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Comprehensive Review and State of Development of Double-Sided Cooled Package Technology for Automotive Power Modules

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ABSTRACT Power modules are core components of inverters in electric vehicles and their packaging technology has a critical impact on system performance and reliability. Conventional single sided cooled power modules have been one of the most common package structures for automotive applications. However, this design limits the performance of IGBT and future SiC power module due to parasitic inductance and heat dissipation issues. Power module packaging technologies have been experiencing extensive changes as the performance expectations of the power semiconductor has increased. Over the past few decades, methods of double-sided cooling have attracted increased interest to enhance the power density of the inverter and effectively reduce their cost. This paper presents a comprehensive review of double-sided cooled packaging technology for automotive power modules. Technical details and innovative features of state-of-the-art automotive power modules from research institutes and major industry manufacturers are reviewed and their path into commercial vehicles is evaluated.

INDEX TERMS Double-sided cooled, inverters, packaging, power density, power electronics cooling, power electronics thermal management, power modules, wide bandgap packaging.

I. INTRODUCTION

There has been a significant global increase of electric vehicle offerings and sales as a result of both consumer demand and government regulations for more environmentally friendly automotive transportation solutions, including hybrid-electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), extended-range electric vehicle (E-REVs) and pure battery electric vehicles (BEVs). Currently, the major limiting factors for EVs (electric vehicles) are range anxiety, cost, and performance. Improvements are need in many of the major components of EVs, including the rechargeable energy storage system (battery), electric motors, and power electronics. An example of these components in General Motors Ultium propulsion system are shown in Fig. 1.

FIGURE 1. General Motors Ultium Propulsion System Layout.

One of the key technical parameters to quantify the integration and packaging efficacy of the power electronics is the volumetric power density, as measured in kW/L. For BEV applications, the space constraints for the power electronics is driven by the large battery size within a given vehicle footprint to achieve acceptable driving range. In hybrid applications, the power electronics must be added into the underhood space alongside the conventional internal combustion engine. The

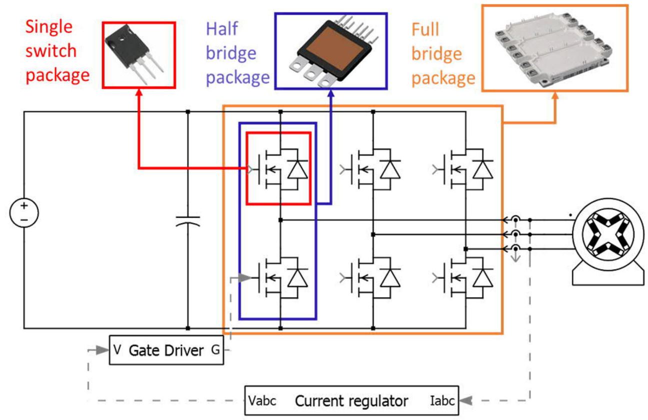


FIGURE 2. **Different packaging forms of power module.**

US Department of Energy's (DOE) power electronics density target for the year 2025 is 100 kW/L, up from 18kW/L in 2020 [1]. This would require replacing the current Si-based power semiconductor devices with wide band gap (WBG) based power semiconductor devices to significantly reduce the size while enabling operation at higher temperatures and frequencies. The DOE Electrical and Electronics Team from US DRIVE partnership also indicated the current cost of 100 kW power inverter is around $ 1000 (USD) with a nominal cost of $ 10 /kW and a target for 2025 of $ 2.7 /kW [1].

The core component in the inverter system is the power module, which contains multiple power semiconductor devices. The power modules dominate the system performance, reliability, size, weight, and cost. Right now the power modules account for 40-50% of the whole cost of the power inverter [1]. To meet the technical and cost targets for power inverters mentioned above, high-performance automotive-qualified power semiconductor devices and dense power module packaging are both required. Although the overall performance of the automotive module is determined by the semiconductor properties, the effective packaging is equally important for the performance of the power module. With the novel design concepts and advanced technologies in materials and processing, the power module packaging should enable operation of the newest semiconductor devices to their limits and ensure the power devices have superior output under the harsh environment in automotive applications.

Except discrete plastic-encapsulated packages that were used in earlier EVs like the Tesla Model S and Model X from 2012 [2], most of the power semiconductor devices are packaged in parallel in a multi-device module, as shown in Fig. 2. The protective case, lead frame, electrical interconnections, and electrically insulating ceramic substrates are also packaged with the semiconductor devices. The module packaging provides thermal management, mechanical support, electrical interconnection, and external connection interfaces. The thermal management requirements become more challenging to meet for the higher power applications as higher current levels escalate heat generation. Effective thermal management not only prevents immediate catastrophic failure, but also decreases failures caused by thermal fatigue and material degradation that is accelerated by high temperatures. The combined challenges of denser packaging and higher heat generation has made thermal management research and important topic both past and the future.

Unlike standardized components often found in low power electronic devices, the automotive power modules often varies from vehicle-to-vehicle [2]–[4]. This is due to the rapid growth of the market and evolving technology, and the widespread use of proprietary designs. In the early stage of EVs, especially when vehicle models were limited, the power module packaging was typically developed by Tier 1 suppliers and OEMs together for specific vehicle applications as the design of power module package was highly dependent on the integration within the inverter and electric drive sub-system. This approach led to fast adaptation of new semiconductors and evolution of the power module packaging between generations of the same vehicle model [5]. As the market grew, different modes of supply chains evolved for power modules, including (1) Tier 1 suppliers with capability from semiconductor wafer to power inverter system, like Hitachi [6], (2) Tier 1 suppliers that developed their own power module packing based on purchased semiconductors, like Viper from Delphi, (3) Tier 2 integrated device manufacturer (IDM) suppliers that developed their own packaging solution, like HybridPACK from Infineon, and (4) Tier 2 suppliers that supply power modules based on purchased semiconductors, like Danfoss.

Recently, power module packaging has been migrating from single-sided cooling to double-sided cooling [7]. Previous reviews covered the various aspects of power module packaging evolution [2]–[4], [8]–[21] and their materials [22]–[26]. The focus of this paper is on the history, current status, and emerging trends for double-sided cooled power module packaging for EV applications. The concept incubation and the various solutions evolved by industry and academia in past 20 years are classified and reviewed, including early explorations, maturation, and current commercialized technologies. By comparing these solutions, a technology evolution path is summarized. The impact of power module packaging on the power density of the power inverter is also studied.

II. THE NEED FOR DOUBLE-SIDED COOLING IN POWER MODULES

The typical structure of the conventional single sided cooled power module architecture is presented in Fig. 3. As previously described, the single sided cooled power module has a low ratio of active components to packaging structure [27]. This module structure also usually comes with relatively high parasitic power loop inductance ranging from 15 nH to 20 nH [24] and high thermal resistance (R_{th}) commonly ranging from 0.1-0.8 K/W [20]. Since semiconductor devices are typically operated at powers up to their thermal limit, improvements to R_{th} can directly enable reduced semiconductor volume, which can have a compounding effect on overall

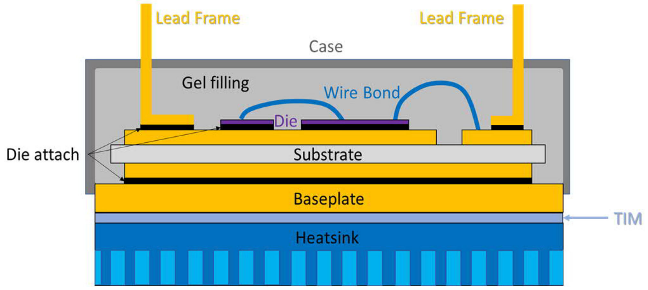


FIGURE 3. **The typical structure of the conventional single sided cooled power module architecture.**

packaging size. Together, these improvements can dramatically reduce power module cost due to reduced material usage. Numerous technical advancements have been made in power module packaging design and materials selection to reduce the R_{th}, including direct liquid cooling [28], advanced bonding techniques [29], transfer/injection mold [30], copper bonding [31], [32], and micro and meander channel networks [33], [34]. Despite these many improvements, the thermal management potential of single sided cooling is approaching its limit and often cannot meet the demands of new applications. For such application, a new strategy is need. Double sided cooling has the potential to take advantage of many of the aforementioned technological advancements to single sided cooled devices but has the inherent thermal advantage of an additional cooling path. This advantage is making double-sided cooling an increasingly popular approach despite often being more challenging to design and implement.

In conventional power module packaging, the top side of the power semiconductor devices are used only for electrical connections while the bottom side is typically attached to a DBC (Direct Bonded Copper) substrate for electrical connection and heat transfer. Wire bonding has been the standard interconnect approach used in power module packaging because of ease-of-use and low production costs. However, this asymmetric package structure has a series of drawbacks, such as large parasitic electric parameters and bending of the die under thermal stress. Although there are some improvements in the wire bonding technology, including replacing Al with Cu or Al ribbon wire bonding, the wire bonds are still the weakest point for power module reliability due to high thermal stresses at the connection points and the relatively low strength of the connection [35]. The wire bonding method is also the major source of the parasitic loss [10]. More importantly, the existence of wire bonding prevents the possibility of dissipating heat from the top of the power semiconductors devices.

