CooliR^2™ - New Power Module Platform for HEV and EV Traction Inverters.

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Abstract

The paper introduces an innovative CooliR^2™ high power semiconductor packaging platform from International Rectifier which offers a practical solution to the challenges posed by the technical requirements of modern HEV and EV traction inverters. The proposed solution breaks with the tradition and offers an innovative, "building block" modular packaging concept revolutionizing the way power modules and power circuits are built. The achievements of the CooliR^2™ platform development program are presented and the major benefits of the innovative packaging technology such as increased current and power density, reduced size and weight, improved thermal management, enhanced reliability and cost reduction potential are presented.

Summary

The adoption and further progress of Hybrid-Electric and Electric Vehicles (HEVs EVs) depends on lowering the cost and providing solutions to the technical challenges of power electronics systems which include: increased reliability, small size, increased power density, and improved thermal management. The conventional, wire bonded, gel filled power modules require many improvements to meet these challenges.

The break-through CooliR^{2TM} packaging concept introduces a new, very large die „discrete package" for power semiconductors addressing all the challenges of modern EV and HEV power converters. This modular packaging approach allows for building very compact power modules or power control circuits without modules using discrete building blocks at lower cost. The modular approach solves the scalability requirements for various power ratings. The CooliR^{2TM} packaging concept does not utilize wire bonds thus eliminates the primary failure mechanism and significantly improves reliability. This packaging concept also offers dual-sided cooling capability which greatly enhances the thermal management and leads to higher power density and improved reliability.

In addition, the CooliR^2™ modules are using the newest generation of IGBTs and Diodes optimized for HEV and EV traction inverters applications. Unique characteristics of these silicon power devices are also presented.

1. EV and HEV traction inverter challenges

The prerequisite to success and mass adoption of the electric and hybrid-electric vehicles is the achievement of lower cost and weight, and higher power density and reliability of automotive power electronics systems. An example of the goals for

improvement of power electronics are the targets established by the United States Council for Automotive Research LLC (USCAR) shown in Table 1.

Table 1: Status and targets for EV and HEV power electronics

	R&D Status	**Targets**		**Change**
	2010	**2015**	**2020**	
Coolant Temperature	90 ^{o}C	105 ^{o}C	105 ^{o}C	**+ 15 ^{o}C**
Cost, $/kW	<7.9	<5.0	<3.3	**> - 60%**
Specific power, kW/kg	>10.8	>12.0	>14.1	**> +30%**
Power density, kW/L	>8.7	>12.0	>13.4	**> +54%**

Source: The United States Council for Automotive Research LLC (USCAR)—U.S. DRIVE Electrical & Electronics Tech Team (EETT).

The fact that the expected power density must come at higher coolant temperature makes it particularly challenging. This means that removal of heat from power semiconductors must be much more efficient, the devices must be capable of operating at higher temperatures and the power losses in the semiconductor devices must be minimized. All these improvements must be achieved simultaneously with higher reliability and at lower cost.

Table 2: Potential Solutions to Market Demands

Potential Solutions	**Market Demands**	**Lower Cost**	**Lower Weight**	**Smaller Size**	**Higher Coolant Temp**	**Higher Reliability**
Semiconductor Devices	Increase Tj max.	**smaller die size**		smaller die size	**compensates for Tcoolant increase**	**higher Tj margin**
	Reduce Conduction Losses	**smaller die size**		smaller die size	**Lower Tj**	higher Tj margin
	Reduce Switching Losses	**smaller die size**		smaller die size	**Lower Tj**	higher Tj margin
Semiconductor Packaging Technology	Reduce Parasitic R, L				lower losses - lower Tj	lower losses - lower Tj
	Reduce Rth, Zth	**smaller die size**			**lower deltaTj-coolant**	**higher Tj margin**
	Reduce Housing Size		X	**X**		
	Eliminate Baseplate	**X**	**X**	X		no solder interface degradation
	Integrate with heatsink		**X**	**X**	**Lower Tj**	no TIM degradation
	Reduce Failure Rate					**X**
	Eliminate Failure Modes					**e.g. eliminate wirebonds**
Semiconductor Package Manufacturing	Simplified Construction	**X**				
	Reduce BOM Cost	**X**				
	Use Standard Building Blocks	**Higher Yield**				
	Use Known-Good Building Blocks	**Higher Yield**				

