ABSTRACT:

Multiscale Defect Dynamics Modeling for Reliability Analysis of Microelectronics

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As microelectronic devices continue to scale down and 3D heterogeneous integration becomes mainstream, the long-term reliability of interconnects, through-silicon vias, and solder interfaces is increasingly governed by thermomechanical stresses that concentrate at the micro- and nanoscale. Under repeated thermal cycling, mismatches in thermal expansion drive localized plastic deformation, damage accumulation, and eventual fracture. Conventional continuum-based approaches, however, cannot capture the size-dependent and defect-mediated nature of deformation that dominates mechanical response at these reduced dimensions, limiting their predictive power for reliability assessment.

In this talk, a multiscale defect dynamics framework will be presented to investigate defect-controlled mechanical behavior in microelectronics under thermal cycling. The framework couples three-dimensional dislocation dynamics (DD) with the finite element method (FEM): the short-range interactions and detailed evolution of the defect microstructure are resolved by the DD model, while the long-range elastic fields and image stresses arising from complex geometries and boundary conditions are handled by FEM. This coupling enables a mechanistic description of phenomena such as dislocation nucleation at crack tips and dislocation–grain boundary interactions, while accommodating the multi-physical driving forces relevant to device operation.

Building on this framework, size-dependent plasticity, stress localization, and the nucleation, growth, and coalescence of damage will be discussed in the context of microelectronic reliability. By comparing predictions against classical phenomenological models, the capability of defect dynamics to capture the underlying physics of failure under thermal and mechanical loading is demonstrated. The proposed approach offers a robust, physics-based pathway for reliability analysis and for establishing computational design guidelines that enhance the durability of next-generation microelectronic systems.

Keywords: Multiscale modeling, Dislocation dynamics, Crystal plasticity finite element model, Thermomechanical reliability, Microelectronics