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Automotive Power Module Packaging: Current Status and Future Trends

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ABSTRACT Semiconductor power modules are core components of power electronics in electrified vehicles. Packaging technology often has a critical impact on module performance and reliability. This paper presents a comprehensive review of the automotive power module packaging technologies. The first part of this paper discusses the driving factors of packaging technology development. In the second section, the design considerations and a primary design process of module packaging are summarized. Besides, major packaging components, such as semiconductor dies, substrates, and die bonding, are introduced based on the conventional packaging structure. Next, technical details and innovative features of state-of-the-art automotive power modules from major suppliers and original equipment manufacturers are reviewed. Most of these modules have been applied in commercial vehicles. In the fourth part, the system integration concept, printed circuit board embedded packaging, three-dimensional packaging, press pack packaging, and advanced materials are categorized as promising trends for automotive applications. The advantages and drawbacks of these trends are discussed, and it is concluded that a preferable overall performance could be achieved by combining multiple technologies.

INDEX TERMS Electric vehicles, power electronics, semiconductor device packaging.

I. INTRODUCTION

The automotive industry is undergoing a paradigm shift in electrification. During the past decades, the electrified vehicle market has been booming [1]. It is forecasted that electrified vehicles will take over 35% of the entire car market by 2040 [2]. Power electronics systems, which account for around 45% cost of the traction system, also have huge market prospects [3]. For example, it is estimated that the traction inverter market will reach $71bn in 2020, almost two times the number of 2012 [4].

The core building blocks of power electronics systems are semiconductor devices. Proper packaging design is necessary to construct a device from bare semiconductor chips. Currently, both discrete devices and multichip modules are adopted in the automotive application. Their basic packaging requirements are mostly similar, while the multichip modules require extra attention to chip spacing and circuit design. As a complex multi-physics system, the packaging should provide not only desirable electrical properties but also excellent thermal and mechanical properties [5]. Table 1 lists the primary design considerations and parameters that are critical for packaging designs [5]–[7]. In automotive applications, some of the factors are even more significant than in common industrial applications. For any automotive part, due to the vast production volume, the cost is one of the most sensitive factors. Also, to extend the driving range, high power density and efficiency are required. Considering the harsh operation condition, the automotive power modules must be able to deal with a wide range of operation temperatures, usually from −40°C to 150°C. In addition, complex vibration loads from the traction system and the road condition put higher reliability requirements on the module, including sufficient mechanical strength, proper sealing, and reliable connectors. For these reasons, the design of automotive modules is more complicated, and there is an urgent need to develop advanced technology [8], [9].

The first generation of automotive power modules followed the industrial standard packaging technologies with a direct bond copper (DBC) substrate, wire-bonding

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TABLE 1. Primary design considerations of module packaging.

Design considerations	Details
Size	Volume, weight, power density, energy density.
Electrical performance	Current rating, voltage rating, switching frequency range, power loss, electrical insulation, electromagnetic interference (EMI).
Thermal management	Temperature distribution, thermal resistance (R_{th}), heat capacity, coefficient of thermal expansion (CTE).
Mechanical strength	Thermal stress distribution, material properties (Tensile strength, flexural strength, peel strength, etc.), external shock and vibration.
Reliability and fatigue	Joints failure, crack propagation, delamination, life-time under temperature and power cycling.
Manufacturability and assembly	Manufacture procedure, process temperature and pressure, external connections.

interconnections, and a baseplate. Examples are the power modules implemented in both the Honda Civic 2006 and Toyota Prius 2004. In the second generation, the packaging structures were more compact and efficient. For example, the Delphi module designed in 2010 applied flip-chip soldering and direct substrate cooling. Also, in 2010, Toyota launched the improved design with ribbon bonding and direct substrate cooling, which reduced the packaging height from 9mm to 3mm [10]. In 2015, Mitsubishi introduced the new J series and J-1 series modules, which applied direct lead bond technologies and alternative substrates [11], [12]. In 2017, a SiC 1-in-1 module was utilized in Tesla Model 3 [13]. This module applied copper ribbon as interconnections and pin fins as the heat sink. Nowadays, with rapid and comprehensive automotive electrification, the module needs to meet stricter requirements. To meet the demand of high-performance EVs and off-road EVs, the power-rating can exceed 200kW. To still maintain a reasonable efficiency at such a high power rating, higher voltage ratings (over 800 V) are preferred. Not to mention the pursuit of lightweight and downsizing [8], [9]. These requirements bring a few challenges to the module packaging. For example, a compact layout helps to increase power density, but it brings challenges to thermal management and reliability. The heat flux will increase with a smaller die area, and smaller packaging makes heat spreading and dissipation limited. The high temperature will further affect the reliability of the bonding, interconnections, and insulation layers. Meanwhile, the precision and reliability of manufacturing processes, such as soldering and sintering, would be more difficult due to the reduced footprint and compact layout. However, these challenges seem unavoidable in future power modules, especially when conventional silicon (Si) devices are being replaced by wide bandgap (WBG) devices that have a smaller footprint. Moreover, since WBGs typically operate at a higher switching speed, the parasitic parameter of the packaging should be further minimized to avoid large spikes and ringing during the switching and achieve a low switching loss. Many emerging packaging concepts have been proposed in response to these challenges. The most promising technologies for automotive applications are discussed in this paper.

A few papers have reviewed the topic of power module packaging. The majority focuses on fundamental knowledge and emerging technologies [14], [15]. In terms of automotive applications, [5], [16], [17] introduced a few renowned power modules from original equipment manufacturers (OEM). In [18], the renowned standards for power module packaging and the related patterns within the last 20 years were reviewed. However, in recent years, new designs have been introduced to the market and literature, which are not included in most existing review papers. There is a lack of review papers covering both technical fundamentals, the latest commercialized designs, the future trends, and the interrelationship between each of these aspects.

This paper summarizes the knowledge differently to fill the gap discussed above. A brief introduction of the background knowledge is given in section II. Then, the latest readily available designs from major automotive suppliers and OEMs within the past few years are presented in Section III. In Section IV, a few prominent technologies are selected as future trends based on the challenges of current designs and requirements of future modules, including integrated packaging, PCB embedded packaging, 3D packaging, press pack packaging, and advanced materials. Finally, conclusions are given in Section V.

II. PACKAGING FUNDAMENTALS

Power semiconductor modules implemented in power converter applications for electrified vehicles operate in harsh environments [19]. Single or multiple semiconductor bare dies must be packaged with other structures to form a device to ensure electrical, thermal, and mechanical reliability. A primary procedure of power module design is summarized in Fig.1 In this flow chart, the requirements should be defined based on the specific automotive application, including the power rating, the voltage rating, the load condition, and the operating environment. In this procedure, a few steps require further explanation. In the topology design step, the number of paralleled dies is basically determined by power loss simulations. The insulation quality is usually evaluated by the electrical field strength and the leakage current. The reliability is usually predicted based on stress-strain profile and tested by temperature cycling and power cycling. Finally, the prototype module should be tested in an automotive traction system to evaluate its system-level performance.

A conventional power module is shown in Fig. 2 where the power devices are mounted onto the substrate with the chosen die-attach technology and the electrical connections formed through the use of bond wires. The following will discuss details in this design.

A. SEMICONDUCTOR DIES

The core components in power electronics devices are the semiconductor dies. Currently, Si Insulated Gate Bipolar Transistors (IGBTs) are widely implemented in

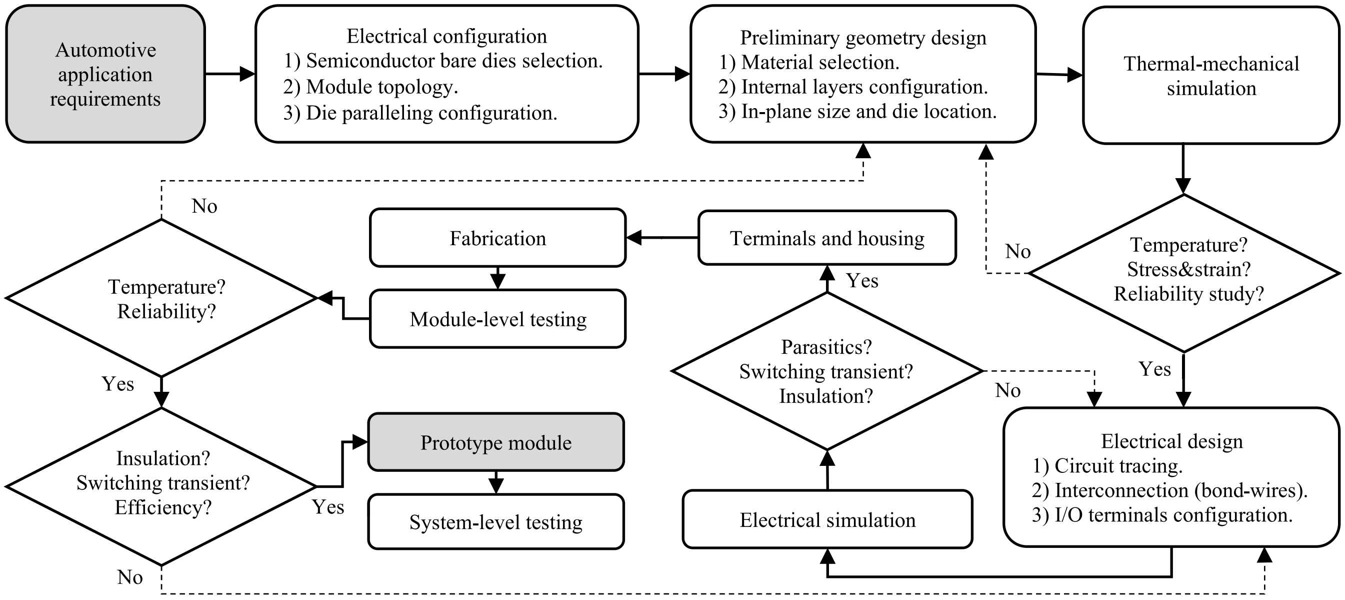


FIGURE 1. Primary design process of power modules.

