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Fundamentals of thermo-sonic copper wire bonding in microelectronics packaging

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Abstract Fine copper wire bonding is capable of making reliable electrical interconnections in microelectronic packages. Copper wires of 0.8–6 mil diameter have been successfully bonded to different bond pad metallized and plated substrate materials such as Al, Cu, Ag, Au and Pd. The three metallurgical related factors; solid-solubility and diffusion of dissimilar contact metals, oxide film breakage and plastic deformation of asperities play a critical role in the bonding. Plastic deformation of an asperity is the most significant factor one has to consider to attain good bonding. Soft aluminum metal (30–40 VHN), with a lower % asperity threshold deformation is easier to wire bond than harder metallic surfaces (Ni, W, Mo, Cr, Co, Ta) of 150–500 VHN. Good adhesion of wire bonding is achieved for the surface roughness (Ra) of 0.01–0.15 μm and 0.02–0.6 μm of bare and plated surfaces respectively. It is rationalized that the application of ultrasonic energy principally breaks the oxide film and deform the asperities, while a compressive force increases the proximity of asperities. Hence wire welds to bond pad surface by molecular attraction and inter diffusion. Storage of copper ball bonds at 175 °C for 100–1,000 h forms copper aluminide at the interface. EDAX and Auger analysis reveal 22 at% Al + 78 at% Cu composition of the aluminides and Cu_3Al_2 empirical formula is calculated, which, does not match with any of the reported copper aluminides. Hardness of the copper ball bonds and stitch bonds are higher than wire exhibiting work hardening of the bonds on processing.

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Introduction

Thermosonic bonding of thin metal wires between bond pads and lead fingers are a common practice in microelectronics packaging industries. Gold wires are largely used in the package. Cu, Pd, Al and Ag metallic wires have been investigated as an alternative to gold wire. However, copper is the prominent material studied to attain a reliable bond. High electrical conductivity, high modulus and the lower cost of copper wire with respect to gold wire are the drive for employing the copper wire bonding technique into IC device production. First, an axi-symmetrical free air ball (FAB) is formed by electrical sparking under a preventive atmosphere. Usually $Ar + 5–10\%H_2$, $N_2 + 5–10\%H_2$ and high purity nitrogen gases are used to create a protective environment. Atsumi et al. [1] observed that Auger analysis revealed extremely low oxidation and a smooth surface by scanning electron microscopy (SEM) when the copper ball is formed under $Ar + 10\%H_2$ shielding gas. The oxide free copper FAB is made to fuse to different metallized and plated surfaces such as Al, Cu, Ag, Au and Pd. The first bonding of the FAB to the bond pad is called ‘‘ball bonding’’. Further connection of the wire to lead frame finger surfaces are referred to as ‘‘stitch bonding’’. Therefore, copper thermosonic wire bonding can be considered as a solid-state welding of two similar or dissimilar metals on the micron scale. The two metal surfaces are bonded with the assistance of compressive force and ultrasonic energy at elevated temperatures. Surface deformation developing frictional forces and inter diffusion between the two metallic surfaces will take place.

A decade ago Patel and Livesay [2] showed that copper wire of 1 mil (25 micron) size can be ball bonded to aluminum metallized pads and wedge bonded to gold plated lead frame fingers. Shear strengths of copper ball bonds were better than gold ball bonds. ST Riches and NR Stockham, private communication have developed consistent copper wire (0.68 mil, 1 mil and 99.99% purity) bonds connecting aluminum thin film bond pads to gold and copper thick films over alumina surfaces. Environmental test at 200 °C for 1,000 h reveal reduction in shear and pull test of ball and wedge bonds respectively. The loss in strength was anticipated due to oxidation of copper wire and no sign of intermetallic growth was observed. Mori et al. [3] investigated high purity copper wire of 6 N (99.9999%) electrolyzed and zone refined cold drawn and tempered wires. The hardness of the 6 N copper wire was 52 VHN. Some dopants were added to further reduce the hardness to 48 VHN. Both types of wire have been used to bond the aluminum pad and bare copper lead frame surfaces of Cu–0.3Cr–0.1Zr–0.05Mg–0.02Si alloy. Various reliability tests showed no degradation of mechanical or electrical characteristics of the device on copper ball bond and stitch bond interconnections [1]. Kurtz et al. [4] also demonstrated similar advantages of copper wire bond. Murali et al. [5] have investigated 1 mil, 2 mil and 3 mil copper ball bonds and mentioned that ball bonds get work hardened due to supply of ultrasonic power and compressive force during bonding. Although, the process of copper wire bonding is established and IC's are being manufactured the basics of copper wire bonding to different metallic surfaces are less understood. Therefore, the present paper discusses the important metallurgical factors that control copper wire bonding to attain good joining.

