Low Temperature Transient Liquid Phase (LTTLTP) Bonding for Au/Cu and Cu/Cu Interconnections

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The Low Temperature Transient Liquid Phase Diffusion Bonding (LTTLTP) process has been used to reduce the residual stresses and hence, improve the thermal fatigue performance of bonds between dissimilar electronic packaging materials. Aluminum oxide plated with either gold or copper has been bonded to copper heatsinks at temperatures less than 160°C, using In-Sn eutectic solders. After two hours at the bonding temperature, Cu/In-Sn/Cu joints exhibit a remelt temperature in excess of 470°C and provide static strengths up to four times greater than the original solder bonds. Au/In-Sn/Cu joints do not exhibit a high remelt temperature due to the formation of a stable Au-In-Sn phase which melts below 130°C. Both types of joints exhibited acceptable thermal fatigue performance for the conditions which were studied.

Introduction

Advances in microelectronics have allowed the integration of tremendous functionality into very small physical structures. But even though design and process technologies evolve and reduce the size of the individual circuit elements, the higher levels of complexity have in fact caused these integrated circuits to grow larger. For these larger components the stress caused by the differential coefficient of thermal expansion (CTE) of materials during attachment must be considered for reliable operation. When a component is attached with a conventional solder, the minimal stress point is at the temperature where the solder solidifies. The component, solder, and substrate contract at different rates and much of the stress due to these contractions becomes locked in the bond. The larger the CTE mismatch and the higher the attachment temperature, the larger the differential contraction. The larger the size of the component, the larger the absolute magnitude of the stress developed.

Matching the CTE of the component to its substrate is possible but can be expensive. Reduction of the bonding temperature using conventional mounting alloys is only possible to the extent that there is an allowance for a reasonable temperature margin in service. Die attach adhesives can allow attachment at a relatively low temperature, but adhesives are limited in both thermal and electrical conductivity, even when filled with metal. Solder alloys are desirable when higher electrical and thermal conductivities are required as with high power silicon or gallium arsenide dies.

The ideal process would attach a component with solder at a low temperature, minimizing the stress level, but would with-

stand higher temperatures to allow higher levels of assembly or permit high temperature operation of the component itself. A joining process called Low Temperature Transient Liquid Phase (LTTLTP) bonding offers this potential.

LTTLTP bonding occurs when some of the base metal dissolves into the solder alloy and causes an isothermal solidification of the bond. The bond reflow temperature becomes much higher than the bonding temperature. With die attach in the 160°C (320°F) temperature range, components can be bonded in the range of power die operating temperatures with lower accumulated stress than with conventional eutectic die attach processes.

Other current chip bonding technologies are Au-Sn eutectic bonding and epoxy bonding. Au-Sn eutectic is favorable because of its high heat dissipation capability. However, its high processing temperature contributes to a high residual stresses. Moreover, although epoxy bonding has the ability to be processed at low bonding temperatures and to exhibit low residual stress, it nevertheless, exhibits low heat dissipation capability. LTTLTP bonding is the only technology among these attach-

Table 1 Comparison of advantages of three bonding technologies

Bonding technologies	Au-Sn Eutectic	Epoxy	LTTLTP
Heat dissipation capability	high	low	<u>high</u>
Processing temperature	high	<u>low</u>	<u>low</u>
Residual stresses	high	<u>low</u>	<u>low</u>

* * Underline represents desired feature.

Note: Only LTTLTP bonding has all the desired characteristics.

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Fig. 1(a) Original thicknesses of Au/In-Sn/Cu samples before heat treatments

Fig. 1(b) Original thicknesses of Cu/In-Sn/Cu samples before heat treatments

Fig. 2 Binary phase diagram of In-Sn [4]

ment processes that has all the desired characteristics (see Table 1).

This paper investigates the development of LTTLP bonding using 52 percent In-48 percent Sn solder material for Au/In-Sn/Cu and Cu/In-Sn/Cu joints. The base materials consist of an aluminum oxide flip chip carrier and a copper heatsink.

Experimental Procedure

LTTLP bonding uses conventional soldering techniques to initiate the bond. The solder joint is then held at the soldering temperature for an extended time such that isothermal solidification occurs.

Materials System. Initially, the Au/In-Sn/Cu system shown in Fig. 1(a) was studied. Later, the Cu/In-Sn/Cu system (see Fig. 1(b)) was proposed as an alternative to Au/In-Sn/Cu system. The Au or Cu electroplated ceramic has dimensions of 2.03 cm × 2.03 cm × 0.15 cm. The Cu spacer dimensions are 0.64 cm × 0.64 cm × 0.08 cm.

Materials Preparation. Samples were manually soldered using 52 percent In-48 percent Sn with RMA-F flux and a solder temperature range of 180°C-205°C (see Fig. 2). This range allows the solder to flow within one to three seconds. The mass of solder paste used was 0.025g. To avoid solder

Fig. 3 Cu/In-Sn/Cu LTTLP bond, HT = 145°C, ST = 180°C, $t = 2.25$ h, RT > 470°C

Fig. 4 Au/In-Sn/Cu LTTLP bond, HT = 145°C, $t = 2.25$ h, RT = 120°C

degradation, the In-Sn paste was refrigerated when not in use. The paste was brought to room temperature before application to avoid condensation residues. Samples were weighed to determine the mass of paste in the bond.

