The GaN Opportunity - Higher Performances and New Challenges

New GaN technology switches offer best in class on-resistance and gate charge, however they need more accurate driving techniques to ensure reliability and avoid overstresses and failures. This paper explains the main technical challenges and solutions to address these needs. **Maurizio Granato, Senior Circuit Design Engineer, and Roberto Massolini, Design Engineer, National's Design Center, Milan, Italy**

The recent and rapid research on wide-bandgap III-nitride semiconductor devices driven by LED, RF power stage, radar, and aerospace enabled the introduction of GaN power FETs, which are able to provide a relevant power density and thermal characteristics improvements over standard Silicon MOSFETs. This new class of devices, with best in class R_{dson} and Q_{gd}, exhibits excellent figure of merit (FOM $= R_{dson} \times Q_{gd}$), high frequency operation and small package footprint, represent the best choice in power converters in which efficiency and power density are a concern. Although these devices can be extremely useful in industrial power electronics applications and improve the efficiency and the regulation of AC/DC and DC/DC converters, they do not come free of challenges.

This article will briefly cover the main features of GaN FETs for power application to really understand trade-offs between the potential benefit achievable with this new disruptive technology and its new class of issues; the central part of the article will emphasize the problem relating to GaN gate driving and it will then conclude introducing the LM5113, which represents the first available driver specifically designed for GaN FETs.

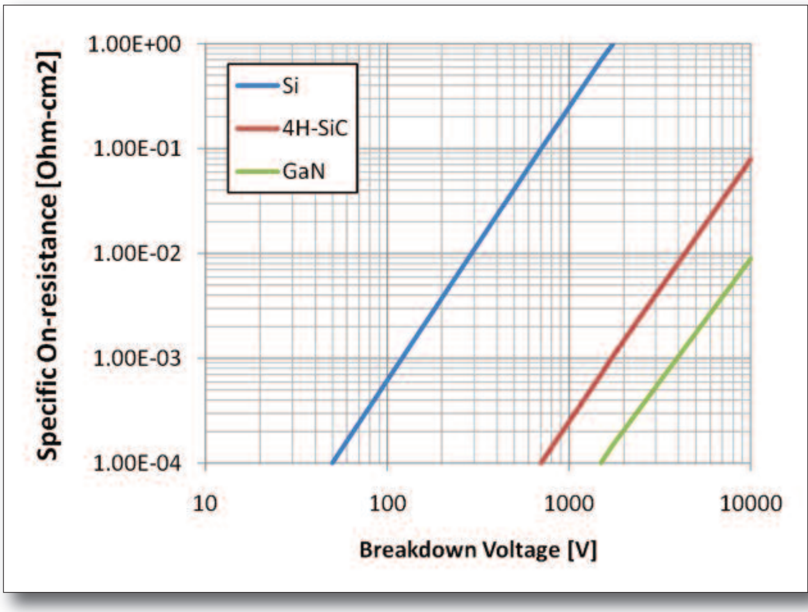

Figure 1: **Technology comparison based on semiconductors physics [Naik]**

GaN FETs overview

Introduced at the end of the '70s, the power MOSFETs have been transformed from mere alternatives to bipolar power transistors to the most widespread devices in the power electronics market, with the result of boosting the strong diffusion of high frequency Switch Mode Power Supplies (SMPS). The evolution of FETs has seen different technologies like TrenchFETs, HEXFETs, Superjunction and many others and provided a slow and continuous improvement in MOSFET switches performances. In recent years the cost-effectiveness of alternative materials (like GaN, SiC) has started to challenge the best Si-based devices providing a disruptive technology change.

