

# A comparative study between 4H-SiC and silicon power PiN diode having the same breakdown voltage 4KV

Atef Jedidi, Hatem Garrab, Kamel Besbes

Microelectronic and Instrumentation UR

FSM, University of Monastir

Monastir, Tunisia

[atef\\_jedidi@yahoo.fr](mailto:atef_jedidi@yahoo.fr), [garhat@yahoo.fr](mailto:garhat@yahoo.fr), [kamel.besbes@fsm.rnu.tn](mailto:kamel.besbes@fsm.rnu.tn)

**Abstract**— The exploitation of silicon carbide semiconductor devices in power electronic field have made exceptional improvements by their fast switching and low dissipated losses especially at high operating temperatures. However, physical performances of silicon power components have reached their limits. This paper presents a comparative study, through numerical simulation and using the finite element method modeling, between 4H-SiC and silicon power PiN diode having the same breakdown voltage “4KV”. This comparative study highlights the benefits of silicon carbide.

**Keywords**—4H-SiC, Numerical Simulation, Diode PiN

## I. INTRODUCTION

The increasing demand for performance of the power devices such as increasing the operating temperature, increase of current-voltage caliber and decrease of the components size leads to reach more and more physical limitations of silicon. For this purpose, the designers of power components thought to use other semiconductor materials having physical characteristics much better than those of silicon.

The physical and electronic properties of silicon carbide (SiC) allow to identify it as a semiconductor material having the potential to replace silicon in certain applications [1], [2]. SiC power devices can operate at extremely high temperatures without suffering from conduction intrinsic effects due to the wide band gap. They can also be operated at levels of very high power density owing to the high thermal conductivity of material. By combining the advantages of SiC, this would bring an important reduction in the size of power systems.

We present in this paper a comparative study, through numerical simulation, between 4H-SiC and silicon PiN diode having the same breakdown voltage 4KV in fact to highlight the advantages of silicon carbide material in the field of power devices.

## II. PHYSICAL PARAMETERS AND MATHEMATICAL SIMULATION MODEL

The numerical simulation based on mathematical equations is of course a necessary step in order to predict the behavior of power devices. The finite element simulators are very accurate,

and are based on the numerical resolution of semiconductor equations (equations of continuity and the Poisson equation). These equations are solved based on a mesh which is a discretization of the structure to be simulated. As part of our work, the modeling of PiN diodes of silicon carbide and silicon are based on the finite element method in order to have accurate simulation of its behavior.

### A. Models used for simulation

The most important physical models are those of the forbidden energy band, carrier mobility, SRH recombination, and ionization coefficients. The values of the coefficients of physical models for the two materials used as well as the geometrical parameters of the two diodes under test are taken from the work of [3], [4].

### B. Bandgap Energy.

The variation of the forbidden energy band (gap) for both materials as a function of operating temperature is expressed by the following expression [5].

$$E_g(T) = E_g(0) - \frac{\alpha T^2}{(T + \beta)} \quad (1)$$

Where T: is the operating temperature.

### C. Carriers' mobility

Electron mobility and the hole mobility are modeled by the equation Caughey-Thomas [6].

$$\mu_n = \frac{700}{1 + \left(\frac{N_A + N_D}{1.97 \times 10^{17}}\right)^{0.61}} \left(\frac{T}{300}\right)^{-2.15} \quad (2)$$

$$\mu_p = 15.9 + \frac{170}{1 + \left(\frac{N_A + N_D}{1.76 \times 10^{19}}\right)^{0.34}} \left(\frac{T}{300}\right)^{-2.15} \quad (3)$$

Where  $N_A$  and  $N_D$  are respectively the concentrations of the donor atoms, and the acceptor atoms

#### D. Generation and recombination

The model, of the recombination rate and generation used, corresponds to that of Shockley-Read-Hall (SRH). The lifetimes of electrons and holes,  $\tau_n$  and  $\tau_p$  are dependent on the doping level.

