CooliR2™ High Power Semiconductor Platform

HEV and EV progress and success have been enabled

The mass adoption of Electric Vehicles (EV) and Hybrid Electric Vehicles (HEV) depends on achieving cost, size and weight reduction and increased reliability of electric power train systems.

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Further progress towards achieving the performance and cost goals of (H)EV traction converters is not possible by making incremental improvements to existing technologies. It is only possible by breaking with tradition and taking an innovative, comprehensive approach including development of dedicated semiconductor devices and packaging concepts. Innovative solutions are needed to meet these challenges.

	R&D Status	Targets	
	2010[a]	2015[b]	2020[b]
Cost, $/kW	<7.9	<5.0	<3.3
Cost, kW/$	>0.127	>0.200	>0.303
Specific power, kW/kg	>10.8	>12.0	>14.1
Power density, kW/L	>8.7	>12.0	>13.4

a. Based on a maximum coolant temperature of 90°C
b. Based on a maximum coolant temperature of 105°C

Table1: Status and Approximate Technical Targets for power Electronics

International Rectifier embarked on this road by developing a complete, innovative, automotive high power semiconductor platform called CooliR™ starting with the development of large IGBTs (CooliRIGBT™) and matching diodes (CooliRDiode™) optimized for application in automotive traction inverters. In order to enable full utilization of these devices, IR is also developing complementary, innovative high power packaging platform including half-bridge modules (CooliR2Bridge™) with dual-sided cooling capability.

Power Semiconductor Switches and Power Module challenges for HEV/EV traction inverter applications

IGBT Diode requirements
Typical automotive traction inverter continuous operation currents are in the 100 Arms to 450 Arms range. The short time (5 to 30 seconds) operation may demand as much as two to three times higher currents. In order to meet these requirements a "large" IGBT and Diode die must be developed. This helps to reduce the number of dice per switch that need to be paralleled and minimizes the packaging complexity.

Very high switch currents are associated with high power losses that create another difficulty – heat removal from the semiconductor die and the module. Minimizing the power losses in semiconductor switches is of great importance.

The requirements for increased power density and very high, short time overload currents demand semiconductor switches capable of operating reliably at junction temperatures exceeding the industrial standard of 150oC.

In order to minimize the conduction losses the voltage drop across the switch during its on-state must be reduced. Consequently, the interconnection resistance contribution to the power losses becomes more significant and needs to be addressed on the device as well as the package levels.

Switching losses are the second most important contributor to the power converter losses. Fast switching devices are required. The challenge is to achieve low switching losses without generating excessive voltage overshoots, ringing and exceeding the EMI limits.

Power Module requirements
Low parasitic inductance of the interconnections is critical to enable fast switching while keeping the voltage overshoots in a safe range.

Low interconnections resistance is critical to minimizing the overall power losses.

The requirement to increase the overall power density of power converters demands very effective thermal management. Power switch packages must shrink in size and at the same time be capable of removing increased amounts of heat.

The conventional packaging and interconnection methods have reached their reliability limits and are incapable of handling the stresses created by modern semiconductor devices operating at temperatures higher than the traditional maximum junction temperature (Tj) of 150oC. A novel packaging approach is needed.

Advantages of the CooliRIGBT™ and CooliRDiode™ devices optimized for EV/HEV traction inverter applications

Electrical performance and discussion

CooliRIGBT™ Static Performance

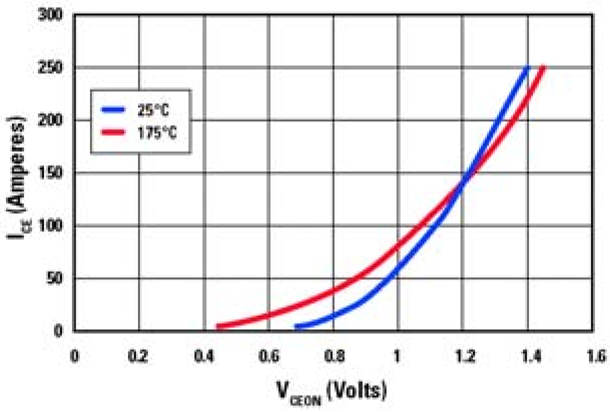
I-V Characteristics
Low conduction losses have been achieved by combination of low Vceon of the IGBT and low interconnection resistance.

