Can Gallium Nitride Replace Silicon?

For the past three decades, Silicon-based power management efficiency and cost have shown steady improvement. In the last few years, however, the rate of improvement has slowed as the Silicon power MOSFET has asymptotically approached its theoretical bounds. Gallium Nitride grown on top of a silicon substrate could displace Silicon across a significant portion of the power management market.

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Power MOSFETs appeared in 1976 as alternatives to bipolar transistors. These majority carrier devices were faster, more rugged, and had higher current gain than their minority-carrier counterparts. As a result, switching power conversion became a commercial reality. AC/DC switching power supplies for early desktop computers were among the earliest volume consumers of power MOSFETs, followed by variable speed motor drives, fluorescent lights, or DC/DC converters.

Many generations of power MOSFETs have been developed by several manufacturers over the years. There are still improvements to be made. For example, Superjunction devices and IGBTs have achieved conductivity improvements beyond the theoretical limits of a simple vertical majority carrier MOSFET. These innovations may still continue for quite some time and will certainly be able to leverage the low cost structure of the power MOSFET and the well-educated base of designers.

Start of GaN in power electronics

HEMT (High Electron Mobility Transistor) GaN transistors appeared in 2004 with depletion-mode RF transistors made by Eudyna Corp. in Japan. Using GaN on Silicon Carbide substrates, Eudyna designed such transistors for the RF market. The HEMT structure demonstrated unusually high electron mobility near the interface between an AlGaN and GaN heterostructure interface. Adapting this phenomenon to Gallium Nitride grown on Silicon Carbide, Eudyna was able to produce benchmark power gain in the multi-gigahertz frequency range. In 2005, Nitronex Corp. introduced the first depletion mode RF HEMT transistor made with GaN on Silicon wafers.

GaN RF transistors have continued to make inroads in RF applications as several other companies have entered in the market. Acceptance outside this market, however, has been limited by device cost as well as the inconvenience of depletion mode operation.

In June 2009 Efficient Power Conversion Corp. (EPC) introduced its first enhancement-mode GaN on Silicon designed specifically as power MOSFET replacements. These products were designed to be produced in high-volume at low cost using standard Silicon manufacturing technology and facilities. The structure is relatively simple as shown in Figure 1. Figure 2 shows a size comparison between Silicon devices and GaN devices rated at 200V.

The new generation of enhancement mode GaN transistor is very similar in its behaviour to existing power MOSFETs and therefore users can greatly leverage their past design experience. Two key areas stand out as requiring special attention: relatively low gate dielectric strength (and finite gate leakage on the order of µA per mm of gate width) and relatively high frequency response.

The first of these two differences, relatively low gate dielectric strength, will be improved as the technology matures. In the mean time, measures need to be taken to eliminate workplace ESD and to design circuits that maintain the gate-to-source voltage below the maximum limits in the data sheet. The second difference, relatively high frequency response, is both a step function improvement over any prior silicon devices, and an added consideration for the user when laying out circuits. For example, small amounts of stray parasitic inductance can cause large overshoot in the gate-to-source voltage that could potentially damage devices.

On the other hand, there are several characteristics that render these devices easier to use than their silicon predecessors. For example, the threshold voltage is

