Enabling Short-Term Over-current Capability of SiC Devices using Microchannel Cooling

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Abstract—Fault clearance time in the power system with renewables generally varies from 0.5-10 cycles (10-667 ms for 50 Hz). Power electronic converters should be able to provide an increased current without exceeding the thermal limits during faults. Accordingly, the heat generated in the semiconductor chip during over-current (OCs) should be removed from the chip as soon as it is generated. In this paper, microchannel (MC) cooling has been investigated through COMSOL simulations for OCs with SiC MOSFETs. The upper limit of the chip temperature has been assumed to be 250 °C as SiC devices do not fail in this temperature range. The duration of OCs is from a few tens of milliseconds to a few seconds. It is concluded that MC cooling has the potential to increase the duration of OC without reaching the assumed upper limit of the temperature.

Index Terms—High-temperature, microchannels, over-currents, power modules, semiconductor devices, silicon carbide

I. INTRODUCTION

The demand for renewables has increased drastically in recent years due to the growing concerns regarding climate change and continuously exhausting fossil fuels. The intermittent nature of renewable energy sources poses challenges in the power system such as sudden power changes. These situations could result in increased currents in the power electronics converters. Unsymmetrical faults in the power system can also result in over-currents (OCs) in the power system in order to feed the reactive power into the system. The fault clearance time could be up to 667 ms (10 cycles) [1].

Various methods have been investigated to keep the chip temperature within thermal limits during current transients as well as during steady-state steady operation. The upper limit of temperature is about 175 °C for Silicon (Si) devices while it would reach 250 °C for Silicon Carbide (SiC) devices in the near future [2], [3]. The limitation of 250 °C for SiC chips comes from the other components of the power module, not the chip itself. Apart from the difference in temperature limits of Si and SiC, other advantages of SiC chips include higher thermal conductivity of SiC and smaller chip size for the same ratings.

The methods investigated to handle OCs are passive methods such as adding heat-absorbing materials below/above the chip and active methods such as using Peltier elements. Using heat-absorbing materials on top of the chip has also been proposed and discussed in detail in [2] and [3]. Heat-absorbing materials could be either sensible materials (which do not change their physical state) or phase change materials (PCMs) [4]. The choice of material depends on the thermal conductivity of the materials (hence, the response time) and the duration of the OCs. Metals, diamond, and graphite have high thermal conductivity as compared to PCMs. Hence, PCMs could have applications in the seconds and minutes range while metals, diamonds, and graphite would have applications for OCs of a few milliseconds to seconds [2], [3]. On the other hand, Peltier elements work on the principle of the thermoelectric effect. However, the application of Peltier elements for transients has not been studied in detail until now [5] but they have been investigated for steady-state operation [6]. Another disadvantage of using Peltier elements is the need for an additional current source which adds complexity to the system.

Microchannels (MCs) have been investigated from the device level to the packaging level to reduce the chip temperature during steady-state operation. This could lead to an increase in the lifetime and power density of the converters [7], [8], [9], [10], [11]. According to the literature reviewed by the authors, MCs cooling has not been investigated for transient OCs at the packaging level. Therefore, the main contribution of this paper is the estimation of the performance of MC cooling with varying numbers of MCs and coolant flow rates for fast transients of a few hundreds of milliseconds and a few seconds for SiC metal-oxide-semiconductor field-effect transistors (MOSFETs). The system considered in this article is similar to the one proposed in [10].

The outline of this paper is as follows. In Section II, the configuration of MCs, various components of power modules, and power modules with MCs are discussed. Section III provides a discussion about enabling the OC capability of SiC MOSFETs. Section IV concludes the article.

II. THEORY AND METHODOLOGY

The configuration of microchannels (MCs) for cooling is shown in Fig. 1. The coolant flow in the MCs is in the direction perpendicular to the heat flux. The MCs are assumed to be built in a copper block and the coolant is deionized water in
the rest of the paper due to the ease of availability of both [10].

\[ R_{\text{tot}} = R_{\text{cond}} + R_{\text{heat}} + R_{\text{conv}}, \]

where \( R_{\text{tot}} \) is the total thermal resistance of the MC block, \( R_{\text{cond}} \) is thermal resistance due to the conduction of the copper below and above the microchannels, \( R_{\text{heat}} \) is thermal resistance because of water heating up, and \( R_{\text{conv}} \) is thermal resistance due to convection in the microchannels.

