Reliability of Electrical Interconnects



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Project ID: APE036

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Overview

Timeline

Project Start Date: FY11

Project End Date: FY14

Percent Complete: 50%

Barriers and Targets

- Efficiency
- Performance and Lifetime

Budget

Total Project Funding:

DOE Share: $1,300K

Funding Received in FY12: $550K

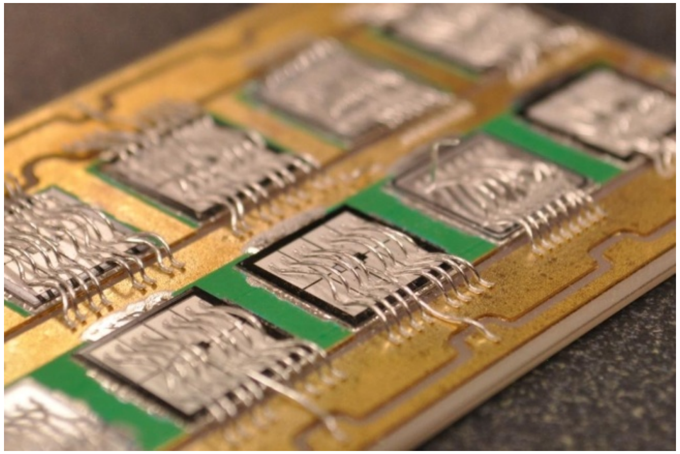
Funding for FY13: $450K

Partners

- Interactions / Collaborations
  - Curamik, Materion Technical Materials, Orthodyne Electronics
- Project Lead
  - National Renewable Energy Laboratory

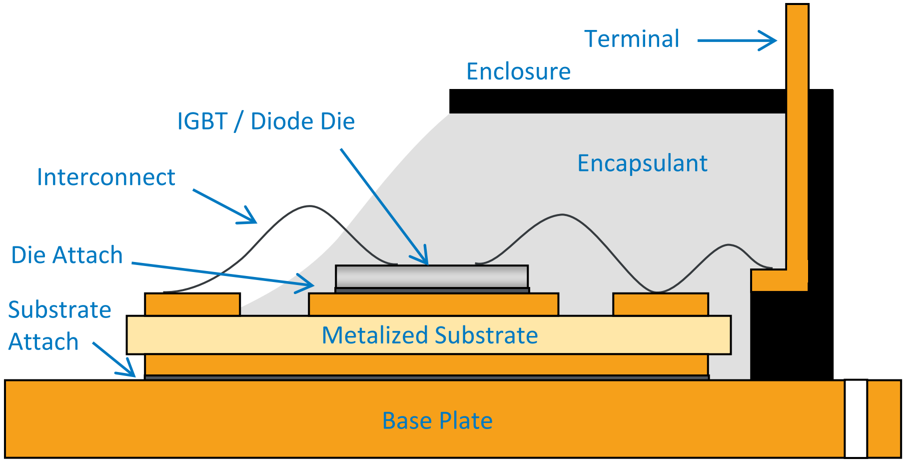
Relevance

- Power electronics rely on wire bonds to electrically connect dies to each other, to a substrate's top metallization layer, or to lead frames
- Bond wire diameter is limited to 500 µm
- Multiple wires bonded in parallel are required for high-current power modules
- Higher power densities and higher operating temperatures require alternative electrical interconnect technologies



Credit: Douglas DeVoto, NREL

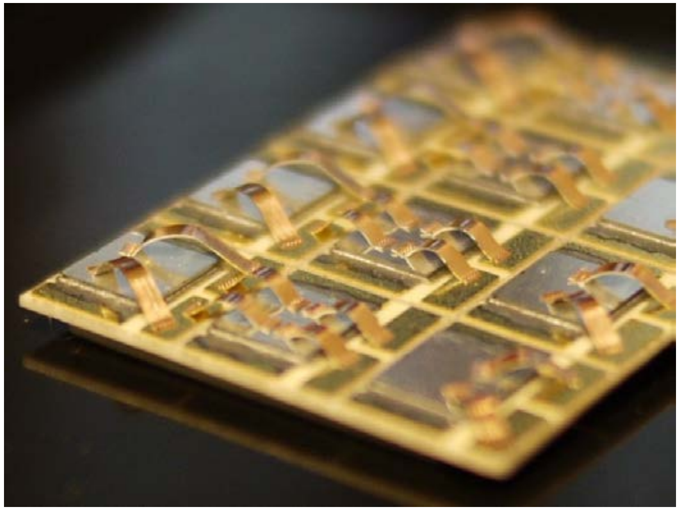
Wire Bonding



Traditional Power Electronics Package

Relevance

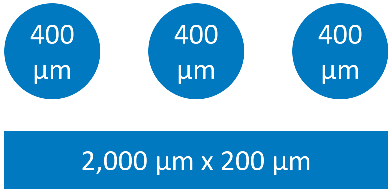
- A transition from round wire interconnects to ribbon interconnects allows for a higher current density and lower loop heights

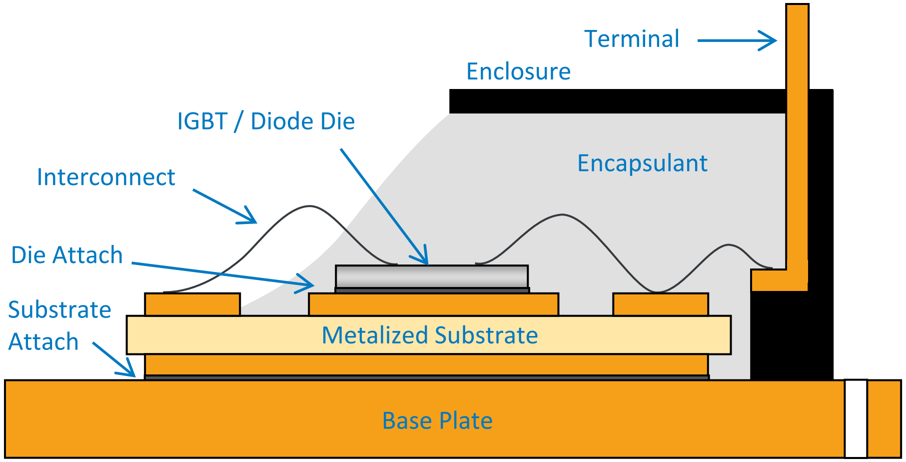


Credit: Douglas DeVoto, NREL

Ribbon Bonding

Three 400-µm wires can be replaced by a single 2,000-µm x 200-µm ribbon





Traditional Power Electronics Package

Objectives

- **Overall Objective**
  - Identify failure modes in emerging interconnect technologies, 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

- **Address Targets**
  - Enable designers to consider advanced interconnect technology to help meet cost, weight, and volume targets without sacrificing reliability

