A Comparative Evaluation of SiC Power Devices for High Performance Domestic Induction Heating

Authors

***Abstract*— This paper presents a comparative evaluation of silicon carbide power devices for the domestic induction heating application which currently has a major industrial, economic and social impact. The compared technologies include MOSFETs, normally-on and normally-off JFETs, as well as BJTs. These devices have been compared according to different figures of merit evaluating conduction and switching performance, efficiency, impact of temperature as well as other driving and protection issues.**

In order to perform the proposed evaluation, a versatile test platform has been developed. As a result of this study, several differential features are identified and discussed, taking into account the pursued induction heating application.

***Keywords*—Induction heating, Silicon Carbide, Wide Bandgap Semiconductors.**

I. Introduction

Power conversion efficiency is a must in modern power electronic systems to help the society advance towards a more efficient and environmentally friendly energetic system. Considering the global energy consumption, a significant part is spent in heating processes used both in industrial and residential applications, which involves electricity and fossil fuels. Among the available heating technologies, induction heating (IH) is nowadays considered as the most advanced [1].

The main benefits of IH are its improved efficiency and performance when compared with classical heating methods. Since it is a contactless energy transfer method, it is a clean and non-invasive technique with significant industrial, domestic and medical applications. Among its widely-spread applications, IH home appliances are highly relevant due to the large number of units installed and its economic and social impact. This technology relies in the correct power converter design in order to implement high efficiency, high performance and cost-effective devices.

Power converters for domestic induction heating [2, 3] were firstly introduced into market during the 80's (Fig. 1). By that time, vertical diffusion MOSFETs were the available devices and the full/half-bridge topologies [4] were selected to achieve a reasonable performance. Later, advances in high voltage MOSFET devices enabled the use of single-switch topologies [5, 6], achieving a cost-effective solution with a significant market penetration. However, these technologies still had serious drawbacks such as their low output power and efficiency, and high cost compared with conventional electrical heating or gas units. A major revolution in domestic induction heating technology happened in the late 90s due to two factors:

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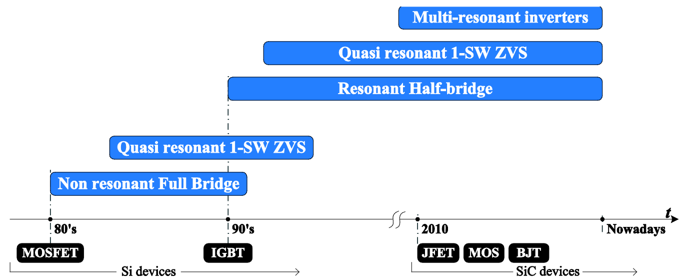


Fig. 1. Historical evolution of power devices and converters for the domestic induction heating application.

resonant power conversion [7] and the development of the IGBT [8]. The former enabled the design of a family of soft-switching converters with improved efficiency and EMC performance whereas the latter allowed the design of reliable and cost-effective implementations for the home appliance mass-market. These advances, together with new flexible architectures [9-12] and advanced control schemes [13-15], made possible a significant technological breakthrough which led to a market share higher than 50% in many European and Asian countries.

Nowadays, advances in power semiconductors technology foresee a second major revolution in IH technology. In particular, new wide band-gap power devices, with silicon carbide (SiC) as the most mature technology, enables a new design paradigm with improved levels of efficiency and performance [16-22]. Among the benefits of the different SiC power devices, the following ones perfectly match IH requirements:

- High temperature [23]: IH hobs have to cope with high ambient temperature due to the heat generated inside and in close elements such as ovens, and the reduced cooling capabilities due to built-in installations.
- High switching speed: Reduced switching losses enable the design of high frequency converters with reduced electromagnetic components. Besides, the use of non-resonant converter topologies can be explored to achieve higher performance implementations while keeping reduced switching losses.
- High voltage: Higher voltage devices enable the implementation of converter topologies with improved overvoltage reliability and reduced current [24], leading to higher efficiency.

Considering these potential benefits, the aim of this paper is to compare the available SiC power devices with a special focus on the induction heating application (Fig. 1). The comparison will include SiC-based unipolar devices such as MOSFETs [25] as well as normally-on and normally-off JFETs [26], and bipolar devices, i.e. BJTs [27]. The main benefits in terms of performance and efficiency will be discussed and compared with current state-of-the-art IH technology, based on Si IGBTs.

The remainder of this paper is organized as follows. Section II details the reference application considered to compare the family of SiC devices with the current state-of-art technology and defines the main figures of merit considered. Section III presents the power device comparison, detailing the proposed test-bench and the main experimental results. Section IV summarizes and discusses the obtained results and, finally, Section V presents the main conclusions of this paper.

II. Reference application

The reference application considered in this study will be an inverter for domestic induction heating applications. The next subsections details the considered topologies as well as the selected SiC-based devices among the available technologies. Finally, the main figures of merit (FOMs) considered in this study are enumerated and briefly explained.

A. Resonant and non-resonant class-D inverter for domestic induction heating

The class-D inverter is the most used topology since the origins of domestic IH due to its good balance between cost and performance. From the original non-resonant topology to the state-of-the-art resonant converters, several million of appliances have been installed featuring this technology.

