What is the future of bonding wire? Will copper entirely replace gold?

C. D. Breach
www.goldbulletin.org

Abstract

Thermosonic ball bonding is a major interconnect process in microelectronics packaging and is positioned to remain one of the key process technologies available to package designers in the near future. However, the main wire material used in fine pitch (FP) and ultra-fine pitch (UFP) ball bonding is gold and with significant increases in gold price, gold ball bonding has become a more costly process that has a considerable economic effect on the assembly of packages used in consumer electronics. An alternative wire material to gold is copper, which is much cheaper and has several technical benefits including better electrical conductivity and has been widely used in discrete and power devices with wire diameters typically larger than 30µm in diameter for many years. However, copper wire behaves quite differently than gold due to its different physical properties, some of which are beneficial and others detrimental to bonding performance. In this article, we briefly review some of the advantages and difficulties with using copper wire advanced packaging and explain why copper cannot replace gold in many applications and why gold offers significant benefits.

ProMat Consultants, 160 Lentor Loop, #08-05 Tower 6, Singapore 789094
E-mail: cbreach@promat-consulting.com

1 Introduction

A significant number of managers and engineers in the microelectronics packaging assembly industry when asked the question that is the title of this article would probably reply 'yes' with little or no hesitation. Copper is generally cheaper, has better electrical conductivity and copper-aluminium intermetallics grow very slowly thereby giving the impression that copper wire on aluminium metallisation is more reliable. However, copper wire bonding has been around a long time and while it has been used a great deal for larger diameter wires (>30µm) in power and discrete devices, there is a question that needs to be asked. *If copper is so good as a bonding wire, why didn't it replace gold in all mainstream applications 30 years ago?* This article attempts to provide some answers to the question about copper's lack of gross replacement of gold by presenting a mini-review of copper and gold bonding wire performance in microelectronics spanning the past 25 years.

As this article goes to press, feedback from process engineers and managers trying to implement robust copper wire bonding processes in place of gold is that implementing copper ball bonding in mass production is not as straightforward as many laboratory scale studies would suggest. A recent industry survey by SEMI [1] confirms the semiconductor industry's top concern over the use of copper wire is in-service reliability. There are two main issues: firstly getting a bonding process that is repeatable with plastic packaged devices so that copper wire can be implemented more widely on more advanced packages. Secondly, there are reliability problems with copper ball bonds on lead frame and plastic packaged devices that perform poorly in temperature cycling (TMCL) and show less than optimum performance in pressure cooker tests (PCT). However, the fact that copper is not a drop-in replacement for gold wire used on devices currently

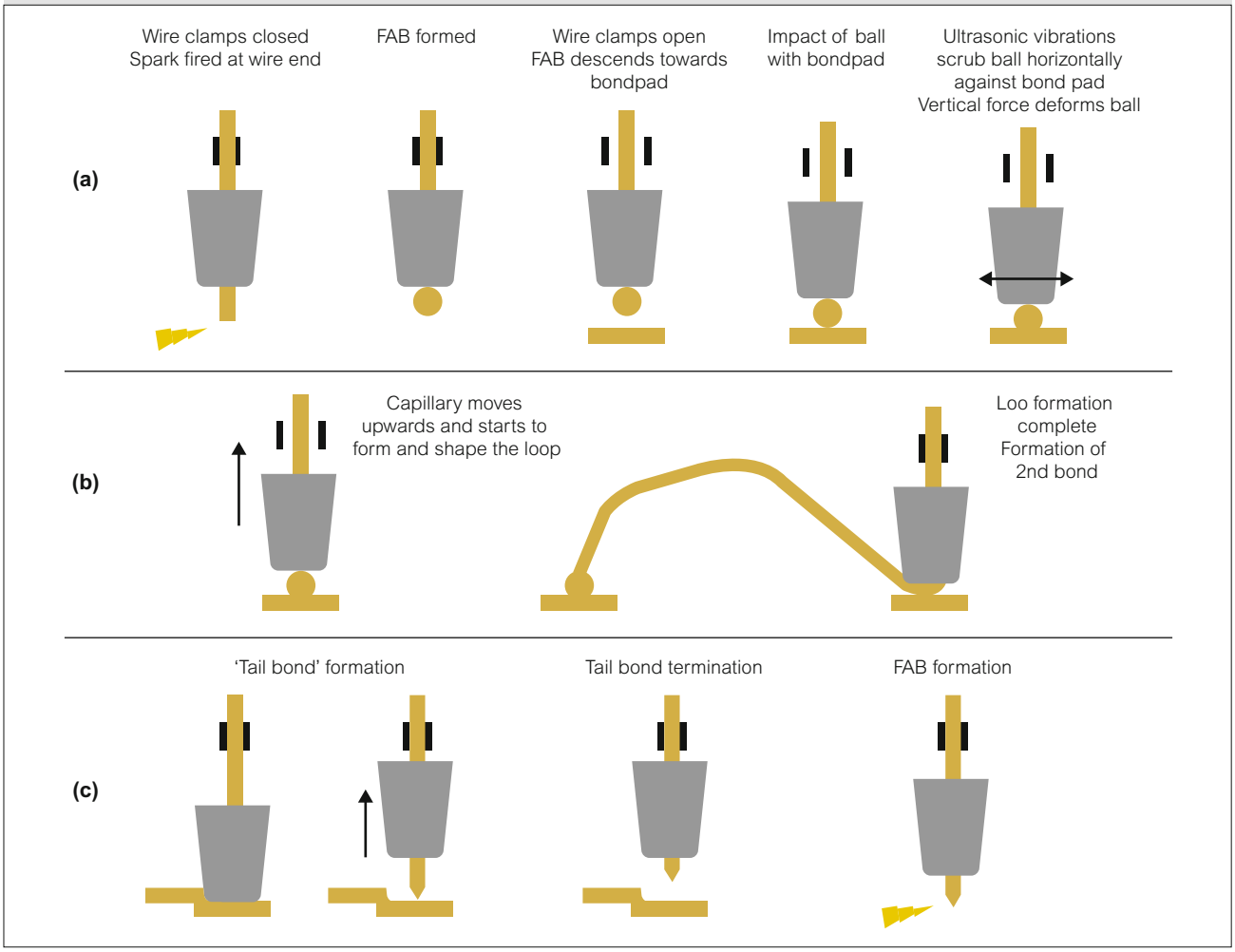
in mass production should not come as a surprise to the many competent materials scientists, physicists and chemists working in the semiconductor industry, who know that copper has quite different physical behaviour to gold and that wire bonded devices have always been designed for easily-bondable gold wire. They are also aware that copper will find its niche and will inevitably and justifiably replace gold in some microelectronics packaging applications but probably not all.

The objective of this article is to be 'objective' in assessing the benefits of gold and copper wire and to provoke thought about how and when each material should be used in microelectronics packaging. It is also the intention to encourage industry to see gold and copper wires as interconnection materials available for microelectronics packaging assembly and encourage intelligent assessment and use of both materials as bonding wires in the same way as any other material in a semiconductor package.

2 The ball bonding process and materials

Some readers of this article may be unfamiliar with the ball bonding process and this section briefly describes the process and introduces some terminology. More detailed information on equipment and process technology can be found in Harman's book [2]. Silicon chips are attached to metal or epoxy-based substrates using silver-filled adhesives but there isn't an electrical connection between the aluminium alloy bond pads on the chip surface and

Figure 1



Schematic (not to scale) of the ball bonding process (a) From left to right, formation of the end of a wire into a free air ball (FAB), the ball descends to the bond pad, the ball impacts the bond pad and ultrasonic vibrations scrub the ball in a shearing action against the pad while simultaneously applying a downward force to deform the ball (b) capillary ascending to start formation of the loop followed start of 2nd bond formation(c) 2nd bond formation and start of tail formation by tensile deformation of the wire, tail bond termination formation of FAB and beginning of a new cycle

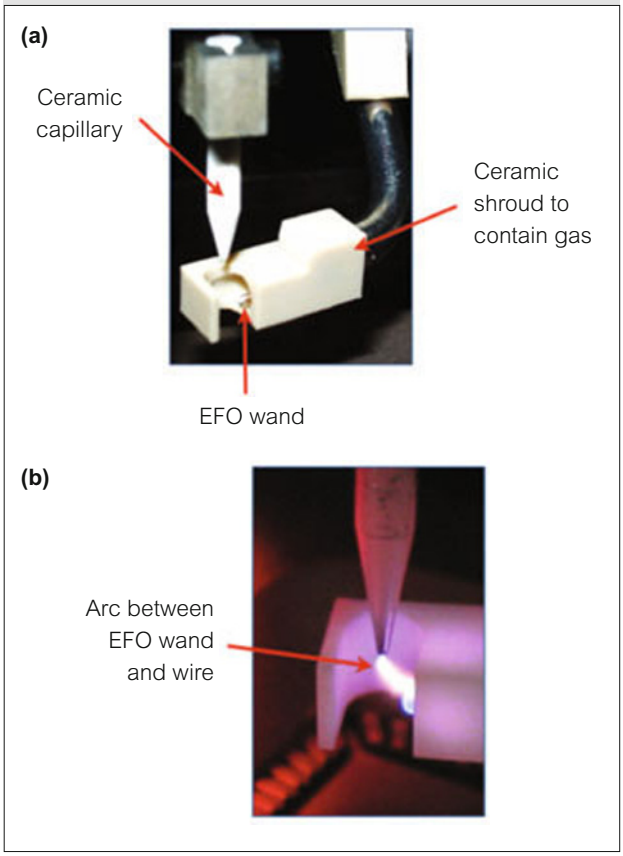
the electrically conducting silver or gold plated leads on the substrate until wires are bonded between the two sites. The process of connecting metal bond pads to substrate leads can be accomplished by ball bonding. Prior to bonding, the substrate and chip are pre-heated on the wire bonder heater stage to a temperature of typically 170°C for an epoxy substrate and 220°C for a metal lead-frame substrate, which aids the welding process. The ball bonding process starts as Fig. 1(a) shows, with the formation of a ball by melting the end of a wire with an electric arc that is produced from an electrode. The ball is commonly known as a free air ball (FAB) and after melting it rapidly solidifies and the FAB consists of several large grains. During ball formation heat also travels along the length of the wire and the grain size varies gradually from the very large grains in the FAB to the finer grains in the wire far from the source of heat. The distance over which the grain size varies is called the heat-affected zone (HAZ). The process of forming the FAB is called electric flame off or EFO for short and the electrode itself is commonly called an EFO wand. The size of the ball formed by the arc depends on the amount of current in milliamps and the duration of the arc.

