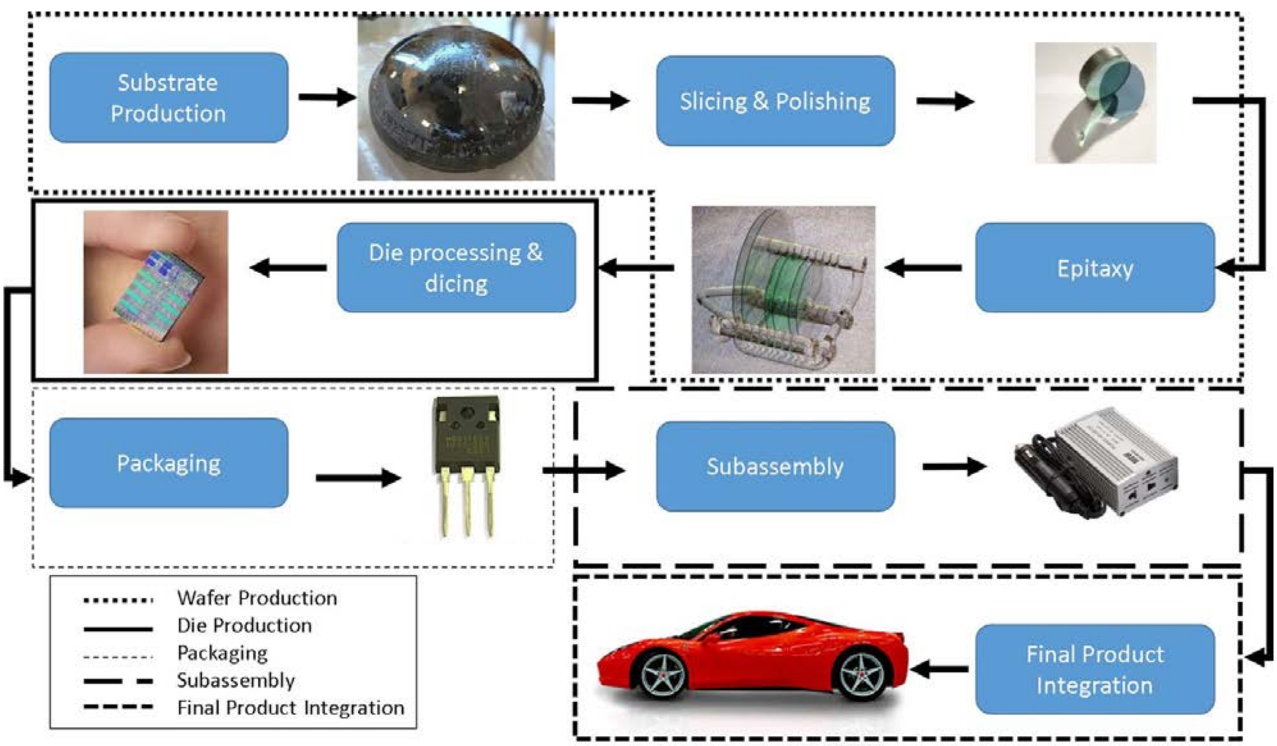
order to achieve the system level benefits of WBG systems, innovation is needed in dielectric materials. Alternative materials are being explored for film capacitors, but none have the desired performance characteristics. For integrating thermal, electrical, and structural components, the primary innovation is the design of circuits and systems to reduce the number of components needed to achieve the desired functionality.

Processes

Figure 2 below shows the steps involved in developing and integrating PE. The overall process breaks down into a few steps:

1. Wafer production
2. Die production
3. Packaging
4. Subassembly
5. Final Product Integration

Figure 2: Power Electronics Manufacturing Process (for Transportation Application)



Source: NextEnergy

The first three steps are specific for the creation of the power semiconductor. Within each of these steps, there exist technological enablers that have an impact on the growth of the supply chain at each step. The opportunities for domestic supply chain companies to see significant growth varies at each step.

Substrate Production

In order to produce the substrate wafer, the first step is to grow the substrate crystal. Table 3 below summarizes the most common processes used in substrate crystal growth.

Table 3: Substrate Crystal Growth Methodologies

Crystal Growth Processes	Used for Production of	Commercialization Status	Growth Rate (mm/hr)	Defect Density (per sq cm)	Cost
Czochralski process	Si	Mature	36-72	N/A	\$25-\$50 for 6" wafer
Float Zone	Si	Mature (limited to about 6" wafer)	120-240	10^2 [6]	\$25-\$50 for 6" wafer
Seeded Sublimation	SiC	Early stages	0.5-5	10^1-10^3	\$190-\$400 for 2" wafer
Hydride Vapor Phase Epitaxy (HVPE)	GaN	Early stages	Up to 1	10^5-10^6	\$400-\$800 for 2" wafer
Ammono-thermal	GaN	Pre-commercial; (estimated TRL 6-7)	.01-.04	10^3-10^4	\$1,900-\$5,000 for 2" wafer

Sources: NextEnergy, Lux Research, NREL, Loyola College, Soraa, PEIC Members

[6] Springer Handbook of Crystal Growth

Only a few crystal growth methodologies are applicable to wide-bandgap materials and the applicability depends on the substrate material. For GaN substrates, HVPE is the common process used, but it is slow when compared to other crystal types and expensive when matching quality provided by SiC. Consequently, GaN semiconductors frequently use alternate substrates, such as Si, SiC, or sapphire.

Slicing & Polishing

Once the substrate crystal is grown, it is then sliced into flat disks at a specific angle relative to the crystal structure and polished. The next step is to add the semiconductor on top, which is accomplished through epitaxy.

Epitaxy

Epitaxy, or epideposition, is the process of adding an additional crystal layer to the crystal structure in a manner that keeps the desired crystal structure intact. This process is used to add the semiconductor contact layer onto the substrate. The contact layer is the layer which connects the different parts of the semiconductor, similar to a “breadboard” for the desired integrated circuit.

There are four different processes for epitaxy:

- Chemical Vapor Deposition (CVD): Used for Si, SiC, GaN devices
- Metal Organic Chemical Vapor Deposition (MOCVD): A variation of CVD used for GaN devices
- Molecular Beam Epitaxy (MBE): Used for Si devices
- Liquid Phase Epitaxy (LPE): Used for Si devices

Die Production

The device production, where the integrated circuit gets added to the semiconductor, is the most complex process in the PE industry. Often consisting of hundreds of steps, this is the crux of the PE manufacturing process. Taking place in a foundry, device fabrication requires the most space and equipment of the whole process. The device fabrication process consists of layering the integrated circuit onto the contact layer, thereby creating the desired device. The primary challenge in this process is contamination control. If pollutants enter the device, the electrical properties are changed and it will no longer function as desired. Consequently, technological advancement in this step is focused on making process improvements to reduce pollutants and better pollutant detection methods. This is particularly important with wide bandgap devices, as the crystal properties make pollutant detection difficulty using traditional processes and equipment. For example detecting contamination particles on the surface of the polished SiC wafer. Multiple devices are constructed simultaneously on the wafer and once this process is complete they are separated to form individual dies.

