Recent GaN Based Power Device Developments

There is an increasing demand for high density power conversion solutions. At the same time, economic, political and social pressures are mounting to increase the power delivery efficiency. For a given power device technology, these two performance metrics, efficiency and density are in conflict and lead to a performance figure of merit of efficiency * density. As silicon based technology is reaching maturity, a truly revolutionary change in this performance FOM requires that a fundamentally new power device technology platform be introduced. **Michael A. Briere, ACOO Enterprises LLC under contract to International Rectifier, USA**

Since the advent of the spontaneous AlGaN-GaN based high electron mobility sheet formation, first discovered by M. Asif Kahn in 1991 [1], significant efforts have been made to bring the inherent capabilities of this exciting material system to bear in practical semiconductor power devices. The combination of high breakdown field strength due to the wide band gap of the III-nitrides, high electron mobility, as well as an unusually high channel electron density, yield a remarkably compelling drift resistance. Such devices also benefit from the reduced gate charge requirements involved in switching the devices on and off. Probably the most exciting attribute of the system involves the easily isolating nature of the inherently lateral devices, permitting unprecedented monolithic integration of power systems.

The trade off between density and efficiency is largely a question of switching frequency. As the switching frequency increases, losses are compounded in the power converter from three main sources: namely the driving losses, the current*voltage overlap of the power devices and the dissipative capacitive losses of the device output impedance. In addition there are core losses in the magnetic element of the output filter inductance. To achieve improved efficiency, it is therefore imperative that improvements in the power device behavior, particularly the requisite input and output charge levels involved in the device switching between on and off states be achieved (Q_{switch}).

Advantages for DC/DC converters

For low voltage DC/DC converters, the density of the power converter is determined, to a large extent, by the size of the output L-C filter. The higher the switching frequency, the smaller the required inductor needed to maintain a given output ripple voltage and the smaller the output capacitor needed to deliver a given transient load current. This situation is compounded for loads such as many CPUs which have very high transient current requirements in order to support the dynamic voltage supply needed. Of course, lower switching losses can be achieved by reducing the semiconductor power switch die size and therefore the die capacitances. This would, however, limit the current handling capability both from a power efficiency standpoint and thermal limitations, due to the finite device specific on-resistance (R_{dson}) induced ohmic losses. Therefore, just as in the case of the power converter, the power device exhibits an equivalent performance figure of merit: R_{dson}*Q_{switch}.

Early results for point of load (POL) DC/DC converters using first generation GaN based devices from International Rectifier have been discussed previously [2,3]. In fact, commercially available products have since been released utilizing this technology platform [3]. The early results for high frequency single stage POL conversion resulted in 86 % peak efficiency at 5 MHz and 81 % efficiency at 10 MHz for 12 V_{in} to 1.8 V_{out} conversion. At the time, simulations suggested that significant improvements in conversion efficiency could be achieved through improved driver and output inductor performance. Figure 1 shows the results of such improvements in the driver circuitry, using the same GaN based device technology platform. As can been seen, this has resulted in about 2 % increase in efficiency at peak loads and 4 to 6 % improvements at light loads, in good agreement with the earlier simulation based predictions. An excellent performance is therefore achieved using first generation GaN based devices with R_{on} * Q_g FOM of 30 mΩnC.

