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Status and advances in Electric Vehicle's power modules packaging technologies

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Abstract

The technology used in the design of the high power density Electric Vehicle (EV) power inverters packaging (power modules electrical, thermal and thermo-mechanical properties) directly affect the power inverter performance, cost, reliability, efficiency and power density. In this paper the technical trends and advances in EV power module packaging technologies will be reviewed and actual manufactured automotive power modules will be evaluated. Advantages and disadvantages of such modules will be highlighted.

1. Introduction

High power density Electric Vehicle (EV) power inverter modules contain multiple power semiconductor switches (IGBTs) and diodes.The module packaging provides electrical interconnections, thermal management, and mechanical support to these semiconductors dies.

In order to develop a power module for EV applications (with excessive ambient temperatures, humidity, vibration and dirt in the EV engine compartment among others) new solutions for module integration and packaging technology are needed. Conflict requirements as maximum power density, efficiency and reliability at low cost, can however only be achieved if the right choice of components is made, innovative solutions and technology developed, and thermal and electrical properties optimized. In this paper the technical trends and advances in EV power module packaging technologies will be reviewed. The aim of all new technologies is to improved technical parameters as thermal impedance, maximum operating temperature, parasitic inductance, thermal conductivity, lifetime, etc. Besides actual manufactured automotive power modules are evaluated and advantages and disadvantages of such modules are discussed in term of these technical parameters.

2. Packaging technologies

Fig. 1 shows a general cross-sectional view of packaging components stack. Denpending of the package configuration desing, some of the parts of the package stack could be eliminated.

The most important parts of the package stack to consider in the development of new packaging designs are: die or semiconductor device, die-attach, DBC, substrate-attach , interconnection technology and the cooling method.

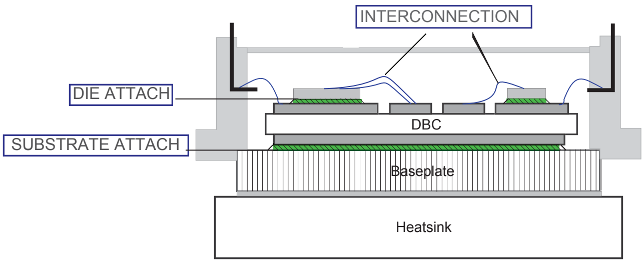


Fig. 1: Cross-sectional view of packaging components stack.

The figure 3 shows a brief comparison of some of actual manufactured automotive power modules packaging technologies.

2.1. Die

There are a lot of different developments to improve dies performance, as advanced architectures on silicon as Trench Field Stop. However, silicon has some physic limits which are difficult to solve. Manufactures are researching into other semiconductor materials, such as SiC and GaN, to obtain more efficiency in the minor size of die.

2.2. Die-attach

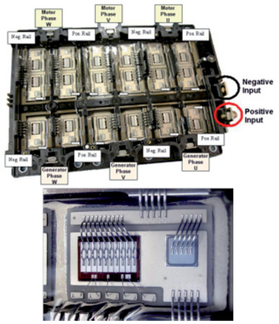
Sintering technology is a well established technology today and has started to replace soldering of chips to DBC substrates already in mass production [1, 2]. Thanks to its unprecedented reliability and thermal behavior this joint technology makes power modules better suited for EV application.

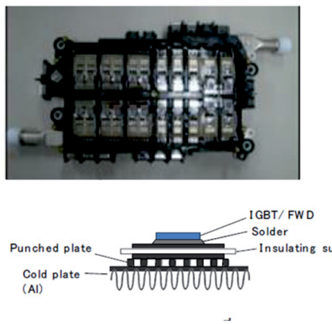
Sintered layers exhibit better thermal, electrical and mechanical properties than solder layers [3]. In Table 1 the advantage of Ag sinter layers are shown.

