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Low Stress Die Attach by Low Temperature Transient Liquid Phase Bonding

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Abstract

A process called Low Temperature Transient Liquid Phase (LTTLP) bonding can allow components to be solder attached in the 60-160°C (140-320°F) temperature range but not remelt until a much higher temperature. Stress is minimized by bonding at a low temperature and the component could be operated at or above the bonding temperature. This paper presents research on LTTLP bonding of silver, gold, and copper. Sixteen solders with melting temperatures between 30°C (85°F) and 157°C (315°F) were studied. Bond formation for each alloy on the three metals was studied by measuring the bond remelting temperature and its development time. Some mechanical shear strength data was also collected. The use of LTTLP bonding for die attach could be particularly advantageous for fragile or temperature sensitive components which require a good electrically and thermally conductive bond.

Key Words: Die Bonding, Low Temperature Soldering, Transient Liquid Phase Bonding, TLP, Low Stress Die Attach

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 withstand 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 (LTTLP) bonding offers this potential.

LTTLP 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 60-160°C (140-320°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. This type of process was originally investigated in the 1960's for die bonding at temperatures of 300°C (572°F) and higher, primarily with indium on gold [1][2].

This paper presents the results of research on low temperature transient liquid phase bonding to silver, gold, and copper using 16 solders with melting temperatures between 30°C (86°F) and 157°C (315°F). The choice of silver, gold and copper as the base metals for evaluation was motivated by their common use on electronic components. The 14 solder alloys and 2 elements chosen were commercially available and all the alloys but one are eutectic compositions.

This study surveyed the ease of low temperature transient liquid phase bond formation for each solder on each of the three base metals by determining the time to high temperature bond formation and its remelting temperature. In some cases mechanical shear strength was measured after varying lengths of time at temperature. A detailed record of this work on LTTLP bonding conducted at MIT may be found in *An Investigation of Low Temperature Transient Liquid Phase Bonding of Silver, Gold and Copper* [3]. It provides an in depth description of the experimental approach, equipment and analysis and contains individual sections presenting the data for each of the solder alloy/base metal systems studied. An overview of the work is presented here with the results summarized in Table 2.

Approach

Low Temperature Transient Liquid Phase bonding was studied by preparing specimens by soldering and holding at a temperature just above the solder melting temperature with a light fixture pressure for varying amounts of time. This time at temperature is termed the *dwell time*. The specimens were then tested to determine the temperature at which the bond would remelt, and how the shear strength of the bond was changed relative to the strength of an equivalent solder joint with no dwell time. Most of the bonding was done in an argon gas glovebox. Since many electronic chip components are adversely affected by the presence of chemical fluxes, an initial attempt was made to join all of the specimens in this dry, oxygen free environment without flux. Most of the solder-base metal combinations which could not be successfully joined in the inert environment were prewetted in air with the aid of mild chemical flux(type RMA), cleaned of the flux residue and then reflowed in the inert environment. The solders with their melting points and their commercial part numbers are listed in Table 1. The solders were packaged in plastic but otherwise exposed to ambient conditions and were used as received with no precleaning. The base metal specimens and the solders were stored in the dry argon atmosphere glovebox over the course of the experiment to minimize any changes due to atmospheric exposure.

Equipment and Specimen Preparation

The experimental test specimens were made from 1.6 mm (1/16") aluminum sheet stock electroplated with the one of the base metals. A thickness of 4 µm (156 µ") of plating was found to be adequate for the solders studied. The remelt temperature specimens (Figure 1) consisted of a 12.7 mm (.5") square plated aluminum bottom and a 7.6 mm (.3") square plated aluminum top joined with a solder alloy and immediately clamped at the nominal fixture pressure and held at the dwell temperature for a specified period of time.