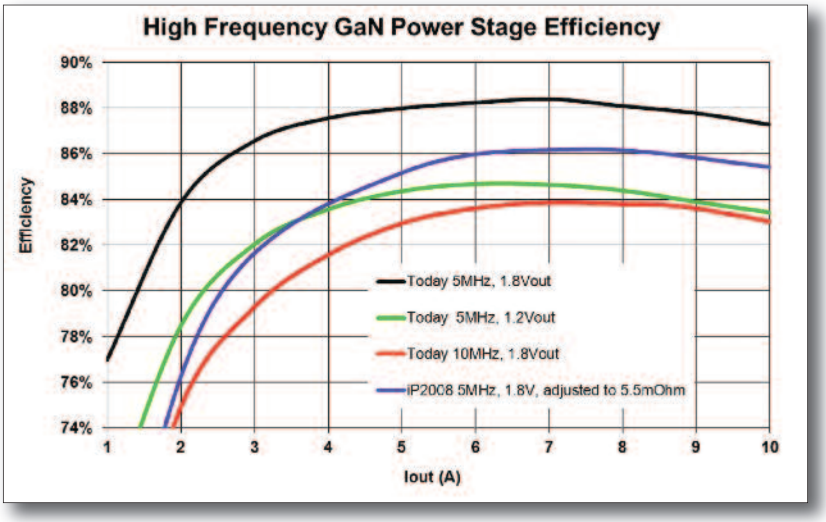

Figure 1: Measured conversion efficiency (including driver and output filter losses) for 12 V_{in} POL DC/DC converters using first generation GaN based 30 V rated switches with a R_{on}*Q_g FOM of 30 mΩnC (including package contributions)

As discussed elsewhere [4], there is a further need to dramatically increase conversion density, in support of many

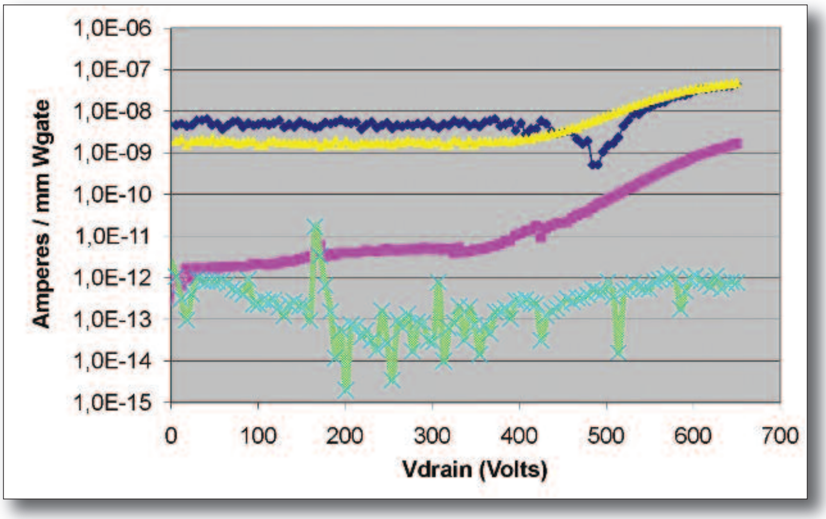

Figure 2: Measured room temperature reverse bias leakage current from drain, source, substrate and gate for a prototype 650 V rated IR GaN device

(>32) core processors. In order to optimize the performance of these complex loads, it is best to provide each core with its own 12 V_{in} power supply. This would require a conversion density of some 75 to 100 A/cm^2 and a subsequent conversion frequency of 30 to 75 MHz. In order to achieve a single stage conversion efficiency of 12 V_{in} to 1.2 V_{out} of 88 %, this frequency requires a power switch FOM of some 2-3 mΩnC. This is an order of magnitude less than the limits possible for Silicon based power devices [5,6], but reasonably above the limit for 30 V GaN HEMT based switches of about 0.5 mΩnC.

It is important that the leakage behavior of the GaN based devices be comparable to that of the incumbent Silicon technology based alternatives. Figure 2 shows the reverse leakage behavior of a prototype 650 V rated GaN based HEMT device at International Rectifier with $V_g = -10$ V at room temperature. As can be seen, the leakage is well behaved and is dominated by the current from between source and drain, with the leakage levels below 0.1 µA/mm up to the 650 V rating. It is impressive to see that the substrate and especially the gate currents are well suppressed throughout the reverse bias voltage range of the device which had 100 mm gate width and a gate length of 3 µm.

High device ruggedness

Device ruggedness in application conditions must also remain uncompromised with respect to expectations established by the incumbent Silicon based technology. Large forward biased safe operating area is an important indication of such robustness and has been demonstrated o 600 V prototype devices to 10 A at 600 V for 100 ns, with V_g-V_P of 4 V. Device stability under accelerated stress conditions for extended periods of time is essential for acceptance in the power electronic community. To date, over 10,000,000 device hours of reliability data has been collected on the low voltage devices released to production by IR in early 2010, with up to 10,000 hours per device. No intrinsic premature device failures have been found to date and parametric stability has been excellent. In addition, initial reliability studies of high voltage GaN based devices have also shown excellent parametric stability to 2000 hours.

