Progress of GaN Transistors

Over the last several years, GaN semiconductors have emerged as a leading technology enabler for the next wave of compact, energy-efficient power conversion systems – ranging from ultra-small adapters, high-power-density PCs, server and telecom power supplies, to highly efficient PV inverters and motion control systems. Continuous progress has been made since the JEDEC qualification of Transphorm's 600 V-rated GaN-on-Si devices in 2013. Systematic voltage-accelerated off-state stress tests and temperature-accelerated on-state stress tests reveal an intrinsic Mean Time to Failure (MTTF) of 8x107 and 3x107 hours at the rated voltage and rated temperature respectively. **Yifeng Wu, Sr. VP Engineering, Transphorm Inc., Goleta, USA**

The TPH3205WS is a first 600V GaN (Gallium Nitride) transistor in a TO-247 package. Offering 63 mΩ on-resistance and 34 A current rating, the device utilizes the source-tab connection design, which reduces EMI at high dv/dt to enable low switching loss and high-speed operation in power supply and inverter applications. An already demonstrated 2.4kW, bridgeless totem-pole PFC design exhibits near 99 % PFC efficiency at 100 kHz operation. The totem-pole PFC, when combined with a GaN-based DC/DC conversion stage, enables a simplified 80 PLUS titanium power supply design providing power densities unachievable with Si-based devices. A static demo of the TPH3205WS used in a 3 kW inverter shows a peak efficiency of 98.8 % at 100 kHz and over 99 % at 50 kHz switching frequency.

Automotive applications with GaN

There has been also strong interest in developing GaN power devices for automotive applications due to the physical arguments of their potential benefits for next generation vehicles. However, most previous reports have been consumed with discussion of device structures, characteristics and challenges in achieving reliability. In passing JEDEC qualification of 600-V rated GaN transistors, reliability can now be assessed to justify GaN's suitability for the stringent automotive applications. Although it will take more time to develop mature manufacturing of high current GaN devices for the main motor drive in an Electric Vehicle (EV), it is now attractive to employ present GaN switch products for auxiliary power blocks up to 6 kW.

Present 600V GaN switch products are well suited to auxiliary power converters due to the improved figure of merit over Si devices and the special ability to perform all the functions of a MOSFET or an IGBT plus a freewheel diode. This is especially attractive for on-board chargers in an EV to deliver bi-directional power flow, which not only serve as a charger but can provide electricity from the EV battery to a camping ground or to one's home in a power outage. A unique topology as shown in Figure 1 can be controlled to be a bridge-less PFC with very high efficiency. The same circuit can also be controlled to reverse the power flow to function as a DC/AC inverter. A performance evaluation was carried out using a half bridge by two 600-V-rated GaN HEMT switches in TO247 with on-resistance of 50 mΩ. These devices are capable of >3.3 kW output power and two interleaved phases can provide >6.6 kW.

The half bridge circuit was first configured as a boost converter driven in synchronous rectification with result shown in Figure 2. The boost ratio is 240 V:400 V and the PWM varies from 100 to 300 kHz. The inductor was made of a Koolmu core with L=268 μH and wire DC resistance of 20 mΩ, sized for continuous current mode in most of the operation range. The input and output storage capacitors are 15 μF and 5 μF respectively. The heat sink and thermal insulator assembly were tested to have an ambient-

