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Commentary

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Breakthrough In Dynamic $R_{DS(ON)}$ Is Making 1200-V E-Mode GaN FETs Viable

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E-mode GaN-on-Si FETs, with their low on-state resistance and fast switching capabilities, have emerged as promising candidates for the next-generation power switches. Compared with SiC MOSFETs, GaN-on-Si switches offer much lower substrate and manufacturing costs, due to their perfect compatibility with the well-developed silicon CMOS technology, which has been further leveraged by the recent success of Infineon's 300-mm GaN-on-Si technology.

These advantages have led to a rapidly growing demand for GaN-on-Si switches in various power applications, such as electric vehicle (EV) chargers and traction inverters; renewable energy systems; and consumer, server, telecom and industrial power supplies. The market has witnessed the successful adoption of GaN-on-Si FETs (with voltage ratings up to 650 V) especially in consumer electronics, providing a strong foundation of confidence for the reliable deployment of higher-voltage GaN devices in more demanding power applications.

Automotive Industry: A Catalyst For 1200-V GaN FETs

The automotive industry, especially with the rise of EVs, is a primary driver for 1200-V GaN technology. As EV manufacturers transition towards higher-voltage systems (like 800-V batteries), there is a growing requirement for power conversion devices that can handle these voltages efficiently and cost effectively.

There are a few other major power semiconductor companies developing 1200-V GaN FETs using the cascode structure or GaN-on-sapphire technology. However, the cascode structure will sacrifice the GaN transistor's fast-switching capability and induce additional parasitics while sapphire substrates have much worse thermal conductivity than silicon that make them unsuitable for high-power applications.

E-mode GaN-on-Si FETs are still particularly advantageous due to their reduced costs, enhanced efficiency, and higher power density, which are essential for onboard chargers, dc-dc converters, and drive inverters in EVs. The efficiency gains from using GaN FETs can lead to extended vehicle range and reduced charging times, making EVs more appealing to consumers.

GaN-On-Si Challenges: Vertical Leakage And Current Collapse

However, developers of GaN-on-Si technology have found it challenging to further increase the breakdown above 1 kV, due to the low critical electric field of the silicon substrate and high defect density in the epitaxial GaN buffer.

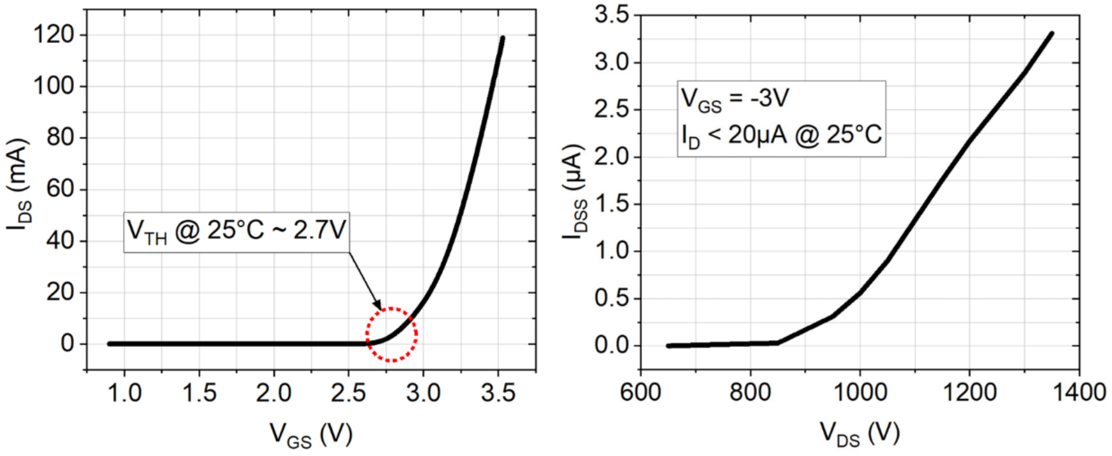
GaNPower (GPI) has pioneered advancements by limiting vertical leakage of substrate and buffer layers to achieve up to 1500-V breakdown voltages for e-mode GaN-on-Si FETs (see the reference). However, another challenge remains: maintaining excellent switching performance at high bus voltages. Effective switching, crucial at bus voltages of 800 V or higher, requires the dynamic drain-source on-resistance ($R_{DS(ON)}$) to stay close to its static value.

Industry and academic studies have indicated dynamic $R_{DS(ON)}$ dispersion and current collapse occur in GaN FETs under high-voltage operation, especially when blocking voltages surpass 700 V. This complicates high-voltage and high-current applications, such as in EV motor drives, due to the increased device heating and efficiency losses. This increase in dynamic $R_{DS(ON)}$ is due to defects and traps in the GaN/AlGaN epi-layers grown on silicon or sapphire substrates, forming a virtual-gate that interacts with conduction electrons, preventing full channel activation.

