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Original scientific paper

A COMPARATIVE STUDY OF SWITCHING PERFORMANCES AND EFFICIENCY OF GaN, SiC AND Si BASED DC-DC CONVERTERS

Marko Kamilovski, Katerina Raleva, Mario Makraduli

Faculty of Electrical Engineering and Information Technologies,
"Ss. Cyril and Methodius" University in Skopje,
Rugjer Bošković bb, P.O.Box 574, 1001 Skopje, Republic of North Macedonia
catherin@feit.ukim.edu.mk

A b s t r a c t: Wide bandgap (WBG) semiconductors offer many advantages over conventional silicon (Si) based devices such as faster switching speeds, lower internal capacitances, smaller size, lower power losses and higher efficiency. Due to their exceptional properties, these materials have gained significant attention in the field of power electronics. The wide bandgap of GaN (gallium-nitride) and the high-temperature tolerance of SiC (silicon carbide) make them ideal candidates for various power applications, from electric vehicles to renewable energy systems. This paper analyzes the overall efficiency and switching performances of three topologies of DC-DC converters in GaN technology and compare them with Si and SiC counterparts. The simulation results for the switching frequencies in the range of 100 kHz to 500 kHz show that the GaN based DC-DC converters provide smaller switching times and superior efficiency when compared to the same Si or SiC based DC-DC converters.

Key words; wide bandgap semiconductors; GaN devices; on-resistance; DC-DC converters; power efficiency; switching times

КОМПАРАТИВНА СТУДИЈА ЗА ПРЕКИНУВАЧКИТЕ КАРАКТЕРИСТИКИ И КОЕФИЦИЕНТОТ НА ПОЛЕЗНО ДЕЈСТВО НА DC-DC КОНВЕРТОРИ ВО GaN, SiC И Si ТЕХНОЛОГИЈА

А п с т р а к т: Полуспроводниците со голема широчина на забранетата зона (WBG) во однос на силициумските полуспроводнички елементи нудат многу предности: поголема брзина на вклучување и исклучување, помала интерна капацитивност, помали димензии, помали загуби на моќност и голем коефициент на полезно дејство. Поради нивните исклучителни својства, овие материјали привлекоа значајно внимание во енергетската електроника. Големата широчина на забранетата зона на GaN (галиумнитрид) и високата температурна толерација на SiC (силициумкарбид) ги прават идеални кандидати за различни енергетски апликации, од електрични возила до системи за обновлива енергија. Во овој труд се прави анализа на прекинувачките карактеристики и на коефициентот на полезно дејство на три топологии на DC-DC конвертори реализирани во GaN-технологија и се споредуваат со истите топологии на конвертори во Si и SiC технологија. Резултатите од симулацијата добиени за прекинувачки фреквенции од 100 kHz до 500 kHz покажуваат дека DC-DC-конверторите со GaN транзистори имаат многу мали времиња на вклучување и исклучување и извонреден коефициент на полезно дејство споредено со DC-DC конвертори базирани на Si и SiC.

Клучни зборови: полуспроводници со голема широчина на забранета зона; GaN електронски елементи; отпорност при вклучена состојба; DC-DC конвертори; коефициент на полезно дејство; прекинувачки времиња

1. INTRODUCTION

Silicon (Si) has been the dominant semiconductor for power electronic devices for over five decades. However, in the continuously evolving world of electronics, the power electronics field imposes unique demands on the next generation of high-voltage, high-current transistors-particularly for switching power supplies or motor drives. Two wide bandgap (WBG) materials that have been at the forefront of this technological revolution are silicon carbide (SiC) and gallium nitride (GaN) [1], [2]. While 4H-SiC technology [3] is mature in terms of crystalline quality and available device performances, gallium nitride (GaN) is still affected by several materials and technology concerns, limiting its full exploitation in power electronics applications [4].

Gallium nitride (GaN) has better material properties compared to Si and SiC (see Table 1). Due to the wider bandgap, higher critical electric field and higher saturation velocity, GaN is a promising semiconductor for the next generation of high-power and high-frequency devices. Also, the intrinsic carrier concentration of GaN is several orders of magnitude lower than Si which gives a possibility of GaN devices to operate at higher temperatures. All of the above mentioned characteristics have made GaN devices a very attractive choice in many applications such as automotive electronics, power supplies, communication infrastructures and other power systems.

Table 1

Relevant physical and electronic properties of Si, 4H-SiC and GaN

Property	Si	4H-SiC	GaN
Bandgap (eV)	1.12	3.2	3.4
Critical field (MV/cm)	0.25	3.0	4.0
Dielectric constant ε	11.8	9.7	9.5
Saturation velocity vs (107 cm/s)	1	2	3
Electron mobility μ (cm^2/Vs)	1350	800	1300 (2DEG)
Intrinsic carrier concentration n_i (cm^{-3}) at 300 K	1010	10−7	10−10
Thermal conductivity k (W/cmK)	1.5	4.9	1.3