We can compare the intrinsic performances of GaN devices to the more mature SiC technology. On one hand, GaN allows for breakdown voltages close to SiC, and twice the electron mobility (in fact, those devices are often named High Electron Mobility Transistors HEMTs); moreover the GaN industry is mature thanks to the developments in optoelectronics (wide application in LEDs) and there are already many suppliers in the market, bringing expectable price reductions compared to SiC. On the other hand, thermal conductivity of GaN is roughly 1/4 of SiC; moreover, power GaN devices development started 10 years after SiC, meaning less maturity and reliability (see Table 1)

The availability of low cost GaN devices has been enhanced by the improvement in process manufacturing techniques and by the adoption of more economic substrates. From the 2-inch very expensive GaN substrates, to the 4-inch SiC substrates, to 6-inch sapphire substrates, to recent growth on Silicon substrates (up to 12-inches), the cost reduction has been massive. On the other hand, this has required a significant effort in engineering to improve device reliability and to keep the high performances, without suffering problems from lattice and thermal expansion mismatch.

The most visible advantage in adopting GaN-based devices is a significant reduction of the on-resistance for a

Materials Property	Si	SiC-4H	GaN
Bandgap [eV]	1.1	3.2	3.4
Critical Field [10^6 V/cm]	0.3	3	3.5
Electron Mobility [cm^2/V-sec]	1450	900	2000
Electron Saturation Velocity [10^6 cm/sec]	10	22	25
Thermal Conductivity [W/cm^2 K]	1.5	5	1.3

Table 1: **Comparison of intrinsic materials properties [Microsemi]**

specific breakdown voltage, or, equivalently, a much higher breakdown voltage for a specific on-resistance. A reasonable expectation over the long run is that SiC based devices will achieve one order of magnitude better R_{dson} with regard to Silicon devices, and GaN based devices will provide a further 2-3x enhancement. Moreover, such a decrease in on-resistance also comes with a significant reduction of the gate charge required to turn-on the device, resulting in a powerful improvement of the R_{dson} x Q_g figure of merit even from the early stages of development of these new components.

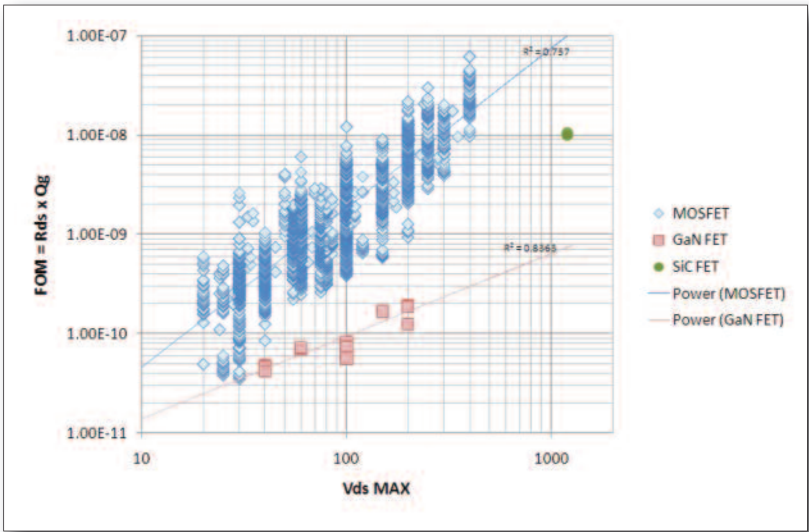

Figure 2: **FOM (R_{ds} x Q_{gd}) for various FET devices currently available on the market. The dots represents different devices, the continuous line is a linear extrapolation for different V_{ds}. It is clear that eGaN will be even more competitive for the future generation which will have much higher BV**

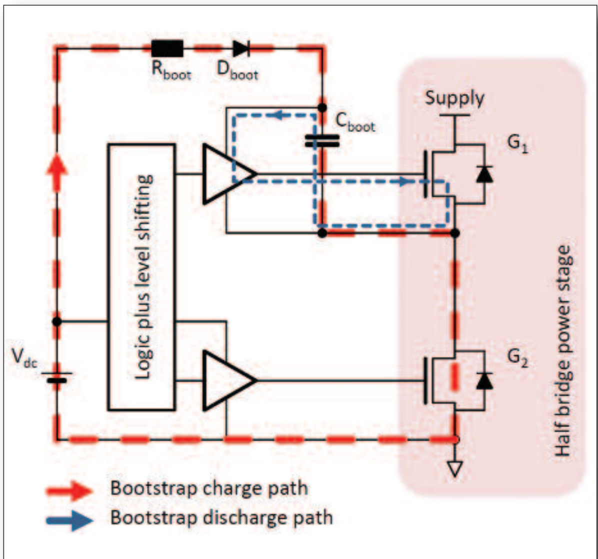

Figure 3: **High voltage half bridge and gate driver, shown are high and low-side driver, bootstrap circuit and level shifter**