Recognizing this, there has been significant research in electronics packaging over the past two decades to move away from wire bonding as an interconnection method [10], and to introduce alternative interconnection technologies such as planar interconnect techniques [4], [13], [14], [21], [25]. In these methods, the power semiconductor devices are interconnected via solder or sinter to copper conductors directly so that the heat can dissipate and transfer through both sides of the power semiconductor device. The additional path in the top of the power semiconductor device due to the elimination of the wire bond enables two parallel cooling paths and therefore a double-sided cooled power module. This design can provide much better heat transfer and greatly reduces the effective R_{th}. Theoretically, double-sided cooling can reduce the R_{th} between the device and the coolant by up to 50% [36].

Double sided cooled power modules have several important advantages over single sided cooled modules. As previously explained, improved thermal performance will reduce the temperature swings and thermal stress within the power module. Eliminating wire bonds also removes one of the major failure modes in convention power module packaging [35]. Therefore, the power cycling capability and reliability of the double sided cooled modules has been shown to be improved by as much as an order of magnitude over single sided cooled modules, leading to increased lifetime [37]. The double-sided cooled module also improves the electrical performance of the power module. Double-sided cooling packaging requires planar power packaging, which minimizes the current loop area. Since the thickness of power semiconductor device is generally less than 0.1 mm, while the height of wire bond is in the range of 3∼4 mm, the loop is reduced dramatically by eliminating the wire bonds. This results in a reduction in electrical parasitic inductance, in addition to electric resistance reduction due to larger bonding areas [37], [38]. Wire-bondless configurations are key as an enabler for silicon carbide device because of their lower parasitic inductance and higher packaging density [39].

The reduction of the R_{th} of the power module can increase the current handling capability and enable operation at higher PWM switching frequency, which improves the utilization of the power semiconductor device. In one example, if the junction to case thermal resistance ($R_{th,\ j-c}$) is reduced from 0.4 to 0.2 K·cm^2/W, the IGBT switch current rating can increase 61% assuming a constant die area, or the die area can be reduced by 38% [36]. Alternatively in another example, for a 70 kVA inverter with 650V of DC link voltage, the total silicon die area (IGBT plus diode area) can be reduced from 12 cm^2 to less than 7 cm^2 if the $R_{th,\ j-c}$ improves from 0.4 to 0.2 K·cm^2/W [20], [40]. However, the typical R_{th} of single sided cooled power modules is around 0.4 K·cm^2/W. Double-sided cooled design is, thus, required to achieve a R_{th} less than 0.2 K·cm^2/W [20], [36].

As can be seen from this discussion, double-sided cooled power module packaging not only provides significant improvements in thermal and electrical performance for power modules, but it also enables higher power density and cost reduction opportunity.

A lot of effort has been put into bringing the concept of double-sided cooling to commercialization. Some initial attempts can be traced back to the 1990s, with various designs proposed over the years by universities, research institutes, and industry suppliers. In the following section, many of these designs will be reviewed, including their background,

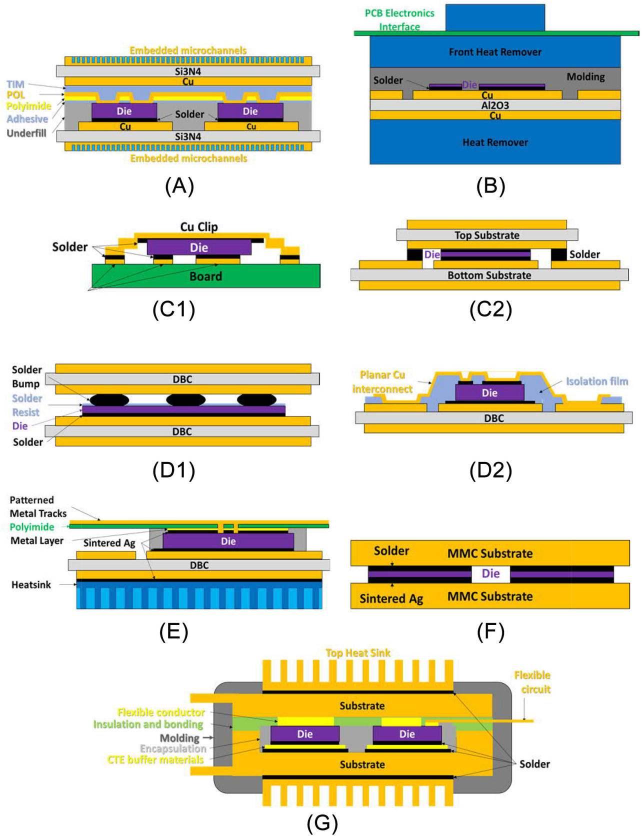


FIGURE 4. **The cross section of early exploration of double-sided cooled power module packaging: (A) POL-kW from GE; (B) double-sided air-cooled packaging from boeing and florida state university; (C1) Direct FET from International Rectifier; (C2) CooliR2 from international rectifier; (D1) PBGA from Siemens; (D2) SiPLIT from siemens; (E) SkiN Semikron; (F) double-sided air-cooled packaging from ABB; (G) PCoB from NCSU.**

application, layout, thermal and electrical performance. These recently developed module package designs are classified into three categories based on timeline and their similarity in module structure and design purpose, including: 1) early exploration of double-sided packaging with only one side liquid cooling or both sides air cooled; 2) development and maturation of double-sided liquid cooled packaging by university and research institutes; and 3) commercialization of double-sided liquid cooled packaging developed by industry suppliers that have been introduced to the market.

III. EARLY EXPLORATION OF DOUBLE-SIDED COOLED PACKAGES

To use the top side of the power devices as an additional thermal path, the convention wire bond interconnection must be replaced by planar packaging. Several concepts had been proposed during the early exploration stage that allow air cooling from the top or from bottom sides. The cross section of some of these power module packaging technologies are illustrated in Fig. 4 and their performance summarized in Table 1. It should be noted that these numbers are cited from specific references and may lack precisely comparable information, including total die area, operating and cooling conditions, or peak power run time.

A) POWER OVERLAY FROM GENERAL ELECTRIC

In 1995, GE Global R&D proposed an embedded power module structure called “Power Overlay (POL)”, in which the wire bond interconnects were replaced with a 50 μm thick Kaption polyimide thin film with surface metallization [63]–[67]. This design reduced the height profile as much as 50% and enabled the top side cooling approach. This technology could handle high operating voltages of up to 2400 V and power dissipation up to 200 W. This is believed to be the first invention that allowed for top sided cooling packaging. A simulation of the GE concept by Fraunhofer in 2006 indicated that R_{th} could be improved by 12∼15% if double-sided cooling can be achieved [17]. In 2009, a double-sided liquid cooling concept was developed based on this POL technology [68]. With the help of novel integral micro-channel heat sink, the junction to fluid thermal resistance ($R_{th,\ j-f}$) for the IGBTs can reach 0.076 K/W [42], [43], achieving up to 40% improvement in R_{th} compared with a conventional single-sided cooled power module [41], [44]. Comparing with wire bond interconnects, this packaging showed 70% lower electrical resistance and 60% lower inductance [44]. The authors also claimed that the POL technology resulted in 40% lower voltage overshoot and 22% lower switching losses compared with conventional power module packaging with wire bond. It also provides up to 4 times package volume reduction due to 2 times smaller area and up to 2 times lower body thickness [41]. This packaging concept was also proposed for SiC-based power semiconductor device [45], [46], [43].

B) DOUBLE-SIDED AIR-COOLED PACKAGING FROM BOEING AND FLORIDA STATE UNIVERSITY

In 2002, Boeing patented a concept for a double-sided air cooled power module packaging by adding an encapsulation layer with epoxy and a heat remover over the top of conventional power module package [69]. Later Florida State University built a 1200V 25A IGBT based prototype based on this concept and reported a 20% reduction of the thermal impedance of this power module packaging over a conventional device [47].