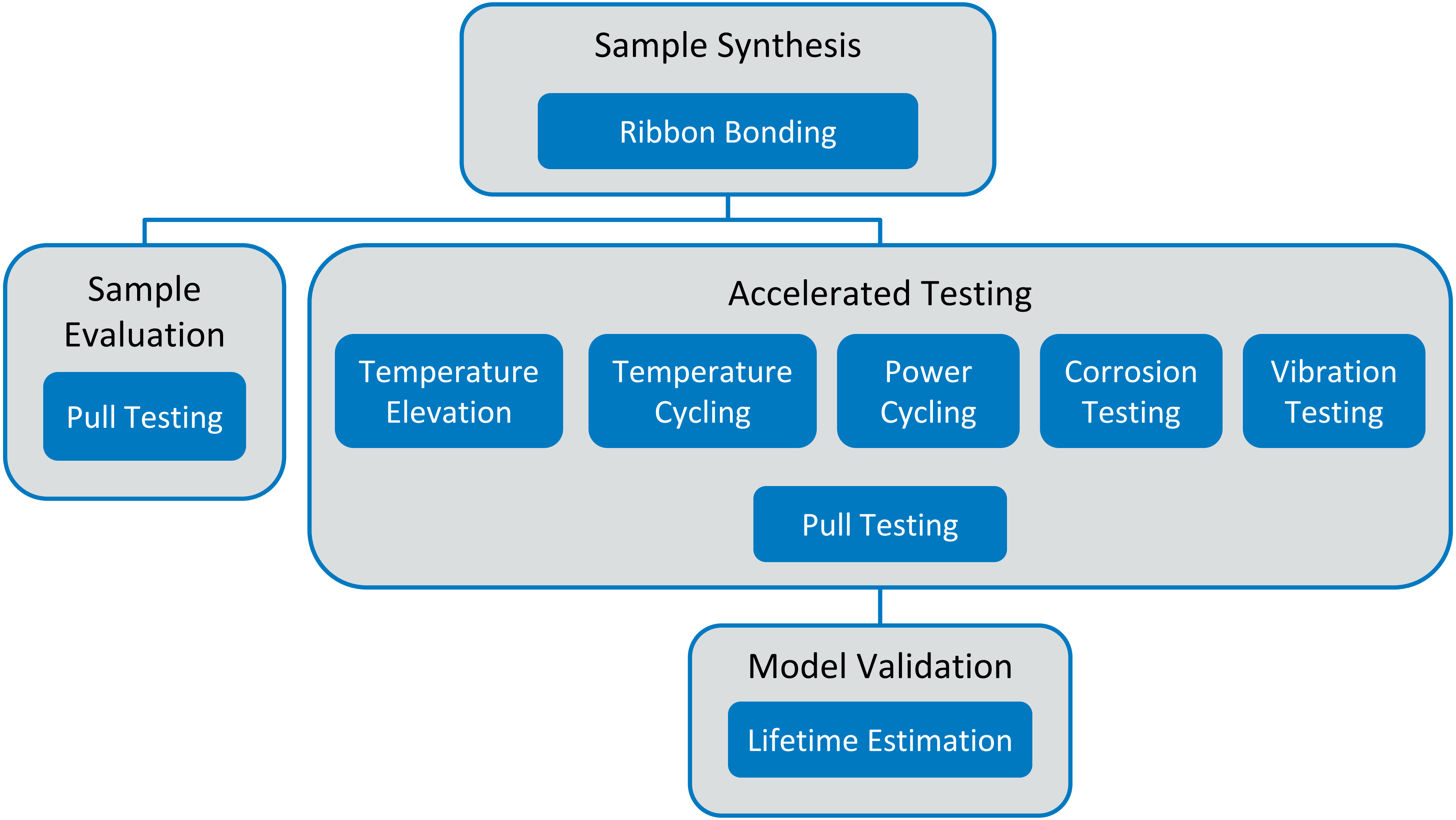
- **Uniqueness and Impacts**
  - Failure modes and PoF models for emerging interconnect technology

Milestones

Date	Description
June 2012	Calculated optimal height to span length ratio in ribbon interconnects to minimize strains during temperature cycling
September 2012	Received initial test substrates from Orthodyne for selected accelerated tests
October 2012	Evaluated initial bond strength of interconnects prior to accelerated testing Go/No-Go Decision: Testing results showed bond strength of interconnects was satisfactory; decision was made to proceed with accelerated tests
December 2012	Initiated elevated temperature and corrosion testing on test substrates
February 2013	Evaluated initial accelerated testing results
May 2013	Complete ribbon bonding at Orthodyne Electronics for 40 additional test substrates
June 2013	Conduct accelerated testing test plan with 40 additional test substrates
November 2013	Evaluate accelerated testing results
March 2014	Develop and validate lifetime estimation models for specific failure modes observed in accelerated tests

Approach

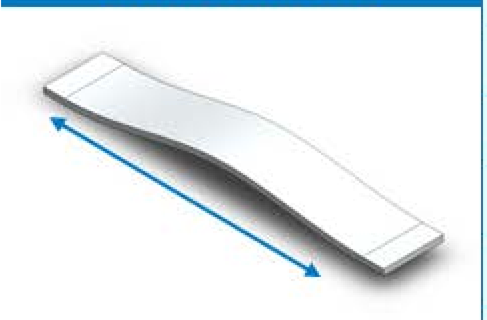
- Identify failure modes in ribbon interconnects, experimentally characterize their life under known conditions, and develop lifetime prediction models



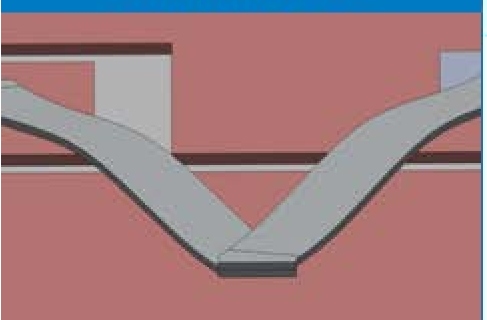
Sample Synthesis

Ribbon Material

Ribbon Span



Stacked Pads



<table>
<tr><th>Criterion</th><th colspan="6">Variation</th></tr>
<tr><td>Material</td><td colspan="3">Al Ribbon</td><td colspan="3">Cu/Al Ribbon</td></tr>
<tr><td>Cross Section (μm)</td><td colspan="3">2,000 x 200</td><td colspan="3">1,000 x 100</td></tr>
<tr><td>Ribbon Span (mm)</td><td colspan="3">10</td><td colspan="3">20</td></tr>
<tr><td>Number of Stitches</td><td colspan="3">Single</td><td colspan="3">Double</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="2">0</td><td colspan="2">20</td><td colspan="2">40</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>
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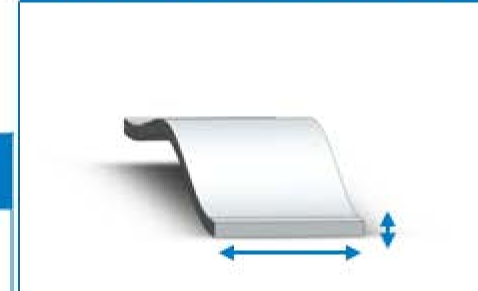
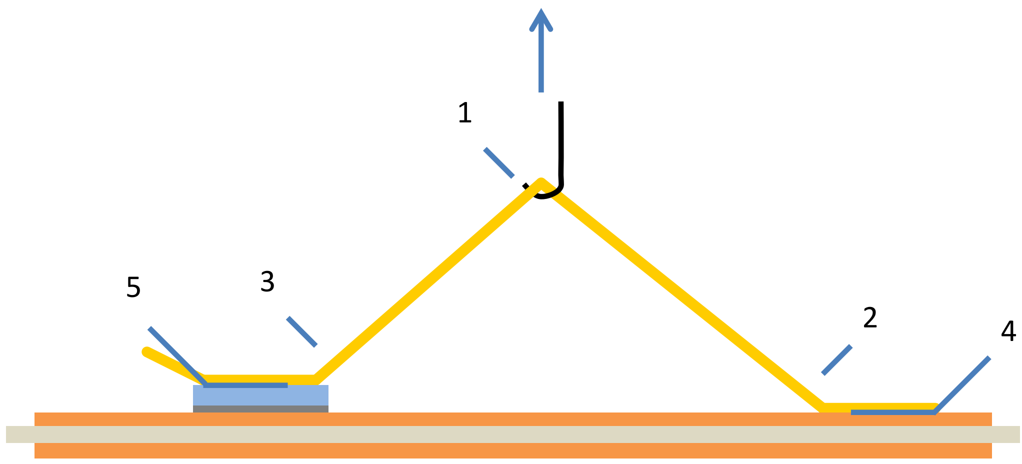
Ribbon Cross Section



