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Mechanism of Wire Bond Shear Testing

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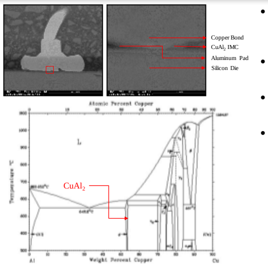
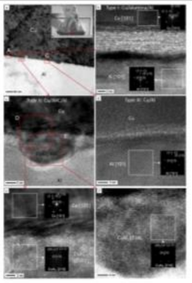
Thermosonic Bond Formation Process in Cu Wire Bonding



- Wire bonds are formed by a thermosonic welding process that involves a combination of ultrasonic energy, mechanical force, time and temperature).
- This method promotes initial IMC formation at a level based on the bonding conditions.
- Ultrasonic + force + temperature → Al_2O_3 fragmentation → promotes Cu-Al inter-diffusion.
- Three interfaces exists between Cu and Al: alumina, $CuAl_2$ IMC and just Cu and Al [1].
  - Alumina prevents interdiffusion, and thus bond formation.
  - $CuAl_2$ layer provides the adhesion and hence determines the strength of bond.
  - Cu and Al that are in contact leads to further IMC growth with temperature aging.

[1] Xu H., Qin I., Clauberg H., Chylak B. and Acoff V.L., "New Observation of Nanoscale Interfacial Evolution in Micro Cu-Al Wire Bonds by in-situ High Resolution TEM Study." Scripta Materialia.

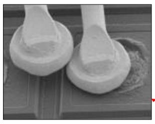
Copper Wire Bond Adhesion Strength – Initial Condition



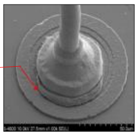
- Prior studies shows higher bond strength with higher $CuAl_2$ IMC area at bond interface.
- In study by Xu et. al.[1] , it was reported that the strength was lower for Cu/alumina/Al compared to Cu/$CuAl_2$/Al and Cu/Al.
- In our previous study, we found higher shear force with greater $CuAl_2$ area.
- Higher ultrasonic power and bonding force used for a long time would lead to greater lateral coverage of $CuAl_2$ → higher shear strength.
- High shear strength ensures good adhesion which ensures electrical contact and is assumed to yield high reliability.
- However, inherent material characteristics and lack of bond optimization can lead to several failure modes.

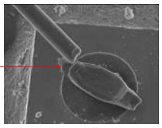
[1] Xu H., Qin I., Clauberg H., Chylak B. and Acoff V.L., "New Observation of Nanoscale Interfacial Evolution in Micro Cu-Al Wire Bonds by in-situ High Resolution TEM Study," Scripta Materialia.

Concerns with Copper Wire Bonding Process



S. No.	Failure Mode	Common Cause
1	BOAC cracks - Failure in the metallization layers under the pad	Non-optimized parameters Weak pad design
2	Excessive aluminum splash [1]	Non-optimized parameters
3	Electrical shorting	Non-optimized parameters Contamination Wire sweeping
4	Ball bond lift off - Failure at the die-bond interface [2]	Non-optimized parameters Contaminated pad Pad corrosion
5	Ball bond neck break - Failure around the neck of the bond [3]	Non-optimized parameters Incorrect wire looping Die-to-package delamination due to molding
6	Break at mid-wire - Failure at wire loop	Wire nicks or damage Tight wire looping Wire sweeping
7	Break at wedge bond – Failure at heel (region of change in cross-sectional area)	Non-optimized parameters Die-to-package delamination due to molding
8	Break at wedge bond - Failure at substrate bond interface	Contamination Non-optimized parameters Oxidized pad Damaged pad



