Finite-Element Thermomechanical Characterization of Perovskite Solar Modules

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Motivation:

A comprehensive understanding of the thermal and mechanical behavior of solar perovskite cells during manufacturing and operation has the potential to increase panel robustness and lifespan.
A finite-element model can predict the threshold temperatures at which mechanical failure will occur in perovskite-silicon tandem modules.

Relevant Background

Differences in the coefficients of thermal expansion (CTE) between the materials that comprise the layers of a solar photovoltaic panel are a driving force for the stress between layers that causes mechanical failure.

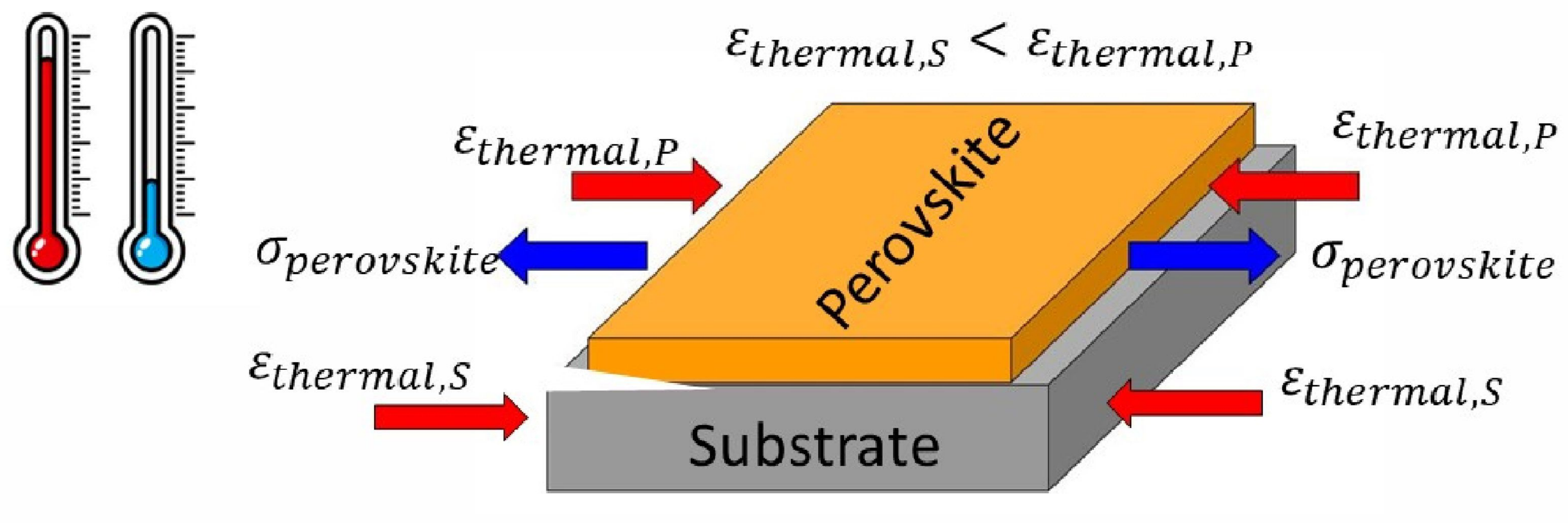

Figure 1: Illustration of stress development at device level due to temperature fluctuation. Differences in deformation caused by CTE differences between perovskite and substrate create stress

Device Scale vs Module Scale:

Going from the device scale (figures 1 and 2) to the module scale (figure 4) brings new challenges. At the module level, more materials in the solar cell layers, larger dimensions, and more complex geometry adds increasing complexity such as non-linear material properties, bending stress, and out of plane stress. Such complexities warrant the use of computational methods such as finite-element analysis (FEA) for mechanical characterization.

The **finite-element method (FEM)** is a numerical approach to solve the partial differential equations that govern the coupled thermal-mechanical phenomena that occur when a solar cell or module is exposed to time-varying environmental temperatures during manufacturing or operation. ANSYS is a simulation software tool that uses the FEM to conduct stress analysis and was used in this study.

