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GaN Based Power Technology Stimulates Revolution in Conversion Electronics

Solution size can shrink by half due to reduced passives count and use of smaller inductors

Envisioning a need for a change in paradigm, IR scientists have developed a ground-breaking gallium nitride (GaN) based power device technology platform that promises to deliver figure of merit (FOM) performance that is at least an order of magnitude better than the current state-of-the-art silicon MOSFETs. Commercially viable, the GaN based power devices will enable solutions that are poised to start a revolution in high density, highly efficient cost effective power conversion technology.

By Tim McDonald, Vice President, Emerging Technologies Group, International Rectifier, El Segundo, Calif.

Before the introduction of power MOSFETs, bipolar transistors were a dominant player in power electronics, and linear supplies reigned the power supply world. However, the launch of the first commercially available silicon MOSFETs (including IR's trademarked HEXFETs), over 30 years ago sparked a new trend in power electronics. Power MOSFETs facilitated rapid adoption of switch mode power supplies making them smaller, lighter and more efficient. Since then MOSFETs have become the power device of choice for many applications. Through the intervening decades, MOSFETs have continued to evolve. From planar HEXFETs to TrenchFETs and superjunction FETs, silicon MOSFETs have made dramatic improvement in figures of merit (FOMs) to effectively serve a variety of applications, as depicted in Figure 1.

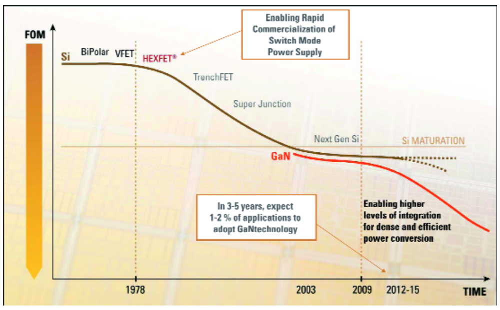

Figure 1. From HEXFETs to TrenchFETs and SJ FETs, Si based power MOSFETs have evolved over three decades to find wide use in the power supply market. But, now the Si based power MOSFET has approached maturity.

More recently MOSFETs have started reaching a performance plateau. As can be seen in Figure 1, the silicon power transistor has approached maturity. Squeezing incremental improvement out of silicon power FETs will cost more and return less.

To meet ever increasing market needs in POWER MOSFET's, IR has developed GaNpowIR™, a revolutionary gallium nitride (GaN) based power device technology platform that promises to deliver performance FOMs ten times better than the existing state-of-the-art silicon devices and has broad potential in a wide variety applications. Similar to the Si Power MOSFET some three decades ago, IR's proprietary gallium nitride-on-silicon (GaN-on-Si) epitaxial process and device fabrication technology herald a new era in high frequency, high density, and cost effective power conversion solutions.

GaNpowIR Technology: A Commercializable Platform

Use of GaN for power applications requires that a substrate is chosen on which to grow the GaN layers. Bulk GaN, SiC and Sapphire wafers all suffer from a mix of drawbacks in cost, volume availability or size. While silicon was an attractive low cost alternative substrate, it remained difficult because of defect formation and strain. Due to intrinsic mismatch in lattice constants and thermal expansion coefficients between the substrate and the epitaxial films, accomplishing reliable, quality GaN-on-Si hetero-epitaxial process has not been an easy path. Significant engineering went into creating a controlled process and methodology to address these problems. Subsequently, the result is an epitaxial film low in defect level and high in uniformity and device reliability. IR's GaNpowIR platform features high volume deposition of GaN based material on low cost 150mm diameter silicon wafers.

Manufacturing cost associated with wafer fabrication is another potential hurdle to commercial viability for GaN. Prior work with GaN has featured expensive process steps such as gold deposition or operations that do not lend themselves to automation. GaNpowIR was developed to run on a standard CMOS line. In addition to lower costs this assures the process can scale well to volume supply. Besides ensuring a better performance/cost ratio with volume supply for commercial applications, the GaNpowIR platform is designed to meet industry standards for quality and robustness. Extensive intrinsic reliability testing has been done and continues in order to characterize failure modes of GaN based power devices. Together with traditional product qualification testing this assures that IR's GaNpowIR devices will operate reliably for their designed useful lifetime.

