Next Generation Power Electronics National Manufacturing Innovation Institute

President Obama announced in January that North Carolina State had been selected to lead one of the nation's most advanced research institutes. According to the White House, the Next Generation Power Electronics Innovation Institute is the first of three new manufacturing innovations institutes created to strengthen the US manufacturing sector, boost advanced manufacturing, and attract the good paying jobs that a growing middle class requires.

The institute is focused on enabling the next generation of energy-efficient, high-power electronic chips and devices by making wide band gap semiconductor technologies cost-competitive with current silicon-based power electronics in the next five years. These improvements will make power electronic devices like motors, consumer electronics, and devices that support our power grid faster, smaller, and more efficient.

DfR Solutions was selected to participate in the institute because of its leadership in the area of power electronics reliability and design in non-silicon based semiconductor devices. DfR Solutions will help develop robust, physics-based models for high power wide band gap (WBG) semiconductor devices and packaging. By incorporating these models into the Sherlock Automated Design Analysis™ tool, critical reliability data will be available to all members of the Innovation Institute. The ability to make physics-based reliability predictions before prototyping will allow manufacturers to streamline product introduction, even with the latest technologies.

Wide Band Gap Introduction

Although solid-state devices have replaced analog circuitry and vacuum electronics in the vast majority of amplifier systems over the past 30 years, the revolution is still not complete. The areas of high radio-frequency (RF) power for communications transmitter and high power switching applications remain untouched. Development of new solid-state devices that fall within these applications or combining multiple semiconductor materials together to operate at high temperatures are among the last frontiers in semiconductor electronics.

Wide-band gap semiconductor technologies have been evolving parallel to other active device technologies. Since the vacuum tube, solid state technologies have been under development to create faster, more powerful, and more reliable active devices. Initially developed in the late 1940s, germanium based devices were surpassed by gallium arsenide (GaAs) devices in the 1980s. Its time to commercial viability was less than that of vacuum tubes but was much longer than the mature development of silicon based devices. Like all advanced technologies, the time to develop and fine tune manufacturing processes drives large-scale commercialization of devices. Relatively inexpensive processes typically take the lead in production and mass distribution of devices, much like VHS taking the lead over BetaMax in the 1980s. This trend can be seen with silicon based devices as the forefront in semiconductor process technologies with its processing ability to scale down feature sizes in accordance to Moore's Law. The high breakdown voltage, high electron mobility and saturation velocity of wide band gap materials, most notably gallium nitride (GaN), has made them an ideal candidate for high power and high temperature applications.

As with the quick commercial viability of gallium arsenide, gallium nitride and silicon carbide are becoming realized as the next important impact in semiconductor technologies. While GaN is being used for low voltage applications, primarily for LEDs, its widespread use for medium to high voltage applications is being limited by the inability to produce large defect-free substrates, its poor thermal conductivity, and our inability to produce MOSFETs and IGBTs with it for power applications.

Material Characterization

In solid state physics, this band gap is the energy range in a solid where no electron state exists. Semiconductor materials have an electrical resistivity between that of a conductor and an insulator. In order for a semiconductor material to conduct electricity, electrons must gain a specific amount of energy (equivalent to its band gap) to jump from the valence band to the conduction band. Because band gap energy tends to decrease with increasing temperatures, semiconductors with smaller band gaps tend to become unstable at high temperatures. Unlike silicon which has a band gap of 1.2eV, wide band gap materials require more energy to initiate electron movement (gallium nitride requires 3.4eV). Therefore, in high temperature applications, wide band gap materials are less (if at all) susceptible to high temperature instability. Furthermore, they have larger thermal conductivity that allows the channel (conduction path) temperature to reach temperatures as high as 300°C. It is worth noting that silicon transistors stop working above 140°C.

Comparison of Wide Band Gap Materials

The following table shows the properties of silicon carbide (SiC) versus gallium nitride (GaN) with a discussion on the characteristics. Note that SiC comes in a variety of different crystal structures and only the common ones are shown.

