Innovative CooliR^2™ Packaging Platform with Dual-side Cooling Advances HEVs and EVs

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Abstract: The paper presents the results of the development of new concept in high power semiconductor packaging technology intended for electric and hybrid-electric vehicle (EV and HEV) traction inverters.

The paper discusses how the novel CooliR^2™ wirebond-less, transfer-molded packaging platform being developed by International Rectifier eliminates the weaknesses of conventional packaging technologies and enables significant inverter system cost savings.

Achieved improvements over traditional power module packaging technologies are discussed and the results such as approx. 80% increase in current rating of power modules, three to four times increase in power density and an order of magnitude improvement in power cycling capability are presented in the paper.

The paper concludes that the CooliR^2™ high power semiconductor packaging platform will revolutionize how the automotive traction inverters are built.

Keywords: EV and HEV traction inverter, IGBT power modules, packaging platform, dual-sided cooling, improved reliability, CooliR^2™.

1. Introduction

Further progress towards mass adoption of the hybrid electric (HEV) and electric vehicles (EV) depends on the industry achieving the cost, size and weight reduction goals for power electronic components and systems. Achieving these goals requires significant improvements in power density and reliability of the electric power train systems.

It will not be possible to do that by making incremental improvements to existing power electronics technologies or adapting components developed for industrial applications. A paradigm shift in power semiconductors and packaging technologies is needed to achieve the necessary targets.

Improvements are needed in power semiconductors as well as in packaging technology. The power semiconductor switches must be designed for optimum performance under the tough conditions imposed by automotive applications. The packaging technology must maximize the utilization of the semiconductor devices, achieve higher power density and provide significant improvement in reliability. All these improvements must come at a lower cost.

International Rectifier addressed all of the above mentioned challenges by developing CooliR™, an innovative high-power packaging platform, together with CooliRIGBT™ and CooliRDiode™, a set of semiconductor devices optimized for EV and HEV power conversion applications.

2. Application specific semiconductor devices

The design of CooliRIGBT™ has been optimized for use in automotive inverter applications. Special emphasis has been put on reduction of conduction and switching losses, increase of breakdown voltage and compatibility with wirebond-less interconnection techniques.

Large, 12 mm x 12 mm trench IGBT dice with a current carrying capability of 300A and a blocking voltage above 680V were developed with solderable metals on both front and back sides (SFM) using 70μm thin wafers.

To improve robustness and utilization of the semiconductor device, the maximum operating junction temperature Tj was increased to 175°C, which is a 25°C increase in comparison to other commercially available devices.

In order to further improve the robustness in motor inverter applications, the IGBTs have guaranteed 6μs short circuit rating. The intended switching frequency range is up to 20kHz so the typical automotive inverter switching frequencies of 10kHz are well within the efficient operating range of the device. The IGBTs are characterized by very low turn-off losses resulting from lack of so called "tail current" which is characteristic for other commercially available devices.

The CooliRDIODE™ has also been optimized for automotive traction inverters. A fast speed soft-recovery diode has been developed with 680V breakdown voltage rating and with solderable metals on both front and back sides of the thin wafer. The CooliRDIODEs™ are fast and exhibit soft, oscillation-free behavior.

3. Paradigm shift in packaging technology

The objective of CooliR^2™ packaging platform development was to create an innovative power semiconductor packaging concept specifically for HEV/EV traction inverter applications which would maximize the utilization of semiconductor devices and be characterized by high power density, effective heat removal capability, low interconnection resistance, low parasitic inductance, extended operating temperature range, high reliability and low cost.

Traditionally, power electronics circuits are implemented with discrete devices housed in industry standard packages (e.g. D^{2}Pak, TO-247, etc.) or power modules.

The "discrete devices" have limited current ratings which result from the die size limitations imposed by space available in the standard packages. The discrete packages are also often limiting the semiconductor device performance due to the current carrying capability of interconnections. Applications requiring semiconductor die sizes exceeding those that could be housed in the discrete package are served by power modules. There is a large performance and cost gap between discrete packages and power modules. The CooliR^2™ package is narrowing or even eliminating this gap.

3.1 The "building block" approach

The innovative CooliR^2™ concept introduces an intermediate package, high-power equivalent of a discrete package, which can accommodate very large die sizes and simplifies the construction of power modules and also enables implementation of customized power circuits without using power modules.

