GaN Power Devices for Micro Inverters

GaN power products are set to have a direct impact on future efficient PV solar inverter/converters. By reducing losses in each stage of the power conversion, GaN based devices will help in increasing total energy harvesting. The integration with driver ICs and other components will drive the size reduction and high volume commerzialisation. **Alberto Guerra and Jason Zhang, International Rectifier, El Segundo, USA**

The PV industry has shown various trends for increasing overall conversion efficiency as well as maximizing the harvesting of solar energy. The specific trend toward an intelligent PV panel requires high efficiency, high reliability and low cost. "In-situ" conversion and "in-situ" pre-regulation with micro-inverters/converters require highly efficient DC/DC stage.

All topologies based on Silicon MOSFETs have intrinsically limited improvement capabilities. Based on state-of-the-art active components and passive components, constrained integration opportunities pose a limit to the technology evolution. Gallium Nitride (GaN) based switches, have a better figure of merit (FOM) than other power components based on Si (Silicon) or SiC (Silicon Carbide) material (Figure 1).

The potential improvement exploitable from the GaN technology is large, based on the material limits. The primary conversion stage of micro-inverters and micro-converters can be designed around well known topologies (Fly-Back, Full Bridge or Buck-Boost). To improve overall conversion efficiency, all these topologies require the power MOSFETs with the lowest possible specific $R_{ON} \times Q_G$ FOM. GaN based MOSFETs show great potential in FOM improvement over the coming years (Figure 2).

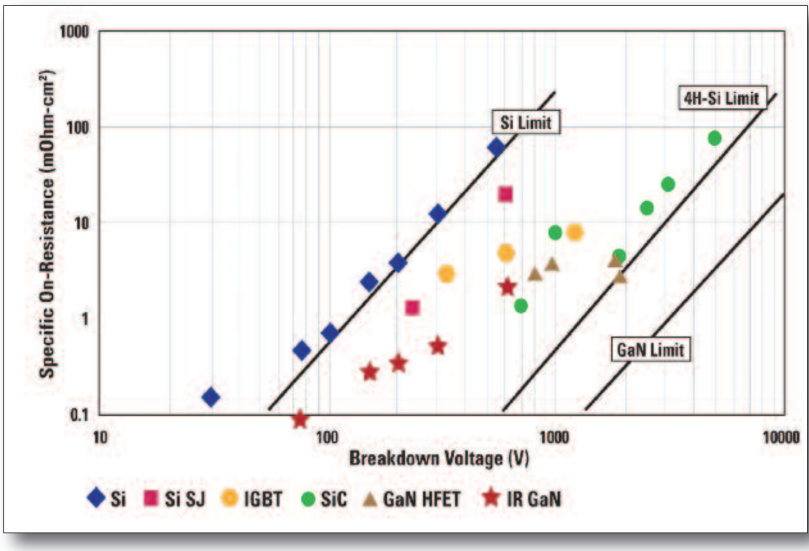

Figure 1: **Comparison of Specific R_{ON} for Si, SiC and GaN.**

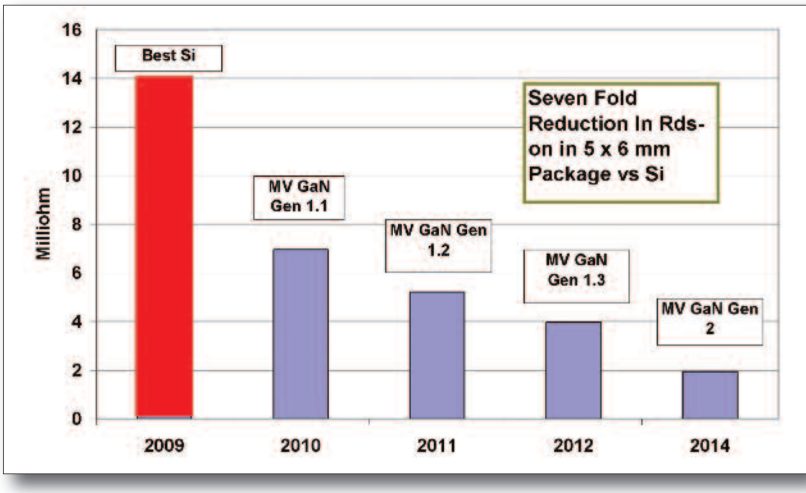

Figure 2: **Possible 150V GaN FOM projection vs. Si MOSFET**

Practical impact of GaN technology in PV applications

GaN technology is characterized by an intrinsic lateral structure, which simplifies packaging by virtually eliminating parasitic elements of wire-bonding stray inductance and parasitic resistance. Moreover, it enables possible integration of multiple switches and driver IC function with protection and monitoring elements within common packaging or monolithic solutions. The integration capabilities of GaN technology can simplify and reduce the cost of design and construction of power circuits for solar inverter applications.