Large trench IGBT dice of 12 mm x 12 mm with solderable metal on both front and back sides (SFM) of the 70 µm thin wafers were successfully developed with a current carrying capability of 300A and a blocking voltage above 700V. Figure 1a shows a photograph of the high power IGBT die. The forward conduction characteristics are shown in Figure 1b.

(a) Top view of the IGBT Die

(b) IGBT forward conduction characteristics

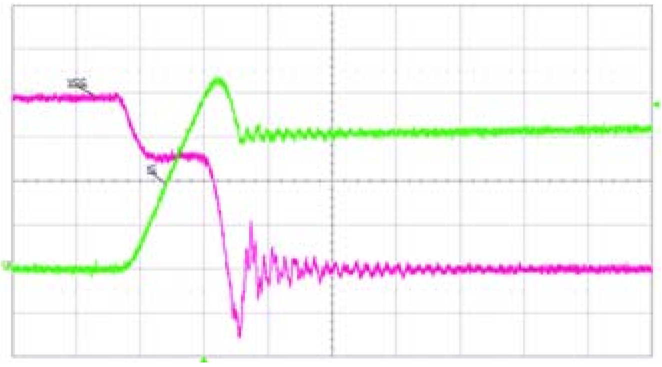
Figure 1 (a): Top view of the IGBT die with SFM and (b). Forward conduction characteristics of IGBT with SFM



Breakdown Voltage
Another challenge posed by automotive power converters is the increasing demand for higher breakdown voltages of the semiconductor power switches beyond the industrial standard of 600V. The need is partially dictated by the increasing battery voltages in order to satisfy higher power demands and also by the wide battery voltage variations between fully charged and discharged state. The most important factor, however, is voltage overshoot during fast switching with high dI/dt. Current slopes exceeding 5,000A/us are not uncommon with modern fast switching devices. Such a high dI/dt in conjunction with the power circuit stray inductance on the order of few tens of nH generates unacceptably high voltage overshoots. International Rectifier's newly developed IGBTs exhibit breakdown voltages far above the rated 680V. The rated voltage is guaranteed all the way down to -40oC.

CooliRIGBT™ Dynamic Performance
The switching performance of IR automotive IGBTs has been optimized for the application. The traction inverter type IGBT's dynamic switching was measured at Vcc=400V and Ic=300A. The current and voltage waveforms are shown in Figure 2. The turn-off speed of the IGBTs is in the range of 200-215 ns at 25°C. The fall-time (t_{fall}) does not vary much with temperature because no electron irradiation is used for lifetime control. The leakage current of the thin IGBTs remains low even at elevated temperatures enabling the operation at Tjmax of 175°C. The leakage current of the 300A IGBT does not exceed 4.5 mA at 600Vat Tj=175°C in contrast to the PT-IGBTs whose Tjmax is limited to 150°C due to a rapid increase in the leakage current with increasing temperature.

Two COOLiRIGBTs™ were assembled into a half bridge module called COOLiR²BRIDGE™. The output characteristics of the IGBTs are shown in Figure 3. The module exhibits a low Vceon of 1.6V at 25°C. The temperature coefficient of COOLiRIGBTTM is positive – the Vceon increases with temperature. This makes the COOLiRIGBTT ideal for paralleling to meet various output power requirements in HEV and EV systems.



