Aluminum Wedge-Wedge Bonding Using Capillary and Ball Bonder

Sarangapani Murali[1], Ei Phyu Phyu Theint[1], Hamdan Faizul Fitri[2], Tan Kean Tiong[2] and Zhang Xi[1]
[1] Innovation, Heraeus Materials Singapore Pte. Ltd., Ang Mo Kio Ave 5, TECHplaceII, Blk 5002#04-07, Singapore-569871, Email: murali.sarangapani@heraeus.com, Ph: +65 6571 7846.
[2] Engineering, Heraeus Materials Malaysia Sdn Bhd 6, Jalan i-Park 1/1, Kawasan Perindustrian i-Park, 81000 Bandar Indahpura, Kulaijaya, Johor, Malaysia.

Abstract
The paper discusses on the bondability and reliability of aluminum (Al) wedge-to-wedge bonding using fine ceramic capillary and ball bonder. Initial trials revealed aluminum build-up and poor capillary life with touch down of 20K or less. Optimizing the process parameters, switching on air-scrub, reducing shape angle to 20° instead of usual 35° and using Al-1wt%Si wire processed with refined grains revealed better capillary life with touch down of 200K without surface burrs. The method is capable of bonding complex looping and sharp acute bends. The data comprising of 1st and 2nd wedge dimensions, wedge pull, wedge shear and fracture mode for 20µm and 50µm Al-1wt%Si wires are presented. High temperature storage of aluminum wedge bonding to different substrate surfaces such as Al-0.5wt%Cu metallization, bare copper and gold plating revealed stable bond. From the wedge pull and tensile data, floor and shelf life of the wire is recommended to be 7days and 6months respectively. Evaluation of gold, copper and silver base bonding wires by this method showed feasible to bond and needs detailed studies to practice. The fusing current of Al-1wt%Si wire for varying diameter from 0.6 to 3mil and wire length from 1 to 20mm are also stated.

Key words
Capillary wedge bonding, CWB, Aluminum bonding wire, wedge-wedge bonding, Al-1wt%Si wire

I. Introduction
Wire bonding is a well established interconnection technique practiced in the microelectronics packaging sector. Metallic wires of gold, copper, silver and aluminum with low resistivity are used for bonding. In addition to high pure metals (4N, 99.99%) doped/alloyed wires are also adopted for the betterment of looping, bondability and reliability performances. Recently, palladium coated copper wire (CuPd) revealed excellent performance equivalent to gold on 2nd bond bondability. Hence, CuPd replaces gold wire bonds up to 50% besides bare copper, alloyed silver and aluminum wires. The size of the wires used normally are in the range of 12 to 75µm (0.6 to 3mil). These fine gold/copper/silver base wires suit well for high speed ball-wedge bonding.

In power electronics, in order to carry high current, thick aluminum wires (100 to 600µm) are wedge-wedge bonded with excellent reliability performance, especially bonded to aluminum bond pad (Al-Al system) or copper surface (Al-Cu system). For this benefit, fine aluminum wires (15 to 75µm) are also wedge-wedge bonded. Figs.1 and 2 provides the fusing current of bonding wires, where aluminum is comparable to copper and slightly higher than gold and silver wires. With increase in diameter, significant increase in fusing current is also noticed. Moreover, with increase in wire length from 1mm to 20mm marginal decrease in fusing current is evident. The fusing current is measured under atmosphere with 300ms input pulse current.

Ball-wedge thermo-sonic bonding is a versatile, cost-effective production process for the last four decades in semiconductor packaging industry. Wedge-wedge ultrasonic bonding of thick aluminum wire is also a known production process for the last few decades. Recent days, packaging device such as stacked die is complex with refined design and fabrication process. Multiple bonding along a line in a single step by connecting few devices and substrates using fine aluminum wire and wedge bonder, termed as “Chain Bonding” is examined. This calls for the development of using high speed ball bonder and capillary for chain of wedge bonding at room temperature without free air ball (FAB) formation and gas purging, which optimize the utility of ball bonder and increase the speed of wedge-wedge bonding (Table.1). Aluminum (Al) wedge-wedge bonding using ceramic capillary and ball bonder at room temperature is a new approach being examined for a few years in the industry [1-7]. The methodology is termed as capillary wedge bonding (CWB). The speed of CWB is slightly faster than the routine ultrasonic wedge bonding (Table.1).

Table.1 Comparison of the three wire bonding techniques.

