NREL
Transforming ENERGY

Advanced Power Electronics Designs – Reliability and Prognostics
(Keystone Project 1)

PI: Douglas DeVoto
National Renewable Energy Laboratory
June 25, 2021

DOE Vehicle Technologies Program
2021 Annual Merit Review and Peer Evaluation Meeting

ELT218

Overview

Timeline

- Project start date: FY 2019
- Project end date: FY 2023
- Percent complete: 50%

Barriers

- Barriers addressed
  - Cost
  - Performance
  - Reliability and lifetime

Budget

- Total project funding: $525K
  - DOE share: $525K
- Funding for FY 2020: $175K
- Funding for FY 2021: $175K

Partners

- Interactions/collaborations
  - Oak Ridge National Laboratory (ORNL)
  - Indiana Integrated Circuits (IIC)
  - DuPont
- Project lead
  - National Renewable Energy Laboratory (NREL)

Relevance

- Wide bandgap (WBG) packaging designs must thermally allow for:
  - Higher operating temperatures
  - Higher heat fluxes/power densities
  - Hot spots
- Coefficient of thermal expansion (CTE) mismatch between layers of the module will impose stresses that can initiate and propagate defects:
  - Attach layer fatigue
  - Interconnect fatigue
- **New package designs must address thermal and reliability concerns and be evaluated under accelerated conditions that approximate real-world conditions.**

Milestones

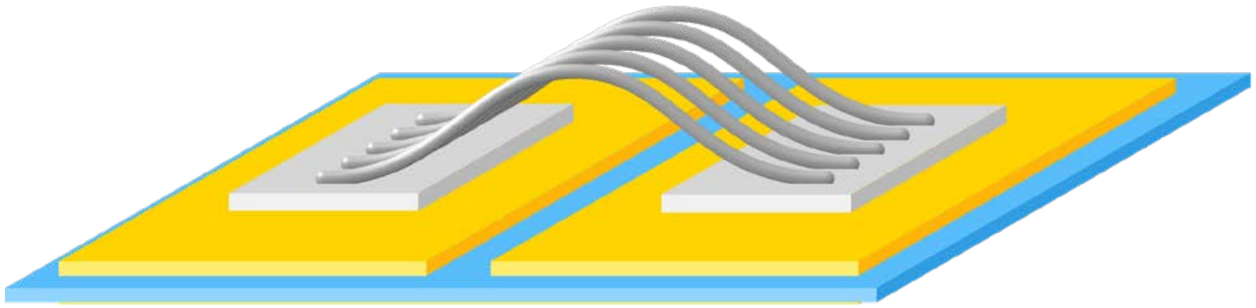
Date/Status	Description
December 2020 *(complete)*	Milestone • Develop thermomechanical model of quilt packaging (QP) geometry to quantify the impact of nodule shapes and sizes under vibration conditions
March 2021 *(complete)*	Go/No-Go • Revise design of quilt-packaged devices with IIC
September 2021 *(in progress)*	Milestone • Characterize devices/packages under thermal aging, thermal cycling, and vibration conditions and monitor component health through electrical precursor measurements
September 2021 *(in progress)*	Milestone • Prepare report on research results

