Physics of Failure of Electrical Interconnects

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Overview

Timeline

Project Start Date: FY11

Project End Date: FY13

Percent Complete: 40%

Barriers and Targets

- Efficiency
- Performance and Lifetime

Budget

Total Project Funding:

DOE Share: $600K

Funding Received in FY11: $300K

Funding for FY12: $300K

Partners

- Interactions/ Collaborations
  - Curamik, Materion Technical Materials, Orthodyne Electronics
- Project lead: NREL

Relevance/Objectives

- Traditional interconnect technologies, such as wire bonding, do not sufficiently meet the needs of the latest power inverters, which function at high frequencies, high power densities, and elevated temperatures.
- Present electrical interconnect technology has limited current-carrying capability.
- Elevated temperatures (>150°C) and temperature cycling can degrade the performance and reliability of interconnects.
- The package size of power modules is being reduced and requires more spatially efficient interconnects.

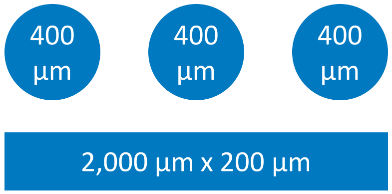
Relevance/Objectives

- **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
- **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

Relevance/Objectives

- A transition from round wire interconnects to ribbon interconnects provides several advantages.

For equivalent current density, three 400-µm wires can be replaced by a single 2,000-µm x 200-µm ribbon.



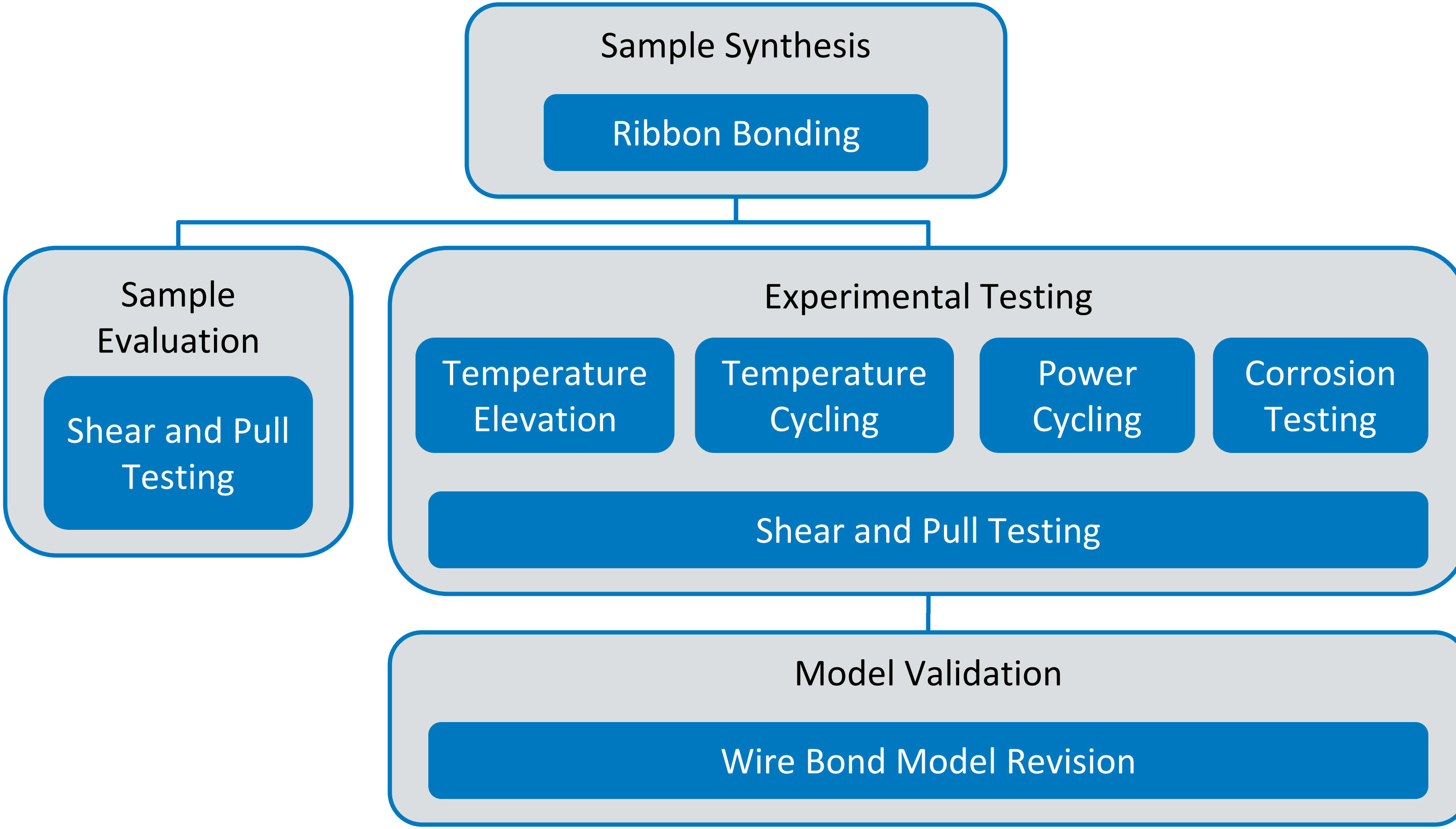
Electrical Advantages	Mechanical Advantages
Higher current density	Higher shear and pull strength
Lower parasitics at high frequencies	Lower profile and minimal sagging
Lower impedance	Stacked bonding capability

