Thermal investigation of power diodes in novel integrated disc type packages

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Abstract. Paper focusses on electro-thermal numerical investigation of a novel disc type package for power diodes integrated with microchannel cooling system. Although the new solution ensures much lower average temperature of an electronic element, it results in much higher temperature non-uniformity obtained within the silicon structure. The distribution can be improved with the aid of redesigned microchannel cooler. The maximum junction temperature reduction of more than 25 °C is possible.

1. Introduction

The problem of heat generation in electronic devices and systems and its efficient dissipation began in 50s of XX century and it evolved differently in various areas of electronics. In power electronics, from early beginnings, the reliability and product’s life are strictly dependent on junction temperatures of power semiconductor devices [1]. High currents and voltages, even in the case of high efficiency power conversion, results in excessive heat losses that must be transferred from the semiconductor structures to maintain their operating temperatures at the safe levels. Hence, in the field of power electronics efficient heat dissipation solutions are so called must-have products [2].

One of the first ideas to increase cooling efficiency in electronic applications was replacement of commonly used air with liquids. Liquid coolants offer much better thermal parameters in comparison to gases e.g. heat transfer coefficient can be increased more than 40 times [2, 3]. Further improvement can be obtained by implementing cooling technique based on microchannel concept.

First microchannel heat sink was proposed by Tuckerman and Pease [4]. The pioneers experimentally proved that the microchannel net with a characteristic dimension of 50 µm incorporated in the silicon substrate was able to dissipate up to 790 W/cm\textsuperscript{2}. The result was obtained for the 0.5 l/min water flow and the pressure drop exceeding 200 kPa. Even though, their solution was designed for VLSI circuits, the first commercially available cooler based on microchannels was offered for power electronics applications [5]. A 3D MCI cooler (3 Dimensional Micro Channel Isolated cooler) was a copper solution integrated with a DBC (Direct Bonded Copper) substrate dedicated for intelligent power modules. Since then, several microchannel heat sinks for power electronics applications have been designed, manufactured and tested [5-7]. All of them offer outstanding thermal parameters due to shortening the heat flow path between the heat source and the cooler, and taking benefits from the characteristic channel dimension reduction.
A novel solution of integrated disc type packages for power semiconductor devices has been developed by team from Lodz University of Technology [3, 8]. Its idea covers embedding of microchannel cooling structure within the supplying electrode of the conventional package. Improved efficiency of the cooling system results from elimination of the interface resistance and implementation of the concept of channels with small characteristic dimensions introduced close to the heat source. The integration of cooling microstructure with disc type case allows eliminating external heat sinks and replacing a double-sided cooling with a single sided solution. It results in weight and size reduction and smaller coolant usage.

Application of very efficient cooling system enhances performance of the power element, but it also leads to much higher non-uniformity of temperature distribution within the semiconductor structure. To analyse and to reduce this phenomenon, electro-thermal simulations have been conducted. Their results and analysis are presented in the paper.

2. Modelled structures
The idea of the novel integrated package is depicted in figure 1a. Figure 1b and figure 1c present one of the cooling microstructure prototypes [9] and the cut across supplying electrode with embedded microchannels, respectively [8]. Preliminary tests of the new package for three inch power diodes have shown 20% improvement in the system thermal resistance [3], while the field tests have confirmed that the microchannel cooler can dissipate up to 5.5 kW implemented as a single-side solution. Nevertheless, the question regarding temperature uniformity within the semiconductor structure has arisen. They have resulted in numerical investigations of the designed packages that have focused on not only temperature non-uniformity but also on potential solutions for its improvement.

The modelled structures are depicted in figure 2. They cover three inch power diodes manufactured on molybdenum discs that are mounted between two copper electrodes. In the case of the conventional solution (see figure 2a), double-sided cooling with the aid of standard cold plates is implemented in a form of convetional boundary conditions applied on external surfaces of the electrodes. In the case of the new package (see figure 2b), the microchannel structure together with the inlet and outlet pipes are integrated only on the cathode side. The conducted thermo-electric simulations do not incorporate detailed analysis of coolant flow, and the liquid cooling process in microchannels is employed as convetional boundary conditions. The approach allows investigating only single quarters of the whole structures.

