# STUDY ON THE APPLICATION OF GALLIUM NITRIDE TRANSISTORS IN POWER ELECTRONICS

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*Abstract* – **Wide bandgap semiconductors have emerged as an attractive option for silicon (Si) replacement in the recent years. Among the new materials, gallium nitride (GaN) has been considered as the most promising candidate. This paper presents an overview of the GaN technology in power electronics. The review focuses on the main aspects of GaN transistors, such as electrical, thermal and economical characteristics. A comparison between Si and GaN switching devices in a family of synchronous buck converters designed for LED lighting applications is also presented. This comparison was performed using synchronous buck converters, designed under same parameters, at five different switching frequencies, ranging from 100 kHz to 1 MHz. Efficiency and temperatures were recorded. GaN based converters presented higher efficiency and lower operating temperatures in all cases, with a maximum efficiency of 96.8% and a minimum of 94.5%. Besides, Si-based converters exhibited a higher performance degradation as switching frequency and dead time increase.**

*Keywords* – **GaN, Gallium Nitride, GaN Transistors, LEDs, Switching Power Supply.**

## I. INTRODUCTION

Since the beginning of power electronics with the development of the mercury-arc rectifier, used in conversion from AC to DC in the railways of the 1920s [1], the world has been transformed by innovations provided by the ability to process energy through electronic circuits. However, only with the development of the silicon (Si) transistor in the 1940s [2], and especially the silicon metal-oxide field effect transistor (MOSFET) in the 1970s [3], the creation of more compact and efficient systems based on switching converters became possible.

It is estimated that, by 2030, 80% of the world's electricity will be, somehow, processed by switched converters [4]. Thereby, it is expected the power semiconductor market surpass $17B by 2020, driven, in particular, by the worldwide trend for more energy efficient devices [5].

The development of more efficient and compact circuits depends on improvements in the semiconductor devices used [6]. The increase of switching frequency has been a recurrent alternative because it allows the miniaturization of passive components in the circuit [7]. However, it is necessary to minimize losses in the semiconductors, since these are one of the major limiting factors in power converters [8].

Many advances have been made in Si semiconductor manufacturing technology, allowing circuits to boost their power density in a virtually linear trend, increasing about tenfold since they appeared in the market [9]. However, as Si technology approaches its theoretical limits of performance, the need for a substitute of the same relevance becomes more evident. The use of new wide bandgap semiconductors such as gallium nitride (GaN) is still rather modest. However, it is expected that this type of semiconductor will share up to 5% of the market in 2020 [5]. The substitution of Si by these new materials may result in substantial gains in converter performance in terms of efficiency, reliability, higher operating voltages and lower thermal management requirements [10], allowing the trend of miniaturization and efficiency increase of power electronics systems continue to evolve.

The replacement of Si MOSFETs by GaN-based devices in applications such as photovoltaic [11], [12], power factor correction [13], [14], audio power amplifiers [3] , envelope tracking [15], wireless energy transfer [16], [17], Light Distancing and Ranging (LiDAR) [18] and motor drivers [19] was already demonstrated.

In this scenario, the paper intends to highlight the potential of GaN to take Si's place in the electronic market in the near future through an overview of main properties and a performance comparison between both technologies.

This work is organized as follows: Section II presents a comparison of materials used in the fabrication of semiconductor devices, showing the relationship between each characteristic of the material and its influence in the produced device. The concept of theoretical limit for a semiconductor technology is also presented; GaN semiconductors and their types, characteristics and constructive aspects are discussed in Section III. Design challenges posed by the emergence of this new technology are introduced in Section IV. Section V shows economical aspects related with the development of GaN-based devices. An experimental comparison between Si- and GaN-based transistors in a DC-DC converter for lighting applications is made in Section VI. Finally, in Section VII, the conclusions of this paper are presented.

## II. MATERIAL SELECTION FOR POWER SEMICONDUCTORS

The quality and characteristics of a semiconductor device are determined by the characteristics of the material used

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in the fabrication process [3], [20]. Table I summarizes some of the key parameters of Si, SiC and GaN [3], [21]. These are some of the most commonly used materials in the power semiconductor industry. In the next subsections, each parameter will be discussed and its implications in the final device will be evaluated.