Fig. 2 (a) shows the converter schematic of the series resonant half-bridge converter [28]. The induction load is modelled as the series connection of an equivalent resistor and an inductor, R_{eq}, L_{eq}, whose values change with frequency, temperature and the inductor-pot system geometry and materials [29-32]. Besides, a resonant capacitor C_r is added to complete the resonant tank. This converter is usually operated above the resonant frequency in ZVS mode to avoid turn-on losses. Thus, lossless snubber capacitors, C_s, are added to reduce turn-off losses [33], which can be critical considering switching frequencies up to 100 kHz and Si-based IGBTs.

This implementation is nowadays the most common among the main manufacturers of high power IH appliances. It achieves a good performance in a cost-effective way. However, there are still serious design challenges to be faced:

- Switching frequency is usually limited below 100 kHz to achieve high efficiency using Si IGBTs, leading to bulky elements in the resonant tank.
- Load dependency is critical because IH load materials and position change constantly [34]. Since resonant power converters are finely tuned, this can have a serious impact in both the converter performance and reliability. Besides, sudden load removal when operating at the resonant frequency may imply the instantaneous power converter failure.
- Multiple load management is mandatory, especially when multi-coil systems are becoming more demanded and have a significant market penetration [9, 29, 35, 36]. In these systems, it is usually difficult to achieve the modulation strategy to achieve the target output power, especially considering the acoustic noise constraints and the low quality factor of the resonant tank which implies overlapped operating bandwidths.

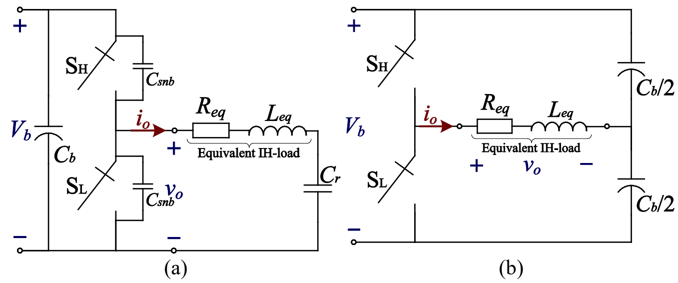


Fig. 2. Resonant (a) and non-resonant (b) half-bridge inverter for IH applications.

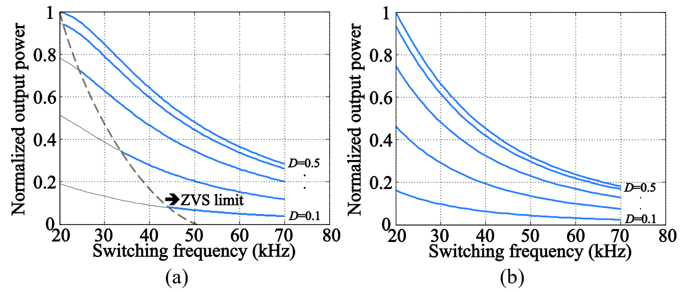


Fig. 3. Output power as a function of the control parameter for the resonant half-bridge inverter with ZVS area (a), and the non-resonant half-bridge inverter (b) for IH applications.

In order to face these challenges, wide bandgap semiconductors offer improved design possibilities. In this paper, rather than proposing a direct device replacement, a topology taking advantage of SiC technology to address the specific challenges of domestic IH is proposed. Thus, the use of a non-resonant half-bridge inverter is proposed (Fig. 2 (b)), relying on the high switching speed of SiC devices. Consequently more versatile implementations can be achieved without compromising the efficiency. Fig. 3 shows the analytical results for the output power as a function of the control parameters, i.e. switching frequency and duty cycle, for both topologies. As it will be later discussed, the non-resonant half-bridge inverter allows a better control and extended ZVS range, at the cost of higher switching losses.

The proposed topology, which was used in the past with limited performance due the power device limitations, has key advantages for the IH application:

- Since SiC devices are used, switching losses are significantly reduced and they do not constrain the design or compromise the efficiency, as it is shown in the experimental verification. Thus, non-resonant topologies can be used which are not limited either by the resonant tank tuning or the snubber capacitor limitations, enabling a ZVS operation in the entire output power range at any load condition.
- The proposed topology is inherently more robust to load changes, since the current is limited in any condition by

TABLE I

SELECTED DEVICES PARAMETERS (T_J = 25 °C)

DEVICE	**Manufacturer**	**Case**	**Main datasheet parameters**	
SiC MOSFET	CREE	To-247	$I_{d,max}$	42 A
			V_{max}	1200 V
			$V_{ce,sat}$	-
			R_{on}	80 mΩ
			t_{fall}	24 ns
			$V_{g,th}$	2.64 V
SiC normally-ON JFET	SemiSouth	To-247	$I_{d,max}$	48 A
			V_{max}	1200 V
			$V_{ce,sat}$	-
			R_{on}	35 mΩ
			t_{fall}	22 ns
			$V_{g,th}$	-5 V
SiC normally-OFF JFET	SemiSouth	To-247	$I_{d,max}$	30 A
			V_{max}	1200 V
			$V_{ce,sat}$	-
			R_{on}	50 mΩ
			t_{fall}	30 ns
			$V_{g,th}$	1 V
SiC BJT	TranSiC (Fairchild)	To-247	$I_{c,max}$	50 A
			V_{max}	1200 V
			$V_{ce,sat}$	0.8 V
			R_{on}	16 mΩ
			t_{fall}	-
			β	30

the induction coil. This avoids undesired transients common in state-of-the-art implementations close to the resonant frequency, which is one of the main reasons of converter failure.