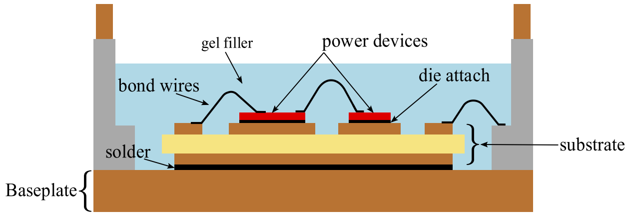


FIGURE 2. Schematic of typical packaging of power module.

power semiconductor devices for electrified transportation applications [20]. Off-the-shelf products also include silicon carbide (SiC) Metal Oxide Semiconductor Field Effect Transistor (MOSFET) based power modules and discrete devices, with the latter being implemented in Tesla's Model S and X [21]. Gallium Nitride (GaN) dies are commercially available but are currently not prevalent due to the larger CTE compared to the Si, thus making the epitaxial growth of GaN very difficult [22].

A shift from Si devices to WBG devices is expected to meet the exceeding demands for higher power density and efficiency in the automotive industry [23]. The electrical and thermal properties for Si, SiC, and GaN are compared in Fig. 3, where a high value is preferable for all the properties shown. As can be observed from Fig. 3, the bandgap energy, breakdown voltage, thermal conductivity, and maximum operating temperature of WBG devices far exceed their Si counterpart [24], [25]. With a higher maximum operating temperature and thermal conductivity, WBG devices could potentially ease thermal management requirements. Generally, SiC power modules are foreseen to be implemented for high voltage applications over 1.2kV, while GaN is typically used for voltages below 650V. The technical advantages of WBGs have already been proven in many works, and the

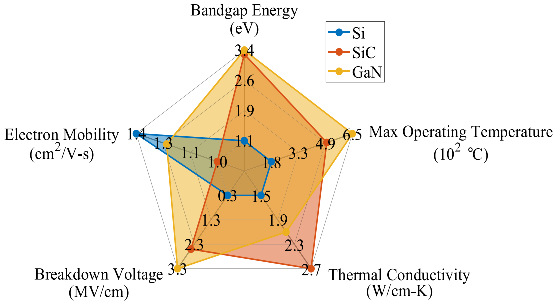


FIGURE 3. Electrical and thermal properties of Si, SiC, and GaN.

prices are forecasted to be decreased tremendously in the near future, mainly due to the adoption in the automotive industry [26].

B. DIE ATTACHMENT AND INTERCONNECTION

Packaging the power devices requires attachment to a substrate and electrical interconnection to the circuit tracing. The major attachment technologies include solders [27], silver-sintering [28], and transient liquid-phase bonding (TLPB) [29], [30]. Properties to consider during material selection include the melting temperature, thermal conductivity, as well as the CTE since this will affect performance degradation during thermal cycling. In-depth reviews of each die attachment technology can be found in [31]–[35].

Currently, Aluminum (Al) bond wires are the predominant interconnection technology in power modules for electrified transportation. Bond wires usually undergo fast and large-scale temperature cycling due to relatively high current density and low thermal capacity [36]. Consequently, cracking and fractures might occur due to high stress, and bond wire lift-off might result due to accumulated elastic strain [37]. In fact, failures of the wire bonding are the dominant failure modes in conventional power modules. Therefore, more advanced wire technologies have been investigated to mitigate the thermal-mechanical challenge, such as Al wire ribbons, Al-Copper (Al-Cu) wires, Al-Cu ribbons, and Cu wires/ribbons [38]–[41]. The aforementioned technologies still use wires, and ultimately, planar interconnect technology and pressure-based bondless connection will allow for higher reliability and lower parasitic inductance [42].

C. SUBSTRATE

Substrates include a conductive layer where the dies are placed, an electrically isolating layer, and another conductive layer to mount to the baseplate. DBC, a ceramic layer with copper bonded on both sides, is the most commonly used substrate in off-the-shelf power modules. To achieve higher temperature cycling capability, the metallic material can be replaced by aluminum, which is called direct bond aluminum (DBA) [43]. Commonly used ceramic materials for the isolating layer include Silicon Nitride (Si3N4), Aluminum Nitride (AlN), Aluminum oxide (Al2O3), and Beryllium oxide (BeO). A comparison of their properties is summarized in [44]. Other substrate technologies, including direct plated copper (DPC), Thick Film, active metal brazed substrate (AMB), and insulated metal substrate (IMS), are available. Their advantages and disadvantages are discussed in [45]–[47].

D. BASEPLATE AND HEATSINK

The substrate is typically soldered onto a baseplate to ensure heat spreading and mechanical support. Usually, to attach a cooling solution to the baseplate, a thermal interface material (TIM) such as thermal paste needs to be applied to eliminate air gaps and reduce the contact resistance. Baseplates are commonly made out of AlSiC or Cu. However, to mitigate their high CTE, metal matrix composites are created to achieve both a low CTE and high thermal conductivity [48]. Typical examples are W-Cu, Mo-Cu, and Cu-Mo-Cu. The properties of these composites vary with the composition ratio. More details of baseplate materials are introduced in [49]–[52].

A typical power module mounted onto a heat sink is shown in Fig.4. However, more advanced solutions include integrating the heat sink into the baseplate itself. Circular pin-fins have been the predominant form implemented for direct cooling of the baseplate.

Separate heat sink solutions for the power module still exist and in the automotive industry predominantly include the horizontal-channel style type of cooling. Different types of fin configurations from flat-plate fins to oval-shaped fins have also been implemented. Micro-channels have been investigated but suffer from higher pressure drops.

E. ENCAPSULATION MATERIALS

An encapsulation material to cover the devices is required under hash operations. Traditionally, there are at least two layers of encapsulation materials. To provide primary insulation and limit leakage current, the top surfaces of the dies are covered with a thin passivation layer, which is usually polyamide materials with a strong breakdown strength of 100-280 kV/mm. Another layer could be deposited above the passivation layer to further insulate different conduction zones within the module, and more importantly, protect the module from the environment [16]. Typically, the material of this layer could be silicone gels, epoxy resins, and silicone elastomer [53]. The thickness of encapsulation materials is determined by voltage and temperature ratings.

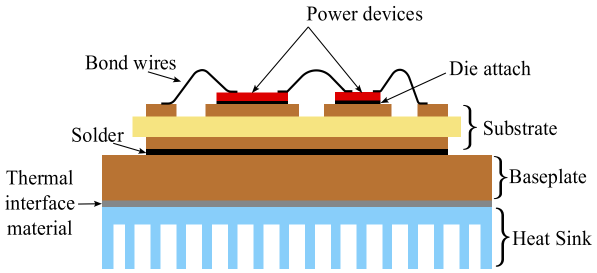


FIGURE 4. Power module mounted onto heat sink solution with TIM.

However, since conventional encapsulation materials have low thermal conductivity, inorganic materials such as ceramics are being investigated [54]. Ceramic encapsulants were shown to increase the power module's lifetime by a factor of 3.5.

III. STATUS

In this section, the most recent automotive power modules are presented. Several papers have already reviewed some designs. For example, [5] provides a description of numerous technical advances implemented by automotive suppliers and OEMs. Among them, one can cite the SKiM and SKiN modules from Semikron, COOLiR2DIE from International Rectifier recently acquired by Infineon, the Si-based Viper developed by Delphi, and power modules from Mitsubishi and Bosch. In addition, Nissan designed its own module for the LEAF pure EV, and Toyota worked in collaboration with Denso to develop a module for the LS600 hybrid. Besides these designs, [17] reported further information regarding the Infineon HybridPACK family, and the module used in the renowned Toyota Prius hybrid.

In the following, power modules that have not been widely reported in the literature will be presented. Complementary information on the modules described in the review papers previously mentioned will also be added. Compared to most traditional designs, these products are innovative in response to the higher demand for next-generation automotive power electronics, mainly focusing on improving energy density and reliability, reducing losses and costs, etc. Details are discussed in the following subsections and summarized in TABLE 2.