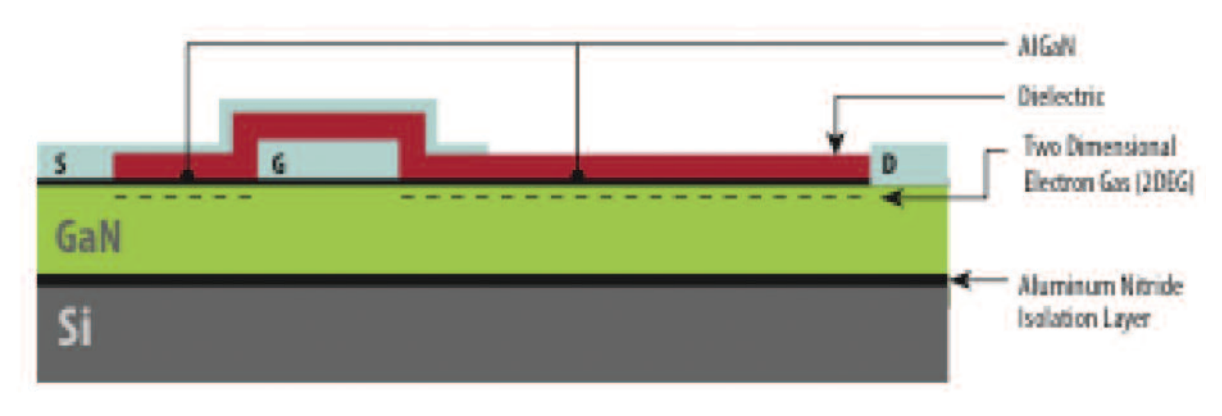

Figure 1: **GaN on Silicon devices have a very simple structure similar to a lateral DMOS and can be processed in a standard CMOS foundry**

Figure 2: Size comparison between Silicon devices and GaN devices rated at 200V

virtually independent of temperature over a wide range, and the on-resistance has a significantly lower temperature coefficient than silicon. GaN transistors are also able to operate at temperatures as high as 300°C, but solder connections to the printed circuit boad prevent practical application much above 125°C. The first commercial enhancement mode parts are therefore characterised up to 125°C.

New capabilities by GaN power transistors

In power MOSFETs there is a basic trade-off between the conductivity and the amount of charge required to switch the device. From this trade-off comes the figure of merit (FOM) called RQ product. This is defined as a device's on-resistance multiplied by the total charge that must be supplied to the gate to switch the device at operating voltage and current. Improvements in this product have been shown to translate into improved conversion efficiency in high frequency DC/DC converters. The absolute value of RQ is also indicative of the minimum pulse widths achievable in a practical circuit. Whereas there have been great improvements in RQ product, Silicon cannot come close to the FOM achieved in first-generation enhancement HEMT (eHEMT) devices already on the market.

The ability to switch quickly and with low power loss means users can go to much lower pulse widths in power conversion circuits. One significant new application needing this capability is non-isolated DC-DC converters. The basic limitation of Silicon power MOSFETs has restricted single-stage, non-isolated buck converters to a practical maximum ratio of input voltage to output voltage of 10:1. Beyond that ratio, the short pulse widths required of the top transistor in the buck circuit result in unacceptably high switching losses and consequently low conversion efficiency. GaN transistors reset this performance bar as indicated in Figure 3.

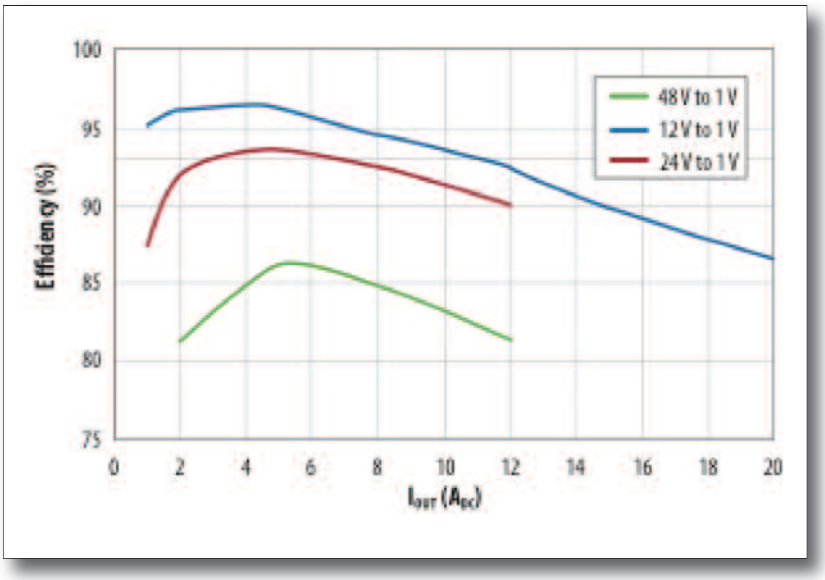

Figure 3: Buck converter efficiency vs current for various input voltages using a single 100V EPC1001 both as the top and bottom transistor

In addition to the added V_{IN}/V_{OUT} range made possible by GaN, existing buck converters can greatly reduce switching losses. AC/DC conversion, synchronous rectification, and power factor correction (PFC) are all candidates for major performance improvement as new GaN transistors rapidly cover the current and voltage range of today's power MOSFETs and IGBTs.

