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Ultra-Compact and Light Weight Intelligent Power Semiconductor Module for Hybrid System

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Abstract

Recently, hybrid electric vehicles are required high power with high fuel efficiency and comfortable large cabin space. An ultra compact intelligent power module for two-motor hybrid electric vehicles which integrates one back-boost chopper and an inverter for a traction motor, an inverter for a power generator has been developed. The module is the world's first released module which has a direct liquid cooling structure with a solder-joined aluminium heat sink. The module achieves a 30-% reduction of volume and a 60-% reduction of weight compared to our conventional models. A heat sink with high cooling capacity and a high-strength solder were newly developed to establish the structure. The module is designed for 700 V/ 400 kVA system and it has an on-chip self protection functions and serial communication interface with a master control unit.

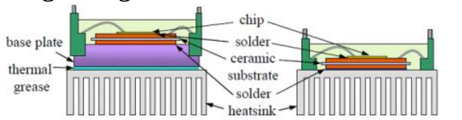
Keywords: intelligent power module, direct liquid cooling, aluminium heat sink, solder joining

1 Introduction

Hybrid electric vehicles consists of motors, batteries and power modules to control them. Characteristics of the power modules are the key issues to make the vehicles more energy-efficient. In particular, volume and weight reduction of them are very important.

Figure 1 (a) shows a conventional indirect cooling structure which has a copper baseplate as a heat sink and the module is mounted on a heatsink through thermal grease to manage heat from semiconductor chips. This structure is convenient for production, but low thermal conductivity of thermal grease results in poor heat dissipation and low fuel efficiency.

Figure 1 (b) shows the newly developed direct cooling structure. Copper is heavy and has poor corrosion resistance to liquid coolant. Therefore, direct cooling structure is better if copper is not used. This structure achieves eliminating thermal grease, lightweight and better corrosion resistance.



(a) Indirect cooling (b) Direct cooling

Fig. 1: Schematic diagram of power modules

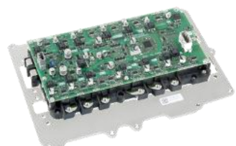


Fig. 2: Newly developed intelligent power module

Figures 2 and 3 show the newly developed intelligent power module (IPM) that came into the market in December 2012. It consists of two power drive units (PDUs) and one voltage control unit (VCU) integrated in one package and controllers on a gate drivers.

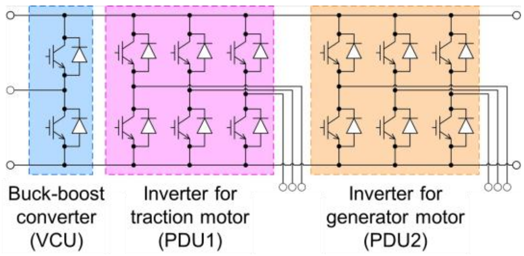


Fig. 3: Main circuit of the IPM in Fig. 2. VCU and PDU consist of insulated gate bipolar transistors (IGBTs) and free wheel diodes (FWDs).

2 Subjects for ultra compact IPM with directly joined aluminium heat sink

To establish the ultra compact structure of the IPM with a three-unit integrated module and a light-weight aluminum heat sink, we have two considered two technologies below.

i) Re-design of the heat sink to increase its cooling capacity

The IPM is driven by high current density and the three units (PDU1, PDU2, VCU) should be simultaneously cooled by the aluminum heat sink. Low thermal conductivity of aluminium compared to copper needs the structural re-design of the heat sink to increase its cooling capacity.

ii) Development of new solder to join insulated metal substrate and aluminium heat sink

For the mass production of the IPM which has a lot of insulated metal substrates and IGBTs / FWDs on them, it is desirable to join the insulated metal substrates to the heat sink by soldering using current production equipments to achieve ost effective productionFor the use of solder, long-time reliability is one of the most important points. Table 1 shows material property of insulating substrates and heat sinks. Solder layer joining insulated metal substrate and aluminum heat sink is usually degraded by mismatch of the coefficient of thermal expansion (CTE). As for the CTE mismatch to insulating substrate, aluminium has 1.4 times larger mismatch than that of copper. Conventional solder such as Sn (Tin) - Ag (Silver) based solder could not provide enough reliability for joining aluminum to insulated metal substrates. Therefore, we had to develop a new solder with high strength and high reliability.

Table 1: Material property of substrates and heat sinks

Material		Thermal Conductivity [W/mK]	Thermal Expansion Coefficient [ppm/K]	Bending Strength [MPa]
Insulating Substrate	Al_2O_3	20	6.7	700
	Si_3N_4	90	3.4	700
	AlN	170	4.6	500
Heat Sink	Cu	393	16.5	-
	Al	170	23.5	-

The design of aluminium heat sink and the development of new solder are described in the following sections.

