Reliability Design Technology for Power Semiconductor Modules

Akira Morozumi
Katsumi Yamada
Tadashi Miyasaka

1. Introduction

The market for power semiconductor modules is spreading not only to general-purpose inverters, servo motor drives, NC machine tools and elevators but also to new applications through the realization of electric vehicles and renewable energy systems.

Fuji Electric has developed various power modules in response to market needs, and as the market expands in the future, the required performance for power modules will surely become diversified and advanced.

This paper introduces our efforts to lengthen the power cycling lifetime of IGBTs (insulated gate bipolar transistors), which is of great importance to the market.

2. Lifetime Evaluation Technology and Failure Mechanism

2.1 Power cycling test

The power cycling test is used to estimate the real operation lifetime of IGBT modules. This test is repeated until a IGBT module fails due to thermal stress generated from the rise and fall of the IGBT chip's junction temperature T_j caused by turning on and off an electrical load, where the IGBT module has been mounted on an air-cooled heat sink. Types of power cycling tests include the ΔT_j power cycling test and the ΔT_c power cycling test (thermal fatigue lifetime test).

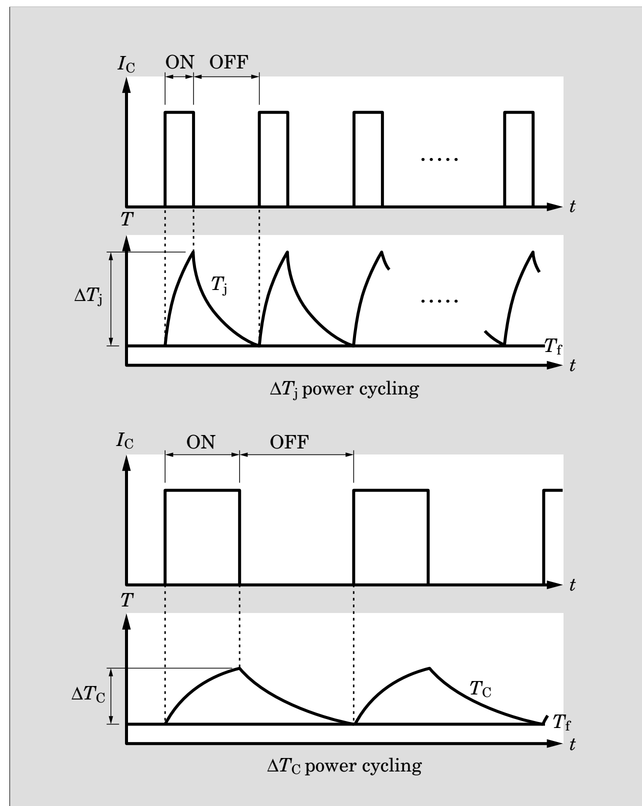
In the ΔT_j power cycling test, the junction temperature is raised and lowered within relative short cycles as shown in Fig. 1. This test is used mainly to evaluate the lifetime of the aluminum wire bond and the solder joint on the underside of a silicon chip. On the other hand, the ΔT_c power cycling test is a heat cycle test whereby in one cycle, current is turned on until the case temperature (T_c) reaches an arbitrary value and then is turned off from that time point until the case temperature returns to the original value prior to when current was on, as shown in Fig. 1. This test is applied mainly to evaluate the lifetime of the solder joint between the DCB substrate and copper base plate as well as the solder joint on the underside of a silicon chip.

2.2 Failure mechanism of the ΔT_j power cycling test

Figure 2 shows the structure of an IGBT module made by Fuji Electric. As in the past, Pb-based solder is used at the joint between the silicon chip and the DCB substrate. The failure mechanisms resulting from power cycling tests of modules using Pb-based solder are as below.

When ΔT_j is approximately 100°C or above, cracks occur at the interface between the silicon chip and the aluminum wire as shown in Fig. 3, due to shear stress generated by mismatched thermal expansion. Propagation of these cracks leads to wire bond lift-off and

Fig.1 Operating conditions of power cycling tests



failure. This failure form is shown in Fig. 4. Wire melting failure is not observed on the emitter bonding pad, and the lift-off surface can be plainly seen. This fact proves that the wire bond has been broken by metal fatigue. In addition, via non-destructive inspection using an acoustic microscope and cross-sectional view of the solder joint, cracks of approximately 1mm aligned in parallel with the interface and originating from the silicon chip outer surface are observed.

