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Failure Mechanisms of Dummy IGBT Assemblies Constructed using Liquid In-Sn/Nb System

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Abstract

Liquid solder joints have previously been proposed in order to improve the reliability of solder joints in general, and especially for those that are operated at elevated temperatures. The solder is designed to melt during high temperature operation, releasing the stresses on the joint. The component will remain mechanically attached to the substrate by use of a polymer underfill or glob-top. Assemblies of dummy insulated gate bipolar transistor (IGBT) devices were constructed using the In-Sn as a low melting point solder and Nb as a barrier layer, on both device bond pads and connecting wires. Silicone and epoxy based adhesives were used as glob top materials, and alumina was used as the substrate. Thermal cycling carried out between -20 and +125 °C lead to rapid joint failure, and analysis of the joints showed that the wires had moved under mechanical tests. Further testing is underway.

Background

Previous studies of liquid solder joint connections [1-5] have postulated that such connections may offer improved reliability over solid solder joints as the properties of the solder after the 1000th thermal cycle are theoretically the same as those after the first thermal cycle. Fatigue damage does not have a chance to accumulate and lead to failure, as the solder melts at a suitable point in the cycle. Despite the potential of the approach, there are few reported results from thermal cycling trials, and hence the motivation of this paper.

One key problem with liquid solders is finding a suitable barrier layer that will form intermetallic compounds (IMC) with the solder, but will have a limited IMC thickness. If IMC layers do not form, then the solder connection will be weak when the solder is solid, although this approach has been advocated in some studies [1,3]. On the other hand, it is well known that IMC formation is much more rapid when the solder is molten.

In previous studies, it has been shown that Nb is a suitable barrier layer that forms IMC layers with the solder, but the IMC layer is self limiting [6,7,8]. Indeed, the IMC layer, composed of NbSn₂ actually decreases in thickness at higher temperatures, as the nucleation rate of IMC crystals is faster, leading to the IMC covering the Nb more quickly, and shutting off the supply of Nb into the solder. The key property of the system that enables this to occur is the lack of diffusion through the IMC. Fig. 1 shows the IMC growth rate as a function of time and temperature. Nb however, cannot be electroplated from aqueous solution, limiting its use to applications where it can be sputtered onto the contacts. Another problem with the Nb barrier layer is that the IMC requires a significant time to form, as Nb dissolves slowly into the solder (see fig.1).

Fig. 1. IMC thickness as a function of time for different temperatures (In-Sn / Nb system)

A second potential problem for liquid solder joints is the expansion that occurs when a solder melts. It has been shown that in flip chip configurations, the pressure generated during phase change can lead to solder extrusion through gaps in the underfill and short circuits. The solder system for the IGBT application was eutectic 52In-48Sn with a melting point of 118 °C and an expansion coefficient of 1% upon phase change compared to 4% in Sn rich solders [9], resulting in much lower pressure generation.

The remainder of the paper outlines the assembly procedure used for the dummy IGBT devices, results of thermal cycling, and analysis and modelling of failure modes.

Silicone glob top dummy IGBT assembly

Assemblies of dummy IGBT devices on alumina substrates were constructed using the 52In-48Sn/Nb system to test the reliability and failure mechanisms. Figs. 2 and 3 present the schematic layout of bond-pads of the dummy IGBT devices and the soldered structure of the IGBT devices assembled using the 52In-48Sn/Nb system. For each assembly, four dummy IGBT devices are assembled on an alumina substrate. The bondpad metallizations of Au/Nb/Al on the IGBT devices are produced using vacuum-sputtering. The Nb and Au must be sputtered consecutively without intermediate exposure to air to avoid oxidation of the Nb. Au is chosen as a suitable wetting surface but use of Ag or other noble metal would also be suitable. They are patterned with two different stencils of stainless steel. The first stencil is for the deposition of Al on both the pads and the tracks, which extends 0.1mm beyond the pads and is 0.2 μm in thickness. The second stencil is for the deposition of 2 - 3 μm thick Nb, followed by the deposition of ~0.2 μm thick Au, without exposure to air, on the pads. The metallizations of Au/Nb/Al

with the similar thicknesses are also deposited on the entire back side of the dummy IGBT device and on the contact metallization of 0.2 mm thick Cu on the alumina substrate. The bondpads of the IGBT devices are connected using Al wires of 0.2 mm in thickness, 5 mm in length and 1.5 – 3.5 mm in width. 0.2/2 - 3 μ m of Au/Nb is deposited at one of the two ends of each of the Al wires, with 0.5 mm in length.

Fig. 2. Plan view and cross section of dummy IGBT assemblies

The assembly was carried out using a holding jig as shown in Fig. 3. The experimental procedure consists of the following steps: (i) put down the base plate and insert the substrate into the recess and the four structural rods into their positions on the base plate; (ii) slide down the stencil to hold the four IGBT chips; (iii) apply solder paste to the substrate; (iv) remove the stencil and slide down spacer 3 onto the rods; (v) slide down the stencil for holding the four IGBT chips again and insert the four IGBT chips; (vi) slide down solder paste stencil and apply solder paste to the bond pads of the IGBT chips; (vii) remove the solder paste stencil and slide down in-order the spacer 2, the first wire stencil, spacer 1 and the second wire stencil onto the rods; (viii) insert the Al wires; (ix) put in oven to reflow; (x) immerse into acetone overnight and then clean using cleaning fluid, Flux-Off® VZ Flux Remover, to remove the residual flux; (xi) put in oven at 240 °C for 24 hours for intermetallic crystals to grow; (xii) remove the constructed assembly of the IGBT devices from the jig; (xiii) apply the first polymer and let it cure and (xiv) apply the second polymer, let it cure. The assembly is now ready for thermal cycling. Note that the In-Sn solder layer connecting the chips to the substrate was not implemented as the Nb layer

sputtered onto the substrate (final metallization Direct Bond Copper) failed to adhere.