Integrating All-GaN-IC For Improved Dynamic Performance

GaNPower has addressed these issues in its third-generation 1200-V technology by developing an innovative all-GaN-IC technique (patent pending). A proprietary GaN-based gate regulating circuit has been monolithically integrated with the power GaN FETs in a single chip, in order to mitigate the effects of these defects and traps. Combined with a previous advanced packaging solution (see the reference), this all-GaN-IC innovation significantly enhances the dynamic switching performance under high-voltage operation (800 V or higher) without considerably compromising the breakdown voltage, which makes cost-effective single-chip 1200-V e-mode GaN-on-Si FETs viable.

GaNPower recently demonstrated robust dynamic switching performance in its third-generation 1200-V 20-A GaN FET across a wide bus voltage range (up to 1 kV), handling a switching current of 20 A. According to the typical I_d-V_g and off-state I_d-V_d curves shown in Fig. 1, the gate threshold voltage has been enhanced to 2.7 V while the good breakdown characteristics were preserved.

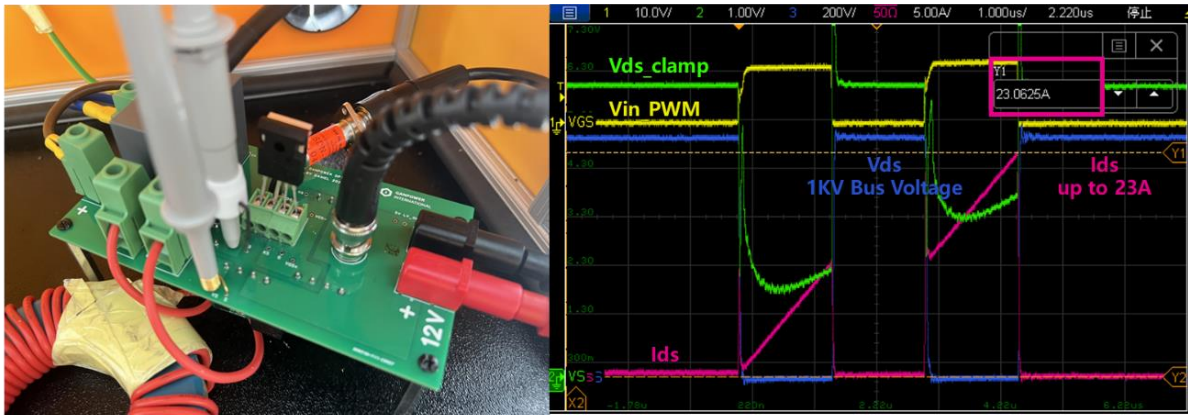


(a) (b)

Fig. 1. Typical I_d-V_g (a) and off-state I_d-V_d (b) curves for GaNPower's third-generation 1200-V/20-A GaN FETs with advanced packaging solution to enhance breakdown voltage and monolithic all-GaN-IC to enhance dynamic switching performance and gate threshold.

Demonstrating Dynamic Performance Of Monolithic 1200V GaN-On-Si FETs

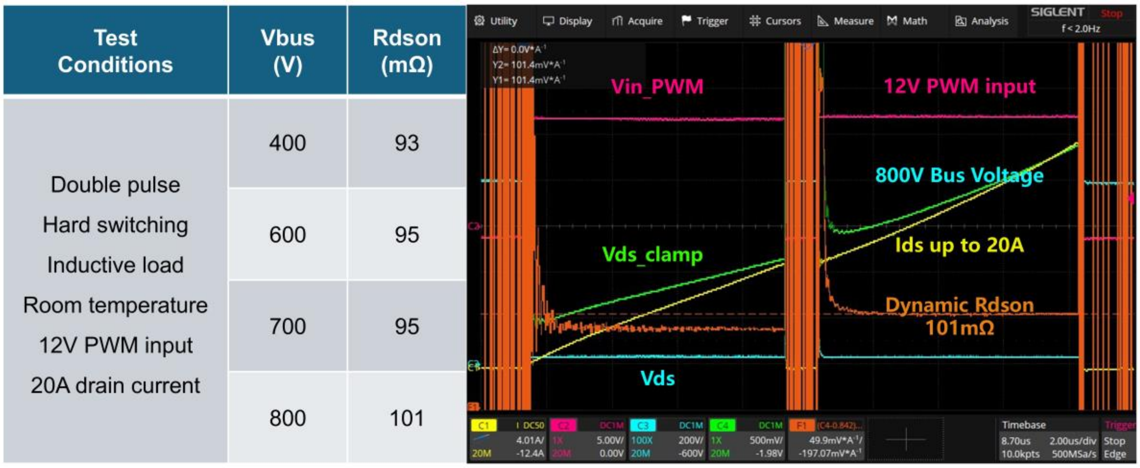
A customized DPT (double-pulse testing) platform, as shown in Fig. 2a equipped with a reliable voltage clamp circuit for accurate dynamic $R_{DS(ON)}$ measurement, was used to evaluate the burst-mode dynamic switching performance of GPI's third-generation 1200-V 20-A GaN FETs. With 12-V PWM input, 1-kV bus voltage, and up to 23-A drain current, all the switching waveforms, as shown in Fig. 2b, are quite clean without considerable ringing or overshoots.