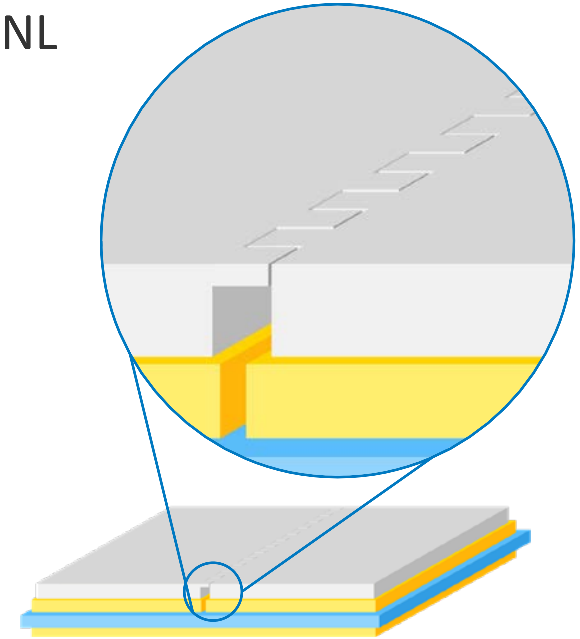
Approach

- **New package designs must address thermal and reliability concerns and be evaluated under accelerated conditions that approximate real-world conditions**
- NREL is closely working with ORNL and industry partners to evaluate new packaging materials and manufacturing techniques for WBG-based traction inverters
  - IIC: QP via a chip-to-chip edge interconnect technology
  - DuPont: ODBC substrate as a replacement of ceramic substrates.

Approach

- Alternative interconnect designs are required as devices are reduced in size and spacing between devices is minimized
- **Traditional wire interconnects or etched substrates for topside electrical connections will be replaced with direct chip-to-chip connection**
- Devices are joined with quilt packaging, eliminating the need for wire bonds or other external electrical connection technology
  - Experimental samples have been designed in collaboration with IIC and ORNL
  - Reliability evaluation was completed at NREL

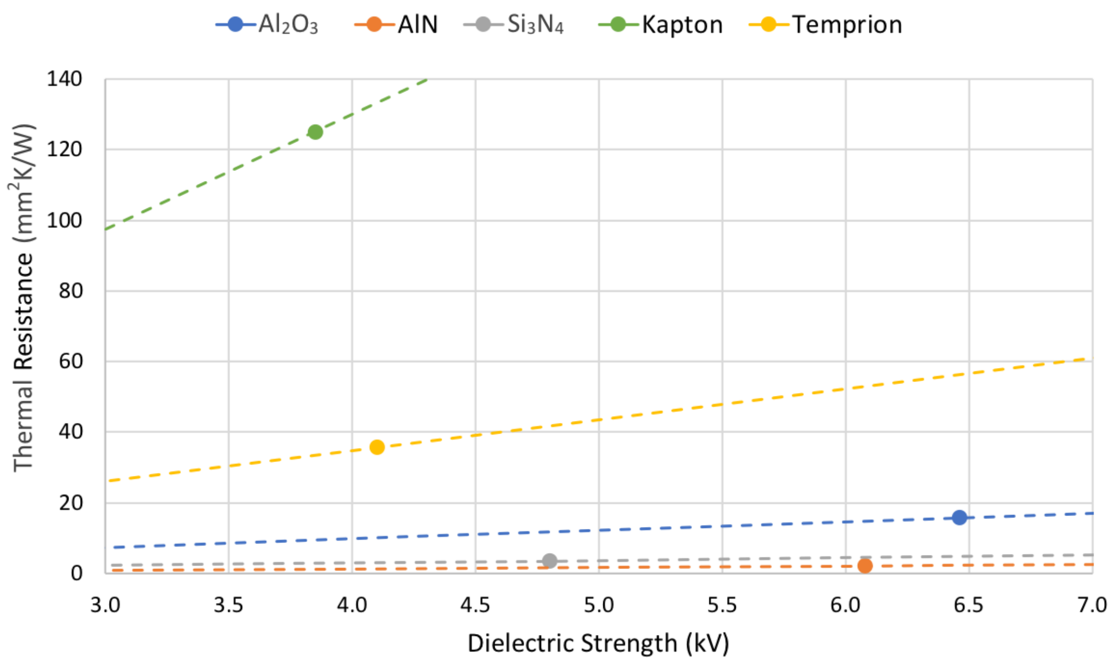




Approach

- **Alternative electrically insulated substrate designs are required to enable reliable packages that operate with higher power densities and higher temperatures**
- Traditional substrate technologies
  - Direct-bond copper (DBC)
    - Oxidation of copper (Cu) foils during bonding lowers melt temperature from 1,083 °C to 1,065 °C
    - Maximum metallization thickness of 1 mm
    - Must have metallization layers on both sides of the ceramic
    - Examples include aluminum oxide (Al_2O_3), aluminum nitride (AlN), and zirconia (ZrO_2)-doped high-performance substrates (HPS)
  - Active metal bonding (AMB)
    - Brazing process with silver-copper (Ag-Cu) alloy between Cu and ceramic at 850°C in vacuum
    - Requires more processing steps and is more expensive than DBC
    - Silicon nitride (Si_3N_4) substrate is an example
- ODBC
  - A polyimide dielectric is bonded with metal through elevated temperature and pressure
  - No limitations in metal material or metallization thickness.

