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600V GaN Schottky Barrier Power Devices for High Volume and Low Cost Applications

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Abstract. The first commercially viable high voltage (>600V) gallium nitride (GaN) Schottky barrier devices are reported. Though GaN does not have any "micropipe" defects, which commonly exists in SiC material, defects like dislocations due to lattice mismatch hamper the material development of GaN high power devices. Improvements in the nitride epitaxial film growth have led to significant reduction of conductive dislocations. Conductive Atomic Force Microscope (CAFM) analysis of conductive dislocations shows only on the order of 10^3 cm^{-2} density of conductive dislocations, which are believed to be responsible for the undesired leakage current. GaN diodes compare to SiC or Si devices demonstrate a significant advantage in the thermal resistance. The insulating properties of Sapphire substrates allow fabrication of the devices in TO220 packages with insulating frame and thermal resistance better than 1.8°C/W compare to 3°C/W of SiC or Si devices with insulating frame. Performance of GaN, SiC and Si devices in the switch mode power supplies is compared.

Introduction

Currently high voltage (>600V) SiC Schottky barrier diodes are challenging the Silicon (Si) dominance in the high-power semiconductor device market. However the expensive price of SiC diode is making it hard to find quick and broad acceptance in the industry. Wide-band gap materials, such as III-Nitride semiconductors, possess excellent electrical and physical properties such as high breakdown field, high electron saturation drift velocity, high electron mobility and high thermal conductivity. Therefore, it has been regarded as a potential semiconductor material for high-temperature power devices with high voltage and current ratings, delivering SiC device performance but considerably cheaper. SiC material has significantly better thermal conductivity compare to Sapphire. Thus it was widely believed that GaN diodes grown on Sapphire substrate will not be able to compete with SiC devices on thermal resistance. Contrary to this wide spread believe, we have demonstrated that the insulating properties of Sapphire substrates enables the creation of devices with insulating frame. The thermal resistance of GaN diodes with an insulating frame is comparable to the thermal resistance of Si and SiC devices with *non*-insulating frame and about 30% lower than the thermal resistance of SiC devices with isolating frame. Performance of GaN diodes in switch mode power supplies show significantly better performance than Si based diodes and performance comparable to SiC devices.

Cost of GaN Materials and Devices

There are three major cost drivers for GaN and SiC devices: substrate cost, substrate size and EPI growth temperature.

Substrate cost. The GaN diodes described in this paper are fabricated on 100 mm Sapphire substrates, which are available from multiple vendors. Production of these substrates is fueled by the strong desire of the multi-billion dollar GaN LED industry to transition to 100 mm substrates. The cost of Sapphire substrates is rapidly declining thanks to the healthy competition and continuous manufacturing improvements. R&D quality 150 mm Sapphire substrates are already available from the leading manufacturers. In contrast, SiC is available at 100 mm size only in very limited R&D quantities with the majority of the development and manufacturing done on 75mm substrates. The approximate cost in $US normalized to the unit area of commercially available SiC, GaN and Si substrates is shown in **Table 1**, which is normalized to the unit area. One could see that Sapphire cost is about *3 times* lower than SiC cost.

SUBSTRATE SIZE AND MATERIAL	COST PER CM^2
75mm SiC	~$6
100mm Sapphire	~$2.2
150mm Silicon	~$0.11

Table 1 Costs for Substrate normalized to unit area

Substrate size. The size of the substrate is critical in driving the manufacturing cost down. Two major factors play the major roles here. The first, the number of chips per substrate is proportional to the square of the substrate diameter. This means that one could get almost *2 times* more chips on 100mm substrate than on 75mm substrates. The second factor is that the majority of semiconductor equipment available today is for 100mm substrates and above. It is much easier to equip a new fab with 100mm equipment than with 75mm equipment and it is much easier to outsource some of the operations.

Growth Temperature. The third major factor driving the difference in the cost of GaN and SiC is EPI growth temperature. GaN is grown at 1000 – 1100 °C compare to SiC grown at 1500 – 1600°C. The temperature of the EPI reactor is proportional to the cost of maintaining the reactor.

GaN Material Improvement

One of most important aspects of realizing nitride power devices is the development of material growth for producing high quality uniform thick epitaxial layers. Although GaN does not have any "micropipe" defects, which commonly exists in SiC material, defects like dislocations due to lattice mismatch growth hamper the material development of GaN high power devices. Innovative MOCVD growth techniques were used to create advanced epitaxial layers. New nucleation and buffer growth techniques were used to reduce the number of dislocations. It is encouraging that examination of our nitride epitaxial film using the Conductive Atomic Force Microscope (CAFM) analysis shows only in the order of 10^3 cm^{-2} density of conductive dislocations, which is believed to responsible for the undesired reverse leakage current. CAFM topographic images used to locate the surface leakage path of the nitride film grown on sapphire are shown in Fig.1 . This low conductive dislocation density allows fabrication of low leakage, reliable devices.