Packaging

The role of packaging is to:

- connect the semiconductor to the circuit board and external circuits
- provide a path for heat dissipation
- protect the die from the external environment

This is done in one of two ways. Packaged semiconductors are packaged either individually as discrete devices, or for more power intensive applications, they are combined with other power semiconductors into a power module. Different processes and challenges exist for packaging discrete devices and power modules. Typically, direct bonded copper (DBC) substrates on printed circuit boards are used as a result of the thermal properties. Packaging is a vital step in ensuring the reliability of a power device. Common failure modes in PE come from packaging failures caused by bond failure as a result of high temperatures, or thermal cycling. Consequently, technological innovations in packaging are focused on improving bond/connector reliability and thermal management. In particular, the bond between the semiconductor and the DBC is an area of active innovation. In light of the emerging performance benefits of WBG devices, packaging innovation is especially critical as devices will run not only at higher temperatures, but also across a larger range of temperatures, thereby enhancing the thermal cycling effects.

Subassembly

For certain applications, the PE system is integrated into a subassembly before being integrated into the final product. During the subassembly stage, the packaged semiconductor must be integrated with electronics components, structural housing, controllers, switches, and thermal management devices to ready the power electronics system for integration with the final product. As a result, the bill of materials of the subassembly is potentially the most diverse of any of the steps in the manufacturing process for PE. This results in subassembly having interaction with a wide range of companies and materials within the supply chain. The technological innovation varies by application and business model. Some common areas of innovation include:

- Reducing total system size and/or weight: particularly relevant for transportation applications
- Developing the capability of functioning at higher environmental temperatures.
- Improving the efficiency of the power conversion product thereby reducing energy loss.
- Developing improved durability of the product.

Final Product Integration

The final stage in PE technology is the integration of the subassembly into the final application. In this step, the goal is to integrate the PE systems into a subassembly or the final product in a way that optimizes the desired properties of the end machine. As a result of increasing performance requirements combined with higher energy efficiency standards, applications engineering to integrate PE is a vital area of technological innovation. The primary innovations in this area involve designing systems to combine PE with other functions in the final product to enable higher efficiency. Examples of this can be broken down by application:

- Automotive: combining the inverter with the motor drives in electric powertrains. This reduces weight and volume by reducing the cumulative occupied space of the inverter and motor drive, thereby enabling higher efficiency
- Aerospace: unifying thermal management systems to reduce need for coolants. Traditionally, PE systems have their own thermal management systems, but with new performance and efficiency requirements, work is being done to cool the PE using existing aircraft fluids, such as jet fuel, without the use of a separate coolant

Application Agnostic Ecosystem Issues

The backbone of any semiconductor is the integrated circuit, which is the circuit within the die that performs the desired function. The die production value chain breaks up into 3 parts, best broken down by process: substrate production, epitaxy, and die processing and dicing.

The first part of the manufacturing process is the substrate production process as described above. Here, the raw materials are the seed and the liquids and gases needed for the respective growth processes. With traditional Si technology, the materials are abundant, and found globally. Si crystals are typically refined from silicon dioxide found in sand. With WBG materials, however, seed materials are much more difficult to obtain. GaN seeds must be specially grown using an expensive time consuming process to get crystals with the desired purity. Seeds must be particularly pure, because as the crystal growth replicates the seed, the defect density increases as the crystal gets larger. Quality GaN seed materials are not easily found in the United States (U.S.), and developing low-cost GaN crystal growth is a universal concern. With SiC, seed crystals are also scarce in the United States. As quality seed material is required to produce quality SiC devices, companies that have developed quality seed materials are unwilling to source this material to potential competitors.

Once the crystal growth is complete, the crystals are polished and then sliced, or sawed, into wafers. There are no raw materials aside from the crystals, diamond polishing compound, and the cleaning chemicals. There is a need for specialized equipment to be able to saw the crystals. With traditional Si technology, the supply chain is robust, however not cost competitive when compared to Asian counterparts. With WBG materials however, there is a need for new equipment to be able to reduce loss and make the sawing more efficient. Since the wide bandgap crystals themselves are expensive to grow, avoiding slicing losses when processing them into wafers is critical to reducing the cost of the device. The losses including kerf loss and wafer damage, however, remain high. Since SiC and GaN crystals are harder than Si, the sawing equipment requires much longer duration of sawing. Therefore, the consumables of the saws, the diamond wire or diamond slurry is consumed at a much higher rate than with Si. New sawing methods can also be develop to reduce sawing losses, which is not currently a focus of domestic activity.

Upon completion of polishing and sawing, the next step is epitaxy. WBG device epitaxy has different challenges than traditional Si epitaxy. Due to the differences in material composition, the processes, raw materials, and equipment needed for WBG epitaxy differ significantly from those needed for Si epitaxy. The two leading companies for MOCVD epitaxy equipment have over 90% market share, and one of these is domestic.

After the epitaxial contact layer is added to the substrate, the next step is the fabrication of the die itself. Often consisting of more than hundreds of steps, the die production is the most complex process within PE manufacturing. Requiring a lot of space, labor, and equipment, this process takes place in a foundry. A foundry is an extremely expensive investment for companies, costing upwards of $1 billion to set up a new foundry. Because of this, the payback period for a new foundry through profitable operations alone is extremely long, and companies often take into account government incentives when looking to set up a new foundry or upgrading an existing foundry to handle new materials and processes. Due to Asian government incentives, foundry activity is largely heading to Asia. The employment of a high skilled workforce for handling materials in this high-value step in the process is limited in the U.S. by the small number of cost-competitive domestic foundries in the growing die fabrication industry.

All of the supply chain issues until the die production stage are application agnostic. For the remaining processes, the supply chain and companies involved are different based on the end application. In the following sections, the implications of application specific market dynamics are explored in further detail.

