Copper Wire in Automotive: Key Challenges and Robust Validation

Alberto Mancaleoni
(Automotive Product Group / Assembly Reliability Principal Eng.)

Fabien Quercia
(Corporate Packaging & Automation – Wire Bonding Process Dev.)

ESCCON 2016
March 1/2/3, 2016

Contents

Roadmap, opportunities and process challenges:

- *Cu implementation vs Package and silicon technology (ST Roadmap)*
- *Cu vs Au: advantages and drawbacks (electrical and thermal performances / mechanical properties / manufacturability windows / compatibility with plastic packaging materials / quality and reliability)*

Failure mechanisms overview:

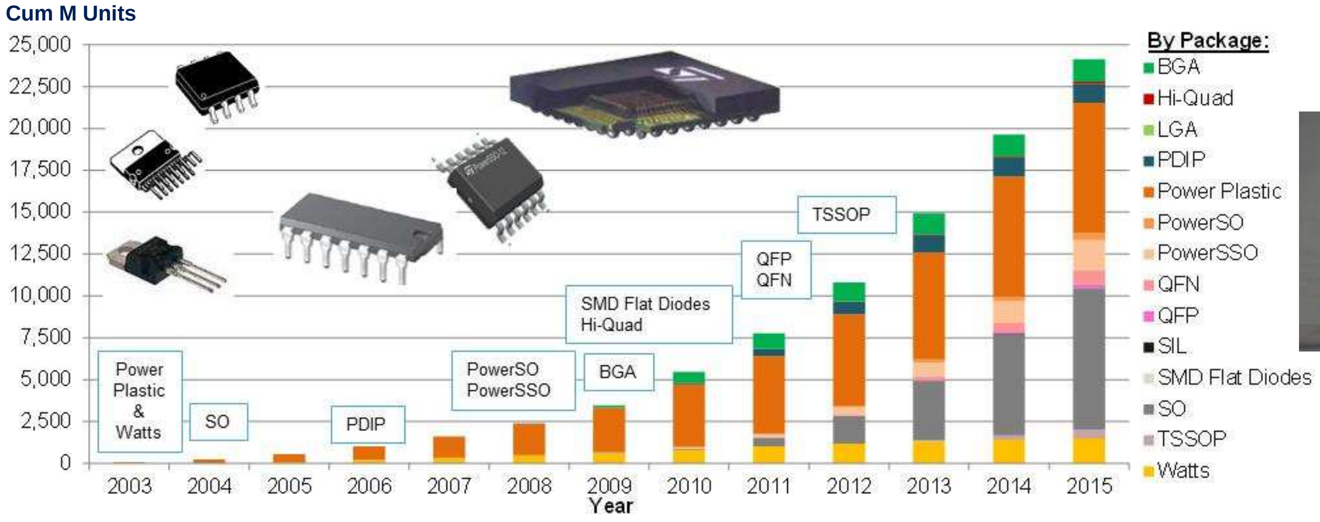
- *CuAl Inter-Metallic Compounds ageing*
- *Thermal fatigue vs plastic package integrity / delamination*
- *Corrosion risk*

Robust validation for automotive application:

- *Test-to-fail and wear-out investigation (failure mode driven reliability tests)*
- *Test-vehicles and corner lots evaluation (bond-pad structure compatibility)*

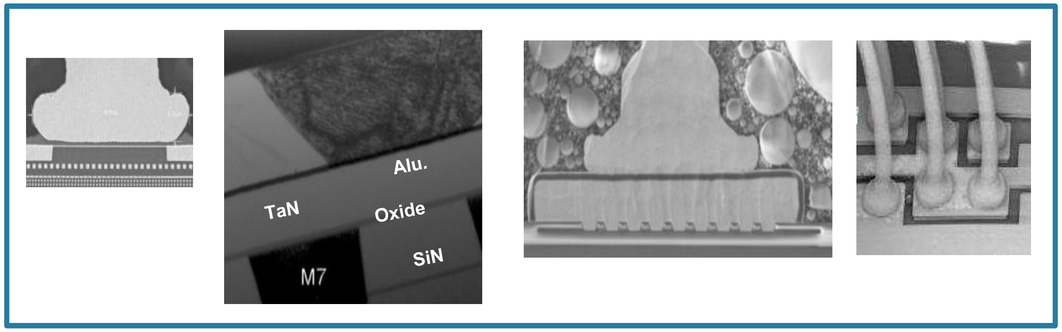
Copper Wire Program

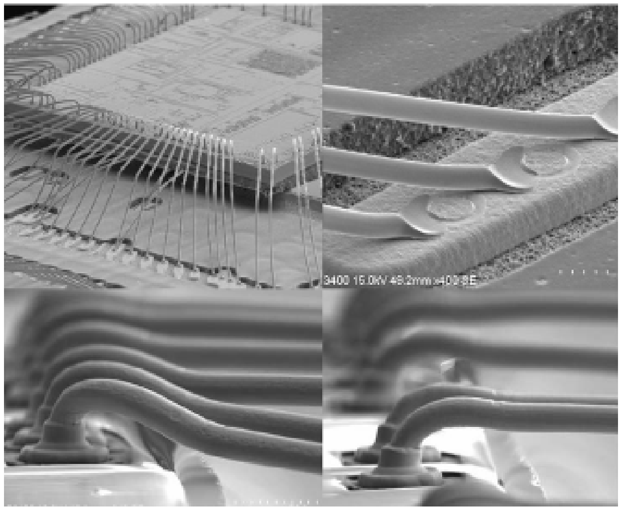
ST Cu wire conversion so far



24.1 B units produced to date (end 2015)

- ✓ 1 B unit / quarter current run rate
- ✓ All packages
- ✓ Most of silicon technologies