CooliR^{2}DIE™ is a complete power switch consisting of an IGBT die and a matching diode die mounted on a ceramic substrate. Voltage rating of 680V and current rating of 300A has been achieved in a 29 mm x 13 mm x 1 mm very compact assembly. Different current ratings of the CooliR^{2}DIE ™ devices with different IGBT and Diode die sizes will also be available.

The primary features of the CooliR^{2}DIE™ package approach are: elimination of wirebonds and elimination of the need to handle super-thin bare die during module assembly.

Two types of CooliR^{2}DIE have been developed. One with the emitter (E) side of the IGBT and the Anode (A) side of the diode attached to the substrate and the other one with the collector (C) side of the IGBT and the cathode (K) side of the diode attached to the substrate.

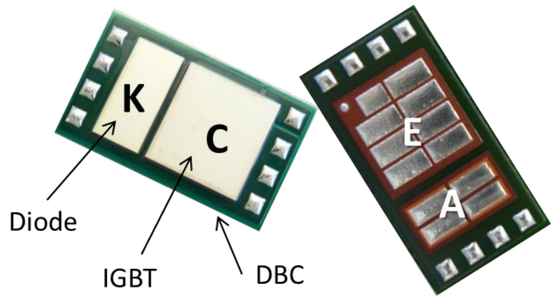


Figure 1. CooliR^{2}DIE^{TM} – a "very large die discrete SMT component"

Having both of these packages available greatly simplifies construction of custom power circuit topologies. Typical implementations use multiple CooliR^{2}DIE™ building blocks attached to a substrate in a fashion similar to mounting surface mounted components. Variety of substrates can be used. Most common one is Direct-Bonded-Copper (DBC) substrate.

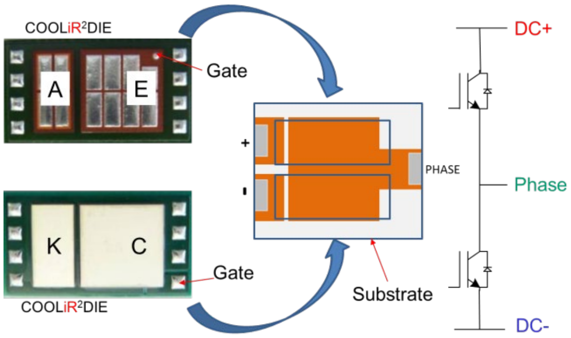


Figure 2. Half-Bridge (also Buck or Boost) construction

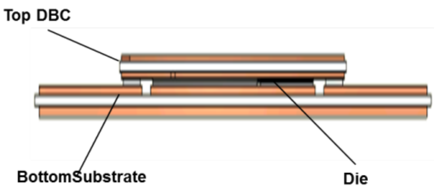


Figure 3. Cross-section of CooliR2DIE(TM) switch mounted on DBC substrate.

The technology is compatible with different die attach techniques including soldering or sintering. CooliR^{2}DIE™ assemblies can be over-molded using transfer molding technology or protected by a gel-filled housing similar to that used by traditional power modules.

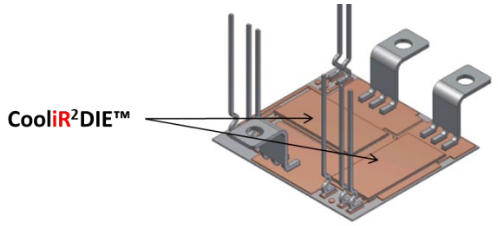


Figure 4. Example of module construction. CooliR^{2}DIE^{TM} mounted on a substrate with leadframe attached.

