Microelectronics Reliability xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Microelectronics Reliability

journal homepage: www.elsevier.com/locate/microrel

Thermal design and characterization of a modular integrated liquid cooled 1200 V-35 A SiC MOSFET bi-directional switch

P. Cova [a,*], A.M. Aliyu [b], A. Castellazzi [b], D. Chiozzi [a], N. Delmonte [a], P. Lasserre [c], N. Pignoloni [a]

[a] Department of Engineering and Architecture, University of Parma, Italy
[b] PEMC Group, University of Nottingham, Nottingham, UK
[c] PRIMES Association, Tarbes, France

ARTICLE INFO

Article history:
Received 19 May 2017
Accepted 26 June 2017
Available online xxxx

Keywords:
High power density
Packaging
System integration
Thermal design
Liquid cooling

ABSTRACT

The aim of this work is the thermal design of a modular direct liquid cooled package for 1200 V–35 A SiC power MOSFETs, in order to take full advantage of the high power density and high frequency performance of these devices, in the development of a modular integrated solution for power converters. An accurate electro-thermal fluid dynamic model is set up and validated by thermal characterization on a prototype; numerical models have been used to study the internal temperature distribution and to propose further optimization.

1. Introduction

The power electronics community demands for increasing frequencies and power density and new semiconductor technologies, based on GaN or SiC power devices, depending on the applications, are gaining market. The transistors are expected to soon reach suitable reliability for deployment in applications such as automotive, traction and aerospace, but the bottleneck is now represented by the packaging, which has to ensure low parasitics, good cooling, compactness, maintainability, modularity and competitive cost. Innovative solutions can be found in literature for specific issues as the cooling integration to the module [1–5] or highly integrated systems to reduce as much as possible the stray inductances [6], sometime with gate-drivers, power stage, and DC-link in the same package as in [7].

A new integrated liquid cooled bi-directional power switch for matrix converters was developed and recently presented in [8], based on 1200 V-35 A SiC power MOSFETs. The aim of the present work is the thermal design optimization of the module presented in [8], in order to better exploit the high power density and high frequency performance of these devices. In particular, since the target was the improvement of the direct liquid cooled modular bi-directional switch, an accurate thermal fluid dynamic model was made and validated by thermal characterization on an early prototype. Then, the numerical model has been used to study the internal temperature distribution, and to propose improvements for the next release.

* Corresponding author.
E-mail address: paolo.cova@unipr.it (P. Cova).

2. The bi-directional SiC power switch

The single module is composed by two transistors connected with the source in common (Fig. 1), and the internal layout, as described in [8] and shown in Fig. 2, was designed to obtain low parasitic inductances and good thermal performance. The devices used in this study are 1200 V-80 mΩ MOSFETs, with dimensions of 3.1×3.6 mm^2 and about 200 μm thick. For a description of the electrical performance, see [8].

This first solution, designed specifically for a bi-directional switch, integrates two MOSFETs chips mounted with the drain terminal onto two separate identical Direct Bonded Copper (DBC) substrates (Fig. 2a); these two substrates are stacked as shown in Fig. 2c, by means of soldered copper (Cu) bumps; two smaller bumps are used (Fig. 2b) to short the source terminals of the two transistors; an additional DBC substrate is partly sandwiched between the other two substrates to realize the power terminals D1 and D2, whereas bond-wires and external leads are used for the gate-drive interconnections (Fig. 2a). The outer cooling surfaces are extended by fins to improve the heat exchange with the liquid flowing in the coolers (Fig. 2d). The cooling is made by inserting the module in a sealed Teflon modular package, which is crossed by the coolant (typically a water-glycol mixture). Fig. 3 gives a sketch of three packaged modules connected together to make a converter.

In [8] preliminary thermal simulations were shown, identifying a limit in the operating conditions, which was far from the full exploitation of the power density capability of the transistors. For instance, single bi-directional switch module dissipating 100 W by each MOSFET, with a 20 °C water flow of 9 l/min, the maximum die temperature was

http://dx.doi.org/10.1016/j.microrel.2017.06.062
0026-2714/

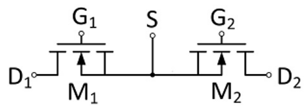

Fig. 1. Electrical diagram of a bi-directional switch.

around 140 °C, which is below of the die limit operating temperature (175 °C), but typically a high value for reliable operation, especially considering solder layers and thermomechanical stresses. Moreover, the earlier numerical model did not account for the power dissipated in the inner connections, which could be not negligible, due to the compact layout.

The effectiveness of the main thermally activated degradation mechanisms of metallic parts (electromigration, chemical reactions, etc.), increases exponentially with temperature and operation above 125 °C is in general not recommended [9,10]. Moreover, solder joints thermomechanical stress increases exponentially with the temperature swing, which, in turn, looking at long-period thermal cycles, is related to the maximum temperature. Then, to increase the reliability of the module, it is mandatory to limit its maximum temperature, since it affects both thermal and thermo-mechanical degradation mechanisms.