Copper vs Gold: A Quick Overview

PROPERTIES	UNITS	Au	Cu	EXPECTED IMPACT IN Cu CONVERSION
Melting Point	°C	1063	1083	No risk: same or higher burn-out threshold
Heat Conductivity	Cal/cm.sec.°C	0.744	0.941	No risk: better heat dissipation
Coef. of Linear Expansion	ppm/C	14.16	16.5	No risk: similar thermal expansion
Electrical Resistivity	µOhm.cm	2.35	1.7	No risk: lower ohmic drops
Modulus of Elasticity	N/mm^2	79000	123000	Better control in wire looping Reduced wire sweeping during mold injection **Higher risk of bond-pad damage (cratering / IMD crack) [#]** **Shorter lifetime in thermal fatigue, if activated [%]**
Tensile Strength	N/mm^2	135	210-370	
µ–Hardness (typical)	Kg/mm^2	66	**115**	
Chemical reactivity	-	Low	**Higher**	**Risk of IMC corrosion in presence of free Cl- and humidity [&]** **Pre-bond Free Air Ball (FAB) oxidation**
IMC formation on Al pad	-	Yes	Yes	IMC evolution at high operating temperature to be characterized

NOTES:

[#] Bond-pad structures must be characterized and often adapted to be “Cu-compatible”

[%] Critical levels of thermal fatigue are mainly activated by delamination around the bond. The 2nd bonding tips of metallic lead-frames are the weakest element. Other key activating factors are wire diameter (thinner is the worse) and lead shape

[&] In ST experience, sensitivity to CuAl Inter-Metallic Compounds (IMC) corrosion has only been observed in very thin Cu diameter (<1mil) and packages with organic substrate (BGA). The key preventive actions have been anyway implemented for all packages and wire diameters

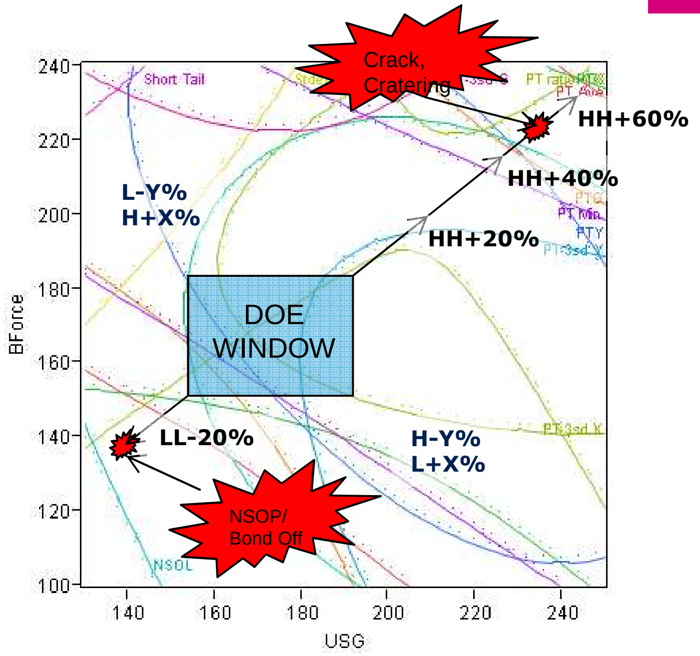
life.augmented

Overview Comparison (Cu vs Au wire)

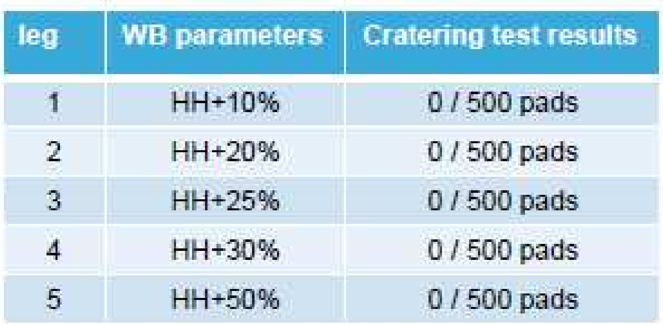
Aspect	Parameter	Cu Wire	Gold Wire	Difference in Copper Wire
Process	Bill of Material	🟢	🟢	Halogen-free mold compound mandatory for copper wire, in line with halogen-free package policy already in place
	Equipment	🟡	🟢	Supply of Forming Gas to avoid oxidation during ball formation
	Process Setting	🟡	🟢	Tighter bond process window needed for copper wire.
Product	Electrical Performance	🟢	🟡	Better for copper wire due to its higher electrical conductivity
	Quality	🟢	🟢	If adequate process recipes and controls are in place, copper wire bonds have the same quality as gold ones.
	Reliability	🟢	🟢	If adequate process recipes and controls are in place, copper wire bonds have the same intrinsic reliability (lifetime) as gold ones.
Process Control	Process / Procedure	🟡	🟢	Special" Handling for Cu wire material to avoid oxidation/contamination (wearing of gloves , more frequent cleaning of tweezers , shorter spool life in production, new nozzle)
Production	Assy Yield / FT Yield	🟡	🟢	Assy Yield is slightly lower with Copper during the package learning curve.
	UPH	🟡	🟢	Gold wire bond speed is 5 % to 8 % faster than copper wire
OVER-ALL COMPARISON		🟢	🟢	Manufacturing performance of copper wire is getting closer and closer to gold wire, with adequate control tightening Reliability performance of well-processed copper wire is equivalent or even better than gold wire one.

