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Understanding Cu-Al Limited-Volume Diffusion Towards Lifetime Prediction for Cu Wire Bonds

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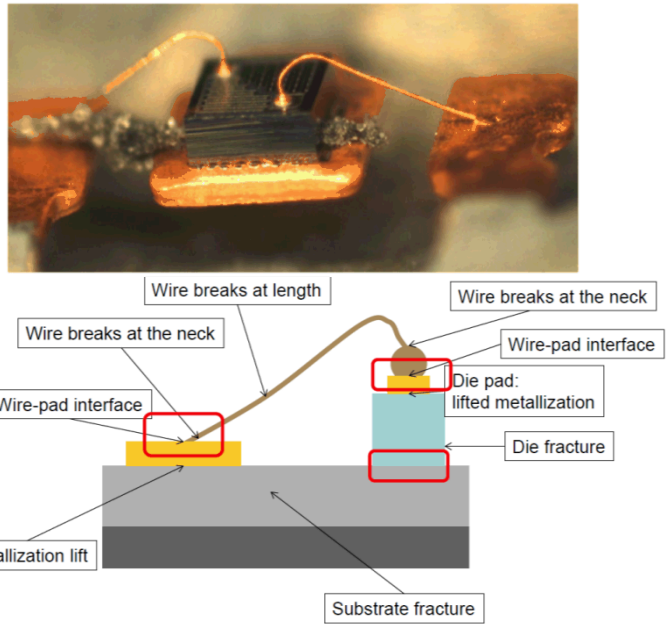
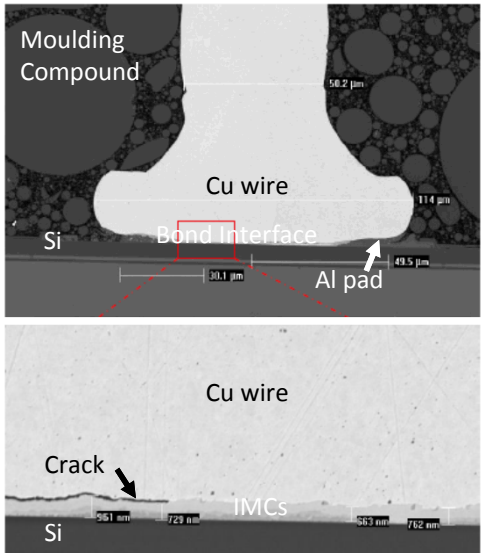
Copper Wire Bonds in Electronic Components

Motivation

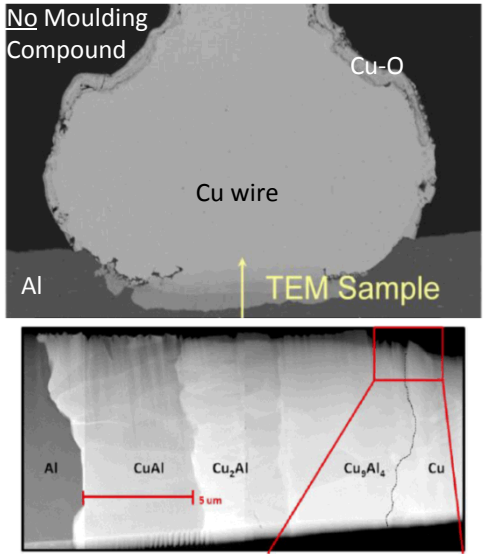
- Cu wire bonds are replacing Au wire bonds. The knowledge base, needed to assess acceptability and lifetime of Cu wires bonded to aluminum (Al) pads for high reliability products, is lacking.
- Cu & Al react to form intermetallic compound (IMC) of varying types/thicknesses across a single bond. Non-uniformity of the IMC layers is not well understood.



B. Paskaleva, *et al*., "Device Reliability TGC-XIV: Fundamentals behind the Growth of Cu-Al Intermetallics," oral presentation at the Spring TGC-XIV. Mar 15-16, 2016. Huntsville, AL.



G.M. O'Halloran, et al. "Planar Analysis of Copper-Aluminium Intermetallics," *Proceedings of the 39th International Symposium for Testing and Failure Analysis*. San Jose, CA. Nov 3-7, 2013.

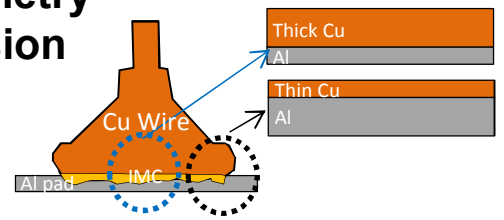


Rene Rongen, et al. "Lifetime Prediction of Cu-Al wire Bonded Contacts for Different Mould Compounds," *Proceedings of the 64th Electronic Components and Technology Conference*. Lake Buena Vista, FL. May 27-30, 2014.