Number of Stitches

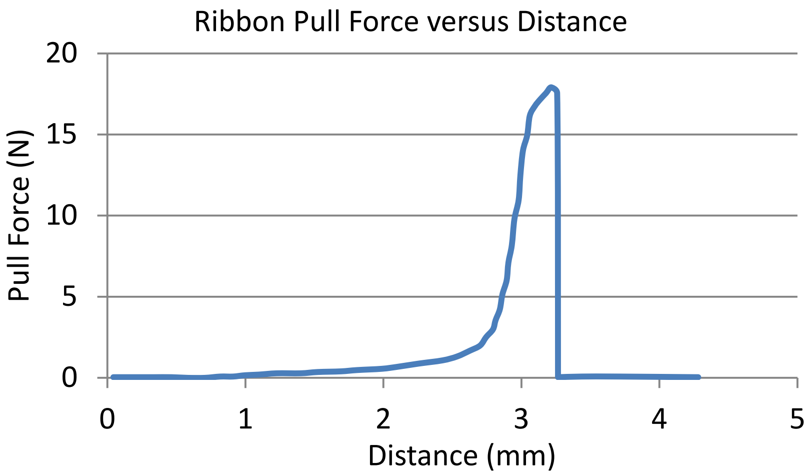
Forced Bond Angle

Sample Evaluation

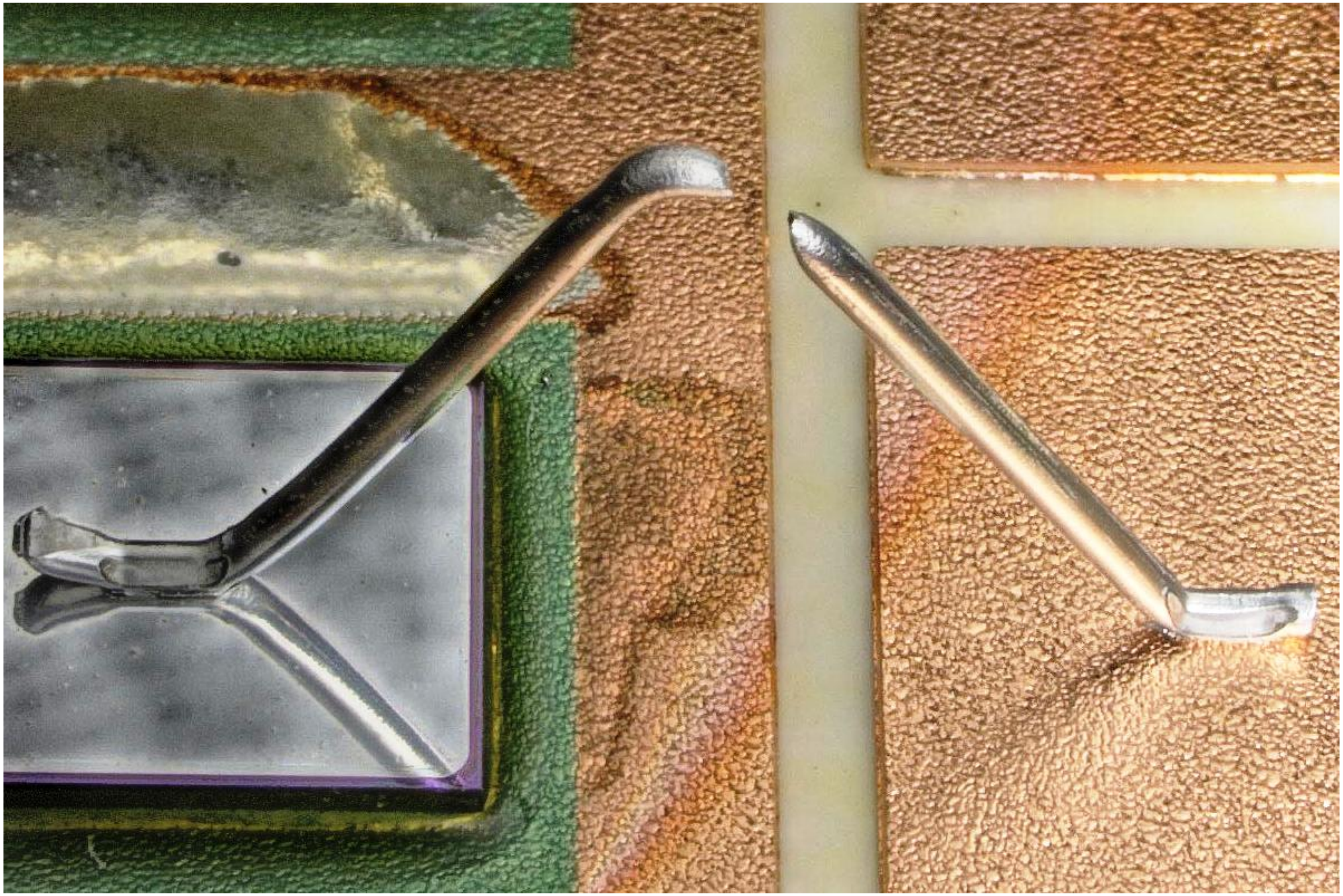


Failure Modes
1: Wire/ribbon break
2: Heel failure – substrate
3: Heel failure – die
4: Bond lift off – substrate
5: Bond lift off – die