**TABLE I**
**Properties of Si, SiC and GaN**

| Parameter | Symbol | Si | SiC | GaN |
|---|---|---|---|---|
| Bandgap ($eV$) | $E_g$ | 1.12 | 3.26 | 3.39 |
| Electron mobility ($cm^2/V \cdot s$) | $\mu_n$ | 1400 | 950 | 1500 |
| Critical field ($MV/cm$) | $E_{crit}$ | 0.23 | 2.2 | 3.3 |
| Permittivity | $\varepsilon_r$ | 11.8 | 9.7 | 9 |
| Thermal conductivity ($W/cm \cdot K$) | $\lambda$ | 1.5 | 3.8 | 1.3 |
| Melting point (°$C$) | - | 1414 | 2730 | 2500 |

### *A. Bandgap*

Semiconductor materials, at absolute zero temperature (0K or -273.15°C), have all their electrons confined in the valence band, thus acquiring characteristics of an electrical insulator. Semiconductors can start conducting electricity, as the temperature increases, if their electrons absorb energy in order to surpass the valence band. The amount of energy required for the electrons to make this transition is called bandgap [22], [23].

This energy is related to the strength of the chemical bonds among atoms in the crystalline structure [22]. The stronger the bond, the harder it is for a free electron to move between atoms. Among the consequences of this phenomenon in power semiconductors, are the lower leakage currents and higher operating temperatures [3].

A larger bandgap allows a material to withstand higher electric fields, making possible to use a smaller semiconductor die for a given voltage. This has a direct impact on the characteristics of the device, as the smaller the die, the lower its electrical resistance and intrinsic capacitances. Consequently its efficiency will increase [21].

Materials with bandgap larger than 3 eV are commonly called wide bandgap semiconductors [6], [10], [24], [25].

### *B. Electron Mobility*

Electron mobility represents the velocity in which an electron can move in the material lattice when propelled by an electrical field, expressed as:

$$\mu_n = \frac{\upsilon}{E} \tag{1}$$

where $\upsilon$ is the drift velocity of the material and $E$ is the critical field applied.

The higher the electron mobility, the lower the resistance of the semiconductor [22]. As seen in Table I, GaN has the higher electron mobility. For this reason, GaN switches are commonly called GaN High Electron Mobility Transistors (GaN HEMTs).

### *C. Critical Field*

The critical field represents the maximum electrical field the material withstands without causing avalanche breakdown [3]. For power semiconductors, this is directly related to the maximum blocking voltage $V_{BR}$, given as:

$$V_{BR} = \frac{1}{2} w_{drift} E_{crit} \tag{2}$$

where $w_{drift}$ is the width of the drift region.

Due to its critical field more than ten times larger than Si, SiC and GaN semiconductors can be made with a drift region ten times smaller for the same blocking voltage [3]. Therefore, the distance between the transistor terminals can be drastically reduced, producing smaller devices with lower resistances and capacitances [25].

It is possible to evaluate the number of electrons $N_D$ between the two terminals (assuming an N-type semiconductor) using the Poisson equation [3]:

$$N_D = \frac{\varepsilon_0 \varepsilon_r E_{crit}}{w_{drift} q}. \tag{3}$$

In this equation $q$ is the charge of the electron ($1.6 \cdot 10^{-12}$ Coulombs) and $\varepsilon_0$ is the permittivity of free space.

Thus, according to (3), if a material has a critical field ten times higher and, therefore, a drift region ten times smaller, the number of electrons between the terminals can be 100 times higher. This explains the superior performance of large bandgap transistor when compared to traditional Si-based devices.

### *D. Theoretical Limits*

One way to translate these material parameters into a device comparison is to evaluate the theoretical limits of a semiconductor material. The ideal on-resistance of a major carrier device (as presented by [3]) is given by:

$$R_{DS(on)} = \frac{w_{drift}}{q \mu_n N_D}. \tag{4}$$

Combining (2), (3) and (4), one can obtain the specific on-resistance or theoretical limit of a semiconductor technology, which is usually measured in $\Omega \cdot m^2$:

$$R_{on(sp)} = \frac{4V_{BR}^3}{E_{crit}^3 \varepsilon_0 \varepsilon_r \mu_n}. \tag{5}$$

Equation (5) relates the maximum blocking voltage of a device with the resistance of a specific die area. These limits are shown in Figure 1 for Si, SiC and GaN along with the data of some devices of different technologies [26], [27].

