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Evaluation of losses in a switching cell using the finite element method. Comparison between silicon and silicon carbide components.

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Abstract – Mixed mode simulations of a buck converter are performed with ISE TCAD tools in order to predict the conduction and the switching losses of the switching cell power devices. Then an averaged model of the converter is built to simulate its electrical and thermal behaviors using either silicon or silicon carbide power components. The proposed method enables to foresee the characteristics of any converter using new components, or new design.

Key words: silicon, silicon carbide, buck converter, mixed-mode simulation, averaged model.

1. Introduction

This paper is focusing on the method used for the evaluation of the electrical and thermal behavior of the switching cell of a DC-DC converter. Electro-thermal simulations of this converter using the finite element method is accurate but not affordable due to a very long CPU time requirement. To overcome this problem, an averaged model has been used taking into account the thermal environment of the active devices. This method is proposed to be used to evaluate the characteristics for a new design of power electronic converter or using new semiconductor material like silicon carbide (SiC).

This method has been applied to silicon carbide (SiC) power components because those should be available on the market in the near future. In fact this wide band-gap semiconductor material features very good physical properties (bandgap energy $E_g = 3$ eV ; critical electric field $E_c \cong 2$ MV.cm⁻¹ ; thermal conductivity $\lambda_{300K} \cong 4.5$ W.K⁻¹cm⁻¹) which are suitable for high temperature, high voltage and also high power applications [1]-[2].

2. Simulation of the converter

2.1. Description of the converter

It is quite well known that any switching behavior in a converter concerns two power semiconductor devices. For the sake of simplicity, the simplest converter including two devices is the switching cell in Fig. 1 and 2. It corresponds to a buck converter in which the inductor and the load have been replaced by a constant current source. The power supply voltage is 600 V and the current rating is 10 A. Two different cases have been considered : one implementing silicon power devices and the other one silicon carbide components.

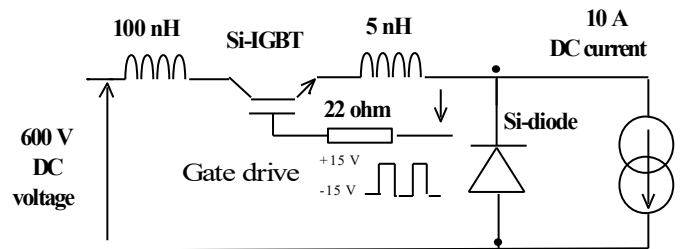


Fig. 1: Details of the Si-device switching cell.

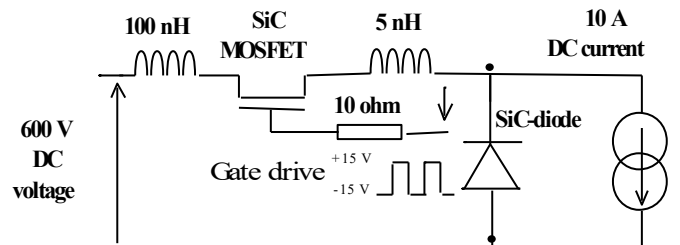


Fig. 2: Details of the SiC-device switching cell.

In case of silicon devices, the controlled switch is an IGBT (Insulated Gate Bipolar Transistor) and the free wheeling diode is a bipolar device as shown in Fig. 1.

Unipolar devices are used in the case of SiC-device converter : the Si IGBT has been replaced by a SiC DI-

MOSFET (Double Implanted MOSFET) and the Si-bipolar diode by a SiC-Schottky diode as shown in Fig. 2. The SiC-Schottky diode features a particularly reduced reverse recovery time with respect to the Si bipolar diode. Parasitic wiring inductors have been considered as these components rule the switching behavior of the diode turn-off at first order. The emitter (or source) inductor represents the internal wiring of the switch module.

2.1 Finite element simulations of the active devices

Finite element method gives access to accurate simulation of the semiconductor devices, representing their highly non-linear behaviors. Both transistors have a bi-dimensional description as shown in Fig. 3 and Fig. 4.

The active area of the IGBT and the MOSFET is 24 mm². Parameters and models of physical parameters of each material have been considered : minority carrier lifetime, mobility and ionization coefficients among others.

