# Wide BandGap Power Devices and Applications; The U.S. Initiative

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***Abstract*—The U.S. offers multiple mechanisms for funding both small and large businesses to promote innovations in science and industry. However, dating back to the 80s many U.S. companies have chosen to take products created domestically and manufacture them overseas. This has been a particularly disturbing trend in the semiconductor business leading to the loss of jobs and technical expertise as students, educated in the U.S., leave for opportunities elsewhere.**

**Efforts to reverse this tendency are being aggressively undertaken through new initiatives funded by the U.S. Department of Energy's (DOE) Advanced Manufacturing Office (AMO). Details of some of these activities, in regards to Wide Bandgap (WBG) semiconductor devices and their applications, are discussed in this paper.**

***Keywords—wide bandgap; NNMI; PowerAmerica; Advanced Manufacturing Office***

## I. INTRODUCTION

Theories accounting for the flight of manufacturing from the U.S. over the last few decades are varied. Studies have attributed substantive job losses to reasons ranging from increased productivity, liberal foreign trade policies, and the effects of trade deficits of manufactured products during and following the economic collapse of 2008 [1].

The exodus of the semiconductor industry overseas to Asia is one sobering example. A 2006 study from the Government Accountability Office (GAO) summarized the offshoring trend in the semiconductor industry: "The US semiconductor industry began offshoring labor-intensive manufacturing operations in the 1960s, followed in the 1970s and 1980s by increased offshoring of complex operations, including wafer fabrication and some research and development (R&D) and design work. Semiconductor assembly and testing was the first to move to Asia, followed by fabrication and, more recently, by some design operations" The GAO attributes this largely to government policies in low-labor-cost countries like Taiwan, China, etc., which "created favorable investment conditions for U.S. semiconductor firms" [2].

While the silicon (Si) semiconductor industry now has a substantial offshore footprint, Wide BandGap (WBG) semiconductor devices are just beginning to become a viable industry. Based on both silicon carbide (SiC) and gallium nitride (GaN), they have the potential to revolutionize power electronics. Their attributes enable products with faster switching speeds, lower losses, higher blocking voltage, and higher temperature operation yielding increased power density, higher efficiency with reduced thermal management requirements.

Whereas the U.S. has led the world in WBG developmental activities over the past few decades it is now at a similar crossroads as the silicon industry was in the 80s regarding commercialization and manufacturing.

The Advanced Manufacturing Office within the U.S. Department of Energy is tasked with developing partnerships to invest in emerging clean energy technologies resulting in the creation of high quality domestic manufacturing jobs. WBG devices offer significant potential in these regards, both in reducing global energy consumption and strengthening the semiconductor manufacturing base in the U.S. Given escalating energy use, $CO_2$ levels, and the increasing need to expand the use of renewable energy sources the need for government leadership in these activities has never been greater.

## II. HISTORICAL PERSPECTIVE

### *A. Impact*

Historically, the U.S. has spearheaded many technological advances through the development of new materials, processes and systems made possible through government funded programs. In the early '70s, a quarter of American workers were employed in manufacturing trades. By 2012 this number had plummeted to 9% [3]. In real numbers, the United States lost 5 million manufacturing jobs between January 2000 and December 2014 [1].

### *B. Scope of the U.S. Manufacturing Delimma*

The U.S. government has invested hundreds of millions of dollars in photovoltaics research and development, yet in 2008 the United States accounted for only 5.6% of the global production of photovoltaics, down from 30% in 1999. Chinese production, by contrast, represented only 1% of the global output of photovoltaics in 1999. By 2008, its global production output had risen to 32%.

In 2007, only 8% of all new semiconductor fabrication plants under construction in the world were located in the U.S. Twelve percent of new fabs were being built in China, 40% in Taiwan, and 6% in South Korea. In 2007, the United States produced 17% of the world output of semiconductors, a number that had been declining since 1995, when the U.S. accounted for 23% of the global output [4].

Between 2000 and 2014, productivity growth slowed noticeably, and the U.S. manufacturing output experienced no net, real growth [1].

## III. Governmental Initiative

New advances in technology have made American production cheaper by increasing productivity and shrinking labor as a share of total costs. 3-D printing, for example, is part of a new trend in "additive manufacturing," where 3-D objects are built through the successive layering of materials from a computerized blueprint [5].