The wire is held within a ceramic bonding tool (capillary) that also contains the FAB and after ball formation the capillary is used to plastically compress and simultaneously weld the FAB to an aluminium alloy bond pad with the aid of ultrasound. The ceramic capillary is constantly exposed to heat during ball formation and friction and wear due to contact with the wire during the bonding process, which results not only in capillary wear but transfer of wire material to the tip of the tool. Capillary 'build up' refers to the accumulation of wire material at the capillary tip. Ceramic capillaries therefore have a finite life measured in number of times the capillary 'touches down' to make a bond. Number of touch-downs is a common measure of capillary life and is dependent on bonding process parameters as well as capillary and wire material properties.

Once the ball is bonded, the process continues as in Fig. 1(b): the desired length of wire is paid out and a loop is formed and formation of a bond between the wire and metallisation on the lead-frame begins with compression of the wire using the capillary and as Fig. 1(c) shows, ultrasound is again used to weld the wire this time to the metal lead on the substrate. On completion of the 2nd bond weld, the wire (clamps closed) is pulled vertically upwards, plastically deforming and tearing away from the 2nd bond, resulting in the formation of a 'tail bond' and termination of the tail bond results in the wire breaking away from the second bond to form a uniform tensile break. The whole process then begins again.

Gold and copper bonding wires are classified by purity. Gold wires begin as 5N or 99.999% pure gold and the properties are controlled by selective doping with other elements (such as Ca, Ce, Pd) in amounts of parts per million by weight. Doping is used to control the strength and stiffness of gold wires to produce 4N (99.99% purity) and 3N (99.9% purity) wires. Gold wires are also produced in 2N purity (99% gold) by adding weight percent amounts of alloy elements and/or dopants. Copper wires are not normally doped because copper suffers from being too strong and alloy elements, dopants and impurities typically increase strength. Copper bonding wires need to be as soft as possible and can be manufactured by drawing 'off the shelf' high purity oxygen free copper. Copper purity also follows the same purity specifications and is commonly sold

Figure 2



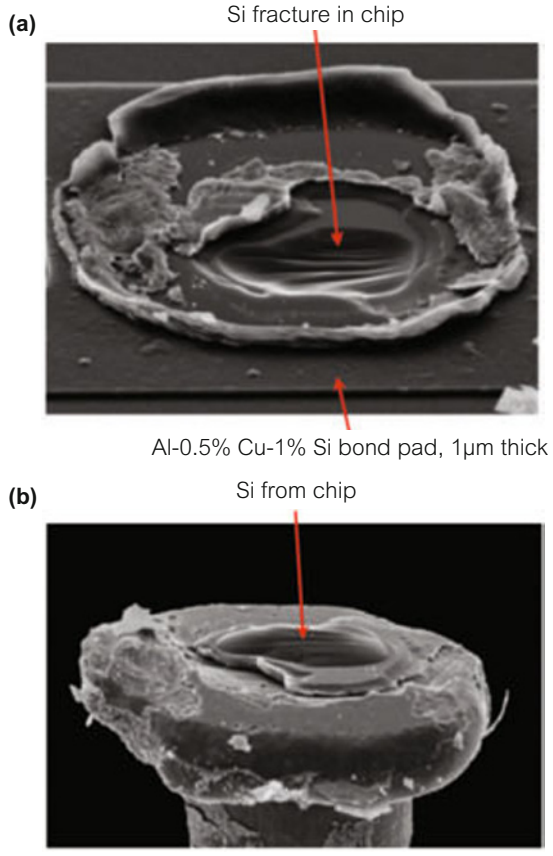
Pictures of the shroud around the EFO electrode (a) prior to formation of the FAB (b) FAB formation [3]. Designs for gas containment vary among bonding equipment manufacturers

as 3N and 4N purity. Higher purity 5N and 6N copper is available but can be much more expensive than 3N and 4N copper.

An important difference between ball bonding with copper and gold is that formation of the copper FABs requires an inert atmosphere to prevent oxide formation. The best atmosphere known at present is forming gas, a combination of 95% N_2 and 5% H_2, the latter acting as an oxygen scavenger. Photographs of the electrode that is used to create an arc, the capillary and a shroud that contains the gas around the FAB is shown in Fig. 2 [3]. Forming the ball inside a gas envelope makes the copper process slightly slower and forming gas adds to manufacturing costs.

Although rare with gold ball bonds, it is possible to cause cratering with copper ball bonding on aluminium bond pads. Cratering is mechanical damage to the silicon underneath the bond pad caused by high ultrasound and/or high forces during bonding. It is possible for the silicon to fracture without leading to any obvious failures but it is common with copper ball bonding to find that after isothermal ageing at elevated temperature, the bond pad, still bonded to a large section of silicon, comes off the chip as Fig. 3 [4] shows.

Figure 3



SEM images after 100 hrs ageing at 175°C showing (a) cratering of Si chip underneath aluminium bond pad (b) matching ball showing Si [4]

3 A brief review of copper versus gold ball bonding

3.1 The ball bonding process

In early studies of copper ball bonding, one of the main problems was bond pad damage caused by the high hardness of copper free air balls, which requires higher ultrasonic power to induce ultrasonic softening and enable easier plastic flow of the FAB with the undesired effect that higher ultrasound intensity also causes plastic flow of the aluminium bond pad. Toyozawa *et al* [5] in 1990 bonded copper balls on 0.8µm thick Al-1%Si bond pad metallization and modelled ball bond deformation. During bonding, the type of bond pad deformation illustrated in Fig. 4(a) was found at low bonding forces, where the ball penetrates the bond pad, often almost reaching the passivation layer and leaving a thick region of bond pad under the centre of the bond. Higher bond force, as illustrated in Fig. 4(b), was found to produce more even deformation of the bond pad under the centre of the ball. However, regardless of bonding process optimization, aluminium deformation around the sides of the ball, referred to as 'squeeze out', remained a feature of the bonding process. During assembly, Toyozawa also observed cratering and cracking of chips, and, as Fig. 5(a) shows, higher ultrasonic power reduced the number of craters and cracks but the size and

Figure 4

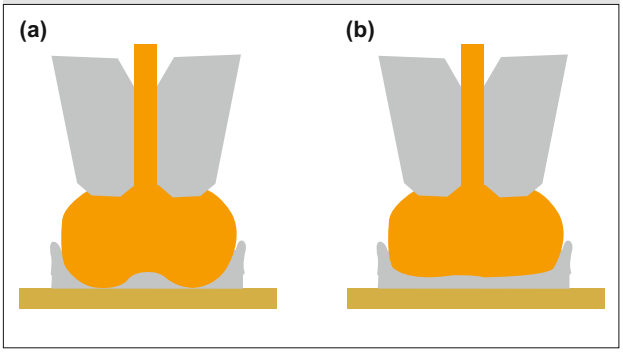
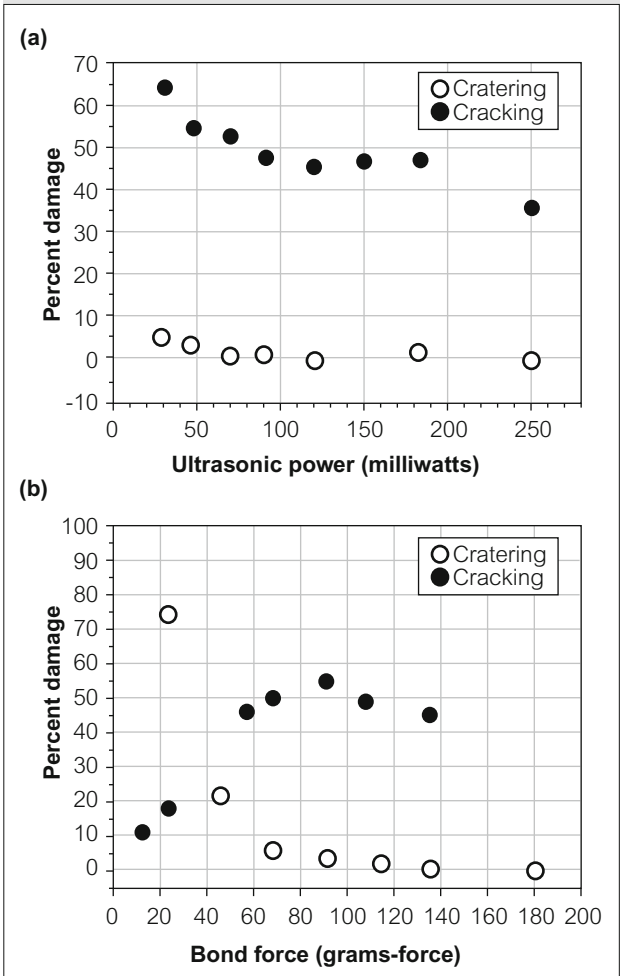


Illustration after Toyozawa et al [5] showing effects of increasing bond force and ultrasound on bond pad deformation and 'squeeze out' with copper ball bonds. (a) Low bond force may result in penetration of the bond pad (b) increasing bond force can sometimes lead to a flatter interface at the ball centre

Figure 5

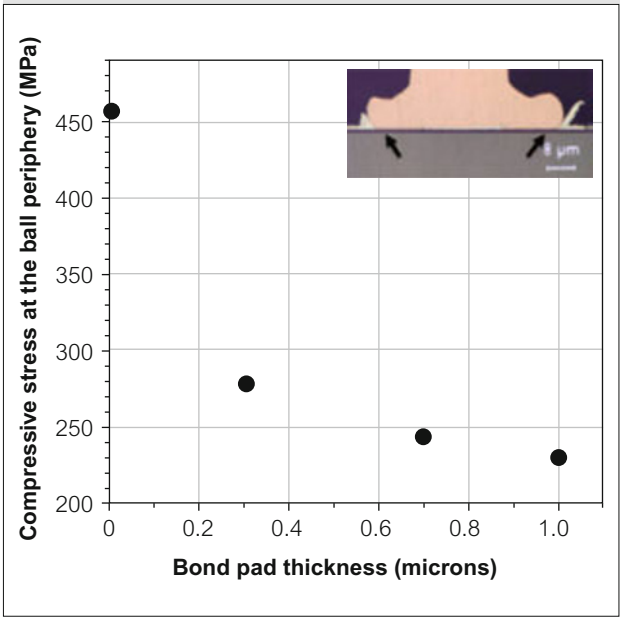


Graphs from Toyozawa et al [5] showing dependence of cratering and cracking on (a) ultrasonic power (b) mechanical bond load

volume of the craters and cracks became larger. It was also found that larger mechanical load in Fig.5(b) significantly reduced cratering and significantly increased cracking, which Toyozawa attributed to modification of the contact mechanics and stresses and strain rates in the ball, causing different stress distributions that alter the deformation pattern of the bond pad. Compressive plastic stresses around the ball periphery (under the inner chamfer region), determined by finite element modelling (Fig. 6), showed that stresses might decrease with thicker bond pads.