User-friendly tools can also make a big difference in how easy it is to apply a new type of device. EPC has developed a set of TSPICE device models available for download. Figure 4 shows a simple circuit and the comparison between actual device performance and the simulated result using the TSPICE model. Whereas more work refining these models needs to be done, the first-generation should provide reasonably reliable circuit performance predictions.

GaN on Silicon processes

GaN on Silicon wafers are produced typically on 150mm substrates (future products will migrate to 200mm) whereas power MOSFETs are produced on anything from 100mm through 200mm substrates by the many manufacturers. Because the GaN devices use standard silicon substrates, there is no cost penalty compared with power MOSFETs fabricated on similar diameter starting material. In fact, there is little cost difference per unit area between 150mm and 200mm silicon wafers and therefore we can conclude that, as far as starting material is concerned, there is no true cost difference per wafer. Taking into account the fact that the GaN device has less device area than a Silicon device with similar current-carrying capability, then the cost per function is lower for GaN.

Silicon epitaxial growth is a mature technology with many companies making highly efficient and automated machines. MOCVD GaN equipment is available from at least two sources, Veeco in the US and Aixtron in Germany. Both make capable and reliable machines whose primary use has been the growth of GaN epitaxy used in the fabrication of LEDs. None of the machines are optimised for GaN on Silicon epitaxy, nor do they have levels of automation that are common on Silicon machines. As a result, GaN epitaxy on Silicon is significantly more expensive than Silicon epitaxy today. But this is not fundamental. Processing times and temperatures, wafer diameter, materials costs, and machine productivity are all on a fast track of improvement with no

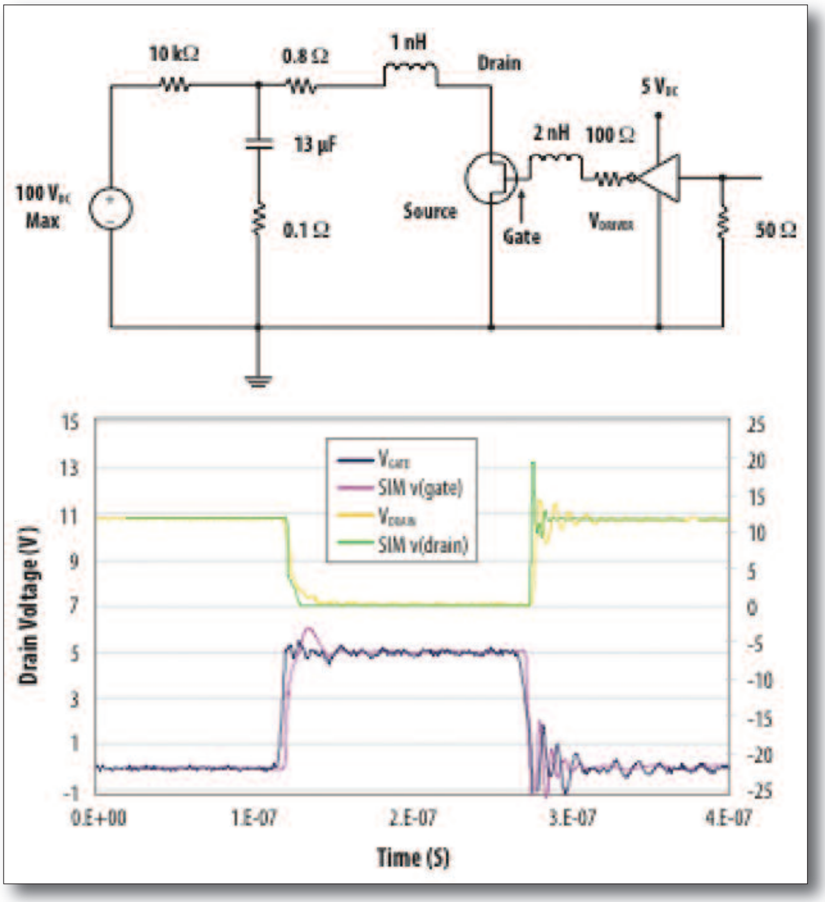

Figure 4: Circuit diagram and oscillogram comparing EPC1001 TSPICE simulation results with actual measured circuit performance

