

Physical Boundaries of Gold and Copper Ball Formation

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Abstract

The use of copper ball bonding instead of the traditional gold ball bonding is rapidly increasing within the semiconductor industry. Characterizing the dominant physical parameters that affect ball formation at the tip of a gold or copper wire becomes essential. Two processes dominate the resulting ball characteristics: (a) Shaping of the melt, i.e., ball formation due to the surface tension force; and (b) Solidification of the melt due to the heat loss. A theoretical order-of-magnitude analysis based on assessment of characteristic times of competing dominant processes was conducted. The analysis indicated that the existence of a critical limiting wire diameter under which solidification is expected to occur prior to complete ball shaping, results in distorted and non-spherical balls. Analysis results agree with experimental data. Nevertheless, the agreement of the qualitative trends and the order-of-magnitude of the results are very meaningful and of great significance. A dimensionless number is presented to support different wire material analysis.

Key words: Wire bonding, Gold wire, Copper wire, Ball formation.

Introduction

During the last decade, there has been an increasing driving force to use copper ball bonding instead of the traditional gold ball bonding. Naturally, the main advantage of copper ball bonding is materials cost reduction as the price of copper is lower than gold. However, bondability issues caused by the oxidation of the copper wire must be overcome, [1] before copper ball bonding is widely accepted in the semiconductor industry. Characterizing the dominant physical parameters that affect ball formation at the tip of a gold or copper wire is a focus of interest. The technique of forming a ball at the tip of the wire is a crucial stage in the ball bonding process [2]. In general, the use of finer wires, as well as smaller ball diameters, is desirable. However, there are indications that a decrease in the wire diameter should be accompanied by an increase in the ball-to-wire diameter ratio to avoid formation of distorted or non-spherical balls. The present investigation presents the qualitative behavior of competing processes that can explain the observed trends. A possible theoretical lower limit of gold and copper wire diameter associated with the ball formation process is revealed.

List of symbols and abbreviations

a - Characteristic acceleration, see Eq. (10).

C_p - Specific heat.

d - Wire diameter.

d_c - Critical wire diameter, see Eq. (33).

dT/dx - Temperature gradient established within the wire.

D - The resulting ball formed diameter.

D_{Nor} - Normalize diameter, see Eq. (32).

F - Characteristic upward force due to surface tension, σ , see Eq. 7 and 9.

$g(\beta)$ - See Eq. (6).

$G_{for}(\beta)$ - Function which, is part of the characteristic ball formation time, see Eq. (13).

$G_{sol}(\beta)$ - Function which, is part of the characteristic solidification time, see Eq. (25).

h - Heat transfer coefficient.

h_m - Heat of melting per unit mass.

k - The ratio between the length of a wire section which, melts by instant of the spark discharge to wire diameter, see equation (1).

ℓ (Index) - Stands for liquid.

L – Length of a wire section that, melts by instant of the spark discharge, see Fig. 1.

m - Melt mass.

$\dot{q}$ - Conduction heat transfer through the wire, see Eq. (15).

Q - Overall latent heat capacity, see Eq. (14).

s (Index) - Stands for solid.

S - The path that, the center of gravity moves from the initial to the final position, see Fig. 1 and Eq. (5).

t_{for} - Characteristic formation time, see Eqs. (11) and (12).

t_{sol} - Characteristic solidification time, see Eqs. (21) and (24).

T_a - Ambient temperature.

T_m - Melting temperature.

α - Thermal diffusivity, see Eq. (23).

β - Ball-to-wire diameter ratio = D/d .

Δx - Axial length over which temperature variation takes place (see Fig. 2).

$\Delta T = T_m - T_a$ - Temperature differences.

$\frac{\Delta T}{\Delta x}$ - Approximate of temperature gradient established within the wire.

θ - The surface tension angle, see Fig. 1.

λ - Heat conduction coefficient.

ρ - Density.

σ - Surface tension.

$\Phi(\beta)$ - Volume correction, percentage of the ball volume, which is part of the wire, see Eq. (3) and Fig. 1.

Physical Modeling

Physical trends can be demonstrated from an order-of-magnitude analysis of the characteristic time of competing processes. One assumes that at the instant of the spark discharge, a section of a length “ L ” at the tip of the gold or copper wire is heated to melting temperature T_m and melts. Two processes that can dominate the resulting ball characteristics are: (a) Shaping of the melt, i.e., ball formation due to the surface tension force; and (b) Solidification of the melt due to the heat loss. Whether the final result will be a symmetrical sphere or a distorted shape depends on the characteristic times of the ball formation process and the heat transfer process. The ball formation time should be shorter than the characteristic solidification time associated with the heat loss in order to avoid “freezing” of a distorted, non spherical-symmetrical shape.

