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Status and Trend of Power Semiconductor Module Packaging for Electric Vehicles

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Abstract

Power semiconductor modules are the core components in power-train system of hybrid and electric vehicles (HEV/EV). With the global interests and efforts to popularize HEV/EV, automotive module has become one of the fast growing sectors of power semiconductor industry. However, the comprehensive requirements in power, frequency, efficiency, robustness, reliability, weight, volume, and cost of automotive module are stringent than industrial products due to extremely high standards of vehicle safety and harsh environment. The development of automotive power module is facing comprehensive challenges in designing of structure, material, and assembly technology. In this chapter, the status and trend of power semiconductor module packaging for HEV/EV are investigated. Firstly, the functionality of power electronics and module in HEV/EV power-train system, as well as the performance requirements by automotive industry, is addressed. A general overview of HEV/EV module design and manufacturing is discussed. Then, the typical state-of-the-art commercial and custom HEV/EV power modules are reviewed and evaluated. Lastly, the packaging trends of automotive module are investigated. The advanced assembly concept and technology are beneficial to thermal management, minimized parasitic parameters, enhancement of thermal and mechanical reliability, and the reduction of weight, volume, and cost.

Keywords: hybrid and electric vehicles, insulated gate bipolar transistor, packaging, power module, reliability

1. Introduction

During the last few decades, people have made great efforts on exploiting sustainable and clean energy to mitigate the global crisis of fossil energy and deterioration of environment. Accordingly, the application systems powered by new and clean energy are developed with high interests. One of the crucial systems is hybrid and electric vehicles (HEV/EVs), which rely fully or partly on electricity which transformed from renewable and clean energy such as solar, wind, and nuclear powers. Therefore, HEV/EV is regarded as environmental-friendly product for the reduction of CO_2 and noise remarkably. Furthermore, the development of HEV/EV is becoming a main policy of most governments and automotive industry, leading to worldwide extensive research and development [1].

Performance		Temp	Reliability	Efficiency	Size/weight	Cost
Power device	High T_{jmax}	√	√		√	√
	Low loss	√	√	√	√	√
Module packaging	Low R_{th}	√	√		√	
	Low R, L	√	√	√		
	No base	√			√	√
	Direct cooling	√	√		√	
	Planar contact	√	√	√	√	
	Ultrasonic welding		√			
	New interconnection	√	√			
	New housing	√	√		√	

Table 1. Dependence of IGBT module performance on power device and assembly.

HEV has dual power sources of internal combustion engine and electric motor, while EV uses electric motor to power only. In both cases, the electric motor is essential to the systems. The motor, on the other hand, acts as a generator for regenerative breaking. The importance of motor in HEV/EV results in high-level significance of power-train system of which the main element is DV/AC inverter. The inverter controls power conversion from battery to motor by power semiconductor devices. Therefore, the core component in the power system of HEV/EV is power semiconductor switches, which are normally insulated gate bipolar transistor (IGBT) and free-wheeling diode (FWD) at the moment [2]. For increasing power, reliability, and prolonging lifetime, IGBT and FWD chips are packaged to module with multiple devices, isolation layer, and protection parts [2–9].

The great interest of developing HEV/EV across the world has motivated massive effort on improving and optimizing automotive modules. These modules always work in harsh environment of high temperature, humidity, mechanical vibration, and shock, and the possibility of chemical contamination. As limited by the space and weight in HEV/EV system,

the module and inverter system should have light and compact packaging. Hence, for driving and controlling HEV/EV efficiently, IGBT modules with high power, efficiency, reliability, light weight, and small size are required, which result in huge challenges to power device and packaging technologies [9, 10–13]. The power module overall performances are determined to a large extent by the electrical, thermal, and mechanical characteristics of both power chips and the way of chips packaging. **Table 1** shows the dependence of IGBT module performance on power device itself and the assembly technologies.

To meet the series of challenges as mentioned above to automotive module packaging, power semiconductor and automotive industries are developing automotive-qualified power chip and module. The advanced power device could not guarantee superior output from a power module, and much of the harsh requirements from HEV/EV systems can be satisfied by the optimized packaging concepts, structures, materials, and technologies together with novel power devices [14, 15]. In this work, the status and trend of power semiconductor module packaging for HEV/EV are investigated. Section 2 addresses the functionality and requirements of power electronics and module in HEV/EV system. A general overview of HEV/EV module design in terms of structure, material, and packaging technologies is discussed in Section 3. In Section 4, the typical state-of-the-art commercial and custom HEV/EV power modules are reviewed and evaluated. The packaging trends of automotive power module are investigated in Section 5.

2. Power semiconductor module in HEV/EV

It is expected that the HEV/EV will be one of the strong growth points for automotive industry in the next few decades with the improvement of performance, evolvement of technologies, and reduction of cost of ownership [1]. **Figure 1** shows the annual light-duty vehicle sales prediction by technology type. Based on Energy Technology Perspectives forecast, EV, Plug-in HEV (PHEV), and HEV will reach sales of 2.5, 5.0, and 10.0 M, respectively, per year by 2020, making the total sales of low carbon vehicles about 18% of the annual sales. By 2030, EV, PHEV, and HEV are expected to sell 9, 25, and 26 M units, respectively, corresponding to 50% of annual automotive market. And by 2050, sales of all kinds of low carbon vehicles will occupy more than 80% of the whole automotive sales [1]. Yole Development suggests that about 25 M cars manufactured will be electrified in 2016, with the majority of them being micro-HEV with low level of electrification, and 5 M will be full HEV, PHEV or EV [16].

With rapid ramp-up sales of HEV/EV in the last decade, power semiconductor industry has seen huge opportunity of power components and system supply. DC/AC inverter market will grow from $45 bn in 2012 to $71 bn in 2020 with more than 28 M units of 2012 and 80 M in 2020 [17]. HEV/EV represents one of the biggest markets for power device and system manufacturers together with the other most attractive motion and conversion applications of photovoltaics (PVs), wind turbines, rail traction, motor drives, and uninterruptible power supplies (UPSs) [17].
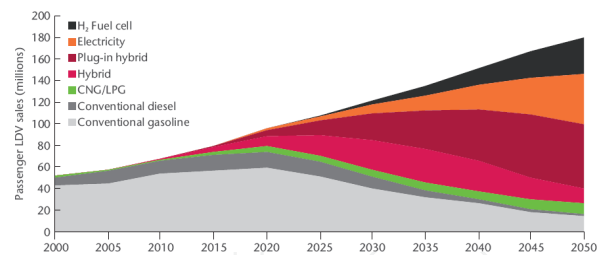
Figure 1. Annual light-duty vehicle sales by technology type, source: IEA 2010.

