Cu Wirebond in PEMs:

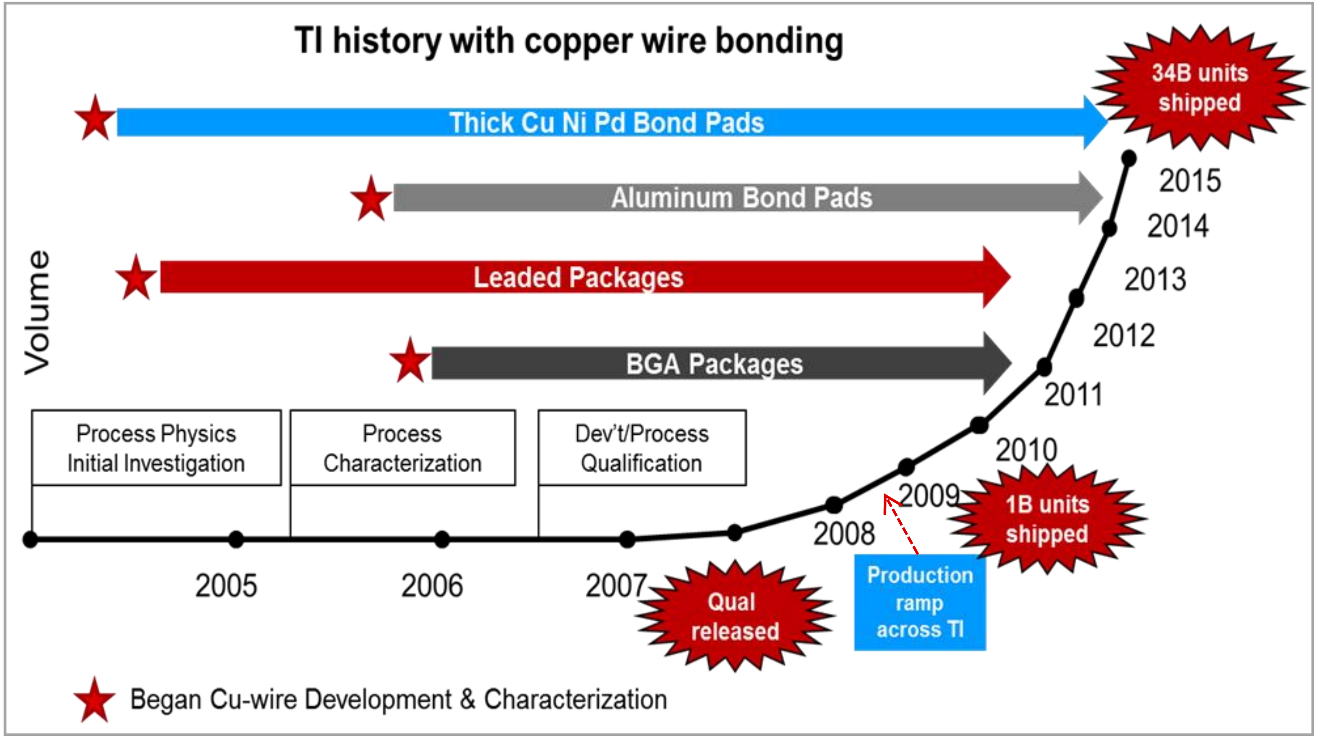
Mukul Saran, Ph.D.

Texas Instruments Inc

Dallas, TX

Texas Instruments

Looking Backwards to Now:



Applications:
- Commercial
- Telecom
- Industrial
- Automotive

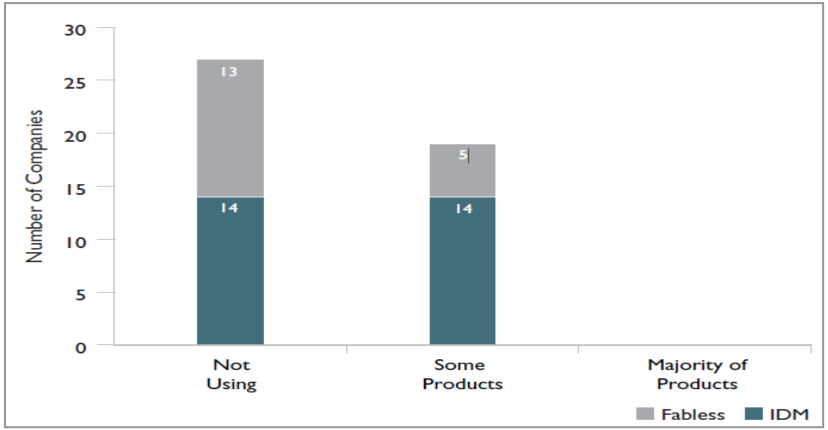
(safety, powertrain, Infotainment etc)

Packages:
All (QFN, QFP, PDIP, SOIC, TSSOP, BGA & others)

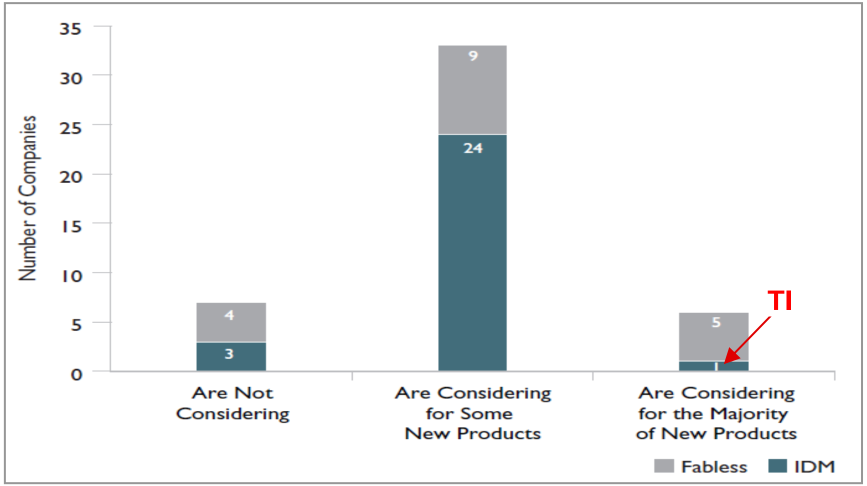
AT sites: > 14
(internal & external)

Rewind to 2010 - Industry Trends Then

Use in Current Products



Planned Use over Next 3 yrs



- ➢Limited use in the global SC Industry, but growing.
- ➢TI was leading the charge in conversion to Cu w/b.

Talking About Cu

- What drove us to Cu?

- How Reliable is it?

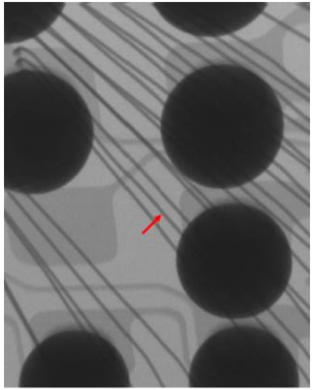
  Very Reliable, but….
  Temperature - Robust
  Temperature-Cycling – Some differences from Au-wire
  Humidity, Bias and Temperature – Requires more attention than Au-wire

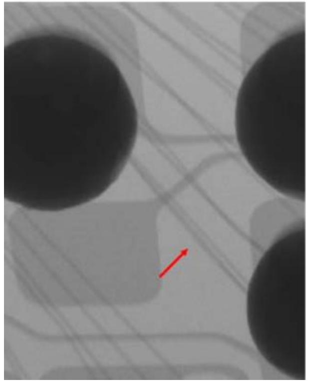
- What Have we Learned

  Development and Qualification:
  Maintaining Quality & Reliability in Production:

- HiRel Concerns

- Summary





Reasons to Choose Cu

Property	Au Wire	Cu Wire	PCC Wire
FAB Hardness (HV) Bond Hardness (HV)	60 80	85-95 128	80-95 w/gradient unknown
Modulus (GPa)	75-100	80-90	80-90 inside 121 outside
CTE (ppm/K)	14.2	16.5	16.5 inside 11.5 outside
Resistivity (μΩ-cm)	2.3	1.7	1.7 inside 1.1 outside
Corrosion Potential (V, SHE)	1.498	0.521	0.987 outside 0.521 inside
Fatigue Resistance	Good even if Delaminated	Good if not delaminated	Unknown
Constituent Distribution	N/A	N/A	Critical, Pd must be on outer FAB

Motivation for Cu

+ **Lower Material Cost**
+ Lower resistivity
+ Higher thermal conductivity
+ Resistant to Kirkendall voids
+ Longer high-temperature storage (HTS) life

=> So, how reliable is Copper?