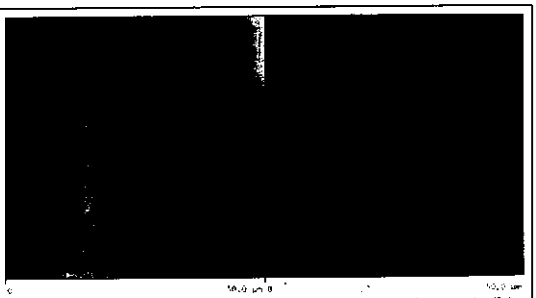

Fig. 1. Typical CAFM (a) tapping mode and (b) scanning mode images of nitride film grown on sapphire. 50 μm x 50 μm scanning shows 2 points of localized current.

Device Characteristics

The GaN Schottky devices are grown on insulating sapphire substrates; the device contacts are made on the top of the wafer. Patented[3] inter-digitated geometry is employed to minimize the lateral spreading resistance and maximize the conducting current with the smallest possible chip size. The device schematic is illustrated in Fig. 2.

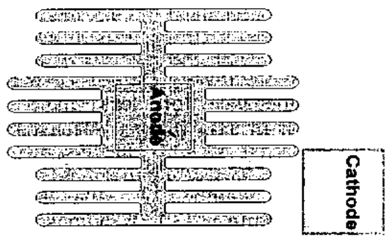

Fig. 2. Schematics of layout of GaN Schottky diode

In Fig. 3(a), the reverse current-voltage characteristics of our fabricated GaN Schottky diodes is shown; the typical leakage current is less than 200μA under a reverse bias of 600V at room temperature and climbs to 1.4mA at an elevated temperature of 125°C. The leakage current was suppressed by the advanced surface preparation and innovative passivation. The same GaN Schottky diode forward current-voltage characteristics demonstrate an ideality factor of 1.04 with a room temperature forward voltage (V_F) of 1.7V at 6A and V_F increased to 2.0V at 125°C, as illustrated in Fig. 3(b).

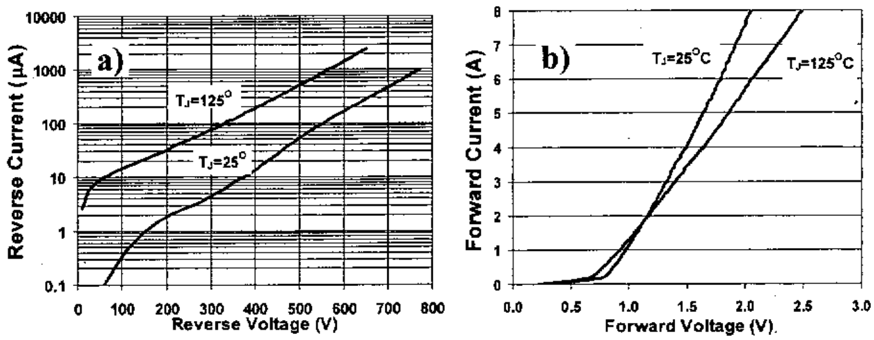

Fig. 3 I-V Characteristics of a 6A/600V GaN Schottky barrier diode

As a majority carrier device, the GaN Schottky diode renders an excellent switching performance with zero reverse recovery time and is independent of temperature, di/dt and current level. The reverse recovery characteristics of the GaN Schottky diode is shown compared to SiC and Si diodes in Fig. 4. As shown, the turn-off characteristics of the GaN Schottky devices are very similar to SiC devices, yet the Si diode exhibits a large amount of the reverse recovery charge, which increases dramatically with temperature, on-current and reverse di/dt.