- Finally, the use of a non-resonant converter ensures ZVS turn-on transitions and avoids soft-switching constrains typical of resonant converters. Consequently, duty cycle control at a fixed frequency can be used. This is specially advantageous when modern multi-coil systems are designed [9], avoiding intermodulation noise and simplifying the EMC design.

Once that the main challenges of domestic IH and the benefits of the proposed approach using SiC devices have been briefly explained, the considered SiC power devices are detailed in next subsection.

B. Power device selection

Among the available SiC-based power devices [17], this analysis include unipolar power devices such as MOSFETs and both normally-on and normally-off JFETS (n-ON JFET, n-OFF JFET), as well as bipolar devices, i.e. BJTs. Table I summarizes the selected devices including its main characteristics. All devices have been selected to have the same case and similar ratings. However, each device exhibits unique characteristics that will lead to different power converter performance, evaluated using the figures of merit (FOM) explained in next subsection.

C. Figures of merit definition

The remainder of this paper will focus on the comparative evaluation of the different silicon carbide device technologies available according to the following figures of merit:

- Switching performance: Since switching losses are one of the constraints of current IH systems, mainly due to the IGBT tail current. This characteristic is essential to ensure a high efficiency implementation.

- Conduction performance: Conduction losses are the main power loss source at maximum power and, therefore, determine the design worst-case conditions.

- Efficiency: This FOM is a weighted evaluation of both switching and conduction performance for a given application. In this case, the results for real domestic induction heating systems will be evaluated.

- Temperature drift: Due to the highly variable temperature conditions inside a built-in appliance, the conduction and switching dependence with temperature is critical.

- Driving and protection: Apart from the cost of the power device itself, additional driving and protection circuitry may be required. This will be also taken into account for a full-picture comparison.

Note that the cost has not been included in the comparison between SiC devices because their production is far from stable and the current costs are not representative and rather defined by R&D costs, marketing, and company policies. Next section details the experimental comparison results as well as the proposed test bench.

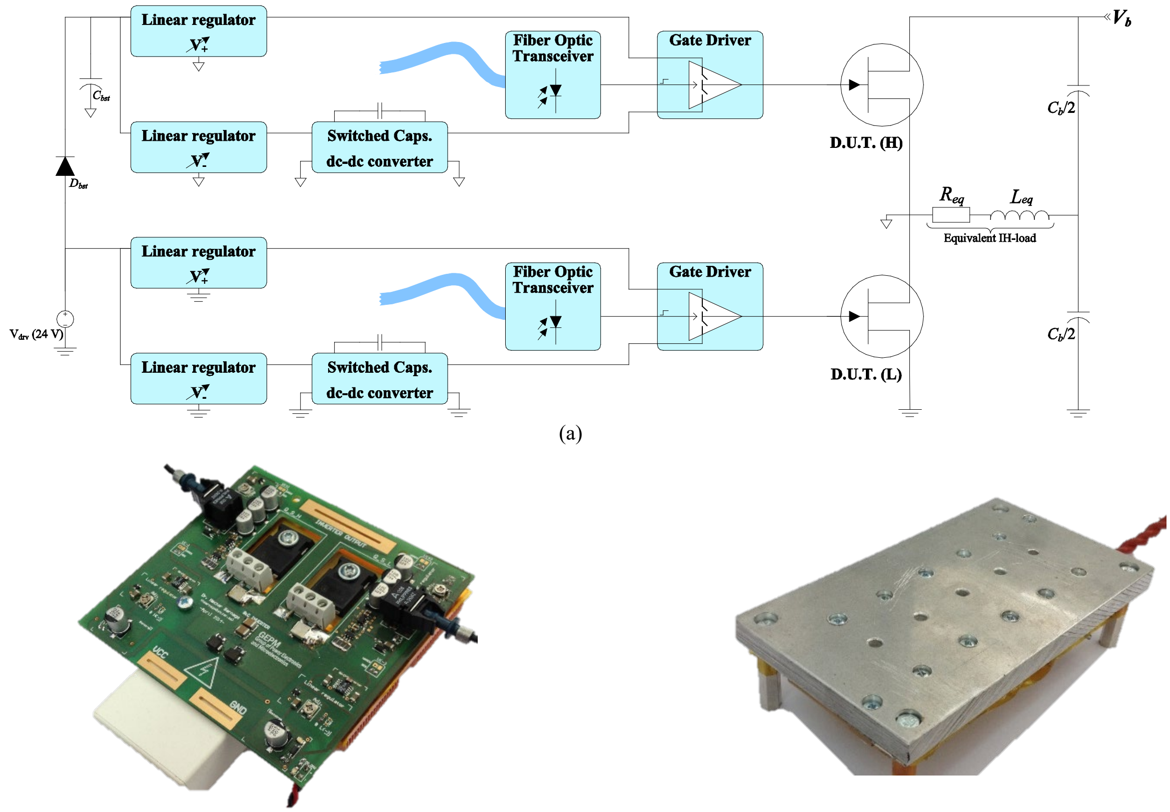
III. POWER DEVICE COMPARISON

The selected SiC-based power devices have been evaluated according to the relevant FOMs for the IH application aforementioned. This section shows the experimental test bench used along with the main experimental results.