How Reliable Is Cu?

=> It can be very reliable well beyond Jedec stress guidelines

Cu-WB Reliability Stress Performance

Reliability Performance

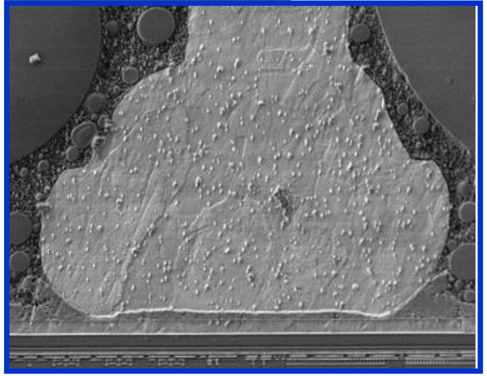
Reliability Stress	Condition	Minimum Required Duration	Duration Passed
Unbias HAST	130C/85%RH	96	504
	110C/85%RH	264	792
BHAST	110C/85%RH	264	792
Temp Humidity Bias	85C/85%RH	1000	1000*
Hi Temp Oper Life	125C	1000	1000
High Temp Storage	150C	1000	2000
Temperature Cycle	-55/125C	700	4000
Thermal Shock	-55/125C	None	2000

* No package defects found

Bond-Shear

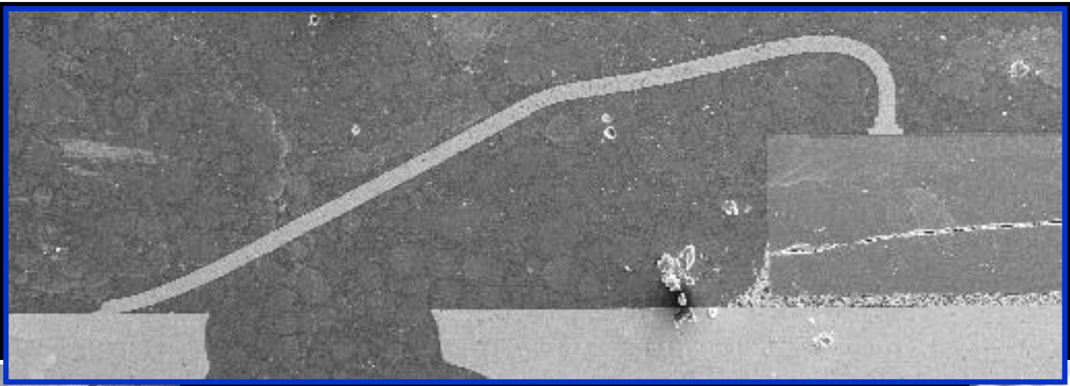
	Shear (g)				Ball X			Ball Y			Shear/Unit Area (mg/um2)		
Unit	Lot 1	Lot 2	Lot 3	Au Control	Lot 1	Lot 2	Lot 3	Lot 1	Lot 2	Lot 3	Lot 1	Lot 2	Lot 3
1	18.85	17.54	17.68	17.68	45.30	42.70	44.52	44.40	45.91	46.28	11.93	11.37	10.92
2	18.85	17.20	17.68	17.68	44.52	43.27	42.72	46.28	45.68	47.10	11.64	11.07	11.16
3	18.67	17.21	18.03	18.03	42.72		42.49	47.10		46.74	11.78		11.53
4	17.81	18.00	17.34	17.34	42.09		45.40	46.74		45.88	11.49		10.60
5	18.44	16.41	18.02	18.02	45.71		43.24	44.63		45.91	11.50		11.55

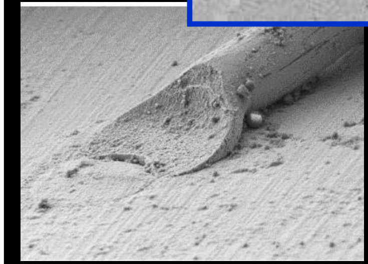
uHAST 672 HRS



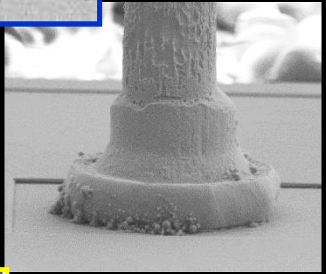
=> Cu-wirebond can demonstrate superior reliability performance in plastic packages

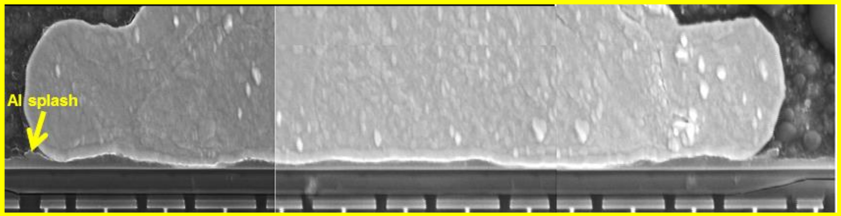
Cu-Wirebond (Post-500TC)





Both Stitch- and Ball-bond remain intact after 500 Temperature Cycles Between -65C/150C. Molded QFN



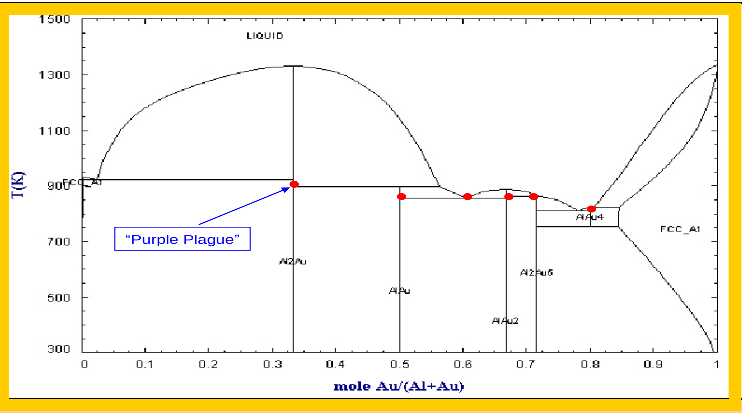


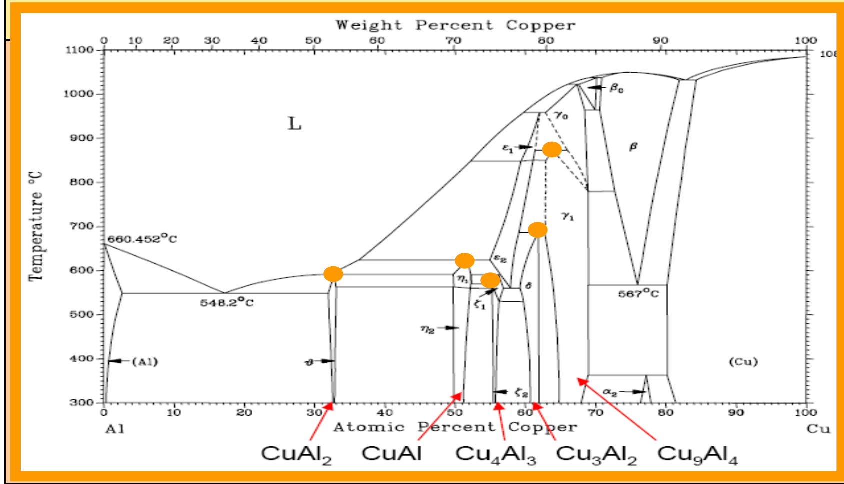
The Basics of Cu-Al IMC

- We know more, now that we can image the IMC using a SEM

IMC Formation – Phase Diagram

$AuAl_2$ – Purple plague (Al wires on Au pads)
AuAl
Au_2Al
Au_5Al_2 – Grows adjacent to Al-pads
Au_4Al – Adjacent to the ball. Can grow at the expense of Au_5Al_2 during HTS. Susceptible to oxidation and corrosion by mold-compd epoxies