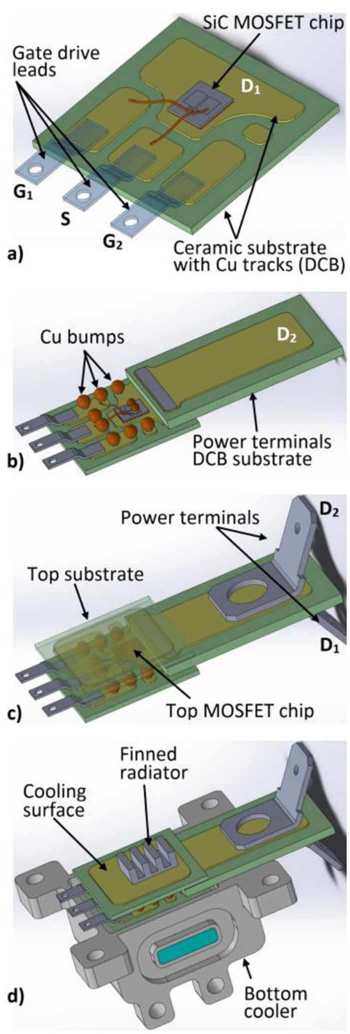

Fig. 2. Layout of the bi-directional power switch contained in a single module.

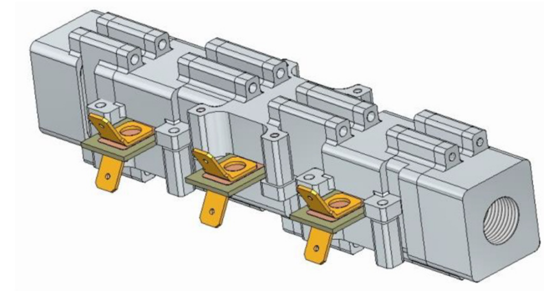

Fig. 3. External view of three packaged modules connected together to make a power converter.

3. Prototype thermal characterization

Since previous thermal fluid dynamic simulations of three modules connected together [8] demonstrated a very small increase of the water temperature from inlet to outlet (less than 1 °C, even with low flow rates), the thermal characterization was performed on a single module.

Fig. 4 shows the schematic diagram of the thermal characterization test bench. The module was cooled by a regulated open water circuit, with a flow meter at the inlet. The temperature of the water at inlet was measured by a k thermocouple, as well as done at the outlet, and a thermometer with resolution of 0.1 °C. The temperature of the external surfaces was measured by an infrared camera (FLIR A325). These surfaces were covered with a thin layer of matt paint in order to obtain the same emissivity by the different parts in the camera view. Fig. 5 shows the single module with a thermocouple placed at the water outlet and the test bench used for the measurements.

To simplify the experimental setup, the MOSFETs were heated simply biasing them in on state and limiting the current by the power supply. This kind of biasing was adopted only for model tuning purposes, and it must be noted that a DC current is then circulated through the source wirebond, although if this does not correspond to the real application. For that reason the current was limited to a safe value of 30 A (15 A per MOSFET). In these conditions the dissipated power per transistor was 26 W. With a 16 °C water flow of 2 l/min the thermal map shown in Fig. 6 was obtained.

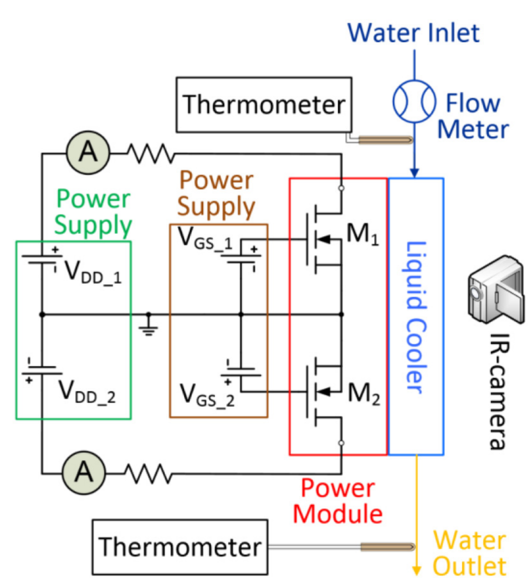

Fig. 4. Schematic diagram of the thermal characterization test bench.

Please cite this article as: P. Cova, et al., Thermal design and characterization of a modular integrated liquid cooled 1200V-35A SiC MOSFET bi-directional switch, Microelectronics Reliability (2017), http://dx.doi.org/10.1016/j.microrel.2017.06.062