The research and development of Soldering materials applied in IGBT modules packaging

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Abstract: Power modules have attracted much attention in the market, especially for high-voltage applications like switch mode power, automotive powertrain. As the requirement of high reliability, high-temperature operation improves, the packaging materials should develop to meet the applications with high properties. In this paper, the soldering materials such as Sn based lead free solder, SnPb solder, Ag-sinter are demonstrated. Soldering materials reliability is described on reliability testing especially for power cycling, temperature cycling testing, thermal shock testing. The concept is based on different applications and soldering process on Si power modules and SiC power modules. Important materials properties of thermal conductivity, CTE (coefficient of thermal expansion), elastic modulus, melting point are discussed. By comparison, Ag sintering process has a good application in high power modulus especially for SiC. SnAg solder also has the potential application in SiC modulus by IMC diffusion soldering technology.

1. Introduction

Semiconductors have gained an increasing market across die design, manufacture, and packaging. Power semiconductors, especially for IGBT modulus, have potential and increasing market. Because IGBT modules can be used in clean energy such as wind and solar power generation, high-voltage switch, electric vehicle. IGBT modules have low turn-off loss, wide range of voltage and current application: Si-IGBTs with 10²~10⁴V, 10⁰~10⁴A; SiC-IGBTs with 10⁴~10⁶V, 10⁴~10⁶A. IGBTs replace the formerly used bipolar power transistors, GTO-thyristors in high power range. For the moment Si-IGBTs have developed relative wind range with 600V, 650V, 1200V, 1700V, 3300V, 4500V, 6500V. SiC-IGBTs are still in the researching stage with less products than Si-IGBT. SiC-IGBT can get higher blocking voltage and more quickly turn-off speed. So SiC-IGBTs will be widely used in high voltage, high current power modules application area. As the IGBTs power increases, IGBT modules need more reliability on packaging materials especially for soldering materials. Al bonding wire lift fatigue and solder lamination are the two main failure modes [1]. As Cu wire and Al clad Cu wire bonding develop with much higher reliability than Al wire, the major failure mode of IGBT bonded by Cu wire or Al clad Cu is the thermal fatigue of the solder joint [2][3]. For the moment, Sn based lead free solder preform or paste, SnPb preform or paste, Silver sinter paste are the main soldering materials in power modules packaging.
SnPb solder is widely used in the electronic packaging because of good wetting, wide range of melting point, and high application reliability in the past. But the poisonous content Pb largely limit the widely application nowadays. And EURO has already forbidden commercial products contend of Pb [4][5][6].

Sn based lead free solder replace the SnPb by its low cost, environmental friendly feature, low soldering temperature and accepted applied reliability. But it can not meet the requirement of higher operation temperature (250℃) with low melting point (below 220℃).

Ag sinter paste can be soldered at 200~260℃ with pressure or non-pressure, but the soldered film’s melting temperature can be 960℃. Silver has excellent electric conductivity and thermal conductivity. So Ag sinter paste can be used in higher operation temperature.

2. Soldering Materials

2.1 Physical Properties

Melting point, CTE, elastic modulus, electric resistivity, thermal conductivity are the main physical properties for soldering materials. The function of soldering materials applied in power modules is to bond the substrate (eg, DBC) and dies (IGBTs, diode, MOSFET–) and conduct the electric and thermal heat. For \( T_m \), the higher melting temperature, the higher operation temperature of modules can stand. For CTE, the lower mismatch between substrate, solder, die can improve the reliability. For elastic modulus, lower elastic modulus may produce microcrack more easily. For electric resistivity, low resistance can produce lower thermal heat helpful for thermal management. For thermal conductivity, good thermal conductivity can improve the heat diffusion effectivity.

| Materials | \( T_m / ^\circ C \) | CTE/ \( \times 10^{-6} K^{-1} \) | Elastic modulus/ Gpa | \( T_c / Wm^{-1} K^{-1} \) | Resistivity / \( 10^{-8} \Omega m \) |
|-----------|-----------------|-----------------|------------------|-----------------|-----------------|
| Sn        | 231             | 2               | 54.4             | 66.6            | 11.4            |
| Pb        | 327             | 29.3            | 16.4             | 34.8            | 20.8            |
| Cu        | 1083            | 17.6            | 123              | 401             | 1.75            |
| Ag        | 961             | 19.5            | 73.2             | 420             | 1.65            |
| Al        | 660             | 23.2            | 68.5             | 237             | 2.83            |

2.2 Sn based alloys

For lead free Sn based soldering and Al wire bonding IGBT modulus, Solder will be the limiting factor of lifetime when delta T<100℃ in power cycling testing, shown as Fig.1 [7]. The lifetime decreases as the operation temperature increases. Because one part, operation temperature increases near the solder melting temperature, which will weaken solder’s mechanical properties; the other part, as swing delta\( T_j \) increases, the mismatch between solder and substrate which lead to the generation of microcrack and degradation, shown as Fig.2 [8].
Figure 1. PC-results of isolated failure mechanisms of classical modules in dependence on temperature.