Recently Shah *et al* [6] examined the ability to reduce stress under bonding pads by using lower than optimum ultrasonic power and/or softer copper wire and found that it was still possible to get good copper ball bonds at lower ultrasonic power.

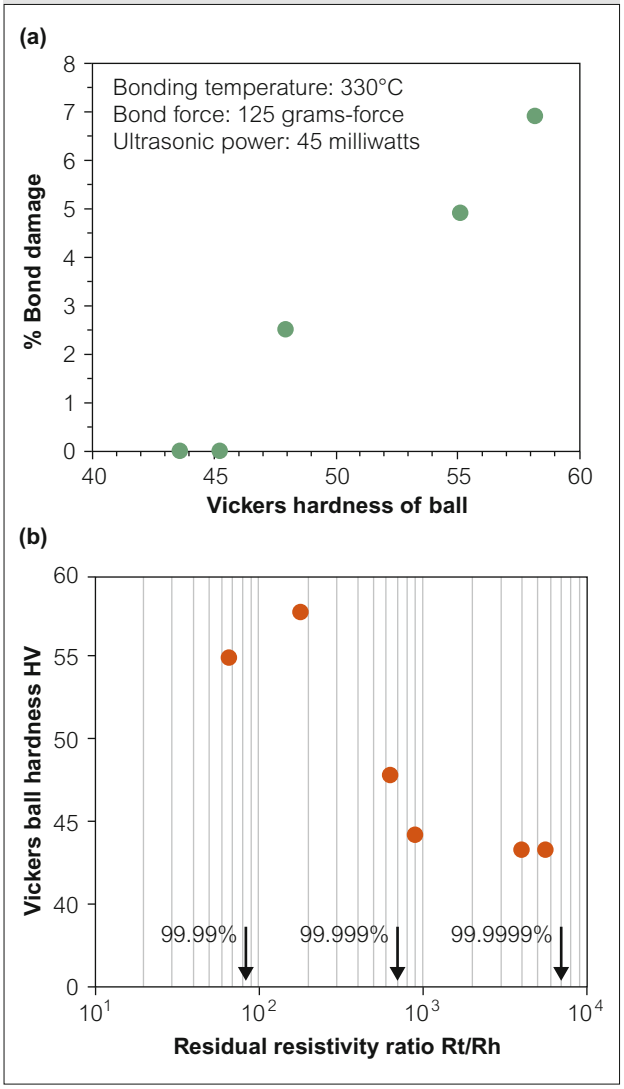
Figure 6



Simulated data from Toyozawa et al [5] showing dependence of peripheral compressive stress on mechanical bond load. Picture illustrates squeeze out due to high stresses

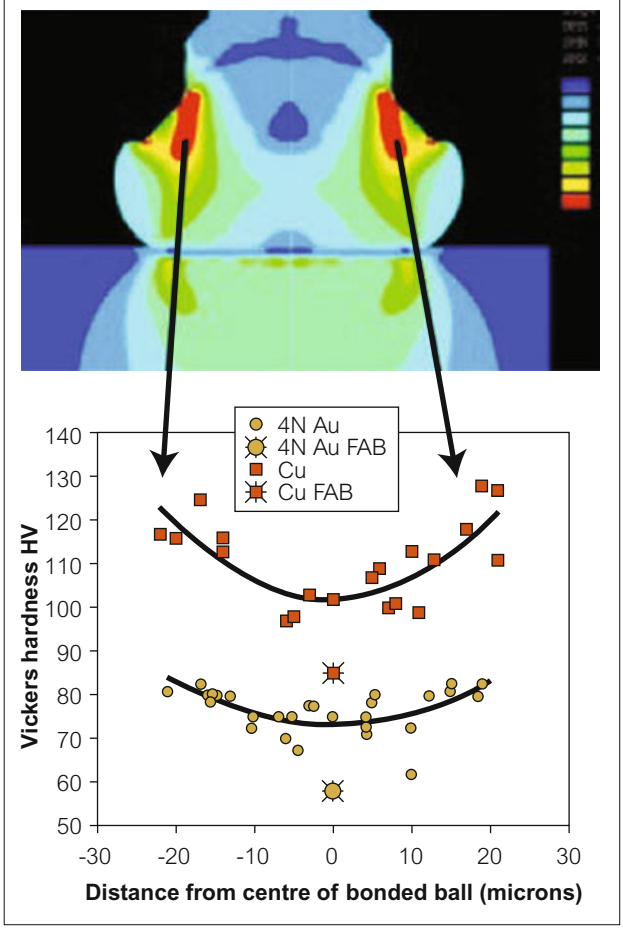
Manipulating the process parameters in the way that Shah has done would be a very convenient way to reduce cratering and bond pad damage but it is uncertain if this approach is reliable and consistent in a mass production environment. From a process engineer's point of view, limiting the ultrasonic power or other parameters may narrow the bonding parameter ranges rather than giving wider process parameter ranges that make the process easier to control. Softer copper wire also provides limited scope for reduction of damage because copper cannot be as soft as gold. Onuki *et al* [7] attempted rather early in the history of copper bonding in 1990 to understand the effects of copper ball hardness on bond pad damage and looked at effects of wire purity and ball formation parameters on the softness of copper balls. Higher free air ball (FAB) hardness occurred with lower purity copper and resulted in greater bond damage, as Fig. 7(a) shows and Fig. 7(b) shows that higher wire purity gave both softer balls and lower residual resistivity. However, as every metallurgist knows, materials like copper that work harden rapidly, will do so more when they are softer and a softer FAB might work harden more than a harder FAB during bonding. Wulff *et al* [8] showed by measuring Vickers hardness of bonded balls (Fig. 8) that gold and copper ball bonds can work-harden and that copper does so more than gold. Hardening can occur where the ball experiences

Figure 7



(a) Bond damage dependence on hardness of copper ball (b) dependence of copper ball hardness on copper wire purity fat levels of 99.99%, 99.999% and 99.9999%. Rt refers to specific resistivity at room temperature and Rh to specific resistivity at liquid nitrogen temperatures [7]

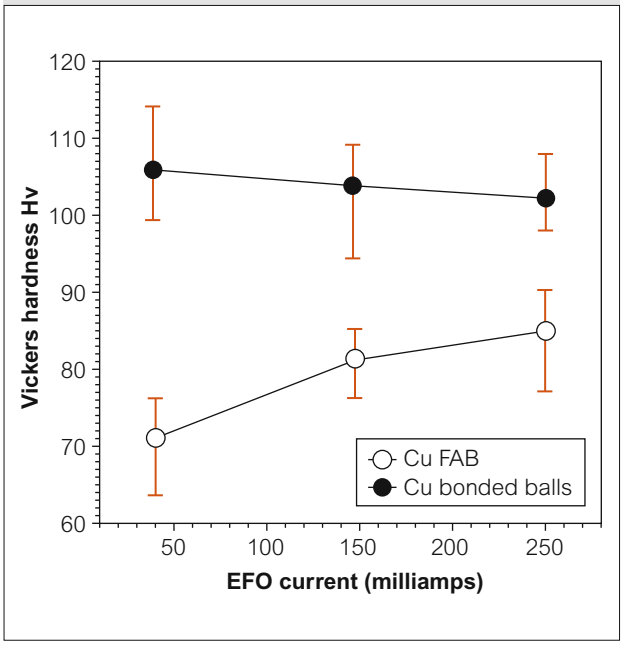
Figure 8



Top image: FEM simulation [4] showing stresses in an as-bonded ball. Bottom graph: Vickers hardness data measured across ball bonds. Data from [8]

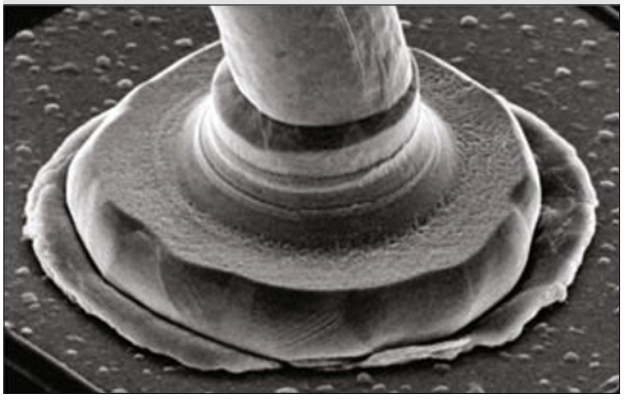
maximum strains and strain gradients. Of course, ball deformation is not uniform and plastic strain and stress distributions, and therefore work hardening in different regions of the ball depends on capillary geometry and bond force [9]. A more recent study varied copper FAB hardness by manipulating EFO current and firing time [10]: high EFO current and short time gave harder copper FABs and not surprisingly, as Fig. 9 shows, the harder FABs did not harden as much during ball bonding. Another way of changing FAB hardness, as with Onuki's earlier study, is to change copper wire purity, as Srikanth *et al* did [11], which resulted in a significant decrease in the number of grains in wires and FABs (and therefore larger grains) with increasing purity. Higher purity wires had lower yield strengths and there was a small reduction in the amount of squeeze out with higher purity wires. However, another study by Onuki *et al* [12] on the influence of FAB grain size in very high purity 99.999% copper wires on temperature cycling was studied and it was concluded that very large grains above the FAB reduce fatigue resistance and are therefore not desirable. From the findings of Onuki [12] and Srikanth [11], very high purity wire would seem to help with reducing squeeze out but are potentially unsuitable from the point of fatigue failures, while lower purity wires have finer grains in the FAB and wire, which might improve fatigue resistance but results in harder wires and potentially greater squeeze out and under pad damage. The fundamental problem of copper wire and FABs is

Figure 9



Effect of harder FABs on change on work hardening of bonded copper balls [10]