On the other hand, when ΔT_j is less than approximately 80°C, cracks occur in the solder joint, due to shear strain generated by the mismatch of thermal expansion between the DCB substrate and the silicon chip. The junction temperature increase due to propagation of these cracks leads to failure of the IGBT. This failure form is shown in Fig. 4. The emitter bonding pad shows traces of burning due to wire melting failure. Meanwhile, cracks in the solder joint are observed throughout the silicon chip. The wire melting failure is caused by melt-off of the wire due to gradual temperature increase of the silicon chip resulted from increasing thermal resistance accompanied by propagation of the cracks.

Consequently, the power cycling lifetime with conventional Pb-based solder structures depends on the wire bond strength because there is almost no damage to the solder itself in the range of relatively high operating temperatures, namely when ΔT_j is about 100°C or greater, and depends on the solder joint in the range of relatively low operating temperatures, when ΔT_j is about 80°C or less.

Fig.2 Vertical structure of IGBT module

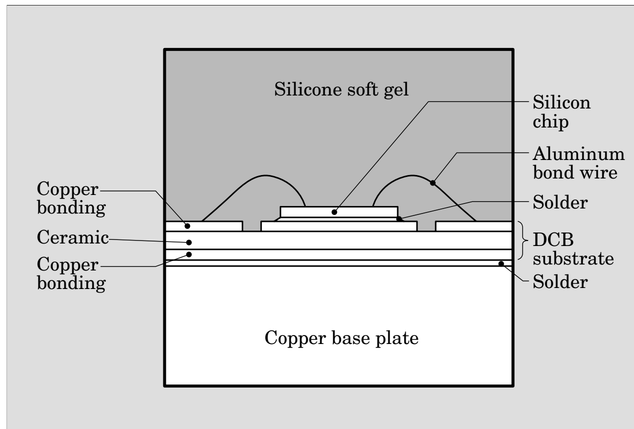
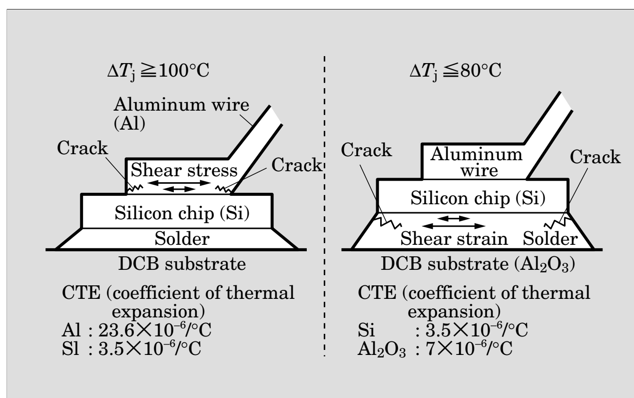


Fig.3 Failure mechanism of power cycling test with Pb-based solder alloy



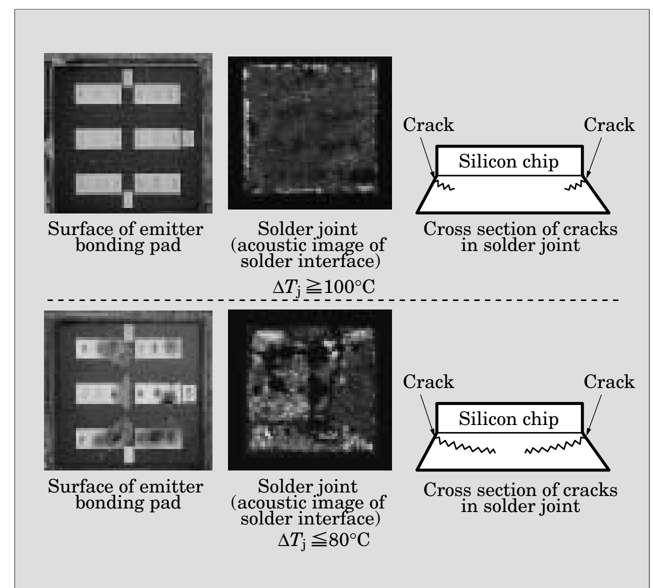
3. Improvement of ΔT_j Power Cycling Lifetime

In chapter 2, it was explained that to prolong the power cycling lifetime, improvements in the wire bond lifetime and the solder joint lifetime are required for the high ΔT_j range and low ΔT_j range, respectively. Since most applications are in a relatively low temperature range such as below 100°C, the improvement of power cycling lifetime in this temperature range, in other words, improvement of the lifetime of the solder joint is a practical necessity.