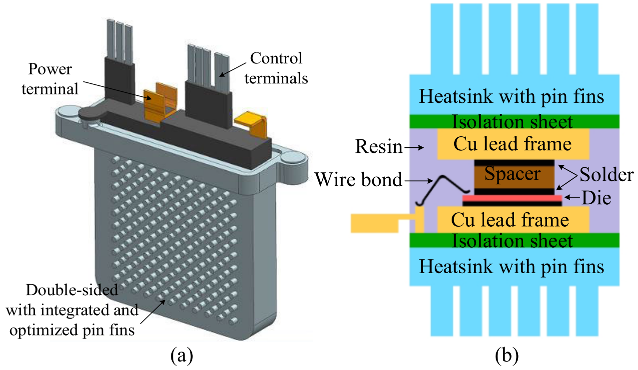
A. HITACHI AUTOMOTIVE SYSTEMS

In response to the need for traction inverters in 450VDC-class EVs, Hitachi developed a half-bridge power module formed

TABLE 2. **Innovative trends in each module.**

Suppliers	Examples of EVs	Module configuration and maximum ratings	Die Interconnection and die attach	Substrate, baseplate assembly, and encapsulation	Cooling
Hitachi	Cadillac CT6 plug-in hybrid (General Motors), S500 and S550 plug-in hybrids (Mercedes Benz), e-tron (Audi)	Half-bridge IGBT, 700V, 325Arms	Cu lead frame soldering	Isolation sheet, removal of the baseplate and thermal grease, resin	Double-sided with integrated and optimized pin fins
Delphi	Volt extended-range EV (Chevrolet)	Single IGBT, 430V, 325Arms	Flip-chip soldering	Direct substrate cooling, CTE-matched ceramic substrates	Double-sided
	Unknown	Single SiC MOSFET, 650V, 285Arms	Ni/Au plated metal stack for top-side soldering or sintering	Unknown	Double-sided
Toyota and Denso	Toyota	Half-bridge IGBT, 650V, 180Arms	Flip-chip soldering on a surface electrode	Isolation sheet	Double-sided
Continental	I-PACE (Jaguar), Range Rover Sport Plug-In Hybrid	Half-bridge IGBT, 450V, 650Arms	Double-sided sintering	AlN DBC ceramics, removal of the baseplate and thermal grease	Single-sided, AlSiC heatsink
STMicroelectronics	Tesla Model 3	Single SiC MOSFET, 650V, 100Arms	Cu ribbon bonding, silver sintering	Unknown	Single-sided pin fins
Mitsubishi Electric	Honda Insight	Half-bridge J-series TPM IGBT, 600V, 300Arms	Al wire bonding, Cu DLB	TCIL, direct substrate cooling, resin	Single-sided
	Unknown	6-in-1 J1-series IGBT family, 650V to 1200V, 300Arms to 1000Arms	Al wire bonding, Cu DLB	Isolation layer, removal of thermal grease	Single-sided with optimized and integrated pin fins
Infineon	Renault Zoe, BWM i3, Volkswagen group	6-in-1 HybridPACK IGBT family, 650V to 750V, 200Arms to 800Arms	Cu wire bonding, diffusion soldering	Different substrate-to-baseplate solder joints	Single-sided pin fins or double-sided
Nissan	Nissan Leaf EV	Custom-made IGBT, 600V, 340Arms	Wire bonding, buffer plate	Isolation sheet replacing of the ceramic substrate, baseplate and the circuit pattern board	Single-sided
Fuji Electric	Honda Accord Hybrid	Boost+6-in-1+6-in-1; 700V, 124kW	Wire bonding	No baseplate	Straight fins direct cooling
	Unknown	High bridge All-SiC; 1200V; 25A to 400A	Cu pins with flexible board.	Thick Cu blocks with Si_3N_4 sheet; no baseplate	Single-sided

by trench IGBT/diode devices rated at 700V, 325Arms maximum. By doing so, the integration of the modules within the inverter is simplified. In [55], a comprehensive review of the different generations is detailed. In its 3rd generation, Hitachi significantly increased the power density and cooling efficiency, thanks to, among other things, double-sided cooling. Fig.5 shows the power module and the internal cross-section. By removing heat from both the top and bottoms side and eliminating thermal grease and baseplate, better heat dissipation is achieved. Experimental results showed that 35% improvement of the thermal resistance is achieved compared to single-sided cooling [56]. In addition, the pin fin design is based on optimization with a genetic algorithm that selects the optimal number of fins, fin spacing, and height while considering the thermal resistance and the pressure losses. Cooling efficiency is also improved by using resin and isolation sheets of high thermal conductivity between the copper lead frame and the heatsink.



(a) (b)

FIGURE 5. **3rd generation Si-IGBT power module from Hitachi: (a) CAD model. (b) Internal cross-section [56].**

Hitachi's technologies, including inverters, DC/DC converters, and electric machines, have been used by many OEMs such as in the Cadillac CT6 plug-in hybrid from

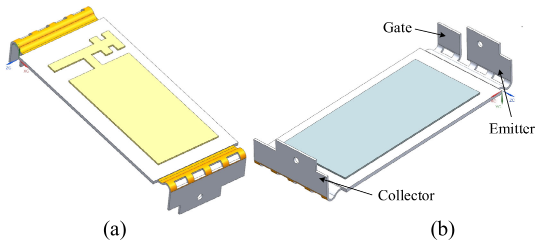


FIGURE 6. **Si-based Viper power module from Delphi. (a) Top view. (b) Bottom view [60].**

General Motors, the S500 and S550 plug-in hybrids from Mercedes Benz, and the Volt from General Motors [57], [58]. Recently, Audi announced that its traction inverter in the 2019 e-tron uses the next-generation IGBT module from Hitachi [59]. Compared to previous versions, the inverter achieved a 160% power density increase.

B. DELPHI TECHNOLOGIES

Delphi Technologies developed an IGBT/diode module in partnership with International Rectifier, called Viper, in a discrete power package. The module is shown in Fig.6. For example, it is used in the Chevrolet Volt extended-range EV [60]. Several technological advances have been combined to reduce cost while increasing reliability and power density [61]. For example, the flip-chip soldering technique was used instead of wire bonds to improve the current distribution and lifetime of the die interconnection. Baseplate materials such as AlSiC were replaced by ceramic substrates with a CTE that matches that of silicon to mitigate the thermal stress. By doing so, less thermal layers were used between the die and the coolant, which reduced the thermal resistance and cost.

More recently, Delphi partnered with Cree, Oak Ridge National Laboratory, and Volvo to develop automotive SiC switches [62], [63]. They designed a SiC-based switch rated at 650V and 285Arms maximum, as shown in Fig.7. Wire bonds were eliminated and replaced by a nickel (Ni)/gold (Au) plated metal stack attached by either top-side soldering or sintering techniques. Double-sided cooling is also implemented. This device is featured by low on-state resistance, which is tested to be around 7 mOhm at room temperature. In comparison to the previous Si module, the SiC-based switch achieved a 70% loss reduction at low currents and 30% at maximum ratings. Moreover, the reliability test showed that this module did not fail after 36000 power cycles with a 100°C difference between the maximum and minimum junction temperature. Featured by low power losses, high cooling efficiency, and high reliability, this device takes advantage of both WBG technologies, planar connection, and double-sided cooling. Although the device was initially developed for 400V bus systems, the packaging allows, in theory, for higher voltages up to 1200V and 500Arms. Given the interest of 800V DC-link traction inverters, Delphi is now working on the production of the next generation of SiC modules.

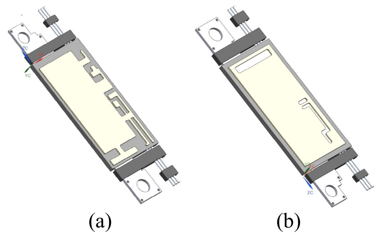


FIGURE 7. **SiC-based Viper switch from Delphi: (a) Top view. (b) Bottom view [62], [63].**

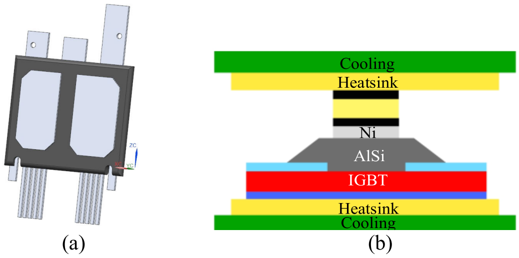


FIGURE 8. **4th generation Si-IGBT power module from Toyota/Denso: (a) CAD model. (b) Internal cross-section [64], [65].**

C. TOYOTA AND DENSO

In collaboration with Denso, Toyota has developed its 4th generation power module, implemented in a power pack unit composed of two inverters and a DC/DC boost converter [64], [65]. This module is mainly targeted at improving the power density and reducing the parasitic inductance. By integrating two IGBT/diodes in a half-bridge configuration rated at 650V, 180Arms, about 22% of the footprint and 55% of the inductance have been reduced, compared to the use of wires to connect discrete switches. The module also features double-sided cooling with isolated sheets, and its card format improves the modularity, as shown in Fig.7 (a). Instead of using wire bonds, the die is attached thanks to flip-chip soldering technique, and soldered to a nickel (Ni) electrode, as displayed in Fig.8 (b). Compared to the previous generation, the IGBT is composed of a super body layer that enables 16% conduction loss improvements, without affecting the switching losses.