General Geometric Dimensions

A section of a length “ L ” of a wire of a diameter “ d ” is melted, where

$$L = kd \quad (1)$$

The resulted formed ball diameter “ D ” can be calculated by using mass conservation and constant density assumption in addition to volume correction. See Fig. 1 - percentage of the ball volume that is part of the wire [3].

$$\frac{\pi d^2 L}{4} = \frac{\pi D^3}{6} \cdot (1 - \Phi) \quad (2)$$

Where β is defined as ball-to-wire diameter ratio, $= D/d$ and:

$$\Phi(\beta) = \frac{1}{4} \left[2 - 3 \left(1 - \frac{1}{\beta^2} \right)^{1/2} + \left(1 - \frac{1}{\beta^2} \right)^{3/2} \right] \quad (3)$$

For $\beta \gg 1$, $\Phi \approx 0$.

Substituting Eq. (1) in Eq. (2) yields:

$$k = \frac{2}{3} \cdot \beta^3 [1 - \Phi(\beta)] \quad (4)$$

For $\beta \gg 1$, $k \approx \frac{2}{3} \cdot \beta^3$

Characteristic Time of Ball Formation

One assumes that the characteristic ball formation time, t_{for} is equal to the time necessary for the center of gravity to move from the initial to the final position, i.e., a path S (see Fig. 1). A volume correction (percentage of the ball volume which is part of the wire) yields [4]:

$$S = \frac{L - g(\beta) \cdot D}{2} \quad (5)$$

Where:

$$g(\beta) = \sqrt{1 - \frac{1}{\beta^2}} + \frac{3}{4} \cdot \left[\frac{\Phi(\beta)}{1 - \Phi(\beta)} \right] \cdot \frac{\left(1 + \sqrt{1 - \frac{1}{\beta^2}} \right)^2}{\left(2 + \sqrt{1 - \frac{1}{\beta^2}} \right)} \quad (6)$$

For $\beta \gg 1$, g becomes 1 and $S = \frac{L - D}{2}$.

The characteristic upward force “ F ” due to surface tension σ is:

$$F = \pi \cdot d \cdot \sigma \cdot \sin(\theta) \quad (7)$$

Where: θ is the surface tension angle (see Fig.1). Simple geometrical relationships yield:

$$\sin(\theta) = \frac{1}{\beta} \quad (8)$$

Inserting Eq. (8) into Eq. (7) yields the characteristic upward force F due to surface tension, σ :

$$F = \pi \cdot D \cdot \sigma \cdot \frac{1}{\beta^2} \quad (9)$$

Characteristic acceleration, a , of the melt mass, m , due to the surface tension force is:

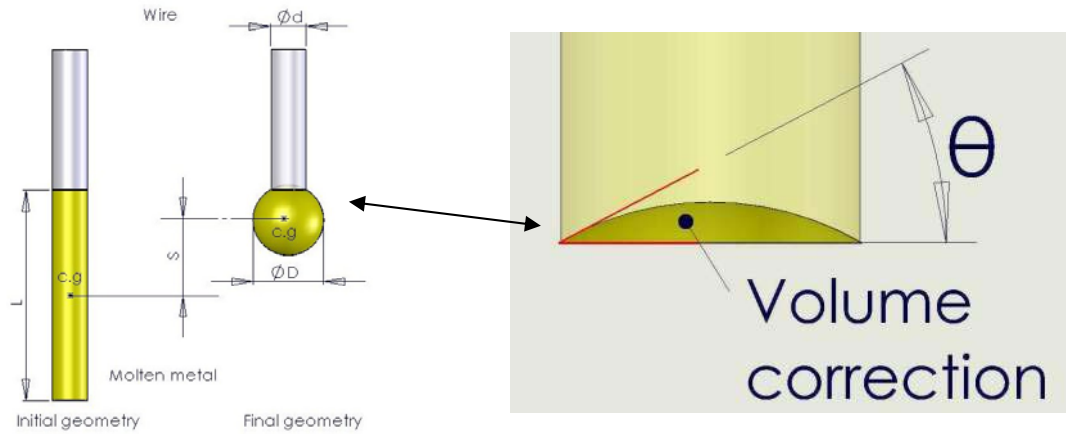


Fig. 1: Ball formation from a molten wire section.