Figure 10



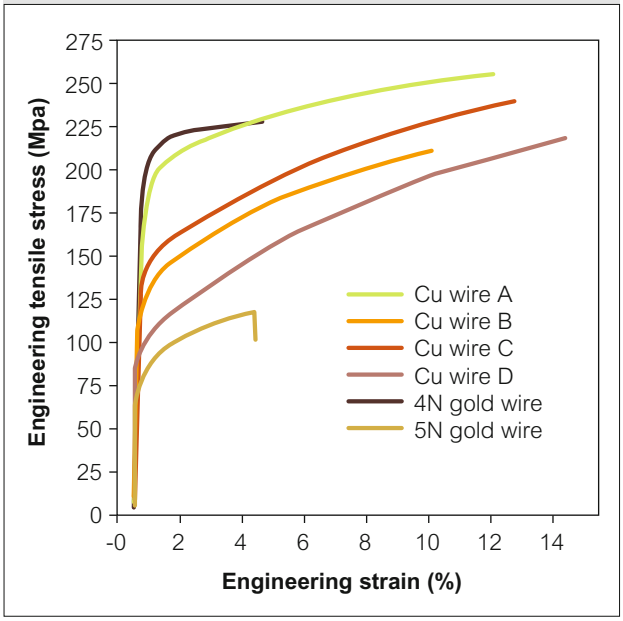
Example of 'squeeze out' of aluminium in a copper ball bond due to high ultrasound [13]

that no matter how process parameters and wire purity is manipulated, copper is intrinsically harder and strain hardens more than gold. Bottom line: copper is not gold. The problem of bond pad damage due to squeeze out may not give problems with high temperature storage but squeezed out regions cause stress gradients and provide sites for crack propagation during stress tests such as temperature cycling and pressure cooker tests (PCT). Fig. 10 shows an example from a recently published review of ball bonding materials science [13] and examples of similar squeeze out can be seen in as-bonded copper ball bonded packages in industry and in recent literature such as the study by Hang *et al* [14].

Bonding problems are not limited to the ball bond. Potential problems exist with the second bond. In 1993, Caers *et al* [15] published data on ball bonding with copper wire that set out conditions necessary to achieve reliable copper ball bonds. Apart from the obvious requirement of a shielding gas to form FABs, it was recognised that more aggressive annealing is required to soften copper wires and make them suitable for bonding, which affects the grain size of the wire. Very large grained wires were found to deform inconsistently during 2nd bond formation, resulting in larger variations in stitch bond dimensions compared with gold, which Caers *et al* attributed to the dependence of deformation on a relatively small number of large grains. They suggested that if wires are mono-crystalline, the stitch bond deformation might be more even more variable, and although they did not explicitly state the reasons for the inconsistency (possibly they thought it obvious), inhomogeneous deformation in single crystals is mainly due to the dependence of plastic stress and strain on crystal orientation. At least one study has made single crystal copper wires [16] and while the dimensional stability of stitch bonds was not studied, it might be expected to affect stitch bond properties.

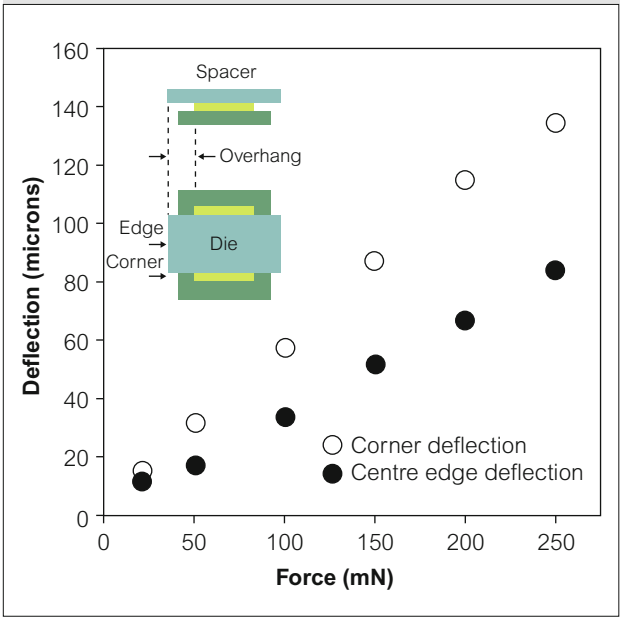
In general, the problems of bonding copper wire are directly related to the physical properties. A simple way to understand the different plastic behaviour of gold and copper wires is to look at tensile test curves. Copper wires from different suppliers are not equal, just like gold wires, and it is important to be aware of the wide difference in mechanical strength and the stress-strain response, as Fig. 11 shows for a variety of copper wires. The difference between the wires in Fig. 11 is that they are made from copper of 4N purity but each is from a different metal supplier. A copper wire manufactured using the same process as gold wire and annealed to the same elongation to break would naturally be stronger than the gold wire. The copper wires used to obtain the data in Fig. 11 were manufactured by the same process and annealed to maximum possible elongation to break to make them as soft as possible. A key feature of the 4N gold wire is the relatively flat plastic stress-strain response, showing that there is little strain hardening. The steep slope of the plastic stress-strain regions of copper wires demonstrates that significant strain hardening occurs. The lack of appreciable strain hardening in

Figure 11



Typical tensile stress-strain curves of gold and copper wire of 25µm diameter [4]

Figure 12



Edge and corner deflection for Au wire bonding on an overhang stacked die. [18]. Corner deflection is greater than edge

gold wire makes it more bonding-friendly relative to copper. Conversely, the higher general stiffness of copper bonding wires, possibly accompanied by more hardening at the kinks formed by plastic bending of the wire during loop formation makes loops with copper wire more resistant to disturbance during transportation and during moulding [17]. However, there is little published supporting data for mould sweep resistance of copper wires.

There may be problems using copper wire in advanced packages such as overhang stacked die. With gold wire bonding, overhang stacked die (see Fig. 12) deflects more at the corners of the chip than at the centre [18]. The higher hardness of copper balls and increased ultrasonic power needed for bonding could pose a problem for use of copper wire bonding in stacked dies. Feedback from industry is that edge and corner deflection is significantly higher with copper wire compared to gold. Of course with pyramid type stacked devices overhang would not be an issue. The use of very thin silicon devices stacked one on the other with adhesive film may prove problematic for wire bonding in general.

A further complication with copper ball bonds, but not necessarily a great handicap, is the difficulty in measuring intermetallic coverage because the phase created during thermosonic bonding that bonds ball to bond pad is simply to thin to be seen with routine methods such as optical and scanning electron microscopy [19]. It is necessary to use transmission electron microscopy [20]. Without the ability to examine the welded area, more care needs to be taken with process optimization to ensure a robust bonding process.

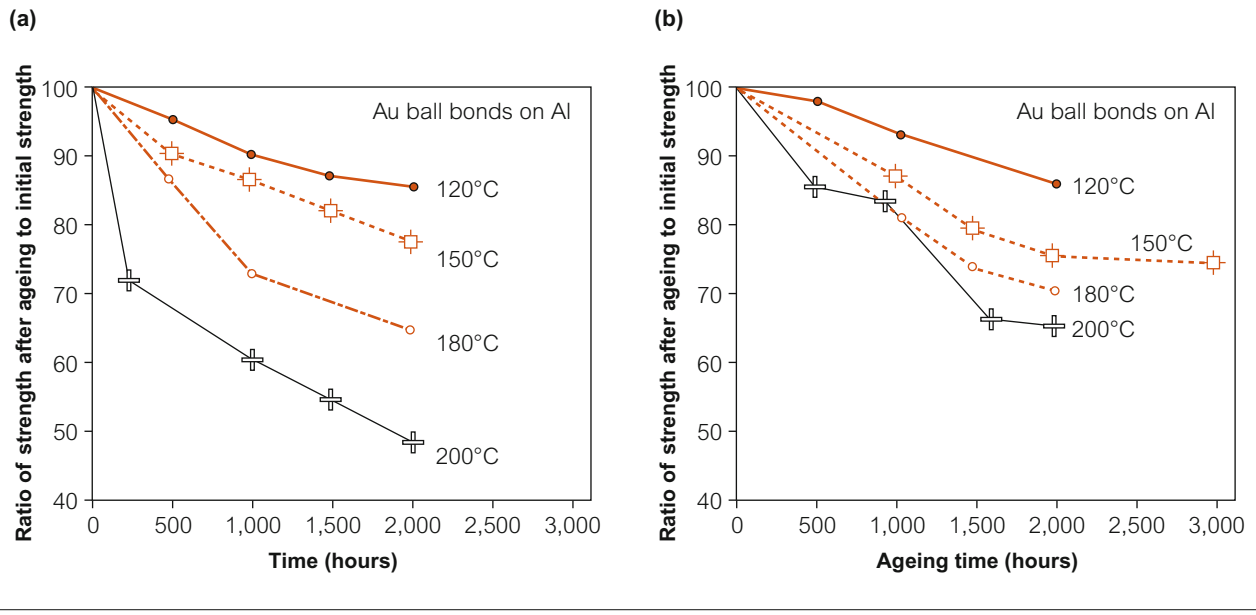
Lastly, an obvious fundamental difference between gold and copper ball bonding is the need to form copper FABs in an inert atmosphere. Although N_2 can be used for ball formation, balls are sometimes off-centred and forming gas is generally used. In addition, copper oxidizes rather slowly at room temperature in the presence of oxygen and there are legitimate concerns about the lifetime of copper wire on bonding machines in mass production. Mildly oxidized wires can still be bonded but the effects on long term reliability should expired (oxidized) copper wire inadvertently be used in mass-produced packages and become part of products, is unknown.