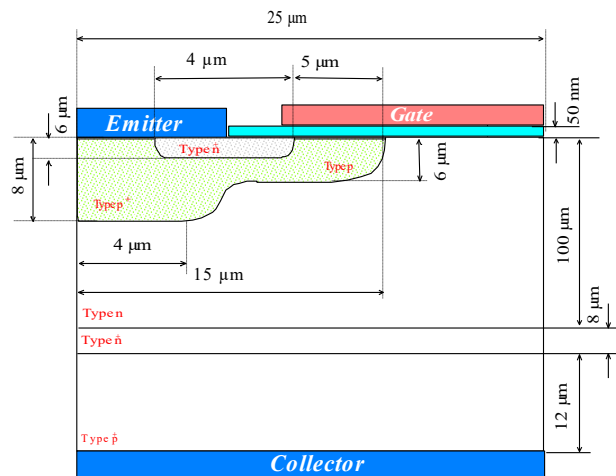


Fig. 3: Structure of the silicon IGBT.

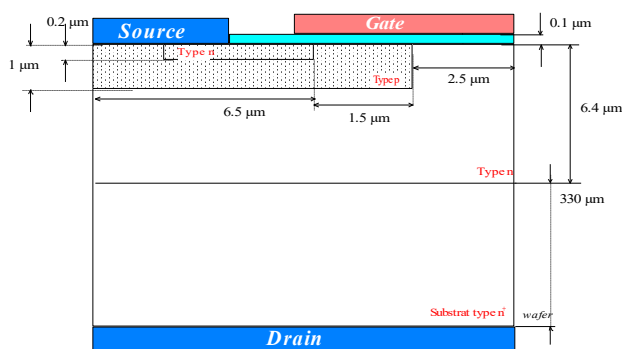


Fig. 4: Structure of the silicon carbide MOSFET

Both diodes are represented by 1-D models to reduce the number of nodes, hence the simulation cost. The thickness of the low doped epitaxial layer are 90 μm and 6 μm for the Si and the SiC diodes respectively. The doping levels and thickness have been designed to sustain at least the voltage and current ratings of the converter. They haven't been optimized since the paper most important purpose is to show the simulation method. The resulting on-state static

Current-Voltage curves of the active devices at 300 K are given on Fig. 5 and 6.

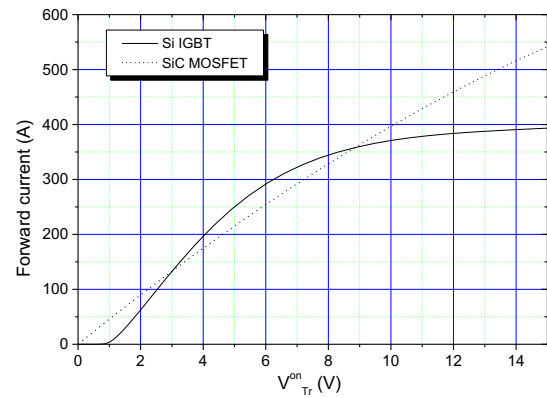


Fig. 5: Comparison of the forward characteristics of the Si IGBT and SiC MOSFET switches at 300 K and V_{GS} = 15 V.

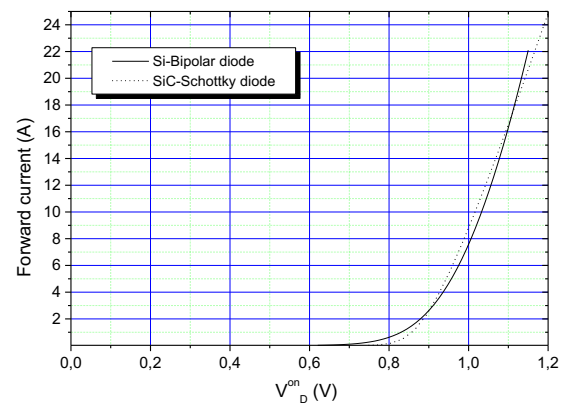


Fig. 6: Comparison of the forward characteristics of the Si bipolar and SiC Schottky diodes at 300 K

2.2. Mixed-mode simulations of the switching characteristics

The simulation mixed mode enables to describe a power electronic system both with accurate models of active devices based on the finite element method and with equivalent electrical-circuit models. The passive components, the voltage and current sources are defined by Spice models. ISE TCAD software is used to perform the mixed mode simulations as well [3].

The switch gate is driven by a +15/-15 V pulse voltage (dV/dt = 3000 V/μs) as described in Fig. 7.

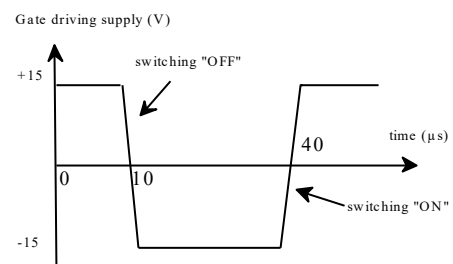


Fig. 7: Waveform of the gate driving circuit voltage supply.