Experimental details

Copper bonding was done in ASM automated wire bonder AB339 Eagle™. Unannealed DHF copper wires of 0.8, 1, 2, 3, 4, 5 and 6 mil sizes and 99.99% purity were used for the study. Copper wire was ultrasonically bonded to metallized bond pad of aluminum and gold of 1 μm thickness. Thicker copper wires (3–6 mil) were bonded to 3–5 μm thick metallization pads to avoid cratering of the die. While, on lead frame fingers the copper wires were bonded to 4–5 μm thick silver plated surfaces. Thickness of other plated (Au, Cu, Pd–Ni) surfaces was between 0.15–1 μm. A gold flash of 50–80 Å was given over palladium–nickel plated fingers.

The FAB was made by controlling the electric flame off (EFO) parameters to the value of 40 mA current, 4.5 kV gap voltage and 0.7 ms time. In the case of thicker copper wire higher current and longer time were employed to form the ball. High purity N_2 or $N_2 + H_2$ gas mixture in the ratio of 95:5 was used with a flow rate ranging between 0.4–1.5 l/min to prevent oxidation during ball formation. Ball bonding of 0.8 and 1 mil wire sizes was done by varying the process parameters; compressive force of 25–46 gf, within 8–10 ms time, ultrasonic power of 110–130 mW and impact velocity of 8–10 mm/s. The stitch bonding was done at varying force of 45–70 gf, 12–14 ms time, ultrasonic power of 350–399 mW and impact velocity of 15–20 mm/s. Temperature was maintained between 175 and 200 °C during bonding at a 138 kHz ultrasonic frequency. Thicker 2–6 mil wires were bonded similarly by employing higher compressive force (220–800 gf) and ultrasonic power (240–700 mW for ball bond and 700–2,000 mW for stitch bond). The ball was formed using same voltage but with higher current of 100–120 mA.

The surfaces were analyzed by Auger electron spectroscopy, X-ray photoelectron spectroscopy (XPS), time of flight-secondary ion mass spectroscopy (TOF-SIMS) and energy dispersive X-ray analysis (EDAX) for surface contaminations and oxide layer growth. Surface roughness was measured using ZYGO profiler 5000. Cross-sectioned samples were observed with an optical microscope, Olympus BX60, and a scanning electron microscope (SEM), LEO Stereo-Scan 440. The metallographically prepared epoxy molded specimens were sputter coated with gold to observe in SEM. Micro hardness was obtained by applying less than 5 g load using 136° indentor angle utilizing Mitutoyo Muk-H3 Vicker's hardness tester.

Results and discussion

The important factors that control metallurgical bonding of two similar or dissimilar metallic surfaces are; solid-solubility of the metals that contact, oxide film breakage, plastic deformation of asperities, surface roughness and temperature at which bonded. The effects of these factors to attain good copper wire bonding are discussed in the forthcoming paragraphs.

Solid-solubility of copper to various metallic surfaces on bonding

Bonding dissimilar metals depends on the solubility of the elements that contact each other. Generally, joining of two metals including thin films are classified in to two types; with and without intermediate phase formation. If an intermediate phase forms then the contact elements inter-diffuse freely with less hindrance. From the binary equilibrium phase diagrams one can understand the intermetallic and solid solution formation between two elements mixed for varying proportions and temperature [6]. The possible thin metallic coatings in IC device to which copper wire bonding can be practiced are Al, Ag, Au, Pd, Pt, Ti, Ta, Ni and Si elemental surfaces.

Aluminum is soluble in copper to as high as 17 at%, forming a solid solution [6] even at a low temperature of around 300 °C. At higher mixing concentration many meta stable and stable intermediate phases such as α, β, θ, γ, ζ, η and ε form. Hence, diffusion between copper and aluminum should be less constrained. However, in non-equilibrium process conditions formation of second phases depends on the concentration and time-temperature of joining.

Silicon is soluble in copper at 852 °C to a maximum of 11.25 at% and at lower temperatures the solubility level decreases [6]. Even at low temperatures, many intermetallic compounds can form within the range of 11–25 at% Si. Mostly aluminum bond pad metallization contains 1 wt% Si, since aluminum and silicon are immiscible they will form a eutectic. During copper ball bonding the silicon particles have a chance to form solid solution or compounds at the copper interface. But, no evidence of them is observed at microscopic level. Moreover, copper ball bonding to polycrystalline silicon deposits or bare silicon wafer are not practiced currently.

Gold is soluble in copper for all proportions from zero to 100% of mixing ratios at temperatures above 400–500 °C [6]. At lower temperatures, CuAu and Cu_3Au ordered compounds form in a range of mixing of 40–80 at%. Au_3Cu forms by peritectoid reaction on the gold enriched side of 60 at% Au. Therefore, inter diffusion between copper and gold might take place without difficulty. Elements palladium and platinum behave in a similar manner to gold.