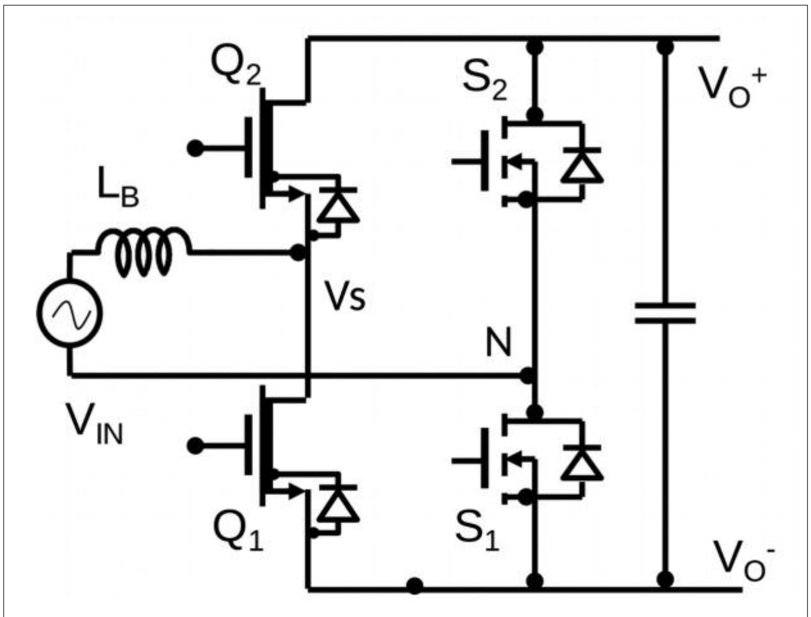

Figure 1: A Totem-pole circuit which can be controlled as either an AC/DC PFC or a DC/AC inverter for reverse current flow. Q1 & Q2 are fast GaN devices (operating at 100-300 kHz) and S1 and S2 are Si MOSFETs (operating at 50-120 Hz). This design can be an efficient front end of a bi-directional on-board EV battery charger

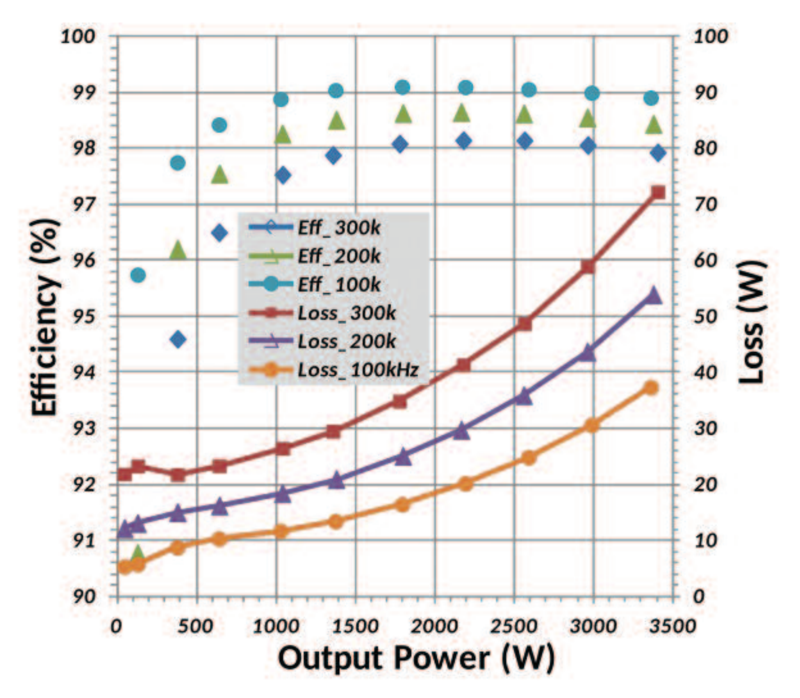

Figure 2: Experimental test result of a half bridge operating as a boost converter using two 50 m?, 600-V rated GaN HEMTs in TO247 packages. The devices are driven in sync-rec mode at boost ratio 240 V:400 V achieving peak efficiency >99 % at 100 kHz and >98 % at 300 kHz, respectively