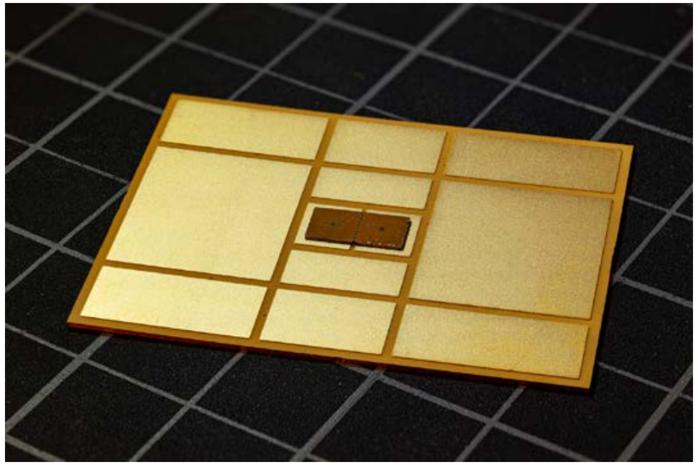
Approach



Insulator	Thickness (µm)	Dielectric Strength (kV/mm)	Dielectric Strength (kV)	Thermal Conductivity (W/[m·K])	Thermal Resistance (mm^2K/W)
Al_2O_3	380	17	6.5	24	16
AlN	380	16	6.1	180	2
Si_3N_4	320	15	4.8	90	4
Kapton	25	154	3.9	0.2	125
Temprion	25	164	4.1	0.7	36

Technical Accomplishments and Progress

- Completed reliability analysis of quilt package devices mounted onto ODBC substrates
- Samples were characterized under accelerated thermal and vibration conditions
  - Sinusoidal Vibration: 20 to 1,000-Hz sweep, 5-g acceleration, 2-hours duration (IEC 60068-2-6)
  - Mechanical Shock: half-sine pulse, 30-g acceleration, 18-ms duration, repeating 3 times (IEC 60068-2-27)
  - Thermal Cycling: −40 °C to 150 °C, 10 °C/min ramp rate, 15-min soak, 1,000 cycles (JESD22-A104D).