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



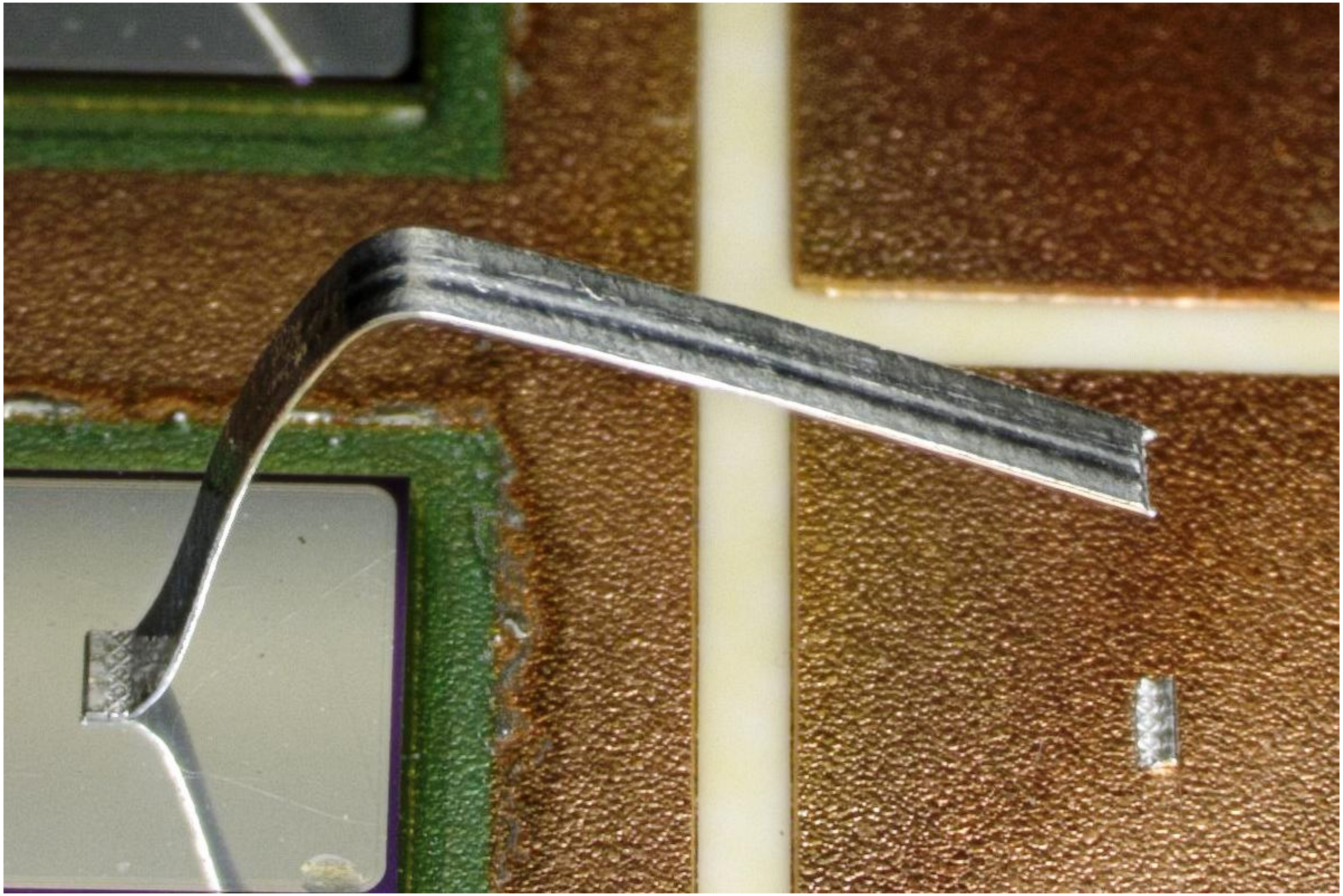
Sample Evaluation – Failure Modes



Credit: Douglas DeVoto, NREL

Wire Break

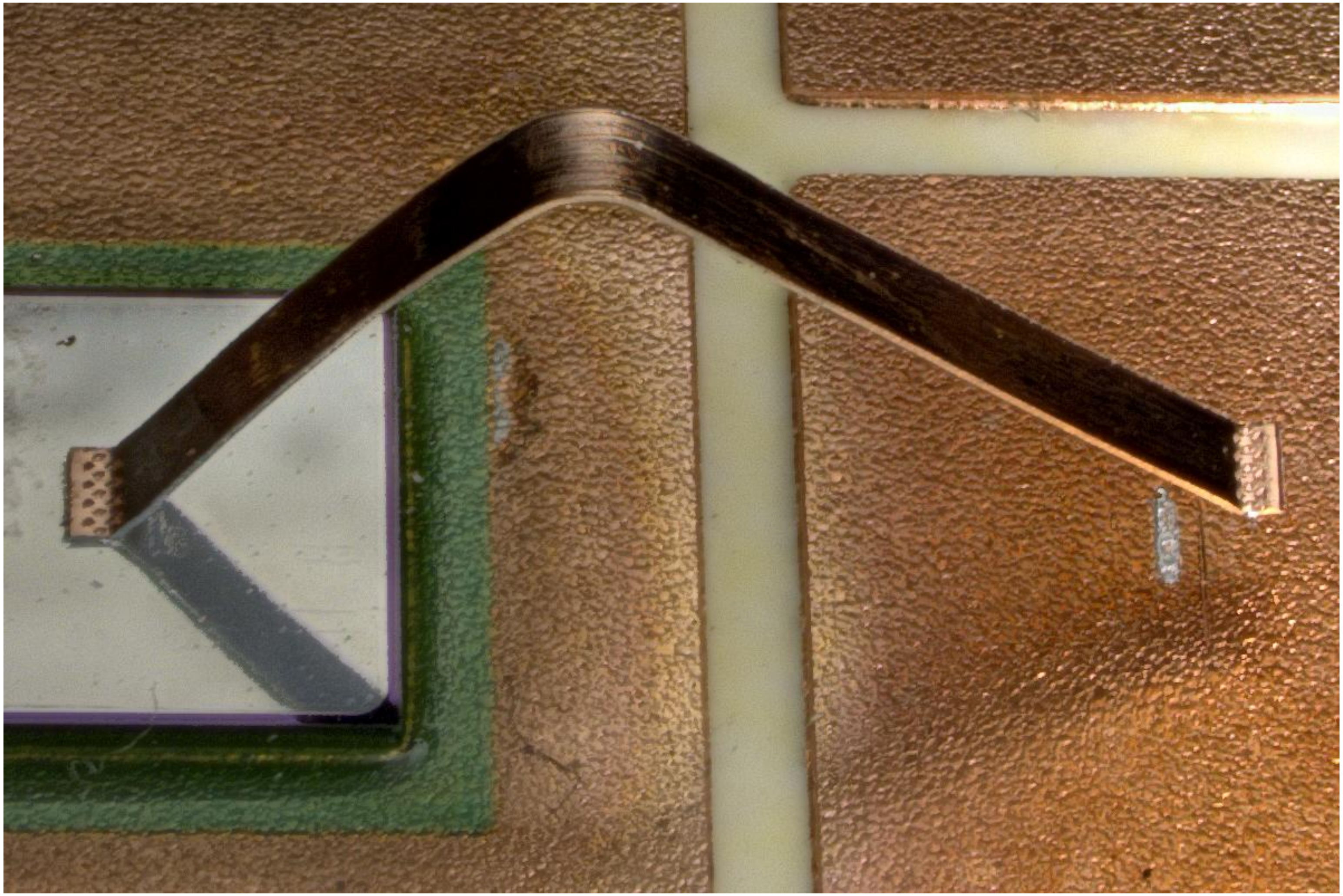
Sample Evaluation – Failure Modes



Credit: Douglas DeVoto, NREL

Heel Failure from Substrate

Sample Evaluation – Failure Modes



Credit: Douglas DeVoto, NREL

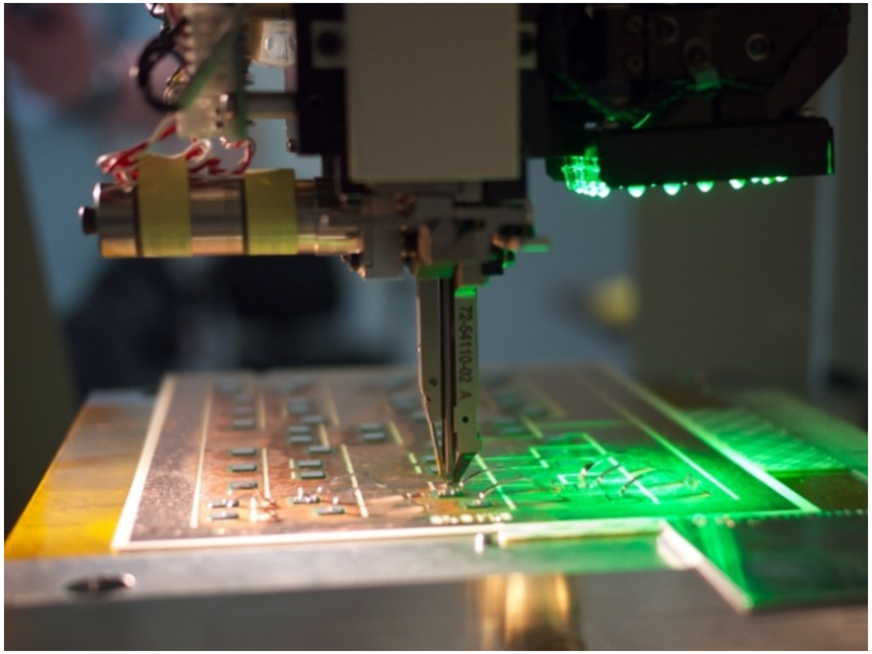
Bond Pad Liftoff from Substrate

Accelerated Testing Plan

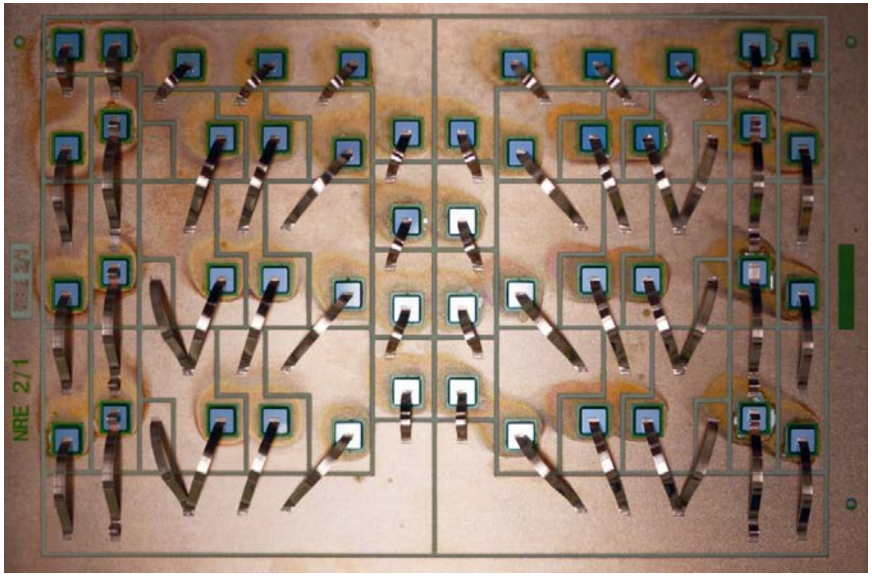
Accelerated Test	Testing Condition	Duration
Temperature Elevation	150°C	1,000 hours
	200°C	96 hours
Temperature Cycling	-40°C to 150°C, 10 min dwell, 5°C/min ramp rates	2,000 cycles
Corrosion Testing	85°C, 85% relative humidity, cycled DC bias	1,000 hours
	121°C, 100% relative humidity	96 hours
Power Cycling	-40°C to 125°C, 10 min dwell, 5°C/min ramp rates, cycled DC bias	1,500 temperature cycles
Vibration Testing	Highly accelerated life test (HALT)	Until interconnect fails

Sample Test Substrates

- Substrate etch pattern completed at Curamik
- Schottky diodes attached to sample substrates at NREL
- Ribbon bonding conducted at Orthodyne Electronics
  - 48 ribbons bonded per board in 12 parallel electrical paths



