



## 2017 RESEARCH HIGHLIGHT IN MANUFACTURING ANALYSIS

# Manufacturing: SiC Power Electronics for Variable Frequency Motor Drives

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### SUMMARY OF FINDINGS

Variations in manufacturing expertise, yields, and access to existing facilities currently have a greater impact on regional costs and manufacturing location decisions for SiC ingots, wafers, chips, and power modules than core country factors such as labor and electricity costs.

### SNAPSHOT:

#### The Market for SiC-Based Motor Drives

- In 2016, the market for SiC devices in motor drives was estimated at \$24.8 million, and it constituted approximately 10% of the total demand for SiC devices (Yole Développement 2016).
- By 2020, demand is projected to reach \$78.8 million, which corresponds to 15%-16% of the total projected demand for that year (Yole Développement 2016).
- The use of SiC power electronics in motor drives can enable total system cost reductions by decreasing the number of required components and the size of passive components. The costs of SiC power electronics are expected to decline as companies move toward fabricating devices on six-inch wafers and scale up production along the value chain.
- Currently, medium-voltage motor drives are often semi-customized and are typically assembled near the end customer. Their large size makes shipping cumbersome, and locating near the end user enables manufacturers to respond rapidly to their customers and to reduce lead times.
- Manufacturing of SiC components currently occurs in locations where there is process know-how, as achieving good yields and high quality are critical for success. Often, manufacturers choose to manufacture in locations where they can utilize existing facilities.

Using a bottom-up approach, we analyzed the costs associated with manufacturing silicon carbide (SiC) ingots, wafers, chips, power modules, and SiC-based variable-frequency motor drives (VFDs). Our analysis indicates that variations in process know-how, manufacturing yields, and access to existing facilities currently have a greater impact on regional costs and manufacturing location decisions for ingots, wafers, chips, and power modules than core country factors such as labor and electricity costs. For these reasons, the United States currently leads the world in the production of SiC wafers, and, along with Japan and Europe, is also a top manufacturer of SiC chips.

For chips and power modules, the ability to modify existing facilities used for manufacturing silicon power electronics (e.g., through the use of contract manufacturing) could provide an opportunity to take advantage

of economies of scale even at low production volumes. While most of these facilities are in Asia, the United States does have several four-inch and six-inch chip fabrication facilities that could be used for this purpose; in fact, X-FAB has recently established a SiC foundry line within its Si chip fabrication facility in Lubbock, Texas.

Our analysis indicates SiC-based, medium-voltage VFD costs would be dominated by the cost of materials and that differences in regional manufacturing costs could be driven almost entirely by differences in labor costs. This is because of the largely manual process currently used to assemble VFDs. However, the large size and semi-customized nature of medium-voltage VFDs means assembly occurs near the customer, even if the customer is located in a region with high labor costs.

### Manufacturing Today

Figure 1 summarizes the manufacturing value chain for SiC-based VFDs as well as the calculated minimum sustainable price (MSP) (Horowitz 2017) for each component and key success factors for manufacturing.

Currently, medium-voltage VFDs with all-SiC power electronics are not commercially available. The technology is relatively new, and the end users—industrial customers in manufacturing and in oil and gas—require long track records of performance and reliability before adopting new technologies. However, in the near term, it is expected that companies manufacturing Si-based medium-voltage drives would also manufacture SiC-based drives. These companies tend to be large multinational firms with assembly plants around the world. Because medium-voltage VFDs are very large and are often semi-

Raw Materials		Wafers	Chips	Modules	VFDs
MSP per VFD		\$1,598	\$3,594	\$13,109	\$176,355
Currently Shipped	Globally	Globally	Globally	Globally	Locally
Success Factors	<ul style="list-style-type: none"> <li>No fundamental resource constraints</li> <li>Limited number of high-purity SiC powder suppliers</li> </ul>	<ul style="list-style-type: none"> <li>Critical to quality</li> <li>Manufacturing yield</li> <li>Process know-how</li> <li>Crystal growth cycle time</li> <li>Access to capital or existing facilities</li> </ul>	<ul style="list-style-type: none"> <li>Critical to quality</li> <li>Manufacturing yield</li> <li>Process know-how</li> <li>Production scale</li> <li>Access to capital or existing facilities</li> </ul>	<ul style="list-style-type: none"> <li>Proven reliability</li> <li>Quality and performance</li> <li>Material cost (SiC chips)</li> <li>Access to capital or existing facilities</li> <li>Production scale</li> </ul>	<ul style="list-style-type: none"> <li>Proximity to customer installation</li> <li>Quality and performance</li> <li>End applications knowledge</li> </ul>