It is clear that GaN has the best relationship between voltage and resistance. Although some Si-based devices were able to surpass its theoretical limits, this evolution took almost 30 years to occur. There are already SiC devices that exceed the best Si MOSFETs in terms of performance. These devices are, however, limited mostly to high voltage applications, mainly due to its production cost.

On the other hand, GaN devices have at the present time superior performance than their Si counterparts and are, still, in the early stages of development. This demonstrates all the potential of this new material to take Si place in the power electronics market in the future.

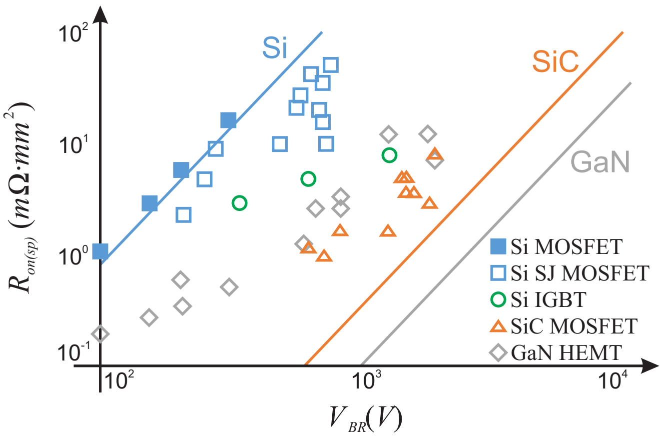

Fig. 1. Theoretical limits of Si, SiC and GaN with specific on-resistance of selected devices.

## III. GALLIUM NITRIDE TRANSISTORS

The first advances in the manufacture of GaN-based transistors during the 90s were focused on radiofrequency (RF) applications [28], [29] being the high electron mobility effect of gallium nitride first demonstrated in 1975 [30]. The first GaN transistors for the RF market appeared in 2004, produced by the companies Eudyna Corporation, CREE, Nitronex and RFMD [3], [31], [32].

In 2005, the process of growth GaN crystals on Si substrates was developed, making it possible the mass production of these devices using the tools already available for the manufacturing of Si semiconductors [3].

The first GaN transistor specifically developed to replace Si MOSFETs in switched applications was developed in 2009 by Efficient Power Conversion [3]. In the same year, the cascode-type GaN transistor was developed, specifically aimed at higher voltage applications [33].

There are currently three types of GaN transistors for power electronics: depletion, enhancement and cascode. The first two are similar to traditional P- and N-type MOSFETs, respectively. The third type consists of a hybrid topology, since it comprises in the same package a Si MOSFET and a GaN HEMT, as it will be detailed below.

### A. Depletion Mode

Depletion mode GaN transistors, or dGaN, are normally on devices, that is, current flows freely between drain and source terminals when no potential is applied to the gate terminal. To switch this type of device to off-state, a negative gate-source voltage needs to be applied [3].

Although having blocking voltages that can exceed 1kV [34], [35], in power electronics applications, this type of transistor is not recommended due to safety reasons. They are yet not commercially available as standalone devices, only demonstrated in academic papers [7], [36], [37] or used in conjunction with Si MOSFETs as it will be explained later on.

### B. Enhancement Mode

Enhancement mode transistors, or eGaN, are normally off, that is, they do not present a path for conducting current between drain and source if no voltage is applied to the gate terminal [3].

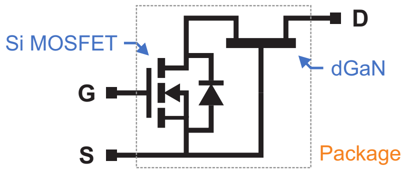

Fig. 2. Typical arrangement of a GaN-based cascode transistor.

This type of transistor has a lower threshold voltage $V_{GS(th)}$ than other semiconductors. Generally, commercial eGaNs allow a maximum driver voltage in the order of 7V [38]. For this reason, both the control circuit and the arrangement of the circuit components require special care to ensure proper operation of the switch.