Specification	Ball Bonding (BB)	Wedge Bonding (WB)	Capillary Wedge bonding (CWB)
Type	Thermosonic	Ultrasonic	Ultrasonic and thermosonic
Bonder	Ball Bonder	Wedge Bonder	Ball Bonder
Speed, wires/s	10 to 16	3 to 6	5 to 8
Frequency, Hz	120 to 140	40 to 80	120 to 140
Free Air Ball Formation	Present	Absent	
Gas Purging	N_2/ Forming Gas	Absent	
Bonding direction between 1st and 2nd bond	360°	Straight and slightly angled say <10°	
Bonding Temperature, °C	150 to 230	Room temperature	Room & elevated temperature
1st Bond	Ball	Wedge	
2nd Bond	Wedge (Stitch)	Wedge	
Bonding Tool	Capillary	Wedge	Capillary
Tool Material	Alumina	Tungsten Carbide, Hardened Steel	Alumina
Wire Type	Au, Cu, CuPd, AFPC, Ag, C-Ag	Al, Au & Cu	Al, Au, C-Ag (Coated Ag)
Diameter, µm	12 to 75	20 to 500	20 to 50

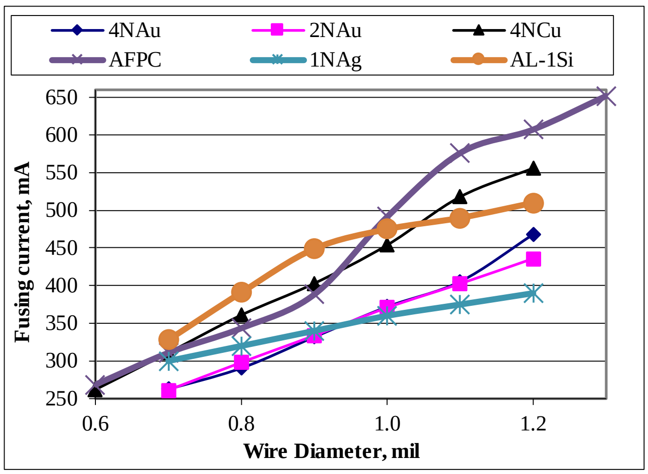


Fig.1 Fusing current of fine bonding wires for varying diameter.

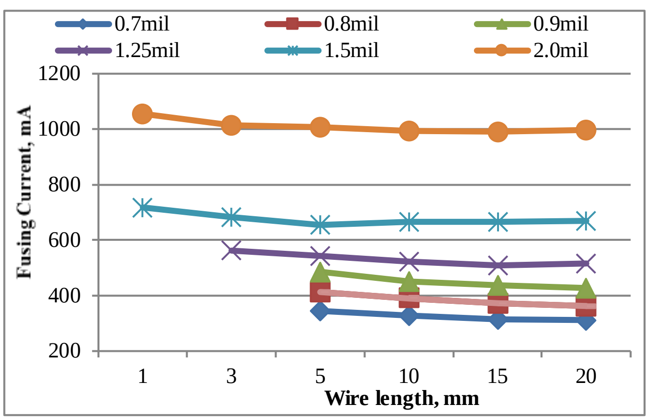


Fig.2 Fusing current of fine Al-1wt%Si wire for varying diameter and length.

The prospective advantage of CWB technique is the high yield during chain of wedge bonding. The capillary used for CWB has zero face angle which is different from commercial capillaries used in ball bonding. The capillary material is a toughened ceramic made of alumina with a low fraction of zirconia. The flat face creates wedge morphology and concurrently transfers the energy to bond the interfaces. Fig.3 illustrates the CWB cycle:

1. starts with deforming the wire to 1st wedge concurrently welding it to the bond pad or substrate
2. followed by looping without heel crack
3. deforming and welding the 2nd wedge to substrate or bond pad
4. adjusting the capillary to tear the wire, and
5. repeating the cycle

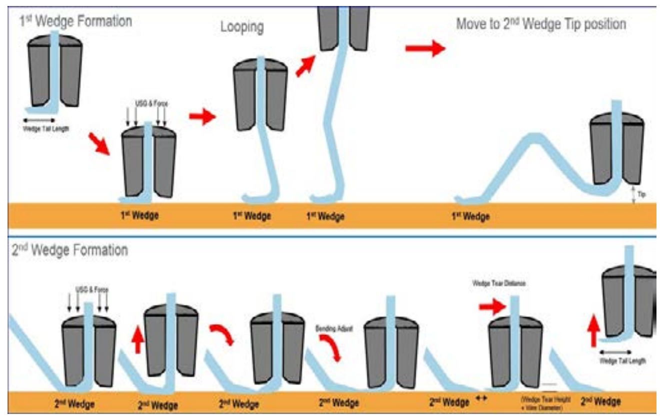


Fig.3 Capillary wedge bonding (CWB) cycle

II. Experimental Process Details

Capillary wedge bonding was practiced using 20µm and 50µm Al-1wt%Si wires. The key CWB process parameters to attain good looping of 1st and 2nd wedges are:

(a) Ultrasonic energy (USG)
(b) Compressive force
(c) Constant velocity
(d) Shape angle (loop)
(e) Air-scrub (is a function where after 2nd wedge bond and when the capillary tip is in air above the wedge as well as when wire clamp is closed. Switching on the scrub function whether inline or perpendicular mode favours an easy wire tear)
(f) Wire tear
(g) Tail tip length
(h) Temperature (ambient and elevated)

For bondability and reliability evaluations, Al-1wt%Si wire was bonded to 1.3µm thick Al-0.5wt%Cu metallization bond pad, bare copper lead frame surface and silver/gold plated lead surfaces. Al-1wt%Si wire with 2 to 5% elongation (EL) is apt for bonding, looping, tearing after 2nd bond and leaving behind short wire for next cycle as the 1st tip of wedge bond.

In addition, gold, copper, palladium coated copper and alloyed silver wires with 6 to 12% EL were examined for CWB. The vital factor to get a good CWB depends on the capillary used, which was specially processed for this methodology. The capillary was made of toughened alumina with zero face angle. The inner chamfer diameter, outer radius, size of the tip were designed different from conventional ball bonding capillary (Fig.4). The capillary was procured from Kulicke & Soffa. CWB was studied using ball bonder IConn-plus, Kulicke and Soffa.

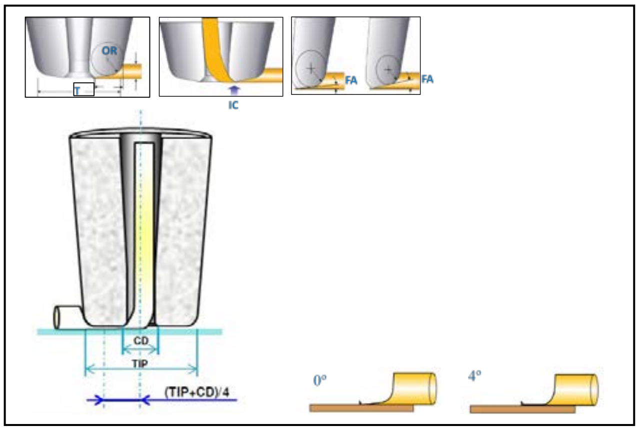


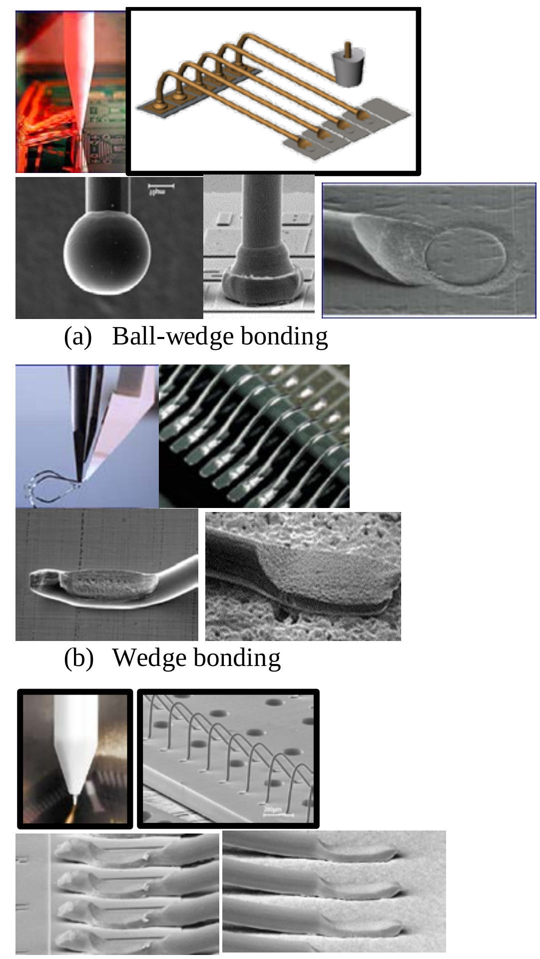
Fig.4 Illustration of capillary dimensions (Tip (T), outer radius (OR), face angle (FA) and inner chamfer (IC)) of a capillary used for CWB.

III. Results and Discussion

The bondability and reliability of CWB of Al-1wt%Si wire on to Al-0.5wt%Cu bond pad are provided in the section. In addition, bondability evaluation of CWB of other bonding wires Cu, CuPd, Ag, C-Ag on aluminum bond pad is feasible and the initial data are also presented.