The expansion of small and mid-size solar installation is opening new alternative venues diverging from the traditional central inverter architecture. Adopting a distributed inverter architecture, micro-inverters or dc-dc solutions, certain advantages over the traditional centralized architecture, are made possible and, among them, the ability to implement maximum power point tracking (MPPT) at the panel level. In addition, these distributed solutions are required to process only the power generated by a single PV panel, typically in the range of 200W; this specific characteristic is opening the possibility for higher degree of power semiconductor integration that in

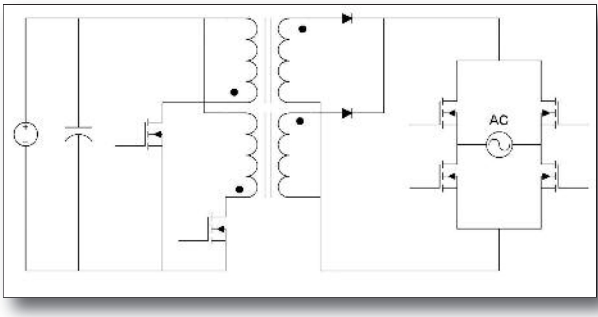

Figure 3: Micro-Inverter simplified schematic

return is going to drive the unit cost down.

A similar trend in power semiconductor integration occurred in the appliance industry a few years ago. More environmentally friendly government energy saving regulation has driven manufacturers of motor drivers and power semiconductors alike, to develop and adopt advanced system integration solutions that have radically reduced the number of components, increased reliability and dramatically reduced costs delivering on the energy savings targets.

In this article we analyze the practical impact of IR GaN technology, when applied to the primary stage of a 200W micro-inverter module and when used in the buck-boost circuit of a power-optimizer DC/DC module, replacing traditional power MOSFET switches. The 200W micro-inverter (DC/AC) used for the comparison and GaN switch evaluation is manufactured by Enphase Energy, while the DC/DC Power Optimizer utilized for the buck-boost topology evaluation, is manufactured by SolarEdge. Both systems, intended for "in-situ" single PV panel connection, have the MPPT (maximum power point tracking) function performed for each panel. Module-level MPPT is generally considered to be faster and more optimal than tracking done at the level of a centralized inverter allowing it to better follow changes in sun irradiance due to environmental factors or weather factors.

Further examples are presented to illustrate the future improvement achievable by applying the GaN technology, in this case high-voltage applications, in centralized inverters with transformer-less advanced topologies.

150V GaN in Flyback converter

Enphase is the leading micro-inverter supplier. Its inverter module is mounted on the back of each solar panel, and its AC output can be directly connected to the AC wiring at any household. This eliminates the high voltage DC wiring, and enables a safe and simple installation.

The simplified circuit diagram of the micro-inverter is shown in Figure 3. An interleaved two-phase Flyback converter is

	Rdson	Qoss	Qgd	Qg	Qrr	BV
IRFS4321	12mΩ	36nC	16nC	71nC	150nC	150V
GaN MV05	5mΩ	55nC	8nC	22nC	5nC	150V
GaN Gen1.1	5mΩ	35nC	5nC	15nC	3nC	150V