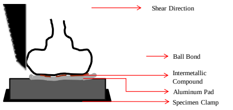


Evaluation Methods for Copper Wire Bonding

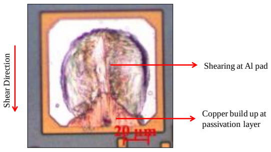
S. No	Test	Standards
1	Physical Appearance of Bond	1. IBM Engineering Specification: 57G9271 2.MIL-STD 883 Method 2010 Visual Inspection 3. NASA Reference Publication 1122 Procedures for Precap Visual Inspection
2	Bond Pull Test	1. Mil-std 883 Method 2011.7 Wire Bond Pull 2. ASTM F458 - 06 Standard Practice for Nondestructive Pull Testing of Wire Bonds
3	Bond Shear Test	1. AEC - Q100-001 REV-C Wire Bond Shear Test 2. JESD22-B116 Wire Bond Shear Test Method 3. ASTM F1269-13 (Au and Cu)
4	SEM profile of ball bonds	1. NASA Reference Publication 1122 Procedures for Precap Visual Inspection
5	Bond ball diameter and height	1. National Bureau of Standards Technical Note 726 2.AmTECH Design Guidelines for Wire Bonding
6	Bond contact area determination	NASA Reference Publication 1122 - Procedure for precap visual inspection
7	% IMC Coverage (Cu)	1. Wire Bonding TASA ID: 8873860 (Cu)
8	Pad Al thickness remaining beneath the bond	1. MOSIS Service - Fully Encapsulated Package Design Guidelines 2. AmTECH Wire Bonding Guideline
9	IMC thickness	1. PEM Guidelines for Screening and Qualification for Space Applications (Section 7.9)
10	Detection of voids or other defects in the bond	1. ESCC Basic Specification No. 2045010 2. MIL STD-883B Method 2010
11	Wire Spool Visual Inspection	1. F 72-06 Standard Specification for Gold Wire for Semiconductor Lead Bonding
12	Wire Density Measurement	F180-094 Standard Test Method for Density of Fine Wire and Ribbon Wire for Electronic Devices
13	Bond Pad Oxidation	1. EAG AN-332 Evaluating Bond Pad Performance

- With all the wire bonding concerns, thorough bonding process evaluation is necessary.
- Several wire bond evaluation "standard" methods exist, some destructive and some non-destructive.
- Most standards are applied to the ball bond as it is the region of interaction of two different metals, failing more often than a monometallic wedge bond.
- Bond shear testing is used as the main indicator for bond quality and reliability.
- The shear test methods and limits were developed for Au wire on Al bond pads. Copper wire bonds have different failure modes and mechanisms not captured in these earlier test standards.

Wire Bond Shear Testing

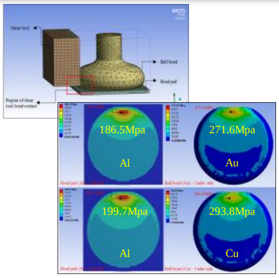


Correct shear mode according to JESD22-B116



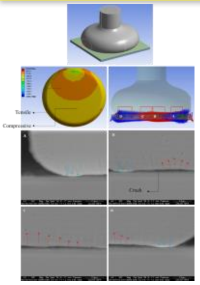
- Bond shear testing - destructive process, performed to find the adhesive strength.
- A calibrated shear test can also be used to get a quick estimate of how much IMC coverage is under the bond.
- There is a lack of adequate information on what level of bond shear strength equates to a reliable copper wire bond. Also, there is no consensus that bond strength is an accurate measure of long term bond reliability.
- Current industry standards only specify a minimum shear strength value per wire diameter, above which the bond is considered good.
- No information on mechanism of shearing in unaged and aged conditions.

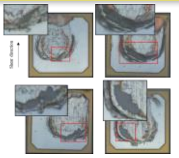
Au vs Cu Bond Shear Test Difference



- Location of failure different in Au compared to Cu wire bonded on Al pad.
- Copper wire bonds shear through the aluminum pad, not through the ball as with gold. Evaluation methods must include aluminum pad thickness effects, not just wire thickness as in current methods.
- Shear force and shear strength increase with increasing bond pad thickness for the same bonding power and duration.
- FEA of bond shear testing – shear tool pushes bond from pad at an applied force.
- Von-Mises stress show higher (than yield) stress in Au and lower stress in Al.
- Higher stress (than yield) in Al and lower stress in Cu.