First production release is planned for the year-end. The first released product will be an integrated package DC-DC power stage using 30V rated GaN transistors designed for applications that buck from a typical 12V down to 1V or lower. Devices featuring higher voltage ratings will be released in 2010 and beyond.

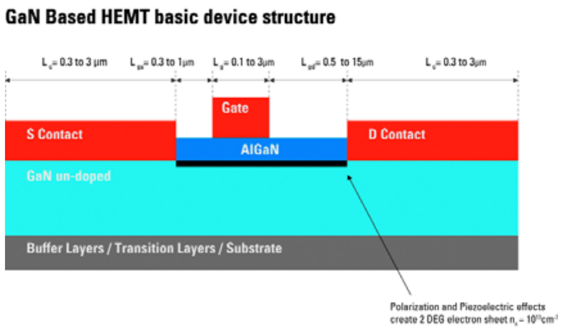

Figure 2. Rudimentary cross section of a GaN-on-Si based high electron mobility transistor (HEMT) structure.

As illustrated in Figure 2, the basic GaN-on-Si device structure is a high electron mobility transistor (HEMT), based on the presence of a two dimensional electron gas (2DEG) spontaneously formed by the intimacy of a thin layer of AlGaN on a high quality GaN surface. Since this device structure is a HFET with a high electron mobility channel which conducts in the absence of applied voltage, the GaN based HEMT is normally-on.

Benefits of GaN-on-Si

A combination of high conduction electron density, high electron mobility and higher bandgap enables the GaN based power HEMT to offer a significant reduction in the device specific on-resistance for a given reverse voltage capability. As shown in the calculated material limit curves for Si, SiC and GaN in Figure 3 at any voltage rating, the specific on resistance for GaN is orders of magnitude smaller than for Si or SiC. After 30 years of development, Si MOSFETs are at, or approaching this physical limit except for cases such as Superjunction FETs or IGBTs that compromise switching performance and process complexity (cost) for lower FOM. More recently SiC based power FET performance figures have been published in the literature. These are seen to offer improved specific on resistance to Si, yet there is room for additional improvement. GaN based FET published performance likewise is now seen to be improved over Si yet there is very substantial future improvement yet to be realized before approaching the material limits. If the cost of production is low enough then a favorable ratio of performance/cost will start driving adoption of GaN over Si based Power MOSFETs. It is precisely to this end that IR's GaNpowIR platform was developed. The measure of performance can be any of several Figures of Merit that can be chosen for their relevancy in each application.

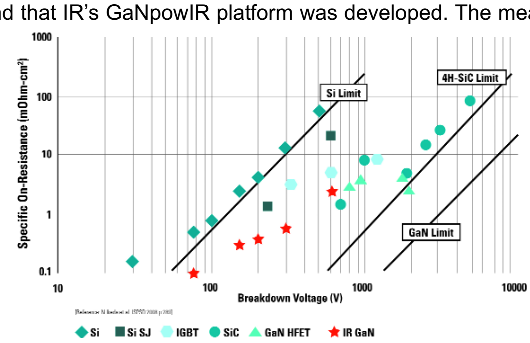

Figure 3. Plotting Specific On Resistance FOM vs reverse voltage rating, calculated material limits for Si , SiC and GaN show orders of magnitude improvement potential for GaN. Performance of GaN based FETs today exceeds silicon but the gap will increase as GaN FETs are further developed.

Realizing the Value

A simple Power Stage value proposition can be defined as efficiency*density/cost. This expression encompasses the well known trade off that must be made between the 3 constituent factors. At any point in time, this value proposition is driven to a large measure by the performance of the best available power device. Consequently, new devices (such as GaNpowIR), with dramatic improvement in R*Qg but only incremental cost increase, result in revolutionary levels of efficiency, density , cost or any tradeoff between the three. Following are some examples of the density and efficiency improvements that GaNpowIR enables.