To investigate the advantages of WBG devices, Denso developed a SiC-based 6-in-1 module composed of six switches to form a voltage source inverter, which features extremely high efficiency and power density, as shown in Fig.9 [66]. Compared to the Si-based inverter, using SiC MOSFETs requires further design care to reduce the stray inductance within the module. By using magnetic cancellation techniques, a low inductance of 10.6nH can be achieved, which reduced the voltage spike by 70% during the switching test. To verify its performance, a 70 kW air-cooled prototype inverter was constructed and measured to have an extremely high power density of 100kW/L, and an efficiency of over 99% [66]. In 2015, Toyota began on-road testing with the Toyota Camry that features a SiC inverter.

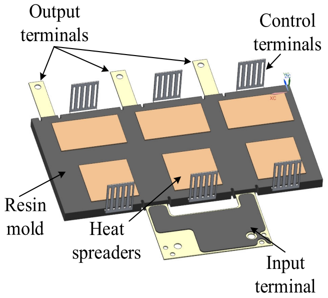


FIGURE 9. SiC-based 6-in-1 power module from Denso [66].

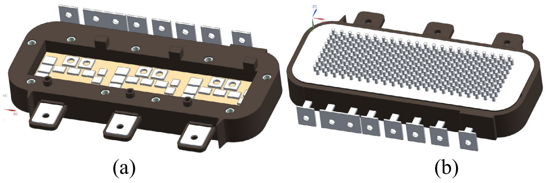


FIGURE 10. Inverter power module from Continental: (a) Top view. (b) Bottom view [67].

D. CONTINENTAL

The new Jaguar I-PACE and the Range Rover Sport Plug-In Hybrid have been introduced in the market recently. However, very little information on their powertrains has been released yet. Nonetheless, it has been announced that the power electronics was developed by Continental.

Continental designed a half-bridge IGBT power modules rated at 450VDC, 650Arms maximum, and combined three of them in a single package to facilitate traction inverter assembly [67]. Fig.10 shows the inverter power module. Lower thermal resistance with direct cooling of the power module has been achieved by removing the copper baseplate and thermal grease. By using CTE-matched materials AlSiC for the heatsink, the mechanical stress is largely reduced, and the power cycling capability is improved by ten times (over 20000 cycles) based on experimental data. Moreover, double-sided sintered technology, which consists of replacing conventional solder by silver (Ag) sintered layers on both sides of the chip, was used as it increases the reliability, lifetime, and power cycling capability.

E. STMicroelectronics

ST Microelectronics is strongly involved in the development of WBG devices and continuously gain popularity in the automotive market. For example, the company supplied SiC MOSFETs to Tesla for its inverter in the Model 3 [13]. Moreover, Renault-Nissan-Mitsubishi recently announced that it would use ST technology for its next-generation onboard chargers.

A few pieces of information have been released on the SiC module implemented in the Tesla Model 3. Fig.11 shows the top and bottom view of the module. This 1-in-1 power module is rated at 650V, 100 Arms maximum, and the package uses silver sintering technology to improve the thermal capability. Bond-wires are replaced by copper lead, which improves the heat dissipation and power capability.

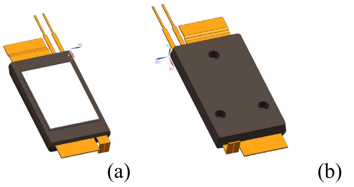


FIGURE 11. SiC power module developed by STMicroelectronics: (a) Top view. (b) Bottom view [13].

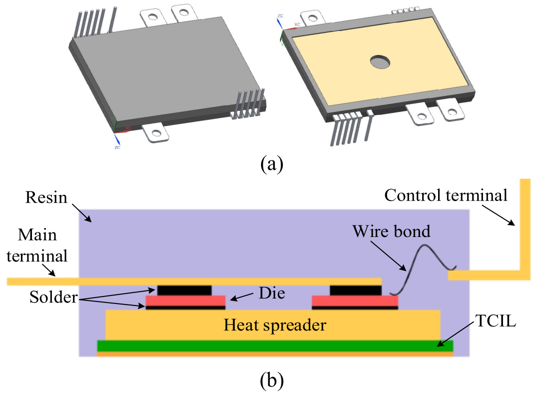


FIGURE 12. Mitsubishi J-series TPM power module: (a) CAD model (top and bottom views). (b) Internal cross-section [11].

F. MITSUBISHI ELECTRIC

Mitsubishi Electric has developed high-power modules with different packages depending on the power rating. For applications up to 50 kW, Mitsubishi manufactured its J-series transfer-molded power module (TPM). It consists of two IGBT/diodes forming a half-bridge in a single package shown in Fig.12 [11]. Instead of using traditional wire bonding, by applying direct lead bond (DLB) technology, the power and thermal cycling capability were increased, while the internal inductance and lead resistance were reduced. Al wire bonds are only used for signals. A thermally conductive electrically isolated layer (TCIL) was also added below a heat spreader to increase heat conduction. Directly soldering the chips on the heat spreader enables better transient thermal performance. Besides, this module features on-chip temperature and current sensors that facilitate fault detection and protection. This module has already been implemented in the Honda Insight [10].

For high-power traction inverters up to 190kW, Mitsubishi developed a new family of 6-in-1 modules, called J1-series, that is composed of six IGBT/diode switches forming a voltage source inverter circuit [12]. The IGBT chips are the 7th generation carrier stored trench technology, which enables reducing power losses by more than 10% compared to previous generations. Similar to the J-series previously presented, the J1-series modules also feature DLB technology and on-chip temperature and current sensors. The package

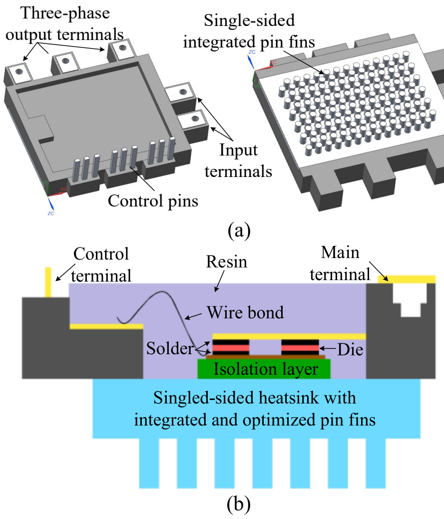


FIGURE 13. Mitsubishi J1-series power module: (a) CAD model (top and bottom views). (b) Internal cross-section [12].

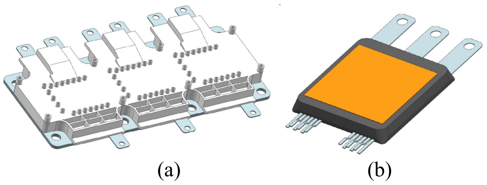


FIGURE 14. Power modules from Infineon: (a) HybridPACK$^{\text{TM}}$ Drive. (b) HybridPACK$^{\text{TM}}$ DSC S2 [73], [74].

layout has been improved by using direct liquid cooling where optimized pin fins are integrated into the module and heatsink grease is no longer required. From experimental results, the thermal resistance is further reduced by 30% [68]. The J1-series module is shown in Fig.13. With a 40% reduction of volume compared with J series, this module has a footprint of 120mm×115.2mm×31mm.

G. INFINEON

Infineon is another world leader in power semiconductors, and many OEMs have adopted its technology in their powertrains [69]. For example, the traction inverter in the BMW i3 and Renault Zoe integrate the HybridPACK 2 power module. Furthermore, Volkswagen announced in 2019 a partnership with Infineon to supply power semiconductors for the new EVs that will be developed in the next ten years.

The HybridPACK$^{\text{TM}}$ family is composed of several IGBT-based modules rated for different power [70], [71]. Several advances have been integrated to improve the efficiency and power density of the modules. As shown in Fig.14 (a), the recently released HybridPACK$^{\text{TM}}$ Drive applied direct pin-fin cooling with a 36% smaller baseplate compared to HybridPACK$^{\text{TM}}$ 2. By reshaping the IGBT dies, the bond wire resistance is reduced by 25%, which lead to a 21% smaller conduction loss and a 29% smaller switching loss from testing. Besides, double-sided cooling technologies are implemented in HybridPACK$^{\text{TM}}$ DSC S2, as shown in Fig.14 (b) [72]. In [73], Infineon performed power cycling tests to evaluate the reliability of its diffusion soldering process and its newly developed package assembly, composed of Cu wire bonds and different substrate-to-baseplate joints. Silver sintering and diffusion soldering, are compared in [74] in terms of reliability. Infineon also started to offer SiC modules with an optimized package for higher power demands.