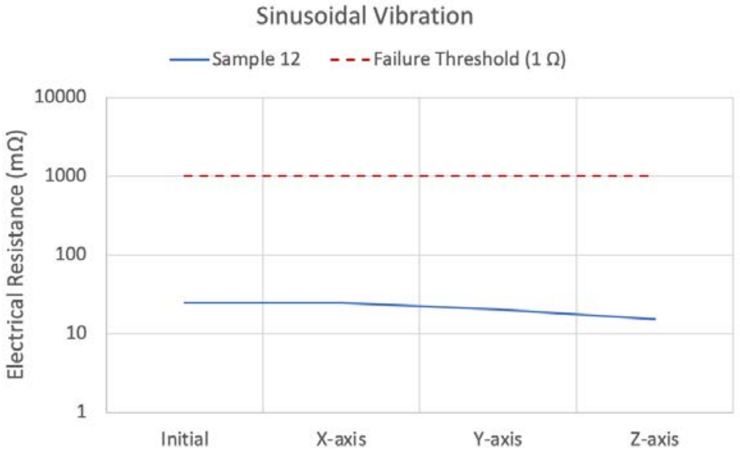
IIC Package on Dupont ODBC Substrate

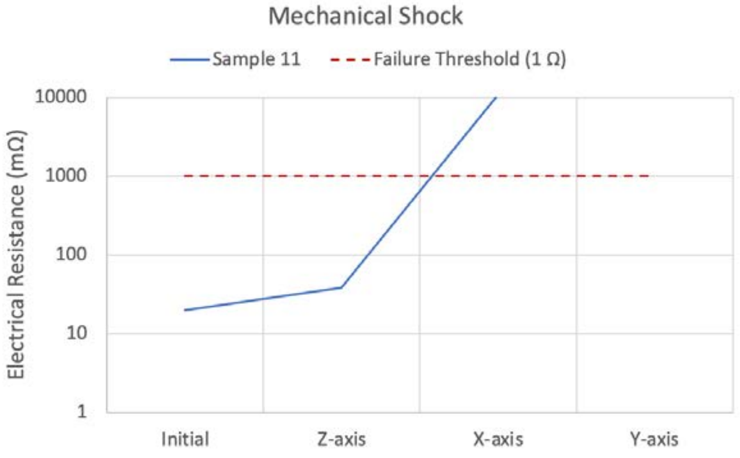
Technical Accomplishments and Progress

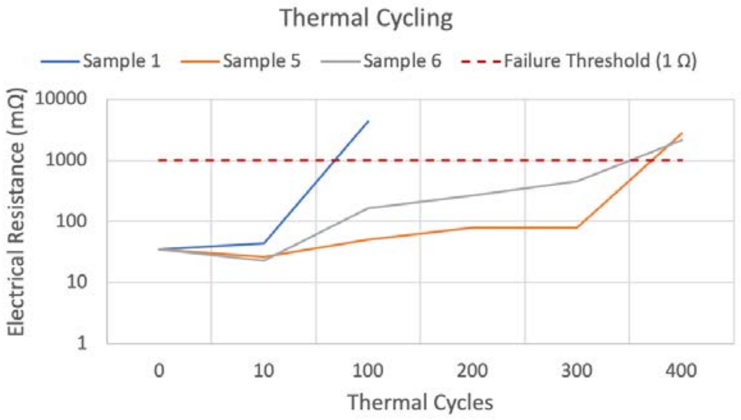
- Electrical resistance measurements increased significantly for all samples that were subjected to mechanical shock and thermal cycling tests.

Quilt Packaging Accelerated Testing Summary

Sample	Nodule Shape	Nodule Length (µm)	Nodule Width (µm)	Accelerated Test	Testing Pass/Fail
1	Triangle	30	100	Thermal Cycling	100 Cycles
5	Triangle	70	300	Thermal Cycling	400 Cycles
6	Rectangle	30	100	Thermal Cycling	400 Cycles
8	Triangle	30	300	Initial Failure	NA
11	Rectangle	70	100	Mechanical Shock	Z + X Axes
12	Rectangle	30	100	Sinusoidal Vibration	Pass



