Evaluation of Fatigue Life Reliability and New Lead Bonding Technology for Power Modules

Authors: *Toshihiro Matsunaga** and *Shingo Sudo***

The authors have developed a fast thermal cycling test method of evaluating the reliability of power modules. The method shortens the time required for a life evaluation test of Al wire bond lift-off to one-quarter of the conventional power cycling test method. The authors have also developed a technology for Cu lead interconnection structures that can be applied for higher current densities of chips and improved productivity, replacing the current Al wiring method.

1. Introduction

Power modules, which are used for an increasingly wide range of industrial applications, are used not only for inverter control of household electric appliances but also for high power applications that include automobiles, electric railroads, and electric power. Today's power modules require far greater reliability with respect to electric performance, insulation efficiency, thermal performance, and strength, and so it is expected that the specifications of such modules will improve. It has also become necessary to rapidly develop and commercialize products of low cost and high reliability. To meet these requirements, we have to improve the accuracy and speed of reliability evaluation techniques and develop products based on new technological concepts.

This paper deals with two types of technology. The first one is a technology for quickly evaluating the thermal fatigue wire lift-off life of Al wire bond used for the main electrode interconnections in power modules, as a means of evaluating the strength reliability for power module wiring structures. The second technology is related to a wiring structure with thin Cu lead as a new bonding method that supersedes the conventional wire bonding method and meets the future needs for high current densities.

2. Strength Reliability Evaluation Technology (Accelerated Testing Technology for Wire Lift-off Life)

The ultrasonic Al wire bonding method is widely used for electric wiring of Si chips in power module. Fig. 1 shows a cross-sectional view of a power module employing this method.

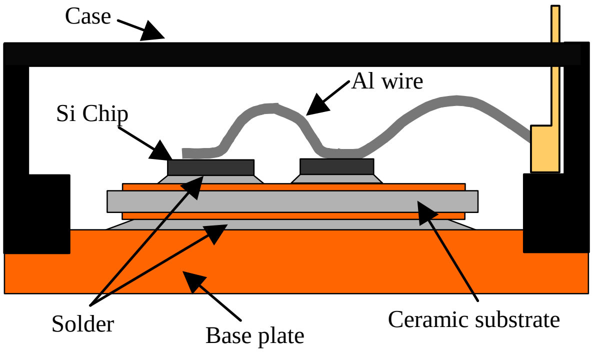

Fig. 1 Cross-sectional view of power module

Since the wire bonds are subjected to cyclic thermal fatigue due to the fall and rise in temperature of the chips which often results in fatigue damage, it is necessary to accurately grasp the fatigue characteristics of wire bonds. In the conventional methods of reliability testing, power cycling tests are conducted, while current is actually supplied and disconnected to/from the power modules, but this is extremely time-consuming. The authors have developed a method for rapidly evaluating thermal fatigue life (fast thermal cycling test method) in which only Al wire bonded chip sections are sampled and thermal stress equivalent to that generated in the power cycling procedure is applied by external heating, as an alternative to the conventional power cycling test method.

Fig. 2 shows the section evaluated in the fast thermal cycling test method. Since fast heating and cooling are involved in the test, the testing equipment uses a high-performance ceramic heater and a heat sink. In addition, a high-precision temperature controller is used for transient temperature changes due to cyclic heating and cooling. Fig. 3 shows an example of the temperature swing for $\Delta T = 100$ K. Temperature control for a thermal cycle of about 2 seconds (per cycle) is possible. Compared with the period required in the conventional power cycling test method, life of wire bond can be evaluated in about one-quarter of the time.

