EVS26
Los Angeles, California, May 6-9, 2012

Quasi-Resonant Flyback DC/DC Converter Using GaN Power Transistors

S. L. Jeng[1], M. T. Peng[2], C. Y. Hsu[3], W. H. Chieng[4], Jet P.H. Shu[5]
[1] *Dept. of Electrical Engineering, Ta Hua Institute of Technology, Hsinchu, Taiwan, aetsl@thit.edu.tw*
[2] *Mechanical and Systems Research Laboratories, Industrial Technology Research Institute, HsinChu, Taiwan*
[3,4] *Dept. of Mechanical Engineering, National Chiao-Tung University, Hsinchu, Taiwan*
[5] *Taiwan Automotive Research Consortium, Taiwan*

Abstract

Quasi-resonant flyback converter is realized with the aim to demonstrate the topology feasibility using the normally-on switching behaviour of the gallium nitride (GaN) power transistor. Reference converters utilize GaN and silicon-based MOSET as the switching devices to compare the electric characteristics, and power losses. Quasi-resonant technology offers reduced turn-on losses, resulting in increased efficiency and lower device temperature. The turn-on losses dominate the power losses as the switching frequency of the power supply increases. The combined advantages of gate charge and on-resistance for GaN in the 60 watt reference converter leads to improve the turn-off conduction loss. GaN based power converter provides up to 7.02% improved efficiency over silicon based MOSFETs. The converter performance improvement opens the possibility of fully exploiting the wide advantages of GaN transistors in power electronic application.

Keywords: GaN HEMT, flyback converter, soft-switching

1 Introduction

Power switching devices play an important role in power electronic application. As silicon based power transistor approaches the end of major improvements in performance and cost, gallium nitride (GaN) power transistor exhibits great potential for future power electronics due to low conduction resistance, low power loss, high switching speed and superior thermal property [1]-[4]. The science behind these new advantages is due to the ability of the substrate material to handle higher power densities. The material properties in which GaN transistors have advances with respect to Si are wide bandgap, high electron mobility, large saturation velocity, high sheet carrier concentration at hetero junction interfaces, and high breakdown field. All these material advantages have great potential of realizing high speed, high voltage, and high temperature power transistors. The electrical characteristics of GaN transistors can further progress the performance of power converters by operating power transistor at higher frequencies, with reduction in the size of passive elements, such as filter inductors and capacitors, and with improvements in terms of achievable bandwidth.

A number of literatures report results related to the advantages of GaN devices used in power converter applications. Saito [5] presented an application of 600V GaN HEMT which on-resistance is only 3.3 $m\Omega \cdot cm^2$. They fabricated a DC/DC down application with 200V input and

200 K to 500 KHz switching frequency. High current density switching of 850 A/cm^2 was achieved in that DC-DC converter circuit. Yoshida demonstrated a DC/AC inverter application which converts 30 V DC to 100V AC [6]. The significant results are the outstanding switching time. As they operated the GaN HFET at 0.37 GHz, the turn-on and turn-off time are 10ns and 11ns respectively. There is one more case, Jordi Everts led his team to construct two DC-DC boost converters with high conversion efficiency [7]. Their E-mode (enhancement mode) GaN transistor features very low gate-charge, 15 nC at 200V V_{DS}. This remarkable characteristic results in good performances in converter's efficiency. An efficiency of 93.9% is presented when the load is 97.5W at 845.2 KHz switching frequency. As the load increase to 106W at 512.5 KHz, the efficiency reaches 96.1%. The above researches show the applications of GaN transistor are available.

GaN transistor is a very low on-resistance and low-charge device. The combined advantages of gate charge and on-resistance in the converter leads to a more efficient system because of the reduced turn-off conduction loss. Another feature offered by GaN transistor is the fast switching speed. Quasi-resonant flyback converters, which represent the structure of choice for use in small and medium power applications, have taken a significant market share over the traditional fixed frequency topology of converter. The quasi-resonant topology reduces the frequency-dependent switching losses within the power switches. Eliminating these losses allows the converter to increase the switching frequency and reduce the inductor/capacitor volume. The quasi-resonant converter is built to demonstrate the advantage and validity of GaN in power supplies and other power applications.