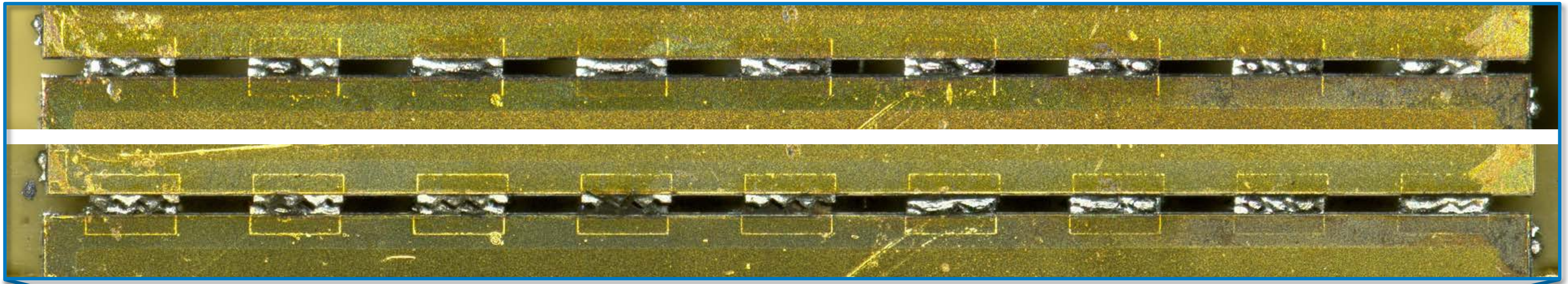




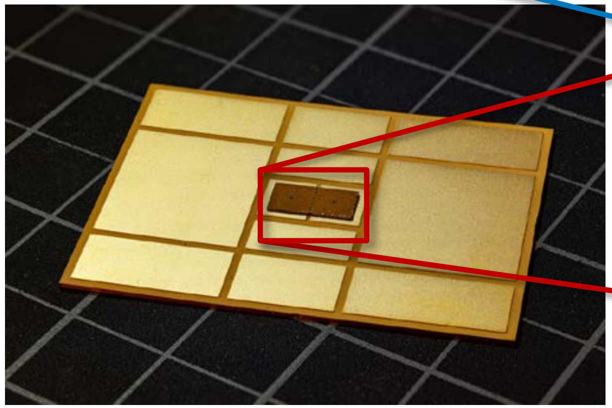
Nodule Electrical Resistance

Technical Accomplishments and Progress

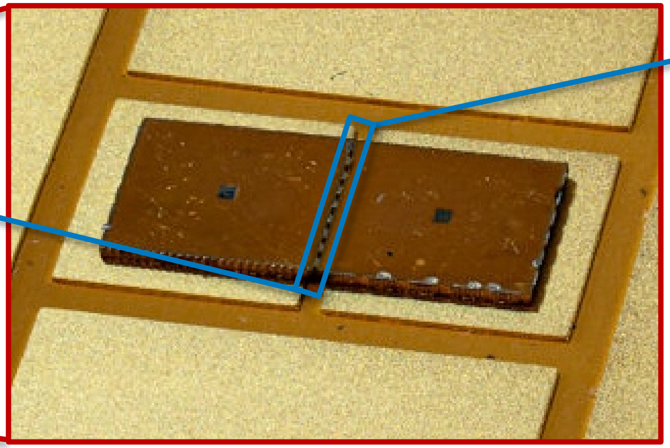
- Microscope images confirmed cracking within the QP structure.



Sample 5 at 0 Cycles (above) and after 400 Thermal Cycles (below)



