The Next stage in the Commercialisation of GaN-Based Power Devices

With the first commercially viable GaN based power device released into production, a new stage of implementation of this transformational technology is taking place. Distinguishing features of the new technology platforms are discussed in this article as well as the related performance of the resulting power devices. The prospective availability of 600V GaN based power devices in a variety of applications including power factor correction for AC/DC converters and motor drive circuits is discussed. **Michael A. Briere, ACOO Enterprises LLC/International Rectifier, USA**

There are an increasing group of academics and industrial suppliers of power semiconductor devices joining the theme that power electronics can play a significant role in the realisation of opportunities to significantly impact global energy consumption, by more than 25% by 2025 [1]. This can be achieved through the use of more efficient working load architectures, enabled by new power electronics, provided that significant and rapid adoption of these architectures occurs. The rate of adoption is determined to a large extent by the economic barriers or incentives involved. The availability of new power electronics based on commercially viable wide band gap semiconductors such as GaN on Silicon power devices fabricated in Silicon foundries, provides the required performance to cost value proposition to enable lower economic barrier to adoption for these energy efficient architectures.

As Silicon based power device technology approaches maturity, it becomes increasingly expensive to achieve even modest improvements in the device figures of merit (FOM) [2]. Necessary further advances in power device performance must be achieved through the use of alternative materials. One of the most promising alternatives to Silicon is Gallium Nitride (GaN).

Even though the basic GaN HEMT (high electron mobility technology) transistor was first invented over 15 years ago by M. Asif Khan [3], significant development efforts on practical power devices using GaN-on-Si technology have been fairly recent, predominantly in the past 5 to 7 years. GaN based power devices are expected to improve rapidly over the next 10 to 20 years. In fact, it is expected that an order of magnitude in improvement in the key device performance FOMs will be achieved over the next 5 years.

Salient features of a power switch

In order to provide a compelling alternative to Silicon based devices, the new GaN based devices must achieve certain performance characteristics. The first amongst these is cost. Cost effective GaN based power devices require the use of large diameter (at least 150mm) Silicon substrates for hetero-epitaxy, as well as device fabrication compatible with high volume silicon CMOS factories. These requirements have been achieved in a platform known as GaNpowIR [2].

It is often promoted that another salient feature necessary for commercially viable GaN based power devices is that their gates be enhancement mode, that is that the device not conduct without an applied bias. The author strongly disagrees with this common proposition. Whereas, it is true that an enhancement mode gate is useful in several applications, and IR has developed several novel approaches to realise this feature, it is not often actually required. In fact, it is relatively straightforward to provide gate drive circuitry to operate depletion mode devices and companies such as IR provide such devices as part of a complete solution.

Potential issues with start-up shoot through are likewise resolved. Amongst the several well established methods of achieving enhancement mode GaN based

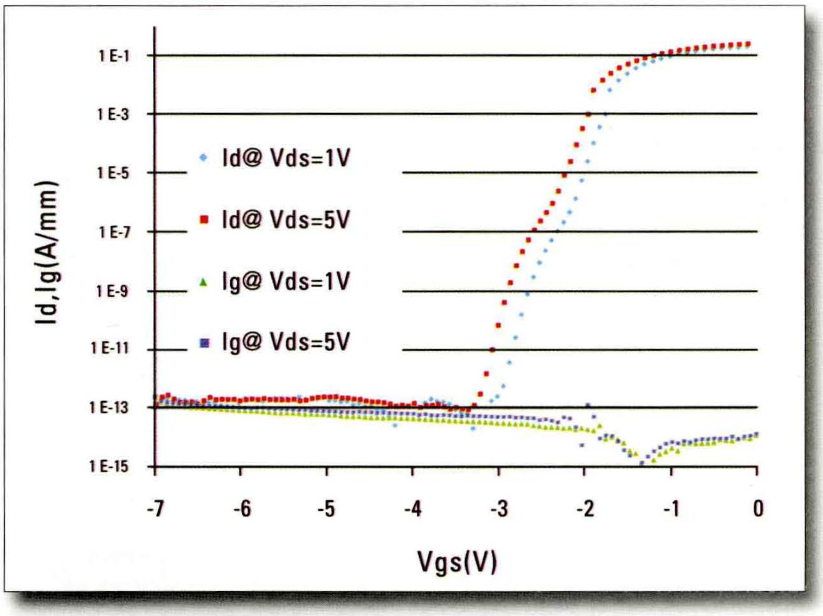

Figure 1: Measured I_d normalised to gate width (850mm) as a function of V_{gs} for V_d = 1V and 5V, L_g = 0.3µm for LV GaNpowIR device