III-a. Morphology, Dimensions and Shear/Pull Properties of Aluminum Wedge by CWB

The morphology of aluminum wedge depends on the shape of the capillary tip geometry and dimensions. The capillary inner diameter tolerance is at least greater than 0.5 to 1D (D is wire diameter) to bond. The wedge morphology of first and second bonds differ by the presence of wedge tip in first bond and its absence in the second bond. The ultrasonic energy and compressive force deforms the wire to wedge shape and concurrently weld the wire surface in contact with the metallized Al bond pad surface (Au plated surface or bare substrate surface). Process optimization is needed for each steps: first wedge bond, looping and second wedge bond. Fig.5 shows the morphology of conventional wedge-wedge bond, stitch (wedge) bond using conventional ball-wedge bond and first and second wedge by CWB. For the present commercially available ball bonder and capillary, the CWB methodology is capable to bond 18 to 50µm (0.7 to 2mil) wire. Thick wire of 3mil is difficult to loop and bond and it is in developmental stage. On optimizing the process and using aluminum wire with optimal elongation showed absence of burrs and wider wedge heel (elephant ear). Generally, heel cracks are absent at time zero of CWB.



(a) Ball-wedge bonding

(b) Wedge bonding

(c) Capillary Wedge bonding (CWB)

Fig.5 Typical SEM images of bonding tool, 1st bond, 2nd bond and looping of the three different modes of bonding.

As a general guideline, first and second wedge pull should break at a minimum wire tensile break load of 30% and the remaining heel should be at least 50% of the wedge area. The wedge width range could be between the minimum capillary tip area ((tip – CD)/2) and bond pad pitch (BPO). The wedge thickness to be in the range between 0.2 and 0.5D. CWB is processed at ambient conditions (20 to 26°C). CWB is a FAB and gas less process with absence of formation of FAB under preventive environment. The wedge pull of 20µm Al-1wt%Si wire bonded to aluminum bond pad surface and silver plated lead finger surface revealed (Fig.6) good bondability, relatively Al-Al bond is stronger than Al-Ag bond. Similarly, wedge pull of 50µm Al-1wt%Si wire bonded to bare Cu lead frame surface showed (Fig.6) good bondability, relatively Al-Al bond is stronger than Al-Cu bond. Both, Al-Cu and Al-Ag bonds are expected to form copper and silver aluminide in nanometer (nm) thickness.

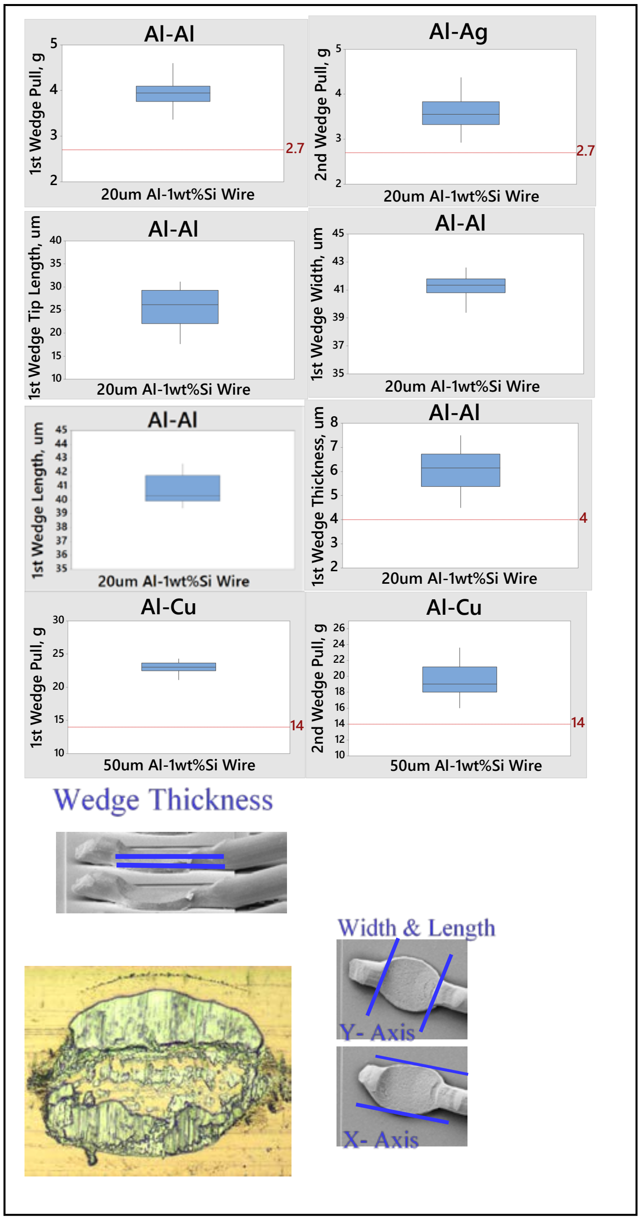


Fig.6 Wedge pull and tip length of 20µm and 50µm Al-1wt%Si wire bonded by CWB. Typical image of shear remain of 50µm Al-1wt%Si wire bonded on Cu lead frame surface.

