NREL
Transforming ENERGY

Advanced Power Electronics Designs – Reliability and Prognostics

Keystone Project 1

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OVERVIEW

Timeline

- Project start date: FY19
- Project end date: FY21
- Percent complete: 15%

Budget

- Total project funding: $175K
- U.S. Department of Energy (DOE) share: $175K
- Funding for FY19: $175K (new start)

Barriers Addressed

- Cost
- Performance
- Reliability and lifetime

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

SUMMARY

Approach

- Collaborate with ORNL and industry partners to evaluate new packaging materials and manufacturing techniques for WBG based traction inverters
- Continue to develop a remaining useful lifetime (RUL) tool that uses drive cycle input data for fatigue models for existing and future packaging designs

Technical Accomplishments

- Completed design of devices connected by quilt packaging
- Completed thermal and reliability evaluation of organic direct-bond-copper (ODBC) substrates
- Demonstrated RUL tool

Collaborations

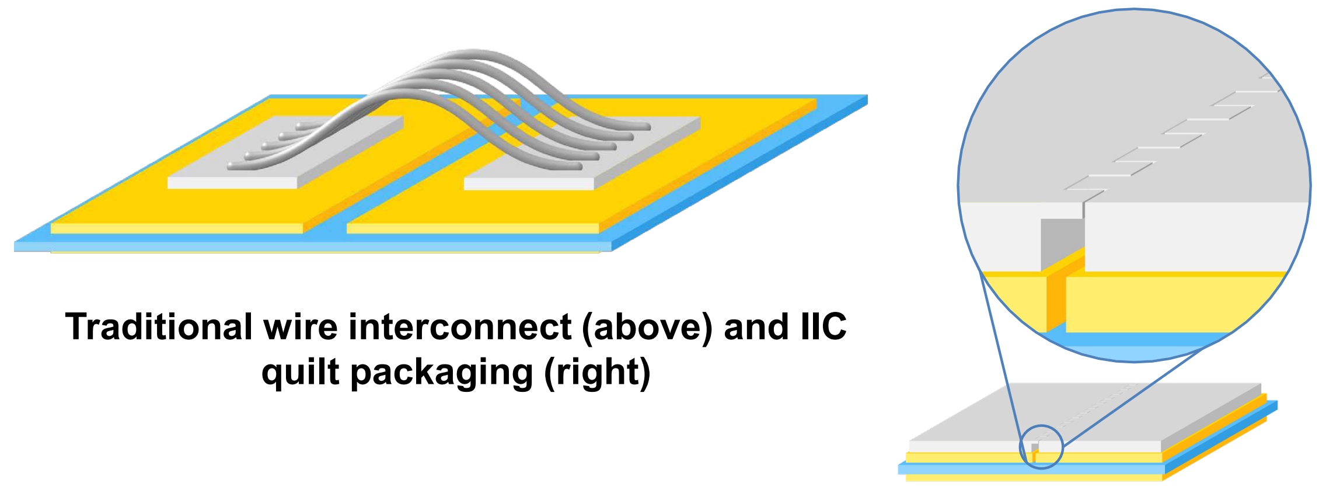
- Oak Ridge National Laboratory (ORNL)
- Indiana Integrated Circuits (IIC)
- DuPont

APPROACH

NREL is closely working with ORNL and industry partners to evaluate new packaging materials and manufacturing techniques for wide-bandgap (WBG)-based traction inverters

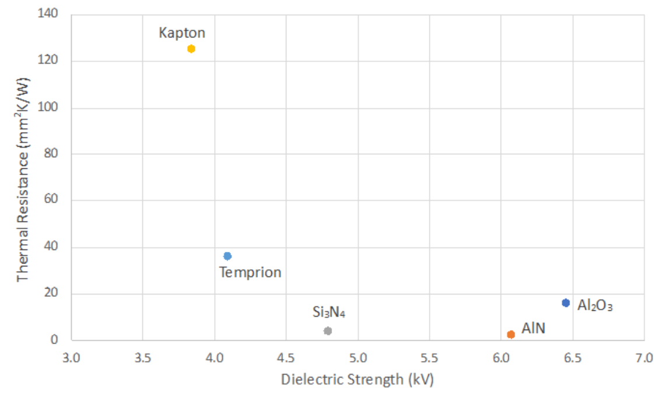
IIC: Quilt Packaging

- 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 edge interconnect technology
- 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 will be completed at NREL