Silver and copper form an eutectic at 780 °C and at 40 at% copper and are immiscible at low temperatures <200 °C. No intermetallics form between the binary system for the entire composition of mixing ratios [6]. Poor solubility at low temperature might be due to differences in atomic size and electronegativity factor. Nickel is soluble in liquid copper and at high temperatures form solid solutions in all proportions of mixing ratios. While at 354.5 °C and lower temperature and at 67.3 at% $\alpha 1$ and $\alpha 2$ phases form. A miscibility gap is mentioned in the Ni-rich side (70 at%). Unlike gold, nickel, silver and silicon atom movement may be hindered in copper wire. Therefore, solid state welding of copper to gold, aluminum, palladium and platinum elements should be comparatively easier than bonding copper to silver, nickel and silicon elements. Nevertheless, elemental solubility of two metallic surfaces alone is not a deciding factor on bonding [7] and the role of other metallurgical factors on bondability has also to be considered.

Effect of oxide layer and surface contaminants on bondability

Gold is an inert metal by nature and probably free of oxide. Other than gold all other elemental surfaces such as Cu, Al, Ag, Pd, Ni, Cr, Ti will form oxide at the surface [7]. Metals exposed to atmosphere at room temperature form an oxide film thickness of 20–100 Å [7]. Increases in temperature will thicken the film. Ball and stitch wire bonding are practiced at 125–225 °C and the samples are held at about this temperature range for a minute or less. Therefore, one can anticipate no predominant growth of the oxide film. Auger analysis of aluminum metallized bond pad surfaces clearly revealed (Fig. 1) an oxygen peak. Depth profile analysis using SIMS's on bare copper lead frame surface identified a copper oxide layer of 2.4 nm thickness (Fig. 2). The oxide layer thickness was calculated from the depth versus oxygen concentration plots to 10% of its peak reduction. Both, aluminum and copper surfaces possess good bondability, Aluminum/copper oxide films exist on the surfaces before joining, however, they are broken in the course of wire bonding. On a bare copper lead frame surface a copper oxide layer thicker than 2.4 nm made it difficult to stitch bond the copper wire.

Hard oxide layers such as aluminum oxide (alumina, 1800 VHN) seen on aluminum are comparatively more difficult to break than soft metallic oxide layers (Table 1) [7–9]. During wire bonding, supplied ultrasonic energy displaces the capillary by ~8 μm, hence first the FAB scrubs the surface breaking the oxide layers (aluminum oxide, copper oxide, silver oxide etc.). Even the oxide film on the FAB and wire surfaces will be broken in order to weld.

Deposits of carbon, fine dirt, epoxy out gassing, fluorine, sulfur etc., are some of the contaminants generally found on the metallized bond pad (aluminum, gold) and plated lead frame finger (silver, copper,

