Decapsulation of Copper Wire Bonded Devices

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Motivation for Switch to Copper Wire Bonding

Advantages of Copper Wire Bonding

- **Copper is much cheaper than Gold (As of Apr 2017: $0.22/oz vs. $1250/oz)**
- Other less critical advantages are lower electrical resistance, and higher thermal conductivity than Au. So smaller wire diameter (18μm) can be used → smaller pad sizes.
- Copper wire has higher mechanical strength and higher stiffness which prevents wire sweep during transfer molding.
- IMC formation in Cu-Al system is much slower than in Au-Al system.

Drawbacks of Copper Wire Bonding

- Higher hardness can cause cracking of BOAC.
- Copper can oxidize during wire bond formation.
- Smaller process window due to harder wire.
- Cu-Al intermetallic compounds prone to corrosion in humid conditions.
- Cu wirebonds are susceptible to a range of failure mechanisms that are different from those for Au wirebonds.

Bonding Wire	Gold	Copper
Density (g/cm^3)	19	8.9
Melting Point (°C)	1064	1085
Electrical Resistivity (Ω-m)	2.21E-08	1.68E-08
Thermal Conductivity (W/mK)	318	401
Young's Modulus (GPa)	78	130
Vickers Hardness (MPa)	216	369

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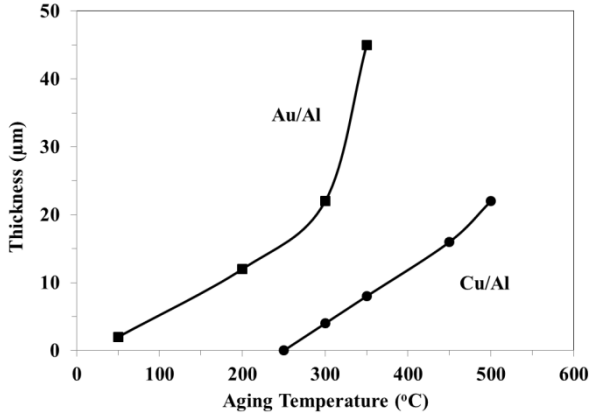
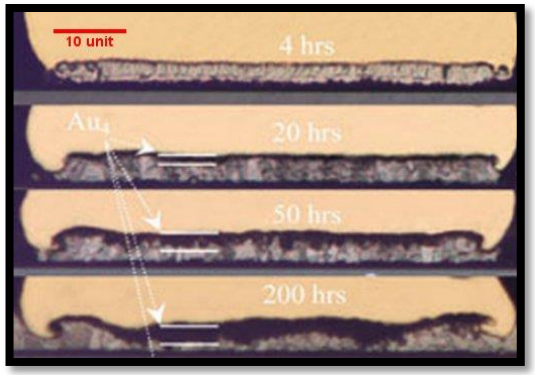
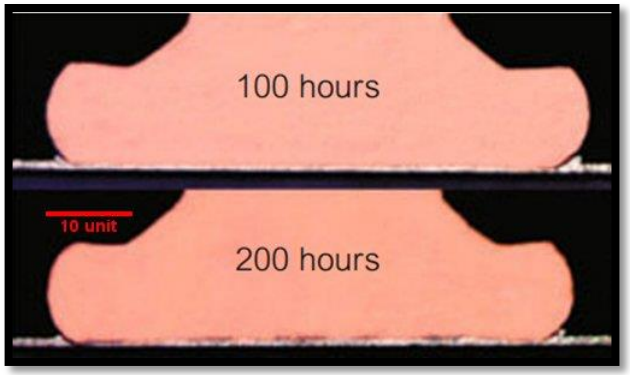
Intermetallic Formation in Copper Wire Bonds

- For small signal devices, Cu wires are ball bonded to either Al or Ni/Au bond pads.
- Diffusion rate of Cu in Al is less than for Au in Al leading to less IMC formation.
- Cu–Al IMCs have lower electrical resistivity and less Joule heating than Au–Al IMCs.
- Kirkendall voiding is very sparse in Cu-Al IMCs, but widely observed in Au-Al IMCs.
- Cu wires bonded to AuNi and AuPdNi finishes do not exhibit voiding upon aging at 150°C for up to 120 days.