Power electronics is one of the essential technologies in HEV/EV research and development. The electricity for driving HEV/EV from grid is needed to be converted a few times before reaching electric motor and accessory appliances. These procedures are controlled by power electronic systems of which the main components are power IGBT modules [4, 5, 9]. **Figure 2** shows the schematic of power-train system in the EV showing the power control systems of converters and inverters. For HEV, the battery could be charged by both the electric grid and the internal combustion engine.
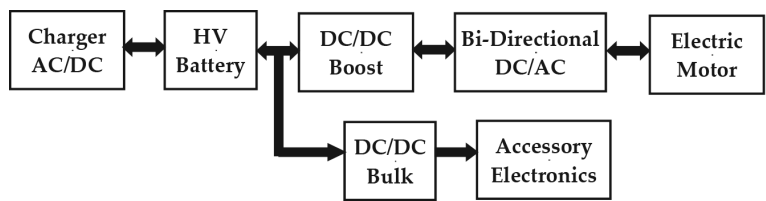

Figure 2. Schematic of power train in the EV.

Power modules are the core parts of inverter and converter systems in **Figure 2**, which dominate the system performance, reliability, size, weight, and the cost. **Figure 3** is an example of an inverter cost breakdown, showing that power module accounts for 30% of the whole cost and its cost reduction is critical to the system. To save size and weight of power systems, the cooling technology and system must be improved as it accounts for about 15% of cost and 30% of weight of the whole system. In 2012, the market was $1.9 bn for power modules which were mostly made with IGBT. At the moment, the average cost of a power module is above $500 in HEV, making a few billions of market in the next few years [17].
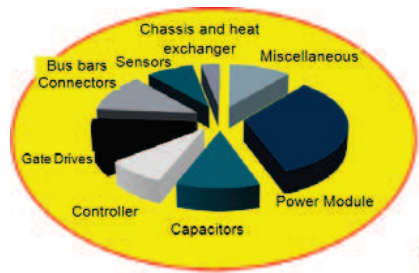

Figure 3. Cost breakdown of an HEV/EV inverter.

In HEV/EV application, the work environment of power system and module is harsh than industry applications. For example, the ambient temperature under the hood may reach 100°C with higher humidity; the HEV manufacturer is looking for sharing engine coolant with power module so the coolant temperature will be up to 105°C; the mechanical vibration and shock are usually strong and unpredictable during the vehicle running. In addition, the reliability, size, weight, and cost are challenges to power module development as the limited space and cost objectives of HEV/EV [9, 10–13]. **Table 2** shows the technology targets for both the power electronics and electric motors in HEV/EV [15].

	Power electronics				Motors		
Year	$/kW	kW/kg	kW/L	$T_{coolant}$	$/kW	kW/kg	kW/L
2010	7.9	10.8	8.7	90°C	11.1	1.2	3.7
2015	5.0	12.0	12.0	105°C	7.0	1.3	5.0
2020	3.3	14.1	13.4	105°C	4.7	1.6	5.7

Table 2. Technology targets for HEV/EV.

The major criteria for evaluating an automotive power module such as the performance, efficiency, reliability, cost, and volume/weight are generally determined by power semiconductor devices, packaging, and manufacturing technology. These criteria can be characterized by a series of technical parameters in aspects of the power module's electrical, thermal, thermomechanical, and mechanical properties, as well as packaging materials and processing techniques. The parameters determining the overall performance of a power module are thermal impedance (resistance and capacitance), operating and maximum junction temperature ($T_{j\ op}$, T_{jmax}), parasitic resistance and inductance, power cycling, thermal cycling/shock, vibration ruggedness, etc. [2–13]. People have made numerous technical advancements to improve these parameters through material and processing development and package structure optimization. **Table 1** lists the potential available solutions to meet the challenges of automotive packaging in the aspects of power semiconductor devices, and power modules packaging. It is supposed that improvement in one technology area is not sufficient at all to overcome all the difficulties and a comprehensive approach is required, and it may be not possible to achieve all the market and technical goals by making improvement to the existing technologies.

3. Overview of design for HEV/EV module

In HEV/EV applications, power modules must have superior performance and reliability than industrial products as the working environment is harsh in temperature, humidity, and vibration [9, 10–13]. The power modules are stressed heavily and frequently by electrical, thermal, and mechanical actions, so the device itself and the packaging parts are required to be robust enough during their operational life. Moreover, the system and device are restricted

by space, weight, and cost of the whole vehicle [2–4]. For these reasons, extensive efforts have been taken to improve the performance and reliability of automotive modules, and a series of optimized design and packaging solutions have been proposed [18–26].

The design of automotive power module should address the performance and reliability issues related to electrical, thermal, and mechanical. They are the main functional aspects that a power module has to serve. The power devices, module structure, materials, and packaging technologies are responsible for these performances, reliability, cost, volume, and weight. The components and technologies affecting power module's overall performance are listed in **Table 3**, and the module's reliability and lifetime are limited by the most unstable parts in the packaging.

Reliability issues		Design optimization
Electrical performance	Blocking	Chip field depletion, passivation
	Gate leakage	Gate oxide, packaging cleanness
	Power loss	Gate, field stop, thickness, parasitics
	Frequency/SOA	Power chip, parasitics
Thermal performance	Resistance, R_{th}	Module structure, material, technology
	Storage	Integrity of plastic, passivation, glue, gel
	Temperature cycling/shock	Joining, interconnection, materials
	Power cycling	Joining, interconnection
Mechanical	Shock/vibration	Bonding, housing

Table 3. Performance and reliability design on automotive power module.

The electrical performance is essential to power module application, with the main parameters affecting system performance are power density, operation temperature, blocking voltage, switching frequency, power dissipation/efficiency, and reverse/short-circuit safety-operating areas (RB/SCSOA). These performances are affected primarily by IGBT and FWD chips. However, the thermal and mechanical performances are mainly dependent on module packaging aspects. Thermal design is a critical step for the enhancement and optimization of thermal resistance, high-/low-temperature storage, thermal cycling, and power cycling, and the mechanical design is beneficial to the module resistant to shock and vibration [14].

3.1. Power chips for HEV/EV module

It is generally believed that the electrical performance and reliability are mainly controlled by power switches. **Figure 4** shows the vertical structure of an advanced IGBT used in HEV/EV modules. The thin-wafer technology, trench gate, and field stop layer are introduced to trade-off conduction and switching losses by which the frequency and efficiency are improved. The power dissipation results from leakage currents are reduced by the optimization of chip

design. High power density, high RBSOA, and SCSOA capabilities are essential to HEV/EV power train, which are objectives of automotive chip design [2–4, 27–31].
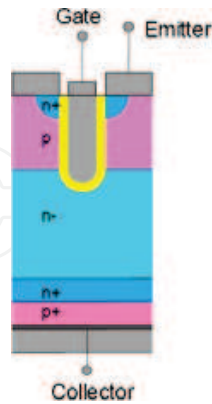

Figure 4. Vertical structure of a trench gate, field stop IGBT in HEV/EV modules [31].

At the moment, the standard fourth-generation IGBT technology is widely adopted by various industries. The thickness of 650 and 1200 V chips is reduced to about 70 and 120 μm, along with trench gate, the saturation voltage and conduction loss are reduced substantially compared to thick and planar gate devices. The frequency and switching loss are also optimized by these structures and field stop layer. Low power dissipation power chips are crucial to HEV/EV industry, which will result in high efficiency and energy saving, low rise of junction temperature (T_j) and therefore the high thermal reliability.