$$\tau_{n,p} = \frac{\tau_{n0,p0}}{1 + \frac{(N_A + N_D)}{10^{16}}} \quad (4)$$

#### E. Ionisation coefficients

The generation of electron-hole pair rate, associated with the impact ionization, is modeled by:

$$\alpha = \gamma a e^{\frac{\gamma b}{|E|}} \quad \text{with} \quad \gamma = \frac{\tanh\left(\frac{\hbar w_0}{2kT_0}\right)}{\tanh\left(\frac{\hbar w_0}{2kT}\right)} \quad (5)$$

The values of the coefficients a and b ionization are those given by [7].

### III. SIMULATION RESULTS

#### A. Breakdown voltage

The breakdown voltage is related to the width and the doping of the lightly doped region ( $N_D$  and  $W_B$ ).

Figure 1, shows that the breakdown voltage of a junction increases as the doping level of the lightly doped layer decreases and when its thickness increases. A good tradeoff between a low voltage drop in the ON state and high breakdown voltage in the off state corresponds to a torque of  $W_B$  and  $N_D$  settings, located in the elbow region [8],[9]. In fact, we will opt for the one which present the smallest thickness and doping highest allowing the passage of field profile of the triangular shape, to the trapezoidal shape form just at the end of the lightly doped region (for parameters optimized). So we can carry out our choice for the SiC diode PiN 4KV with a thickness of 30 microns with a doping level equal to  $2.2 \times 10^{15} \text{ cm}^{-3}$ . Similarly for the PiN diode Silicon 4KV the thickness of the central zone is equal to 300 microns with a doping  $2.3 \times 10^{13} \text{ cm}^{-3}$ .

We performed some simulations to see the profile of the electric field for the PiN diode silicon and silicon carbide. We note from the figure 3 and 4 that the critical electric field for the 4H-SiC 4KV diode, as mentioned in the literature, is almost ten times higher than that of silicon. We can also conclude from figures 1 and 2, that for an equal reverse breakdown voltage, a component in SiC can be achieved with a thickness more than eight times lower than that of silicon.

These improvements can create a component with a lower resistance and therefore obtain a weaker loss at the ON state. On the other hand, the silicon carbide requires the having components with working voltage above 10 KV voltage, which are inaccessible for silicon and therefore can reduce the number of silicon components in series to ensure a certain voltage.

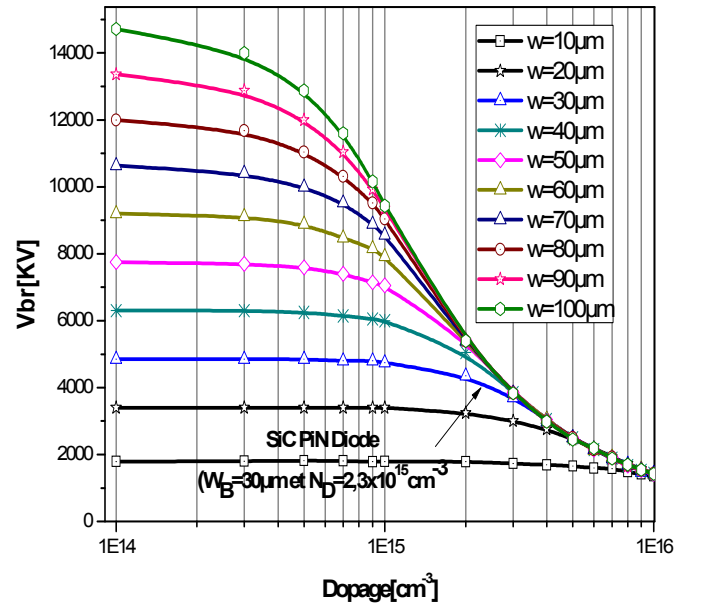


Fig.1. Breakdown voltage of SiC PiN diode according to  $N_D$  and  $W_B$  of the lightly doped region simulated by DESSIS-ISE.