Transportation Ecosystem Issues

The transportation industry has four main processes within the PE supply chain:

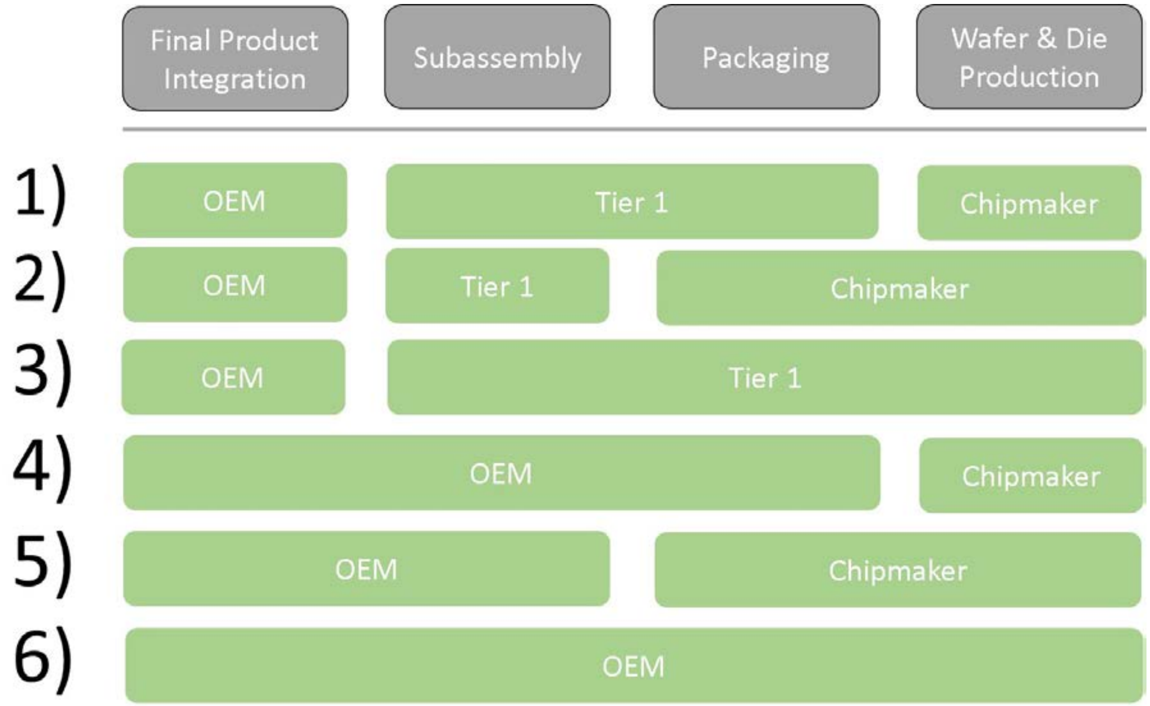
1. Wafer & Die production
2. Packaging
3. Subassembly
4. Final product

These different supply chain levels are driven by the process for developing a PE product. While each level within the supply chain has separate competing companies, there are some companies that compete across several of the four supply chain levels. Different markets may have different levels of vertical integration. The supply chain for automotive PE largely breaks up into four general segments. The first segment is the production of the die itself. The die is then packaged into discrete devices or power modules, depending on the application. These discrete devices and modules are then integrated into the final product, sometimes going through a subassembly step, depending on the application and business model.

The automotive supply chain varies by business model. There are six primary business models in the industry, which shape the supply chain. Figure 3 below shows the six different business models, based on the allocations of the four main tasks between the three main company types in the supply chain:

- OEMs (Original Equipment Manufacturers): Examples in the automotive space include Ford, GM, Chrysler, and Toyota
- Tier 1 Suppliers: Subassembly manufacturers who sell their assemblies directly to the OEMs for final integration. Examples are Magna, Delphi, and Bosch
- Chipmaker: Companies whose primary focus is die production. Examples are Infineon, International Rectifier, and Cree.

Figure 3: Business Models for Transportation Applications



Source: NextEnergy

Overall, the PE trends in the transportation market have led to three key opportunities for further development within the supply chain:

1. Volume and weight constraints contribute to the interest in WBG materials for vehicle applications; aerospace is an early adopter of WBG in commercial applications to meet space and temperature requirements
2. Long development cycles for transportation and length of service of vehicles results in the need for longer and more robust durability and reliability testing
3. A lack of engineering talent is source of concern for future growth and competitiveness with foreign companies in the transportation industry

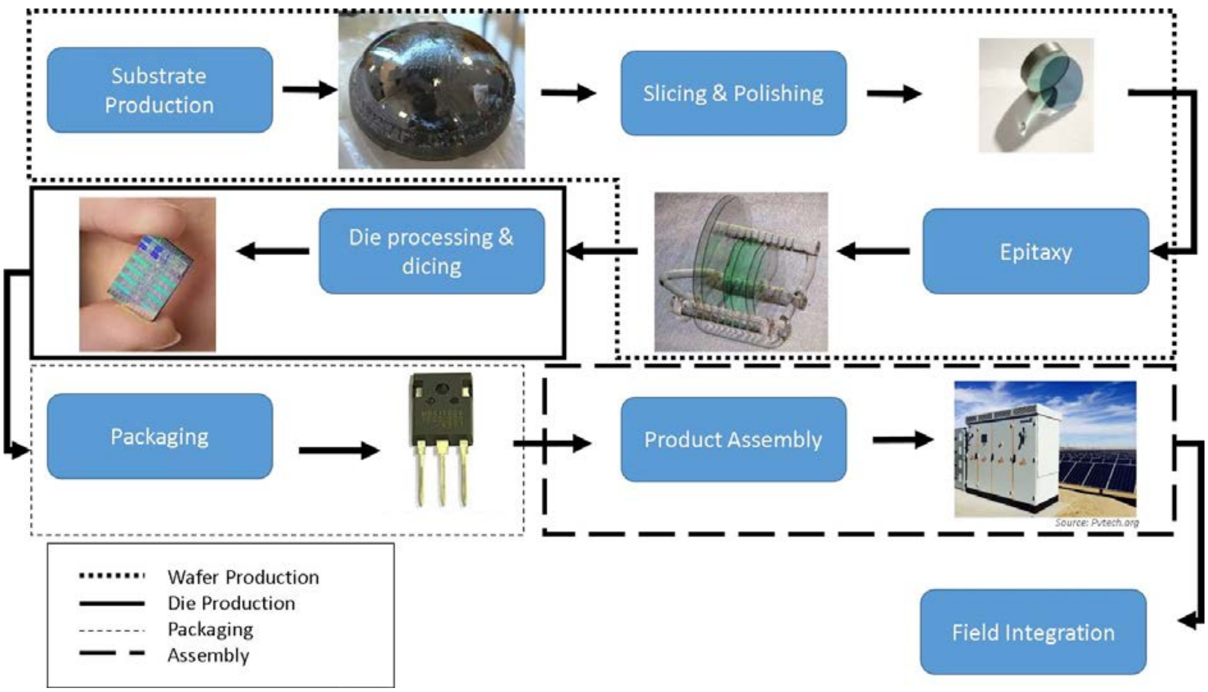
Renewable Energy Ecosystem Issues

The supply chain for renewables varies by the type of renewable generation technology. Wind turbines are large rotating machines with some similar market characteristics to either the transportation or industrial motors. The solar energy technology is more unique because the inverters used with DC panels can be engineered in a couple of different ways:

- Single large inverters designed to accept from 1kW to 1,000kW of DC current from an array of solar panels (depending on the size of the array) to produce a large AC current from a single or handful of inverters
- A series of 200W to 1,000W microinverters that serve each panel individually (depending on the panel size) to produce a large AC current from the array

Much of the PE early supply chain for renewables is similar to transportation and energy efficiency markets. As stated earlier, the wafer production is independent of the final renewables market integration. The die production and packaging companies are similar between the different renewables markets. However, the product assembly is where the renewables market sees divergence within the supply chain from other markets as the final field integration is more a typical sourcing or purchasing relationship similar to other product components. A field integrator may specify a specific set of characteristics for the inverter to match the expected load from the renewable generation source without specifically identifying the brand or manufacturer of the inverter. Unlike transportation, where in many cases the manufacturer of the final product (the vehicle OEM) may do the product integration or assembly, in the case of renewables, the PE is a completed standalone product and is integrated into the system in the field.

Figure 4: Renewables Power Electronics Product Flow

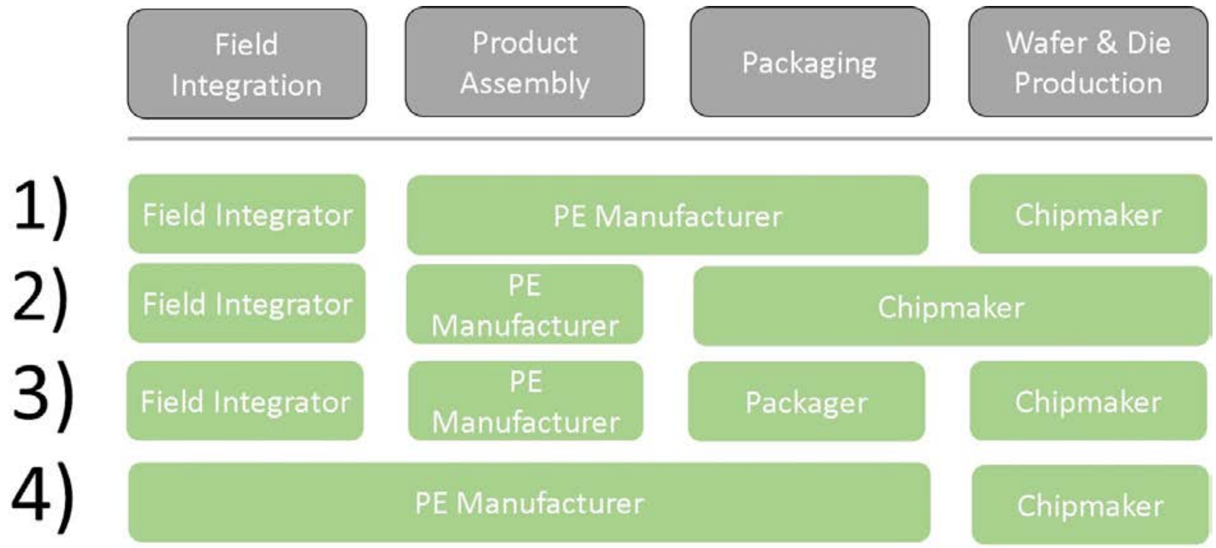


Source: NextEnergy

Within the renewables market, the supply chain follows basically three business models:

1. The final product manufacturer does everything after die production
2. Die production and packaging are a separate supplier to the PE manufacturer which does final product assembly
3. The PE manufacturer is only doing the final assembly and each step of the process is completed by different suppliers in the supply chain
4. The renewables field integrator is the same company that does PE manufacturing and packaging

Figure 5: Renewables Supply Chain



Source: NextEnergy

The first three business models are the most common, while the fourth is used by only a handful of large companies such as GE Energy that work with utilities to develop wind or solar farms for grid scale renewable generation. The supply chain within renewables has some segmentation between large, global PE manufacturers and smaller regional PE manufacturers. Larger, global, PE manufacturers tend to be more vertically integrated, while smaller more regional companies tend to do the final production but work with members of the supply chain for packaging.

GE Energy, Toshiba, Hitachi, ABB, and Mitsubishi are large global competitors that are able to compete at every level of the supply chain through final assembly (model 1 above). These companies do use suppliers however for specific components within the assembly of final products and are not manufacturing every component of the PE product. The level of integration likely varies by power level as well. The gaps in these companies' supply chain lie within the component level products (capacitors, heat sinks, magnetic materials), while the die production, packaging and assembly are most likely to be outsourced to capitalize on specific innovative technologies such as SiC or GaN. Other large manufacturers known for solar inverters such as SMA, Sungrow, Samil Power generally do the final assembly but utilize partners for parts further up the supply chain (utilizing either model 2 or model 3 above).

The end result is that a number of trends impacting the renewables market are identified by participants in this research, including:

1. The global nature of the renewables end market makes for a global supply chain
2. New packaging trends that incorporate energy storage in solar and wind development which contributes to greater need for application engineering talent

3. Long warranty and high reliability requirements of up to 25 years exposing needs for greater and more standardized testing within WBG materials to meet these needs

Energy Efficiency Ecosystem Issues

Power electronics products in the energy efficiency space are used to reduce energy usage by energy-intensive appliances and equipment. The leading markets in this space are power supplies, industrial motor drives, and uninterruptible power supplies (UPS), according to Yole Development. Table 4 below shows the global activity for power supplies targeting the computer, consumer, medical, and telecommunications applications. Most of the activity in these markets is taking place in Asia, specifically in Taiwan. Therefore, there is a gap in globally competitive American companies in this space.