Comparison of Au-Al and Cu-Al IMC thickness after 5 hours of aging with different temperature [26]





Comparison of Au-Al and Cu-Al IMC thickness annealed at 175°C [2]

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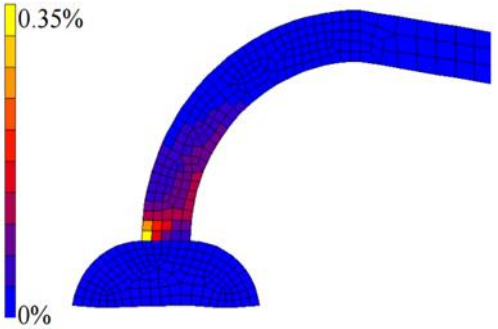
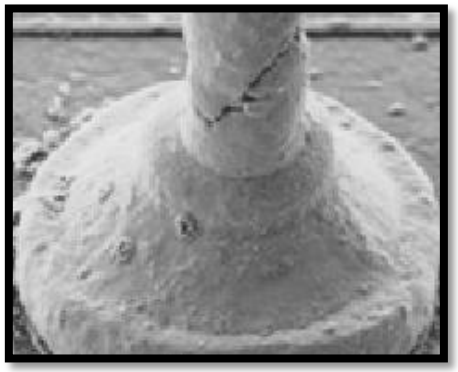
Failure Mechanisms in Copper Wire-Bonding Wire Bond Axial Fatigue

- Green molding compounds used in electronic packages lower moisture sensitivity, reduce thermal mismatch between die and mold compound, reduce environmental hazards and lower cost.
- These molding compounds have high silica filings (>85%) leading to lower coefficient of thermal expansion (CTE) than the traditional molding compounds.
- Copper wires can break due to axial thermo-mechanical stresses between the "green" molding compound and the wire.
- This is due to higher thermal mismatch of green mold compounds (~10 X 10^{-6}/K) with copper (17 X 10^{-6}/K) than with gold (14 X 10^{-6}/K).
- Cracking of wires leads to increased resistance, and eventually to an open circuit.
- Such micro cracks in wires may not be observed from cross sectioning due to smearing of copper. However, decapsulation of the device can be used to observe this.



Plastic strain induced by one temperature cycle due to GMC on copper wire bond [25]



Wire axial fatigue crack [25]

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Other Copper Wire Bond Failure Mechanisms

Failure Site	Failure Modes	Failure Mechanisms	Failure Load	Failure Models
Under pad metallization – Crack [1]	Resistance Change/ Open Circuit	Fracture	Bonding Stress	-
Bond Pad - Aluminum Splash [5]	Short Circuit	Aluminum Extrusion	Bonding Stress, Temperature and Ultrasonic Force	-
Ball bond - Bond pad interface	Resistance Change	IMC Growth [6]	Temperature Aging	Arrhenius Model
Ball bond - Bond pad interface	Resistance Change/Open Circuit	Corrosion [7]	Temperature, Relative Humidity and Ionic Contamination	Peck's Law [24]
Ball neck – Crack [8]	Resistance Change/ Open Circuit	Axial Fatigue	ΔT→ Mismatch in Thermal Expansion Between Wire and Mold Compound	[Adam 1973]
Mid Wire – Crack [8]	Resistance Change/Open Circuit	Flexural Fatigue	ΔT→ Mismatch in Thermal Expansion Between Die and Lead	Coffin-Manson Model
Heel – Crack [8]	Resistance Change/Open Circuit	Flexural Fatigue	ΔT→ Global Mismatch in Thermal Expansion Between Die and Lead	Hu Pecht and Dasgupta Model
Heel - Lift off [8]	Open Circuit	Fatigue	ΔT→ Local Mismatch in Thermal Expansion Between Wire and Bond Pad	Basquin's Fatigue Model

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What needs to be done to ensure reliability?

- Manufacturers are using the same qualification tests for copper bonded devices as for gold bonded devices, even though damage accumulates differently in these two interconnections, and the failure mechanisms and models are significantly different.
- Passing the standard qualification tests does not guarantee equal reliability in the field and the tests themselves may be irrelevant for the new failure mechanisms occurring in the Cu bonded devices.
- Differences between Au and Cu wire bonding need to be understood in order to design appropriate reliability tests.
- Therefore, it is necessary to conduct research assessing and mitigating the risk of using Cu wire bonded parts. This includes investigating issues of long term storage, intermetallic formation, and the development of fundamental failure mechanism models.
- Conducting research on copper wire bonded devices requires failure analysis procedures including a technique for decapsulation to protect copper wire bonds.

