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Research Article

Technical Barriers and Development of Cu Wirebonding in Nanoelectronics Device Packaging

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Bondpad cratering, Cu ball bond interface corrosion, IMD (intermetal dielectric) cracking, and uncontrolled post-wirebond staging are the key technical barriers in Cu wire development. This paper discusses the UHAST (unbiased HAST) reliability performance of Cu wire used in fine-pitch BGA package. In-depth failure analysis has been carried out to identify the failure mechanism under various assembly conditions. Obviously green mold compound, low-halogen substrate, optimized Cu bonding parameters, assembly staging time after wirebonding, and anneal baking after wirebonding are key success factors for Cu wire development in nanoelectronic packaging. Failure mechanisms of Cu ball bonds after UHAST test and CuAl IMC failure characteristics have been proposed and discussed in this paper.

1. Introduction

Cu wirebonding is widely adopted in recent nanoelectronic packaging due to its conductivity, material properties, and cost effectiveness. However, there are few key technical barriers to be seriously considered in order to get a full transition from Au to Cu ball bonds in semiconductor packages. Post-unbiased HAST Cu wire resistive open failures were widely investigated by researchers and mainly are attributed to CuAl IMC interface corrosion [1–6]. Chan [7], Chee [8], and Tan and Yarmo [9] found that silicon cratering is a failure mode as a result of overbonding parameter especially with Cu wire. Effects of molding compound pH level and Cl^- content (in ppm) on UHAST reliability test have been investigated by Su [10]. Some researchers proposed palladium-coated Cu wire to be used instead of bare Cu wire [11]. Tan et al. [4] reported Cu ball bonds are more susceptible to CuAl corrosion cracking postreliability stress in such tests as Autoclave, HAST test, and HTSL (high temperature storage life). Yow and Eu [12, 13] reported on the implementation of an extra high temperature bake after wirebonding, but prior to encapsulation, to grow CuAl intermetallic layer and increase Cu ball strength. CuAl IMC formation dominates the bond reliability, and IMC phases of CuAl have been widely investigated [14–19]. It is crucial to conduct and identify those key technical barriers with Cu wirebonding in nanoelectronic device packaging which will ensure successful Cu wirebonding deployment in high pin count and nanoscale devices. In this study, the bond reliability under different factors such as green and non-green package materials, optimized and excessive bonding conditions, assembly staging time, and resulting bond shear per square mil of Cu bond are investigated in the testing of UHAST. The failure mechanism at bond interface and proposal for resolving these technical barriers to Cu wirebonding are established.

2. Experimental

2.1. Materials and Preparation of Cu Wirebond Package with 90 nm Device. The key materials used include 0.8 mil Cu wire, fine pitch BGA packages, 90 nm low-k devices which were packaged into fortified fine pitch BGA package, and green (<20 ppm chloride in content) and non-green (>20 ppm or uncontrolled of chloride content) molding compound and substrates. The 90 nm, low-k devices had