*Advanced Technology R&D Center **Manufacturing Engineering Center

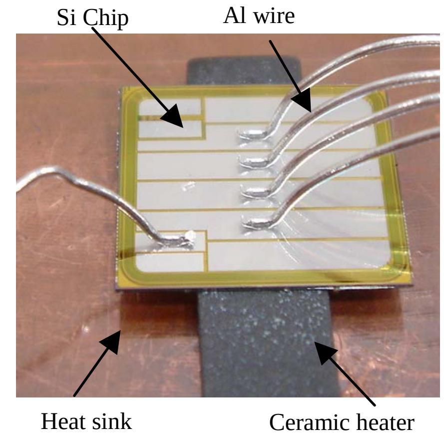

Fig. 2 Photograph of fast thermal cycling test

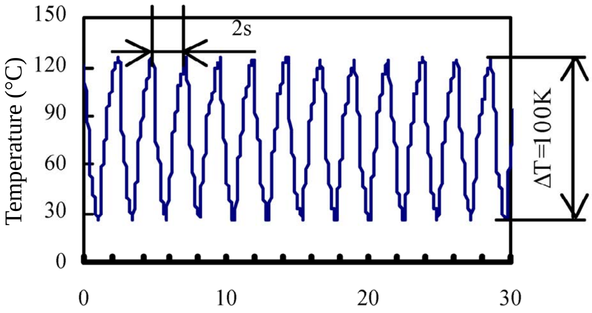

Fig. 3 Profile of temperature swing (ΔT = 100 K)

Fig. 4 shows the results of evaluating the influence of the thermal cycle temperature range ΔT (50 to 100 K with a minimum junction temperature of T_{min} = 25°C) on the life of wire bond lift-off in the fast thermal cycling test. The values indicated agree well with the results of life obtained by the power cycling test conducted by Cova et al.(1)

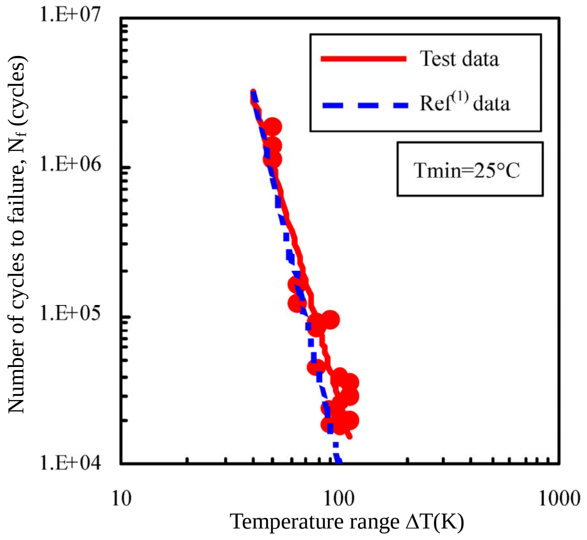

Fig. 4 Relation between number of cycles to failure and ΔT

The authors have thus confirmed that the new fast thermal cycling test method can evaluate the life of wire bond lift-off more quickly than the conventional method, without having to prepare actual modules. The new test method will enable the influence of chip specifications and wire bonding conditions to be evaluated more quickly and so greatly speed up product development.

3. Bonding Technology (Cu lead interconnection structure)

With the recent developments of power semiconductor chips, chips of higher current densities with reduced areas required for a fixed current value are common today. As a result, the conventional wire bonding method is reaching its limit for the capacity of feeding current through wires. Besides, in the case of a power module of several hundred amperes, the module requires a huge number of Al wires which reduces productivity, so new interconnection techniques are needed to replace the conventional Al wire interconnection method. Several methods have been proposed, including the metal post structure method that employs flip-chip bonding (2).

Mitsubishi Electric Corporation is developing a new wiring structure that will meet the future needs for high current densities of chips as well as improved productivity for similar module configurations as the current Al wire bonded devices. That is, the structure will replace the Al wire interconnection on the chip for high current power modules, with Cu lead interconnection in which the Cu lead is placed on the chip by soldering.

Power modules require high reliability and thermal cycle performance due to the environments in which they are used. There is a concern that lead interconnection methods may deteriorate the electrical characteristics due to damage to the soldered junctions by thermal cycling. Therefore, we conducted a thermal cycling test of a lead bond module to identify the changes in characteristics.