Copper Wire Bonds in Electronic Components

Motivation

- Cu wire bonds are replacing Au wire bonds. The knowledge base, needed to assess acceptability and lifetime of Cu wires bonded to aluminum (Al) pads for high reliability products, is lacking.
- Cu & Al react to form intermetallic compound (IMC) of varying types/thicknesses across a single bond. Non-uniformity of the IMC layers is not well understood.
- **Need to understand effects of bond geometry and aging on Cu-Al limited-volume diffusion and resulting joint degradation.**

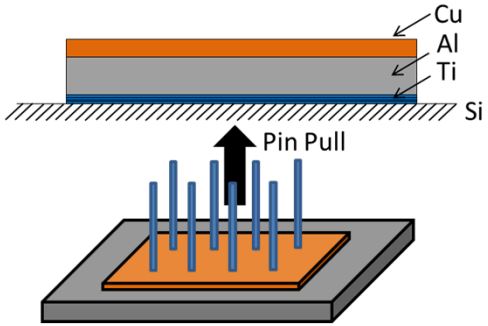


Varying Cu:Al Ratio

Cu	Al
2.0μm	0.2μm
2.0μm	2.0μm
0.2μm	2.0μm

Approach

- Age thin film stacks of varying Cu:Al ratio between 0-300 days at 50°C-300°C. Determine thin film integrity via mechanical testing (pin pulling). Determine Cu-Al solid-state interface reactions in multiple aging conditions. Focus on:
  - Room Temperature (baseline)
  - 0-100 days at 150°C

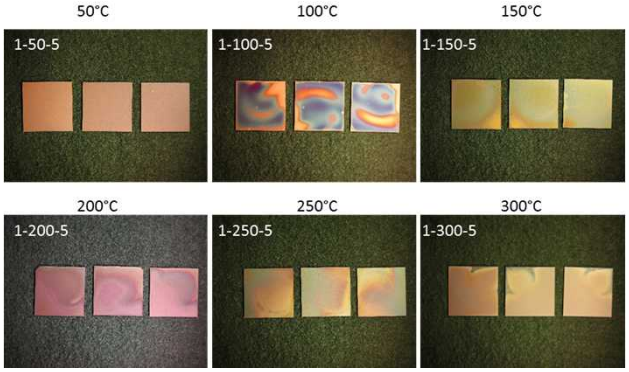


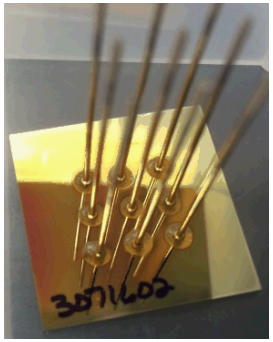
Leg work to establish diffusivity of Al into Cu as a function of aging temperature, time, and varying Cu:Al ratio.

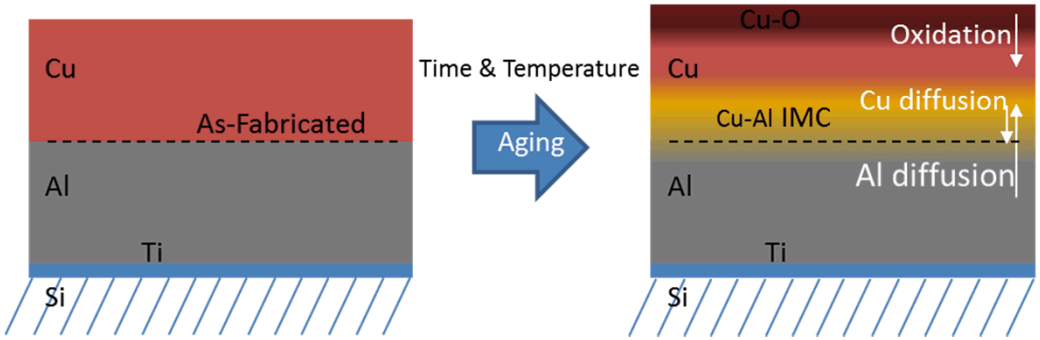
Approach

- **The long-term reliability of the Cu wires bonded to Al pads is determined by potential degradation modes resulting from solid-state reactions that occur at elevated temperature environments.**

Aging parameters
Temperatures: 50, 100, 150, 200, 250, 300°C
Time: 0, 5, 10, 25, 50, 100, 150, 200, 300 days





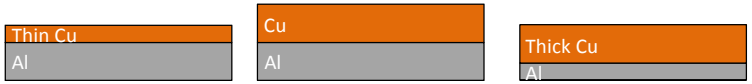


In some cases, Ti and Si may diffuse towards the film top surface.

