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Wide Band Gap Semiconductor Technology for Energy Efficiency

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Abstract. The attributes and benefits of wide-bandgap (WBG) semiconductors are rapidly becoming known, as their use in power electronics applications continues to gain industry acceptance. However, hurdles still exist in achieving widespread market acceptance, on a par with traditional silicon power devices. Primary challenges include reducing device costs and the expansion of a workforce trained in their use. The Department of Energy (DOE) is actively fostering development activities to expand application spaces, achieve acceptable cost reduction targets and grow the acceptance of WBG devices to realize DOEs core missions of more efficient energy generation, greenhouse gas reduction and energy security within the U.S. This paper discusses currently funded activities and application areas that are suitable for WBG introduction. A detailed cost roadmap for SiC device introduction is also presented.

Introduction

Emerging WBG semiconductor devices based on both silicon carbide (SiC) and gallium nitride (GaN) have the potential to revolutionize power electronics through faster switching speeds, lower losses, and higher blocking voltages, relative to standard silicon-based devices. Additionally, their attributes enable higher temperature operation yielding increased power density with reduced thermal management requirements. To date, the advantages demonstrated by WBG power electronics have yet to be fully realized due to their high costs, perceived reliability concerns, the availability of optimal packaging and drive electronics, and the lack of a workforce versed in their benefits and use.

Multiple applications can directly benefit from the intrinsic characteristics of WBG devices. A significant opportunity for SiC, with far reaching implications, relates to climate change. To combat the effects of global warming, it has become imperative to limit worldwide greenhouse gas emissions. Today, grid tied renewable energy offers an alternative approach to power generation but necessitates large energy storage requirements. *The development of high voltage silicon carbide semiconductors is seen as an enabling technology facilitating a focused movement towards expanding renewable energy sources with minimal storage.*

The U.S. Department of Energy (DOE) and the Clean Energy Manufacturing Innovation Institute, “PowerAmerica”, led by North Carolina State University (NCSU), are actively addressing issues relating to the market acceptance and deployment of WBG devices. The Institute, a collaborative effort between industry, universities and government laboratories, focuses on enabling and fostering the manufacture of cost competitive WBG semiconductors and growing the industry through the development of educational programs and training.

Work funded by DOE and ongoing efforts at the PowerAmerica Institute will be instrumental in achieving goals for more efficient, clean energy alternatives in the future.

Energy Perspective

Currently the U.S. mix of energy sources is primarily constituted by petroleum, natural gas, coal, and nuclear power with a relatively small mix of renewables (9%). It is predicted that the growth of renewable energy will occur at a fairly modest pace over the next few decades, expanding to possibly 18% by 2040, largely through increases in solar and wind power generation [1].

To counteract and reduce the occurrences of devastating climatic events, an even more aggressive scale up in renewable power is needed. However, accomplishing this with today's silicon based power electronics is problematic. In addition to being relatively slow, their use necessitates massive, cost prohibitive amounts of storage.

The maturation and implementation of cost competitive, high voltage SiC technologies coupled with high bandwidth smart inverters will be instrumental in growing the renewable energy base in the U.S. through new methods of grid control and regulation. The superior response times of SiC inverters can provide frequency and voltage control in sub cycle time increments, compensating for decreased inertia in the grid brought about by a higher penetration of renewable energy with minimal storage. [2, 3]

The higher efficiency of wide band gap based power electronics can further aid in directly decreasing the generation of greenhouse gases through insertion into other industries including industrial motor drives, and electric and hybrid vehicles. Their deployment in these sectors will harvest second order benefits by lowering overall system size and cost, accelerating their market growth.

Wide Band gap Device Application Areas

SiC and GaN devices are seen to have unique capabilities that can benefit different power electronics markets. GaN based electronics are optimally suited for 200-900V applications which include power supplies, laptop adapters, and micro and string solar inverters up to 10kW. SiC power device development is more mature with a variety of devices currently available in the marketplace. Power electronics based upon SiC semiconductors are suitable for applications that require 900-15kV unipolar devices. These can include high power string solar inverters as well as central solar and fuel cell inverters up to several megawatts. Advanced automotive inverters, quick chargers, power distribution in data servers and medium voltage variable speed drives (VSD) for high power motors are suitable applications, as well as the grid tied high bandwidth inverters and power flow controllers, previously mentioned.

Transportation. The abundance of light duty vehicles in the U.S. currently contributes to approximately 20% of CO_2 emissions and 70% of the nation's petroleum consumption. To address these issues rigid corporate CAFE standards have been enacted by the last two U.S Presidents. Currently the fleet economy standard for light duty vehicles and small trucks for 2025 has been set at 54.5 mpg [4]. It is projected that accomplishing this goal will result in ~4B barrels of oil and 2B metric tons of greenhouse gases being saved in the period between 2017-2025 [5]. Similar standards have been enacted in other countries in response to growing problems with pollution, available resource and health issues. It is seen that the partial or full electrification of vehicular drive trains will have significant implications on these numbers.

