Power Electronics Materials and Bonded Interfaces – Reliability and Lifetime

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FY19–FY24; Year 4 of 6
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OVERVIEW

- Project start: October 2018
- Project end: September 2024 (70% completion)
- Total project funding (to date): $700,000; DOE share: $700,000; funding for FY21: $175,000; funding for FY22: $175,000
- Technical barriers addressed: cost, size and weight, performance, reliability and lifetime.

RELEVANCE

- Wide-bandgap devices such as silicon carbide and gallium nitride enable low-cost, lightweight, and power-dense automotive power electronics; however, these technologies are currently limited by power electronics packaging.
- It is critical that the packaging design and materials withstand the high-temperature operational environment introduced by the wide-bandgap devices; bonded interfaces must be reliable under extreme thermal stress conditions.
- The main objective of this project is to evaluate the reliability and study the failure mechanisms of bonded interface materials for high-temperature power electronics applications.

COLLABORATIONS

- Virginia Tech: technical partner on the synthesis of sintered silver bonds.
- Georgia Tech: technical partner on the synthesis of Cu-Al bonds.
- Oak Ridge National Laboratory, Ames Laboratory, and Sandia National Laboratories: technical guidance and discussion.

SUMMARY

- Formulated a lifetime prediction model of sintered silver by correlating experimental crack growth data with strain energy density outputs from modeling.
- Conducted the reliability evaluation of Cu-Al samples under a thermal cycling profile of −40°C to 200°C; initial bond quality needs to be improved.
- Initiated a time-series analysis on C-SAM images under thermal cycling to develop an image-based lifetime prediction model.
- Next steps include thermal cycling of polymeric bonded interfaces and investigating machine-learning techniques for time-series forecasting.

ACKNOWLEDGMENTS

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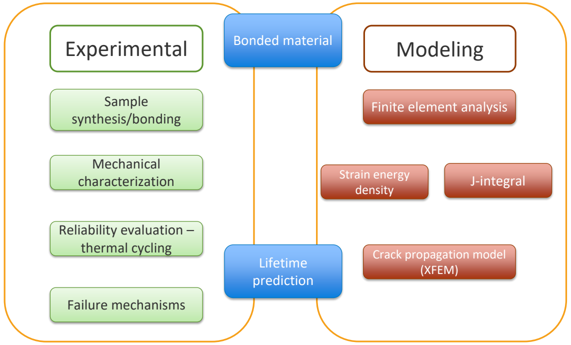
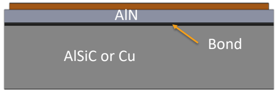
APPROACH



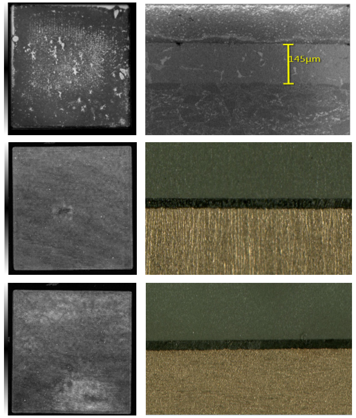
Experimental
Sample synthesis/bonding
Mechanical characterization
Reliability evaluation – thermal cycling
Failure mechanisms
Bonded material
Lifetime prediction
Modeling
Finite element analysis
Strain energy density
J-integral
Crack propagation model (XFEM)

Al: aluminum, AlN: aluminum nitride, AlSiC: aluminum silicon-carbide, C-SAM: C-mode scanning acoustic microscope, Cu: copper, SEM: scanning electron microscope

Sample configuration



- Materials considered in this project are sintered silver, Cu–Al transient liquid-phase alloy, and polymeric interfaces.
- These materials are bonded in a sample configuration and subjected to −40°C to 200°C thermal cycling profile.
- The thermomechanical degradation behavior of materials will be monitored at periodic cyclic intervals through C-SAM imaging and thermal resistance measurements.
- After thermal cycling, samples will be cross-sectioned to study the failure mechanisms, and lifetime prediction models will be developed.