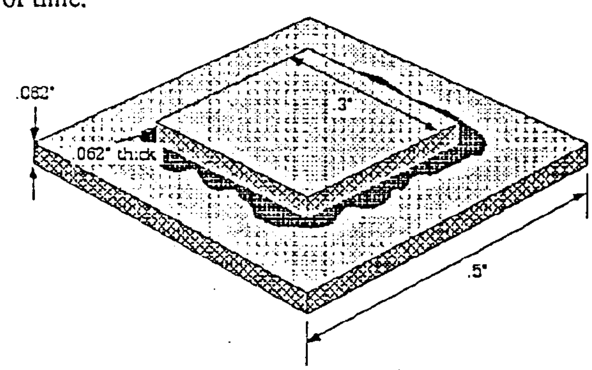

Figure 1. Outline drawing of a remelt temperature specimen. Base and top are 1.6 mm (1/16") aluminum plated with the appropriate metal and attached with solder.

The specimen size was intended to be representative of a sizable chip component. Joining of the specimens was done on a modified 90 mm (3 1/2") diameter hotplate with a temperature controller which maintained the hotplate temperature to within +/- 1°C. The best results were obtained when the initial soldering temperature was at least 15°C (27°F) above the liquidus of the solder alloy. Remelt temperature specimens were made by placing the top and the bottom with a measured amount of solder on the hotplate to preheat. After the solder on the bottom had melted, the top was picked up with tweezers, turned over, and gently scrubbed over the bottom until the solder wet both surfaces. A solder volume was chosen such that space between the top and bottom was filled with solder and some excess solder was apparent around all 4 sides of the top. The specimen was then immediately transferred to the temperature dwell apparatus and clamped for the prescribed dwell time.

The dwell apparatus was made from a 190 mm (7 1/2") square hotplate with an external temperature controller to maintain the temperature within +/- 1°C of the dwell temperature. The dwell temperature used was about 10°C (18°F) higher than the solder melting point in most cases. The apparatus had 8 rows of 5 stations each with Vlier plunger setscrews to hold specimens at temperature with a constant pressure. A schematic of a representative section of the specimen dwell apparatus is shown in figure 2.

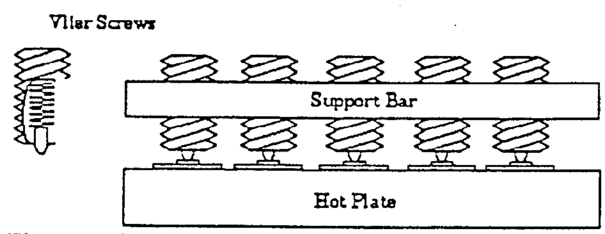

Figure 2. Representative section of dwell apparatus showing specimens clamped under spring loaded setscrews on heated baseplate.

The setscrews chosen for this experiment produced about .45 kg (1 lb) of pressure each. This equates to about 75 KPa (11 psi) pressure applied during dwell. The spring plunger compressed the bond squeezing out any excess solder making a thin, consistent bondline 25-50 µm (1-2 mils) thick. Specimens remained fixtured this way for the specified dwell period, were then removed and allowed to cool prior to any analysis.

Analysis

An apparatus was designed to determine the bond melting point after different lengths of time at the dwell temperature. The temperature specimen fit into a fixture which applied a shear load with a stainless steel foot to the top of the specimen. The upper part of this fixture (figure 3) was inserted into a tube furnace which was ramped from 100 to 600°C (212 to 1112°F) in 5 minutes. The temperature where the specimen top separated from the bottom was called the ***remelt temperature***. The rapid heating minimized the contribution of additional time at temperature to further development of the LTTLP bond. The test temperature was limited to a 600°C (1112°F) maximum by the aluminum specimen substrate.

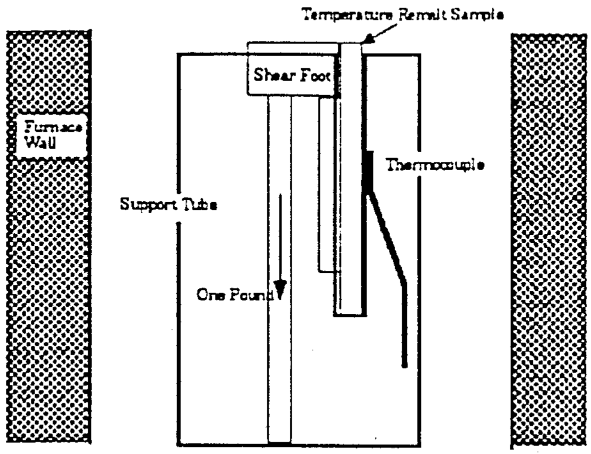

Figure 3. Drawing of the top portion of the remelt temperature test fixture showing shear foot loading the specimen. This portion is in the furnace with the shear loading spring placed externally.

