The characterization and application of chip topside bonding materials for power modules packaging: a review

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Abstract: Bonding material is one weak point in power modules packaging, and can limit the lifetime of power modules. Multiple bonding materials have been manufactured and applied in the power modules such as aluminum wire, copper wire, aluminum ribbon, copper ribbon, Al-clad-Cu wire, direct-bonding-lead. For bonded power modules packaging, bonding ability, electrical and thermal conductivity, current carrying capacity, working reliability are the main applying properties of bonding materials. This paper demonstrates the characterization, failure mode & failure mechanism, life-time calculation model of the normal used bonding materials and estimates the developing tendency.

1 Introduction
Power modules (such as IGBTs, IGCTs, MOSFETs) are key components widely applied in power transmission & distribution (HVDC, FACTS, STATCOM), industry (medium or low voltage drives, UPSs, rectifiers), traction (main and auxiliary drives, track side power supply), renewable energy (wind turbines and solar), new energy vehicles (main drives, charging pile). As the demand of high power density and high power increases in the market, high functional requirement of power semiconductors and packaging materials drive the development of wide band semiconductor and new packaging materials. Al bonding wire plays an important role in traditional modules packaging by its low cost, good bonding ability on chip surface, good electrical conductivity and acceptable reliability. But as the high power modules develops, Al bonding wire can’t meet the requirement of high density current per wire and long working lifetime. Then new bonding materials such as Al ribbon, Cu wire, Al-clad Cu wire, Cu ribbon, DLB (direct lead bonding), Clip-Bonding develope and come into application.

This paper presents the characterization, failure mode and failure mechanism of traditional and summarizes new bonding materials. Lifetime model of power modules with wire bonding packaging is also described. The difference of different bonding materials application applied in low-Middle power and high power modules are discussed. The aim of this content is to guide mature bonding materials can be used in right power modules and explore the developing tendency of packaging materials.

2 Chip Topside Bonding Materials for Power modules
The function of chip topside bonding materials is not only collecting and transferring the current but also protecting the gate or emitter from damage by bonding power.

2.1 Al wire
Aluminum wire connect the power chips top-surface with diameters from 100 to 500 micrometers, and transport the electrical current. The maximum electrical current can be 10A per wire with 500 um in on-state mode[1]. Al wires are usually parallely bonded on the power chips to meet the requirement of
high current capacity (from 50A to 300A per chip). The topside of the silicon chip is almost evaporated by Aluminum. So this type dies pad can be easily bonded by Al wire without IMC, which can form a stable inter-surface between Al wire and chip pad.

In order to predict the lifetime of modules, reliability testings like power cycling test or thermal cycling test, are necessary to calculate the packaging materials. For lead free Sn based soldering and Al wire bonding IGBT modulus, Al wires will be the limiting factor of lifetime when $\Delta T>100^\circ C$ in power cycling testing, shown as Fig.1.

![Figure 1. PC-results of isolated failure mechanism of classical modules in dependence on temperature[2].](image1)

Bond lift off and heel crack are the main failure mode after power cycling testing, shown as Fig.2. In order to research the failure mechanism of wire lift-off, paper[3] describes that the root reason is the mismatch of CTE between silicon and aluminum in the temperature variation process. Which can produce repeated thermal stress and results in microcracks in soldering interface layer. Eventually, some delamination voids appear and lead to wire lift-off.

![Figure 2. Lift off (left)[4] and heel crack (right)[5](image2)

Reconstruction of metallization can also explain the phenomenon[6]. Fig.3 shows that the aluminum grain coarsened because of reconstruction by increasing working temperature. Which reduce the density of contact layer and lead to increasing the contact resistivity and increase the $V_f$ a little. Then an impact on the current distribution in the device will reduce the lifetime of power modules under thermal stress conditions.
Figure 3. REM images show the augmentation of contact reconstruction with increasing maximum cycle temperature $T_{\text{high}}$ during power cycling, left $T_{\text{high}}=125^\circ\text{C}$, middle $T_{\text{high}}=171^\circ\text{C}$, right $T_{\text{high}}=200^\circ\text{C}$.