Key to numerous applications in power electronics are conversion processes, in which switching frequencies have a major influence on device dimensions. Operation at higher frequencies provides a reduction in dimensions and weight of passive elements, which is especially important for compact DC-DC converters. The reduced power losses offered by gallium nitride, as well as the high temperature coefficient, allow reducing the size of the heat sinks, and thus reducing the dimensions of the converters. Many studies have shown the significant improvement in switching performances and efficiency when GaN transistors are used in DC-DC converters. In [5], a 160 W GaN-HEMT based synchronous boost converter is compared with a Si based converter with the same specifications in terms of efficiency and power losses over a wide range of operating conditions. The results (simulation and experiments) show that GaN has an efficiency of over 98.5% over the frequency range of 100–400 kHz. Ref. [6] presents a GaN-based flyback converter that achieves a maximum power conversion efficiency of 99.6% at 1 MHz. The switching performances and efficiency for a bidirectional buck-boost converter operating in buck mode were analyzed in [7]. In it, the cascode GaN-FET based converter showed lower switching losses and higher overall efficiency than the Si-CoolMOS based converter, due to the low on-state resistance and ultra-low reverse recovery charge of the cascode GaN-FET. Similar analysis for both, buck and boost mode of the bidirectional buck-boost converter was performed in [8], where an e-mode GaN is used instead of cascode mode. Ref. [9] presents a comparison of Si and GaN based buck converter, where the results show that GaN based buck converters show higher efficiency at higher frequencies and for different load currents. A comparative study between Si, SiC and GaN based buck converters is presented in [10], where the wide bandgap semiconductors show better overall performances than the Si-MOSFET with the GaN-FET edging out the SiC-MOSFET in both efficiency and switching performance. In [11], the analysis shows that GaN-HEMT based boost converter show much lower losses and consequently higher efficiency compared to their Si-MOSFET counterpart. Moreover, the converters are compared in terms of power density and cost. GaN-HEMTs show overall higher power density and even though they are costlier than Si-MOSFETs, their cost gap may close in the future with the further development of GaN technology. Also, the study compares the performance of hard-switched and soft-switched converters. The simulation and experimental results show that hard-switched converters have a better overall performance.

The goal of this paper is to investigate the advantages of using GaN devices in different topologies of DC-DC converters operating in continuous conduction mode (CCM) compared to SiC and Si switches. A method for selecting the optimal power switch in GaN technology for a given DC-DC converter application is presented. The simulation results of the most popular DC-DC topologies (buck, boost and buck-boost) with GaN, SiC and Si switches were performed and some relevant conclusions were derived. The paper is organized as follows: the topology of the three chosen DC-DC converters is presented in Section 2. Section 3 explains the parameters that affect the performances of the analyzed DC-DC converters, while in Section 4 are given the simulation results for all three converter topologies. In the last section, final conclusions are summarized.

2. SELECTED TOPOLOGIES FOR THE SIMULATIONS

Figure 1 presents the buck converter circuit diagram. It is used to step down the input voltage to a certain value according to the equation $V_{out}/V_{in} = D$, where D is the duty cycle.

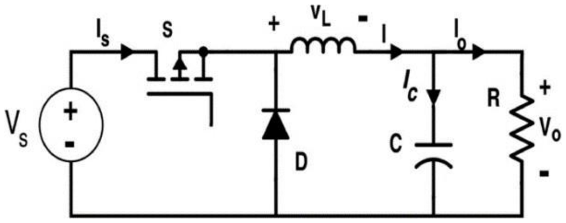


Fig. 1. Buck converter circuit diagram

The boost converter is used to step-up (increase) the input voltage to a certain output voltage value. Its circuit diagram is presented in Figure 2. The equation $V_{out}/V_{in} = 1/(1–D)$ gives the relation between input voltage, output voltage and duty cycle.

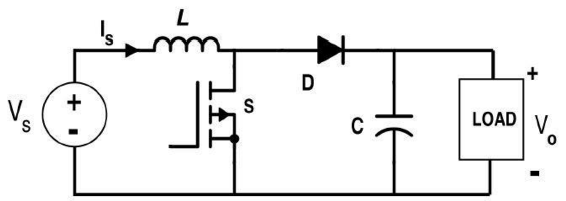


Fig. 2. Boost converter circuit diagram

The bidirectional buck-boost converter circuit diagram is shown in Figure 3. It consists of two switches, two capacitors, an inductor, and a load. The two diodes represent the anti-parallel body diodes of the power MOSFETs. This converter has two modes of operation: buck-mode and boost-mode.

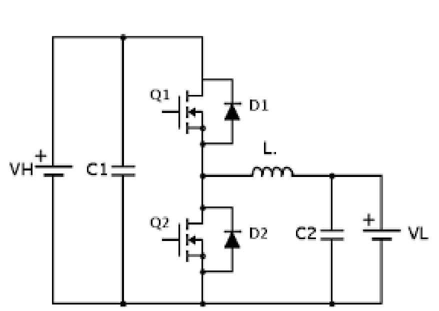


Fig. 3. Bidirectional buck-boost converter circuit diagram

3. PARAMETERS THAT AFFECT CONVERTER PERFORMANCES

The performance of a DC-DC converter is dependent on several factors: the switching frequency, the selected switch, the size of the passive elements, ripple of the output voltage and inductor current, etc. When selecting the switch three factors should be considered: voltage and current rating, on-resistance and the switching speed of the switch. The latter two are very important in the overall performance of the converter. Selecting a switch with optimal on-resistance can lead to lower power dissipation in the switch during the on-processes. On the other hand, faster switching speed leads to lower power dissipation during the switching process. By lowering these power losses an overall higher efficiency can be achieved in the DC-DC converter.

The key parameters that determine the performance of DC-DC converters according to the analyzed literature are the switching times and the efficiency of the converter.

The efficiency of DC-DC converters is calculated by:

$$\eta = P_o / (P_o + P_{loss}), \quad (1)$$

where P_o is the output power and P_{loss} is the total power losses in the converter. The power losses of the selected converter are defined as the sum of the power losses in the switch (P_{switch}), power losses in the passive elements (P_L, P_C), power losses in the diode (P_{diode}) and losses in the gate driver (P_{drive}) as shown in equation (2):

$$P_{loss} = P_{switch} + P_{diode} + P_C + P_L + P_{drive} \quad (2)$$

In terms of power losses during the switching, the power loss in the switch is of the outmost interest. It can be divided in switching losses and conduction losses of the switch. The switching losses occur when the switch changes from on to off state and vice versa. These power losses are dependent on the parasitic components of the switch and the switching frequency. On the other hand, the conduction losses of the switch are proportional to the on-resistance (R_{on}).