The temperature was sensed by a thermocouple in direct contact with the base of the specimen. The remelt temperature measurement was determined to be accurate to +/- 10°C (18°F) of the reported remelt temperature. The force to separate the specimens at remelting was provided by a spring outside of the hot zone which produced a minimum .45 kg (1 lb) shear force. This translates to about a 69 KPa (10 psi) shear force on a 7.6 mm (.3") square specimen top. This amount of force was empirically determined to be adequate to positively separate the temperature specimen when the bond remelted. This was not intended as a quantitative high temperature shear test.

Shear test specimens were prepared like the remelt specimens except that the shear bottoms were 7.6 mm (.3") square, and the tops were either 2.5 x 5 mm (.1" x .2") rectangles or 2.5 mm (.1") squares. The smaller specimen size was necessary to accommodate the limits of the die shear tester. The size of the top used was based on the shear strength of the solder tested. The shear tester was originally custom built for testing silicon die shear over a 0 to 55 kg (120 lb) range. All testing was performed at ~25°C (77°F) ambient temperature with a shear loading rate of 2.3 kgs/second (5 lbs/sec). The primary value of this testing is to determine whether the low temperature transient liquid phase bonded joint is grossly weaker or stronger than a normal solder joint of equivalent thickness. The results of shear testing are summarized in the comments in Table 2. More complete shear data is presented graphically in ref[3].

Conclusions

This investigation has shown that low temperature transient liquid phase (LTTLP) bonding occurs with regularity with the majority of the low melting temperature alloys studied bonding to gold, silver, and copper. High temperature bonds can be made with the proper heat treatment (dwell time) below 165°C (329°F). In most cases this bonding was done without the use of a chemical flux but the use of flux did not interfere with the development of LTTLP bonds. The results show a substantial frequency of occurrence of LTTLP bonding depending on the judgement criteria used. For dwell times of 24 hours or less about two thirds of the alloy-base metal systems develop a bond with a minimum 300°C (572°F) remelting temperature. Over half show a minimum 425°C (797°F) remelting temperature using the same dwell criterion and one third of the systems show a minimum 300°C (572°F) remelting temperature with 2 hours or less of dwell time.

Shear behavior did not correlate well with the remelt temperature behavior where enough data were taken to be indicative. The shear strength was sometimes increasing, sometimes decreasing, sometimes constant, and sometimes erratic. Microscopic study of the fracture surfaces showed ductile failure for those alloys which were not well developed into LTTLP bonds, and more brittle failure where a high melting point bonds formed. When the LTTLP bond was accompanied by a planar intermetallic formation the bond fractured in a plane and strength was minimal. This occurred most often in the simple binary systems. In the multicomponent systems where growth across the bondline was irregular or columnar, the bond did not fracture in a plane and the force required to rip apart the interlocking structure increased its strength. The multicomponent systems are more metallurgically complex and so are more difficult to analyze but probably have the most potential for application.

In most cases the LTTLP bonds were as strong or stronger than an equivalent conventional solder bond but each system that showed promise should be thoroughly mechanically characterized before use. Determination of shear strength at elevated temperatures is important. If the mechanical properties of some of these systems correlate with the melting temperature these bonds may be robust at high temperatures. Testing at different shear loads and rates would also be prudent to determine the creep and fatigue resistance. Within any system, changing the dwell temperature, the joining technique or the fixturing pressure can change the strength or speed of development of an LTTLP bond. These are parameters that can be varied for process refinement.