Figure 2. Ultrasonic image of half-bridges after power cycle testing of soldered modules with aluminum cladded copper bonds with $t_{on}=2s$ and $\Delta T_j=70K$, $P_v=2.4W/mm^2$

J Mei [9], investigated the heat dissipation and studied the microstructural evolution of SnAg4.0Cu0.5 solder joints. The research illustrates that recrystallization and coarsening of precipitates take place earlier and in larger extent in the anode side of the solder joint (20°C higher temperature than cathode side), providing high-angle grain boundaries which are favorable sites for cracks to propagate. Fig. 3 shows that microcracks are formed at the edge of the solder standoff and the corner of the component, later propagate, resulting in resistance increment and an open circuit eventually.
Paper [10] discussed the influence of warpage, substrate ceramic thickness, baseplate thickness, solder layer thickness, substrate size and temperature profile on solder layer between DBC and baseplate in the temperature cycling testing: Crack propagation speed with warp concavely substrates is significantly faster than planar and convexly warping substrates which displays the best; Increasing the thickness of the ceramic layer shows a highly detrimental influence on reliability because of the increasing of CTE mismatch; For thicker baseplate, due to higher thermally deformable mass exerts more force on the solder during temperature swings which will lead to produce microcracks easily; Rate of crack growth increases with increasing solder layer thickness; Absolute delaminated area in three different substrate sizes are roughly equal; Higher $T_{j_{\max}}$ and higher $\Delta T$ increase the propagation of microcrack.

Compared with eutectic SnPb the intermetallic of Pb-free solders grow more slowly because of the higher activation energy (1.05eV, eutectic SnPb 0.95eV) of intermetallic growth [11]. The side wise reaction indicates that SnPb consume Cu faster than SnAg3.5, shown as Fig.4[11].
2.3 Ag sinter paste
Bulk silver is a good thermal and electronic conductor, but its melting point is too high as about 960°C to be applied in the die soldering materials. Nowadays, many researching projects have focused on the nano-Ag materials [12]. Nano scale materials’ melting point is lower than bulk silver according to high surface energy. Process temperature below 360°C with appropriate time can be accepted which can not affect die’s functions seriously. Researchers utilize the high surface energy of silver materials as 30~80nm nanosilver particles or 100~1000nm submicron silver flakes to connect die and copper (substrate surface) at 220~260°C. Nanosilver particles or submicron silver flakes sinter at 220~260°C by active atom diffusing between nearby particles or flakes.

Silver sintered power device has high reliability because of its higher melting point and elastic modulus than SnAg solders. The failure mode of sintered device is mainly wire bonding failure by power cycling testing [7].

Paper [13] researched the development of thermal shock-resistant of sintering silver film between DBC and GaN. The die shear stress strength dose not decrease much after 1000 cycles of thermal shock with condition of -55°C~250°C in 30min, as Fig.5. The cracks increase as the thermal shock testing cycles increase, shown as Fig.6. Because silver grain size increase and consume the smaller silver particles, as shown in Fig.7.

Figure 5. Change of die-shear strength by thermal shocks

Figure 6. Microstructure evolution by during thermal shocks (a) initial (b) 300cycles (c) 500cycles (d) 1000cycles
2.4 IMC Solder

In order to improve the melting point of chip-to-substrate joint materials, new materials or process technology have to be considered. Diffusion soldering technology can produce chip-to-substrate IMC solder film (Fig. 8) [14] with higher melting temperature and elastic modulus (Table 2). Higher temperature and higher elastic modulus of IMC need a much higher activation energy for crack propagation in solder joint. So microcracks are more difficultly generated in the Cu/Sn IMC film than Sn alloy film.

Table 2 Melting point and Elastic modulus of IMC solder content

| Materials | Tm/C   | Elastic Modulus/Gpa |
|-----------|--------|---------------------|
| SnAg3.5   | 220    | 51                  |
| Cu3Sn     | 676    | 135                 |
| Cu6Sn5    | 415    | 117                 |
| Cu        | 1064   | 127                 |

According to the diffusion law, the diffusion amount between solder and base metal can be described as follow. So improving $dC/dx$, soldering temperature and time can increase the diffusing soldering thickness.

\[ d_m = -DS(dC/dx)d_t \]

- $d_m$ – the diffusion amount of solder
- $D$ - diffusion coefficient
- $S$ – diffusion area
- $dC/dx$ – the concentration gradient of diffusion content in the diffusing direction
- $d_t$ – diffusion time

Figure 7. Thermal cycle dependence Ag grain evolution

Figure 8. Cross section of a diffusion soldered sample [14]
IMC film has higher reliability than Sn alloy film. After PC sec ($T_{j_{\text{max}}}=165\sim171^\circ\text{C}$, swing d$T_j=132\sim144^\circ\text{C}$, cycle times $t_{\text{on}}=2s$, $t_{\text{off}}=2.2s$) testing, the following failure analysis reveals no degradation of Cu wire bond interconnects and diffusion soldered joint. Finally, a degradation area is found at a delimitation of the substrate metallization (Fig.9) [14].

Figure 9. Cross section of a power cycling test structure after failure. The delamination of the Cu from the Al$_2$O$_3$ ceramic has been identified as the root cause for failure.

Diffusion soldering technology also has been used in SiC diode packaging [15]. Conventional solder with a few 10um thick is replaced by a very thin (~20um) metal layer on the chip backside (Fig.10). Intermetallic diffusion process appears in the chip-lead frame heating up. The thermal resistance of diffusion soldering between junction and case is reduce by ~40% shown as Fig.11.

Figure 10. Cross section image of die attach for (a) conventional solder and (b) diffusion solder. The bond line thickness is significantly reduced by the use of diffusion soldering. In (a), the inhomogeneous solder thickness can be seen, which lead to a die tilt.
3. Conclusion
As wide bandgap semiconductor (SiC, GaN) develops, power modules can be operated at higher temperature larger than 250°C. Then new soldering materials or technologies with higher reliability like silver sintering and IMC diffusing technology act as an important role in the power modules packaging. But Sn-base lead-free alloys are still the main soldering materials for Si power modules because of mature process and equipment for the moment. Especially, IMC diffusing technology also use Sn-based alloys with similar process and produce pure IMC soldering film with higher melting and higher elastic modules. Pure IMC solder layer also can be used higher operation temperature in SiC or GaN modulus.

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