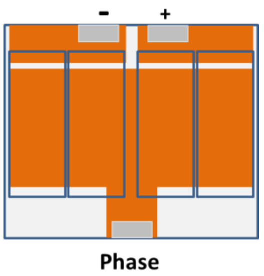


Figure 5. Half-Bridge layout with double current rating

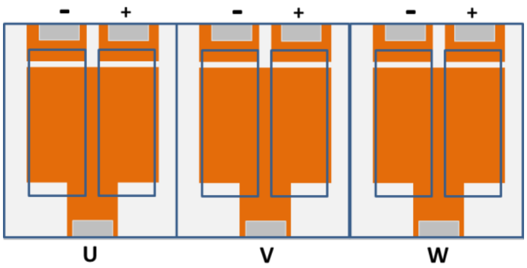


Figure 6. Three phase bridge layout example

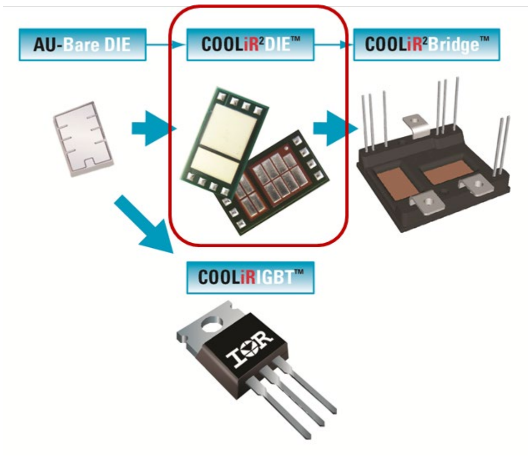


Figure 7. CooliR^{2TM} Platform Concept

CooliR^{2}DIE™ package is the core element of the CooliR^2™ packaging platform. It's a universal "building block" that can be used as a surface mounted "discrete component" to build power circuits without using modules or as a pre-packaged die subassembly in a power module.

CooliR^{2TM} platform brings a paradigm shift to the way power electronics systems are going to be built.

4. CooliR^2™ Packaging Platform

4.1 The "building block" approach advantages

Cost reduction: As it was shown in the previous section, the CooliR^{2}DIE™ building block greatly simplifies construction of power circuits or power modules. It also provides flexibility in creating different circuit topologies and scalability of power ratings by using standard building blocks. It enables system integrators to build power conversion circuits without using modules. It simplifies module manufacturing process by eliminating the need to handle super-thin bare die and wirebonding it. In addition, the CooliR^{2}DIE™ comes as a pre-assembled, fully tested component, thus increases the system or module manufacturing yield.

Mechatronics enabler (more cost saving options): Using CooliR^{2}DIE™ to build power circuits opens up the possibility to optimize their physical size, weight, current rating and form factor. It is possible now to reduce or even eliminate the cost of the traditional package, its housing, leadframe, etc. by integrating the power circuit with the electro-mechanical device it controls. Significant savings can be achieved by integrating the inverter with electric motor so they can share common housing, cooling system and other hardware.

Figure 8. Example of mechatronics assembly

These options do not exist with commercially available standard power modules. There is very little flexibility in selecting the power module's form factor or current rating. Custom modules are expensive.

Additional system level cost reduction comes from better utilization of power semiconductor devices in the CooliR^{2}DIE™ packages thanks to their enhanced mechanical, electrical and thermal performance.

4.2 Electrical performance improvements

Lower package resistance: Replacing the wirebonds with wide copper planes which are attached to the entire surface of the semiconductor die results in greatly reduced interconnection resistance. The resistance of a 20mil diameter Al wirebond is approx. 0.0013 Ohms/cm. For comparison, the resistance of the 12mm wide, 0.3mm thick copper plane is approx. 0.000065 Ohms/cm. It would take 20 wires with 20mil diameter to achieve the same low resistance what is not practically possible.

The achieved Die-Free-Package-Resistance of the 300A rated CooliR^{2}DIE™ is < 100 uOhms. The 300A rated power module built using CooliR^{2}DIE™ blocks has a total package resistance of < 0.5 mOhms. This is approx. 0.5 mOhms less than the resistance of similarly rated wirebonded module. The seemingly small difference in resistance results in 0.15V lower voltage drop at 300A. This results in 45W reduction of conduction losses per phase or approx. 5% reduction of the overall inverter losses.

Lower parasitic inductance: CooliR^{2}DIE™ mounted on the main substrate creates a "strip line" like structure. This results in lower inductance of the switch and plays important role in elimination of voltage overshoots and ringing which is present in circuits with higher stray inductance.

Measuring the low inductance of CooliR^2™ structure accurately is very challenging. For the purpose of illustrating the order of magnitude improvement from using the "strip line" concept of CooliR^{2}DIE™, approximate calculations could be performed using the following formulas.

$$L_{bondwire} \approx \frac{\mu_0 \mu_r}{2\pi} cosh^{-1} \frac{2h}{d} \qquad (h \gg d) \quad (1)$$

