Reliability of Electrical Interconnects

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National Renewable Energy Laboratory

Annual Merit Review and Peer Evaluation Meeting

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PR-5400-61358

Project ID: APE036

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Overview

Timeline

- **Project Start Date:** FY11
- **Project End Date:** FY14
- **Percent Complete:** 80%

Barriers and Targets

- Efficiency
- Performance and Lifetime

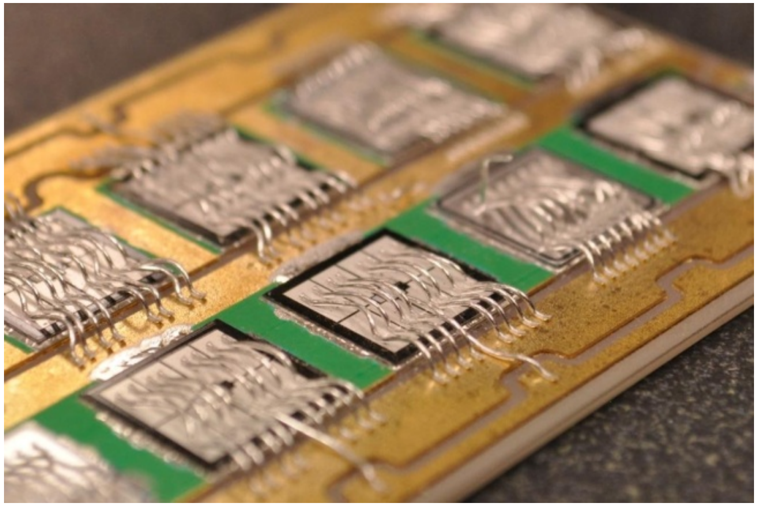
Budget

- **Total Project Funding:**
  DOE Share: $1,600K
- **Funding Received in FY13:** $450K
- **Funding for FY14:** $300K

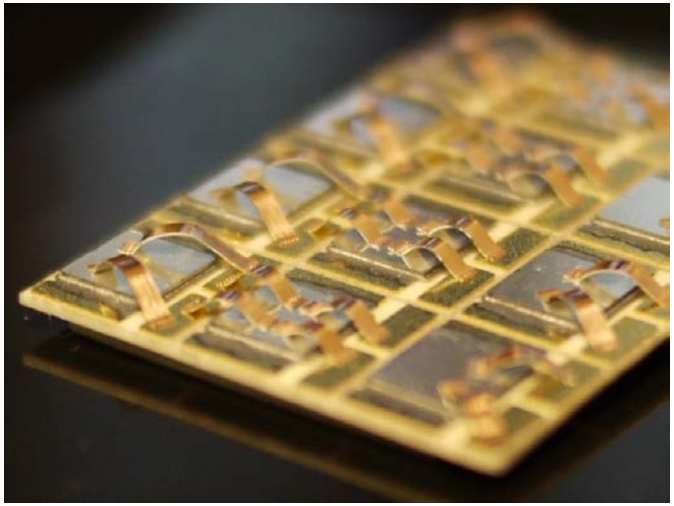
Partners

- Interactions/Collaborations
  - Curamik, Kulicke and Soffa
- Project Lead
  - National Renewable Energy Laboratory

Relevance

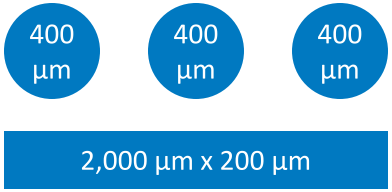


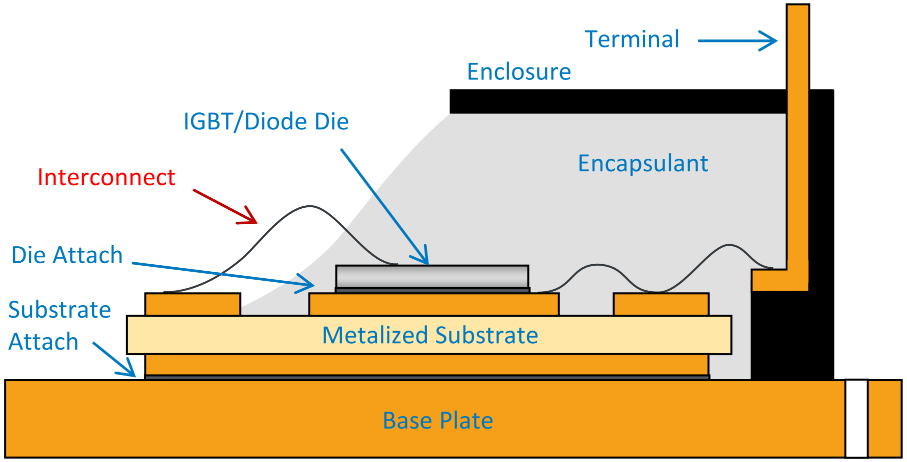
Wire Bonding



Ribbon Bonding

Three 400-µm wires can be replaced by a single 2,000-µm x 200-µm ribbon for equivalent current carrying capability.





Traditional Power Electronics Package

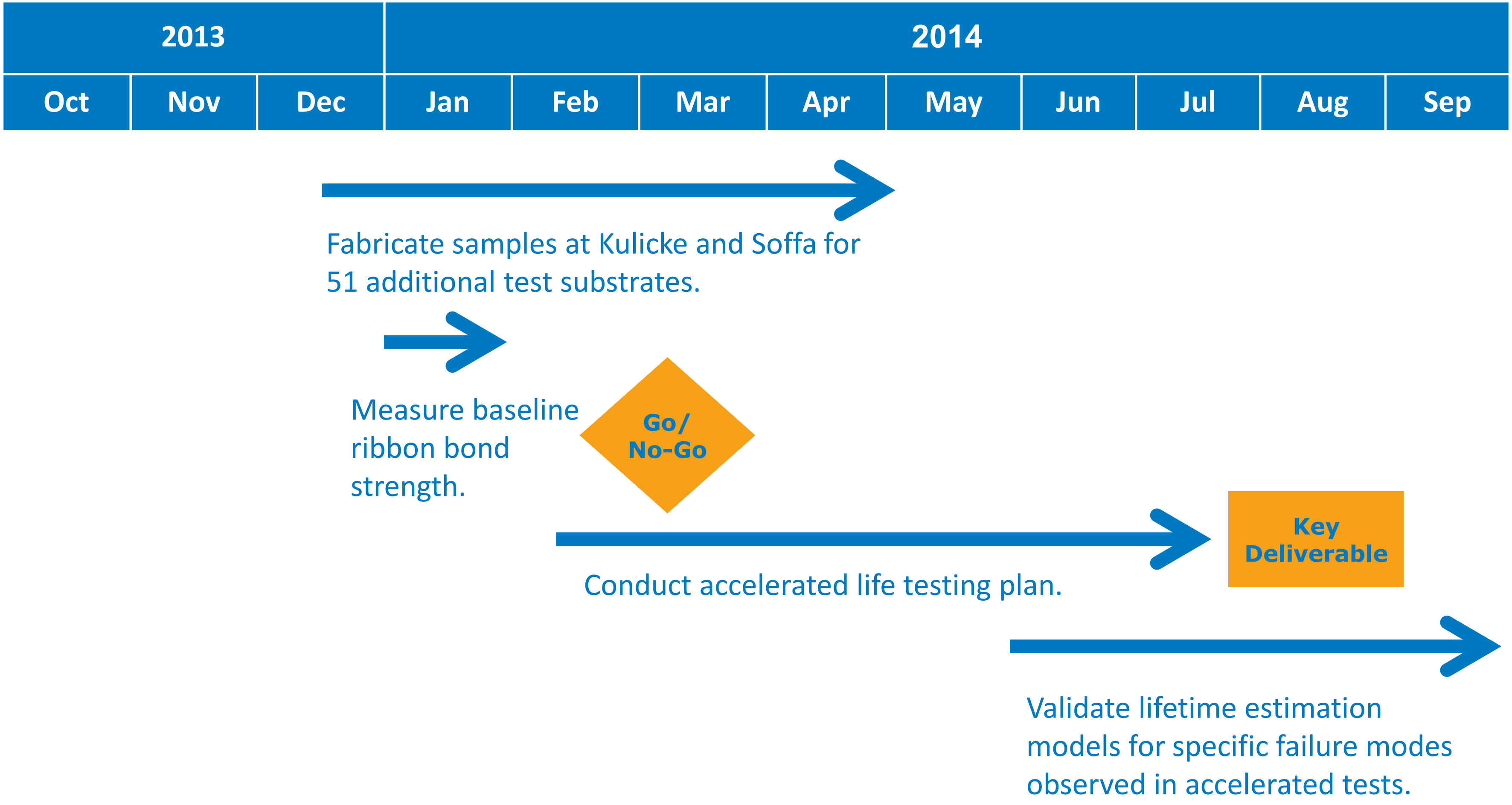
Relevance

- **Technology Benefits**
  - A transition from round wire interconnects to ribbon interconnects allows for higher current densities, lower inductances, and lower loop heights.