3.1 Improvement of solder joint lifetime

In order to prolong the thermal fatigue lifetime of a solder joint, minimizing shear strain generated in the solder joint is most effective. In general, it is said that lead-rich solder has a longer lifetime in the higher shear strain range ($\Delta\gamma$), and tin-rich solder has a longer lifetime in the lower $\Delta\gamma$ range. It can be estimated that application of a tin-rich solder would be effective at the solder joint between the silicon chip and the DCB substrate, since the generated shear strain therein is relatively low, namely less than 1% according to the results of finite element method (FEM) analysis. Furthermore, the strain generated at the solder joint is related to the elastic modulus of the solder, and solder with higher yield strength (resisting

Fig.4 Failure form after power cycling test of modules using Pb-based solder



strength against plastic deformation) generates lower strain. Accordingly, tin-rich solder is more effective to realize a longer lifetime under the same ΔT_j because of its higher yield strength.

3.1.1 Examination of new lead-free solder alloy

With the precondition that lead-free solder should be used in due consideration of the environment, the Sn/Ag based solder alloy has been selected as the basic composition to be examined. The reason is that Sn/Ag based solder alloy has relatively better balance of properties among the lead-free solders. However, lead-free solder – not limited only to the Sn/Ag based solder alloy – has the disadvantage of inferior wettability compared with Pb-based solder. Accordingly, Fuji Electric has developed a new lead-free Sn/Ag based solder alloy which possesses an excellent level of mechanical properties and the same wettability as Pb-based solder by optimizing various additional elements and their quantities. The properties of this new solder alloy are shown in Table 1.

3.1.2 Estimation of solder joint lifetime with FEM analysis

Two-dimensional elastic-plastic thermal stress analysis utilizing FEM was performed for both the newly developed Sn/Ag based solder and the Pb-based solder to determine the strain generated at the solder joint and estimate the lifetime. The results of analysis are shown in Table 2.

When the results are compared under the same temperature condition, it can be seen that the new Sn/Ag based solder alloy has a smaller strain and longer lifetime compared with the Pb-based solder. This result is attributed to the mechanical properties of the new Sn/Ag based solder alloy, having 2.4 times higher yield strength and higher creep strength than the Pb-based solder.

Table 1 Properties of newly developed lead-free Sn/Ag solder alloy

Items		New Sn/Ag solder alloy	Sn3.5Ag solder alloy	Conventional Pb-based solder alloy
Mechanical properties	Yield strength (MPa)	53	38	22
	Elongation (%)	19	18	25
	Creep rate (% h)	0.09	0.20	1.30
Wettability	Spreading (%)	100	50	100
	Contact angle (°)	17	27	9
	Wetting force (mN)	0.39	0.36	0.41

Table 2 Result of thermal stress FEM analysis for solder joint

Solders	ΔT_j (°C)	$\Delta\gamma$ (%)	Number of cycles to failure of solder joint
New Sn/Ag solder	50	0.14	2.0×10^7
	80	0.22	2.7×10^5
Conventional Pb-based solder	50	0.23	2.7×10^5
	80	0.36	5.0×10^4

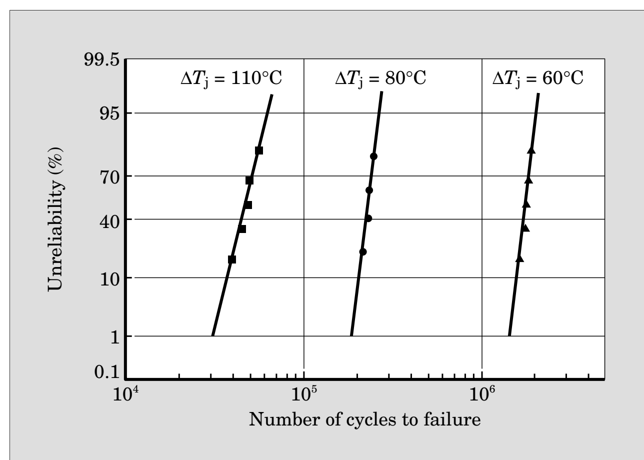
3.2 Examination of ΔT_j power cycling lifetime (with new Sn/Ag based solder)

In order to clarify the power cycling lifetime of IGBT modules using Sn/Ag based solder, tests are performed under various operating temperatures ΔT_j. The lifetime is defined to be 1% of the unreliability rate ($F(t)$), obtained by plotting the number of cycles to failure on Weibull probability paper. The operating temperatures, which are arbitrarily set, are measured at the joint, case and heat sink, using IR thermography and thermocoupling. Figure 5 shows the results of the 1,200V-75A series IGBT module at 60°C, 80°C and 110°C of ΔT_j. It can be understood that the lifetime is 1.3×10^6 cycles, 1.7×10^5 cycles and 3×10^4 cycles at 60°C, 80°C and 110°C of ΔT_j, respectively.