### C. Cascode

Cascode type transistors, or cGaN, are hybrids formed from the connection of a high-voltage dGaN transistor with a low-voltage Si MOSFET [33]. Figure 2 shows the schematic of this device.

This arrangement allows the development of a normally off semiconductor that withstand larger driver voltages (determined by the Si MOSFET used) [39]. The command signal is applied directly to the Si MOSFET, which controls the conduction of the GaN transistor. When in conduction, the current flows through both semiconductors and, when blocked, the voltage is applied on the GaN transistor.

In this configuration, the on-resistance of the low-voltage MOSFET is much lower than that of the GaN transistor, the latter having a dominant behavior in relation to conduction losses [39]. If a smaller voltage GaN transistor is used, the participation of the MOSFET in the on-resistance of the final semiconductor increases, eliminating the advantages of using a hybrid topology. For this reason, cascode transistors are only feasible for blocking voltages greater than 200V [3].

## IV. DESIGN CHALLENGES

With the use of a new and still little explored technology, there is a need to deepen the techniques used in the design of the circuits in which these new products are inserted.

It is important to emphasize that GaN transistors have a lateral structure, that is, the conduction of the electrons between the terminals occurs in the horizontal plane, allowing the device terminals to be placed side by side in the semiconductor die [40]. Among the advantages of this arrangement are the lower capacitances of the device and the absence of wired connections between die and external terminals, drastically reducing the parasitic resistances and inductances of the device [37], [41].

Simple processes such as soldering become decisive in the operation of the converter, as in the case of the GaN transistors used in this paper, where most of the heat lost in the switch is dissipated on the printed circuit board through the terminals.

Moreover, despite guaranteeing lower switching losses and thus allowing higher switching frequencies, the lower capacitances of the GaN semiconductors also make them more sensitive to the parasitic components of the circuit in which they are inserted. In fact, as the switching frequency increases, the parasitic components inserted in the current path become the limiting factor [42]. As demonstrated by [42], a 1.2 nH difference in the parasitic inductance in series with the switches of a synchronous buck can cause up to 75% increase in the peak voltage applied to the main switch of the converter.

Techniques such as the use of multilayer printed circuit boards and the insertion of decoupling capacitors under the switches are recommended by manufacturers in order to minimize the effects of circuit's parasitic inductances [38], [42].

## V. TECHNOLOGY COST

One of the factors that determines the characteristics and, specially the cost of GaN transistors is the crystalline substrate in which the layers of GaN and other materials that constitute such devices are deposited [43]. Due to the compatibility of atomic structures, GaN substrates are the ideal choice for use in the fabrication process. However, the availability of material and manufacturing costs makes the use of GaN substrates uncommon [3]. In applications such as LEDs and RF transistors, sapphire substrates are widely used [44]. However, due mainly to its low thermal conductivity, this material is not commonly applied in transistors for power electronics. SiC on the other hand, presents excellent thermal and electrical properties [26]. Its cost, however, is quite high. In the last years, there has been an investment in the research and development of GaN semiconductors with Si substrates, allowing cost reduction by using the existing Si semiconductor production structure [3]. For this reason, the majority of commercially available GaN transistors is, nowadays, made with Si substrates.

Figure 3 highlights the key characteristics of Si and SiC as substrate for producing GaN HEMTs. Outer rings represent better characteristics for device fabrication.

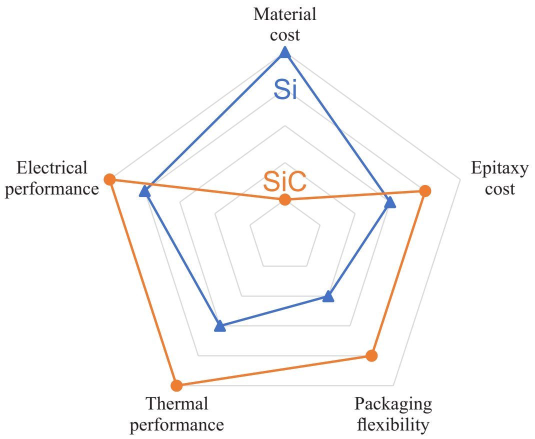

Fig. 3. Characteristics of Si and SiC as substrate for GaN transistors.