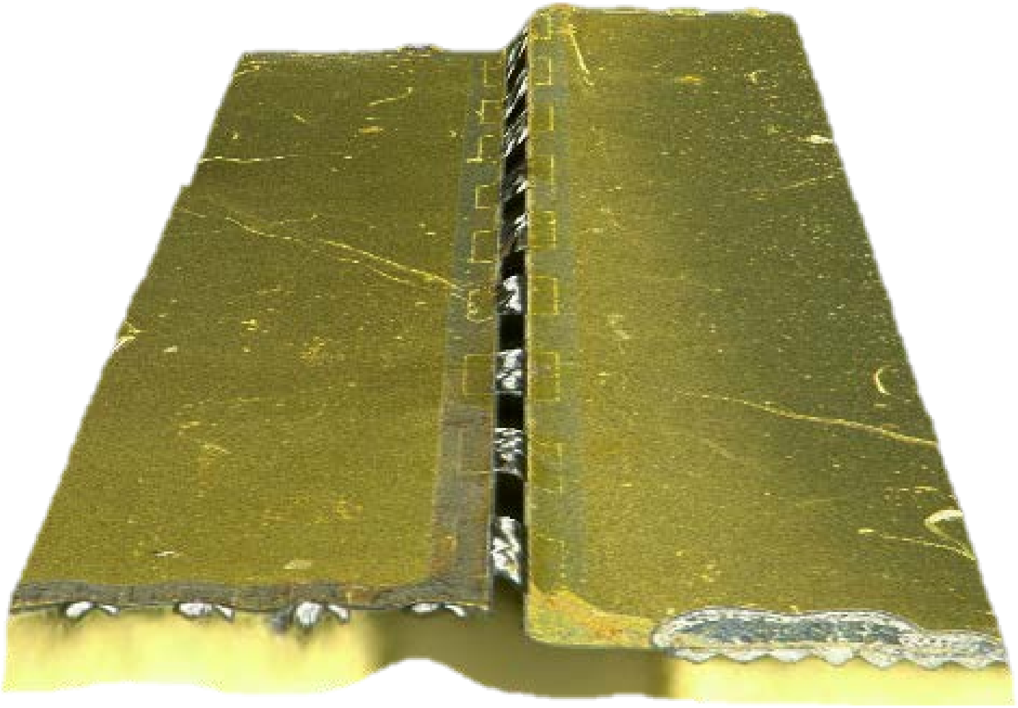
IIC Package on Dupont ODBC Substrate



IIC Package

Technical Accomplishments and Progress

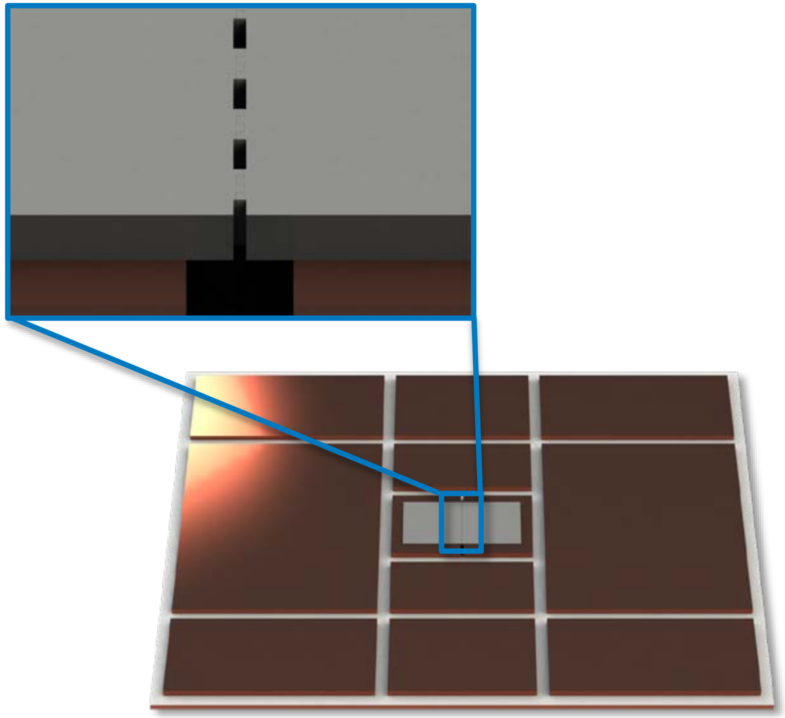
- Microscope images confirmed cracking within the QP structure
- Cracking was initiated by a torsional stress caused by the tilting of one of the dies due to weak die-attach.