To foster advances and promote the expansion of new, energy efficient technologies and manufacturing in the U.S. President Obama proposed the creation of a National Network for Manufacturing Innovation (NNMI)—a $1 billion effort that was launched in August 2012 with the National Additive Manufacturing Innovation Institute, in Youngstown, Ohio. In January 2014 President Obama also announced the formation of PowerAmerica, an NNMI Institute focusing on enabling large-scale production of wide bandgap semiconductors with the goal of revolutionizing energy efficiency across multiple application platforms with WBG semiconductors. This has been followed by Institutes focusing across a broad spectrum of manufacturing sectors including critical materials, digital manufacturing, light-weight metals and advanced composites manufacturing.

### A. *Wide Bandgap Semiconductors*

The development of advanced WBG crystal growth, wafer fabrication and device processing technologies owe their beginnings to support from a variety of U.S. Government programs. Beginning in the late 80s organizations such as the Air Force and Army Research Labs, Office of Naval Research, Missile Defense Agency, and the Defense Advanced Research Projects Agency sponsored hundreds of millions of dollars and decades of work at universities, industry and government laboratories. Initially, this work was focused on "proof-of-concept" critical enabling technologies to assure a domestic source for current and future Department of Defense (DOD) system requirements.

Silicon carbide has now advanced well past this point with the introduction of the first commercial SiC Schottky diode in 2001. However widespread commercialization, particularly of switches, has become mired in 'The Valley of Death'. The slow adoption rate of WBG devices can be attributed to several factors:

1. <u>High Prices</u> – due chiefly to low sales and manufacturing volumes.
2. <u>Inexperience with WBG devices</u>—the electronics community is traditionally *slow to change* and adapt to new technologies.
3. <u>Value Proposition and Integration</u>—Demonstrations of WBG devices in real applications have been limited to PFC and PV Converter applications at 100W-5kW power levels. Real benefits in terms of higher efficiency, reduced weight, volume and lower systems cost have not been quantified and shared in a wide-spread manner. In addition, many of the *packaging and triggering issues*, required to make WBG devices work in actual applications, haven't been adequately addressed [6].
4. <u>Immature Design Infrastructure</u>--Design tools such as PDK design rules, circuit, thermal, and gate drive designs need to be more fully developed and available for insertion.

In part because of improvements in wafer fabrication and production volume increases, device costs have declined dramatically since the first SiC Schottky diode was produced from a $5,000, two-inch wafer. 100mm SiC wafers have decreased in price from $1,200–$1,400 in 2009 to $600–$750 in 2012 [7].

However, due to relatively low production volumes and the high costs of establishing a dedicated process line the move to 150mm wafers has been slow. This has contributed to the continuing high cost of SiC relative to silicon.

### B. *PowerAmerica*

The silicon semiconductor industry was offshored to countries, such as China and Taiwan, primarily due to government subsidies offered for the necessary infrastructure development such as buildings and manufacturing equipment. The result was a devastated U.S. semiconductor industry with design, foundries and packaging being off-shored on a massive scale. A larger more lasting impact has been, and will continue to be felt, in the loss of technological innovation in the U.S. as the educated workforce migrates overseas to support the expanding foundry supply chain.

The situation for WBG semiconductors is somewhat different. Currently, WBG devices are being manufactured on 150mm diameter wafers with the future move to 200mm in 4-5 years. There is currently ample 150mm and 200mm fab capacity in the U.S. with 0.35 to 0.5 micron design rules. While these fabs are antiques compared to the state of the art 300 mm fabs overseas, they are perfectly suited for WBG power device manufacturing. As the infrastructure is readily available domestically there is no major incentive to off-shore WBG device manufacturing.

To hasten WBG market adoption, the U.S. Department of Energy and North Carolina State University (NCSU) formed the PowerAmerica Institute. The vision of the Institute is to promote energy savings technologies through the deployment of WBG power electronics and the subsequent development of a manufacturing base in the U.S. Located in Raleigh, North Carolina PowerAmerica is a consortium of universities, industries and government laboratories all focusing on solving issues to establish a more compelling value proposition for WBG semiconductors.