![Figure 1](image1.png)

**Figure 1.** The outline of the integrated package (a) with microchannel cooling structure (b) integrated as a single-side cooling solution. Photo of the cut across supplying electrode (c) with exposed net of parallel microchannels with rectangular cross-sections.
The series of simulations have been conducted with the aid of ANSYS software for the following assumptions and boundary conditions (for more details see [2]):

- diode modelled as an equivalent resistivity calculated from the isothermal I-V characteristics of the real measured devices (DB3-3500 by Kubara LAMINA [10]);
- current ranging from 1500 to 4000 A, applied on the bottom surface of the anode electrode;
- voltage of 0 V, on the upper surface of the cathode side;
- cooling microstructure in accordance with the data gathered in table 1;
- cooling introduced as convectional boundary condition for:
  - conventional package: film coefficient of 23 800 W/m²K (calculated from the assumed case to coolant thermal resistance of 0,01 K/W), and reference coolant temperature of 40 °C;
  - integrated package: film coefficient of 40 000 W/m²K (highest experimentally derived values by Author) for the microchannel and inlet and outlet chamber walls and film coefficient of 1 000 W/m²K for the pipe walls, reference coolant temperature of 40 °C;

Table 1. Geometries of tested microchannel structures.

| STRUCTURE NAME | NUMBER OF CHANNELS | SEPARATING WALL THICKNESS | MICROCHANNEL LENGTH |
|----------------|---------------------|---------------------------|---------------------|
| 25-microchannels | 25                  | 1,0 mm                    | 36,5 mm             |
| 37-microchannels  | 37                  | 0,5 mm                    | 36,5 mm             |
| 48-microchannels  | 48                  | 0,5 mm                    | 29,4 mm             |

The outline of 25-microchannels cooling structure embedded in the closing electrode of the disc type package accompanied by modifications of 37-microchannels and 48-microchannels is depicted in figure 3. In the case of two first geometries 32% of the surface is not covered by either channels or inlet or outlet chambers, while in the latter one, the value is reduced below 16%. On the other hand, bigger manifold chambers results in higher local current densities.
3. Results and discussion

Sample temperature distributions on the surface of the power diodes encapsulated in the conventional package and in the integrated ones with different cooling microstructure geometries, obtained for current of 4000 A, are presented in figure 4.

Figure 3. Views of embedded microchannel structures: (a) 25-microchannels, (b) 37-microchannels, (c) 48-microchannels.

Figure 4. Temperature distribution on the surface of the power diode encapsulated in: (a) the conventional package, (b) the integrated package with 25-microchannel cooler, (c) the integrated package with 37-microchannel cooler, (d) the integrated package with 48-microchannel cooler.
To illustrate better the differences among the investigated structures, temperature changes along the radius on the surface of the disc type power semiconductor structure have been analysed. In the case of novel packages, paths perpendicular and parallel to set of microchannels are considered, while for the conventional ones, a path along arbitrary chosen radius is taken. Figure 5 depicts temperature variation as a function of the distance from the diode centre obtained for the current of 4000 A.

It can be noticed that microchannel structures assures very efficient heat transfer even while implemented as a single-sided solution. In the close proximity of microcoolers, temperature is much lower (less than 20 ºC higher that the coolant temperature). Temperature difference along the radius may exceed 35 ºC. Although the value is reduced to 21 ºC for the geometry with higher ratio of liquid flow area to diode surface. In the structure, temperature uniformity is also improved; although the highest uniformity is reached for the conventional package with cold plates mounted on both sides.

![Figure 5. Temperature distribution along different paths on the surface of the diodes obtained for 4000 A and various packages.](image)

The problem of non-uniformity can be also reduced by applying lower currents. Figure 6 depicts the results obtained for the conventional and 25-microchannel packages (the worst investigated scenario) for the current range from 1500 A to 4000 A. With the dotted lines, the results obtained for the conventional package are marked. Embedded microchannel coolers causes temperature to be reduced of at least 10º C or more than 30 ºC for current of 1500 A and 4000 A, respectively. The maximum value is still reported for the novel solution, although the difference is below 2,5 ºC and it decreases with the current drop.

It is worth to mention that the thermal resistances junction to cooling medium calculated for minimum, average and maximum temperatures equal 5,8 K/kW, 9,8 K/kW, and 13,2 K/kW, respectively. The values change negligibly with the increase of current within the tested range. 36% reduction of thermal resistance is possible by optimising the geometry, so the bigger area is covered by the cooler, like in 48-microchannel structure. Further optimisation of the investigated solutions is necessary.
Figure 6. Temperature distribution on the surface of the diode along the path perpendicular to microchannels for different currents. With dotted lines results for conventional packages are depicted.

4. Conclusions

Paper covers electro-thermal numerical investigations of the novel disc type package for power diodes. Due to integration of the housing with the microchannel cooling system, the new solution is characterised by a lower weight, more compact dimensions and improved thermal parameters in comparison to conventional systems.

The conducted series of simulations has confirmed that the new solution ensures much lower average temperature of the encapsulated electronic element, even if microchannel coolers are implemented as single-sided solutions. On the other hand, high temperature non-uniformity within the semiconductor structure, especially for high currents, has been observed (exceeding difference of 35 °C for 4000 A). Its reduction is possible by optimisation of cooling microstructure geometry. The use of 48 shorter microchannels instead of 25 longer ones allows lowering the maximum junction temperature of more than 25 °C.

5. References

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