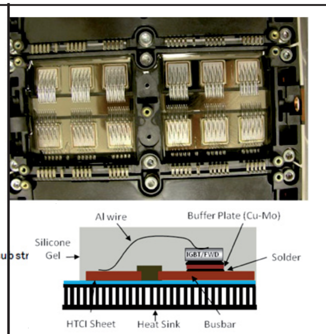
	Ag sinter layer	**Ag Solder layer**	**Factor**
Melting point (C)	961	221	4
Elec.conduc.(MS/m)	41	7.8	5
Ther.conduc.(W/mK)	250	70	4
Density (g/cm_3)	8.5	8.4	1
CTE (μm/mK)	19	28	1
Tensil strength (Mpa)	55	30	2

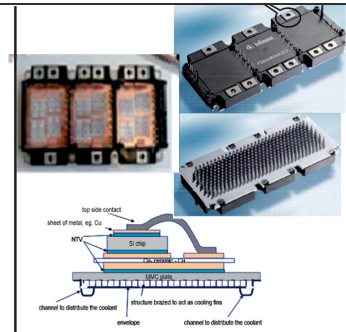
Tab. 1: Comparison of important properties of solder layer and sintered silver layer.

Semicron SKIM 63/93 is one of the EV power module which does not contain any soldering interconnect. The chips are sintered to a DBC substrate, and the power and auxiliary contacts are pressed to this substrate. The module does not have a base plate and the substrate is in direct contact with the heat sink [4].









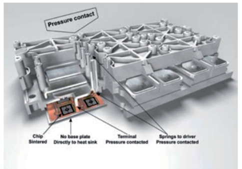
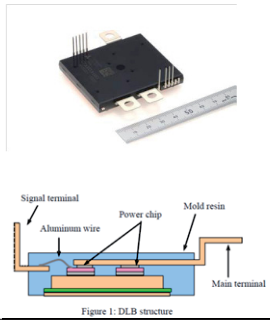
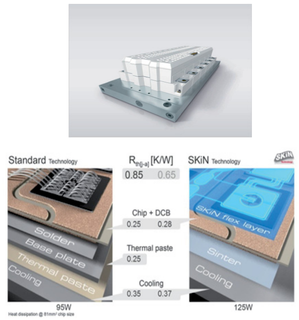
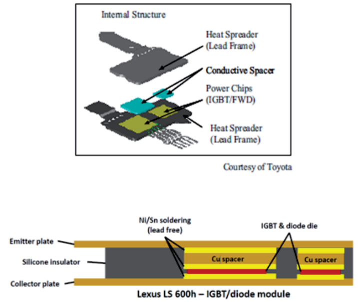
	Toyota Prius 2004	Toyota Prius III 2010	Nissan LEAF	HybridPack 1 >30kW	HybridPack 2 >80kW
IGBT-die	Die Wire bonding (Al wires)	Die Ribbon wiring (Al)	Die Wire bonding (Al wires)	Die Wire bonding (Al wires)	Die Al Wire bonds /copper bonded terminals
Die-attach	Solder	Solder	Solder Lead (Pb)-free	Solder	Solder
DBC substrate	DBA Al AlN DBA Al	DBA Al AlN DBA Al	Placa de Cu-Mo Solder Lead (Pb)-free Cu bar	DBC Cu DBC Al2O3 DBC Cu	DBC Cu DBC Al2O3 DBC Cu
	Solder Baseplate	Directly bonded by brazing No base plate (3)	No base plate	Solder Copper base plate	Solder Coopper base plate with pin-fins
TIM	ZnO Thermal Paste	No TIM	No TIM. New HTCI sheet	TIM	No TIM
Heat sink	Al cold plate	Direct bond cooler. Cold plate	Cold plate	Al cold plate	No Cold plate.
Cooling method	Indirect cooling	Direct Cooling	Microchannel cold plate.	Indirect Cooling	Direct cooling. Pin fins base plate.
Advantages		* No base plate. * No TIM layer. * Al Ribbond bonds. * Integrated cooler structure. * Achives 30% improvement in thermal performance.	* No base plate. * No TIM layer. * HTCI layer: (Heat radiating and insulating sheet) * Cu-Mo layer Compensate CTE difference between the bus bar and die. *Solder Lead (Pb)-free power module.		* No capa TIM. * No Cold plate. * Direct cooled base plate. Integrated cooler.
Disadvantages	* Standar packaging	*Buffer layer between DBA and cold plate worsen thermal conductivity .	*Large electrial parasitic parameters.	* Standar packaging	* Difficulty in pin fin manufacture. * Difficult integration of cooler. * Large electrial parasitic parameters.