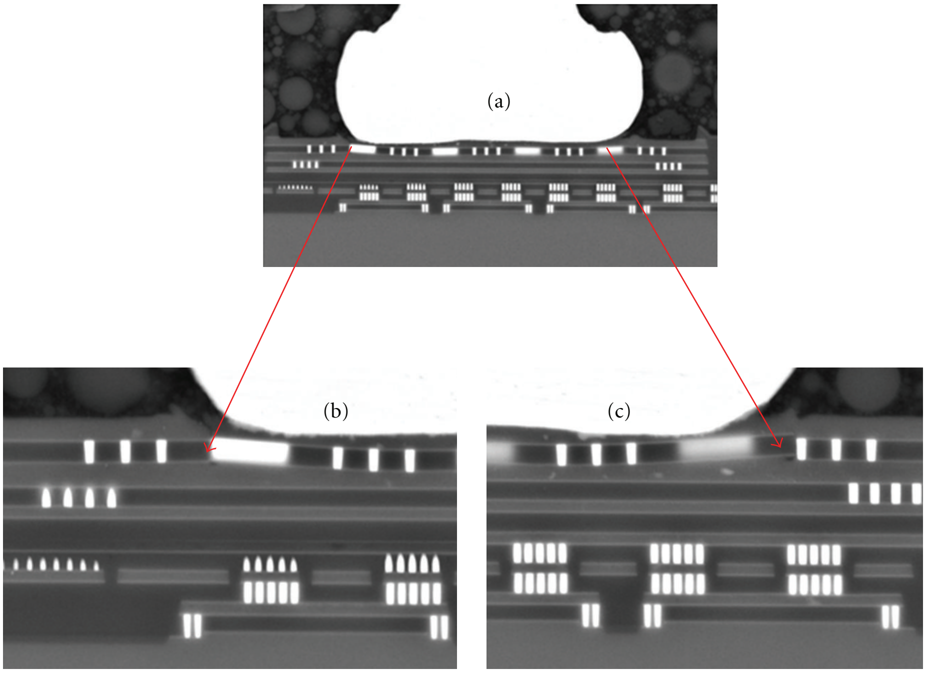

Figure 1: (a) Cratering at both Cu ball bond edges of leg no. 2 (b) and (c) IMD (Inter Metal Dielectric crater and crack) at silicon level.

top Al metallization bondpads of 0.80 um. In this Cu wire development study, there are total 7 legs comprising of bare Cu wire bonded on Fine pitch 64-ball BGA packages on a 2-layer substrate. The corresponding sample size is tabulated in Table 1. After electrical test, good samples were then subjected for preconditioning and 3-time reflow at 260°C as described in JEDEC IPC-STD 020 standard, followed by unbiased HAST (UHAST) stress testing per JESD22-118 at (130°C/85% RH) [20]. Electrical testing was conducted after 96 hours of stress to check Cu ball bond integrity in terms of its moisture reliability with various conditions. Results of UHAST reliability test of our evaluation are tabulated in Table 1.

2.2. Reliability Testing of Nanoelectronic Package. As mentioned, prior to Unbiased HAST reliability stress test, the nanoelectronic packages were subjected to preconditioning (30°C, 60% RH) for 192 hours in a temperature and humidity chamber, followed by 3 cycles of reflow at 260°C by using reflow chamber as per JEDEC STD 020 standard. The moisture reliability testing was performed using a UHAST chamber and the sample electrical testing was performed at room and hot temperatures. First, samples were heated from room temperature and humidity to 130°C and 85% RH humidity. The samples were stressed in this environment for 96 hours. After 96 hours, electrical open, short, and device datasheet functionality was verified by using a commercial electrical tester. Microstructure of failing units was determined by using cross-section and SEM (scanning electron microscopy), and a chemical composition analysis was conducted by using EDX (energy dispersive X-ray).

3. Results and Discussion

3.1. Silicon Cratering and IMD Cracking

3.1.1. Key Challenges and Development. Cu wire is well identified as a harder material compared to Au wire in nanoelectronic packaging. Cratering (latent or otherwise) is one of the bonding failures attributed to over-bonding and appears as damage to the layers under bondpads [1, 2, 9]. Large stresses can be imparted on the layers under the bondpad as well as the silicon, leading to open failures. Sometimes, improper bonding over thin top Al metallization (<1.0 μm in thickness) will induce IMD (Inter-Metal Dielectric) cracking as depicted in Figure 1(a). It is crucial to implement optimized bonding parameters in devices with thin active circuits under bonding pads with Cu ball bonding [2, 3, 7, 8]. In our evaluation, overbonding parameter in Leg no. 2 is found with UHAST 96 hr opens which is attributed to IMD cracking as shown in Figures 1(a), 1(b), and 1(c).

According to the observation of Chen et al. after Cu wirebonding, there is a residual stress remaining around the perimeter of the Cu ball bond, primarily due to the capillary bonding pressure. The maximum residual stress gradient under pad occurs at the bond periphery [6] and is the primary root cause of IMD collapse and cracking beneath Cu ball bond. Hence it is a crucial step in Cu wirebonding development to identify and optimize the bonding parameter window in order to eliminate silicon cratering and IMD cracking. Severe IMD cracks may also cause cratering during wire pull test, and Tan and Yarmo [9] reported the silicon cratering during wire pull test after reliability tests.

Table 1: Cu wirebonding reliability development study.