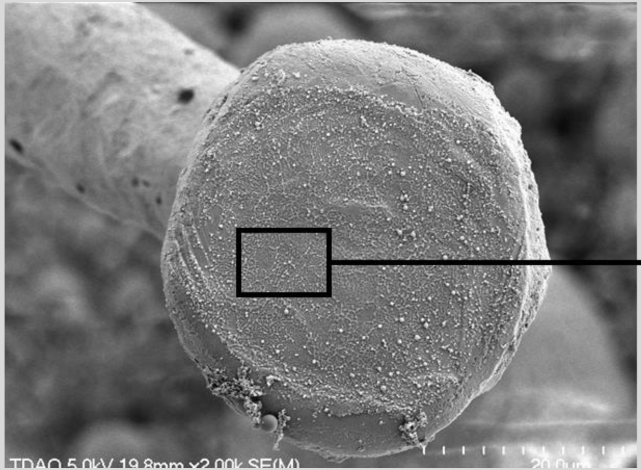


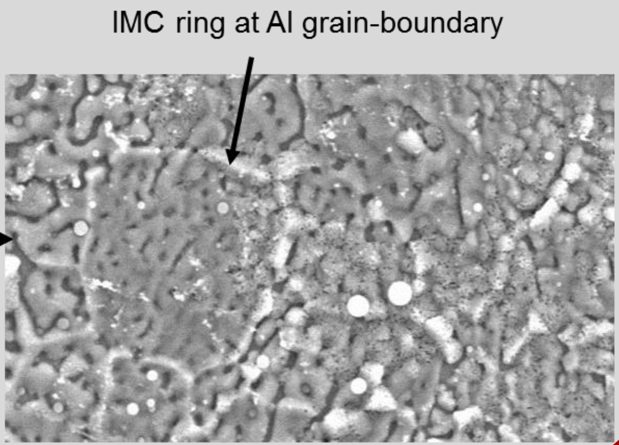
$CuAl_2$	White-Yellow
CuAl	Grey
Cu_4Al_3	White--yellow
Cu_3Al_2	
Cu_9Al_4	Adjacent to Cu-ball

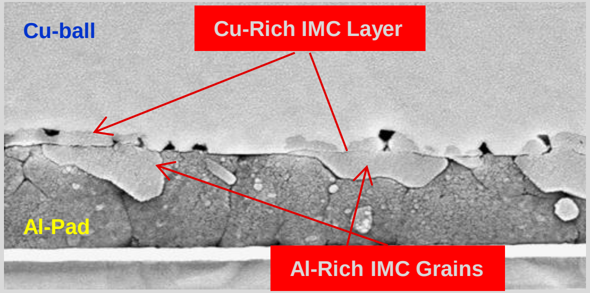
At shorter storage times <200hr, a grey phase is dominant. At longer times, yellow phases are seen.

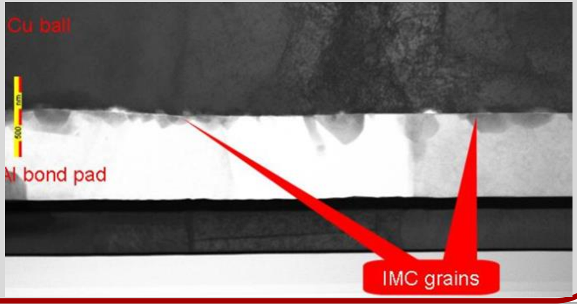
Phase determination is difficult in as-bonded samples due to very thin layers. The above results were obtained after 250C storage. The results may be different at lower temperatures.

The Basics





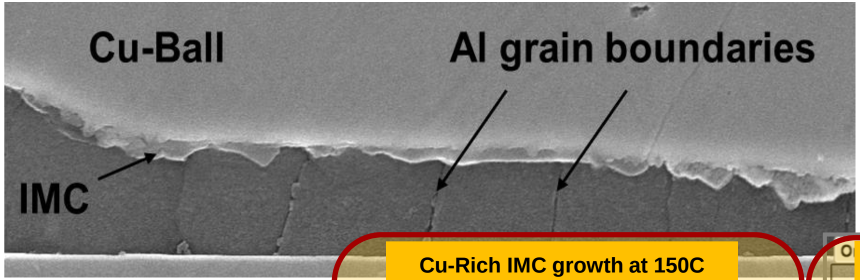




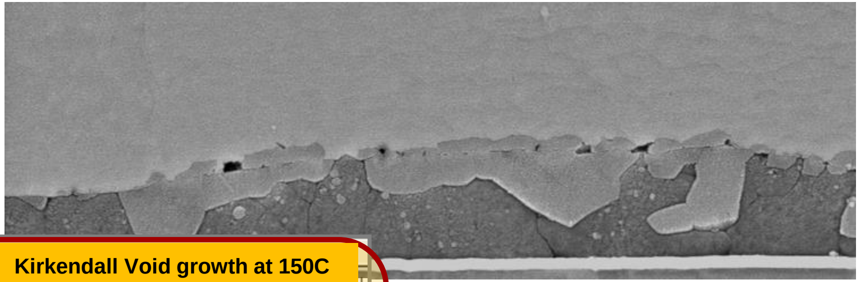
Ref: Copeland & Saran,, Copper to Aluminum bonding: IMC Characterization through New Mechanical Sectioning Methods, Proc 36th International Symposium for Testing and Failure Analysis, ISTFA 2010

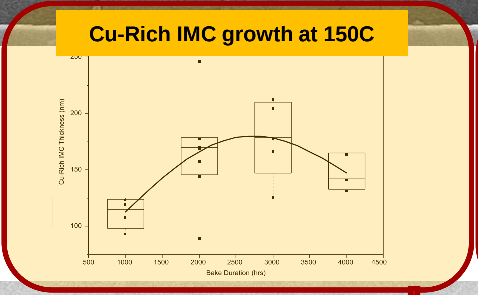
Stable against Kirkendall Voiding

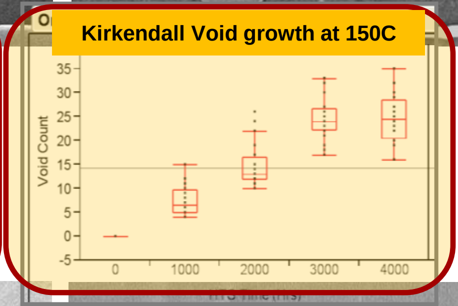
As-molded



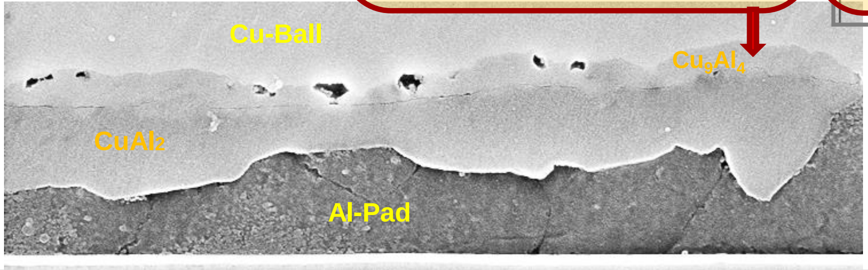
2000hrs HTSL



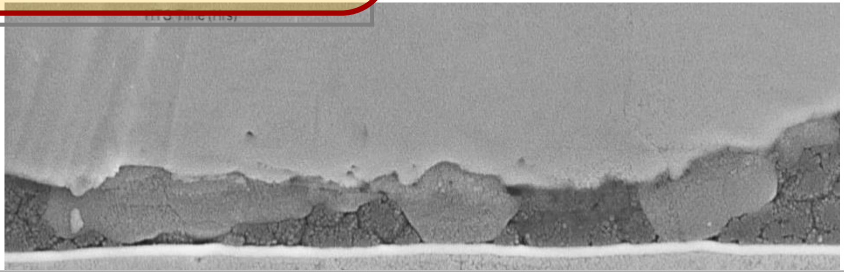




3000hrs HTSL



4000hrs HTSL



Ref: Copeland & Saran,, Copper to Aluminum bonding: IMC Characterization through New Mechanical Sectioning Methods, Proc 36th International Symposium for Testing and Failure Analysis, ISTFA 2010

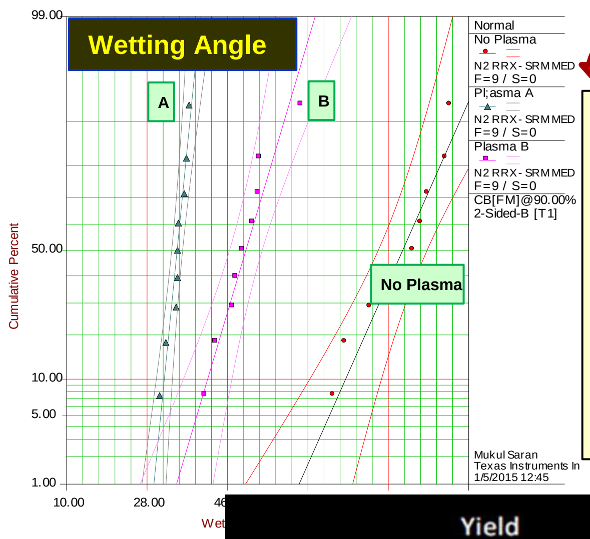
What Have We Learnt?