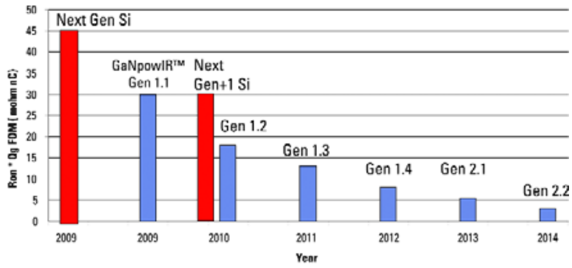

*Figure 4. Ongoing refinements promise a 10x reduction in RDS(on)*Qg FOM for 30 V GaN-on-Si based power devices within five years of introduction of GaNpowIR platform.*

As mentioned, GaN based power devices realize a significant drop in gate charge, Qg. Device switching FOM R_{DS}(on)*Qg is much lower than for silicon. Simulated results presented in Figure 4 project continuous improvements in R*Qg FOM for low voltage (30V) GaN power devices. Based on data from prototypes and planned improvements, the first generation GaN-on-Si based HEMTs will deliver about 33% improvement in RQ FOM over the state-of-the-art silicon MOSFETs. By 2014, this FOM performance is expected to be less than 5 m Ω-nC, an order of magnitude better than next generation MOSFETs.

What does this mean for density of a specific application? Figure 5 shows an application improvement roadmap that parallels GaN improvement (portrayed in Figure 4) for the case of microprocessor voltage regulation solutions for servers. Shown are the solution footprint and efficiency for an example case providing 100A, converting from 12V:1.2V. IN 2007, the best then available silicon based solutions allowed a solution size of 1.4 square inches at 85% efficiency. GaNpowIR power stage capability late this year will make it possible

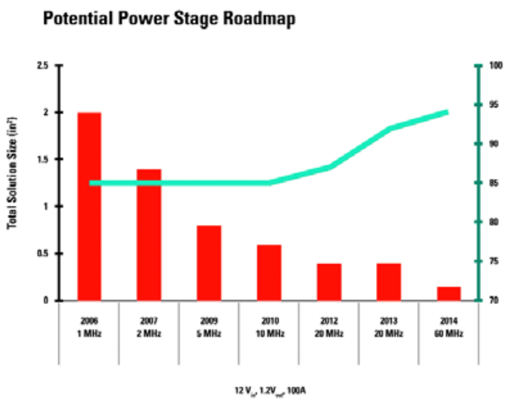

Figure 5. This GaN power stage roadmap illustrates the impact of the improvements shown in figure 6 on the size and power conversion efficiency of a multiphase 100 A, 12 V to 1.2 V DC-DC converter.

to raise frequency to 5 MHz while holding efficiency constant. This means solution size can shrink by half due to reduced passives count and use of smaller inductors enabled by the higher frequency operation. Through 2011 projected improvements in GaN will allow solution size to shrink further while holding efficiency constant. Starting 2012 the improvements in GaN will allow use of high enough frequency that the solution can be moved closer to the load, culminating in 2014 with a copackaging of Microprocessor and buck converter. As the regulator is located closer to the load, system parasitic losses (inductor, load line, etc) reduce dramatically. Though converter efficiency is held constant at 85%, overall system efficiency increases (due lower parasitic losses). Overall, improvements in GaNpowIR are projected to enable almost tenfold total solution size shrink.

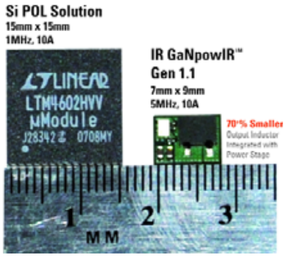

Figure 6. Featuring a GaN based Power Stage, IR's prototype 10 A POL converter operates at 5 MHz to deliver efficiency that is comparable to today's silicon solution switching at 1 MHz, but at less than one-third the size.

To test new levels of power conversion density without loss of efficiency, IR has developed and demonstrated a prototype 5 MHz point-of-load (POL) converter featuring a GaN based power stage. This module is designed for a 12 V input and 1.8 V (typical) output at 10 A load current. Switching at 5 MHz, this GaN based POL module delivers efficiency that is higher than for today's typical commercial solution but at less than one third the size. (See Figure 6). Occupying a 7x 9 mm footprint, this fully functional GaN based 5 MHz module demonstrated 86.5% efficiency at 10 A load.