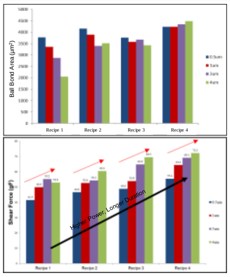
Shearing Mechanism at Initial Condition





- FEA and experimental results compared to understand bond shearing mechanism.
- Stress directions from FEA shows compression of pad at region under contact of shear tool with bond.
- And tensile stress region close to the axis of bond.
- Partially sheared bonds were cross-sectioned. SEM images show compression of bond near the periphery and a separation between bond and pad at bond axis.
- Post shear images show region of displaced Al (exposing die) confirming FEA results of compressive force at this region.
- Thus thickness of Al will affect shear result at initial condition.

Dependence of Shear Force to Pad Thickness



- Thicker pad results in a higher shear force of bonds.
- Three reasons could contribute to the observed increasing trend of shear force:

❌ **Increase in IMC % coverage in thick pads**

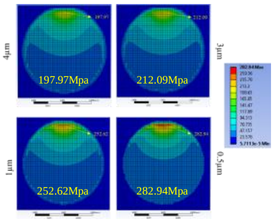
- IMC % coverage increases with increase in parameter, but is not dependent on pad thickness.

❌ **Difference in shear mode**

- Shear occurs at bond pad region - type IIB (shear at Al pad) mode consistent with the JESD22-B116B standard.
- Remaining aluminium visible in all cases.
- Thus cratering or pad peeling not the reason for high shear strength.

✓ **Stress distribution in thick pads**

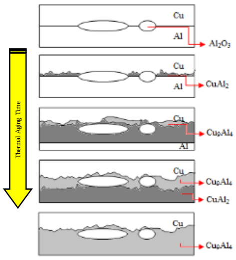
Dependence of Shear Force to Pad Thickness



	FEA Relative Shear Strength in pad Al for stress on Cu ball of 12gF			
Pad Thickness (µm)	0.5	1	3	4
Von-Mises Stress (MPa)	283	252.6	212	198
Relative Change (%)	43	27.6	7.1	0

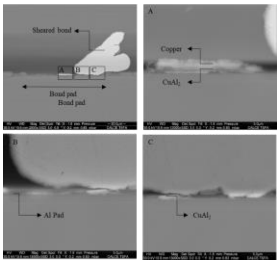
- Stress distribution on bond pad layer 0.25um beneath the surface shown.
- Applied force 12gF causes stress of 197Mpa in 4um pad, close to yield strength of Al (200Mpa).
- Pad shearing would initiate at this stress. However, stress in 0.5um pad is 282Mpa, indicating shear would have already occurred.
- **Stress in 0.5um was found to be 43% higher than that in 4um, for the same applied force.**
- This proves that thicker pad allows for greater stress distribution and hence force required to failure is higher.

Thermal Aging of Cu-Al System



- With annealing at high temperature, initially formed $CuAl_2$ grows in thickness.
- This happens by influx of Cu atoms into Al, thereby consuming the Al pad.
- $CuAl_2$ is the dominant phase until the consumption of all of the Al in bond pad.
- After which, Cu_9Al_4 becomes the dominant phase.
- Thus Cu_9Al_4 growth depends on remaining Al thickness under the bond.
- With growth of Cu-Al brittle IMCs at interface, failure location becomes different.

Shearing Mechanism in Aged Condition



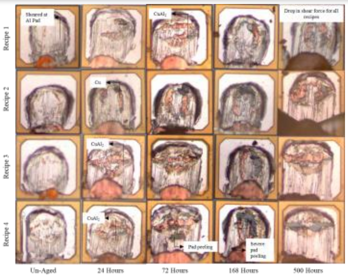
- Bonds were aged (200ºC for 24 hours), sheared, potted and cross-sectioned to observe failure interface. Failure found to be different from un-aged condition.

A: Failure in Cu bulk. $CuAl_2$ found adhering to Al.