Further, the expressions for \( R_{\text{cond}} \), \( R_{\text{heat}} \), and \( R_{\text{conv}} \) are given by

\[ R_{\text{cond}} = \frac{t}{k.A} \]

\[ R_{\text{heat}} = \frac{1}{\rho.C_p.f_l} \]

\[ R_{\text{conv}} = \frac{1}{h.A_{\text{channels}}} \]

in which \( t \) is the thickness of the copper for conduction, \( k \) is the thermal conductivity of copper, \( A \) is area for effective flow of heat, \( \rho \) is density of water, \( C_p \) is specific heat capacity of water, \( f_l \) is flow of coolant (water in this case), \( h \) is heat transfer coefficient of water, and \( A_{\text{channels}} \) is total effective area of microchannels.

The complete power module with MCs attached is shown in Fig. 2 with the module structure taken from [2].

### III. Simulations

This section discusses the performance of an MC block and MC cooling in the power module. The finite element method (FEM) has been used in COMSOL for simulations. The MCs in the power module are designed with equal channel width and channel gap as this provides optimum proportions for having the minimum thermal resistance [13]. Similarly, the top and base thickness of the microchannel are equal and kept to a value of 0.2 mm to ensure minimum thermal resistance. The physics used in COMSOL is ‘Heat Transfer in Solids and Liquid’ with ‘Laminar flow’ added to the time-dependent study. The MCs are designed with a fully developed flow that operates only during the OC condition. OC has been achieved by implementing a user-defined heat rate function for the heat source in the ‘Heat Transfer in Solids and Liquid’ physics. The maximum coolant flow rate at the inlet of the channels (sum of all flow rates of the individual channel) is 1.73 ml/s as this flow rate can be easily achievable by a micropump of few mW [10] and has a low-pressure drop compared to higher flow rates. The inlet temperature of the coolant (water) is 40 °C. A tetrahedral mesh with boundary layers specifically defined for the MC is designed for an unobstructed laminar flow in the system. The power module is simulated for different numbers of MCs and varying flow rates for a duration of 120 s with a time step of 1 s, where an OC is applied to the module at 60 s.

#### A. Simulation of microchannel block

The performance of the standalone MC block (Fig. 1) is estimated by COMSOL simulations and the equations illustrated in the previous section. The size of the block for futuristic SiC chips is 1 cm x 1 cm with the heat flux of 400 W/cm² [2]. The height of the complete MC block is 1.62 mm.

The calculations of thermal resistances for different numbers of MCs (5, 10 and 15) and flow rates (0.3 ml/s, 1 ml/s and 1.73 ml/s) are shown in Table I.

<table>
<thead>
<tr>
<th>Flow rate (ml/s)</th>
<th>Number of MCs</th>
<th>5</th>
<th>10</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.3</td>
<td>2.1113</td>
<td>1.0843</td>
<td>0.7398</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>1.4481</td>
<td>0.7257</td>
<td>0.4457</td>
</tr>
<tr>
<td></td>
<td>1.73</td>
<td>1.2156</td>
<td>0.6185</td>
<td>0.3777</td>
</tr>
</tbody>
</table>

Fig. 3 shows the properties and performance of an MC block with an initial temperature of 100°C. It can be observed in Figs. 3a and 3b that the thermal resistance of the MC block decreases with an increasing number of MCs and increasing flow rates. Fig. 3c shows the average temperature of the MC block surface close to the heat source (MOSFET in the further discussion). The maximum flow rate of the coolant is assumed to be 1.73 ml/s as this flow rate is easily achievable by a small micropump. For a fixed number of MCs, the temperature decreases with increasing coolant flow rate. Similarly, the temperature decreases with an increasing number of MCs with

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Fig. 1: Configuration of microchannels

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Fig. 2: Configuration of microchannels with the power module

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Fig. 3: Simulation results for different flow rates and number of MCs.
(a) Thermal resistance of MC block with flow rate and number of MCs

(b) Thermal resistance with flow rate for a fixed number of MCs

(c) MC block performance with all flow rates and number of MCs

Fig. 3: Performance of MC block with different flow rates and number of MCs

a fixed flow rate. Hence, the temperature is the lowest for the maximum coolant flow rate and maximum number of MCs.

**B. Simulation of complete power module**

This section illustrates the simulation setup for estimating the performance of MCs for a SiC MOSFET power module as shown in Fig. 4. The footprint and the size of the SiC MOSFET are chosen to be the same as that of the Si IGBT in the module SKM50GB12T4 [14]. The heatsink, baseplate, and DBC have been reduced to half as only one MOSFET is considered in the simulations. This is illustrated in Table II. The simulations are performed for 5, 10, and 15 MCs with the flow rates 0.3 ml/s, 1 ml/s, and 1.73 ml/s.