Perovskite on Substrate Model:

A simple FEA model was created to measure the stress in a perovskite thin film on a silicon substrate. The results were compared to the experimentally measured stress found by Rolston et al [2].

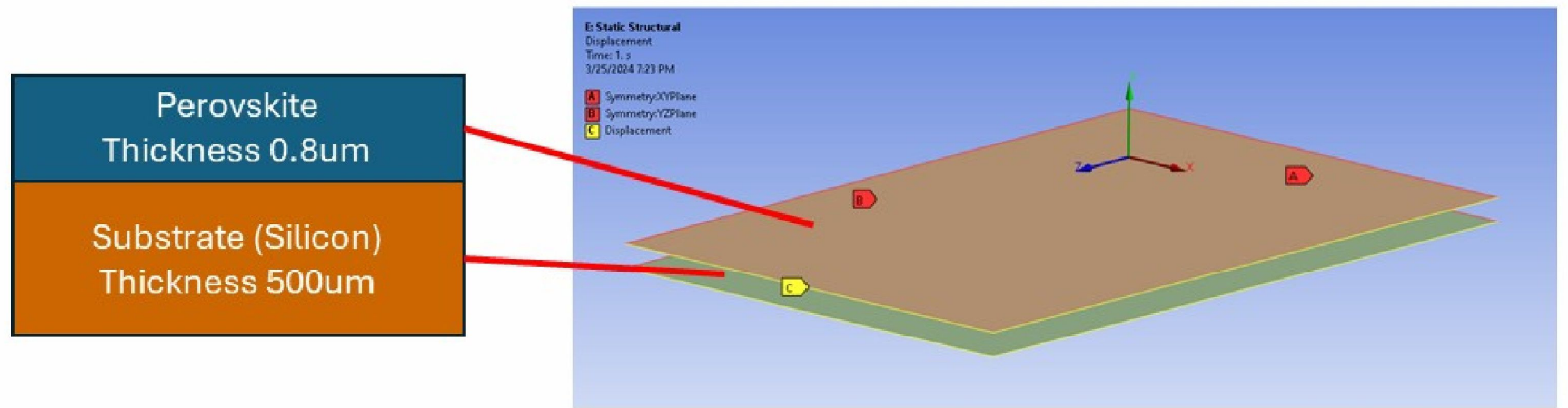

Figure 2: Illustration of perovskite on substrate model (left) and implementation into ANSYS Workbench with model boundary conditions (right)

Model assumptions:

- Material properties are isotropic, constant with respect to temperature, and linear elastic
- Out-of-plane stress and deformation is negligible
- Conduction resistance is negligible due to the material thickness