Knowledge is Power!

We have learnt a lot over the years!

Bond-Surface Cleanliness

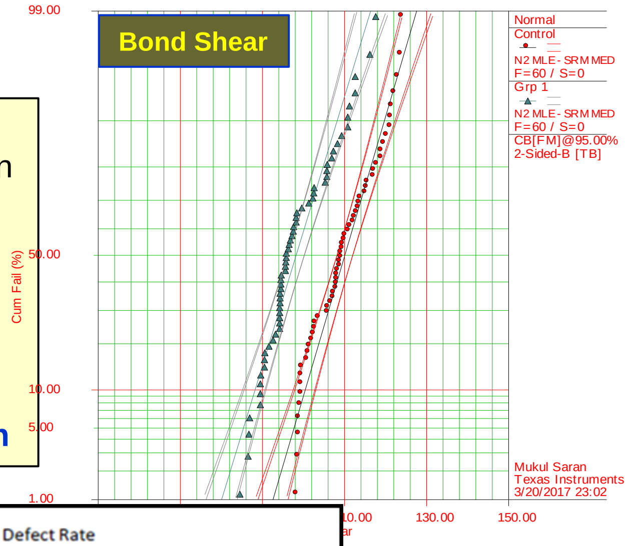
Plasma Treatments

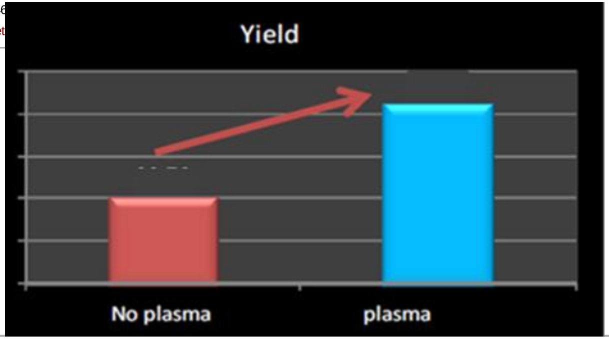


μ1=85.2222, σ1=9.9673, ρ=0.9568
μ2=34.7333, σ2=2.2314, ρ=0.9606
μ3=50.1111, σ3=6.6684, ρ=0.9688

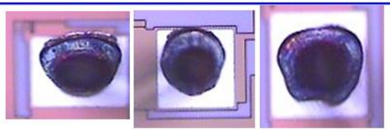
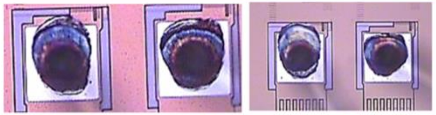
Conclusions:

- Plasma reduces the wetting angle on bonding surface
- Longer Power/exposure (A vs B) improves wetting angle
- Benefits yield, NSOL and NSOP
- Bond-shear strength increases
- ***Surface cleanliness more critical than Au due to limited IMC growth***





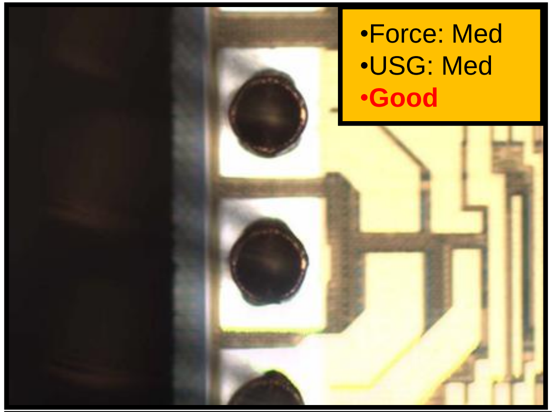
Sensitivity To Si Bond-Pad Stack

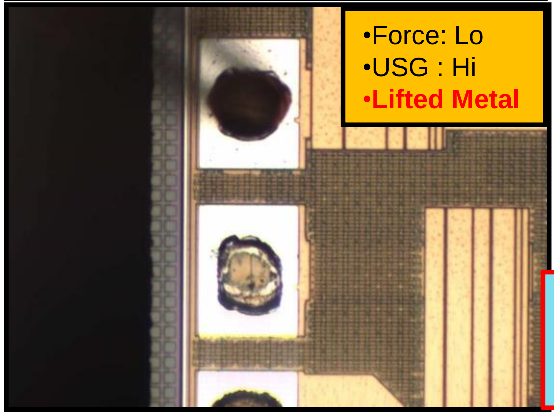
	Al-0.5%Cu	Al-2%Cu
Low-K Dielec Sandwich + Pad Reinforcement	Abnormal	 Abnormal ball of Wafer no.05 Abnormal
Oxide/SOG Sandwich + No Pad Reinforcement	 Abnormal ball of Wafer no.04 Abnormal	** Bond Parameters Optimized For This Stack up ** High Bond-Parameters (force/power) were used Used the same set on all other stack-ups Normal

- ➢ Changing underlying bond-pad structure impacts Wirebond outcomes.

=> Bonding recipes may require optimization for different bond-pad metallizations

Bond-Pad Damage



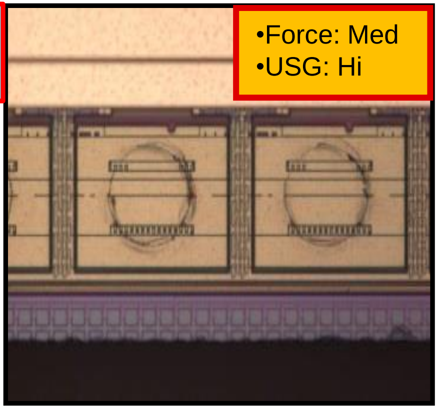


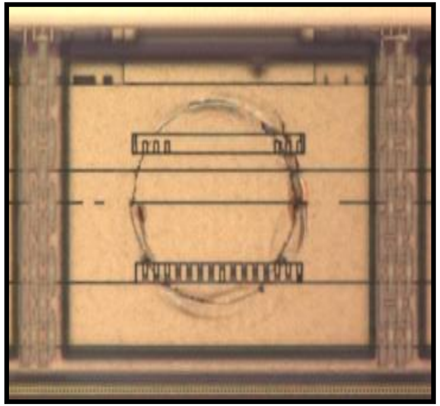
Lifted Metal @ Bond and/or at Wirepull

Lower bond parameter range than Au, for damage-free bonding

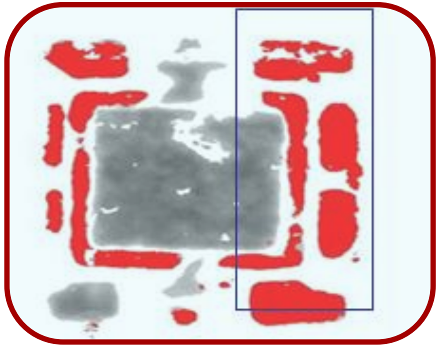
Post-assembly or reliability fails due to Lifted Metal or Crater crack growth during Temperature Cycling