This investigation of low temperature transient liquid phase bonding has uncovered many more questions than answers. A better understanding of the scientific fundamentals could allow development of solder alloys specific to base metals which would form optimum LTTLP bonds. These custom solder alloys would produce the desired high melting point, shear strength and other properties optimized for an application. The challenge is to make a bond develop in a short enough time to make LTTLP bonding a commercially attractive process. Recent research at MIT [4] has evaluated 52% indium/ 48% tin on gold and copper in more depth and added fundamental information to the understanding of LTTLP bonding.

While some characteristics are common to all of the solder alloy/base metal systems, enough variation exists to make many of these systems interesting from purely a scientific point of view. Very little tabulated information on diffusion rates, intermetallic formation and structure, or other basic information exists about metal behavior in this very low temperature range. Further study of LTTLP bonding mechanisms could be a vehicle for fundamental research as well as development of a valuable bonding process.

References

[1]L. Bernstein & H. Bartholomew, *Applications of Solid-Liquid Interdiffusion (SLID) Bonding in Integrated-Circuit Fabrication*, Transactions of the Metallurgical Society of AIME, Vol 236, March 1966, pp 405-412.

[2]L. Bernstein, *Semiconductor Joining by the Solid-Liquid-Interdiffusion (SLID) Process*, Journal of the Electrochemical Society, December 1966, pp 1282-1288.

[3]J.W. Roman, *Low Temperature Transient Liquid Phase Bonding of Silver, Gold and Copper*, MIT Master's Thesis, Cambridge, MA (May 1991).

[4]M.M. Hou, *Low Temperature Transient Liquid Phase Bonding for Electronic Packaging*, MIT Master's Thesis, Cambridge, MA (May 1992).

TABLE 1

Ref ID	Solder alloy Composition	Indalloy number	Ostalloy number	Melting point	Tensile[1] strength
A	100% Indium	4	313	156.7°C	575
B	97% Indium, 3% Silver	290	296	146°C	800
C	80% Indium, 15% Lead, 5% Silver	2	298300	149°C	2550
D	52% Indium, 48% Tin	1E	244	118°C	1720
E	44% Indium, 42% Tin, 14% Cadmium	8	200	93°C	2632
F	58% Bismuth, 42% Tin	281	281	138°C	8000
G	46% Bismuth, 34% Tin, 20% Lead	42	-	100°C	
H	55.5% Bismuth, 44.5% Lead	255	255	124°C	6400
I	50% Bismuth, 26.7% Lead, 13.3% Tin, 10% Cadmium	158	158	70°C	5990
J	49% Bismuth, 21 Indium, 18% Lead, 12% Tin	136	136	58°C	6300
K	44.7% Bismuth, 22.6% Lead, 19.1% Indium, 8.3% Tin, 5.3% Cadmium	117	117	47°C	5400
L	67% Bismuth, 33% Indium	53	229	109°C	-
M	66.3% Indium, 33.7% Bismuth	162	162	72°C	
N	60% Bismuth, 40% Cadmium	86	291	144°C	
O	74% Indium, 26% Cadmium	253	253	123°C	
P	100% Gallium	-	-	29.8°C	

Table 1. The solders listed above are identified with letters which refer to Table 2. All are eutectic alloys except *A* and *P* which are elemental and *C* where the liquidus temperature is given as the melting point.

Indalloy is a brand name of: The Indium Corporation of America, Utica, N.Y.
Ostalloy is a brand name of: Arconium Speciality Alloys, Providence, R.I