(a) (b)

Fig. 2. One GPI third-generation 1200-V/20-A GaN FET is tested on a customized DPT platform equipped with an accurate dynamic $R_{DS(ON)}$ extraction module (a). DPT results at 23-A drain current and 1-kV bus voltage demonstrate good switching performance under high voltage and current conditions at 25°C.

The dynamic $R_{DS(ON)}$ values under various voltages (400 to 800 V) at the device's rated current (20 A) have been extracted and summarized in Fig. 3a. A less than 10% increase in the $R_{DS(ON)}$ from 400-V to 800-V bus voltage demonstrates a successful mitigation of dynamic $R_{DS(ON)}$ dispersion.



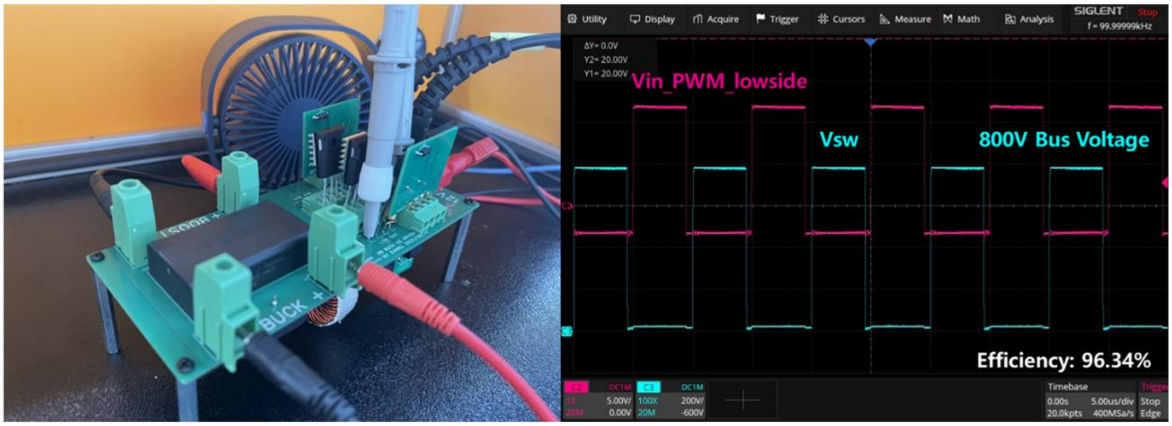
Test Conditions	Vbus (V)	Rdson (mΩ)
Double pulse Hard switching Inductive load Room temperature 12V PWM input 20A drain current	400	93
	600	95
	700	95
	800	101

(a) (b)

Fig. 3. Dynamic $R_{DS(ON)}$ test conditions and results summary for a GPI third-generation 1200-V/20-A GaN FET under various bus voltages (a). DPT switching waveforms for a GPI third-generation 1200-V/20-A GaN FET at 20-A drain current and 800-V bus voltage with the extracted dynamic $R_{DS(ON)}$ result (b).

A customized half-bridge buck testing platform with a high-saturation toroidal power inductor and a constant 128-Ω high-power resistor load, as shown in Fig. 4a, was built for the continuous hard-switched evaluation. Two GPI third-generation 1200-V 20-A GaN FETs with suitable heat sinks were installed on the main test board and proper fan cooling was used during the tests.

With a 100-kHz switching frequency, 12-V PWM input and 800-V bus voltage, the buck converter achieved a peak efficiency of 96.34% at a maximum power input of 1 kW (limited by lab equipment). Fig. 4b demonstrated good continuous hard-switching waveforms without substantial ringing and overshoot at an 800-V bus voltage.



(a) (b)

Fig. 4. Customized half-bridge buck evaluation platform where two GPI third-generation 1200-V/20-A GaN FETs were tested under continuous hard-switching (a). 100-kHz hard-switching waveforms at 800-V bus voltage and 1-kW input power (b).

The Path Forward For 1200-V E-Mode GaN FETs

More rigorous reliability qualification testing on a large scale of GPI's 1200-V 20-A GaN FETs is in progress to make sure the third-generation 1200-V technology is reliable and optimized in practical industry applications. However, results obtained to date confirm that GaNPower's third-generation 1200-V technology, integrating advanced packaging with the all-GaN-IC technique, considerably enhances the breakdown voltage of e-mode GaN-on-Si FETs while preserving good dynamic switching performance under high-voltage operation (800 V or higher). Engineering samples of GPI's 1200-V, 20-A GaN FETs in a TO247-4 package are now available for selected customers to evaluate in their applications.

Reference

"Packaging for Lateral High Voltage GaN Power Devices," U.S. Patent 11,107,755 B2, Li et al.

About The Authors

Daniel Wan is the principal engineer at GaNPower International where he leads a team dedicated to the verification, evaluation, and optimization of discrete GaN switches and GaN-IC modules, with a focus on high-voltage and high-power applications. Daniel is also a Ph.D. candidate in materials engineering at the University of British Columbia and has extensive experience with GaN HEMT processes, testing, and applications. He can be reached at daniel@iganpower.com.

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