3.3 Failure mechanism of modules using Sn/Ag solder

According to failure form inspection of power cycling tests of 60°C and 110°C ΔT_j, intense wire melting failure on the emitter wire bonding pad and severe solder damage were observed after the power cycling test at 110°C ΔT_j. On the other hand, no wire melting failure and very slight solder damage were observed after the power cycling test at 60°C ΔT_j, however, the generation of cracks was observed in the solder but it was very slight. From these failure forms, it is estimated that the power cycling lifetime of new Sn/Ag based solder depends on that of the solder joint when ΔT_j is higher than about 110°C, and depends on that of the wire bonds when ΔT_j is lower than about 60°C. This fact differs from the failure mechanism of Pb-based solder mentioned in section 2.2. In addition, the crack propagation form in the solder joint also differs between new Sn/Ag based solder and Pb-based solder. In the case of Pb-based solder that is easy to deform plastically, cracks propagate along the acting

Fig.5 Weibull plot of power cycling test results of modules using Sn/Ag solder (1,200V-75A)



direction of shear stress starting from the fillet, where stress is concentrated as shown in Fig. 6. However, in the case of new Sn/Ag based solder with high yield strength, the propagation of cracks is nearly concentric, originating almost directly under the silicon chip center. Furthermore, a characteristic of the cracks generated in new Sn/Ag based solder is that they are vertical or reticulated cracks, are parallel to the thick direction of the solder, and propagate selectively along the tin grain boundary. From these facts, it is supposed that deterioration of Pb-based solder is caused by plastic deformation due to strain, while deterioration of Sn/Ag based solder is caused by thermal damage due to the grain growth of tin.

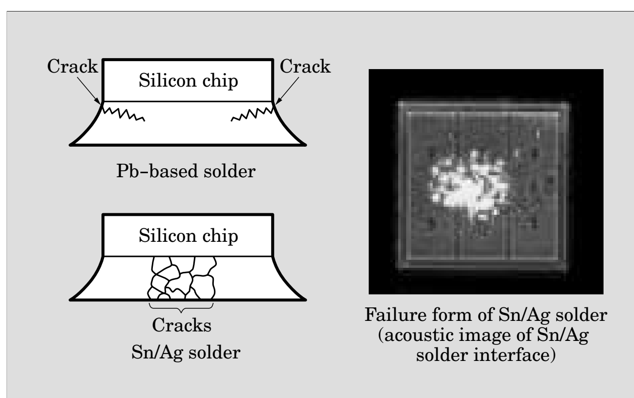
4. Power Cycling Lifetime Curve of Modules Using Sn/Ag Solder

4.1 Relation between lifetime of wire bond/solder joint and a module's lifetime

From consideration of the above, it is understood that the power cycling lifetime of modules using new Sn/Ag based solder is comprised of the lifetimes of the wire bond, the solder joint and the area in which these coexist as shown in Fig. 7. Thereupon, fatigue lifetime of the wire bond and the solder joint are calculated from detailed analysis of the failure lifetime in power cycling tests and from FEM stress analysis of the wire bond and solder joint. Figure 8 is obtained by plotting the calculated lifetimes of each joint and the lifetime of IGBT modules on the same graph. This graph indicates that the lifetime of a solder joint is in close proximity to the lifetime of the module. On the other hand, the lifetime of wire bond intersects the module lifetime at about 50°C ΔT_j and falls below the module lifetime at lower temperatures.

Consequently, fatigue damage of the solder joint rarely occurs in the range of ΔT_j less than 50°C, and the module lifetime depends on the lifetime of wire bond fatigue. While, in the range of ΔT_j greater than 50°C, the lifetime of solder joints exceeds the module lifetime in this examination, but in actuality, both lifetimes are judged as almost the same.