Leg	Wire	Experimental parameter	Green/non-green materials	UHAST 96 hr results (no. of failures/sample size)
1	Cu wire	Nominal bonding parameter	Green substrate Green mold compound	0/25
2	Cu wire	High bonding parameter	Green substrate Green mold compound	1/25
3	Cu wire	Green mold compound (<20 ppm Cl^-)	Green substrate Green mold compound	0/50
4	Cu wire	Non-green mold compound (>20 ppm Cl^-)	Green substrate Non-green mold compound	31/50
5	Cu wire	3-days staging after wirebond	Green substrate Green mold compound	0/50
6	Cu wire	7-days staging after wirebond	Green substrate Green mold compound	2/50
7	Cu wire	10-days staging after wirebond	Green substrate Green mold compound	1/50

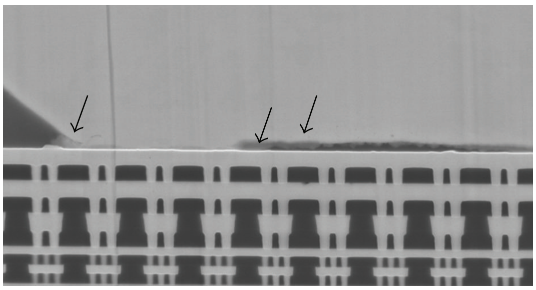

Figure 2: Initial CuAl IMC formation starts at both edges of Cu ball bond periphery.

Table 2: EDX analysis of CuAl IMC crack region post-UHAST 96 hr opens: non-green mold compound (Leg 4).

Leg	Element	Atomic %
4 (non-green mold compound)	O	8.64
	Al	8.17
	Si	1.89
	Cl	0.68
	Cu	78.23
	Ta	2.40

Hang et al. posit that the deformation microstructures at Cu ball bond periphery also decrease the activation energy of metal atoms for interdiffusion and accelerate the initial CuAl IMC formation at the edge of Cu ball bond [14]. We also observed similar initial CuAl IMC formation at ball bond edges as shown in Figure 2.

3.2. Effects of Green Packaging Material

3.2.1. Green Molding Compound and Substrate. Leg no. 4 (Cu wirebond package which is assembled with non-green molding compound) observed severe post-UHAST 96 hr opens and Cu ball bond interfacial corrosion/cracking. Elemental analysis (EDX) was performed on failing Cu ball bonds and it revealed presence of 0.68 atomic % of Cl as indicated in Figure 3(a) and in Table 2. The presence of Cl in the EDX spectrum is believed to originate from the non green molding compound itself used in Leg 4.

Representative Cu ball bond FIB cross-section SEM images confirm CuAl interface corrosion/cracking as shown in Figure 3(b) The detail of the mechanism of Cu ball bond interfacial corrosion and later cracking with non-green molding compound is addressed in a subsequent section. However, the data indicate the importance of implementation of Cu wirebonding in nanoelectronic packaging with green molding compound and substrate material in BGA laminates.

There is no presence of Cl^- in the Cu ball bond of UHAST 96 hr survivors (for Leg 3). SEM cross-section results as shown in Figures 4(a), 4(b), and 4(c) for green mold compound leg (Leg no. 3) show normal IMC growth and solid bonding.

Confirmation on UHAST survivor from Leg 3 (Green mold compound) indicates no presence of Cl^- element at center of CuAl IMC region. Table 3 tabulates the detailed EDX analysis results.

Su [10] reported that the green mold compound used in Cu wirebond package will affect the biased HAST reliability failure rate. The data indicated a striking effect on the reliability based on the pH and Cl content in mold compound. The lower the pH (more acidic) and the higher the Cl content are, the poorer the reliability is. CuAl IMCs are generally more susceptible to moisture corrosion and the impacts of corrosion have been reported in recent Cu ball bond studies [1, 4, 5, 10, 21–23]. Hence, green mold compound with a preferably low Cl content and high pH is recommended for use in Cu wirebonding for high volume manufacturing and to ensure moisture reliability performance.

3.3. Effects of Post-Wirebond-Staging Time and Extra Thermal Treatment. It has been a challenge to ensure Cu ball bond integrity in nanoelectronic packaging through various wire

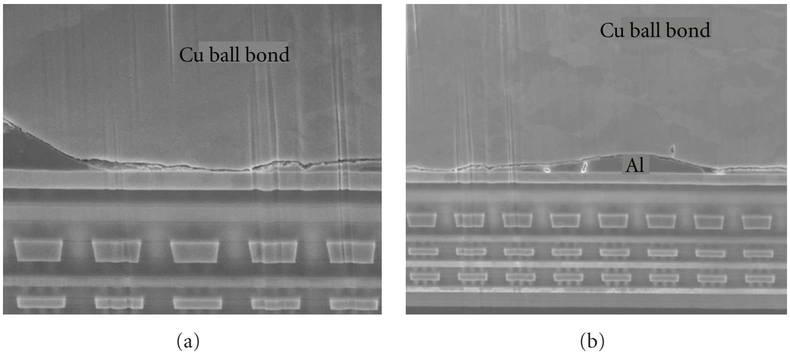

FIGURE 3: (a) CuAl IMC crack region post-UHAST 96 hr opens (b) Cu ball bond corrosion and interface cracking between CuAl IMC of Leg no. 4.

