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Improved life of IGBT module suitable for electric propulsion system

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Abstract

For the IGBT module which is used for automotive propulsion, the lifetime is required equal to the car. For example, the requirement is 150,000 miles in 15 years. The parts which compose IGBT module are joined by solder. The lifetime of the module is reduced because of the crack in solder layers which occurs by repetition of temperature differences. From the results of our study, the solder which contains tin (Sn) and antimony (Sb) is suitable for automotive. The developed solder achieves more than 20,000 cycle lifetime of the thermal fatigue life test with 80 °C of temperature difference, which exceeds the lifetime of the actual vehicle use.

Keywords: IGBT module, Antimony, Temperature cycle, Reliability, Thermal fatigue life, HEV

1 Introduction

Battery electric vehicle (BEV), hybrid electric vehicle (HEV), fuel cell electric vehicle (FCEV) is driven by one or more electric motors. An electric motor is supplied with electric power by an IGBT module which is composed of IGBT chips and diode chips. The required lifetime for a vehicle is generally 150,000 miles in 15years. In the auto-motive application, when cars used with parking outdoor during the lifetime period of 15 years, it is necessary to assume that the repeat of the temperature change which is larger than the man-aged environment causes the function-deterioration of the electronic systems. Below, the modelling of the temperature cycle at a vehi-cle, and the life-estimation way for acceleration test, and the advantage of tin based solder contained antimony are shown.

2 Mechanism of solder layer degradation

IGBT module consists of many different material layers, such as Si die, solder, DCB (Direct Cop-per Bonding) substrate and base plate. These materials have different coefficient of thermal expansion (CTE). There are plural solder joining stratums inside. One is between the power chip and the insulating-substrate and the other is between the insulating-substrate and the base plate. (See Figure 1) These solder layers are between materials with different thermal expansion coefficient, the crack grows because of the stress in-side of solder layers. That is the main cause to make lifetime of the module decline. [1] In general, power modules designed for industrial use are difficult to make lifetime sufficient for automotive use. For automotive use, reliability is a big issue, therefore assembling method and structure have been improved continuously. For the early type of HEV inverter, lower CTE and more expensive materials, such as Cu-Mo or Al-SiC, were used as a base plate of IGBT modules because of decreasing stress in the solder upon it. [2]

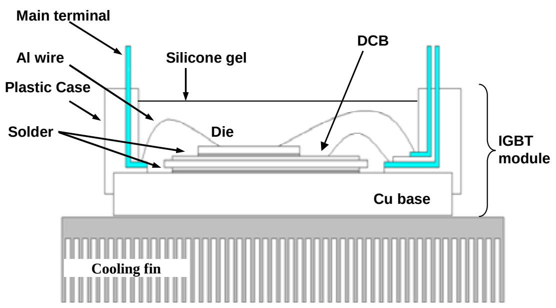

Figure1: Cross section of IGBT Module

The solder material between base plate and insulation is important to extend thermal cycle life in case of using low cost Cu base plate. [3] In order to keep high reliability, progress of the solder joint technology is strongly required. In assembly process, solder solidifies when its temperature becomes below the melting point. Therefore, the stress in the solder layer is the smallest at temperature near the melting point and the stress increases as much as lower temperature. However, only leaving in the extended period in the low temperature (e.g. at -40°C), the crack doesn't occur in the solder layer. The crack is propagated by a mechanism that the solder structure changes under the hot environments and the grain grows, the crack occurs to the grain boundary which was being damaged with the stress at the cold time. Therefore, it is valid improving the lifetime to restrain the growth of the grain at the hot time and to reduce a stress at the cold time. A temperature cycle's lifetime is improved because little structure changes at high temperature and suppressed grain growth in the solder which was composed of tin and antimony. (See Figure 2)

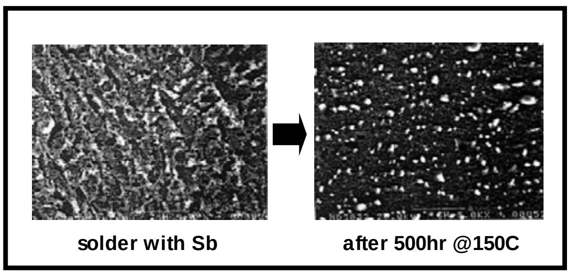

Figure2: Cross sections of solder with Sn and Sb(antimony) after 500hr at 150°C. The grain growth is suppressed.