Table 4: Leading Global Power Supply Companies

Company	Location	Sales ($mil)
Delta Electronics	Taiwan	4065
Emerson Network Power	USA	2160
Lite-On Technology	Taiwan	1460
Flextronics	Singapore	1050
Chicony Power	Taiwan	835
Acbel	Taiwan	730
Salcomp	Finland	681
Eltek	Norway	590
FSP Group	Taiwan	586
Meanwell	Taiwan	568
TDK-Lambda	Japan	550
Murata	Japan	530
Phihong	Taiwan	444
GE Energy Critical Power	USA	430
Shindengen	Japan	250

Source: Micro-Tech Consultants

For the UPS and industrial motor drive markets, the market structure is very similar:

1. Power module manufacturing: For both UPS and industrial motor drives, the die must first be packaged into a power module before being used in the end application. In these markets, the responsibility for packaging falls on the chipmaker, and the packaged units are then sold for integration into end use.

2. End use integration: The end user of the PE, in these cases the UPS and motor manufacturers, source the power modules from the chipmaker and integrate them into their respective products. For these markets, size is not a driver, whereas efficiency and reliability are, therefore the end user is not too concerned with buying prepackaged modules.

Table 5: UPS and Industrial Motor Drives Companies

	UPS	Industrial Motor Drive
Power Module Maker	infineon, Mitsubishi, ST Micro, Fuji Electric, Toshiba, ABB, Fairchild, Semikron, Microsemi, IR	Mitsubishi, Infineon, Toshiba, Hitachi, ABB
End User	Eaton, Emerson, Liebert, GE, APC, Schneider, Mitsubishi, Fuji Electric	ABB, Siemens, Danfoss, Yaskawa, Rockwell, WEG, Vacon, Parker, Leroy Somer, Baldor, Emerson, Converteam

Source: NextEnergy

As shown by Table 5, U.S. firms have a solid presence as end users of industrial motor drive market, but not in the power module manufacturing layer. A gap in the supply chain, therefore, is a power module manufacturer in this space. Given that in these markets, the chipmaker is often the power module manufacturer, the U.S. supply chain is weak in chipmakers for industrial applications because of the strength and costs of the Asian foundries.

The key trends that discussed during interviews within the energy efficiency markets included three main trends. First, the lack of power engineering talent is causing firms to conduct their own training. Second, the industry is already seeing acceptably high efficiency from the PE utilized for electric industrial motors where efficiency is above 95%, so additional incremental gains will likely not have significant return on investments from efficiency alone. Finally, the third key trend is that safety is the primary motivator within many segments of the market and greater testing of WBG materials would be helpful in proving the safety record of the materials.

As discussed during the Industry Summit, one of the applications for which the efficiency gain of WBG systems is significant is in data centers. According to the Natural Resources Defense Council, the energy used by data centers in the US is projected to grow by over 50% by 2020. While large data centers contribute heavily to this usage, a large portion of the inefficiency comes from small and medium sized data centers, which do not always use the most efficient available technology. Data centers are one of the largest growing markets for UPS systems and this is a significant opportunity for the domestic industry to take a leadership role. Data centers are of further interest because of the importance of thermal management. Cooling data centers is a major cost concern and utilization of WBG systems and better thermal management could help reduce this cost significantly. As a result, these are both areas that the US has the potential to take a leadership role in.

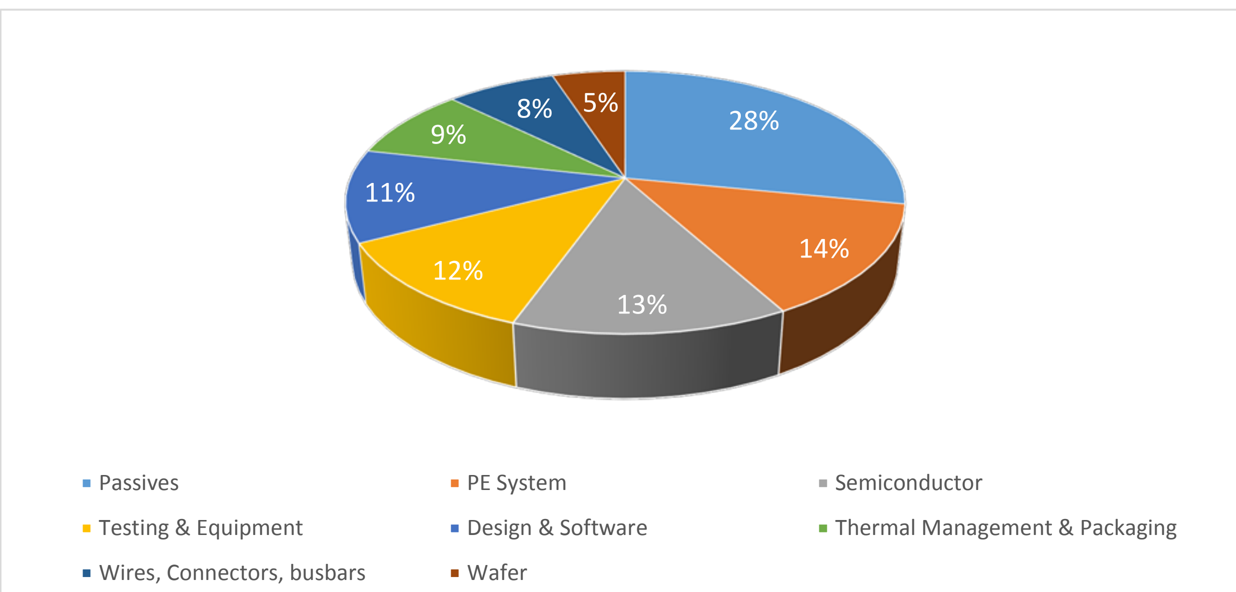
Supply Chain Gaps

Within the U.S. PE market, both gaps and strengths are being identified by those interviewed for this research. The gaps can be broken down into three types: materials gaps, process gaps, and other gaps. The strengths in the supply chain are focused on the engineering of PE including the design engineering at the early stage of a product and the application engineering which is the step to integrate the PE into the final product or for field integration. Application engineers work closely with the end customers to ensure that the products meet requirements and specifications. Because this step is so critical to final delivery, many interviewed for this research felt this would be difficult to move outside the U.S., if the end customer is a U.S. based entity.

Current Domestic Activity

There are hundreds of active US headquartered companies in the power electronics space. Figure 6 below shows the relative number of domestic companies identified in this research active in each portion of the power electronics supply chain. This is a representation of the number of domestic-headquartered companies that are active in each space; these companies do not necessarily have manufacturing operations in the US. Of the 238 companies identified, the plurality (28%) are active in the production of passive components, including materials, magnetics, circuit boards, and gate drivers. Many of these companies are focused in products targeting niche markets, such as military and defense applications, with low volumes. The next largest segment is the system-level integrators (14%), closely followed by semiconductor companies (13%). System-level companies include tier-one transportation suppliers and inverter, rectifier, and power supply manufacturers. The high activity in these two areas is vital to enabling the US to drive new technology into the market and establish global leadership in PE. In addition, the numerous testing & equipment providers (12%) and design, simulation, and software companies (11%) contribute to the domestic strength in innovation and engineering.