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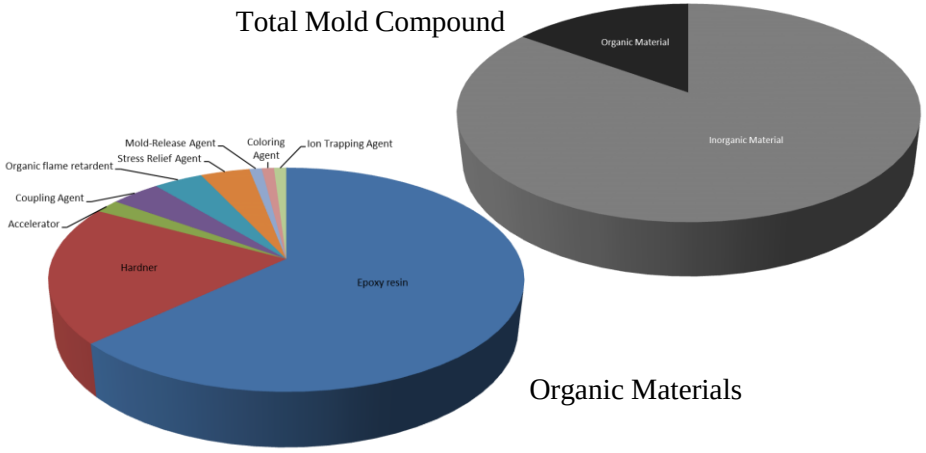
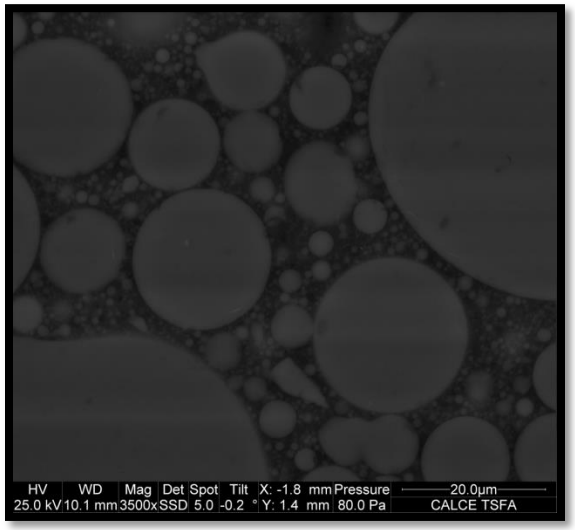
Mold Compound Decapsulation

- Mold compound is made of a mixture of inorganic and organic materials.
- Inorganic material comprises of the majority of mold compound by weight (~70-90%) and is comprised of fillers and inorganic flame retardants.
- Organic material (8-20%) is comprised of epoxy resins, hardener, flame retardants, mold release agents, ion trapping agents, coloring agents, stress release agents and coupling agents[19].
- Black region on the image shows epoxy resin while the grey circles show the inorganic fillers.





Cross section of molding compound on an encapsulated device

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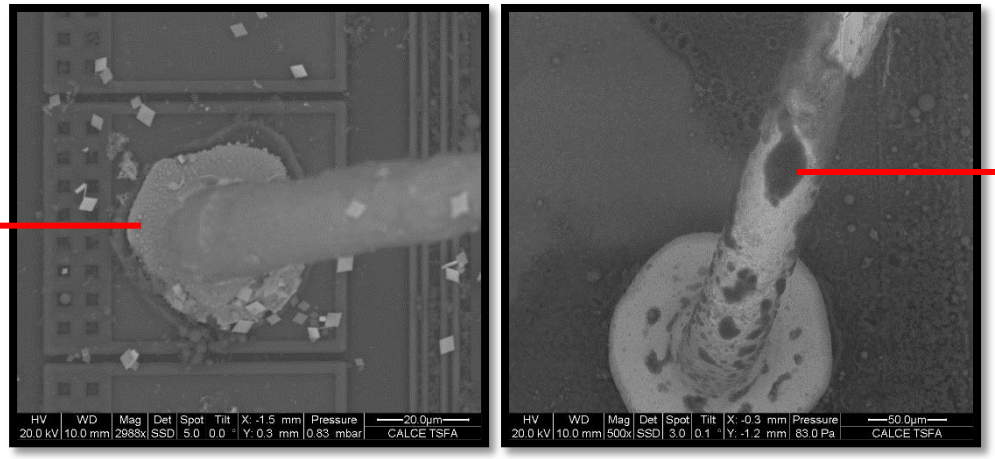
Motivation for New Decapsulation Technique

- A study of the degradation of wire bonds requires performing failure analysis, including bond shear and pull tests, which require the device be decapsulated.
- Traditional gold wire decapsulation methods are based on using fuming nitric acid to remove the thermoset polymer while leaving the gold wires intact.
- These methods cannot be used with copper wire because the nitric acid reacts with copper, forming copper (II) nitrate.

$$Cu + 4HNO_3 \rightarrow Cu(NO_3)_2 + 2H_2O + 2NO_2 \uparrow$$

Severely etched ball bond



Deep pits on wire

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Decapsulation Techniques

- Laser and plasma based decapsulation methods are expensive and difficult to control.
- Several studies[11,12,14,15] have shown decapsulation with mixed nitric and sulfuric acid. However, this has been shown to reveal both the ball and wedge bonds on very small components, but only the ball bond on larger devices.
- To expose both ball and wedge bonds, the exposure time is long and a method to protect the copper wire is needed.
- A three-step mixed acid decapsulation process is used to perform this.
- Nitronium ions are produced upon mixing nitric and sulfuric acid, which act to degrade the molding compound.

$$H_2SO_4 + HNO_3 \rightarrow HSO_4^- + NO_2^+ + H_2O$$

- The bisulfate ions formed are used to create a coating over the copper wire that prevents it from reacting with nitric acid.

