Planar Bond All: A New Packaging Technology for Advanced Automotive Power Modules

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Abstract—A novel packaging structure for liquid cooled automotive power modules is developed. It features sandwiching power semiconductor switches between two symmetric substrates, which serve electrical interconnection and insulation. Two mini coolers are directly bonded to the outside of these substrates, allowing double sided, integrated cooling. The power switches in a popular phase leg electrical topology are orientated in a face up/facedown three-dimensional (3-D) interconnection configuration. The bonding areas between dies and substrates, substrates and coolers are designed to use identical materials and formed in one heating process, in which a special fixture has been made so that a high efficiency production can be implemented. Combining these features with the thermal and electrical advancements, this packaging technology offers dramatically comprehensive improvements in power module’s cost effectiveness, electrical conversion efficiency and thermal management, as demonstrated by a planar bond packaged prototype of a 200A/1200V phase leg power module.

I. INTRODUCTION

The tough challenges facing the power electronics systems in hybrid electric vehicles (HEVs) and all electric vehicles (EVs) require intensive improvements of all parts in cost, reliability, functionality, power density, and efficiency, etc. Among them the power modules, which are comprised of multiple power semiconductor switches, are most critical part to meet these objectives. The power semiconductor switches such as insulated gate bipolar transistors (IGBTs), and diodes are thin, fragile slices made of Si, SiC, or GaN, etc., called dies. These switch dies are arranged within the module to fulfill electrical functions in the form of inverter and converter topologies. Module packaging serves to provide electrical interconnections, thermal management and mechanical support to these semiconductor dies. Due to the vertical semiconductor structure of these switch dies, the fundamental packaging components include base plate, substrate, die attach (die bottom), interconnect (die top), encapsulate, power terminals and single pins. The advancement of power modules depends greatly on improvement of power packaging technology through advances in structure, materials and processing technology. Characterization of these improvements depends on a group of technical performance parameters of power modules in aspects of electrical, thermal, mechanical and thermo-mechanical properties. These parameters include parasitic electrical parameters, thermal impedance, operation temperature, power and thermal cycling capability, vibration, stress strength, weight, volume, etc.

The first generation automotive power modules were manufactured with standard wire bond packaging technology [1], including soldering die attach, wire bond interconnect, silicon gel encapsulate, and multiple/hybrid manufacturing processes. They are mounted onto a cold plate with thermal interface material (TiM) such as thermal grease. The second generation modules employ a variety of advanced packaging technologies such as integrated cooling [2], direct copper lead top interconnection [3], and double sided copper bonding [4] and others [5-13]. All these technologies brought only partial improvement in power module performance.

This paper presents an integrated power module packaging technology, which achieves a comprehensive improvement in all aspects of power module technical performance. The technical details, such as packaging structure and associated packaging process technology is demonstrated with a new 200 A, 1200 V phase leg power module prototype. The improvements in performance and manufacturability result in considerable strides toward achieving targets for power electronics systems in modern electric drive vehicles.

II. PLANAR BOND POWER MODULE PACKAGING

A. Planar Bond Power Module

The graph in Figure 1 (a) is an electric schematic of a typical phase leg configuration, which consists of two switch units, upper IGBT/diode pair and lower IGBT/diode pair. It is a building block for various electric power converters,
in inverters in automotive power electronics systems. Schematic of the packaging structure for this phase leg power module is shown in Fig. 1 (b). The IGBT and diode dies are mounted between two insulated substrates such as direct bond copper (DBC) ceramic boards. The electrical interconnection is achieved by conductively bonding switch dies to the copper on two DBCs, which are patterned to form a circuitry and match with the electrode pads layout on dies. The DBC substrates offer electrical insulation with their ceramic slice inside. This symmetric planar bond package offers the flexibility of switch die arrangement. It is shown in Fig. 1 (b) that the upper switch pair and lower switch pair in phase leg are oriented physically in a face-up/face down configuration. This makes use of dies’ vertical semiconductor (electrode) structure, i. e., electrodes are arranged on both top and bottom surfaces of the dies. This layout change, compared to wire bond packaging one, results in the change of the main power flow loop from X-Y plane to X-Z plane. Due to the thickness of switch die in the range 0.1mm, compared to length/width of 10mm, the enclosed area of the loop is reduced dramatically, leading to an enormous reduction in electrically parasitic inductance in addition to electric resistance reduction due to larger bond areas and large Cu electric conduction traces.

