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Extended Abstracts of the 2012 International Conference on Solid State Devices and Materials, Kyoto, 2012, pp889-890

GaN Power Electronics and Applications

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1. Introduction

With GaN-based power devices for microwave applications commercially available on the market [1], the development of GaN-based transistors and diodes in power electronics for electric power conversion has gained primary focus[2][3]. The low on-resistance and high working frequency characteristics of GaN devices enable high conversion efficiency leading to energy savings. Here we report the new development of 600V class GaN power diodes and transistors for power conversion applications.

2. GaN devices – Diodes and Transistors

GaN epitaxial layers were grown by MOCVD on 4"-6" Si substrates for low cost production. These epitaxial layers were developed to achieve both a high breakdown field and a low channel resistance. Depletion mode GaN-based HEMTs and Schottky barrier diodes were then manufactured in our fabrication facilities.

The GaN diode employs a Schottky barrier and also takes advantage of the low-resistance 2-DEG conduction layers. The DC forward voltage (Vf) at 6A is about 1.3V while dynamic Vf measured immediately after a cathode bias of 500V is less than 20% different from DC value. The typical off-state leakage curves of a 6A diode are shown in Fig.1a. The reverse leakage at 600V is about 5-20μA at room temperature and is maintained below 400 μA at 150°C.

The typical off-state drain leakage and gate leakage of 0.11Ω HEMTs are shown in Fig.1b. At V_D=600V, the room temperature drain leakage is <100nA and gate leakage is <20nA. At 150C, the typical drain leakage is <10μA and gate leakage is about <1μA. Good dispersion control is the key to achieve a low on-resistance in switching operation. The increase of dynamic on-resistance from static to 500V is less than 20%.

3. Packaged device characteristics

The Schottky barrier GaN diode in TO-220 has a dynamic forward voltage of <1.6V at 6A and 25°C. Pulsed current is 60 A at 25 °C and continuous current is rated as 9A at 100 °C and 6.2A at 125°C.

The normally-off transistor solution was achieved with a hybrid approach at the package level. As shown in Fig.2, a normally-off low-voltage Si FET was connected to normally-on high-voltage GaN HEMT in series while the gate of the GaN HEMT was connected to the source of the Si FET. This hybrid configuration produced an over-all device with positive threshold voltage, safe in case of faulty gate control. Moreover, it provides the compatibility with existing Si drivers, as well as the freedom to optimize the high voltage GaN HEMTs without complication for input circuits.

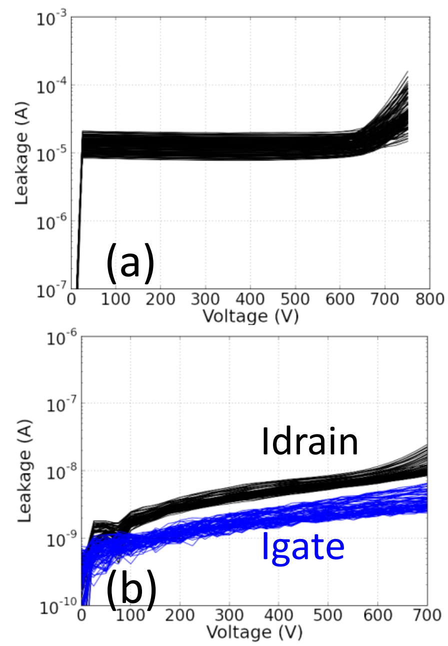

Figure 1. (a) Leakage curves of a 6A,600V GaN diode. (b) Drain and gate leakage curves of 0.11Ω GaN HEMT.

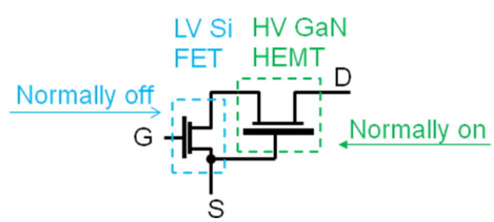

Figure 2. Schematic diagram of the hybrid approach for enhancement-mode FET, using D-mode HV GaN HEMT and E-mode Si FET.

The hybrid GaN HEMT in TO-220 has a gate threshold of +2.1V typical at 1mA drain current and the drain leakage is less than 10 μA at V_G=0V and V_D=600V. The dynamic on-resistance is 0.15Ω typical and 0.18Ω maximum. The pulsed drain current is 70 A at a V_G=8V and V_D=10V. The continuous drain current is 14A at a case temperature of 25 °C.