3.2. Design for low stray inductance

The parasitic parameters such as resistance (R), stray inductance (L_S), and capacitance have adverse effects on power dissipation, switching speed, and RB/SCSOA. One of the main objectives of automotive module design is to achieve low parasitic parameters. L_S is considered as the chief factor affecting IGBT module's performance and reliability. During the switching, an overshoot voltage (V_{OS}), equal to the product of L_S and current-varying rate, will be applied on the device terminals. If the sum of V_{OS} and DC-link voltage is higher than that of device-blocking voltage (V_{CES}), IGBT will be broken down. RB/SCSOA is then reduced because of the V_{OS} accordingly. The speed of automotive modules is much higher than industrial applications, resulting in high V_{OS} and reliability problems.

L_S of an IGBT module results from the substrate metal parts, bonding wires, conduct bus bars, control, and auxiliary pins. Design rules for minimizing the parasitic effects are proposed including reductions of current loop geometrical length and area [32], laminated bus bar, planar chip interconnection by using metal lead or PCB [2, 19, 32]. **Figure 5** shows an optimized substrate layout with minimum stray inductance. In this half-bridge substrate, the commutate path and area through DC+ and DC− are reduced to relatively small levels, leading to a small V_{OS} during IGBT switching-off verified by both simulation and module test [32]. It is supposed that the commutation loop length and area are valuable indicators of low L_S substrate design.
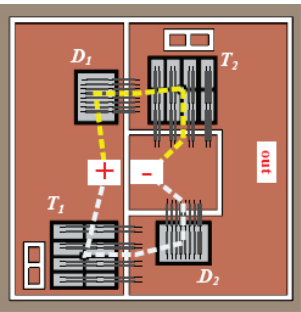
Figure 5. Optimized current loop dimensions with minimum stray inductance (Right) [32].

Thick and short bus bar and wires are effective to minimize L_S of a module. Due to substrate design, this bus bar may not be applicable. Furthermore, the laminated sandwich layout bus bars are verified as effective low L_S design solution [31]. The bonding wire-free concept, such as direct lead bond (DLB) [20, 21], double-side soldering/sintering on PCB or top-layer substrate [31] are good solutions to lower L_S.

Figure 6 shows a novel concept of double-side bonding in which bonding wire is eliminated. Therefore, L_S can be reduced, wire bonds failure is avoided, and the heat transfer efficiency is enhanced significantly by spreading through both sides of the chips. The planar IGBT module has been developed and applied in HEV/EV with great interest by the industry [20, 21].
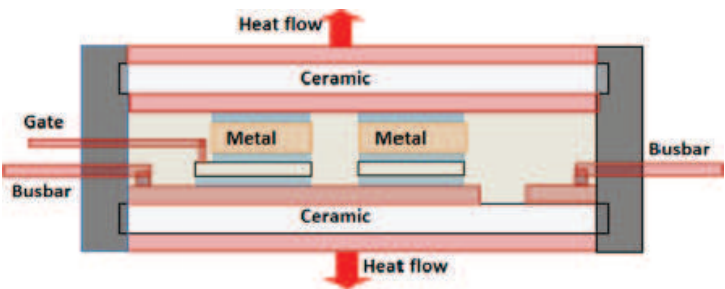

Figure 6. A planar interconnection concept for automotive module assembly [14].

3.3. Thermal design for automotive module

Thermal performance and reliability are of most importance for automotive IGBT modules as the ambient temperature is very high under the hood. On the other hand, the active power cycling and surging are more frequent than other applications that happen in the acceleration and deceleration stages. Therefore, large passive and active temperature excursions always occur in an automotive module operation. For the sake of cost and system complexity, customers prefer the traction inverter to share cooling system with the engine, meaning that the temperature of coolant could be up to 105°C in the near future. The abovementioned problems result in serious reliability problems on power module joining and interconnection parts. The solder layers of chip attach, substrate attach, and bus bar attach are prone to

delamination and failure because of fatigue finally due to high absolute temperature and high temperature swing (ΔT_j), and the bonding wires will be cracked or lifted off [33–35].

Reliability and lifetime of a power module is limited by the weakest point of the above parts. It is reported that power module lifetime reduces exponentially with the minimum/maximum junction temperature (T_{jmin}/T_{jmax}) and temperature swing. An outstanding thermal design gives smaller ΔT_j from the low thermal resistance of junction to case ($R_{th\,j-c}$) and junction to heat sink ($R_{th\,j-h}$) and enhances reliability [33–35].

Thermal design of IGBT module lies in the chip and packaging structure and materials. By elevating T_{jmax} of chips, the reliability will be enhanced as the improvement of electrical performance, and the requirement of module design will be mitigated. Currently, the fourth IGBT chips have a T_{jmax} of 150°C, and it is proposed that T_{jmax} of next-generation automotive module should reach 175°C, which requires redesigns in chip-doping profile, passivation, and metal materials.

To enhance reliability and prolong lifetime, power dissipated in chips and parasitic components must be spread with high efficiency, which can be achieved by low $R_{th\,i-c}$. Design for low $R_{th\,j-c}$ is dependent on the optimization of module structure and material. The high thermal conductivity ceramic such as AlN and Si_3N_4, and Cu or AlSiC baseplate with optimized thickness, direct cooling structure without using thermal grease are proved effective solutions to reduce the overall $R_{th\,j-h}$. However, the thermal performance should be traded off with reliability, weight, and cost. **Figure 7(a)** shows that a direct cooling pin-fin baseplate can reduce the $R_{th\,j-h}$ of conventional module by about 50% because of eliminating the grease layer [4, 18, 22, 23]. The direct liquid cooling (DLC) pin fins can be optimized in terms of efficiency, shape, layout, material, and cost. **Figure 7(b)** shows an automotive IGBT module with optimized Al in-line pin fins, in which the weight and cost are saved by maintaining merits of low thermal resistance and high reliability. Thermal simulation shows that the power switches work at the safe temperature envelop during the highest transient and continuous power output stages of a passenger car sharing 105°C cooling of the engine. Lifetime of the module is predicted under a real mission, which shows that it is capable of meeting the requirements with high coolant temperature [3].
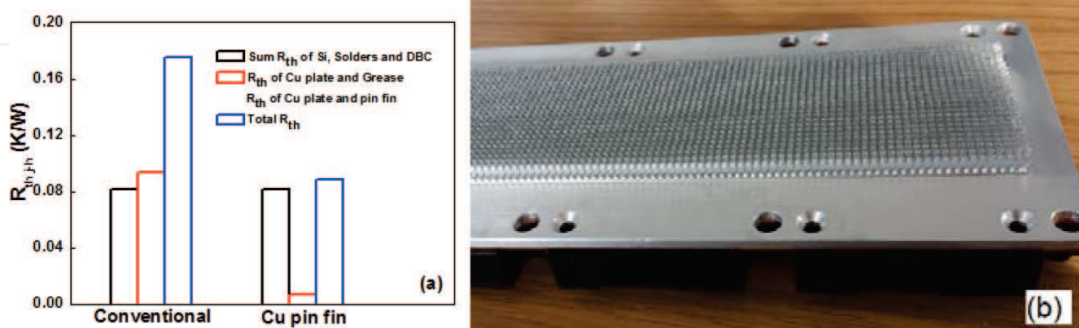

Figure 7. Comparison of $R_{th\,j-h}$ between conventional and direct cooling modules (a) and automotive IGBT module with optimized Al in-line pin fins (b).