fundamental limit far away from Silicon limits. Within the next few years, assuming widespread adoption of GaN, it is expected that the cost of the GaN epitaxy will approach that of Silicon epitaxy.

The simple structure depicted in Figure 1 is not complicated to build in a standard Silicon wafer fab. Processing temperatures are similar to Silicon CMOS, and cross contamination can easily be managed. Today, EPC processes all their wafers in Episil Inc., a well-established foundry in Taiwan.

In the assembly process there are significant differences favouring the cost structure of GaN on Silicon devices whereas the testing costs are equivalent.

Silicon power MOSFETs need a surrounding package typically made of a copper leadframe, some aluminum, gold, or copper wires, all in a molded epoxy envelope. Connections need to be made to the top and bottom of the vertical silicon device, the plastic molding is needed to keep moisture from penetrating to the active device, and there needs to be a means of getting the heat out of the part. Establishedl power MOSFET packages such as the SO8, TO220, or DPAK add cost, electrical and thermal resistance, and increase reliability and quality risks to the product. GaN on Silicon can be used as a "flip chip" without compromise of electrical, thermal, or reliability characteristics.

Referring to Figure 5 it can be seen that the active device region is isolated from the Silicon substrate much like a Silicon-on-Sapphire device. As a result, the active GaN device can be completely encapsulated by passivating layers. In addition, the Silicon substrate can be directly attached to a heatsink for excellent thermal performance.

In short, GaN on Silicon eliminates the need for a package and therefore also reduces cost, wasted board space, added thermal and electrical resistance, and the most common reliability issues plaguing packaged power devices.

Is GaN reliable?

The cumulative reliability information available on Silicon power MOSFETs is staggering. Many years of work have gone into understanding failure mechanisms, controlling and refining processes, and designing products that have distinguished themselves as the highly-reliable backbone of any power conversion system. GaN on Silicon are just beginning this journey. Preliminary results, however, are encouraging. As of the date of this writing, EPC has established the basic capability of enhancement mode GaN on Silicon. A full reliability report with greater statistics is expected to be published later in March 2010.

Future directions

There are profound improvements that can be made in basic device performance as measured by the RQ figure of merit. As we learn more about the material and the process, a factor of 2 improvement can be reasonably expected over the next three years and a factor of 10 over the next ten years. We can also expect devices to emerge with much higher breakdown voltage in the near future as EPC plans to introduce 600 V devices in the second half of 2010 and other companies have discussed openly their intentions in this area. Higher voltages for GaN transistors with undoubtedly follow.