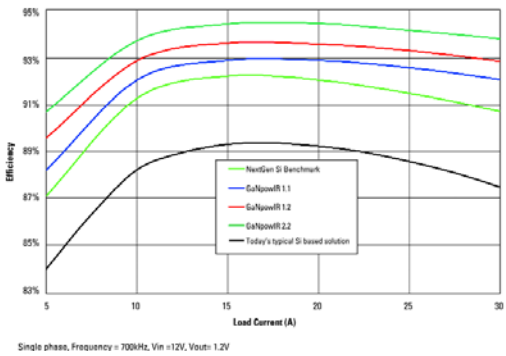

Figure 7. GaNpowIR enables dramatically higher efficiency in sync buck voltage regulator applications such as Notebook computers, Servers, DDR miscellaneous Point of Load converters. The result is reduced electricity cost and a greener planet.

As mentioned, GaNpowIR delivers new levels of power conversion efficiency. Figure 7 shows improvements in 12V: 1.2V buck conversion efficiency that GaN enables relative to today's silicon solution. For a single phase buck converter the GaNpowIR R*Qg improvement roadmap of Figure 4 translates in 2009 to >3% improvement in peak efficiency over today's typical silicon based solution. With projected improvements GaNpowIR will deliver 94.5% efficiency within 5 years. This is 5% improvement over today's solution. In applications such as Enterprise Power this represents a huge reduction in system operating cost (due less electricity usage and cooling load) and is a significant carbon footprint reduction.

GaNpowIR will also revolutionize power conversion at higher voltages. A combination of measured and projected results for a 200V rated GaN device in a 5 x 6 mm package shows that Rds(on) will initially be up to 3 x lower than silicon based FET's while ongoing improvements in GaN technology should result in an order of magnitude improvement within 5 years. As depicted in Figure 8 these results suggest that by 2014, the R_{DS}(on) for a 200 V GaN switch in a 5 x 6 mm package will be less than 5 mΩ which can be compared with 50 mOhm for today's similarly constrained Silicon power MOSFET.

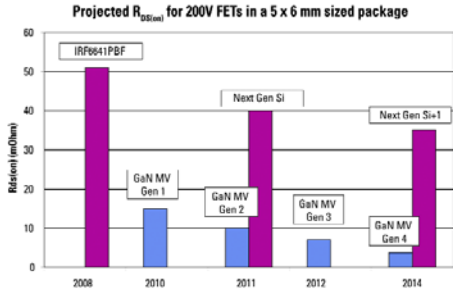

Figure 8. By 2014, the RDS(on) for a 200 V GaN-on-Si based HEMT will be less than 5 mΩ, an order of magnitude better than today's silicon MOSFETs.

At even higher voltages IR has demonstrated GaN based rectifiers that rival SiC in reverse recovery behavior. Figure 9 shows that the low reverse recovery characteristics (Irr) for both GaN and SiC diodes are identical, and both are much lower than state-of-the-art 600V ultrafast silcon diodes. The low reverse recovery current (Irr) is essentially due to the absence of minority carriers. The result is a fast and quiet switching behavior of GaN, which eliminates or greatly reduces otherwise needed filtering circuitry. GaN based diodes cost much less to produce than SiC diodes due to the cost effectiveness of the GaN on Si GaNpowIR platform.

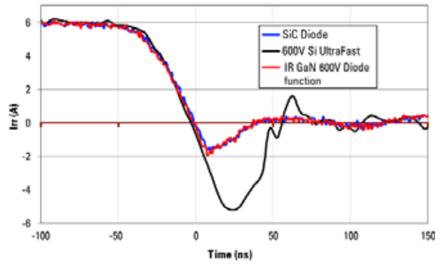

Figure 9. Low reverse recovery characteristics for GaN and SiC diodes are identical, but far superior to the state-of-the-art silicon diodes.

In Summary

GaN based Power FET's such as those produced by IR's GaNpowIR platform have now reached performance that exceeds silicon based solutions with great further improvement anticipated (similar to Silicon MOSFET's in the '80's and '90's). The result is a dramatic increase in the achievable levels of power conversion density, efficiency and cost effectiveness. IR's GaNpowIR platform has been developed to commercialize these improvements: to provide GaN based power conversion solutions which exceed today's performance and cost effectiveness with high quality, reliability and delivery levels. Prototypes have been developed and demonstrated to highlight capability of early GaN based devices. Projected improvement roadmaps anticipate up to tenfold improvement in key figures of merit. Products are due for introduction starting with integrated DC:DC power stages in late 2009 with further releases to follow

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