Balancing these two power losses is crucial in order to achieve higher overall efficiency of the specific power converter. In [12] a method for selecting the optimal power switch for a given dc-dc converter application is presented. The method uses datasheet information for the on-resistance (R_{on}) and the effective output capacitance ($C_{o(er)}$) and is demonstrated using a family of commercial Si and

SiC-MOSFETs. The specific technological parameters of the analyzed switch family can be grouped by the constant k.

$$R_{on} \cdot C_{oss} = k\,. \qquad (3)$$

Since the output capacitance (C_{OSS}) is quite nonlinear, the effective output capacitance ($C_{o(er)}$), defined as the capacitance that gives the same stored energy as the C_{OSS} while the drain-to-source voltage is rising from 0 to 80% of the drain-source breakdown voltage, can be used in the Eq. 3. Thus the equation can be rewritten as:

$$R_{on} \cdot C_{O(er)} = k\,. \qquad (4)$$

The conduction losses of the switch can be expressed by the equation:

$$P_{conduction} = D \cdot R_{on} \cdot I^2, \qquad (5)$$

where D is the duty cycle, R_{on} is the on-resistance of the switch, and I is the root-mean square drain current.

The switching losses due to the charging/discharging of $C_{o(er)}$ are expressed as:

$$P_{switching} = f \cdot C_{O(er)} \cdot V^2, \qquad (6)$$

where f is the switching frequency and V is the drain-source voltage. Using the Eq. (4), one can express the switching losses in terms of the on-resistance as:

$$P_{switching} = f \cdot k \cdot V^2 / R_{on}\,. \qquad (7)$$

Combining (5) and (7), the total power loss can be expressed as:

$$P_{total} = D \cdot R_{on} \cdot I^2 + f \cdot k \cdot V^2 / R_{on}\,. \qquad (8)$$

In order to minimize the total power loss with respect to R_{on}, the derivative of (8) is set to zero and the optimal R_{on} is derived as:

$$R_{on} = \frac{V}{t} \cdot \frac{\sqrt{f \cdot k}}{D}\,. \qquad (9)$$

The minimum of the total power loss can be achieved for a specific R_{on}, that depends on V, I, f, k and D, as shown in (9).

In order to verify this method for switches in GaN technology, a family of five 650V GaN-HEMTs by GaN-Systems is analyzed. The boost converter topology in which the switches were analyzed was arbitrarily chosen for the verification of the method. The GaN switches used in the simulations in Section 4 for the different converter topologies were chosen using the method presented in this section.

The parameters of each GaN-HEMT for drain-to-source voltage of 400 V is given in Table 2. The value of constant k is calculated using Eq. (4). The mean value of all k's is 4.953 ps and it is used in the further calculations. Using equations (5) and (7) the conduction, switching and total power losses are calculated for three different switching frequencies and are presented in Tables 3 – 5.

Table 2

Datasheet parameters of the analyzed GaN switches

Switch	R_{on} (mΩ)	C_{oss} (IpF)	$C_{o(er)}$ (pF)	k (ps)
GS66502B	200	17	25	5,00
GS66504B	100	31	47	4.70
GS66506T	67	49	73	4.89
GS66508T	50	65	100	5.00
GS66516T	25	126	207	5.18

Table 3

Power losses for a frequency of 100 kHz (W)

Switch	$P_{conduction}$	$P_{switching}$	P_{total}
GS66502B	8.44	0.40	8.83
GS66504B	4.24	0.79	5.01
GS66506T	2.83	1.18	4.00
GS66508T	2.11	1.58	3.69
GS66516T	1.06	3.17	4.22

Table 4

Power losses for a frequency of 200 kHz (W)

Switch	$P_{conduction}$	$P_{switching}$	P_{total}
GS66502B	8.44	0.79	9.22
GS66504B	4.22	1.58	5.80
GS66506T	2.83	2.36	5.19
GS66508T	2.11	3.16	5.27
GS66516T	1.055	6.32	7.38

Table 5

Power losses for a frequency of 500 kHz (W)

Switch	$P_{conduction}$	$P_{switching}$	P_{total}
GS66502B	8.44	1.98	10.42
GS66504B	4.22	3.96	8.18
GS66506T	2.83	5.91	8.74
GS66508T	2.11	7.92	10.00
GS66516T	1.06	15.84	16.90

The obtained results are graphically presented in Figures 4 – 6 with the green dotted line representing the switch with the lowest power losses and thus optimal on-resistance. From these figures, one can conclude that optimal value of the on-resistance R_{on} increases as the switching frequency is increased, which follows the trend seen in [12]. For switching frequency of 100 kHz, using switch GS66508T results in the lowest total power loss. The case for f = 200 kHz confirms the selection of switch GS66506T, used in the boost converter simulations in Section 4, as the switch which has the lowest power loss and thus the highest efficiency in the boost converter under the specified parameters.

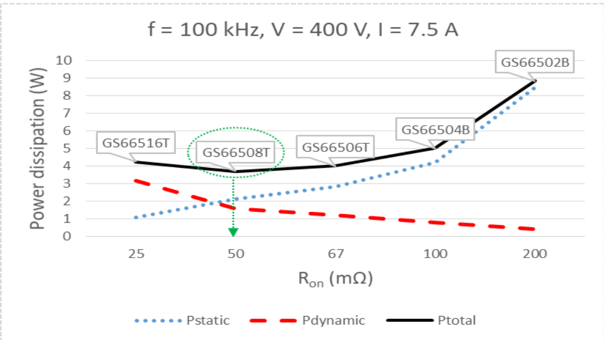


Fig. 4. Total power dissipation vs. on-resistance for a switching frequency of 100 kHz

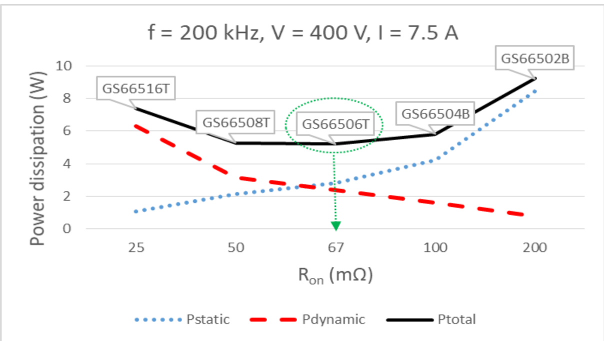


Fig. 5. Total power dissipation vs. on-resistance for a switching frequency of 200 kHz