Parameters Robust Validation

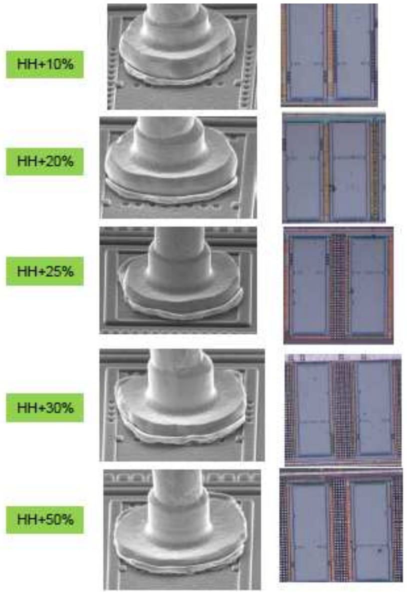
- ✓ The DOE output is a “Process Window”, e.g. the allowed range for the key bonding parameters across the optimized setting “NN” (Nominal force / Nominal ultra-sonic power):
    - ✓ NN + 7% => HH (Highest force / Highest power)
    - ✓ NN - 7% => LL (Lowest force / Lowest power)
- ✓ The “Robust Validation” consists in pushing the key parameters beyond the HH and LL limits until a wire-bonding defect occurs:
    - ✓ Pad crack / Cratering / Peeling at HH + X%
    - ✓ Bond-off (non stick on pad) at LL - Y%
- ✓ X and Y should reach at least 10% to assure:
    - ✓ Good manufacturability vs materials / equipment natural spreads;
    - ✓ Robust reliability performance vs field environment.



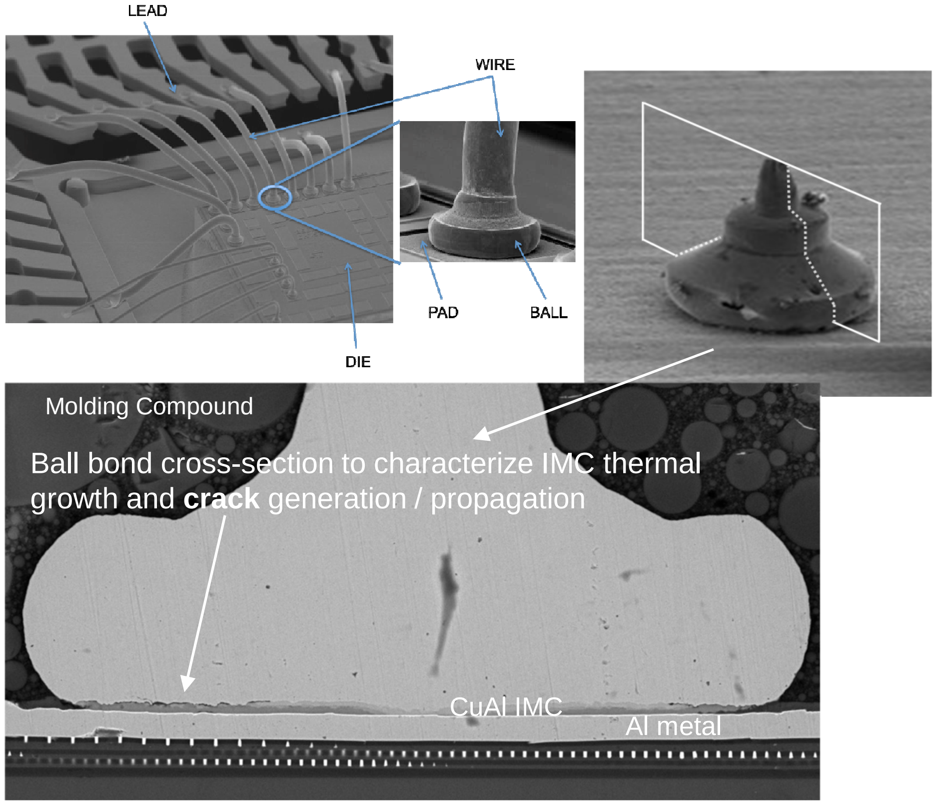
<u>Example from 0.8 mils bare copper validation on a Low-k device:</u>



leg	WB parameters	Cratering test results
1	HH+10%	0 / 500 pads
2	HH+20%	0 / 500 pads
3	HH+25%	0 / 500 pads
4	HH+30%	0 / 500 pads
5	HH+50%	0 / 500 pads

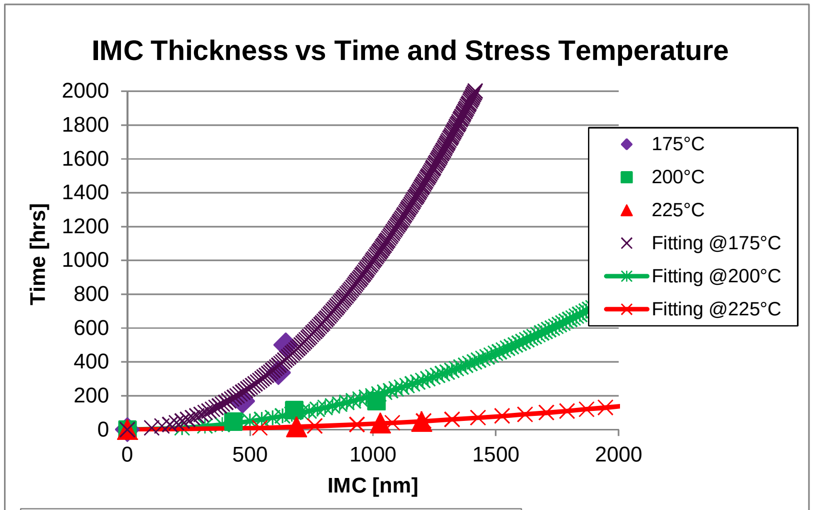


CuAl Inter-Metallic Compounds -1



Ball bond cross-section to characterize IMC thermal growth and **crack** generation / propagation

- ✓ IMC between Cu (bond) and Al (pad) change in thickness and composition due to operating temperature;
- ✓ The IMC ageing process, combined with molding compound mechanical stress, can ultimately result in a crack generation and propagation;
- ✓ Arrhenius law, through the estimation of the “Activation Energy” E_A, provides an effective model to predict the achievable lifetime as a function of use conditions:



$$x(t) = \sqrt{kt}$$

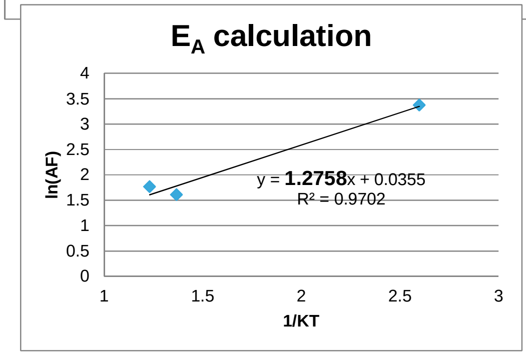
where:

x = CuAl thickness
t = storage time
k = temperature coefficient, given by:

$$k = k_0 e^{-\frac{E_A}{KT}}$$

where:

K_0 = constant
E_A = activation energy (eV)
T = absolute temperature
K = Boltzman constant = 8.625×10^{-5} eV



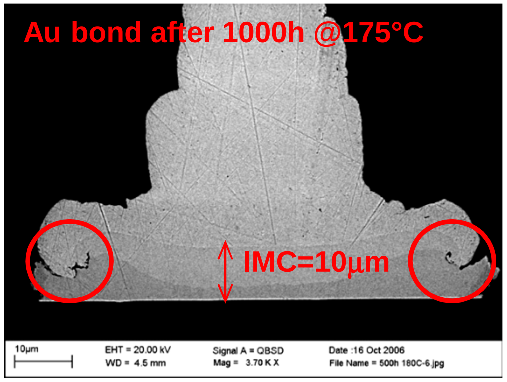
E_A≈1.25eV

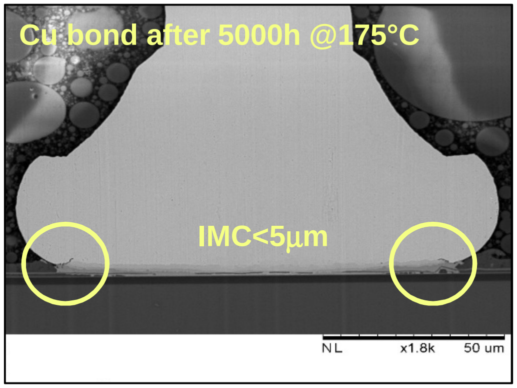
(0.8 mil PCC Wire)

CuAl Inter-Metallic Compounds -2

COMPARED TO GOLD WIRE:

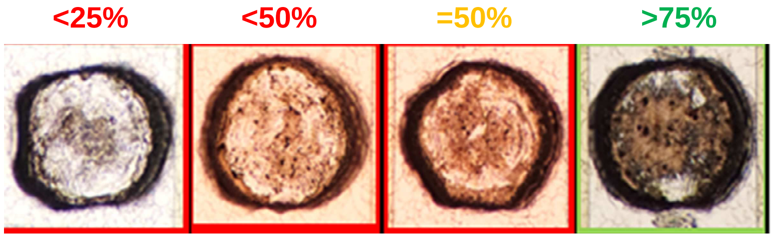
- ✓ The IMC growth is much faster in Au bonds, which suffer of the same intrinsic mechanism if bonded on Al pads. Due to that, Cu bonds lifetime potential, at the same temperature conditions, is equal or longer.
- ✓ The ultimate degradation of aged Au bonds is sometimes worsened by the growth of “Kirkendall voids” (unbalanced diffusion of the two source metals), while Cu bonds failure mode is more related to crack propagation.





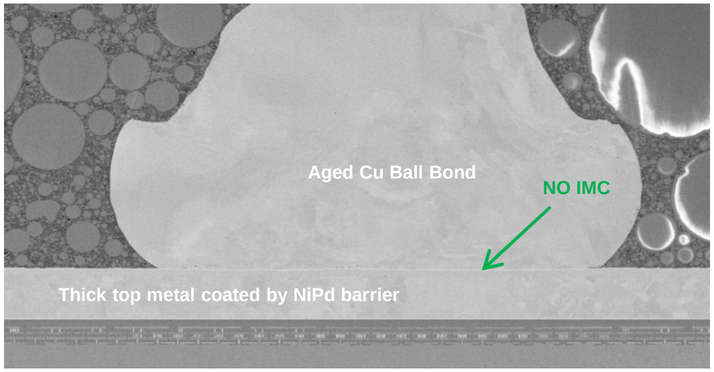
PREVENTION:

- ✓ IMC coverage maximization during process setup => crack stoppage at the bond perimeter / propagation inhibited

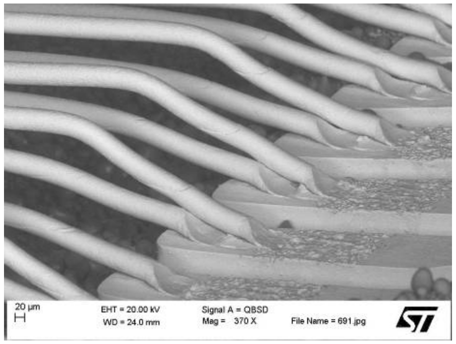


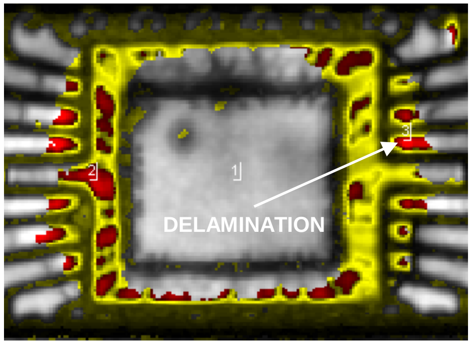
ROBUST SOLUTION:

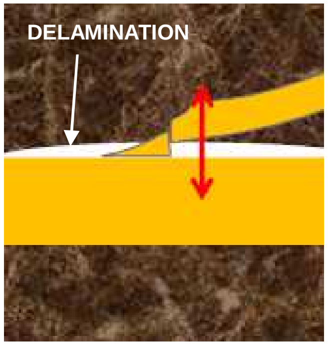
- ✓ Use of Over-Pad Metallurgy: the bond interface is IMC-free, and therefore not sensitive to thermal ageing (unlimited lifetime)
- ✓ OPMs can also offer the advantage to protect the bond-pad structure against mechanical stress / damage during the bonding process, allowing active structures to be integrated below.