C) DIRECT FET AND COOLIR2 FROM INTERNATIONAL RECTIFIER

In 2001, International Rectifier developed a power packaging technology called Direct FET [48], [49]. A passivation system was used to separate and define the source and gate pads on the MOSFET die, and a copper cover was applied to the top side of the power semiconductor device to connect power semiconductor devices with the printed circuit board. This copper cover also facilitated the concept of double-sided cooling, either through forced air with or without additional

TABLE 1 The Performance of Double-Sided Cooled Power Module Packaging Technologies From Industry

Supplier	Technology	Year	Voltage	Current	Si or SiC	Thermal Resistance*	Inductance	Other benefit	Reference
			V	A					
GE	Power Overlay (POL)	1995	1200	200	Si	0.076 K/W, 40% ↓	60% ↓	voltage overshoots: 40% ↓ lower switching losses 22% ↓	[41][42] [43][44]
		2012			SiC				[45] [46]
Boeing		2002	1200	25	Si	20% ↓			[47]
IR	DirectFET	2001			Si				[48][49]
	CooliR2	2010	650	300	Si	30-39% ↓	12 nH	max current capability: 30% ↑ Die area: 38% ↓ IGBT switch current: 61% ↑	[50] [37] [51] [52] [36]
Siemens	PBGA	2004	40		Si	0.34~0.44 K/W			[53]
	SiPLIT	2012			Si	0.55 K/W, 20% ↓	6 nH	Reliability: ↑	[54]
						0.321~0.345 K/W, 15% ↓			[55]
Semikron	SkiN	2011	600	400	Si	0.44 Kcm^2/W, 35% ↓		Reliability: ×200 ↑	[56]
						0.194 K/W, 23-28% ↓		surge current limit: 27% ↑	[57][58]
		2016	1200	400	SiC		1.4 nH		[59]
ABB		2011	1200	600	Si		18~20 nH	Output current: 35% ↑ Die area: 10% ↓	[60][61]
NCSU	PCoB	2016	1200	100	Si	0.5 K/W	8 nH		[62]

*For precise comparison percentage and assumptions, please see reference

fins or by using a thermally conductive gap-filling medium to conduct to a suitable heatsink with or without liquid cooling.

Additionally, International Rectifier developed a second packaging solution called CooliR2 in 2010 [50], [51], which provided an alternative way to achieve double-sided cooling [52], [37]. The semiconductor device in the CooliR2$^{\text{TM}}$ packaging platform is sandwiched between two substrates to achieve double sided cooling. The $R_{th,\ j-f}$ is expected to be reduced by 39% compared with single sided cooling [37], [50]. The simulation result indicated that the $R_{th,\ j-f}$ when operating the power module under double-sided cooling was 0.071 K/W at 5 LPM per heat sink and the value under single sided cooling was 0.095 K/W at 10 LPM [52], which means a 32% improvement with the same total flow rate through the heat sinks. Measurements found a 30% improvement in the steady state $R_{th,\ j-f}$ from single sided cooling to double-sided cooling, agreeing well with the simulation result [52]. The reliability of the CooliR2 power module package also improved due to the elimination of the wire bond [37], [50]. The inductance of the 480A rated CooliR2Bridge$^{\text{TM}}$ measured from DC+ to DC- terminals is about 12 nH [37], [50]. The combination of lower on-state voltage and larger heat exchange area due to the solderable front metal (SFM) on this power module increased the current carrying capability of the IGBT power semiconductor device by 30% [51]. Alternatively, the die area can potentially be reduced by 38%, or the switch current rating of the IGBT power semiconductor device can be increased by up to 61% [36]. Inverter level testing found the maximum current capability of the inverter with double-sided cooling was 33% higher than the single-sided cooled power module, while the cooling fluid temperature and maximum IGBT junction temperature were kept the same [52].

In 2011, IR also reported another form of double-sided cooled power module concept, using 2 mm thick Cu clips for a 300A 650 V Si-based IGBT power module package to eliminate wire bonds and provide an additional cooling path [70]. The number of cycles was increased by 260% for this Cu clip wire-bondless IGBT power module as compared with the conventional wire bond IGBT power module. International Rectifier become part of Infineon in 2015.

D) POWER BALL GRID ARRAY & SIPLIT FROM SIEMENS

In 2004, Siemens proposed a power module packaging concept called “Power Ball Grid Array” (PBGA) [53]. In this concept, the power semiconductor devices are soldered between two DBC substrates. While the collector of a die is connected to the lower DBC substrate by large area soldering, the upper gate and emitter pads are connected to the upper DBC substrate via solder bumps. The simulation result from Fraunhofer indicated that R_{th} can improve 31-44% when double-sided cooling can be achieved [17].

Later, Siemens reported their power module packaging solution called “Siemens Planar Interconnect Technology” (SiPLIT) in 2012 [54]. In this power module packaging, the entire power semiconductor device was coated with a soft, epoxy-based insulation film applied by a vacuum-based lamination process. The copper plating over vias or openings of this conformally deposited insulation layer formed interconnections for power semiconductor devices. The typical thickness of the copper plating is 50-200 µm, depending on die rated currents and thermal impedance requirements. The measured R_{th} of this power module packaging was 0.55 K/W, 20% lower than that of conventional Al wire bond power module packaging, which was 0.69 K/W under the same power loss [54]. In another study, the R_{th} of this planar interconnection SiPLIT power module packaging reached 0.321-0.345 K/W, 15% lower than the compared single sided cooled packaging [55]. Although the copper interconnects on the top side of the power semiconductor device did provide additional thermal paths compared with a single sided cooled power module, it can only provide limited improvement without liquid cooling on the top side. Since the copper connection was attached on the surfaces of DBC substrate and dies, less than 6 nH of stray inductance of the interconnects was measured for this copper planar interconnect, compared with 11 nH from the conventional wire bond power module packing. The reliability of this SiPLIT power module packaging also improved remarkably compared with the convention Al wire bond power module packaging [54].

E) SKIN FROM SEMIKRON

In 2011, Semikron developed a double-sided planar bond phase-leg power module, named SkiN [56], [57], [71], [72]. This all-sintered package was the first flex foil type of package close to commercialization and was also considered a major step towards both wire-bondless interconnections and 3D integration. In SKiN packaging, the top substrate was essentially a flexible printed circuit board of polyimide with metal traces printed on both sides serving as the interconnection with the top side of the power semiconductor device. All the joining interfaces between the two sides of the power semiconductor device and substrates, as well as between the substrates and heat sink were bonded by silver sintering, which enabled higher temperature operation than conventional soldered connections. The thermal resistance of junction to ambient ($R_{th,\ j-a}$) of the SKiN power module was reported as 0.44 K·cm^2/W, which is 35% lower than the conventional power module [56], or $R_{th,\ j-f}$ of 0.194 K/W, which is 23-28% lower than the convention power module [57], [58]. It should be noted that the improvement of R_{th} is due to sintered silver with higher thermal conductivity and reduced lateral temperature gradient via the flexible circuit board [57]. For reliability, the SKiN power module can survive up to 500 k cycles when cycling the junction from 40 °C to 150 °C within a 10 second cycle, whereas a conventional power module would exhibit significant fatigue at 20 to 40 k cycles [56], which is an improvement of almost 200 times relative to the conventional power module design [57], [71]. As the loop height was reduced, the parasitic inductance of the wire-bondless SKiN power module showed a reduction up to 10% over a conventional power module package with wire bond [57]. The surge current limit for the SKiN power module also increased by about 27% [57].

In 2016, this SKiN power module packaging was used for a 1200V 400A SiC-based power semiconductor device and achieved a total commutation stray inductance of less than 1.4nH [59]. However, since the major thermal path is still single sided, through a bottom integrated heat sink, the improvement in the thermal performance was limited.

F) DOUBLE-SIDED AIR-COOLED PACKAGING FROM ABB

In 2011, ABB Corporate Research developed a high-power 1.2kV, 600A double-sided air cooled IGBT press pack module [60], [61]. The Si-based IGBT power semiconductor devices were soldered between two metal matrix composite (MMC) substrate plates using a eutectic alloy with a high melting temperature to form a double-sided cooled press-pack power module. Therefore, the wire bonding of the emitter and anode was completely replaced, but it was still used to connect the gate of an IGBT. The internal inductances were 18-20 nH for different power module packaging. The inverter level test indicated a 35% higher output current with 90% of the silicon area compared with a 400-kW state-of-the-art industrial inverter with the same dimension.

G) POWER CHIP ON BUS PACKAGING FROM NCSU

In 2016, North Carolina State University (NCSU) proposed a Power Chip on Bus (PCoB) concept for double-sided air cool power module packaging [62]. In their 1200V 100A SiC power module, the $R_{th,\ j-a}$ could achieve 0.5K/W at air flow rate of about 15 CFM, compared with 0.6∼1K/W from a single side liquid-cooled power module. This power module also achieved 8 nH power loop parasitic inductance.

IV. DEVELOPMENT OF PACKAGES WITH DOUBLE-SIDED LIQUID COOLING

Double sided liquid cooling of the power modules is clearly advantageous to maximize heat dissipation. However, enabling double-sided cooling requires many changes to the power module packaging and materials that bring with them practical challenges to implementation. The cross section of several proposed power module packaging technologies are illustrated in Fig. 5 and their performance is summarized in Table 2.