Property	6H-SiC	4H-SiC	GaN
Band gap (eV)	3.03	3.26	3.45
Breakdown Field (KV/cm)	2500	2200	2000
Electron Mobility (cm^2/V-s)	500	1000	1250
Hole Mobility (cm^2/V-s)	101	115	850
Saturated E-Drift Velocity (10E7/cm)	2	2	2.2
Thermal Conductivity (W/cm-K)	4.9	4.9	1.3
Thermal Expansion (x10E-6/K)	3.8	4.2	5.6

- Band gap
  A higher band gap allows operation at a greater temperature. GaN shows an advantage in this area however the temperature limitation on devices is set by external means such as the package of the device and the system level packaging. For example SiC diodes can

operate > 200°C but they could be packaged in standard TO-220 which is limited to < 200°C.

- Breakdown Field
  A greater breakdown field is required for higher voltage devices. SiC has an advantage over GaN in this area but not significant. Either material would be a good choice for high voltage operation. The maximum operating voltage of the device will determine the minimum thickness of the material. However, along the die edge there could be dendritic growth of metals due to the high electric fields and this will also be a limiting factor.

- Mobility and Saturated Velocity
  The mobility of the holes and electrons determine the speed of the device at low fields. The higher numbers indicate a faster device and GaN excel in this area for RF applications. However, this is at low fields. The saturated velocity is the maximum velocity of the holes/electrons at high electric fields. This is the critical parameter determining speed of materials in switching applications whether its low power digital gates or high power switch devices like MOSFETs. GaN has only a slight advantage over SiC in this case.

- Thermal Conductivity
  The higher the thermal conductivity, the lower the thermal resistance and easier it is to bring heat out of the junction. This will directly affect R_{JC} (Thermal resistance from junction to case) which is an important parameter in power devices. Especially for high voltage devices where a thick Epi layer substrate for high voltage breakdown is used which can result in a high thermal resistance. From the chart, SiC is significantly better than GaN which would make SiC a superior semiconductor material for power applications.

- Thermal Expansion
  Thermal expansion can cause issues with die structure and packaging of the device. For example if the difference in thermal expansion is too great between materials like the substrate and oxide, there is a greater chance of cracking. Compared to other semiconductor materials, GaN is high.

Power Applications

Standard silicon semiconductor devices such as MOSFETs and BJTs designed for high frequency purposes are fundamentally limited in their RF power generation capability by a low breakdown voltage. Their relatively poor thermal conductivity makes it difficult to engineer a device for adequate thermal resistance. Typically, devices designed for high RF output power tend to operate at elevated temperatures, which in turn limits device performance. Power device designs use high currents which drive the need for devices with larger cross sectional areas. Larger cross sectional areas produce low impedance inputs which makes matching impedances quite difficult.

High power silicon MOSFETs have high on-resistance due to the trade-off characteristics between the on-resistance and its breakdown voltage. Therefore, a large chip area is required to minimize device conduction loss and increase the device capacitance. Gallium nitride high electron mobility transistors (HEMTs) on the other hand have a significantly less on-resistance. Therefore, the chip area can be greatly reduced while maintaining a low on-resistance and low device capacitance. As a result, the gate-driving frequency can be possibly 100x greater than silicon power MOSFETs.

Silicon Carbide is often used for power applications. Its advantages over silicon devices are it has superior thermal conductivity (4.9 W/cm-K over 1.5 W/cm-K) and approximately three times its band gap. However, there have been ongoing reliability issues with silicon carbide devices over the last three decades. Like SiC, gallium nitride has its own set of development issues, but it may prove to be a better solution for medium to high voltage applications.