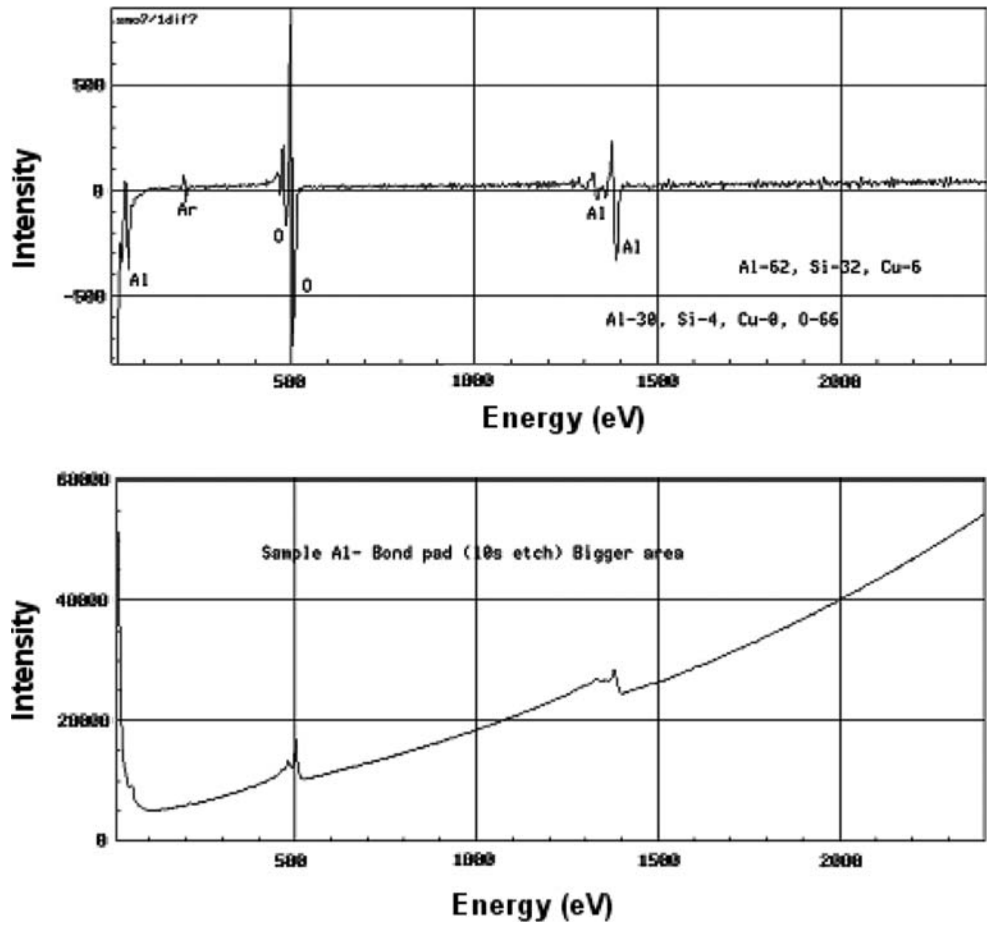

Fig. 1 Auger spectroscopy analysis of aluminium bond pad metallisation surface

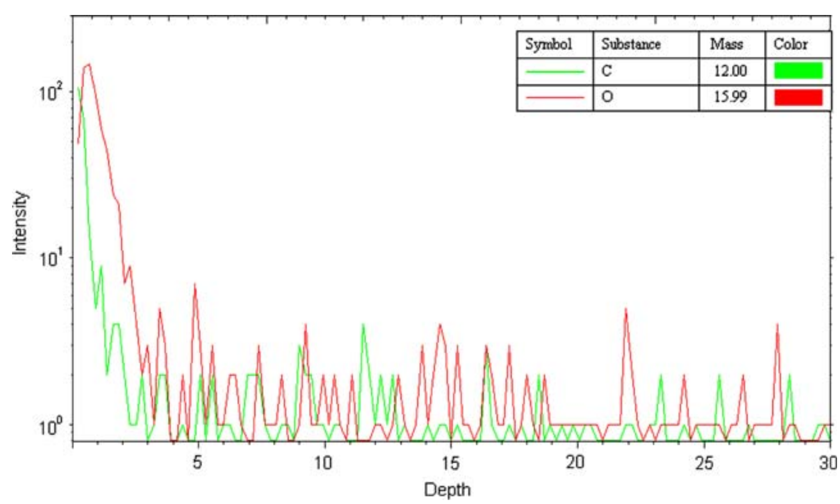

Fig. 2 SIMS depth profile analysis of bare copper lead finger surface

gold, palladium) surfaces [10]. Figure 3 shows an example of poly dimethyl siloxane (commercially termed as silicone) deposition on the Pd/Ni plated lead frame finger surface with gold flash. Deposition of the compound causes the non-stick on lead (NSOL) problem. The analysis was conducted using XPS and TOF-SIMS on the top 5 nm of the surface.

Surface roughness and plastic deformation of asperities of bondable surfaces

Before gold ball bonding and aluminum wedge bonding the surfaces were cleaned by different methods that produce roughness in the range of 1–10 μm and these surfaces influence bondability [10]. However, presently

Table 1 Mechanical properties of pure metals and their oxide layers [7–9]

Metal	Vickers hardness, VHN (Kg/mm^2)	(Asperity) threshold def. (%)	Tensile strength, MPa	Surface oxide	Oxide hardness, VHN (Kg/mm^2)
Indium (In)	<10	10	3	In_2O_3	800
Lithium (Li)	<5	10	–	Li_2O	110
Thallium (Tl)	5	20	8–9	Tl_2O	35
Bismuth (Bi)	19	10 (95 °C)	5–20	Bi_2O_3	450
Lead (Pb)	4	17	18	PbO	23
Tin (Sn)	7.2	20	15	SnO	380
Cadmium (Cd)	23	15	64	CdO	80
Magnesium (Mg)	35–45	>40	190–260	MgO	550
Aluminum (Al)	35–48	40	47–66	Al_2O_3	1800 (2600)
Lanthanum (La)	40	–	–	La_2O_3	–
Gold (Au)	20–60	–	131	–	–
Titanium (Ti)	60–90	–	250	TiO_2	(713–1121)
Copper (Cu)	49–87	78	217	Cu_2O	160
Iron (Fe)	60	81	200–310	Fe_2O_3	670
Silver (Ag)	25–95	–	142–180	Ag_2O	135
Platinum (Pt)	40–100	–	127–253	Pt_2O_3	–
Palladium (Pd)	37–100	–	190–330	PdO	–
Zirconium	85–100	–	300	ZrO_2	(1019–1121)
Niobium (Nb)	115–160	–	287–920	NbO	–
Nickel (Ni)	45–220	89	315–493	NiO	480
Tantalum (Ta)	90–200	–	207–472	TaO	–
Chromium (Cr)	90–220	–	83–420	Cr_2O_3	(2955)
Molybdenum (Mo)	187–250	–	517–1300	MoO	–
Cobalt (Co)	104–320	–	400–703	CoO	–
Tungsten (W)	360–500	–	840–1300	WO	–
Silicon (Si)	254	–	–	SiO_2	(1103–1300)
Yttrium (Y)	45–127	–	132–459	Y_2O_3	–
Vanadium (V)	55–180	–	–		–
Zinc (Zn)	30–45	–	40–113	ZnO	250

in microelectronic packaging industries, bond pads are metallized (aluminum or gold) to micro or nano-roughness levels. Measurement of surface roughness (Ra) of hundreds of aluminum and gold metallized surfaces lies within the range of 0.03–0.08 μm and bonding to this smooth surface does not cause a problem.