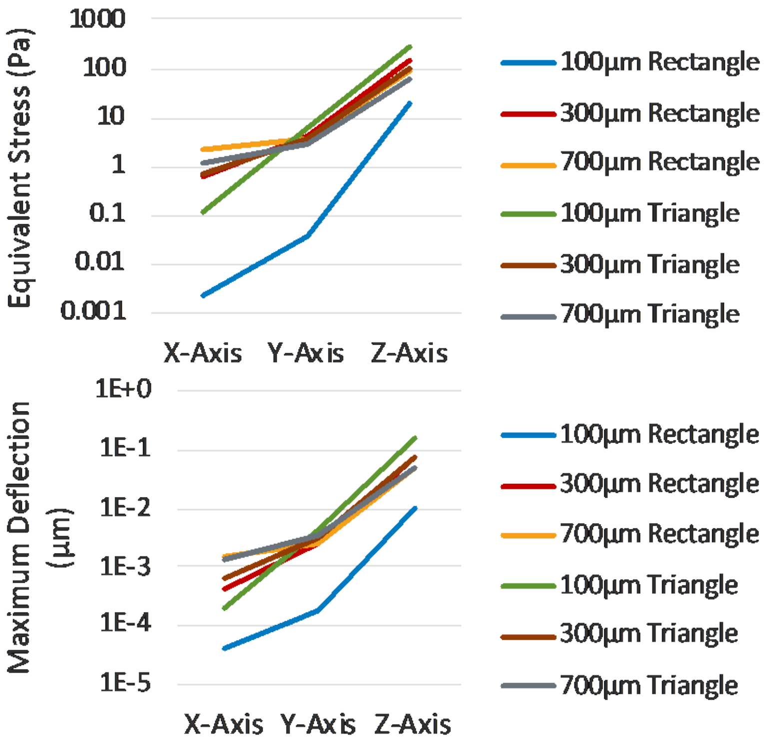
Sample 5 after 400 Thermal Cycles

Technical Accomplishments and Progress

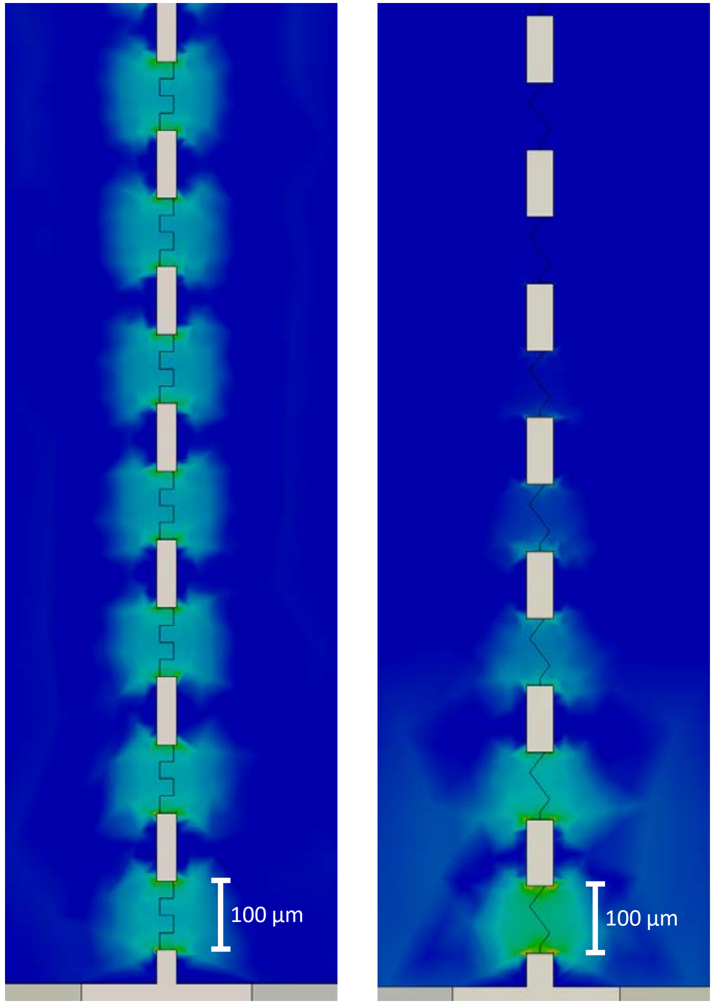
- Developed thermomechanical model of QP geometry to quantify the impact of nodule shapes and sizes under vibration conditions; 100µm rectangle geometry had the lowest deflection and equivalent stress values.



Model Package Geometry



Equivalent Stress (top) and Maximum Deflection (bottom) under Vibration Conditions



Stress Concentrations for 100µm Rectangle (left) and Triangle (right) Geometries

Responses to Previous Year Reviewers' Comments

The work is focusing on critical issues and new technologies that are needed. The reviewer would like to have seen this project take a broader look at interconnects, insulators, and conductors for power electronics.

As this project develops, the PI hopes to collaborate with additional companies that address other power electronics components.

The reviewer would like to see more involvement with vehicle OEMs.

IIC, DuPont, and this project's PI have presented to the US DRIVE Electrical and Electronics Team (EETT) on these technologies, but additional interactions would be beneficial.

Sending out developed packages to industry with request to test these packages for a targeted application could accelerate commercialization of underlining technology.