3 Design of aluminium heat sink

The aluminum heat sink was designed according to the following two steps: (1) design of flow path to provide coolant with as low temperature as possible, (2) optimization of flow-speed distribution to match it to the distribution of heat sources (IGBT chips).

3.1 Design of flow path

Figure 4 shows the dependence of the IGBT junction temperature on coolant temperature for various flow speed of the coolant. is the chip was assumed that an IGBT chip on a heat sink is cooled by coolant flowing through the heat sink.

As shown in this figure, the junction temperature strongly depends on the coolant temperature. Using low-temperature coolant is very effective to reduce junction temperature even if it makes flow speed a little slower.

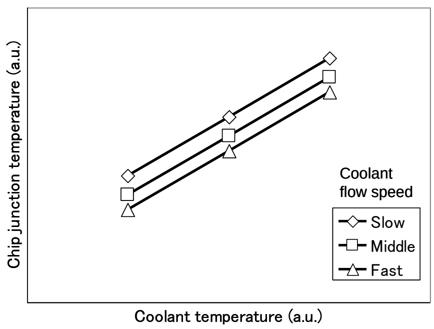


Fig. 4: IGBT junction temperature dependence on coolant temperature and flow speed

Our IPM has many heat sources (IGBT and FWD chips) in it as shown in Fig. 3. To keep the coolant temperature low with this structure, it is essential

to design the flow path to make the number of chips on it minimum.
Figure 5 shows schematic diagrams of our heat sink and examples of flow path. The number of chips on the flow path type B is less than that of type A which is widely used for this shape of heat sink. We found by thermal fluid analysis that the flow path type B brings better cooling capacity of the heat sink even though the flow speed of the coolant in the flow of type B is slower than that of type A.

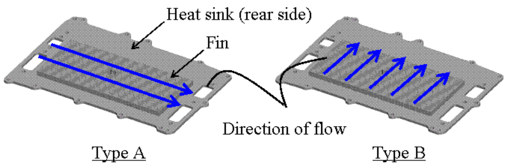
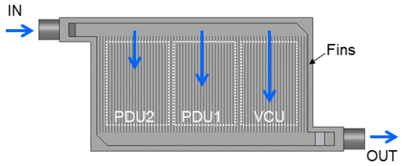


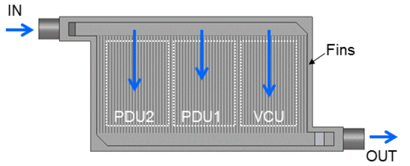
Fig. 5: Flow path of coolant through the heat sink

3.2 Optimization of flow distribution

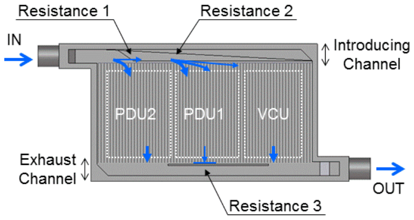
Figure 6 shows the flow speed distribution of the coolant flowing through the heat sink. The flow speed monotonically increases as the distance from inlet increases if the structure of the heat sink is quite simple as shown in Fig. 6 (a).
Since the heating power of PDU2 and VCU are higher than that of PDU1 in our case, the coolant flow speed under PDU2 and VCU should be higher than PDU1, as shown in Fig. 6 (b). The flow resistance by designing the shape of the introducing and the exhaust channel. Finally we found the optimized shape shown in Fig. 6 (c) [1].



(a) Flow speed distribution before optimization



(b) Expected flow speed distribution



(c) Structure to obtain the expected flow distribution

Fig. 6: Schematic diagrams of flow-speed distribution

Figure 7 shows the junction temperature of IGBTs before and after optimization of flow speed distribution. The optimization successfully resulted in the desired maximum junction temperature and close to target junction temperature in each unit [2].

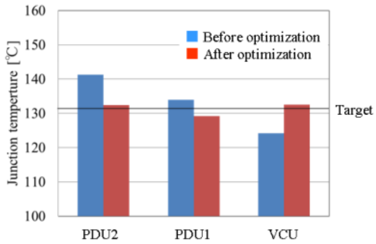
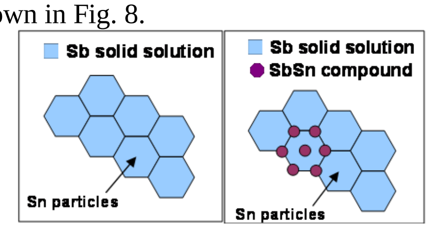


Fig. 7: Junction temperature of IGBTs before/after optimization of flow speed distribution