The use of wide band gap devices in power electronics in traction inverters, chargers and DC/DC converters can result in more efficient and smaller volume circuits requiring less cooling requirements. This in turn will reduce battery requirements through lower vehicle weight. It is estimated that for every 10% weight reduction in a vehicle a 6-7% gain can be achieved in fuel economy. [6]

Industrial Motor Drive Systems. The manufacturing sector in the United States is responsible for 12% of the Gross Domestic Product and employs 12 million Americans. Industrial electric motor systems are employed in a wide range of manufacturing applications including fans, pump, compressors, grinding mill, metal rolling, mine hoist and refineries. In 2013 the DOE Advanced

Manufacturing Office calculated that very large motors (greater than .075 MW) consumed approximately 59% of industrial energy use, even though they comprised only 2.8% of all industrial motors [6]. By replacing fixed speed motor systems, which rely on mechanical means to regulate their output (resulting in 30%-80% of wasted energy), with variable speed drives it is estimated that 3.3% to 8.9% of total U.S. electricity consumption can be saved. This scenario assumes a 90% deployment rate of VSDs [7].

By integrating high speed megawatt motors with drives based on SiC devices operating at increased frequencies, higher efficiency and power density can be realized. To promote the conversion to more efficient electric drives in U.S. manufacturing industries the DOE has begun funding work ($27 M over 3 years) in the development of medium voltage, high frequency motor drive systems using SiC devices. These efforts are targeted to reduce motor size by 5x, require less rare earth magnets, and develop SiC based variable speed drives that will result in an overall 30-80% energy savings per motor system.

DC Distribution in Data Centers. Data centers have been growing at a rate of 20% annually over the past decade. With increasing cloud computing and big data, it is expected that data centers alone will consume 10% of the total electricity by 2020. Currently the majority of data centers operate primarily off of a 12 V bus system internal to the rack. This introduces large i^2R copper losses. With the rapidly expanding need for data servers these inefficiencies have compounded and today represent significant levels of power consumption. It has been estimated that by improving the efficiency of power supplies in Information Technology (IT) equipment by 1%, 20 TWhr of energy can be saved. This corresponds to the equivalent of five nuclear power plants [8].

Systems can utilize higher voltages, such as proposed 380 VDC distribution systems, to achieve higher efficiency. By employing WBG semiconductors, losses can be further reduced and higher frequency operation enabled, resulting in simpler and significantly higher power density systems. It is anticipated that 5-10X power density improvement can be made over present silicon based systems through higher frequency operation using GaN devices in DC/DC converters and PFC circuits.

PowerAmerica

The formation of PowerAmerica was announced by President Obama in January of 2014 with budgeted funding for 5 years at $140M. The partnership is expanding rapidly and presently is comprised of members from multiple Universities, and National Laboratories as well as Industrial leaders involved in power electronics at the device, module and application levels.

The structure of the Institute revolves around five focus areas; 1) strategic development of WBG power electronics including road mapping activities, 2) implementation of a Fabless Foundry model for both GaN and SiC technologies, 3) the development and manufacture of low cost power modules, 4) demonstration of the benefits of WBG devices in various power applications, and 5) the education and training of students in WBG technologies.

The concept of the Fabless Foundry Model drives the Institute’s work in reducing the price of 1.2 kV WBG semiconductors to 10 cents/A, or lower within 5 years. This involves supplementing commercial 6” silicon foundries with the additional equipment necessary to manufacture WBG devices, thereby capitalizing on the foundry’s existing infrastructure, idle time and overhead costs. This model also provides a means for companies and institutions to combine their wafer and epilayer needs so that better prices can be negotiated from vendors through higher volume sales.

XFAB of Lubbock, Texas, a key member of the partnership, works within PowerAmerica to provide an open foundry; enabling companies, research laboratories and university groups the opportunity to develop SiC devices at reduced costs while expanding the WBG knowledge base.

Concurrent with the establishment of manufacturing capabilities multiple Institute partners are involved in device development and qualification activities. These include NCSU, USCi, NRL, CREE, ABB, UCSB, ASU, Monolith Semiconductor and Transphorm.

Cost Roadmap for WBG Devices. 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.

Referring to Fig. 1, a DMOSFET structure with a pitch of 5μm has been modeled. It has p^+ contact regions placed orthogonally to the n^+ contacts. This structure was modeled at various voltage ranges.

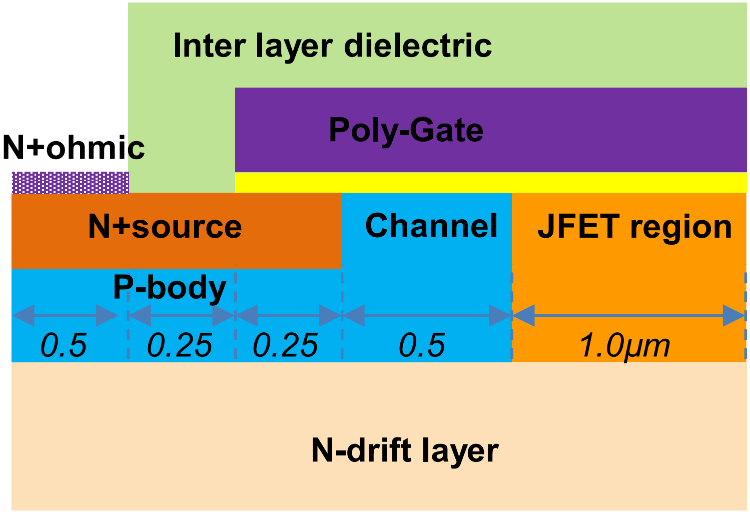

Fig. 1 Cross section of the MOSFET structure modeled.