GaN devices manufacturers forecast an improvement of one order of magnitude for this FOM of the 2014 devices with regard to the Silicon performances in 2009, allowing for significant efficiency improvements in high switching frequency converters and driving towards stronger overall miniaturization.

Although GaN is populating many of the recent headlines and has outstanding FOM (see Figure 2), these new technologies will not completely replace current devices, but rather complement them and reach high levels of popularity in specific applications, like high frequency, high power SMPS. Their advantages are not anyway coming for free and sometimes their usage requires knowledge that is new to most. For example all power designers are familiar with MOSFETs gate driver essential features and are aware of integrated ICs like the LM51XX and many others which could be used to effectively drive standard Silicon switches, but not many know the basic characteristics that a GaN FETs driver should have.

GaN driver main characteristics

In principle a gate driver for this new class of devices does not differ much from a conventional MOSFET driver: in both cases this circuit is essentially a power amplifier that is used to interface low output power controllers, which provide a PWM logic signal, to the power switch; additional features include single or double input, with automatic dead-time control.

The gate driver has to accomplish two main tasks: provide suitable voltage levels to drive the switch with low impedance output and high current capabilities and propagate the signal to the low and high-side buffer with correct timing and accuracy. On these two main aspects a dedicated GaN driver should provide some specific characteristics specifically aimed to avoid overstresses and increase switch lifetime: GaN electrical requirements to maintain reliability are highly specific and deeply different from the ones of conventional MOSFETs.

High current capabilities and DC bias

High current sinking/drawing capability of the gate driver is the most important feature of a MOSFET driver, allowing fast charge and discharge of the Miller capacitance in the power switch and ensuring fast transition, thus minimizing the switching losses in the converter. In this case there is no difference in a GaN driver: high peak current and low impedance output are still essential characteristics. Even if the power losses associated with gate charge are largely reduced, Miller cap are still present and does not scale equally and induce losses that can only be minimised achieving high commutation speed.

Accurate gate driver supply voltage

HEMT eGaN devices allow only small headroom between the recommended gate source voltage and the maximum gate source voltage that they can withstand. For example EPC GaN FETs give the best R_{dson} performances when turned on with 5V V_{gs}, but they allow only 6V maximum gate voltage. This characteristic requires very accurate gate voltage, which is hard to achieve for high-side floating bootstrapped supplies.

From Figure 3 it is possible to observe the basic working principle of a bootstrap circuit; when OUT (source voltage of the high-side FET) is pulled below the controller Vdc, the Cboot is charged following the red bootstrap current path. The final VBS that is released by the boostrap circuit after OUT is pulled up is $V_{BS} = V_{dc}$-Vf_{dboot}+V_{fG1}. V_{fdboot} is the bootstrap diode forward drop and V_{fG1} is the reverse-direction 'diode' voltage of the GaN device. Due to the intrinsic feature of enhancement mode GaN FETs VfG1 is larger than a Silicon bootstrap diode forward voltage, resulting in boostrap voltage larger than V_{dc}.

To fully exploit the switches R_{dson} at 5V and ensure a reliable operation without exceeding the maximum gate rating, it is necessary to use additional circuitry to regulate the output voltage of the bootstrap circuit. Even for the low-side driver, the stringent requirements on the gate-source voltage pose some issues on the accurate control of the turn on voltage to avoid overshoots and call for some accurate layout design.