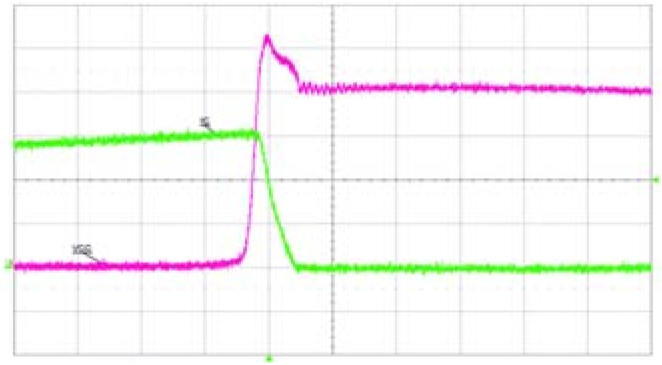


Figure 2: Turn-on and turn-off waveforms of CooliRIGBT™. (Vcc=400V, Ice=300A, 25?C, Turn-on – 200 ns/div, Turn-off – 500 ns/div, tfall = ~214 ns, Eoff = ~45 mJ)

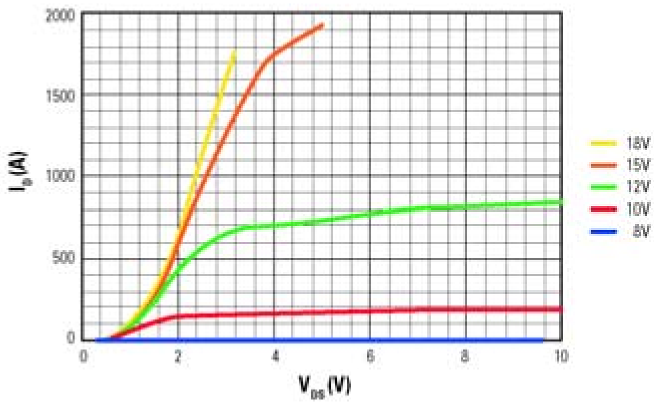


Figure 3: Typical output characteristics of COOLiRIGBTs™ in the COOLiR²BRIDGE™ module

The turn-on waveforms of COOLiRIGBT™ are oscillation-free. The turn-on and turn-off power dissipation of IGBTs were measured at 25°C and 150°C. The turn-on power loss of COOLiRIGBT™ shows a very small increase of only 3.8% when temperature is changed from 25°C to 150°C, This suggests the reverse recovery of the new COOLiRDiodeTM is not very sensitive to the operating temperature of the inverter.

The turn-off of the COOLiRIGBT™ is very fast with a t_{fall} time of 70 ns at 25°C and 90 ns at 150°C. The turn-off power dissipation of COOLiRIGBT™ is increased by 22% at 150°C. Table 2 summarizes the average switching characteristics of IGBTs and diodes in the COOLiR²BRIDGE™ module.

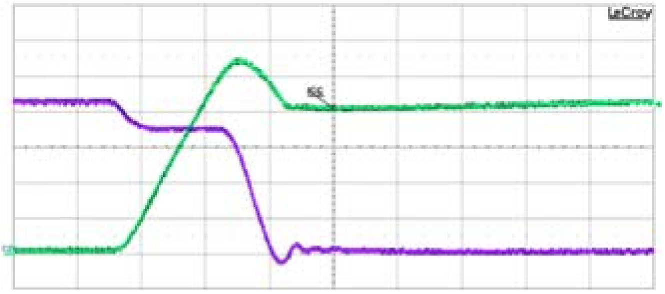


Figure 4a: The turn-on waveforms of COOLiRIGBTTM at 25°C. Vcc=240V; Ic=270A; Rg=6.8Wm, 200 ns/div.

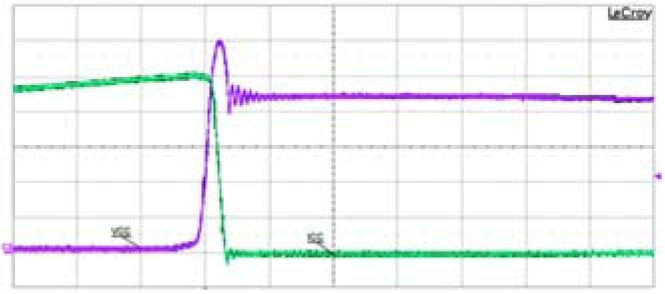


Figure 4b: The turn-off waveforms of COOLiRIGBTTM at 25°C. Vcc=240V; Ic=270A; Rg=6.8Wm, 500 ns/div.

