On the Transition from Silicon to GaN-Based Drive Inverters

The recent announcement by several well established suppliers, notably Panasonic and International Rectifier of the near term availability of 600 V rated GaN based devices to the power electronics market, has prompted significant interest in the nature of the resulting transition from Silicon to GaN based inverters for motor drives. Several inherent advantages of GaN based HEMTs, including one to two orders of magnitude reduction in reverse recovery charge, as well as significantly higher current handling capability and lower equivalent on resistance for a given device active area, have already been shown to reduce power losses in actual use conditions of applications such as appliances and electric vehicle drive trains by more than a factor of 2. **Michael A Briere, ACOO Enterprises LLC (under contract to International Rectifier), USA**

The linear I-V behavior of the GaN (Gallium Nitride) based HEMTs (High Electron Mobility Transistors) is particularly advantageous at lighter loads, where the significant overhead of the Si based bipolar device results in large power losses. Inverter densities for these same applications have been shown to be improved from between a factor of 2 to 3 for electric vehicle systems and over a factor of 10 for appliance motor drives. Despite these overwhelming advantages, the adoption rate will be determined by the design cycles of the power electronic system suppliers, which are typically two to four years.

IGBTs versus GaN

In typical offline motor drive circuits today, the switch function is accomplished by a Silicon based insulated gate bipolar transistor (IGBT). The same bipolar effect that provides for relatively low equivalent on-resistance at higher loads, compared to Silicon based unipolar MOSFETs, would add too much reverse recovery charge (Q_{rr}) to be practically useful in switching applications.

Together with the fact that the motor drive application requires a recirculating path for back EMF (electro-magnetic force) induced current from the inductive load, that is the motor windings, when the associated switch is turned off, an external diode is usually co-packaged with the IGBT. This diode is often about half the die size of the IGBT switch and adds significantly to the footprint of the packaged solution. In addition, the significant reverse recovery charge characteristics of this recirculating diode creates significant noise and adds to the power loss of the switching circuit. Although there have been some recent efforts to use SiC-based diodes to eliminate this reverse recovery charge, the cost of such a solution makes it practically prohibited. Another characteristic of the IGBT based solution is that the inherent built in potential of the bipolar transistor produces a large voltage drop across the switch, typically more than 1 V, even for relatively light load currents, for instance of a few hundred mA.

As many motor drive applications, such as refrigerator compressors, spend most time in such light load conditions, this effect has a significant impact on achievable efficiencies in these applications. In addition, as state of the art IGBTs are vertical channel devices, integration is impractical. This makes the IGBT based solution for low power motor drive applications relatively large and expensive to implement. Each of these drawbacks are addressed by the use of commercially viable GaN based power devices as switches in motor drive applications.

In the case of a commercially viable GaN based power device, such as a

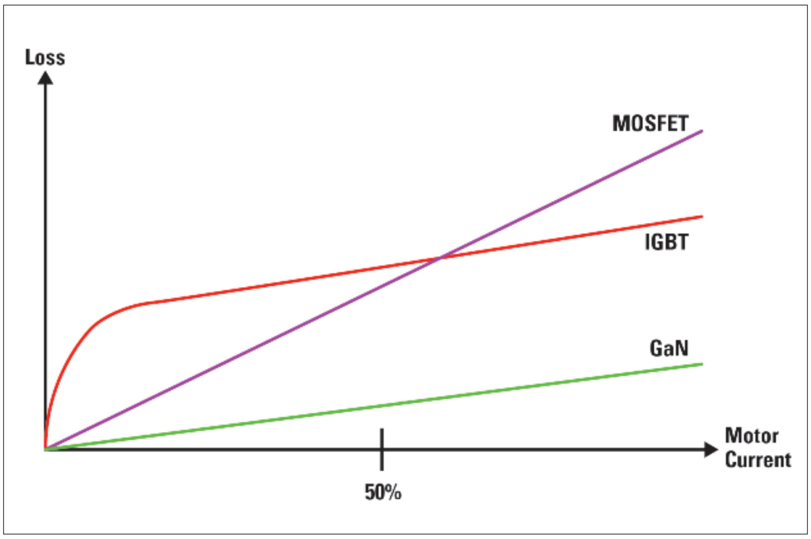

Figure 1: **A representation of the voltage vs current output characteristics of Silicon based IGBTs and MOSFETs compared to that of GaN based switches**