Baseplate free- and double-side-cooling modules are proposed for automotive application for their good thermal performance as shown in **Figure 8** [20, 36]. The baseplate-free module can benefit to $R_{th\,j\text{-}h}$, weight, and cost, and the double-side-cooling structure can increase further the heat transfer efficiency. Both the modules are successfully applied in HEV/EV.
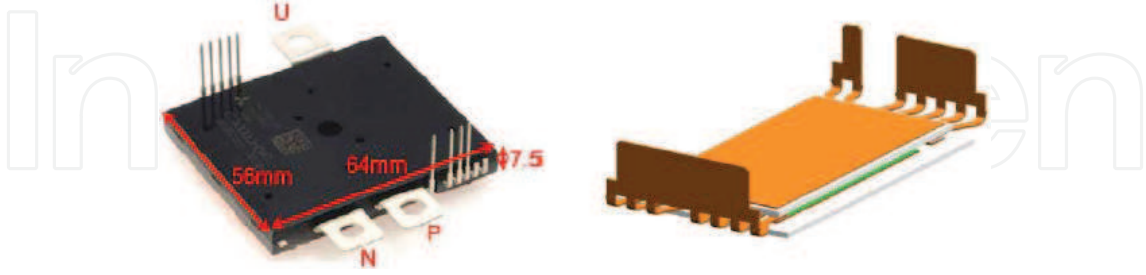

Figure 8. Baseplate-free (Left) [20] and double-side cooling [36] automotive modules.

3.4. Technology design for automotive module

Although low $R_{th\,j\text{-}c}$ reduces ΔT_j at constant power loss level, the high T_{jmin}/T_{jmax} together with ΔT_j can degrade gradually module's weakest point such as wire bonds, die attach solder layer, conduct lead, and substrate attach solder layer. The planar and next-generation copper-bonding wires with novel soldering technology are effective solutions to this instability. The novel die attachment technologies such as silver sintering and transient liquid phase sintering (TPLS) are verified to improve the power cycling capability by orders of magnitude. **Figure 9** shows lifetime comparison of copper wire incorporated with novel soldering and conventional Al wire and soldering, soldered and sintered die attachment [37, 38].
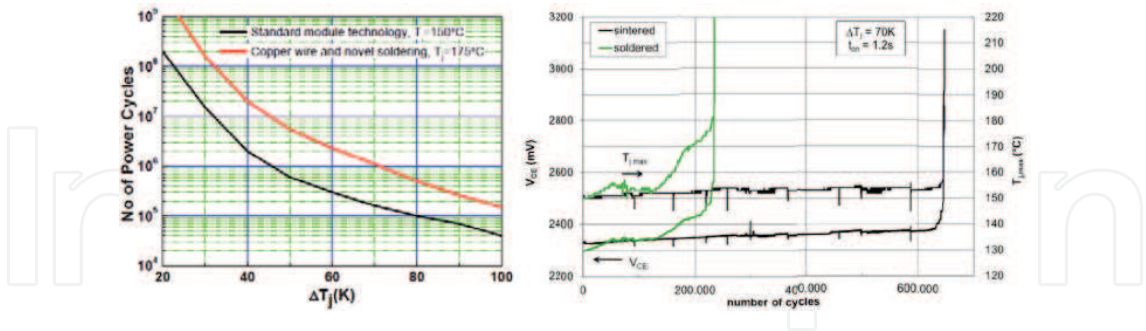

Figure 9. Improvement of lifetime by copper wire with novel soldering (Left) [37], lifetime comparison of modules with soldered and sintered die attach [38].

The mechanical shock and vibration affect mostly on the conduct bus bar and pins, which happen frequently in the running of an automobile. The strength of contacts should be enhanced in order to meet automotive standard that requires the module to be tested for 2 h per axis at more than 10 g for vibration, and three times at each direction and more than 100 g for shock. The ultrasonic welding with injection-molded housing (**Figure 10(a)**) as well as pressure contact is designed for achieving the mechanical reliability standard. **Figure 10(b)**

shows that the reliability of bonding can be enhanced by ultrasonic welding, as negligible degradation of bonding tensile strength was found [39].
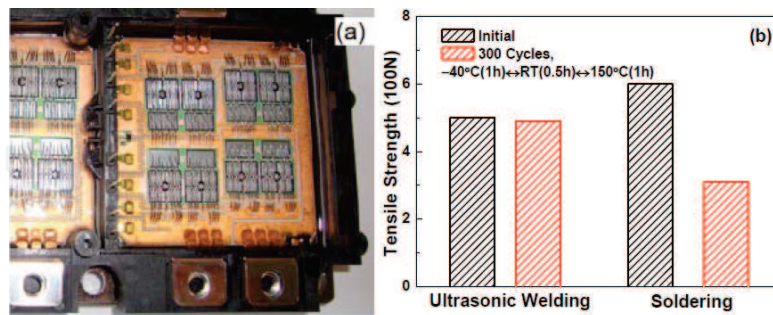

Figure 10. Ultrasonic welded terminals and pins in a HEV/EV module (a), and the reliability comparison with soldered terminals (b) [39].

4. State-of-the-art HEV/EV power module

In this section, the typical state-of-the-art commercial and custom HEV/EV power modules are reviewed and evaluated. The design and manufacture of automotive power module were following industrial power module packaging standard at the beginning. The conventional structure and technologies were applied in automotive module, which was the sandwich structure including plain baseplate and direct bond copper (DBC) substrate interconnected by solder reflowing and wire bonding. The structure and technologies are difficult to meet HEV/EV requirements in thermal and mechanical performance, as well as in the reliability, lifetime, cost, volume, and weight. Therefore, power semiconductor and automotive industry had developed a series of power modules dedicated for HEV/EV application as described in the following.

4.1. Direct liquid-cooled HEV/EV power module

Direct liquid cooling (DLC) was supposed to be an efficient solution to HEV/EV modules with its advantages of efficiency, integration, weight, and size [2–4]. A typical DLC module integrates liquid-cooling structure such as pin fins into the baseplate, which can flow through coolant without an external heat sink. Therefore, the traditional thermal interface layer between baseplate and heat sink is eliminated, and the un-uniformity and degradation of thermal grease will be avoided as well. It is reported that the $R_{th\,j\text{-}h}$ could be reduced by 50% of plain plate in the application, resulting in much lower ΔT_j and reinforcement of the reliability and lifetime. Therefore, the pin-fin DLC IGBT module is a good solution to HEV/EV power systems not only in the aspects of reliability but also performance, cost, and weight [2–4, 18, 22, 23].