Fig. 5 shows a photo of a power MOSFET chip having an edge of 12 mm and a thickness of 0.3 mm with Al wiring. Fig. 6 shows a photo of the same MOSFET chip with Cu lead bonded. A cross-sectional view of the lead bond module is shown in Fig. 7. The Al wire bond module has 16 wires of φ = 400 μm on the chip. The lead interconnection has a Cu plate having a thickness of 0.2 mm and a width of 11 mm on the chip, which are bonded with Sn-Ag-Cu solder having a thickness of about 0.1 mm. For thermal cycling, a range between –40°C and +125°C (10 minutes respectively) is used. For the intermediate measurement, the on-state resistance ($R_{DS\,(ON)}$) of the MOSFET chip was measured to check the deterioration of module characteristics.

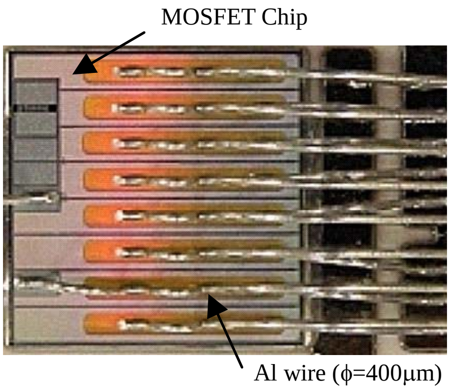

Fig. 5 Top view of the chip in the wire bond module

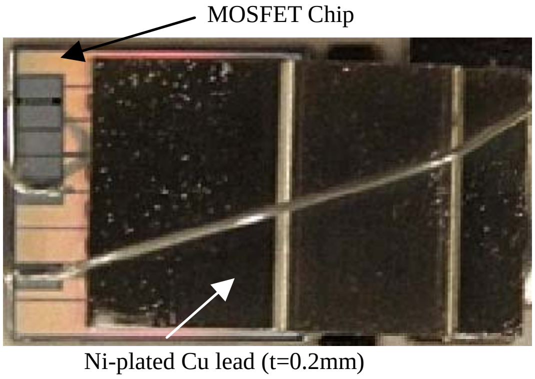

Fig. 6 Top view of the chip in the lead bond module

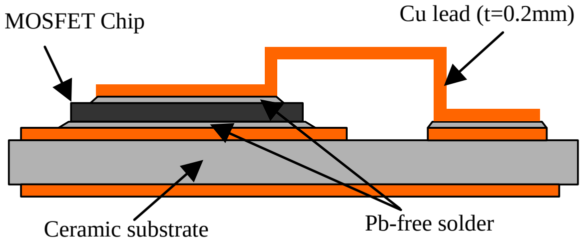

Fig. 7 Cross-sectional view of the lead bond module

Fig. 8 shows the number of cycles in the thermal cycling test and the transition of $R_{DS\,(ON)}$. With the wire bond structure, the resistance did not show changes up to 3000 cycles, while the lead bond interconnection showed an increase in resistance of approximately 1.5 times at 1000 cycles; it propagated a crack fully through the solder between the chip and lead after 2000 cycles, and finally open-circuit occurred. A crack in the solder propagates due to the strain in the solder layer resulting from the difference in coefficient of thermal expansion of Si chip and Cu lead. Reducing the strain in solder is an effective way of preventing the crack growth. Cracks may also be prevented by reducing the rigidity of the lead by using thinner leads, although this may increase the overall resistance of the interconnection. Therefore, we decided to use a lead shape that has a comb-shaped bonding area on the chip, with each split tooth portion having the same thickness, so that the rigidity of the lead at the solder-bonded junction could be lowered to effectively reduce the strain in the solder caused by the difference in coefficient of thermal expansion. Fig. 9 shows a photo of a comb-shaped lead interconnection. The comb teeth are formed such that they cover eight areas divided by the gate interconnection on the chip and are fixed by soldering. The width of each comb tooth is 0.8 mm.