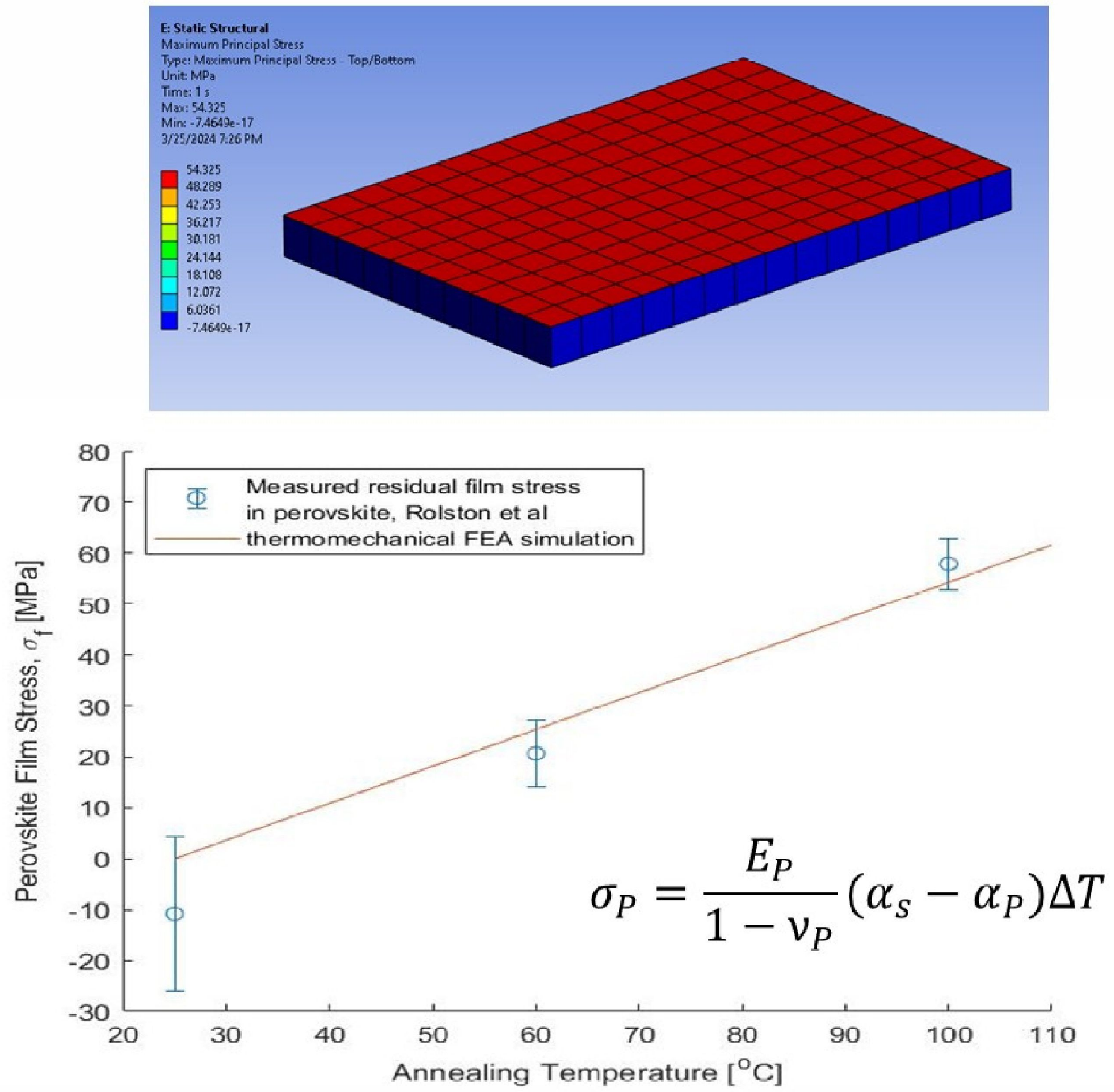

Figure 3: Principal Stress in Perovskite and Substrate after cooling from 100°C to 25°C (top) Relationship between perovskite stress and annealing temperature (bottom)

Methodology:

1. Validate that FEA can be used at the substrate/device level.
2. Develop module-scale model that accurately predicts the region of experimentally-observed module delamination.
3. Confirm accuracy of model by showing reduction in stress with thicker encapsulants.
4. Estimate value of stress at which module with 300um thick encapsulant will experience delamination failure.

Future Work:

Future models will focus on modeling the mechanical behavior of a full module by incorporating the non-linear material properties of the encapsulant polymer. The material stack will be simplified to just consider the silicon and perovskite layers between the encapsulant.

Encapsulating polymers in solar cells have several non-linearities:

- Significant variation of the Young's Modulus and CTE with respect to temperature
- Viscoelasticity causes dampening/energy loss effect from viscous behavior of polymers.