Pin pulling → determine interface strength
Cross-section → understand failure modes
Auger Profile → understand elemental diffusion

Common Failure Modes

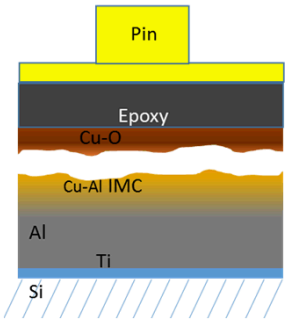
- **The long-term reliability of the Cu wires bonded to Al pads is determined by potential degradation modes resulting from solid-state reactions that occur at elevated temperature environments.**
- Observed failure modes include:

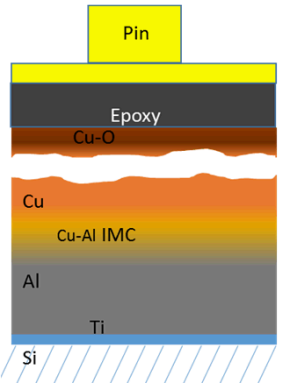


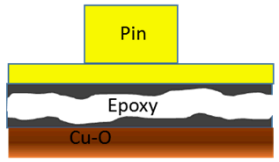
Pin Pull Failure Modes		Chem 1	Chem 3	Chem 5
As-Received	Cu thickness (um)	0.2	2.0	2.0
	Al thickness (um)	2.0	2.0	0.2
50°C	25 days	Epoxy Breakage	Epoxy Breakage	Epoxy Breakage
	50 days	Epoxy Breakage	Epoxy Breakage	Epoxy Breakage
	100 days	Epoxy Breakage	Epoxy Breakage	Epoxy Breakage
100°C	25 days	Epoxy // Cu-O	Epoxy Breakage	Epoxy Breakage
	50 days	N/A	N/A	N/A
	100 days	Epoxy // Cu-O	Pin // Epoxy	Epoxy // Cu-O
150°C	25 days	Cu-O // Cu-Al	Cu-O // Cu	Cu-Al alloy breakage
	50 days	Cu-O // Cu-Al	Cu-O // Cu	Cu-Al alloy breakage
	100 days	Cu-O // Cu-Al	Cu-O // Cu	Cu-Al alloy breakage
200°C	25 days	Cu-O // Cu-Al	Cu-Al alloy breakage	Cu-Al alloy breakage
	50 days	N/A	N/A	N/A
	100 days	Cu-O // Cu-Al	Cu-Al alloy breakage	Cu-Al alloy breakage

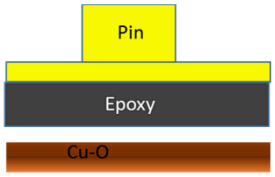
Multiple failure modes may occur in one sample; we listed the dominant failure mode.

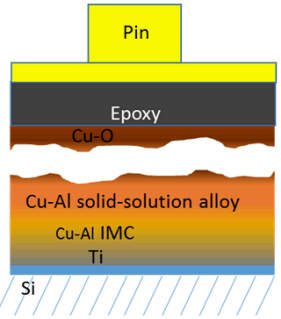
//	Thin film separation between two layers
N/A	Failure mode not confirmed