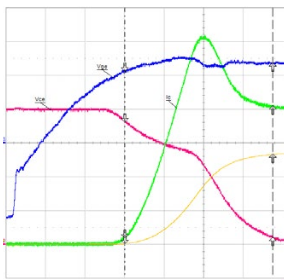
*Legend: **Bold text** – major influence, Normal text – secondary influence*

Table 2 lists potential solutions available to the designers of power semiconductor devices, power modules and power conversion systems. It is evident that improvement in one technology area is not sufficient and a comprehensive approach is needed. Achieving the market and technical goals will not be possible by making incremental improvements to existing technologies. It will require an innovative solution that breaks with tradition. The CooliR^{2}™ power semiconductor platform is an example of such innovation.

2. Optimizing semiconductor devices for EV and HEV inverters

The target of the CooliR^{2}™ power semiconductor platform development was to address all the technical and cost challenges concurrently. This goal necessitated simultaneous development of the power semiconductor devices and the packaging concept. This unique approach allowed for achieving ultimate synergy between optimized power semiconductor devices enabling the packaging concept which maximizes their performance.

To meet these goals new IGBT (CooliRIGBT™) and new diode (CooliRDIODE™) were developed and optimized for use in automotive inverters. Emphasis was put on low power losses, increased current density, higher breakdown voltage, improved robustness and compatibility with wirebond-less interconnection techniques and dual-sided cooling. A fast, low saturation voltage, trench IGBT and a fast, soft recovery diode were developed. The super-thin die of both devices has a blocking voltage of 680V and solderable metals (SFM) on the front and back sides. Maximum junction temperature of 175^{o}C helps increasing the power density and maximizes the utilization of the device. The 25^{o}C increase in maximum junction temperature addresses the expected 15^{o}C increase of coolant temperature and provides additional 10^{o}C margin for increased reliability, higher peak power or higher power density. The devices rated breakdown voltage is 680V down to -40^{o}C and is exceeding 700V at higher junction temperatures. The higher breakdown voltage provides the needed robustness and allows for better utilization of the devices' fast switching characteristics. It makes them more tolerant to the voltage overshoots generated by stray inductances of the inverter power circuit. This is especially important during turn-off following overloads or short circuit events.


a) Turn-on

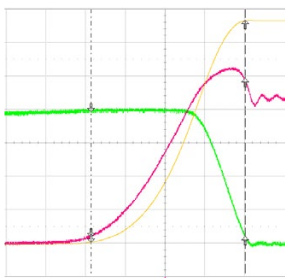

b) Turn-off

Figure 1: Turn-on and turn-off waveforms of CooliRIGBT™ with free-wheeling CooliRDIODE^{TM} (Vdc = 400V, Ic = 400A, 100ns/div)

Further increase of robustness is provided by the 6us short circuit rating of the CooliRIGBT™. The devices were optimized for switching frequencies up to 20 kHz thus are very efficient at the typical 10 kHz automotive inverter switching frequencies.

The CooliRDIODE™ can be further optimized with low reverse recovery losses for motor driving inverters or low forward voltage drop for generator applications.
The SFM allows for using wirebond-less packaging techniques and leads to lower interconnection resistance and inductance, and enables dual-sided cooling.

3. Optimizing power semiconductor packaging technology

The goals of CooliR^2™ packaging platform development are listed in Table 2. The objective was to address all of the technical challenges simultaneously. In order to maximize the utilization of the semiconductors it was necessary to reduce the interconnection resistance and inductance as well as improve heat removal. It became apparent that the wirebonding technology used in conventional power modules is one of the major limiting factors. It reduces reliability and makes removal of heat from the die possible on one side only. Another factor taken into consideration was manufacturing yield improvement. The major problems are: handling of the super-thin die and low yield on power module manufacturing level due to difficulty in testing of the die at high power level.

The development effort resulted in a totally new packaging concept – an intermediate package called CooliR^{2}DIE^{TM} – bridging the gap between discrete devices and power modules. The IGBT and Diode dice have been “pre-packaged” and “pre-tested” in order to address the previously mentioned challenges.