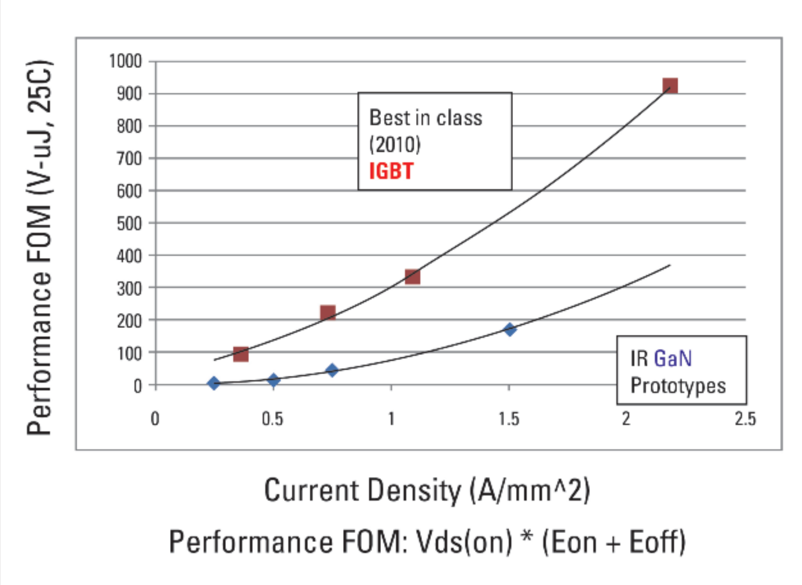

Figure 2: Measured forward voltage drop * switching energy for state of the art IGBTs and early prototype GaN based cascoded switches vs current density

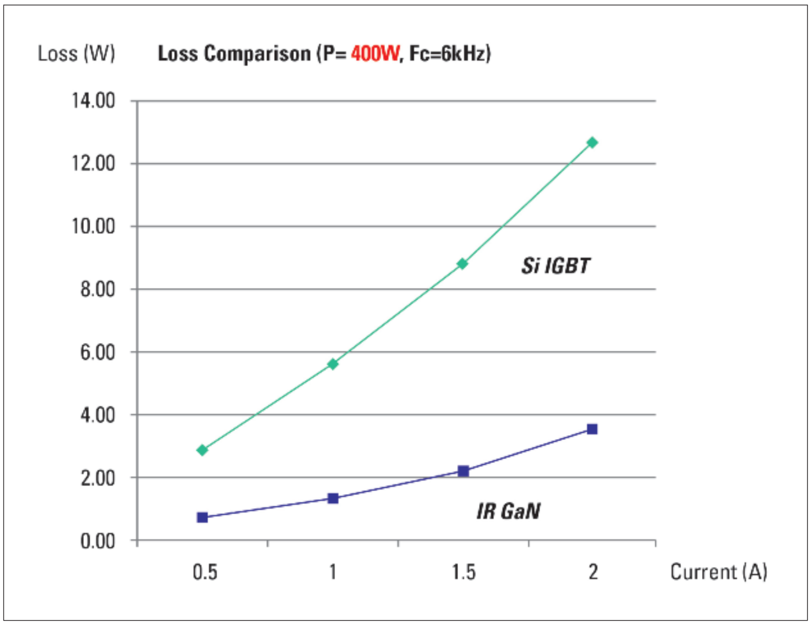

Figure 3: Comparison of power loss in nominal 400 W motor drive inverter using Silicon based IGBTs or GaN based cascoded switches

cascoded GaN HEMT from International Rectifier's GaNpowIR® technology platform, the performance to cost advantage in comparison to state of the art Silicon based IGBTs is quite remarkable. The recirculating function is provided by the body diode of the low voltage Silicon FET cascoded with the high voltage GaN based HEMT. This low voltage diode exhibits a small fraction, e.g. less than 10 %, of the reverse recovery charge characteristics of the high voltage diode used with the IGBT. This leads to much cleaner switching waveforms and less circuit noise. In addition the cascoded LV FET is much smaller, e.g. less than 10 %, than the GaN based HEMT, representing little extra area or cost.

The on resistance of the current first generation GaN based cascoded switch is much less, e.g. a factor of 2 to 3, per active area, than state of the art 6th and 7th generation Silicon based IGBTs. In addition, it has been shown that GaN based cascoded switches can process more than 2 times the current density, per active area, (> 900 A/cm^{2}) as state of the art Silicon based IGBTs. In this way, the inherent die size required for a given application at full power can be significantly smaller for the GaN based switches. Alternatively, the maximum full power that can be processed for a given inherent die size, or package size, can be significantly greater when using GaN based switches.

Perhaps more strikingly, the unipolar nature of the GaN based device causes the output characteristics to be linear through light load, in contrast to the significant overhead of the built in potential of the bipolar device, as shown in Figure 1.