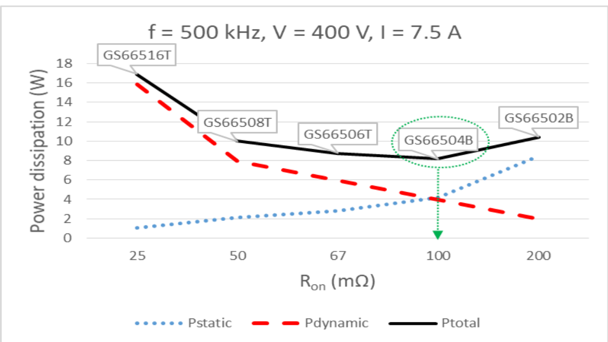


Fig. 6. Total power dissipation vs. on-resistance or a switching frequency of 500 kHz

The analyzed GaN switches were then simulated using the parameters of the boost converter in Section 4, given in Table 8. Figure 7 shows the simulation results in terms of overall efficiency of the boost converter for a switching frequency of 100, 200, and 500 kHz. The results show that for the switching frequency of 200 kHz, using switch GS66506T results in the highest efficiency of the boost converter, while for the frequencies of 100 and 500 kHz the optimal switches are GS66508T and GS66504B, respectively. Thus the calculated results match the obtained simulation results.

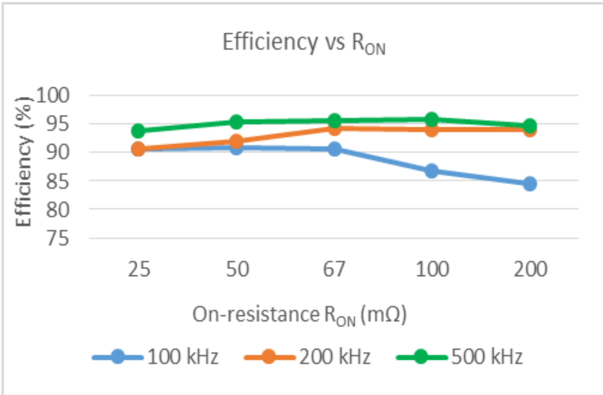


Fig. 7. Simulation of efficiency results for switching frequency of 100, 200, and 500 kHz

4. SIMULATION RESULTS

Three types of switches for each of the three topologies have been used in simulations: Si-MOSFET, SiC-MOSFET and GaN-HEMT/FET, with the models being provided by the manufacturer's producers. There are a large number of GaN models found in literature, which are developed by academia. The manufacturer models capture device-specific parameters and behavior that might not be fully reflected in the literature-based models, which could affect simulation accuracy for the particular device. When compared to the models of the manufacturers, these model have several disadvantages. Some of those disadvantages are: absence of thermal modeling, inability to reproduce both static and dynamic behavior, limited scope of focus (some models focus on certain aspects of device behavior), compatibility with other GaN-devices, high computational complexity, etc. In addition, literature/ academia based models might lack the extensive validation against measured data that manufacturer provided models undergo. With that being said, GaN models provided by their manufacturers are a better choice for fast and accurate simulations.

All simulations are performed in continuous conduction mode (CCM) where the current flowing through the inductor never reaches zero during its commutation period. In CCM the output voltage of the converter depends only on the duty cycle. On the other hand, in discontinuous conduction mode (DCM) the output voltage depends on multiple factors (switching frequency, duty cycle, inductor size). Additionally, DCM allows the use of smaller inductors (thus reducing the overall converter size) and decreases the power dissipation which occurs during the switching processes since the current at the start of each switching process is equal to zero. In CCM mode, there is greater power dissipation in the switches during the switching transitions, which significantly impacts the overall behavior of the converters. Nonetheless, this power dissipation in the switch is critical in the scope of this research; hence, the continuous current mode was chosen for analysis.

The inductor and capacitor used in the converters are dependent on the working conditions of the converter. The equations for the inductance (L) and capacitance (C) according to [13] are:

$$L = \left(V_0 \cdot \frac{1-D}{\Delta i_L \cdot fsw}\right) \tag{10}$$

$$C = \frac{1-D}{8 \cdot L \cdot \left(\frac{\Delta V_0}{V_0}\right) \cdot fsw} \tag{11}$$

$$L = \frac{Vin \cdot D}{\Delta i_L \cdot fsw} \tag{12}$$

$$C = \frac{D}{R \cdot \left(\frac{\Delta V_0}{V_0}\right) \cdot fsw} \tag{13}$$

where V_{in}, V_o, D, f_{sw}, Δi_L, ΔV_0 and R are the input voltage, output voltage, duty cycle, switching frequency, inductor current ripple, output voltage ripple, and resistance (load), respectively. Equations (10) and (11) are used for the buck converter and the buck-mode of the bidirectional buck-boost converter, while (12) and (13) are used for the boost converter as well as the boost-mode of the bidirectional buck-boost converter.

4.1. *Buck converter*

A DC-DC buck converter is used to step down the input voltage from 48 V to 12 V, using a GaN-FET (EPC2045), SCT20N120 (SiC-MOSFET) and a Si-MOSFET (FDA18N50) and the results are compared. The basic parameters of the converter are given in Table 6, while Table 7 shows the important parameters of the GaN-FET, SiC-MOSFET and Si-MOSFET, all of which were selected to have a similar current rating. The important waveforms of the simulated buck convertor are shown in Figure 7.