3.2 Reliability

3.2.1 Reliability studies 1980-2002

A great deal of interesting work was performed and several key studies were published from the mid 1980s onwards. Onuki *et al* [21] compared reliability performance of gold and copper ball bonds after ageing at temperatures between 120°C and 200°C. Data from that study, in Fig. 13(a) and Fig.13(b),

Figure 13

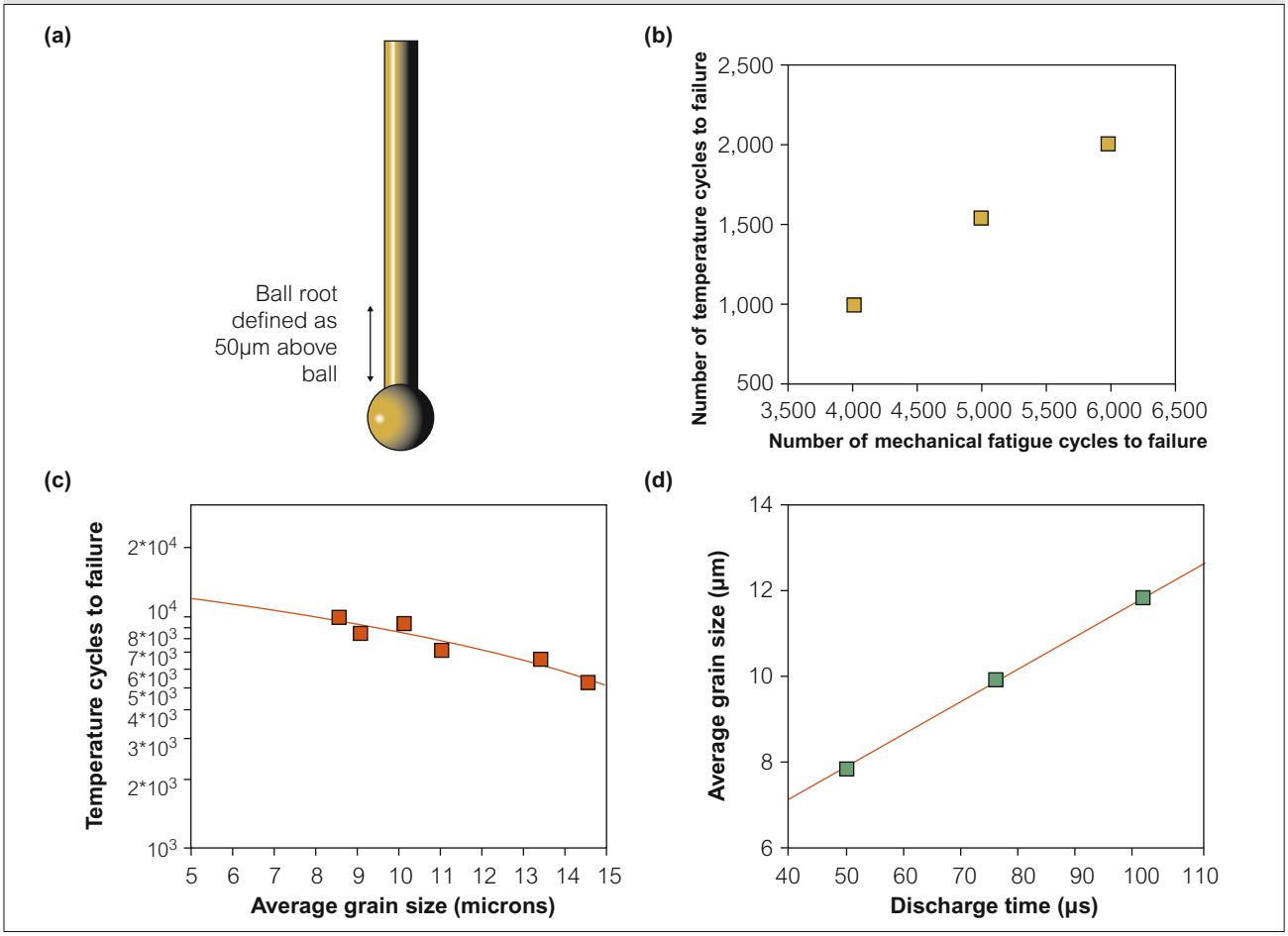


Data from Onuki [21] for 30µm Au and Cu bonding wire on 1.3µm thick Al metallization. (a) Shear strength of Au ball bonds (b) shear strength of Cu ball bonds

show the change in shear strength (normalized) of gold and copper ball bonds made with 30µm diameter wires on 1.3µm thick aluminium bond pad metallization of unspecified composition after isothermal ageing (high temperature storage testing or HTST). Compared with modern ball bonding the bonding site temperature was very high at 330°C. From Fig. 13, both gold and copper wire lost strength during ageing, the strength loss increasing with temperature. The time to reach 50% of initial shear strength after ageing at 150°C was used to compare the reliability of gold and copper wires and while gold wires reached 50% bond strength after 10,000 hours, copper bonds required 40,000 hours, at which point the thicknesses of Au-Al and Cu-Al intermetallics were 7 microns and 2 microns respectively. From these data it was concluded that copper was more reliable than gold. Intermetallic phases observed with gold wire were Au_4Al, Au_5Al_2 (Au_8Al_3), Au_2Al, AuAl and $AuAl_2$ and for copper wire, CuAl and $CuAl_2$, but not all compounds occurred at each ageing temperature. Onuki reported that for both wire types, strength loss was due to ball lifts within intermetallic phases despite the much slower intermetallic growth rate with copper. With devices encapsulated in epoxy moulding compound, more degradation was found with gold wire than copper. Finally Onuki concluded "*The reliability tests of resin-molded IC's indicated that copper ball bonding gives at least the same level of reliability as that of the conventional gold ball bonding*." A second study by Onuki *et al* [22] in 1991, looked at the effects of copper grain size in FABs in an effort to explain temperature cycling failures. High purity copper wires (99.999%) were used and a region called the ball root was defined that extended 50µm from the neck of the FAB, which Fig. 14(a) illustrates. It had been observed that resin encapsulated devices after temperature cycling failed by severing of the wire in the region of the FAB and a correlation between temperature cycles to wire failure and fatigue cycles was made and is shown in Fig. 14(b). Failures occurred in the ball root and the conclusion was drawn that if the grain size in the ball root exceeds 10µm copper wires are more susceptible to fatigue failure. Fig. 14(c) shows the dependence of temperature cycles required to cause failure on grain size in the root. Grain size in the FAB and the FAB root also depends on the current and the time used to form the ball. The longer the discharge time, the larger the FAB, and the larger the grain size as Fig. 14(d) shows.

A study by Khoury *et al* in 1990 [23] compared Au and Cu bonding wires on Al, Al-Cu and Al-Si-Cu bond pad metallization of unspecified thickness. Bond pad compositions were not given. Specimens were assembled and electrically tested and different

Figure 14



(a) Illustration of the ball 'root' defined by Onuki et al. (b) graph of number of temperature cycles to failure versus number of mechanical fatigue cycles to failure (c) graph of number of temperature cycles to failure versus grain size in the root of FABs (d) dependence of average ball root grain size on spark time. Data re-plotted from Onuki et al [22]

batches subjected to high temperature storage at 145°C, pressure cooker test (PCT) at 121°C, 2 atm, isothermal ageing at 85°C at 85% RH and temperature cycling from -65°C to +150°C. Forming gas for copper wire (5% H_2/95% N_2) and the bonding conditions for the devices were quite different, with the copper bonded devices being preheated to 300°C while the gold bonded devices were preheated to 200°C. Failures were not found with gold or copper wires. Table 1 shows one set of results for Al-Cu-Si bond pads that are also representative of Al and Al-Cu bond pads. Khoury's conclusion: "*The reliability data indicate that copper wire bonding is at least equal to that of the conventional gold wire bonding. The results of this paper show that a copper ball bond assembly process can be developed for mass production which will equal and potentially surpass the performance and reliability of the present gold ball bond assembly process*". Another statement made was "*The difference in intermetallic growth rates between Au and Cu wire processed devices suggest that Cu wire bonded devices will have greater reliability than Au wire bonded devices*". However, with no failures within intermetallics or traceable to intermetallic growth rate the latter statement seems unfounded, at least based on the results presented in the article. Toyozawa et al's reliability tests [5] drew much the same conclusion as Khoury *et al*, which is that copper and gold had similar performance in a variety of tests as the data in Table 2 show.

Another key study in 1995 by Nguyen *et al* [24] reached much the same conclusions as the previously described studies, i.e. that copper is at least as reliable as gold and that copper could become dominant. The properties of the wires that were used are given in Table 3. The elongation to break was also not specified and it is doubtful

Table 1: Reliability test results of Cu and Au bonding wire from Khoury et al [23] on Al-Cu-Si bond pads

Test	Condition	No. of samples		Test duration		No. of failures	
		Au	Cu	Au	Cu	Au	Cu
Operating life	145	100	240	3000 hours	4000 hours	0	0
Temperature cycling	65°C - +150°C	100	350	4000 cycles	4000 cycles	0	0
Thermal shock	65°C - +150°C	100	80	1000 cycles	1000 cycles	0	0
High temperature storage	170°C	80	80	2000 hours	1800 hours	0	0
Pressure, temperature humidity under bias	121°C, 2 atm	45	80	528 hours	528 hours	0	0
Temperature humidity under bias	85°C/85% RH	45	80	1000 hours	1000 hours	0	0

Table 2: Reliability test results of Cu and Au bonding wire from Toyozawa et al [5] on Al-1%Si bond pads

Test	Condition	No. of samples		Test duration	No. of failures	
	Au	Cu			Au	Cu
Temperature cycling	-65°C - +150°C	100	100	300 cycles	0	0
High temperature storage	125°C	100	100	2000 hours	0	0
Pressure cooker test	121°C, 2 atm	100	100	1000 hours	0	0
Temperature humidity under bias	85°C/85% RH	100	100	2000 hours	0	0

Table 3: Properties of Au and Cu wires used by Nguyen et al [24]. Some values converted from imperial to SI units

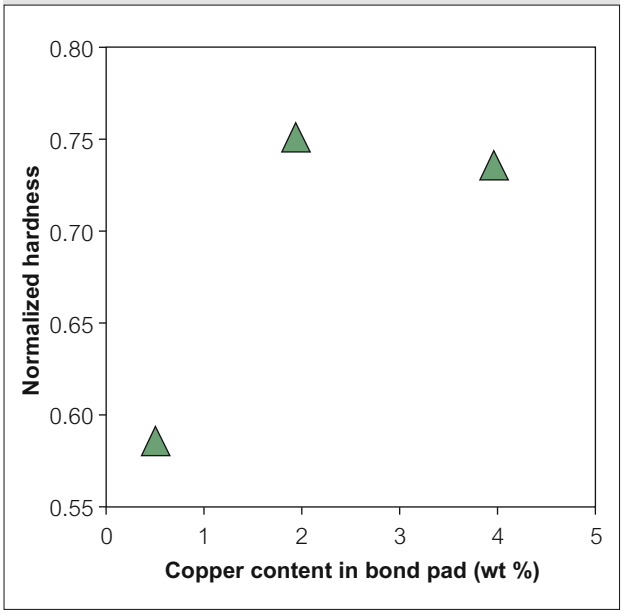
Properties	Gold	Copper
Diameter (microns)	37.5	37.5
Modulus (GPa)	79	110
Tensile strength (MPa)	159	222
Hardness (Knoop)	61	70-76
Purity (%)	99.99	99.997
Dopant (ppm)	Be, Ca	Ti, Yt, B
Ball shear (grams force)	80	120
Pull strength (grams force)	8	22

that Ti, Yt and B in copper were deliberately added dopants; they are more likely impurities. However, the objective of the paper was to examine the effect of copper content of aluminium bond pads on bond pad hardness and find a composition that was bondable and harder so that squeeze out of the aluminium bond pad was reduced or eliminated. Bond pads were deposited with various amounts of copper (the bond pad thickness was not stated) and the hardness (see Fig. 15) was found to reach a maximum at 2%. Reliability data in Table 4 shows the performance of copper and gold to be the same but a concern with high Cu content is corrosion of Al in the bond pad during assembly and potentially poor ball bond formation [25]. During the period from 1995 to 2002, there were few studies of note on copper, except for Tan *et al* [26] in 2002, which described silicon cratering as '..a major hurdle to overcome..' and like previous studies concluded