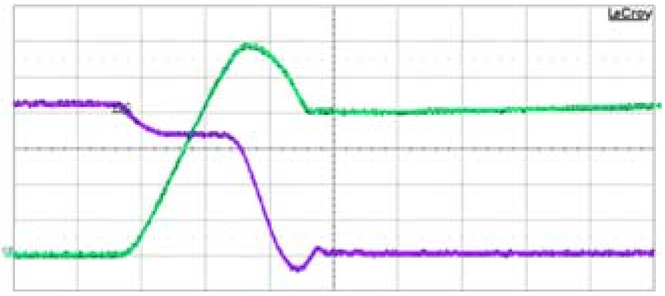


Figure 5a: The turn-on waveforms of COOLiRIGBTTM at 150°C. Vcc=240V; Ic=270A; Rg=6.8Wm, 200 ns/div.

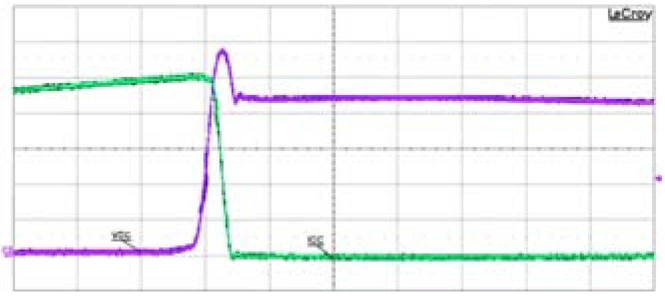


Figure 5b: The turn-off waveforms of COOLiRIGBTTM at 150°C. Vcc=240V; Ic=270A; Rg=6.8Wm, 500 ns/div.

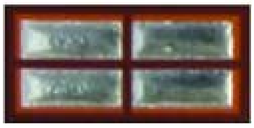
	Eon, μJ	Eoff, μJ	tfall, ns
25C	15730	7860	70
150C	16328	9620	90

Table 2: Summary of switching characteristics of CooliR2IGBT™ Test conditions: VCC=240V; Ic=270A; Rg=6.8Ωμ.

CooliRDiode™ Static Performance

Optimal performance of IGBT modules in an HEV/EV power train requires compatible diodes with fast speed and soft recovery to minimize the turn-on loss of the IGBT and to reduce the voltage overshoot and oscillation which are commonly observed in many power conversion applications. In this paper, we report 300A, 700V diodes

with solderable metals on both front and back sides of the 70 µm thin wafers. A top view of the diode chip and its static characteristics are shown in Figure 6a and 6b, respectively.



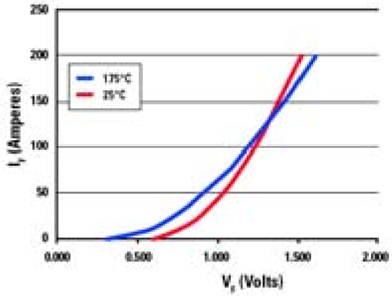


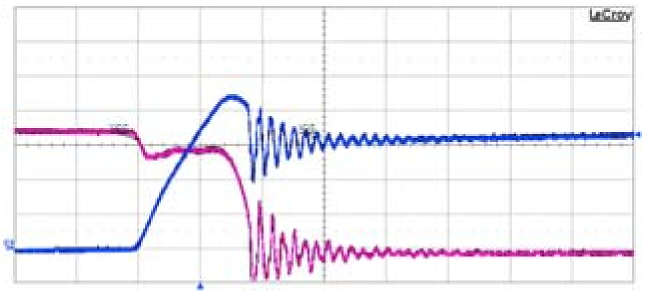
Figure 6a: Top view of the diode

Figure 6b: Forward conduction characteristics of the diode

CooliRDiode™ Dynamic Performance

The turn-on power dissipation of IGBTs and Electro-Magnetic Interference (EMI) noise are strongly dependent upon the reverse recovery characteristics of the FWD's. IR has successfully developed soft recovery diodes which exhibit oscillation-free feature while maintaining the low turn-on power dissipation for IGBTs. Figure 7 compares the turn-on waveforms of IGBTs using previous generation fast recovery diodes and the newly developed diodes without oscillation.