(1) DLB_ Direct Lead Bonded. Cu leads are soldered directly on top of all switches dies (direct lead). These interconnection componenets reduce the package parasitic resistance. Such bonding by direct Cu soldering requires a so-called solderable front metal (SFM) of die top electrodes.

(2) SKIN technology: comprises the sintering of power chips to a substrate, a top side sintering of the power chips to a flexible circuit board and the sintering of the substrate to a pin-fin heat sink .

(3) A buffer plate with punched holes, which was inserted to release the stresses between the cooler and DBA caused by the CTE mismatch.

Fig. 2: Comparison of some of actual manufactured automotive power modules packaging technologies.

				
	Semicron SKIM 63/93	Módulo J1-Serie . Mitsibishi Electric	Semicron Skiip 4	Toyota Lexus 600h
IGBT-die	Die Al Wire bonding	Die (SFM) (1) Cu Direct Lead Bonding. DLB	Die No wire bonding (SKIN Technology) (2)	Die (SFM) (1) Planar Cu plates. Gate by wire bonding
Die-attach	Sintering (Skinnter Technology)	Solder Lead (Pb)-free power module	Sintering (Ag sintering)	Solder Lead (Pb)-free power module
DBC substrate	DBC Cu DBC Al2O3/AlN DBC Cu	Cu T-PM Cu	DBC Cu DBC Al2O3/AlN DBC Cu	Cu Cu
	Pressure contact No base plate	Solder Lead (Pb)-free power module	Sintering technology No base plate	Solder Lead (Pb)-free power module
TIM	Pressure contact technology	TIM	No TIM	Doble TIM
Heat sink	Cold plate.	Cold plate	Cold plate	Cold plate
Cooling method	Indirect Cooling	Doble side cooling.	Indirect cooling	Double side cooling
Advantages	* No base plate. * Solder free Ag sintered die-attach (Skinnter Technology). * Pressure points close to the chips provides low thermal resistance.	*DLB : Direct PlanarLead Bonded * Double side cooling. * No DBC. A thick Cu/TCIL/Cu DB structure replace de DBC.	* No wire bonding. SKIN technology (2) * No base plate. * Ag sintered die-attach. (Skinnter Technology). * NoTIM	* No base plate. * Double side planar interconnection. (3) * Double side cooling.
Disadvantages	* Large electrial parasitic parameters. * Difficult integration of cooler.	* Module level assembly needed. * Doble TIM layer. * Poor thermal propieties of TCIL.		* Ceramic slice insulation and double TIM layer. * Complex inverter (electrical and thermal). assembly.

(1) DLB_ Direct Lead Bonded. Cu leads are soldered directly on top of all switches dies (direct lead). These interconnection componenets reduce the package parasitic resistance. Such bonding by direct Cu soldering requires a so-called solderable front metal (SFM) of die top electrodes.

(2) SKIN technology: comprises the sintering of power chips to a substrate, a top side sintering of the power chips to a flexible circuit board and the sintering of the substrate to a pin-fin heat sink .

(3) A buffer plate with punched holes, which was inserted to release the stresses between the cooler and DBA caused by the CTE mismatch.

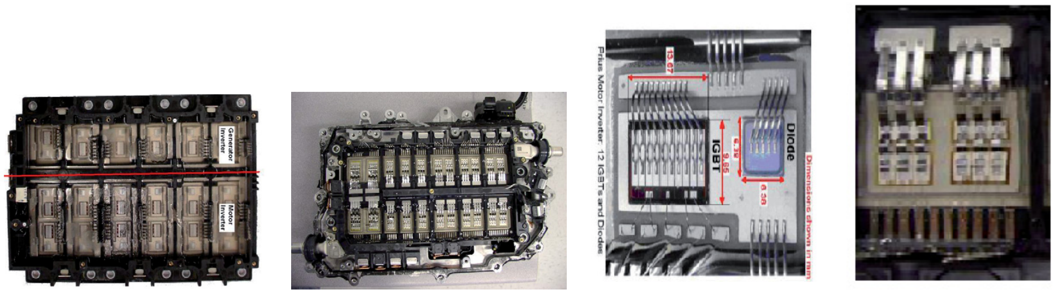
Fig. 3: Comparison of some of actual manufactured automotive power modules packaging technologies.