Compared with similarly-rated state-of-the-art Si super-junction MOSFETs on the market, this first generation GaN-on-Si HEMT has better performance in on-resistance, gate charge and output charging energy.

4. Converter and Inverter applications

A continuous-mode 230V-400V dc-to-dc boost converter built with total GaN solution using a 0.15Ω GaN HEMT and 4A GaN diode, both fabricated on Si substrate, is shown in fig.3a [4]. The circuit implementation features a

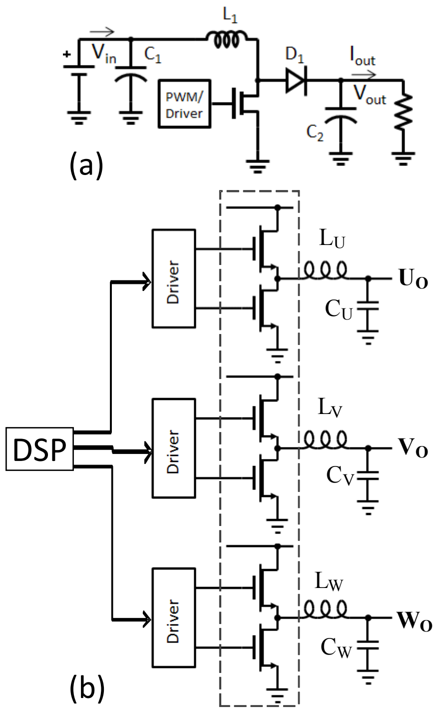

Figure 3. (a) Boost converter with GaN Diode and HEMT at ratio of 230V:400V at 100kHz (b) Motor Drive Inverter with GaN HEMT at 16kHz.

text-book like design with no gate compensation networks and snubber. The switching action as observed from an oscilloscope is fast yet with little spikes. The peak efficiency of >99% is achieved at an output power of 400-600W (Fig.4a). The efficiency maintains above 98.8% from 200 W to 1250W. Our extensive tests with state-of-the-art Si counterparts in the same converter circuit indicated these first-generation GaN-on-Si devices reduced device loss by 25-50%.

The hybrid GaN HEMT is also capable of diode-free hard-switched bridge applications at high frequencies. 600-V 6-in-1 power modules with on-resistance of 150 mΩ per switch were developed for operation at 100 kHz and higher. The high PWM frequency allows integration of compact output filters resulting in a 3-phase pure-sine-wave inverter (Fig. 3b) for PV or motor drive application. An actual motor operation test at 100-kHz PWM has revealed significant electro-mechanical efficiency boost by the GaN inverter by 8%, 4% and 2% at low, mid and high load respectively, compared to a state-of-the-art IGBT inverter at 16 kHz (Fig.4b).

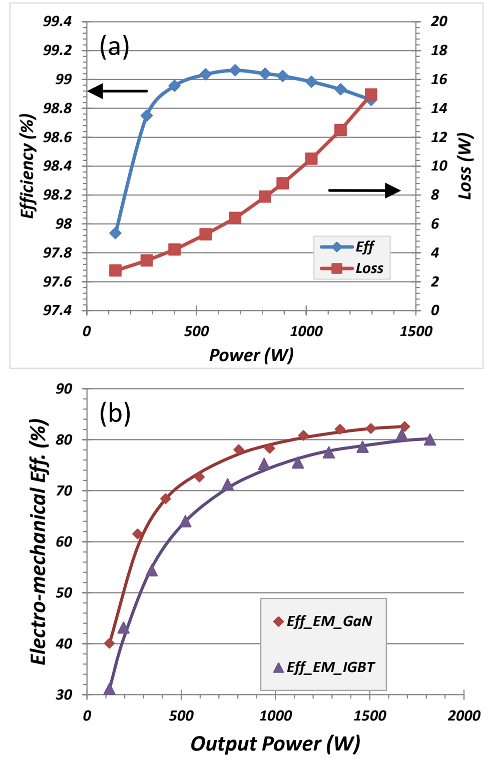

Figure 4. (a) Efficiency and loss of boost converter at ratio of 230V:400V and at 100kHz (b) Efficiency of Motor Drive Inverter with GaN at 100kHz compared to state-of-the-art IGBT inverter at 16kHz.

5. Summary

Development of high-quality GaN device manufacturing technology on Si substrate has generated low-cost, viable 600V class GaN HEMTs and diodes. These first generation GaN on Si devices proved to be superior in actual electric power conversion applications, indicating a promising start of next generation efficient power products.

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