- **Overall Objective**
  - Identify failure modes in ribbon bonds, experimentally characterize their life under known conditions, and develop and validate physics-of-failure (PoF) models that predict life under use conditions.
  - Test and model ribbon bonds to prove they exhibit equivalent or greater reliability than industry-accepted wire bond technology.

- **Uniqueness and Impacts**
  - Failure modes and PoF models for emerging interconnect technology.

Milestones



2013

2014

Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug Sep

Fabricate samples at Kulicke and Soffa for 51 additional test substrates.

Measure baseline ribbon bond strength.

Go/ No-Go

Conduct accelerated life testing plan.

Key Deliverable

Validate lifetime estimation models for specific failure modes observed in accelerated tests.

Go/No-Go: Ribbon bonds must meet minimum pull strength before proceeding with accelerated tests.

Key Deliverable: Report on the reliability of ribbon bond technology to industry.

Overview

Sample Synthesis

- Bond Pad Optimization
- Ribbon Bonding

Accelerated Testing

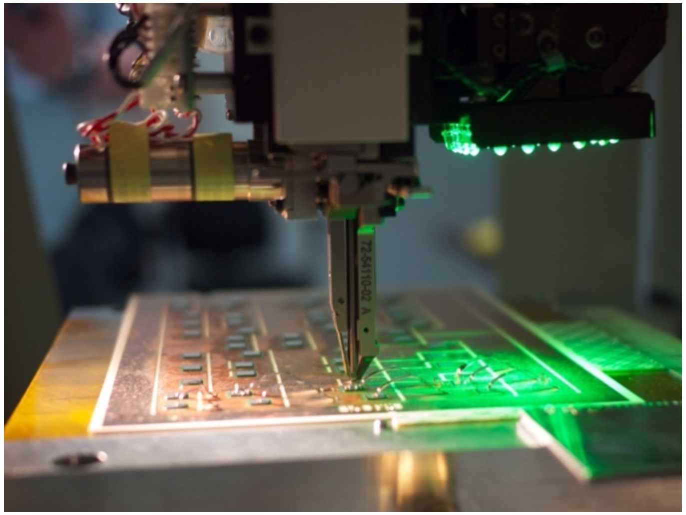
- Temperature Elevation
- Temperature Cycling
- Corrosion Testing
- Power Cycling
- Vibration Testing

Sample Evaluation

- Pull Testing

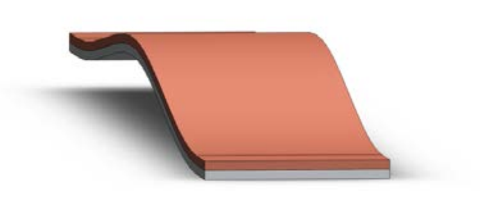
Model Validation

- Lifetime Estimation

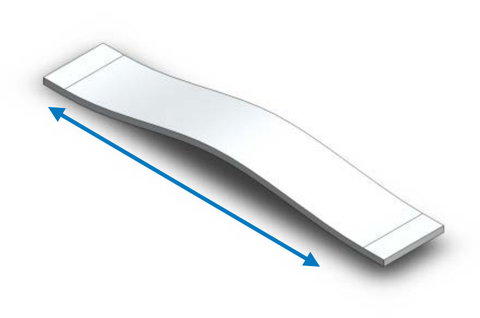


Sample Synthesis

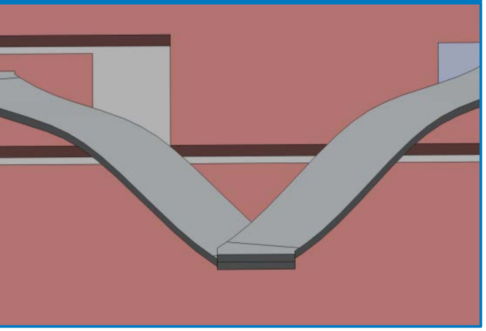
Ribbon Material



Ribbon Span

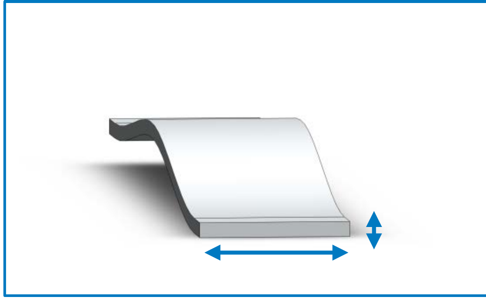


Stacked Pads

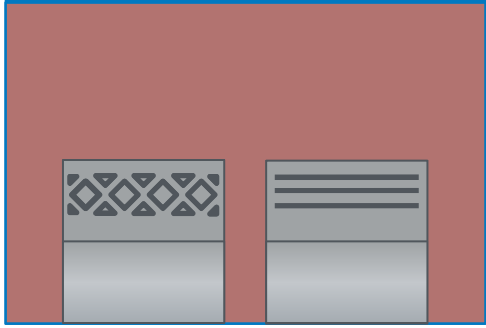


<table>
<tr><th>Criterion</th><th colspan="6">Variation</th></tr>
<tr><td>Bonding Material</td><td colspan="2">Al Ribbon</td><td colspan="2">Cu/Al-Clad Ribbon</td><td colspan="2">Al Wire</td></tr>
<tr><td>Cross Section (µm)</td><td colspan="2">2,000 x 200 Ribbon</td><td colspan="2">1,000 x 100 Ribbon</td><td colspan="2">300⌀ Wire</td></tr>
<tr><td>Ribbon Span (mm)</td><td colspan="3">10</td><td colspan="3">20</td></tr>
<tr><td>Tool Pattern</td><td colspan="3">Waffle</td><td colspan="3">Three-Ridge</td></tr>
<tr><td>Ribbon Stacking</td><td colspan="3">Not Stacked</td><td colspan="3">Stacked</td></tr>
<tr><td>Forced Bond Angle (°)</td><td colspan="3">0</td><td colspan="3">20</td></tr>
<tr><td>Bonding Power Level</td><td colspan="3">Low</td><td colspan="3">High</td></tr>
<tr><td>Bond Pad Interface</td><td colspan="3">Cu</td><td colspan="3">Si (Al)</td></tr>
</table>