PowerAmerica is addressing the higher costs of WBG devices through the successful establishment of a fabless model. Through re-purposing 150mm and 200mm Si foundries in the U.S. WBG power devices can be manufactured with the relatively small investments necessary to support unique WBG process steps such as high temperature implantation and annealing, contact formation, backside processing etc. This requires an investment of $12-15M, which can be shared between the U.S. government and the foundry partner. Minimizing capital expenditures results in lower process costs/wafer provided the fab is loaded with standard Si processes running on the same line. In addition, aggregating the demand for WBG substrates and epilayers in one or two fabs raises volume sales leading to lower material costs. Lower process costs in a fully depreciated and loaded foundry coupled with reduced material costs will result in significant reduction of prices for WBG devices.

PowerAmerica has adopted a hybrid model for the WBG foundry. The companies that have developed their own integrated process for diodes and switches can export their processes to the foundry. The processes from different companies are kept confidential. A more generally available process called the PowerAmerica process has been created which will be managed, maintained, and continuously improved by NCSU. This standard process will be available to companies and universities that are new to WBG technology. In this manner, a new product can be developed with a $10-15M investment as opposed to $100-200M required to re-invent the wheel. This will also promote new businesses through venture capital investment.

A second pillar of the PowerAmerica Institute's work is device packaging. This is an area where the U.S. is highly deficient, as semiconductor assembly and packaging was off-shored in the 1970's. It will be difficult to re-build this capacity from scratch. However, WBG devices offer a unique opportunity in this regard since they require special packages with reduced parasitic inductance, reduced thermal impedance and higher temperature operation. Standard Si packages will not work well for WBG devices. Thus there is an opportunity to utilize what little Si packaging capacity the U.S. does have in modules and re-purpose it for WBG devices by using special layouts for minimizing parasitics, using new base-plate materials (potentially additively manufactured) for lower thermal impedance and double side contacts for increased cooling as well as low inductance and new potting compounds for higher temperature operation. This will provide an opportunity for innovation and where U.S. universities can team with packaging partners to create a superior product.

A third focus area of the Institute is the demonstration of projects to highlight the benefits of WBG devices in Power Electronics in terms of smaller size, reduced bill of materials and higher efficiency. This requires new topologies, new gate drivers for faster switching and entirely different methods to layout PCBs to minimize inductance, avoid ringing etc. This is an area where U.S. universities can make important contributions while also training the next generation of graduate students who will drive the future adoption of WBG devices. At PowerAmerica, projects with industry-university partnership are desirable but not necessary since the idea is to create demonstrations to prove the value proposition of WBG based power electronics. Some active projects involve using WBG devices in laptop adapters, PV string inverters, UPS, Variable Speed Drives (VSD) and inverters for heavy-duty vehicles.

Workforce development and training is also a foundational leg of the Institute as well as a U.S. Government priority. It is necessary to create a workforce that is familiar with designing power electronics using WBG devices to continue to move the needle forward in WBG adoption into the future. The best place to do this is graduate training in universities where Power Electronics is a strong discipline. In addition to training graduate students through PowerAmerica funded power electronics projects, two traineeship programs at Virginia Tech and the University of Tennessee, Knoxville have been established by DOE to produce a mix of MS and PhD students well versed in the art of designing with WBG devices. These students will enter the workforce in the next few years and will help accelerate the adoption of WBG devices in various applications. Some students will become future faculty members and will help train a new generation of graduate students allowing a chain reaction to continue for the next hundred years.

### *C. Value Proposition*

The concept of the fabless foundry model drives PowerAmerica's goal to reduce the price of 1200V WBG semiconductors to 10 cents/A, or lower within 5 years. A cost reduction roadmap based on cost models and the fabless foundry concept has been developed and shows the feasibility of achieving Institute WBG price goals in 3-5 years.

Assuming the cost of a 150mm SiC substrate and epilayer, as shown in Table 1, a processing cost of $800/wafer in a commercial silicon foundry (this can be reduced to $550/wafer in high volume), and adding a gross margin of 50% (price = 2x the cost), the projected prices of SiC chips are shown in Table 1. The price for a 1.2kV, 20A SiC chip is calculated to be 4.6 cents/A, significantly below the PowerAmerica's target of 10 cents/A. The 15kV SiC chip is calculated to be priced at $2.74/A, assuming a yield of 54% and $3000 for the 150 mm substrate and epilayer.

If the industry can approach these numbers in 3-5 years the device demand will grow exponentially across multiple applications. It is expected that 200mm SiC substrates will be available by 2020. Larger substrates combined with the availability of alternatives to SiC MOSFETs, such as JFETs and BJTs, which are simpler to fabricate with higher yields, will also aid in cost reductions.