Spurious turn on due to high dV/dt

The increased switching frequency of SMPS that employ GaN FET and the much smaller output capacitance Cds introduce some performance advantages, but also some driving constraints. The presence of really fast dV/dt (that can reach peaks of 30 kV/μs) together with the unfavourable ratio between gate drain capacitance and gate source capacitance (the EPC60V has almost comparable Q_{gd} and Q_{gs}) increase the risk of Miller turn-on and direct conduction of the half bridge leg to dangerous levels.

In order to address this issue, the pull down resistor of the driver should be kept as low as possible: down to values below 1Ω. On the other hand, an option to adjust the pull-up resistor is also often required to improve EMI and overshoots control. The typical MOSFET driver has a single output driver and the correct tuning of pull-up and pull-down resistor is obtained through the use of an anti-parallel diode. Due to the stringent constraint in pull-down resistance and voltage levels, the GaN FET driver needs to split gate driver output for turn-on and turn-off paths.

High-side driver constraints

When driving GaN FETs, the dead-time generally hurts the overall efficiency of the converter. The reason is that the GaN devices have no standard anti-parallel diode (only majority carriers are involved in GaN device conduction) so there is zero recovery time and a reverse forward drop higher than the one in reverse diode for the Silicon MOSFET.

The approach taken by the industry to keep the diode conduction at a minimum level, given the really fast turn off time of GaN FET (typically lower than 10 ns) is to not apply the usual dead-time before turning on the other device in the same leg, but to fine tune the driver for a 5 ns ± 2 ns dead-time interval that minimises the body diode conduction losses and guarantees safe operation without shoot-through in the leg.

In order to provide such an accurate dead time, the propagation delay matching between high-side and low-side is a parameter of concern. Generally keeping it in a range of 2 ns or less is enough to prevent the shoot through or cross-conduction in the circuit.

LM5113 makes GaN simpler

Until few months ago the only viable solution to use GaN FET in an accurate and reliable way was to deepen the knowledge of the aforementioned issues and eventually build a discrete components gate driver. Now National Semiconductor introduces the first dedicated gate driver for GaN devices.

National's LM5113 is a 100V bridge driver for enhancement-mode GaN FETs that implements all the necessary techniques to ensure safe and reliable operation. It has a fully integrated high-side bootstrap diode that further simplifies the application development and minimises PCB area occupation. The device also regulates the high-side floating bootstrap capacitor voltage at approximately 5.25V to optimally drive GaN power FETs without exceeding the maximum gate-source voltage rating.

The LM5113 also provides independent logic inputs for the high-side and low-side drivers, enabling flexibility for use in a variety of both isolated and non-isolated power supply topologies. The fast propagation delay and the superior delay matching make it suitable for high speed applications and minimization of reverse diode losses. The device also features independent sink and source outputs for flexibility of the turn-on strength with respect to the turn-off strength. A low impedance pull down path of 0.5Ω provides a fast, reliable turn-off mechanism for the low threshold voltage of GaN power FETs, helping to maximise efficiency in high frequency power supply designs (see Figure 4/5).