This planar bond structure also exposes the top surfaces as extra thermal paths for power switches. The heat removing from hot power switch dies is improved much by applying double sided cooling (here focused on forced liquid technique). In addition, the special mini-coolers are designed to be directly attached to the power stage by planar bond layers, as depicted in Fig. 1 (b). The direct cooler bonding, instead of stacking through TIM layer, leads to the further thermal resistance reduction in the thermal paths.

The mismatch of the thermo-mechanical parameters, including CTE difference between multiple hybrid materials and structure asymmetry, is a major failure mechanism of conventional power module. The sandwiched dies mount offers symmetrically mechanical support, while the replacement of bond wires by planar bonds reduces the complexity of material combination. They are all advantageous to contain the deformation due to mismatched thermal expansion while power switches operate with large amount of heat generated.

B. Planar_Bond_All Packaging Technology

The above module structure design alters the multiple hybrid bonding forms in the conventional packaging structure into a few identical planar bonds. To accomplish this paradigm shift of packaging scheme, a special packaging process technology has been developed, in which as shown in Fig. 2, all packaging components are assembled into a fixture firstly. The components include patterned substrates, bare dies, shims, bonding material (premade such as solder foil), power terminals and signal pins, as well as mini coolers, etc. The second step involves heating up the assemblies to form the bonds and create the final packages. It can be seen that this manufacture process not only reduces the conventional multiple hybrid packaging processes to two steps, but also make batch process possible. The simplicity of the process helps reduce costs and improve the manufacturability of the modules greatly. The technology is called Planar_Bond_All, representing the features in packaging structure and process.

Fig. 3 (a) is a photograph of the prototype power module employed above packaging technology. It is with one phase leg (half bridge) electrical configuration, comprised of two pairs of single silicon IGBT, diode dies, both rated at 200A/1200V. The module body measures in 52mm x 30mm x 2mm, excluding the terminals and pins. The soldering process is employed to form these planar bonding because of its good electrical conductivity and processing feasibility. The special front metallization of power semiconductor dies, instead of conventional aluminum (designed for wire bonding), was created by prefabrating the power semiconductor dies in wafer level. The power terminals [positive, neutral, and negative (P, O, and N)] and signal pins (G_U, E_U, and G_L, E_L) are also mounted between the two substrates to form compact input/output connectors.
This module has designed to be cooled from both sides, as depicted in Fig. 1 (b). Various configurations can be employed for double sided cooling. Fig. 3 (b) shows an example that two copper flat tube cold plates (mini-cooler) are integrated to the power module. The effective cooling area is 58mm x 30mm, the tube thickness is 3 mm. Made of all copper and being with a unique internal criss-crossed fin structure, this mini cold plate offers thermal resistivity of 0.33cm²°C/W at water coolant flow rate of 1 GPM, which is superior to conventional cold plate.

III. CHARACTERIZATION OF PACKAGING PERFORMANCE

The performance parameters of the prototype are among the important indicators of the packaging design and manufacture. Various experimental measurement methods and multi-physics simulation tools have been used to intensively characterize the electrical and thermal performance of the module packaging.

A. Electrical Characterization

The electrical performance of module packaging can be described by the electric components (resistance, inductance and capacitance) added onto the semiconductors’ electric components.

Fig. 4 presents an electric circuit diagram of half bridge inverter with parasitic electric resistance and inductance, which is attributed to the electrical interconnection path in planar bond power module. This lumped element model was developed by employing an electromagnetic simulation tool, MAXWELL Q3D Extractor, in which the effective electric components (lumped elements) were calculated physically based on the electric and electromagnetic fields when current going through these conduction path sections. The sum of lumped elements along a main power path from terminal Positive through upper IGBT and then lower diode to terminal Negative, are usually the representative parameters.
of a packaging structure. In this planar bond power module, the total inductance $L$ is 12.08 nH, while the total resistance $R$ equals 0.22 mΩ. For comparison, the parasitic electrical parameters in a conventional wire bond packaged power module with the same power semiconductor dies were also extracted. The analogous values for the major parameters defined above are $L=50.3$ nH, and $R=2.35$ mΩ.