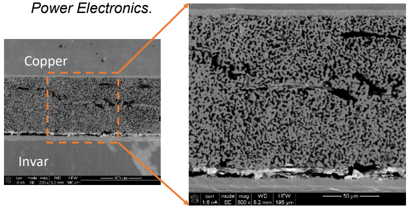


C-SAM images (left) and cross-sectional images (right) of Cu-Al bond (top), HM-3 (center), and HM-4 (bottom) polymeric material bonds.

ACCOMPLISHMENTS AND PROGRESS

Sintered Silver

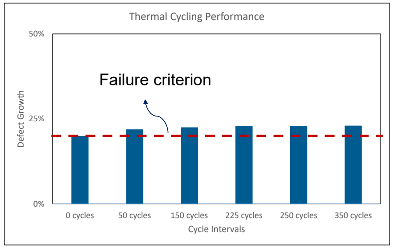
- Developed a lifetime prediction model of sintered silver incorporating its thermomechanical behavior at 200°C.
- Cross-sectioned and obtained SEM images of sintered silver samples to reveal the failure mechanisms under thermal cycling.
- Published a journal paper - describing the synthesis process, reliability experiments, thermomechanical modeling, and lifetime prediction model of sintered silver - in the *IEEE Journal of Emerging and Selected Topics in Power Electronics*.



SEM image of sintered silver

Transient Liquid-Phase Alloy

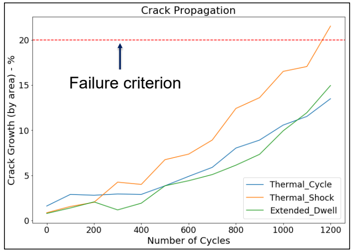
- Thermal cycling of Cu-Al alloy samples have completed 350 cycles under −40°C to 200°C.
- Initial void fraction of these samples is around 20%; synthesis process needs to be changed to achieve <5% void fraction.
- Thermal resistance measurements exhibited a significant variance; the trend does not match with the defect growth analysis.



Defect growth of Cu-Al alloys under thermal cycling

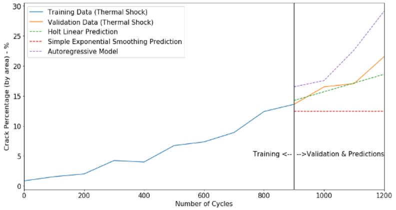
Time-Series Analysis

- Investigated different statistical models for time-series forecasting to create an image-based lifetime prediction model.
- In this exercise, the data are the C-SAM images of bonded interfaces at different stages of thermal cycling.
- Developed a Python script to compute the void fractions from the C-SAM images of 63Pb37Sn solder.



Defect growth of Cu-Al alloys under thermal cycling

ACCOMPLISHMENTS (contd.)



Crack growth forecasting of different statistical models

- Void fraction data computed from C-SAM images were split into training set and validation set. As a starting point, the forecasting is limited to thermal shock profile.
- The model predictions were implemented using the statsmodels module in Python.
- Among the different models studied, Holt linear model seems to provide the most accurate prediction in terms of root mean square error.

CHALLENGES AND BARRIERS

- Synthesis profile and parameters of Cu-Al bond need to be optimized to reduce the initial void fraction to acceptable levels (<5%).
- Polymeric bonded materials show promising initial bond quality; its thermomechanical performance needs to be evaluated under high-temperature cycling conditions.
- Limited data sets might prove to be challenging for developing accurate crack growth rate models; creating additional data using synthetic techniques needs to be investigated.

FUTURE WORK

- Conduct accelerated thermal cycling of Cu/Al bond samples under different temperature profiles: −40°C to 200°C and −40°C to 175°C.
- Investigate the feasibility of statistical models for multiple time-series forecasting to incorporate additional thermal profiles. Also, implement machine-learning techniques such as long short-term memory networks for time-series forecasting and compare with statistical models.
- Identify new material compositions for reliable operation at high temperature through experimental and data-driven modeling approaches.

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

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