DLC module with pin-fin plate is excellent in delivering higher power than plain base or baseplate-free modules, and the converter system with DLC module is compact and reliable.

Figure 11 shows the commercial DLC modules with pin-fin plate. A technology trend for IGBT module cooling in HEV/EV power-train system uses coolant with elevated temperature, so the power device can share cooling system with engine at up to 105°C liquid [3, 8]. This will simplify power electronics system without separate cooling circuit, resulting in the reduction of overall cost, weight, and volume of whole vehicle. However, high-temperature cooling has huge adverse effects on reliability and lifetime of power module, and may result in exceeding of $T_{j\,max}$. The direct liquid cooling is generally believed as an efficient thermal management with high cooling efficiency at high-temperature applications. The application of DLC module in HEV/EV has been widely accepted [3–5, 40].
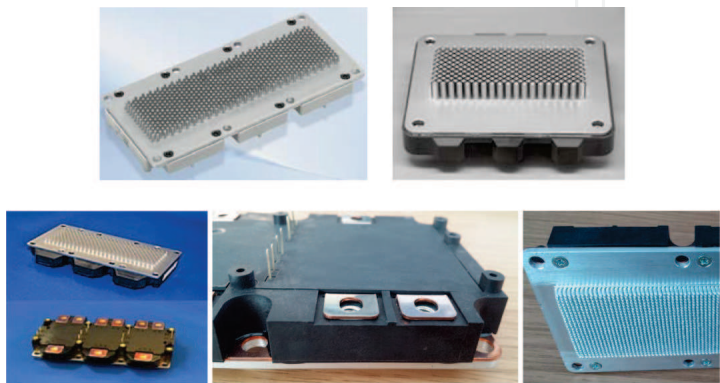

Figure 11. The commercial DLC modules for HEV/EV power system.

The manufacture complexity and cost of pin-fin baseplate are high compared to plain plate at the moment, and the new technologies are required to integrate DLC structure into external cooling path.

Figure 12 shows an integrated cooler structure [2] with the direct bonded Al (DBA) substrates are directly bonded (by brazing) onto specially fabricated cold plate to realize direct cooling of the power module. The integrated module and cooling structure eliminates the conventional baseplate and thermal interface layer. It achieves 30% improvement in thermal performance. The assembly includes a buffer plate with punched holes for releasing the stresses between the cooler and DBA caused by a coefficient of thermal expansion (CTE) mismatch. The Al ribbons were used to replace Al wires for improving the reliability and electric parasitic parameters of die interconnections.
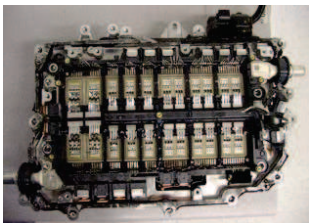

Figure 12. Integrated automotive power system with baseplate-free module and cold plate [2].

4.2. Baseplate and solder-free automotive power module

The state-of-the-art IGBT modules are based on a solder construction for chips attaching to substrate and substrate attaching to baseplate. Investigations have shown that these solder layers constitute the weakness of power semiconductor module as they demonstrate fatigue when exposed to active and passive temperature cycling. **Figure 13** shows an automotive power module named SKiM by Semikron, which is designed with high reliability to meet the demands of automotive applications in terms of shock and vibration stability, as well as high-temperature capability and service life [31].
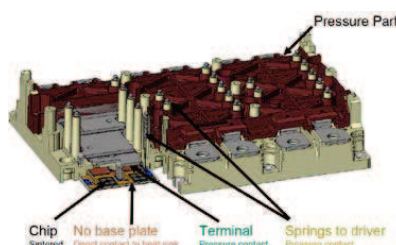

Figure 13. Baseplate and solder-free automotive power module [31].

The module features a pressure-contact low-profile housing that boasts the advantages of 100% solder-free module, Pb-free, and spring contacts for auxiliary contacts. The chips are sintered by silver on substrate, achieving a very high-power cycling capability. The sinter joint is a thin silver layer whose thermal resistance is superior to that of a soldered joint. Due to the high melting point of silver (960°C), no joining fatigue occurs, resulting in an increased service life [31].

The pressure contact of bus bar and auxiliary pins results in very low thermal and ohmic resistance and high thermal reliability. The laminated sandwich main terminals as shown in **Figure 14** benefits to a very low stray inductance and therefore improves the reliability, efficiency, and electrical performance. The single chip is connected symmetrically in **Figure 15**, leading to similar stray inductances for the individual chips and a homogeneous current distribution [31]. The baseplate-free structure has advantages of low volume and lightweight, but a thermal interface layer must be applied to improve the contact between substrate and heat sink, which deteriorates the thermal performance and reliability.
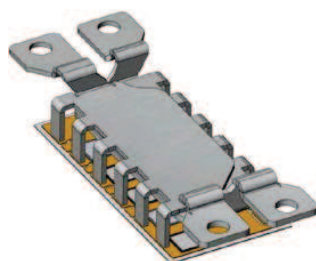

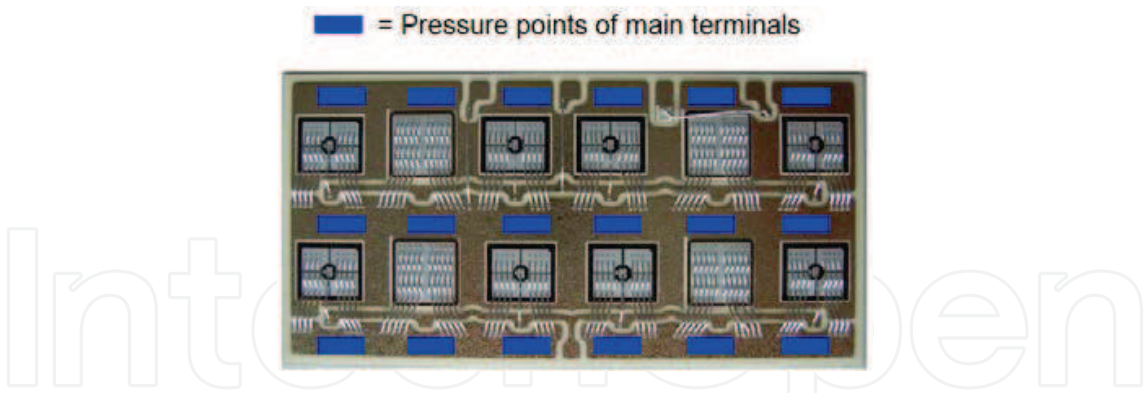**Figure 14.** Main terminals with sandwich structure and low inductance [31].

Figure 15. The substrate with symmetrically chip layout and terminal pressure contact areas [31].

