A 97.8% Efficient GaN HEMT Boost Converter With 300-W Output Power at 1 MHz

Yifeng Wu, Matt Jacob-Mitos, Marcia L. Moore, and Sten Heikman

***Abstract*—A 175-to-350 V hard-switched boost converter was constructed using a high-voltage GaN high-electron-mobility transistor grown on SiC substrate. The high speed and low on-resistance of the wide-band-gap device enabled extremely fast switching transients and low losses, resulting in a high conversion efficiency of 97.8% with 300-W output power at 1 MHz. The maximum efficiency was 98.0% at 214-W output power, well exceeding the state of the art of Si-based converters at similar frequencies.**

***Index Terms*—Converter, efficiency, GaN, high voltage, high-electron-mobility transistors (HEMTs), power device, switching power supply.**

I. INTRODUCTION

GAN-BASED high-electron-mobility transistors (HEMTs) have been proven to be outstanding candidates for future microwave (in the gigahertz range) power applications [1]–[5]. Their benefit to lower frequency (in the megahertz range) power switching applications has also been recognized [6]. There has been a consistent trend to increase switching frequencies for more compact power supplies [7], and GaN devices are well suited for loss reduction in such operations due to their high mobility and high breakdown field. A boost converter, which is typically used in a power-factor-correction (PFC) front end, is a good vehicle to demonstrate the advantage of a GaN switch. Although encouraging, previous effort in such an attempt [8] failed to show much efficiency improvement over the best Si MOSFET counterparts [9]. This was attributed to both immature device technology, including a degraded dynamic on-resistance due to trapping effects, and nonoptimum choice of circuit components [8]. Here, we present a high-efficiency boost converter using an improved high-voltage GaN HEMT on SiC substrate, which successfully cuts the conversion loss of the previous state of the art by 60% under similar voltage conversion ratio and modulation frequencies.

II. DEVICE FABRICATION AND CONVERTER CONSTRUCTION

The GaN HEMT in this letter is a high-voltage version of previous depletion-mode microwave devices [2]. The device structure is shown in the top inset of Fig. 1. The epi-layers consist of an AlGaN layer, a thin AlN interlayer, and a GaN buffer with Fe doping, all grown on a Cree HPSI SiC substrate. The device features double field plates, with the first as an integral part of the gate and the second connected to the source. The gate length is about 1.2 μm, and the gate–drain spacing is 18 μm. The lengths of the two field plates are 1.5 and 5 μm, respectively. The device has a gate periphery of 18 mm, which is arranged within a 1-mm^2 area. The finished device was die-attached on a Cu-based metal package, with the source terminal connected to the metal body, the gate and drain terminals wire-bonded to the input and output leads. The I–V characteristics of the packaged device are shown in Fig. 1, exhibiting a full-channel current greater than 8 A and an on-resistance of 0.63 Ω at a gate bias of +2 V. The pinchoff was about -3 V, and the breakdown voltage was higher than 900 V.