GaN has two major issues when compared to SiC in power applications. The thermal conductivity with GaN is low compared to SiC and even to standard Silicon devices. This limits the devices to lower power applications than SiC. Another issue is that the native oxide processing has not been resolved for GaN power devices. Without an oxide, neither a MOSFET nor IGBT can be developed with GaN at this time. Only possible device is a JFET with a simple structure but the use will be limited. GaN does have a higher mobility and saturation velocity which allows it to be an excellent device for RF and optical applications. Reviewing papers and some manufacturer's websites, the focus for GaN is mainly on RF applications where a premium for the part can be charged for the extra boost in performance. Even if comparable SiC power devices were made with GaN, the cost will always be higher due to lower yield and more processing steps.

Device Structures

Wide band gap materials' unique properties allow the creation of new device types that are not possible with silicon alone. Alloying gallium nitride's material properties with those of similar semiconductors allow unique transistor types to be developed. Because of its unique attributes, gallium nitride is key for HEMTs in microwave power applications. It allows much greater switching frequencies that can switch high power circuitry. GaN HEMTs also have better noise performance than MESFETs. The end use scenarios for GaN devices include cell phones, base stations, high-performance military electronics (e.g., discrete device in hybrid assembly and in MMICs for power amplification) low noise receivers, and switching power supplies.

Apart from HEMTs, gallium nitride is also advantageous for use in other well established device types commonly manufactured using silicon processes. GaN-based diodes will enable the design and production of Switch Mode Power Supplies (SMPS) for computers, consumer applications, and industrial products that are smaller, more efficient, and lower cost. GaN HEMT WiMAX devices will provide critical size and energy benefits to amplifiers. Cree announced that their GaN HEMTs will help deliver a solution that is 25-percent smaller and at least twice as energy efficient as competing systems. Smaller, lighter and more efficient power amplifiers are now used more successfully in certain applications, such as airborne high-definition broadcasting, as a direct result. Amplifiers of this type are used in blimps and in aircraft that provide television broadcast feeds of *Sunday Night Football* on NBC. The key advantages offered by GaN technology for RF power electronics reside in the combination of higher output power density (even at high frequency), higher output impedance (easier matching), larger bandwidth and better linearity than other existing technologies.

Heterojunction bipolar transistors (HBT) offer several important advantages over FETs. HBTs generally have better threshold uniformity, better device linearity, and lower phase noise than FETs. In addition, the HBT structure inherently offers a higher ratio of output current to parasitic capacitance. Another important application for HBT is in high voltage switching applications where it may be desirable to switch high voltages at relatively high frequencies. The gallium nitride process also provides a stable substrate to create passive component structures. This ability will reduce the need for passives on package and reduce the interconnect layers.

Industry Limitations

Wide band gap devices could eliminate up to 90% of the power losses associated with converting between alternating and direct current (AC/DC). It can also handle voltages more than 10X of silicon devices and at more than twice the temperature. The limitation which make market insertion and industry acceptance difficult is the lack of guidance for accelerated testing and semiconductor reliability assessments. The importance of WBG device reliability testing is being vastly underestimated and overlooked. This task is not being done at the universities (an exception being the newly formed NC Institute) and is too costly for start-up and research and development firms to undertake. Without this data to bridge the gap between manufacturers and end users, OEMs cannot carry the technology forward.

The NC Institute may provide the support platform necessary where industry wide band gap development plans can be directly aligned across the supply chain and accelerated to market. The reliability issues and system benefits of WBG-based and Si-based applications can then be properly benchmarked and quantified. Once this information is generated, reliability metrics and benchmarking of cost-performance data points can be utilized to aid market adoption. The structure of the institute may enable the market to align product development specifications efficiently and provide duty cycle data points back into the database to better understand failure modes and root cause analysis. A standard could then be drafted for WBG device reliability testing.

Continued Discussion

DfR Solutions, in our support of the Next Generation Power Electronics Innovation Institute, will be sharing some of our experiences and knowledge on wide band gap and other semiconductor technology topics through a series of articles in our newsletter. These topics will include devices and device structures, conducting reliability assessments (physical, electrical, mechanical), failure mechanisms, designing and performing accelerated testing and technology applications. If you would like to read about a particular WBG or semiconductor topic, please email Ed Wyrwas (ewyrwas@dfrsolutions.com).