4 Development of high-strength and high-reliability solder

4.1 Selection of solder material

In order to realize high efficient direct cooling structure, the joining material with low heat resistance and long fatigue lifetime is required.
There are two methods for metal strengthening mechanism: solid-solution strengthening and precipitation strengthening.
Conventional Sn-Ag based solder is an alloy of precipitation strengthening type. Its mechanical property is excellent but easily deteriorated at high temperature because grain boundary of Sn becomes weak in order that Ag_3Sn compound may condense and carry out coarsening of the alloy [3].
Therefore we decided to develop a new solder which has both mechanisms of precipitation and solid-solution strengthening. We focused on Sb (Antimony) which is one of the representative elements together with In (Indium) for Sn to express solid-solution strengthening [4].
Sb dissolves in Sn grains and restrains the grain growth of Sn under high temperature [5, 6]. It is expected to express precipitation strengthening in addition to solid-solution strengthening if the content of Sb is over the limit of its solid solubility as shown in Fig. 8.



(a) (b)
Fig. 8: Strengthening of Sn-Sb solder
(a) Sb content < Solid solubility limit
(b) Sb content > Solid solubility limit

4.2 Strength and reliability of newly developed Sn-Sb solder

Four kinds of Sn-Sb based solder in which different amount of Sb, type 1-4, in order to evaluate various kinds of performances.
(Sb content: type 1 < type 2 < type 3 < type 4).
The tensile strengths of four types of Sn-Sb solder at room temperature are shown in Fig. 9. The Sb content of type 1 is below solid solubility limit, and that of type 2-4 is over the limit of their solid solubility. It is revealed that the tensile strength increased as the amount of Sb increased. It is noted that the tensile strength dramatically increased in solder type 2 compared to that of type 1. This can be attributed to the change of strengthening mechanisms between these two samples. No dramatic increase in tensile stress was seen in solder type 3 and 4 in comparison to type 2, showing that no big change in strengthening mechanism among these samples.
The solderability degraded as Sb content increased (no data shown). Therefore, We considered solder type 3 optimum and investigated its thermal cycling capability.

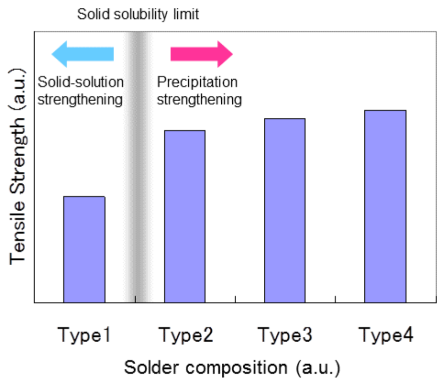
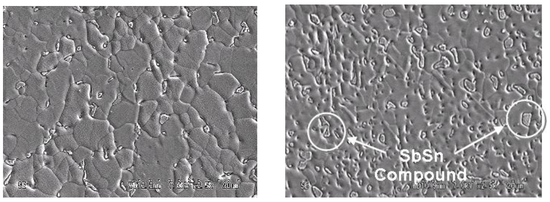


Fig. 9: Tensile strength of solders at room temperature

The microstructure of the solder type 1 and type 3 are shown in Fig. 10. In the structure of type 1, the deposit compound of Sb-Sn is only a little observed since Sb solved in the Sn. On the other hand, some amount of the deposit compound of Sb-Sn is widely seen in the structure of type 3.



(a) Sn-Sb Type 1 (b) Sn-Sb Type 3
Fig. 10: Micro structure of the solders

Figure 11 shows the tensile strength change of conventional Sn-Ag and Sn-Sb solders after high temperature storage test. Both solders have similar initial strength. However, the strength of Sn-Ag solder significantly decreased after 1000 hours at 150 °C and 175 °C, while Sn-Sb solder strength was not changed.

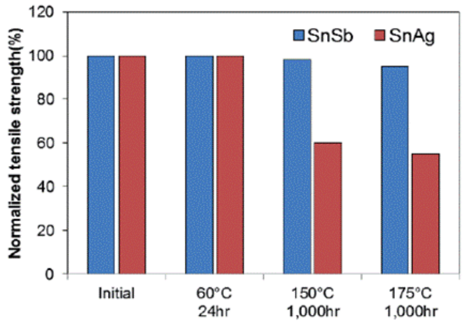


Fig. 11: Tensile strength of the solders after high temperature storage test

4.3 Reliability of insulated metal substrate / aluminium plate structure joined by Sn-Sb solder

Figure 12 shows the increase of the relative crack length during temperature cycle test. Here, insulated metal substrate and aluminium heat sink were joined with Sn-Sb solder. The results for conventional Sn-Ag solder are also shown as comparison. The relative crack length means the ratio of crack length from the corner to the diagonal length in insulated metal substrate.
It can be found that the crack length of Sn-Sb solder is small, derived from high tensile strength. On the other hand, that of Sn-Ag solder is large and it increased as the number of thermal cycle increased.
It is clearly shown that the thermal cycling capability of solder strongly depends on tensile strength. Sn-Sb solder is much stronger than Sn-Ag solder.