Heat Treatment. Prior to heat treatment, all samples were fixtured using Vlier screws [2] with 16 psi of pressure to produce a uniform bondline and to expel excess solder. A bondline of approximately 25 μm to 50 μm thickness was produced [3]. After soldering, both the Au/In-Sn/Cu and the Cu/In-Sn/Cu samples were heat treated at HT = 145°C with bonding times of $t = 0.5$ -13 hours.

Temperature Testing (Remelt Test). Shear testing at elevated temperatures was used to determine the remelt temperature of the bond after it has been heat treated [1]. The remelt temperature is related indirectly to the bond creep strength.

Characterization. Composition profiles were measured with the use of the Scanning Electron Microscope and the Microprobe (EPMA). The trends indicate which constituent is the diffusion limiting species, which constituent phases are present, and the relative amounts of the constituents.

Determining Reliability of Bonds. Thermal cycling was performed up to 2500 cycles from 0°C to 70°C. The cycle period was 4 minutes 10 seconds with a ramp rate of 5 sec and a dwell time of 2 minutes. Room temperature shear tests were performed to test the mechanical strength of bonds before and after thermal cycling and thus, to indicate bond reliability over time.

Results and Discussion

Bond Structure. Figure 3 illustrates the Cu/In-Sn/Cu system after completion of the LTTLP bond after a 2.25 hour heat treatment at 145°C. The black material in the lower portion of the figure is the aluminum oxide substrate. This is

Fig. 5 Composition Profile: bond composition versus bond distance; Cu/In-Sn/Cu system, solder $T = 180-205^{\circ}\text{C}$, $t = 2.25\text{ h}$, $T = 145^{\circ}\text{C}$

Fig. 6 Composition distribution of Fig. 5

Fig. 7 Composition profile: bond composition versus bond distance; Au/In-Sn/Cu system, solder $T = 180-205^{\circ}\text{C}$, $t = 2.25\text{ h}$, $T = 145^{\circ}\text{C}$

Fig. 8 Composition distribution for Fig. 7

followed by a layer of manganese and molybdenum used to metallize the ceramic substrate and an electroless nickel plate. Next, is the plated copper layer followed by the Cu-In-Sn LTTLP bond. The second solid copper piece is seen at the top of this figure. After the heat treatment, the copper plate has been reduced from $28\mu\text{m}$ thickness to approximately $7\mu\text{m}$.

Figure 4 shows a similar bond made in the Au/In-Sn/Cu system. The original gold plate adjacent to the manganese molybdenum had a nickel underplate, however, none of the gold plate nor the underplate is present after LTTLP. It is seen that the In-Sn solder has a strong tendency to dissolve the gold plating.

This is confirmed by the microprobe traces. Figures 5 and 6 show the results for the Cu/In-Sn/Cu system bonded at

Table 2 Thermal cycling data: Cu/In-Sn/Cu system, HT = 145°C , ST > 180°C , $t = 2.25\text{ hr}$, RT > 470°C

Cycles	Pressure (psi)
0	2010
1000	1976
1500	1696
1500	2032
1500	2008
1500	1808
2500	2032
2500	2008
2500	2016

Table 3 Thermal cycling data: Au/In-Sn/Cu system, HT = 145°C , ST > 180°C , $t = 2.25\text{ hr}$, RT > 470°C

Cycles	Pressure (psi)
0	1760
1500	1168
2500	2032
2500	2032
2500	1448
2500	920
2500	1464
2500	936

Fig. 9 Composition profiles of 50 percent In-50 percent Sn in Au/In-Sn/Cu system at $t = 0$ and $t > 0$

145°C . It is seen that there are two intermediate Cu-In-Sn phases present between the solid copper adherends.

Figures 7 and 8 show the microprobe results of the Au/In-Sn/Cu system after LTTLP at 145°C . Although there is more scatter in the data, comparison of this data with similar samples processed at 149°C and 153°C , and 157°C show that three phases are present. Phases A and B are essentially the same as those found in the Cu/In-Sn/Cu system; however, phase C is an In rich phase containing approximately 25 percent gold.

As will be discussed subsequently, the differences between these two bond systems can be understood by considering the diffusion tendencies of In and Sn in both Au and Cu substrates.

Bond Strength. The consistency of the bond creep strength is strongly correlated with the remelt temperature. For the Au/In-Sn/Cu system, the LTTLP bond exhibited a remelt temperature of 120°C and had considerable variation in strength from sample to sample (see Table 3). For the Cu/In-Sn/Cu system, the remelt temperature was greater than 470°C and had a shear strength of more than 2000 psi after a heat treatment of 2.25 hours. Table 2 shows that the joint strength was much less variable than in the Au/In-Sn/Cu system. There were no significant changes in shear stress in the Cu/In-

Fig. 10(a) Activity of In in Au versus mole fraction of In in Au at $T = 723\text{ K}$

Fig. 10(b) Activity of Sn in Au versus mole fraction of Sn in Au at $T = 823\text{ K}$

Fig. 10(c) Activity of In in Cu versus mole fraction of In in Cu at $T = 1013\text{ K}$

Fig. 10(d) Activity of Sn in Cu versus mole fraction of Sn in Cu at 1400 K

Sn/Cu joint after thermal cycling samples up to about 2500 cycles. The Au/In-Sn/Cu joint did show greater variations in strength after thermal cycling.