Figure 1. The SiC-based VFD value chain and a summary of the calculated minimum sustainable price (MSP) and key success factors for each link in the value chain  
Data are from NREL analysis.

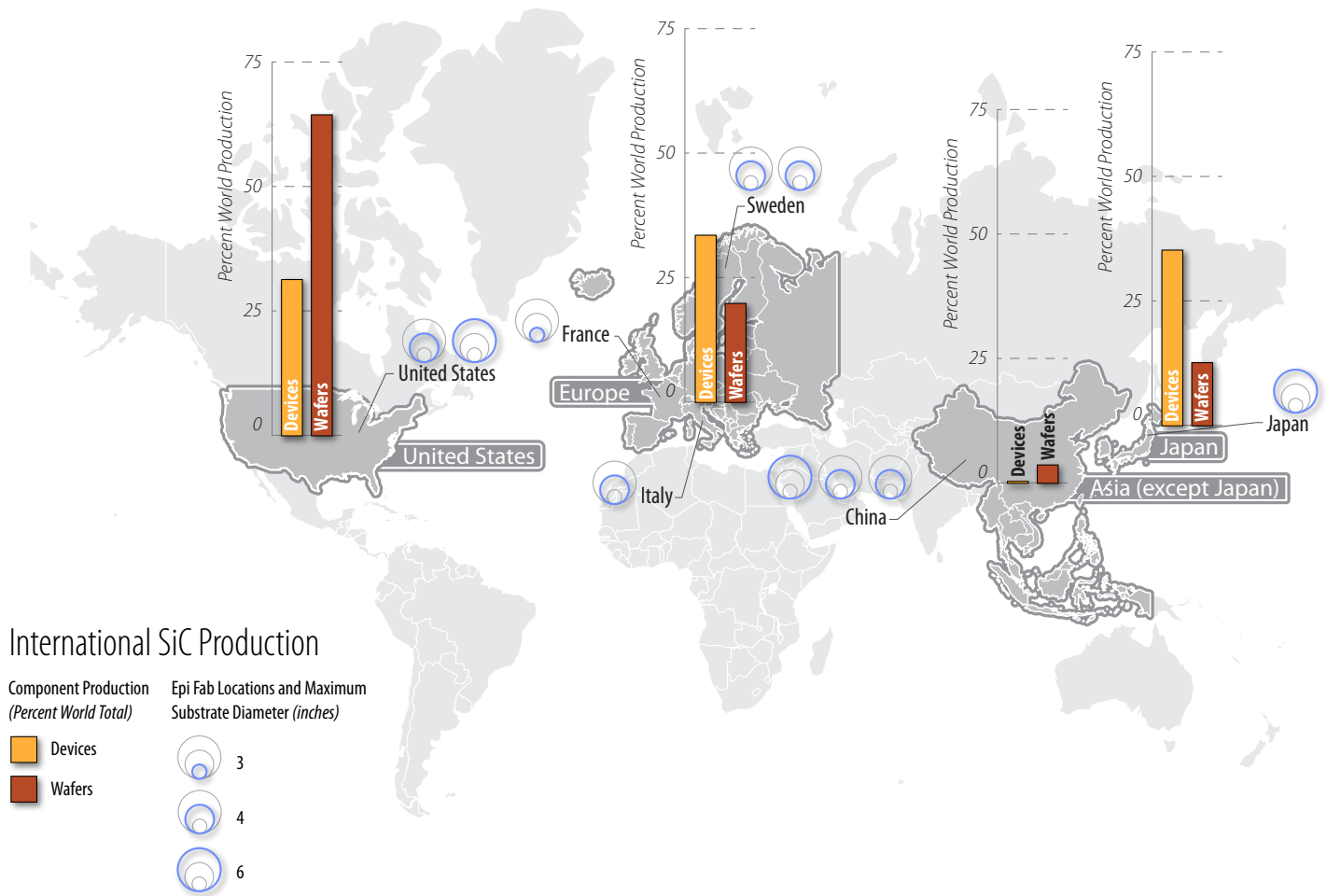


Figure 2. Global manufacturing locations for SiC wafers and devices (chips)