Traditional wire interconnect (above) and IIC quilt packaging (right)

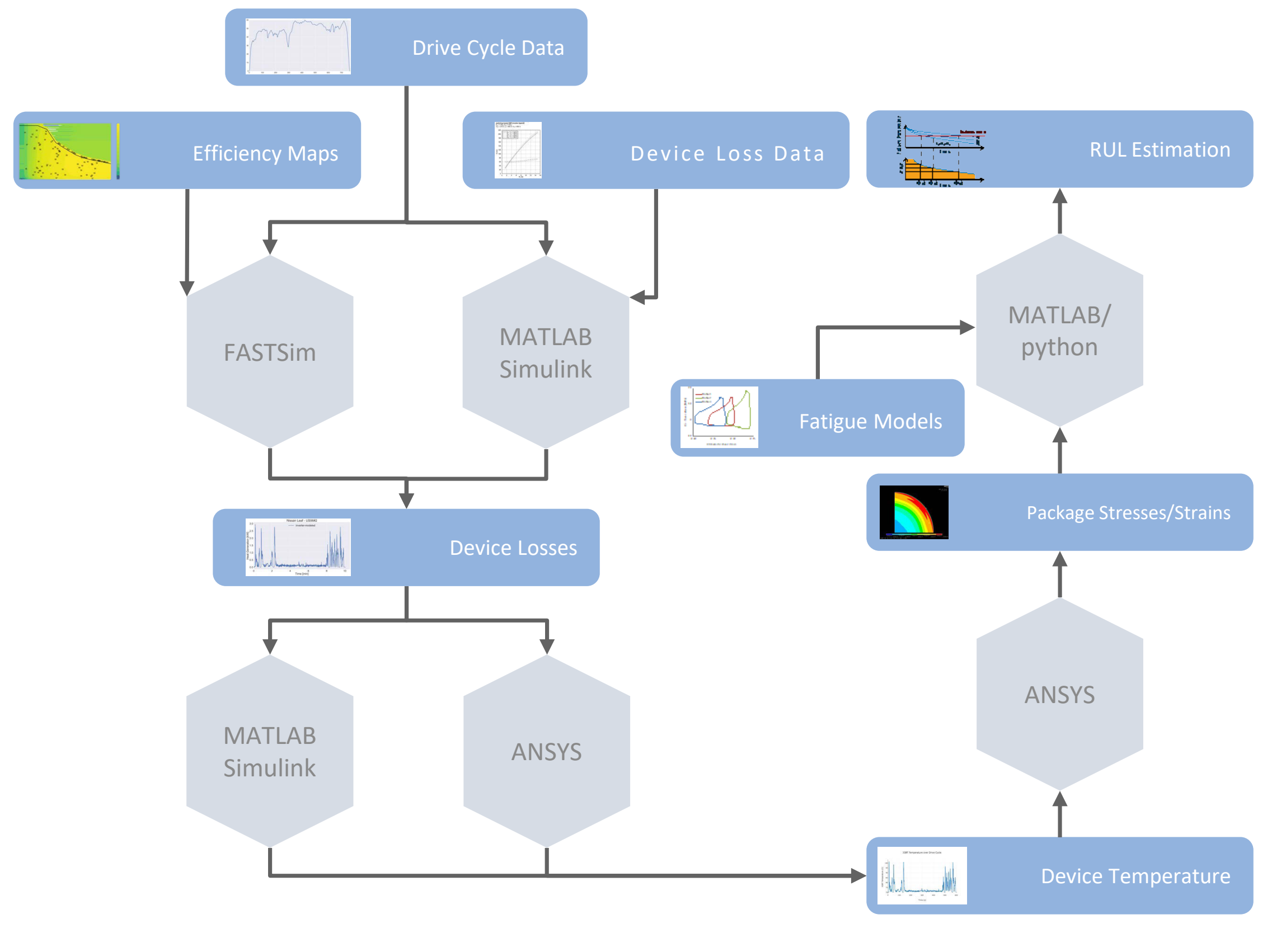
DuPont: ODBC Substrate

- 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



Prognostics

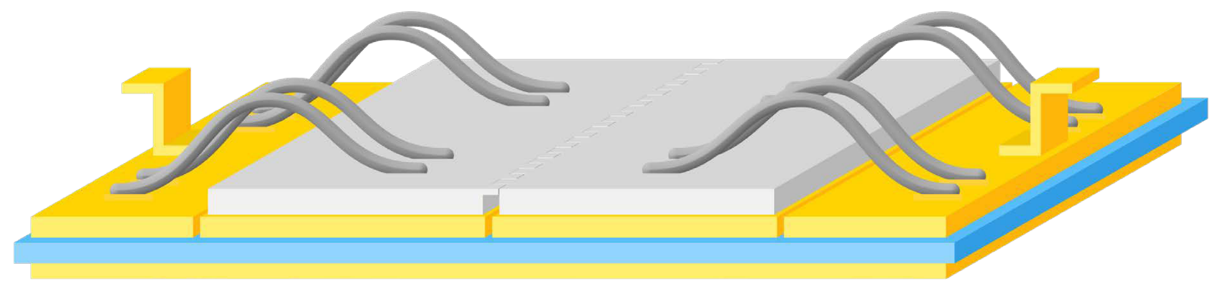
A RUL tool that uses drive cycle input data for fatigue models will evaluate