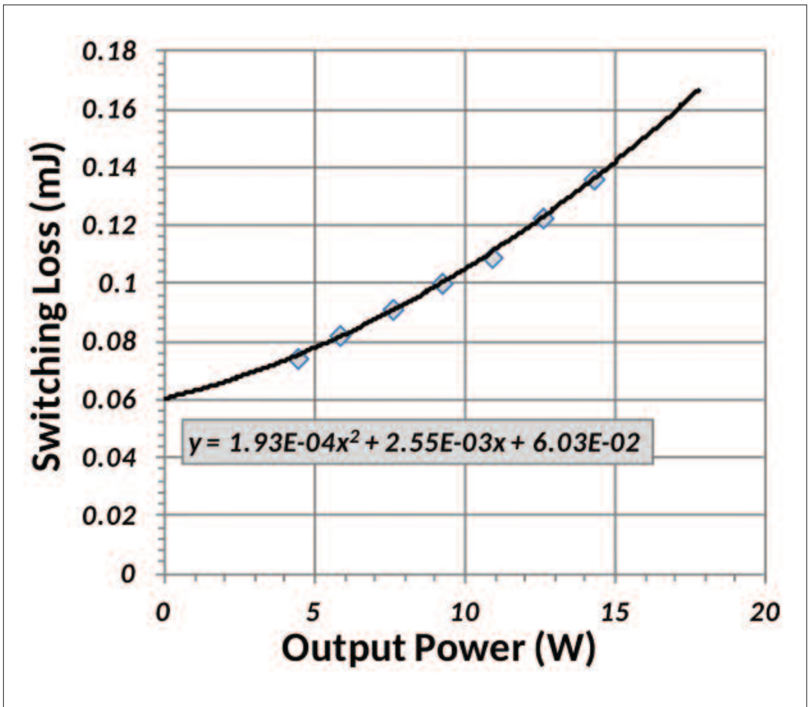

Figure 3: Switching loss (including turn-on and turn-off) as a function of current at 400 V for the 600-V, 50 m? GaN half bridge converter

to-case thermal resistance of 2.7 K/W for each device, while the junction-to-case thermal resistance of each packaged device is 1 K/W. All circuit losses are included in the performance plot and each data point was captured after thermal equilibrium in an air ambient of 25°C. As already mentioned above the converter delivers >3.3 kW output power with a peak efficiency >99 % at 100 kHz and >98 % at 300 kHz respectively. This high level of performance is not possible with Si devices at such high PWM frequencies, which is key to a compact circuit and system design.

With the data available at various inductor current levels and frequencies, as well as the magnetic losses of the inductor at corresponding frequencies and voltage excitations tested in a separate fixture, the switching losses as a function of current is then extracted as seen in Figure 3. This together with the thermal characteristics of the device and the heat-sink assembly allows the construction of a simulation model to predict performance including loss breakdown and junction temperature as a function of power and frequency. The modeling result is verified in Figure 4 with almost identical overlaps of experimental data.

At 100 kHz, the high device efficiency well above 99 % up to full load translates to a total device dissipation of only 28 W at the output power of 3.4 kW, resulting in a junction temperature of 76°C. It is device physics that switching losses increase at higher frequencies for any semiconductor. The merit of GaN is to extend that to a much higher frequency while maintaining a reasonably low loss to prevent overheating. The GaN half bridge has no issue operating at 3.4 kW and 300 kHz with a junction temperature 140°C, well below the 175°C specification limit. Compared to traditional Si devices at 12-50 kHz, the GaN transistors open up a large design space