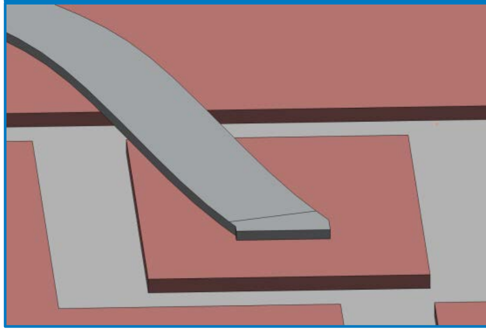
Ribbon Cross Section



Tool Pattern

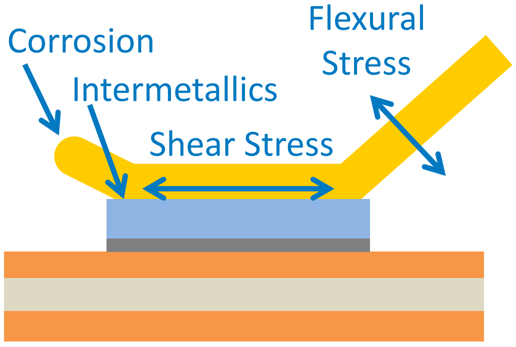


Forced Bond Angle

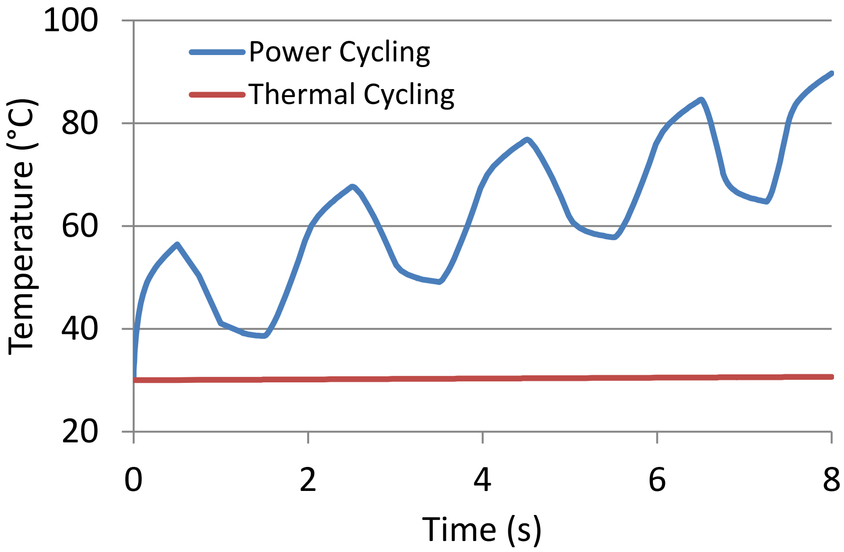


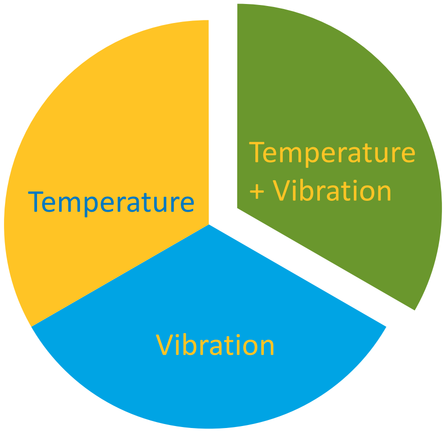
Accelerated Testing Plan

Accelerated Test	Testing Condition	Duration	Standard
Initial Pull Test	-	-	-
Temperature Elevation	150°C	500/1,000 hours	JESD22-A103D
Temperature Cycling	-40°C to 150°C, less than 20 second transition time	1,500/3,000 cycles	JESD22-A104D
Corrosion Testing	130°C, 85% relative humidity	96 hours	JESD22-A110D
	110°C, 85% relative humidity	264 hours	JESD22-A110D
	121°C, 100% relative humidity	96 hours	JESD22-102D
Power Cycling	40°C to 120°C, ~ 2 second cycled DC bias	3,000 cycles	JESD22-A105C
Vibration Testing	Combined vibration and thermal cycling	Until interconnect fails	HALT

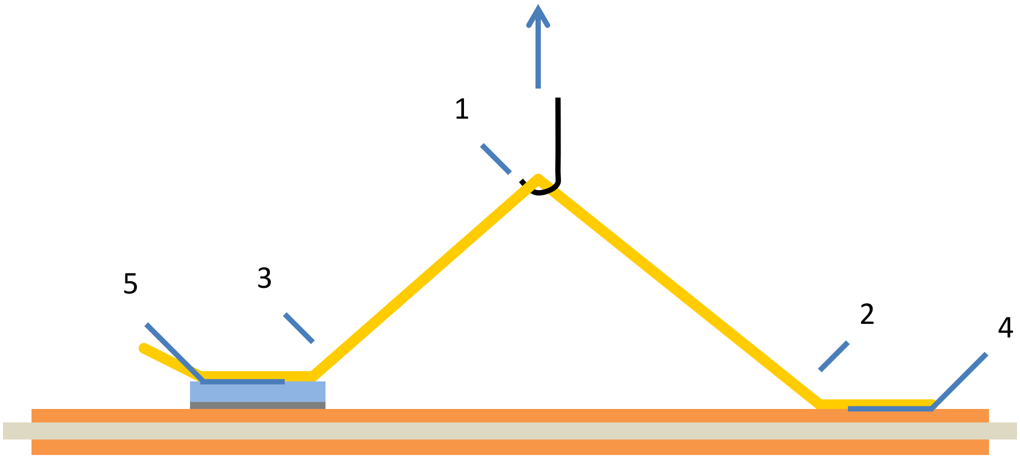


CTE (x 10^{-6}/K)
Silicon: 2.6
Copper: 16.5
Aluminum: 22.7



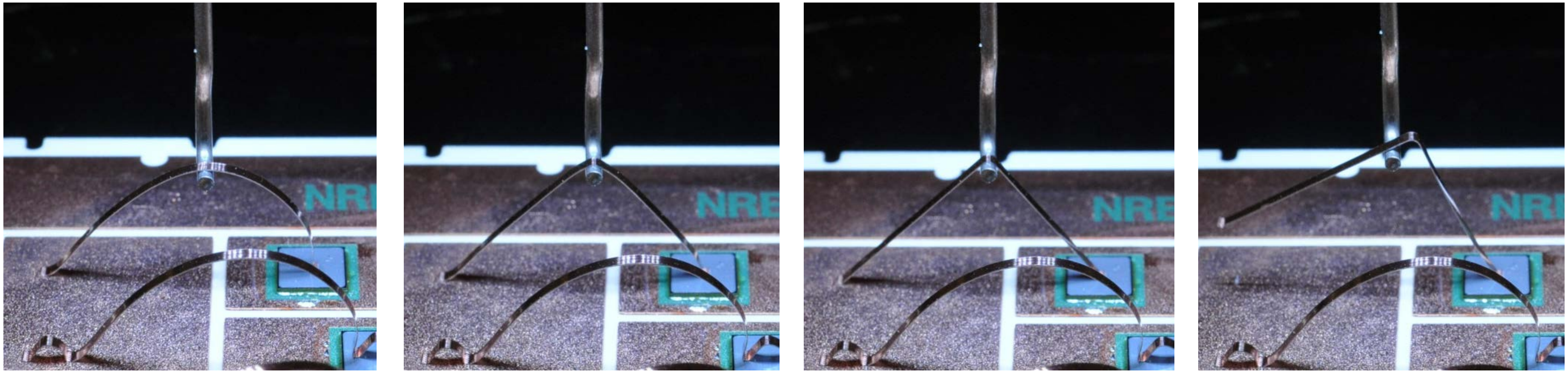


Sample Evaluation

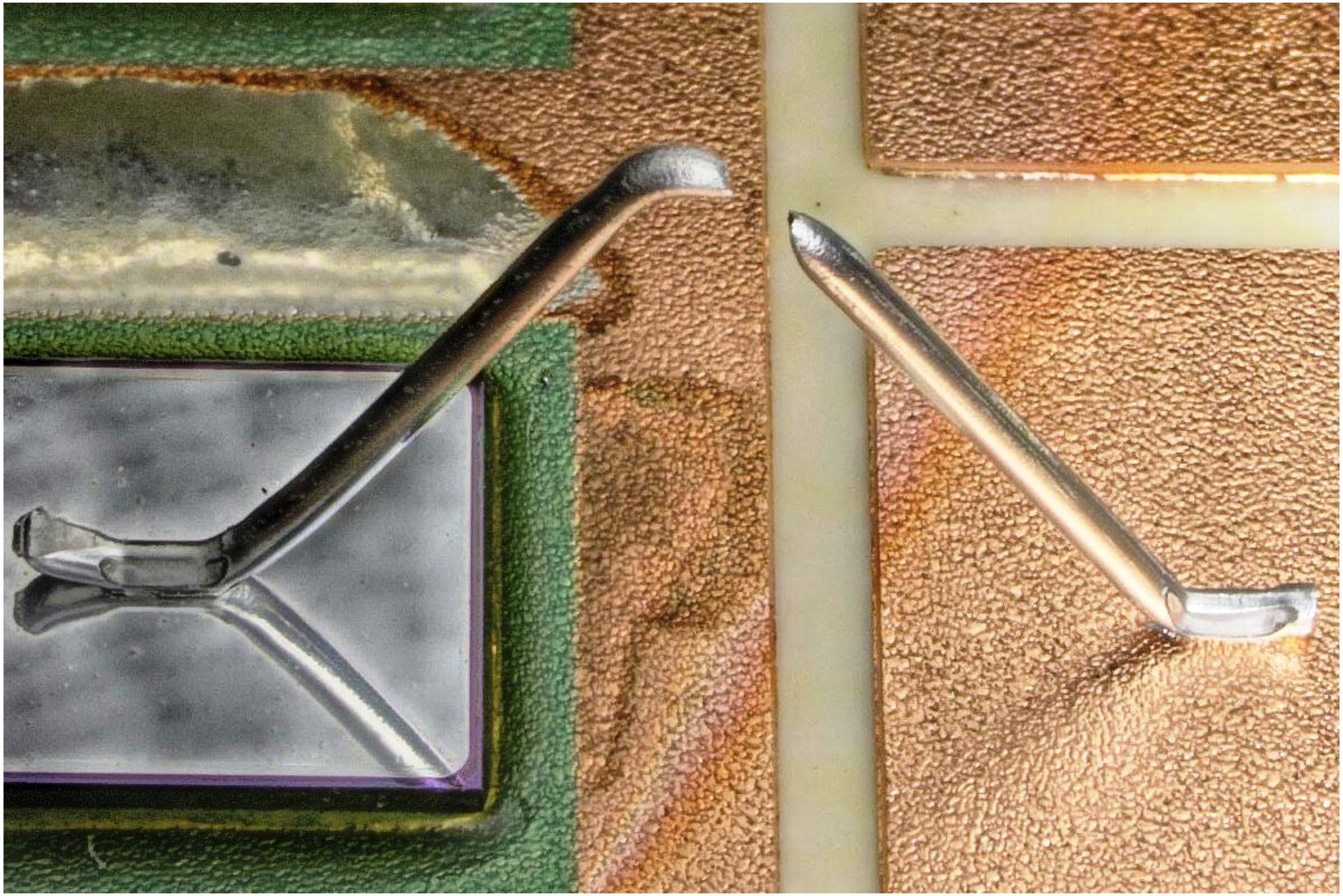


Failure Modes
1: Wire/ribbon break
2: Heel failure – substrate
3: Heel failure – die
4: Bond lift-off – substrate
5: Bond lift-off – die

- Ribbon pull testing indicates the strength of the ribbon bond.
- Bond strength and failure mode is recorded for each bond.