Surface roughness of plated lead frame fingers or to bare copper lead frame fingers to which copper wire will be stitch bonded varies largely. Ra measured for these surfaces vary between 0.02 and 1.34 μm. A typical lead frame surface roughness measured in a Zygo profiler is shown in Fig. 4. For Au, Cu, Ag and Pd plated surface roughness of up to 0.5–0.6 μm exhibited good bonding. Furthermore, an increase in the roughness causes NSOL resulting in poor bondability. The failure rate increases when Ra value is close to or above 1 μm. Considering bare copper lead frame, Ra greater than 0.15 μm causes NSOL. However, smooth surfaces of 0.02–0.15 μm Ra show stitch bonds attaining at least 5 gf breaking load. Roughness measured on the copper FAB spherical surface and wire surface reveal around 0.17–0.55 μm Ra. No literature so far provides the critical Ra value of the surfaces for wire bonding.

Surfaces are assumed to consist of hills and valleys and the asperities contact are important for joining [7]. Bhushan [11] in his modeling analysis of contact mechanics of rough surfaces mentions that when two surfaces with micro roughness come in contact, the contact happens at multiple asperities of arbitrary shapes, varying sizes and heights. Deformation at the asperity contact can be elastic or elastic-plastic. Rabinovich et al. [12] in their modeling of adhesion force prediction of 10 nm rough surface and particles considered the interaction between particles and asperities (contact forces) while, ignoring the interaction of the particles with the underlying surfaces (non-contact forces). Mann and Pethica [13] in their study on nano-contacts explained that nano-indentation at a speed of 10 nm/s deformed nanometer scale asperities in GaAs (100) sample. Hence, asperity deformation even at nanometer level is important for adhesion of two metal surfaces in contact. Asperity deformation behaviors

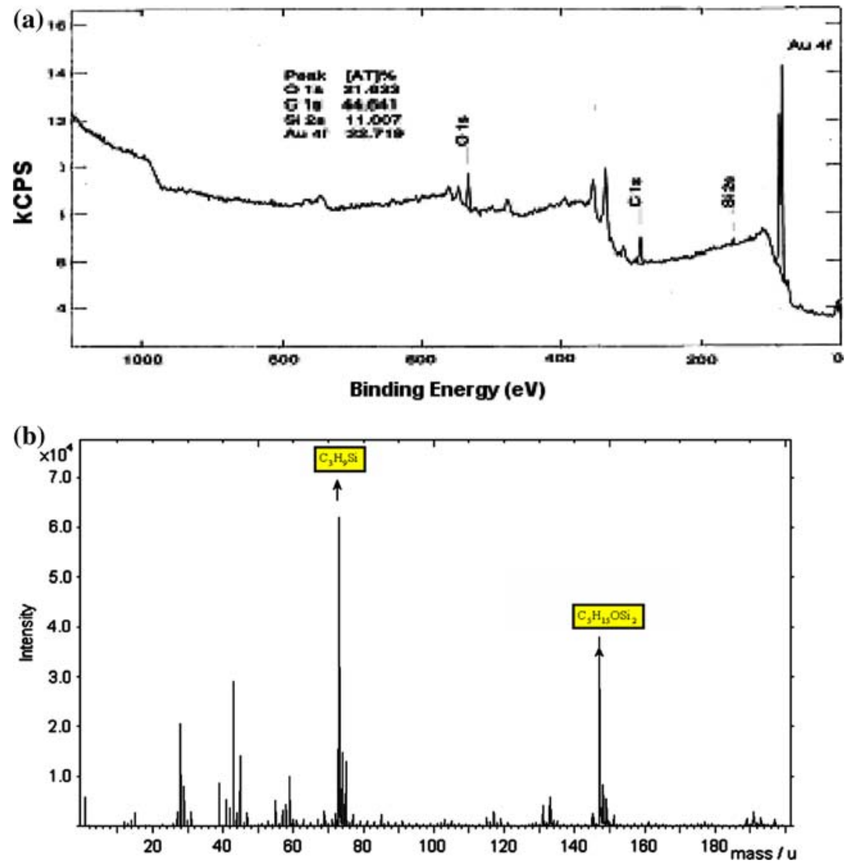

Fig. 3 (**a**) XPS and (**b**) SIMS elemental analysis on the Pd/Ni plated lead frame surface with gold flash. Strong peaks of two of the molecules of poly dimethyl siloxane are evident in SIMS analysis

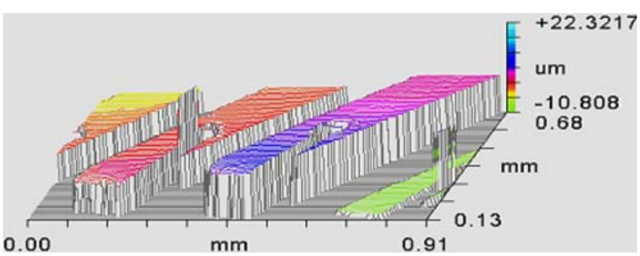

Fig. 4 Surface roughness (Ra = 0.15–0.194 μm) measured on the silver-plated lead frame fingers using Zygo surface profiler

are explained [14] by models such as wear model, smearing flattened asperities, flaking, and chip cutting, in copper wire bonding all of the possible models can be active.