Fig. 8 to 11 show the current and voltage waveforms during the switch turn-on and turn-off (IGBT or MOSFET). Times are given with respect to the driving circuit.

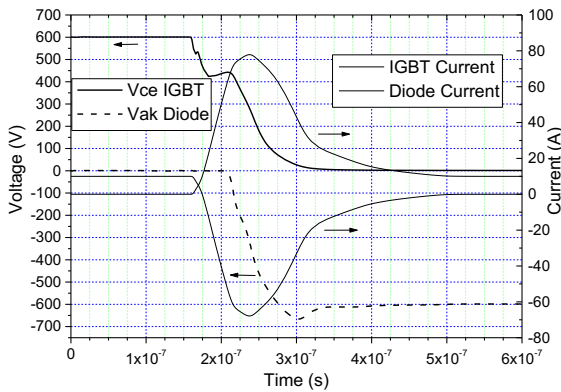


Fig. 8: Simulated currents and voltages in the silicon IGBT and diode during the IGBT turn-on transient.

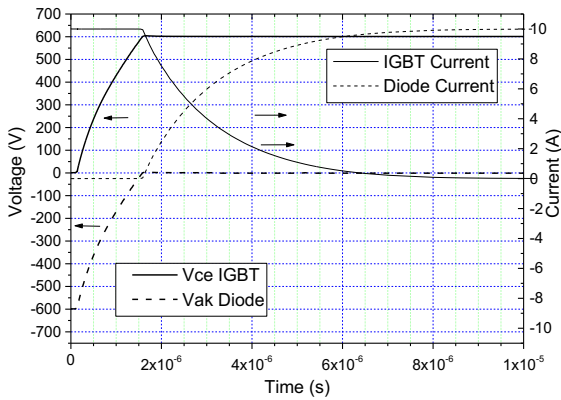


Fig. 9: Simulated currents and voltages in the silicon IGBT and diode during the IGBT turn-off transient.

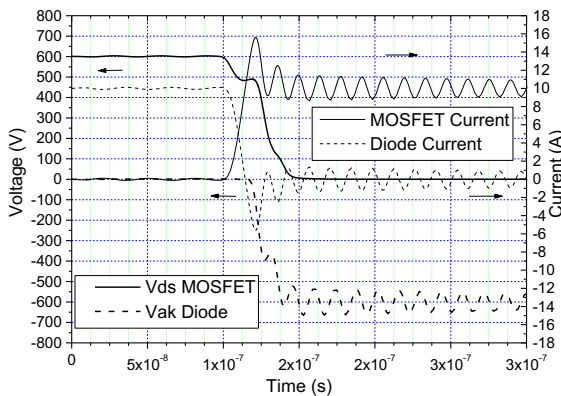


Fig. 10: Simulated currents and voltages in the SiC-MOSFET and Schottky diode during the MOSFET turn-on transient.

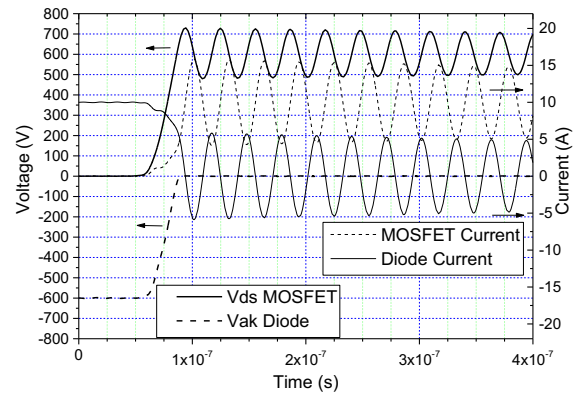


Fig. 11: Simulated currents and voltages in the SiC-MOSFET and Schottky diode during the MOSFET turn-off transient.

The switching time of the SiC-device converter is much shorter but oscillations characterize a very bad damping ratio, which could lead to severe electromagnetic compliance constraints. This is due to a very low equivalent resistance of Schottky and MOSFET devices.

3. Building of the averaged model

The electro-thermal simulation of such a converter requires a very long CPU-time for only one electrical period. The time constant for the thermal system is in the range of seconds. It means that, for a frequency of 10 kHz, more than 10^4 switching periods are needed to reach the thermal stability of the converter. From a simulation point of view, it is not affordable, and leads to use an averaged model for the converter. The algorithm that guides the construction of non-linear averaged models has been described by Allard et al. [4].