A) DOUBLE-SIDED LIQUID COOLED PACKAGING FROM ALSTOM

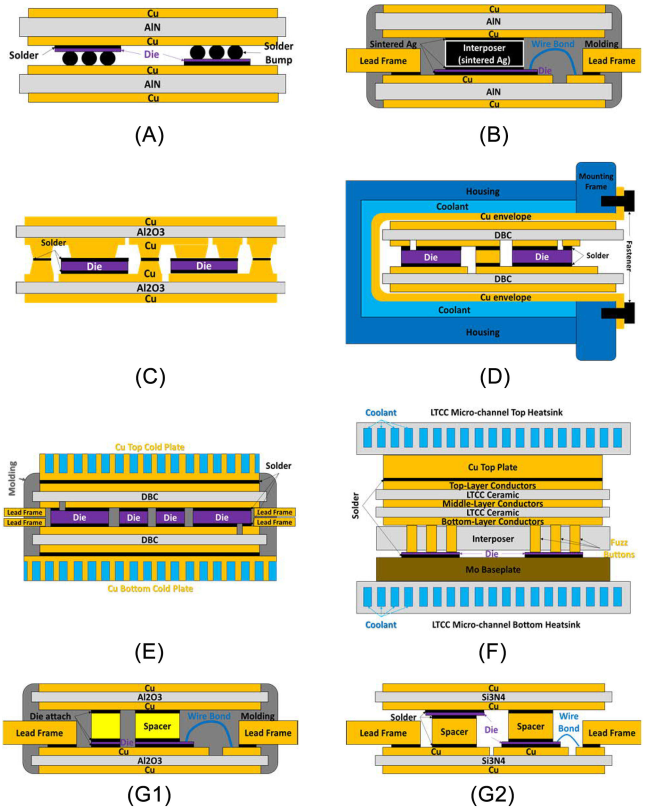
In 2001, Alstom and CEA/LETI proposed what is believed to be the first double-sided liquid cooled packaging concept reported in the literature [73]. In this packaging, the 1600V 50A IGBT power semiconductor devices were sandwiched between two DBC AlN substrates. The wire bonds were replaced with flip die Sn–Pb–Ag solder bumps to achieve double-sided cooling. Microchannel heat sinks were brazed to the DBC substrate with Sn–Pb solder to reduce the R_{th} of the power module. Thermal testing indicated the R_{th} of this double-sided cooled module was as low as 0.13 K·cm^2/W. The authors reported that their concept could reduce the maximum temperature on the power semiconductor devices by 30% and increase the dissipated power by 76% [73].

Alstom partnered with ETH Zurich and Grenoble Electrical Engineering Laboratory and developed a 3300V 1200A double-sided cooled power module [74]–[76] in 2006. Two substrates were sandwiched with the “Surface Power Bump” technology and liquid cooling was carried out through finned metal devices. Two rows of modules could be assembled back-to-back and mounted together with the cooling device. The system allowed heat dissipation of 200 W/cm^2 with ΔT of 45K and the volume of the power module system was reduced from 74 L (including aluminum heat sink) to 6.4 L (excluding

TABLE 2 **The Performance of Various Double-Sided Liquid Cooled Power Module Packaging Concept**

Supplier	Technology	Year	blocking Voltage	Current	Si or SiC	Thermal Resistance*	Inductance	Other benefit	Reference
			V	A					
Alstom/ CEA/LETI		2001	1600	50	Si	0.13 K·cm²/W		maximum T the die: 30%↓ dissipated power: 76% ↑	[73]
Alstom /ETH		2006	3300	1200	Si	heat dissipation of 200 W/cm² with ΔT of 45K			[74] [75][76]
CPES		2021	1200	149	SiC	30% ↓ of Tj			[90]
Denso/ University of Nottingham		2007	1200	15	Si	0.4 K/W, 60% ↓	10 nH		[91] [92]
Fraunhofer		2008	600	200	Si	40% ↓			[93][94]
	Slot	2009							[27]
Oak Ridge	planar bond all	2012	600	200	Si	0.26 °C/W	10.5 nH		[95] [96]
		2012	1200	200	Si	0.33 cm² ·°C/W, 38% ↓			[38][97]
		2014	1200	100	SiC				[98] [99]
		2017	1200	90	SiC		1.63 nH, 70% ↓		[100] [101]
University of Arkansas		2016	1200		SiC	1 K/W	4.3 nH		[102] [103]
Tianjin University		2019	650	240	Si	0.273 K/W, 18.8% ↓			[104]
Xi'an Jiaotong University	Interleaved Planar Packaging	2020	1200		SiC	~0.025 K/W	3.8 nH	Even thermal distribution	[105]

*For precise comparison percentage and assumptions, please see reference



(A) (B) (C) (D) (E) (F) (G1) (G2)

FIGURE 5. **The cross section of double-sided liquid cooled power module packaging: (A) from Alstom partnered with ETH; (B) from CPES; (C) from denso and university of nottingham; (D) from Fraunhofer; (E) planar bond all from Oak Ridge National Lab; (F) from university of arkansas; (G1) from tianjin university; (G2) from Xi'an Jiaotong University.**

liquid air heat exchanger) and the weight from 56 kg to 3 kg [19].

B) DOUBLE-SIDED PACKAGING FROM VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

Since 1999, the Center for Power Electronics Systems (CPES) in Virginia Polytechnic Institute and State University (Virginia Tech) proposed a series of novel power module packaging technologies, including the "metal posts interconnected parallel plate structure" (MPIPPS) in 1999 [77], "flip-die-on-flex" in 2001 [78], "embedded power" in 2004 [79], [80], "embedded power packaging" in 2005 [81], [82], "embedded die module" (ECM) in 2007 [83], "high-voltage embedded power" (HVEP) in 2008 [84], "planar package" in 2010 [85]–[87], "hybrid packaging" in 2013 [88], and "bidirectional module" in 2014 [89]. All of these technologies used direct attachment of bulk copper instead of wire-bonding for interconnecting the power semiconductor devices. In 2021, they proposed a 1200V, 149A SiC double-sided liquid cooled power module with interposers made by sintered silver [90]. By assuming a convection coefficient of 8000 $W/m^2 \cdot K$ for water cooling and a convection coefficient of 20 $W/m^2 \cdot K$ for air cooling, the simulation result indicated the effect of double-sided cooling leads to an approximately 30% reduction of the junction temperature over that with single sided cooling.

C) DOUBLE-SIDED LIQUID COOLING FROM DENSO AND UNIVERSITY OF NOTTINGHAM

In 2007, Denso and University of Nottingham reported a compact integrated 1200V 15A power electronic module [91],

[92]. In this double-sided liquid cooling package, a substrate sandwich structure permitted double sided cooling of the embedded power semiconductor devices and handled the mechanical stresses both within the module and at the heat exchanger interface. Measurements on this double-side cooled structure showed $R_{th,\ j-a}$ was lower than 0.4 K/W, which was less than 40% of that of the baseline conventional power module [91]. A 10 kW 3-phase inverter with this power module achieved a power density of 17 kW/kg and parasitic inductances of about 10 nH [92].

D) DOUBLE-SIDED LIQUID COOLING FROM FRAUNHOFER

In 2008, Fraunhofer IZM proposed a double-sided direct liquid cooling concept that did not require the use of spacers [93], [94]. Two pairs of 600V 200A Infineon IGBT power semiconductors and diodes were bonded to AlN DBC substrates on both sides with SnAg solder to form a sandwich structure. The cooling media flowed directly on the external side of both substrates. The $R_{th,\ j-f}$ of this double-sided direct liquid cooled power module packaging was 0.084-0.11 K/W for a 100 mm^2 die area, depending on the flow rate, which was an improvement of 40% compared to their conventional single side cooled power module baseline.

Later, Fraunhofer IISB proposed another new slot concept in 2009 [27]. The power semiconductor device was sandwiched by two DBC substrates, and then inserted into a metal envelope with direct contact to the liquid coolant from both sides. Therefore, the thin metal flange provided the mechanical fixation while the ceramic dielectric layer was not stressed by mounting forces. Only the absolute minimum necessary number of material layers was used, and they believed their design could be easily integrated into an inverter.

E) PLANAR BOND ALL CONCEPT FROM OAK RIDGE NATIONAL LAB

Sponsored by the US Department of Energy, Oak Ridge National Lab proposed a new planar interconnection configuration called the “Planar Bond All” concept in 2012 [38], [95], [96]. Both the power module packaging and the cooling structure was patented [106], [107]. Two pairs of Si-based IGBT power semiconductor devices were symmetrically sandwiched by two patterned DBC substrates to form one phase leg (half bridge) for both 600V 200A grade [95], [96] and 1200V 200A grade [38], [97] systems. Special metallization was applied to the surface of power semiconductor devices. The authors considered this structure to be an “improved version” of the “Press-pack” concept. Compared with the conventional wire bond power module packaging process, this concept provides a large bond area, a thick tracing pattern, enables double-sided cooling capability, and dramatically reduces the complexity of the power module manufacturing process [38], [95]. Double-sided cooling was achieved by two copper flat tube cold plates [38], [96], [97]. The thermal characterization measurement indicated the double-sided cooling of this planar module packaging had a specific $R_{th,\ j-f}$ of 0.33 cm^2·K/W, which was 38% lower than 0.541 cm^2·K/W measured from their conventional single sided cooling baseline [38], [97]. The measured $R_{th,\ j-f}$ (0.26 K/W) was also in good agreement with the simulation result (0.25 K/W) [96]. Due to larger bond areas and thick conduction paths, the total inductance of this planar power module prototype was much lower than that of the conventional wire bond power module package; 12.08 nH vs. 50.3 nH from simulation and 10.5 nH vs. 31.9 nH from experiment results [38], [95], [97]. The total electrical resistance was also significantly reduced [38], [95], [97].