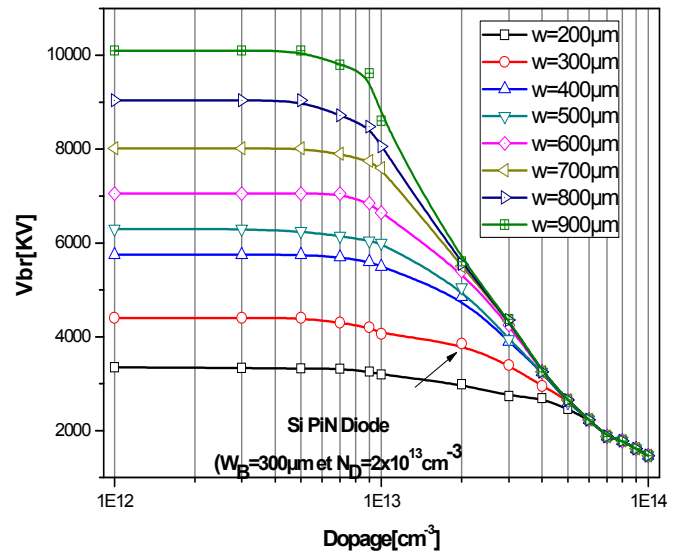


Fig.2. Breakdown voltage of silicon PiN diode according to  $N_D$  and  $W_B$  of the lightly doped region simulated by DESSIS-ISE.

#### B. The PiN diode transient behavior during its turn-off phase

To perform simulations with a high level of precision during the opening of the PiN diode, it is necessary to design and model a suitable test circuit. Accurate modeling of a test circuit was developed in the work of [10], [11] to predict the exact behavior of the diode during its reverse recovery. We implemented the circuit in the simulator DESSIS-ISE.

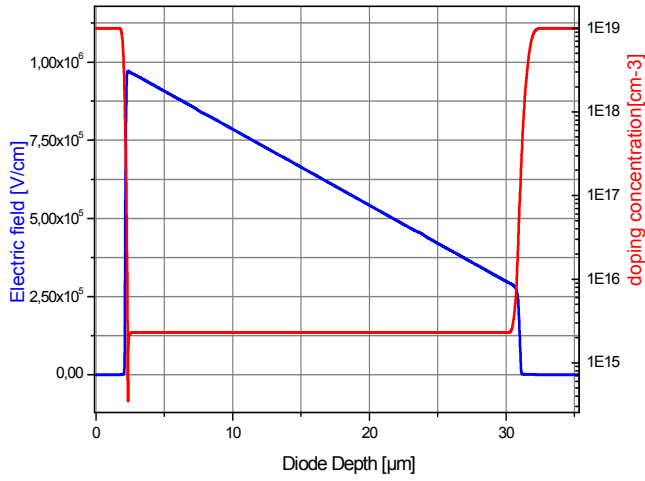


Fig.3. Electrical field repartition inside the 4H-SiC PiN diode structure corresponding to its breakdown voltage.