A. Experimental test bench

In order to evaluate the main characteristics of the power devices for the IH application, a versatile class-D inverter has been implemented. The proposed test bench (Fig. 4(a)) can accommodate the different selected devices and their special driving requirements by the use of an isolated configurable gate drive circuit. In order to reduce stray elements, a compact PCB (Fig. 4(b)) has been implemented and optimized to enable the evaluation of different devices, and a temperature-controlled hotplate allows to perform measurements at different controlled operating temperatures (Fig. 4(c)).

As it has been previously explained, the proposed converter is operated in a non-resonant operating mode, achieving ZVS during the turn-on transition and hard switching during the turn-off transition. The IH load equivalent circuit is R_{eq} = 2.85 Ω and L_{eq} = 18 µH, and a small snubber capacitor C_{snb} = 3.3 nF is used to limit dv/dt. The output power can be controlled both through the switching frequency and the duty cycle. Fig. 5 shows the main converter waveforms for a fixed switching frequency, f_s = 20 kHz, and different output powers, P_o, for different duty cycles, D.



(a)

(b) (c)

Fig. 4. Versatile evaluation test bench: (a) schematic, (b) PCB, and (c) hotplate.

B. Figures of merit evaluation

Using the experimental test-bench previously detailed, the FOMs explained in Section II have been evaluated. This subsection shows the main experimental results for the different power devices.

- *Switching performance*

As it has been previously explained, the turn-on transition is performed under ZVS conditions, so the switching performance analysis is focused on the turn-off transient. Fig. 6 shows the main experimental waveforms during the turn-off transient for the MOSFET, n-ON JFET, n-OFF JFET, and BJT, respectively, for ambient temperature equal to 25 ºC and 125 ºC. These measurements have been performed and verified using both a Tektronix TCP0030 probe and a PEM-UK ultramini Rogowsky coil. The main results are summarized in Table I.

From these results, it can be seen that the fastest device is the n-OFF JFET with a switching time of 37 ns, whereas the n-ON JFET almost doubles this value with 67 ns. The BJT devices achieves a 100 ns turn-off time, whereas the MOSFET devices are the slowest with 123 ns. In all cases, the switching performance can be considered excellent for the application and allows to implement the proposed non-resonant class-D inverter with no significant efficiency penalty.