The layout of the power modules does not consider an anti-parallel diode as the SiC MOSFETs have body diodes that can be used for free-wheeling if needed [15]. The current density (318 A/cm²) and ON-state resistance ($R_{DS(on)}$) are taken from the datasheet of CPM3-1200-0013A [16], [17]. The values for switching energies are taken from the datasheet E3M0021120K from Wolfspeed as this MOSFET has similar current and voltage ratings as the module used in the simulations.

The MOSFET is assumed to be utilized in a DC/DC converter with a duty cycle of 50% with no blanking time. Hence, the free-wheeling diode is not needed. The switching frequency is kept at 7.5 kHz. The rated value of current for the MOSFET is estimated to be 263.95 A ($R_{DS(on)} = 5.02 \text{ m}Ω$). The variation of $R_{DS(on)}$ for SiC MOSFETs with junction temperature from ambient temperature to 250 °C is 100 % which is estimated by datasheet and extrapolation for 250 °C, so, calculations for losses have been simplified by choosing the average values of $R_{DS(on)}$ at room temperature, 100 and 250 °C. Since power electronics converters are generally designed with safety margins of 30-60% [14], the nominal value of the current SiC MOSFET is assumed to be 158.37 A. The calculation of losses of the SiC MOSFET is performed using the general equations for MOSFET using (5) and (6). These general equations for the MOSFET losses are given in [18]. The values of switching energies for the MOSFET are estimated by interpolation using the datasheet E3M0021120K

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**TABLE II: Dimensions of the components of the power module as shown in Fig. 2**

<table>
<thead>
<tr>
<th>Component</th>
<th>Dimensions (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOSFET</td>
<td>9.1 × 9.1 × 0.35</td>
</tr>
<tr>
<td>MCs block complete</td>
<td>9.1 × 9.1 × 1.62</td>
</tr>
<tr>
<td>Width with 5 MCs</td>
<td>0.8273</td>
</tr>
<tr>
<td>Width with 10 MCs</td>
<td>0.4333</td>
</tr>
<tr>
<td>Width with 15 MCs</td>
<td>0.2935</td>
</tr>
<tr>
<td>Substrate</td>
<td>45 × 22 × 0.635</td>
</tr>
<tr>
<td>Base plate</td>
<td>54 × 22 × 2</td>
</tr>
<tr>
<td>Heatsink (Heat transfer coefficient)</td>
<td>800 W/m²·K</td>
</tr>
</tbody>
</table>

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by Wolfspeed [19]. The conduction losses are given by $P_{cond}$

$$P_{cond} = R_{DS(on)} \cdot I_{Drms}^2$$  \hspace{1cm} (5)$$

in which $R_{DS(on)}$ is the ON-state resistance of the MOSFET, $I_{Drms}$ is the rms value of the drain current. The switching losses ($P_{sw}$) are given by

$$P_{sw} = (E_{on} + E_{off}) \cdot f_{sw}$$ \hspace{1cm} (6)$$

where $E_{on}$ and $E_{off}$ are the turn-on and turn-off energies for the MOSFET for their corresponding current values, and $f_{sw}$ is the switching frequency.

The total power losses are calculated for nominal values of current (Nom), two times of OC (2 OC), three times of OC (3 OC), and four times of OC (4 OC) and tabulated in Table III.

TABLE III: Total losses (conduction + switching) in Watts (W) for SiC power module with one MOSFET

<table>
<thead>
<tr>
<th>Device</th>
<th>158.37 A</th>
<th>316.75 A</th>
<th>475.12 A</th>
<th>633.45 A</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Nom)</td>
<td>104.4</td>
<td>505.65</td>
<td>1069.01</td>
<td>1851.3</td>
</tr>
<tr>
<td>(2 OC)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(3 OC)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(4 OC)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The thermal resistance of the MC block with the same area as that of chip is shown in Fig. 5.

![Fig. 5: Temperature of MOSFET with 0.3 ml/s](image1)

Figs. 6, 7 and 8 show the thermal performance of MCs with different flow rates for 2 OC, 3 OC and 4 OC respectively. The upper limit of the average MOSFET temperature is limited to 250 °C. The OC is applied at 60 s for all the cases after the power module reaches a steady state.