## VI. PERFORMANCE COMPARISON

This section presents a comparison between Si and GaN devices in a family of synchronous buck converters used as drivers for a high power LED.

A previous version of this work was published by the authors in [45]. For this paper, the loss analysis was redone using the SIMETRIX/Simplis simulator due to its "efficiency analysis" tool.

### A. Power Topology

The converter used in this work is a synchronous buck converter operating in continuous conduction mode (CCM). Five different switching frequencies were selected, 100 kHz, 250 kHz, 500 kHz, 750 kHz and 1 MHz. Figure 4 shows the converter circuit.

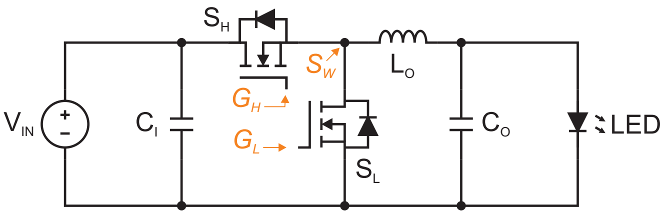

Fig. 4. Synchronous buck converter with LED load.

In order to establish a fair comparison between Si and GaN devices, two identical converters were built for each switching frequency, one with Si switches and one with GaN transistors.

Table II presents the main parameters of each converter. A Bridgelux BXRC-50C4000-F-24 power LED was used as load in all the cases.

TABLE II
Converters Specifications

| Parameter | Symbol | Value |
|---|---|---|
| Input voltage (V) | $V_{IN}$ | 48 |
| Output voltage (V) | $V_{OUT}$ | 28.3 |
| Output current (A) | $I_{OUT}$ | 0.8 |
| Output power (W) | $P_{OUT}$ | 22.6 |
| Switching frequency (kHz) | $f_{SW}$ | 100-1000 |
| Inductor current ripple (%) | $\Delta IL_O$ | 30 |
| Output voltage ripple (%) | $\Delta V_O$ | 1 |

The Si-based converters use the IRF7492 MOSFET from International Rectifier while the GaN switches used in the prototypes are the enhancement mode EPC2012 from Efficient Power Conversion. These devices were selected because of their similarity, especially regarding the voltages and currents capabilities. Table III shows the main parameters of the semiconductors.

TABLE III
Switches Specifications

| Parameter | IRF7492 | EPC2012 |
|---|---|---|
| Drain-source voltage (V) | 200 | 200 |
| Continuous drain current (A) | 3.7 | 3 |
| Maximum on-resistance (mΩ) | 79 | 100 |
| Typical on-resistance (mΩ) | 64 | 70 |
| Total gate charge (nC) | 39 | 1.5 |
| Package | SO8 | LGA |

In the synchronous buck converter, the switches operate in a complementary way with a dead time between the turn-off of one switch and the turn-on of the other. During this short period of time, current flows through the intrinsic diode of the low-side transistor. Gallium nitride devices are known for the lack of a p-n junction intrinsic body diode, but instead, they conduct current through the channel when reversed biased. This characteristic provides zero reverse recovery losses, but adds a higher voltage drop (approximately twice the voltage drop of Si body diodes) when conducting during this interval.

In order to investigate the effects of this behavior in the converter performance, each prototype was tested with and without an external diode (MBR2H100 from On Semiconductor) connected in parallel with the low-side switch. Besides, two different dead time values were tested in each case, 25 ns and 50 ns.

The inductor and the input and output capacitors of the converters were designed according to the parameters presented before and the closest commercially available value was chosen in each case. For simplicity, the input capacitor value was set to match the output one.

The same printed circuit board (PCB) layout was used for both technologies at all frequencies, in order to minimize possible mismatches caused by parasitic components of the tracks, such as resistances and inductances. Due to different voltage levels of gate drivers, two separate PCBs were made for them. The connections between the driver board and the converter itself were made using spring-loaded pins. Figure 5 shows the built converters for Si (top) and GaN (bottom). As it can be observed, a generic footprint that can fit both SO8 and LGA packages was used for the transistors.