Fig.6 shows the distribution of 1st wedge dimensions (width, length, thickness and tip length) processed using 20µm and 50µm Al-1wt%Si wires by CWB. The remaining aluminum after shear for 50µm Al-1wt%Si wire bonded to Cu lead frame surface is about 50% (Fig.6). Usually, the variation of wedge shear for 50µm wire is high when the tool height is positioned 2µm above the Al bond pad surface. The standard deviation is further high for 20µm wire wedge bond due to significant pick-up of soft Al on the tip of wedge tool. Currently, wedge shear measurement for the fine aluminum wire bond is a challenge. For both 1st and 2nd wedge, the heel area is smooth with no sign of cracks or tool marks. Table.2 provides with the specification of Al wedge by CWB method for varying diameter.

Table.2 Specification of wedge dimensions/properties and looping for varying Al-1wt%Si wire diameter.

Wire Diameter, µm		18	20	23	25	50	61
1st Wedge	Width, µm	35 to 45	35 to 45	40 to 50	40 to 50	45 to 60	45 to 60
	Thickness, µm	4 to 8	4.5 to 9	5 to 10	5.5 to 12	10.5 to 25	12.5 to 30
	Pull, g (min.)	2.1	2.7	3.9	4.5	15	18
	Shear, g	-	-	-	-	85	-
	Al remain after shear, % (min.)	50					
	Tip Length Consistency, µm (max.)	17	20	22	25	50	60
2nd Wedge	Width, µm	35 to 45	35 to 45	40 to 50	40 to 50	45 to 60	45 to 60
	Thickness, µm	4 to 8	4.5 to 9	5 to 10	5.5 to 12	10.5 to 25	12.5 to 30
	Pull, g (min.)	2.1	2.7	3.9	4.5	15	18
	Shear, g	-	-	-	-	85	-
	Al remain after shear, % (min.)	50					
Looping	Type	Normal				Normal & Acute Angle	
	Length, mm (max.)	3.25	3.25	3.25	3.25	3.81	3.81
	Height, µm (max.)	203	254	305	355	686	800
	Height Consistency, µm (max.)	17	20	22	25	50	60
Burr		Absent					

III-b. Capillary Life of CWB of Al-1wt%Si wire

For a normal loop, CWB of 20µm Al-1wt%Si wire using capillary with 0° face angle reveals 20K touch down, the capillary clogs and terminates the bonding. The tests are performed using BGA device with 1.3µm thick Al-0.5wt%Cu bond pads and 0.5µm thick Au plated lead surfaces. When loop shape angle is reduced and air-scrub function is turned-on after second wedge, better capillary life of 200K touch down is achieved. Then the capillary clogs, and unusable to bond 20µm Al-1wt%Si wire (Fig.7). Similarly, capillary clog is noticed after 20K when 50µm Al-1wt%Si wire is bonded to bare copper lead frame surface. However, 50µm Al-1wt%Si wire can bond above 200K touch down by switching on the air-scrub and reducing the loop shape angle. The observations are confirmed by the second trial evaluations. Moreover, Al-1wt%Si wire is also processed with refined grains to improve the capillary life.

With reference to conventional ball-wedge bonding of fine Au/Cu/Ag wires, usually 1 million touch down is achieved. For conventional wedge-wedge bonding, hardened steel tool clogs in the range of 40 to 100K touch down. However, the tool is cleaned chemically and continued for 300K touch down or longer. In the case of novel CWB process, a detailed study is necessary to improve the capillary life and is currently considered as the limitation of this process.

III-c. Reliability of CWB of Al-1wt%Si wire bonded to Al-0.5wt%Cu bond pad (Al-Al) and Cu lead frame surface (Al-Cu)

It is a well known fact that the bondability and reliability of similar metal welding of Al wire to Al bond pad is the best. Figs.8 and 9 shows thermal ageing (high temperature storage (HTS)) of 20µm Al-1wt%Si wire welded to Al-0.5wt%Cu bond pad is stable up to 1000h of storage at 175°C. The initial drop in wedge pull after 100h is due to change in grain structure of the wire, consequently reducing the tensile break load (Table.3, wire stored at elevated temperature and measured its tensile break load). Cross-sectional observation of the thermal aged Al-Al interface revealed good diffusion bonding without formation of intermetallics.

The Al-Ag system is unstable and wedge lift within 200h of storage as Al and pure Ag (plated surface is >99% Ag) atoms inter-diffuse rapidly at the interface causing Kirkendall void formation.