It is imperative that such catastrophic failure mechanisms such as the "inverse piezo-electric effect", found in metal-semiconductor gated GaN based HEMTs [7] be eliminated. Under all applied accelerated stress conditions, no physical degradation of the AlGaN barrier has been found in IRs insulated gate GaN based devices as is commonly reported for metal-semiconductor gated devices.

Commonly reported trapping related instability phenomenon such as current collapse or dynamic R_{dson} [8] must likewise be minimized beyond concern. Figure 3 shows the R_{dson} measured within 1 µs of applying varying reverse bias conditions for early 600 V GaNpowIR prototypes. As can

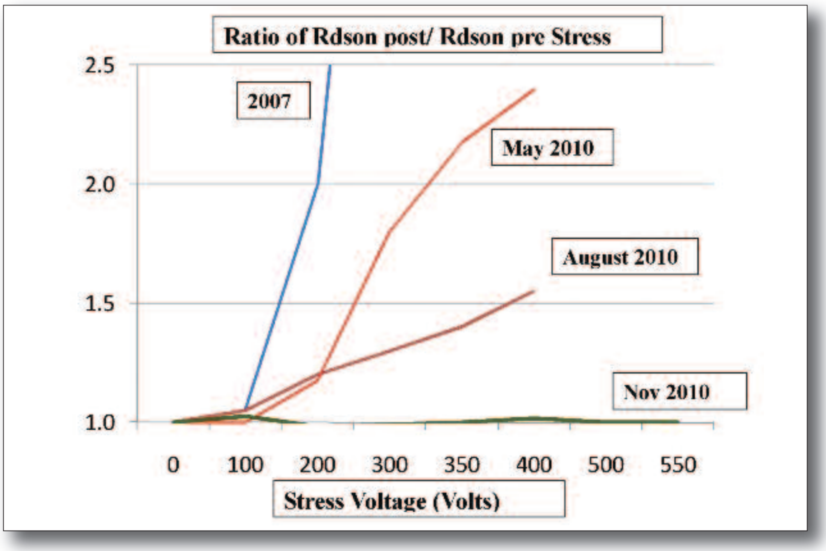

Figure 3: Measured improvement in the dynamic R_{dson} effect, defined as the ratio of R_{dson} post and pre applied reverse bias stress voltage, as measured within 1 µs of the transition between the off-state and the on-state

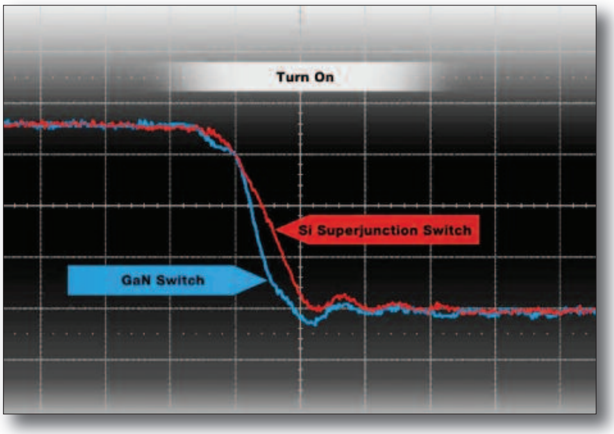

Figure 4: Turn on waveform for a 430 W capable power factor correction circuit boosting from 150 to 350 V at 100 kHz using 120 m_ GaN switches or state of the art 99 mΩ Silicon superjunction MOSFETs. The timescale is 10 ns/div, the voltage scale is 100 V/div and the average current is 1 A (in both cases a SiC diode was used for the rectifying function)