$$L_{plane} \approx \frac{\mu_0 \mu_r h}{w} \qquad (w \gg h, h > t) \quad (2)$$

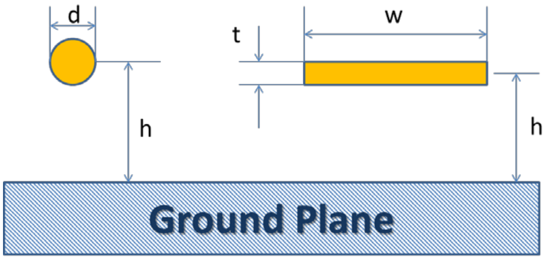


Figure 9. Inductance calculation models

It should be noted that the formulas do not take into account the shape of the wirebond which is normally bowed what increases the inductance. For accurate estimate, the effect of using multiple wirebonds should also be taken into account. Multiple wirebonds reduce the inductance. However, due to mutual coupling between the bondwires, the overall inductance of multiple wirebonds is not inversely proportional to the number of parallel wires but is always higher than L_{wire}/n where n is the number of wirebonds (e.g. the inductance of 5 parallel wirebonds will be only approx. 2 times lower than the inductance of one wirebond).

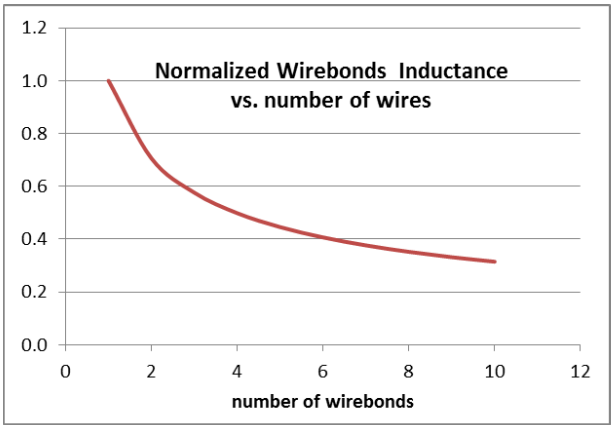


Figure 10. Normalized wirebond inductance vs. number of wirebonds in parallel.

The inductance of single wirebond of the same length as the length of CooliR^{2}DIE™ is approx. 5 to 10 times higher than the inductance of the CooliR^{2}DIE™. It is evident that even using large number of wirebonds in parallel will not reduce the inductance to match the low inductance of the CooliR^{2}DIE™.

The reduced inductance of the switches contributes to the reduction of the overall module inductance. The inductance of the 480A rated half-bridge module measured from the DC+ to DC- terminal is only approx. 12nH.

The low inductance of the module is reflected in the quality of switching waveforms exhibiting lower voltage overshoots and less ringing.

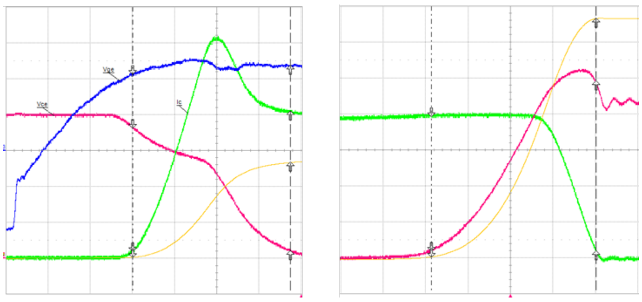


Figure 11. Turn-on and turn-off waveforms of the CooliR²Bridge™ module (400V/400A, 100ns/div)

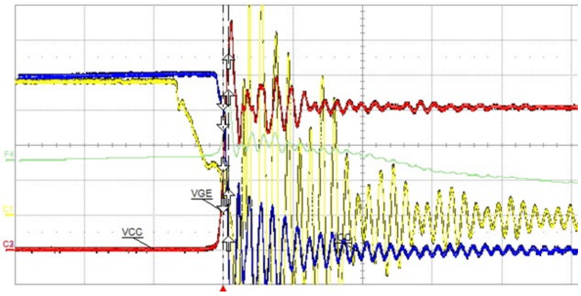


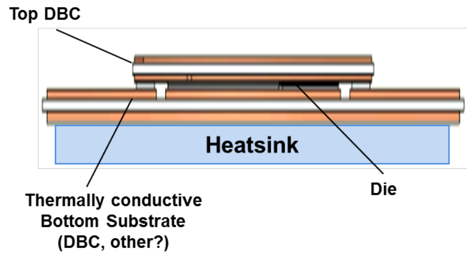
Figure 12. Turn-off waveforms of a module with high inductance