$$a = \frac{F}{m} = \frac{\pi \cdot D \cdot \sigma \cdot \frac{1}{\beta^2}}{\rho_\ell \left(\frac{\pi D^3}{6} \right) \cdot (1 - \Phi)} = \frac{6\sigma}{\rho_\ell D^2} \cdot \frac{1}{\beta^2 \cdot (1 - \Phi)} \quad (10)$$

The index “ ℓ ” stands for liquid while index “ s ” represents solid. The characteristic ball formation time can, now, be evaluated from the acceleration and path [see Eqs. (5) and (10)], namely:

$$t_{for} = \left(\frac{2s}{a} \right)^{\frac{1}{2}} = \left(\frac{L - g(\beta) \cdot D}{a} \right)^{\frac{1}{2}} = \left[\frac{\rho_\ell D^2 (L - g(\beta) \cdot D) \cdot \beta^2 \cdot (1 - \Phi(\beta))}{6\sigma} \right]^{\frac{1}{2}} \quad (11)$$

Substituting Eq. (1) in Eq. (11), one obtains:

$$t_{for} = G_{for}(\beta) \cdot d^{\frac{3}{2}} \quad (12)$$

Where:

$$G_{for}(\beta) = \left(\frac{\rho_\ell}{6\sigma} \right)^{\frac{1}{2}} \left[(k(\beta) - \beta \cdot g(\beta)) \cdot \beta^4 \cdot (1 - \Phi(\beta)) \right]^{\frac{1}{2}} \quad (13)$$

$\Phi(\beta)$, $k(\beta)$ and $g(\beta)$ are defined in Eqs. (3), (4) and (6), respectively.

Characteristic Solidification Time

Due to the enormous heat conductivity of gold or copper, one can assume that the heat loss from the molten ball is mainly via heat conduction through the wire. The physical model considers an initial situation of a mass “ m ” of molten gold or copper at a wire tip, when the overall latent heat capacity is:

$$Q = mh_m = \rho_\ell \frac{\pi D^3}{6} (1 - \Phi) \cdot h_m \quad (14)$$

Where h_m stand for the melting heat per unit mass and ρ is the density.

The conduction heat transfer through the wire is:

$$\dot{q} = \lambda_s \frac{dT}{dx} \cdot \frac{\pi d^2}{4} \quad (15)$$

Where λ_s is the heat conduction coefficient and

dT/dx is the temperature gradient established within the wire. Indeed, a transient heat loss process takes place. Nevertheless, its characteristic rate can be assessed from a quasi-steady-state gradient established at the end of the solidification process. One may approximate this gradient as:

$$\frac{dT}{dx} = \frac{\Delta T}{\Delta x} \quad (16)$$

Where $\Delta T = T_m - T_a$ is the temperature difference between the melting temperature and the ambient temperature, and Δx is the axial length over which temperature variation takes place (see Fig. 2). If Biot number, which defined according to

the article notation as $\left(\frac{h \cdot d}{\lambda_s} \right) \cdot \frac{\beta}{6}$ where h stand

for Heat transfer coefficient, is equal to $\frac{1}{4} \left(\frac{d}{\Delta x} \right)$,

then the heat transfer, which is presented at Eq. (15), is identical to the heat transfer of a very long fin. The temperature at the end of the fin is essentially that of the surrounding [5]. Energy balance at this stage yields equality between the thermal energy contained within the wire and the overall heat released from the ball due to solidification:

$$\rho_\ell \frac{\pi D^3}{6} (1 - \Phi) \cdot h_m = \rho_s \frac{\pi d^2}{4} \Delta x \cdot C_{p,s} \frac{\Delta T}{2} \quad (17)$$

Where C_p - Specific heat.

Hence:

$$\Delta x = \frac{4 \cdot \rho_\ell \cdot h_m \cdot D^3 \cdot (1 - \Phi)}{3 \cdot \rho_s \cdot c_{p,s} \cdot \Delta T \cdot d^2} \quad (18)$$

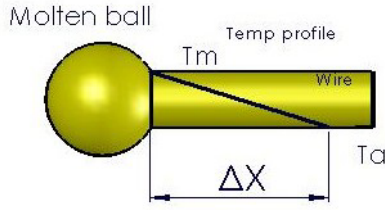


Fig. 2. Temperature gradient within the gold or copper wire.