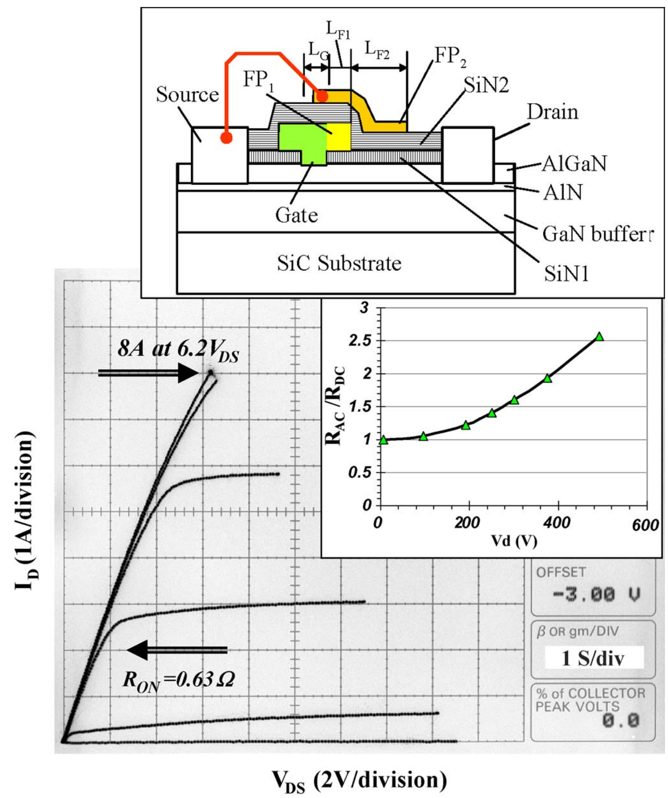

Fig. 1. I–V characteristics of the GaN HEMT switch (V_{gs} start: +2 V, step: -1 V). (Upper inset) Device structure ($t_{\mathrm{SiN1}} \sim 100$ nm; $t_{\mathrm{SiN2}} \sim 200$ nm). (Lower inset) Dynamic resistance versus blocking voltage normalized to its dc value.

A major concern with GaN-based HEMTs has been the increase in dynamic on-resistance under high-voltage swings

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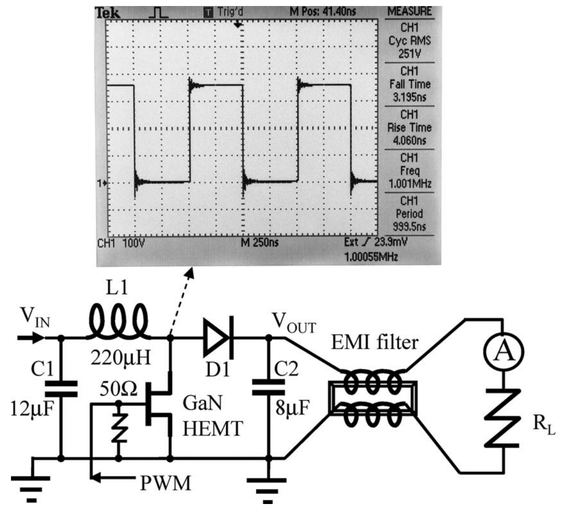


Fig. 2. Circuit diagram of the boost converter. (Inset) Waveform at the drain of the GaN switch showing hard-switched characteristics with blocking voltage greater than 350 V and rise and fall times of 4.2 and 3.2 ns, respectively. Note that the equipment response was ∼2 ns. The actual switching transient should be much faster than the recorded switching transient.

("dynamic on-resistance" is defined as the instantaneous on-resistance of a device shortly after a high-voltage event). This phenomenon is associated with high-field trapping and directly impacts conduction loss during switching operations. Extensive process development focusing on the quality of epi-growth and SiN passivation was conducted in our laboratories to produce low-trapping devices. Resistive and inductive switching tests were performed to characterize the devices at various voltages. The lower inset of Fig. 1 shows the ratio of ac dynamic on-resistance R_{AC} to dc on-resistance R_{DC} for a developed device as a function of the blocking voltage obtained from an inductive switching test with 1-μs pulses and 1% duty cycle. It is seen that, although not fully eliminated, the increase in dynamic on-resistance is only 75% at 350 V, which much improved from the previous report of 330% [8]. The system response limit for the switching test was about 2 ns, which, although adequate for characterizing Si and SiC MOSFETs, is too slow to resolve the storage charges of the GaN HEMT.

