Si vs. GaN vs. SiC: Which process and supplier are best for my power design?

Steve Taranovich - March 15, 2013

As silicon (Si), gallium-nitride (GaN), and silicon-carbide (SiC) processes are maturing, so, too, are their suppliers’ expertise and creativity. It is worthwhile to examine the pros and cons of each process, as well as what is unique about the suppliers of the power elements fabricated on these processes. All of these components factor into the decision on the right solution for a particular design. That solution will be a culmination of process maturity and robustness, as well as supplier expertise, support, and capability—and even some intangibles.

GaN and SiC are wide-bandgap (WBG) materials, which means the energy required for an electron to jump from the top of the valence band to the bottom of the conduction band within the semiconductor is typically larger than one or two electron volts (eV). SiC and GaN semiconductors are also commonly referred to as compound semiconductors, because they comprise multiple elements from the periodic table. Si is a mature incumbent in this arena.

As the race toward leadership in the power element continues to evolve, industry experts have said that by mid-2013 about half a dozen GaN, Si, and SiC suppliers will reveal process enhancements, new architectures, and the latest new capabilities that will bring new choices and tools to the industry. We discuss some of these companies and technologies here.

**Efficient Power Conversion**

Efficient Power Conversion (EPC) started its GaN efforts five years ago and targeted markets with voltages of 200V and under. The company grows its GaN as an epitaxial layer on silicon.

The two-dimensional electron gas (2DEG) transport mechanism in GaN allows higher mobility of carriers in GaN than in SiC or Si. The 2DEG is on the surface and so lends itself to a lateral device structure; as a result, all of the terminals are located on top of the device.

A problem in existing devices is that the 2DEG in a normally on structure requires a negative voltage on the gate electrode to turn the device off (depletion mode). EPC understood that the power-conversion market would more naturally want to be normally off, so three years ago it developed enhancement-mode GaN (eGaN) devices that are manufactured in the same facility as silicon ICs (Figure 1).
SiC is also used to manufacture power transistors, but because SiC does not have an electron-gas structure, only vertical conduction devices are practical. With a vertical conduction device in GaN or SiC, 1- to 2-kV breakdown voltage levels are easier to reach than with Si. SiC requires an expensive fab, too, because existing Si fab processes are not compatible.

For the future, EPC has plans to go to 900V, which would require a vertical device structure. In that case, SiC has a better thermal conductivity than GaN. GaN, however, has the performance advantage at low voltage and high power and a cost advantage at all voltages. The company predicts the battle between SiC and GaN will begin at the 900V levels and move upward.

In the inverter market for photovoltaic (PV) panels, small to medium-sized inverters with one inverter per panel would ideally fit with EPC’s strategy of 900V or less. Higher-voltage devices would fit the central inverter market, which needs to connect a high number of panels together into a big, higher-voltage inverter. This architecture would cause cost and efficiency problems. If one PV panel fails, it would need to be removed from the system to avoid bringing down the entire unit, and efficiency would be lost. If the inverter is trying to convert a lower voltage to the grid-level voltages, however, efficiency would be lost in the inverter itself.

Differences in board space can be seen in a bus converter design for Si and eGaN (Figure 2). GaN transistors are extremely fast. As a result, the system is far more sensitive to the layout than it is with slower Si devices. In particular, stray inductance plays a larger role in the overall system efficiency. Hundreds of picohenries will significantly affect performance.
Stacked devices are better than bond-wire connections. GaN needs no package—it is inert to its environment—and so EPC uses a packageless design. This approach greatly reduces any resistive, inductive, and thermal problems. EPC plans to eventually integrate the driver into the FET.

Episil, EPC’s Taiwan-based CMOS foundry, uses 6-in. wafers. EPC plans to scale to 8-in. wafers in the years to come.

The entire process is compatible with silicon except for one machine, which grows the layers of GaN on Si. The metal organic chemical vapor deposition (MOCVD) epitaxial reactor was designed for blue LEDs and is therefore not optimized for eGaN FETs. This is the only step that is more expensive than a straight Si process, so, as the cost of growing epitaxial GaN decreases with improved MOCVD-equipment technology, cost differences compared with Si will become negligible and ultimately disappear.

**GaN systems**

In speed, temperature, and power handling, GaN is set to displace Si power devices as they reach their performance limits. GaN is the technology that will allow the implementation of essential future “cleantech” innovations, where power, weight, and volumetric efficiency are key requirements.

GaN devices offer five key characteristics: high dielectric strength, high operating temperature, high current density, high switching speed, and low on-resistance (Figure 3). These characteristics flow from its electrical properties, which, when compared with Si, offer 10 times higher electrical breakdown, higher operating temperature, and exceptional carrier mobility.
Figure 3 GaN has five key characteristics, which make it advantageous in power-supply and RF circuits (courtesy GaN Systems).