Ribbon Bonding

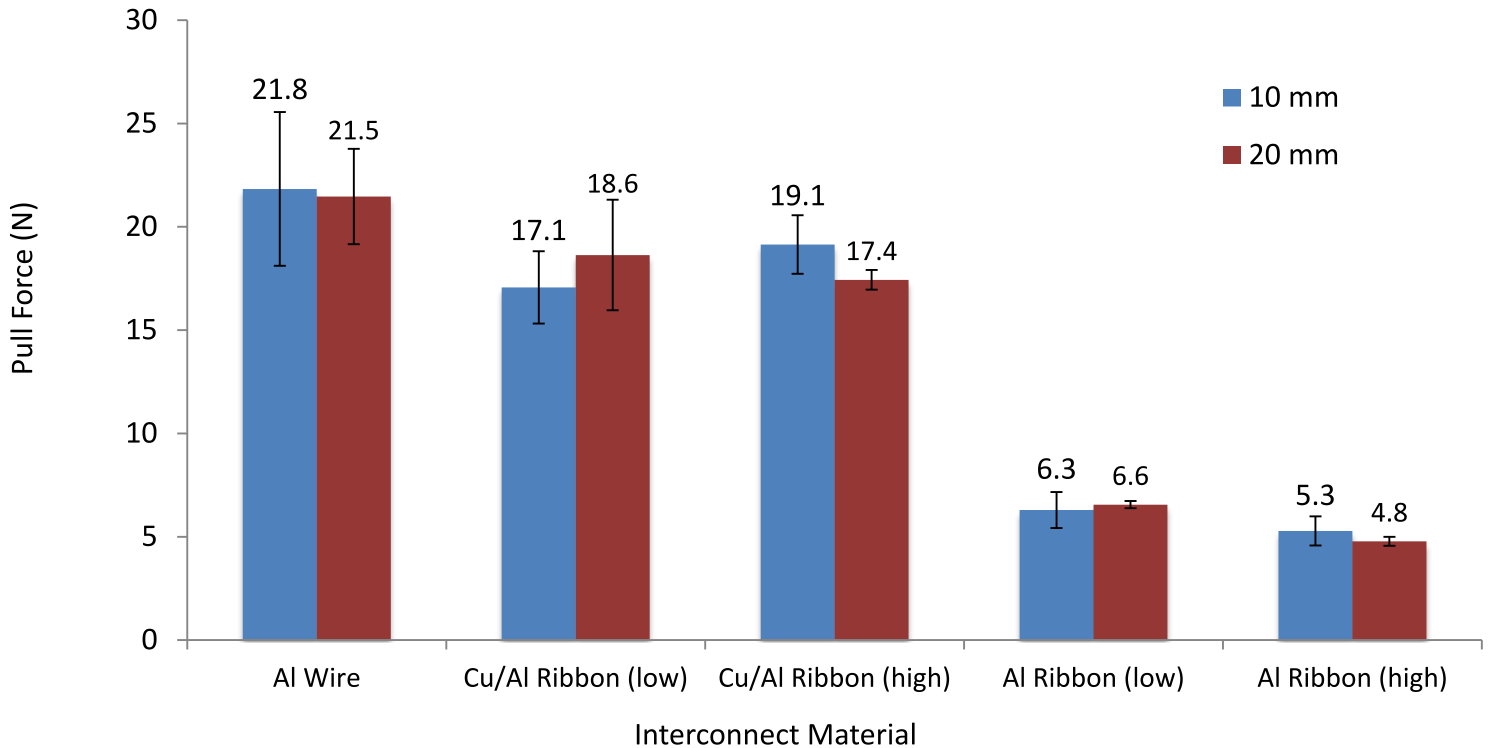


Test Board Layout

Credit: Douglas DeVoto, NREL (all photos)

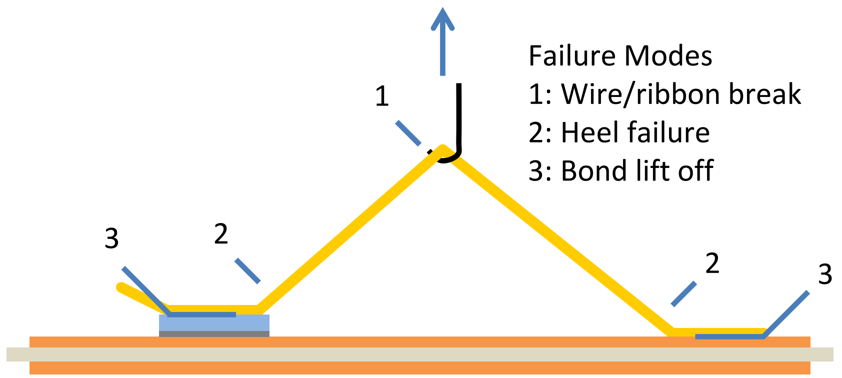
Interconnect Evaluation – Baseline

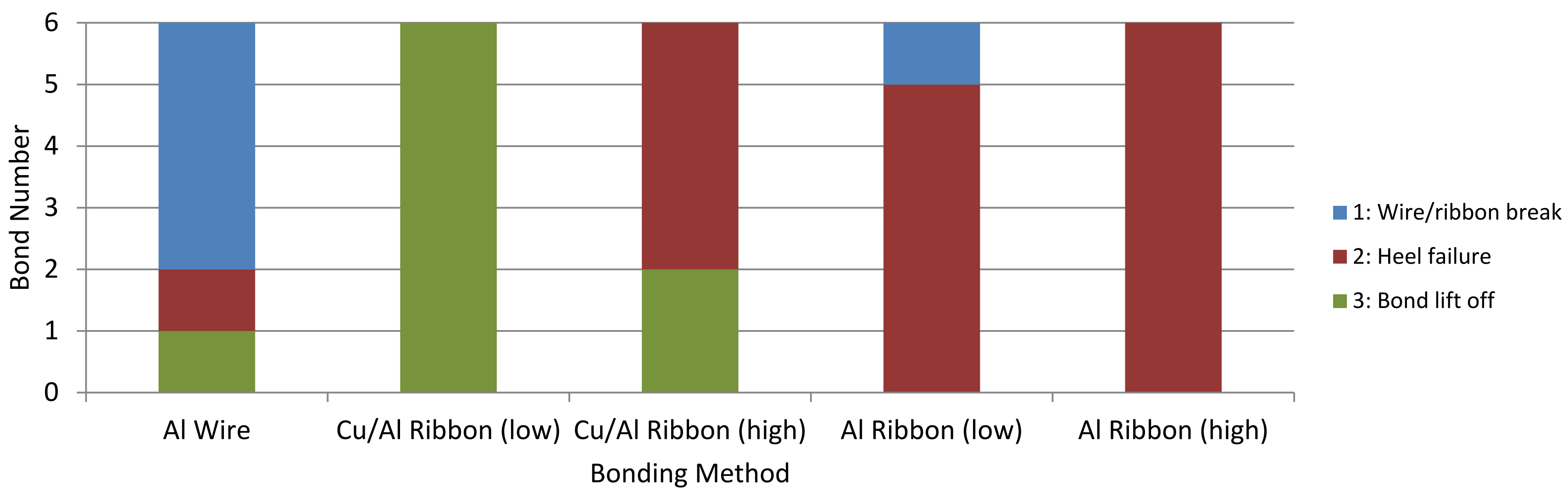
- Initial pull testing was completed on test substrates prior to accelerated testing
  - Al wire has a cross-section of 500 µm
  - Ribbon interconnects have 1,000 µm x 100 µm cross-sections
  - Bonding power for ribbon interconnects is specified as either low or high



Interconnect Evaluation – Baseline

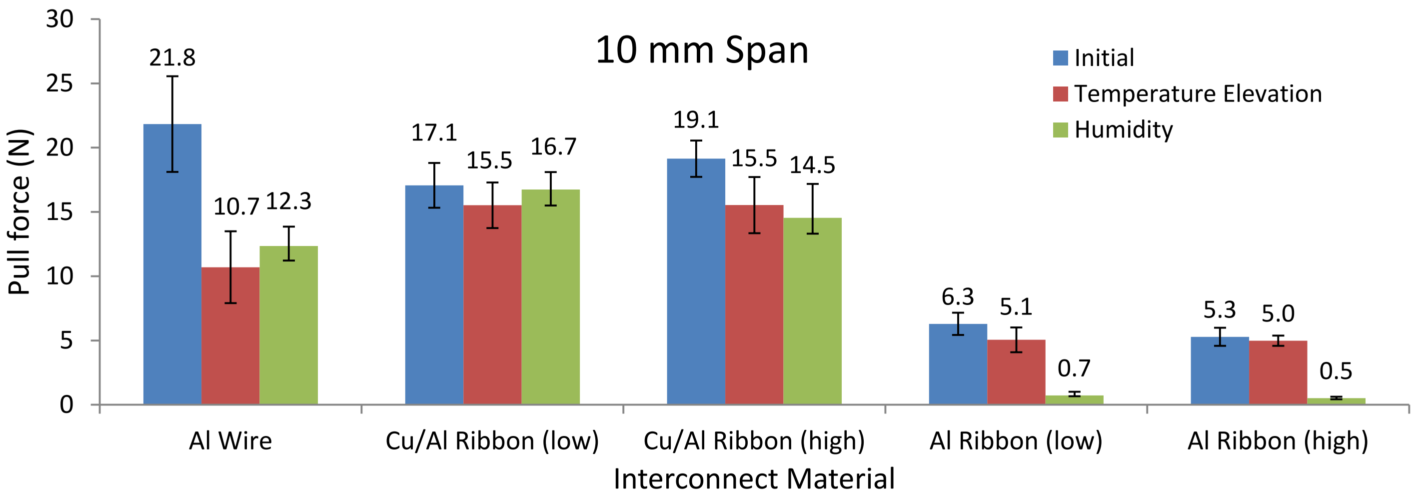
- The failure mode was recorded for each bond prior to accelerated testing
  - Al wire bonds primarily failed within the wire near the test hook
  - Increasing bonding power shifted Cu/Al ribbon failures from bond pad lift offs to heel failures
  - Al ribbon bonds exhibited heel failures