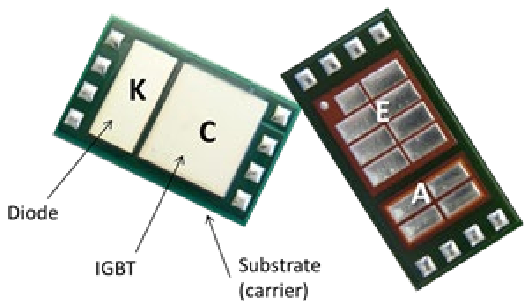


Figure 1: CooliR^{2}DIE^{TM} – a ”very large die discrete SMT component”

CooliR^{2}DIE™ is a co-pack power switch consisting of an IGBT die and a diode die mounted on a substrate. The very compact assembly rated 680V and 300A measures just 29 mm x 13 mm x 1 mm.

The technology is compatible with various substrate materials (e.g. DBC) and die attach techniques. CooliR^{2}DIE^{TM} can be treated as a surface mounted component – a “building block” – and can be used to build power modules or power conversion circuits without power modules in a fashion similar to using discrete power devices.

3.1 Providing circuit topology and power rating flexibility

The core element of the ColiR^2™ packaging platform is the CooliR^{2}DIE™ package. It is the building block enabling easy implementation of various power conversion circuits or modules. As can be seen in Figure 3 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. Custom configuration of various power conversion topologies is greatly simplified by the availability of both versions.

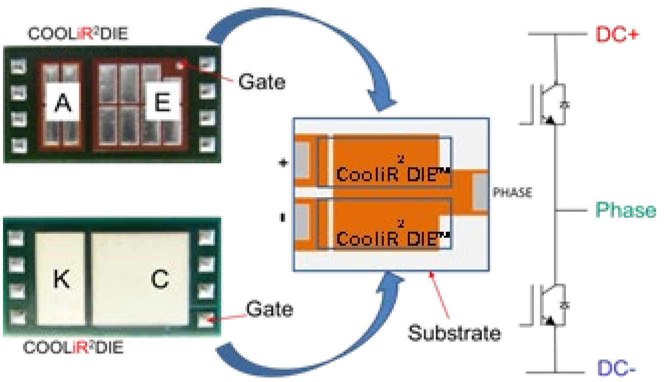


Figure 4: Example of half-bridge, Boost or Buck topologies implementation

Complete half-bridge power module implemented with CooliR^{2}DIE™ becomes a CooliR^{2}Bridge™.

Increasing power rating can be achieved by paralleling of the CooliR^{2}DIE devices. Devices with different die sizes can also be manufactured.

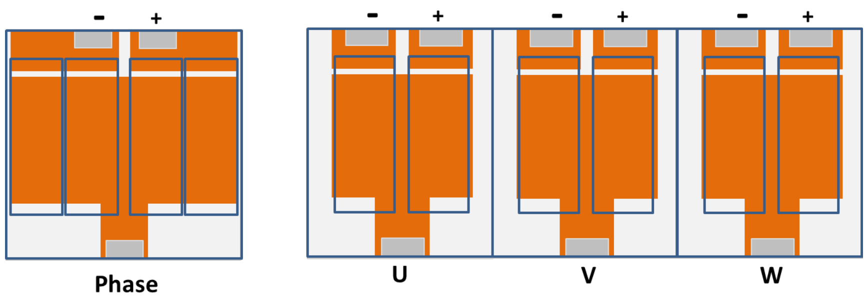


Figure 5: Half-Bridge with double current rating and Three-Phase-Bridge examples

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, protected by a gel-filled housing similar to that used by traditional power modules or different encapsulation techniques.

CooliR^{2TM} platform provides multiple packaging benefits including the possibility to create mechatronics assemblies (e.g. integrated motor-inverter assembly).

3.2 Improving thermal management

The main challenges facing the EV and HEV power electronics come from the higher power density and increased coolant temperature requirements. In addition to reduction of power losses, finding a better method of removing heat from semiconductor die is essential. With the size of power electronics shrinking, the area

available for heat transfer shrinks as well. Incremental improvements of thermal resistance through selection of different substrate or thermal interface materials, improvement of heatsink design are possible but provide only limited gains and increase cost. However, taking advantage of both sides of the die to remove heat provides immediate potential to double the heat transfer. Ultimately, with the dual-sided cooling, less expensive substrate and thermal interface materials could be used and still achieve higher power density.

The semiconductor die in the CooliR^2™ packaging platform, is sandwiched between two substrates so the heat removal is possible through both sides of the package.