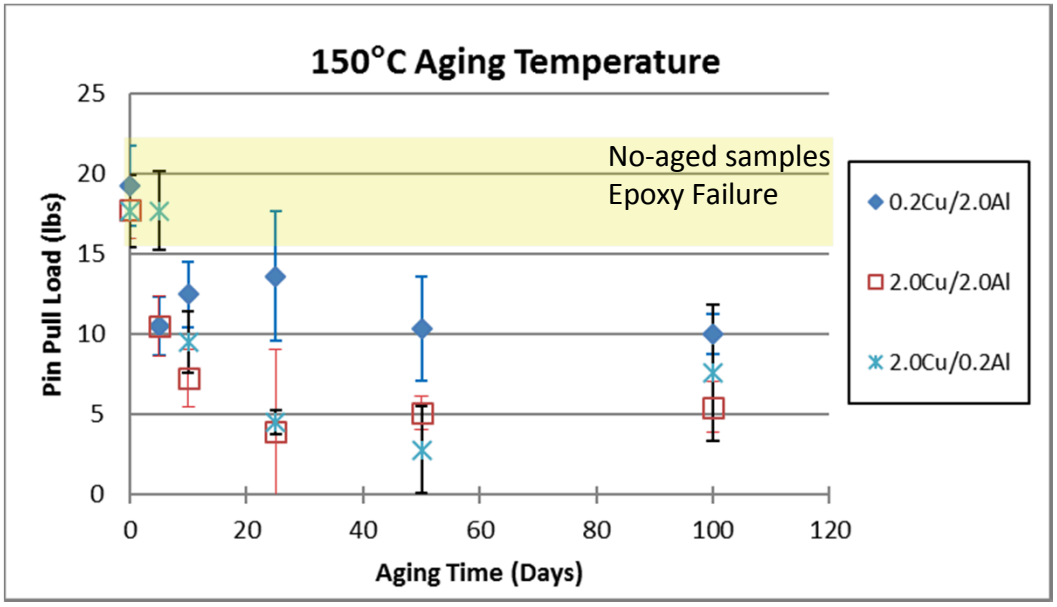




150°C Aged Thin Films

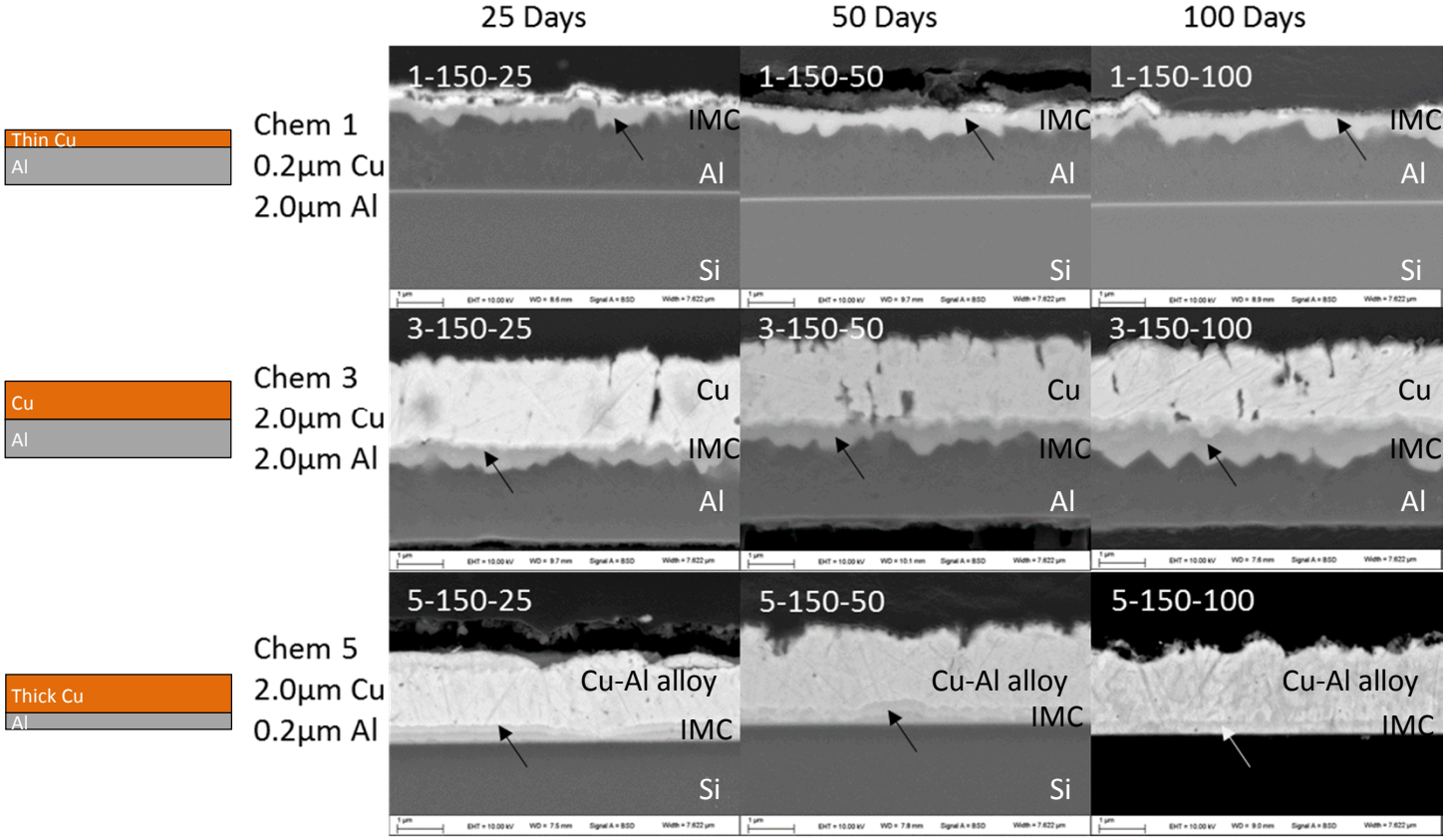
- **The long-term reliability of the Cu wires bonded to Al pads is determined by potential degradation modes resulting from solid-state reactions that occur at elevated temperature environments.**
- Failure modes - similar across 25-100 days but different for each Cu:Al ratio.