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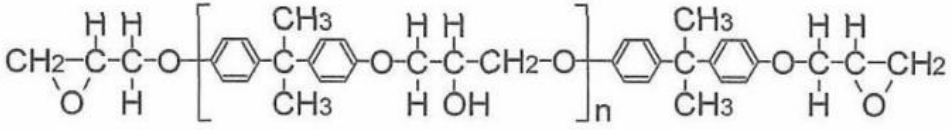
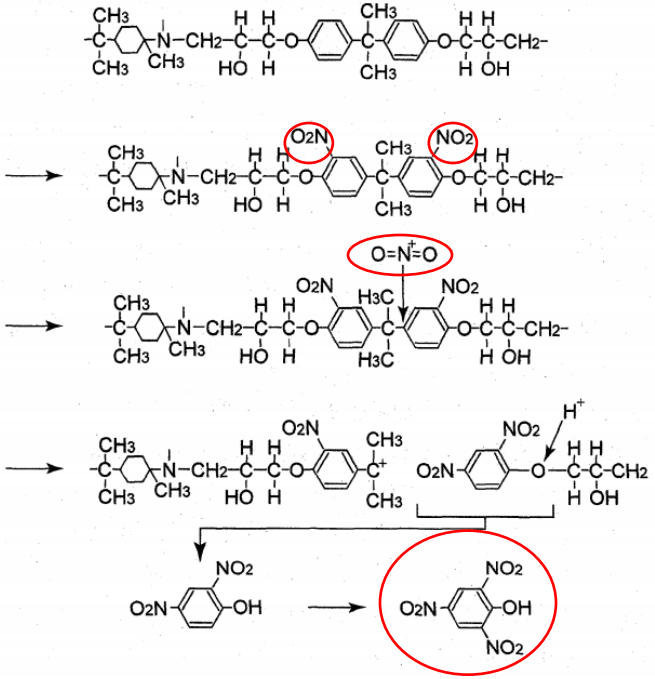
Mechanism of Mold Compound Decapsulation

- Bisphenol A epoxy resin is the most common type found in mold compound.



- Upon contact with mixed nitric and sulfuric acid, the resin undergoes decomposition.



- NO_2^+, produced by mixing nitric and sulfuric acid, attacks the resin and replaces hydrogen atoms from the benzene ring in the bisphenol A part of the resin.
- Abundance of NO_2^+ causes continuation of the reaction by breaking the main chain and subsequent nitration.
- Finally a 2,4,6-trinitrophenol is produced from one end of the chain.
- And the process continues until all of the epoxy resin is decomposed or until NO_2 is used up.

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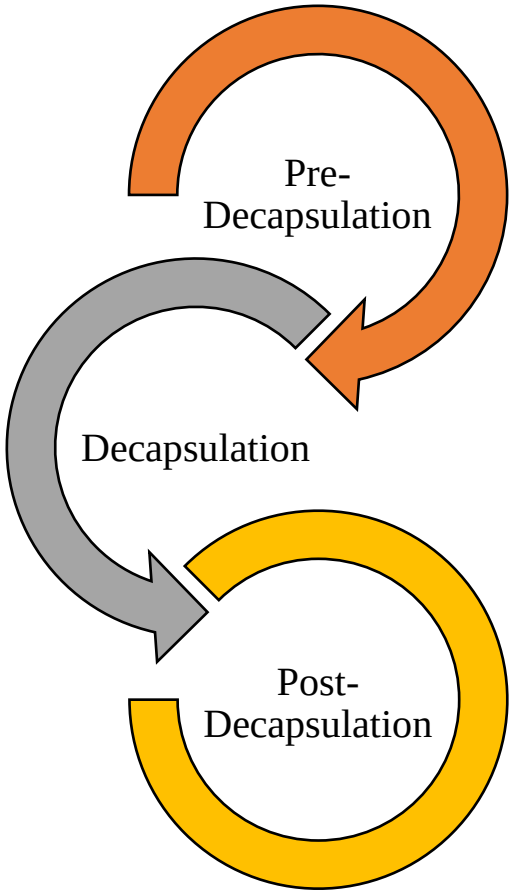
Decapsulation Technique for Cu Wire Bond Devices

The decapsulation step removes the bulk of the encapsulant containing the copper wires above the component. An electrolysis method is employed.



The pre-decapsulation step is done to remove excess molding compound from above the device without revealing the wires, easing the next step in the process.

1. Mechanical Milling
2. Acid Etching

The post-decapsulation step involves revealing a clean metal wire surface after completion of the decapsulation.