The reviewer raises a good idea. Transitioning these packaging concepts to industry for commercialization is a critical goal. Sharing a development platform would enable a more rapid transfer of lessons learned to industry partners.

**Any proposed future work is subject to change based on funding levels.*

Collaboration and Coordination

- ORNL
  - Laboratory partner for design and assembly of power electronics modules
- IIC
  - Industry partner for quilt packaging technology
- DuPont
  - Industry partner for ODBC technology.

Remaining Challenges and Barriers

- Thermal and reliability concerns of new electrical connect technology must be experimentally evaluated
  - Thermal modeling has been completed to determine impact of positioning devices more closely to each other
  - Experimental characterization will be performed to evaluate nodule reliability under power, thermal, and vibration conditions
- New substrate technologies may be susceptible to unforeseen failure mechanisms
  - Past reliability evaluation of ODBC substrates has been promising, but full module assembly and evaluation in collaboration with ORNL is needed.

Proposed Future Research

- FY 2021
  - Evaluate second round of devices/packages under thermal and vibration conditions
  - Attach devices to thick-metallization ODBC substrates and thermally cycle samples to evaluate device-attach reliability
- FY 2022
  - Evaluate thermal and reliability performance of assembled half-bridge module in collaboration with ORNL, IIC, and DuPont.

**Any proposed future work is subject to change based on funding levels.*

Summary

Relevance

- New package designs must address thermal and reliability concerns and be evaluated under accelerated conditions that approximate real-world conditions

Approach

- Collaborate with ORNL and industry partners to evaluate new packaging materials and manufacturing techniques for WBG-based traction inverters

Technical Accomplishments

- Completed accelerated testing of devices connected by quilt packaging and mounted to ODBC substrates
- Completed thermomechanical modeling of devices connected by quilt packaging and mounted to ODBC substrates

Collaborations

- ORNL
- IIC
- DuPont.

Acknowledgments

Susan Rogers, U.S. Department of Energy

NREL EDT Task Leader

Sreekant Narumanchi
Sreekant.Narumanchi@nrel.gov
Phone: (303)-275-4062

Team Members

NREL: Joshua Major, Paul Paret
ORNL: Emre Gurpinar
IIC: Jason Kulick, Jackson Lu, Edit Varga
DuPont: Tim Scott, Rajesh Tripathi
Flex Power Control: Greg Smith

For more information, contact

Principal Investigator:
Douglas DeVoto
douglas.devoto@nrel.gov
Phone: (303)-275-4256

Thank You

www.nrel.gov

NREL/PR-5400-79924

This work was authored, in part, by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Vehicle Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government.

NREL Transforming ENERGY

Reviewer-Only Slides

Publications and Presentations

Publications

- DeVoto, D. 2019. "Advanced Power Electronics Designs – Reliability and Prognostics." 2020 DOE VTO Annual Report.

Presentations

- DeVoto, D. 2020. "Advanced Power Electronics Designs, Power Electronics Material and Bonded Interfaces." Presented to the DOE VTO Electrical and Electronics Technical Team, March 2021.

Records of Invention/Patents

- DeVoto, D.; Major, J.; Bennion, K.; Narumanchi, S.; Paret, P.; Moreno, G.; and Cousineau, E. 2019. "Electronics Packaging using Organic Electrically Insulating Layers." ROI 19-15, Non-Provisional Patent Application Numbers PCT/US19/65147 and 16/707,179, filed on December 9, 2019.

Critical Assumptions and Issues

- Working with private industry involves protection of their intellectual property and limits public disclosure of traction inverter designs
  - Industry partners have presented directly to the U.S. Driving Research and Innovation for Vehicle efficiency and Energy sustainability (DRIVE) Electrical & Electronics Tech Team (EETT) and could be contacted for questions and additional information
- The increase in power density from proposed packaging designs may require more aggressive cooling techniques
  - Accurate thermal modeling and experimental testing of proposed designs will enable an informed selection of appropriate cooling techniques that balance cooling performance with cost, volume/weight, and reliability targets.