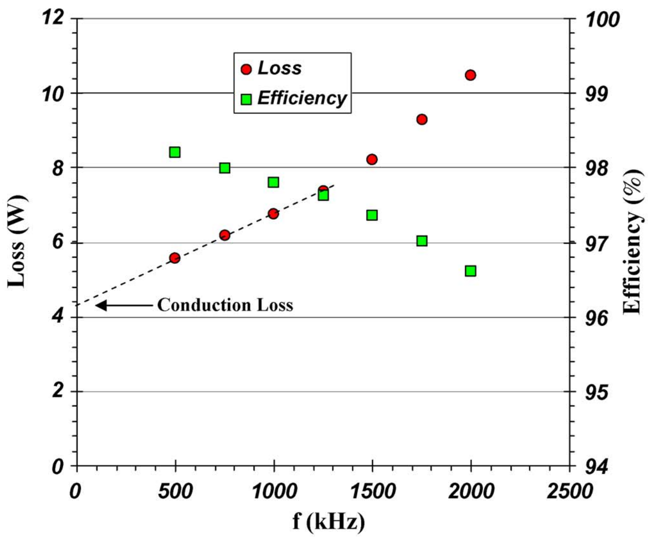
A diagram of the circuit under study is shown in Fig. 2. The design target was a PFC-compatible 175–350-V boost converter with 300-W output power that is suitable for a typical desktop computer. The main circuit consists of an inductor (L1) and a GaN HEMT switch, a rectifying diode (D1), and two filtration capacitors (C1 and C2). The inductor absorbs energy from the input line when the GaN switch is on and releases the stored energy to the load at twice the input voltage when the switch is off. The converter was built on a two-layer printed circuit board, with the backside soldered on an 8-mm-thick aluminum base, which served as the ground and the heat sink. The metal body of the packaged GaN HEMT was bolted on the aluminum base for excellent grounding and heat removal. 600-V SiC Schottky diodes were chosen in our experiment due to their superior switching characteristics with zero recovery current. Size optimization determined that a 1-A-rated CSD01060 diode from Cree Inc. offered the lowest sum of conduction and charging losses. The rest of the components used included high-voltage metal-film capacitors and an air-core inductor based on laboratory availability. At the gate input of the GaN HEMT, a pulse-width-modulation signal with +3 V high and −6 V low at 50% duty cycle was directly supplied by a pulse generator with a 50-Ω source impedance. At the output of the converter, two clip-on electromagnetic interference ferrite chokes were applied to eliminate radio frequency interferences for accurate current reading to the load.

III. Performance and Discussion

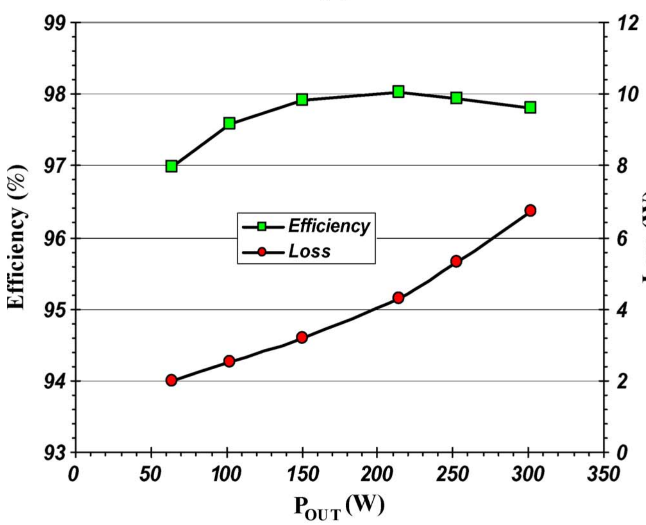
The converter was tested with digital meters calibrated against a certified Agilent 34401A multimeter to ensure accuracy. The waveforms of interest were monitored with a Tektronix oscilloscope through a 1:100 voltage probe. The inset of Fig. 2 shows the signal at the drain of the GaN switch when operating with 301.4-W output power at 1-MHz modulation frequency. The actual operation parameters included a duty cycle of 50.8% and a dc input and output of 176.0 V at 1.751 A and 354.1 V at 0.8513 A, respectively. The waveform demonstrates well-behaved hard-switched characteristics with very fast rise and fall times of about 4.1 and 3.2 ns, respectively. Taking into account the system response limit of ∼2 ns and the probe loading, the actual transients should be below 2 ns. This fast switching action without a low-impedance driver is a major advantage of the high-speed GaN HEMT with ultra-low storage charges, which drastically cuts down crossover losses.