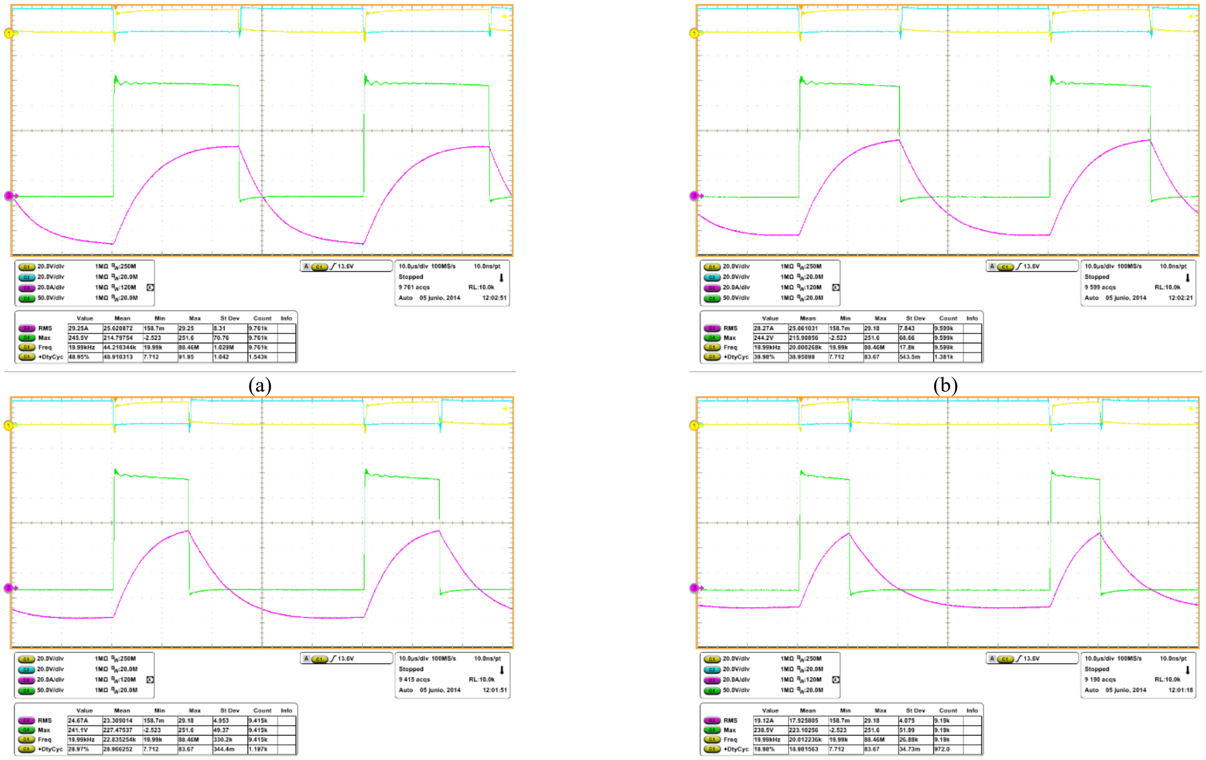
TABLE II
SWITCHING PERFORMANCE COMPARISON

DEVICE	d*i*/d*t* @ 25 ºC	d*i*/d*t* @ 125 ºC
SiC MOSFET	373 A/µs	264 A/µs
SiC normally-ON JFET	482 A/µs	477 A/µs
SiC normally-OFF JFET	907 A/µs	867 A/µs
SiC BJT	469 A/µs	304 A/µs

It is remarkable that the JFET devices offer a temperature independent behavior, which means that the turn-off transitions do not change regardless the ambient temperature. This is especially important in IH applications, where the temperature can quickly change from 25ºC to 125ºC depending on the appliance operation and the surrounding elements and devices. When using the other transistors, variations up to 30% for MOSFET and 35% for BJT are shown.

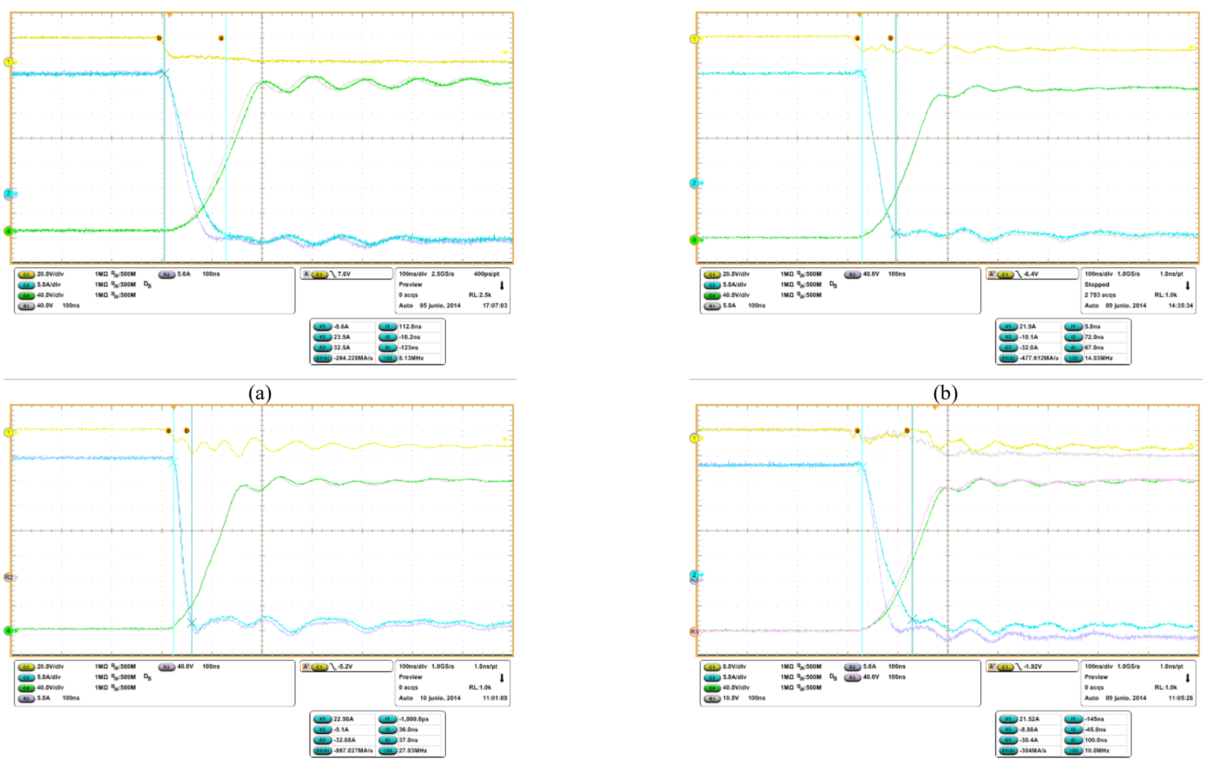
- *Conduction performance*

Since switching losses are significantly reduced with SiC technology, conduction performance will set the final converter efficiency. The on-state voltage for different current levels and temperatures has been measured, and the obtained results are summarized in Fig. 7 and Table III.



(a) (b) (c) (d)

Fig. 5. Main experimental waveforms for an IH load with R_{eq} = 2.85, L_{eq} = 18 µH and f_s = 20 kHz. (a) D = 50%, P_o = 2 kW; (b) D = 40% , P_o = 1 kW;(c) D = 30% , P_o = 0.6 kW; and (d) D = 20%, P_o = 0.4 kW. From top to bottom: control signals (20 V/div), low-side device voltage (50 V/div), and inductor current (20 A/div).