Fig. 12 shows the electrical schematic of the switching cell inside the buck converter. The inputs are V_1 and I_2 , and the outputs are I_1 and V_2 . The inputs are imposed by the external circuit of the switching cell. The outputs are controlled by the switching cell.

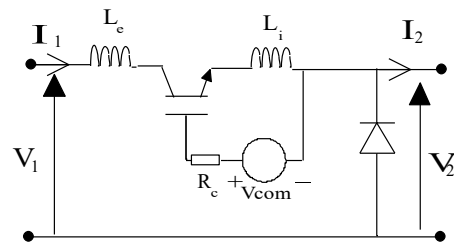


Fig. 12: Details of the switching cell model.

The frequency hypothesis underlying the averaged model technique implies that the inputs are constant over an electrical period.

3.1. Calculation of the losses

Losses of the converter can be divided in two parts : conduction and switching losses. From the switching characteristics during “ON” and “OFF” transients as shown in Fig 8 to 11 losses and virtual switching delays

are calculated for both converters for three different uniform temperatures (300 – 380 and 450 K) at 5 different current ratings (2 – 5 – 7 – 10 and 15 A). Losses are calculated in both power devices with the following relations for the outputs [5] :

$$\bar{V}_2 = (\bar{V}_1 - V_{Tr}^{on}) \times \left[D + \frac{-\delta_{V_D}}{T} \right] - V_D^{on} \left[1 - D + \frac{\delta_{V_D}}{T} \right]$$

$$\bar{I}_1 = \bar{I}_2 \left[D + \frac{\delta_{I_{Tr}}}{T} \right]$$

where V_{Tr}^{on} , I_{Tr} , V_D^{on} , I_D are the transistor and diode on-state voltage drops and currents, D and T the duty cycle and the period,

and where δ_{V_D} and $\delta_{I_{Tr}}$ are the virtual switching delays and are calculated with the following relations :

$$\delta_{V_D} = \delta_{V_D}^{off} - \delta_{V_D}^{on}$$

$$\delta_{I_{Tr}} = \delta_{I_{Tr}}^{off} - \delta_{I_{Tr}}^{on}$$

The evolution of different variables have been fitted with regard to temperature. The losses in the active devices were calculated using the following relations :

$$P_{Tr} = I_2 \times V_{Tr}^{on} \times D + \frac{P_{Tr}^{Switching}}{T}$$

$$P_{Diode} = I_2 \times V_D^{on} \times (1-D) + \frac{P_{Diode}^{Switching}}{T}$$

where $P_{Tr}^{Switching}$ and $P_D^{Switching}$ are the switching power losses of the transistor and the diode.

A new thermal model of the converter has been added to the previous model to estimate the temperature behavior. The semiconductor, insulator and heat sink material (aluminum) were considered. Each layer is modeled by a resistor and a capacitor due to the electrical and thermal analogy between voltage and temperature, current and thermal flux. The thermal model was built with several finite elements as shown in Fig. 13.

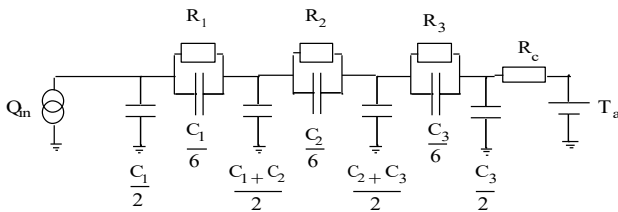


Fig 13: Thermal model of the power components.

Q_{in} is the power losses provided by the component, and T_a is the ambient temperature.

4. Results

This complete model has been implemented in simulator Matlab/Simulink [5] ; it enables to perform very fast simulation (in a few seconds) and to predict the electrical and thermal behaviors of the two converters in a wide range of operating conditions.

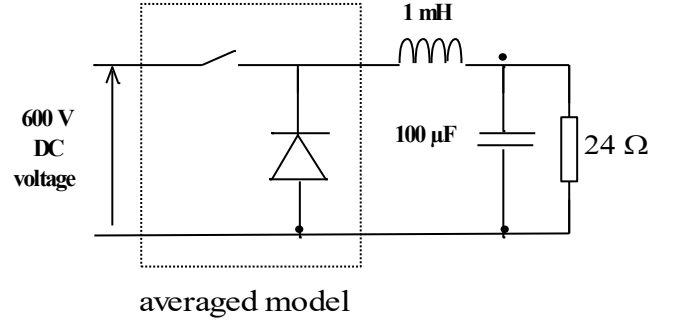


Fig 14: Implementation of the switching cell averaged model in a Buck-converter.