Figure 6: Domestic Power Electronics Companies by Activity

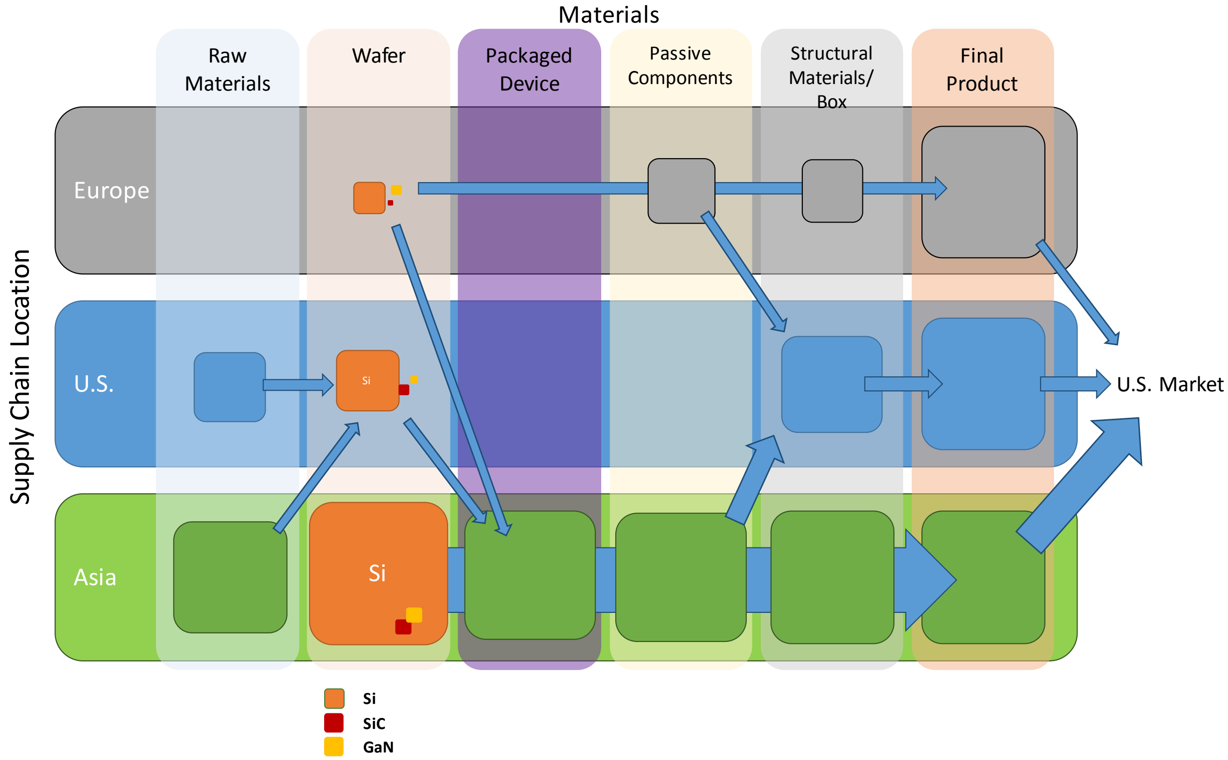


Source: NextEnergy

Materials Gaps

Materials gaps refer to physical products that are unavailable for purchase domestically. As shown by Figure 7 below, two of the key gaps identified within the material flow are the devices themselves and passive components. The device production for Si is largely occurring in Asia with modest amounts occurring in the U.S. and Europe, and a significant portion of the Asian market is sourcing from China, Taiwan, and Japan. This is primarily a result of foundries requiring high capital expenditure and the cost of regulatory compliance being much higher in the U.S. than in Asia. The passive materials are also for the most part coming Asia with the bulk of this coming out of China. The combination of lower environmental regulation compliance costs, low labor costs, and inexpensive, well-developed raw material and equipment supply chain give Asia the edge in both of these materials.

Figure 7: U.S. Power Electronics Materials Flow



Source: NextEnergy

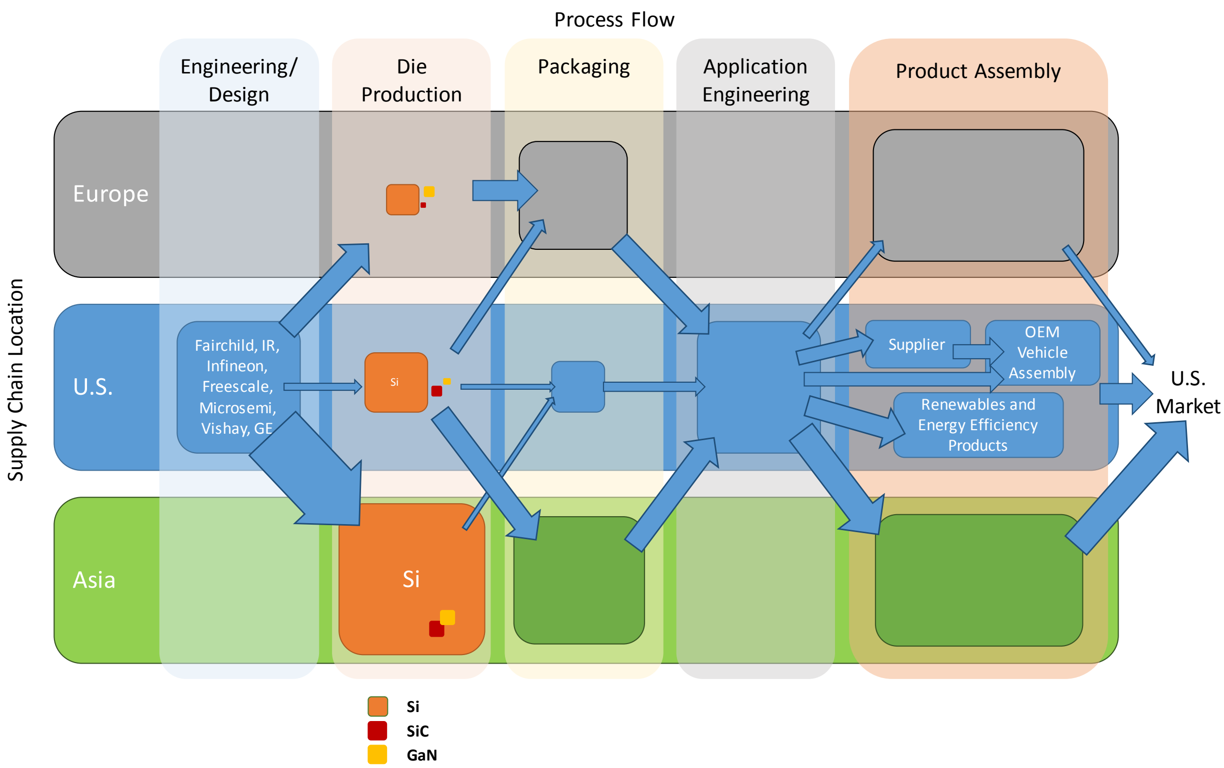
While the U.S. does have production of WBG materials, the supply chain for this also comes from a mix of suppliers within the U.S. and Asia. The bulk of the European influence on the chip market is with the production equipment where Germany has several strong competitors for equipment. Outside WBG materials, the Si based chip production is mostly coming from Asian markets. Once overseas, a majority of the materials remains in Asia until the final product is brought back into the U.S. market. Some companies did state that the final assembly with structural materials (aluminum, steel, or plastics) is sourced from within the U.S. Several companies also indicated that magnetic materials are largely unavailable from U.S. suppliers and therefore come mostly from outside the U.S. as well.