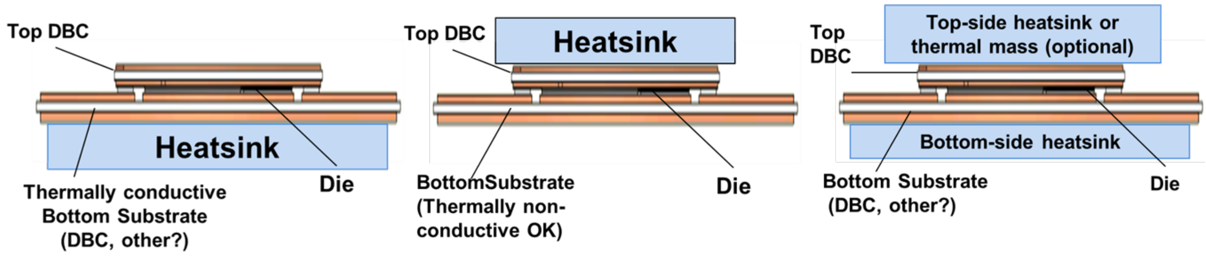


Figure 6: Various cooling options for CooliR^{2}DIE™

As shown in Figure 6, it is possible to thermally connect the CooliR^{2}DIE™ or CooliR^2™ module to the heatsink using just the thermal grease or other thermal interface material (TIM). It is also possible to solder, sinter or use different methods of attaching the CooliR^{2}DIE™ or CooliR^2™ module to the heatsink or a base plate. Different methods of construction result in different thermal resistances from junction to coolant as shown in Table 3.

Table 3: Thermal resistance junction to coolant for different construction methods

			Solder die attach			Sintered die attach		
			w/o Base Plate	with Base Plate	with DLC Base Plate	w/o Base Plate	with Base Plate	with DLC Base Plate
Layer	Z [mm]	K [W/mK]	Rth [K/W]	Rth [K/W]	Rth [K/W]	Rth [K/W]	Rth [K/W]	Rth [K/W]
IGBT die solder	0.1	25	0.040	0.040	0.040			
IGBT die sintered	0.05	250				0.002	0.002	0.002
DBC Cu	0.3	380	0.007	0.007	0.007	0.007	0.007	0.007
DBC Al2O3	0.38	24	0.141	0.141	0.141	0.141	0.141	0.141
DBC Cu	0.3	380	0.007	0.007	0.007	0.007	0.007	0.007
TIM (thermal grease)	0.05	3	0.133			0.133		
Solder	0.15	25		0.047	0.047		0.047	0.047
Baseplate (Copper)	3	380		0.038			0.038	
TIM (thermal grease)	0.1	3		0.109			0.109	
Sink-->coolant			0.199	0.122	0.189	0.199	0.122	0.189
Rth j-coolant [^{o}C*cm^2/W]			**0.527**	**0.510**	**0.431**	**0.489**	**0.472**	**0.393**

Note: DLC Base Plate – Direct Liquid Cooled Base Plate

The best performance is achieved with IGBT die sintered to the CooliR^{2}Bridge™ substrate which is attached to a direct liquid cooled base plate.

Different types of substrates can also be used in the CooliR^{2TM} platform. Some examples are presented in Table 4.

Table 4: CooliR^{2}DIE^{TM} Rth j-c with different substrates (per 1cm^2)

Substrate type	Insulator thickness [mm]	Copper thickness [mm]	$R_{th\ j\text{-}c}$ [°C*cm^2/W]
Alumina	0.38	0.2	0.1822
	0.38	0.3	0.1764
	0.25	0.2	0.1382
AlN	0.38	0.2	0.1033

The thermal resistance from junction to case depends more on the type and thickness of the ceramic layer than the thickness of the copper layers. However, the copper layers thickness plays an important role in lowering the resistance of the interconnections and improving temperature equalization across the semiconductor die.

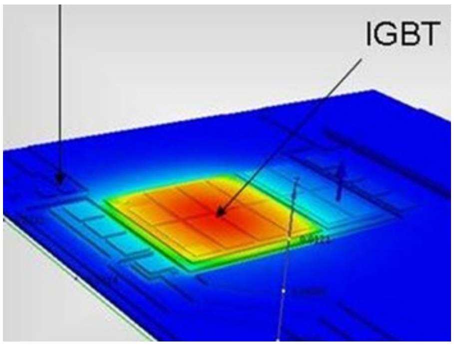


Figure 7. IGBT die temperature distribution.