failure mechanisms for existing and future packaging designs



ACCOMPLISHMENTS AND PROGRESS

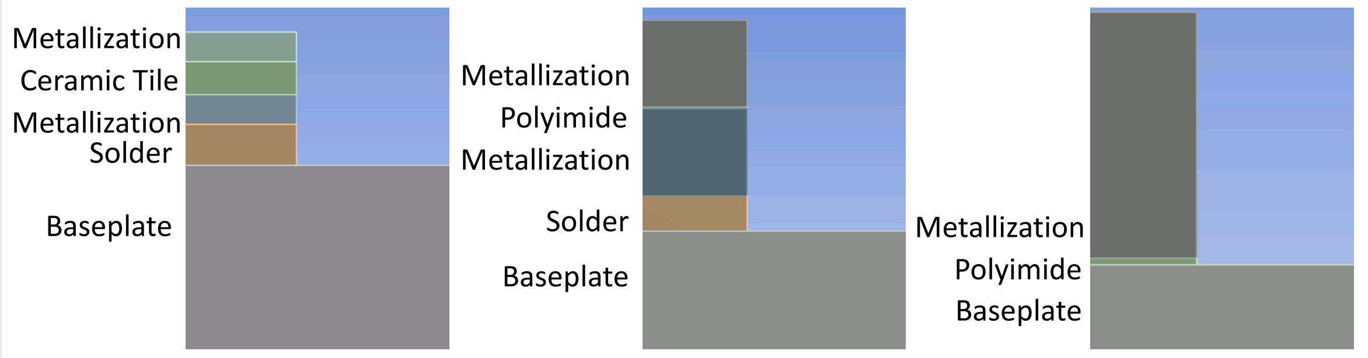
IIC: Quilt Packaging

- In collaboration with ORNL and IIC, initial device geometry has been designed
- Devices will be mounted to substrates, and reliability of connections will be evaluated