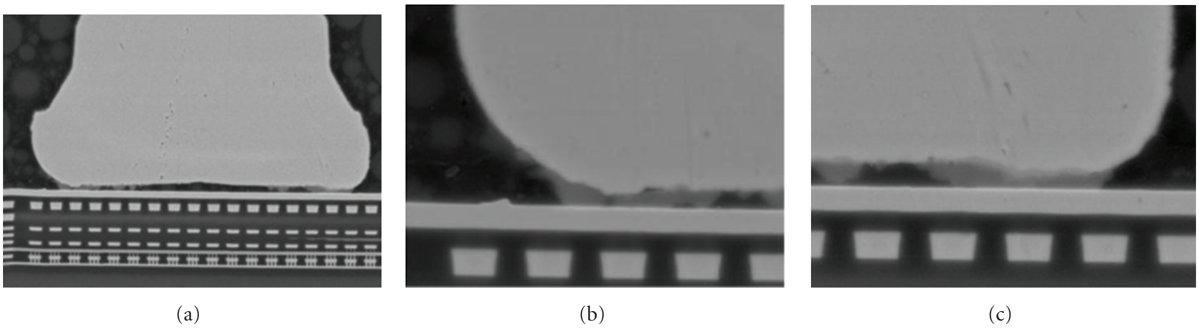

FIGURE 4: (a) Cu ball bond, (b) and (c) edges of Cu ball bonds—no Cu ball bond corrosion or weaknesses with Green molding compound (Leg no. 3).

TABLE 3: EDX analysis of CuAl IMC crack region post-UHAST 96 hr opens: green mold compound (Leg 3).

Leg	Element	Atomic %
3 (Green mold compound)	O	1.48
	Al	11.02
	Si	0.98
	Cu	83.14
	Ta	3.38

bonding enhancement approaches. Yow and Eu [12, 13] reported on the implementation of an extra high temperature baking post-wirebonding step prior to encapsulation to grow CuAl intermetallic layer and increase Cu ball strength. This can subsequently reduce Cu ball bond intrinsic stresses and in turn eliminate or mitigate bondpad cratering especially with harder Cu wire. The bake temperature can be as high as 125°C for 4 hours. Dry metal corrosion (oxidation in an O_2-containing environment at high temperatures) results in a metal-oxide (MxOy) formation on the surface of the metal. In our case, Legs 5, 6, and 7 of Cu wirebonded units were staged at production floor for several days and subsequently sent through preconditioning and UHAST test to check the effects of assembly staging time on UHAST reliability performance (as tabulated in Table 1).

In our Cu wirebonding staging studies (Leg 5–7), wirebonded units were staged at the production floor for a number of days prior to package encapsulation or molding step. Assembly staging time should normally be closely monitored and controlled to prevent Cu ball bond oxidation at production floor, and based on the results of our evaluation (Leg no. 5 to Leg no. 7), it appears to be that the appropriate staging time after Cu wirebond step to encapsulation step should be gated to less than 3 days, as UHAST 96 hr opens are observed with 7 days and 10 days of staging time. However, some industry data recommends bare Cu wire spool lifespan to be controlled less than 10 days on the factory floor [1]. The effect of assembly staging time on UHAST reliability of Cu ball bond is crucial to understand and could vary based on the assembly process and material set. The detailed failure mechanism is proposed as in (1) to (4) as follows:

$$\mathrm{Cu} + \mathrm{O_2} \longrightarrow 2\mathrm{CuO} \quad \text{(Cu oxide layer—dry metal oxidation)}, \tag{1}$$

$$\mathrm{CuO} + \mathrm{H_2O} \longrightarrow \mathrm{Cu(OH)_2} \quad \text{(wet corrosion and hydrolysis of Cu oxide under UHAST)}, \tag{2}$$

$$\mathrm{Cu_9Al_4} + 4\mathrm{O_2} + \mathrm{H_2O} \longrightarrow 4\mathrm{Al} + 9\mathrm{CuO} + \mathrm{H_2} \quad \text{(oxidation of CuAl IMC—in humid air environment)}, \tag{3}$$

$$2\mathrm{CuAl_2} + \frac{1}{2}\mathrm{O_2} + \mathrm{H_2O} \longrightarrow 4\mathrm{Al} + 2\mathrm{CuO} + \mathrm{H_2} \quad \text{(oxidation of CuAl IMC—in humid air environment)}. \tag{4}$$

