ARTICLE IN PRESS

MR-12042; No of Pages 6

Microelectronics Reliability xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Microelectronics Reliability

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

Thermal design optimization of novel modular power converter assembly enabling higher performance, reliability and availability

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ARTICLE INFO

Article history:
Received 24 June 2016
Accepted 6 July 2016
Available online xxxx

Keywords:
High power density
Packaging
System integration
Inverter
Thermal design

ABSTRACT

An alternative integration scheme for a half-bridge switch using 70 μm thin Si IGBTs and diodes is presented. This flat switch, which is designed for high-frequency application with high power density, exhibits high strength, high toughness, low parasitic inductance and high thermal conductivity. Such a novel assembly approach is suitable to optimize performance, reliability and availability of the power system in which it is used. The paper focuses on the thermal performance of this assembly at normal and extreme operating conditions, studied by means of FEM thermo-fluidynamic simulations of the module integrated with connectors and liquid cooler, and thermal measurement performed on an early prototype. Improved solutions are also investigated by the FE model.

1. Introduction

Power modules are widely spread, for various applications, such as industrial electric motor driving and welding, automotive and conversion of renewable energies. Required features of the power converters are increasing in terms of occupied volume, power quality, efficiency, reliability, maintainability, modularity, and 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], sometimes with gate-drivers, power stage, and DC-link in the same package, as in [7]. This last feature is particularly important in power switches designed for high frequency (i.e. MHz) application.

From the reliability point of view, for high power density assemblies, optimization of the thermal design is a key issue and must be carefully conducted by coupling thermal characterization performed on early prototypes and 3D thermal modeling.

In this work, we show the development of a modular prototype integrating a Half Bridge Switch (HBS), a double-side liquid cooler and customized connectors to interface quickly gate-driver, input, and load side PCBs and maximize the maintainability, that could be worse in a single package integrated system. The paper mainly focuses on the study of the thermal performance of the system, by using FEM analysis.

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2. The double flat power switch

In a previous work [8,9] the authors developed a highly integrated double power switch, in half bridge configuration, based on 70 μm thin IGBTs and diodes rated at 600 V/200 A, on advanced ceramic substrate technology, featuring double-etched patterned copper tracks for a fully wireless double-sided cooling. Such an assembly could be suitable for applications also with SiC devices, due to its low parasitic inductance, low thermal resistance, and high strength. A schematic of the internal connections is given in Fig. 1a, while Fig. 1b and c show an exploded view of the stacked HBS and a picture of it, respectively. More details of the HBS technology can be found in [8,9].

This novel assembly is designed for high frequency plug in connectors, allowing optimization of performance, reliability and availability of the power system by means the following features.

- **Performance** - The highly integrated double-sided cooled fully wireless switch construction, with high-frequency-compatible interconnections at system level, enables improvement of: a) EM performance, with reduction of electrical (reduction/elimination of voltage overshoot) and electro-thermal (reduction of switching losses) stresses on Si devices; b) power density, by the highly integrated nature of the solid-state switch, and embedment of passives and auxiliary electronic components (e.g., gate-drivers, sensors) within the connector framework.
- **Reliability** - Thermo-mechanical stress and resulting degradation can be reduced by containing temperature swings (by direct substrate cooling), and improving temperature gradients (effect of double-sided cooling) in the power device structure.