1. Solvent Cleaning

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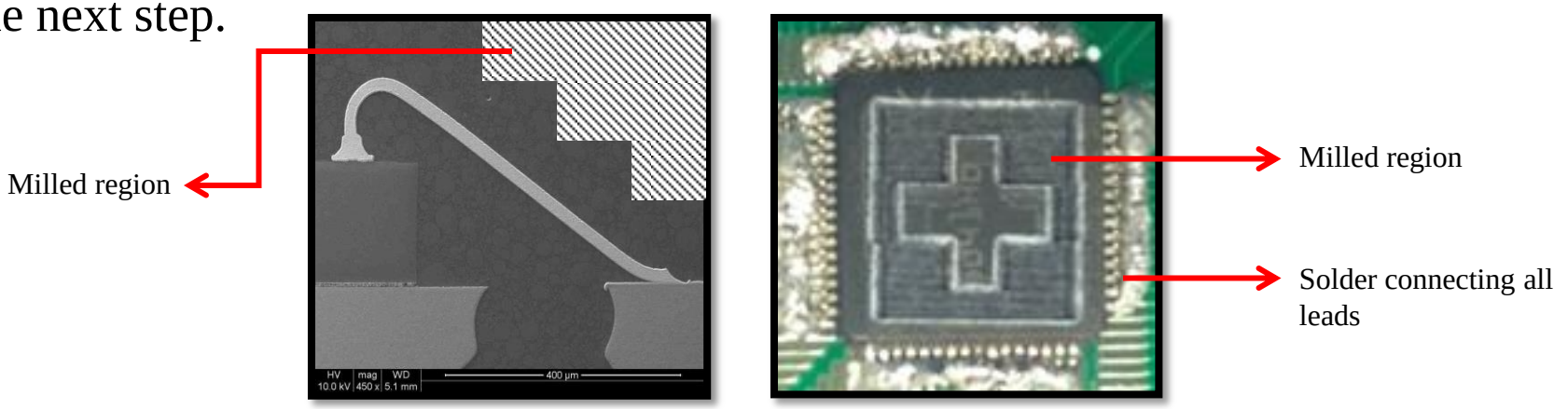
Decapsulation Technique for Cu Wire Bond Devices - Pre Decapsulation Process

- Pre-decapsulation is done to make a pocket in the molding compound.
- This pocket speeds the decapsulation process and restricts the etching area [11].
- This pre-decapsulation can be done in one of the following two ways:
  - A mechanical milling process can be used to make the pocket.
  - An acid etching process can be done with nitric acid for short durations, using kapton tape used to restrict the lateral spread of acid [12].
- X-Ray imaging can be used to ensure the pre-decapsulation process does not affect the immediate wire region.
- Solder is then used to connect all leads to shunt them together in preparation for the next step.



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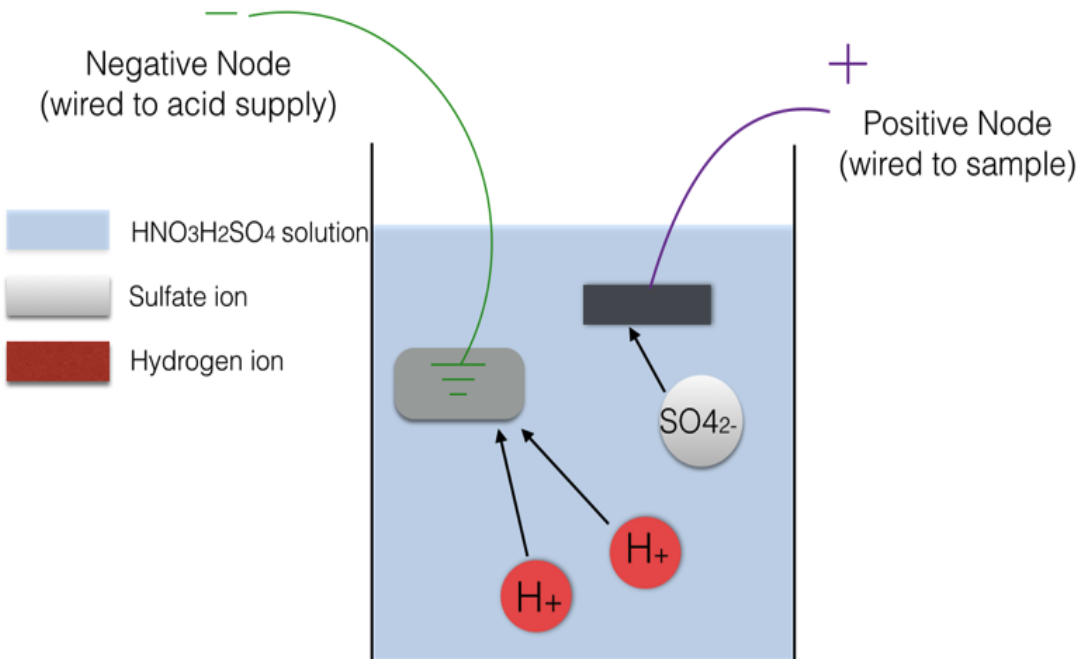
Decapsulation Technique for Cu Wire Bond Devices - Electrolysis Method



- All the leads of the device are shorted together using solder and connected to the anode of a DC power supply.
- The cathode of the DC power supply is immersed in the mixed nitric and sulfuric acid bath.
- Negatively charged sulfate ions created by reduction of the HSO_4^- ions form a layer on the positively charged copper wire preventing it from being etched.
- Positively charged hydrogen ions move toward the cathode and are reduced to hydrogen gas.
- Process is done until both ball and wedge wire bonds are visible.
- Every few seconds, the device is cleaned with acetone to see if the etch is complete.