This power module packaging concept was also adapted to a 1200 V, 100A phase leg all-SiC-based power module prototype in 2014 [98], [99]. The double-sided liquid cooling structure was also improved by bonding copper pin-fin base plates directly to the power package on each side with a soldering process, and then assembling the system with a specially designed coolant manifold to provide the liquid passageways. The experimental results indicated similar improvements from this power module packaging compared with their conventional power module packaging baseline.

Based on a similar concept, Oak Ridge National Lab and the University of Tennessee further improved the 3D layout of their double-sided cooled SiC-based power module packaging in 2017. The simulation results show a power loop inductance of 1.63 nH, and a more than 60% reduction from experiment result compared with the baseline double-sided cooled power module [100], [101].

F) DOUBLE-SIDED PACKAGING FROM UNIVERSITY OF ARKANSAS

In 2012, University of Arkansas developed their wire-bondless, double-sided cooled power electronic module for 6.5kV, 50A rated SiC SGTO (Super Gate Turn Off Thyristor) with a 6.5kV SiC PiN Diode [108], [109]. The DBC substrates with nickel plating were directly bonded to power semiconductor devices using a Pb95Sn05 solder. Since the top side was cooled by air only, the improvement in thermal performance was limited. Later, low temperature co-fired ceramic (LTCC) substrate carrier and nano-silver paste was used while the baseplate was removed [110], [111]. The thermal simulation showed that double-sided cooling can reduce the maximum junction temperature and has a more pronounced influence at lower heat transfer coefficients. The simulation also indicated that the parasitic inductances of the LTCC-based wire-bondless module was smaller than those of the wire-bonded module. In 2016, miniature and flexible press pins called “fuzz buttons” were used in a low-profile interposer and a stacking structure with a clamping block was used to press pack the power module [102], [103]. The simulation indicated the $R_{th,\ j-f}$ was about 1 K/W. Due to the ultra-thin heatsinks, the commutation loop inductance of the half-bridge stack was only 4.3 nH at 100 kHz.

TABLE 3 The Performance of Various Double-Sided Liquid Cooled Power Module Packaging Product for Automotive Application

Supplier	Technology	Application / Status	Voltage	Current	Layout	Wire bond	Dimension	Max Temp	Thermal Resistance		Parasitic Inductance	Reference
									Rth j-c	Rth j-f		
			V	A			mm	C	K/W	K/W	nH	
Denso		MY2008 Lexus LS600h			1 in 1	Yes	48×38×5	150		0.203* ~0.225		[112][113]
		MY2013 Toyota Camry										
		MY2016 Toyota Gen 4 Prius			2 in 1		48×38×5×0.78				55% ↓	[114][115]
Delphi	Viper	MY2016 Chevrolet Volt			1 in 1	No			33% ↓			[116][117]
Hitachi	DWDSCPM	MY2016 Cadillac CT6			2 in 1	Yes			35% ↓		25% ↓	[118][119]
		MY2019 Audi e-Tron			2 in 1							[120]
		MY2020 SAIC-GM Buick Velite 6 PHEV			2 in 1							
		MY2020 Porsche Taycan			2 in 1							[121]
Infineon	DSC				2 in 1	Yes	42×42×4.7		0.11*	70% ↓	13nH, 40% ↓	[122]
	DSC S1	Available since 2017	700	400	2 in 1	Yes	42×42×4.7	175	0.1	0.24	15	[123]
	DSC S2	On request	750	450	2 in 1	Yes	42×42×4.7	175				[124]
	DSC L	Available since 2016	700	200	6 in 1	Yes	86 43×6	150	0.18	0.35	20	[125]
On semiconductor	VE−Trac Dual		750	550	2 in 1	No	50.7×55×4.7	175	0.05	0.14	8	[126]
CRRC/ Dynex			650	600	2 in 1	No	55×47×5	175	0.018-0.03*	0.0889-0.094	4.6	[127][128][129][130][131]
BYD		2018Q4 SOP	1200	200								[132]

*Calculated or simulated

G) OTHER DOUBLE-SIDED PACKAGING ACADEMIA

Since 2018, several research institutes have proposed double-sided packaging concepts.

In 2019, Tianjin University (TJU) proposed a double-sided half bridge package for a 1200V/600A IGBT power module [133] and a 650V/240A IGBT power module [104]. By assuming the heat transfer coefficient of water cooling as 2000 or 3000 W/m^2·K, the simulation result gave a $R_{th,\ j-f}$ of 0.273 K/W, which is 18.8% lower than that under the single-sided cooling condition [104].

In 2020, Xi'an Jiaotong University (XJTU) proposed a novel packaging structured called "interleaved double-sided packaging structure" [134]. Compared with a double-sided structure with all die on the same side, this structure can reduce thermal coupling effects by extending the two adjacent dies' "thermal" distance. Later, a 1200V 3.25 mΩ half-bridge SiC power module based on this concept was fabricated and the simulation result indicated an equivalent thermal resistances of 0.025 K/W [105].

In 2020, Huazhong University of Science and Technology (HUST) proposed a novel double-sided cooling 1200V/294A SiC inverter leg and reported the thermal resistance of 0.146 K/W from simulation [135].

Since 2018, the Chinese Academy of Science (CAS) have designed a 1200V 600A planar double-side cooled IGBT power module [136] and 1200V 200A planar double-side cooled Si-IGBT & SiC-MOSFET power module [137]. However, no thermal resistance performance was reported.

V. COMMERCIALIZED DOUBLE-SIDED LIQUID COOLED PACKAGES

Building on the aforementioned developments, double-sided liquid cooled packages are beginning to be offered for sale by leading suppliers and is being implemented by automotive vehicle manufacturers. This section will discuss some examples of commercially available double-sided cooled power modules.

A) DOUBLE-SIDED LIQUID COOLED PACKAGES IN VEHICLES

The design structure, including the cross section, appearance, thermal path and the cooling structure of above power module packaging technologies adapted in vehicles are illustrated in Fig. 6 while their performances are summarized in Table 3.

A) DOUBLE-SIDED LIQUID COOLED PACKAGING FROM DENSO

The first double-sided liquid cooled power module implemented on a vehicle was from Denso and Toyota in the MY2008 Lexus LS 600h [112]. This system was analyzed by Oak Ridge National Lab in 2009 [113]. Denso filed a series of patents for this technology since 2004 [138]–[141]. In this

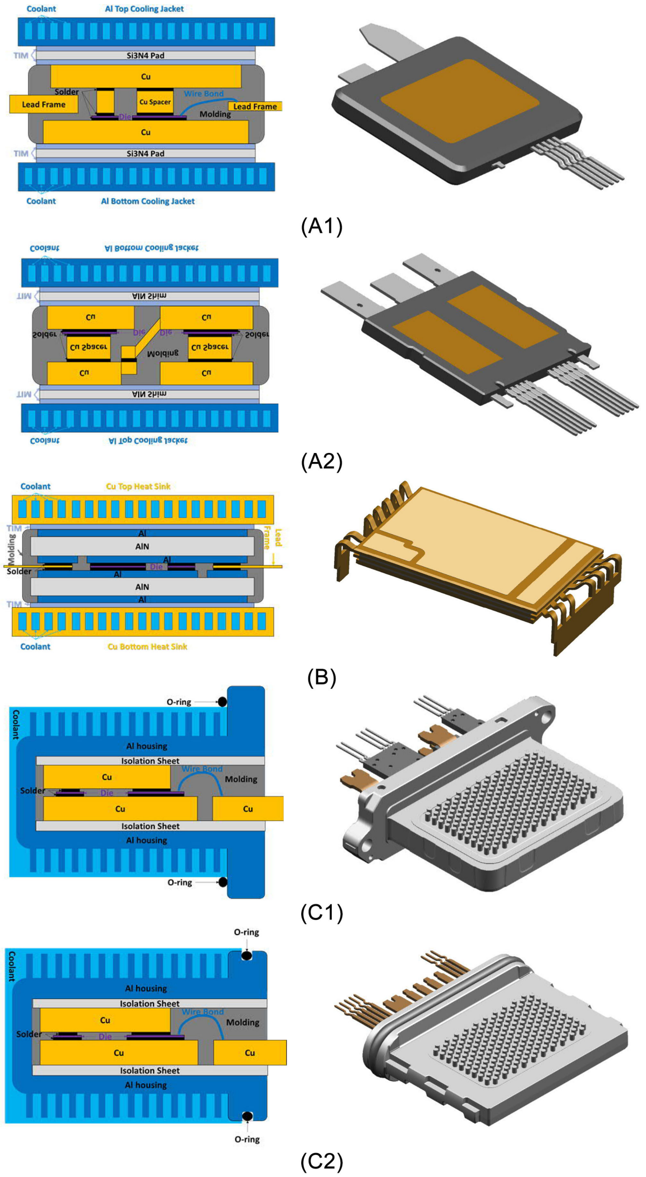


FIGURE 6. **The cross section and appearance of double-sided liquid cooled power module packages: (A1) from MY2008 Lexus LS600h; (A2) from MY2016 Toyota Gen 4 Prius; (B) from MY2016 Chevrolet Volt; (C1) from MY2016 cadillac CT6; (C2) from MY2019 Audi e-Tron.**