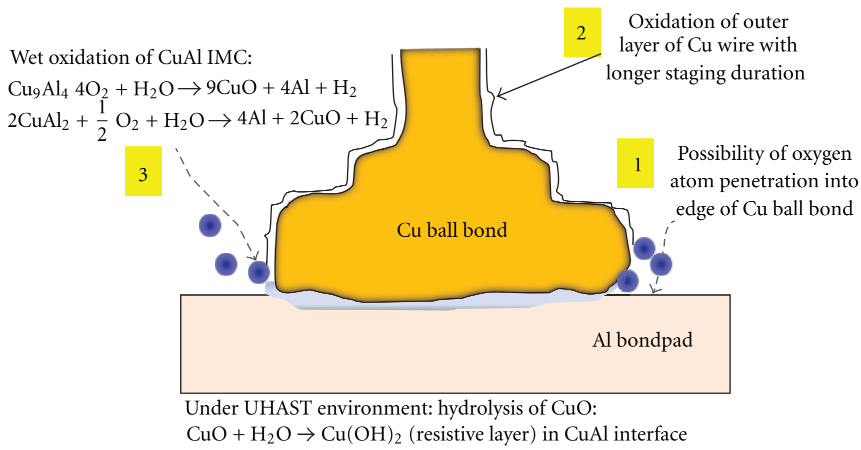

Figure 5: Proposed Cu ball bond oxidation mechanism due to long staging at production floor and induced resistive opens after UHAST reliability test.

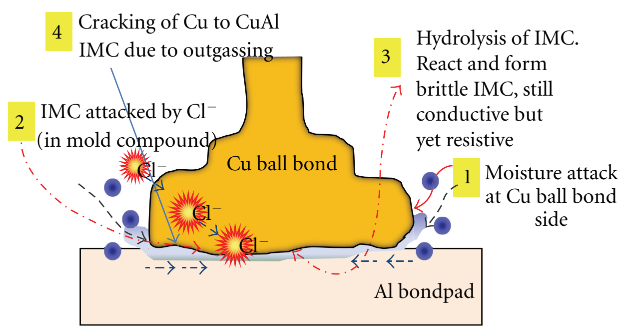

Figure 6: Proposed Cu ball bond corrosion failure mechanism in UHAST tests (Legs no. 4, 6, and 7).

Equation (2) reveals the wet oxidation of CuO to form $Cu(OH)_2$ which is an insulative layer which will induce opens after UHAST stress test (as in Figure 5) [1, 2]. Oxygen gas will penetrate into the edge of Cu ball bond and induce oxidation of CuAl IMC (in this case the majority of IMCs are Cu_9Al_4 and $CuAl_2$) as shown in (3) and (4) [10]. Oxidation in humid air environment during staging will produce CuO which is a resistive layer in CuAl interface. CuO will undergo wet oxidation in UHAST test environmental test and $Cu(OH)_2$ will be produced. This usually ended up with high peak of O in EDX analysis of an open failure after UHAST test. Our UHAST opens after UHAST 96 hr also indicated presence of O peak (8.64 atomic %) in Table 2.

3.4. Failure Mechanisms of Cu Ball Bond Wet Corrosion under UHAST. The Cu ball bond opens after unbiased HAST test mainly induced by Cl ionic content in mold compound. Figure 6 illustrates typical Cu ball bond failure mechanism. The initial formation of CuAl IMC beneath Cu ball bond is dominated by Cu_9Al_4 and $CuAl_2$ [10]. As mentioned before, pH and Cl ionic contents are critical parameters for mold compound.