- Test and model ribbon bonds to prove they exhibit equivalent or greater reliability than industry-accepted wire bond technology
- Demonstrate that ribbon bonds enable the required power density for high-power inverters in automotive vehicles
- Quantify ribbon bond advantages for packaging of automotive power electronic devices

Milestones

Date	Milestone or Go/No-Go Decision
August 2011	Finalized ribbon layout to evaluate bonds under a variety of geometries and sent etch pattern and solder mask out for substrate fabrication.
September 2011	Increased laboratory capabilities by acquiring a mechanical tester for ribbon pull and ribbon bond shear testing.
January 2012	Prepared sample substrates for ribbon bonding. Received test substrates and attached diodes to copper surface.
March 2012	Bonded ribbons to test substrates. Ribbon bonding conducted at Orthodyne Electronics.
May 2012	Conduct accelerated testing.
September 2012	Report on initial accelerated testing results.

Approach/Strategy



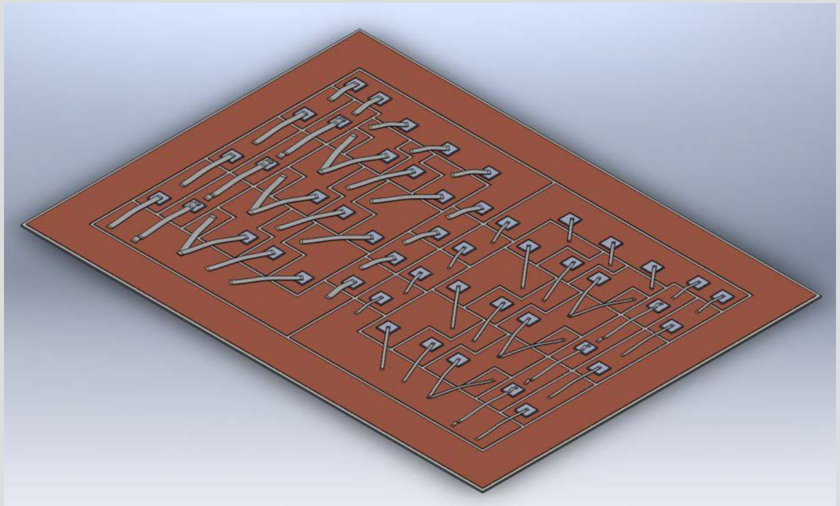
Approach: Sample Synthesis

Ribbon Materials

Ribbon Cross Section

Ribbon Span and Loop Height

Test Sample



Pad Length and Number of Stitches

Stacked Pads

Forced Angle

Approach: Experimental Testing

Wire/Ribbon Puller

Credit: Douglas DeVoto, NREL

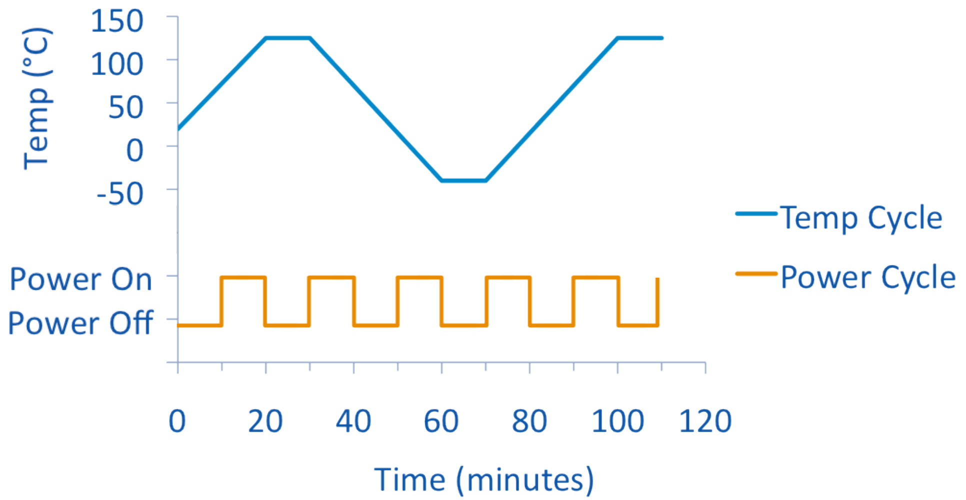
- Sample Evaluation
  - Ribbon pull testing indicates the strength of the ribbon bond.