Fig.6 Crack propagation form of solder joint after power cycling test



4.2 Reliability for power cycling of modules using Sn/Ag solder

As mentioned in section 4.1, the power cycling lifetime curve of IGBT modules using new Sn/Ag based solder has an inflection point at 50°C ΔT_j. As shown in Table 3, these modules achieve a longer lifetime than conventional modules that use Pb-based solder. In particular, the difference in lifetimes is remarkable at the relatively low operation temperature range of less than 100°C. This achievement of longer lifetime in the

Fig.7 Relation of power cycling lifetime and failure mode

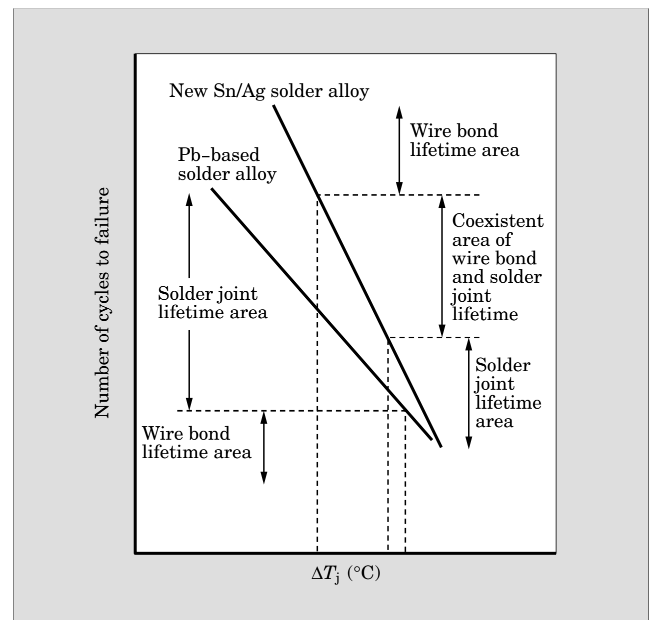


Fig.8 Power cycling lifetime curve of modules using new Sn/Ag solder alloy

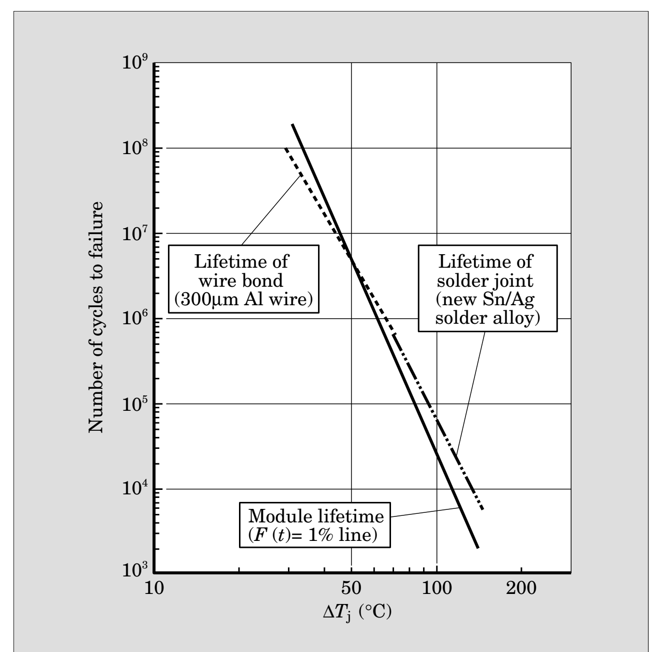


Table 3 Power cycling lifetime of modules under estimation of $F(t)$=1%

Operating temperatures	Modules using new Sn/Ag solder	Modules using conventional Pb-based solder
ΔT_j =100°C	2.5×10^4	1.7×10^4
ΔT_j =60°C	1.3×10^6	1.8×10^5
ΔT_j =30°C	8.0×10^7	5.0×10^6

power cycling test is attributed to improved mechanical properties of the new Sn/Ag based solder and to maintaining a good wettability equivalent to Pb-based solder.

5. Conclusion

In the preceding chapters, our efforts to increase the power cycling lifetime has been presented in the context of reliability design for power semiconductor modules. New Sn/Ag lead-free solder with excellent mechanical properties and wettability has been newly developed, and can contribute to improved reliability of the modules. Through the longer power cycling lifetime, miniaturization and price-reduction of the devices are expected. Fuji Electric will endeavor to continue to respond to the needs of a market that is becoming increasingly more demanding.