As can be seen in Figure 7 the die temperature is very uniform. Only the edges of the die are slightly cooler mainly due to the lateral heat spreading effect in the copper layers of the substrate and in the heatsink.

3.2 Dual-sided cooling – thermal management breakthrough

The real breakthrough of the CooliR^{2TM} platform in improving of the thermal management comes from implementing the dual-sided cooling concept.
Theoretically, the dual-sided cooling can reduce the junction-case thermal resistance by half.

$$Rth\,j-c\,DUAL-SIDED = \frac{1}{\frac{1}{Rth\,j-c\,BOTTOM}+\frac{1}{Rth\,j-c\,TOP}} \quad (1)$$

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

$$\boldsymbol{Rth\,j-c\,DUAL-SIDED = \frac{Rth\,j-c\,BOTTOM}{2}} \tag{2}$$

In a practical implementation it is not always possible to achieve identical thermal resistance on both sides of the module due to 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 Rth junction-coolant is still only approx. 61% of the bottom-side Rth j-c.

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

$$\boldsymbol{\approx 0.61*Rth\,j-c\,BOTTOM} \tag{3}$$

Even under the assumption that the heat transfer through the top surface is 40% lower than that through the bottom surface, the overall reduction of Rth junction-coolant allows for approx. 50% increase in the current rating of the power module. This improvement alone is already close to meeting the expected power density improvement of 54% as outlined in Table 1. Taking into account the maximum rated junction temperature increase of the CooliR™ semiconductor devices by 25 ^{o}C, there is an additional power density increase potential of approx. 19% for a combined increase of approx. 80%.

It is worth noting that these power density improvements are possible using conservative assumptions and before taking into account the possible power module size reduction.

4. Improving reliability

Reliability expectations of EV and HEV power electronics are extremely high and exceed by far the reliability standards for industrial applications. Most of the power modules used in EV and HEV inverters originated from industrial designs and are being gradually improved in order to meet the requirements of modern automotive applications. The CooliR^{2TM} technology is breaking with the tradition and offers a quantum-leap in reliability by eliminating the primary failure mode – wirebonding – instead of making just incremental reliability improvements. This is in addition to other reliability enhancements inherent to the technology. The results and the comparison with reliability of the state-of-the-art commercially available power module technologies are shown in Figure 8.

CooliR^{2}Bridge™ 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. The improvement in power cycling capability is the result of elimination of wirebonds. The technology is expected to reach even higher number of cycles in the next trial.

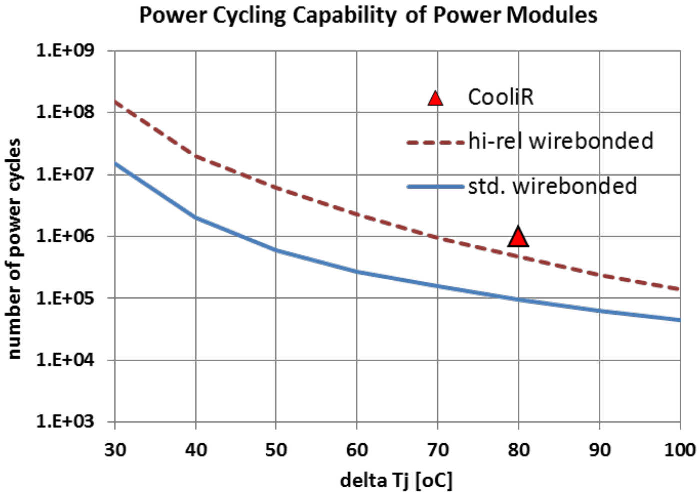


Figure 8. Power Cycling capability of power modules

5. Improving electrical performance

The main improvements to electrical performance of power circuits built using the CooliR^{2}DIE™ or the CooliR^{2}Bridge™ come from reduction of interconnection resistance and reduction of stray inductance.