As an example, Fig 15 presents the operating temperatures of the Si-IGBT and diode versus time for the converter shown on Fig. 14, working at 10 kHz with a 40 % duty cycle.

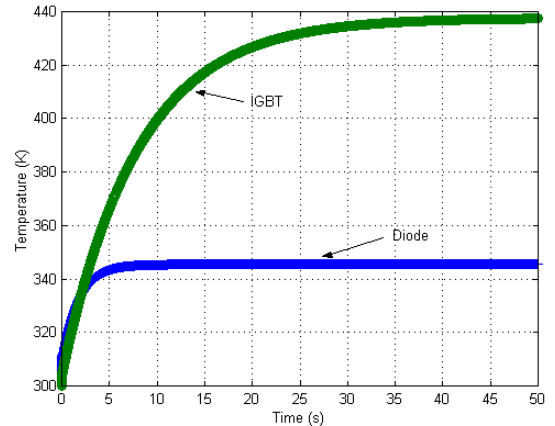


Fig 15: Operating temperature of the Si-IGBT and diode. (10 kHz operating frequency, 40 % duty cycle).

Fig. 16 and 17 show the maximum operating temperature of the active devices versus frequency. For the semiconductor parameter assumptions considered in this study, the maximal operating frequency of the Si-based converter is around 60 kHz, due to the diode temperature reaching the silicon limitation. On the contrary, it is found that the SiC converter would be able to work at higher frequency with lower temperature thanks to reduced conduction and switching losses.

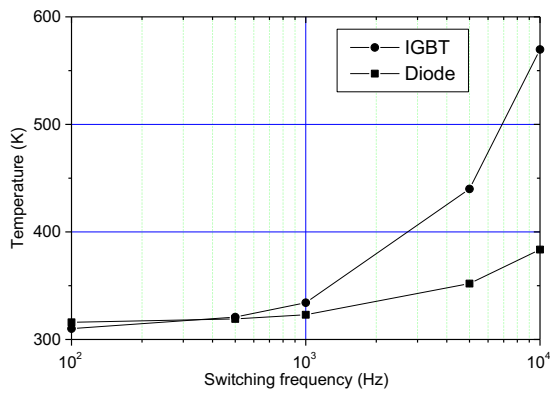


Fig 16: Operating temperature of the Si components versus frequency.

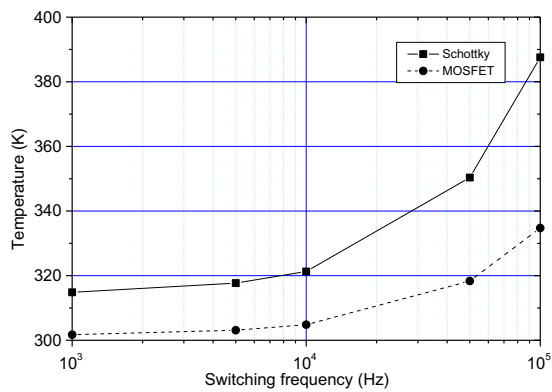


Fig 17: Operating temperature of the SiC components versus frequency.

Fig. 14 shows that SiC device temperature remains acceptable at much higher thermal resistance of the heat sink, as compared to Si devices, for the same operating frequency.

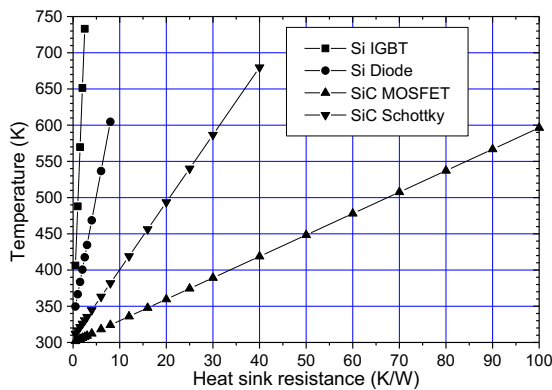


Fig 18: Operating temperature of both components versus heat sink resistance. (operating frequency is 10 kHz).

5. Conclusion

The goal of this paper is to show that it is possible to estimate the energy losses in a real converter before realization. So it is a design method. Using simulation both switching and conduction losses are estimated for Si

and SiC devices. Then the behavior and the design of the converter are obtained using an averaged model of the converter [4] taking into account the following parameters : current rating, frequency and temperature. An electro-thermal model was developed. Using this model, implemented in Matlab/Simulink, a comparison of the losses was performed for both Si and SiC based converter. Keeping in mind the hypothesis made on SiC parameters, it seems that SiC would have better characteristics for high temperature and high frequency applications, which could be used to reduce the size of the heat sink.

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