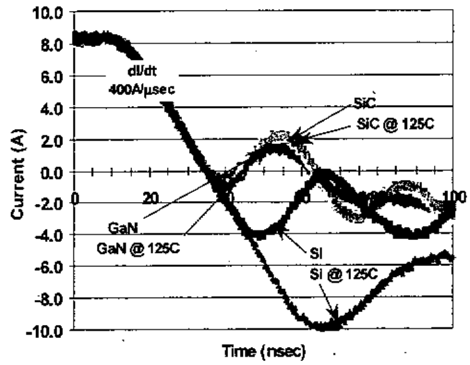

Fig. 4 Temperature-independent reverse recovery time characteristics of GaN Schottky diodes

Advantage of GaN diodes for Packages

The additional advantage of GaN devices compare to SiC is isolated frame. The GaN Schottky devices were packaged in plastic TO-220 packages with a thermal impedance of less than 2.0°C/W. The junction to case thermal resistance of GaN devices with isolated frame is ~1.8°C/W compare to the same number for SiC devices with ***non***-isolated frame or >3°C/W with isolated frame. The isolation of the frame is achieved by utilizing isolation properties of the sapphire substrate. This patent pending[4] approach eliminates the need to isolate the frame from the heat sink. The package schematic is illustrated in Fig. 5.

	6 A GaN Diode	6 A SiC Diode
Leakage at 600V, T_j= 25 °C	100 - 400 μA	50 - 200 μA
Forward Voltage @ T_j= 25 °C	1.6 – 2.0 V	1.6 – 2.0 V

Table 2. Performance comparison of SiC and GaN devices

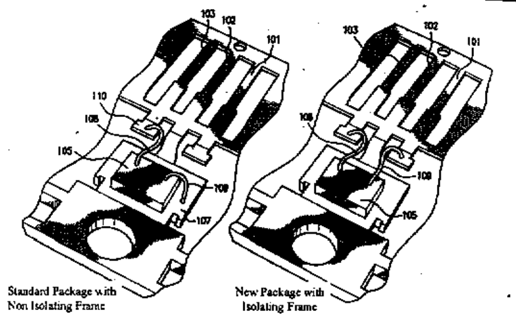

Fig. 5. GaN Schottky devices grown on sapphire substrate allows making packages with isolating frame

In the case of the Si or SiC devices one of the electrodes must be at the bottom of the device making the contact with the frame. In the case of GaN devices both contacts are made on the top of the device. Sapphire is a perfect insulator easily providing more than 2400V isolation from the frame if the wire bonds are made to the legs that are not connected with the frame. The advantage for the power supply designers is significant reduction of the thermal resistance. It could be utilized by either allowing heat sinks with higher temperature or running the heat sink at the same temperature and decreasing the junction temperature of the diode. With an 8A and 2.5V forward voltage device about 20W are expected to dissipate on the device. If the heat sink is at 100°C, then typical Si or SiC device with 3°C/W junction to case thermal resistance will operate with the junction temperature of 160°C. Comparable GaN device with 1.8°C/W thermal resistance will operate at 136°C. Significantly lower junction temperature of the GaN diode leads to better reliability of the device.

Performance of GaN diodes in the systems

The performance study SiC diodes versus GaN diodes was conducted in commercially available switch mode power supplies (SMPS). The study carried out by simply swapping out the diodes in the same system and two identical commercial (1000W, 48 V) ac-dc power supplies were tested. Two SiC devices, Infineon's SDT06560 (6A, 600V), were replaced with two GaN VSD06060 (6A, 600V) diodes in one of the power supply's power factor correction circuits (PFC). The DC characteristics of the SiC and GaN devices are compared in the Table 2. The simplified SiC

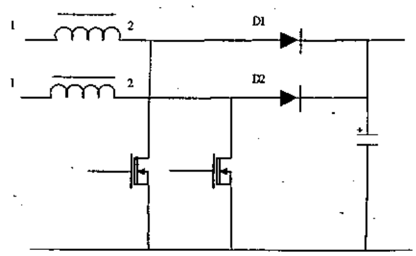

Fig. 6. Simplified power factor correction circuit with SiC diodes

based PFC is shown in Fig. 6. The operating temperature of the diode heat sinks and diodes of both power supplies were monitored by attached thermocouples. The efficiency and the temperatures were measured at different power supply input voltages and with different loads for different power outputs. The reported efficiency represents the total power supply efficiency, not only the power correction circuit efficiency. The efficiency was measured using Yokogawa WT3000 Power analyzer. The efficiencies of the entire power supply, using SiC and GaN diodes with 88V, 100V, 135V, 185V and 230V inputs were measured and no measurable differences between two power supplies were obseved at room temperature and 72°C. The electrical load was adjusted for 1000W, 750W, 500W, 250W, and 100W output power. Figure 7 depicts the efficiency of the power supply and the temperature of the heatsink at 100V and 230V inputs at 72°C ambient temperature. These tests clearly demonstrate that GaN diodes could perform as well as SiC diodes in the systems