2 Enhancement mode GaN

The transfer characteristic of an enhancement mode GaN power transistor is similar to an n-channel power MOSFETs. Applying a positive bias higher than the threshold between the gate and source terminals causes a field effect, which attracts electrons that generate a bidirectional channel to direct the current from the drain to the source, and turns the device on. When the bias is removed from the gate, the electrons under the gate plate are dispersed into the gallium nitride material and create a depletion region between the drain and source. Consequently, the enhancement mode GaN is a positive voltage turn-on device: it requires a positive voltage to turn it on and a zero voltage to turn it off.

Designing a gate driver that operates the GaN to its full switching performance presents major technical challenge in the system. There are two important parameters that affect the gate drive circuit design. First, the threshold of the GaN transistor is about 1.6V, which is generally lower than that of silicon based MOSFET. When the GaN needs to be held off, the total resistance path between gate and source must be considered for avoiding turning off due to miller dv/dt glitch. Secondly, the maximum allowable gate-source voltage is 6V. As there is negligible gate-drive loss penalty, the GaN should be driven with the full 5V. There is only 1V headroom between the gate drive voltage and the absolute maximum rating voltage. Compared with MOSFET, an accurate gate-drive voltage is required, but it is difficult to achieve for gate drive supply regulation in the converter application. As GaN has low required gate-drive voltage, total gate-drive losses will be reduced.

3 Operation of quasi-resonant flyback converter

Flyback converter is a buck-boost converter with the inductor split to form a transformer so the voltage ratios are multiplied with an additional advantage of isolation. It is the most common topologies used for isolated DC/DC conversion. Schematically, quasi-resonant (QR) topologies are minor modifications of the standard flyback converter. A quasi-resonant topology is designed to reduce the frequency-dependent switching losses within the power switches and rectifiers. Figure 1 shows the basic configuration of flyback converter with RCD clamp circuit. The RCD circuit protects the primary switching transistor from exceeding its breakdown voltage BV_{DSS}. Fig.

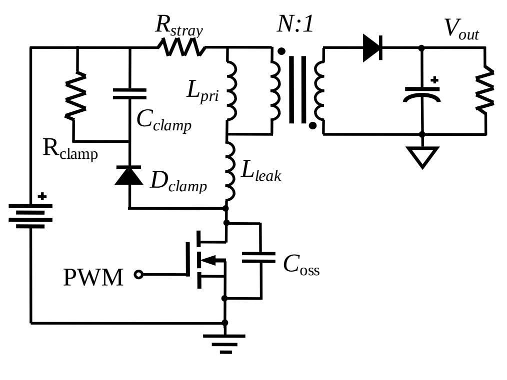


Figure 1. Quasi-resonant flyback converter.

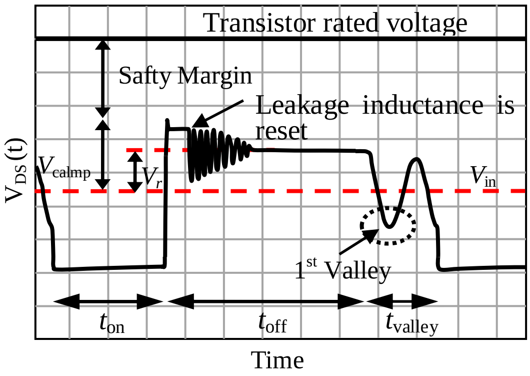


Figure 2. Drain-source waveform of flyback converter.

2 depicts a typical flyback converter drain–source waveform. The drain-source voltage will be the sum of the input voltage, the reflected voltage from output and the peak primary current times characteristic impedance of the circuit. When the switching device is closed, the current ramps up in the primary inductance L_{pri} and the drain–source voltage is close to zero. The input voltage V_{in} appears across the primary inductance L_{pri}. The input power stores in the primary inductance and output capacitor solely supplies the load because the output rectifier diode is open.