2.3. Interconnection technologies

Interconnectors add extra power losses by parasitic electric inductance, resistance, and capacitance. To reduce these parasitic parameters and improve the reliability, new interconnection techniques have been developed: Ribbon bonding, Direct Lead bonding (DLB) and Copper bonding. Changing the wire interconnection configuration to a planar or symmetric package will bring enormously comprehensive benefits.

In the Toyota Prius Hybrid III 2010 Toyota employed Al ribbons to replace Al wires which helps improve the reliability and electric parasitic parameters of die interconnections.

Figures 4(a) and 4(b) show Toyota Prius Hybrid 2004 and Toyota Prius Hybrid III 2010 power modules. Furthermore, figures 4(c) and 4(d) show in detail wire bonding and ribbon bonding interconection technologies.



(a) (b) (c) (d)

Fig. 4: Power modules interconnecton technologies (a) *Wire bonds*, Toyota Prius Hybrid 2004. (b)*Ribbon bonding*, Toyota Prius Hybrid 2010. (c) *Wire bonding* detail. (d) *Ribbon bonding* detail.

Most recently, Copper(Cu) wire bonding has been introduced as a new alternative contact technology. This technology reveals several significant advantages as higher thermal conductivity, higher electrical conductivity and lower cost, over Aluminium bond wires [5, 6]. Infineon, employed Copper wire bonds in the ”Infineon .XT” technology [7].

Table 2 shows a general comparison of the relevant material properties of both Copper and Aluminium.

	Aluminium	**Copper**	**Copper/Aluminium**
Elec. Resistivity	2,7 $\mu\Omega \cdot cm$	1,7 $\mu\Omega \cdot cm$	-40%
Elec.conduc.	$220\ W/m \cdot K$	$400\ W/m \cdot K$	$+5\%$
CTE	25 ppm	16,5 ppm	-35%

Tab. 2: Comparison of important properties of Copper and Aluminium

SEMIKRON also has developed the “SKIN Technology” [8]. In this architecture wire bonds are replaced by a flexible board which is sintered onto the chip surface. The SKiN flex layers take over the function of the bond wires. They allow an increase of about 25$\%$ surge current in the power module due to the sintered layer on the chip tops. Compared to conventional power modules the additional performance allows an approximate doubling of the current density. Excellent thermal and electrical properties of the sintered layers increase the module lifetime up to tenfold [3]. Figure 5 shows the comparison of standard connection technology and SKIN technology.

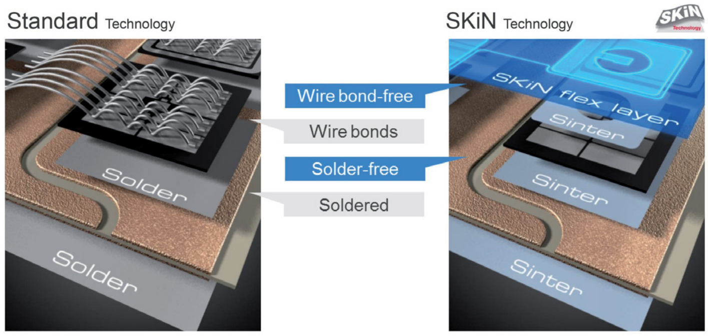


Fig. 5: Comparison of standard connection technology and SKIN technology. Picture is from [4]

Other example is the CooliR [9] platform from International Rectifier. The solderable front metal (SFM) allows soldered or sintered die attachment on both sides of the die. This enables wire bondless packaging techniques replacing it by DLB technology. Mitsubishi also developed a Cu lead bonded TPM automotive module [10].

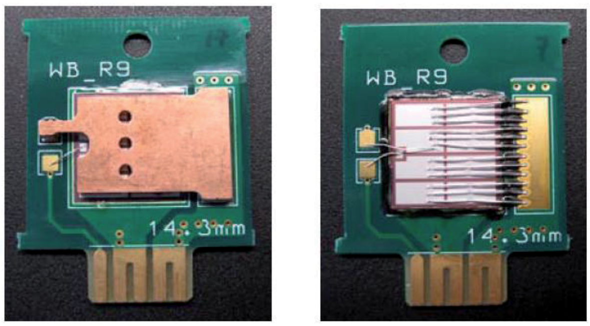


Fig. 6: International Rectifier packaged and wire bond packaged power IGBTs.