Sn-Ag and Sn-Sb solders were investigated for the joint. The Sn-Ag solder is a standard lead free solder having a dispersion strength of Ag3Sn particles in network-shaped subgrains. On the other hand, the Sn-Sb system solder is an alloy with solid solution hardening. Figure 3 exhibits the change rate of tensile strength with thermal-aging test.

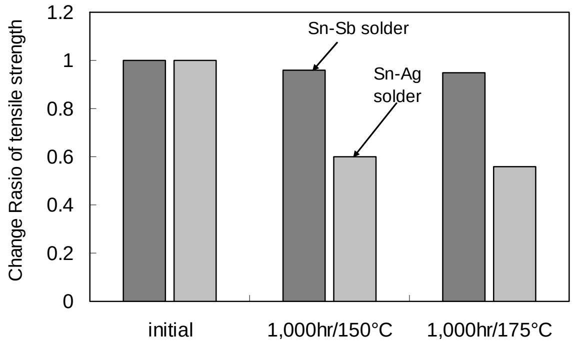

Figure3: Experimental results of change rasio of tensile strength under the thermal aging test

The tensile strength of Sn-Ag solder decreased to about 60% after 1000hr at 175 °C compared with initial state. On the other hand, the Sn-Sb solder tensile strength has slightly changed. The slowness of grain growth in solder causes the difference of the results. Figure 4 shows comparison of ultrasonic photos between Sn-Ag solder and Sn-Sb solder after 2,000 temperature cycles of δTc=145°C. (-40°C to 105°C) White areas indicate crack growth inside solder. Cracks in the Sn-Sb solder grow more slowly than that in the Sn-Ag solder. [2] Also the slowness of grain growth in solder causes the difference. Then Sn-Sb solder is considered to be suitable for high temperature and high reliability modules. For automotive use, low cost cupper base plate is able to be applied by the Sn-Sb solder. In addition, low stress design for the innards is used to reduce a stress at the cold time.

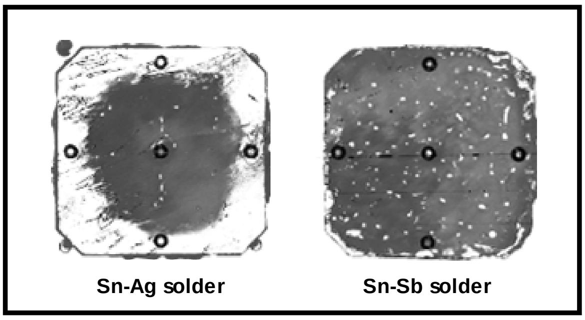

Figure4: Comparison of crack areas between Sn-Ag solder and Sn-Sb solder after 2,000 temperature cycles of δTc=145°C.

3 Thermal Fatigue life test

3.1 The acceleration test condition and the outcome

The lifetime of the IGBT module can be examined in the accelerated temperature cycle test which is harder than practical use to short the evaluating time. It is possible to estimate with thermal fatigue life test. The test method is shown in figure 5, base plate temperature rises by thermal radiation of power chips.

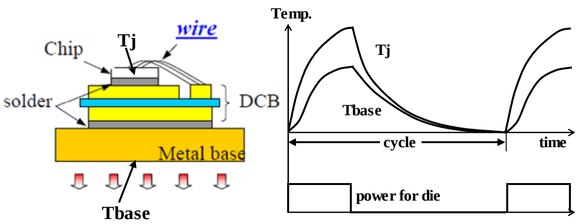

Figure5: Method of thermal fatigue life test

The temperature difference is defined by that of base plate. The change of the thermal resistance upon the thermal fatigue life test which was accelerated using conventional solder and developed solder is shown in figure 6, the tested temperature difference is 80°C. When using the solder which doesn't contain antimony, the thermal resistance begins to increase more than 10,000 cycles. In case of the solder which contains antimony, as for 20,000 cycles, the thermal resistance doesn't start to increase. Therefore, by using the solder which contains antimony, more than twice of longer life can be achieved to the conventional solder.