At the switch opening, the voltage on the primary inductance reverses and the drain–source quickly climbs up. The rectifier at the secondary side conducts, and the energy transfer between primary and secondary takes place. Output voltage flies back on the primary side, over primary inductance *Lpri*. The leakage inductance L_{leak} together with C_{oss} causes the rising slope of the drain voltage. The clamping diode D_{clamp} conducts and absorbs the energy of the leakage inductance into the clamping RC circuit when the drain-source voltage reaches a level of the sum of the V_{in} and V_{clamp}. This action naturally limits the further excursion of the drain-source voltage. The extra energy of the leakage inductance will then turn to store in the clamping capacitor and be released on the clamping resister by the next cycle.

When the primary current reaches zero, the drain-source voltage reaches a plateau, which is equal to $V_{in} + (V_{out} + V_f) \cdot N$, where N is the primary to secondary turn ratio, V_{out} the output voltage and V_f the diode forward voltage drop. The transformer core is fully demagnetized and the secondary diode stops conducting. The primary inductance L_{pri} together with all the surrounding capacitive elements Ctot forms the resonating tank. A damped oscillation occurs on the drain, exhibiting the following frequency value:

$$f_{ring} = \frac{1}{2\pi\sqrt{L_{pri} \times C_{oss}}} \quad (1)$$

Peaks and valleys appear. Quasi-resonant switching technique is to wait the drain-source voltage down to the valley. The switching device restarts to turn on before flyback energy is completely depleted from the transformer. The device is no longer the seat of heavy turn–on losses engendered by capacitive effects. Quasi–resonant converters exhibit a highly variable switching frequency which depends on the input/output operating conditions. The switching frequency is decreased step by step by changing valley as the load decreases. Once the controller selects a valley, it stays locked in this valley until the output power changes significantly.

4 QR flyback converter design

Design the major parameters of quasi-resonant flyback converter by following steps [8]:

(a) Determine the turns ratio between the primary to secondary turn ratio:

$$N = \frac{\alpha\left(V_{out} + V_f\right)}{V_{DS(\max)} - V_{in}} \quad (2)$$

(b) Calculate the primary peak current:

$$I_{pri(peak)} = \frac{2P_{out}}{\eta}\left(\frac{N}{V_{out} + V_f} + \frac{1}{V_{in}} + \pi\sqrt{\frac{\eta C_{oss} f_{sw(\min)}}{2P_{out}}}\right) \quad (3)$$

(c) Calculate the primary inductance:

$$L_{pri} = \frac{2P_{out}}{I^2_{pri(peak)} f_{sw(\min)} \eta} \quad (4)$$

(d) Calculate maximum duty ratio:

$$d = \frac{I_{pri(peak)} L_{pri} f_{sw(\min)}}{V_{in}} \quad (5)$$

(e) Calculate the primary rms current:

$$I_{pri(rms)} = I_{pri(peak)}\sqrt{\frac{d}{3}} \quad (6)$$

(f) Calculate the secondary rms current:

$$I_{\sec(rms)} = \frac{I_{pri(peak)}}{N}\sqrt{\frac{1-d}{3}} \quad (7)$$

where

α define the relationship between the clamping voltage and the reflected voltage on the primary inductance. The value of 3.5 is selected.

V_{in}, V_{out} input and output voltages, respectively

V_f the diode forward voltage drop
$V_{DS(max)}$ typically 70% of transistor's BV_{DSS}
P_{out} output power
η estimation conversion efficiency. The value of 0.85 is selected.
$f_{sw(min)}$ switching frequency at full load

5 Experiment setup

Figure 3 shows the design of the 60 watt flyback converter with quasi−resonant topology, operating with a variable switching frequency from 60 kHz to 120 kHz, an input voltage of 48V, and output voltage of 5V. The basic converter circuit is comprised of PWM controller NCP1380 [9], flyback transformer, switching power devices, and its associated secondary rectifiers. Compared to the traditional power conversion scheme utilizing MOSFET with the same breakdown voltage BV_{DSS}, GaN provides improved efficiency, higher power density and overall system performance. Table 1 summarizes the significant electric parameters for the GaN [10] and MOSFET [11].

Figure 3. Experiment setup.

Table1. Electrical characteristics of GaN and MOSFET used in the referenced converter.