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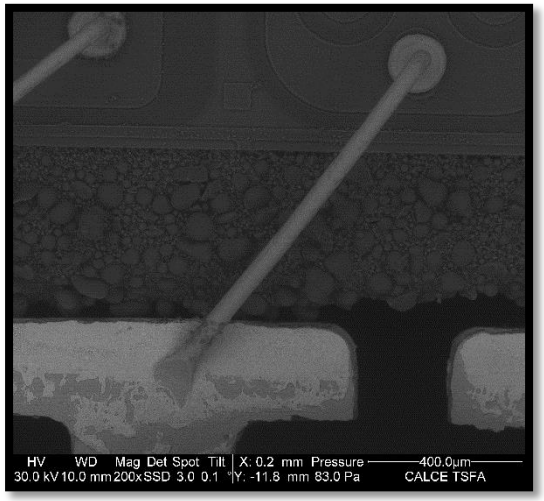
Decapsulation Technique for Cu Wire Bond Devices - Post Decapsulation Process

- The sulfate coating from the electrolysis remains on the copper wire bonds after decapsulation
- Encapsulant residue can also be loosely stuck on the die surface or between wire bonds.
- Solvent cleaning
  - Acetone is used to clean the device post decapsulation to remove remaining acid.
  - Hot water is then sprayed on the device to remove the sulfate coating.
  - Isopropanol is used to remove water on the device from the previous step.

Sulfate coating

Before Solvent Cleaning



After Solvent Cleaning

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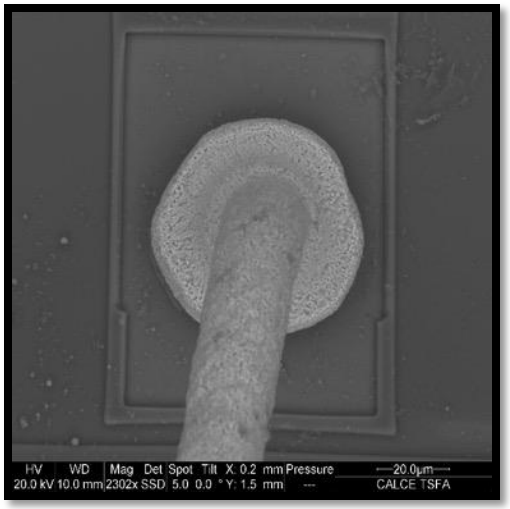
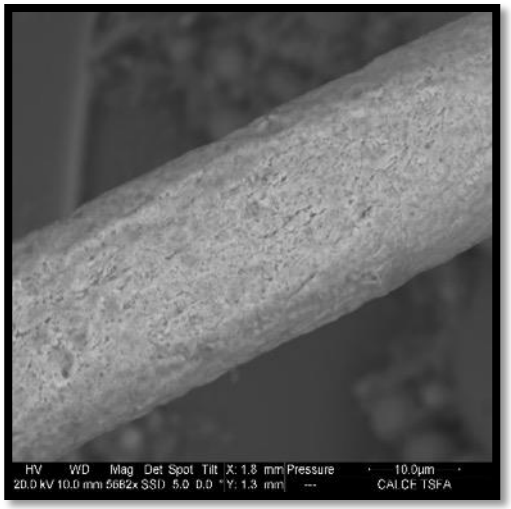
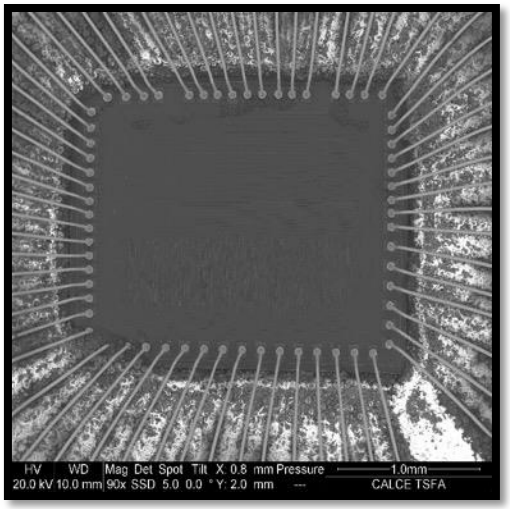
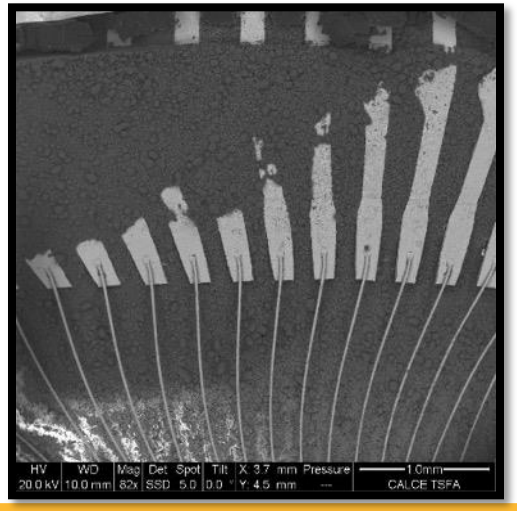
Result of Three Step Decapsulation Process