Pin Pull Failure Modes		Chem 1	Chem 3	Chem 5
As-Received	Cu thickness (um)	0.2	2.0	2.0
	Al thickness (um)	2.0	2.0	0.2
150°C	25 days	Cu-O // Cu-Al	Cu-O // Cu	Cu-Al alloy breakage
	50 days	Cu-O // Cu-Al	Cu-O // Cu	Cu-Al alloy breakage
	100 days	Cu-O // Cu-Al	Cu-O // Cu	Cu-Al alloy breakage



150°C Aged Thin Films

- **The long-term reliability of the Cu wires bonded to Al pads is determined by potential degradation modes resulting from solid-state reactions that occur at elevated temperature environments.**
- Failure modes - similar across 25-100 days but different for each Cu:Al ratio. Chemical potentials, driving the diffusion, are different for each Cu:Al ratio.



Cu completely consumed by oxidation and IMC formation

Cu and Al sources not completely consumed.

BREAKAGE in Cu-Al SOLID-SOLN ALLOY

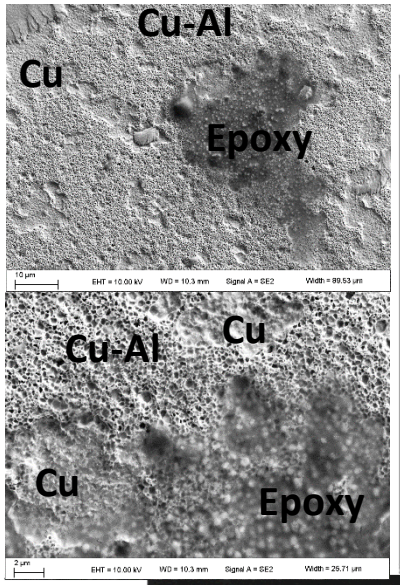
Al completely consumed by IMC formation and α-Cu solid-solution alloy

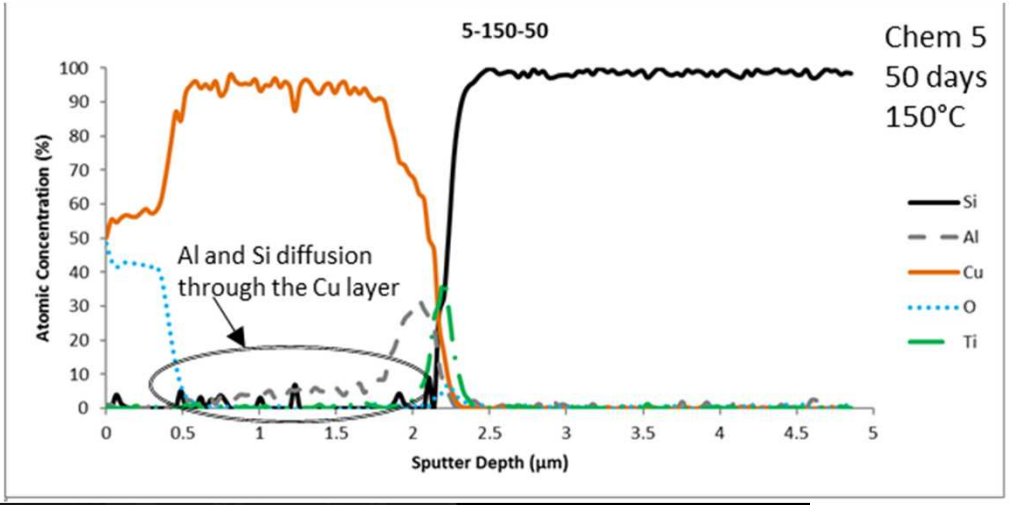
150°C Aged Thin Films – 2.0µmCu / 0.2µmAl

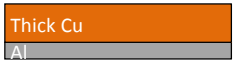
- **The long-term reliability of the Cu wires bonded to Al pads is determined by potential degradation modes resulting from solid-state reactions that occur at elevated temperature environments.**
- Auger diffusion profiles showed evidence of **Si** & Al diffusion towards surface.