1 Indium Corporation Technical Bulletins #J-2-1M, 4-79 and #102-73-1M, 4-79

TABLE 2

Ref ID	Base Metal	Dwell Temp (°C)	Dwell Time (hrs)	Remelt Temp (°C)	Comments
A	silver	165	3	450	shear strength increases then drops after 10 hrs at dwell temperature
A	gold	165	1	500	shear strength increases more than 5x after 10 hrs but does not drop off like on silver
A	copper	165	3	500	shear strength goes to zero after tens of hrs of dwell
B	silver	155	18	550	very similar to A on silver; one specimen made to confirm behavior; no shear data
B	gold	155	1	500	little change in shear strength to 4 hrs
B	copper	155	3	500	behavior similar to A on copper
C	silver	155	24	500	single specimen to confirm similar behavior to B on silver
C	gold	155	1	400	behavior similar to A and B; no shear data
C	copper	155	24	500	single specimen, similar to A and B; no shear data
D	silver	130	60	130	no significant change in remelting temp or shear strength
D	gold	130	2	400	remelting temp for specimens at 150°C for 2000 hrs also 400°C+; shear strength higher after 100hrs @ 130°C then lower after 1000hrs at 150°C, not investigated between
D	copper	130	1	500	shear strength erratic out to 100hrs @ 130°C, indications of decline in strength at 1000hrs @ 150°C
E	silver	110	20	500	not investigated at less than 20 hrs; no shear data
E	gold	110 110	18 72	250 400	slow development of LTTLP bonding indicated
E	copper	110	1	500	slight increase in shear strength for dwell times to 40 hrs; required flux to wet copper
F	silver	150	2	500	high shear strength unchanged out to 40 hrs @ 150°C
F	gold	150 150	11 96	200 200	after initial 50°C change no remelt temp increase to 96 hrs; erratic shear behavior
F	copper	150	1	500	LTTLP bond formation erratic; shear strength steadily declined out to 100 hrs
G	silver	110	26	500	LTTLP bond slow to form relative to F on silver; shear strength constant
G	gold	110	72	250	single specimen, minimal indication of LTTLP bond; no shear testing
G	copper	110	26	500	one specimen; required flux to wet copper; no shear data
H	silver	135	25	500	behaves like F but LTTLP bond slower to develop; shear strength constant to 20 hrs
H	gold	130	26	165	one specimen, similar to F,G; no shear data
H	copper	-	-	-	would not wet to copper, no specimen prepared

TABLE 2 continued

Ref ID	Base Metal	Dwell Temp (°C)	Dwell Time (hrs)	Remelt Temp (°C)	Comments
I	silver	80	72	500	LTTLP bond slow to form; shear strength constant to 72 hrs dwell time
I	gold	110	26	<100	one specimen, no LTTLP bonding seen after dwell @ 40°C above solder liquidus; no shear testing; required flux
I	copper	110	26	<100	one specimen, same results as above, very difficult wetting even with flux
J	silver	80 110	72 48	500 500	110°C dwell specimen formed a LTTLP bond @ 48 hrs indicating temperature acceleration; shear strength increased to 72 hrs
J	gold	110	26	370	single remelt temp specimen; shear strength constant to 48 hrs @ 110°C
J	copper	110	26	500	one specimen, faster LTTLP bond formation than I ; no shear data; required flux
K	silver	110 110	26 48	400 500	small number of specimens, no investigation of less than 26 hr dwell; no shear data
K	gold	110	26	<100	one specimen, marginal wetting on gold with flux; no shear data
K	copper	110	10	300	remelting temps from 100 - 600°C seen from 0 - 10 hrs, very erratic remelt temp behavior but consistent increase in shear strength out to 50 hrs dwell time
L	silver	120	13	300	one specimen, some indication of LTTLP bond; no shear data
L	gold	-	-	-	poor wetting without flux prevented preparation of specimen
L	copper	-	-	-	same as above; did not try with flux
M	silver	110	24	580	one specimen; no shear data
M	gold	-	-	-	poor wetting without flux prevented preparation of specimen; no attempt to prepare with flux
M	copper	-	-	-	no specimen prepared, very poor wetting
N	silver	155	4	240	one specimen; no shear data
N	gold	155	4	340	one specimen, marginal wetting without flux; no shear data
N	copper	155	4	580	one specimen; no shear data
O	silver	135	11	540	marginal wetting without flux; no shear data
O	gold	-	-	-	poor wetting without flux, no specimen prepared
O	copper	-	-	-	poor wetting without flux, no specimen prepared
P	silver	150	2	-	specimen had no strength after dwell; lower temp dwell produced similar results
P	gold	150	25	-	same as above
P	copper	150	16	-	same as above

Table 2. Identification letters refer to solders listed in Table 1. Remelt temperatures listed are representative minimums, see ref[3] for complete data.