In β terms:

$$\Delta x = \frac{4}{3} \cdot \left(\frac{\rho_l}{\rho_s} \right) \cdot \left(\frac{h_m}{C_{p,s} \cdot \Delta T} \right) \cdot \beta^3 \cdot (1 - \Phi) \cdot d \quad (19)$$

Now, the characteristic solidification time t_{sol} can be evaluated from the overall heat capacity and the heat transfer rate:

$$t_{sol} = Q / \dot{q} \quad (20)$$

Eq. (20) yields:

$$t_{sol} = \frac{m h_m}{\lambda_s \cdot \frac{dT}{dx} \frac{\pi d^2}{4}} \quad (21)$$

Substituting the ball mass “m” from Eq. (14), the conduction heat transfer from Eq. (15), using the temperature gradient from Eqs. (16) and (18), yields:

$$t_{sol} = \left(\frac{8}{9 \cdot \alpha_s} \right) \cdot \left(\frac{h_m}{C_{p,s} \cdot \Delta T} \right)^2 \cdot \left(\frac{\rho_l}{\rho_s} \right)^2 \cdot (1 - \Phi)^2 \cdot \frac{D^6}{d^4} \quad (22)$$

Where α_s is the thermal diffusivity of solid gold or copper.

$$\alpha_s = \left(\frac{\lambda}{\rho c_p} \right)_s \quad (23)$$

In terms of the ball-to-wire diameter ratio β , one

$$\text{obtains } t_{sol} = G_{sol}(\beta) \cdot d^2 \quad (24)$$

Where:

$$G_{sol}(\beta) = \left(\frac{8}{9 \alpha_s} \right) \cdot \left(\frac{h_m}{C_{p,s} \Delta T} \right)^2 \cdot \left(\frac{\rho_l}{\rho_s} \right)^2 \cdot (1 - \Phi(\beta))^2 \cdot \beta^6 \quad (25)$$

Qualitative Conclusions

Order-of-magnitude analysis of dominant phenomena during the ball formation has identified two major competing processes: the shaping or formation process and the solidification

(heat loss) process. As previously mentioned, in order for a spherical ball to be formed, the formation process has to be faster than the solidification process. In other words, the characteristic time of the former has to be shorter than the characteristic time of the later.

$$t_{for} < t_{sol} \quad (26)$$

The main qualitative result of the analysis is that the characteristic times of the two competing processes have different dependence on the wire diameter where:

$$t_{for} \propto d^{\frac{3}{2}} \quad (27)$$

$$t_{sol} \propto d^2 \quad (28)$$

For given geometrical parameters (constant k or β), such a situation could lead to a critical wire diameter, d_c . For wires of diameters smaller than the critical diameter $t_{sol} < t_{for}$, the material might solidify and a symmetrical sphere will form.

For larger wire diameters, $t_{for} < t_{sol}$, a symmetrical ball will form before solidification (see Fig. 3). This conclusion reveals a possible lower limit of wire diameter which enables tip gold or copper ball formation.

The model indicates the role of another important factor, namely the geometrical parameter k or β . For relatively large values of k or β , the formation time depends on k and β approximately as:

$$t_{for} \propto k^{\frac{4}{3}} \propto \beta^4 \quad (29)$$

Whereas the solidification time is relative

$$\text{to: } t_{sol} \propto k^2 \propto \beta^6 \quad (30)$$

It is obvious that under such conditions, the geometrical parameters have a greater effect on the solidification process. Therefore, when decreasing the wire diameter approaching a tighter competition between the solidification and formation processes, it should be easier to form a ball for larger k or β (as it will decrease the critical wire diameter). This conclusion is in agreement with the actual trend observed in the ball bonding process.

To calculate the critical wire diameter, d_c as a function of ball-to-wire diameter ratio, β ; t_{for}

must be equal to t_{sol} .