    - A strong bond will cause the ribbon to fail at its heel.
    - A poor bond will cause the ribbon to lift off the pad.
  - Ribbon pad shear testing evaluates the adhesion strength between the ribbon and substrate.
- Temperature Elevation
  - Samples subjected to high-temperature storage testing will highlight thermally activated failure mechanisms.
  - Samples will be stored under two test conditions: at 150°C for 1,000 hours and 200°C for 96 hours (JEDEC* 22-A103-D).
  - Shear and pull testing will monitor changes to bond strength, and cross sectioning will monitor the development of intermetallic compounds.
- Temperature Cycling
  - Alternating temperature extremes will test the ability of interconnects to withstand thermally induced mechanical stresses.
  - Samples will be cycled from –40°C to 150°C for 2,000 cycles, with ramp rates of 10°C/minute and dwell/soak times of 10 minutes (JEDEC 22-104-D).

* JEDEC: Joint Electron Device Engineering Council

Approach: Experimental Testing

- Power Cycling
  - Interconnects will be subjected to a periodically applied operating bias while they experience high and low temperature extremes (JEDEC 22-A105-C).
  - This test simulates worst-case temperature conditions and will be conducted for 1,500 temperature cycles.

Temperature Extremes (°C)	Transition Time Between Temperature Extremes	Dwell Time at Each Temperature Extreme
-40 (+0, -10) to +125 (+10, -0)	30 minutes	10 minutes