5.1 Lower interconnection resistance

The wirebonds have been replaced with copper planes contacting the entire die surface. This not only reduced the resistance but also improved current distribution in the die. For comparison, it would take approx. 20 wires with diameter of 20 mil to achieve the low resistance of 12 mm wide and 0.3 mm thick copper plane. It is not practically possible to place such a large number of bond wires in the same space.
The actual Die-Free-Package-Resistance of the 300A rated CooliR^{2}DIE™ is < 100 microOhms. 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. This small difference in resistance results in 0.15V lower voltage drop at 300A and in 45W reduction of conduction losses per phase. This reduces the overall inverter losses by approx. 5%.

5.1 Lower parasitic inductance

Reduction of stray inductance is of paramount importance with modern fast switching semiconductor devices. Fast switching speeds are desired in order to decrease

switching losses but at the same time high current slew rates (dI/dt) combined with high stray inductance cause large voltage overshoots. Very often, with conventional power modules, the switching speeds must be deliberately reduced to keep the voltage overshoots below the maximum breakdown voltage of the devices. This leads to underutilization of the semiconductor devices due to packaging limitations.

The CooliR^{2TM} platform concept's goal was to maximize the utilization of the semiconductors by taking advantage of the packaging technology capabilities. Firstly, the semiconductor devices were developed with 680V voltage breakdown rating instead of the traditional 600V typical for the industrial and earlier traction applications. Secondly, the package stray inductance has been reduced by eliminating wirebonds and creating strip-line type of structure to reduce the voltage overshoots and enable faster switching speeds. It is estimated that the inductance of CooliR^{2}DIE™ is approx. 2-3 times lower than the inductance of similar wirebonded switch. The inductance of the 480A rated CooliR^{2}Bridge™ measured from DC+ to DC- terminals is approx. 12 nH. Most of the inductance is introduced by the power terminals and the main substrate layout and can be minimized further.

6. Reducing size and weight

The benefits of the CooliR^{2TM} technology are not only limited to the improvements in thermal management, reliability and electrical performance. Power modules developed with CooliR^{2}DIE™ concept demonstrate the potential to significantly reduce the size and weight of power modules and power conversion systems. Table 5 shows the results achieved with CooliR^{2TM} technology in comparison with the state-of-of-the-art commercially available modules.

Table 5: Size and weight comparison

Module type	Ratings [V/A]	Config	Volume [liter]	Weight [gram]	Volume Ratio	Weight Ratio	Current Density
Wirebonded and gel filled - 1	650V/400A	3 phase	0.136	485	1	1	1
Wirebonded and gel filled – 2 (w/pin-fin base plate)	650V/800A	3 phase	0.421	1250	3.1	2.58	0.65
Transfer molded wirebondless - M	600V/300A	1 phase	0.027 (0.081)*	100 (300)*	0.60*	0.62*	1.25*
CooliR^{2}Bridge™ A	650V/300A	1 phase	0.020 (0.060)*	35 (105)*	0.44*	0.22*	1.70*
CooliR^{2}Bridge™ B	680V/480A	1 phase	0.026 (0.078)*	75 (225)*	0.57*	0.46*	2.10*

*) for three 1 phase modules

7. Conclusions

The paper demonstrated that achieving the USCAR targets presented in Table 1 is not only possible but the targets can even be exceeded.

The current density of power modules built with the CooliR^{2}DIE™ has been improved by approx. 50 % thanks to the dual-sided cooling capability. The additional 20% improvement comes from increasing the maximum junction temperature by 25^{o}C for a combined improvement of approx. 80%. After taking into account the anticipated coolant temperature increase of 15^{o}C, a 62% increase of current rating can still be achieved. This translates into 62% power density increase without even reducing the size of the power converter.

In addition, the CooliR^{2TM} platform allows for approx. 50% reduction of the size and similar reduction of the weight of the power modules. Applying the CooliR^{2}DIE™ concept to mechatronics has the potential to increase the power density further.

The power density increase and the size and weight reduction come in addition to significant electrical performance and an order of magnitude reliability improvement as compared with the traditional wirebonded, gel-filled power module technology.

Using the CooliR^{2TM} technology also leads to cost reduction of the power electronics systems thanks to offering a standard, pre-tested building block which simplifies manufacturing of power modules and increases yield but also enables power circuits' construction without using power modules.

The CooliR^{2TM} power semiconductor platform for EV and HEV inverters shows a realistic path to achieving and exceeding the USCAR performance targets and the industry expectations for reliability of automotive power electronics while offering an innovative concept to break-away from the traditional power module approach.

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