Using Eqs. (12), (13), (24) and (25), the resultant critical wire diameter is:

$$(31)$$

$$d_c = \left(\frac{G_{for}(\beta)}{G_{sol}(\beta)} \right)^{\frac{1}{2}} = \frac{\left(\frac{\rho_l}{6 \cdot \sigma} \right)}{\left(\frac{8}{9 \cdot \alpha_s} \right)^{\frac{1}{2}} \cdot \left(\frac{h_m}{C_{p,s} \cdot \Delta T} \right)^{\frac{1}{2}} \cdot \left(\frac{\rho_l}{\rho_s} \right)^{\frac{1}{2}}} \cdot \frac{[k(\beta) - \beta \cdot g(\beta)] \cdot \beta^4 \cdot (1 - \Phi(\beta))}{(1 - \Phi(\beta))^4 \cdot \beta^{12}}$$

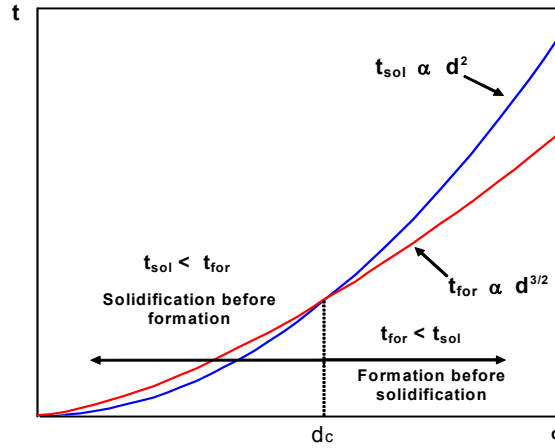


Fig. 3: Qualitative behavior of formation and solidification characteristic times indicating a possible lower limit for wire diameter, d_c , below which solidification occurs before complete ball formation.

By defining the normalize diameter, D_{Nor} as:

$$D_{Nor} = \frac{\left(\frac{\rho_l}{6 \cdot \sigma}\right)}{\left(\frac{8}{9} \cdot \alpha_s\right)^2 \cdot \left(\frac{h_m}{C_{p,s} \cdot \Delta T}\right)^4 \cdot \left(\frac{\rho_l}{\rho_s}\right)^4} \quad (32)$$

Eq. (31) Becomes:

$$\frac{d_c}{D_{Nor}} = \frac{k(\beta) - \beta \cdot g(\beta)}{(1 - \Phi(\beta))^3 \cdot \beta^8} \quad (33)$$

Function of only Ball-to-wire diameter ratio.

Eq. (33) can be illustrated by Fig. 4:

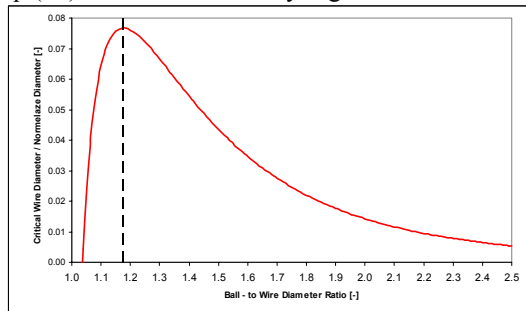


Fig. 4: Normalize Critical Diameter, $\frac{d_c}{D_{Nor}}$ as a function of Ball-to-wire diameter ratio, β .

Experiment Procedure

The formation of a Free Air Ball (FAB) is typically a function of Electronic Flame-Off (EFO) at current and firing time as well as during the surrounding gas (forming gas or ambient air) flow [7]. A complete K&S Model Maxum automatic wire bonder equipped with a copper kit was used during the experiment.



Fig. 5: K&S patented copper ball bonding kit.

To prevent copper ball oxidation during the flame-off process, a special EFO wand was used that was surrounded by special glass tube (see Fig. 5). Forming gas (95%N₂, 5%H₂) is supplied via a small tube to insure FAB formation in a reducing environment. Varying the EFO current while keeping the gas flow and firing time constant produces a direct correlation between the EFO current (hence energy) and FAB diameter. By using a special looping profile, each of the bonded wires was bonded only at its second bond, leaving the FAB un-deformed and in an upward position. A variety of K&S gold and copper bonding wires were used with various wire diameters. The gold wires, as well as the copper wires, were originated from the same melt. For each copper wire diameter, a proper "fire-time" was set in a way that the obtained FAB is round without any distortions due to a lack in spark energy. Once the EFO "fire-time" was fixed, the FAB formation was only a function of the EFO current. The FAB diameter was measured using an optical microscope (Field of view ~200 [μm]). Each of the measuring point's values represented an average of 20 FAB consecutive measurements.

Quantitative Results and Discussion

Tables 1 and 2 summarize the resultant ball diameter average and standard deviation (STD) as a function of EFO current, wire diameter and the forming gas flow rate for gold and copper wire, respectively.

Table 3 summarizes the resulting minimum FAB and the corresponding critical ball-to-wire diameter ratio, β . Small tube to insure FAB formation in a reducing environment.