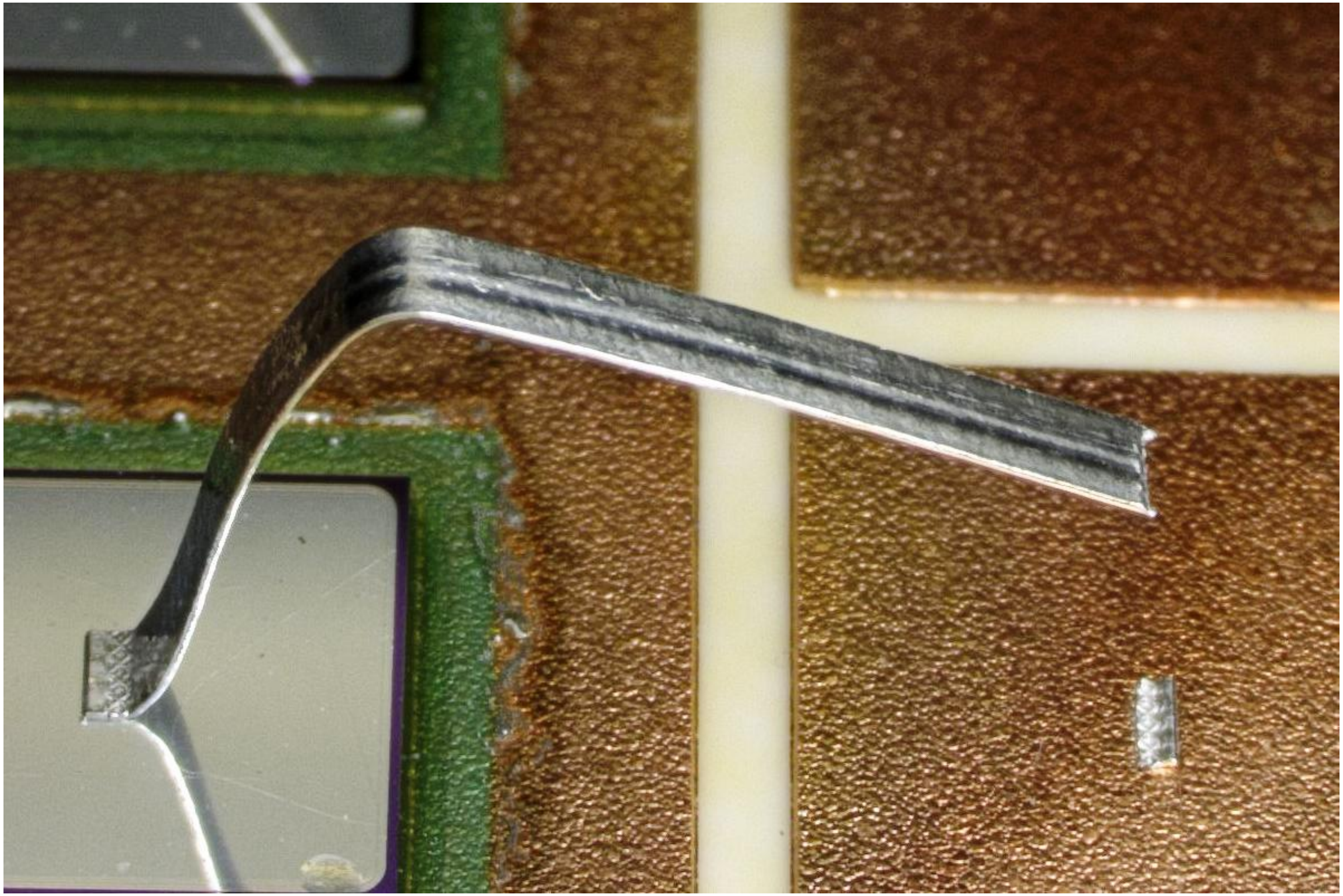


Sample Evaluation



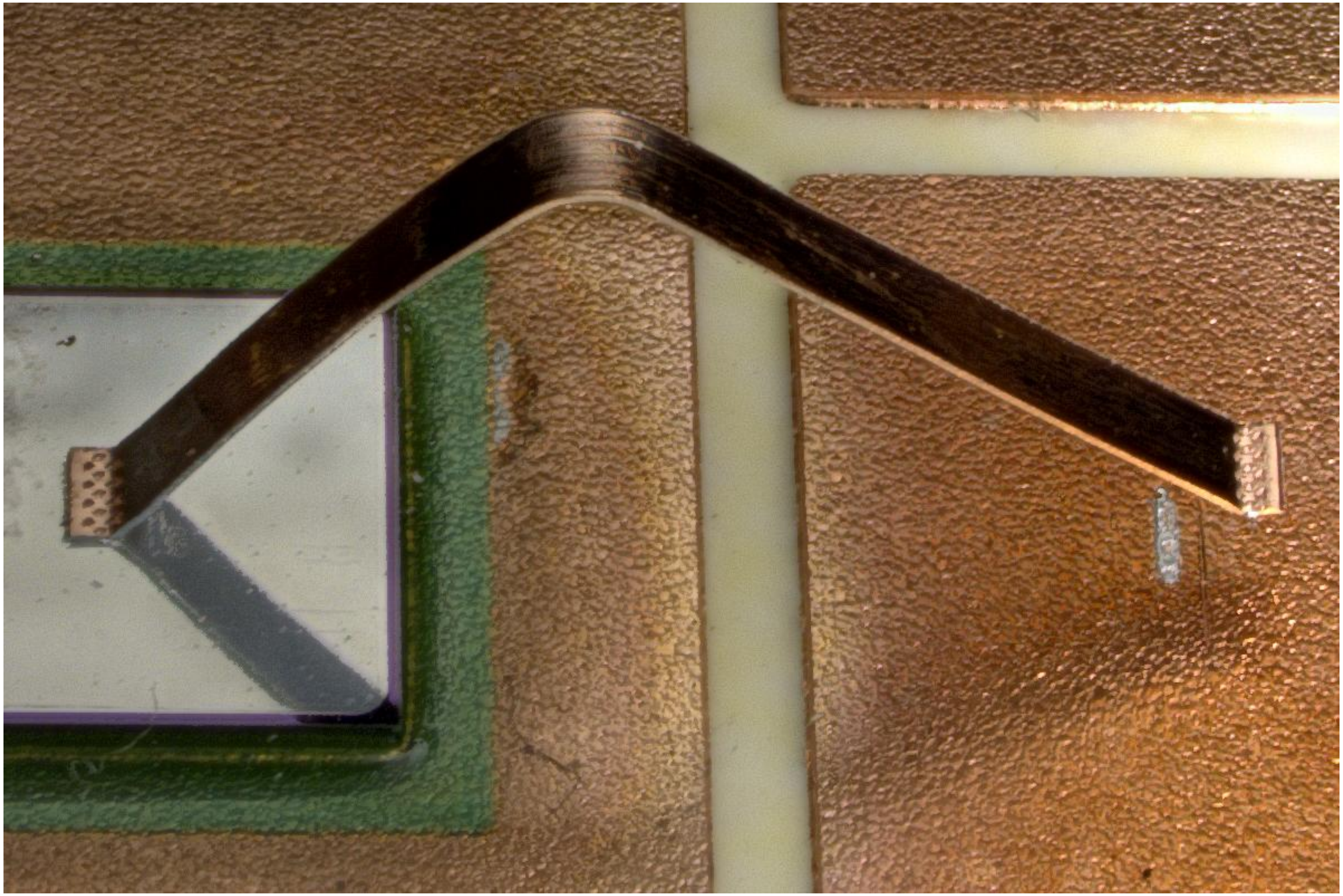
Failure Mode: Wire Break

Sample Evaluation



Failure Mode: Heel Failure from Substrate

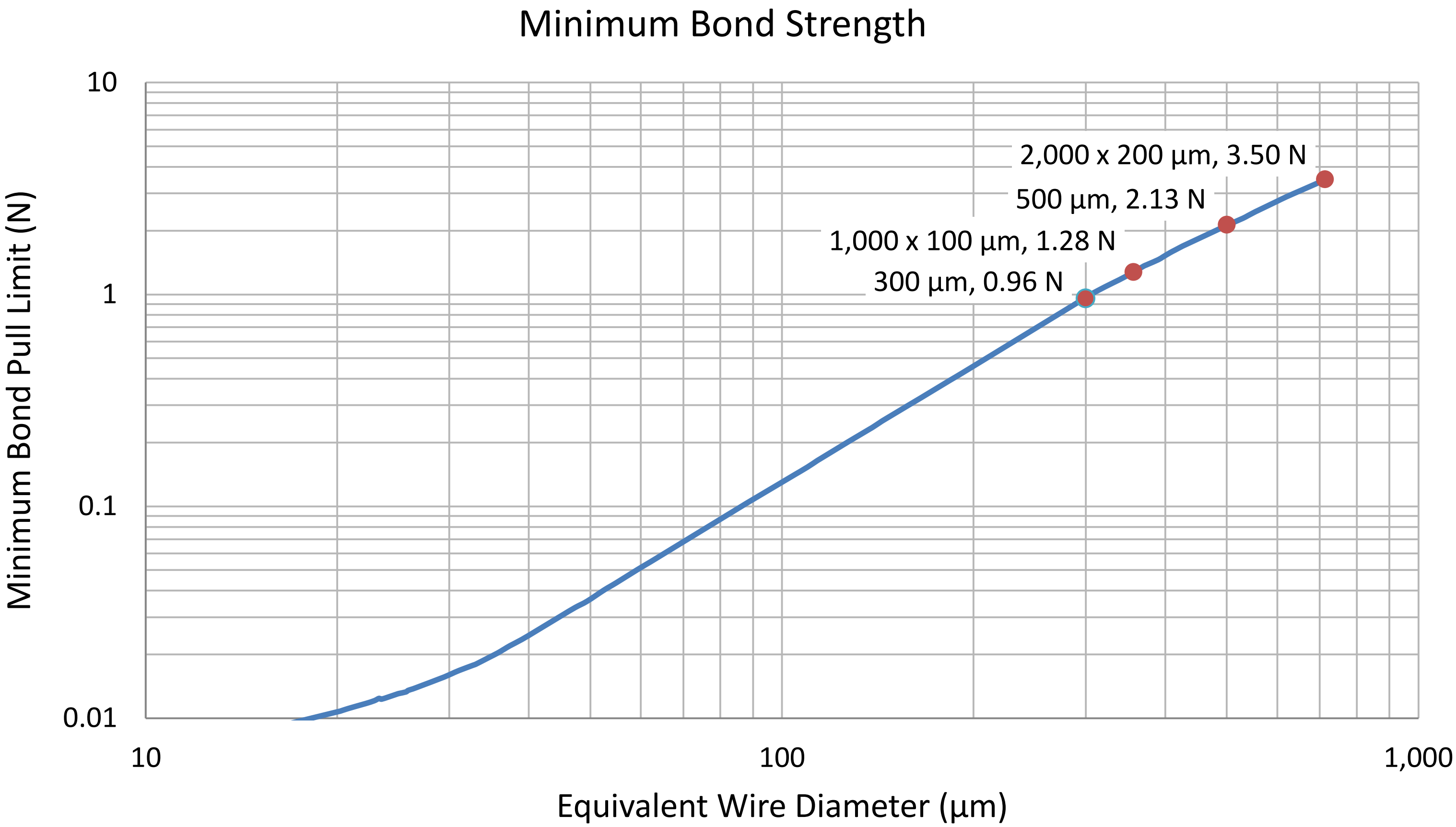
Sample Evaluation



Failure Mode: Bond Pad Lift-off from Substrate

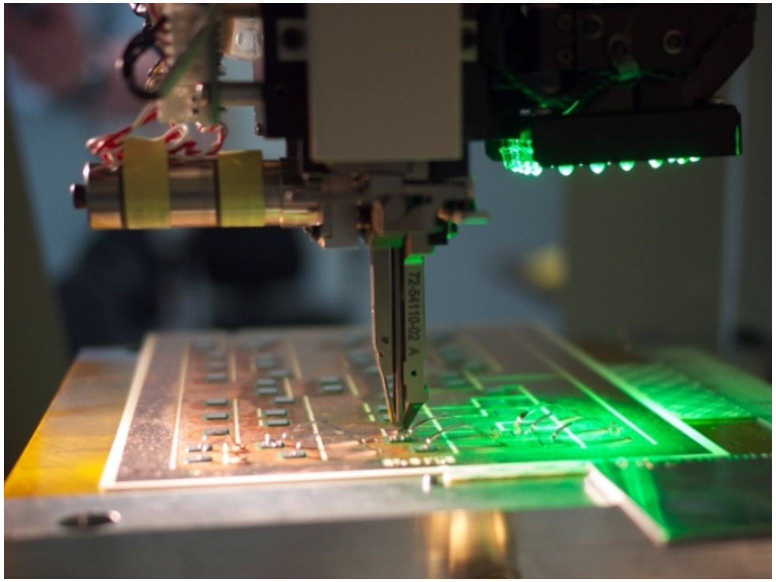
Sample Evaluation