The parasitic electrical inductance was also measured with double pulse test, in which the inductive load. From the voltage overshoot added onto turn off voltage transition and current decrease rate, the parasitic inductance involved in the current loop can be calculated. Fig. 5 shows the current and voltage waveforms during turning off of an IGBT in planar module. It can be seen that over 100 V voltage overshoot, measured at signal pins, add on the blocking voltage, which set at 300 V of bus voltage. This voltage overshoot comes from the voltage drop on inductance along whole current loop, including power module and test circuit. To separate the test circuit one, a voltage waveform across the power terminals was also recorded. The difference of voltage overshoot between these waveforms attributes to the parasitic inductance of packaging itself. In summary, the calculated and measured parasitic inductance values are listed in Table I. It can be seen that the inductance of the planar power module is less than one third of that with wire bond module.

Planar interconnection allows large contacts and switch unit orientation of face up-face down switch die pairs. These measures make the parasitic resistance and inductance reduce dramatically. The smaller parasitic electric parameters cause the power losses reduction in switches and conduction paths, resulting in improvement of power conversion efficiency [14].

### Table I. Parasitic Inductance with Packaging Interconnection

<table>
<thead>
<tr>
<th>Inductance (nH)</th>
<th>Experimental Value</th>
<th>Calculated Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planar Bond, Lower IGBT</td>
<td>10.5</td>
<td>6.3</td>
</tr>
<tr>
<td>Wire Bond-Lower IGBT</td>
<td>31.9</td>
<td>23.5</td>
</tr>
</tbody>
</table>

B. Thermal Characterization

The thermal performance of a power module can be modeled as a multiple orders of thermal resistance and capacitance network in series. The thermal capacitance determines the transient response of the power module to power dissipation in switches; while the thermal resistance determines the cooling efficiency. The characterization of the thermal parameters has been performed with different methods.

Fig. 6 (a) shows a 3-D computational fluid dynamics (CFD) model, in which the geometry parameters of module

![Figure 6](image_url)

(a)

![Figure 6](image_url)

(b)

Figure 6. Thermal performance simulation of planar bond power module: (a) 3-D model and (b) temperature distribution at typical cooling conditions.
structure and materials properties are defined. The heat transfer process from dies to coolant is simulated and the thermal performance is then analyzed. Fig. 6 (b) presents the temperature distribution in power stage of planar power module at conditions as followings: the power loss is 100W on IGBT, 70W on diode; the coolant flow rate is at 2.5GPM; the coolant temperature at inlet is 65°C. From these data, the thermal parameter network can be extracted.

The same parameters were obtained by experimental thermal tests through emulating real operation of power modules. In typical thermoelectric method, the self-temperature sensor parameter of switch such as Vf for diodes and Vce for IGBT, is as a junction temperature meter, due to their sensitivity to temperature. Once a pulsed power was pumped into and heat up the IGBT, its temperature will increase and be stabilized at certain temperature. Then the power is cut off, the IGBT will cool down from this high temperature. By processing the cooling down temperature curves and input power data, the thermal parameters (resistance and capacitance) with the module can be obtained [15]. For fair evaluation of thermal performance of a packaging assembly, the specific thermal resistance was taken as a figure of merit, which is a normalized parameter by die size, die size*thermal resistance. Here, the thermal path includes all thermal stacking elements from coolant inlet to junction of switch die. Fig. 7 presents the specific thermal resistance value of this planar bond module with two mini coolers, as depicted in Fig. 3 (b). For comparison, other two representative automotive power modules were also measured using same method and shown in Fig. 7. The wire bond one, that was mounted on a cold plate with thermal grease, is with specific thermal resistivity of 0.541 cm²·°C/W; while the integrated single side cooling one, which has a rigid bond between module and cold plate, is with 0.47 cm²·°C/W. The double sided cooling of the planar module assembly reduces the specific thermal resistivity to 0.33 cm²·°C/W, which is 38% lower than that of the first generation module assembly.

The die size used in a power module is proportional to the specific thermal resistance of module assembly. With smaller thermal resistance, the semiconductor die size can be tailored to be smaller for a certain power rating, which is a critical factor to reduce the cost of power modules.

IV. CONCLUSION

A power module packaging technology, based on all planar bonds of power semiconductor and other package components, has been developed and applied in fabrication of a 200A/1200V phase leg power module. The electrical and thermal performance parameters have been characterized with simulation and experimental measurement tools. The improved performance and anticipated cost reduction of the packaging process will result in considerable strides toward achieving power density and cost targets for automotive power electronics systems.

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REFERENCES


Figure 7. Thermal resistance of planar bond power module and comparison with industrial modules.