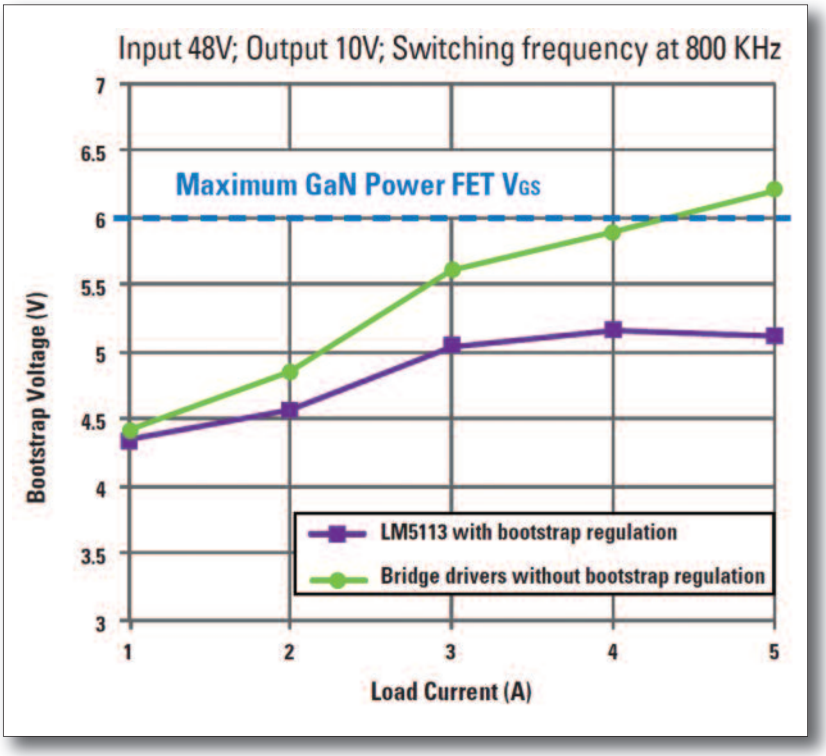

Figure 4: **Output regulation of bootstrap voltage**

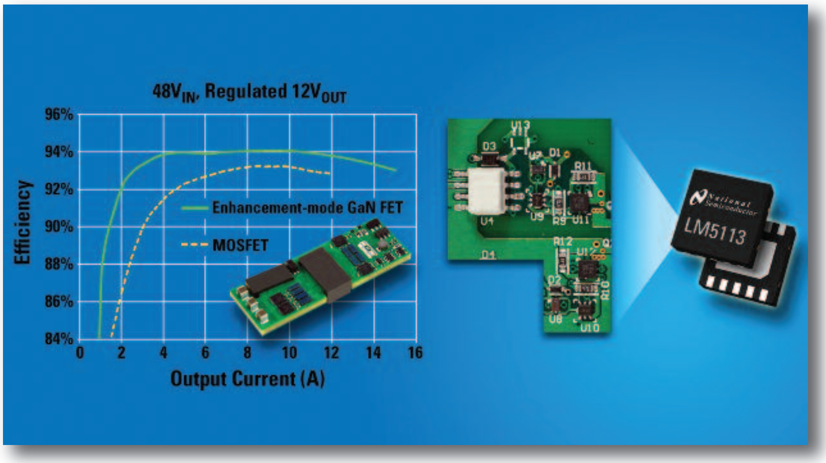

Figure 5: Size comparison of the LM5113 with a discrete solution

Conclusions

A short overview of the technological improvements in solid state switches for power electronics over the years, mainly driven by the endless research for the missing efficiency percentage point, has shown how GaN technology has strong proliferation potential, thanks to a combination of advantages which make it now very appealing in a broad range of application. The most visible effect of this explicit potential is the response of the semiconductor industry, which is now starting to propose dedicated driving solutions.

National's LM5113 was born after this careful analysis of the incredible potential of GaN devices, and recognizing the issues arising in driving these devices in the most appropriate way: leveraging the performance improvements and avoiding the dangerous overstresses. As we have seen, the dedicated driver allows the power application designer to be safe in terms of accurate gate-source voltage control, dead-time management, spurious turn-on control, and driver asymmetry; a number of additional capabilities complete an important basket of crucial features which can be found in this new class of integrated drivers for GaN devices, delivered into the most miniaturized footprint.

Literature

[Naik] H. Naik, "4H-SiC Lateral MOSFETs on (0001), (000-1) and (11-20) oriented SiC substrates" Master's Thesis, Rensselaer Polytechnic Institute, Troy, NY, 2009.

[LM5113] National Semiconductor datasheets "5A, 100V Half-Bridge Gate Driver for Enhancement Mode GaN FETs", Power Electronics Europe 5/2011, pages 14-16

[Briere] "GaN-based power devices offer game-changing potential in power-conversion electronics" Michael A. Briere, ACOO Enterprises LLC

[Strydom] "How 2 Get the Most Out of GaN Power Transistors" by Johan Strydom, Efficient Power Conversion, El Segundo, Calif

[Microsemi] "Gallium Nitride (GaN) versus Silicon Carbide (SiC) In the High Frequency (RF) and Power Switching Applications" Microsemi application note.