- The minimum bond strength is specified by MIL-STD-883H Method 2011.8.
  - Minimum bond strength requirement increases with respect to increasing interconnect cross-sectional area.

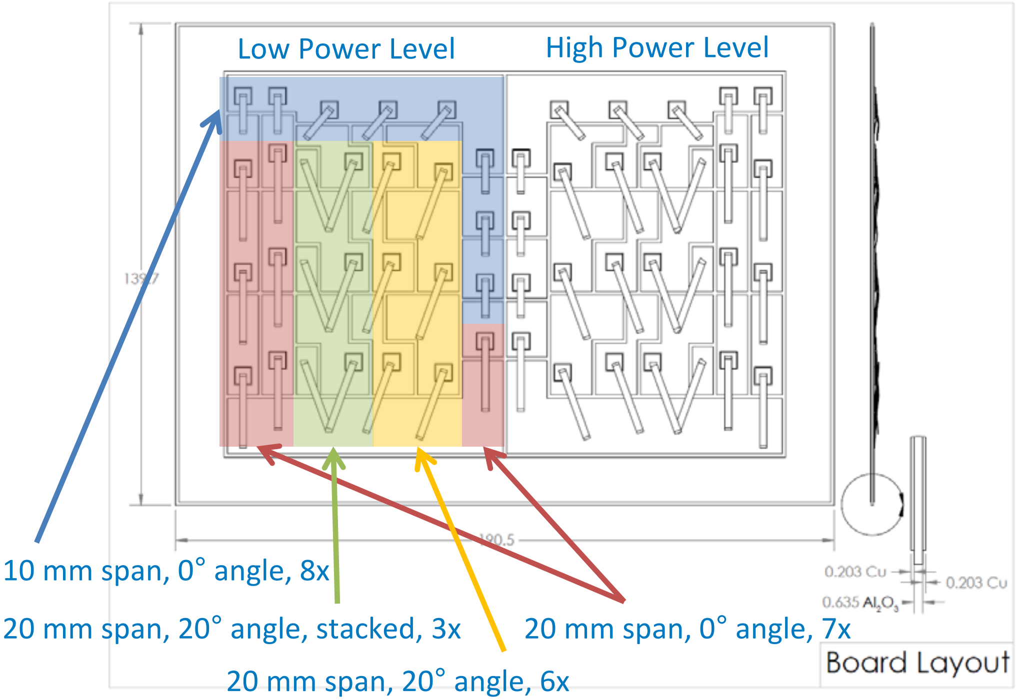


Sample Test Substrates

- 51 test boards bonded at Kulicke and Soffa.
  - 48 ribbons bonded per board in 12 parallel electrical paths.
  - Loop height to span ratio is 1:2.2.