For heel crack failure mode, Fig.4 shows the cross section wire bond interface where heel cracks appear in the reliability testing. Fig.4 (right) present that the down-side Al wire grain is refined in the bonding process, and the cracks propagate along the interface between fine grain and coarse grain under thermal stress conditions. Marian[7] has also researched the microstructural evolution of ultrasonic bonded aluminum wires. The grain size becomes smaller and the dislocation density changes to higher near the interface between Al wire and chip topside metallization. And fine grain and higher dislocation density of grain can prevent the propagation of crack shown as Fig. 5.

Figure 4. (left) Ordinary BF microscopy image of the interface between Al wire and chip surface; (middle) Cross-sectional image of the Al wire heel failure mode; (right) Cross-sectional image of the sample from (middle) subjected to electro-etching to see granular structure[8].

Fig 5. Microstructure (IPF-map) of the wire bonds after (a) 100,000 APC in front of the crack tip and (b) after 300,000 cycles with the schematic location of the as-bonded microstructural gradient.

In the industry application of power modules, module’s shortage usually can cause Al wire’s failure. When the Al wire packaged high voltage modules is shorted, Al wires can’t stand large current and high temperature. Then Al wires will melt or vaporize and lead to explosion by open circuit.

2.2 Cu heavy wire
Copper heavy wire exhibit much higher electrical and thermal conductivity than Al wires. And Copper’s CTE is more closely to Si compared to Al, so the mismatch between Cu and Si is lower than Al-Si. But chip topside Al metallization is too soft for heavy copper wires bonding. So copper metallization as the
final front side has been developed shown as Fig6[9]. Cu bonding wires can meet the requirements of a 200°C application. Karsten test the Cu wires bonding reliabilities by power cycling with following setup: \( \Delta T_j=130^\circ C, T_{j,max}=160-180^\circ C, T_{on}=15-30\text{sec}, T_{off}=30-60\text{sec} \). Copper heavy wires bonding modules with diffusion soldering can achieve more than 100,000 cycles which is ten times compared to today’s power cycling reliability of Al wire bonding modules.

Figure 6. Ceramic substrate with 400um Cu wire bonds on Cu metallised IGBTs

Figure 7. DTS technology sample[10]

Bur for the moment copper metallization is rarely manufactured on power chips upside. One reason is that copper metallization is hard to be done as thick metallization as Aluminum with appropriate cost; the other one is that the oxidation of copper is more easily propagated in air than Al or Ag metallization. To overcome this difficulty of copper metallization, Heraeus R&D team has developed DTS technology (Die top system technology). The thick copper foil is sintered on silver metallization of chip upside, shown as Fig.7. Then thick copper wire can be easily bonded on copper foil on chip upside. DTS package can improve the current capability 1.5 times than traditional Al wire packaging, and increase the power cycling 50 times than solder and Al wire packaging.

2.3 Al-Clad Cu wire

Al-clad copper wire[11] (shown as Fig.8) is made of Aluminium & Copper composite materials and take the advantage of both Al and Cu. Al has a good bonding flexibility with soft hardness matched with novel Al/Ag chip surface, while Cu has a higher conductivity with hard hardness.

Figure 8. Cross section of a 300um Al/Cu wire bond

Fig.9 shows that, Al-clad Cu wire exhibit an higher improvement of 31~46% than Al wire. The samples were fabricated with pure Al and Al-clad 300um-wire with different lengths (12mm, 18mm, 22mm) and tested at constant temperature of 80°C. Fig.10 presents the power cycling results of Al wire
and Al-clad wire bonded on sintered chip. The lifetime of Al-clad wire is 3.7 times of Al wire at testing condition of \( T_{j,max} = 175^\circ C, \Delta T = 135^\circ C, t_{on} = 2s \).

2.4 Ribbon

Ribbon bonding technology has been developed in recent years in terms of high current carrying capability and high power cycling reliability. Paper[12] describe the reliability of aluminium ribbon bonds compared with aluminium wire bonds by simulation. A single ribbon of W2000um*H200um can replace three D400um wires with lower temperature in power electronic module. And the dominant failure mode in ribbon bond is bond lifting shown as Fig.10. The failure mechanism is similar with Al wire lifting off mode.

