Whitepaper
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Smart Package Upgrade to Improve Power Density and Lifetime in Heavy-Duty Vehicles

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Abstract

Electrified drive trains in heavy-duty vehicles pose a challenge for semiconductors in a multitude of ways. One key element includes the highly repetitive load cycles that define demanding lifetime requirements for power modules. An upgrade of the well-established EconoDUAL™3 package is presented: a ribbon-bond structure on the backside significantly improves the thermal performance with an open, liquid-cooled heat sink, without altering the other parts of the power module. The thermal characterization of single modules is followed by application tests and lifetime considerations. The ribbon-bond upgrade enables an increase in output current by more than 20%, or correspondingly, a significant increase in lifetime for a given load profile.

Table of contents

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1 Introduction

The European Union estimates that trucks, buses and construction machinery contribute about 25 % of the CO_2 emission caused by traffic [1]. With the overall goal of reduced CO_2 emissions in mind, there is a trend towards electrification in both passenger cars as well as in heavy-duty vehicles. While the general concepts of electrification are similar in both fields, there are different requirements when it comes to power semiconductors.

Especially, the mode of operation for buses and delivery vehicles, which is dominated by highly repetitive start-stop operation during a whole day, places high demands on the lifetime of semiconductors in the application. The technical solution is a liquid-cooled heat sink that allows for lower R_{th} in comparison to air-cooled systems. The obvious benefits are reduced overall temperatures, and thus temperature ripple, resulting in improved lifetime for a given mission profile and power rating.

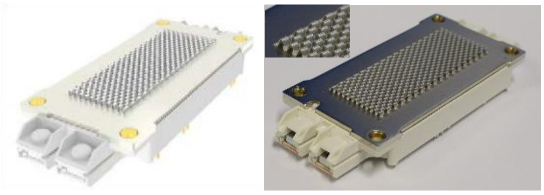

Fig. 1 Schematic and actual image of the module backside with ribbon-bond structure.

A smart package upgrade for standard power modules with flat baseplate is presented, where ribbon-bonds are attached on the backside of the module. On the one hand, this improves the surface area towards the liquid, and at the same time, the structure allows for enhanced turbulence in the liquid, both resulting in better thermal transfer and a reduction in R_{th}. The concept can be used for standard power modules and is an additional last step in the manufacturing process. Hence, there is no impact on other package parameters except for an improvement of the thermal path.

2 Concept

Liquid-cooled heat sinks are already a standard solution in both passenger e-cars and e-buses, with two different concepts: cold plate solutions provide a closed liquid system, where the power module is mounted on top with thermal grease between module and heat sink – as done in air-cooled systems. The well-defined interface between power module and heat sink allows for easy optimization of both parts individually, and standardized heat sink components may be used. On the other hand, a better overall performance can be reached with open heat sink systems, where the backside of the power module is in direct contact with the liquid.
Besides using the flat module mentioned above, the so-called PinFin structure has proven to be an efficient way of cooling that is widely used, see e.g. [2]. Though such a baseplate with extruded structures is an excellent technical solution, an alternative approach is the installation of a ribbonbond structure on the manufactured module instead, see Fig. 1. It adds only a single additional step at the end of the manufacturing process, while all other properties of the power module remain unchanged. The process itself is very robust and thus makes it a very easy-touse approach for direct liquid-cooled power modules.
A closed heat sink is characterized by the two parameters, volume flow and resulting pressure drop Δp, where the latter is a direct consequence of the internal construction. In an open system, however, the latter is a *combined* parameter of heat sink and power module: For a given heat sink design, the pressure drop is low for a flat baseplate, and will be higher with a PinFin or ribbon-bond structure and the same heat sink. Consequently, the heat sink design needs to be adapted to the power module's backside structure in order to achieve best thermal performance.
To account for the impact of the heat sink, the thermal path for three different solutions is compared. Application tests provide a direct insight into the junction temperatures, and subsequent lifetime calculations show clear advantages of the ribbon-bond solution in combination with an open, liquid-cooled heat sink.

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3 R_{th} measurements

R_{th} measurements were done based on the EconoDUAL™ 3 package, with a halfbridge configuration and a nominal current of 900 Amp [3]. Details of the package in combination with the latest IGBT7 chip technology have been described in other literature [4]. Three different cooling options have been investigated:

A) with thermal grease, to be mounted onto a closed heat sink and without direct contact to the liquid

B) with the plain baseplate mounted onto an open heat sink with direct contact to the liquid

C) with ribbon-bond solution, mounted onto an open heat sink

For the latter two options, the only directly accessible value is R_{thjf}, given as

$$R_{thjf} = (T_{vj} - T_f) / P_v$$

with the junction temperature T_{vj}, power losses at the respective device P_V, and the fluid inlet temperature T_f. Fig. 2 shows both the heat sink and the backside of the module with the ribbon-bond structures. The heat-sink footprint is only slightly larger than the power module, with an additional height of 25 mm.