a)



b)

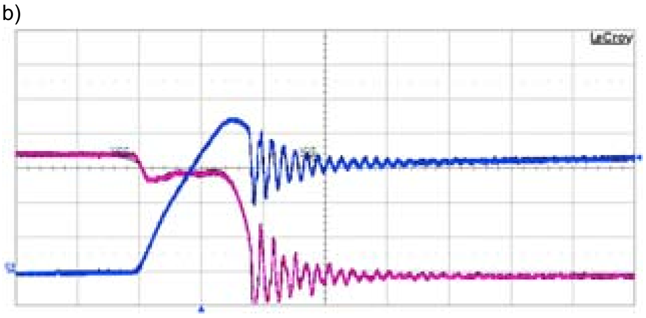


Figure 7: Comparison of FWDs with (a) ringing and (b) oscillation-free

The reverse recovery waveforms of the COOLiRDiode™ are shown in Figure 8. The diode exhibits low reverse recovery current without oscillation. The clean waveforms obtained from COOLiR²BRIDGE™ module are also a proof that the modules implemented with COOLiRDiode™ and COOLiRIGBT™ have very low parasitics compared with standard IGBT modules assembled by a wire bond approach.

Power module concept and development

A modern power semiconductor packaging concept for HEV/EV traction inverter applications must be characterized by high power density, effective heat removal capability, low interconnection resistance, low parasitic inductance, extended operating temperature range and high reliability.

Innovative packaging platform for HEV and EV traction inverters
Building Block approach

Traditional semiconductor packaging concepts are based on three packaging levels: bare die, discrete package or power module. IR's new approach introduces an intermediate semiconductor device package - CooliR²DIE™.

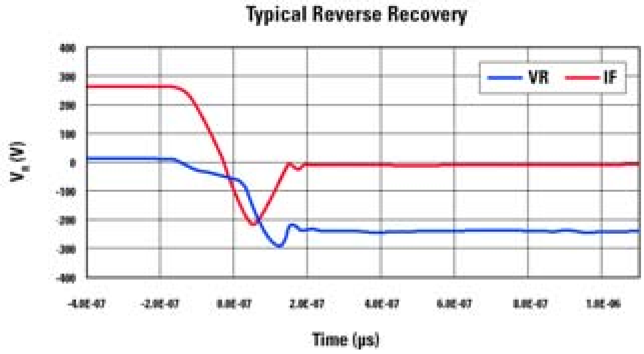


Figure 8:Typical reverse recovery waveforms of the FWD diodes in the COOLiR2BRIDGE™ module.

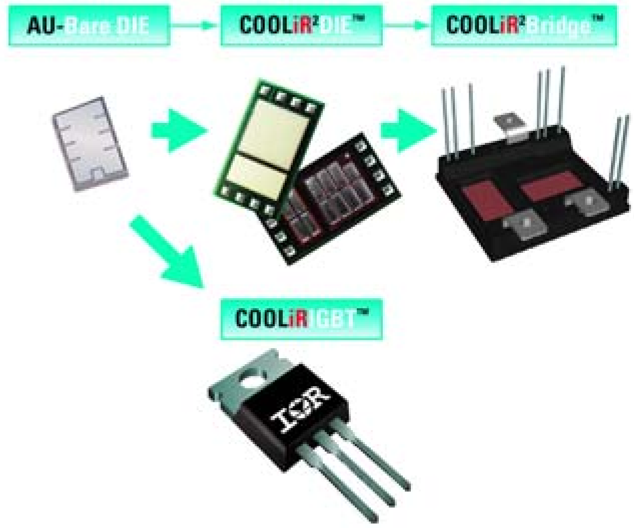


Figure 9: CooliR™ and CooliR2™ - International Rectifier's Automotive High Power Platform for HEV and EV applications

CooliR²DIE™

The foundation of the innovative CoolIR²™ platform is the "building block" approach. While bare-die is the fundamental building element of all semiconductor devices, CooliR²DIE™ is the new "building block" of all high power modules.