- Breakage in Cu-Al solid solution alloy. Role of Si? Need to investigate.
- Thin Al pad = limited Al source → large extent of joint degradation

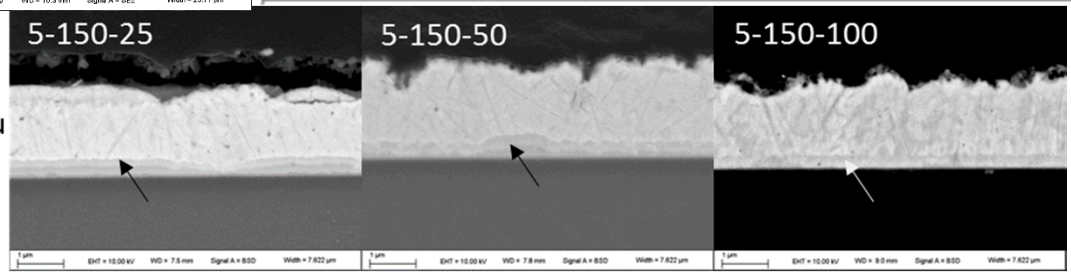
SEM of top film fracture surface







Chem 5
2.0µm Cu
0.2µm Al

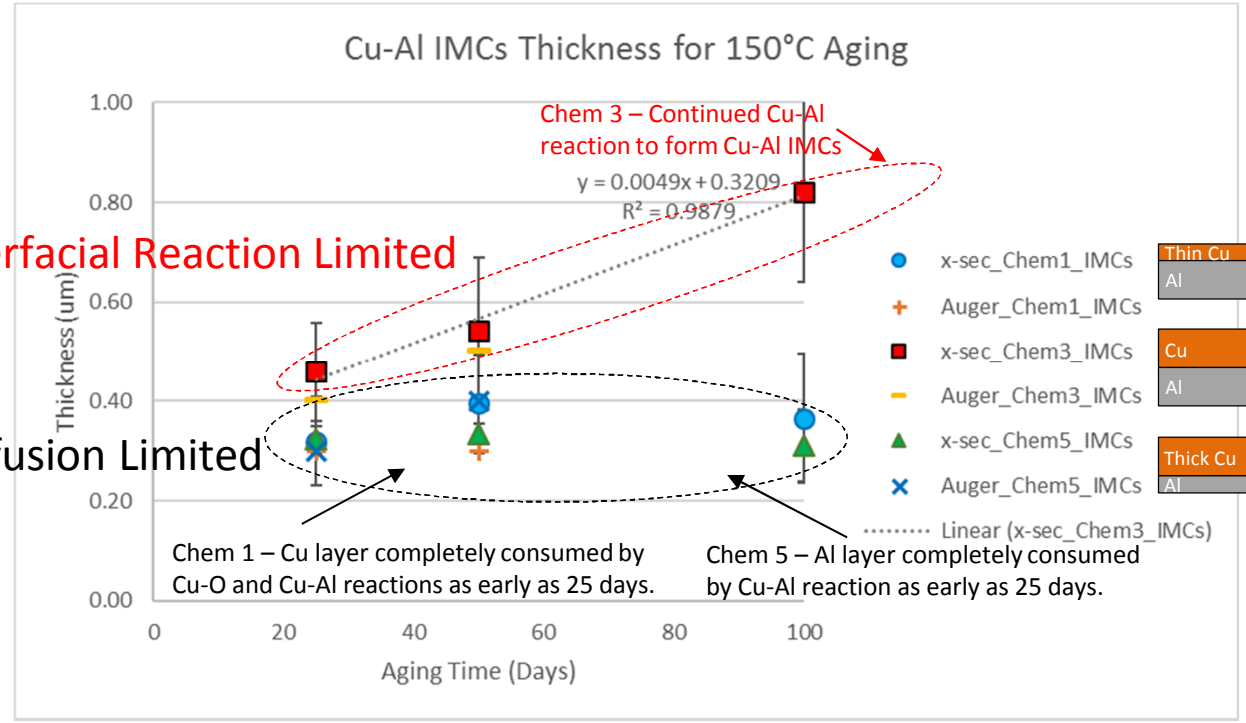


BREAKAGE in Cu-Al SOLID-SOLN ALLOY

Al completely consumed by IMC formation and α-Cu solid-solution alloy

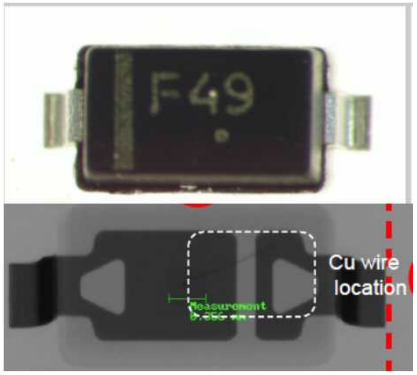
150°C Aged Thin Films – IMC thickness

- **The long-term reliability of the Cu wires bonded to Al pads is determined by potential degradation modes resulting from solid-state reactions that occur at elevated temperature environments.**