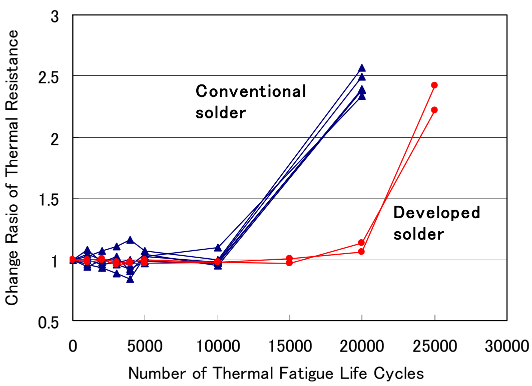

Figure6: Change of thermal resistance

3.2 Life curve of Sn-Sb solder

The thermal fatigue life cycle vs. temperature difference of Sn-Sb solder joint is obtained experimentally and shown in figure 7. The Nf indicates failure cycle number of solder layer because of the crack growth. By considering the thermal fatigue lifetime curve below, it would be able to estimate an accelerated test condition and actual life time.

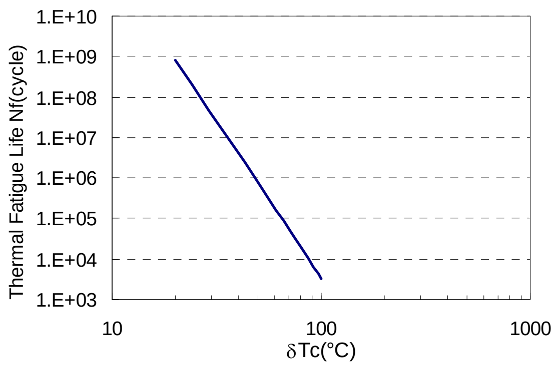

Figure7: Thermal fatigue life and difference of temperature for Sn-Sb solder

4 Temperature cycle in automotive use

Vehicles are used under various conditions from cold districts to tropical zone, and then they are driven in various traction situations. It is important to confirm that if an electronic device satisfies or not the requirement of the lifetime, but it is difficult to test under the actual condition all the time, because it would take long term to confirm the life. Though it is possible to imitate some severe conditions to test, it should take over 5 to 10 years to conclude. We need to make a model of temperature cycle that should be most severe condition and then we need acceleration condition to be able to test in practice. Before the estimation, we assumed that electronic devices are placed below the hood and cooled by separated water loop. The maximum temperature of cooling water is supposed to be 80°C.

4.1 Modelling of temperature cycle

The biggest gap of temperature is observed in winter, lowest temperature in human dwelling area is -20°C in practice, the difference between -20°C to 80°C is 100 degree. In other seasons, average temperature is assumed to be 20°C, the temperature difference is 60 degree. In a day, 10 times starting from cold state, 100 times engine stopping by traffic jam and signal, 300 times accelerating and braking rapidly, these are assumed and estimated for 15 years. (See figure 8) Temperature change of cooling water makes alternation of base plate temperature slowly. It in-creases stress inside the solder between base plate and DCB substrate, it should be considered about influence for temperature cycle capability. [4] The heat generated from IGBT chips makes additional alternation inside the module, it in-crease stress of the solder. [5] This paper de-scribes mainly the influences of slowly changing temperature by thermal radiation from power chip and lifetime of the solder between DCB and base plate.

items	δ temp	estimation	required
Number of cold start in winter	100°C	Tc=-20°C to 80°C 5/day x 20day/year x 15year	1,500
Number of cold start in other seasons	60°C	Tc= 20°C to 80°C 10/day x 250day/year x 15year	45,000
Number of engine stop by traffic reason	40°C	Tj=105°C to 65°C 100/day x 250day/year x 15year	450,000
Rapid acceleration Sudden brake	60°C	Tj=125°C to 65°C 300/day x 250day/year x 15year	1,350,000