4.3. Direct lead bond automotive module

A Transfer-mold power (TPM) packaged by direct lead bond (DLB) technology was released to automotive power electronics market by Mitsubishi and Bosch [20, 21, 41], which makes HEV/EV applications more reliable and compact. **Figure 16** shows the power module samples, the low profile, and compact package achieved by the concept.
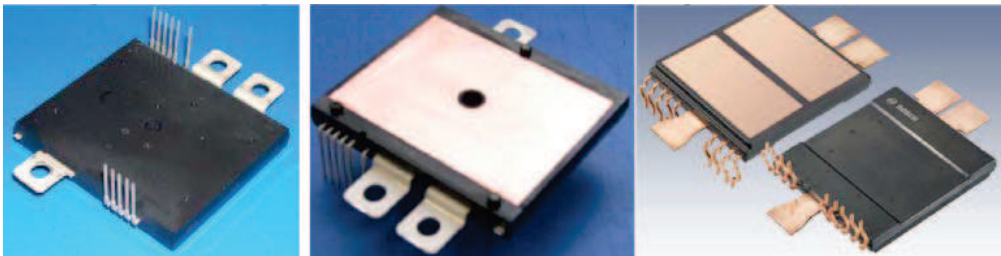

Figure 16. TPM automotive module prototypes from Mitsubishi and Bosch (Right) [20, 41].

The internal cross section of the packaging structure is shown in **Figure 17**. The transfer-mold case chips are bonded on heat spreader and on lead frame directly (DLB) by lead-free solder, the TCIL is attached on the heat spreader for electrical isolation and contact with external heat sink.
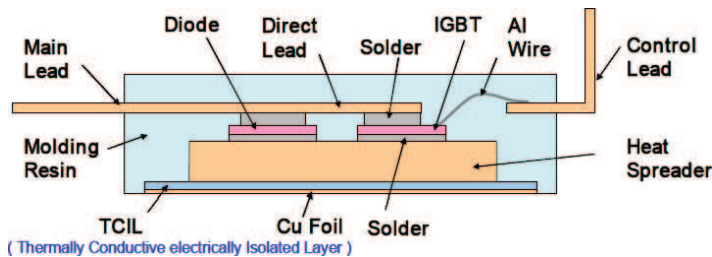

Figure 17. The internal cross section of TPM module with DLB [20].

DLB is the key feature of the module, by which the internal lead resistance is decreased to 50% and the self-inductance is decreased to 60% compared with the classically wire-bonded TPM module. The large solder contact area of DLB results in a uniform chip surface temperature distribution and a small thermal resistance. The integrated heat spreader reduces the contact thermal resistance and transient thermal impedance. The construction provides a larger area of heat flow between junction and case. The features of DLB TPM automotive has enhanced almost 30 times of power and thermal cycling capability compared with the conventional module case assembled with wire bond technology. In addition, the on-chip temperature and current sensors are integrated into the IGBT die, enabling a precise, safe, and fast over temperature protection, and detects and turns off a short-circuit situation without the IGBT entering a de-saturation phase [20, 21, 41].

As the evolution of the first generation of DLB module, a six-in-one HEV/EV module bonded by DLB and integrated with direct water-cooled Al fin was developed [21]. The adoption of these innovative technologies has led to improved thermal performance of 30%, and has reduced the footprint by 40% and the module weight by 76%. **Figure 18** shows the module prototypes and internal structure. The Al cooling fin was integrated into module for direct liquid cooling. DLB is employed that has extensive advantages to power density, thermal and electrical performance, reliability, etc. The Al cooling fins have lower thermal conductivity compared to Cu pin-fin structure, but they have high durability when exposing directly to coolant and are much lighter. Compared to the first-generation DLB modules of **Figure 16**, as much as 76% weight reduction and 30% thermal performance improvement were achieved based on the same current and voltage for three-phase HEV/EV motor drives [21].
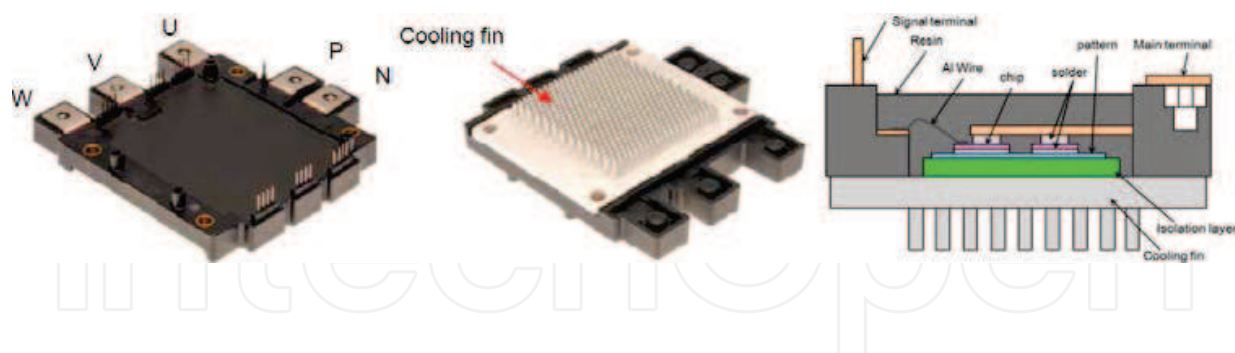

Figure 18. The prototypes and package structure of a high performance, compact size, and light-weight HEV/EV power module [21].

The custom power module in Nissan LEAF pure EV shown in **Figure 19** has the same concept of DLB [2]. The power semiconductor dies are attached onto Cu plate, which is an electrical terminal and is wire bonded to other terminals to form a half-bridge configuration. The large-area Cu bus bars act as heat spreader and are mounted onto external cold plate through a separated electrical insulator sheet. The sheet has a special composition and offers high thermal conductivity.
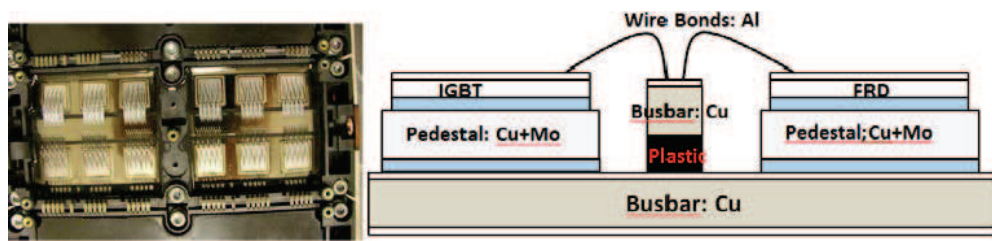
Figure 19. The custom module for Nissan LEAF and its schematic of cross-sectional view [2].

4.4. Planar interconnection and double-sided-cooled automotive module

In a conventional module packaging, the top electrodes of die are electrically interconnected by bonding Al wires, while the whole bottom metal surfaces are soldered onto insulating ceramic with direct bond copper or aluminum surfaces. This asymmetric package structure has a series of drawbacks such as large parasitic electric parameters, deformation of die subjected to thermomechanical stress, small thermal conduction path through the top of die, etc.

Therefore, changing the top interconnection configuration to a planar or symmetric package will bring comprehensive benefits to thermal, electrical, and reliability. With a planar inter-connection, the die can be connected to cold plates at both sides to achieve double-sided cooling, and the thermal performance can be enhanced accordingly. This will eliminate the traditional bonding wires but require that front metal of chips must be solderable [19].