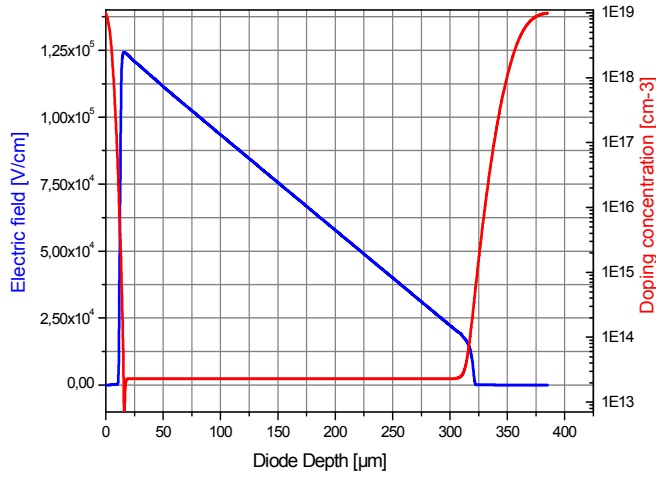
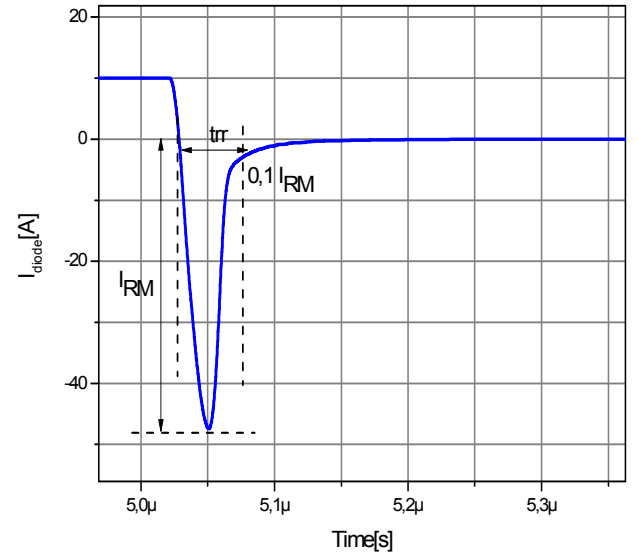
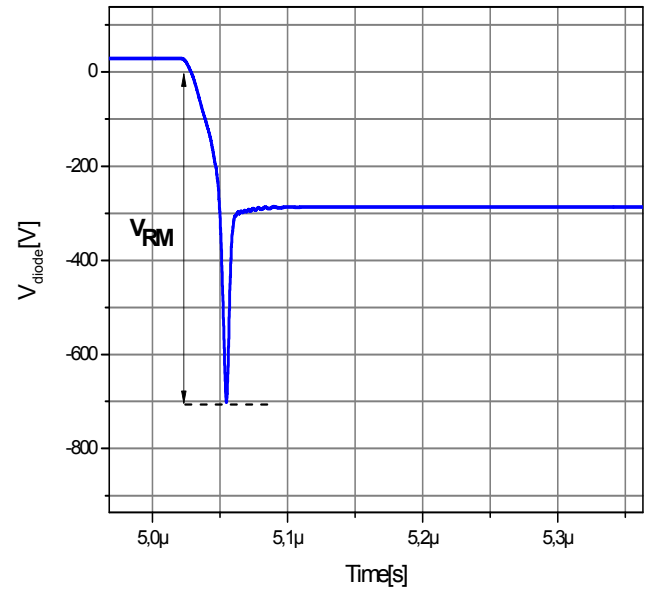


Fig.4. Electrical field repartition inside the silicon PiN diode structure corresponding to its breakdown voltage.

A numerical model (SPICE level-3) was selected in the library of the simulator to describe the electrical behavior of the MOSFET. A finite element model was considered for the PiN diode. DESSIS-ISE brings together all the data and allows simulations in mixed mode. An example of the waveform of the current, and the voltage across the two prototype PiN diode of silicon carbide and silicon in the openings are shown in figure 5. On these characteristics the main parameters of switching of the PiN diode are shown. We note from these curves that the recovery time of the 4H-SiC PiN diode 4kV is equal to 18 ns which are 28 % of that of the diode Silicon 4kV. This shows that the 4 K V PiN diode silicon carbide can have faster switching due to the low amount of charge stored in the base  $Q_{tr}$  than the silicon PiN diode, and therefore there will be lower losses in the opening of 4H-SiC 4kV PiN diode compared to the silicon diode.