	GaN	MOSFET
$V_{GS(max)}$	6 V	20 V
$V_{GS(th)}$	1.4 V	3 V
BV_{DSS}	200 V	200 V
I_D	12 A	18 A
$R_{DS(ON)}$	18 mΩ	150 mΩ
Q_{Gate}	7.5 nC	55 nC
Q_{GD}	3.5 nC	21 nC
C_{oss}	200 pF	310 pF
C_{iss}	440 pF	1200 pF

As previous mention, the maximum allowable gate-source voltage $V_{GS(max)}$ for GaN is 6V, which is low in comparison with MOSFET. It is not available to directly active GaN because the output voltage of driving pin for external switching device is about 12V during normal operation according to the electrical specification of PWM controller. A suitable gate-driving circuit to fully manipulation GaN is essential in the reference circuit.

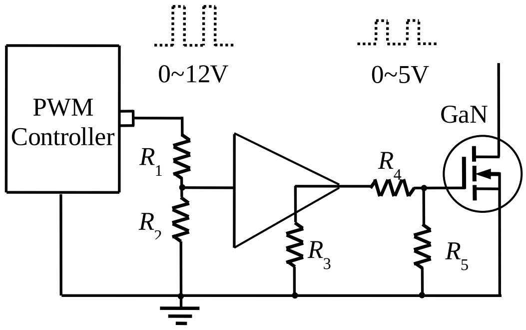


Figure 4. Level shifting of gate signal for GaN.

As shown in Fig. 4, a gate driver circuit is added between the switching output pin of the PWM controller and the gate terminal of GaN. A pair of resistors R_1 and R_2, forms a voltage divider bias circuit to reduce the original PWM signal level. A significant characteristic offered by GaN is low threshold voltage. Due to the hyper-fast switching characteristics of the GaN power transistor, high *dV/dt* is present and cause high current to flow in the *Cgd* capacitor. It is necessary to limit the total resistance path between the gate and source terminals. To avoid the risk of Miller turn-on or the dV/dt glitch, the gate-drive output impedance R_3 must be minimized. The requirement for GaN gate driver is that output impedance should be chosen to have 500 mΩ or less for high dV/dt of 20 V/ns [12]. The gate resistor R_4 of 90Ω is connected between the gate driver output and gate terminal, which is adjusted to do trade-off between driving speed, voltage-overshoot control and ringing for improved EMI. The resistor R_4 of 1kΩ is connected between the gate and the ground to avoid any inadvertent GaN switching on due to noise. The accurate regulation of the gate drive level that the ring and peak voltage does not exceed the 6V maximum rating is required. It is not easy to maintain the gate drive level for whole operating conditions in the converter design.

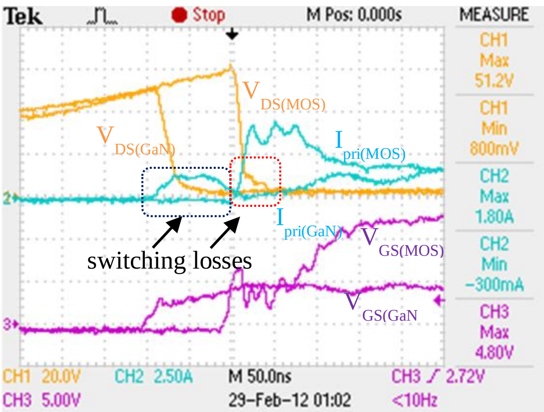
6 Experimental results

Quasi–resonant flyback converter reveals a highly variable switching frequency which depends on the output operating conditions. To accomplish the necessary design of the circuit components, the switching frequency of 100 KHz is first selected as a given operating point. The major parameters based on Eqs (2) ~ (7) for both GaN and MOSFET devices are listed in Table 2.