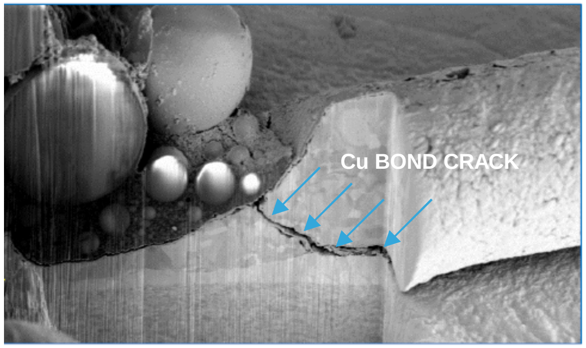


Thermal Fatigue in Cu Wire Bonds









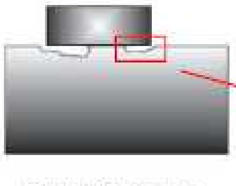
- ✓ It mainly affects 2nd bond - stitch-bond on package lead-frame
- ✓ Activated by Molding Compound delamination at lead-tip interface
- ✓ Different TCE between MC and copper lead, in presence of delamination, induces thermal fatigue on the stitch-bond during temperature cycling
- ✓ Copper bonds are more sensitive to thermal fatigue cracks than Au bonds

PREVENTION:

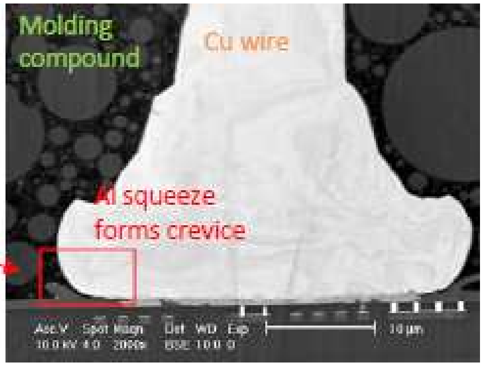
- ✓ Thin Cu wires (1.2mil or smaller) cannot normally “survive” to automotive mission profiles in presence of systematic delamination. Larger leads with extended bonding areas plated by noble metals (Ag, Au) represent the worst-case condition. Also thick Cu wires must be anyway characterized vs thermal fatigue through extended reliability testing, mainly TC, after pre-treatments able to induce a worst-case delamination.
- ✓ A robust eradication of thermal fatigue risk, especially in thin Cu wire, requires a “delamination-free” package. The most common approach is to improve the adhesion by appropriate selection of molding compounds (low-stress / high adhesion) and surface treatments of the lead-frame to enhance the adhesion by chemical or physical bonds.

Copper Bond Corrosion

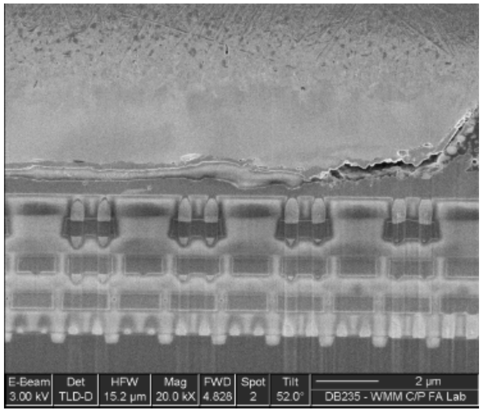
THE CORROSION MECHANISM is well described by the “Crevice Corrosion” model: the chemical reaction site is offered by the physiological “crevice” produced during the wire-bonding operation at the bond edge

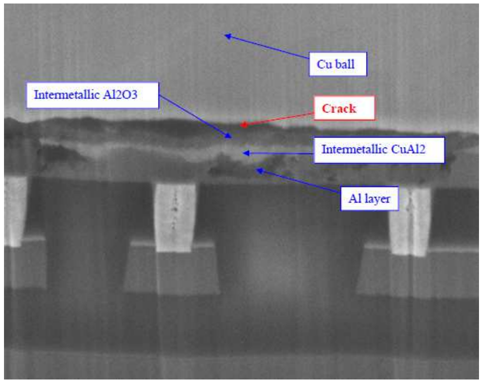


Crevice Corrosion



ACTIVATING FACTORS: small geometries (fine-pitch bonding with Cu diam. <1mil), poor IMC coverage, ionic impurities in the package materials (Cl in particular) or environmental contamination in the assembly line

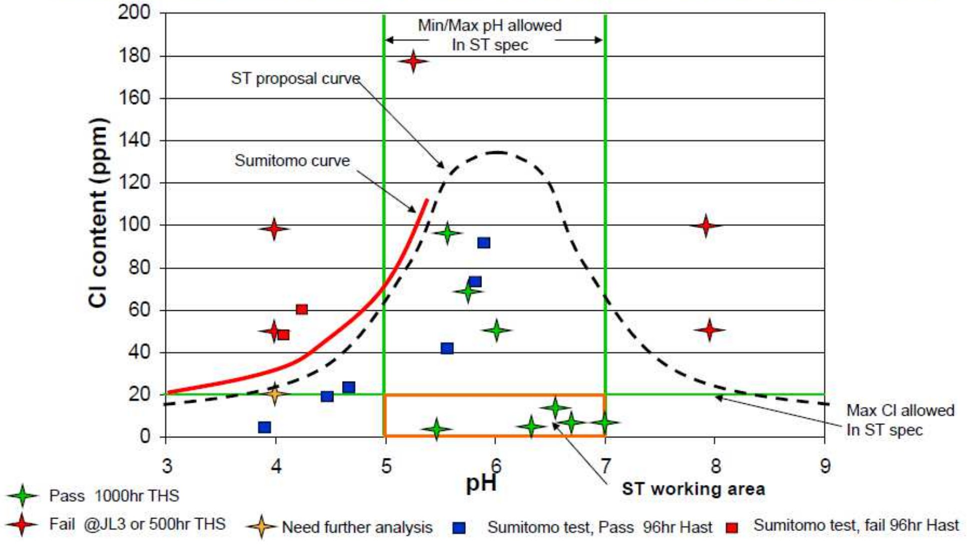




PREVENTION:

- ✓ IMC coverage optimization during wire-bonding setup
- ✓ Clean handling procedures at the assembly line
- ✓ Dedicated tightening of package materials specification for pH and Cl content (15-20 ppm maximum):

Graph extracted from Sumitomo Bakelite Co presentation and updated with ST data



life.augmented

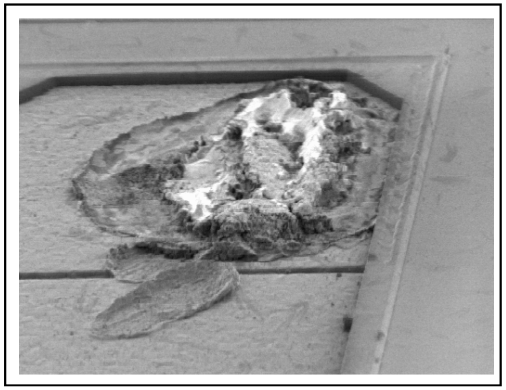
Test-to-Fail and Wear-out Investigation

- *STRESS MATRIX driven by failure mechanism(s) expectation, based on the involved technology mix (silicon + package) and mission profiles*
- *LIFETIME MARGIN assessed by pushing the key stress tests until 2x applicable AEC-Q100 Grade (or specific mission profile upon customer agreement)*
- *PHYSICAL ANALYSIS of stressed samples systematically performed in order to quantify degradation processes activation (if any)*

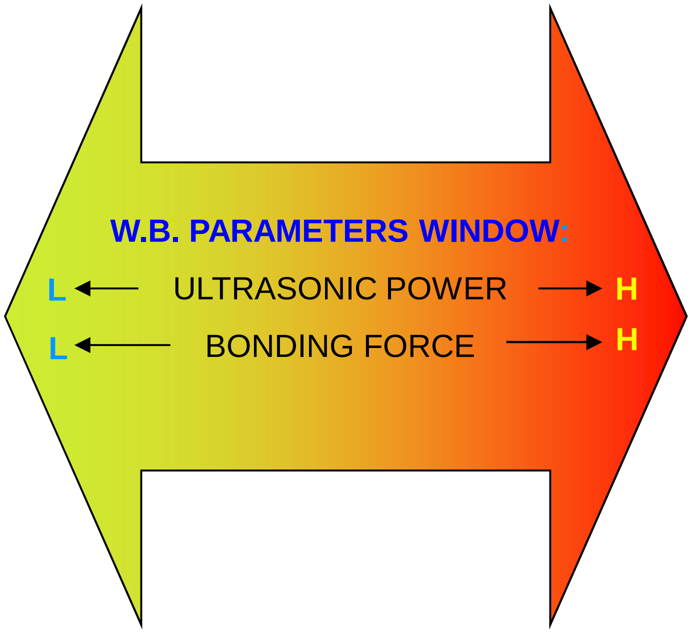
Failure mechanism	Key activating stress factor / stress methods	Most sensitive detection methods
Bond-pad damage	Temperature excursion / **TC**, PTC	Electrical (functional) test Physical: bond-pad chemical delayering
Thermal fatigue on 2nd bond	Temperature excursion / **TC**, PTC	Electrical (functional) test Physical: SAM-driven wire pull test / SEM
CuAl IMC thermal ageing	High temperature / **HTSL**, HTOL	Electrical (functional) test Wire pull test / 1st bond cross sections
CuAl IMC corrosion	Temperature + humidity / **AC**, **uHAST**, **THB**	Electrical (functional) test VI / Wire pull test / 1st bond cross sections

Test Vehicles and Corner Lots Evaluation

- *TEST-VEHICLE(S) and QUALIFICATION LOTS are chosen to offer a worst-case sensitiveness to the key failure-mechanisms inside the target qualification perimeter; this is identified by a same wire-bonding equipment, package raw materials, bonding process parameters and tools, wire type and size, silicon technology and relevant bond-pad structures (sequence of layers, layout rules).*
- *CORNER LOTS are included in reliability sampling, in order to demonstrate compliance with long-term lifetime requirements at the extreme settings allowed for the wire-bonding parameters (highest and lowest points of the process window)*



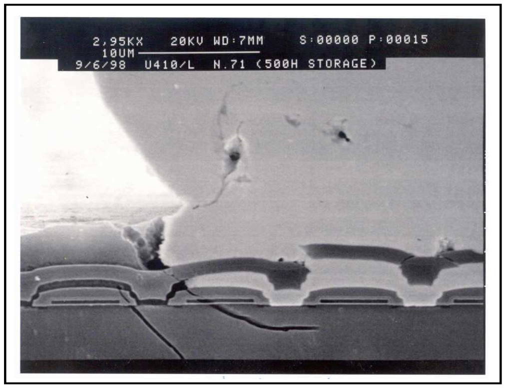
INSUFFICIENT INTERMETALLIC
WEAK BONDING



W.B. PARAMETERS WINDOW:

L ← ULTRASONIC POWER → H

L ← BONDING FORCE → H



CRACK OF IMD LAYERS
ACTIVE METAL SHORTING

- *LL corner to assess CuAl IMC formation capability => THERMAL AGEING (HTSL)*
- *HH corner to assess preservation of bondpad integrity => TEMPERATURE CYCLING (TC)*