4.3 Thermal performance improvements

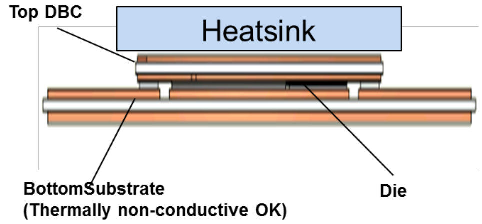
Achieving high power density requires limiting power losses of the semiconductor devices and improving heat transfer to the coolant. Modern power semiconductors achieve higher current densities and as a result of that become physically smaller. The smaller size provides cost benefits. However, removing heat thru the smaller area becomes more challenging. It requires more efficient heatsinks as well as substrate and thermal interface materials with higher thermal conductivity. All of these measures increase system cost. The ultimate solution is to reduce the die size and simultaneously increase the heat transfer area by taking advantage of both sides of the semiconductor die. This measure alone has the potential of decreasing the junction to coolant thermal resistance by half. Ultimately, lower cost system built with less expensive substrate and thermal interface materials could still achieve higher power density.

Flexibility in cooling method: The semiconductor die in the CooliR²™ packaging platform, is sandwiched between two substrates. The heat removal is possible through either side of the package. The thermal resistance from the semiconductor die junction to case (Rth junction-case) is approximately the same on either side of the package.

a)



b)



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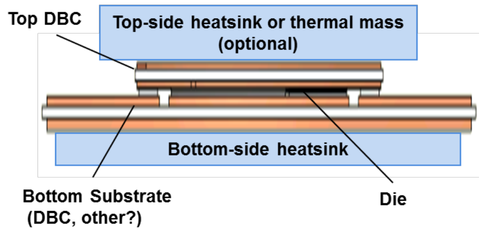

Figure 13. CooliR2DIE(TM) possible cooling methods:

a) bottom-side, b) top-side, c) dual-sided

The CooliR²™ modules offer even more degrees of flexibility. The modules can be used without the conventional base plate or optionally, a base plate or a direct-liquid-cooled heatsink can be attached to the substrate.

No base plate: The cooling methods shown in Figure 13 assume the external surface of the substrate to be in contact with the heatsink through a layer of thermal interface material (TIM). In this simplest implementation no additional base plate is used. The transfer molded package provides enough mechanical stiffness so the application of proper amount of pressure required for good thermal interface to the heatsink is possible without cracking the substrate. It will be shown later that elimination of baseplate doesn't have significant effect on the steady state junction-heatsink thermal resistance. The short term transient thermal impedance without

baseplate exhibits shorter thermal time constant, but it can be improved by adding thermal mass to one of the cooling surfaces as shown in Figure 13 b). The additional thermal mass can be provided in form of a mounting metal clamp (as shown in Figure 14) without adding the cost of a base plate.

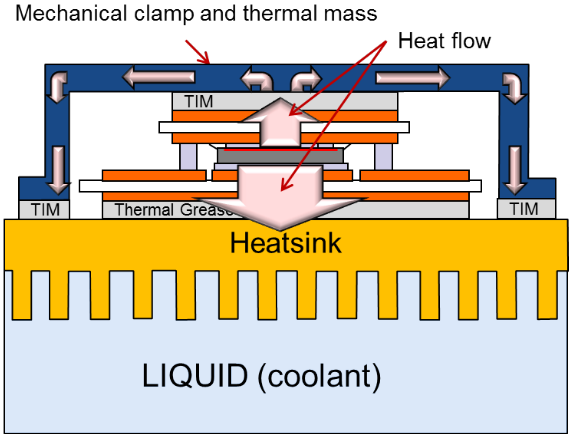

Figure 14. Mechanical clamp as a thermal mass

There are significant gains from elimination of the base plate including: lower cost and weight, and elimination of potential solder attach reliability issues resulting from long term temperature cycling.

With base plate: Conventional power modules use base plate as a mechanical support for the fragile substrate as well as to provide lateral heat spreading capability. As mentioned previously, the additional benefit of base plate is added thermal mass which lowers the transient thermal impedance and increases short term overload capability of the power module. The baseplate can be easily added to the CooliR^2™ module if required.

With direct-liquid-cooled heatsink: Similarly to the baseplate, a liquid cooled heatsink can be attached to the substrate on either side of the module. The CooliR™ technology makes it possible to build a single-side or dual-side direct-liquid-cooled module.

Thermal stack analysis: For the purpose of understanding the contribution of various layers of the thermal stack let's assume the die is sandwiched between two layers of Alumina DBC and the die is soldered on both sides. Let's further assume single-sided cooling and thermal grease used as a thermal interface material (TIM) between the module and the liquid cooled heatsink as shown in Figure 15**.**

The interesting result of the thermal resistance comparison shown in Table 1 is the relatively high junction-sink thermal resistance of the module with base plate which results from the contribution of the two additional layers – solder and base plate. This negative effect is partially compensated by the heat spreading effect of the baseplate which increases the area of the heat transfer through the TIM to the heatsink and to the coolant.