B: Failure between $CuAl_2$ and Cu. Al found under $CuAl_2$.

- Interfacial failure is different from that in bulk. Comparison of strain energy release rate at the interfaces to that of critical value can be used to predict shear force that causes failure.
- Interfacial strength between Cu-$CuAl_2$ and $CuAl_2$-Al are different from Cu-Al (initial condition). Characterization of these interfacial values will be beneficial to predict shear force.

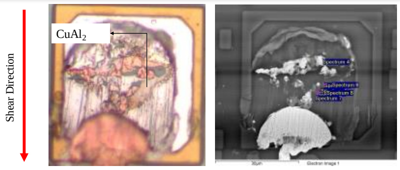
Shearing Mechanism in Aged Condition



- Post shear images shown for different recipes and aging conditions.
- Sheared regions show $CuAl_2$ (brown) and Cu in aged conditions.
- Long aging (72 hours) shows more $CuAl_2$ coverage.
- With extended aging times (168 and 500 hours), pad peeling is observed due to complete consumption of Al by $CuAl_2$.
- Overall trend of increase in shear force is due to larger bond area with higher power and time used in bonding.

Bonding recipe	**Ultrasonic power (watts)**	**Bonding force (gF)**	**Time (ms)**
1	0.7	0.5	0.5
2	1.2	0.5	1.5
3	2	0.5	1.5
4	2.5	0.5	1.5

Shearing Mechanism in Aged Condition

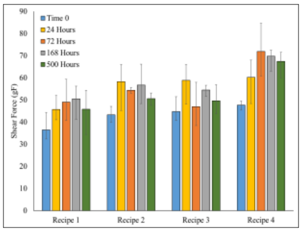


Post shear image of bond made with recipe 3 aged for 24 hours at 200°C.

Spectrum No.	C	O	Al	Si	Ti	Cu	Cu:Al
1	11.68	28.65	2.09	55.32	0.91	1.35	1:1.5
2	9.58	29.01	2.99	56.2	0.84	1.38	1:2
3	8.76	27.72	3.04	58.15	0.78	1.55	1:2
4	19.77	12.22	8.7	29.43	1.07	28.81	-
5	9.83	27.82	2.92	57.01	0.76	1.66	1:1.75
6	9.65	27.19	3.43	57.44	0.81	1.48	1:2
7	10.51	26.42	2.89	57.44	0.79	1.95	1:1.5
8	11.48	27.21	2.9	56.62	0.41	1.38	1:2

Brown color region is confirmed to be $CuAl_2$ from EDS measurements.

Shearing Mechanism in Aged Condition



- Further aging to 72, 168 and 500 hours led to difference in shear force and shear location.
- In all four different recipes, shear force reaches a maximum and then drops – time where deleterious effect of IMC thickness takes over benefit of IMC coverage.
- Overall, shear force is higher with recipe 4 – higher bond area provides greater chance of IMC coverage.
- Shear force even after 500 hours of thermal aging is higher than initial time – but post shear analysis shows pad peeling for all recipes.
- Thus, shear force captures interfacial changes with thermal aging but is dependent on several factors such as remaining Al thickness, aging time, etc.

Summary

- Thermosonic wire bonding process – forms three distinct interfaces between Cu and Al.
- Quality of bond is based on several factors of which adhesion strength is most important.
- Many evaluation methods exist to judge bond quality, of which bond shear test is most widely used.
- However, mechanism of wire bond shear testing not well understood – relation of shear force to failure location, interfacial changes, etc.
- Initial shear test depends on wire material:
  - Au bond: Failure in Au bulk.
  - Cu bond: failure in Al pad.
- For Cu bonds, Al pad thickness becomes an important parameter.
- With thermal aging – interfacial changes through growth of IMCs contribute to change in shear.
  - Failure changes from Al to in-between $CuAl_2$ and Cu or in Cu bulk.
- Extended aging of up to 500 hours at 200ºC showed different failure regions and a trend in shear force.
  - Shear force increases and then drops. Maximum shear force found with larger bonds that have greater potential for lateral coverage of IMC.