Under-pad Damage



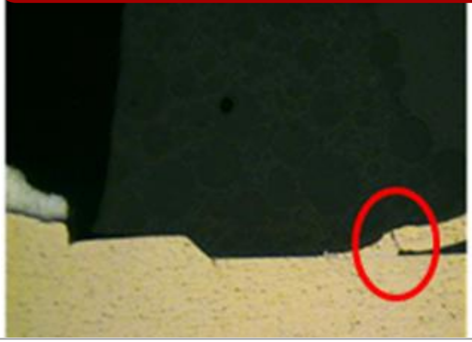


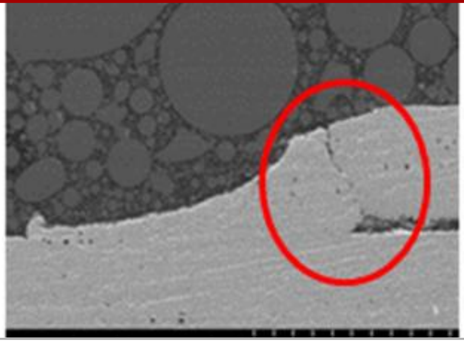
Dangers with Delamination – Stitch Cracks

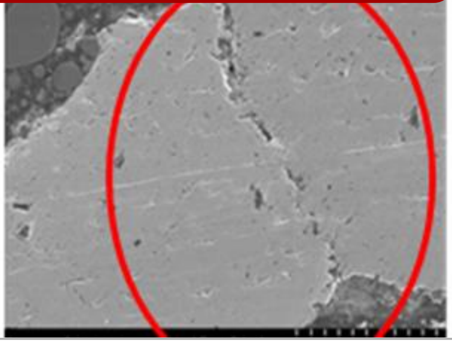


CSAM images show delamination after pre-conditioning in the die attach-pad areas, as well as on leadfinger areas

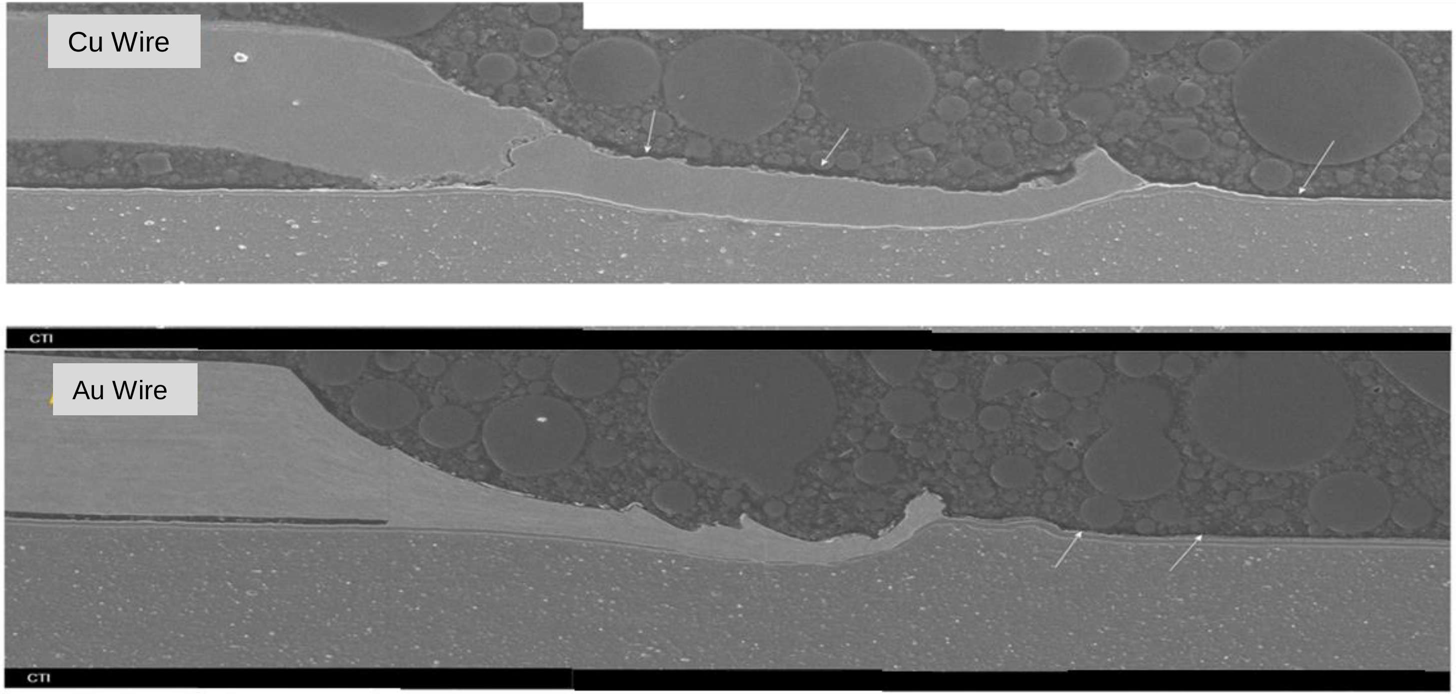
Mold-compound delamination can result in stitch-fracture during Temperature Cycling due to thermo-mechanical fatigue. Copper undergoes work hardening during stitch formation process.





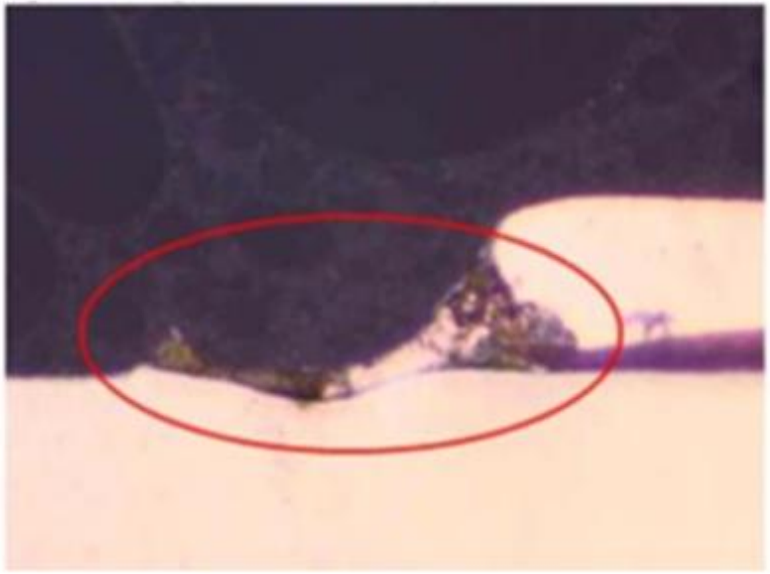


Mold-Delamination and Stitch Crack

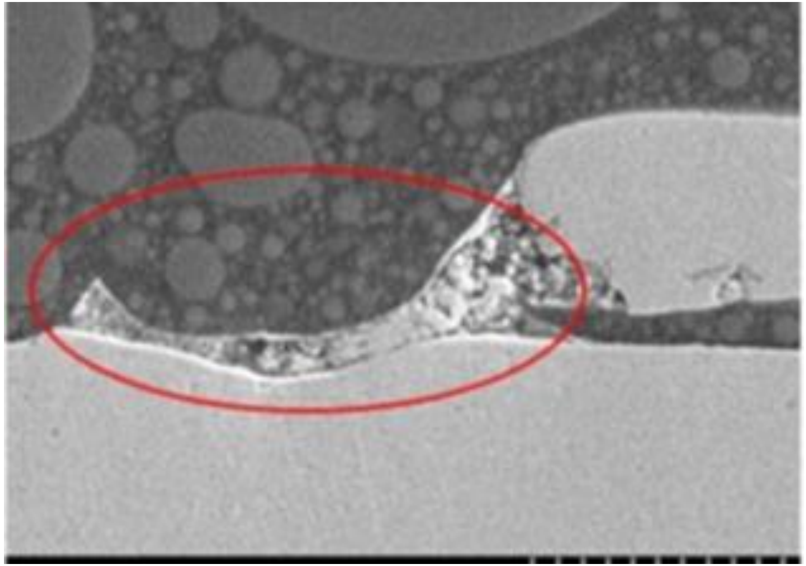


Cu Wire –vs- Au Wire Stitch After **1000 T/C**; Au Wire Had No Damage. Both have delamination t0 and after 1000 T/C. Arrows indicate mold-compound delamination