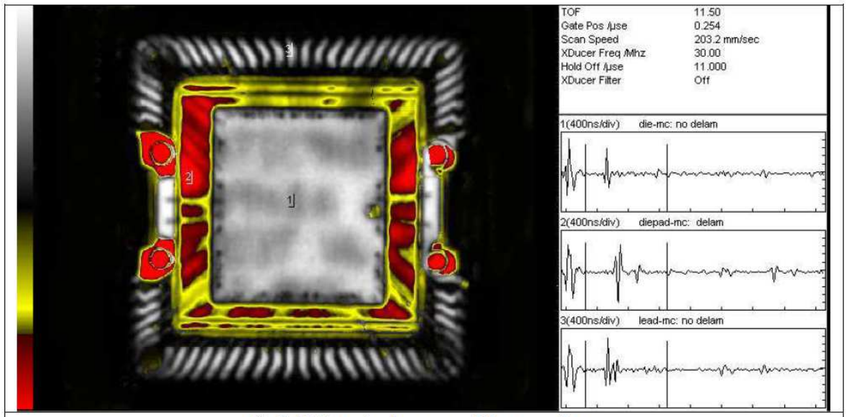
Physical Assessment Flow - Example

Stressed devices (min 5 units) → *SAM inspection* → *DECAP* → *Internal VI SEM inspection* → *Wire Pull Test* → *Data Review (additional analysis?)*

SAM inspection:
- *Die surface*
- *Lead-tips*
- *Die-pad*

Internal VI SEM inspection:
- *Ball bonds*
- *Stitch bonds*

Wire Pull Test:
- *STD pull mode*
- *All wire types*
- *Pin # traceability*



TOF 11.50
Gate Pos /µse 0.254
Scan Speed 203.2 mm/sec
XDucer Freq /Mhz 30.00
Hold Off /µse 11.000
XDucer Filter Off

1(400ns/div) die-mc: no delam

2(400ns/div) diepad-mc: delam

3(400ns/div) lead-mc: no delam

C-SAM typical case with waveform

Lot	Sample size	Defective parts (delamination)		
		die-mold (C-scan)	l/f-mold (C-scan)	diepad-mold (C-scan)
NN	10	0/10	0/10	*10/10
HH	10	0/10	0/10	*10/10
LL	10	0/10	0/10	*10/10
Transducer frequency (MHz)		30	30	30

* Uncritical delamination (no wire bonds)

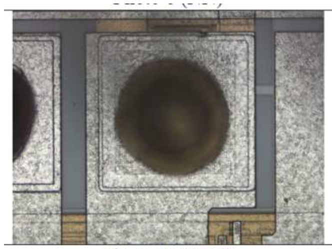


Photo 11 (Au 3)

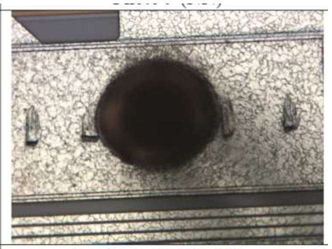


Photo 12 (Cu 2.5)

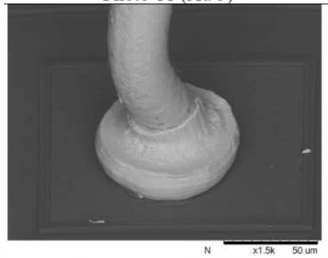


Photo 5 (Au 1.3 mils)

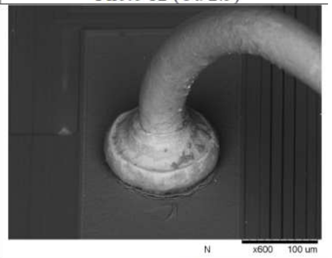


Photo 6 (Cu 2.5 mils)

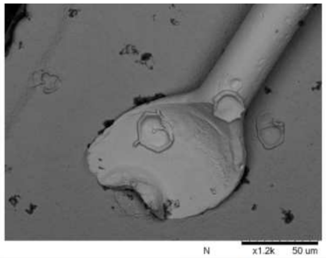


Photo 2 (Au 1.3 mils)

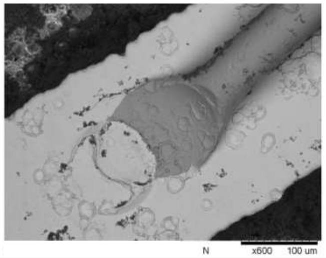


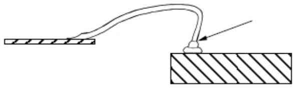
Photo 3 (Cu 2.5 mils)

life.augmented

Wire Bond Integrity Testing - Example

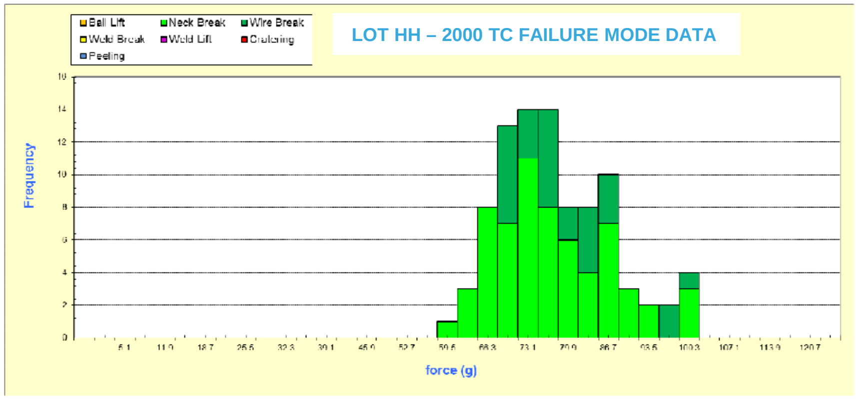
Wire type : Cu 2.5 mil
LSL (g) : 23

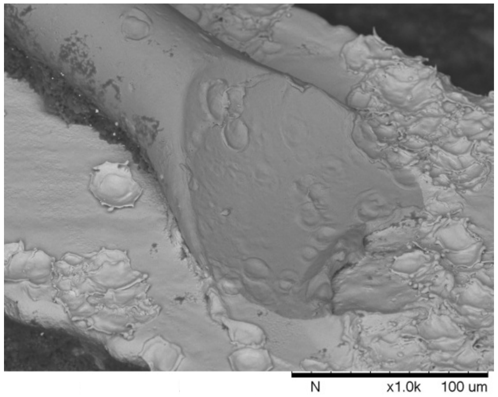
Sample size (pcs) : 5
Sample size (wires) : 90