Taking advantage of these properties, GaN Systems has successfully developed transistors with a key switching figure of merit two orders of magnitude better than that attainable with silicon. This together with GaN’s inherent negligible charge storage permits the design of power switching circuits with formerly unheard of efficiencies, small size, and very low heat losses. Using a unique, proprietary, custom “island” transistor topology, the company has overcome the limitation of device operating current associated with traditional “finger” designs. This design approach is applicable to processes that grow a GaN epitaxial layer on base wafers of either SiC or Si. As a result, very low costs can be achieved for fast switches operating at 600V or below built on large-diameter silicon wafers, while operating voltages in excess of 1200V can be achieved using higher-cost SiC base wafers.

At operating voltages below 1200V, the vastly superior mutual conductance afforded by the electron gas that forms the channel of the GaN HEMT is responsible for the devices’ two orders of magnitude improved key figure of merit (the product of on-resistance and total gate charge).

SiC gate drives typically require a tightly controlled 20V swing. The island-design GaN devices can be driven with a 5V swing and present significantly lower gate capacitance. GaN-on-Si wafers cost perhaps one-tenth of SiC wafers while having up to four times the area. The GaN Systems island devices also occupy less than half the area of equivalent-performance MOSFET SiC die.

GaN Systems’ flip-chip approach to assembly—using copper posts—eliminates the inductance of traditional bond wires. This becomes important with the achievable switching speeds of some 40V per nanosecond. The scalable design topology and the elimination of large switch currents flowing in the on-chip metallization offer the prospect of transistors capable of switching hundreds of amps.

The design also allows packaging approaches for high-power applications that facilitate cooling from both faces of the chip. The GaN switches can be mounted directly onto a custom CMOS driver chip that offers a strong degree of noise immunity and galvanic isolation and can be simply assembled into power subsystem modules.
Cree

Cree is in a unique position in the industry in that it uses a GaN process for its RF devices and an SiC process for its power devices. Due to its in-depth knowledge and use of both processes, the company has made a conscious decision to use SiC for high voltages.

Cree’s target market for SiC power devices is 1200V and 1700V solutions, with 600V coming later. At higher voltages, SiC unipolar devices have an advantage over bipolar Si. The challenge at 600V is that Si has better performance, while Si CoolMOS and insulated-gate bipolar transistors (IGBTs) are lower cost.

The primary advantage of SiC MOSFETs is their very low switching losses, which increase efficiency and enable higher-frequency operation. In addition, the SiC MOSFET’s positive temperature coefficient allows easy paralleling to obtain higher operating currents.

SiC has been successfully tested at 10-kV levels. Cree targets future MOSFETs at around the 3.3- and 6.5-kV levels and at 10 kV. IGBTs have that market now, but SiC’s low switching losses would provide significant performance advantages. Even at frequencies below 4 kHz, SiC MOSFETs substantially reduce losses compared with IGBTs at these voltages.

Figure 4 All-SiC modules can eventually lead to higher integration in one process. The Cree module shown here measures 87.5×50 mm.

Cree’s goal is to go to 6-in. wafers from the current 4-in. and a die shrink for high current and 600V to 10 kV over the next few years to lower cost. The company will be able to do this on its existing 4-in. line and convert in situ with no process change. It already has a 6-in. separate LED line. Cree will fill its 4-in. line to capacity and then move to 6 in.—a good business decision. The wafers have already been sampled along with 6-in. EPI. All of the company’s tools are 6-in.-capable now, and all
processes are in-house for SiC.

Avago, Texas Instruments, and Ixys have driver ICs for their products. Cree feels that good layout and keeping the driver close to the power element will suffice for a good signal without ringing, even though it uses these types of separate Si drivers instead of integrated drivers like an Si MOSFET process can.

As for comparison with IGBTs, SiC MOSFETs’ figure of merit at 1200V is less than 20% of switching losses of an IGBT and less than 10% at 1700V. SiC switching losses are much lower than those of IGBTs; the conduction losses are lower, too. Cree’s 100A half-bridge module can replace a 200A IGBT and switch at two to three times the frequency with better efficiency (Figure 4).

The company’s case as to why SiC can replace Si: SiC is two times better than Si in terms of current and five times better in terms of frequency, with lower thermal losses.

As far as GaN is concerned, Cree has a 6-in. RF line now and is the number 1 supplier in switching. Knowing both SiC and GaN, it chose SiC for power, which is more efficient than Si or GaN. At the same current capability, the company’s SiC devices will be smaller than a GaN device.

**Texas Instruments**

Early in 2009, TI acquired Ciclon Semiconductor Device Corp, a maker of NexFET MOSFET technology. TI’s NexFET power switches are under 30V and synergistic with the company’s silicon MOSFET drivers and switching controllers (Figure 5). Having both types of devices on the same process allows for easier integration into a monolithic die containing driver and power elements. This setup eliminates any connection or bonding-wire parasitics that can cause ringing at higher-speed switching between a discrete driver and a power device whether they are on the same or a different process.