Process Gaps

Examining the supply chain from a process flow perspective, the gaps look a bit different. Following the process flow is essentially the process of following the flow of dollars in and out of the regions within the supply chain. There is not an attempt to quantify the specific dollars being spent. In figure 8, an estimation of the ratio of spending at different supply chain tiers is shown by the width of the arrow depicting the process flow, but this is not a precise estimate and should be analyzed with that consideration.

The PE product process flow in the U.S. confirms the gaps revealed in the materials flow: die production and packaging is largely being completed outside the U.S. However, the process flow does point to an area of U.S. strength in application engineering. Numerous interviews revealed that application engineering is centered in the U.S. in order to put engineering close to the final market for the product and to simplify communications with the product manufacturer. Yet, final product assembly often is off-shored as the labor costs are significantly lower in several Asian markets, particularly China, Malaysia, and Taiwan.

Figure 8: U.S. Power Electronics Process Flow



Source: NextEnergy

For the majority of the supply chain from a process perspective looks similar whether discussing the transportation, renewables, or energy efficiency markets. However, the process flow for the PE products does have an additional step with the transportation markets as the final PE product is often integrated into subassemblies within vehicles.

While the final product for solar, UPS, and industrial motors is often a separate physical box that may be sold separately from the equipment and integrated by the final customer or system installer, the transportation market and some companies within the wind turbine market have a slightly different process for the final product assembly. In these markets, the final OEM or a tier one supplier integrates a sub-assembly of the PE products into another system, such as installation within the electric motor or transmission housing or within the battery pack. In this regard, there is an additional step before final sale of the product.

Other Supply Chain Gaps

One of the other major supply gaps that our research has revealed are talent gaps. Universally, the single biggest concern for the domestic PE industry, as verified at the Industry Summit, is the lack of domestic power engineering talent. This is a result of many factors:

1. Lack of university programs in power engineering: there are not many domestic programs in the field of power engineering. This number has significantly reduced over the last few decades and universities are continuing down this path.
2. Lack of student interest in power engineering: despite the plethora of opportunities for power engineers, American students are not interested in pursuing power engineering careers. This could be a result of poor marketing and awareness and the field not being perceived as “sexy”
3. Not enough focus on practical industrial training: The limited programs that are in power engineering domestically tend to focus on early stage fundamental scientific breakthroughs, rather than practical market ready engineering, thereby creating “too many PhDs and not enough useful engineers”

In addition to talent, the other major gap that has repeatedly come up in discussion is the knowledge gap within the industry. There are two primary components of this:

- While the US is strong in fundamental research, there are low levels of manufacturing IP in the US. Technologies that are developed domestically are often manufactured overseas because the US ecosystem does not provide the necessary structure to ease the transition between proof of concept and market ready product
- The lack of vertical integration or virtual vertical integration within the industry causes inefficient information transfer. The needs of final product manufacturers are not effectively communicated to the chipmakers as a result of the fragmentation of the industry. In Europe and Asia, the major players in the PE industry have significant vertical integration, or established partnerships so that innovation is driven by internal needs of the companies and is effectively communicated, therefore accelerating R&D

Other gaps, or market issues, impacting the U.S. PE supply chain have been discussed but may not be universal issues for all competitors in the marketplace. These include:

- The fact that there are gaps in the supply chain in the U.S. is not universally perceived as a problem. The supply chain currently has a strong international base, so it is easy for companies to work with international suppliers for specific parts within the supply chain. Some companies seek lower labor rates for the assembly of final products, while some seek less cost due to the regulatory environment. Companies that struggle to work with European or Asian firms are more likely to work with U.S. distributors of products sourced overseas, which again adds a layer of cost into the products.
- Several firms mentioned that the burden of environmental laws adds significant cost to the products being manufactured in the U.S. One circuit board manufacturer stated that more than 3% of its total revenue is spent on environmental compliance. Some of this is due to multiple layers of regulations on the same issue. With the federal, state, and local regulators all requiring different paper work to regulate the same type of resource (such as water or air emissions), this adds an additional bureaucratic headaches to management of the environmental compliance.

Conclusions

The challenge for growing the U.S. PE supply chain is one of multiple facets. The U.S. either does not have supply chain base for several different materials required for PE or the existing base is small. This includes the passive materials and magnetic materials. These items are produced in large part outside the U.S. due to a combination of high capital costs for equipment, a large potential environmental impact requiring significant environmental monitoring and control costs in the U.S., or raw materials that are not produced in the U.S., such as with magnetic materials. Passive and magnetic materials therefore are part of an entrenched, robust global supply chain for materials that capitalizes on utilize raw materials sourced outside the U.S. with lower regulatory compliance and labor costs.

The challenges within the domestic supply chain are exacerbated by manufacturing processes that largely take place outside the U.S. The device fabrication process takes place within a foundry, which was mentioned as a significant capital cost. This investment has already been made in large part in Asia and it would likely be extremely challenging for U.S. to compete without significant support to offset the capital costs. Additionally, labor intensive processes, such as final product assembly, are often outsourced in order to capitalize on low cost labor. The result is a supply chain that often finds several processes are less costly outside the U.S. where labor and regulatory costs have a lower impact on companies.