Perhaps the greatest opportunity for GaN to impact the performance of power

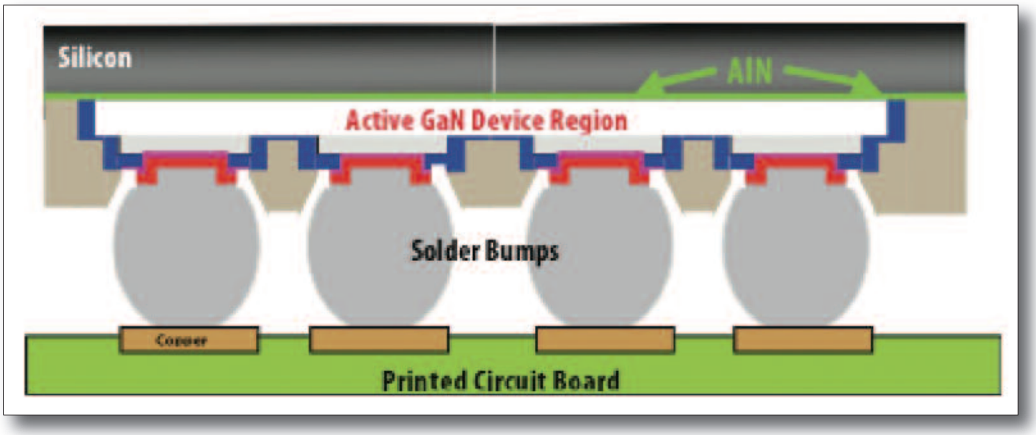

Figure 5: GaN on Silicon can be used as a "flip chip" where the active device is isolated from the silicon substrate and can be completely encapsulated prior to singulation

Figure 6: Power transistor with on-board drivers

conversion systems comes from the intrinsic ability to integrate both power-level and signal-level devices on the same substrate. GaN on Silicon, much like SOI, has no significant parasitic interaction between components, allowing designers to easily develop monolithic power systems on a single chip. Figure 6 shows a power transistor with on-board drivers from EPC.

Conclusion

In the late 1970's the pioneers in the development of power MOSFETs believed they had a technology that would displace bipolar transistors completely. Thirty years later, we still have plenty of applications that prefer bipolar transistors over power MOSFETs but the size of the power MOSFET market is many times larger than the bipolar market largely due to all the new applications and new markets enabled by that breakthrough technology.

Today, we are at that same threshold with enhancement mode GaN on Silicon. Like the power MOSFET of 1976, we are beginning an exciting journey with new products and breakthrough capabilities almost monthly. The power MOSFET is not dead, but is nearing the end of the road of major improvements in performance and cost. GaN will most probably become the dominant technology over the next decade due to its large advantages in both performance and cost; advantage gaps that promise to widen as we quickly climb the learning curve.

Literature

Alex Lidow PhD, CEO, Efficient Power Conversion Corporation, El Segundo, USA. Is it the End of the Road for Silicon in Power Conversion? Keynote of CIPS 2010, March 16 - 18, Nuremberg, Germany

EPC launches 40V to 200V EM GaN Power Transistors

EPC's enhancement mode (normally-off) GaN technology was explicitly developed to replace power MOSFETs. The products are produced in a standard silicon CMOS foundry on 150mm (6 inch) Silicon wafers. The use of this low-cost infrastructure has allowed to price the initial product offerings aggressively in order to accelerate the conversion from silicon power MOSFETs.

Spanning a range of 40V to 200V, and 4mΩ to 100mΩ, these power transistors have significant performance advantages over Silicon-based power MOSFETs. Applications that can benefit are DC/DC power supplies, point-of-load converters, class D audio amplifiers, notebook and netbook computers, LED drive circuits, telecom base stations, and cell phones, to name just a few. "Our GaN-on-Silicon power transistors represent a major breakthrough in power conversion technology since the development of the commercial power MOSFET. We have developed a very cost effective and reliable technology that is also very easy for anyone with power MOSFET experience to use in a way that will significantly boost their power management system performance", commented Alex Lidow, EPC's co-founder and CEO.

Established in 2007, EPC is a fabless company with subcontract manufacturing in Taiwan. EPC's key markets include voltage controllers, LED boost converters, power MOSFET and IGBT replacements, drivers, power amplifiers and RF MOSFETs. EPC's founders are committed to developing GaN products to be used as cost-effective Silicon product replacements. EPC's products for applications requiring 200V or less are available for purchase on Digi-Key's global websites. Additionally, these parts will be featured in future print and online catalogs. "Digi-Key has the fastest global logistics and the most efficient supply chain of any distributor with which I have worked over the last 30 years", Lidow said. "This will translate into fast and easy service to our global customer base who want to replace their power MOSFETs". "EPC's GaN-based power management products bring intriguing next-generation breakthrough benefits to existing MOSFET and Bipolar solutions, we are thrilled to be the first to offer these innovative products to the engineering community", said Dave Doherty, Digi-Key's VP of semiconductor product.

The product is priced between $0.80 and $5.00 in 1k quantities and can be ordered at http://digikey.com/Suppliers/us/Efficient-Power-Conversion.page?lang=en