The combination of lower on-state forward voltage drop and simultaneously significantly reduced switching charge leads to a 3 to 4 fold improvement in power processing performance, in the form of reduced conduction loss multiplied by switching loss, as shown in Figure 2. This improved device performance translates directly into improved efficiency in a motor drive inverter application. As seen in Figure 3, the power loss associated with the motor drive inverter in a typical appliance application at a nominal 400 W, shows more than a 3 fold reduction in power loss when using IR's 600 V rated GaNpowIR® devices compared to state of the art Silicon based trench IGBTs. In particular the light load efficiency is dramatically improved, in agreement with device physics based expectations. In addition, as can be seen in Figure 4, the density of the GaN based solution is 10 times that of the Silicon solution. Most impressively, the GaN based solution does not require a heat sink as the Silicon based solution does, making the practical density advantage a factor of 100.

These impressive results are even more remarkable considering the relative immaturity of the GaN based power device technology compared to the well established and mature Silicon based IGBT technology. It is expected that future engineering efforts will hone the GaN based technology to close to its physically determined performance limits, an expected improvement of at least a factor of ten, over the coming decade. As astounding as this situation appears for enabling advances in future power electronic systems, it represents only a small fraction of the nascent potential present in GaN based power electronics.

Novel architectures on the horizon

One great avenue of innovation involves the development of new circuit topologies that take a full advantage of the inherent benefits and capabilities associated with GaN based power devices, whereas the previous discussion only involved the drop in replacement of GaN based devices into circuits designed explicitly for Silicon based switches. An example of such a topology change would be the replacement of the half bridge, phase leg, approach using

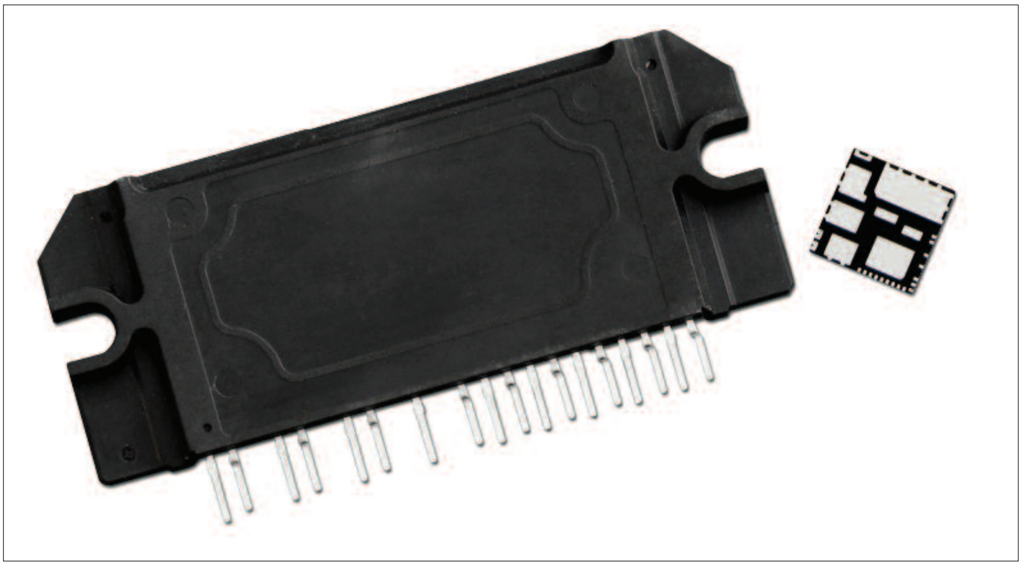

Figure 4: Picture of actual IGBT based (left) and GaN cascade based (right) nominal packaged 400 W inverters used in measurements of Figure 3

IGBTs for motor drive with a 3-switch approach of a matrix converter. Though the advantages of matrix converter topologies have been extensively discussed for at least 20 years, implementation has been hampered by the lack of an adequate bi-directional power switch. GaN based HEMTs are inherently bi-directional capable, enabling the realization of commercially viable matrix converters.

Perhaps the greatest potential innovation for power electronics using GaN based devices is in the field of integration. As GaN HEMTs are inherently integratable, as opposed to state of the art Silicon based power devices, a great revolution in performance, cost, reliability and novel functionality is now made possible. Exciting!

Despite these overwhelming advantages, the adoption rate for GaN based devices will naturally be determined by the design cycles of the power electronic system suppliers, which are typically two to four years. Of course, it is possible that compelling competitive advantages may drive more rapid design cycles as economic factors become more evident.