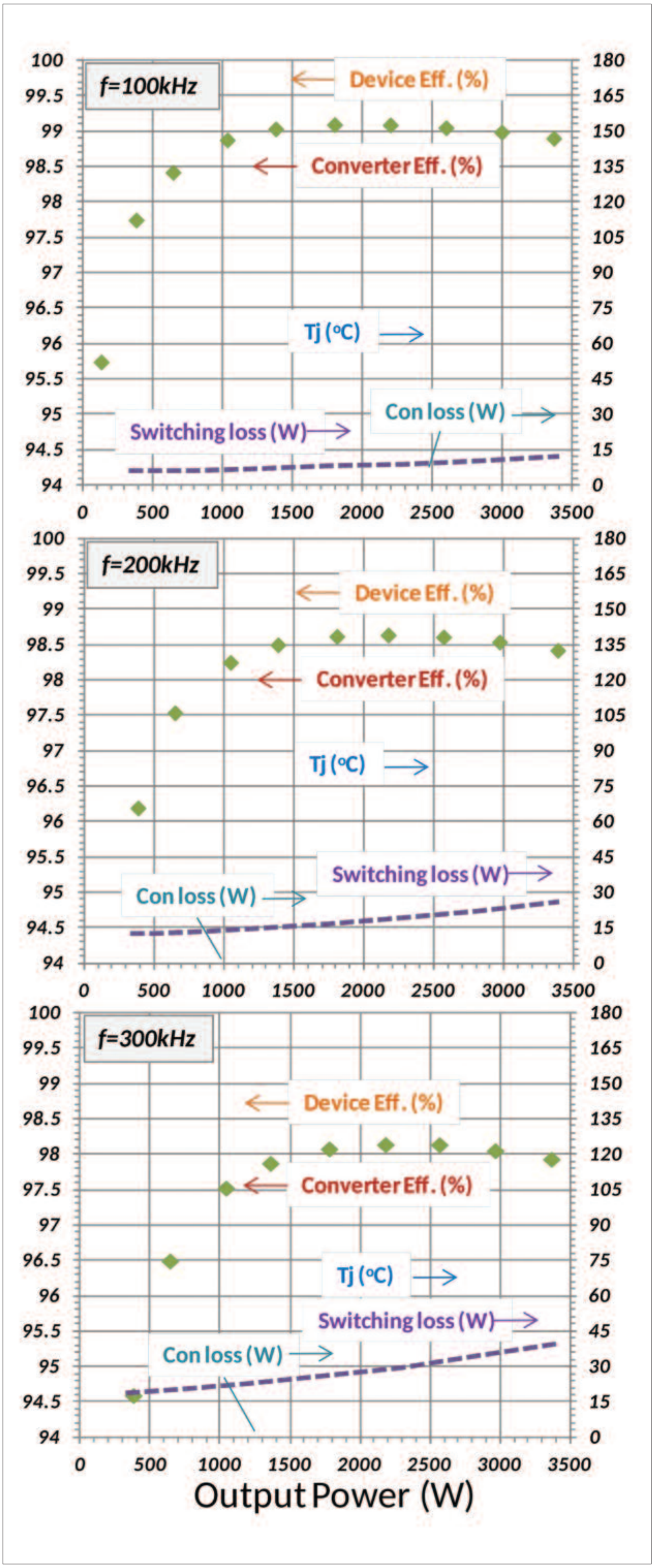

Figure 4: Modeled result of the GaN half bridge converter with experimental data in green diamonds to confirm validity. PWM frequencies were 100, 200 and 300 kHz, respectively. The heat-sink thermal resistance from package to ambient is 2.7 K/W for each device and ambient temperature 24°C

for designers striving for compact power circuits.

GaN and cooling

There is a strong interest with EV makers to consolidate all cooling systems in a vehicle into an integrated one, where the fluid temperature could be as high as 105°C. The same sim7ulation model is applied to such a case assuming a conservative case-to-fluid thermal resistance of 1.5 K/W for each device package (a total of 2.5 K/W from junction to fluid). The inductor was assumed to have a magnetic loss of 3 W and a DC resistance of 20 mΩ which can be made small at high frequencies. Input and output passives were assumed to have 10 mΩ series resistances respectively. The test results using PWM frequencies 50, 100 and 200 kHz show that even in such a stringent situation the GaN half bridge is comfortable operating at 50 kHz and 100 kHz, with a maximum junction temperature of 140°C and 150°C respectively, well under the 175°C limit. At 200 kHz, full load junction rises to 165°C with a headroom of 10 K. This results show great promise for such applications although actual tests need to perform for in-system validation.

Conclusions

GaN high voltage devices turned a new leaf after the first product qualification in 2013 and have now shown systematic intrinsic reliability data that aligns to automotive applications. An analysis based on experimentally validated model indicated outstanding performance for the GaN bridge topology in compact on-board bi-directional EV chargers operating at much higher PWM frequencies than that of typical Si-based circuits, even at elevated coolant temperatures up to 105°C. Although to achieve and to maintain mature manufacturing similar to today's Si still require investment and time, there is little doubt that these new power devices will help open up a new design space for attractive future products in this industry.

Literature

Wu, Y: "Progress of GaN Transistors for Automotive Applications", PCIM Europe 2015, Special Session "Power GaN in Automotive Applications"