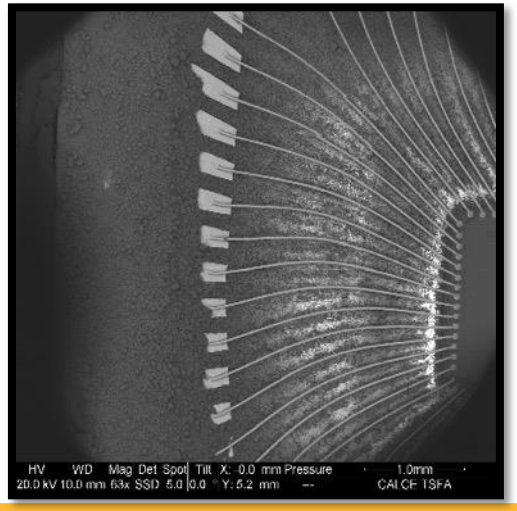








Package Type	64 - TQFP
Package Dimension	12.2 X 12.2 X 1.2 mm
Wire Diameter	20 μm



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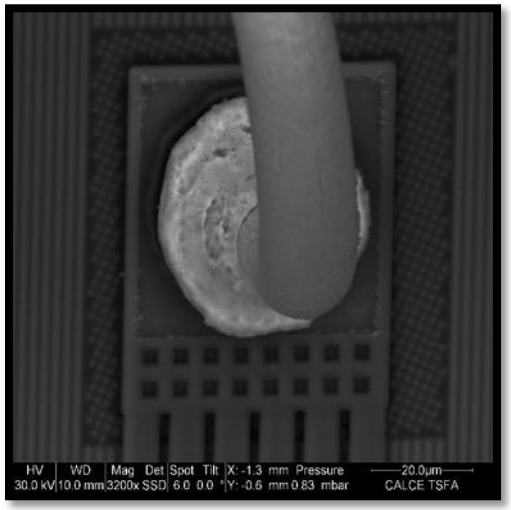
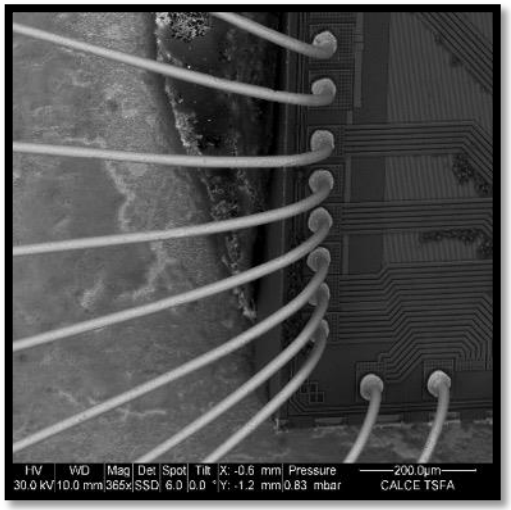
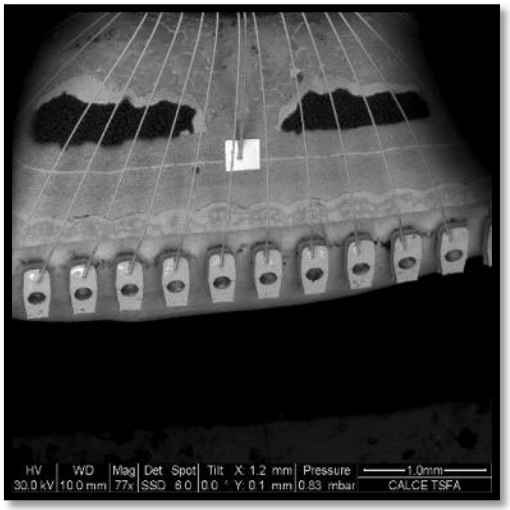
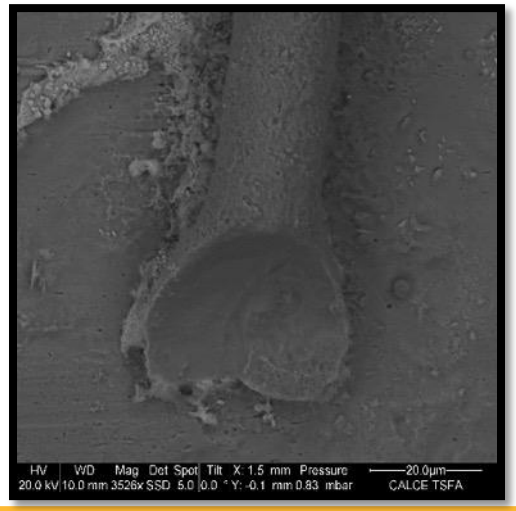
Result of Three Step Decapsulation Process