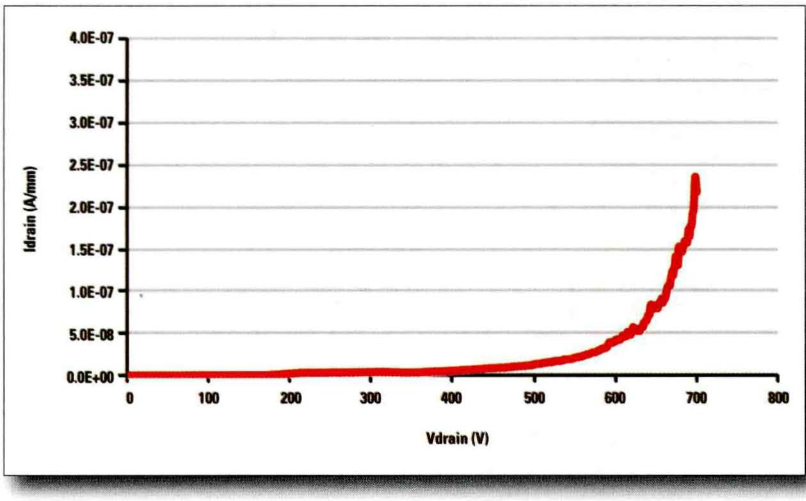

Figure 2: I_d **(A/mm) vs** V_{ds} **(V) for early HV GaNpowIR HFET,** $V_{gate} = -10V$

power devices is the use of thinned AlGaN buffer layers [4] and p-n junction gates using Mg doped GaN or AlGaN layers under the gate metal [5]. The first generally suffers from significant degradation in device performance (R_{dson} and I_{dsat}), and while the second suffers to a lesser extent in these FOMs, it exhibits significant gate leakage, especially when the gate junction is forward biased or at elevated operating temperatures. Several improved approaches to achieving normally-off switch performance have already been developed.

What is clearly required however, and commonly inadequately addressed, is that the leakage currents of the device be well controlled. Much of the reported constructions for GaN devices to date utilise Schottky gates and subsequently exhibit device leakage in operation of mA/mm of gate width. For a power device, which often has an effective gate width on the order of 1m, such gate leakage would result in an unacceptable power loss/heating. Similarly, the maximum operating voltage has often been specified at reverse bias source-drain current densities of mA/mm of gate width. To be commercially viable, leakage currents need to be reduced across the specified operating range to less than 1µA/mm. This has been achieved through the combined use of a proprietary insulated gate construction and improved III-Nitride epitaxial film quality. This has resulted in gate and drain-source leakages for low voltage devices of <10pA/mm, as shown in Figure1. The resulting ratio of I_{on}/I_{off} of 10^{12} is substantially better than reported elsewhere for GaN based devices and even exceeds that of comparable Silicon based power devices.

Such results are also achievable for higher voltage devices. Figure 2 shows the drain leakage current at breakdown for a 100mm wide device, capable of saturation currents of greater than 20A ($V_g = 0V$), is <50nA/mm at 600V. Here the ratio of I_{on}/I_{off} is 10^7, where Ioff is measured at 600V drain bias and a gate voltage of -10V.

Another salient feature of power devices is the switching performance. As has been previously reported [2], the initial GaNpowIR products are low voltage (30V) DC/DC power stage modules. In many high performance low voltage applications, it is the $R_{(on)} * Q_{sw}$ FOM which is critical to many of the low voltage applications. In this regard, the GaN HEMTs are expected to achieve more than an order of magnitude improvement over state-of- the-art Silicon devices within the next 5 years [2]. Quantitatively, this means a $R_{(on)} * Q_g$ device performance of less than 4mΩ * nC compared to next generation Silicon FOM of 45mΩ * nC.

Similarly, for many high voltage applications, the $V_{ceon} * (E_{off} + E_{on})$ FOM is a determanent value proposition. As in the case of Silicon Carbide (SiC) based power device, GaN based HEMT devices operate with majority carriers, making the reverse recovery switching times and associated losses far lower than the alternatives provided by Silicon based, Superjunction and Bipolar devices. Figure 3 shows a comparison in turn-off behaviour for early IR GaNpowIR 600 V rated devices, best in class Superjunction FETs and IGBTs. As can be seen, the GaN based devices represent over an order of magnitude reduction in E_{off} compared to IGBTs and nearly a factor of 2 compared to Superjunction devices. Together with significant improvements in R_{dson}, GaN based power devices provide far superiour performance compared to Silicon based alternatives. IR will release its 600V GaN based power device technology platform to production by the end of 2011. The first products will include normally-off power switches and rectifiers for use in applications such as PFC AC/DC converters, motor drives, solar inverters and lighting.