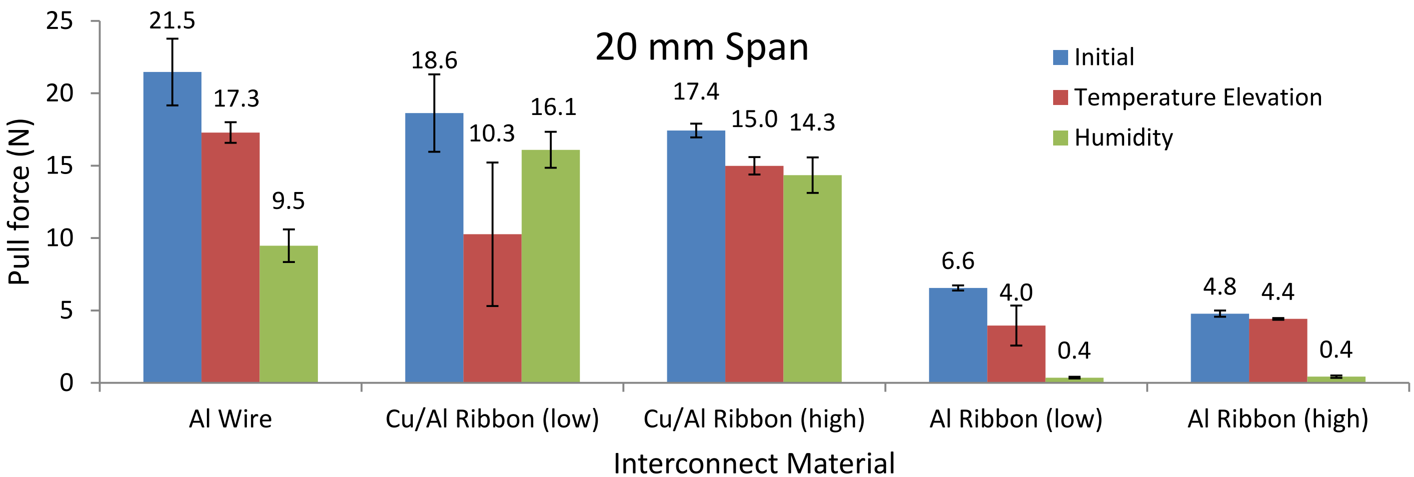




Interconnect Evaluation – Post Accelerated Testing

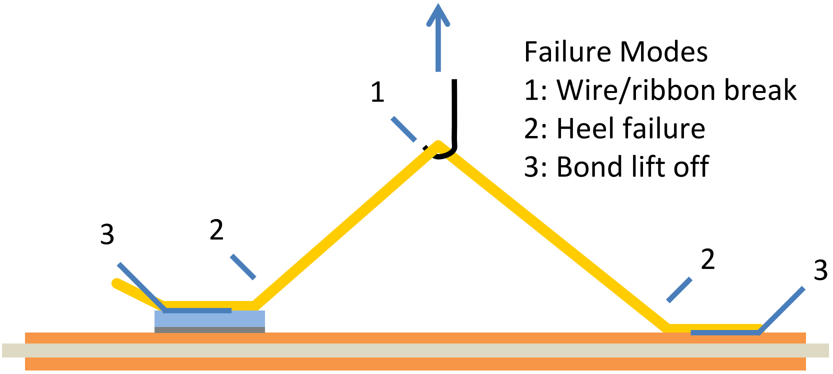
Accelerated Test	Testing Condition	Duration
Temperature Elevation	200°C	144 hours
Corrosion	121°C, 100% relative humidity	144 hours

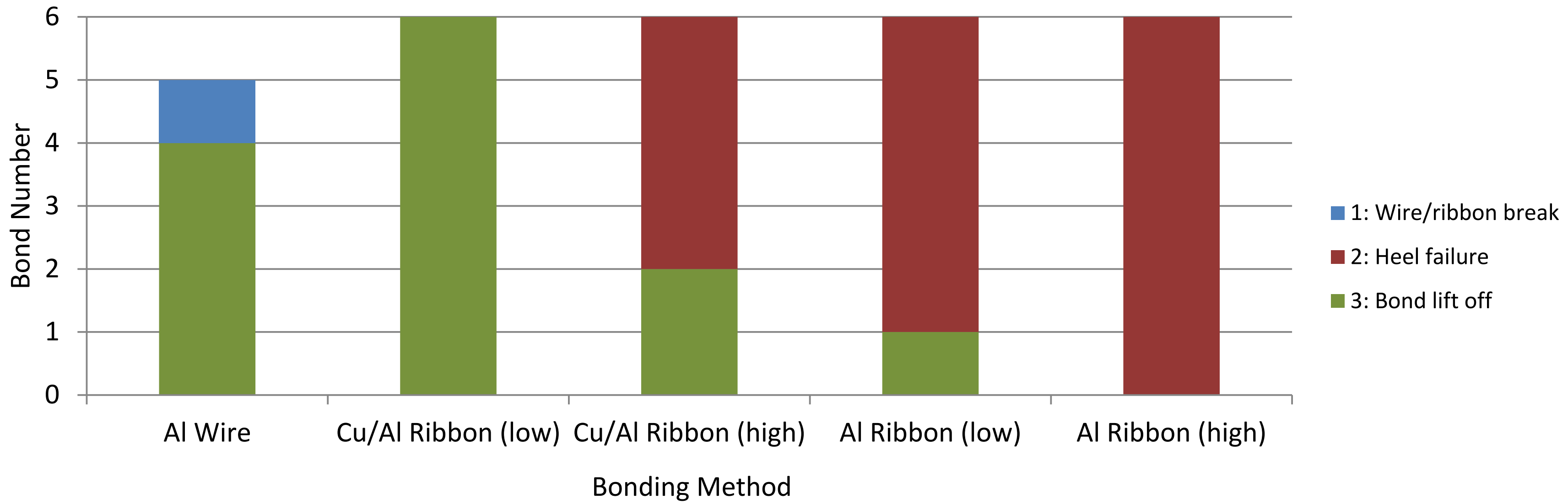




Interconnect Evaluation – Temperature Elevation

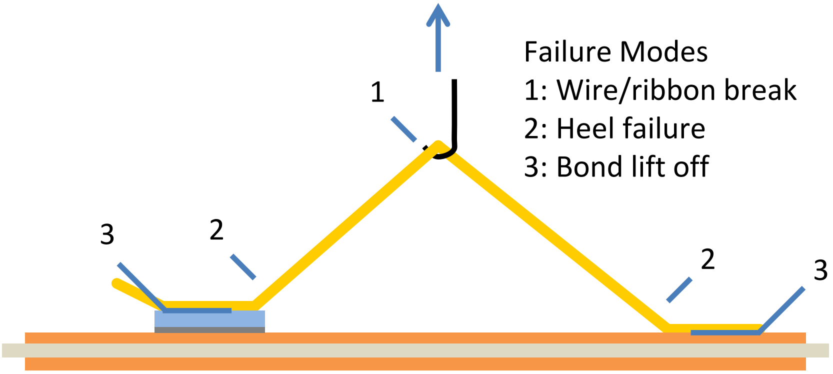
- The failure mode was recorded for each bond after temperature elevation testing
  - Al wire breaks from initial pull tests shifted to bond pad lift off failures
  - Al and Cu/Al ribbon failure modes remained the same