IIC test sample design with quilt packaging

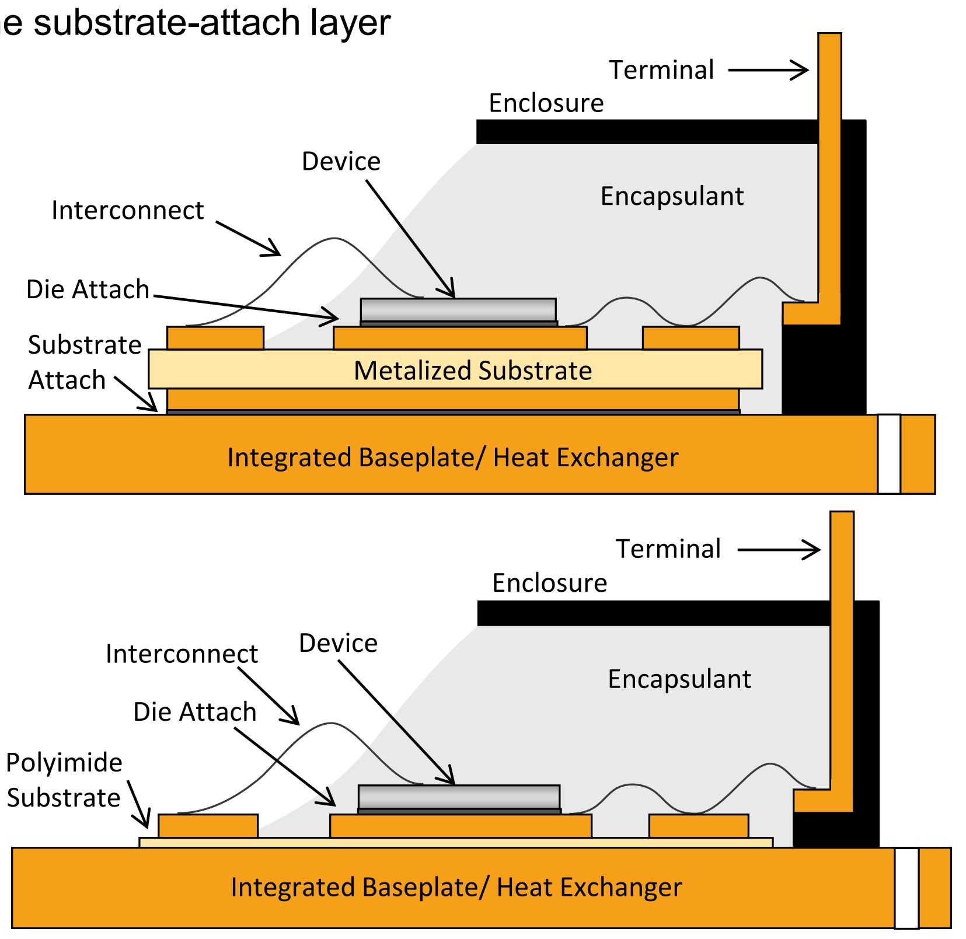
DuPont: ODBC Substrate

- Thermal impact of alternative DuPont ODBC substrate designs has been modeled



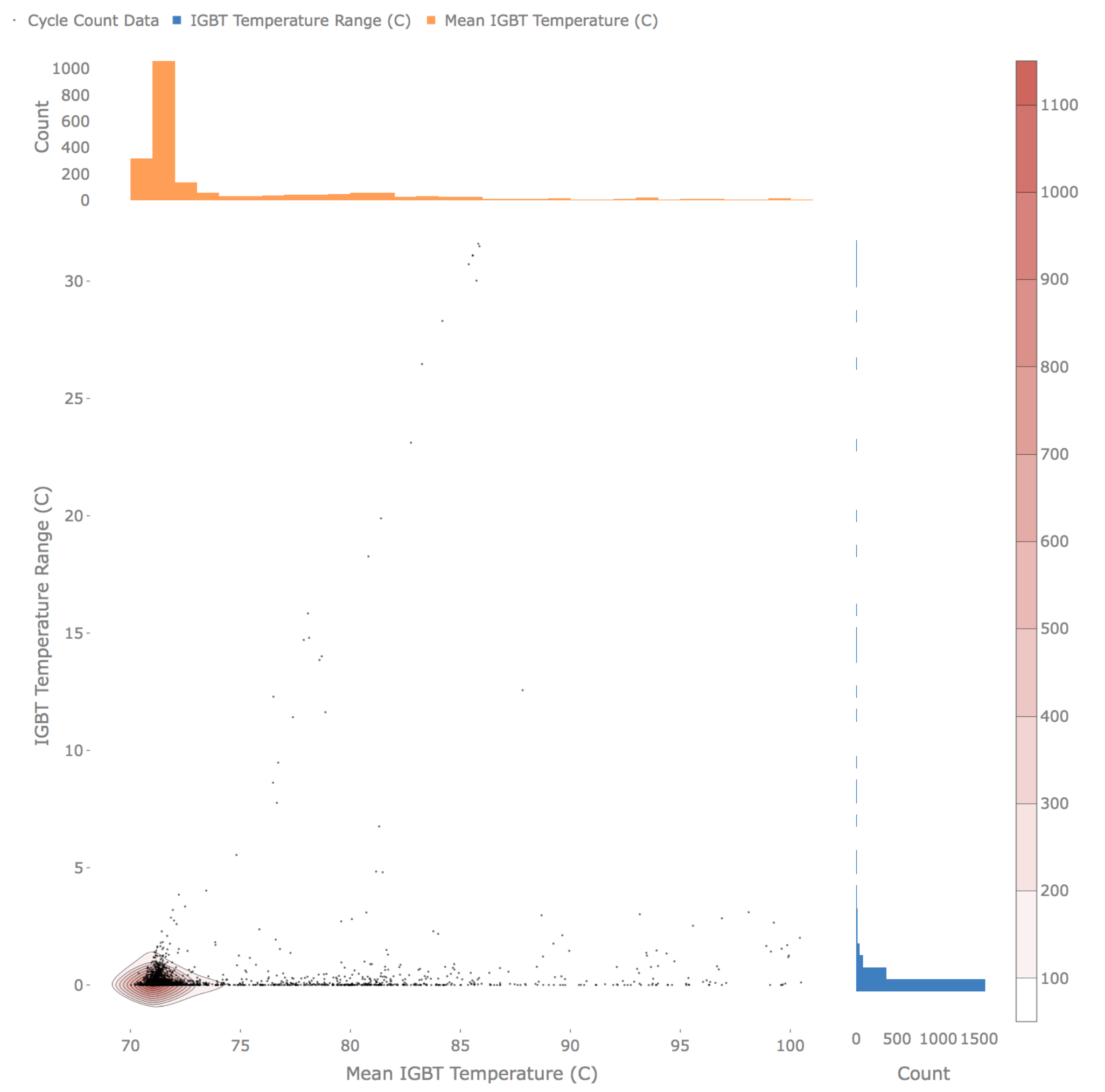
Industry Standard
ODBC Substrate
ODBC Simplified Substrate

- No significant decrease in electrical or thermal performance has been observed
  - Thermal Shock: -40°C to 200°C, 5-minute dwells
  - Thermal Aging: 175°C
  - Power Cycling: 40°C to 200°C
  - ODBC substrates have reached 5,000 thermal shock cycles, 1,900 thermal aging hours, and 2,200 power cycles
- Integration of ODBC substrate into a power module can enable thicker metallization layers or the elimination of the bottom metallization layer and the substrate-attach layer



Prognostics

Device mean temperature and cyclical temperature range data can be calculated from drive cycle data and efficiency maps and inputted into fatigue models