The concept of planar IGBT packaging without bonding wires is shown in **Figure 6**, and the planar modules were developed for HEV/EV and aerospace industries. By soldering or sintering semiconductor chips to copper leads directly or to DBC system, the module can be cooled by liquid or forced air at both sides, which provides 70% higher cooling efficiency than a conventional single-side cooling module. A joining layer on a chip active area will spread heat easily and result in low-junction temperature and high reliability [15, 19]. The removal of bonding wires has advantages on reliability as wire bonds are prone to failure during operation because of the high intermittent temperature cycling from the junction. On the other hand, the parasitic resistance and inductance are reduced accordingly by large area contact, which improves efficiency and dynamic performance such as the safe operating areas of RBSOA and SCSOA [2, 6].

IR has presented a new power management platform approach for HEV/EV to help address the need to reduce the size, weight, and system cost of electric power-train components while increasing system reliability for long lifetime, low maintenance, and low warranty cost. The packaging platform named CooliR^2™ characterizes wire bond frees and transfer-mold technologies that addresses all the HEV/EV module packaging challenges. The IGBT and diode called CooliR^{2}DIE were designed for the platform. The IGBT has reduction of conduction and switching losses, increases of blocking voltage, and compatibility with wire bond-free interconnection techniques, and the switching frequency and maximum T_j were increased to

20 kHz and 175°C, respectively. The diode was optimized for automotive traction by fast-speed soft recovery with oscillation-free behavior [15, 19, 42].

Figure 20 shows the CooliR^{2}DIE as building blocks and the construction of a half-bridge package by using the die. The building-block approach of CooliR$^{2\text{TM}}$ platform has advantages of cost reduction and mechatronics enabler. The electrical performance of package is improved with lower resistance and parasitic inductance. The cooling method is flexible for no baseplate cooling, or attaching a baseplate or direct liquid-cooled heat sink to substrate. The transient thermal impedance and die temperature distribution are improved in the packaging. In addition, the reliability and power density are increased by the wirebond less, dual-sided cooling and higher T_{jmax} solutions.
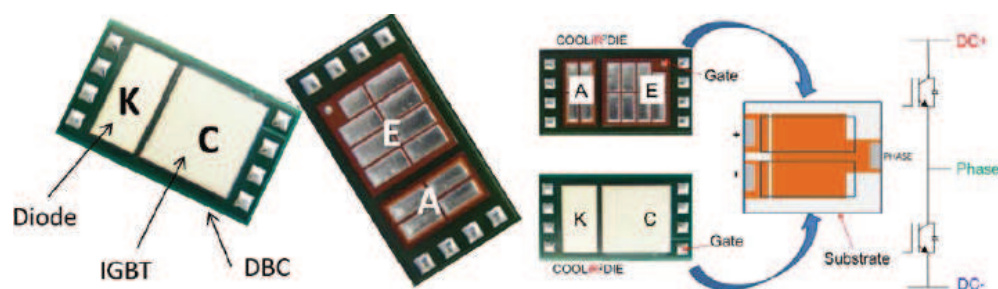

Figure 20. CooliR^{2}DIE building block and the construction of a half-bridge package by using CooliR^{2}DIE [42].

Figure 21 shows a custom automotive power module for Toyota LS600, in which two planar Cu plates are directly soldered onto power electrodes on the dies from both surfaces. The module is encapsulated with transfer-molded compound while keeping the Cu plates exposed to the outside for acting as heat sinks to transfer device heat to a cold plate (cooling tube) from two surfaces [2]. Therefore, the module's thermal resistance is reduced dramatically. Insulator layers are required at both sides between power module and cold plate as the module is nonelectrically isolated.
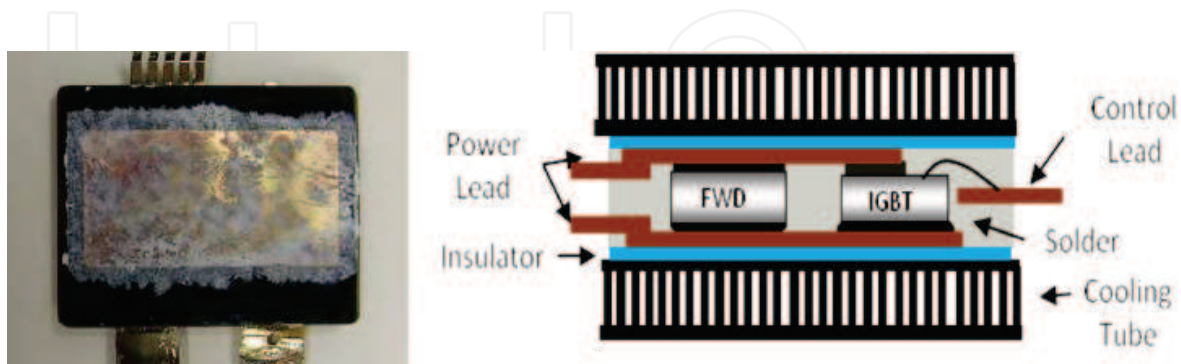

Figure 21. Custom power modules of Toyota LS600 and its schematic of cross-sectional view [2].

In **Figure 22**, Delphi planar [36] power module for dual-side cooling is shown. The DBC isolates module to external heat sink. It is a co-packaged IGBT and diode unit that needs next-level

interconnection to form power inverters, so the pressure must be controlled to ensure the press contact between all package units and cold plates for double-sided cooling. However, the assembly complexity of electrical interconnections is difficult and costly at inverter-level packaging.
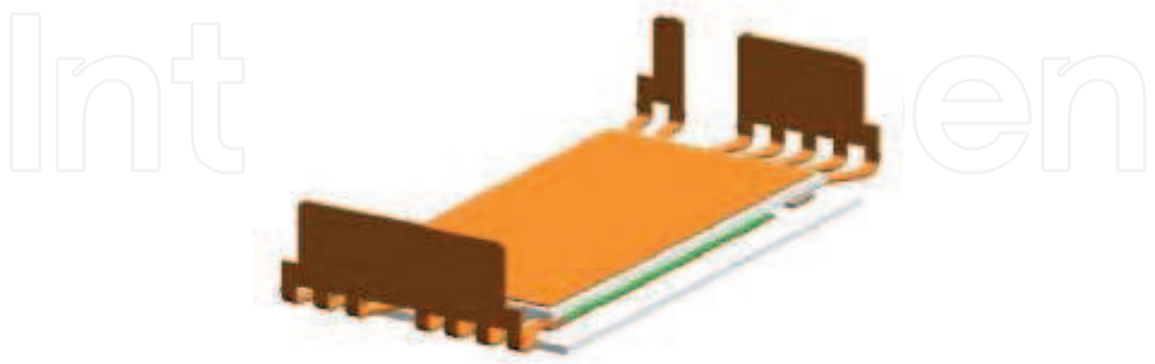

Figure 22. Delphi planar bond power module with dual-side cooling [36].