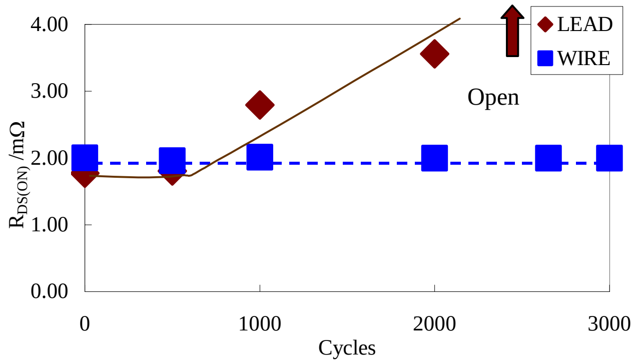

Fig. 8 Transition of on-state resistance in the thermal cycling test, comparing the lead bond with the wire bond

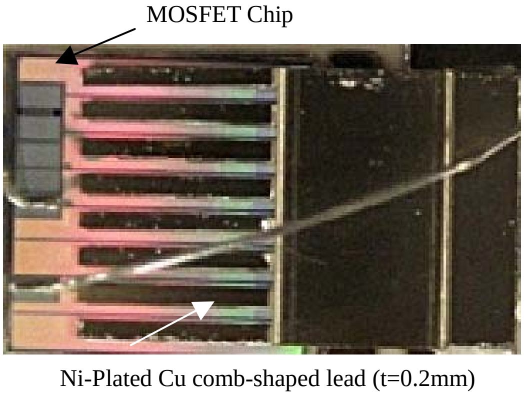

Fig. 9 Top view of the chip in the comb lead bond module

The authors also confirmed the transition of $R_{DS\,(ON)}$ of the comb-lead interconnection modules in a thermal cycling test with a temperature range of –40°C through +125°C. Fig. 10 shows the number of cycles and the transition of $R_{DS\,(ON)}$.

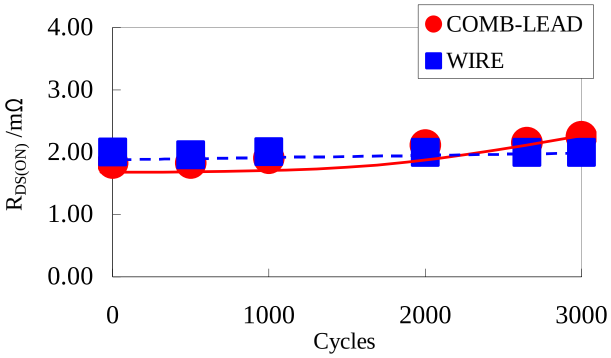

Fig. 10 Transition of on-state resistance under the thermal cycling test, comparing the comb lead bond with the wire bond

The thermal cycling test clearly shows that the comb-shaped lead interconnection structure can keep the increase in $R_{DS\ (ON)}$ beyond 1000 cycles. Furthermore, the structure does not suffer an open-circuit at 3000 cycles, with the increase in $R_{DS\ (ON)}$ suppressed to around 10%.

4. Conclusion

The authors have developed and confirmed the effectiveness of a fast thermal cycling test method for evaluating the life of Al wire bond lift-off more quickly than the conventional method, for evaluating the reliability of power modules. The authors have also proposed a Cu lead interconnection structure as a new interconnection method and proved that use of the comb-shaped lead divided into teeth is effective in preventing cracks in the solder used to bond the chip and lead under thermal cycling conditions.

References:

(1) P. Cova and F. Fantini, “On the effect of power cycling stress on IGBT modules”, Microelectronics Reliability 38, (1998), pp. 1347–1352.

(2) X. Liu and G. Lu, “Power Chip Interconnection: From Wire Bonding to Area Bonding”, IMAPS2000, Boston, (2000), pp. 264–269.