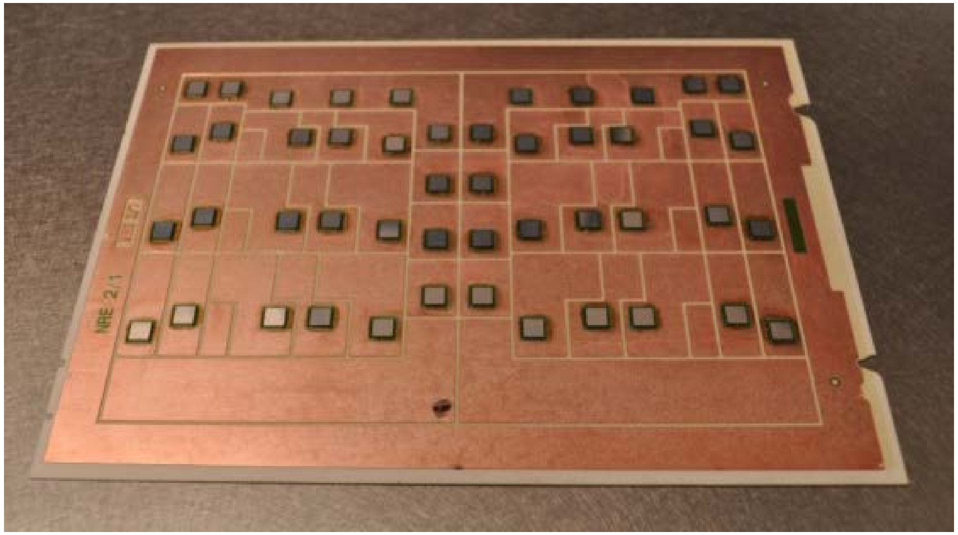


- Corrosion Testing
  - A high humidity environment will be used to test the corrosion resistance of the ribbons and bonds.
  - Humidity bias: Interconnects will be placed in an 85°C, 85% relative humidity environment for 1,000 hours. A DC bias will be applied (JEDEC 22-A101-C).
  - Unbiased accelerated moisture resistance: Samples will be subjected to 121°C, 100% relative humidity environment for 96 hours (JEDEC 22-A102-D).

Sample Preparation

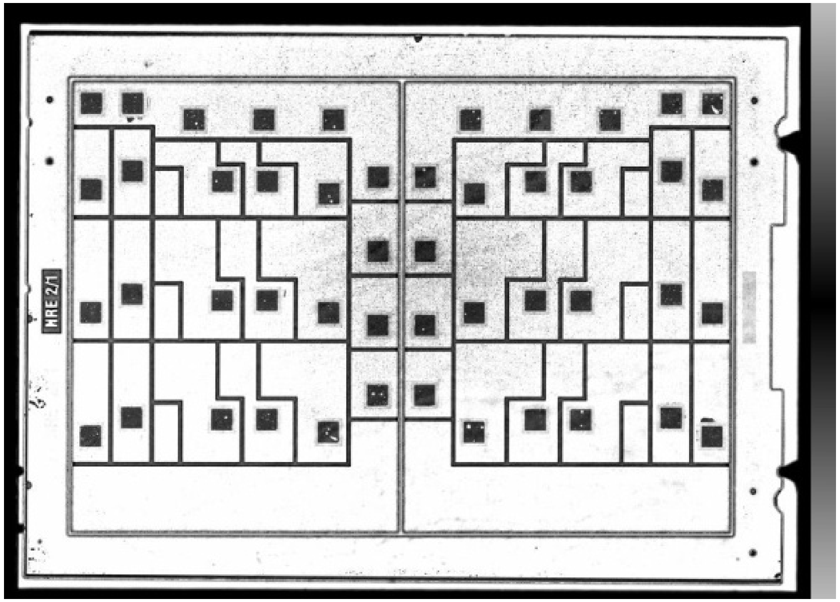
- Schottky diodes attached to sample substrates
  - 48 diodes soldered per board in 12 parallel electrical paths
- Solder bond quality inspected with C-mode scanning acoustic microscope (C-SAM)
- Mild HCl solution removed copper oxidation layer