Diffusion Trends. The difference in remelt behavior and strength variability can be understood by considering the thermodynamics of the two systems. Figure 9a shows a schematic of the Au/50 percent In-50 percent Sn/Cu system's composition profile at $t=0$ seconds. If diffusion is dependent on composition gradients, at $t>0$ diffusion occurs and the composition gradients in the Au and Cu phases on either side of the joint are relatively similar as shown in Fig. 9(b). But in fact, the driving force for diffusion is not a composition gradient, but it is the chemical potential gradient.

Figures 10(a), (b), and (d) shows the activities of the Au-In, Au-Sn, and Cu-Sn binary systems based on the activities as

Fig. 11(a) Activity profiles of In in Cu and Au at $t=0$ and $t>0$

Fig. 11(b) Activity profiles of Sn in Cu and Au at $t=0$ and $t>0$

given in [5]. For Cu-In, only the heat of mixing is available. Approximate activities of Cu-In were calculated assuming regular solution behavior [6] as seen in Fig. 10(c). It is clear from these graphs that gold greatly decreases the activity of In and Sn while the activity of these alloying elements in copper is much closer to an ideal solution. If the diffusivities of In and Sn in the Cu and Au systems were equal and were controlled by the composition gradients, a symmetric dissolution profile such as Fig. 9(b) would result. In fact, the driving force for diffusion is the activity gradient which, as shown in Figs. 11(a) and 11(b) is much steeper on the Au side of the joint. As a result the In-Sn alloy dissolves all of the Au layer present on the substrate, forming a low melting phase of 25 percent Au, 60 percent In, 8 percent Sn, 7 percent Cu.

The In and Sn have such low activities in this phase that there is this phase that there is insufficient activity gradient to diffuse the In and Sn into the adjacent Cu-rich phase. Thus diffusion is essentially stopped before isothermal solidification occurs.

This activity pattern suggests that In and Sn in the In-Sn solder, which are at a high energy state, are preferentially diffusing towards the Au interface, which will contain In and Sn at a much lower energy state. Because the presence of Au alloyed with In and Sn presents a more stable state, diffusion of In and Sn to the Cu interface is much slower, and the LTTLP bond does not form as readily.

Differential Scanning Calorimetry (DSC) measurements were made on bulk samples with compositions similar to Phases B and C seen in Figs. 6 and 8. The results verify that the melting point of phase C for the Au/In-Sn/Cu system is about 120°C, and the melting point of phase B for the Cu/In-Sn/Cu system is 605°C. This suggests that the presence of an Au-rich phase C acts as a severe melting point depressant causing the bond to fail at 120°C.

Conclusions

The LTTLP bond process for Cu/In-Sn/Cu joints exhibit remelt temperatures greater than 470°C and thus greater bond strengths than the Au/In-Sn/Cu system, which forms a stable low melting Au-In-Sn phase. In and Sn, originally at a high energy state in the solder, preferentially diffuse to the lower activity state created at the Au interface. Au traps the In and Sn so that diffusion times for the In-Sn-Au phase into the adjacent Cu rich phase are very long. Thus, the Cu/In-Sn/Cu system is more advantageous due to its ability to produce high melting intermetallics at short bonding times. These higher melting phases are more resistant to deterioration during thermal cycling than are Au/In-Sn/Cu bonds.

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References

- 1 Roman, J., and Eagar, T., "Low Stress Die Attach by Low Temperature Transient Liquid Phase Bonding," *ISMH*, 1992.
- 2 Roman, J., "An Investigation of Low Temperature Transient Liquid Phase Bonding of Silver, Gold, and Copper," MIT S. M. thesis, Dept. of Materials Science and Engineering, 1991.
- 3 MacDonald, W. D., Eagar, T. W., "Transient Liquid Phase Bonding Processes," *The Metal Science of Joining*, Metallurgical Society, Warrenton, PA. 93, ed., Cieslak, M. J., Perepezko, J. H., Kang, S., Glicksman, M. E., 1991.
- 4 Massalski, T. B., *Binary Alloy Phase Diagrams*, Vol. 3, The Materials Information Society, 1990.
- 5 Hultgren, R., Desai, P. D., Hawkins, D. T., Gleiser, M., Kelley, K., *Selected Values of the Thermodynamic Properties of Binary Alloys*, American Society for Metals, Metals Park, Ohio. 1973, pp. 283, 747, 1035.
- 6 Gaskell, D. R., *Introduction to Metallurgical Thermodynamics*, Hemisphere Publishing Corporation, 1981.