Tables 1: Ball diameter average and (STD) as a function of EFO current, wire diameter and the forming gas flow rate for gold wire [μm].

Flow [SCFH]	W.D [mil]	EFO Current [mA]													
		12	14	16	18	20	25	30	35	40	45	50	60		
0	0.7		21.1 -0.6	25.1 -0.7	28.8 -0.6	31.9 -0.4	36.1 -0.6	40 -0.3	42.7 -0.5	45.3 -0.6	47.7 -0.8	50 -0.8	50.7 -1		
	0.8				26.3 -1.4	29.7 -0.9	36.2 -0.9	40 -0.9	44.5 -0.8	47.1 -0.6	50.2 -0.8	52.8 -0.5	54 -2.4		
	1			24.6 -0.6	28.4 -0.8	31 -0.6	35.9 -0.6	N.A	42.4 -0.5	N.A	47.1 -0.6	49 -0.7	52.6 -0.8		
	1.2			43.1 -0.6	51.6 -0.5	57.6 -0.5	63 -0.6	76 -2.1	80.6 -3.4	74.5 -4.1	73 -6	74.5 -6.8	74.7 -5.4		
0.9	0.8				25.8 -0.8	28 -0.6	35.6 -0.7	37.4 -3	44.4 -0.7	47.1 -1.1	50.1 -0.6	51.5 -1	56.7 -1.1		
	1		N.A		27.1 -0.6	32.9 -0.8	42.4 -0.5	49.3 -0.5	53.4 -4.2	58 -0.8	61.1 -0.6	65.2 -0.6	N.A		
	1.2		40.5 -0.5	48.8 -0.6	56 -1.4	61.3 -0.6	70 -1.8	78.1 -1.3	78.6 -3.4	78.7 -4	77.8 -2.5	75.5 -5.9	74 -4.3		
1.8	0.8			22.3 -0.6	26.2 -0.6	29.7 -1.7	36.3 -1.3	40.7 -1.2	44.3 -1.3	48.4 -0.4	50.8 -0.6	53.5 -0.7	57.2 -0.5		
	1.2		37.9 -1.8	47.2 -0.9	53 -1.1	59 -1.1	69.6 -0.9	76.6 -1.5	82.9 -1.4	82.3 -3.9	77.6 -6.1	75.2 -3.6	69.3 -7.2		
Un round FAB															
Minimum FAB															

Tables 2: Ball diameter average and (STD) as a function of EFO current, wire diameter and the forming gas flow rate for copper wire [μm].

Flow [SCFH]	W.D [mil]	EFO Current [mA]																	
		24	25	26	28	30	31	32	33	34	35	36	38	40	45	50	55	60	
0.9	0.8	N.A			N.A	25 -2.6	24 -2.5	N.A	27 -3.6	N.A	29 -4.2	N.A	N.A	32 -3.3	39 -2.2	43 -2	N.A	47 -1	
	1	N.A			31 -0.7	33 -1.6	N.A	36 -3	N.A	39 -3	N.A	43 -0.7	45 -1	48 -0.7	52 -1	56 -0.9	59 -0.8	62 -0.5	
	1.2	56 -1.4	N.A	59.6 -1	63 -1	66 -1	N.A	68 -1.3	N.A	70 -2.5	N.A	72 -2.6	N.A	77 -2	79 -3.9	81 -4	76 -3.9	74 -5.6	
1.8	0.8	N.A	23 -1.3	N.A	N.A	30 -2.7	31 -2.6	N.A	33 -2.3	N.A	34 -2.7	N.A	N.A	38 -2.7	39 -3.5	44 -1.7	45 -1.5	47 -2.3	
	1.2	N.A		56.6 -1.4	61 -1.1	63 -1.9	N.A	67 -1.3	N.A	68 -1.3	N.A	71 -1.4	N.A	74 -1.3	77 -2.2	81 -2.4	78 -5.1	77 -6.8	
Un round FAB																			
Minimum FAB																			