http://dx.doi.org/10.1016/j.microrel.2016.07.019
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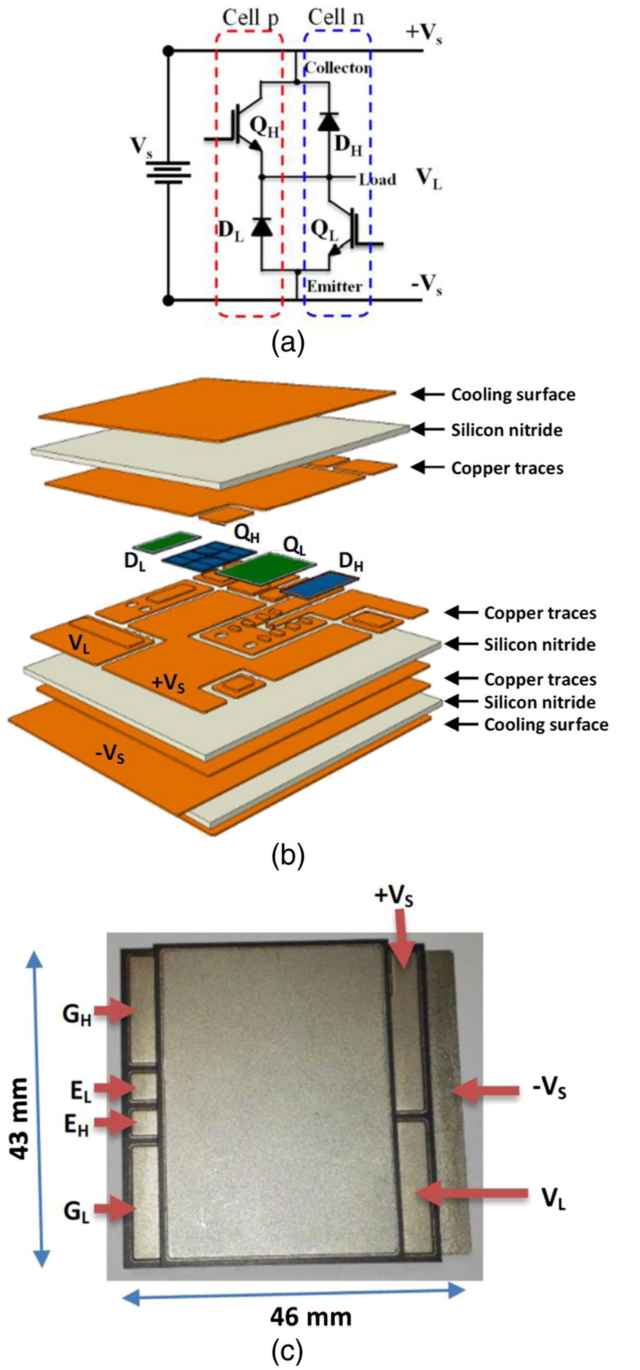

Fig. 1. Configuration of HBS: a) schematic diagram; b) exploded view of the stacked HBS; c) picture of the HBS prototype.

- **Availability** - The modular assembly approach enables for enhanced system maintenance and repair, requiring only the replacement of the individual system component that has failed. This can have a significant impact on the running cost of the equipment in some application.

The bottleneck of this solution could be the high power density, which implies the use of highly efficient heatsinks (e.g. air forced or liquid cooling). In this case the possibility of a double-sided cooling has been exploited, because of the stacked layout of the HBS.

The next section illustrates a modular prototype integrating HBS, double-side liquid cooler and customized connectors to interface quickly gate-driver, input, and load side PCBs.

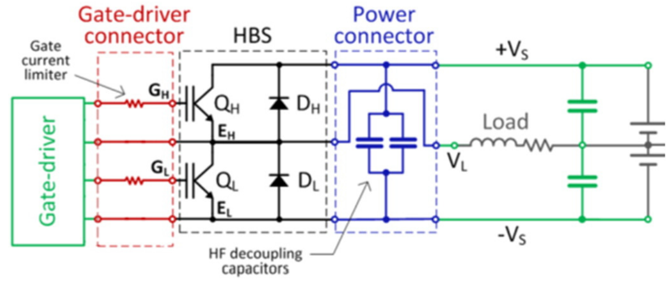

Fig. 2. Schematic of a single-phase inverter made with an HBS module. The gate-driver and load sections can be made by PCBs.

3. The integrated HBS module prototype

In order to optimize the prototype, new quick-mount connectors with integrated capacitors and resistors have been designed between the module and the supply along with the load and drivers. Such interconnect reduces the volume of the system as much as possible and enables quick mounting. Integrated capacitors decouple the DC source by the high frequency oscillations generated during switching, thus reducing the hassle in the design of the whole conversion system. Fig. 2 reports a schematic of a single-phase inverter made by the HBS module.

Two different test setups were tested, with and without the two capacitors embedded in the load side connector. Details of the connectors design and electrical characterization can be found in [10]. All the thermal analysis and design described in this paper deal with the version of the converter without the output capacitors, since it represents the worst case for power dissipation.

3.1. The integrated liquid cooler

Since the total heat generated in the HBS has been estimated to be up to 300 W, it is necessary to use a highly efficient cooling system, therefore an ad-hoc double-side liquid cooler was designed. The water cooling system flow path was conceived to directly target to the hot spot (open area in the red rectangle shown in Fig. 3), where the power devices are located. The liquid flows from the inlet toward the top cooling surface, turns down, and flows via the bottom cooling area of the switch to the outlet. Rectangular gaskets were designed to seal the plastic and the switch cooling surface. Finally, the cooling system is assembled and fixed using screws. A photograph of the whole integrated inverter module prototype is shown in Fig. 4. It is worth to note that this is a laboratory prototype, not optimized for long term reliability. Material choice options are available (including Aluminum) to ensure long lifetimes. Sealing can also be enhanced in a number of ways to contribute to structural stability and integrity.

Fig. 3. The liquid cooler applied to the HBS.