Fig. 3. Sketch and photograph of assembly jig used to hold substrates, die and wires in place.

Fig. 4 shows scanning electronic microscopy (SEM) images showing the excellent interconnect between the Al wire and the bond pad after step (x).

Fig. 4. SEM images of solder joints together with close-ups of device metallization (left) and wire (right).

The reliability of the constructed assemblies were tested and analyzed subject to thermal cycling between -20 and +125 °C. It was found that contact resistance between solder and wire was initially low, but after thermal cycling, pressure on

the wires was needed to get similar low contact resistance. After 800 thermal cycles, the assembly was cross-sectioned and the Al wires were found to have lost contact with the main bulk of molten In-Sn. As shown in Fig. 2, some In-Sn solder still remained, together with the Al wire.

Fig. 5. SEM images of solder joints after 800 thermal cycles together with close-ups of device metallization (right) and wire (left).

The high expansion and shrinkage of the silicone subject to the thermal cycling (CTE of ACCAS 1821 silicone is 302 ppm / °C) was initially considered as the dominating factor causing the failure of the solder joint. Then finite element (FE) modelling using ABAQUS was developed to simulate the displacements of the Al wires during the thermal cycling. Results showed small movement of the Al wire (~10 microns) after one thermal cycle, treating the silicone as elastic, and cannot explain the extraction of the wires from the solder. Further analysis of the assembly, defining the silicone as a non-linear hyperelastic material did show relatively larger displacements of around 50 microns at the bottom of the wire. Even if these figures were accurate, they still do not reach the level of movements required to extract the wire from the solder. A more likely explanation is lower adhesion strength between the wire and the adhesive, and this is currently being tested. Fig. 6. shows the model geometry for a single wire, and Fig. 7. shows the predicted vertical displacement of the bottom of the wire.

Fig. 6. Finite element simulation geometry of single wire

Fig. 7. Vertical displacement of wire due to thermal expansion of silicone through one temperature cycle.

Epoxy glob top dummy IGBT assembly

A second set of assemblies were constructed using an epoxy based glob top to mechanically support the bonding between Al wires and the solder (Fig. 8). Three glob tops were used as listed in Table 1. The dummy test chips this time were produced by Qudos Ltd. using standard semiconductor industry processes, followed by sputtering of Nb and Au layers. Along with the In/Sn liquid solder assemblies, standard Sn/Ag/Cu assemblies were also constructed using the same epoxy glob top materials, to use as a control.

Fig. 8. Sketch of epoxy adhesive assemblies

The cure schedule for the adhesives is important as previous studies have shown that if the adhesive is cured above the melting point of the solder then problems arise. This is basically because the glob top materials have a very high viscosity compared to the liquid solder and consequently displace the liquid solder from the bond pads during cure. The table shows the recommended cure schedules for the adhesives, but during the trials, the first stage of curing was reduced to 120°C in each case, for a longer period of time.

In the case of adhesives A and B, failure occurred before 100 thermal cycles. However, for C, assemblies have lasted 310 cycles without any failures. Examination of the failed assemblies is on-going to determine failure modes.

Table 1. Package reliability result.

Adhesive	A	B	C
T _g (°C)	>55	126	121
CTE ppm / °C	<40	46 (140)	35 (125)
Flexural Modulus (GPa)	8.1	6.0	9.2
Service Temperat- ure (°C)		<177	<177
Cure Schedule	(i) 15 min @ 120°C (ii) 30 min @ 100°C	(i) 20 min @ 150°C (ii) 16 hrs @ 80°C (iii) 4 hrs @ 93°C	(i) 20 min @ 150°C (ii) 1.5 hrs @ 140°C (iii) 2 hrs @

Conclusions

The liquid solder concept has been tested to examine whether superior reliability can be achieved compared to high melting point solder joints. The results to date suggest that the adhesive properties critically determine whether the assembly will survive the first few thermal cycles. Experiments are underway to determine the cause of this critical behaviour and whether the long term reliability of assemblies is indeed superior to that of conventional solid solder joints.

Attempts have also been made to utilize the liquid solder concept without the use of Nb, using conventional contact metallizations such as Cu [10] and Ni-P [11-12], and also Ni-P-W [13]. This is because Nb requires vacuum deposition methods which are relatively expensive. For these metallizations, In-Sn was replaced by Sn-Bi-X with a melting point of approximately 138°C. The solder contained an additive, X, added at 1-2wt%, from amongst Al, Cr, Si, Zn, Ag, Au, Ru, Ti, Pt, Nb and Cu. However, none of these solder and substrate combinations approached the lifetime achievable using the Nb substrate either because the IMC was not stable for longer than 1 month at 200°C or because the reactive element, X, oxidized at the surface of the solder before wetting the contact metallizations. Hence, only Nb appears to be an appropriate barrier metallization for liquid solder interconnects at the present time.

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