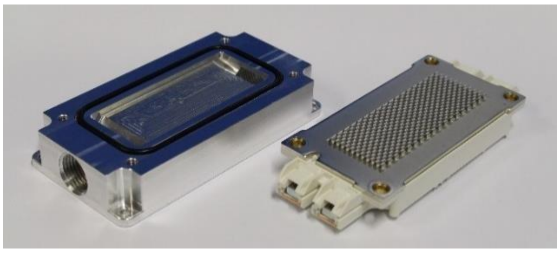

Fig. 2 Open heat sink (left) and module with ribbon-bond structures (right) on the backside.

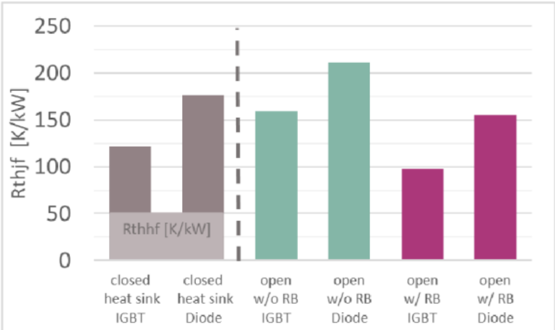

Fig. 3 Comparison of thermal resistance for the three different approaches as measured for IGBT and diode at 10 l/min.

Fig. 3 shows the resulting thermal resistance for all three concepts. All three heat-sink solutions are operated at a volume flow of 10 l/min. For the closed heat sink, the R_{thjh} is measured using standard thermal grease. A typical R_{thhf} = 50 K/kW *per switch* is included in the graph as a reference.
As expected, the direct water-cooled system with ribbon-bonds is superior to the other two variant variants, as the thermal path is much more immediate. The solution without ribbon-bonds is much weaker in terms of R_{thjf}, which is expected, since the flat baseplate does not provide additional turbulence and no additional heat transfer surface.

Fig. 4 shows in addition the R_{thjf} as a function of volume flow, together with the resulting pressure drop Δp in the inset. As expected, the thermal performance improves with volume flow, and overall the thermal performance for the ribbon-bond solution is significantly better. This comes in addition with a weaker dependence on volume flow: A highly turbulent flow is introduced through the ribbon-bonds by default, whereas in the flat baseplate scenario turbulence needs to be generated via the volume flow. The increase in R_{thjf} at small values is also explained by this effect: Below a certain threshold, there is always a steeper increase in R_{thjf}, and this threshold is shifted towards lower volume flow in the case of the ribbon-bonds.

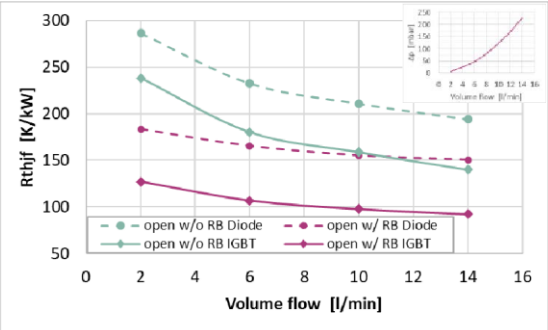

Fig. 4 R_{thjf} variation as function of volume flow. The solution without RB shows a steeper dependence below 6 l/min, and in general a higher sensitivity on volume flow.

As mentioned above, the thermal performance of the power module on a liquid-cooled heat sink is clearly given by the operating parameters in the application – e.g. the volume flow –, and by the construction itself. The latter is represented by the pressure drop across the heat sink as given in the inset of Fig. 4: For the heatsink as used above, the plain baseplate results in a low pressure drop and thus relatively high R_{thjf} value. The ribbon-bond structure on the module introduces additional resistance to the coolant flow and thus shows a corresponding increase in pressure drop. To further gain performance at a given volume flow in the application, the construction of the heat sink itself can be modified: If a higher pressure drop is accepted at a given flow, another gain in thermal performance of the power module is possible. Here, a proper balance between volume flow, pressure drop, and complexity of the heat sink design need to be found, depending on the system design and usually involving flow simulations. Especially, the question of parallel vs series connection of heat sink elements will have a significant impact on thermal performance and resulting pressure drop.
Other aspects, like sealing of module towards heat sink and long-term stability against corrosion, have been discussed previously [5].