2.4. Power substrate DBC

The DBC is the medium on which are located the semiconductors (IGBTs and diodes). Its aim is to provide a mechanical construction, electrical insulation and evacuate adequately heat from semiconductors. The DBC (Direct Bond Copper) or DBA is composed of three layers, the first and last one metal (Cu or Al) and the intermediate ceramic (electrically insulating).

The trend is to make the ceramic layer (electrically insulating) thinner and the metal layer (Cu or Al) thicker in order to improve the heat transport. However, the CTE mismatch between the ceramic layer and the metal layer is an issue. Therefore, some new power substrates schemes have been made.

Based on EV application requirements, in the TPM module developed by Mitsubishi Electric a thick Cu / thin TCIL /thin Cu structure replaces the DBA. The TCIL (Thermal Conductive Insulation layer) is made of especial insulation resin and has a good thermal conduction capability [10]. The power module in Nissan LEAF has the same configuration. The IGBT is soldered to a thick Co-Mo spacer for CTE matching. Curamic also introduces a new hybrid substrate (where the cooling channels are integrated directly into a DBC substrate) comprising of cooper, ceramic and aluminum [11].

3. Cooling methods

Conventional power modules cooling options based on natural air cooled and forced air cooled heat sinks are not able to meet the existing demand for cooling the power modules used in traction applications such as EV. Very high current density, excessive ambient temperatures, humidity, vibration and dirt in the engine compartment among others can lead to premature rupture of the power module if the cooling system is not designed properly.

The following factors influence the reliability of the cooling options [7]:

- The contact area to the coolant.
- Turbulence in the water flow.
- The volumetric flow rate as a function of the pressure drop.
- The heat storage capability of the coolant.
- The coolant temperature.
- Heat conduction and spreading in the heat sink.

Liquid cooling solutions can be divided into two groups: indirect and direct liquid cooling.

Indirect cooling means that the power module is assembled on a closed cooler, e.g. a cold plate. When dealing with cold plates, it is necessary to apply a layer of TIM between the power module and the cold plate, which significantly reduces the cooling system performance [12].

In direct liquid cooling systems the coolant is in direct contact with the surface to be cooled and eliminates the layer of TIM. The cooling efficiency is improved by increasing the surface area. Various designs can be distinguished:

- Pin fins base plates. Liquid flow through pin fins formed directly on base plates [13].
- Spray cooling. This method used the principle of spraying the liquid coolant onto the surface either as droplets or jet. Cooling may be applied from one side or both sides [14].
- Jet impingement cooling [15]. Danfoss Silicon Power has developed a system called “Shower power” which is based on this technique. Here, a plastic insert with many parallel holes in the heat sink opening creates turbulent and vertical flow ensures good and even cooling [16].
- Microchannel coolers built into cold plate or integrated with DBC substrate or into specially customized package design [17].
- Two-phase cooling. Oak Ridge National Laboratory (ORNL) has developed a system based on Two-phase cooling technology with automotive air conditioning R-134a coolant [18].
- Double side cooling. This enables a further reduction of the thermal resistance. It doubles the effective area of the heat dissipation. Denso in cooperation with Universities of Cambridge, Oxford and Nottingham [19], Fraunhofer Institute IZM [20] and Semikron (SKIN Technology) among others, have developed a module based on this technology.

4. Conclusions

The combination of a reliable die attach technique, a reliable top contact technology, as well as a good thermal, thermo-mechanical and electrical design, associated with the successful combination of different materials are crucial factors to integrate successfully power electronic in EV propulsion system. Trends are to replace soft solder contacts by sintering and diffusion soldering, to replace Al wire bonds by Direct Lead bonding (DLB) and Copper bonding, and to employed new liquid cooling methods (microchannel, thermoelectric cooling, two phase cooling, double side cooling) for improving the thermal performance of EV high-power modules.

5. Acknowledgment

This work has been carried out inside the Research and Education Unit UFI11/16 of the UPV/EHU and supported by the Department of Education, Universities and Research of the Basque Government within the fund for research groups of the Basque university system IT394-10 and by the University of the Basque Country. This work has been supported by the Ministerio de Economa y Competitividad of Spain within the project DPI2014-53685-C2-2-R and FEDER funds.

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