Table 6

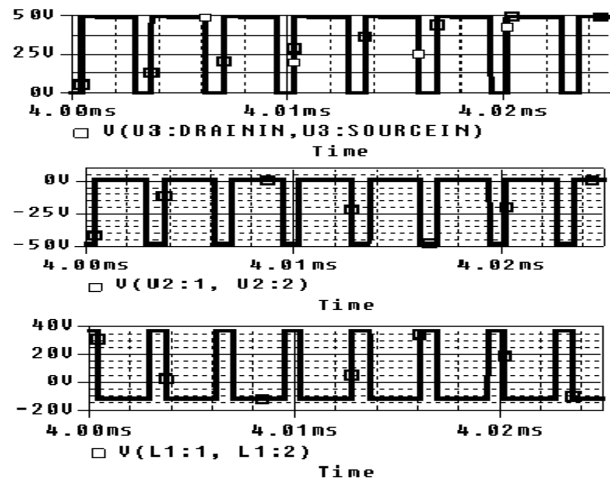
Parameters of the buck converter

Parameter	Value
Input voltage	48 V
Output voltage	12 V
Output current	6 A
Duty cycle	0.25
Switching frequency	100 – 500 kHz

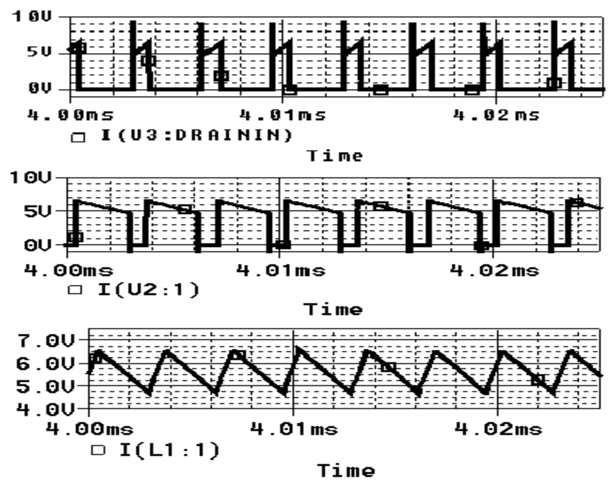
Table 7

Parameters of the used switches in buck converter

Parameter	FDA18N50 Si-MOSFET	SCT20N120 SiC-MOSFET	EPC2045 GaN-FET
Breakdown voltage	500 V	1200 V	100 V
Current	19 A	20 A	16 A
On-resistance	220 mΩ	189 mΩ	7 mΩ



a)



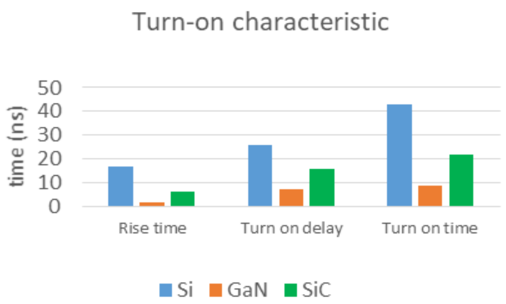
b)

Fig. 8. Key waveforms of the buck converter: a) switch voltage (top), diode voltage (middle) and inductor voltage (bottom); b) switch current (top), diode current (middle) and inductor current (bottom)

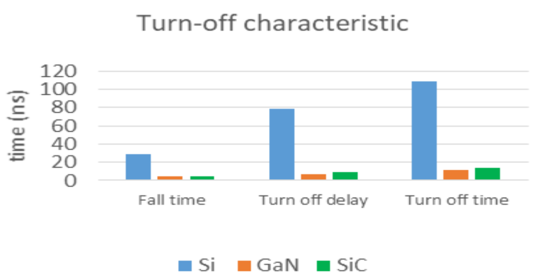
a) *Switching characteristics*

The switching performance of the buck convertor is analyzed in terms of on-delay, off-delay, rise and fall time, as well as the total on and off times. Both circuits are tested under the same switching frequency of 300 kHz. The Si-MOSFET requires a gate-source voltage of 15 V to securely turn on the switch and the SiC-MOSFET requires +18 V gate-source voltage for turn-on and –3 V for turn-off. The GaN-FET has a very low reverse recovery charge and it requires a gate-source voltage of +6 V for turning-on and –3 V for turning-off.

The turn-on time is calculated as the sum of the rise time and turn-on delay, where the rise time is the time from 90% to 10% of the fall of the drain-source voltage (V_{DS}) and the turn-on delay is the time between 10% of the rise of the gate-source voltage and 90% of V_{DS}. Similarly, the turn off -time is the sum of the fall time (time from 10% to 90% of the rise of V_{DS}) and the turn-off delay (time between 90% of the fall of V_{GS} and 10% of the rise of V_{DS}). Simulation results, presented in Figure 9, show that the GaN-FET has a turn-on time of around 8.9 ns which is almost five times smaller than the turn-on time of the Si-MOSFET (42.7 ns), while the SiC-MOSFET has halt the turn-on time of the Si-MOSFET (21.6 ns). In addition, the turn-off time of the GaN-FET is 11.57 ns and the turn-off time of the SiC-MOSFET is 13.9 ns, which are nearly ten times lower than the Si-MOSFET (108.3 ns).



a)



b)

Fig. 9. Switching characteristic of the buck converter a) turn-on and b) turn-off characteristics

b) *Efficiency*

The power losses in the gate driver are neglected in this analysis. By using the above mentioned formulas and operating under a switching frequency of 300 kHz, the efficiency of the buck converter with the Si-MOSFET is 88.8%, with the SiC-MOSFET is 90.6% while the efficiency of the same converter with a GaN-FET switch is 92.8%. The results are as expected due to GaN's lower on-state resistance, which results in lower conduction losses. As seen from the switching characteristics, GaN has a much shorter on and off times which result in an even lower switching losses.

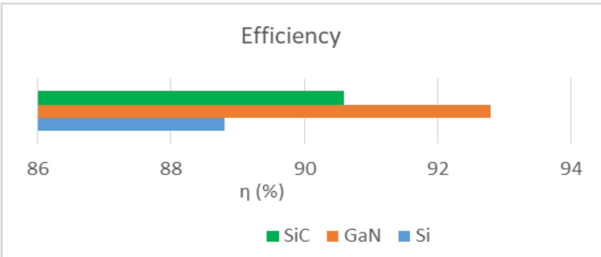


Fig. 10. Buck converter efficiency results for a switching frequency of 300 kHz

4.2. *Boost converter*

The boost converter is used to step-up the input voltage of 100 V to 400 V at the output, using GaN-HEMT, SiC-MOSFET and Si-MOSFET switches. The parameters of the boost converter are given in Table 8. The important parameters for each of the selected switches are given in Table 9.