An earlier investigation [7] on roll-bonding defined that asperity deformation is required to initiate welding. Below the threshold deformation of asperity, welding does not take place. The threshold deformation for aluminum is 40%, while only 1% or less deformation is needed to crack the oxide film [7]. Hence, oxide film can be easily broken by the supplied energy when two surfaces contact each other. Table 1 consolidates the hardness and tensile strength of some pure metals, threshold deformation of certain metals and hardness of some oxides as presented in Table 1. When purity of the metal changes the hardness of the metal varies widely, for example nickel of 99.99% pure has a hardness of 90 VHN while slightly less pure of 99.4% posses a hardness of 220 VHN (hard metal). No correlation between hardness of the oxide layer and threshold deformation of the metals are evident (Table 1). However, to some extent correlation between hardness and threshold deformation of the metals are observed. The threshold deformation relates to asperity threshold deformation. The softer the metal the lower the % threshold deformation, therefore, qualitatively the hardness of metals can be compared to threshold deformation of the metals since limited data on threshold deformation is available in the literature.

The hardness of the copper wires used is within 65–85 VHN and FAB also exhibited the same hardness. Bond pad metallized with aluminum is softer (32–40 VHN) than gold, copper, silver plating of 50–70 VHN. While, the hardness of the package lead frame finger with 25–50 nm gold flash on 0.2 μm palladium coating over nickel plating was 210 VHN.

Supply of ultrasonic energy and compressive force during wire bonding breaks the thin oxide layer and plastically deforms the asperities of the plated and metallized surfaces. Perhaps, ultrasonic energy dominates over compressive force when breaking the oxide layer and deforming asperities. While, compressive force increases the proximity of the asperities. Thus, it is molecular attraction between the frictionally deformed solids that leads to inter-atomic diffusion bonding that causes the FAB/wire to adhere to the metallized or plated surfaces. Hence, both the applied sources of energy play a critical role in copper wire welding. Soft metal surface asperities will easily deform but hard metal surface asperities are difficult to deform. Even FAB and wire surfaces oxide film will break and asperities deform to weld. In the process of wire bonding; a spherical FAB deforms to a bell shape, round wire deforms into a fish tail shape and metallized bond pad aluminum squeezes out from the edges (Fig. 5a).

With an Ra of 0.02–0.15 μm the bare copper surface can deform and weld, while, the rough surface with Ra >0.15 μm may need enormous ultrasonic energy to deform the asperity and weld the surface. In the case of plated surfaces during the application of ultrasonic energy and compressive force, the surface plastically deforms (flow) revealing squeeze out of metals. Hence, the plated surface can tolerate up to 0.5–0.6 μm roughness and still deform and bond to the surface. Again, rougher plated surfaces with a Ra of 1 μm needs an enormous amount of ultrasonic energy to deform the asperities to bond.

Influence of temperature on wire bonding

Thermosonic bonding is performed in a temperature range of 175–200 °C. Some organic substrate packages are bonded at 100–125 °C. Ultrasonic contact (rubbing) of the two surfaces will also produce heat. But, the information as to what level the bonding surfaces are heated up is unknown. However, the bonding at elevated temperature benefits in the following ways;

- Softens the metal surface oxide layers so they crack at lower loads.
- Softens the metals, especially plastic deformation of asperities will be easier.
- Improves the atomic diffusion and solubility of the metals at the interface.
- Provides additional energy other than thermal and pressure to aid wire bonding.

Copper bonding to gold is easy because (1) both the metals are diffusible in to each other, (2) no oxide layer exists on gold surface and (3) gold is soft and highly malleable. Similarly, copper bonding to aluminum surface is comparable due to softness of metallized aluminum and good diffusion of both of elements. However, care has to be taken not to form a thick aluminum oxide film since it is a hard oxide. Even though, copper and silver are immiscible and inter diffusion of the two atomic species is not clear, (1) the low hardness of the pure silver plating and (2) soft silver oxide growth on the surface makes