(a)



(b)

Fig.5. Current (a) and voltage (b) waveform across the silicon PiN diode during its turn-off stage as simulated by DESSIS-ISE ( $I_F = 10A$ ,  $V_R = 300V$ ,  $W_B = 300\mu m$ ,  $N_D = 2.3 \times 10^{15} cm^{-3}$ ,  $X_{jp} = 16\mu m$  et  $X_{jn} = 45\mu m$ )

### C. Temperature effect on the PIN diode transient behavior during its turn-off phase

The realization of SiC power diodes require better performance compared to silicon which is due to its ability to work at high operating temperatures. Indeed, the increase in operating temperature results in a considerable increase in the intrinsic concentration ( $n_i = T^{3/2} \exp(-E_g / 2kT)$ ). The main problem occurs when the intrinsic concentration becomes not negligible compared to the impurity concentration in the lightly doped base region, which provides the breakdown voltage.

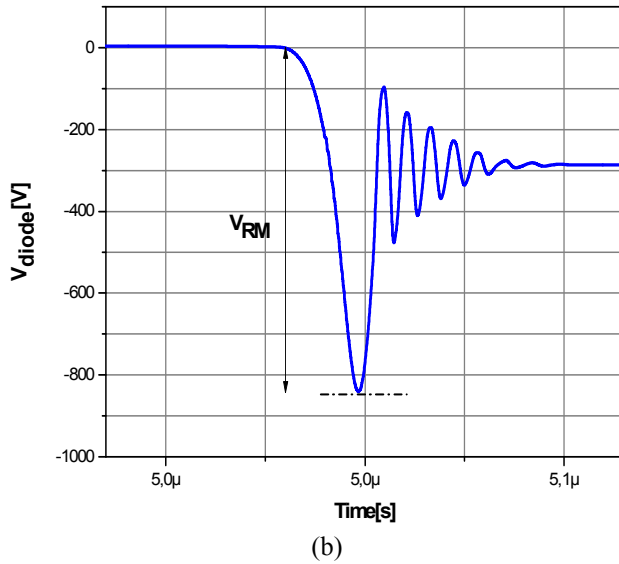
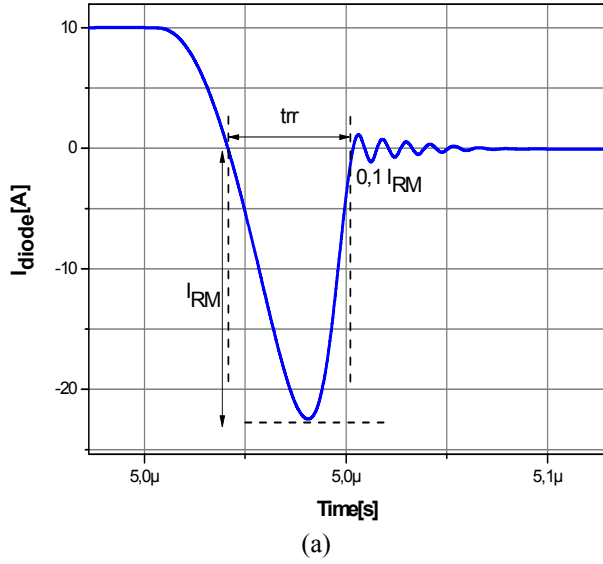


Fig.6. Current (a) and voltage (b) waveform across the silicon carbide PiN diode during its turn-off stage as simulated by DESSIS-ISE ( $I_F = 10A$ ,  $V_R = 300V$ ,  $W_B = 30\mu m$ ,  $N_D = 2.2 \times 10^{15} cm^{-3}$ ,  $X_{jp} = 0.6\mu m$  et  $X_{jn} = 4\mu m$ )

Before studying the effect of operating temperature on the dissipated losses in the opening of the diode, we will analyze the influence of temperature on the main parameters of the switching diode.