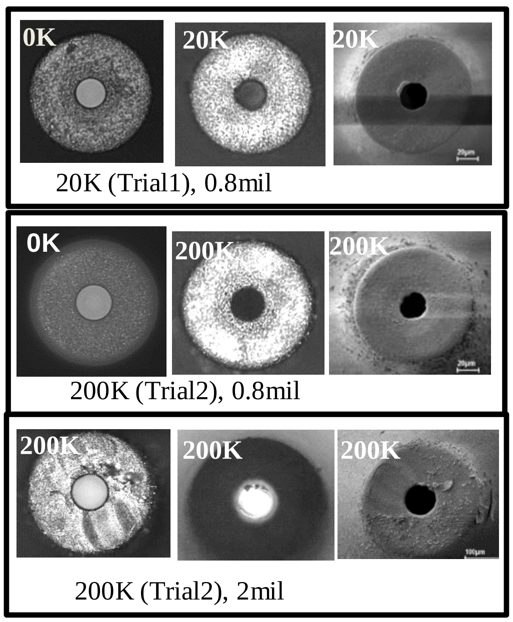


Fig.7 Observation of capillary clogging in an optical scope transmitting light through capillary hole (left and mid image). SEM observation of Al burrs on the capillary tip after 20K and 200K touch downs (right).

Wire Size, µm	Wire Break load, g	
	Before storage	Stored for 100h at 175°C
20	8.1	3.3
50	47.7	24.2

Table.3 Break load of Al-1wt%Si wire on storing at 175°C.

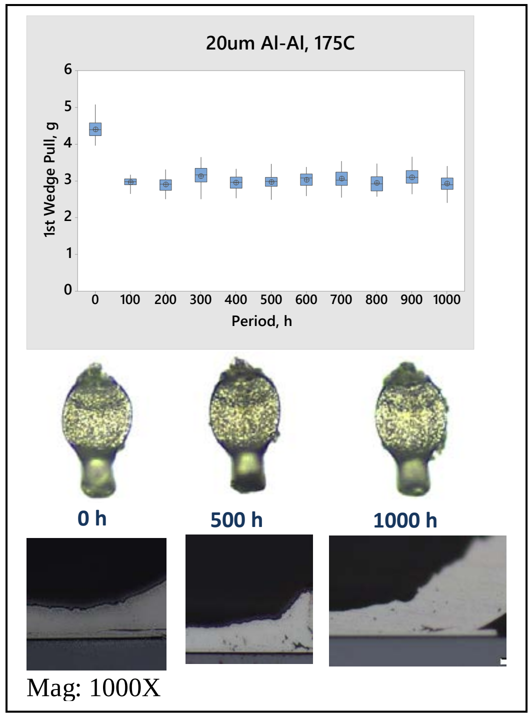


Fig.8 Thermal ageing of Al-Al (20µm) system.

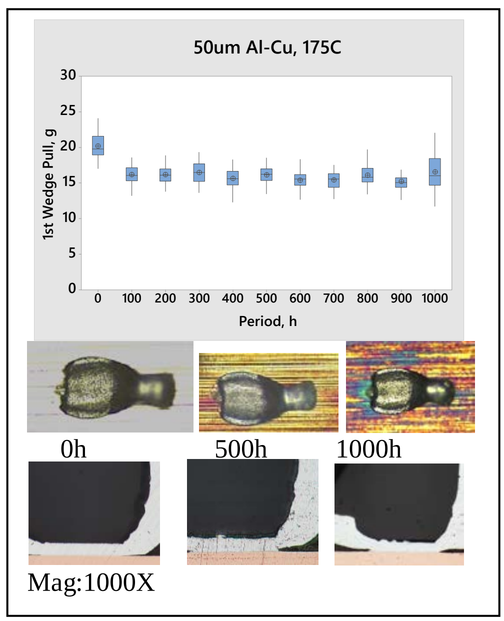


Fig.9 Thermal ageing of Al-Cu (50µm) system.

Thermal ageing of 50µm Al-1wt%Si wire welded to bare copper lead frame surface revealed stable wedge pull up to 1000h of storage at 175°C. Similar to 20µm wire bonds, 50µm wire bonds on wedge pull also drop after storing at an elevated temperature of 175°C due to grain structure changes and lowering the break load of the wire (Table.3, wire stored at elevated temperature and measured its tensile break load). The growth of copper aluminide to a thickness of about 0.8µm after 1000h of storage is observed at the interface. Kirkendall voids are absent at the interface, the behavior is similar to copper ball bond to Al bond pad [8].

III-d. Floor and Shelf life of Al-1wt%Si wire

Al-1wt%Si wire surface is prone for oxidation alike any 5N/4N aluminum wire and its thickness is expected to be in nanometer or sub-micron similar to aluminum bond pad surface [9, 10]. The aluminum wire surface oxidation is stable, does not grow at room temperature or elevated temperature say up to 70°C. Whereas, in high humid atmosphere or exposed to chlorine or sulfur or alkali rich environment [11], the surface aluminum oxide is expected to break and further corrode or thicken the oxide scaling. Usually, aluminum wire is sealed under atmosphere using plastic cover unlike copper wire which is usually vacuum sealed. Thus, similar to copper wire, floor and shelf life of aluminum wedge/wire is examined.