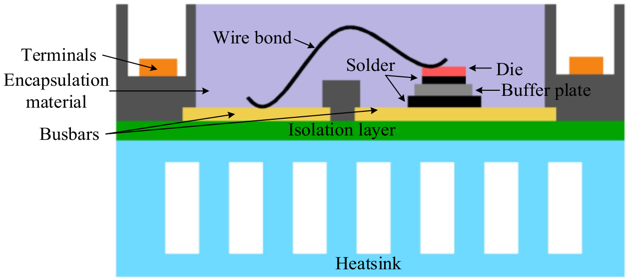


FIGURE 15. Cross-section of the power module in the Nissan LEAF [75].

H. NISSAN LEAF

In its pure EV LEAF, Nissan designed its own custom semiconductors [75]. This module investigated several packaging technologies to enhance heat dissipation and mitigate thermal stress, which could potentially improve reliability. Unlike a traditional structure, the die is directly soldered to a buffer plate made of Cu-Mo alloy, and the latter is soldered to the busbars. This reduces the stress caused by a CTE mismatch between the die and the busbar. The ceramic substrate, baseplate, and the circuit pattern board have been removed. Instead, a sheet made of silicon with ‘‘special fillers’’ has been added between the busbar and the heatsink to provide thermal conduction and electrical insulation [76]. Fig.15 shows the internal cross-section of the module.

I. FUJI ELECTRIC

Fuji Electric has been investigating automotive power modules since the 1980s. Several generations of IGBT modules have been proposed during the past few decades [77]. The renowned Fuji IGBT intelligent power module (IPM) was implemented in Honda Accord Hybrid since 2012. This module includes a boost converter and two three-phase inverters and is mainly packaged with conventional technology. However, instead of applying a regular baseplate, a direct-cooling heatsink with straight fins is bonded to the substrate. Due to the compact integration of systems, this design enhanced power density, system-level reliability, and multiple performances. The module is shown in Fig.16 [78], [79].

In recent years, Fuji has been leading the research on SiC technology, especially the trench gate SiC. Several full-SiC power modules have been introduced based on new packaging technology, as shown in Fig. 17 [80]. To reduce the stray inductance and the switching loss, copper pins and a flexible board were applied to construct the interconnections instead

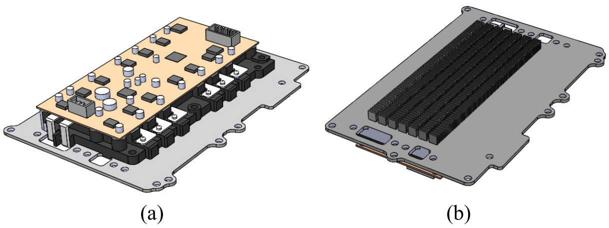

(a) (b)

FIGURE 16. IPM from Fuji Electric/Honda Accord Hybrid: (a) Top view. (b) Bottom view with integrate straight pins [78], [79].

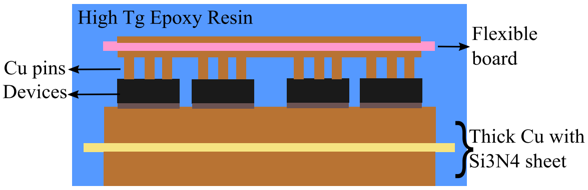


FIGURE 17. Section view of Fuji Electric SiC modules [80].

of bond wires. The encapsulation is formed by a high glass transition temperature (Tg) epoxy resin to improve reliability. A comparative study indicated that this new packaging design has over 30 times the power cycling ability than the traditional structure. Meanwhile, the switching loss is reduced by over 57% compared to Si devices with traditional packaging and 17% compared to SiC devices with traditional packaging [81] according to the switching test.

TABLE 3. Advantages and challenges of selected technologies.

Concept	Advantages	Challenges
System integration	Reduced system complexity; reduced parasitic inductance and resistance; improved power density; improved system reliability.	Increased difficulty in manufacture; increased difficulty in thermal management;
PCB embedded packaging	Convenience for system integration; reduced parasitic inductance and resistance; improved power density; improved system-level reliability. reduced cost;	Lower maximum operation temperature; Lower bonding strength between layers
Press-pack packaging	Reduced system complexity; reduced cost; improved joint reliability; improved manufacturability and ease of assembly; higher modularity.	Pressure sensitivity; contact resistance of thermal and electrical conduction.
High complexity 3D packaging	Convenience for system integration; improved power density; additional heat dissipation paths; higher modularity.	Increased system complexity; increased difficulty in manufacture and assembly.

IV. FUTURE TRENDS

As discussed above, the large-scale promotion of high-performance electric vehicles places higher requirements on power modules, including but not limited to cost, maximum rating, switching characteristics, heat dissipation performance, reliability, and insulation. In the latest commercial vehicle power modules, there have been many innovative designs to improve the limitations of the traditional DBC-based packages in one or multiple aspects. However, there is still a long way to go before a design perfectly addresses most of the challenges, especially with the promotion of WBG devices. Recently, various novel packaging concepts and designs are emerging in academia and industry. Several concepts are particularly promising for automotive applications and are studied in this section. Each of them satisfies some of the requirements discussed above. However, they have not been widely implemented in the industry because of their limitations. Their advantages and challenges are summarized in Table 3. In practice, these concepts are often combined to compensate for each other's shortcomings.

A. SYSTEM INTEGRATION

System integration can enhance reliability, increase power density, improve switching performance and efficiency. It is considered one of the mainstream directions for future automotive power modules. Currently, integrating the gate driver circuit is the most widely investigated method of system integration. This method usually results in a shorter conduction loop with lower parasitic parameters, which can increase the switching speed and reduce the switching loss [82], [83]. Moreover, by system integration, the number of parts of the entire power electronics system is reduced, especially the connections, which improves the much-respected system reliability in the automotive application.

Some conventional packaging structures can still be used to integrate components, such as DBC substrates and wire bonding [82]. For example, the University of Texas at Austin introduced a 1200 V SiC MOSFET half-bridge module packaged together with the gate driver integrated circuits (ICs) on a DBC substrate [82], [84]. The design is shown in Fig.18 (a). Through system integration, it eliminates the common source inductance and external gate resistance, minimizes stray inductances. Compared with conventional TO-247 packaging, this design has improved switching behavior in high-frequency operation and over 75% reduction of turn-off losses at high temperatures.

Another gate driver integrated module with an AlN DBC is shown in Fig.18 (b). Verified in a Class E resonant converter, this module achieves a low drain-source inductance of 6.3 nH. Meanwhile, the junction-to-ambient thermal resistance of the DBC mounted gate driver IC is decreased tremendously from 98K/W to 46K/W compared with that of separate gate driver on a PCB [85].

With a similar approach, Arkansas Power Electronics International (APEI) introduced another gate driver integrated SiC power module designed for a bridgeless-boost

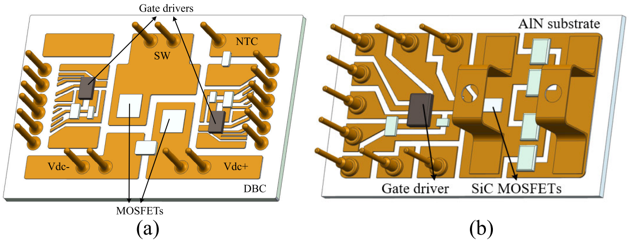


FIGURE 18. DBC based gate driver integrated modules [82], [86].

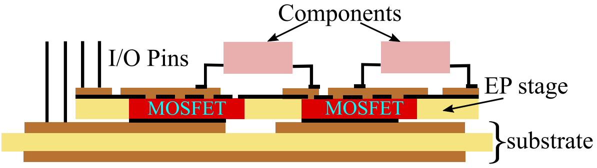


FIGURE 19. Integrated packaging design with EP stage [87].

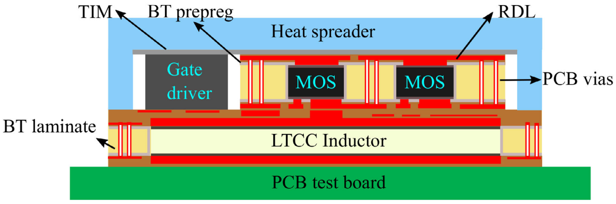


FIGURE 20. PCB Embedded package with LTCC inductor [91].

converter used as a battery charger for electrified vehicles [86].

In [87], the gate driver ICs, the current sensors, and the ceramic capacitors are co-packaged on a planar structure. Meanwhile, the MOSFETs are mounted in a ceramic embedded power stage (EP), as shown in Fig.19. A similar planar structure is reported in [88]. In [89], the possibilities of integrating GaN devices and gate drivers are studied, a new packaging combining conventional DBC with PCB embedded technology is proposed.