CooliR²DIE™ is an "intermediate" package comprising IGBT and Diode pre-packaged on a DBC substrate forming basic power switch. Both the IGBT and the Diode are SFM type (solderable on both sides) that eliminate the need for wirebonding and allows the CooliR²DIE™ to be used as a surface mounted component.

COOLiR²DIE™ has the ratings of 680V and 300A, a small footprint of 29 mm x 13 mm and is only approx. 1 mm thick. This is the most compact IGBT package reported today.

CooliR²DIE™ is a basic power switch that can be used in many different configurations of power modules including inverter half-bridges, three-phase bridges, buck, boost and H-bridges for DC-DC converter applications.

CooliR²DIE™ eliminates the need to handle ultra-thin die during module manufacturing and eliminates the wirebonding process thus greatly reducing cost and simplifying the manufacturing process.

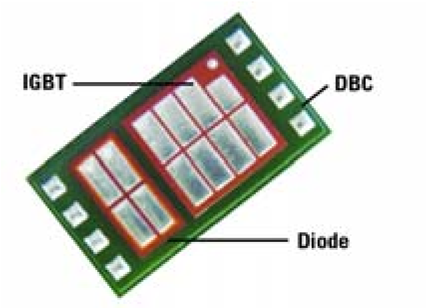


Figure 10a: Top view of CooliR²DIE™

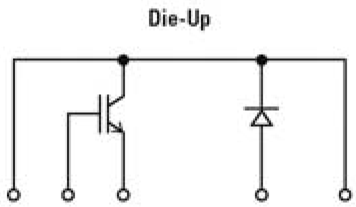


Figure 10b: Electrical schematic of CooliR²DIE™

Eliminating weak links – wirebond-less package
Reducing the interconnections resistance – lowering conduction losses

One of the drawbacks of traditional wirebonds is their resistance. Only limited number of wires can be placed on the surface of a power device. Some improvement is possible by using copper wires, ribbon or copper-clip.

A reduction of 390 mV in Vceon at Ice=300A was achieved by IR with the Cu-clip IGBTs as compared with the IGBTs packaged with wire-bonds, as shown in Figure 11.

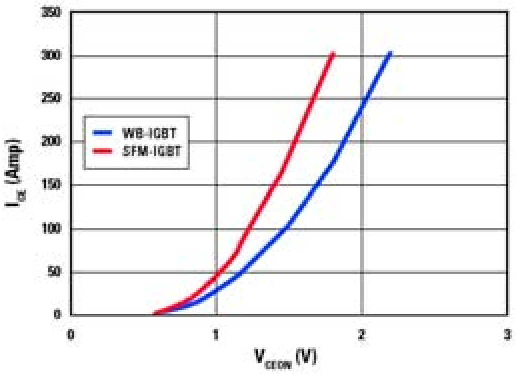


Figure 11: I-V curves for wirebonded (WB-IGBT) and Cu-clip inter-connected (SFM-IGBT) devices.

Similar improvement is achieved in the COOLiR2DIETM package where the interconnections are implemented with the copper layer on the DBC. The additional metallization on die used in the COOLiR2DIETM reduces the resistance further.

CooliR²Bridge™	< 0.5 m	no wirebonds
Module 1	1.0 m	wirebonds
Module 2	0.8 m (per switch)	wirebonds

Table 3: Package resistance comparison of CooliR²Bridge™ module in comparison with commercially available HEV/EV type modules

Reducing stray inductance – improving switching performance
The inductance of wirebonds is a significant contributor to the overall stray inductance of a power module. Due to the mutual coupling effect, multiple wirebonds reduce the inductance less than proportionally to the number of wires. As can be seen in Table 4, the inductance of copper plane is approximately two times lower than that of six bond wires.