Minimising parasitics in packaging

Another challenge for the realisation of commercially viable low voltage GaN devices is the effective conduction of the source-drain current from the internal to the external device terminals. This has been accomplished through a flip-chip die, eliminating wire bonding and minimising other package related parasitics (see Figure 4).

In addition to issues in placement and handling, there are several performance issues that must be addressed to fully realise the advantages of such GaN based flip-chip power devices. The spreading resistance of the substrate used to interpose the device in the application circuit can represent a 20 to 50% addition to the intrinsic (die) device FOM. Parasitic inductance in the substrate layout can produce undesirable ringing. An integrated approach which optimises the power switch interface with the application board, as well as the gate driver and minimises parasitic related behaviour is provided by

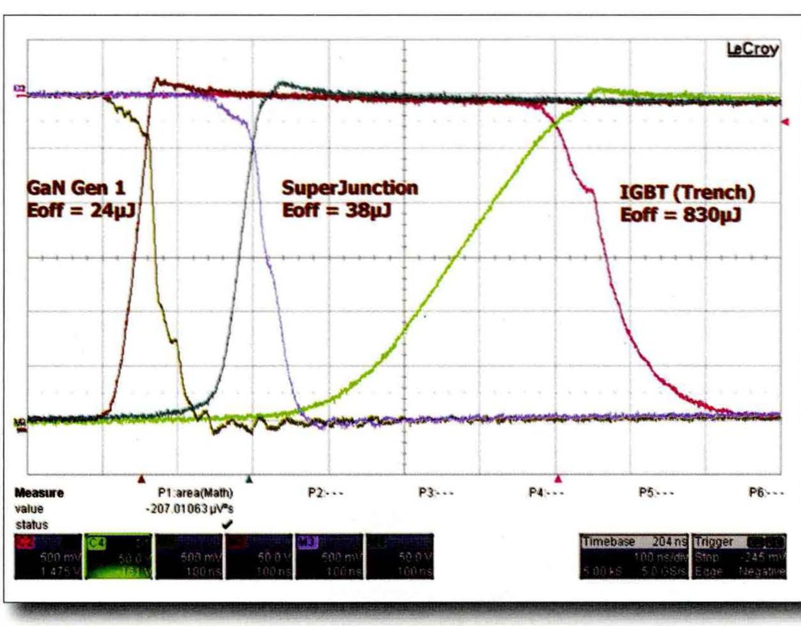

Figure 3: Turn-off waveforms for 600V rated IR GaNPowIR HEMT, Superjunction and IGBT devices (measured E_{off} **are 24µJ, 38µJ and 830µJ, respectively)**

the iPowIR product platform. An optimised driver also provides for achieving the maximum performance benefits afforded by the GaN based power devices, through intelligent deadtime control. For these reasons, the first GaNpowIR product is the iP 2010, a fully integrated and performance optimised solution, as shown in Figure 5. The target of a useable FOM of 30mΩ * nC for this first generation technology platform as packaged in the

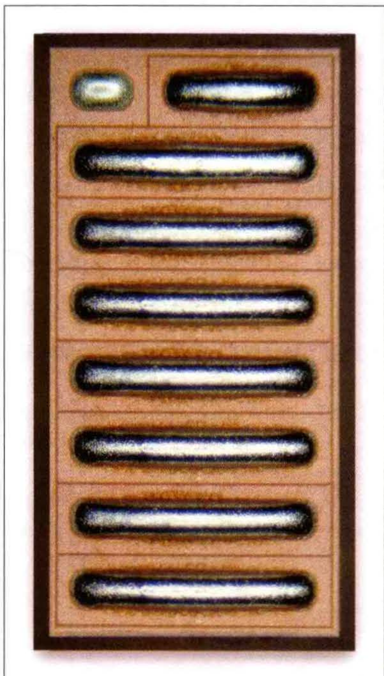

Figure 4: Topside view of a flip-chip GaNpowIR device

iP2010 has been achieved [2].

Finally, the stability of device in-circuit performance is a prerequisite to commercialisation. The stability of all critical FOMs for the GaNpowIR technology platform is excellent under accelerated conditions for > 4000 hrs. In fact, over 2,000,000 device hours of reliability testing has shown performance in line with silicon based device specifications. Tests have included gate stress, reverse bias stress, constant current (2x specification), temperature humidity bias, package testing for MSL and temperature cycling, high temperature operating life and intermittent operating life tests.