Failure mode		**2000 TC (-50+150°C)**		
		HH	**LL**	**NN**
2-3: NECK BREAK+WIRE BREAK 	**mean (g)**	77.9	73.3	74.7
	stdev (g)	9.5	6.9	5.5
	min (g)	59.0	59.4	50.3
	max (g)	101.5	98.1	83.0
	occurrence	100%	100%	100%

Stress duration: 2x AEC-Q100 Grade 1

Wire-bonding corner lots computed separately





All stitch-bonds are SEM-inspected before pull, especially if bonded on delaminated tips (previously identified by SAM scanning

WIRE-PULL TEST AFTER TC: acceptance criteria based on breaking load distribution and failure modes:

- ✓ *All values distributed within 3σ from AVG, with σ < 10% AVG (N.A. for very thin Cu, <1mil)*
- ✓ *Any change in failure mode from time-0 need to be understood (i.e. physically modeled)*
- ✓ *WARNING: possible source of artifacts are mold compound removal recipe or pull method itself*
- ✓ *Cross sections (1st or 2nd bond) helpful for failure mode understanding, but poorly effective as primary investigation method (low statistics and partial information about the overall bond morphology)*

Cu Wire in Automotive - Conclusion

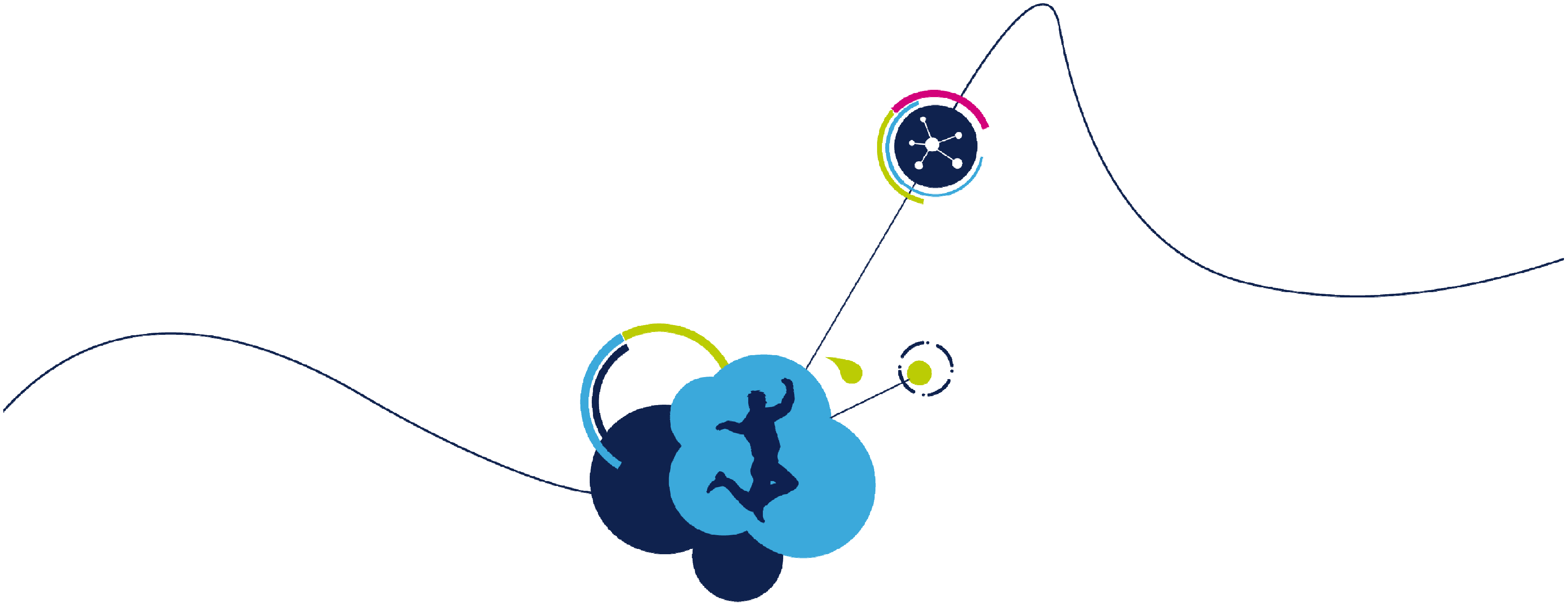
✓***Cu Wire-bonding*** *is today a mature technology for package – silicon interconnection in ST: developed for consumer market as first step, it has been successfully extended to most of the* ***Automotive*** *product families during the last 5/6 years.*

✓*A key enabler for the safe implementation of Cu wire-bonding is a* ***"Robust Validation"*** *approach and mindset, at two complementary levels:*

  ✓***Assembly process:*** *the "manufacturability window" has to be characterized for each different bond-pad structure, wire size and bond equipment: the most probable defect causes have to be identified through a* ***"look for failure"*** *approach, and prevented with a* ***known and controlled margin****.*

  ✓***Reliability assessment:*** *the traditional "test to pass" method has to be replaced by a* ***"test to fail"*** *engineering mindset, applying* ***extended stress duration*** *and* ***"corner samples"*** *to maximize the probability of failure process activation.*

✓*Thanks to this enhanced methodology, a solid* ***failure mechanisms knowledge*** *and modeling can be achieved. Consequently, the most appropriate solutions will be identified on the basis of the* ***real field requirements****, addressed through a* ***shared mission profile*** *along the supply chain.*



THANK YOU!