Dangers with Delamination: Stitch Corrosion

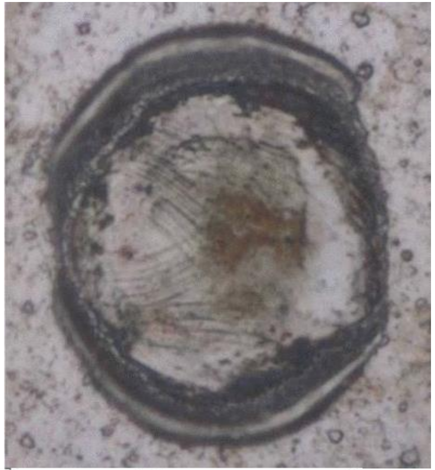


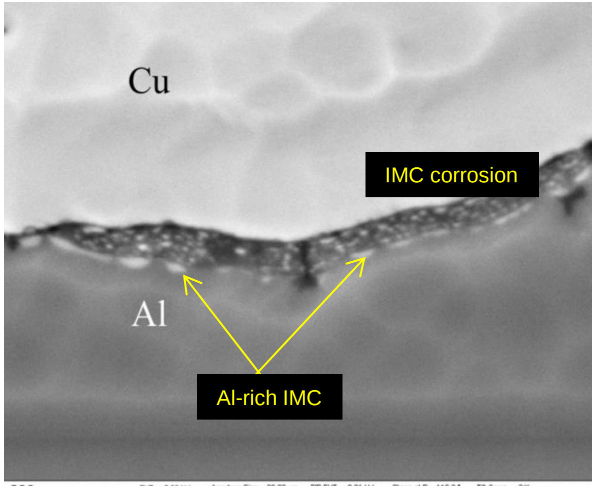
- ***How did the corrosion happen inside***?
  - Delaminations reduce product robustness
  - Au-wire does not corrode

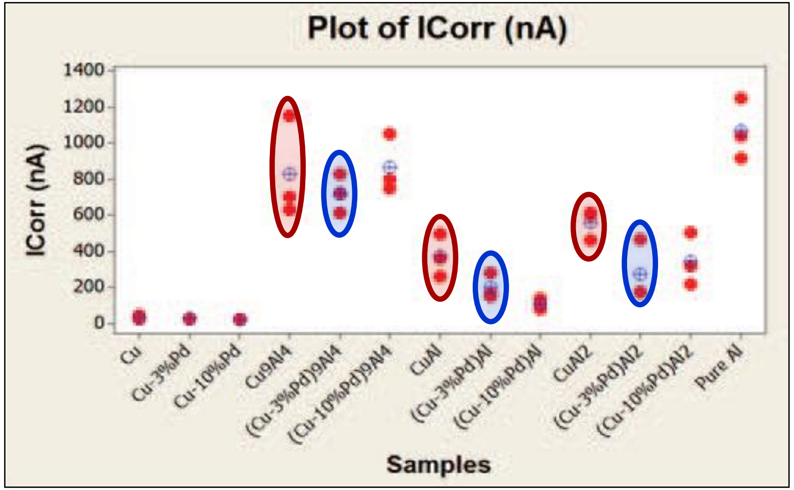


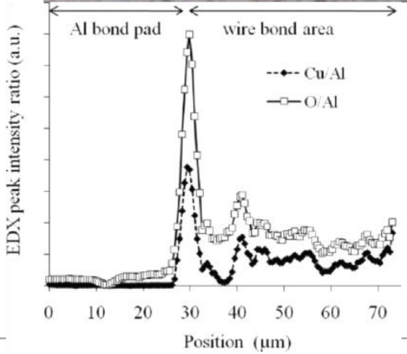
- Initially strong bonds can fail this way
- ***Robustness demands package integrity*** at 'Time-zero' and under stress

Corrosion of Cu-Al Bonds





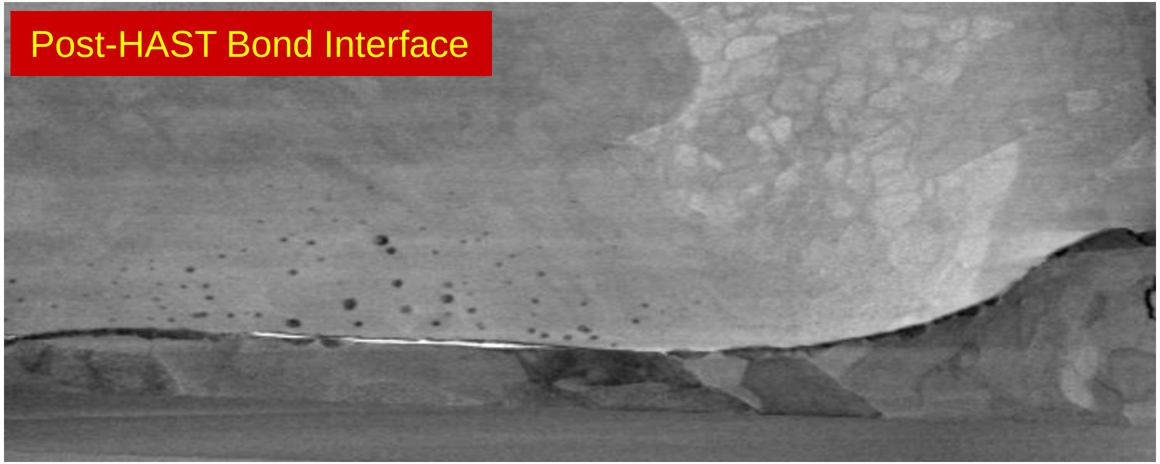


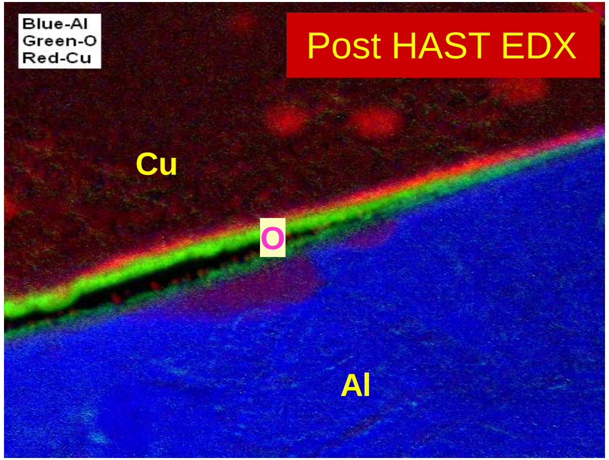


- Cu_9Al_4 is the most susceptible to corrosion
- Addition of Pd in Cu IMC slightly improves the corrosion resistance

On the intermetallic corrosion of Cu-Al wire bonds, Tim Boettcher et al, pp 585-590, EPTC 2010
Evaluation of the Corrosion Performance of Cu-Al Intermetallic Compounds and the Effect of Pd Addition, Adeline Lim et al, EPTC 2015