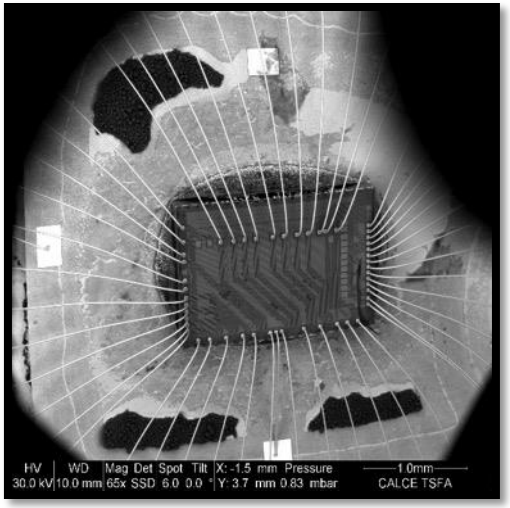








Package Type	48 - QFN
Package Dimension	6 X 6 X 1.2 mm
Wire Diameter	17 µm



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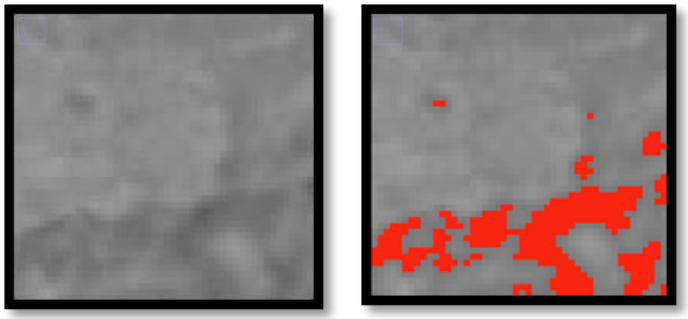
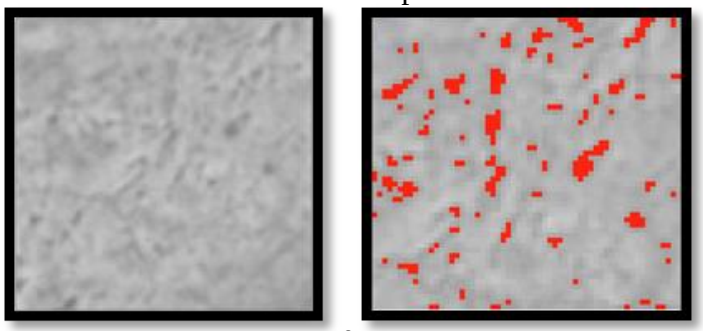
Analysis of Decapsulated Device

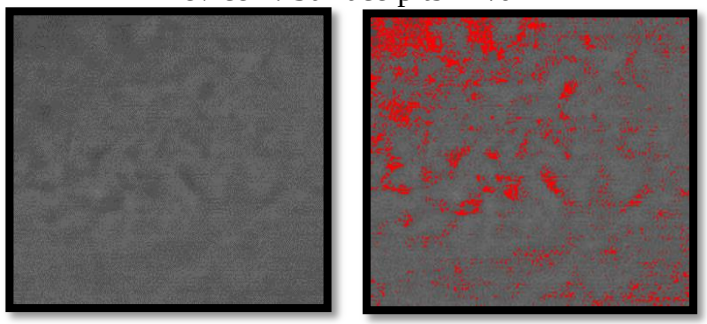
- Effectiveness of decapsulation process is usually found by measuring the reduction in wire diameter.
- Wire manufacturer claims there could be variations in diameter due to the manufacturing process.
- Surface pitting is considered to be a better indication of effectiveness of decapsulation process.
- Imaging software was used to measure variation in grey scale of the SEM image and directly correlated to surface pits.
  - Device 1: ~15% surface pits
  - Device 2: ~7% surface pits
- Three-step decapsulation process etches copper minimally or in some cases not at all.



Device 1: Surface pits ~15%



Device 2: Surface pits ~7%



Device 2: Surface pits ~9%

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Summary

- Copper wire bonding is driven by the increasing price of gold. Copper wires also have the advantages of superior electrical and thermal conductivity and limited intermetallic growth.
- However, several failure mechanisms are related to copper wire bonding, including axial wire fatigue and corrosion.
- Failure analysis requires performing decapsulation of the device. Ball bonds and wedge bonds, BOTH need to be revealed to conduct bond shear and pull tests.
- Previous methods show only partial decapsulation for larger devices, revealing only ball bonds.
- The three step process shown here was able to reveal ball AND wedge bonds of all wire bonds, with minimal or no degradation of wires.

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QUESTIONS

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