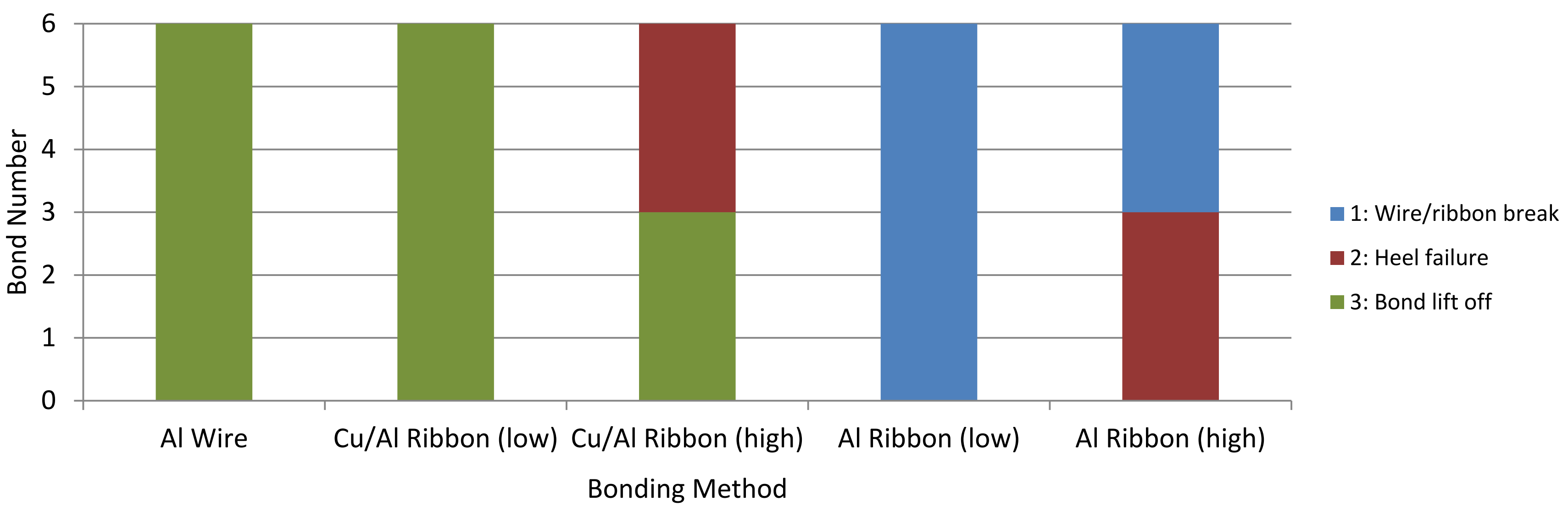




Interconnect Evaluation – Corrosion

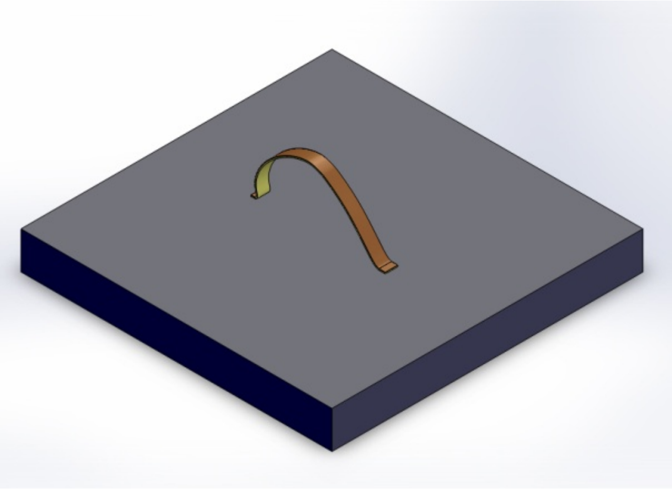
- The failure mode was recorded for each bond after corrosion testing
  - Al wire breaks from initial pull tests shifted to bond pad lift off failures
  - Cu/Al ribbon failure modes remained the same
  - Al ribbon heel failures shifted to ribbon breaks



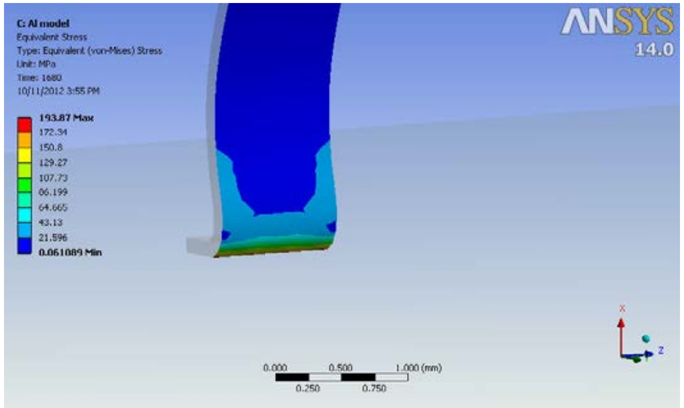


Model Development

- Analytical model
  - Theory of curved beams used to calculate the strain induced in the ribbon bond
  - Optimal loop geometry calculated to be 1:2.2 height to span length ratio
- Finite element analysis (FEA) model
  - Maximum deflection, Von Mises stress, and strain calculated for Al ribbon profile
- Lifetime estimations will be developed for specific failure modes observed in accelerated tests



FEA Model of 1,000 μm x 100 μm Al Ribbon



Maximum Stress at Heel Location

Collaboration and Coordination

- Partners
  - **Curamik** (Industry): technical partner on substrate design
  - **Materion Technical Materials** (Industry): technical partner on ribbon material
  - **Orthodyne Electronics** (Industry): technical partner on wire and ribbon bonding procedure

Proposed Future Work (FY13)

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

Proposed Future Work (FY14)

- Complete reliability evaluation of ribbon interconnects and perform reliability testing for additional interconnect technologies, such as planar interconnects or flex foil
- Apply PoF models to a production module with ribbon bonding

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**
  - Synthesis of 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
  - Comprehensive reliability testing, including temperature elevation, temperature cycling, power cycling, and corrosion testing
  - Revision of 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, Materion Technical Materials, Orthodyne Electronics
- **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
  - Develop lifetime estimation models for specific failure modes observed in accelerated tests
  - Perform reliability testing and develop PoF models for additional interconnect technologies, such as planar interconnects or flex foil
  - Apply PoF models to a production module with ribbon bonding

NATIONAL RENEWABLE ENERGY LABORATORY

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