Table 1: Si Power MOSFET and GaN switch comparison

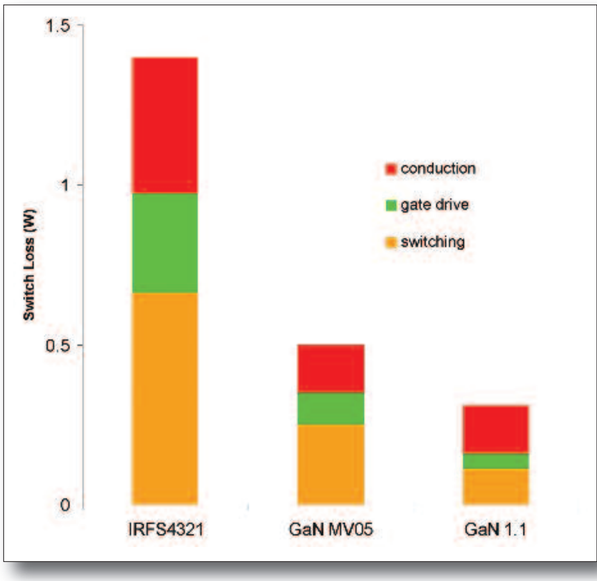

Figure 4: Primary switch power loss breakdown at 170W

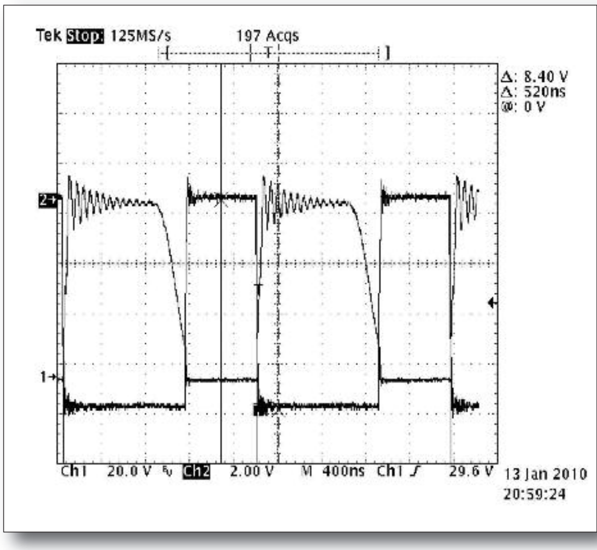

Figure 5: GaN switching waveforms (V_{ds} and V_{gs})

followed by an inverter bridge. The performance is compared by replacing the primary switches with GaN devices. Table 1 compares the parameteric differences between Silicon and GaN switches. GaN MV05 is the sample that is used in this study. GaN Gen1.1 represents GaN device that would be made available later this year. It is obvious that GaN has a significant FOM advantage over Silicon at 150V, which translates into major $R_{ds(on)}$ and Q_g reduction with smaller die size.

The IRF4321 is a D2Pak power MOSFET while the GaN switches are smaller enough to be housed in a much smaller PQFN package (5mm x 6mm). PCB layout was not fully optimized to take advantage of the smaller footprint but simply for a fast drop-in replacement.

A power loss modeling is performed to understand the loss breakdown and explain the performance. Shown in Figure 4, significant power loss reduction of the switch has been predicted from the simulation due to fast switching, low $R_{ds(on)}$ and reduced package parasitic. As illustrated in Figures 5 and 6, much cleaner switching waveforms have been observed in the circuit, even when GaN switches faster. This is contributed by the lateral nature of GaN power device and how it is packaged. Also thermal pictures were taken. At 160W, GaN is slightly warmer (64°C vs. 57°C) even with reduced power loss. This is due to much smaller package size of PQFN comparing to D_Pak.

The measured efficiency (with constant DC voltage of 300V feeding the second stage H-Bridge), is shown in Figure 7. Due to other losses in the circuit, the power loss reduction due to the primary switch is translated into 0.6% efficiency improvement at the system level. With the optimized Gen1.1, power loss will be reduced by another 20% for the switch, which will reduce the temperature rise of 5mm x 6mm PQFN package.