4 Application tests

Since the R_{th} measurement setups for open and closed heat-sink systems are clearly different, an analysis of the junction temperature during application conditions can serve as a fair comparison. Fig. 5 shows the general application test setup for the ribbon-bond solution, where power module, water inlet, load contacts, and gate driver board are easily recognized. The junction temperatures as a function of output current I_{rms} are accessed using open black-painted modules and a thermal camera. Additional operating conditions are given in Table 1. Another test setup with a closed heat sink was used in the same way to characterize a standard power module.

Switching frequency	4 kHz
Modulation index	1
Gate-emitter voltage	-15/+15 V
DC-link voltage	600 V
cos phi	0.9
Water inlet temperature	50 °C

Tab. 1 Operating conditions during application test.

Fig. 6 shows a comparison of two temperature measurements for the closed solution (A) and open heat sink with ribbonbond solution (C) at the same operating conditions. The advantage of the ribbonbond solution having clearly lower temperatures is immediately visible.

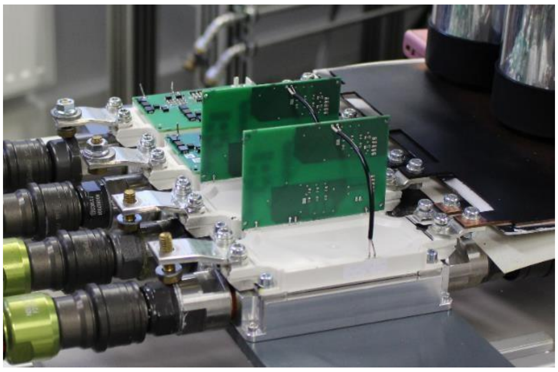

Fig. 5 Application test setup, where power module, water inlet, load contacts, and gate driver board are easily recognized. During temperature measurements, the modules are open.

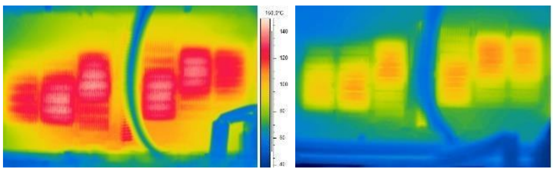

Fig. 6 Temperature measurement for the closed (left) and open heat sink with ribbonbonds (right) solution, both operating at 500 A Irms and 15 l/min volume flow, using the same temperature scale.

The average temperature across the chips T_{vj} is taken from these images and used for further analysis. Fig. 7 shows T_{vj} for different operating conditions for solutions (A) and (C). The water inlet temperature is shown as a horizontal line to indicate the maximum temperature ripple for each operating condition. Again, solutions with open heat sink and ribbon-bonds operate at a much lower temperature, and a higher volume flow further reduces T_{vj}. At a volume flow of 15 l/min and I_{rms} = 500 A, a temperature decrease of 25 K is reached. In turn, also the temperature ripples during a mission profile will be lower. This is highly attractive for heavy-duty vehicles, where the maximum temperature during operation is often limited in order to avoid large temperature swings and the related lifetime consumption. Alternatively, the ribbonbond solution allows for an increase in output current by up to 30 %, which in addition offers an increase in power density as well.

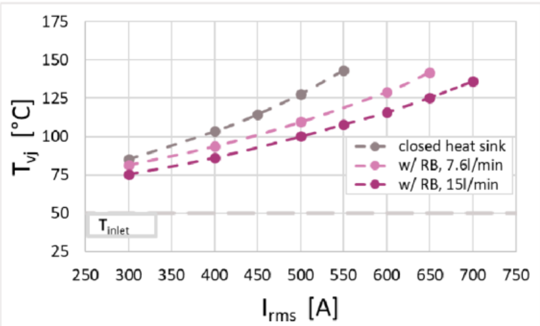

Fig. 7 Temperature as measured with the thermal camera, for closed heat sink with 15 l/min and for open heat sink with ribbonbonds at different flow rates.

The discussion so far has focused on a single half-bridge module with an individual heat sink. For constellations with more than one module, a decision has to be made between parallel and series connection of the individual heat sink units, which will have an impact on the volume flow and pressure drop of the complete system. Besides overall design and geometry considerations, a parallel configuration supports low pressure drop across all units, whereas a series connection supports low volume flow at the cost of higher pressure drops along the system. The R_{thjf} at the module level that is achieved with a given heat-sink design clearly depends on the configuration of the cooling system.