ABB Semiconductors[13] has researched Al ribbon bonding compared with Cu-plated ribbon bonding (Fig.11). The power cycling times of Cu plated Al ribbon bonding modules can be improved to 2 times than no plating Al ribbon bonding modules.

2.5 Direct lead bonding

Direct-lead-bonding (DLB) technology replace the wire bonding by soldering or sintering the inner copper lead on the chip emitter surface, shown as Fig.12[14]. DLB would reduce the emitter contact resistance and internal inductance by almost 50% and 57%[15][16]. W.Sanfins studied the short-circuit failure and metallic reforming on DLB. DLB could give a ten times lower fault residual resistance \( R_{ce} \) than wire-bonding modules.

![Figure 12. (a) wire bonding structure;(b)Direct bonding structure.](image)

![Figure 13. Clip Bonding](image)

Clip Bonding is similar with DLB without power lead frame, shown as Fig.13. Copper foil is bonded on chip and substrate by sintering technology instead of wires. It can support more power cycles[17] and temperature shock cycles[18] than traditional bonding materials.

3 Lifetime predicted models

In order to predict the lifetime of standard power modules, project LESIT has tested a lot of modules with different \( \Delta T_j \) and medium temperatures \( T_m \) shown as Fig14. The relationship with cycles to failure \( N_f \) and temperature swing \( \Delta T_j \) can be approximated with the equation

\[
N_f = A \cdot \Delta T_j^n \cdot \exp \left( \frac{E_a}{k_B \cdot T_m} \right)
\]
In this equation, parameters $A=302,500$, $\Delta T_j$ is given power cycling temperature swing, activation $E_a=9.89\times10^{-20} J$, Boltzmann-constant $k_B = 1.38\times10^{-23} JK^{-1}$, $T_m$ is given power cycling medium temperature and $\alpha=-5.039$. This equation can be called LESIT model which was applied on traditional packaging technology with Al wire bonding and chip soldering. According to the testing results, LESIT model can be considered as an empirical lifetime model.

LESIT model can’t match well with power cycles to failure when $\Delta T_j$ is above 100K shown as Fig.15. Then a new statistical equation come out as below, and also can be called CIPS 08 model.

$$N_f = K \cdot \Delta T_j^\beta_1 \cdot \exp \left( \frac{\beta_2}{T_{low}} \right) \cdot P_{\beta_3} \cdot V^{\beta_4} \cdot D^{\beta_5}$$

The calculation parameters $\beta_1=-4.416$, $\beta_2=1285$, $\beta_3=-0.463$, $\beta_4=-0.716$, $\beta_5=-0.761$, $\beta_6=-0.5$ and $T_{low}$ is low power cycling temperature. So power modules suppliers can predict the lifetime of modules by failure model mainly by power cycling. When power cycles is equal or more than $N_f$ results from failure model such as LESIT or CIPS 08, then the power cycling testing pass.

As technology develops, Sn-based soldering materials can’t support higher working temperature, so new silver sintering or IMC soldering (liquid phase diffusing soldering) materials can be applied[19]. And new chip topside bonding materials also replace Al wires, so statistic mode established traditional packaging technology can’t predict the lifetime of new modules packaged by sintering, Cu wire bonding modules or others.

4 Conclusions
With the increasing demand for high power density in limited space, SiC or GaN power modules develops quickly. The current loading ability of Al wires and reliability can’t meet higher current capacity. Compared with Al wires, Cu wires or DLB can stand shortage of high power module and decrease the probability of explosion by shortage of high voltage modules. Then traditional Al wire bonding with solder packaging materials and technology will be replaced by Copper wires/ribbons, DLB, clip bonding, with sintering materials and technology. But ribbons are less flexible than wires because of the changeable bonding direction. So Cu heavy wires, DLB, Clip Bonding may be used more widely than ribbons in power modules packaging, especially as IGBTs. And new lifetime predicted models will be hot researching point applied in next generation modules.

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