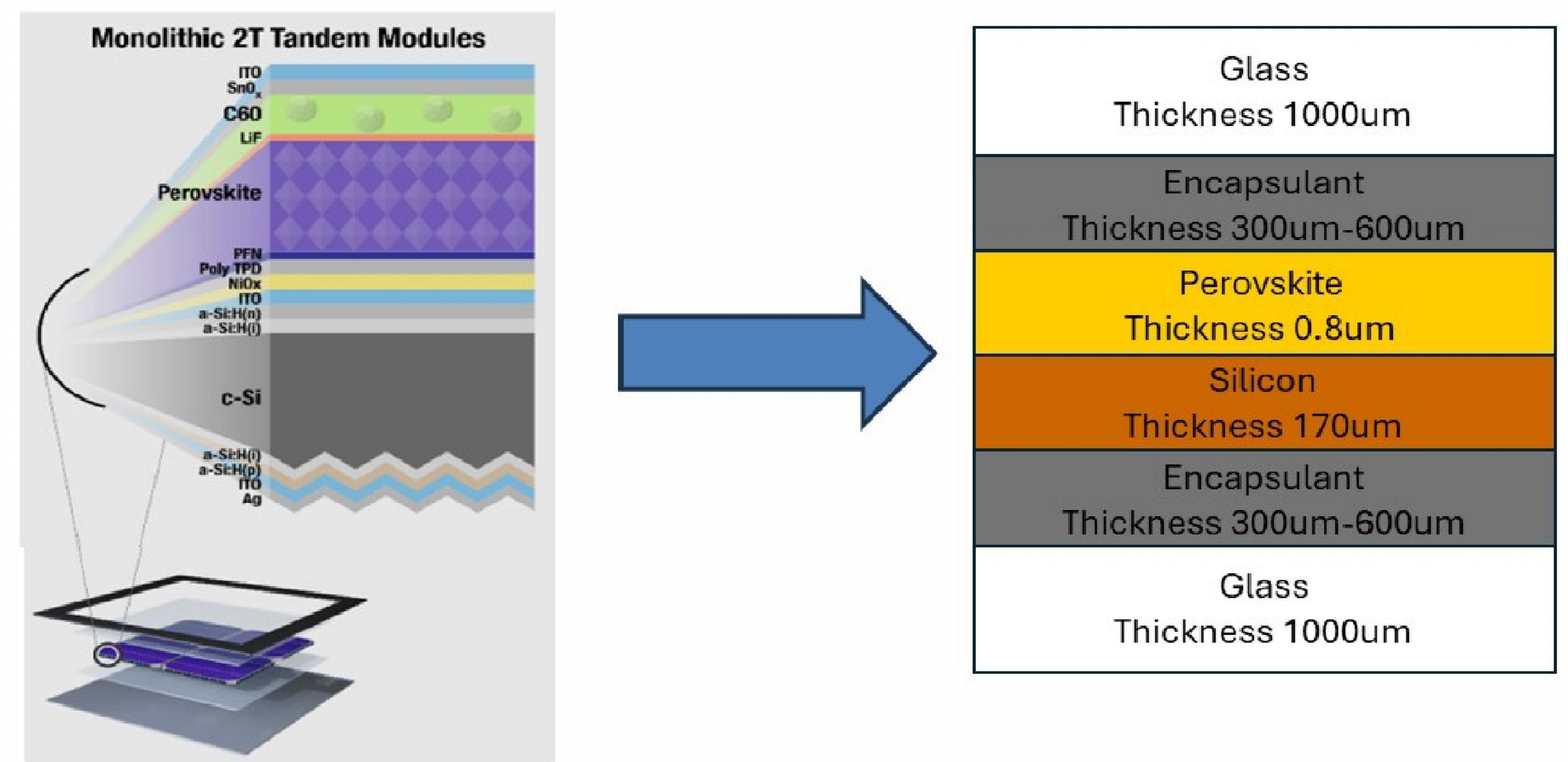

Figure 4: Illustration of future models. Complete stack of materials in a silicon-perovskite tandem module (left) and simplified stack of materials for future thermomechanical analysis (right)

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References:
[1] Cheacharoen, R., Rolston, N., et al., Energy Environ. Sci 2018, 11, 144-150
[2] Rolston, N., et al., Adv. Energy Mater. 2018, 8, 29.
[3] Dietrich, S., et al., Proceedings of SPIE - The International Society for Optical Engineering 2010.

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