- Chem 1 & Chem 5 → Cu-Al IMCs layer thickness of 0.3-0.4 µm. The Cu and Al sources were depleted, resulting in no significant Cu-Al IMCs growth after 25 days.
- Chem 3 → Cu-Al IMCs thickness increases linearly (R^2 = 0.99) at the rate of ~5 nm per day between 25 and 100 day of aging at 150°C.

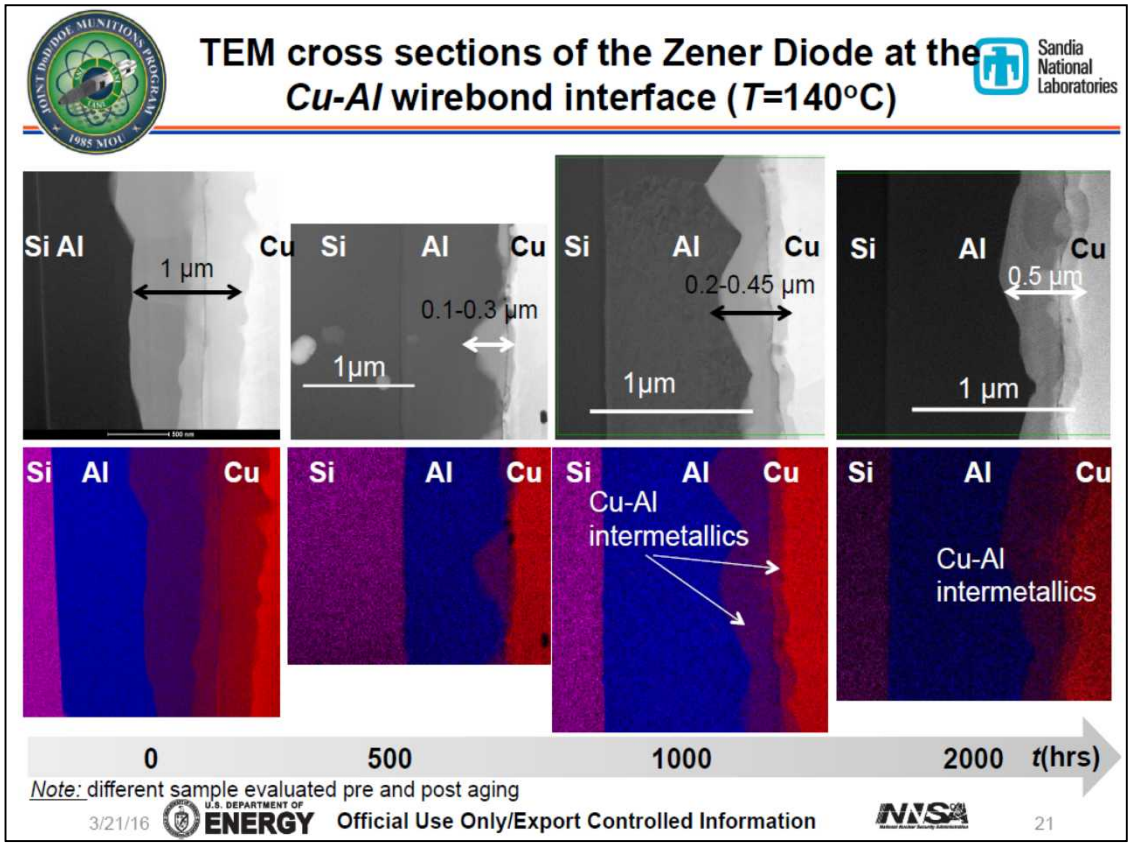


140°C Aged Test Vehicle – IMC Thickness

- **The long-term reliability of the Cu wires bonded to Al pads is determined by potential degradation modes resulting from solid-state reactions that occur at elevated temperature environments.**
- TEM cross-sections of the Zener Diodes at the Cu-Al wire bond interface after aging at 140°C for 500 hours (21 days), 1000 hours (42 days), and 2000 hours (83 days)