Table 4: Reliability test results of Cu and Au bonding wire from Nguyen et al [24] on Al-2%Cu bond pads

Test	Condition	Read Point	Gold control	Lot A	Lot B
Autoclave (PCT)	121°C, 2 atm	168 hr	0/77	0/77	0/77
		336 hr	0/77	0/77	0/77
		500 hr	0/77	0/77	0/77
Operating life	500 hr @150°C	72 hr	0/77	0/77	0/77
		336 hr	0/77	0/77	0/77
		500 hr	0/77	0/77	0/77
Temperature/humidity bias	85°C/85% RH	168 hr	0/77	0/77	0/77
Temperature cycleling	-65°C - +150°C	100 cycles	0/77	0/77	0/77
		500 cycles	0/77	0/77	0/77
		1000 cycles	0/77	0/77	0/77
		2000 cycles	0/77	0/77	0/77

Figure 15



Dependence of the hardness of Al-Cu bond pads on copper content. Data reproduced from Nguyen et al [24]. Hardness normalised with respect to a control film

that higher ultrasound needed to soften copper balls causes more cratering and that harder bond pads could help in eliminating cratering. Tan described PCT experiments on un-moulded copper ball bonds [27] bonded at 350°C and observed high shear forces with time and a drastic reduction of shear force due to corrosion and formation of copper and aluminium oxides. Cratering initially increased but decreased as the shear strength of the ball bonds reduced which was attributed to formation of oxides that weakened the bond and caused interfacial failure.

Most of the tests described up to this point show that copper and gold can give similar mechanical performance in the usual stress tests. Reliability test results conducted in 1993 by Caers *et al* [15], in Table 5, also show that the wires had similar mechanical performance but resistance changes of ball bonds after isothermal ageing at various temperatures in Fig. 16 show a clear benefit of copper wire over gold. Copper wire showed significantly less change in resistance than gold, which is not evidence for lack of reliability but shows that bond resistance might be higher with gold ball bonds. Higher bond resistance can affect signal speed and copper ball bonds may therefore have an advantage of lower bond resistance over time.

3.2.2 Reliability studies 2003 to present

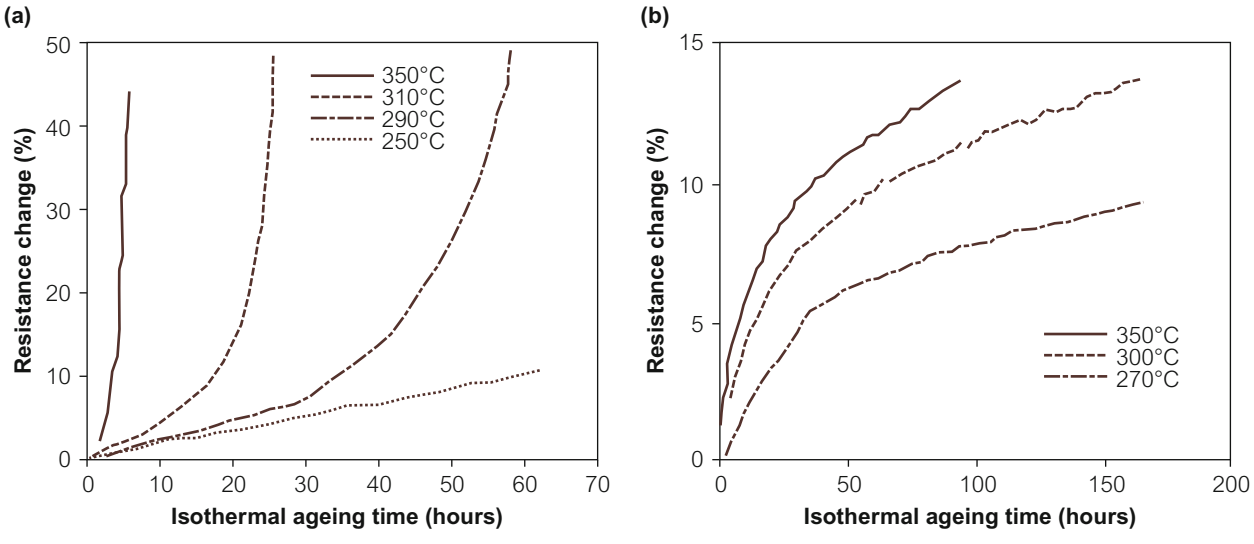
Interest in the cost savings potential of copper wire increased during the 2003-2004 period. Development activities tended to focus on the process and the details of intermetallic growth in copper ball bonds. Several studies set out to confirm that changes in the bonding process (smaller balls, lower bonding temperatures) did not alter the behaviour of copper ball bonds during bonding and reliability testing. The problems associated with copper ball bonding on aluminium alloy bond pads remained and Murali *et al* studied FAB hardness and cratering [28] in 25µm, 50µm and 75µm copper wires in 2003 and Srikanth *et al* [29] published similar data in 2004. Both papers draw essentially the same conclusion that FABs harden significantly during the copper bonding process. Another paper by Murali *et al* [30] compared intermetallic growth in gold and copper ball bonds and concluded that after 2 days ageing at 175°C there was little intermetallic growth in the

Table 5: No. of failures and lot size of Cu and Au bonding wire from Caers et al [15] on Al-1% Si bond pads

Test	Condition	Duration	Cu wire (failures/lot size)	Au wire (failures/lot size)
Temperature cycles	-65°C - +150°C	200 cycles	0/100	0/25
HAST (highly accelerated steam test)	132°C, 85% RH	72 hours	0/50	0/25
PCT (pressure cooker test)	120°C, 2 atm, 100% RH	200 hours	0/100	0/25
HTSL (high temperature storage life)	175°C	1000 hours	0/50	0/25
SHTL	150°C, 6V	1000 hours	0/50	0/25

No. of failures and lot size of Cu and Au bonding wire from Caers et al [15] on Al-1% Si bond pads

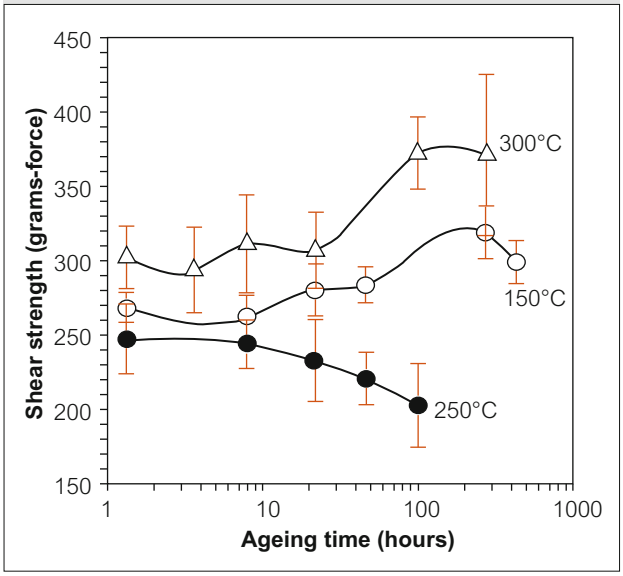
Figure 16



Resistance change of ball bonds after isothermal ageing. (a) gold (b) copper [15]

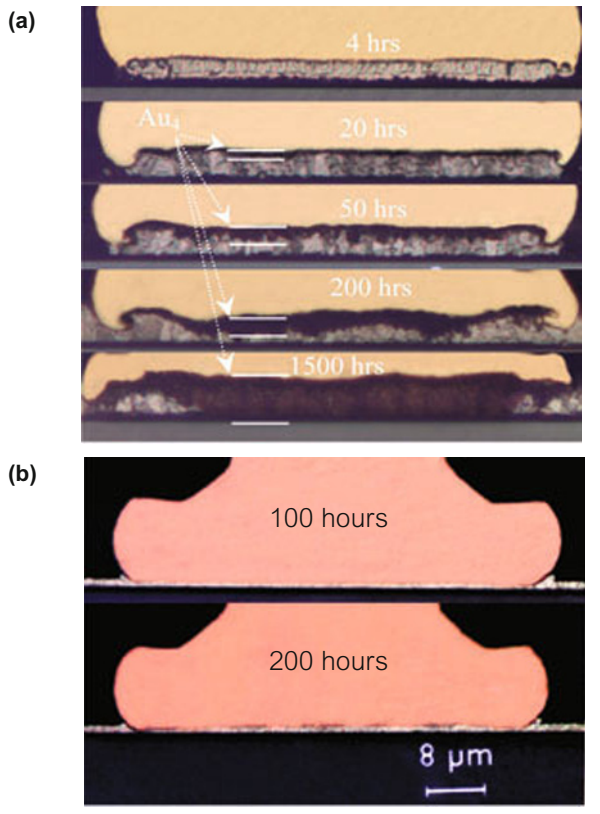
copper ball bond. In 2003 Kim *et al* [31] annealed copper ball bonds at 150°C, 250°C and 350°C and measured intermetallic thickness without a gold control annealed under identical conditions. Shear strengths are shown in Fig. 17 and failure modes of copper ball bonds at various temperatures are summarised in Table 6. At 150°C, shear strength slowly increased with time and failure occurred at the copper to aluminium interface, defined as a mode A failure. At 250°C shear strength steadily decreased due to mainly mode B failure at the intermetallic – SiO_2 interface. At 300°C, shear strength increased significantly and at long times failed in the copper ball, a mode C failure, which was attributed to annealing and softening of the ball. A paper by Wulff *et al* in 2004 [19] studied bonded ball hardness and high temperature storage of copper ball bonds at 250°C. Intermetallic growth in copper ball bonds was much faster because of the higher temperature. In 2005 Wulff *et al* [32] published a study on intermetallic growth in copper and gold ball bonds. Cross-sections of copper ball bonds aged at 175°C in Fig. 18 illustrate visually how rapidly gold intermetallics grow compared with copper intermetallics and phases were easily visible. The graph in Fig. 19 [13] shows that intermetallic growth for gold and copper ball bonds is generally parabolic but very much slower with copper. Examination of etched specimens of copper ball bonds in Fig. 20 revealed that in addition to bulk interdiffusion, ageing at higher temperature caused Cu-Al intermetallic growth along grain boundaries. In 2005 Saraswati