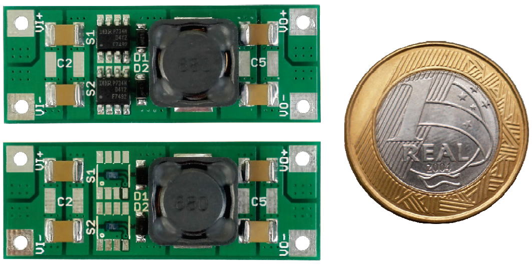

Fig. 5. Converter prototypes using Si (top) and GaN (bottom).

### B. Driver Circuit

Two complementary PWM signals were used to drive the switches. These signals were generated by a Texas Instruments F28377S Digital Signal Processor with selectable frequency, duty cycle and dead time between both signals. The high precision PWM module was used to ensure accurate timings even at high frequencies. The above-mentioned parameters were set manually prior to operation in order to obtain the right output power at the load.

The silicon-based driver circuit uses the MAX15019 IC from Maxim Integrated with an external bootstrap diode used to reduce power dissipation inside the IC package. The supply voltage for the Si gate driver is 10 V. For the GaN driver, a LM5113 from National Semiconductor was chosen. This IC is specifically designed for enhancement mode GaN switches, as it provides a regulated high-side voltage to avoid damage to the semiconductors as the output load increases. The supply voltage for this driver is 5 V.

As stated earlier, the driver board was separated from the power board to keep the same layout. The layouts for the driver boards were designed to be as similar as possible. Figure 6 presents the gate drivers' circuits.

### C. Measurement Setup

The overall efficiency was measured with a Yokogawa WT1800 Precision Power Analyzer, while the temperatures were recorded with a Fluke Ti32 Thermal Imaging Camera. The power consumption of the drivers was not considered.

The results were taken after thermal stabilization, which occurs usually after two minutes of operation. The only exceptions were the Si prototypes at 750 kHz and 1 MHz in which the high-side transistor reached a temperature that could potentially damage the device, so the test was stopped and the data logged when this switch temperature exceeded 100°C. No heatsink or air cooling system was used in any of the prototypes.

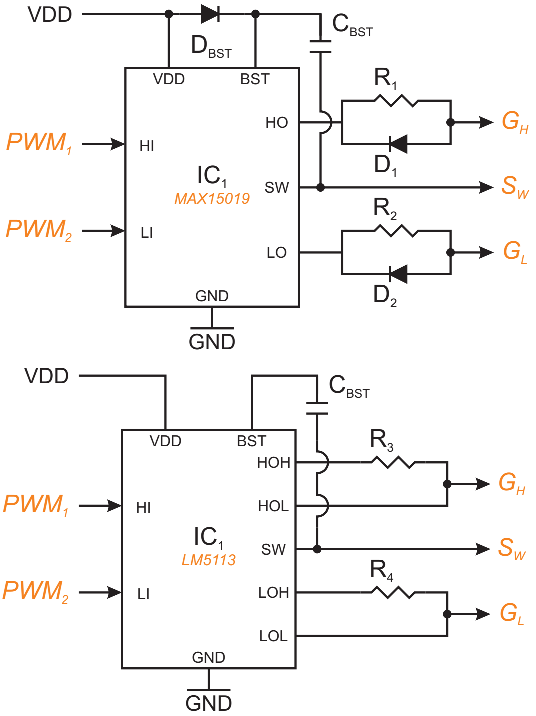

Fig. 6. Si (top) and GaN (bottom) driver circuits.

### D. Experimental Results

Figure 7 shows the efficiency plots for the converters without and with the parallel diode, respectively. At 100 kHz, both semiconductors presented very similar performance. At higher frequencies however, where the switching losses are dominant, GaN devices exhibit better efficiency.

Furthermore, not only the GaN-based converters present higher efficiency in almost all scenarios, but also the performance decay when increasing the switching frequency is less significant in this type of semiconductor. Over the entire frequency range, from 100 kHz to 1 MHz, the difference between the highest and the lowest efficiency with GaN was only 2.3% in the worst case, with parallel diode and a 25 ns dead time. Without external diode, the difference was only 1.8% for the same dead time, yielding that despite GaN transistors have a higher reverse voltage drop than Si, the benefits of not having reverse recovery losses overcome this issue for applications where the switch has to conduct current reverse biased for a short period of time. For the Si-based converters, the efficiency decay was 5.4% and 4.5% under the same conditions.