Table 3: Minimum FAB and the corresponding critical ball-to-wire diameter ratio

Material	Flow	Wire	Wire	Critical Ball-to- wire diameter ratio	Minimum Ball formed diameter		Minimum EFO Current	Fire Time
	Rate	Diameter	Diameter		[μm]			
	[SCFH]	[mil]	[mil]		Avg.	STD	[mA]	[μSec]
Gold	0	0.7	0.7	1.19	21.1	0.6	14	150
		0.8	0.8	1.46	29.8	0.9	20	182
		1	1	0.97	24.6	0.6	16	350
		1.2	1.2	1.41	43.1	0.6	16	1000
	0.9	0.8	0.8	1.38	28	0.6	20	182
		1	1	1.07	27.1	0.6	18	350
		1.2	1.2	1.33	40.5	0.5	14	1000
	1.8	0.8	0.8	1.1	22.3	0.6	16	182
1.2		1.2	1.55	47.2	0.9	16	1000	
Copper	0.9	0.8	0.8	1.91	38.8	2.2	40	182
		1	1	1.22	31	0.7	28	350
		1.2	1.2	2.16	66	1	30	1000
	1.8	0.8	0.8	2.21	45	1.5	35	182
		1.2	1.2	2	60.9	1.1	28	1000

Engineers should be very careful when using quantitative values since they are based on an order-of-magnitude analysis that makes use of characteristic, not precise values. Nevertheless, if the resulting characteristic times of the competing processes are found to be of the same order, it means that one may be operating near a problematic limit of the process. The physical properties of gold and copper gathered from the literature, [5, 6]. Represents average values over the ranges of interest. Inserting normalized critical

diameter $\frac{d_c}{D_{Nor}}$ as a function of ball-to-wire

diameter ratio, β (using the physical properties) relative to the theoretical line (Equation (33) and Figure 4) in addition to ± 10 [%] bar of the specific heat and the heat conduction coefficient, yielded (Fig. 6) actual results vs. a theoretical order-of-magnitude model.

From results, it was concluded that the gold wire resulted in lower values than the theoretical line. Furthermore, the copper wire resulted in higher values than the theoretical line predicted.

It is important to emphasize that this analysis is only an *order-of-magnitude* calculation. For example, small changes in characteristic solidification time can cause partial solidification resulting in a distort Free Air Ball.

Furthermore, it was found that, in general, D_{Nor} was extremely sensitive to the thermal properties and, in particular, to the specific heat $C_{p,s}$ and the heat conduction coefficient λ_s . Reducing the same gold wire properties by 10 [%], D_{Nor} reduced by ~ 34 [%] to 1022 [μm] from 1556 [μm]. Similarly, a reduction of gold wire properties by 20 [%] imposed a reduction of D_{Nor} by ~ 59 [%] to 638 [μm]. This "pushed" the results to the theoretical line. By using the information from [6] (Chapter 4, Page 147) regarding the heat conduction coefficient as a function of temperature, the extrapolation value was about 8 [%] smaller at 800 [K] which was used at the characteristic formation and solidification time for a range of wire diameters from 5 [μm] to 30 [μm] and a ball-to-wire diameter ratio, β from 1.15 to 1.6 [-], the following observations were noted:

- Two competing processes, namely ball formation (shaping) and solidification, had very similar characteristic times (of the order of microseconds; typical value ~ 10 [μs]).
- D_{Nor} of copper relative to gold was found to be 0.26, indicating that the critical diameter of copper was higher than gold for the same ball-to-wire ratio.

Axial length over which temperature variation took place, Δx (see Fig. 2) of copper was almost similar to gold. This suggests that Δx can be correlated to the Heat Affected Zone (HAZ).

The critical wire diameter for which the solidification time curve crosses the formation time curve appeared to be relatively close to the actual wire diameters used in the ball bonding process. In fact, the actual wire diameters in the different test conditions appeared to be slightly larger than the corresponding critical diameters in these conditions for the copper wire and the opposite for the gold wire. Increasing the geometric parameters "k" or " β " resulted in an increase of the two characteristic times under consideration. However, this increase was not by the same factors, resulting in decrease of the critical diameter. This result indicated that when working with smaller wire diameters, an increase of the geometric factor may be required, namely, larger ball-to-wire diameter ratios. Figure 6 presents the dependence of the critical diameter d_c on β and shows, on the same graph, the conditions corresponding to the actual experiments that yielded symmetrical balls. Actual test conditions seem to follow, yet a little higher or lower, than the theoretical limit, exhibiting excellent agreement with the trend of variation of d_c with β (or k).

The agreement of the qualitative trends and the order-of-magnitude of the results are very meaningful and of great significance.