bondwires	inductance [nH]
1	10.4
2	7.4
3	6.1
4	5.2
5	4.7
6	4.2
via substrate	2.3

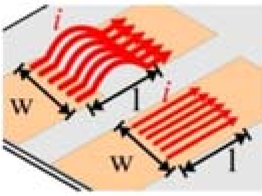


Table 4: Inductance of wirebonds vs. copper plane

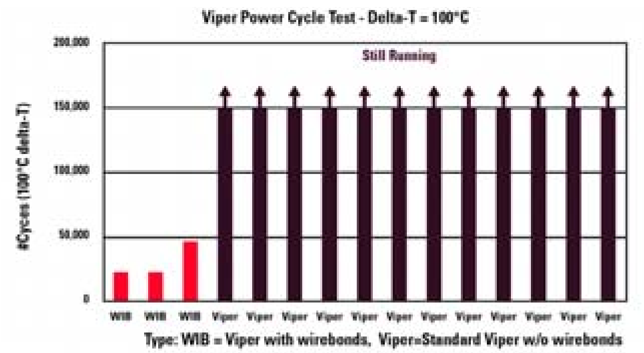
Module	Inductance
CooliR^{2}Bridge™	< 15 nH (+ terminal to – terminal)
Module 1	30 nH (+ terminal to – terminal)
Module 2	14 nH (per switch)

Table 5: CooliR²Bridge™ module inductance compared with commercially available HEV/EV type modules

Improving Reliability - eliminating wirebond failures
Wirebonds are the primary cause of power module failures due to high temperature swings and constant thermal expansion and contraction of the wirebonds during operation. The bond wire cracking and lift-off is the most critical factor limiting the life of power modules. Various innovations such as copper wires, aluminum-clad copper wires, ribbon, etc. were introduced to extend the power cycling life expectancy of power modules. The improvements are often insufficient to meet the reliability requirements of demanding automotive applications.

The ultimate solution is to eliminate the wirebonds entirely.

Figure 12 shows the results of power cycling test performed on IGBT and Diode die wirebonded in one case and installed in a wirebond-less package in the other case with ΔTj =100°C. The cycling capability of the wirebond-less package is at least three times higher.



Source: Novel Component Packaging for High Current Applications Using Power Semiconductor Devices - MIT Paris 2009
Figure 12: Power cycling capabilities of wirebonded and wirebond-less interconnections

Cool, Cooler, CooliR²™ - improving heat transfer
The thin IGBTs with dual solderable metal on top and bottom of the die enable double-sided cooling packages.

The junction-to-case thermal resistance of the COOLiR²DIE™ is equivalent to the thermal resistance of the traditional, one-sided cooling $R_{\theta jc\_Bottom}$ in parallel with the top-side $R_{\theta jc\_Top}$.

$$\frac{1}{R_{\theta jc\_CooliR^2DIE(TM)}} = \frac{1}{R_{\theta jc\_BOTTOM}} + \frac{1}{R_{\theta jc\_TOP}} \quad (1)$$

Theoretically, the heat transfer with dual-sided cooling can be doubled and the thermal resistance of junction to coolant reduced by 50%. Taking practical limitations into account, a 50% increase in module current rating can be easily achieved.

CooliR²Module™
Two units of COOLiR²DIE™ were assembled to make a half bridge module called COOLiR²BRIDGE™. The modules are capable of blocking 680V and conducting 300A in one of the smallest packages in the industry measuring only 50 mm x 45 mm x 7 mm and are setting a tough to meet standard for power density.

Figure13: Dual-side cooled COOLiR²BRIDGE™ modules.

Higher current rating modules have also been developed by paralleling multiple COOLiR²DIE™. One of them is rated 680V and 480A.

Summary
COOLiRIGBTs™ and COOLiRDiodes™ with performance optimized for automotive inverters have been successfully developed. Dual solderable metal on top and bottom of the die, offer a wirebond-less assembly option with increased electrical and thermal performance, enhanced reliability and lower manufacturing costs [3, 4].

The wirebond-less package building block called COOLiR²Die™ allows for double sided cooling, improves the reliability and further improves the performance of the COOLiRIGBTs™ and COOLiRDiodes™.

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