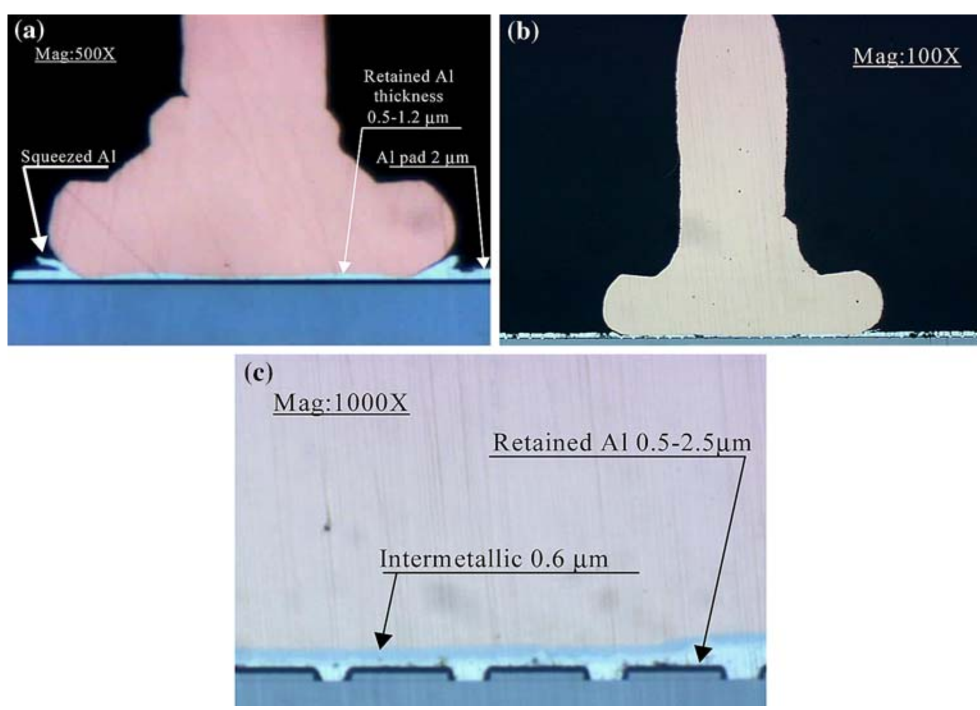

Fig. 5 Microstructures of copper ball bonding for the conditions (**a**) 0.8-mil wire, (**b**) 4 mil wire and thermal aged for 1,000 h at 175 °C and (**c**) at a higher magnification of (**b**)

copper wire bonding on silver plated surfaces a feasible process. From the present observations copper wire can also be bonded to other soft metals such as Mg, La and Ti.

In the case of copper wire bonding to a nickel plated surface, the bonding may be difficult because; (1) diffusion of the metals may be slightly difficult, (2) surface oxide is moderately hard and (3) hardness of nickel metal is high at 200–220 VHN (asperity threshold deformation of nickel is also very high). Therefore, copper bonding to other hard metallic surfaces Mo, Co, W, Cr and Zn may also be difficult. If the temperature of the plated finger surface is raised say to greater than 400 °C, one may achieve the wire bonding to the hard metallic surfaces too. But, IC devices have their own limitations with respect to processing at temperatures of 400 °C and above. High magnitude of ultrasonic power can deform hard metal surface asperities and facilitate welding.

Intermetallic phase formation at the bond interface

Except copper FAB bonding to silver, other metals such as Al, Au, and Pd have a high chance of forming intermediate phases. Thermal aging thickens the intermetallic compound; however, growth of intermetallic compound strengthens the bond. Murali et al. [15] in an investigation of copper ball bonding of 1 mil wire to Al–1 wt% Si–0.5 wt% Cu metallized bond pad mention intermetallic compound formation was absent. Even thermal aging for periods up to 5 h at 175–200 °C does not show growth of the intermetallic compound. The difference in atomic radii between copper and aluminum atoms of up to +10.5% misfit can hinder the atom movements along the interface leading to incomplete solid solubility and no growth of copper aluminides [15]. However, Tan and Abdul [16] have studied, copper ball bonding of 2 mil wire to Al–1 wt% Si bond pad, and observed intermetallic growth on aging the ball bonds at 150–200 °C for 100–1,000 h.

Studies on aging at 175 °C for 100–1,000 h of the copper ball bond made using 4 mil wire size to Al–1 wt% Si–0.5 wt% Cu alloy metallized bond pad found a thin layer of copper aluminide growth at the interface. Cross-section of the ball bonds revealed growth of the intermetallic to 0.6–1 μm thickness (Fig. 5 b, c). Dissolving the aluminum in 20% NaOH solution and analyzing the ball bond interface by Auger depth profile showed the formation of intermetallic up to 0.6 μm (Fig. 6). EDAX and Auger elemental analysis revealed 22 at% Al + 78 at% Cu composition of the aluminide; this corresponds to Cu_3Al_2 which does not match to any of the reported copper aluminides. The formula was calculated as per the standard procedure [17].