Fig. 6 represents the performance of 5, 10, and 15 MCs with flow rates of 0.3 ml/s, 1 ml/s, and 1.73 ml/s for two times of OC. The average temperature of the MOSFET for the nominal value of current before the OC occurs is approximately 105 °C. The thermal resistance of the MC block decreases with an increasing number of MCs. Hence, the temperature is the least for 15 MCs for all values of flow rates in Figs. 6a, 6b and 6c. Similarly, the thermal resistance decreases with an increase in flow rate for a fixed number of MCs. Hence, the temperature is the least for 1.73 ml/s. Fig. 6c has the least temperature and maximum OC duration as compared to Figs. 6a and 6b for the same number of MCs. In Figs. 6a, 6b and 6c with 15 MCs, the temperature during the OCs is almost constant. This is due to the high rate of heat removal because of the higher number of MCs and higher flow rates. The standard power module reaches 250 °C in 0.75 s for two times OC while in all the cases with MCs, the temperature during the OC (from 60 s onwards) does not reach 250 °C for 15 MCs with all flow rates and 10 MCs with flow rates of 1 ml/s and 1.73 ml/s. Hence, OC can be handled for even more than 20 s without the temperature reaching 250 °C. However, for the rest of the cases (5 MCs with all flow rates and 10 MCs with 0.3 ml/s), the duration for OC is increased as compared to the standard module before the temperature of the SiC MOSFET reaches 250 °C.
Similar observations have been made for three times of OC as shown in Fig. 7. The duration before the temperature reaches 250 °C for the standard module is 30 ms. This duration is increased to approximately 120 ms (with flow rate of 0.3 ml/s and 5 MCs in Fig. 7a) to 1 s (with flow rate of 1.73 ml/s for 15 MCs in Fig. 7c).

Similarly, the duration of OC is increased from 10 ms to approximately 35 ms (Fig. 8a) to 50 ms (Fig. 8c) for 4 OC. It can be observed that there is no significant difference in the duration of OC for 10 and 15 MCs because the heat flux during 4 OC reaches 2235.6 W/cm². Hence, the upper limit for the rate of heat removal is reached for 10 MCs and there is no further increment in the rate of heat removal from the SiC MOSFET even if the number of MCs is increased to 15 MCs. Duration for all OCs with all MCs and flow rates are summarised in Table IV.

IV. CONCLUSION

As discussed in Section III-A, simulation of an MC block with 5, 10, and 15 MCs has been performed with an initial temperature 100 °C for the flow rates of 0.3 ml/s, 1 ml/s, and 1.73 ml/s. As seen in Table I, the thermal resistance decreases with an increased number of MCs and increasing flow rates as seen in Fig. 3. Hence, the thermal resistance in
The OC duration is the number of MCs and flow rates are concluded in Table IV.

Duration of all the OCs under consideration with different number of MCs has been discussed. The duration to withstand OCs has increased significantly in all the cases with 5, 10, and 15 MCs. For two times of OC, this duration is extended to the range of 120 ms to 1 s from 30 ms while for four times OC, the range is increased to 35 ms to 50 ms from 10 ms.

The flow rate of 1.73 ml/s can be easily achieved by a small micropump consuming a few mW of power as discussed in [10]. Since the MC block is made of copper which is an electrical conductor, the same block can be used to connect the device to the external circuit. This would lead to the elimination of bondwires and hence, resulting in increased reliability.

All the cases considered is the least for 15 MCs and 1.73 ml/s flow rate. Fig. 3c shows the performance of all the cases.

In section III-B, the performance of the power module with MCs has been discussed. The duration to withstand OCs has increased significantly in all the cases with 5, 10, and 15 MCs with various flow rates (from 0.3 ml/s to 1.73 ml/s). The duration of all the OCs under consideration with different number of MCs and flow rates are concluded in Table IV. The OC duration is > 20 s for all the cases with flow rates and number of MCs for two times of OC, except for the cases with a flow rate of 0.3 ml/s for 5 and 10 MCs, and 1 ml/s for 5 MCs. For three times of OC, this duration is extended to the range of 120 ms to 1 s from 30 ms while for four times OC, the range is increased to 35 ms to 50 ms from 10 ms.

The flow rate of 1.73 ml/s can be easily achieved by a small micropump consuming a few mW of power as discussed in [10]. Since the MC block is made of copper which is an electrical conductor, the same block can be used to connect the device to the external circuit. This would lead to the elimination of bondwires and hence, resulting in increased reliability.

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