**Figure 5** Texas Instruments’ NexFET technology smoothly fits in power-management point-of-load applications.

Snubbers can be used to reduce ringing, but efficiency would be lost as a result. GaN switching devices certainly have attractive properties, especially above 10 MHz, except for the potential driver/power-device interconnect issues.
Packaging technology is an important part of TI’s NexFET solutions, giving them optimal performance. To optimize the performance of a typical voltage regulator, especially for CPUs, you need to minimize the parasitic inductances and resistances in the power circuit formed by the two MOSFETs in the buck power stage. TI accomplished both of these requirements through a unique packaging approach. To achieve a small footprint and the lowest parasitic possible, a stacking topology is used in the NexFET PowerStack package design. PowerStack reduces power consumption by approximately 20% (at 20A) and can reduce device temperatures by more than 30%.

In the GaN arena, TI offers GaN FET driver solutions such as the LM5114, a 7.6A single, low-side driver with independent source and sink outputs, and the LM5113, a 100V integrated half-bridge driver that solves the challenges of driving GaN power FETs. Compared with discrete implementations, these drivers provide significant PCB-area savings to achieve solid power density and efficiency while simplifying the task of reliably driving GaN FETs.

**Rohm Semiconductor**

Rohm Semiconductor’s MOSFET manufacturing involves the SiC bulk wafer, epitaxial growth, the power device, and, finally, the integrated power module. With its Japan-based corporate location, Rohm enjoys a solid relationship with the automotive industry. The company also offers a mature SiC Schottky barrier diode (SBD) line. The SiC SBD has 3% to 5% lower forward-voltage drop than Si SBDs.

The SiC MOSFET combines all three key desirable features of the ideal power-element switch (**Table 1**).

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<tr>
<th>TABLE 1 SWITCHING-DEVICE FEATURES</th>
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<tbody>
<tr>
<td><strong>SiC MOSFET</strong></td>
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<tr>
<td>Breakdown voltage</td>
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<tr>
<td>On-resistance</td>
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<tr>
<td>Switching speed</td>
</tr>
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Rohm’s MOSFET line, although relatively new, was expected to have a 1700V device in 1Q13 based on second-generation technology. By the end of 2013, the company plans to have packaging higher than its existing temperature devices, which are at 175°C. This allows operation at somewhat lower temperatures than 175°C without a heat sink.

Rohm feels it has the small-package advantage among its competitors, as well as modules that are optimized for performance (**Figure 6**).
Figure 6 An all-SiC module greatly reduces power losses by eliminating any Si lossy components (courtesy Rohm Semiconductor).

Microsemi

Microsemi uses the technology customers feel will optimize their designs—Si, SiC, or GaN—from processes performed in-house as well as at outside foundries. It is just getting started with GaN from 40 to 200V for space and high reliability.

GaN is a defect-laden material as compared with SiC and Si, but the company uses the technology of growing GaN on SiC, which minimizes defects. It can reach 1200V on SiC vs. Si and with better efficiency.

Microsemi targets high-temperature applications with its solutions that have the advantages of not needing a heat sink, such as their use in “downhole” applications and in engines where temperature cycling would likely cause major mechanical failures with most processes (Figure 7).

Figure 7 In this chart showing semiconductor materials and frequency regions, the green box outlines Microsemi’s application space.
International Rectifier IR’s goal is to target the 20 to 1200V market with better switch on-resistance vs. the V rating of the device to get lower resistance in a smaller package. The figure of merit, based on switch on-resistance, is dramatically improved in the power device, depending on the process and breakdown voltage (Figure 8). Keeping an eye on a good performance/cost ratio compared with Si is key.

Figure 8 Figure of merit, based on switch on-resistance, is dramatically improved in the power device, depending on the process and breakdown voltage (courtesy IR).

The company believes that GaN on Si is better than SiC to compete with pure-Si devices. It has in-house processes for Si and GaN and uses the technology of growing GaN as well as hetero epitaxial GaN on Si.

While MOSFET drain-to-source on-resistance is a focus, keeping in mind lower cost, higher efficiency, and better density—or a combination of these characteristics—is also important. GaN devices’ value proposition in the power-management chain is evident, as shown in Figure 9.

Figure 9 GaN has a good value proposition in the power-management chain because it can be used throughout the design, adding performance improvements (courtesy IR).
Class D audio with GaN at higher frequencies gives better noise and harmonic distortion, and the same is true for a power switch.

IR believes that SiC is great at 1500V and above, compared with Si, especially in applications such as electric trains and PV inverters.

A market exists for GaN in automobiles and computer power supplies. IR says early adopters are low-end consumer designs such as class D audio and power supplies, and the design-in time is 18 to 24 months. This is a good near-term market. The five- to seven-year auto- and medical-market cycle is another promising area as the company’s product matures.

There are far more selection criteria than what appears in a data sheet or in a simple comparison of Si, GaN, and SiC processes. Consider every aspect of both the supplier and the process, as well as other intangibles, such as experience with and longevity of the process, unique configurations, and synergy with other parts of the system design. Delve deeply into all that is available in this power-element industry that most designers would not consider, and your design will be unique, robust, and the best fit possible for the system’s overall needs.