Ribbon Bonding



10 mm span, 0° angle, 8x

20 mm span, 20° angle, stacked, 3x

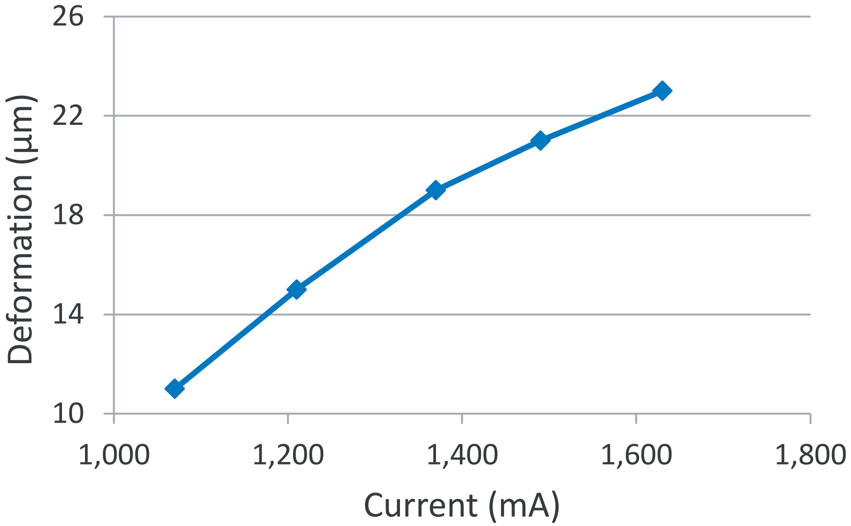
20 mm span, 0° angle, 7x

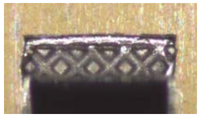
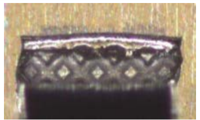
20 mm span, 20° angle, 6x

Test Board Layout

Bond Optimization

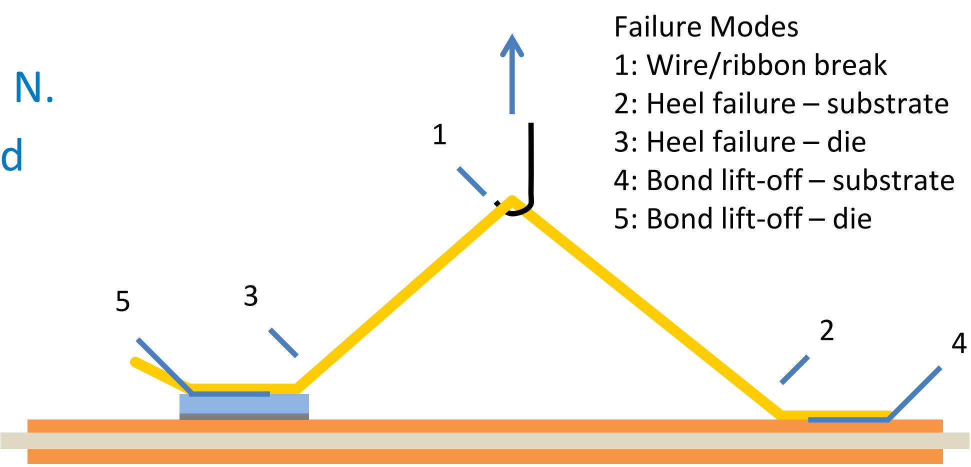
- Ultrasonic bonding power, force, and application time contribute to the quality of the bond pad.
- Bond quality is measured by:
  - Bond pad deformation
  - Pull strength
  - Failure mode.
- Deformation pattern depth increases with increasing current levels.



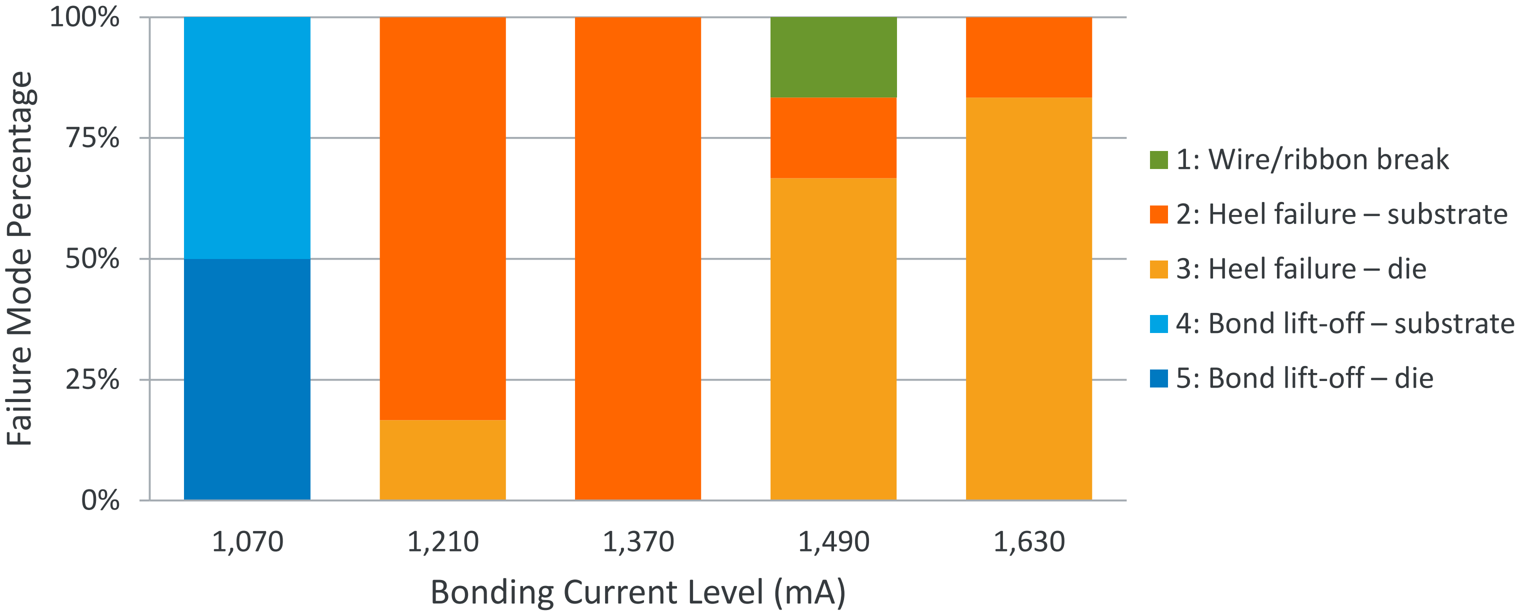
Current (mA)	Deformation (µm)	Deformation (visual)
1,070	11	
1,210	15	
1,370	19	
1,490	21	
1,630	23	

Bond Optimization

- Pull strength of test bonds was measured to be approximately 9.8 N.
- Pull failure modes varied with bond current levels.
    - These criteria were used for final selection of optimized bonding current level.

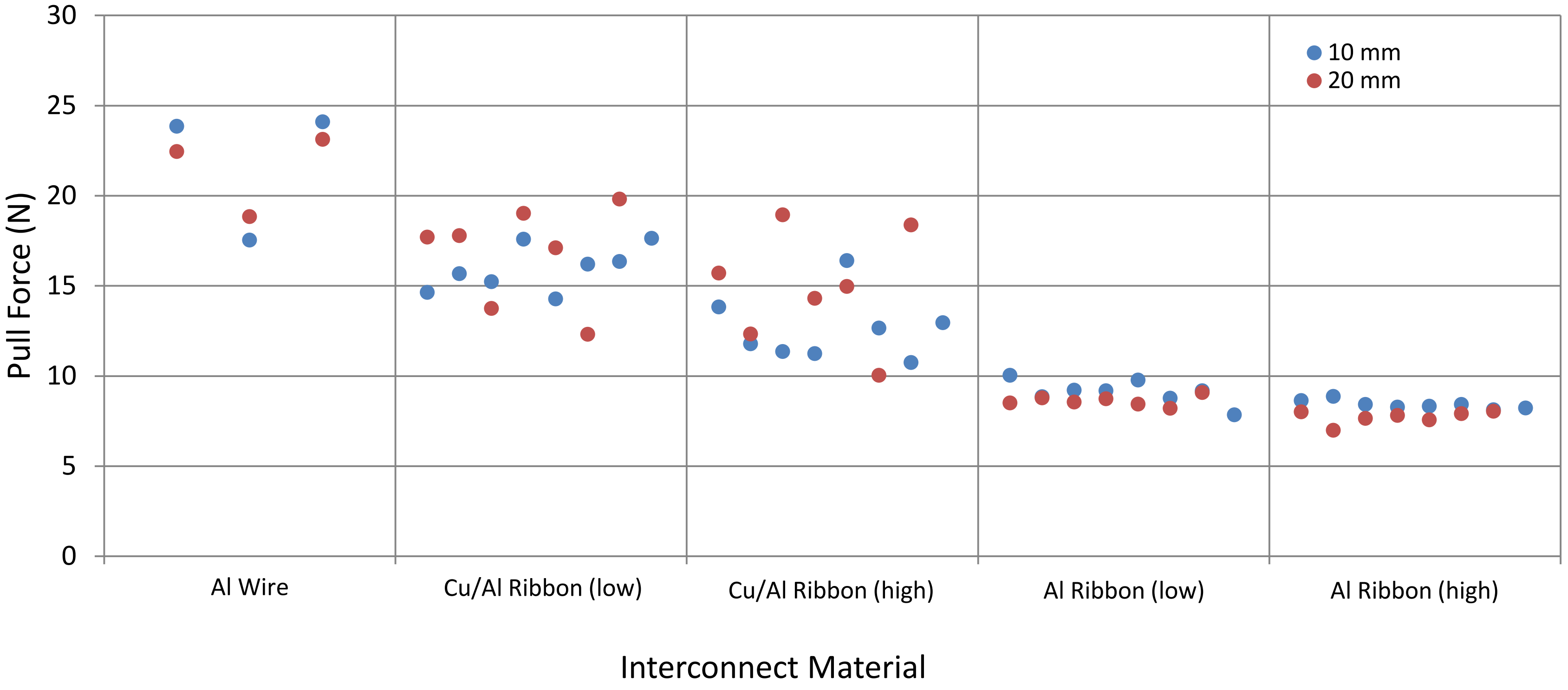


Failure Modes
1: Wire/ribbon break
2: Heel failure – substrate
3: Heel failure – die
4: Bond lift-off – substrate
5: Bond lift-off – die