The domestic opportunity may be best in the SiC devices which already have a small footprint in the U.S. Shipping the materials makes them more susceptible to damage and companies are already focusing on research and development for the materials. Internationally, there is competition for SiC production, but one of the global leaders, Dow Corning is located domestically. The competing WBG material, GaN may also offer an opportunity. Cree does GaN production in North Carolina for military and radio frequency (RF) applications, but bulk production of GaN is also being done in Asia to date already for many firms. The opportunity for WBG materials will require quick action to capture the supply chain.

The most likely area where the U.S. can influence the market is within the design and engineering education. These are areas of strength for the U.S. and require additional resources and recruiting to remain strengths.

Appendix A: Industry Summit Report

2015 PEIC Annual Industry Summit Summary

Tuesday March 17th, 2015 at Charlotte Convention Center, 6:30-8:30 PM

In support of the AMTech program to strengthen the domestic power electronics ecosystem, the Power Electronics Industry Collaborative (PEIC) hosted the 2015 PEIC Annual Industry Summit in Charlotte, NC at the Charlotte Convention Center. Designed to gather industry feedback for the supply chain gap analysis, the Summit brought together twenty-nine industry participants for a discussion around market and technological drivers for innovation, opportunities for increased industry collaboration, and adding further detail to our understanding of the domestic supply chain.

Participants were strategically assigned to five tables to provide maximum industry diversity at each table and to ensure that everyone had adequate opportunity to express their thoughts. The breakout discussions followed a presentation of the research findings to date. Each table had a discussion moderator from NextEnergy or Sandia National Laboratory to optimize the focus of the discussions and to ensure equality of information among participants. The breakout discussions lasted approximately an hour. Some of the findings are detailed in this report.

<u>Key takeaways</u>

- There is a big “Valley of Death” stretching over many of the advanced technologies in the power electronics supply chain, so government support is important to reduce risk
    - There may be opportunity to gain creditability or reputation in adjacent markets, such as pursuing microgrid applications to build reliability data for larger grid applications
- There needs to be more coordination across the industry as new semiconductor capabilities are driving needs for increased capabilities in other components
    - Passive materials and thermal control mentioned as areas needing more work
    - Packaging and reliability improvements are integral to adopting new technology
- The United States needs an ecosystem around power electronics. Focusing on one piece of the supply chain will not bring manufacturing back to the United States if all the other pieces are absent.
    - Integration of the entire system into a final application is what the US is good at and is where the high value employment is – requires a lot of work/engineering and is high value
- Technology transfer from universities and labs to industry continues to be a challenge
    - Easy to get funding for fundamental research
    - Process for university and private industry collaboration is fraught with politics and discourages greater investment
- Systems level knowledge is key to establish market leadership
    - Understanding how innovations on component or device level affect full system cost and functionality is essential to establishing market leadership in emerging technologies

Discussion Summary

<u>Opportunities for collaboration</u>

- US has opportunity to lead at system level benefits, but industry fragmentation is restricting flow of information. Other nations have strong vertical integration that is advantageous for introducing new innovations to market
- Data centers if the US are a market of tremendous growth. Leadership in this field is not yet established and emerging technology can shape the market in the near. US has several companies actively competing in this space and through increased collaboration with other members of the supply chain, a robust ecosystem can be developed, leading to market leadership
- Technological innovations in one field drives need for innovation in other fields, so increased collaboration among industry is vital to establishing technological leadership. Example: fast switching drives require faster magnetics
- Public private partnership to create a “Grand Challenge” for power electronics innovation where US HQ companies can pull advanced power electronics into products or operations

<u>Innovation Drivers</u>

- Reducing size and cost while improving thermal performance is key for transportation
- Next generation packaging is an area of potential strength for the US
- Regulatory push for increased efficiency drives innovation in better power conversion technologies
- Growth of data centers driving need or more efficient power conversion and higher temperature capabilities
- Proving that efficiency gains have higher value than initial cost is vital to driving innovation
- Develop a quality standard for certain applications that increases need for higher quality products

<u>Supply Chain Gaps</u>

- The supply chain and manufacturing ecosystem for applications that has left the US will not come back
- Need to focus on emerging applications
- Government support is currently spread thin across multiple potential innovations but not enough in any one to establish global leadership
- Result is that early breakthroughs happen in US but manufacturing takes place elsewhere
- Leads to a large “valley of death” for technology development in the US: technology that is proven does not get the investment needed to enable manufacturability
- Cannot focus on only one component of system, support needs to be given to entire ecosystem because even if component A is made in the US, all of the other components are still being made abroad

WBG Challenges & Opportunities

- Reliability uncertainty makes industry hesitant to use in applications that have high warranty requirements
- Limited sources of WBG materials and WBG capable components
- Cost-effectiveness is more significant than efficiency gains due to increased cost and reliability risk
- Systems level understanding and leadership will drive global competitiveness

Talent Development

- Cost of acquisition of talent is a big concern. US companies are competing and paying top dollar to power electronics engineering graduates from the limited amount of universities offering power electronics degrees (Virginia Tech, MSU)
- US needs to cultivate power electronics talent
- Product design and application engineering represent the opportunity for most jobs in the economy and is an area of strength currently for the US. Focus should be on maintaining this advantage rather than bringing back foundries
- Academic programs are “too academic”: there is a lot of concentration on very narrowly defined & esoteric areas with no chance of it making it into industry
- Technology related competitions and challenges (like solar-car race) are great at getting students integrated into the industry

Appendix B: Glossary

AMTech: Advanced Manufacturing Technology Consortia (NIST)

CVD: Chemical Vapor Deposition

Die: Unconnected semiconductor chip containing the device

Device: Single function circuitry constructed on the die within the semiconductor material. Note that “discrete device” refers to a packaged single function component.

GaN: Gallium Nitride

MOSFET: Metal–oxide semiconductor field-effect transistor

HPVE: hydride vapor phase epitaxy

IGBT: Insulated-gate bipolar transistor

kV: Kilovolt

kW: Kilowatt

LPE: Liquid Phase Epitaxy

MW: Megawatt

MBE: Molecular Beam Epitaxy

MOCVD: Metal Organic Chemical Vapor Deposition

NIST: National Institute of Science and Technology

OEM: Original Equipment Manufacturer

PE: Power electronics

PEIC: Power Electronics Industry Collaborative

RF: Radio Frequency

Si: Silicon

SiC: Silicon Carbide

UPS: Un-Interruptible Power Supply

WBG: Wide Band Gap