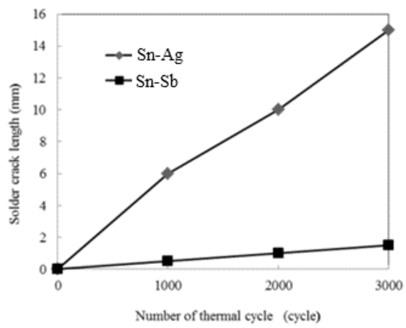


Fig. 12: Change of the crack length in the solder layer between insulated metal substrate and aluminum heat sink during thermal cycle test

Figure 13 shows the comparison of scanning acoustic microscope images after 3000 temperature cycles of delta T = 145 ^{o}C (-40 to 105 ^{o}C). The white area indicates the crack grown in the solder layer.

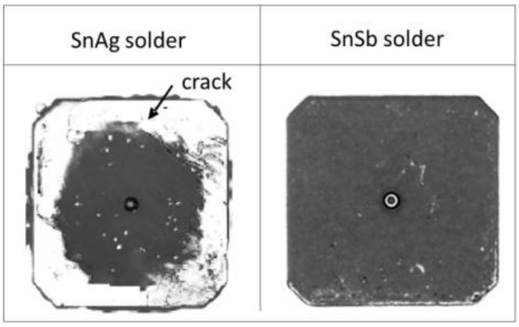


Fig. 13: Scanning Acoustic Microscope image of insulated metal substrate / aluminum plate samples

The result also suggest that the newly developed Sn-Sb solder is much stronger than conventional Sn-Ag solder caused by its high intensity and ductility which we think is based on the synergistic effect of precipitation strengthening of Sn-Sb compound and solid solution strengthening of Sb.

5 Specification of the newly developed IPM

The key specifications of the developed IPM are shown in Table 2. This IPM is for two-motor system of hybrid electric vehicles and it enabled the maximum system voltage of 700 V and output power of 400 kVA in total. This high boost voltage leads to downsizing and improvement of the system efficiency. The latest model of Fuji's 6th-generation 1200 V IGBT chips with Field Stop structure are used.
The protection functions for IGBT are integrated in the Gate Drive IC which is also our developed products. The voltage control logic has been designed to realizing the fast response and the stability for ordered voltage from the master controller. The IPM can output following information through serial communication interface: junction temperature of IGBTs, the measured voltage value and the failure status by using the serial communication.

Table 2: Specification of the newly developed IPM

	Feautres
Structure	Aluminum-Direct-Cooling realizes High cooling efficiency with durability for Automotive requirement.
System Configuration	1200V/250A・500A 14 in 1 Intelligent Power Module for Inverter of Traction Motor, Inverter of Generator Motor and Buck-boost Converter of Hybrid Electric Vehicle.
	Maximum output : 400kVA (system voltage : 700V)
	Including Gate Drive circuit and protection for IGBT.
	Including Gate Drive power supply circuits.
	IPM status communicates by Serial Communication.
	Buck-boost converter controls DC voltage.
Control Function	IPM status(temperature, voltage and failure information) is transmitted by Serial Communication.
	Buck-boost converter is controlled by a original control logic which was developed for this product.

6 Conclusions

The intelligent power module for two-motor hybrid electric vehicles. A direct liquid cooling structure with a solder-joined aluminum heat sink was adopted for the first time in the world to establish the highly integrated module with two inverters and one chopper in a package.
For the aluminum heat sink, we found that proper design of flow path and flow-speed distribution of coolant is essential to obtain high cooling capacity. The flow path was designed to make the number of heat sources on it minimum and the flow-speed distribution was controlled by flow resistances on the channels to match the distribution of heat sources to achieve the required cooling capacity.
For the solder joining, we developed a Sn-Sb based high-strength and high-reliabilty solder. We found that the Sn-Sb solder with proper Sb content is strengthened by the precipitation strengthening of Sn-Sb compound in addition to the solution strengthening of Sb without losing practical solderability. It enabled the direct joining of insulated metal substrates and aluminium heat sink with enough strength and long-time reliability.

The newly developed intelligent power module consists of two power drive units, a voltage control unit and controllers on a gate driver. It came into the market in December 2012.

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