Sample Substrate



Credit: Douglas DeVoto, NREL

C-SAM of Soldered Diodes



Ribbon Bonding

- Ribbon bonding conducted at Orthodyne Electronics
- 48 ribbons of various geometries attached to test substrates
- In addition to aluminum (Al) and copper clad aluminum (Cu/Al) ribbon bonding materials, Al wire bonding material is used as a baseline

<table>
<tr><th>Criterion</th><th colspan="7">Variation</th></tr>
<tr><td>Bonding Material</td><td colspan="2">Al ribbon</td><td colspan="3">Cu/Al ribbon</td><td colspan="2">Al wire</td></tr>
<tr><td>Cross Section (µm)</td><td>2,000 x 200 ribbon</td><td colspan="2">1,000 x 100 ribbon</td><td colspan="3">300⌀ wire</td><td>500⌀ wire</td></tr>
<tr><td>Ribbon Span (mm)</td><td colspan="3">10</td><td colspan="4">20</td></tr>
<tr><td>Number of Stitches</td><td colspan="3">Single</td><td colspan="4">Double</td></tr>
<tr><td>Ribbon Stacking</td><td colspan="3">Not Stacked</td><td colspan="4">Stacked</td></tr>
<tr><td>Bond Angle (°)</td><td colspan="2">0</td><td colspan="2">20</td><td colspan="3">40</td></tr>
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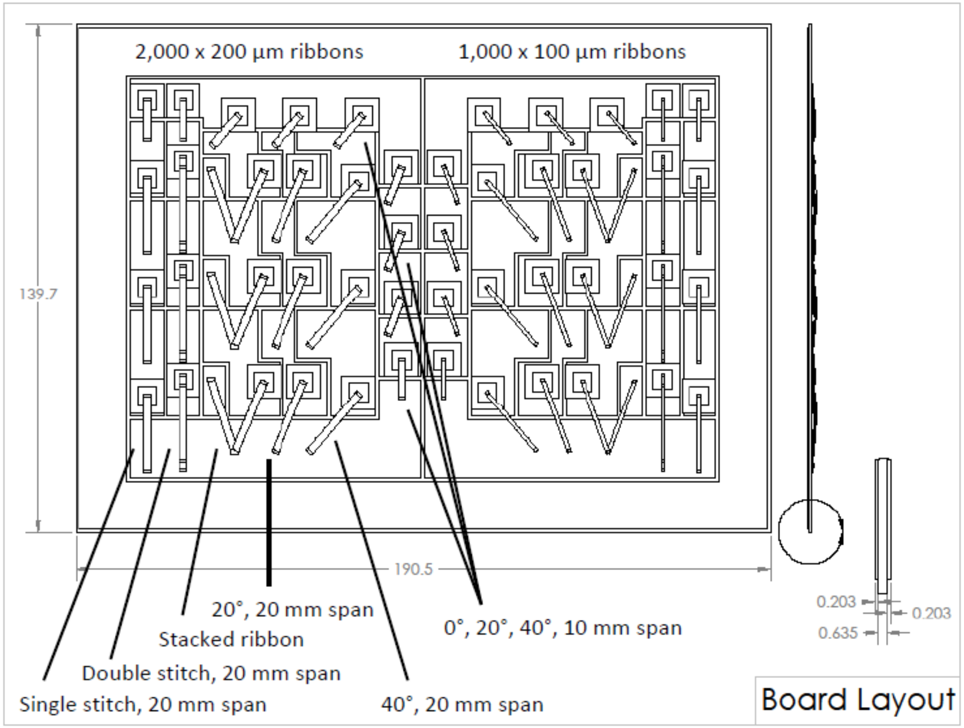
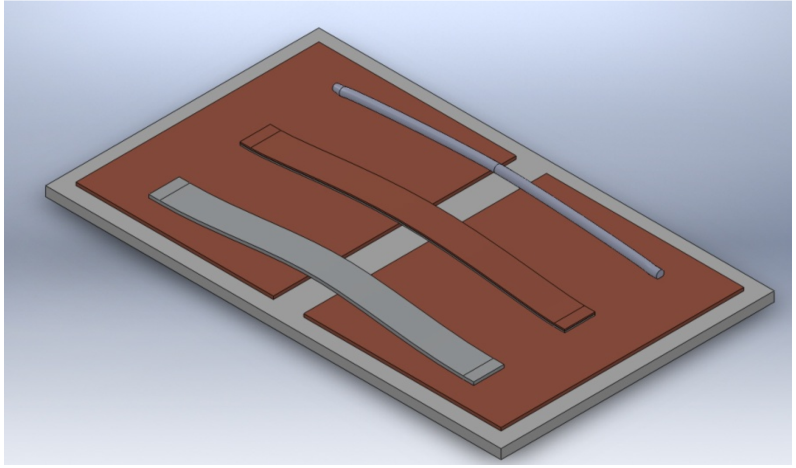