As the carriers' lifetime increases with the network temperature, the amount of charges collected in the base region during its conduction is much more important for high temperatures as shown in figure 7. An example, in the maximum operating temperature of  $T = 460K$  for the PiN diode of silicon, the amount of charge for the PiN diode 4H-SiC is equal to  $2.10^{-8} C$  while it is 0.6% of that of the 4kV PiN silicon diode. The increase in the operating temperature causes an increase in the amount of stored charge in the PiN diode during its conduction phase. Therefore the diode

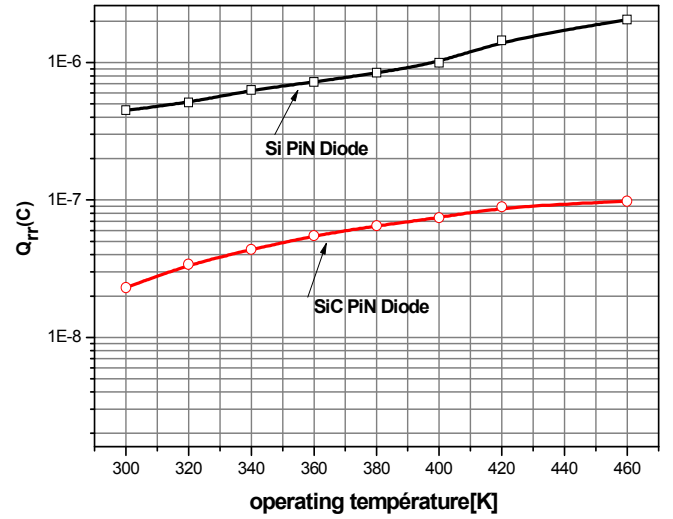


Fig.7. Variation of  $Q_{rr}$  parameter according to operating temperature as simulated by DESSIS-ISE

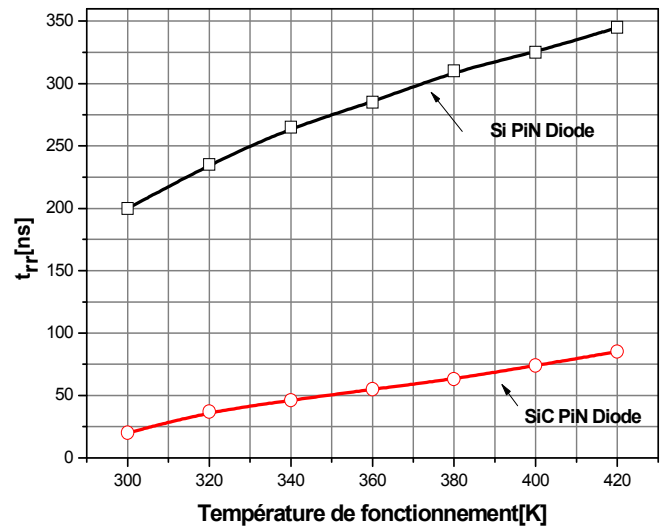


Fig.8. Variation of  $t_{rr}$  parameter according to operating temperature as simulated by DESSIS-ISE

requires a longer time for the removal of these charges. This is why the recovery time  $t_{rr}$  is directly proportional compared to the operating temperature as shown in figure 8. We can therefore conclude that the silicon carbide PiN diodes are much faster than silicon one.

We performed some simulation to visualize the evolution of maximum reverse current  $I_{RM}$  and the maximum reverse voltage as a function of operating temperature. Figure 9 and 10 shows that the maximum reverse current  $I_{RM}$  is directly proportional to the operating temperature, whereas the maximum reverse voltage is reversely proportional to the operating temperature for the two 4KV silicon and silicon carbide diodes. The power loss of a semiconductor device is generally obtained by integrating the instantaneous dissipated

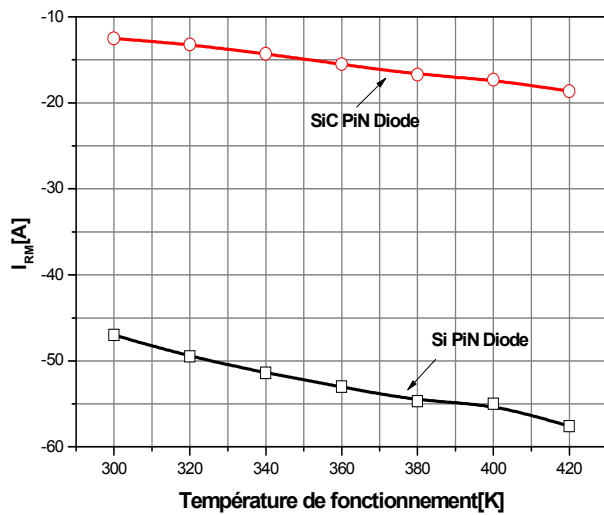


Fig. 9. Variation of  $I_{RM}$  parameter according to operating temperature as simulated by DESSIS-ISE