In fact, integrating components into a PCB is another promising approach to achieve system integration, which can be implemented either by embedding or surface mounting methods. Mitsubishi Electric R&D Center Europe (MERCE) introduces a design where the switches are directly embedded into a PCB section called power stage and are closely integrated with gate driver ICs, a ceramic capacitor, and an inductor section. It can achieve a fast switching of 58kV/μS without ringing [90]. This module is a typical example of integrating multiple electronic components into one package in addition to the gate driver ICs. Similarly, in Fig. 20, the gate driver and a low-temperature co-fired ceramic (LTCC) inductor are packaged together in a PCB system [91].

Other than the examples studied above, the power module can also be integrated with the cooling system [92]–[96], sensors [97], [98], busbars [94], [99], EMI filter [100].

Different types of integration can benefit the system in different ways. Nevertheless, there still exist a few limiting factors for the wide use of system integrations in the automotive industry. For example, the manufacturing process needs to be carefully considered while designing the module because system integration might increase manufacturing complexity and cost. Since it is for automotive applications, the process also needs to be compatible with automated mass production. Secondly, in such a compact system, the heat is generated from multiple sources and might cause a high heat flux due to reduced volume. Meanwhile, the area available for heat dissipation is also limited. Besides, additional concerns for thermal management exist, such as the maximum durable temperature of other electronic components in an integrated power module. Thus, advanced technologies for reducing thermal resistance and improving heat dissipation are usually necessary for integrated power modules. Those shortcomings could be minimized by combining other technologies such as PCB embedded technology and advanced cooling methods.

B. PCB EMBEDDED TECHNOLOGY

The biggest advantage of PCB embedded packaging is the convenience of system integration, as explained above. Thus, it has most of the advantages of system integrated packaging. When the chip is embedded in the PCB, the system volume could be furtherly reduced, and the reliability could be improved. Due to the maturity of the PCB process, this technology reduces the manufacturing difficulty and cost and improves system reliability. Thus, it is even more attractive than other embedded technologies for electrified vehicle applications that require cost-effective and durable solutions [101]–[103]. So far, this method has been applied in the packaging of Si IGBT, SiC MOSFET, and GaN [101], [104]. The first embedded technology, High-Density Interconnection (HDI) technology, was introduced by General Electric in the late 1980s. Since then, this concept has been developed rapidly in both industry and academia, especially in Europe. Fig.21 illustrates the typical process of PCB embedded packaging for top connecting devices provided by AT&S, where all the layers are stacked up from the bottom copper foil [105].

Another process is introduced in Fig. 22, where the embedding of the devices is treated as a post-process after the laminate‘s lay-up [106]. In addition, in [107], a fan-out process is investigated, which uses panel-level physical vapor deposition and redistribution layers technologies to achieve die attachments and interconnections.

In PCB embedded packaging, conventional chip bonding technologies are still applicable, such as soldering [108] and sintering [103]. Especially, nano-silver sintering is widely used due to its high thermal conductivity and low CTE [109]. However, the wire-bonding connection is no longer suitable here. Instead, the conduction paths are usually formed by the copper traces and vias. The structural complexity of the mixed area of vias and the embedding materials creates challenges for analysis, such as modeling the thermal conductivity and electrical conductivity of those areas. [91] reported an equivalent thermal conductivity model of the vias.

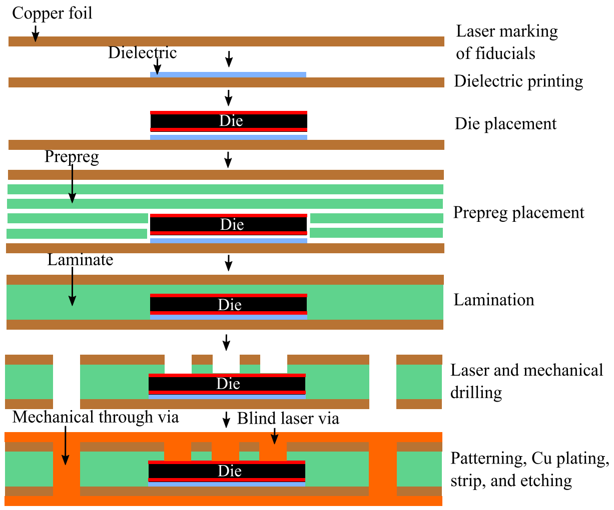


FIGURE 21. AT&S embedding process [105].

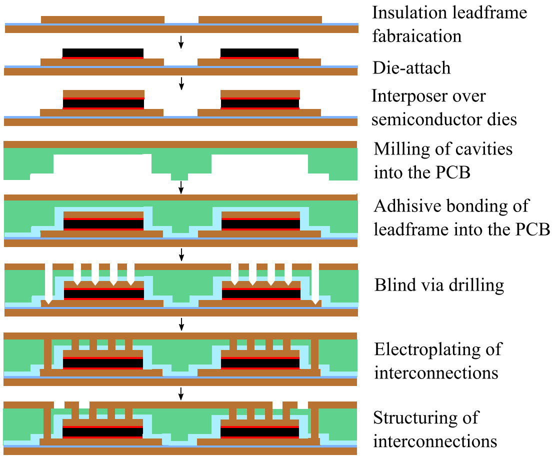


FIGURE 22. Post-process embedding method [106].

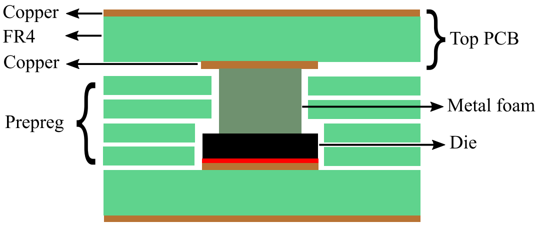


FIGURE 23. Metal foam connection embedded in PCB [108].

For high power PCBs, thicker copper layers up to 1 mm are required. In [90], four thin copper layers connect the die pads, four thick copper layers conduct large currents and spread excessive heat. Laser drilled micro-vias are utilized to connect vertically stacked SiC chips, while copper layers are connected through larger vias. Another interesting interconnection method is reported in [108], where a pressed "metal foam" is used to connect the chip top-side metallization and the copper layer, as shown in Fig. 23.

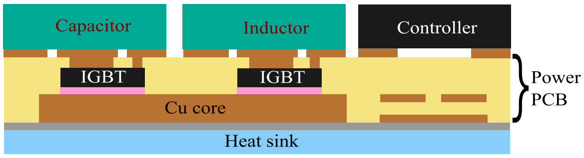


FIGURE 24. HI-LEVEL module for automotive application [103].

The selection of embedding material is critical in this technology. First, higher glass-transition (Tg) temperature is required to ensure high-temperature stability. Besides, proper thermal-mechanical and dielectric performance are necessary. A study from the Delft University of Technology proposed that bismaleimide-triazine (BT) for embedding materials is a good selection for embedding material [91], [102]. BT is characterized to have a high Tg as 260°C and a matched CTE of 5.3×10^{-6}/°C. Another important point to note is the metallization of the chip pad, standard aluminum pad or tin pad for wire-bonding are not compatible with the formation of vias. Instead, copper and nickel palladium are preferred [101], [103].

More examples of PCB embedded modules that match the rating and requirements of automotive applications are introduced in both industry and academia. In [106], the University of Applied Science Kempten introduced a 1200V/25A high bridge IGBT module. In [103], the EU project "HERMES" designed a module integrated with surface mounted devices and the heatsink. In [109], a 10 kW IGBT high bridge module from Fraunhofer IZM is reported. In [104], ABB Corporation reveals a 1200V/25A IGBT inverter module. A design from The German project HI-LEVEL targeted for automotive applications is illustrated in Fig.24 [103].

The main challenge for this technology is the thermal-mechanical problem. The maximum operating temperature is limited due to the low Tg and high CTE of conventional PCB materials compared with those of semiconductor materials. For example, common FR4-based prepregs and laminates usually have a relatively low Tg around 150-190 °C and high CTE over 15×10^{-6}/°C. When the module operates at a high temperature, not only does the embedding material become unstable, but also high thermal stress is induced. Besides, the bonding strength is relatively low. Take FR-4 PCB laminates as an example, the peel strength is around 0.9-1.25 N/mm [110], while for a DBC board, it could be 3-6 N/mm [111]. For those reasons, the power rating of PCB embedded modules is limited. Currently, most of the modules with this technology can only handle 50kW power or less, which hinders its widespread use in the automotive market. Advanced materials and high-performance thermal management are needed to address these challenges.