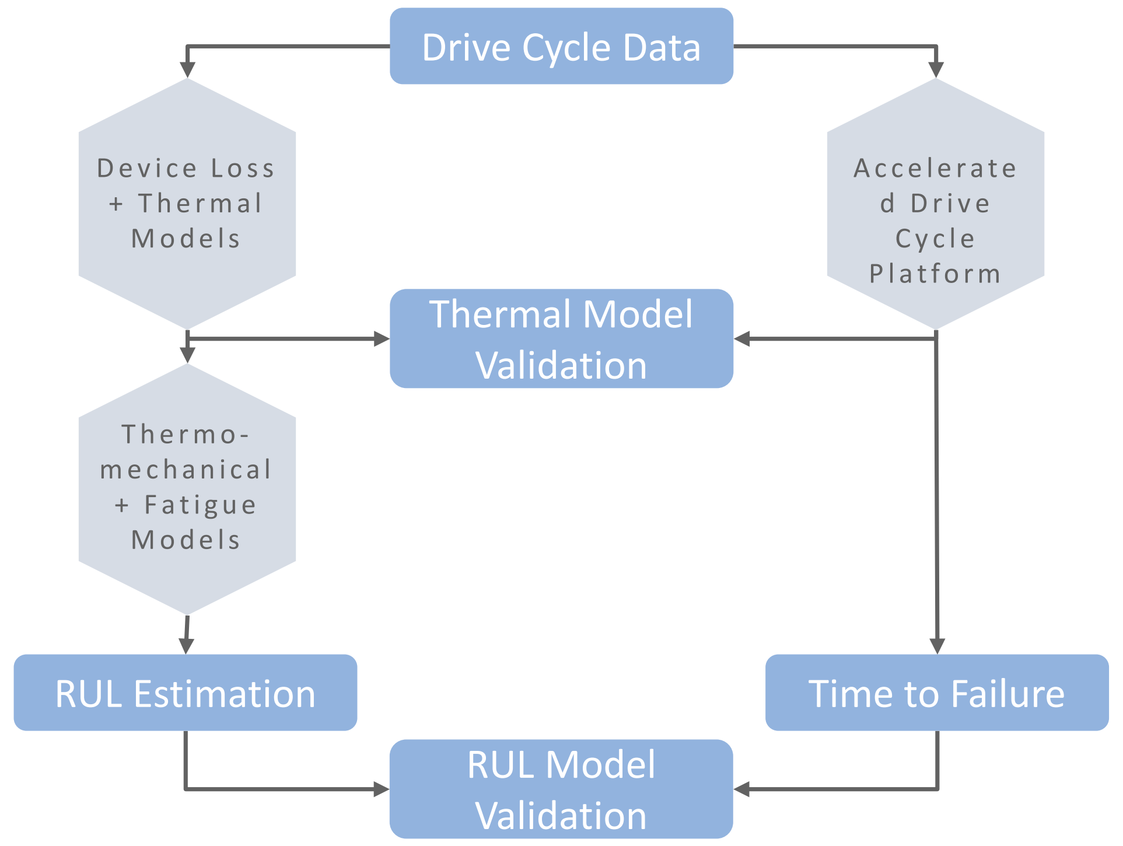


CHALLENGES AND BARRIERS

- Thermal and reliability concerns of new electrical connect technology must be experimentally evaluated
  - Thermal modeling will determine impact of positioning devices more closely to each other
- Experimental characterization will evaluate nodule reliability under power and thermal cycling
- 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
- RUL estimation accuracy is dependent on quality of drive cycle input data and validation
  - NREL is working closely with several industry partners to utilize quality drive cycle data

PROPOSED FUTURE RESEARCH

- FY19
  - Complete thermal modeling of packages integrating devices with quilt packaging technology and ODBC substrates
  - Evaluate quilt packaging reliability under power and thermal cycling
- FY20
  - Evaluate thermal and reliability performance of assembled half bridge module in collaboration with ORNL, IIC, and DuPont
  - Validate RUL tool with experimental results from Accelerated Drive Cycle Platform



COLLABORATION AND COORDINATION

ORNL

(Emre Gurpinar) Laboratory partner for design and assembly of power electronics modules

IIC

(Jason Kulick, Jackson Lu, Edit Varga) Industry partner for quilt packaging

DUPONT

(Gregory Blackman, Rajesh Tripathi, Claire Wemp) Industry partner for ODBC technology

Flex Power Control

(Greg Smith) Partner for industry coordination of next generation power module designs

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