The converter was tested at a range of switching frequencies of 500 kHz–2 MHz, with the same load drawing about 300-W power, as shown in Fig. 3(a). The conversion efficiency was 98.2% at 500 kHz, gradually reducing to 97.8% at 1 MHz and further tailing down to 96.6% at 2 MHz. To our knowledge, these are the highest efficiency levels ever reported for a hard-switched converter at the corresponding frequencies. Theoretically, with the same power level, the conduction loss remains constant, whereas the switching loss linearly increases with frequency. In Fig. 3(a), however, the slope of the increase in total loss becomes higher at elevated frequencies, which could be an effect of the reduced skin depth in the inductor windings and in the capacitor metal films. Nonetheless, the total conduction loss can still be estimated by extending the data points in the lower frequency range to dc, as indicated by the dotted line in Fig. 3(a). Of the 4.3-W conduction loss determined in this manner, 1.84 W is allocated to the GaN HEMT (where 1.68 W is due to its 1.1-Ω dynamic on-resistance and 0.16 W is due to the OFF-state drain leakage current of 0.93 mA at 354 V); 1.4 W is allocated to the SiC Schottky diode, with its forward voltage drop of 1.6 V at the operation current; and 1.06 W is allocated to the inductor. Improving the dynamic on-resistance of the GaN HEMT to its dc value could reduce the conduction loss by 0.73 W, which is about 0.24% of the input power.

At 1 MHz, the difference between the total and conduction losses is 2.47 W, which is switching related. The charging loss of the SiC Schottky diode was experimentally determined to be 0.76 W. Doubling the diode size reduced the forward conduction loss by 0.2 W but boosted the charging loss by



(a)



(b)

Fig. 3. Efficiency and total loss (a) as a function of switching frequency at 300-W output power and (b) as a function of output power at 1 MHz. The peak efficiency of 98% at 214 W is the highest for a hard-switched converter at 1 MHz to date.

0.76 W, resulting in a net increase in loss of 0.56 W. The charging loss and crossover switching losses of the GaN HEMT are estimated to be ∼0.7 W, based on a calculated total output charge of 2 nC and a current switching time of 1.5 nS. The remainder of the switching loss (∼1.0 W) is attributed to the ac losses of the inductor and the rest of the components.

Compared to the previous GaN converter by Saito *et al.* [8], the conduction loss associated with device on-resistance is reduced from 1.7% to 0.55%, mostly due to the successful reduction in dynamic on-resistance from 400% to 175% of the dc values. The loss by the Schottky diode is decreased from 2.8% to 0.7% as a result of correct sizing in our circuit implementation.

As a summary of the analysis, the total loss associated with the GaN HEMT is about 0.82% of the input power. The Schottky diode accounts for 0.7%. The inductor and other components are responsible for 0.68%. Hence, further efficiency improvement requires loss reduction in all the important components involved. Perfecting the GaN device alone is no longer enough.

The converter was also investigated at 1 MHz with various loads, as shown in Fig. 3(b). The power efficiency was maintained above 97% for output power ranging from 60 to 300 W. The peak efficiency was 98.0% at 214 W. This is a considerable improvement from the 95% maximum efficiency for the best-reported Si-based converters at similar frequencies [9]. The decrease in power loss from 5% to 2% translates to a 60% reduction of thermal burden, which is a substantial benefit to system design.

IV. Conclusion

A 175-to-350 V hard-switched boost converter was explored to investigate the benefit of high-voltage GaN HEMT switches. The low storage charges and low on-resistance of the depletion-mode GaN device enabled extremely fast switching transients and very low losses. A high power efficiency in the range of 97%–98% was achieved with an output power in the range of 60–300 W at 1 MHz. The peak efficiency of 98% at 214 W represents the highest conversion efficiency of any switching converter at 1 MHz to date. While enhancement-mode devices are preferred in switching power applications, this result clearly shows the promise of the wide-band-gap GaN device in this area.

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