Data are from Yole Développement (2016).

customized for specific applications, firms almost always assemble them in their facilities that are closest to local markets. In 2015, the United States was the largest market for medium-voltage drives by revenue (30.0%). It was followed closely by China (28.6%) and Europe (24.7%) (Zhou 2016).

SiC power modules are currently manufactured in the United States, Europe, and Asia. However, contract manufacturing in Asia is primarily used for volume production. Existing contract manufacturing facilities that produce Si power modules can be used for SiC with minimal modification.

This allows companies to benefit from economies of scale and existing supply chains with low or no capital equipment requirements. Quantitative data on SiC power module production volumes by country are not available, and existing trade codes do not provide sufficient specificity to track trade flows of these modules.

SiC chip production is currently split roughly equally among the United States, Europe, and Japan, as shown in Figure 2. The vast majority of production is carried out by large, vertically integrated multinational companies that are already established in the power electronics industry.

Production is also dominated by a few key players, with the top seven manufacturers having over 95% of the market share. These companies have benefited greatly from their knowledge of both power electronics manufacturing and end applications, as well as access to existing production facilities. There have been several new entrants in SiC chip manufacturing in recent years, including several companies from China that have benefited from government investments to develop local production facilities.



The United States currently produces the majority of the world's SiC wafers. Wafers are also produced in Europe (Germany, Sweden, and Russia), Japan, and, to a lesser degree, China and South Korea. The quality of SiC wafers is critical to the performance of components farther down the value chain, and so companies that have been able to create high-quality wafers have been most successful. Additionally, manufacturing yield is a primary driver of wafer manufacturing costs, so firms that can achieve the highest yields and have deep knowledge of the process are at an advantage. Most firms have chosen to locate manufacturing where they can use existing facilities to minimize required investments and benefit from existing knowledge and capabilities. Some companies (e.g., Dow Corning) have leveraged their own

facility space, while others have acquired companies with existing SiC substrate manufacturing facilities and expertise (e.g., ROHM's acquisition of SiCrystal in 2010). Cree already produced SiC substrates in high volumes for the light-emitting diode market, allowing it to build expertise and realize additional economies of scale that would not be possible given the level of current demand for SiC power electronics.

### Manufacturing Costs and Sustainable Price Requirements

Figure 3 shows the cost breakdown for a SiC-based, medium-voltage VFD. The cost and MSP for the VFD, as well as the c-Si power electronics used in the VFD, were calculated using NREL's bottom-up cost methodology (Horowitz, Remo, and Reese 2017). As can be seen from the figure, the total cost is dominated

by the materials costs, which include the SiC power modules, VFD housing and cooling, the transformer, the SiC power modules, and other electronic components (e.g., gate drivers and filters). For this design, over half the materials cost was for the transformers, and 14% of the materials costs were due to the SiC power modules. Transformers costs will vary by design and the voltage of the distribution line; eventually, high-voltage SiC power electronics could allow for the elimination of the transformer in some cases.