Table 8

Parameters of the boost converter

Parameter	Value
Input voltage	100 V
Output voltage	400 V
Output current	1.25 A
Duty cycle	0.75
Switching frequency	100 – 500 kHz

Table 9.

Parameters of boost converter switch

Parameter	IPA60R120 P Si-MOSFET	SCT3120Al SiC-MOSFET	GS66506T GaN-HEMT
Breakdown voltage	650 V	650 V	650 V
Current	26 A	21 A	22.5 A
On-resistance	120 mΩ	120 mΩ	67 mΩ

The key waveforms of the boost converter are presented in Figure 11.

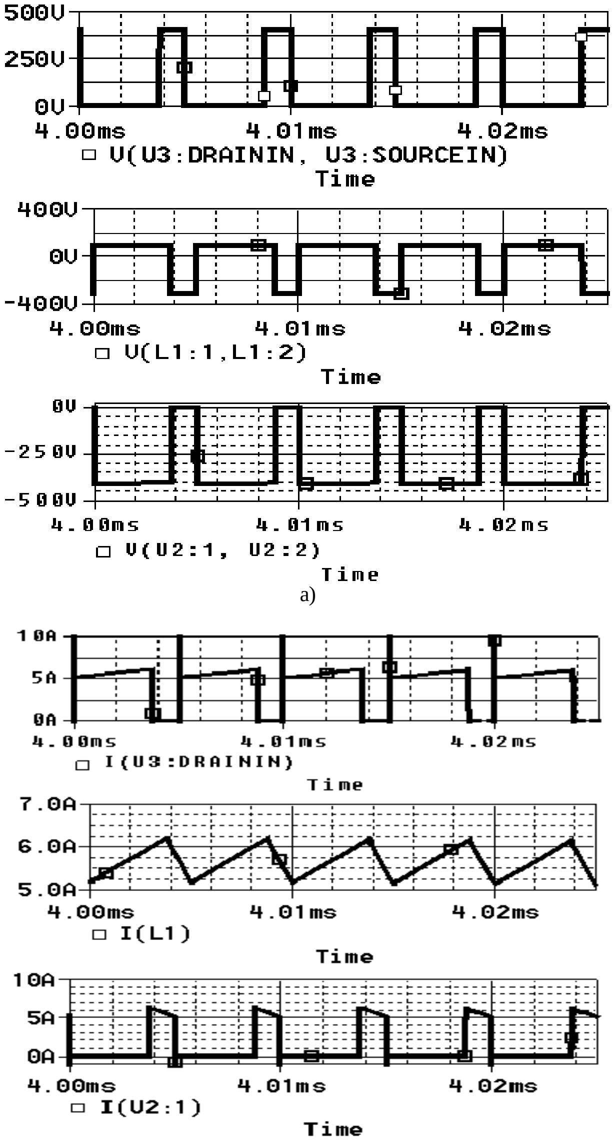


Fig. 11. Key waveforms of the boost converter: a) switch voltage (top), inductor voltage (middle) and diode voltage (bottom); b) switch current (top), inductor current (middle), and diode current (bottom)

a) *Switching characteristics*

In this analysis both circuits are evaluated operating in boost converter mode at a switching frequency of 200 kHz. The E-series Si power MOSFET (SIHG24N65E) is driven on by a 12 V source. The GaN-HEMT (GS66506T) is turned on by a 6 V gate-source voltage and turned off by applying a –3 V, while the SiC-MOSFET (SCT3120A) is turned on with 18V and turned off with –3V. Figure 12 presents the simulation results for the switching characteristics for both circuits. Both turn-on and turn-off time of the GaN switch, which are 8.2 ns and 22 ns, respectively, are almost three times smaller than the Si turn-on (22.1 ns) and turn-off (57.6 ns) times. The SiC-MOSFET has a similar turn-on time to the Si-MOSFET (27.2 ns) and the smallest turn-off time of 19.14 ns.

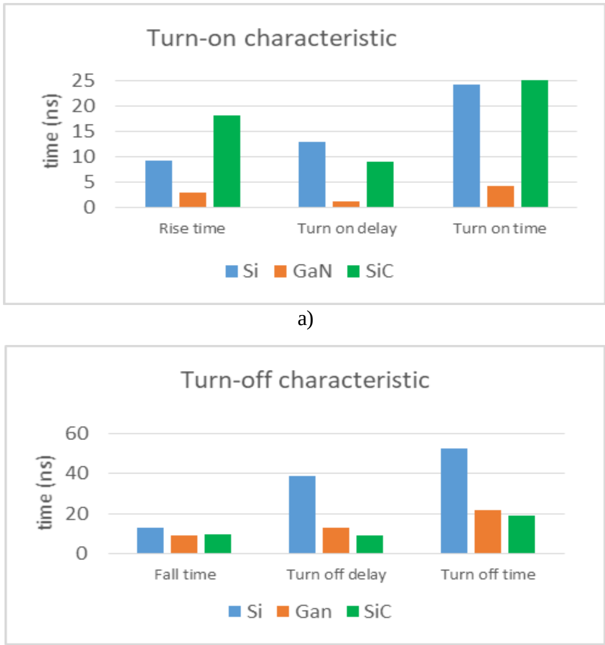


Fig. 12. Switching characteristic of the boost converter a) turn-on b) turn-off

b) *Efficiency*

The efficiency of the boost converter is calculated using the same formulas as explained in Section 3. The E-series Si power MOSFET shows better performance than most of the conventionally used Si-MOSFETS and therefore it is expected to have a higher efficiency. Calculated at a frequency of 200 kHz. The efficiency of the boost converter is 91.8% with Si-MOSFET, 92.7% with SiC-MOSFET and 94.2% with GaN-HEMT for a switching frequency of 200 kHz. Simulation results in terms of efficiency are presented in Figure 13.