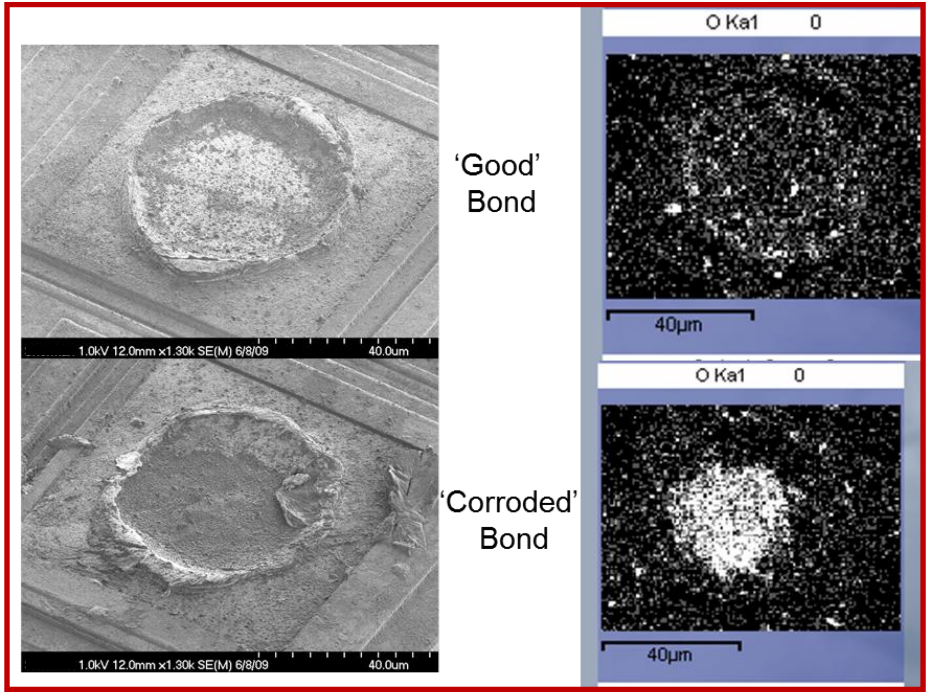
Corrosion of Cu-Al Bonds



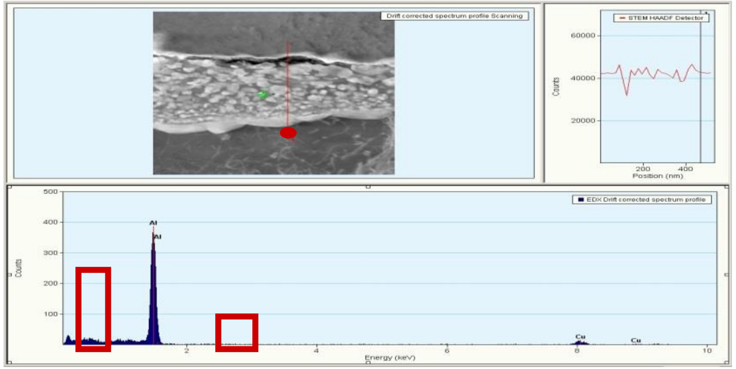


- Cu bond interface corrodes by oxidation of the Cu/Al interface.
- Separation occurs in the oxidized IMC layer towards the interface with Al
- Separation can occur even in regions which may have previously grown an IMC.
- A well-formed bond with high bond-strength can fail easily due to corrosion

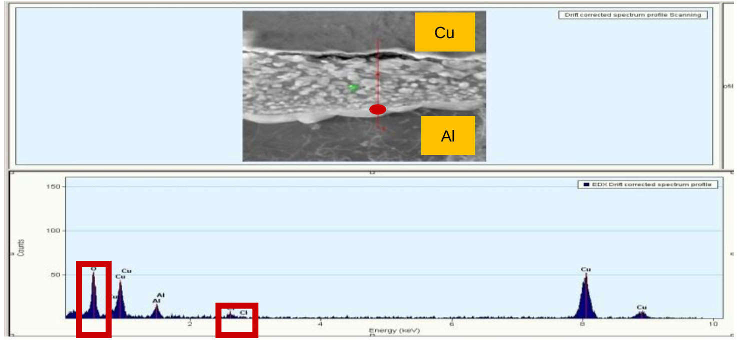
Cu-Al IMC Corrosion - Chlorine



No O or Cl in Aluminum just below the interface.



Cl & O in layer between Al & Cu.

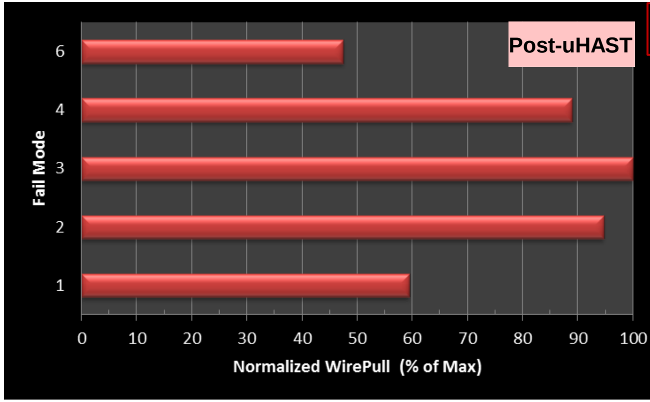


Mold-Compounds: Role in Cu Corrosion

Supplier	Mold-Compd	Autoclave (121C, 100%RH, 2atm)	ub_HAST (110C / 85% RH)	ub_HAST (130C / 85% RH)	Biased HAST (130C/85% RH)	THB (85C/85% RH)
		-	Passed	-	-	Passed
		-	Passed	-	-	Passed
		-	Passed	-	-	Passed
		-	Passed	-	-	Passed
		-	Passed	-	-	Passed
		-	Passed	Passed	Passed	Passed
		Passed	-	-	In Qual	-
		Passed	-	Passed	-	In Qual
		Passed	-	-	Passed	-
		Passed	-	-	Passed	-
		No Plan	No Plan	No Plan	No Plan	No Plan
		Passed	-	-	No Plan	-
		Passed	-	-	Passed	-
		Passed	-	-	Passed	-
		Planned	-	-	Planned	-
		Passed	-	-	Failed	-
		Passed	-	-	Passed	-
		Passed	-	-	Passed	-
		Failed	-	Passed	Failed	-

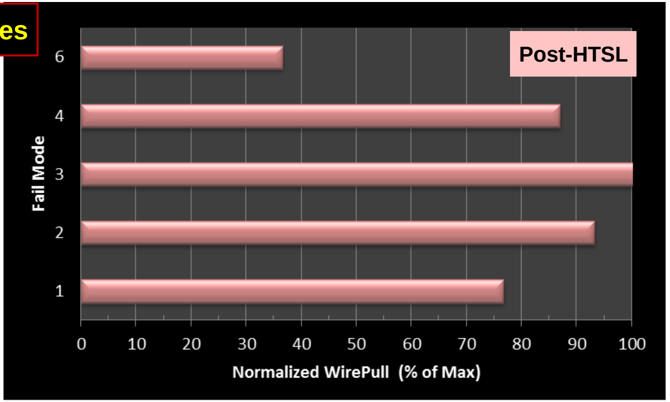
- Biased-HAST corrosion is prominent for certain mold-compounds, even if they are ‘green’
- Autoclave can also show corrosion without bias.
- Failures do not correlate with residual Cl specs for the mold-compd.

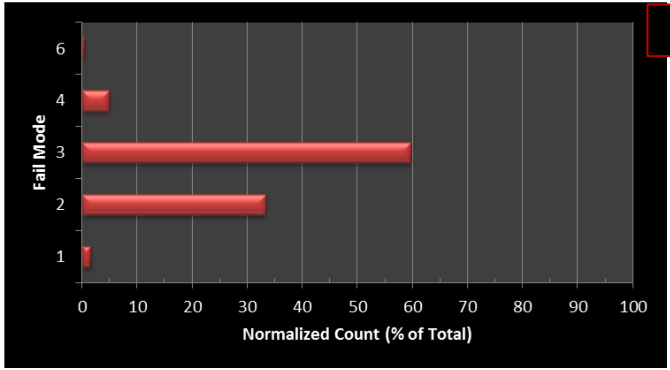
Wirepull: Exposure to Humidity or Temperature



Relative Strengths of Wirepull Fail-Modes

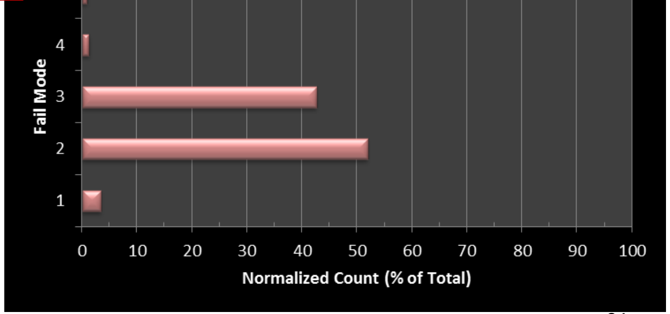
Mode1	Lifted ball
Mode2	Brk @ ball nck
Mode3	Brk @ mid-span
Mode4	Brk @ stitch heel
Mode5	Lifted stitch
Mode6	Lifted metal





Occurrence Frequency of Fail-Modes

- Post-stress Peak WP is the same
- No lifted stitches observed
- **Lifted metal has low-strength**
- HTS and UHAST can highlight
- HTS can accelerate Lifted Ball



What Have We Learnt?
Looking Back

Development and Qualification:

- √ *Development Process –*
  - √ *engaging the supply chain (engineering/fab/AT/suppliers)*
  - √ *Corner DOE's – making the bonds fails*
- √ *Reliability/Robustness by Design*
  - √ *Selecting Bill of Materials – mold-compounds, Chlorine, Au/Pd-Coated Cu, Roughened leadframes, capillaries*
  - √ *Bonding-Recipe Development – Process Technology, Device layout, bond-window*
  - √ *Reliability- Relationship to initial bond-strength*
  - √ *Package integrity – delamination in packages – bond-breaks, corrosion*
- √ *Enabling Techniques –*
  - √ *SEM x-sections of IMCs,*
  - √ *laser decapsulation,*
  - √ *Bond-pad IMC mapping,*
  - √ *Rapid in-line bond-inspection for over-bonding checks*
  - √ *Au- vs Cu-identification in encapsulated devices*
  - √ *TEM analysis techniques*

What Have We Learnt?