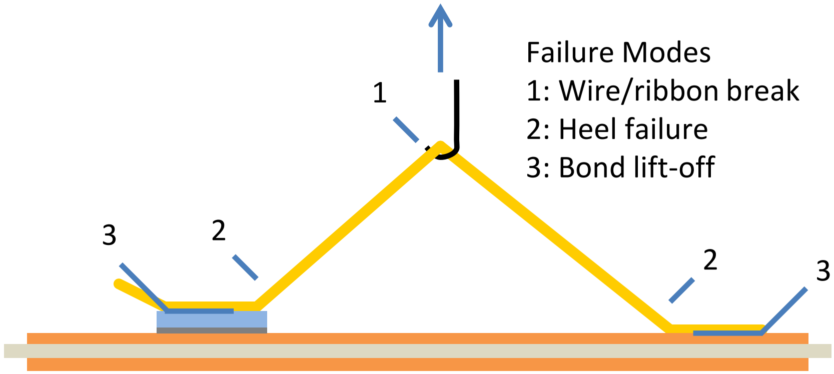
Baseline Evaluation

- Initial pull testing was completed on test substrates prior to accelerated testing:
    - Al wire has a cross-section of 500 µm.
    - Ribbon interconnects have 1,000 µm x 100 µm cross-sections.
    - Bonding power for ribbon interconnects is specified as either low or high.

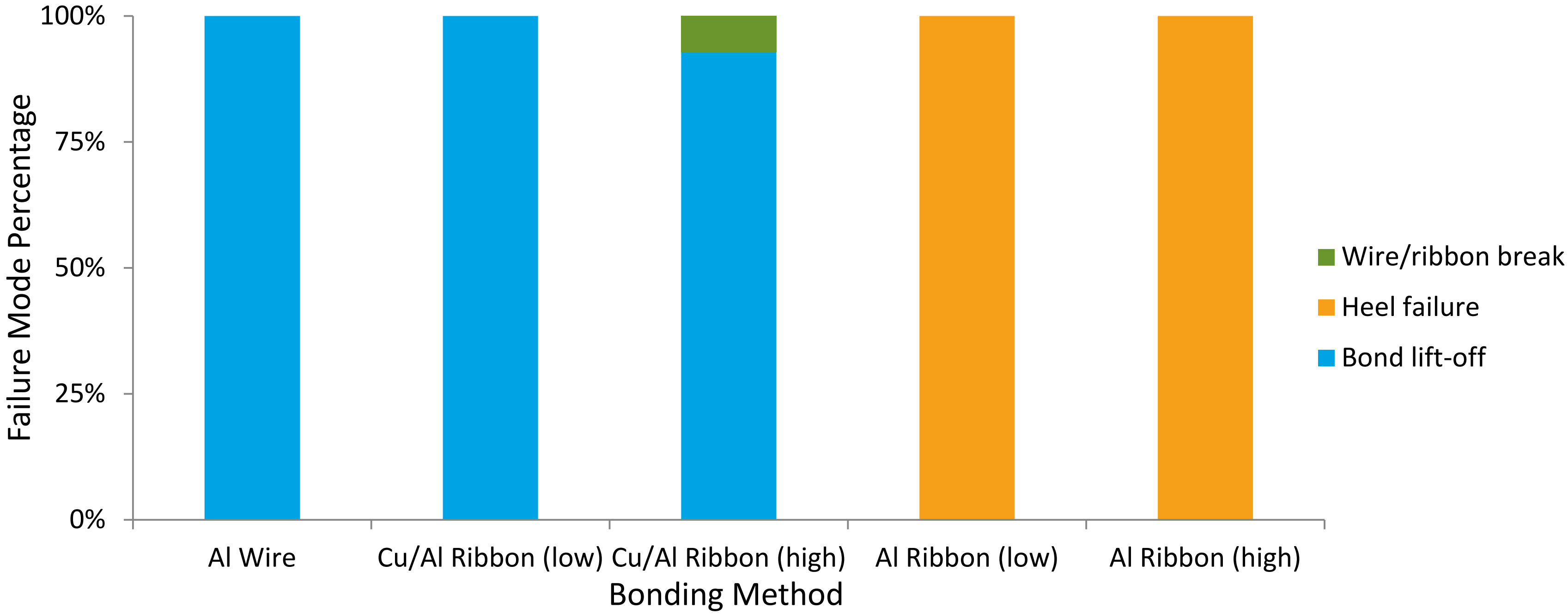


Baseline Evaluation

- The failure mode was recorded for each bond prior to accelerated testing:
    - Al wire bonds and Cu/Al-clad ribbon failures showed bond lift-off failures.
    - Al ribbon bonds exhibited heel failures.

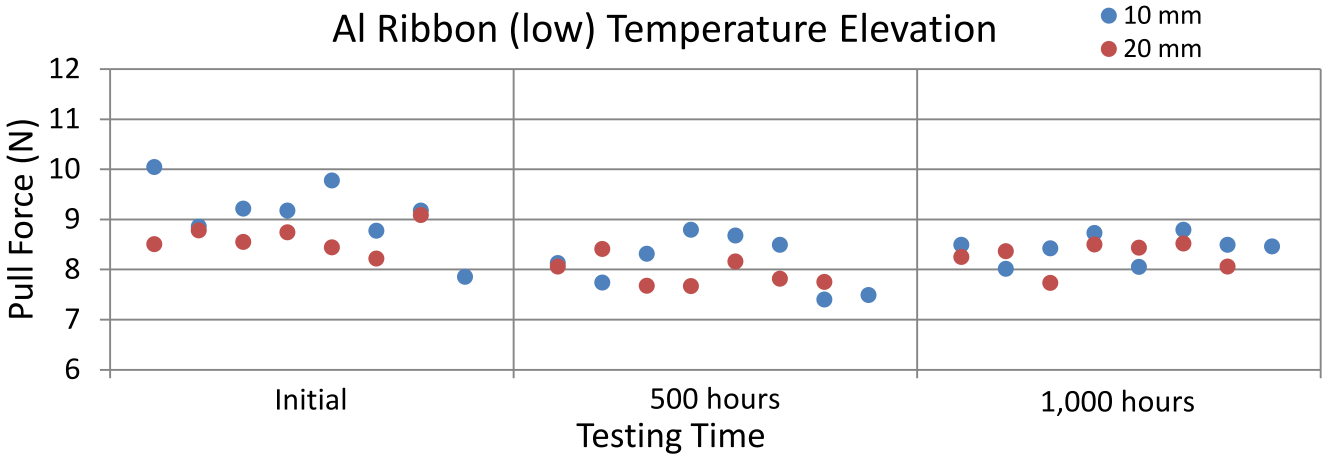


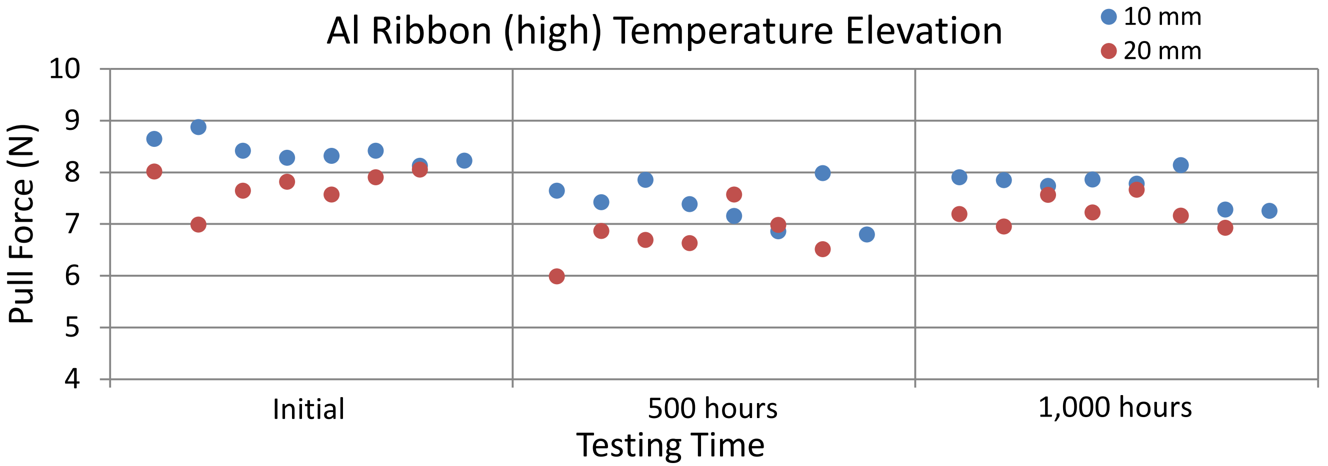
Failure Modes
1: Wire/ribbon break
2: Heel failure
3: Bond lift-off