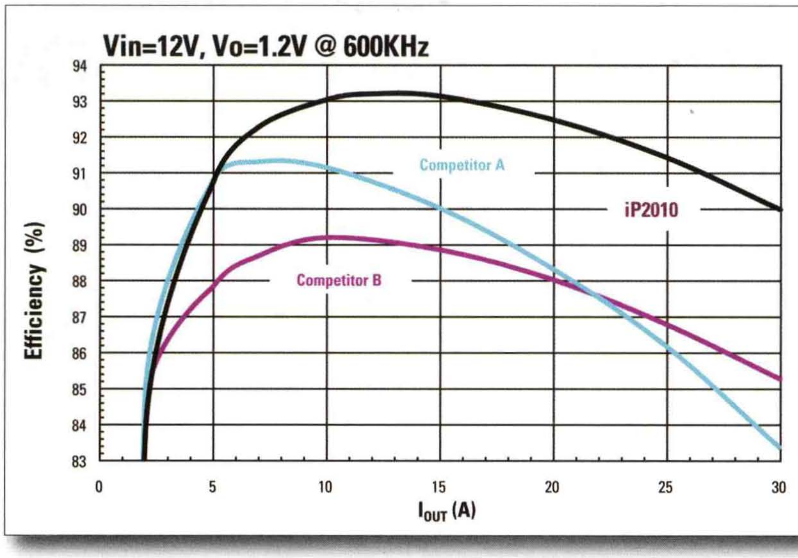

Figure 6: Measured power conversion efficiency for initial GaNpowIR product (iP2010), a $12V_{in}$ to $1.2V_{out}$ POL converter power stage operating at 600kHz compared to two Silicon based alternatives

First GaNpowIR release

The first product release to production on the IR GaNpowIR technology platform is a 30A capable 12V buck converter power stage product. It incorporates the control and synchronous rectifying switches together with the intelligent gate driver in a low parasitic LGA package. Figure 6 shows the measured power conversion efficiency for this first generation GaN product compared to competitive silicon based solutions.

Here it can be seen that the GaN based power devices provide up to 4.5% improved conversion efficiency over state-of-the-art Silicon FETs. In addition, by enabling this high efficiency at 600kHz, this GaN based power solution enables the use of all ceramic capacitors in the power converter, thereby enhancing system reliability. As has been previously discussed [2] further improvements in LV GaN based power devices (e.g. RQ < 5) will allow for truly revolutionary performance of efficient (85 to 90%) single stage power conversion (e.g. 12V to 1.2V) at >50MHz frequencies, eliminating much of the output filter components, significantly reducing costs, and shrinking the converter size by more than a factor of 10. The resulting simultaneous improvement in power conversion density, efficiency and cost represents the true value of GaN based power device development for LV applications.

Perhaps even more importantly, the IR GaNpowIR technology represents a cost effective platform for power integrated circuits, incorporating a range of voltage capable devices with best in class performance. This will allow system on a chip integration, such as complete AC/DC LV conversion and high power monolithic inverters for motor drives and power distribution. More than the replacement of Silicon discrete devices with GaN based devices, this platform opens a new era for integrated power conversion.

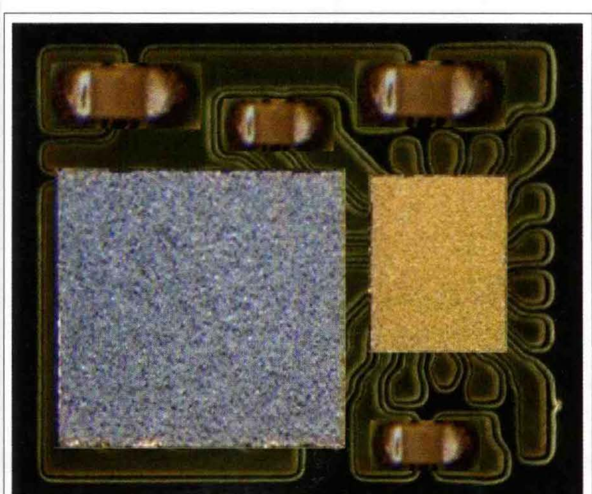

Figure 5: iP 2010 product layout, including an all flip-chip design with monolithic control and synchronous FETs and intelligent driver IC, as well as local charge storage for optimal performance

Conclusion

IR has released its first commercially viable GaN based power device platform to production, overcoming several significant barriers, particularly cost. First products focus on low voltage applications, though expansion into high voltage device products is expected by the end of 2011. More than the replacement of Silicon discrete devices with GaN based devices, this platform opens a new era for integrated power conversion.

Literature

[1] Briere, M.A., S2k Conference 2005 and Lidow, A., APEC 2005 Planery Talk

[2] M.A. Briere, Proceedings of PCIM Europe 2009 and Briere, M.A., Power Electronics Europe (7), October / November 2008 pp. 29-31

[3] Khan, M.A. et.al, Appl. Phys. Lett (63) p.3470, 1993.

[4] M. A. Khan, et.al.Phys. Lett., vol. 68, pp. 514-516, 1996.

[5] X. Hu, et.al. Electron. Lett., vol. 36, pp. 753-754 2000.