Figure 17



Ball shear strength versus ageing time at various temperatures [31]. Lines are an aid to guide the eye and are not intended to imply data fitting

Figure 18



Optical images of (a) gold ball bonds (b) copper ball bonds annealed at 175°C. Intermetallic growth in copper is very slow in comparison to gold [32]

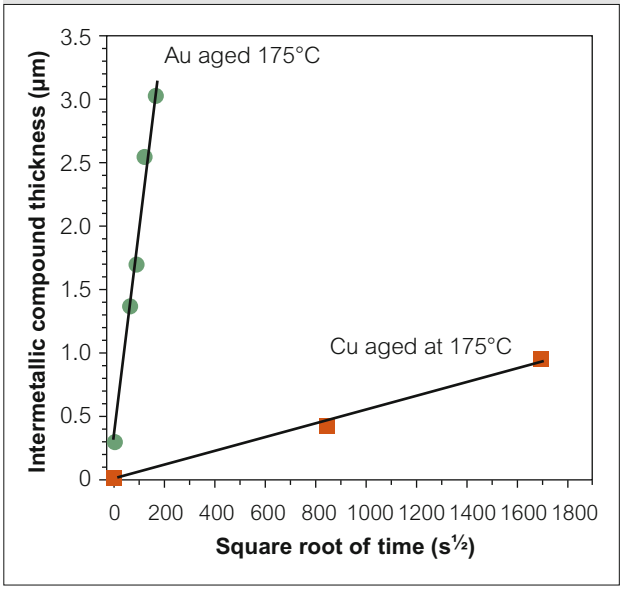
Table 6: Summary of failure modes at various temperatures in the study of Kim et al [31]

Temperature (°C)	Failure mode
150	Cu-Al interface (Mode A).
250	Minor occurrence of Cu-Al interface (Mode A), majority failure at intermetallic – SiO_2 interface due to weak adhesion (Mode B).
300	Mode A up to 25 hours, failure within the Cu ball at times greater than 25 hours (Mode C) due to recrystallization and softening of the Cu ball.

et al [4] observed moderate decreases in pull strength with ageing time were observed at 175°C but the shear force was quite stable, as Fig. 21 shows. It is possible that the reduction in pull strength at 175°C is due to annealing and softening of copper at the ball neck. In contrast, Fig. 22 showed quite drastic reductions in pull and shear strength after ageing at 200°C. Cratering was not observed in the as-bonded devices but occurred in aged devices at both temperatures. Table 7 shows that with wires 1-3,less cratering was found after ageing at 175°C than at 200°C. Wire 4 was an exception, showing more cratering at 175°C than at 200°C. There was no pattern to the cratering after ageing. More recently, Hang et al [14] have found cracking of Cu-Al intermetallics after high temperature storage of encapsulated copper ball bonds at 250°C.

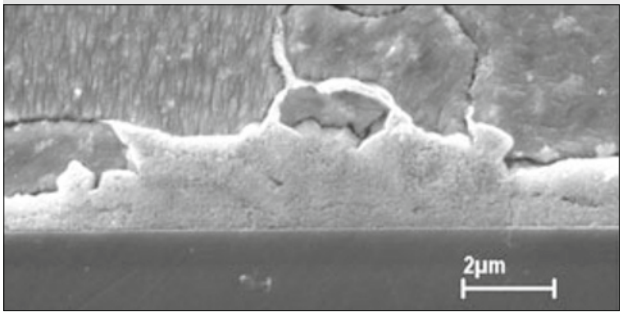
With renewed interest in copper wire bonding over the past several years there has been extensive evaluation of copper wire in industry. HTST generally demonstrates that although gold wire intermetallic growth is much more rapid than copper wire, gold ball bonds can be generally as reliable as copper. For that reason, copper wire appears capable of replacing gold in low-end as well as advanced packages. However, over the past few years a problem has emerged. Copper ball bonds can easily fail temperature cycling (TMCL) and pressure cooker testing (PCT). There are few published studies regarding this phenomenon but it is a real problem faced by industry. The problem is serious enough that it is stalling the widespread adoption of copper and sweeping replacement of gold in all applications. Perhaps one of the issues with passing such tests is bond pad squeeze out that thins the

Figure 19



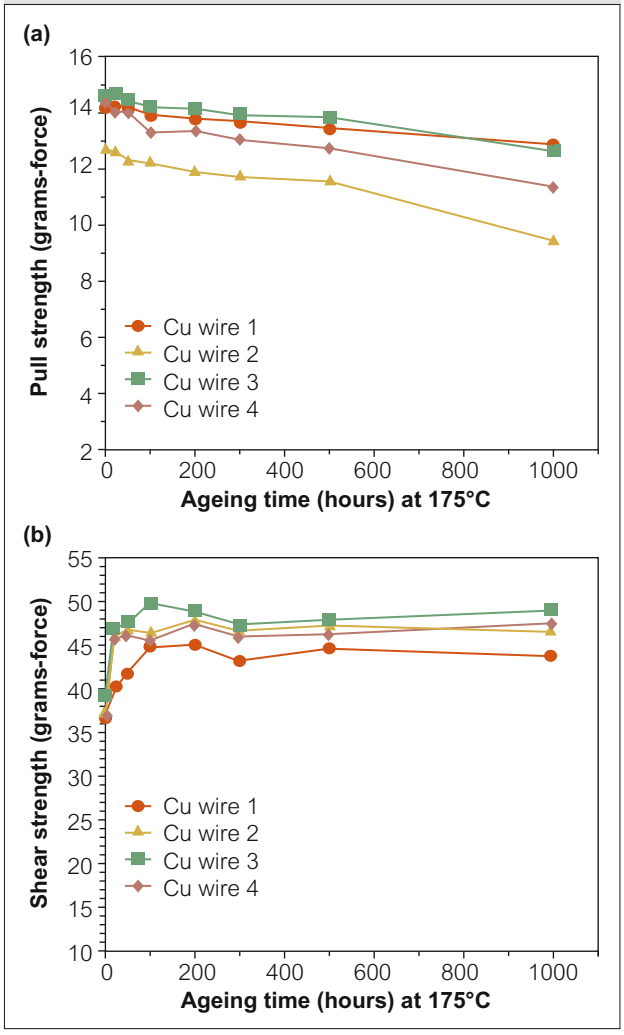
Growth of Au-Al and Cu-Al intermetallics during isothermal ageing at 175°C [13]

Figure 20



SEM images of an etched copper ball bond annealed at 250°C for 200 hours showing growth of a phase along the grain boundaries of the ball (c) 1000 hours [32]

Figure 21



Mechanical strength after ageing at 175°C. (a) Pull strength (b) shear strength [4]

bond pad at certain locations as seen in Fig. 10. Thinning may resulting in stress gradients and potential for crack formation at the ball periphery during TMCL tests whereas it is possible that stresses in the ball and between the ball and bond pad anneal out during HTST. One of the first published studies regarding this problem was by Kaimori *et al* [33], which compared encapsulated 25µm diameter copper and gold wire and proposed a solution in the form of Pd-coated copper wire. Kaimori's results, summarized in Table 8, show that copper wires did not perform well in PCT and TCL relative to gold and a copper wire electroplated with palladium. Another recent study by Uno *et al* [34] also found the PCT performance of Cu wire encapsulated with a moulding compound poor relative to a palladium plated copper wire. Shear force data in Fig. 23 show less deterioration of Pd-coated Cu wires compared with copper. Uno *et al* attribute the improvement in performance to formation of a Cu-Pd phase in the Cu FAB that welds to the Al bond pad and forms a Cu-Pd-Al compound. However, while Pd-coated Cu wire appears to improve the PCT reliability, further data needs to be gathered on a larger scale to properly assess its potential to improve reliability performance. More recently, Vath *et al* [35] performed HTST tests with Pd coated copper, 4N gold and copper wire, concluding that Pd coated wire gave the best performance, followed by 4N gold with bare copper wire in third place. Industry feedback is that currently, performance is somewhat improved relative to copper but there are insufficient data from which to draw clear and reliable conclusions.

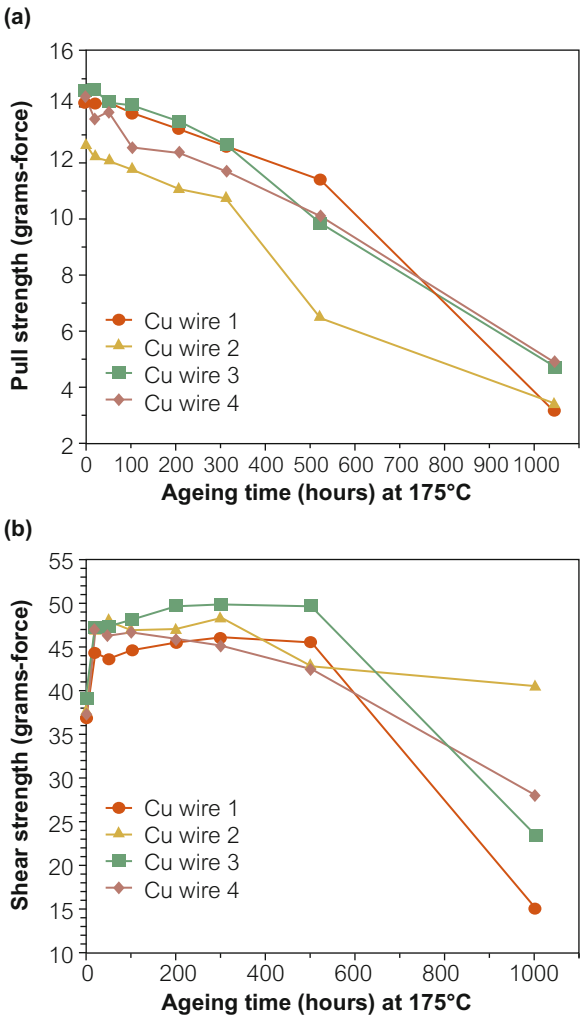
3.3 The business and economics of replacing gold with copper

To the non-materials scientist, it is easy to demand that gold replaces with copper in existing devices and all new wire bond chip designs in order to save costs. It seems, on paper, a trivial exercise to maintain device metallization as it is and replace gold with copper. If customers want copper wire to replace gold, bonding wire and equipment companies are obliged to try to provide that solution. The greatest pressure to have copper bonding capability is probably on sub-contractors, any one of which, if unable to demonstrate copper process capability, can probably expect to appear deficient in their capability and process knowledge, which may affect their image, perhaps limiting their business potential and profits. On the other hand, it is in the interests of wire and equipment companies to promote the uptake of copper wire bonding, promote the superiority of their technical solutions and support to sub-contractors and try to gain a premium and high reputation for copper bonding wires and process capability. The sale of copper kits that can be retrofitted to existing bonding machines or included as part of new orders is an important and profitable revenue stream for bonding equipment manufacturers.