Looking Back

Maintaining Quality & Reliability

√ *Assembly process compatibility and integration (die-attach, plasma, trim-n-form, etc)*

√ *Manufacturing Discipline - Bonder set-ups, bonder-to-bonder matching, handling & cleanliness, across-the-board assembly process controls, preventive maintenance*

√ *Automation in assembly lines – recipe locks, change control*

√ *Monitoring:*

SITE	PULLOUT_ DATE	LOT	COMPLIANCE_ PERIOD	RELCODE	RELDB_ STATUS	FINISH DATE	REVIEWED DATE
MLA	2017-01-05	9211260	1	MLAREL.17.SN74HCT3.01001	Completed	2017-02-17	2017-02-17
MLA	2017-01-10	7003865	1	MLAREL.17.SN74LVC2.01001	Completed	2017-02-22	2017-02-22
MLA	2017-01-10	7019179	1	MLAREL.17.UCC2720101001	Completed	2017-03-02	2017-03-02
MLA	2017-01-10	9123533	1	MLAREL.17.LMZ34002.01001	Completed	2017-03-06	2017-03-06
MLA	2017-01-02	9116674	1	MLAREL.17.2T6000QR.01001	Completed	2017-02-24	2017-02-24
MLA	2017-01-10	7032027	1	MLAREL.17.TPS84620.01001	Completed	2017-03-06	2017-03-06
MLA	2017-01-04	9232145	1	MLAREL.17.CD4051BM.01001	Completed	2017-02-17	2017-02-17
MLA	2017-01-05	9187661	1	MLAREL.17.CD74HC20.01002	Completed	2017-02-17	2017-02-17
MLA	2017-01-08	9222643	1	MLAREL.17.ADS1254E.01001	Completed	2017-02-22	2017-02-22
MLA	2017-01-10	7011797	1	MLAREL.17.SN74LVC2.01002	Completed	2017-02-22	2017-02-22
MLA	2017-01-02	9171964	1	MLAREL.17.7S220ATR.01001	Completed	2017-02-27	2017-02-27
MLA	2017-01-03	9171684	1	MLAREL.17.TLC7528C.01001	Completed	2017-02-22	2017-02-22

Hunting out the pesky Cu-‘killers’:

Manufacturing materials/environments (consumables, facilities, storage conditions, transportation, floor life, personnel etc)

Navigating to a better place

- *Get a handle on Chlorine*
- *Control Delamination in packages*
- *Identify better material solutions*
- *Decapsulation for wirepull analysis.*

HiRel Concerns

Critical Applications

- Critical Applications; Application-specific harsh environments
  - Avionics
  - Munitions
  - Missile Systems
  - Long term dormant storage
  - Extensive temperature cycling
  - High humidity

- Potential risks identified by the industry – not unique to HiRel
  - Bond integrity (Cu bonding to aluminum requires much tighter process controls and environments)[1]
  - Sporadic DPPM level corrosion due to mold compound interaction[2]
  - Bondwire breaks during temperature cycling (Higher CTE of Cu than Au, resulting in a higher failure rate in the presence of delamination)[3]
  - Corrosion at stitch-bonds due to moisture/solvent ingress in conjunction with delamination (not seen with Au wire)

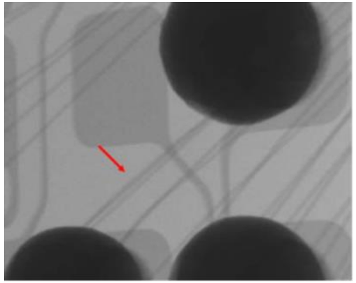
- Commercial qualifications do not use sequential stresses. Additional application-level qualifications necessary

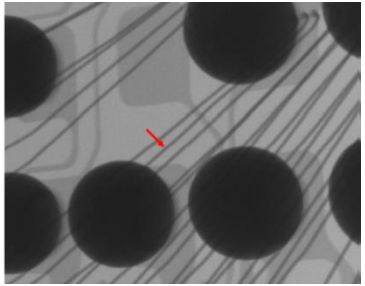
[1] Luke England and Tom Jiang. “Reliability of Cu Wire Bonding to Al Metallization”. Electronic Components and Technology Conference. 2007.
[2] Hui Teng, et al. “Effect of Moisture and Temperature on Al-Cu Interfacial Strength”. International Conference on Electronic Packaging Technology & High Density Packaging, 2008.
[3] Bart Vandevelde and Geert Willems. “Early fatigue failures in Cooper wire bonds inside packages with low CTE Green Mold Compounds”. 4th ESTC Conference. 2012, Amsterdam, The Netherlands.

Defense OEM Concern

- COTS copper bondwire identification
  - Mixed copper and gold bondwire devices in end system prior to customer qualification
  - A simple method to identify the wire-type, base on Atomic number differences between Au and Cu: X-Ray

Cu





Au

Summary

- Cu-wirebond is
  - intrinsically capable of high reliability in plastic packages
  - sensitive to several external factors and environments
  - in production for several years in a variety of commercial & Industrial applications

- Key care-abouts for reliability in commercial applications are
  - Bond integrity
  - Sporadic DPPM level corrosion
  - Corrosion and bond-cracks when package-integrity is compromised

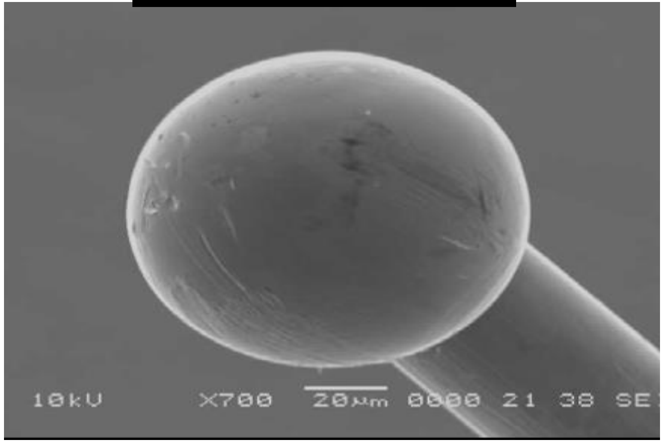
Summary

- Cu-wirebond requires attention to the following key areas
  - Design/Structure of Bond-pads on the die
  - Selection of Package Materials
  - Design & Control of Assembly Processes (e.g. DOE, die-attach, mold, trim-form etc)
  - A new mindset on the factory floor, and manufacturing discipline
  - Seamless collaboration between Device-manufacturer, Assembly/Test and their suppliers

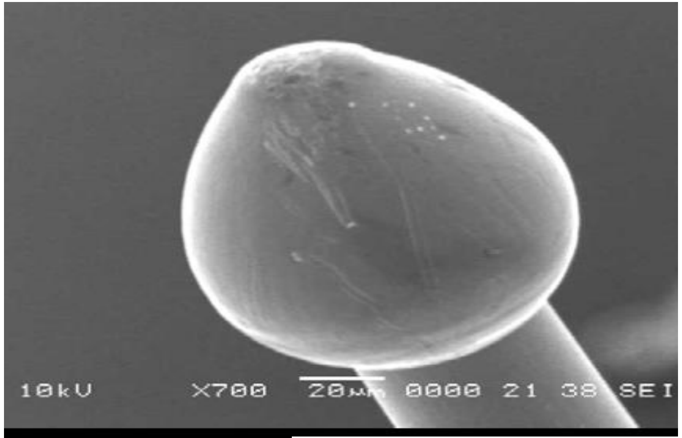
Back Up

Free-Air Ball Formation

Desired FAB shape



- ➢ **Oxidation of Cu during EFO leads to distorted ball during cool-down.**



Distorted FAB

- ➢ **Oxidized ball presents bonding challenges – NSOP or pad-damage.**

Copper Wire Bond Process