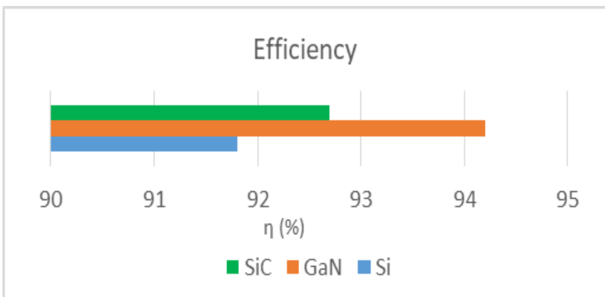


Fig. 13. Efficiency results for switching frequency of 200 kHz

4.3. *Bidirectional buck-boost converter*

In this analysis a bidirectional buck-boost converter is chosen. Both the buck and boost mode of operation are used under the same operating conditions and the parameters are calculated by using the same equations as for the buck and boost converter. The full list of parameters for the bidirectional buck-boost converter operating in both modes is given in Table 10. The three switches (Si-Cool-MOS, SiC-MOSFET and GaN-FET) were selected based on their similar electrical specifications and parameters as well as the suitability in the converter's operating mode and the method presented in Section 3. Their electrical specifications are given in Table 11.

Table 10

Parameters for buck mode of the bidirectional buck-boost converter

Parameters	Value
High side voltage	400 V
Low side voltage	96 V
Power rating	500 W
Duty cycle	0.24 and 0.76, respectively
Switching frequency	100 – 500 kHz

Table 11

Electrical specifications of chosen switches

Parameter	IPA65R045C Si-MOSFET	SCT20N120 SiC-MOSFET	GS66508B GaN-HEMT
Breakdown voltage	700 V	1200 V	650 V
Current	18 A	20 A	30 A
On-resistance	45 mΩ	190 mΩ	50 mΩ

a) *Switching characteristics*

The Si-CoolMOS has an overall better performance compared to other state of the art Si-MOSFETs. Its lower on state resistance and higher switching speeds lowers the conduction and switching losses. In comparison with the previous Si-MOSFETS, the Si-CoolMOS has the overall lowest turn-on and turn-off times. On the other hand, GaN-FET has an even smaller on-resistance and lower reverse recovery charge, resulting in a higher switching speed. Figure 14 shows the turn-on and turn-off characteristic. The GaN based converter for both modes of operation has exceptionally lower on and off times. For the buck mode the turn-on time for the GaN-FET is 10.92 ns, while the SiC-MOSFET and Si-Cool-MOS turn-on time are 25.2 ns and 26.4 ns, respectively. On the other hand, the boost mode has longer turn-on time for the Si-Cool-MOS with 121.77 ns, the SiC-MOSFET with 24.91 ns, and the GaN-FET has a turn-on time of 10.96 ns. The turn-off times for the GaN-FET are 10.97 ns for the buck mode and 10.96 ns for the boost mode. The SiC-MOSFET follows second with turn-off times of 18.82 ns and 18.23 ns for the buck and boost mode, respectively. The Si-CoolMOS has the longest turn-off times with a turn-off time of 34.58 ns for the buck mode, and 110.5 ns for the boost mode of operation.

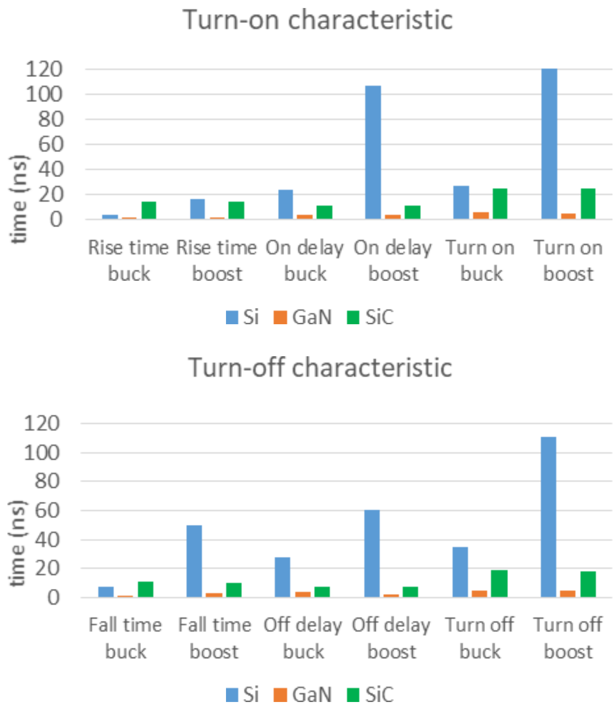


Fig. 14. Switching characteristic for both modes of operation: turn-on (top) and turn-off (bottom)

b) *Efficiency*

Similarly, to the buck and boost converter, the efficiency is calculated using equations (1) and (2). Using a switching frequency of 100 kHz, for the buck mode of operation the efficiency of the Si-CoolMOS is 91.8%, 92% for the SiC-MOSFET, while the GaN-FET based converter shows an efficiency of around 92.3%. On the other hand, when operating in boost mode, the efficiency of the Si based converter is 95.7%, 95.8 for the SiC based bidirectional converter and 96% for the GaN based converter. The results are shown in Figure 15.