Table 7. The occurrence of cratering after HTST [4]

	HTST at 175°C					Total No. of craters
	100 h	200 h	300 h	500 h	1000 h	
Wire 1	0	0	0	0	0	0
Wire 2	0	0	0	0	0	0
Wire 3	0	0	0	0	2	2
Wire 4	4	8	0	0	0	12
	HTST at 200°C					
	100 h	**200 h**	**300 h**	**500 h**	**1000 h**	
Wire 1	0	0	2	1	0	3
Wire 2	1	0	2	5	0	8
Wire 3	0	0	2	0	2	4
Wire 4	1	0	0	0	0	1

Figure 22

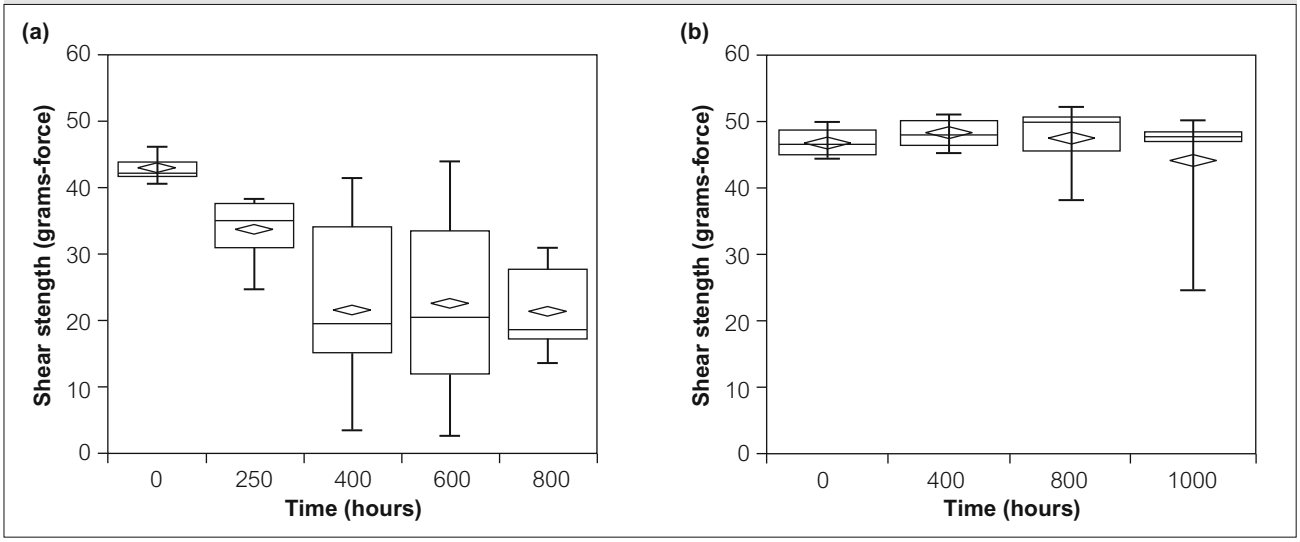


Mechanical strength after ageing at 200°C. (a) Pull strength (b) shear strength [4]

Table 8. Percentage of Pd-plated Cu, Au and Cu wire failures in TCL, THB, PCT and solder reflow tests [33]

Test	Duration	% Failures by wire type		
		Pd-plated Cu	Au	Cu
TCL (-65-150°C)	1000 cycles	0	0	91
THB (85°C, 85%RH, 10V)	1000 hours	0	0	3
PCT (121°C, 100%RH, 2 atm)	125 hours	0	0	95
Solder reflow (260°C)	3 times	0	0	0

Figure 23



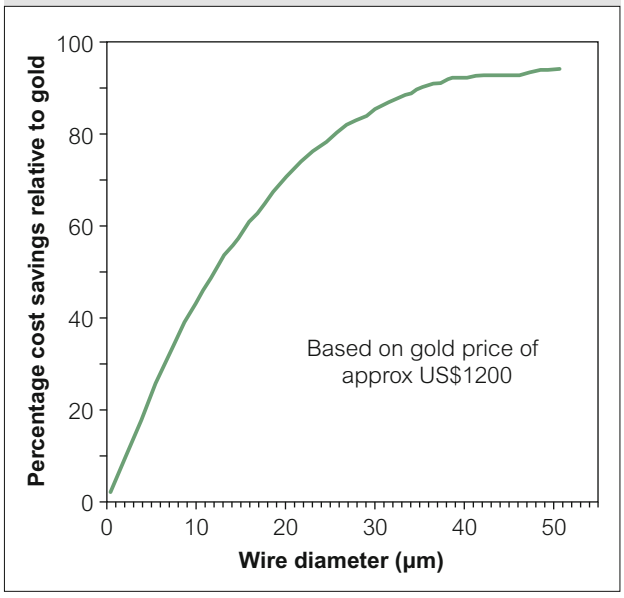
Box plot of shear force after PCT for (a) bare Cu wire and (b) Pd-coated Cu wire (data re-plotted from [34])

The primary motivation for uptake of copper wire bonding is however, more strongly cost driven rather than motivated by very clear and distinct process, performance or reliability advantages. Inevitably there will be cases where using copper may enhance device performance and as industry gains more experience with copper, it is sure to invade areas where gold has been dominant. Wire cost considered alone can result in significant savings as Fig. 24 [36] shows and the savings are more at larger wire diameter. In terms of the relative cost of manufacturing a package with copper and gold wire, it is possible to make savings simply based on the lower cost of copper. Ramos [37] presented an overview of copper wire bonding costs citing the example of a QFN (Quad Flat No-lead) package (a particular type of chip assembly) with 85 wires per device. Fig. 25 shows Ramos' estimate that there is an increase in the manufacturing costs (overhead) of about 10% for this particular example while wire cost savings are in the region of 85%. Capillary life tends to be shorter with copper wire because it is harder, which means increased capillary consumption and additional cost from the slightly lower throughput due to the use of forming gas. Ramos' conclusions are that implementation of copper wire bonding requires careful consideration of investment, process engineering and logistics and of course package type is important too. Implementing copper is possible with lower cost packages but may have serious implications for high reliability applications such as military, medical and automotive electronics.

4 Summary, conclusions and final comments

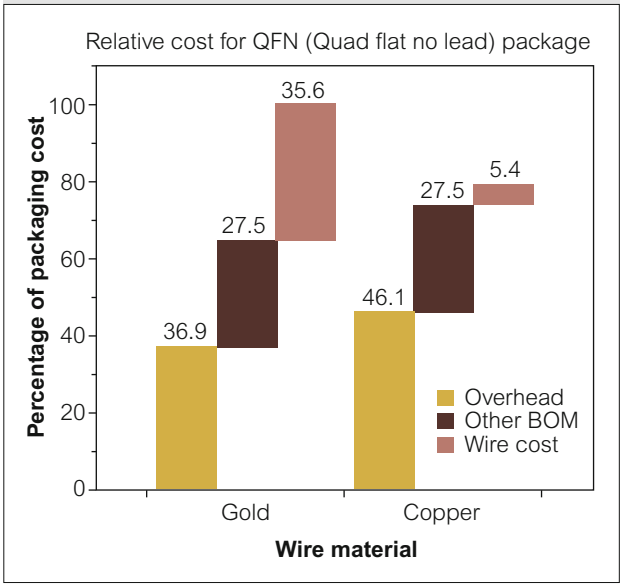
While larger diameter copper wire has been utilized in many applications for some considerable time, copper bonding wire is not a 'drop in' solution for gold wire and should not be seen as such in fine and ultra-fine pitch applications. Copper wire from different suppliers can differ considerably in purity and mechanical properties and while process

Figure 24



Cost savings when using copper wire instead of gold as a function of wire diameter. After Dittmer [36]

Figure 25



Relative cost of manufacturing a QFN (Quad Flat No-lead) package with 85 wires per device in a matrix of 9x9 devices. Data after Ramos [37]

parameter manipulation and capillary geometry offer limited control of bonded ball properties, stitch bond response depends on as-drawn wire properties. Put simply, copper is not gold and it is unreasonable, given the different physical and chemical characteristics of each metal, to expect copper simply to bond in the same way as gold.

From a performance point of view, gold can be as reliable as copper wire in HTST but copper is facing problems in more challenging stress tests such as temperature cycleling and PCT that is driving the evaluation of Pd-coated Cu wires. There is no doubt that copper can and should replace gold wherever viable but the main driving force to do so, at present, is cost reduction. However, it has yet to be understood how processes after copper wire bonding are affected by replacing gold with copper. At the moment there isn't a clear cost model for implementing copper wire bonding and it is uncertain if there are cost savings or cost penalties with downstream processes.

There is clearly a place for copper wire bonding in fine and possibly ultra-fine wire bonding but it is likely that rather than replacing gold wire entirely, copper wire bonding will become another process tool alongside gold wire bonding, flip chip, TSV (through silicon via) and other interconnect methods, which microelectronics package designers can consider for package assembly.

About the author

Dr. Christopher Breach owns and manages ProMat Consultants. His expertise is in the areas of polymer physics and physical chemistry, materials characterization, materials science and engineering in microelectronics packaging, intermetallics and interdiffusion, bonding wire (micro-alloy) design. He earned his PhD in physics & physical chemistry of polymer blends (sponsored by the Defence Research Agency) from Brunel University, London. He has held senior management positions in assembly materials for electronics packaging and capital equipment. His postdoctoral research was sponsored by ICI at the Department of Physics, Cavendish Laboratory, University of Cambridge on contact mechanics between polymers, polymer interdiffusion (reptation) and the physics of bi-material fracture. He is a Chartered Scientist, Chartered Physicist and Professional Member of the Institute of Physics. He is also a member of The Institute of Electrical and Electronics Engineers (IEEE), the Materials Research Society (MRS) and the Electrochemical Society (ECS).

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