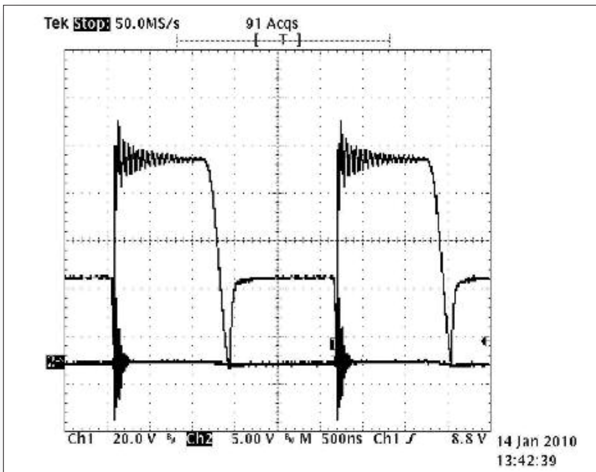

Figure 6: D²Pak MOSFET waveforms (V_{ds} and V_{gs})

150V GaN power optimizer DC/DC stage

SolarEdge, another leader with innovative solutions for PV solar power management, offers a different architecture. Its DC/DC Optimizer module is mounted on each solar panel with local MPPT, and the output of multiple panels will be connected in series. The resulting high-voltage DC bus is distributed to a central inverter (without MPPT internal stage), which feeds AC power into the grid. This implementation also simplifies installation and provides excellent overall efficiency and performance. The Power Optimizer is designed to work with a standard Silicon based PV panel as well as a Thin Films PV panel. The example analyzed in this case is for Si-based PV panels with average output voltage of 40V.

Buck-boost topology (Figure 8) is used in each DC/DC converter module, which has the ability to regulate its output voltage above or below the panel voltage. The comparison study was done through simulation. All four switches are replaced with mid voltage GaN devices.

Table 2 compares the parametric differences between a Silicon MOSFET and a GaN switch. GaN MV05 is the sample that is used in this study. Even with 50V voltage rating difference, GaN still offers significant $R_{ds(on)}$ reduction with smaller die size. GaN Gen1.1 represents a 100V GaN device that would be released later this year.

The overall efficiency of the power stage of the power optimizer module, based on

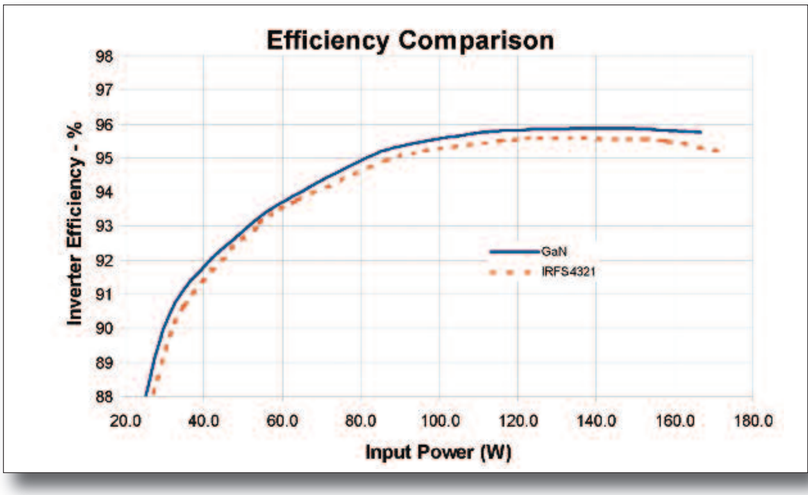

Figure 7: Single phase efficiency comparison at constant DC bus voltage of 300V

the sun irradiation model has been simulated and shown in Figure 9. With the improved switches, the power loss is reduced almost by half, and DC/DC converter efficiency is approaching 99% due to significantly reduced gate charge and $R_{ds(on)}$ and the lack of body diode reverse recovery loss.

The centralized inverter (without MPPT functionality) adds 1.5 to 2% efficiency loss in the final conversion process of feeding the electric power into the AC grid, with an estimated total conversion efficiency ≥ 97.5%. GaN HV MOSFETs, can provide further efficiency improvement to the system string inverter as well as to the micro-inverter H-bridge.

GaN switch in transformer-less topologies

Recent studies have demonstrated the possibility to achieve ~99% peak efficiency in transformer-less PV inverter designs when specific topologies like Heric, H5 or 3-level half bridge and SiC JFETs are employed. When traditional Silicon IGBTs and/or Super Junction HV FET are used, the peak efficiency can reach ~98%.

Prototypes of HV GaN MOSFET (75mΩ/650V) in a TO-220 package (Cascode configurations) were tested in switching mode to compare turn-on and turn-off performance vs. traditional Trench IGBT and Super Junction HV FET. The reverse recovery time of the GaN MOSFET body diode is less than 19ns and the turn-off energy 24μJ (E_{off} SJ = 38μJ, Trench IGBT = 830μJ).