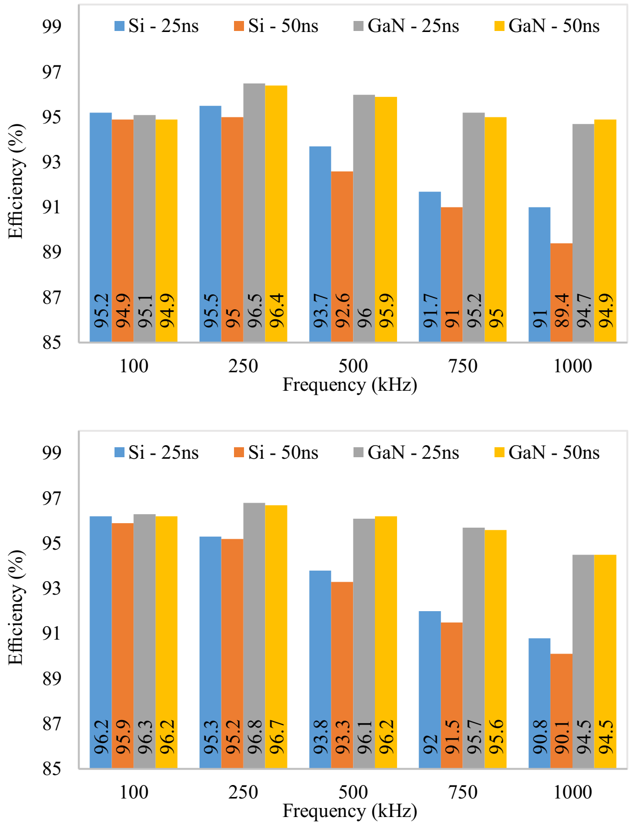

Fig. 7. Efficiency results of the tested converters without (top) and with (bottom) parallel diode.

### *E. Loss Analysis*

The development of analytical models for GaN transistors is currently a key topic for high frequency converters. Different models with different levels of complexity were demonstrated in the past few years [41], [46]–[48]. Factors such as switching frequency, converter topology and parasitic elements play a major role in the circuit's behavior, directly impacting the model. This result in models that are only suited for one application and/or switching frequency.

As demonstrated by [47], the insertion of current and voltage probes in the circuit to measure the power loss, adds parasitic components into the power loop, modifying the switching behavior. For this reason, probes for measuring the dissipated power in each element of the converter were not included in the PCB. Thus, the power loss breakdown was obtained by simulation. SIMetrix/SIMPLIS simulator was chosen in order to obtain a better approximation of the components models near the operation point. SPICE models provided by the component manufacturers were used to extract the parameters used in simulation. The gate driver circuits were also modeled. Figure 8 presents the simulation results of the converter in one of the four tested cases, without the diode in parallel with the low side switch and a dead time of 25 ns. The absolute error between the simulation and experimental results was below 4.5% for all cases with an average of 2.65%. The components temperature was not considered in the simulation. As can be seen in Figure 8, the losses of the inductor play a major role in the overall efficiency for both Si and GaN switches at low frequencies, while switching losses become more pronounced as the frequency increases, especially in the Si-based converter. This yields that, despite having less on-resistance than GaN, the parasitic capacitances and inductances of the Si device result in decreasing the converter efficiency. Furthermore, in the GaN-based converter, the losses are better distributed in the circuit, especially at higher frequencies.

## VII. CONCLUSIONS

Large bandgap semiconductors, such as SiC and especially GaN, have emerged in recent years as possible substitutes for Si devices so that power electronics can continue to exceed limits and increase the performance of static converters. In this way, higher power densities, higher operating frequencies and lower volumes can be achieved without sacrificing system efficiency.

Unlike Si devices, GaN semiconductors are still in their early stages of development, and still have a long way to go, both in terms of performance improvements and manufacturing costs. Despite having virtually no participation in the power electronics market, GaN semiconductors are already present in the academic environment in many applications. Their characteristics such as higher operating temperatures, lower intrinsic capacitances and higher blocking voltages capabilities make them promising candidates to replace Si in the next few years.