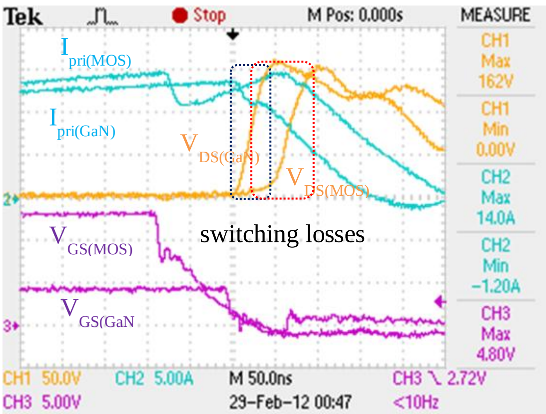
Table 2. Major parameters of the quasi-resonant flyback converters

	EPC1010	IRF 640
N	0.38	0.38
$I_{pri(peak)}$	13.1 A	12.6 A
L_{pri}	8.23 µH	8.89 µH
d	0.23	0.243
$I_{pri(rms)}$	3.63 A	3.59 A
$I_{sec(rms)}$	17.47 A	17.32 A

The turn-on and turn-off waveforms for both the GaN and MOSFET devices are compared in Fig. 5. According the electric characteristics of the devices shown in Table 1, the input capacitor C_{iss} of GaN is small when compared with silicon MOSFETs, enabling very short delay times and excellent controllability in low duty-cycle applications. GaN, features a gate charge Q_{gate}



(a) On switching



(b) Off switching

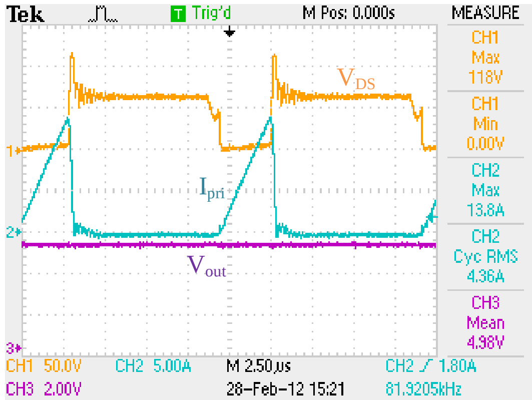
Figure 5. Switching transient waveform.

which is lower than existing MOSFET for improved switching and drive efficiency. GaN and MOSFET are driven by a gate-source voltage of 5V and 12V, respectively. The comparisons of turn-on and turn-off time for both devices are listed in Table 3. The improved switching time of the GaN is due to about the low miller charge (Q_{GD}).

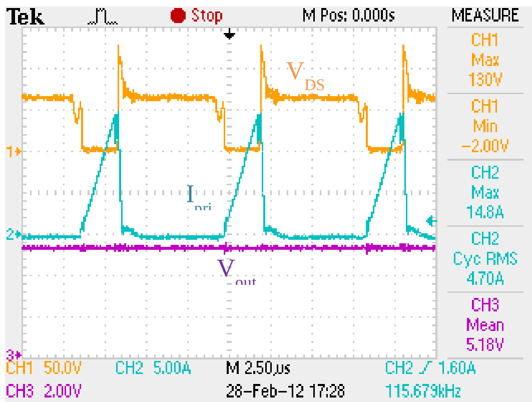
Table 3: Turn-on and turn-off time

	GaN	MOSFET
Turn-on	43 ns	47 ns
Turn-off	44 ns	173 ns

Figure 6 shows the waveforms of the drain-source voltage, the primary inductor current, and the output voltage. The voltage spikes across the drain-source terminals are adequately clamped to about 118V and 130V by RCD clamping circuit



(a) GaN based converter



(b) MOSFET based converter

Figure 6. Valley switching waveforms.

during off-time. Since the maximum stress on the switching devices is 130V, the breakdown voltage of 200V for these two devices is available. The two switching devices are turned on with less switching losses when the drain-source voltage V_{ds} is near the first valley where the voltage is minimum. The switching frequencies for both GaN and MOSFET are 110 KHz and 130KHz, respectively.