Compared to the Super Junction and IGBT technology, the recovery time was 270ns and 140ns (with recovery current of 38A and 13A). In PV inverters efficiency is no longer the problem to solve; however the cost to achieve it is the problem. Because the GaN Epi is grown on Si substrates, large diameters (6 to 12") are readily available in large quantities at low cost ~ $ 0.50/cm². SiC JFETs, used to demonstrate >98% efficiency in traditional string inverters, are available only in smaller 4" substrates (projected at 6" in 2013), which has a cost of ~20$/cm².

	Rdson	Qoss	Qgd	Qg	Qrr	BV
IRF6644	10.3mΩ	34nC	11.5nC	35nC	69nC	100V
GaN MV05	5mΩ	55nC	8nC	22nC	5nC	150V
GaN Gen1.1	5mΩ	25nC	4nC	10nC	2nC	100V

Table 2: Parametric differences between a Silicon MOSFET and a GaN switch

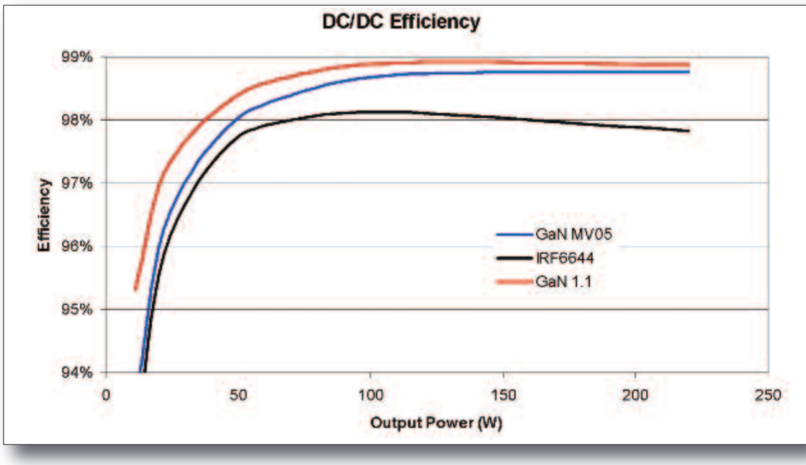

Figure 9: Buck-boost efficiency at 40Vin

GaN on Si substrate is compatible with established high volume manufacturing facilities and equipment and has the potential to deliver the proper performance/cost benefit.

Conclusions

Improvements in total efficiency in innovative PV solar power DC/AC inverter and DC/DC converters have been demonstrated. Performance comparison of high voltage normally-off GaN FETs versus Silicon based devices has been presented. Further work is planned to evaluate final GaN product in optimized application layout as well as in the HV output stage of micro-inverter and string inverter. The possibility to operate GaN switches and diodes at higher frequency, offer the possibility to replace the large and expensive inductors used today, with smaller and hence cheaper ones. The new IR GaN technology when coupled with advanced MCM packaging technology and HV driver IC will enable designers of micro-inverters or power converters or centralized PV inverters, to design, make and market better, cheaper and more efficient products.

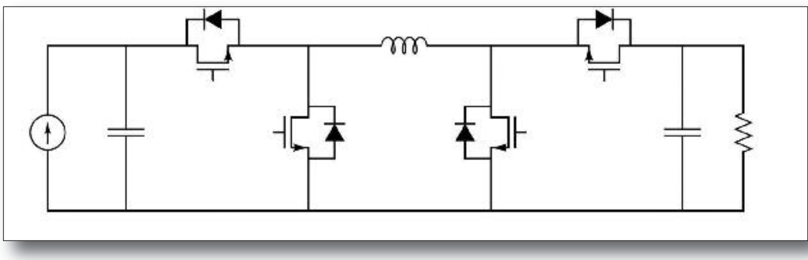

Figure 8: Buck-boost schematic

Literature

Alberto Guerra: "(GaN)-based power device technology and its impact on future Efficient Solar grid connected micro-inverters, power optimizers and string inverters", PEE Special Session "Power Electronics for Efficient Inverters in Renewable Energy Applications", PCIM Europe 2010, May 4, Room Paris