The Semikron double-sided planar power module using SkiN technology is shown in **Figure 23**. The die top connection is a flex circuit board, and all the joining interfaces between two sides of die and substrate, and DBC and heat sink, are bonded by Ag-sintering process. This provides very high thermal and power cycling reliability, as well as good thermal and electrical performance [43].
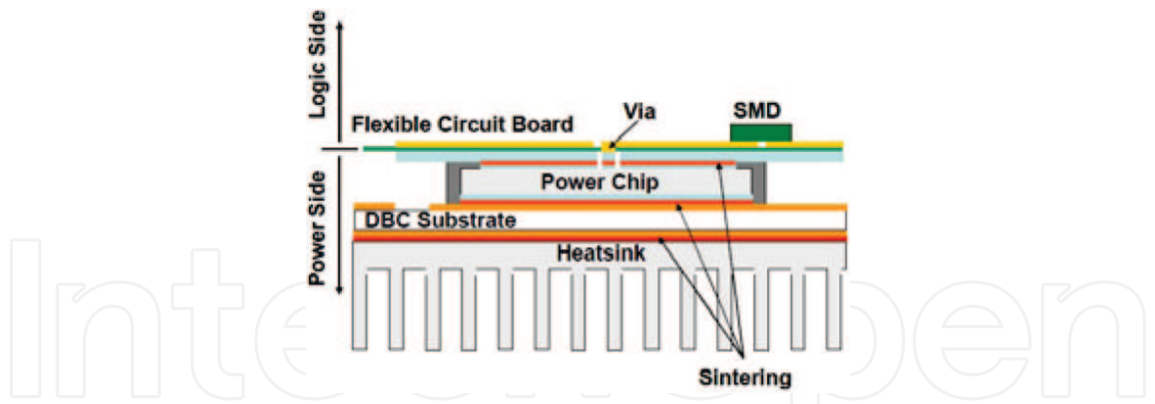

Figure 23. Schematic of cross-sectional view of Semikron SKiN power module [43].

5. Packaging trend of HEV/EV power module

The standard of power module for passenger car is stringent than industrial and CAV (Commercial, construction, and agricultural vehicles) products. Therefore, the advanced packaging structure, material, and technology must be investigated.

5.1. Novel structures in automotive module packaging

As mentioned above, the direct liquid cooling power module is becoming a standard solution to HEV/EV power packaging. The power density is improved as its excellent thermal performance and compact integration with heat sink, which is also the volume and weight. $T_{j\,max}$ can be well controlled by reduction significantly of $R_{th\,j-h}$, so the reliability and lifetime are enhanced. By using the advanced cooling structures into module baseplate such as the two-phase change flat pipe, vapor chamber and microchamber, etc., the heat transfer efficiency, volume, and weight are further improved.

The baseplate-free module has the advantages in volume, weight, and cost, which is preferred by automotive customers. However, the module with direct substrate cooling structures is more attractive for cooling efficiency, thermal performance together with the benefits of baseplate-free module.

The planar structure is a more advanced packaging trend for automotive module, a top isolation substrate, a flexible PCB or contacting leads are bonded to chip-top contact areas. The bonding wires are eliminated resulting in series benefits in parasitics reduction, temperature uniformity, and reliability. Therefore, the power density, thermal performance, reliability, volume, and weight are improved. By using a top substrate, the module can be cooled from both sides of a chip, increasing the cooling efficiency by more than 30% of a traditional one-side cooling structure.

5.2. Advanced materials for automotive module packaging

The selection of advanced packaging materials is essential to module performance and reliability, the advanced materials for power semiconductor die, substrate, baseplate, interconnection, and housing are proposed for automotive power packaging.

SiC devices such as MOSFET and Schottky Barrier Diode (SBD) are becoming popular in automotive power module market as its excellent material performance in electrical and thermal. The high bandgap makes SiC devices competent to high-temperature, high-voltage, and high-efficiency applications. Its thermal conductivity is about three times than Si, which is beneficial to high-temperature and high-power density requirements. The doubled electron saturation speed in SiC leads it as best candidate to high-frequency applications. In addition, the GaN devices are developed quickly for automotive product as the same reasons of SiC devices.

Si_3N_4 substrate is proposed for high performance and reliability power module packaging as its trade-off advantages of CTE, thermal, and mechanical performance. Although Si_3N_4 is not selected widely at the moment, the reduction of cost in the near future will make it a first choice in automotive module packaging.

AlSiC baseplate with direct liquid cooling pin-fin structure has been extensively proposed in passenger car and sport-racing cars. The reasons also lie in its overall performance advantages of CTE match with semiconductor and substrate materials, good thermal and mechanical features, and lightweight, etc. The advanced interconnection materials such as lead-free solder

and copper bonding wire are developed for enhancing reliability and lifetime of automotive module.

The new housing materials are applied in injection molding, transfer molding, and hematic supply high temperature and high mechanical reliability, which are becoming the mainstream housing of automotive module.

5.3. The trend of assembly technology

The assembly technology is essential to power module performance and reliability, so advanced joining and interconnection technologies are being developed for automotive packaging. The trends of joining interfaces between die, substrate, and baseplate are high and stable tensile strength solder layer formed by SnSb, high temperature and reliability intermetallic solder layer formed by transient liquid phase sintering (TPLS), or superior silver-sintered layer. SnSb soldering is an easy and cost-effective way by traditional process; however, TPLS and silver sintering have more reliability benefits.

The conventional Al wire bonding interconnection technique will be replaced by copper wire bonding and planar contacts such as direct lead and flexible PCB bonding. Copper wire bonding improves current and thermal capability, and the reliability, which the planar packaging results in high current, low parasitics, low loss, uniform temperature, and high reliability.

The interconnection of bus bar and pin is usually soldered to substrate in an industrial power module, which have low thermal and mechanical reliability. Recently, ultrasonic welding, which results in quite high bonding strength and pressure contact, is proposed in automotive power packaging. Both enhance thermal and mechanical reliability significantly by eliminating interface layers.

6. Summary

Development of hybrid and electric vehicles (HEV/EV) has brought challenges to power semiconductor industry in automotive power module packaging. As the essential role of power module plays in HEV/EV power-train system, people have made great efforts to improve electrical and thermal performance, reliability, volume/weight, and cost of automotive module. Many innovative designs in power module structure, material, and assembly technology have been proposed based on conventional power module packaging.

In this chapter, the status and trend of automotive standard power module packaging are reported. We have discussed the importance and functionality of power electronics and module in HEV/EV power-train system, and summarized the performance requirements by automotive industry. The designs of structure, material, and packaging technologies for high thermal, electrical performance, and high reliability for HEV/EV module are investigated. An overview of the typical state-of-the-art commercial and custom HEV/EV power modules, including direct liquid cooled, baseplate, and solder free, direct lead bonded, planar intercon-

nection and double-sided cooled, are analyzed. The details of novel structures, advanced packaging materials, and trends of assembly technology are proposed to instruct automotive module designs.

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