Post-Accelerated Testing Evaluation

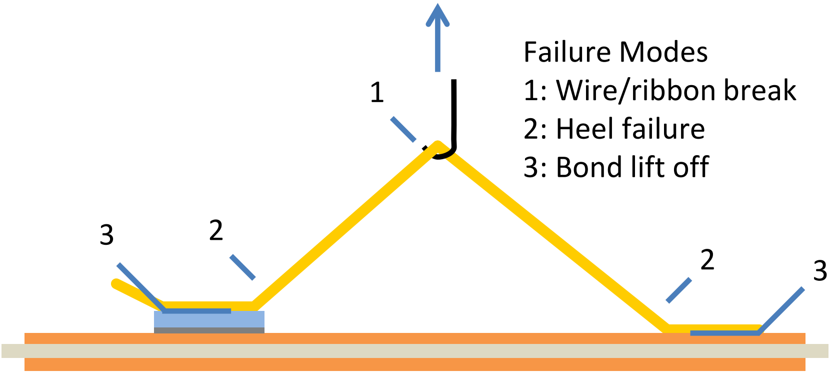
Accelerated Test	Testing Condition	Duration
Temperature Elevation	150°C	500/1,000 hours



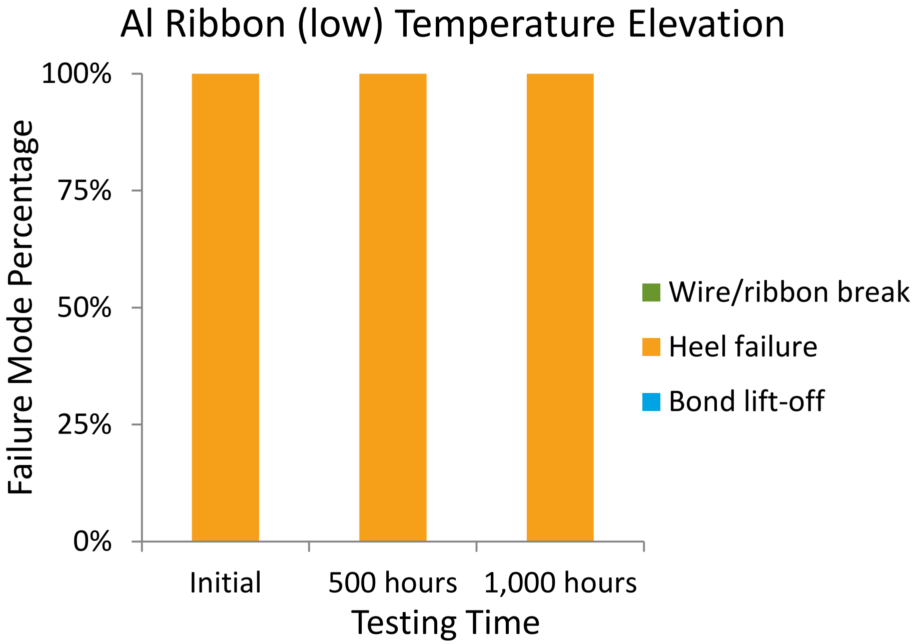


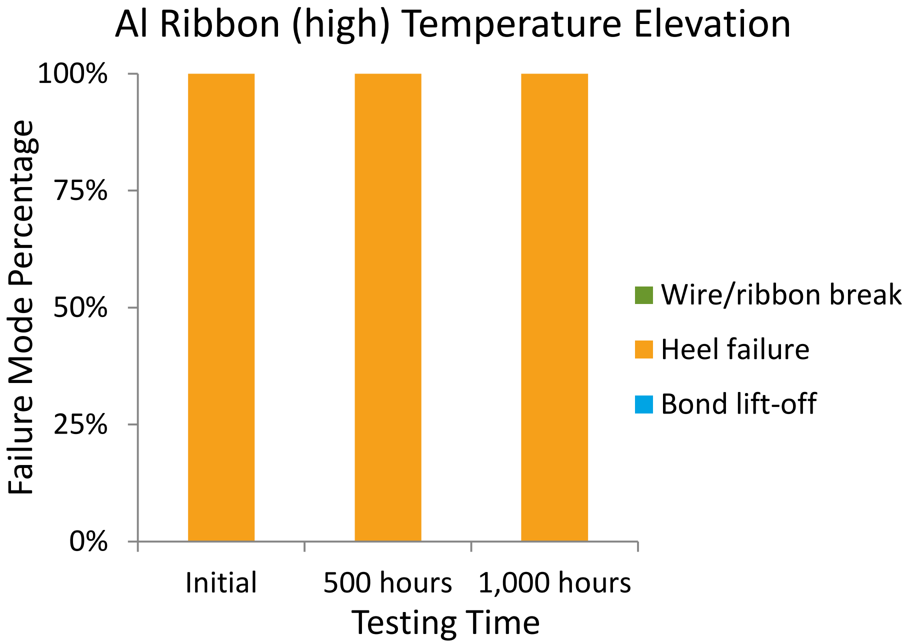
Temperature Elevation Evaluation

- The failure mode was recorded for each bond after temperature elevation testing:
  - Al ribbon heel failure mode remained the same through temperature elevation testing.



Failure Modes
1: Wire/ribbon break
2: Heel failure
3: Bond lift off





Responses to Previous Year Reviewers’ Comments

The reviewer requested that the summary provide general observations and conclusions.

Knowledge transfer of failure modes to industry is a key milestone of this project.

… it was unclear to the reviewer how ultrasonic ribbon bonding labor and new equipment costs compares to standard wire bonding.

In many cases, wire bonding equipment can be retrofitted to add ribbon bonding capability.

The reviewer suggested that in the future an EV component manufacturer might be added to the collaborators.

Knowledge transfer to manufacturers will be accomplished through industry visits.

Collaboration and Coordination

- Partners
  - **Curamik** (Industry): technical partner on substrate design
  - **Kulicke and Soffa** (Industry): technical partner on wire and ribbon bonding procedure

Remaining Challenges and Barriers

- The design-of-experiments required to cover all combinations is large:
  - Strategically choosing key experiments reduces the overall set of combinations.
  - Sought experience from the technical community to guide our choices in experimental tests and ribbon bonding geometries.

Proposed Future Work (FY14)

- Complete thermal, power, and environmental testing on ribbon bonds.
- Report on mechanical reliability of ribbon bonds under testing, and make recommendations to industry partners.
- Validate lifetime estimation models for specific failure modes observed in accelerated tests.

Summary

- **DOE Mission Support:**
  - Transitioning from wire bonding to ribbon bonding manufacturing will advance power electronics technology for compact, reliable packaging with higher current capabilities.
- **Approach:**
  - Synthesize ribbon bonds with varying material (Al, Cu/Al) and geometry (cross section, span and loop height, pad length, number of stitches, stacked pads, and forced angles) parameters.
  - Conduct comprehensive reliability testing, including temperature elevation, temperature cycling, power cycling, and corrosion testing.
  - Revise wire bond models to be applicable to ribbon bonding.
- **Accomplishments:**
  - Test samples were synthesized, and reliability testing was initiated.
  - Initial accelerated tests and interconnect bond strength evaluations were completed.

Summary

- **Collaborations:**
  - Curamik, Kulicke and Soffa
- **Future Work:**
  - Complete thermal, power, and environmental testing on ribbon bonds.
  - Report on mechanical reliability of ribbon bonds under testing and make recommendations to industry partners.
  - Validate lifetime estimation models for specific failure modes observed in accelerated tests.

Acknowledgments:

Susan Rogers and Steven Boyd,
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