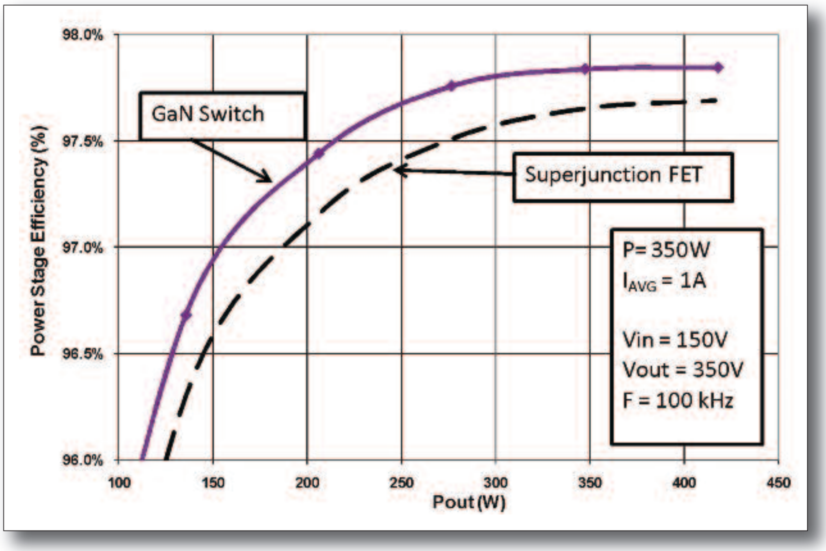

Figure 5 above: **Measured conversion efficiency of the boost circuitry for a 430 W capable power factor correction circuit boosting from 150 to 350 V at 100 kHz using 120 mΩ GaN switches or state of the art 99 mΩ Silicon superjunction MOSFETs (in both cases a SiC diode was used for the rectifying function)**

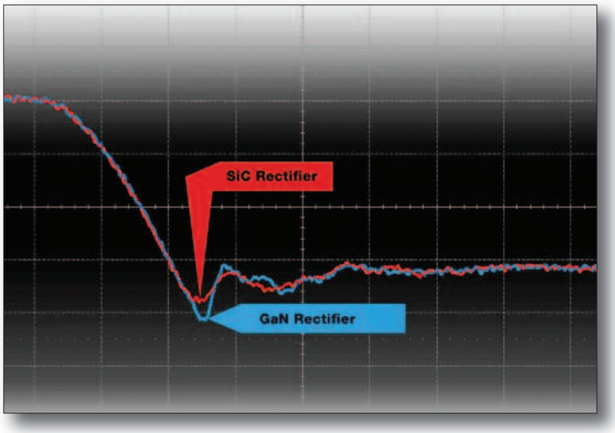

Figure 6: **Switching waveforms of an early prototype 600 V GaN cascaded rectifier and a best in class SiC Schottky diode. Both devices are rated for 6A with a $V_f < 2$ V at 150°C. The difference in measured Qr (which is predominantly capacitive) is a few nC**

be seen, the commonly reported trapping effects have been effectively minimized in this platform.

GaN and PFC

Lowering the cost of high performance AC/DC power supplies using power factor correction (PFC) boost circuitry is another application where GaN based power devices provides an unprecedented combination of efficiency, switching speed and cost effectiveness. Figure 4 shows the turn on waveform of a 600 V cascaded GaNpowIR switch used in the control switch function of the PFC boost circuit, compared to that of a state of the art 99 mΩ Si superjunction MOSFET, both in TO-220 packages. As can be seen, the GaN based switch has superior switching characteristics. This manifests itself as improved power conversion efficiency, as can be seen in Figure 5, for this 430 W capable PFC circuit operated at 100 kHz. Cascoded GaN based rectifiers provide essentially the same performance as high cost SiC Schottky diodes, as shown in Figure 6, for 6 A rated devices. This will allow wide adoption of high efficiency PFC circuits. In addition, the availability of lower cost, high-performance wide band gap semiconductor based switches and rectifiers will promote wide spread adoption of efficient converters, such as inverters for distributed solar power generation, saving 2-3 % in energy loss [9], representing a full decade of improvement in solar cell efficiency.

HV GaN and drives

One of the greatest opportunities for world-wide energy conservation involves the use of efficient permanent magnet motors driven by inverters in appliances, such as air conditioners, refrigerators and clothes washers. In addition, the increasing electrification of transportation drive systems will require improved inverter electronics for both the primary and auxiliary electronic systems. The incumbent technology for these motor drive applications are Silicon based trench IGBTs. Figure 7 shows a comparison between state of the art 600 V rated Silicon trench IGBTs and prototype first generation 600 V rated GaNpowIR devices in terms of conduction*switching loss FOM. As can be seen the GaN based devices perform remarkably better. What is truly exciting is that an order of magnitude further improvement in performance for GaN based power devices is potential over the coming decade.