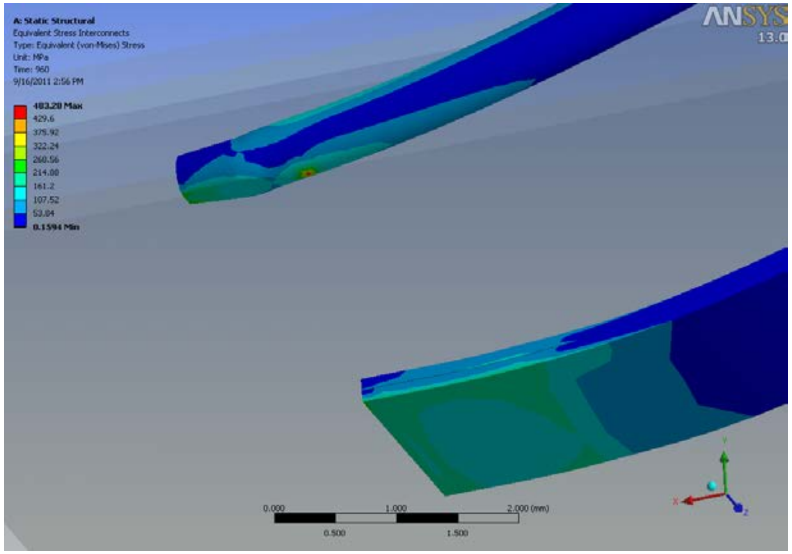
Board Layout

Flexure Fatigue Modeling

- The geometries of an Al wire bond, an Al ribbon bond, and a Cu/Al ribbon bond have been evaluated using the ANSYS finite element software package.
- Under the same loading conditions, the ribbon bonds exhibit less deflection than the wire bond.
- Stress concentrations present in the heel are lower in the ribbon geometries.
- Von Mises stress predictions in the heel location of interconnects are higher than the stress predicted by closed-form analytical models, resulting in a more conservative lifetime prediction.
- Models will be validated by experimental deflection measurements of bonds undergoing temperature cycling.

Wire and ribbon test geometry and equivalent von Mises stresses at bond heels





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 (FY12)

- Determine ribbon bond strength through pull and shear tests
- Complete thermal, power and environmental testing on ribbon bonds
- Report on mechanical reliability of ribbon bonds under testing and make recommendations to industry partners
- Update 2D wire bond models to be applicable for ribbon bonds

Proposed Future Work (FY13)

- 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

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**
  - Industry partners have been selected for collaboration on ribbon bonding interconnect technology.
  - Ribbon material and geometry have been selected for testing.
  - Test samples have been synthesized, and reliability testing has been initiated.

Summary

- **Collaborations**
  - Curamik, Materion Technical Materials, Orthodyne Electronics
- **Future Work**
  - Determine ribbon bond strength through pull and shear tests
  - Complete thermal, power and environmental testing on ribbon bonds
  - Report on mechanical reliability of ribbon bonds under testing and make recommendations to industry partners
  - Update 2D wire bond models to be applicable for ribbon bonds
  - 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

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