design, a pair of IGBT and diode dies were packaged into one switch unit and, instead of the typical direct bond copper (DBC) or direct bond aluminum (DBA) ceramic substrates, two planar copper plates served as the emitter and collector. These were directly soldered onto power electrodes on the power semiconductor devices from both surfaces. Together with a copper spacer, this formed the topside interconnections and addressed the current handling and heat spreading that the topside of the DBC substrate provided in a typical package. The spacers were made to address the varying power device thicknesses. The switch unit was encapsulated with epoxy molding compound by transfer molding. The copper plates act as heat sinks to transfer heat generated by the power semiconductor devices to the cooling jackets from the two surfaces. Si3N4 tiles were inserted between each power module and the cooling jacket for electrical isolation. Thermal grease was applied on both sides of the ceramic tiles to aid in heat transfer [25]. Although the wire bond connections at the top of the IGBT and diodes were replaced by the conductive spacers to facilitate heat removal from the emitter side of the devices [113], the gate electrode was still connected by bond wire to the output pin [21]. With this double-sided liquid cooled packaging structure, the estimated maximum R_{th} was 0.203 K/W from simulation, compared with 0.452 K/W for the conventional single-sided cooled baseline [112]. This was in good agreement with the experimental results [112]. However, four layers of thermal grease in each power module added R_{th} to the thermal path and diminished the effects of the double-sided cooling. This power module packaging technology also achieved improved heat dissipation at the expense of added complexity in the cooling structure. Nevertheless, with the maximum current per die increased from 200A to 300A, only 24 switches were required to meet the inverter target power requirements compared with 40 in the baseline design.

Later, the MY2010 Toyota Gen 3 Prius still used the conventional single sided cooled power module while the MY2013 Toyota Camry and MY2016 Toyota Gen 4 Prius utilized a similar double-sided liquid cooled power module design. One of the major improvements in the MY2016 Toyota Gen 4 Prius was the “2-in-1” power card compared with the “1-in-1” type power card in MY2008 Lexus LS 600h [114], [115]. Two pairs of power IGBT and diode dies were packaged into one switch unit to form a half bridge, so only seven (7) switch unit modules were used for two three-phase inverters and a one-phase-leg converter, and the power stack size was reduced 22%. Instead of Si_3N_4 tiles, AlN shims were used in the MY2016 Toyota Gen 4 Prius [142]. Since then, this power module has become a standard component used in a wide range of Toyota HEV products, including MY2017 Corolla HEV, MY2018 Camry HEV and MY2020 Highlander HEV.

Based on the similar concept, Denso developed a 6-in-1 SiC-based power module using double-sided air cool for high performance of power electronics systems in 2014 [130].

B) VIPER FROM DELPHI

In 2008, Delphi developed their double-sided cooling technology called “Viper” [144]–[146]. A pair of IGBT power semiconductor devices and diode units were co-packaged by AlN DBA to form one switch per module so it can be cooled from both sides. The flip-chip soldering technique was used instead of wire bonds to improve the current distribution and lifetime of the die interconnection. It was unclear how the height discrepancies between IGBT and diode were addressed because no spacer was illustrated. Nevertheless, Delphi claimed that this power module packaging technology allowed up to 50% less power semiconductor area for the same performance

[146], while the inverter could achieve 30% volume reduction, 40% mass reduction, and 25% higher power density than a conventional inverter [147].

In 2016, GM first applied this technology in the MY2016 Chevrolet Gen 2 Volt EREV [116], [117]. The power module packaging was soldered on the drive board and cooled by two copper metal injection molded heatsinks with pressure applied by springs. Compared with conventional single sided cooled power module on the MY2012 Chevrolet Gen 1 Volt EREV, the thermal impedance per 100 mm^2 was reduced by 33%, while the power density of the inverter increased to 17.3 kVA/L. It was believed this Viper power module packaging technology has been used on the Volvo XC90 T8 PHEV, Geely's Lynk & Co 03 PHEV [148].

Delphi also scaled this Viper power module packaging for 650V 500A and 1200V 480A SiC-based power semiconductor devices and achieved a low R_{th} of 0.065 K/W [149]. It also demonstrated a very high-power density of the inverter, 45kW/L for 650V and 58kW/L for 1200V. In 2019, Delphi announced its 800V SiC-based inverter with Viper power module packaging technology [150].

C) DWDSCPM FROM HITACHI

In 2013, Hitachi announced their novel "Direct Water and Double-Sided Cooled Power Module" (DWDSCPM) [6], [151], [152], [153] with a series of patents [154]–[158] going back to 2009. An aluminum bag-formed fin was designed to hold the mold block in which 650V 500A IGBT power semiconductor devices were implemented in a twin lead frame.

The power semiconductor devices were sandwiched by insulating layers from both sides without thermal grease. The bag-formed cooling pocket had pin fins on both sides and formed a flange on a power and control terminal side for coolant sealing. The power module was then inserted into the cooled waterway in the inverter case. Instead of wire bonding, the lead frame for the emitter side of the IGBT was soldered. This lead frame was joined to the heat sink via an insulating material. This inverter could be constructed with three of these power modules because of the 2-in-1 configuration. As the metal leads, insulators, and fins form a single structure, this not only reduces the installation area by half compared with conventional single-sided power module, it also dramatically reduced the R_{th}. The test result showed that the $R_{th,\ j-f}$ of the DWDSCPM power module packaging was 0.17 K/W; 35% lower than that of a conventional single-sided direct water-cooled power module, or 50% lower than a conventional single-sided indirect water-cooled power module. This design therefore enables high power density in the inverter [151], while the architecture reportedly eased inverter design [159]

This power module packaging was first used in the Mercedes Benz MY2015 S500 PHEV and S550 PHEV [160], with a size reduction of about 40% and an increase in power output by around 40% compared to their previous generation product. In 2016, this power module packaging was used on the GM MY2016 Cadillac CT6 PHEV which enabled the power density of the inverter to increase to 23 kVA/L [118], [119].

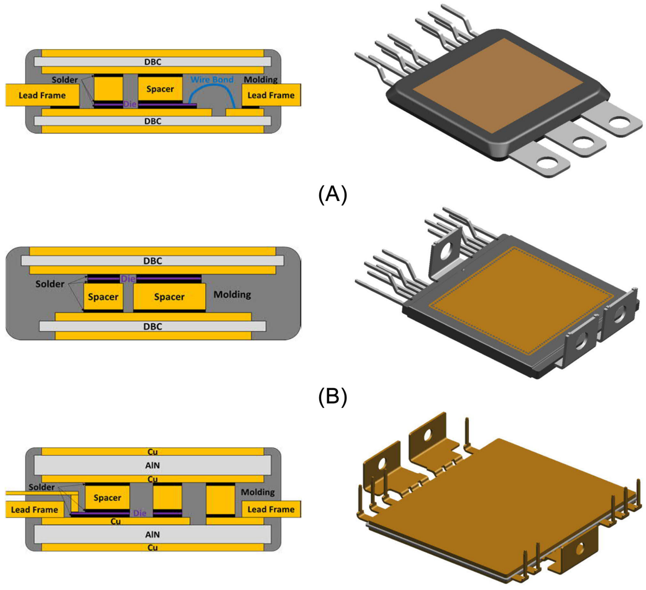
Later Hitachi updated the design of this power module. The terminal configuration and the surface finishing of the aluminum casing were optimized compared from the early design. The sealing structure also changed from facial seal to radial seal to reduce the footprint. In 2019, Audi MY2019 e-Tron used this new version of the power module packaging technology [161], [162]. It was reported that the power density output of this inverter was increased by 160% compared with the previous generation [162] and reached 30kW/L [120]. Hitachi also developed an 800V compatible inverter based on this power module package for Porsche MY2020 Taycan EV by changing the power device from a 700V to a 1200V product that could withstand the higher voltage. Other improvements included higher voltage insulation structural components, optimization of the terminal shape of the power module, and adoption of conductor laminated insulation sheets [121]. The power density of this inverter reached 94.3kVA/L [163]. SAIC-GM MY2020 Buick Velite 6 PHEV later used this product.

B) COMMERCIALLY AVAILABLE DOUBLE-SIDED COOLED PACKAGES

In addition to already commercialized power module systems, there are similar technologies being developed by other suppliers that are or will be commercially available in the near future. The design structure, including the cross section, appearance, thermal path and the cooling structure of these power module packaging products are listed in Fig. 7 while their performances are summarized in Table 3.