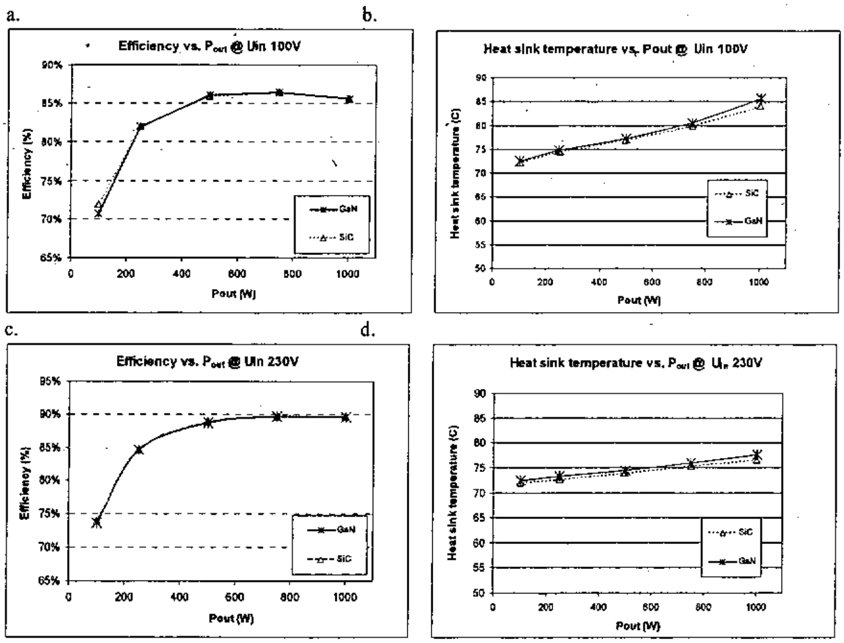

Fig. 7. The Efficiency (left hand side graphs) and Heat Sink Temperature (right hand side graphs) of Power Supplies with SiC and GaN Diodes at 70°C –a&b 100V and c&d 230V input. No difference in the system performance could be measured.

Emission measurement tests. The emission measurement tests were performed according to standards for Class B equipment. All measurements were performed in a shielded room. The tests were performed with inputs of 120V and 220V AC 60Hz, and output 48V/ 16.75A. No measurable differences in operation of SiC and GaN devices were observed. Fig. 8 depicts the results with 120V inputs. SiC and GaN power supplies have the same behavior, i.e. the quasi peaks are well below the class B requirement.

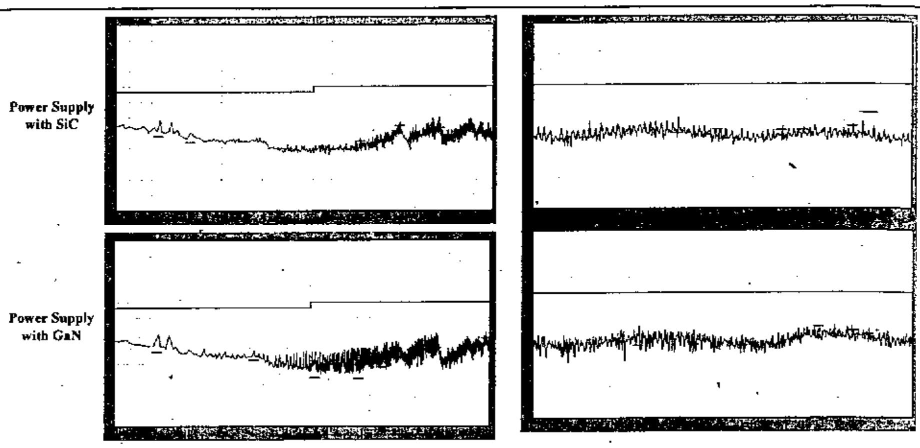

Fig. 8. Conducted Emission Measurement Tests. Input 120V AC 60Hz; Output 48V 16.75A. SiC and GaN power supplies have the same behavior, i.e. the quasi peaks are well below the class B requirement. The plots on the left are from 0.7 GHz to 30GHz and the plots on the right are from 25 GHz to 30GHz

Summary

We have demonstrated the first commercially viable high voltage (>600V) gallium nitride Schottky barrier device. The device exhibits excellent electrical and thermal characteristics. Developments in the EPI growth techniques allowed creation of superior GaN material with very low density of conductive dislocations. The insulating properties of Sapphire substrates allows creation of the devices with much better thermal performance than SiC or Si devices. The study of a power supply utilizing GaN diodes showed the same performance compared to the SiC diodes over the entire range of output powers at both room temperature and elevated temperature (72°C). The lower cost of GaN diodes could open the door for wide adoption of this devices for power supply applications .

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