For floor life, 20µm Al-1wt%Si wire seal is opened and stored on the bonder for 30days and tested for wedge bonding. The wedge pull is stable until 7days and starts to vary slightly from 8th day onwards (Fig.10). The wire surface observed on SEM and EDX analysis showed clean wire surface without oxidation. Hence, floor life of aluminum wire is recommended as 7days, though no significant change is noticed on tensile properties until 30days.

For shelf life, sealed aluminum wires (without vacuum – 300µm 5N purity aluminum wire (Al-H11), 50µm Al-1wt%Si) stored in an air-conditioned room is examined every month for tensile break load and wedge pull. On the day of testing, the seal is broken and the wire is bonded for wedge pull measurement. Fig.10 shows stable wedge pull for 6months and a slight decrease on further storage. Hence, 6months is recommended as shelf life of aluminum wires, even though the tensile test showed no predominant variation up to one year of storage.

III-e. CWB of 20µm Au/Cu/CuPd/Ag Wires

The commercially available fine bonding wires of gold, copper and silver are examined by CWB method. The method is capable to CWB for all the tested 20µm wires (Fig.11) at room temperature. The wedge shape needs improvement which depends on the tensile properties of the wire and CWB process parameters. The elongation and break load of the tested wires are provided in Table.4, where the break load can be near to the value of Al wires or slightly higher. Fine tuning the tensile properties and CWB process optimization of individual wires revealed good wedge-wedge bonding. The 12 to 16% elongation copper wire used for ball bonding find difficult to tear by CWB after second wedge. Modifying the capillary tip and bonding at elevated temperature, perhaps creates a good bond heel.

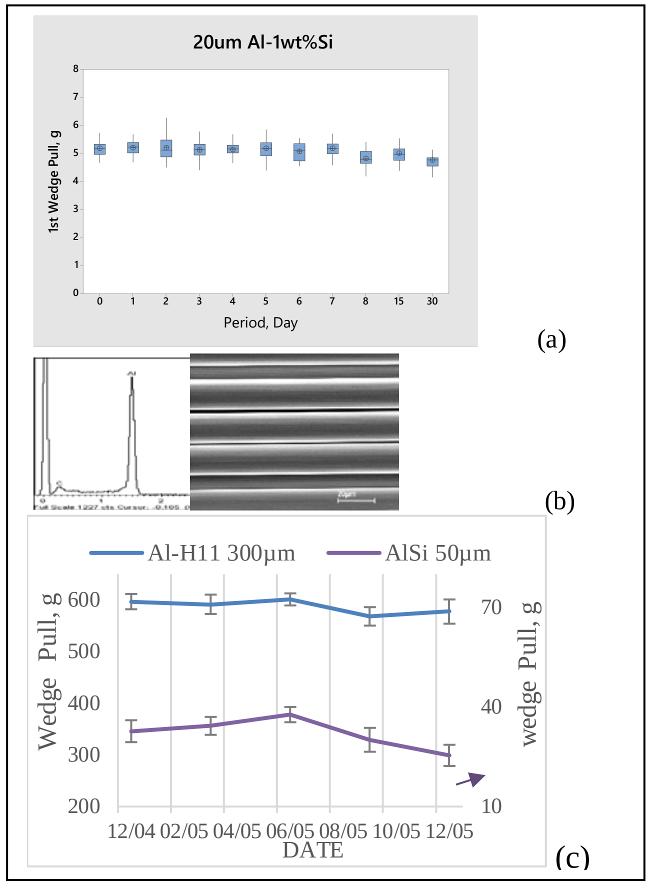


Fig.10 Floor and shelf life of aluminum wires: (a) floor life of 20µm Al-1wt%Si wire, (b) SEM-EDX analysis of Al-1wt%Si wire surface after 7days of floor life and (c) shelf life of Al wires.

Table.4 Mechanical properties of bonding wires tested for CWB.

20µm Wire	Elongation, %	Break load, g	Micro-hardness, HV
Al-1wt%Si	1 to 5	6 to 10	72 to 80
Coated Ag (C-Ag)	1 to 5	6 to 10	72 to 80
1N alloyed Ag (95.5% Ag)	6 to 10	6 to 12	70 to 80
4NCu	6 to 10	6 to 12	85 to 95
Pd coated Cu (CuPd)	6 to 10	6 to 12	90 to 105