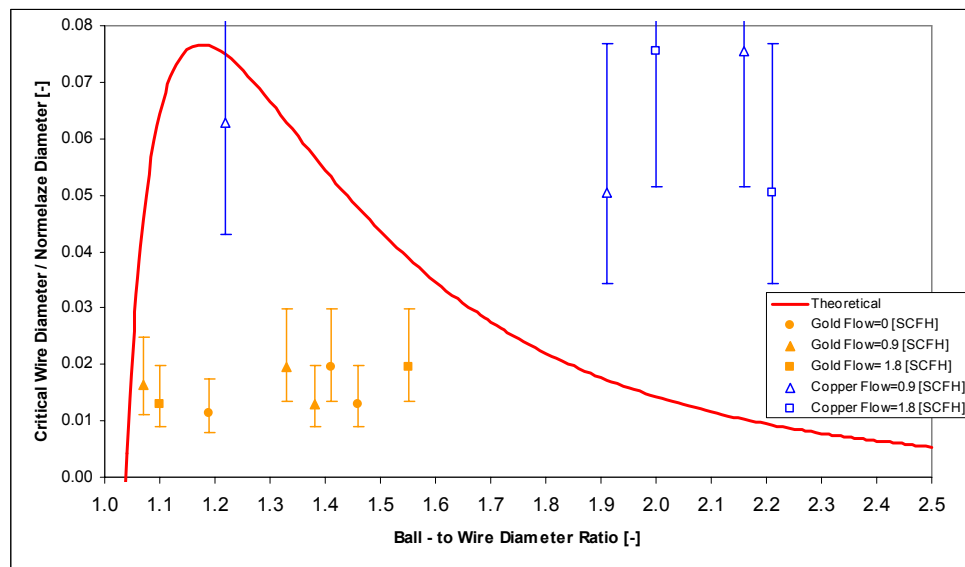


Fig. 6: Actual results vs. a theoretical order-of-magnitude model.

Conclusions

The maximum normalized theoretical critical

diameter $\frac{d_c}{D_{Nor}}$ is ~ 0.0767 [-] and occurs at

$\beta \sim 1.175$ [-] (see Fig. 4).

A theoretical analysis, based on the assessment of characteristic times of competing dominant processes during ball formation via melting of the tip of a gold or copper wire, reveals that the formation (shaping) process and the solidification process have very similar characteristic times. The different dependence found for each of these

processes, namely for $t_{for} \propto d^{\frac{3}{2}}$ and $t_{sol} \propto d^2$, indicates the existence of a critical limiting wire diameter under which solidification is expected to occur prior to complete shaping of the ball, resulting in distorted, non-spherical balls. Larger ball-to-wire diameter ratios β were found to lower the critical diameters, enabling the use of smaller wire diameters.

The analysis explained the experimental trends, showing a need to increase β when decreasing wire diameters. It also revealed that experimental data of successful ball formation are situated somewhat above the critical diameter limit, exhibiting a very similar trend.

Acknowledgment

The authors wish to thank Mr. Giyora Gur, Mrs. Miriam Kuperstich and Mrs. Yonit Gordon for their major contribution in experimental and edit procedure.

References

- [1] Shingo Kaimori, Tsuyoshi Nonalku, Akira Mizoguchi, "The Development of Cu Bonding with Oxidation Resistant Metal Coating", IEEE Transactions on Advance Packaging, Vol. 29, No 2, pp. 227-231, (2006).
- [2] Jonathan Tan, Zhao Wei Zhong, Hong Meng Ho, "Wire – bonding process development for low – k materials", Microelectronic Engineering, 81, pp. 75-82, (2005).
- [3] Murray R. Spiegel, "Mathematical Handbook of Formulas and Tables", McGraw-Hill Book Company, New York, P.9 – 4.41, (1968).
- [4] Harris J. W. and Stoker, H., "Handbook of Mathematics and Computational", Chapter 4.8.4 - Spherical Segment (Spherical Cap), New York, Springer Verlag, P.107, (1998).
- [5] J.P.Holman, "Heat Transfer", Fifth edition, McGRAW-HILL, pp. 38-41, p.636, (1981).
- [6] David R. Lide, "The CRC Handbook of Chemistry and Physics", Chapters 4,512, and 15, CRC Taylor & Francis, 73th. Edition, London, Tokyo, (1992 - 1993).
- [7] Yee Chen Tan, Boon Hoe Toh, Hong Meng Ho, Jonathan Tan "Free Air Ball Modeling for Gold Wire Bonding for Different Wire Diameters", IMAPS Taiwan Technical Symposium, pp. 42-47, (2006).