Work hardening of copper ball and stitch bonding

The hardness of the copper wires used in the industries is between 65–85 VHN. After bonding the ball bonds and stitch bonds possess hardnesses of 95–115 VHN and 110–130 VHN respectively. The application of ultrasonic energy during the joining process work hardens the copper bonds. A typical example of micro hardness measurements on 6 mil copper ball bond and stitch bond are shown in Fig. 7. All the size of the wires from 0.8 to 6 mil diameter reveals the same behavior. Observation of slip bands, micro bands and deformation cells (sub-grains) probably created by the application of ultrasonic energy are attributed to the work hardening of ball bonds [5].

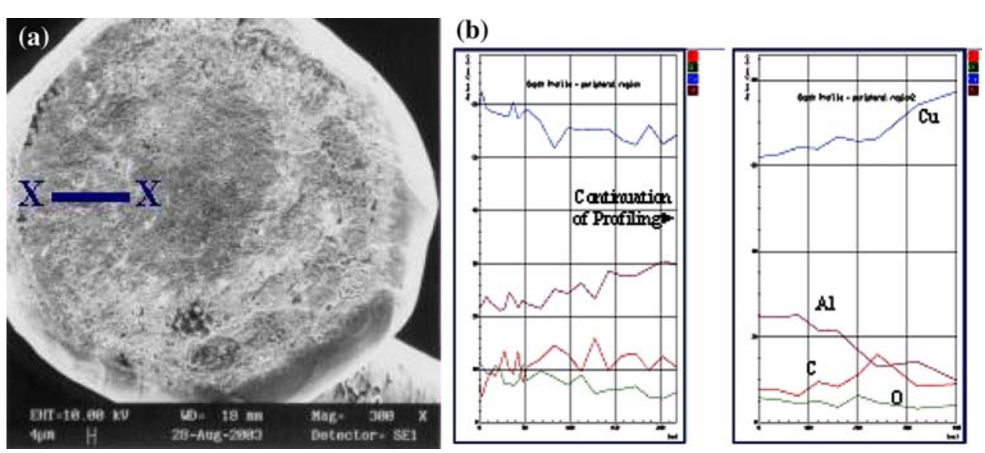

Fig. 6 Auger depth profile analysis at X-X section of the 4 mil Cu ball bond at the peripheral region. Presence of Al up to 620 nm depth is evident

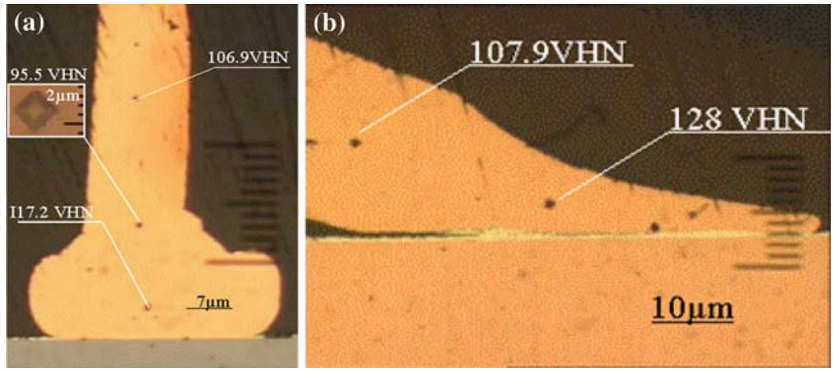

Fig. 7 Micro hardness of the (**a**) copper ball bond and (**b**) stitch bond of 6 mil diameter wire

Conclusions

(a) The bonding of copper is becoming a mature process similar to gold wire bonding. Copper wires of 0.8–6 mil sizes were successfully used for interconnections. The wire was bonded to Al, Cu, Ag, Au and Pd metallized or plated surfaces.

(b) Three metallurgical factors, solubility of dissimilar metals, oxide film breakage and plastic deformation of asperities play a critical role on the bonding. Asperity of plastic deformation is the most significant factor to attain good bonding. Softer metals like Al (30–40 VHN) with lower % threshold deformation are easier to wire bond than harder metallic surfaces (150–500 VHN). Even, hard oxide layers such as alumina will be broken at low energy.

(c) Surface roughness (Ra) of 0.02–0.6 μm for plated lead frame finger surfaces and 0.01–0.15 μm for bare copper lead frame finger surfaces provide good adhesion and bondability.

(d) Supply of ultrasonic energy cracks the oxide films and deforms the asperities. Simultaneously compression of the bonds increases the proximity of the asperities. Therefore, molecular attraction and interdiffusion at the interface takes place welding the smashed copper ball to bond pad surfaces.

(e) Thermal aging of copper ball bonds at 175 °C for 100–1,000 h form copper aluminide at the interface. Auger depth profile and cross-section of the ball bonds reveal 0.6–1 μm thickness growth. EDAX and Auger analysis of the compound show 22 at% Al and the rest copper giving an empirical formula of Cu_3Al_2 which does not match with any of the reported copper aluminides.

(f) Micro hardness of the copper ball bonds and stitch bonds are higher than the copper wire indicating that bonds get work hardened in the process of thermosonic bonding.

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