7 Power loss calculation

Among the power losses generated by all components, switching device losses occupy about up 30%. Power losses in a switching device can be divided into three groups: (a) gate charge losses, (b) conduction losses and (c) switching losses. [13], [14]

$$P_{Tran} = P_{Gate} + P_{Cond} + P_{Swi(on)} + P_{Swi(off)} \quad (8)$$

where

P_{Tran} total power loss of a transistor
P_{Gate} gate charge power loss of a transistor
P_{Cond} conduction loss of a transistor
$P_{Swi(on)}$ switching loss at transistor turn-on
$P_{Swi(off)}$ switching loss at transistor turn-off

Gate driver circuit offers sufficient gate charge (Q_{Gate}) energy to fully turn on or off the transistor. This quantity of gate charge power dissipation is associated with the gate driving voltage and switching frequency.

$$P_{Gate} = Q_{Gate} V_{driving} f_{sw} \quad (9)$$

where

Q_{Gate} total gate charge of a transistor
$V_{driving}$ driving voltage
f_{sw} switching frequency at full load

According the transistor electronic datasheet in Table 1 and switching waveforms shown in Fig. 5, the Q_{Gate} of GaN is 7.5 nC, the switching frequency is about 110 KHz, and the gate driver operation voltage is 5 V. On the other hand, MOSFET's Q_{Gate} is 55 nC, switching frequency is 130 KHz and the controller operation voltage is 12V. The power dissipation on the GaN and MOSFET are 3.075 mW and 76.56 mW. Gate charge losses are appreciable at high switching frequency.

Conduction losses are caused by channel on-state resistance, $R_{DS(on)}$. The lower on-resistance will result in lower power loss. The power dissipation when the switching device is turned fully on :

$$P_{Cond} = I_{D(rms)}^2 R_{DS(on)} \quad (10)$$

where

$I_{D(rms)}$ rms current of drain
$R_{DS(on)}$ on-resistance of a transistor

Given that the on-resistance of GaN is 18 mΩ and the rms drain current is 4.76A, the conduction loss of the GaN is calculated as 0.342W. Similarly, the conduction loss of the MOSFET with on-resistance 150 mΩ and the rms drain current of 4.53A yields 3.31W.

Switching losses are caused by voltage and current overlaps during short switching transitions, which can be separated into turn-on and turn-off sequences. The turn-on switching loss is a process of discharging capacitances on a drain node.

$$P_{swi(on)} = f_{sw} \int_0^{t_{on}} V_{DS}(t) I_{DS}(t) \cdot dt \quad (11)$$

Similarly, the turn-off switching loss is about the overlapping area of the falling drain current and rising drain-source voltage at the turn-off transient.

The equation replaces the time integration for the sake of calculation the turn-off loss.

$$P_{swi(on)} = f_{sw} \int_0^{t_{off}} V_{DS}(t) I_{DS}(t) \cdot dt \quad (12)$$

According to the switching waveforms for the drain current and voltage of these two switching devices shown in Fig.5, the measurement results of turn-on losses $P_{swi(on)}$ for GaN and MOSFET are 0.039W and 0.119W, respectively. Similarly, the turn-off losses are 3.075W and 4.140W. The technology of quasi-resonant conversion offers apparently improvement in the turn-on losses, resulting in increased efficiency. As GaN takes the advantage of lower total gate charge, it somehow shrinks the overlapping time when turning a transistor off. GaN saves 1.065W of turn-off losses in comparison with MOS transistor. Table 4 summarizes the power losses of these two devices. It is clear that the turn-off loss is dominant in this converter circuit when the high switching frequency is performed. GaN based power converter provides up to 7.02% improved efficiency over silicon MOSFETs.

Table 4. Power losses for GaN and MOSFET devices

	GaN (A)	MOSFET (B)	Improvement ((A)-(B))/60W
P_{Gate}	0.004 W	0.102 W	0.098 W
P_{Cond}	0.342 W	3.310 W	2.968 W
$P_{swi(on)}$	0.039W	0.119W	0.08 W
$P_{swi(off)}$	3.075 W	4.140 W	1.065 W
Total	3.461 W	7.671 W	4.211 W(7.02%)

8 Conclusion

Quasi-resonant flyback DC/DC converters have been designed and implemented using GaN transistors, which demonstrate the performances and compare the potentials between GaN and silicon based MOSFET in power electronics. Power losses are major consideration in converter applications. The conduct loss is the dominant component of the total losses as the transistor operates at quasi-resonant condition. The combined advantages of low on-resistance and gate charge for the GaN lead to a high efficient system because of the reduced conduction loss. The experimental results shown fully confirm the possibility to exploit the excellent characteristics of GaN devices in power electronics. Quasi-resonant switching offers reduced turn-on losses, resulting in increased efficiency and lower device temperature. When the switching frequency increases, the turn-off losses dominate the power losses. GaN based power converter provides up to 7.02% improved conversion efficiency over silicon MOSFETs.