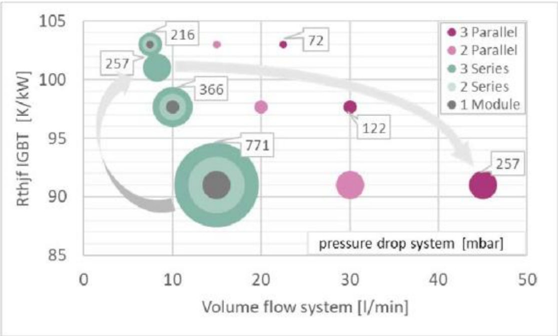

Fig. 8 Based on the given heat-sink design for one module, the effect of system configuration (i.e. number of modules, parallel vs series connection of heat sink) is shown. For different volume flow, the pressure drop is given in mbar and indicated by the diameter, together with the resulting $R_{thif.}$

Fig. 8 indicates this as a guideline. A single module achieves the lowest R_{thjf} with a volume flow of 15 l/min and a resulting pressure drop indicated by the diameter of the disc. The same R_{thjf} is reached for each power module with heat-sink units connected in parallel, while the volume flow per module adds up to a very high volume flow of 45 l/min at system level. For series connection of the individual heat-sink units, a much higher pressure drop needs to be supported by the system in order to achieve lowest R_{thjf}. If the pressure drop is the limiting parameter in the system, the total volume flow needs to be reduced accordingly. In series connection, this comes with a lower flow per individual unit, and thus, increased Rthjf. However, a thorough analysis of the coolant system is highly recommended as a separate task.

5 Lifetime considerations

Another crucial parameter in bus applications is the lifetime of the power module. Especially inner-city transport deals with a high number of start-stop events that prove to be very demanding in terms of power cycling (PC). The PC capability of a power module is provided by the manufacturer, where the applied test method should be checked, as this may have a significant impact on the test result [6]. Since the ribbon-bond concept is an add-on to the bottom side of the module only, the general PC capability is the same as for standard modules. Taking this as a given, the improved thermal performance as described above leads to reduced temperature ripple and thus improved lifetime for a given mission profile and target lifetime, see also, e.g. [7,8].

To get a first insight into the advantages of the new concept, a simple comparison is made: the maximum temperature swing is between the inlet temperature and T_{vj} at a given I_{rms}. Assuming that this is the only temperature ripple present in a single load cycle, the number of possible cycles is directly given by the PC curve. Fig. 9 shows the resulting relative lifetime for the different scenarios.

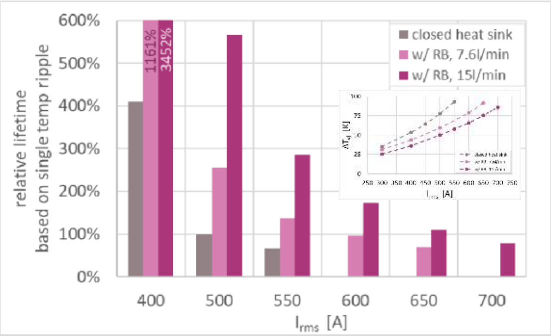

Fig. 9 Relative lifetime, assuming only a single temperature ripple at the given Irms. The inset shows the temperature ripple for the respective solution.

Based on the simple picture, an increase in lifetime by a factor of at least two to five is recognized at an output current of 500 A. In the other view, the output current may be increased by 20 % to more than 30 %, depending on volume flow, for the same package, without sacrificing lifetime. These are very promising estimates, especially keeping in mind that the power module itself with electrical configuration and gate driver board is not altered at all. The only difference is a change from a cold-plate to an open heat-sink solution.

To get a much more accurate understanding of the absolute lifetime, a detailed calculation based on the rain-flow analysis [9] is required. This analysis will – besides details on the power module and heat-sink configuration – also require a dedicated mission profile.

6 Conclusion

This article describes the benefits of a smart package upgrade for the EconoDUAL™ 3 platform. With ribbonbonds attached to the backside of the power module, and all other components left untouched, a much better thermal performance is achieved. This can be used to easily increase the output current by more than 20 %, or to significantly improve the lifetime capability of the power module at given operating conditions. The latter is especially attractive in heaty-duty applications like e-busses or delivery vehicles, where start-stop operation defines high lifetime requirements for the power module.

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