Under unbiased HAST moist environment, ionic Cl attacks Cu_9Al_4 and $CuAl_2$ IMC. The ionic Cl originates from the mold compound and forms an intermediate product of $AlCl_3$ (reactive if under moisture environment such as unbiased HAST/PCT/biased HAST test) as shown in (5) and (6) below [21]. We propose the Cl^- attack from the edge of Cu ball bond as indicated in Figure 7:

$$Cu_9Al_4 + 12Cl^- \longrightarrow 4AlCl_3 + 9Cu, \quad (5)$$

$$CuAl_2 + 6Cl^- \longrightarrow 2AlCl_3 + Cu. \quad (6)$$

Hydrolysis of IMC and $AlCl_3$ (intermediate product) under a moisture-rich environment forms aluminium (III) oxide which is a resistive layer and ionic Cl is usually found at the corroded ball bond. Cl also has been found in our EDX analysis as shown in Figure 3(a). Equation (3) indicates the hydrolysis of Cu_9Al_4 into Al_2O_3 and outgassing:

$$Cu_9Al_4 + 6H_2O \longrightarrow 2(Al_2O_3) + 6H_2 + 9Cu \quad \text{(outgassing which might cause IMC cracks)}, \quad (7)$$

$$CuAl_2 + 3H_2O \longrightarrow Al_2O_3 + Cu + 3H_2 \quad \text{(outgassing which might cause IMC cracks)}, \quad (8)$$

$$2AlCl_3 + 3H_2O \longrightarrow Al_2O_3 + 6HCl \quad \text{(acidic)}. \quad (9)$$

Cracking of the interface of Cu to the Cu IMC might be due to outgassing of H_2 during hydrolysis (as shown in (7) and (8)) in between Cu IMC to Cu ball bonds. Cracking usually starts at Cu ball bond periphery and will propagate towards center of Cu ball bond [1]. Hence, it is advisable to utilize greener mold compound and low-halogen substrate materials in the substrate (solder mask material specifically) to be used for Cu wirebond packages. Equation (9) explains that aluminium trichloride will undergo hydrolysis under high humidity of UHAST (85% RH) and produce acidic environment. This also explains the Cl present in EDX analysis of corroded Cu ball bond with non-green mold compound. Tan et al. [4] described the corrosion mainly found

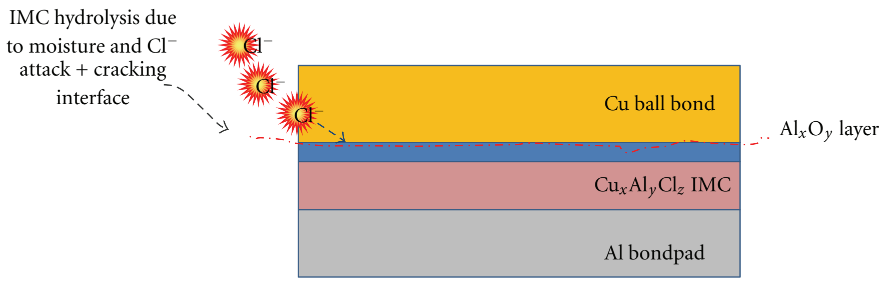

Figure 7: Proposed Cu ball bond corrosion failure mechanism in UHAST tests (Leg no. 4, 6, and Leg no. 7) Cl^- attack from the edge of Cu ball bond.

at CuAl IMC interface. Hence, some researchers recommend Palladium-coated Cu wire to be deployed to minimize the Cu ball bond corrosion under moisture reliability condition [2, 11, 22, 24].

4. Conclusion

In Cu wirebonding evaluations on 90 nm devices, we have successfully identified the key technical barriers of Cu wire deployment in BGA laminate and its suitable package bill of material.

(1) Excessive ultrasonic bonding force will cause IMD cracks and in worse case silicon cratering will happen during wire pull [1, 2].

(2) Green molding compound (with high-pH and low-Cl content) and low-halogen substrate material should be used in Cu wirebond package to ensure UHAST reliability [1, 10].

(3) Failure mechanism of post-UHAST 96 hr open failures for Cu ball bond belongs to CuAl IMC interfacial corrosion and cracking. Cu_9Al_4 and $CuAl_2$ react with ionic Cl to form $AlCl_3$ which is reactive and will further react with moisture (in UHAST) to form a weak Al_2O_3 insulative layer.

(4) Assembly staging time should be controlled to 3 days or less after Cu wirebond step prior to molding. It is recommended to store unmolded units in an N_2 cabinet [1].

(5) Cu ball bond oxidation mechanism is a combination of a dry oxidation process occurring at the Cu ball bond wire, forming a CuO liner oxide layer. The CuAl IMC (Cu_9Al_4 and $CuAl_2$ primarily) will react with O_2 to form CuO. CuO will undergo wet oxidation in UHAST test environmental test and $Cu(OH)_2$ will be produced.

(6) Some industrial researchers reported an increase in Cu ball bond strength after an extra thermal treatment after Cu wirebonding. The bake temperature can be as high as 125°C for 4 hours baking duration in oven [12, 13].

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