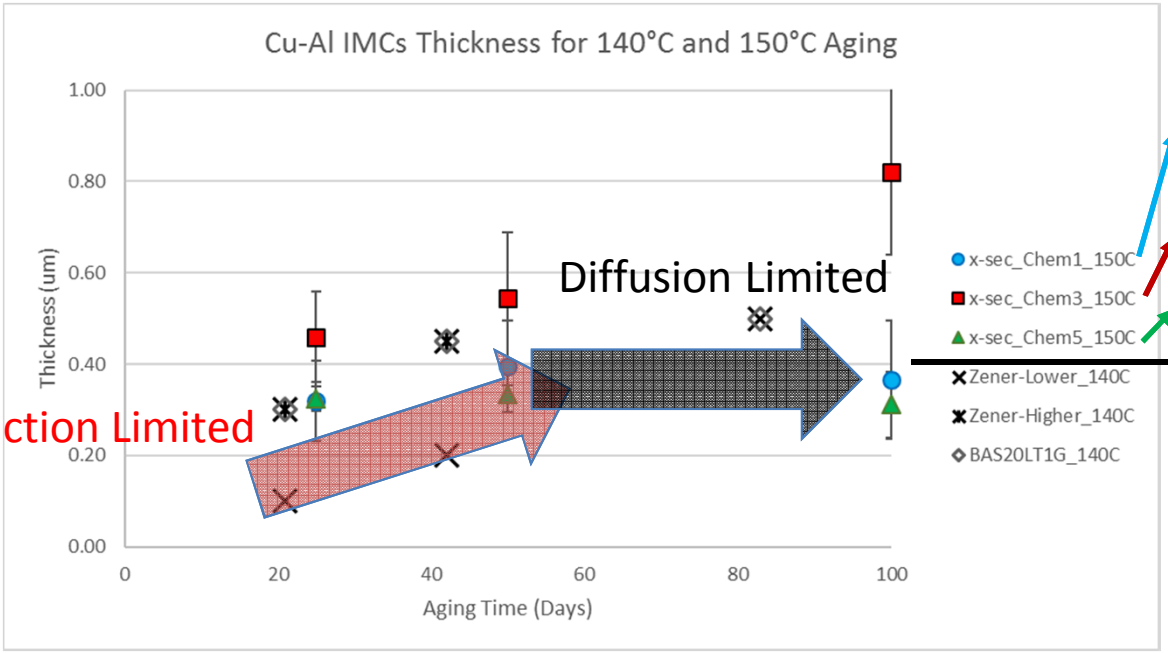


Accelerated test vehicle from JMP work by B. Paskaleva & T. Buchheit.



Comparison to Accelerated Aged Test Vehicle

- **The long-term reliability of the Cu wires bonded to Al pads is determined by potential degradation modes resulting from solid-state reactions that occur at elevated temperature environments.**
- IMC thicknesses in the accelerated test vehicles increased at
  - a high rate from 21 to 42 days → Chem 3 from 25 to 100 days.
    - Interfacial reaction controlled the growth rate of IMC.
  - a lower rate from 42 to 83 days → Chem 1 & Chem 5 aged >25 days.
    - Diffusion controlled the growth rate of IMC.



Summary

- The fundamental diffusion couple aging study allowed more systematic investigation of the effects of Cu:Al ratio and aging parameters on the microstructure evolution and IMC growth.

- Began to build a knowledge base on how Cu wire bonds age, using thin film diffusion couples and selective comparison to accelerated aged test vehicles for validation.

- Initially, IMC growth is controlled by interfacial reaction rate (linear with time). Over time, Cu and/or Al sources become limited and IMC growth is controlled by diffusion and is significantly slowed down.

  Extreme high Cu:Al ratios, where Al becomes the limited resource showed failure due to *breakage in such Cu-Al solid solution* alloy layer with possible involvement of Si and/or Si reaction within the film stack—weakening the joint. **Practically, the implication is that "thin" pure Al pads should not be used.**

- The materials parameters collected in the fundamental study will be used to determine diffusivity as a function of temperature, time, and Cu:Al ratios and will be used as inputs to build a lifetime prediction model of Cu wire bond aging in future work.

The authors would like to thank Mark Grazier, Carl Smith, Deidre Hirschfeld, Andrew Vackel, Regan Stinnett, Joe Puskar, Biliana Paskaleva, Tom Buchheit, Rob Sorenson, and many others for their contributions and valuable discussions.

Thank you for your attention!
Questions?

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