A) DSC FROM INFINEON

In 2015, Infineon reported their double-sided cooled package aimed for automotive applications [122]. Compared with Denso's power module packaging technology, Infineon's solution combines double-sided cooling and electrical insulation into a more integrated package. The copper layer in the DBC substrates acts as a heat spreader while the ceramic layer provides the electrical insulation. The power semiconductor devices are soldered onto the substrate to transfer the heat and current. A spacer is applied to the top of the power semiconductor device to adjust the height, which not only improves manufacturability but also provides the necessary space to integrate multiple safety features like current and temperature sensors for improved inverter protection. The emitter current of the IGBT power semiconductor device was conducted through the spacers soldered on top of the die, though the signal pins were still connected with wire bonds. Infineon reported an overall improvement of R_{th} of 70%, or $R_{th,\ j-c}$ of 0.11 K/W compared to an adiabatic top. If direct liquid cooling was applied and the thermal interface materials was eliminated, the R_{th} can further improve by more than 30% and allow use of the same module for up to 40 % higher



(C)

FIGURE 7. **The cross section and appearance of double-sided liquid cooled power module packaging: (A) from infineon DSC; (B) from on semiconductor VE-Trac Dual; (C) from CRRC.**

power [122]. This power module packaging can achieve a stray inductance of only 13 nH. Concept studies showed that combining the double-sided cooled power module packaging and direct cooling of the integrated ceramic substrate have the potential to bring up to 40% foot print reduction of the power module for a given power level compared to the state of the art one sided cooled modules [164]. This design offers flexibility and scalability via stacking to support various packaging methods inside different power electronics systems. In 2017, Infineon commercialized this technology in their product HybridPACK DSC-S FF400R07A01E3 [123], [165]. Infineon also proposed to add a direct water cooling structure to the backside of the substrates to generate a turbulent cooling liquid flow and improve the $R_{th,\ j-f}$ by 20%, compared with indirect double-sided cooling [166].

B) VE-TRAC DUAL FROM ON SEMICONDUCTOR

ON Semiconductor, another power semiconductor IDM supplier, also started to supply 750V double-sided liquid cooled power modules called VE-Trac Dual in 2019, which includes NVG800A75L4DSC (750 V, 800 A) and NVG400A120L2SDSC (1200 V, 400 A) [126]. This module consists of two IGBTs in a half−bridge configuration. It is a wire-bondless module with stray inductance less than 7 nH. A dual sided liquid cooled heatsink was provided as reference design, achieving a $R_{th,\ j-c}$ for the IGBT of 0.05 K/W and $R_{th,\ j-f}$ of 0.14 K/W in the data sheet.

Based on a similar packaging, On Semiconductor also developed a series of 900V-1200V range SiC based power module VE-Trac B2-SiC. AlN substrate and silver sintering was used and the $R_{th,\ j-f}$ is less than 0.115 K/W.

C) DOUBLE-SIDED COOLED PACKAGING FROM CRRC

In 2016, Dynex Power (acquired by CRRC Corporation Limited in 2015, the world's largest rolling stock manufacturer) proposed their double-sided liquid cooled power module packaging for automotive applications [127]–[131]. A 650V 600A half bridge power module is designed and built by attaching power semiconductor devices to both sides of two planar AMB AlN substrates with PbSn5Ag2.5 solder [128]–[131]. Thermal simulation showed that the $R_{th,\ j-c}$ of the double-sided cooled power module was 0.018K/W [128], [131] to 0.03 K/W [130], while the experimental results indicate the $R_{th,\ j-f}$ of this power module packaging is between 0.0889 K/W [129] and 0.094 K/W [127]. The lifetime of this double-sided cooled power module was reported as six times that of a single sided direct liquid cooled module [128]. With planar bonding in the double-sided cooled power module, the parasitic inductance is about 4.6nH including the spacer and metal on the top substrate [128], a reduction of more than 50% compared with a conventional single-sided cooled module [127]. Extremely low parasitic resistance of 0.2 mΩ is also achieved, much lower than 0.8-1.0 mΩ of the conventional wire bond power module packaging [129]. With this technology, the power density of the inverter increased by more than 30% [127].

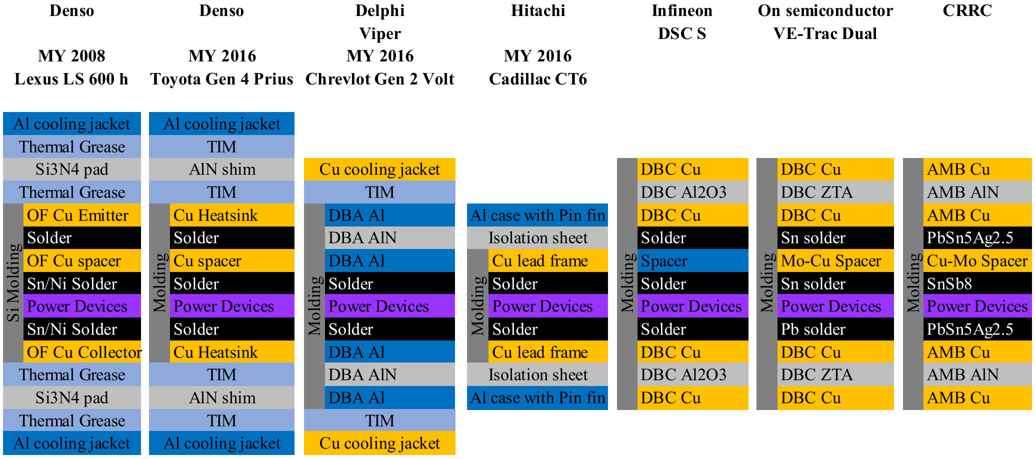
D) DOUBLE-SIDED COOLED PACKAGING FROM BYD

BYD appears to be the only OEM in the world to have its own power semiconductor device design and manufacturing capability, from wafer to module, for both Si-based IGBT and SiC-based MOSFET. In their technology roadmap for power semiconductors announced in 2018, a double-sided liquid cooled Si-based power module was presented [132]. It was claimed for SORP in 2018 Q4 at that time. They also showed a SiC-based power module with conventional single sided packaging and it was reported for production in BYD MY2020 Han BEV [167].

The inner structure for some of the commercialized double-sided cooled modules have been compared in Fig. 8. It is evident that advanced materials and processes are required to improve the performance of current Si-based power semiconductor devices to take full advantage of SiC power semiconductor devices with double-sided liquid cooled power module packaging. The materials used in the packaged assembly must not only survive the exposure to the required temperatures, but also work reliably, and have an acceptable performance in the specified temperature range. The key materials include those for die attach, interconnection, substrate, and encapsulation.

VI. SUMMARY OF DOUBLE-SIDED COOLED POWER MODULE IN AUTOMOTIVE APPLICATION

The double-sided cooled power module packaging from the previous discussion has been plotted against time in Fig. 9. Regardless of the power semiconductor device type (Si-based IGBT or SiC-based MOSFET) and the cooling path (double-sided air cooled, or bottom sided liquid cooled with top sided



Denso MY 2008 Lexus LS 600 h	Denso MY 2016 Toyota Gen 4 Prius	Delphi Viper MY 2016 Chrevlot Gen 2 Volt	Hitachi MY 2016 Cadillac CT6	Infineon DSC S	On semiconductor VE-Trac Dual	CRRC
Al cooling jacket	Al cooling jacket					
Thermal Grease	TIM					
Si3N4 pad	AlN shim	Cu cooling jacket		DBC Cu	DBC Cu	AMB Cu
Thermal Grease	TIM	TIM		DBC Al2O3	DBC ZTA	AMB AlN
OF Cu Emitter	Cu Heatsink	DBA Al	Al case with Pin fin	DBC Cu	DBC Cu	AMB Cu
Solder	Solder	DBA AlN	Isolation sheet	Solder	Sn solder	PbSn5Ag2.5
OF Cu spacer	Cu spacer	DBA Al	Cu lead frame	Spacer	Mo-Cu Spacer	Cu-Mo Spacer
Sn/Ni Solder	Solder	Solder	Solder	Solder	Sn solder	SnSb8
Power Devices	Power Devices	Power Devices	Power Devices	Power Devices	Power Devices	Power Devices
Sn/Ni Solder	Solder	Solder	Solder	Solder	Pb solder	PbSn5Ag2.5
OF Cu Collector	Cu Heatsink	DBA Al	Cu lead frame	DBC Cu	DBC Cu	AMB Cu
Thermal Grease	TIM	DBA AlN	Isolation sheet	DBC Al2O3	DBC ZTA	AMB AlN
Si3N4 pad	AlN shim	DBA Al	Al case with Pin fin	DBC Cu	DBC Cu	AMB Cu
Thermal Grease	TIM	TIM				
Al cooling jacket	Al cooling jacket	Cu cooling jacket				

FIGURE 8. The inner structure of the double-sided cooling module for automotive application.