Figure8: Temperature cycle numbers in actual use
One-column figure

4.2 Estimation of the life

The parameters which influences the lifetime of the solder layer are the high temperature which contributes for the grain to grow and the low temperature by which the stress strength is contributed to. In the actual vehicle use, the largest temperature difference is the case which starting up from the condition which was cooled to the outside air temperature, reaches highest driving temperature. Considering the time which the vehicle cools fully takes about 1 hour, the number of start-up from outside temperature is an aver-age of 5 times on a day in winter, 10 times in other seasons. Considering daily minimum temperature, it is -20°C in winter, 20°C in other sea-sons, and operating temperature of cooling water is 80°C. The temperature difference stress of whole life is estimated by summating of 3 major conditions as 1,500 cycles with 100°C, 45,000 cycles with 60°C, and 450,000 cycles with 40°C. The condition of rapid acceleration and sudden brake is not necessary to be considered for thermal fatigue life but for power cycle life beyond dies. We assumed that the growth of deterioration under one temperature condition becomes linear. Considering the life curve of Fig. 7, 1,500 cycles of 100 degree is equivalent to about 40% of the life. In the same way, 45,000 cycles of 60 degree is equivalent to about 40% of the life, and 450,000 cycles of 40 degree is equivalent to 10% of the life. After all, the summation of major 3 conditions is under 100%. The thermal fatigue life curve of Fig. 7 is enough to satisfy the requirement of most severe automotive use.

5 Temperature detection

It is important but difficult to detect temperature of power semiconductor chips, because they are installed deep inside the packages.

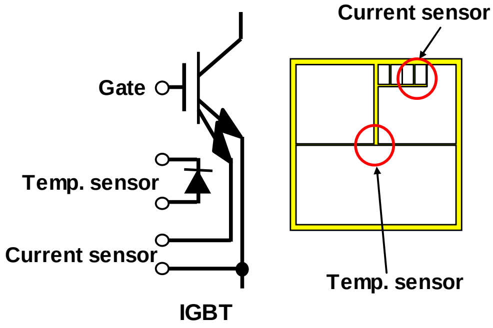

Figure9: IGBT die with temperature sensor

Figure 9 shows an idea of temperature detection function of IGBT die. A temperature sensor is located center of the die, there is large temperature difference between die and base plate. When heat radiates from the die, a thermistor on the base plate doesn't indicate temperature of the die exactly. It becomes possible to output the die temperature by using the sensor. Figure 10 shows thermal view of IGBT die with heat radiation. By this technology, we could know the thermal state inside the module and could control the load optimized.

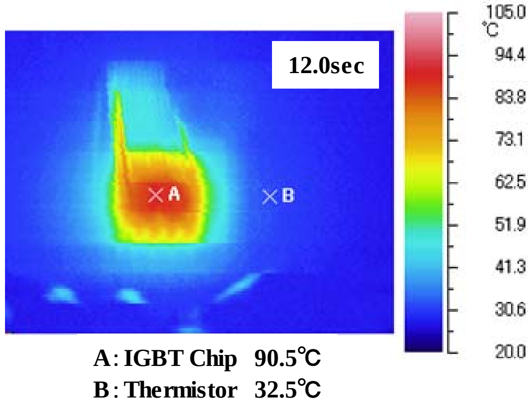

Figure10: Temperature detection and distribution around die

6 IGBT module to achieve a lifetime toward vehicles

The thermal fatigue life of the IGBT modules for the vehicle propulsion which used developed lead free solder sufficiently meets the period of service which is expected. Each IGBT has temperature sensor and current sensor, it becomes possible to control the current, to protect from heavy load. This compact module has the ability to supply electric power which drives an about 20-kW motor. It is the RoHS compliant product. (See Figure 11)

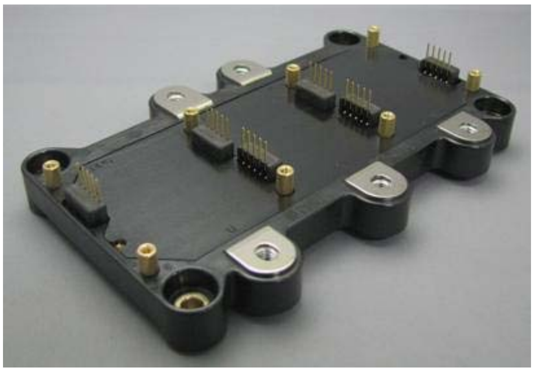

Figure11: HEV Pack (300A-600V 6-pack)

7 Conclusion

Antimony is expected to prolong the life of modules by adding to solder materials. There is a steady effect not only for Sn solder but also for Sn-Ag solder. We proposed the acceleration test way of confirming that the IGBT module has sufficient lifetime for automotive application. Then, we showed that the required lifetime could be achieved in using lead free solder with antimony and we developed the IGBT module for the HEV which used this technology.

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