C. PRESS-PACK PACKAGING

The pressure-based assembly is another direction in module packaging design. It is well known that reliability is one of the most important concerns in automotive systems. In a conventional power module system, the failure at the joints is a very

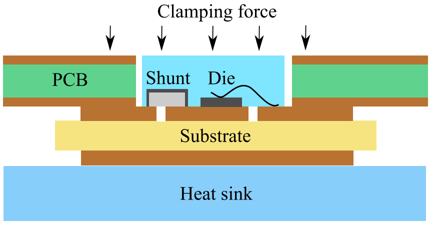
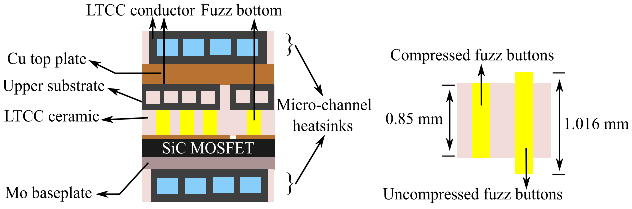


FIGURE 25. **Press-pack structure with flat press down fixture [115].**



(a) Section view (b) Fuzzy bottom concept

FIGURE 26. **Press-pack structure with fuzzy bottom [93].**

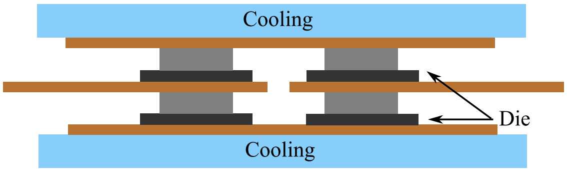


FIGURE 27. **Press pack module using Mo pins [99].**

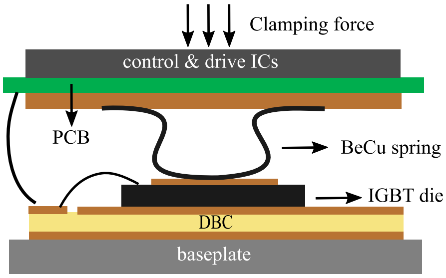


FIGURE 28. **Press pack IGBT module with BeCu spring [116].**

common failure mode. In a press-pack power module, joints are formed by pressure-based bonding, which is simpler and more reliable compared to other connection methods, such as wire bonding, soldering, and sintering. Another possible benefit is a reduced cost due to simplified structure manufacturing, making it favorable to the automotive industry. Moreover, it is a highly modular approach. Thus, it is convenient to construct parallel, series, and half-bridge topologies [93]. However, the electric and thermal conductivity of this type of joints is highly pressure-sensitive [112]. Proper clamping pressure is always required to ensure an acceptable thermal and electrical contact resistance, which is inevitable due to surface roughness and structural deformation. An approximate conclusion is made in [113], [114], that an 8-65kN/cm^2 of pressure is necessary for press pack IGBT dies to provide the desired functionality. Fig.25 illustrates a basic press-pack structure where a flat press down fixture is used to balance the clamping force [115].

Pressure-based connections can also be achieved by using compressible interposers. For example, Fig.26 introduces a pressure contact interposer with a flexible structure named "fuzz button" applied in a chip stacked 3D packaging [93]. This structure not only allows a greater tolerance for clamping pressure distribution but also minimizes the skin effect when conducting current. The clamping pressure is applied by the Molybdenum (Mo) and Cu plates.

Mo material is widely used in press-pack modules due to its CTE matching with semiconductor chips [99], [112]. Another example is shown in Fig.27, where Mo pins are placed between the chips and the copper plates.

Beryllium (Be) material is also an option for pressure-based connections due to its high strength, high fatigue resistance, and high thermal conductivity. A Be/Cu string is used to construct a press pack IGBT module [116], as shown in Fig.28.

Despite its improved reliability, the press pack structure still faces a few failure modes. A conclusion is made in [112] that the internal pressure increases and decreases during power cycling and temperature cycling, which could lead to possible fatigue for those press-pack packaging. Further, [117] explained that two possible failure mechanisms of the press-pack structure are micro-electrical discharge and damage of the gate oxide. Besides, vibration can also affect the stability of clamping pressure. In automotive applications, wide-range vibration and temperature cycling are inevitable. Therefore, a strict analysis needs to be done to ensure that the clamping force is always in a favorable range under any harsh conditions to avoid affecting the thermal and electrical conduction.

D. HIGH COMPLEXITY 3D PACKAGING

The three-dimensional package structure offers more possibilities for module design in terms of better thermal management and easier system integration. Generally, 3D package structures are inevitably combined with other package technologies. In this way, different packaging technologies can easily be combined and compensate for each other's limitations to better meet the requirements of future automotive applications. For example, in [90] and [102], the designs have the features of both a 3D package and a PCB embedded package. While in [90], the module integrated the gate driver and other components. Most of the press-pack modules can also be classified as the 3D packaging, such as the examples in Fig.26 and Fig.27. However, there exist many other 3D packaging designs with higher structural complexity.

The double-sided cooling packaging is a typical example, which is achieved by replacing top side wire-bonding by a copper clip or other planar connections. A typical example is the renowned POL module from General Electric. As shown in Fig. 29, the interconnection is achieved by laser-drilled vias on a polyimide/Cu layer, which forms flat surfaces at the top

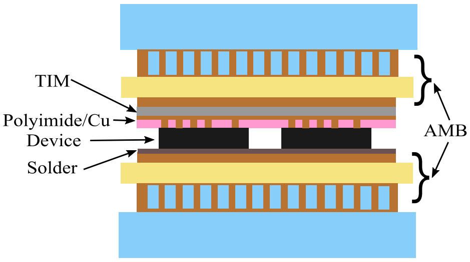
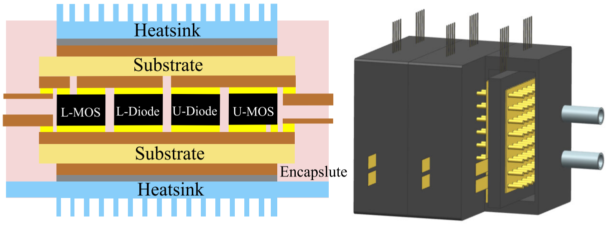


FIGURE 29. Double-side cooling POL module from GE [118], [119].



(a) Single phase leg (b) Stacked assembly

FIGURE 30. Modular double-side cooling 3D packaging [120].

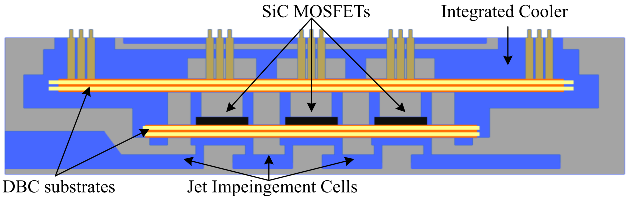
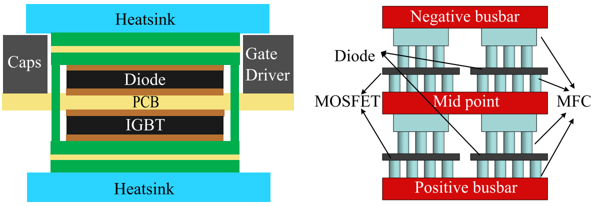
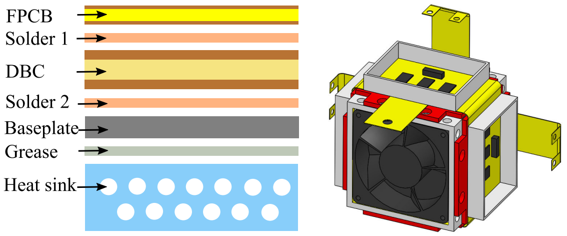


FIGURE 31. Jet impingement double-side cooling design [96].



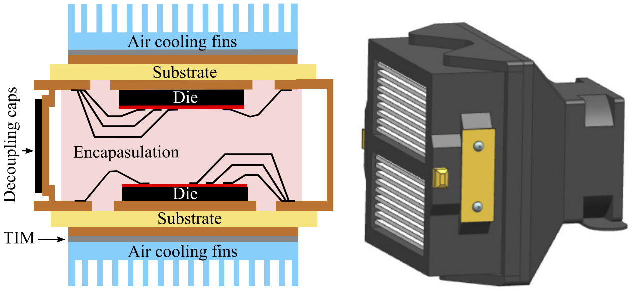
(a) (b)

FIGURE 32. CoC packaging examples [94], [122].



(a) Section view (b) Final assembly

FIGURE 33. PCB embedded packaging using BT material [92].



(a) Section view (b) Final assembly

FIGURE 34. Air cooling module from ORNL [123].

side. Two active metal brazed (AMB) substrates integrated with micro-channels are bonded to both sides to enhance cooling efficiency. The junction-to-fluid thermal resistance is 0.076 K/W for the IGBTs and 0.136 K/W for the diodes, which is around 50% reduction compared with the single-side version [118], [119]. Based on a similar concept, Oak Ridge National Laboratory (ORNL) developed an integrated power electronics building block [120]. It achieves a 40% reduction of thermal resistance compared with single-sided cooling. Furthermore, this design is cost-effective and convenient to be integrated as a full module, as shown in Fig.30.

Another double-sided design based on jet impingement direct cooling is illustrated in Fig.31, which can achieve the lowest junction to ambient R_{th} of 0.38 K/W. In this module, four layers of DBA substrates are vertically stacked around the SiC MOSFETs as interconnections to minimize the commutation loop [96].