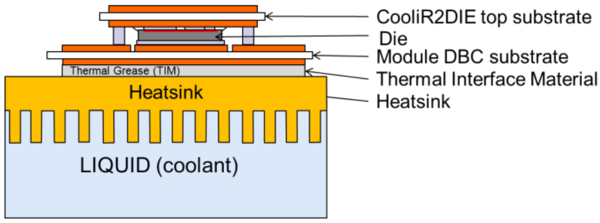

Figure 15. CooliR^{2}DIE^{TM} thermal stack with single-sided cooling

Table 1. Rth junction-sink comparison (per 1cm^2)

without base plate

Layer	thickness Z [mm]	conductivity K [W/mK]	Rth [K/W]	contribution %
IGBT solder	0.1	25	0.040	8%
DBC Cu	0.3	380	0.007	1%
DBC Al2O3	0.38	24	0.141	27%
DBC Cu	0.3	380	0.007	1%
TIM (thermal grease)	0.05	3	0.133	25%
		Rth j-sink	**0.328**	

with base plate

Layer	thickness Z [mm]	conductivity K [W/mK]	Rth [K/W]	contribution %
IGBT solder	0.1	25	0.040	9%
DBC Cu	0.3	380	0.007	2%
DBC Al2O3	0.38	24	0.141	30%
DBC Cu	0.3	380	0.007	1%
Solder	0.15	25	0.047	10%
Baseplate (Copper)	3	380	0.038	8%
TIM (thermal grease)	0.1	3	0.109	23%
		Rth j-sink	**0.388**	

with direct liquid-cooled baseplate

Layer	thickness Z [mm]	conductivity K [W/mK]	Rth [K/W]	contribution %
IGBT solder	0.1	25	0.040	8%
DBC Cu	0.3	380	0.007	1%
DBC Al2O3	0.38	24	0.141	27%
DBC Cu	0.3	380	0.007	1%
Solder	0.15	25	0.047	9%
		Rth j-sink	**0.242**	

The best result is achieved with the direct-liquid-cooled heatsink soldered to the module's substrate. Simulation results show approx. 10% to 15% lower Rth j-coolant. The benefit comes from the fact that the relatively high thermal impedance of the thermal grease is replaced with lower thermal resistance of the solder.

In this case however, the durability of the seal between direct-liquid-cooled heatsink and the rest of the liquid cooling system is the main concern.

Rth measurement results with different substrate materials:

Thermal resistance junction-case of the CooliR^{2}DIE (see Figure 11) with different substrate materials has been measured. The results are presented in Table 2.

Table 2. CooliR^{2}DIE^{TM} Rth j-c with different substrates (per 1cm^2)

Substrate type	Insulator thickness [mm]	Copper thickness [mm]	$R_{th\ j\text{-}c}$ [^{o}C/W]	
Alumina	0.38	0.2	0.1822	100%
	0.38	0.3	0.1764	91.8%
	0.25	0.2	0.1382	71.9%
AlN	0.38	0.2	0.1033	53.7%

As it was shown earlier in Table 1, it is evident that the contribution of ceramic material thickness and type has much greater influence on the overall Rt j-c than the thickness of copper layers.

Dual-sided cooling: Regardless of the type of substrate and the choice of module construction, with or without the base plate or direct-liquid-cooled heatsink, the CooliR^2™ module platform offers the additional option of single-sided or dual-sided cooling.

Theoretically, the dual-sided cooling can reduce the junction-case thermal resistance by half.

$$\boldsymbol{Rth\,j-c\,DUAL-SIDED} = \frac{\mathbf{1}}{\frac{\mathbf{1}}{\boldsymbol{Rth\,j-c\,BOTTOM}}+\frac{\mathbf{1}}{\boldsymbol{Rth\,j-c\,TOP}}}$$

$$\frac{\mathbf{1}}{\frac{\mathbf{1}}{\boldsymbol{Rth\,j-c\,BOTTOM}}+\frac{\mathbf{1}}{\boldsymbol{Rth\,j-c\,TOP}}} \qquad (3)$$

Where $\boldsymbol{Rth\,j-c\,BOTTOM}$ is the thermal resistance from junction to the bottom cooling surface of the module. $\boldsymbol{Rth\,j-c\,TOP}$ is the thermal resistance from junction to the bottom cooling surface of the module.