In addition, issues that are still little explored at local level, like layout choices and their implications on the final product still need to be improved. With this, the problems faced in the transition between switches from Si to GaN can be reduced.

Regarding the LED driver, the experimental comparison showed superior performance of GaN transistors in almost all tested cases. Despite having a higher on-resistance than the IRF7492, the smaller capacitances of the EPC2012 demonstrated that the switching losses play a major role in the overall efficiency of the converter, especially at higher frequencies.

The presented results highlight the potential of GaN for taking the silicon place in the power electronics market in the future. As the demand for more compact and efficient converter increases, the need for high performance devices also grows. Besides, the silicon technology is approaching its theoretical limits. Therefore, it creates an encouragement for the insertion of GaN devices in the market in the near future.

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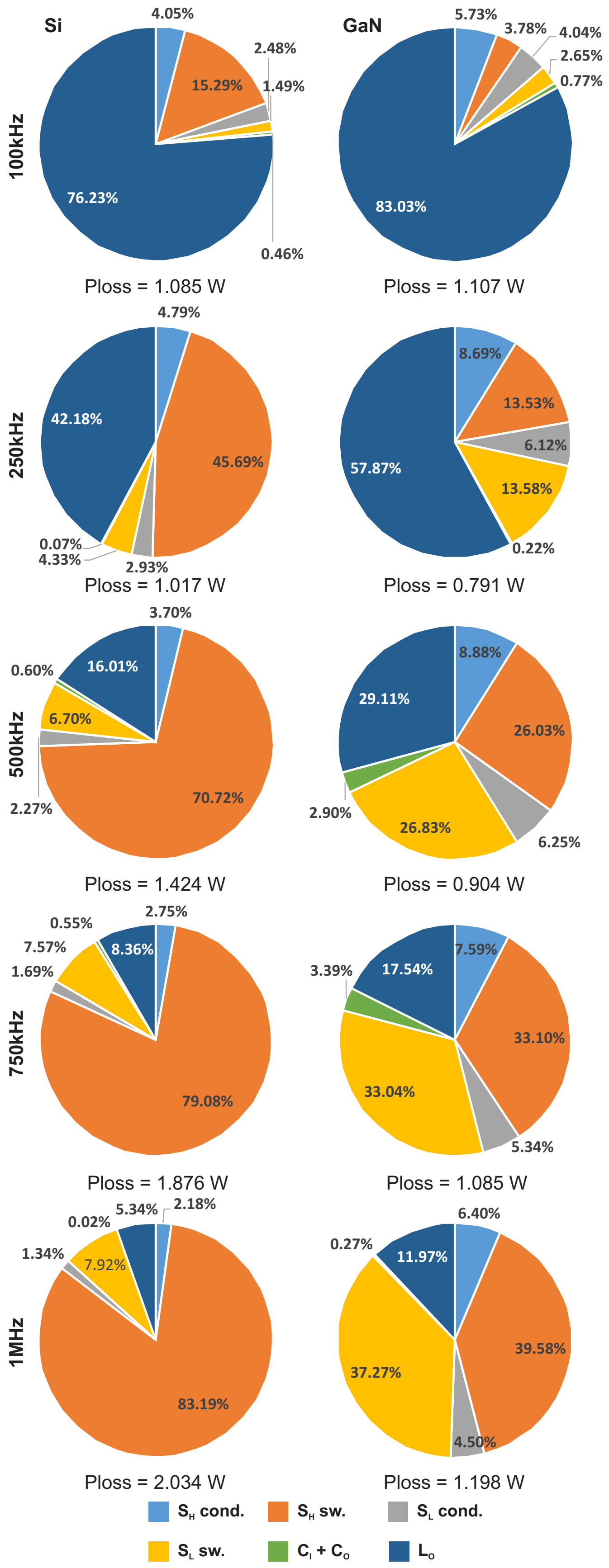

Fig. 8. Losses distribution. $S_H$ *cond*. and $S_L$ *cond*. are the conduction losses in the high and low side switches, respectively; $S_H$ *sw.* and $S_L$ *sw.* are the switching losses in the high and low side switches, respectively; $C_I + C_O$ is the total loss in the capacitors and $L_O$ is the total inductor loss.

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