## IV. Conclusion and Future Work

Building on the successful commercialization of low voltage SiC semiconductors, the next step in the advancement of SiC would be the development of higher voltage devices for grid applications.

As more and more distributed energy resources are connected to the high voltage distribution macrogrid (13.8kV in the U.S.), the concept of an asynchronous microgrid is emerging. By utilizing back-to-back AC to DC and DC to AC converters, complete isolation of the voltage, frequency and phase angle of the macrogrid from the microgrid can be realized-- necessary for stability. In the event of an outage, the macrogrid can receive power from the microgrid and vice versa. Furthermore, the isolation allows the macrogrid and

**Table 1. Calculation of Price/Amp for 20A max, various voltage SiC chips in a high volume commercial 150mm Si Foundry**

| | 1.2kV | 1.7kV | 3.3kV | 4.5kV | 6.5kV | 10kV | 15kV |
|---|---|---|---|---|---|---|---|
| Drift layer doping [$cm^{-3}$] | $1\times10^{16}$ | $7\times10^{15}$ | $3\times10^{15}$ | $2\times10^{15}$ | $1.2\times10^{15}$ | $7\times10^{14}$ | $4\times10^{14}$ |
| Drift layer thickness [μm] | 10 | 15 | 30 | 40 | 60 | 95 | 145 |
| $R_{onsp}$ [mohm-$cm^2$] | 1.7 | 2.5 | 7.8 | 14.5 | 34.0 | 89.1 | 237.8 |
| Chip Area [$mm^2$] | 3.7 | 4.5 | 8.0 | 11.0 | 17.3 | 29.5 | 50.9 |
| Yield [%] | 86.8 | 86 | 83 | 80.6 | 75.7 | 67 | 54 |
| Packing factor | 0.945 | 0.939 | 0.925 | 0.914 | 0.902 | 0.890 | 0.846 |
| Price for 150 mm SiC + epilayer [$] | 800 | 881 | 1126 | 1289 | 1615 | 2185 | 3000 |
| *Price per Amp ($/A) (50% Gross margin assumed)* | | | | | | | |
| Price ($/A) for 20 A max. | 0.046 | 0.061 | 0.131 | 0.203 | 0.399 | 0.960 | 2.744 |

microgrid to add or subtract assets on either side without any ripple effect.

Currently, AC to DC and DC to AC converters employ massive 50/60Hz transformers and silicon based power electronics. The size of these units is substantial – a typical 2MVA unit is the size of a huge shipping container.

The converters generally use low voltage Si IGBTs and require massive amounts of liquid cooling due to extremely high currents. Additionally, the switching frequency is usually low, resulting in large passive elements.

A good case for 10-15kV SiC MOSFET based AC-DC-AC converters can be made to replace the above mentioned converters resulting in a much reduced footprint and lower cost. The large 50/60 Hz transformers on either end can be eliminated with a high frequency transformer inside the SiC based converter providing the necessary galvanic isolation.

Smaller and cost competitive SiC based units will make it possible to proliferate asynchronous microgrids as we approach a goal of >50% penetration of renewables.

Once commercialized, these high-voltage SiC devices can also be used for medium voltage VSDs for large industrial motors, saving roughly 5% of end-use electricity in the U.S., provided 90% penetration can be achieved [8].

As the cost of WBG devices comes down to within 2x of Si, industry will be convinced of the benefits of WBG based power electronics as they utilize them in more applications. An expanding workforce comprised of skilled MS and PhD graduates able to utilize these devices in new energy efficient, high power dense systems will also be imperative in accelerating the adoption and establishing a WBG manufacturing base in the U.S.

It is predicted that the WBG industry could snowball into a billion dollar chip business and a $10B or more power electronics industry by 2020.

While bolstering U.S. semiconductor manufacturing is an important goal, the larger goal of realizing more global energy efficiency is achieved when worldwide adoption of WBG devices takes place. To this end, it is hoped that other countries will adopt similar models and adjust them in accordance with their prevailing economic conditions. To a large extent, this is already happening. No one country will eventually dominate the WBG industry. Rather, the hope is that the manufacture and the fruits of WBG technology will be somewhat evenly distributed around the world.

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