For $\boldsymbol{Rth\,j-c\,BOTTOM} = \boldsymbol{Rth\,j-c\,TOP}$

$$\boldsymbol{Rth\,j-c\,DUAL-SIDED} = \frac{\boldsymbol{Rth\,j-c\,BOTTOM}}{\mathbf{2}} \qquad (4)$$

In a practical implementation it may be difficult to achieve identical thermal performance on both sides of the module. Some of the reasons are mechanical tolerances and uneven thickness of the thermal interface material on both sides. However, even assuming the $\boldsymbol{Rth\,j-c\,TOP}$ is 60% higher than the $\boldsymbol{Rth\,j-c\,BOTTOM}$, it can be shown that the overall dual-sided cooling thermal resistance is still only approx. 61% of the $\boldsymbol{Rth\,j-c\,BOTTOM}$.

$$\boldsymbol{Rth\,j-c\,DUAL-SIDED} =$$

$$= \frac{\mathbf{1}}{\frac{\mathbf{1}}{\boldsymbol{Rth\,j-c\,BOTTOM}}+\frac{\mathbf{1}}{\mathbf{1.6}*\boldsymbol{Rth\,j-c\,BOTTOM}}} =$$

$$\approx \mathbf{0.61} * \boldsymbol{Rth\,j-c\,BOTTOM} \quad (5)$$

The 39% reduction of junction-coolant thermal resistance allows approx. 50% increase of the power module current rating.

Transient thermal impedance: Due to the presence of relatively large copper planes and ceramic substrate on both sides of the semiconductor die the thermal mass of CooliR^{2}DIE™ is larger than that of a conventional wirebonded die. In the transfer molded module, the mold compound provides some additional thermal mass as well. An example of the transient thermal impedance of CooliR^{2}DIE™ without mold compound is shown in Figure 16. The steady state is reached at approx. 10s.

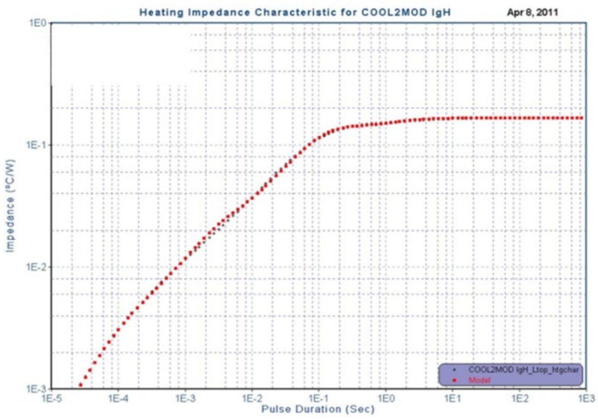

Figure 16. Example of CooliR^{2}DIE^{TM} transient thermal impedance Zth(t).

The increased thermal time constant of CooliR^{2}DIE™ helps reducing junction temperature variations by providing an averaging effect for pulses with duration of less than 1s.

The main influence on the module's thermal time constant for pulses with duration exceeding 1s comes from the presence or absence of a base plate and the properties of the thermal interface material and the heatsink. As it was mentioned earlier, addition of a base plate, direct-liquid-cooled heatsink or thermal mass attached to the top or bottom

cooling surface of the CooliR²DIE™ is possible and will greatly increase the thermal time constant.

Improved die temperature distribution: In a wirebonded module, the current flows in or out of the die through a number of wirebonds attached to the die surface in “discrete” locations. This results in a non-uniform current distribution where the current and therefore the heat generation is “crowded” at the wirebonds attachment points. In addition, the center of the die is usually much hotter than the edges due to the fact that the heat from the edges can more easily spread laterally to the cooler areas of the heatsink.

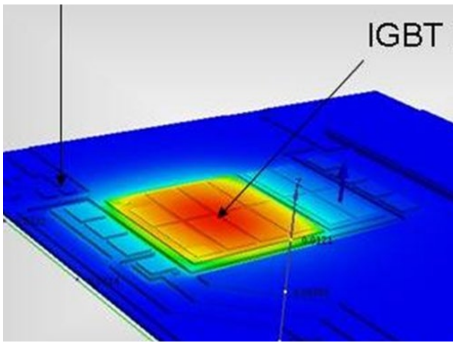

Figure 17. IGBT die uniform temperature distribution

The “sandwich” structure of the CooliR²DIE™ and particularly the absence of wirebonds results in better equalized die surface temperature. The temperature gradient between the center of the die and its edges is much smaller than in a wirebonded die because in the CooliR²DIE™ package, the die is attached to copper planes on both sides. This helps the lateral heat spreading and creates more uniform die temperature. The elimination of hot spots results in safer operation and increased current rating of the semiconductor switch.