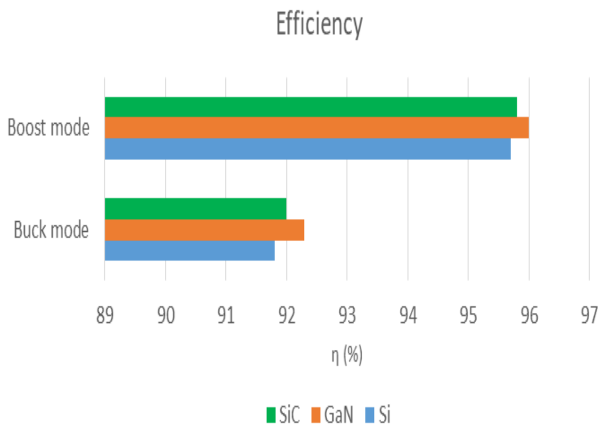


Fig. 15. Efficiency results for switching frequency of 100 kHz

Influence of the operating frequency on efficiency and switching times

Simulations were performed for all converters at different operating frequencies. As the switching frequency increases, the passive components are optimized accordingly using the equations (10)–(13) to calculate the appropriate capacitance and inductance for the different frequencies. Tables 12 to 15 show the change in efficiency and switching times as the frequency is increased from 100 kHz to 500 kHz with a step of 100 kHz for each of the analyzed converters. The switching times vary with the change of frequency. As it can be seen GaN devices show superior efficiency and switching times even at higher frequencies.

Table 12

Buck converter performance for the frequency range of 100 kHz – 500 kHz

Frequency (kHz)	t_{on} (ns)			t_{off} (ns)			η (%)		
	Si	SiC	GaN	Si	SiC	GaN	Si	SiC	GaN
100	40.91	21.51	**9.10**	110.40	13.10	**11.69**	90.0	91.40	**93.1**
200	40.38	21.45	**8.99**	107.84	13.33	**12.12**	89.7	91.10	**93.1**
300	42.70	21.6	**8.90**	108.30	13.90	**11.57**	88.8	90.10	**92.8**
400	45.00	21.13	**11.70**	109.46	13.77	**12**	88.2	89.92	**92.7**
500	41.87	20.98	**9.00**	108.80	13.86	**11.8**	87.6	89.60	**92.6**

Table 13

Boost converter performance for the frequency range of 100 kHz – 500 kHz

Frequency (kHz)	t_{on} (ns)			t_{off} (ns)			η (%)		
	Si	SiC	GaN	Si	SiC	GaN	Si	SiC	GaN
100	25.20	27.3	**4.63**	66.2	19.00	**17.50**	90.72	**92.90**	90.7
200	24.30	27.2	**4.3**	52.4	**19.44**	22.00	92.40	92.70	**94.2**
300	23.22	26.4	**4.50**	72.32	**20.00**	20.60	92.48	93.32	**95.1**
400	23.53	26.64	**5.40**	69.2	**20.41**	20.55	92.70	93.37	**95.4**
500	22.87	27.00	**5.43**	66	**20.17**	20.35	93.22	93.40	**95.6**

Table 14

Buck-boost (buck mode) converter performance for the frequency range of 100 kHz – 500 kHz

Frequency (kHz)	t_{on} (ns)			t_{off} (ns)			η (%)		
	Si	SiC	GaN	Si	SiC	GaN	Si	SiC	GaN
100	26.4	25.10	**5.27**	34.58	18.82	**5.23**	91.8	92.0	**92.3**
200	80.0	25.00	**5.35**	120	18.82	**5.20**	90.7	**91.8**	91.6
300	83.0	25.00	**5.27**	123	18.85	**5.18**	88.8	**90.5**	90.3
400	91.7	25.10	**5.24**	122	18.85	**5.20**	85.3	89.5	**89.7**
500	118.0	25.09	**5.23**	105	18.9	**5.20**	84.2	88.2	**88.6**

Table 15

Buck-boost (boost mode) converter performance for the frequency range of 100 kHz – 500 kHz

Frequency (kHz)	t_{on} (ns)			t_{off} (ns)			η (%)		
	Si	SiC	GaN	Si	SiC	GaN	Si	SiC	GaN
100	121.77	24.91	5.20	110.5	18.23	5.22	95.7	95.8	96.0
200	122.7	24.94	5.26	111.5	18.72	5.29	94.2	94.4	94.8
300	121.5	24.91	5.12	91.2	18.66	5.07	92.3	93.1	93.4
400	117.00	24.92	5.20	137.5	18.70	5.18	90.7	91.8	92.1
500	119.8	24.90	5.23	89.5	18.86	5.22	88.9	90.8	91.3

5. CONCLUSION

The paper presents a comparative study of switching performances and efficiency of the basic topologies of DC-DC converters in GaN, SiC and Si technologies. The simulation results show that the WBG devices, especially GaN devices, offer better performance (switching times and efficiency) than the state of the art Si devices. In all WBG based converter topologies, the switching times (on and off times) are notably smaller than the ones of the Si based converters. Furthermore, the results show that the WBG switches make the converters more efficient than their Si counterpart, with the efficiency of the GaN based converters never falling below 90%. Even though the technology of SiC and GaN devices is not as developed as the Si technology, these results show that the use of WBG semiconductors can improve the overall performance of DC-DC converters. The switching times of GaN switches are smaller than those of SiC switches for the entire frequency range of 100 kHz to 500 kHz and in some instances the difference is significant. On the other hand, the efficiency results show similar values for the switching frequency of 100 kHz, but as the frequency increases up to 500 kHz GaN switches stand out as the better choice for high frequency and low-medium voltage applications for DC-DC converters.

The popularity of GaN technologies in power electronics continues to rise with the ever growing demand for greater efficiency, higher frequencies and lower cost of production. When compared to Si and SiC, GaN technology is relatively young and has some material and technology concerns, mostly the production of GaN substrates, which limits its full potential. Another area of concern is the modelling of GaN-devices. Although, there are available manufacturer models, the proposed models for GaN transistors in the literature required several improvements such as, modelling of the parasitic components and their behavior and thermal modelling. These improvements will lead to faster and more accurate models, which is critical when predicting the behavior and reliability of the devices under different working conditions. Analyzing DC-DC converters in the discontinuous conduction mode (DCM) can be another area of future work. In it, special focus will be given to the effect of the passive elements (especially the inductor) on the converter performance.

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