(a) (b) (c) (d)

Fig. 6. Main waveforms during turn-off transition at 25 ºC and 125 ºC for the SiC-based MOSFET (a), n-ON JFET (b), n-OFF JFET (c), and BJT (d). From top to bottom: control signal, device current (5 A/div), and device voltage (40 V/div); time: 100 ns/div. Maximum di/dt achieved is shown in measurement window: (a) MOSFET: 123 ns, (b) n-ON JFET: 67 ns, (c) n-OFF JFET: 37 ns, and (d) BJT: 100 ns.

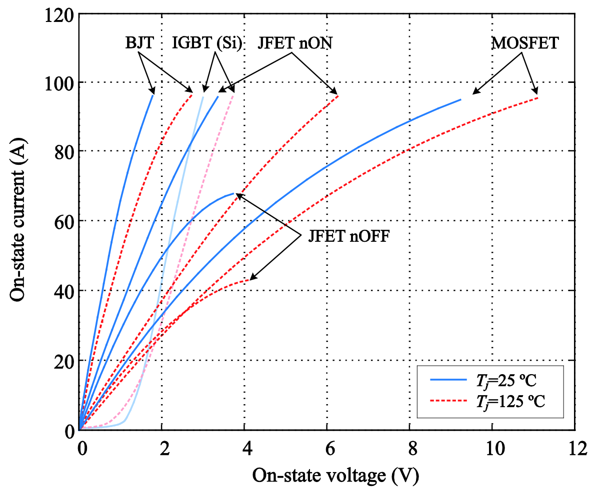


Fig. 7. Measured on-state voltage for different current levels and operating temperatures for the SiC MOSFET, n-ON JFET, n-OFF JFET, and BJT, and state-of-the-art Si IGBT.

TABLE III
CONDUCTION PERFORMANCE COMPARISON (I_{DEV}=40 A)

DEVICE	V_{on} @ 25 ºC	V_{on} @ 125 ºC
SiC MOSFET	2.4 V	3.1 V
SiC normally-ON JFET	1.2 V	2.2 V
SiC normally-OFF JFET	1.5 V	3.2 V
SiC BJT	0.6 V	0.8 V
Si IGBT	2 V	2.3 V

Since not all the devices have exactly the same die size/ratings, the on-state voltage has significant variations. MOSFET devices exhibit the highest on-state voltage, especially as the current goes higher, whereas BJT devices achieve the lowest one. JFET devices are in an intermediate range, with a better performance of normally-on devices due to their simpler structure.

There are several results worth to be highlighted. Firstly, SiC BJTs do not exhibit the typical bipolar behavior and they perform as a highly resistive component, typical of FET devices, with remarkably good conduction. Secondly, in contrast with switching performance, JFET devices exhibit a high dependence with temperature. As it has been previously explained, this is critical for the IH application, since the variable and high temperatures do not allow to take the most of the device performance.

- *Efficiency*

The efficiency of the power converter has been measured as the ratio between the output and input power using a Yokogawa PZ4000 power analyzer. Since the experimental conditions are exactly the same for all devices, useful comparative results are obtained.

Efficiency is a weighted sum of switching and conduction performance. Considering that the switching performance of

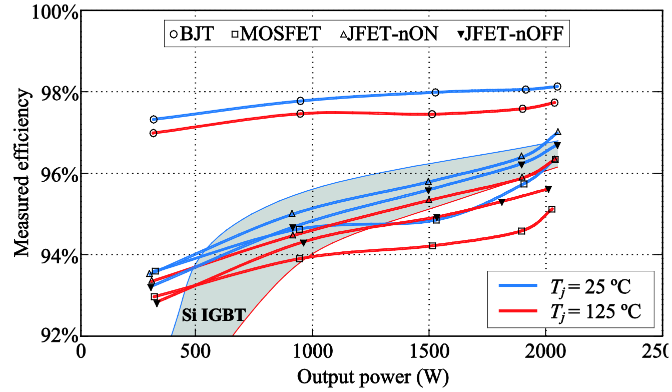


Fig. 8. Efficiency comparison in the complete power operating range for the SiC MOSFET, n-ON JFET, n-OFF JFET, and BJT devices for different operating temperatures. State of the art Si IGBT has been included for comparison.

SiC devices is very good compared with the silicon counterpart, most of the power loss will be dominated by conduction losses.

Fig. 8 shows the main efficiency results for the considered devices at different operating temperatures. It can be seen that BJT devices achieve the higher efficiency whereas MOSFET devices obtain the lowest due to the high conduction losses. JFET devices are in an intermediate range with a significant temperature-dependent performance and a higher efficiency of the normally-on devices due to their better conduction performance.

It is important to note that IH systems operate during a significant part of the time at medium output power levels, depending mainly on the socio-cultural and culinary background of each individual. For this reason, it is essential to evaluate not only the peak efficiency but also the averaged efficiency in the complete operating range. A similar issue occurs in photovoltaic systems, where efficiency under different power ratings is essential. To evaluate this aspect, the Euro and CEC averaged efficiency values were defined [37]. These same averaged values have been evaluated for the proposed devices, obtaining the values summarized in Table IV. These values allow getting a more realistic efficiency value of the appliance. It can be seen that BJT devices achieve even better results, not only due to their higher peak efficiency, but also because of the flat efficiency curve over the whole operating range.

Finally, it is important to remark that all devices achieve higher efficiency levels than the state-of-the-art Si-based resonant converters, which means that a significant performance and potential cost improvement is possible with SiC technology without compromising the converter efficiency.