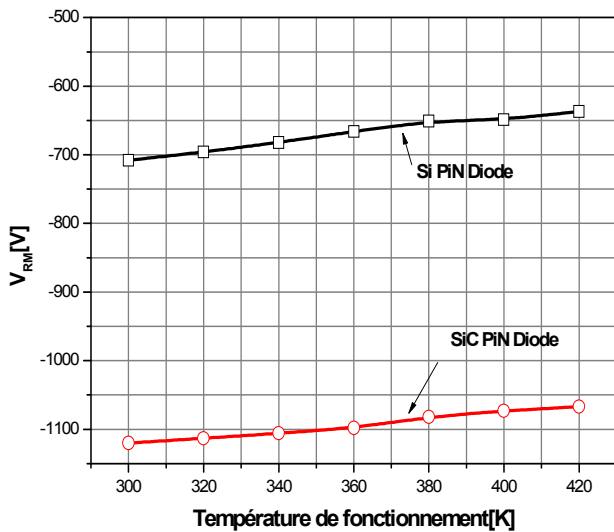


Fig. 10. Variation of  $V_{RM}$  parameter according to operating temperature as simulated by DESSIS-ISE

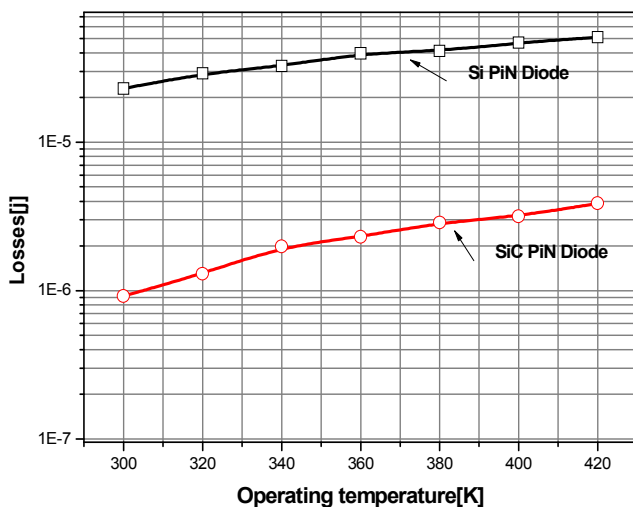


Fig. 11. Dissipated losses during the silicon carbide and silicon PiN diodes turn-off, simulated by DESSIS-ISE

power by the device. The instantaneous power strongly depends on the switch settings of the component. Figure 11 shows the power loss for different operating temperatures for the two tested diodes at their openings.

From these curves we can deduce that the dissipated losses by the 4KV silicon diodes during their openings are nearly 10 times more sensitive regarding changes in their operating temperature compared to those of 4 KV SiC diodes. Therefore, the SiC 4KV diodes are much more stable regarding the changes in operating temperature.

#### IV. CONCLUSION

In this paper, the performance of silicon carbide material has been highlighted for the Power PiN diode. A comparative study, through numerical simulation, between silicon and 4H silicon carbide having the same breakdown voltage has been achieved. In this study, we have deduced that the 4H-SiC PiN diodes has several performances than those of silicon. Indeed, this study allowed us to conclude that the realization of silicon carbide PiN diodes have lead to ultra-fast switching and hence these SiC components are dedicated to operate for high frequency applications. On the other hand, the dissipated power losses by these SiC components are much lower than those dissipated by the silicon components due to the small amount of stored charge in the base region of the SiC PiN diode.

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