One of the key FOM for the power switch if the specific on resistance. Figure 8 shows a possible roadmap for performance improvements for GaN based devices, leading to a factor of 8 improvement compared to state of the art Silicon based superjunction devices in the available on resistance in a given package (e.g. TO-220) over the next four years.

Conclusions

The availability of cost effective, high quality, robust, high performance GaN based power devices will enable truly innovative improvements in power electronic density, efficiencies and costs in the coming years.

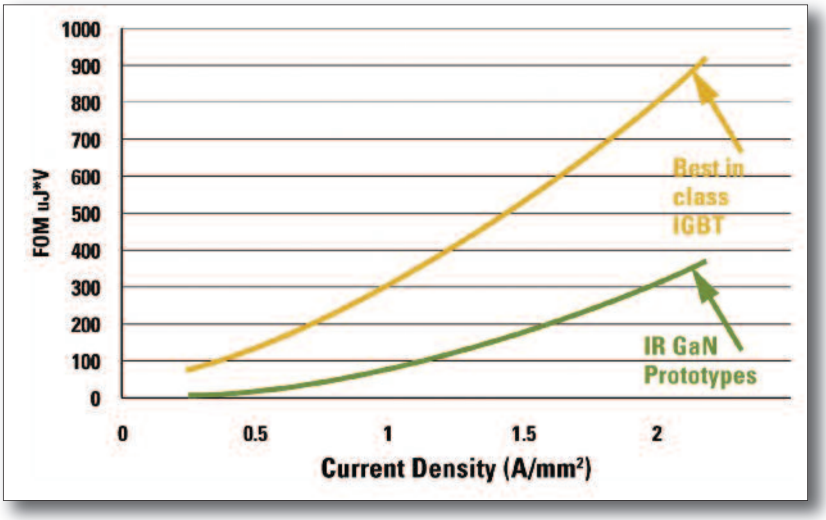

Figure 7: **Measured performance comparison between state of the art 600 V rated silicon based trench IGBTs and prototype first generation 600 V rated GaN based devices in terms of conduction * switching loss figure of merit [V_{on}*(E_{off}+E_{on})] vs current density at 25°C**

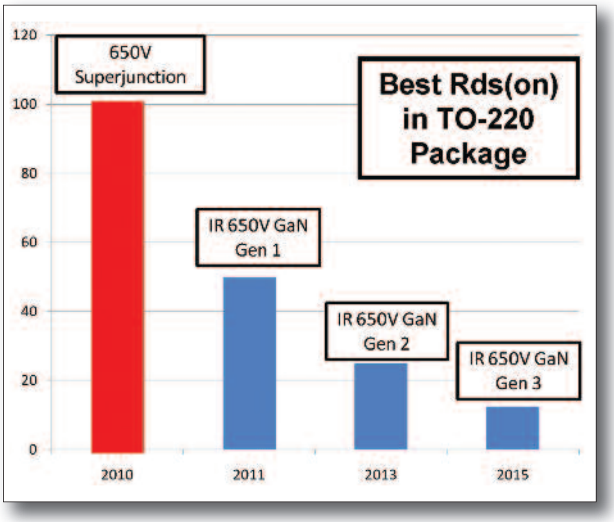

Figure 8: **Possible 650 V GaN based power switch performance roadmap, showing an 8 fold improvement over state of the art Silicon devices within the next four years**

From more efficient solar panel based inverters to higher density efficient permanent magnet based motion control systems to lighter weight and denser inverters for electrified vehicles, as well as next generation integrated DC/DC power supplies for electronics, GaN based power devices will revolutionize the industry. This technology platform strongly supports the objective to enable lower system costs to promote the adoption of efficient systems that significantly reduce worldwide power consumption [10].

It is tempting to relate the introduction of these devices to that of power MOSFETs some 30 years ago, which revolutionized power electronics by enabling compact cost effective switching regulator based power supplies. However, it appears more likely that this paradigm shift will have aspects of the greater character of the revolution in data processing which occurred through the development of large scale and very large scale integrated circuits. This is due to the intrinsically integrated nature of the lateral GaN based device platform, allowing integration without performance compromise, a feat not possible in vertical silicon based power device technology. This will provide an entirely new level of performance, density, robustness and cost effectiveness. This paper was one of the highlights at PEE's Special PCIM 2011 Session "High Frequency Switching Devices and Applications".

Literature

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