The doping and drift layer thickness values are shown in Table 1 along with modeled values for specific on resistances. The average inversion layer mobility was assumed to be 20 $cm^2/V\cdot s$ and the substrate thickness 180 μm. The chip size was calculated for a maximum current rating of 20 A (junction temperature of 150°C) assuming a gate pad size of 0.4 mm^2, dicing lane of 50 μm and edge termination width of 5 times the drift-layer thickness. A 5 mm exclusion zone around the periphery of the wafer was assumed. The yield was calculated based on the simple Poisson's model (Eq. 1),

$$Y=Y_0e^{-DA}, \qquad (1)$$

Y_0 is the process yield (assumed to be 90%), D is the number of defects per cm^2 in the epilayer and A is the area of the chip in cm^2. A value of D=1 per cm^2 was assumed in these calculations. This number has been validated in recent years through experimental evidence from the best quality substrates and epilayers [9]. The exact value of D, of course, depends on the substrate and epi vendor. It is expected that with zero micropipe density wafers and minimizing the fall-down of Si particles during epitaxy, values of D below 1 cm^2 can be achieved in the future.

Assuming the cost of a 150 mm SiC substrate and epilayer, as shown in Table 1, a processing cost of $800/wafer production in a commercial silicon foundry (this can be reduced to $500/wafer in high volume, according to X-FAB), and adding a gross margin of 50% (price = 2x the cost), the projected price of SiC chips is shown in Table 1. The price for a 1.2 kV, 20 A SiC chip is calculated to be 4.6 cents/A, significantly below the PowerAmerica target of 10 cents/A. The 15 kV SiC chip is calculated to be priced at $2.74/A, assuming a yield of 54% and $3000 for the 150 mm substrate+epilayer.

If the industry can approach these numbers in 3-5 years then the device demand will grow exponentially across multiple applications. Furthermore, 200 mm SiC substrates, expected by 2020, will further reduce the cost of SiC MOSFETs. Other devices such as JFETs and BJTs. are expected to cost significantly less due to their superior on-resistance.

Table 1. Calculation of Price/Amp for 20A max rated SiC chips a different voltages in a high volume commercial 150 mm Si Foundry.

	1.2kV	1.7kV	3.3kV	4.5kV	6.5kV	10kV	15kV
Drift layer doping [cm^{-3}]	1×10^{16}	7×10^{15}	3×10^{15}	2×10^{15}	1.2×10^{15}	7×10^{14}	4×10^{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

Workforce Development and Training. Workforce development and training is a foundational leg of the Institute. Power electronics technicians and engineers have broad knowledge in the use of Si but the landscape of students graduating with experience in WBG semiconductors cannot support and promote the expected growth of the WBG market over the next 10 years. NCSU is reaching out to the broader academic community to develop innovative training materials to educate the next generation of power electronics students and instructors through the development of programs in both WBG technologies and their applications.

Recently, an additional initiative, funded at $5 M over 5 years, has been launched by DOE to expand training of university students in WBG technologies. It will provide stipends and tuition to directly support U.S. citizens at various domestic universities. The universities will be tasked with WBG curriculum development and providing hands-on training of graduate students in the applications and use of WBG devices.

Vertical GaN Power Devices. While SiC diodes and transistors have been in the market for some time lateral GaN on Si power devices are relatively new. Additionally, the development of vertical GaN device technologies on bulk GaN substrates is rapidly being scaled up to high currents. p-n junction diodes have reached 100 A DC current levels with 400 A pulse capabilities, while exhibiting low leakage currents at reverse bias voltages of 700 V. Smaller diodes, demonstrated earlier, have achieved blocking voltages of 3.7 kV and 2.6 kV at low resistances. In addition to ongoing work at Power America multiple teams are also working on vertical GaN transistors under the DOE ARPA-E (Advanced Research Projects Agency-Energy) SWITCHES (Strategies for Wide Bandgap, Inexpensive Transistors for Controlling High-Efficiency Systems) program, which began in 2013. The program goals are the achievement of 1200 V, 100 A diodes and transistors with 3 $m\Omega*cm^2$ resistance at V_{GS} = 15 V while also developing improved GaN substrates.

Summary

Capitalizing on the growing impetus for higher energy savings and reduced greenhouse gases, the market for WBG semiconductors could double every 2 years resulting in a $3B market within the next 10 years. DOE and PowerAmerica's activities towards reducing device costs through the commercial foundry approach while educating the next generation of power electronic students will be instrumental in enabling future global manufacturing and market opportunities.

Finally, the use of high frequency, high voltage SiC based smart inverters can facilitate dramatic increases in the growth of renewable sources of energy without the need for immense amounts of storage, leading to significant reductions of greenhouse gases in the foreseeable future.

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