- *Temperature drift*

At this point, the impact of the temperature in the device performance has been analyzed in both conduction and switching performance. It is important to remark that IH appliances are exposed to high and highly variant ambient temperatures, so this parameter is essential during the design process to ensure a proper converter efficiency and performance. Besides, positive thermal feedback is a potential mechanism of converter failure which should be avoided.

TABLE IV

AVERAGED EFFICIENCY COMPARISON

DEVICE	EURO (25ºC/125ºC)	CEC (25ºC/125ºC)
SiC MOSFET	94.6%/93.9%	94.4%/93.6%
SiC normally-ON JFET	95.1%/94.6%	94.7%/94.3%
SiC normally-OFF JFET	94.8%/94.2%	94.4%/93.9%
SiC BJT	97.8%/97.4%	97.7%/97.4%
Si IGBT	96.2%/96.1%	95.1%/94.9%

TABLE V

DEVICE PERFORMANCE COMPARISON FROM 25 ºC TO 125 ºC

DEVICE	ΔV_{on} (I_{DEV}=40 A)	Δt_{fall}	$\Delta\eta$ (CEC)
SiC MOSFET	24,2%	29,2%	0.8%
SiC normally-ON JFET	85,4%	1,0%	0.4%
SiC normally-OFF JFET	126,7%	4,4%	0.6%
SiC BJT	31,7%	34,5%	0.4%
Si IGBT	15,1 %	-	1.2%

As a general conclusion, all devices increase power losses with temperature. This effect is clearly shown in Fig. 8, where the efficiency obtained at high temperatures is lower for all devices. Table V summarizes the observed impact of temperature in the different measurements.

MOSFET and BJT devices exhibit a moderate conduction and switching performance degradation, with values close to 30%. However, normally-ON and, specially, normally-OFF JFET devices, feature a conduction voltage increase up to 85% and 126%, respectively. This aspect is critical and may prevent these devices from being used in low-frequency applications with highly variable ambient temperature. However, switching losses for JFET devices are highly constant, making these devices suitable for high frequency IH applications such as heating of non-ferromagnetic materials or magnetic nanoparticles for medical applications at frequencies in the MHz range.

- *Driving and protection*

MOSFET and normally-OFF JFET devices are most easy to drive devices among the selected ones. These devices exhibit normally-off behavior and isolated gate with low input capacitance, allowing the use of standard gate-drive circuits. However, it is important to note that the low threshold voltage of normally-OFF JFET devices implies, in practice, the use of negative driving voltage to avoid undesired activations which may significantly degrade the efficiency or even destroy the device (Fig. 9(a)).

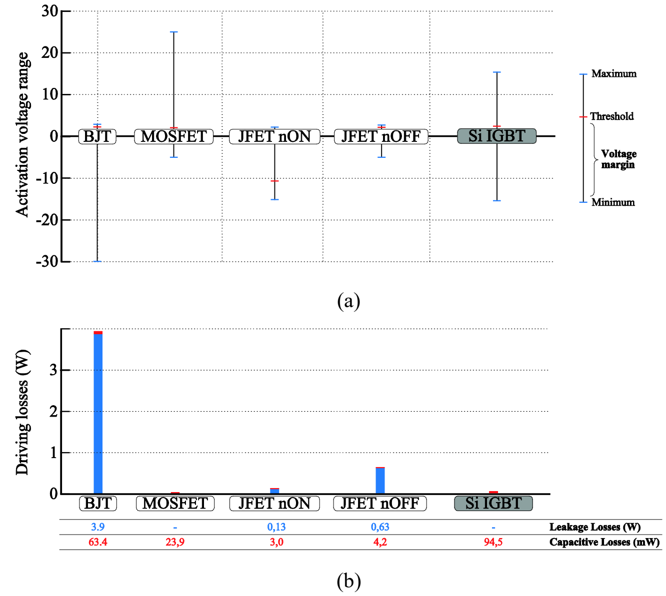


Fig. 9. Main activation properties. Activation voltage range (a) and driving losses comparison (b).

Normally-ON devices add complexity to the design because of the need of a negative voltage to turn OFF the devices plus a start-up circuit to prevent undesired activations when the appliance is turning on or off. This is a challenging issue for home appliances, where a reliable and cost-effective implementation is mandatory.

Finally, BJT devices, in spite of their excellent performance, have their main drawback when designing the gate drive circuit because of their relatively low gain, e.g. typically β=30 (Fig. 9b). This implies the use of auxiliary circuits [38-41], many of them already used in the past for Si-based BJTs, increasing the system complexity. This effect is also present, in a lighter manner, in JFET devices due to gate-to-source leakage current, special in normally-on devices.

IV. DISCUSSION

Along this paper, several differential features have been identified and evaluated for the selected SiC based devices. All of them exhibit a superior performance with significant benefits for future high performance IH systems, but with specific features that must be carefully considered. Fig. 10 shows a radar chart summarizing the analysis performed in this paper.

BJT devices exhibit the best conduction and efficiency performance. Besides, their temperature performance is also satisfactory, making them suitable for IH systems. However, their complex driving may prevent the adoption of this technology for cost-effective systems. JFET devices exhibit a well-balanced set of characteristics that make them suitable in the mid-term for IH systems, especially the n-OFF version due to gate drive simplicity and reliability. However, their temperature-dependent operation must be carefully addressed.