Chip-on-chip (CoC) packaging is another 3D packaging concept with higher complexity in the vertical dimension. In this way, the conduction path can be greatly shortened. The design shown in Fig.27 is a typical example [99]. This module features reduced cell stray inductance and EMI coupling. Similar designs are reported in [95], [112]. Besides, researchers are also working on embedding the stacked chip structure into PCB [121], as shown in Fig.32 (a) [122]. In Fig.32 (b), a high thermal performance half-bridge module from U.S. Army Research Laboratory is illustrated. This module features a structure called multi-functional components (MFC) used to dissipate heat and conduct current, as well as maintain low mechanical stress [94].

The potential of 3D packaging is not just in the vertical direction. For example, Fig.33 illustrates a hybrid 3D packaging [92] for a 1200V/120A SiC half-bridge module. In this design, power devices are placed on three faces of a cubic module, while the interconnection is achieved by combining DBC substrate and flexible PCB. This structure provides a higher degree of system integration with only 0.79nH inductance.

Another example is shown in Fig.34, developed by ORNL, which features a genetic algorithm optimized 3D-printing air-cooled heatsink. These designs prove that air-cooled power converters could achieve competitive power density with a properly designed fin structure and reduced power losses [123]. A similar design is reported in [124].

TABLE 4. Technical details of novel packaging designs.

Reference	Technology	Topology and maximum ratings	Dimension (mm)	Rth (K/W)	Stray inductance (nH)	Turn on/off speed (kV/µs)	Others
[82], [86]	Gate driver /components integration	Half bridge; 800V; 46A	36×24	4.12 (j-a)	NA	96/39	75% reduction of turn/off loss
[87]	Gate driver/components integration; ceramic embedded	Half bridge; 500V; 24A	28.5×27.3×8	2.2-3.3 (j-a)	6.7	17/16	NA
[107]	PCB embedded	Half bridge; 1200V; ≥20A	15×15×0.36	0.256-0.455 (j-h)	1.24	NA	Panel-level PVD; RDL
[90]	Gate driver/components integration; PCB embedded	Half bridge; 600V;30A	NA	NA	5.3	58/NA	NA
[115]	Press-pack; components integration	Half-bridge; 800V; 23A	NA	0.4 (j-h)	3	19/NA	NA
[93]	Press-pack; double-side cooling; 3D layout	Half bridge; ≥600V;120A	NA	1 (j-a)	4.3	NA	Fuzzy button interposer; LTCC
[120]	Double-sided cooling; Modular 3D layout	Half bridge; 1200V; 100A	40×40×2	0.33 (j-a)	12.8	NA	NA
[118]	Integrated micro-channel double-sided cooling;	Half-bridge; 1200V; 200A	NA	0.076-0.136 (j-a)	2.6	NA	AMB substrate.
[96]	Integrated jet impingement cooling; integrated components	Half bridge; 10kV	83.3×68.2×24.7	0.38 (j-a)	NA	NA	Multi-layer DBA
[122]	CoC; 3D layout; components integration	Half bridge; 800V; 25kW	30×30	NA	1.24	NA	NA
[94]	CoC; 3D layout; MFC interconnection	Half bridge	30×25×10	0.25 (j-a)	NA	NA	Dielectric direct cooling
[92]	Modular 3D layout; components integration integrated air cooling	Half bridge; 1200V; 120A	44.3×45.5×44.3	NA	1.64	42.7/33	Flexible PCB

Although high complexity 3D packaging provides greater possibilities for the combination of different packaging technologies, the increase in layout complexity also poses challenges to manufacturing and reliability. New processing technologies to meet the requirements of the automotive application need further study.

E. ADVANCED MATERIALS

The material selection for the system is critical for all package structures. Due to the harsh operating conditions, automotive power electronics systems have stricter requirements on the performance of packaging materials. Materials with high thermal conductivity and matched CTE are always preferred. Meanwhile, strong mechanical properties are invariably required to improve reliability, such as high flexural strength, peel strength, tensile strength, shear strength, and fracture toughness. In the literature, many new materials with excellent properties have also been extensively studied. The bonding layer and the die attachment are usually the most vulnerable part in terms of resisting thermal stress. To enhance the widely-used nano-silver sintering bonding, [125] summarized the methods to improve thermal stability and mechanical performance. The study indicates that both higher densification and processing pressure could result in a higher initial shear strength, which could improve reliability. However, the processing cost and difficulty might increase as well. Specific materials are also designed and analyzed. For rapid ultrasonic-assisted soldering, a Ni_3Sn_4-composed die bonded interface was investigated in [126]. Although the re-melting temperature of this method is slightly lower than nano-silver sintering, it could enable a faster and cheaper bonding process. Another study presented in [127] highlights the fact that Cu-Sn intermetallic compounds (IMCs) could achieve a higher re-melting temperature (415 °C for Cu_6Sn_5 and 676 °C for Cu_3Sn) than commonly-used Pb-Sn, which improves the bonding stability in high-temperature operations as well. The encapsulants material is also a bottleneck for the high-temperature application. In [128], high-temperature polymeric encapsulants are summarized. Polyimide, bismaleimide, and cyanate ester (CE) are recommended for high-temperature applications due to their high T_g. However, their high CTE would bring challenges for thermal stress control. The polymer with advanced fillers, such as Al_2O_3 and ZrW_2O_4, are under investigation to achieve both low CTE and high durable-temperature. An example is in [129], where epoxy composites were filled with alumina and achieved enhanced thermal conductivity up to 2.06W/m-K. The embedding material in PCB embedded packaging is faced with similar challenges to the encapsulant materials. Compared with common FR-4, the BT material has a low CTE of 5.3×10^{-6}/°C, a higher thermal conductivity of 0.8 W/m-K, and a high T_g up to 260 °C [91]. The LTCC also receives extensive attention due to its matched CTE. However, its high thermal resistance and thin metallization thickness limit its application in high power situations. A double-sided cooling ceramic embedding packaging using LTCC is reported in [130], [131]. In fact, ceramic PCB technology has received more and more attention since it provides more possibilities for embedded packaging.

Table 4 summarizes the key properties of several typical power modules using these novel technologies. As shown in the table, most designs involve multiple technologies. It can also be verified from the table that both system integration and 3D layout can achieve low stray inductance and fast switching speed. Besides, the embedded packaging can largely reduce the size. However, its maximum rating is still limited. 3D packaging provides a great opportunity for implementing advanced cooling solutions to reduce thermal resistance. To summarize, each technology demonstrates its advantages for automotive applications. By combining different technologies, they can exploit their strengths to compensate for the disadvantages of others to achieve a good overall performance and make the module more suitable for wide use in automotive applications.

V. CONCLUSION

This paper provides a comprehensive review of the background knowledge, state-of-the-art commercial designs, and the future trends of power module packaging in the automotive application.

The major components of a traditional packaging design were introduced in Section II. The application prospects of different semiconductor dies were discussed by comparing the properties of Si, SiC, and GaN. The die attachment and interconnections form the electrical conduction and mechanical bonding between the die and external circuits. Soldering, silver sintering, and TLPB are three mainstream bonding approaches, and their properties are studied. The substrate provides not only patterning but also thermal conduction. The baseplate and heat sink are responsible for dissipating the heat. The filler material provides electric insulation and improves reliability in harsh operating conditions.

The current automotive power modules in the market are introduced in section III with an in-depth introduction to their packaging design. Most of them have been used in commercial electrified vehicles. Hitachi, Toyota, Continental, Infineon, Mitsubishi Electronics, and Fuji Electric launched multichip modules, while single-chip devices are introduced by Delphi, STMicroelectronics, and Nissan. It can be noticed that SiC modules have entered the market with the examples of the SiC-based viper switch from Delphi and the STMicroelectronics device used in Tesla Model 3. Regarding the die attachment, soldering and sintering are most commonly used. For interconnections, planar connections are gradually replacing wire bonding. DBC is still the prevalent substrate choice. However, alternative substrate technologies such as direct-bonded insulation sheets were implemented. Pin fin structure was extensively used in heatsink design and double-sided cooling grew from a research concept to a widely implemented technology.

Based on current challenges and ascending requirements, the future trends of promising power module packaging for the automotive industry were summarized in Section IV. To meet the demand of higher power density, the major trends include system integration and compact structure, which can be represented by gate driver integrated packaging, PCB embedded packaging, 3D packaging. Moreover, the improved thermal and electrical properties with those packaging concepts could be improved. Besides, novel connection technologies such as press pack are studied. Material selection is critical to every component inside a module. Advanced materials are emerging to solve the bottleneck in performance and reliability.

In addition to what is mentioned in this paper, many other innovative design cases have emerged in academia and industry. With the deepening research of module packaging, the next generation of automotive power electronics systems will be fully upgraded from all aspects.

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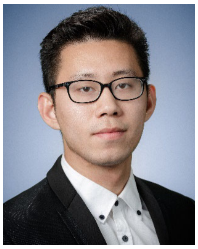

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