4.4 Increased reliability

Electric and hybrid-electric vehicle applications are demanding reliability and durability levels going well beyond the levels required by industrial applications. Many power modules used in automotive traction inverters originated from the industrial family of products. The power module industry has been making continuous efforts to improve the reliability of power modules for EV and HEV inverters as can be seen in Figure 18.

The primary failure mode limiting the life of power modules is the wirebonding failure. The temperature swings inside of the module package are leading to wirebond cracking and lift-off failures. To make an order of magnitude improvement in reliability it is necessary to break-away from traditional interconnection methods. Elimination of wirebonds in the CooliR²™ packaging platform resulted in a significant improvement in power cycling capability.

CooliR²Bridge™ power modules were power cycled with constant current, using 2 s on-time and 4 s off-time to achieve delta Tj of 80°C and Tj max of 150°C. The test was stopped after the modules reached 998,000 cycles. It is expected to reach even higher number of cycles in the next trial.

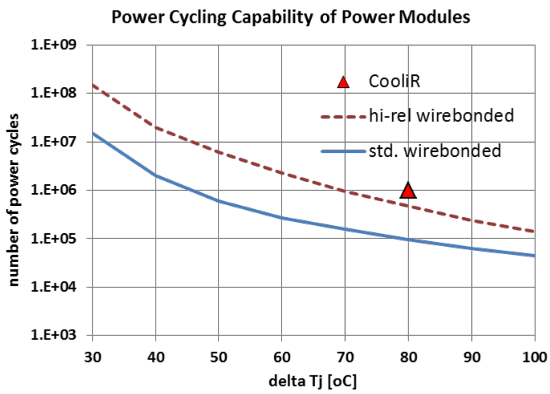

Figure 18. Power cycling capability of power modules

The results shown in Figure 18 prove that the elimination of wirebonds and the most common failure mode leads to a superior reliability.

4.5 Higher power density

The higher power density of CooliR™ power modules was achieved thanks to several improvements over the traditional packaging technologies. The dual-sided cooling itself resulted in approx. 50% higher current rating from the same semiconductor die area. The semiconductor power devices developed for CooliR²™ platform have maximum rated junction temperature Tjmax = 175°C. The additional 25°C allows approx. 20% of additional current rating increase. The overall effect is approx. 80% higher current rating of the power module.

In addition, the power module size has been shrunk by approx. 50% and the weight reduced by the same factor or more depending on the technology used as a reference.

The overall power density improvement achieved with the CooliR²™ technology with dual sided cooling is on the order of over 300% as compared to conventional, wirebonded and gel-filled power modules.

The above estimate still does not take into account the improvements resulting from lower inductance

resulting in lower voltage overshoots which allow higher dI/dt and reduce switching losses, and lower interconnection resistance reducing the conduction losses by up to 5%.

5. Conclusion

This paper introduced novel high power semiconductors packaging concept and illustrated the potential of the new package to advance the EV and HEV technology and its adoption by contributing to lowering the cost, improving performance and reliability of the power electronics converters.

The electrical, thermal and reliability improvements have been demonstrated. It was shown that the CooliR^2™ packaging technology and especially the innovative CooliR^{2}Die™ package open new possibilities for the design of the EV and HEV traction inverters. They provide the path to break away from the traditional single-sided heatsink and power module "brick" approach and design the inverter into a smaller, lighter, dual-side cooled housing with flexible form factor. Seamlessly integrating an inverter with motor and building mechatronics devices is now possible. The concept of the novel high power semiconductor packaging technology described in the paper has the potential to revolutionize the way the power converters are being built.

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7. References

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8. Glossary

CooliR^2™:	Trademark of dual-side cooling enabled semiconductor packaging platform
DBC:	Direct-Bonded-Copper (also known as DCB)
EV:	Electric Vehicle
HEV:	Hybrid Electric Vehicle
IGBT:	Insulated Gate Bipolar Transistor
K:	Thermal conductivity [W/mK]
Rth:	Thermal resistance [^{o}C/W]
SFM:	Solderable Front Metal
TIM:	Thermal Interface Material
Tj:	Semiconductor junction temperature
Zth(t):	Transient thermal impedance