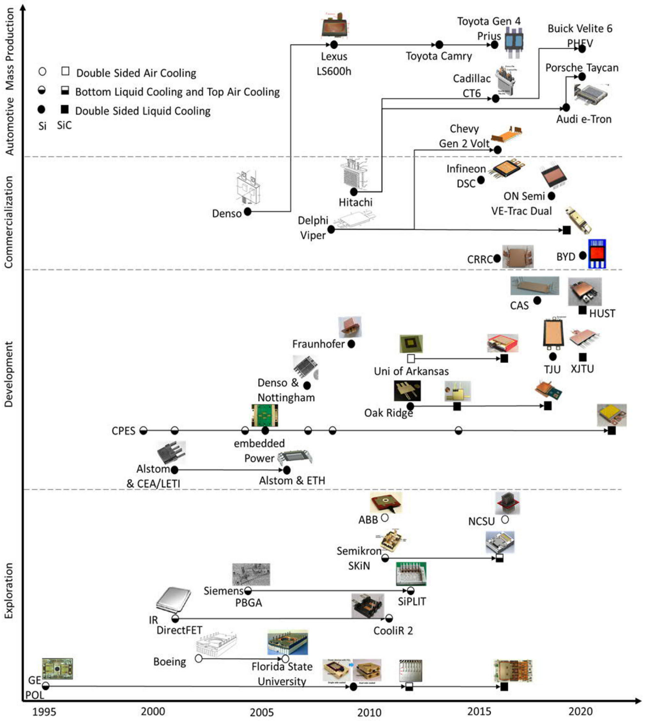


FIGURE 9. The double-sided cooled power module packaging concept and product over years.

air cooled, or double-sided liquid cooled), the development of power modules can be categorized into four categories: 1) academic exploration carried out by universities, research institutes and national labs; 2) Research and development in collaboration between industry and universities; 3) Commercial product development by major industry players; 4) Mass production by automotive OEMs and suppliers. During these four stages, the technology evolved with a clear trend:

- From 1995 to 2010: The exploration of wire-bondless and planar packaging to enable a top side cooling path.
- From 2001 to 2015: the development of double-sided liquid cooling with breakthrough commercialization.
- From 2015 onwards: Mass commercialization with several double-sided liquid cooled modules from different suppliers implemented on EV.

The most recent efforts from both the academic community and industry partners indicates that double-sided cooled package development has also accelerated to enable the silicon carbide-based power semiconductor devices.

As the core component in the inverter system of electric vehicle, the evolution of the power module impacts the inverter performance, reliability, and power density. The volume and power information of traction inverters from various vehicles over the past two decades have been collected from various references [168], [169], and their power density is plotted in Fig. 10.

These numbers are based on various references and may lack precisely comparable information including operating and cooling conditions and peak run time, leading to sometimes unfair comparisons. Regardless, power density gradually increased over the years with technology improvements in power semiconductor devices and power module packaging. Since 2016 several EVs have used double side cooled packages and it is expected that more automotive power modules will move away from conventional single-sided liquid cooling to adopt double-sided liquid cooling due to its superior thermal management and electrical parasitic control.It should be noted that the DOE Electrical and Electronics Team from US DRIVE partnership set the 2025 target for inverter power density as 100 kW/L. That requires not only a significant improvement in the power semiconductor materials, but also improvements to the power module packaging, including the architecture, materials, and process. In terms of thermal management, the required heat flux management is expected to reach between 500 W/cm^2 and 1 kW/cm^2. The double-sided cooled packaging will be key to achieving these targets.

The current double-sided cooled power module packaging still has some drawbacks. For most of the proposed designs,

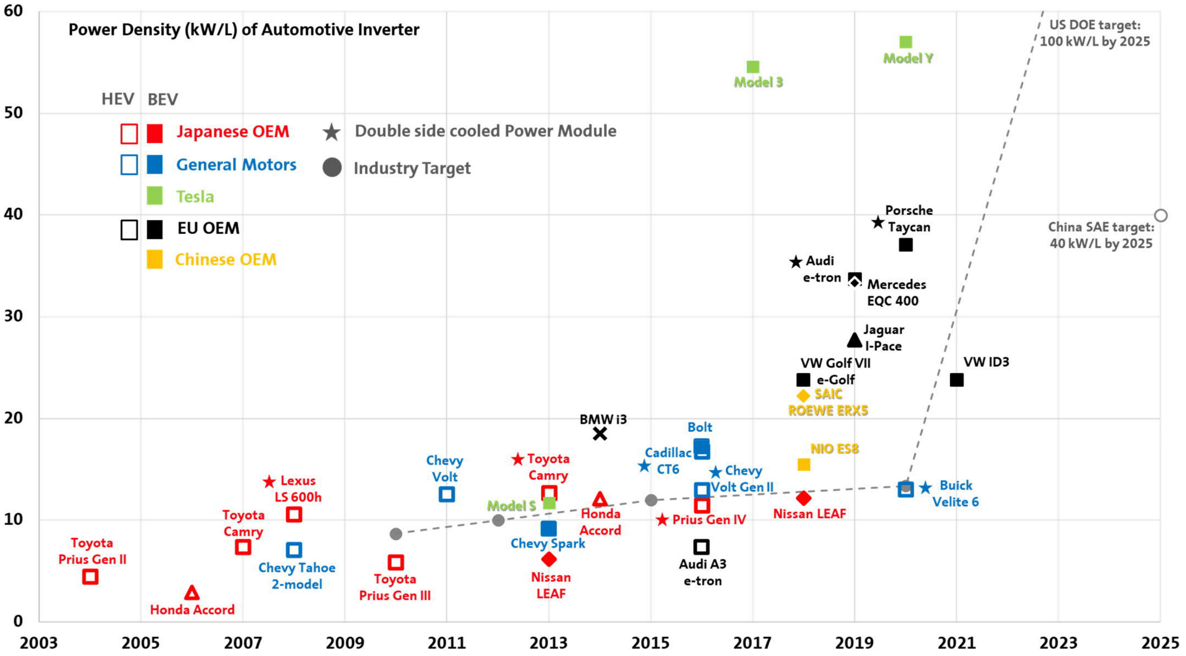


FIGURE 10. The power density of traction inverter from various EV.

a complicated and expensive clamping system and special designed cooling manifolds are required to keep the whole power stack together and achieve the cooling effect. The sealing interface between the power module and coolant can also be challenging if direct cooling is pursued. In some designs, the use of thermal interface materials (TIM) diminishes the advantage of low R_{th} from double-sided cooled packaging. While the double-sided cooling structure has very low thermal resistance, its parasitic capacitance between each copper layer is relatively large which can cause common mode currents [170]. The orientation of the power busbar and the gate driver terminals in different forms of double-sided power module packaging also create system design constraints on cooling stack design and gate driver board position [171]. The power module packaging from suppliers have been migrating to architectures with modularity, as they are typically friendly for performance and functional optimization as well as easily manufacturable and economical. [7].

Besides traditional automotive suppliers, there is a trend of new suppliers like LG, CRRC, and Huawei developing modules due to the high projected volume of EV. It should be noted that the power module packaging development is driven by several different applications, including grid applications for wind and solar energy, electric high-speed trains, and aerospace. Unlike these examples, the automotive application has some unique requirements, and it should be carefully considered during the design of the automotive power module packaging, especially for suppliers from other industries. With the trend of integration of the power electronics, electric motors, and gearing into the electric drive, it also requires OEMs to have more understanding of the impact of power module packaging on the whole system.

As previously mentioned, power module packaging is far from standardized for automotive applications. Even within conventional single-sided cooled power modules, various packaging solutions have been proposed by different suppliers. This brings a tremendous burden for OEMs and suppliers in product development and evaluation. As double-sided cooled packaging starts to evolve, it is expected that two or three standardized packaging solutions will be defined within the industry. It should not only provide the flexibility to integrate different types and numbers of power semiconductors devices that fit with different vehicle applications, but also significantly reduce the cost and timing for product development by standardizing power module packaging as a commodity.

VII. CONCLUSION

Effective thermal management is critical for Si and SiC power modules in automotive applications to allow higher power density and reliability. Compared with conventional single sided cooled power module packaging, the concept of double-sided cooling can significantly improve heat removal capability, semiconductor utilization, and electrical parasitics.

Since the concept was first reported in 1990s, both academia and industry have investigated double-sided cooling, resulting in its implementation on a production electric vehicle inverter in 2008. Since the mid-2010s, the approach has grown in popularity and more suppliers and OEMs are adopting this advantageous packaging technology. The current work focuses on power modules with better performance, reliability, and cost by utilizing planar interconnects, improved materials, and newer processes.

As the technology around the materials and construction of double-sided cooling of power modules matures, the industry will benefit from standardization of the packaging geometries. This will enable faster and lower cost development of new inverters, while still enabling further innovation within the module itself. This standardization, coupled with multiphysics design with double sided cooling, will be critical to the market growth of EVs by improving their value proposition over internal combustion engine powered vehicles.

The design and selection of the power module for an EV is based upon comprehensive analysis of reliability, cost, efficiency, and size. There is no compromise on reliability, however, cost, size and efficiency are evaluated together due to which these characteristics can compensate for each other in the electric drive system. A double-sided cooled power module is inherently more compact and efficient but its commercial use in mass production GM EV is determined by cost per power throughput compared to conventional power modules.

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