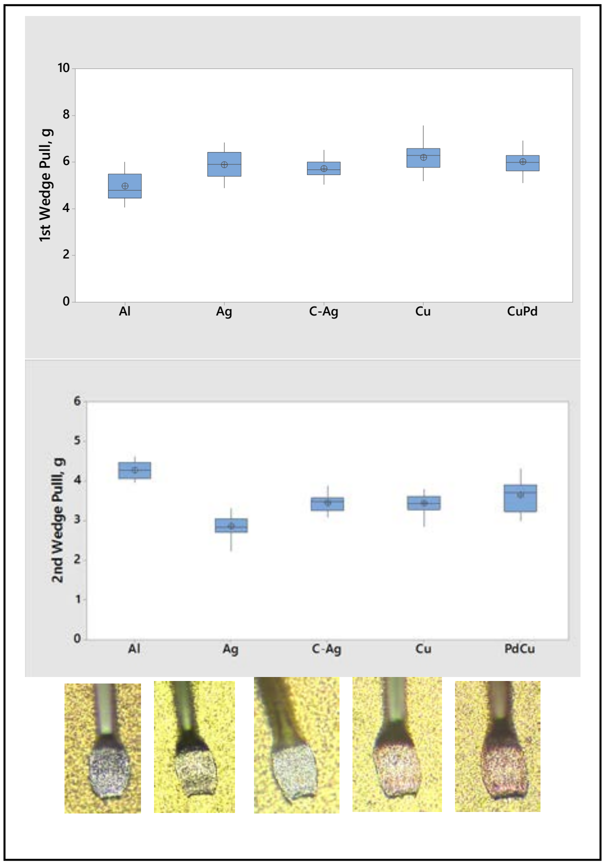


Fig. 11 Wedge pull and images of 1NAg, C-Ag, 4NCu and CuPd bonding wires

To summarize, fine Al-1wt%Si wire in the diameter range from 18 to 50µm is bondable by a new capillary wedge bonding (CWB) approach. The features of wedge bonding 1st and 2nd are well defined and feasible to be practiced as interconnects in semiconductor packaging devices. Aluminum wire bonded to aluminum bond pad and copper lead frame are stable on thermal ageing at 175°C for 1000h. Other copper and silver base (coated, alloyed, doped and bare) bonding wires are also feasible to bond on aluminum bond pad and gold plated surface by CWB. This feasibility study is encouraging and needs further detailed investigation on capillary tip geometry, process optimization, wire properties, elevated temperature bonding, etc., for high productivity chain bonding.

Acknowledgment

We sincerely thank Dr. Thomas Sven, Mr. Tok Chee Wei, Ms. Zaiton, Mr. Dick Juergen, Mr. Joshua, Mr. Eric Tan, Mr. Steven Wong and Mrs. Suhaila for their support.

References

[1] http://www.shinkawa.com/en/ir/library/pdf/annual/140814annual_report2014.pdf
[2] Yoshihito Hagiwara, Naoki Sekine, Koichi Takahashi, Yasuo Nagashima and Motoki Nakazawa, “Wire bonding apparatus and bonding,” U.S. Patent 0138426 A1, May 22, 2014.
[3] Naoki Sekine, Motoki Nakazawa and Yasuo, “Wire bonding apparatus and method of manufacturing semiconductor device,” U.S. Patent 0249063 A1, September 3, 2015.
[4] Naoki Sekine and Motoki Nakazawa, “Method of manufacturing semiconductor device and wire bonding apparatus,” U.S. Patent 0351535 A1, December 1, 2016.
[5] Naoki Sekine, “Wire bonding apparatus and method of manufacturing semiconductor device,” U.S. Patent 0351537 A1, December 1, 2016.
[6] Naoki Sekine, “Semiconductor device manufacturing method, semiconductor device, and wire bonding apparatus,” U.S. Patent, 0358880 A1, December 8, 2016.
[7] Yoshihito Hagiwara and Nobuo Takahashi, “Method for producing semiconductor device and wire bonding apparatus,” U.S. Patent, 0365330 A1, December 15, 2016.
[8] S. Murali, N. Srikanth and Charles Vath J III (2003b), “An analysis of intermetallic formation of Au and Cu ball bonding on thermal aging”, Mater Res Bull, vol. 38, pp. 637–646.
[9] H. Xu, C. Liu, V.V. Silberschmidt, S.S. Pramana, T.J. White, Z. Chen, V. L. Acoff, “Behavior of aluminum oxide, intermetallics and voids in Cu–Al wire bonds,” Acta Materialia, vol. 59, 2011, pp. 5661–5673.
[10] H. Xu, C. Liu, V. V. Silberschmidt, Z. Chen, J. Wei and M. Sivakumar, “Effect of bonding duration and substrate temperature in copper ball bonding on aluminium pads: A TEM study of interfacial evolution,” Microelectronics Reliability, vol. 51, 2011, pp. 113-118.
[11] Mars G. Fontana, *Corrosion Engineering.* Singapore: McGraw-Hill International Editions, 1987, 3rd Edition.