Regional cost differences are driven by differences in labor rates, and can be significant. This is because the VFD is assembled in a largely manual fashion. However, we found that assembly of medium-voltage VFDs is sited near the

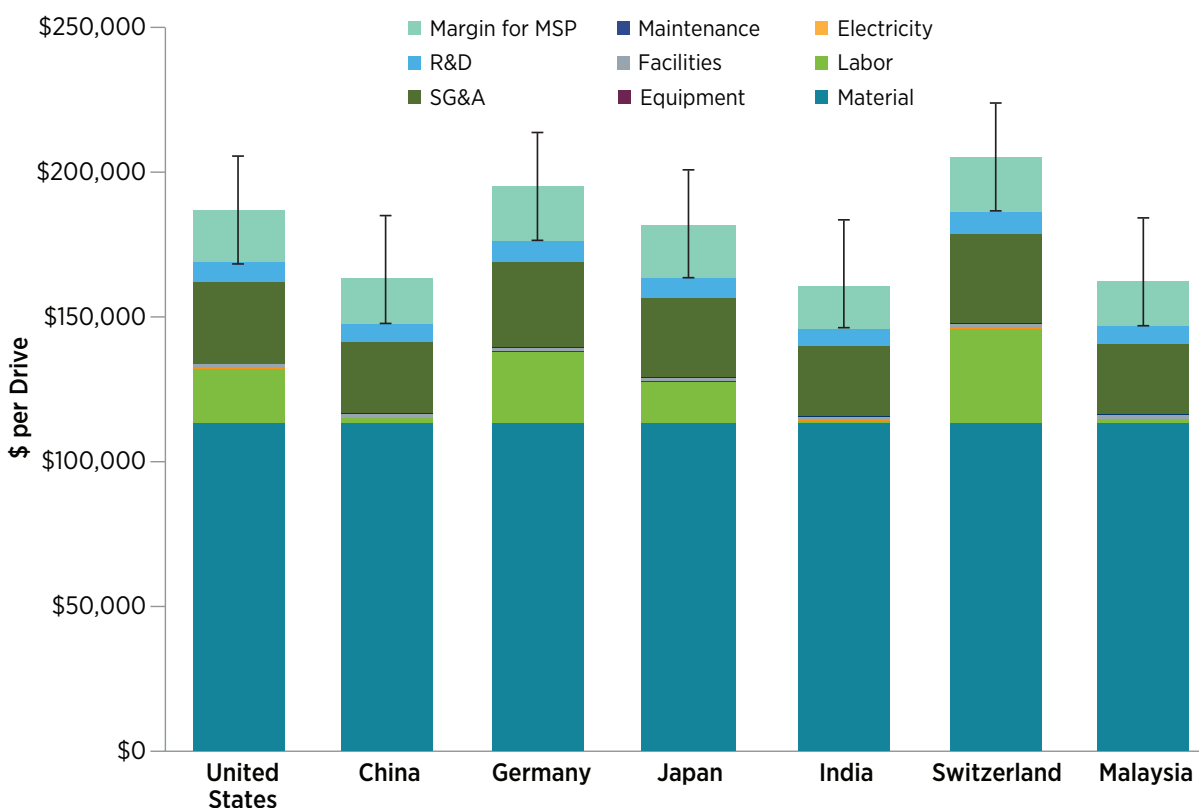


Figure 3. The calculated regional manufacturing costs and sustainable price requirements, by country, for a one-megawatt SiC-based VFD. Data are from an NREL cost analysis.

end customer (i.e., demand), despite these differences in costs, due to the lead time and expense involved with shipping these very large drives, as well as the benefit manufacturers derive from being able to quickly respond to customer needs. Cost breakdowns for the SiC wafers, chips, and power modules are included in our forthcoming report.

## Opportunity Space

Motor drives represent an area of expected growth for SiC power electronics. While we have only limited data on the market for SiC diodes and transistors in AC drives, market reports predict the size of the market will grow from just under \$20 million in 2015 to over \$100 million in 2021 (Yole 2016). This includes the market for all AC drives, not just those in

the medium-voltage class. It is also anticipated that some applications will incorporate full SiC power electronics during this period, as opposed to using hybrid solutions with SiC diodes and Si transistors. However, Si components are still expected to dominate the overall power electronics market for the foreseeable future, with the SiC market share expected to increase from 1.7% in 2015 to 3.9% in 2021.

## Learn More

See the technical report on this work: *Global Cost and Competitiveness Issues in Manufacturing SiC Power Electronics for Medium Voltage Motor Drives*.

This work was also presented at Motor Drives & Systems 2017.

## References

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