Power Electronics Materials and Bonded Interfaces – Reliability and Lifetime

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FY19–FY23; Year 3 of 5
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OVERVIEW

- Project start – October, 2018
- Project end – September, 2023 (50% completion)
- Total project funding (to date) – $525K, DOE share – $525K, funding for FY20 – $175K, funding for FY21 – $175K
- 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 electronic applications.

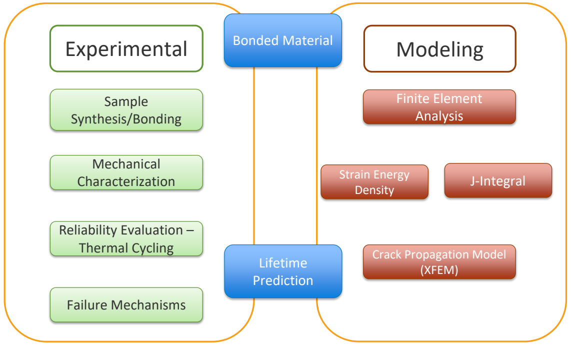
COLLABORATIONS

- 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: technical guidance and discussion

SUMMARY

- Conducted the reliability evaluation of sintered silver under a thermal cycling profile of −40°C to 200°C; 95Pb5Sn solder exhibited better thermomechanical performance than sintered silver.
- Formulated a lifetime prediction model of sintered silver by correlating experimental crack growth data with strain energy density outputs from modeling.
- Developed a 2D crack propagation model of sintered silver using the extended finite element method.
- Evaluated the bonding quality of Cu/Al bonds after synthesis; additional refinements are required to reduce the defect fraction.

APPROACH



Experimental
Sample Synthesis/Bonding
Mechanical Characterization
Reliability Evaluation – Thermal Cycling
Failure Mechanisms

Bonded Material
Lifetime Prediction

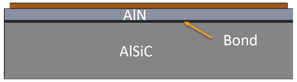
Modeling
Finite Element Analysis
Strain Energy Density
J-Integral
Crack Propagation Model (XFEM)

Al: aluminum, AlN: aluminum nitride, AlSiC: aluminum silicon-carbide, DBA – direct bond aluminum, DBC – direct bond copper, Cu: copper , C-SAM: C-mode scanning acoustic microscope, SEM: scanning electron microscope, XFEM: extended finite element method

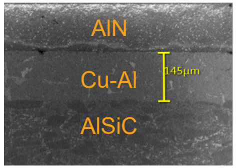
Sintered silver

Samples with three different bond diameters were fabricated: 22 mm (left), 16 mm (center), and 10 mm (right)

Cu–Al transient bond



- Materials considered in this project are sintered silver and Cu–Al transient liquid-phase alloy.
- These materials are bonded in a sample configuration and subjected to −40°C to 200°C thermal cycling profile.
- C-SAM images of the bond material at periodic cycling intervals would be obtained and analyzed to calculate crack growth rates.

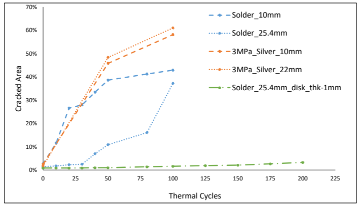


SEM image of Cu–Al bond

- A lifetime prediction model correlating the crack growth rates and modeling outputs will be developed.

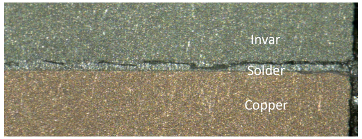
ACCOMPLISHMENTS AND PROGRESS

- Solder (95Pb5Sn) samples exhibited higher reliability than sintered silver under a thermal cycling profile of −40°C to 200°C at both 10-mm- and 25.4-mm-diameter configurations.
- The lower the outer disk thickness, the higher the reliability.
- A correlation was established between the strain energy density results and the experimentally measured crack growth rates of sintered silver to formulate a lifetime prediction model.

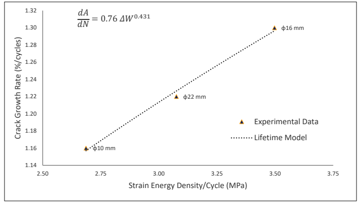


Crack growth comparison of low-pressure-assisted (3 MPa) sintered silver and solder samples under thermal cycling

- The fracture mode of solder was observed to be predominantly adhesive in nature.
- Simulations computed lower values of strain energy density for solder compared to sintered silver.

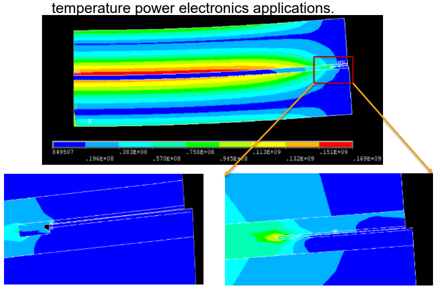


Crack propagation in solder



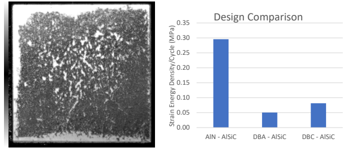
Lifetime prediction model of sintered silver

- Developed a preliminary 2D crack propagation model of sintered silver using XFEM.
- This model is currently limited to linear elastic properties; future iterations will incorporate inelastic deformation behavior and thermal cycling loads.
- The model will be extended to other materials for high-temperature power electronics applications.



Crack propagation model of sintered silver: von-Mises stress plot of the bond between Cu and Invar at the start of a temperature change from 25ºC to 200ºC (top); detailed view of the crack (bottom right); crack status at 200ºC (bottom left)

ACCOMPLISHMENTS (contd.)



C-SAM image of a Cu-Al bond between AlSiC and AlN (left), strain energy density results of Cu-Al bond under different sample configurations (right)

- Conducted non-linear thermomechanical simulations to study the deformation behavior of Cu-Al bond under thermal cycling.
- Suitable constitutive models for the Cu-Al bond do not exist; used a kinematic hardening model based on Al stress-strain data as an approximation.
- Simulations results indicate that a Cu-Al bond between DBA and AlSiC is more reliable than AlN and AlSiC however, this trend may change with a more appropriate constitutive model; also, it is experimentally challenging to create a Cu-Al bond with DBA.

CHALLENGES AND BARRIERS

- Correlation between simulations and experimental results is hard to establish due to the macroscopic nature of modeling and microstructural causes of failure mechanisms in bonded materials.
- While current formulations of sintered silver may work for small-area attach (die-attach), novel material compositions and microstructures need to be identified for large-area attach layers with sufficient reliability.
- Synthesis profile and parameters of Cu-Al bond need to be optimized to reduce the initial void fraction to acceptable levels (<5%).

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.
- Expand the microstructural crack propagation model to include physics at lower length and time scales and establish microstructure-property relationships to accelerate novel high-temperature material development.
- 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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