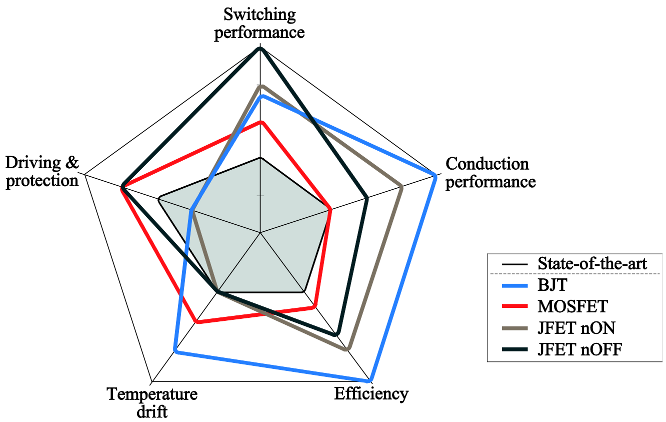


Fig. 10. Radar chart for technology comparison considering the defined FOMs.

Finally, MOSFET technology still needs to improve conduction performance and appears as one promising technology in the long-term.

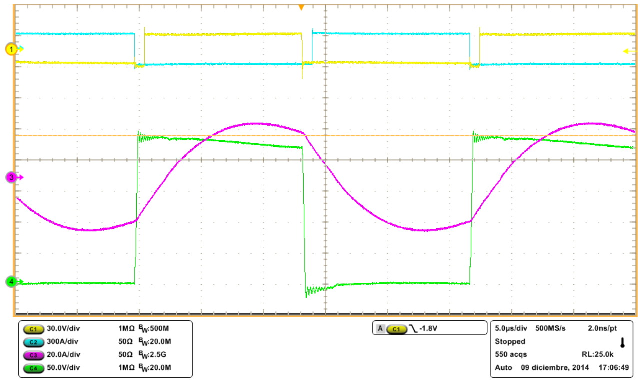
Comparing the evaluated SiC-based devices with state-of-the-art technology, they provide superior performance leading to improved efficiency. Fig. 11 shows the main waveforms of a state-of-the-art resonant converter featuring Si IGBTs. In this figure, it can be seen that turn-off losses are highly relevant due to the IGBT tailing current (Fig. 11(b)). Therefore, it has been demonstrate that it is possible to implement non-resonant inverters with SiC technology while achieving high efficiency, leading to significant advantages for induction heating application in terms of reliability and multi-load control. Consequently, SiC technology has to be considered as a key enabling technology for future IH systems.

It is important to note that there are additional constraints such as cost and the industrial investments and developments that have not been taken into account on this analysis. As of today, most of BJT and JFET technology development is on stand-by due to economic and licenses issues, while MOSFET technology is still under development and commercially available. The evolution of each technology will depend on the sum of the technical factors analyzed in this paper together with industrial interest.

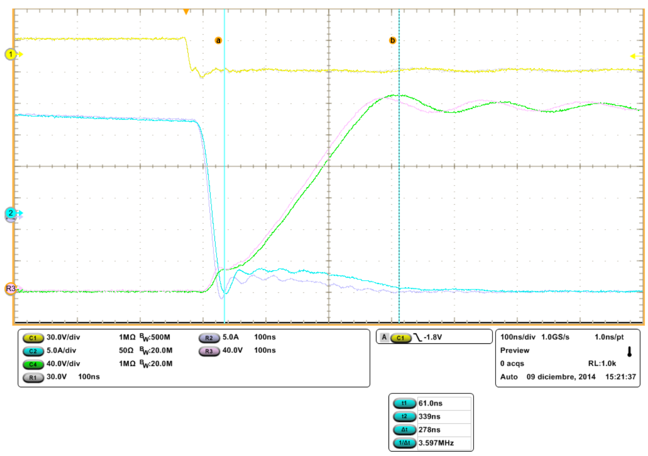
V. Conclusions

This paper has presented an experimental comparative evaluation of different silicon carbide power devices applied to domestic induction heating systems. In order to carry out the experimental evaluation, a versatile test platform has been designed, allowing the measurement of conduction and switching performance, as well as the efficiency and its variations with temperature.

As a conclusion of this study, several differential features have been identified. SiC-based BJT devices have obtained the best efficiency in the operating range outperforming other technologies due to its reduced conduction losses at the cost of more complex driving. The impact of temperature, which is a key in IH systems, has also been analyzed obtaining a remarkable constant switching performance in JFET devices, which make them suitable for high frequency IH systems, but



(a)



(b)

Fig. 11. Resonant converter featuring state-of-the-art Si IGBT: main waveforms (a) and switching performance during a turn-off transition for T_j=25 and 125 ºC (b), where the tail current can be appreciated. From top to bottom: gate signals, output voltage and load/device current.

not low frequency systems, where the conduction losses are highly increased with temperature.

The final adoption of one technology will depend not only on technical aspects, such as the ones analyzed in this paper, but also industrial and commercial constrains. Nowadays, JFET and BJT technologies have slowed their development, leaving MOSFET devices as the most promising ones in the mid-term.

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