GaN power transistor offers significant advantage in this topology converter. These advantages can enhance conversion efficiency, and reduce converter volume. Considering the suitability of the GaN transistors for the power switching applications, the quasi-resonant flyback converter constitutes a good candidate in that field. GaN power transistors provide comparable electric characteristics to other MOSFET transistors. The reference design presented in this application demonstrates that GaN power transistor is adopted in the quasi-resonant flyback converter for improving power efficiency. GaN power transistors offer performance improvements well beyond the realm of silicon based power MOSFETs, and are more and more being used in switching power devices.

Acknowledgment

The authors would like to thank the National Science Council of the Republic of China, Taiwan, for financially supporting this research under Contract No. NSC-100-2218-E-009-001.

References

[1] *Development of GaN power module*, ITRI internal report, 2011

[2] B. J. Baliga, *Power semiconductor device figure of merit for highfrequency applications*, IEEE Elect. Dev. Lett., Vol. 10, 1989, 455

[3] K. Yao, F. C. Lee, *A Novel Resonant Gate Driver for High Frequency Synchronous Buck Converters*, IEEE Transaction on Power Electronics, Vol. 17, No. 2, March 2002, 180-186

[4] M.A. Khan, G. Simin, S.G. Pytel, A. Monti, E. Santi, J.L. Hudgins, *New Developments in Gallium Nitride and the Impact on Power Electronics*, PESC '05. IEEE 36th, June 2005, pp 15-26

[5] W. Saito, Y. Takada, M. Kuraguchi, K. Tsuda, I. Omura, T. Ogura, *600V AlGaN/GaN Power-HEMT Design, Fabrication and Demonstration on High Voltage DC-DC Converter*, IEDM '03 Technical Digest. IEEE International, Dec. 2003, 23.7.1 - 23.7.4

[6] S. Yoshida, J. Li, T. Wada, H. Takehara, *High-Power AlGaN/GaN HFET with a Lower On-state Resistance and a Higher Switching Time for a Inverter Circuit*, ISPSD '03. 2003 IEEE 15th International Symposium, April 2003, 58-61

[7] J. Everts, J. Das, J. V. Keybus, J. Genoe, M. Germain, J. Driesen, *A High-Efficiency, High-Frequency Boost Converter using Enhancement Mode GaN DHFETs on Silicon*, ECCE, 2010 IEEE, Sept. 2010, 3296-3302

[8] Design of a QR Adapter with Improved Efficiency and Low Standby Power, http://www.onsemi.cn/pub_link/Collateral/TND377-D.PDF

[9] NCP1380 datasheet, http://www.onsemi.cn/pub_link/Collateral/NCP1380-D.PDF, accessed on Oct. 2011

[10] EPC1010 datasheet, http://epc-co.com/epc/documents/datasheets/EPC1010_datasheet_final.pdf

[11] IRF640 datasheet, http://www.datasheetcatalog.com/datasheets_pdf/I/R/F/6/IRF640.shtml

[12] Driving eGaN Transistors for Maximum Performance, http://epc-co.com/epc/documents/articles/EPC_Driving_eGaN_Transistors_fro_Maximum_Performance.pdf

[13] *Power Supply Engineer's Guide to Calculate Dissipation for MOSFETs in High-Power Supplies*, Application Note 1832, Maxim Integrated Products, Dec 26, 2002

[14] Z.J., Shen, Y. Xiong, X. Cheng, Y. Fu and P. Kumar, *Power MOSFET Switching Loss Analysis: A New Insight*, 41st IAS Annual Meeting on Industry Applications Conference, 8-12 Oct. 2006