DuraMAT
Durable Module Materials Consortium

Characterization of Interconnects

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Disruptive Acceleration Science

Awarded FY22 Core Modelling Call

Period of Performance: 2.5 Y
Funding: $1.277 M

Capability Goals

- Evaluate strengths and weaknesses of modern cell interconnect designs with combined-accelerated stress testing (C-AST) to screen multiple climates along with finite element and failure analysis to determine potential for a 50-year life. Field validation in Alaska (cold) and Arizona (Hot)

Accomplishments

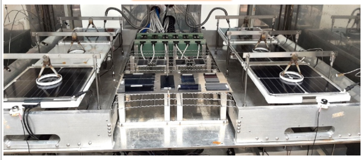
- Surveyed new interconnect technologies
- Acquired five types of modules with novel interconnects and started testing
- Developing Remote-Dynamic Mechanical Acceleration tool
- Characterized low-temperature solder wire interconnects, their geometry and materials
- Created FEA mesh for low-temperature soldered wire interconnected cells and module

Outcomes and Impact

- Development of accelerated testing capabilities to de-risk cell interconnects, identify weaknesses not captured by existing standardized tests, and validate interconnects for a 50-year life
- Develop methods of characterization to assess the degradation of interconnects
- Enable predictive rate models with material forensics and FEA
- Show C-AST's ability to find interconnect failures and benchmark it relative to other test methods.

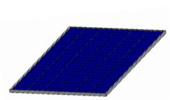
Project Overview

ACCELERATED TESTING



Realistic Modeling of wire-interconnected modules

Geometries and boundary conditions allow wire movement over a module exposure to be calculated and used as a metric for degradation by metallization wearing

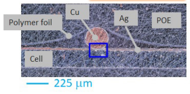


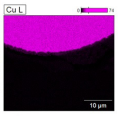
Model for full wire-interconnected module

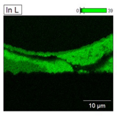
C-AST: stress factors applied at extremes and in combinations of natural environment :

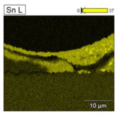
- Heat
- Light
- Humidity
  - Condensing
  - Non-condensing
- Mechanical pressure
- System voltage

CHARACTERIZATION





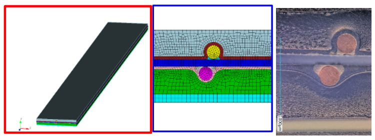




Focus on characterization of low-temperature solder wire interconnects

Capability developed for metallographic analysis on 2018 generation modules with low-temperature solder-interconnects
- -Cu wire ∅ (typically 200-300 µm)
- -Peripheral solder coating (SnIn → SnBi)
- -Polymer foil materials (recently PET & POE)

FEA MODELING



low-temperature solder wire interconnects along a half-cut cell

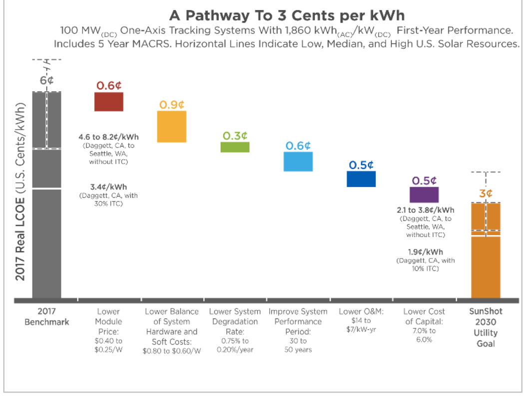
Modeled geometries and materials correspond to those measured

ACCELERATED TESTING

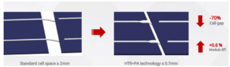
Remote Source Dynamic Mechanical Acceleration Tool

By separating the speaker enclosure from the module, and transmitting the induced pressure wave through a tube, the module may be placed within an environmental chamber while the speaker enclosure remains in ambient laboratory conditions.

Cost Drivers



Evaluation of Emerging Module Interconnect Technologies

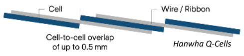


Canadian Solar

Packing cells closer together: manufacturers are flattening the multi-wire between cells to reduce cracking from stress concentration

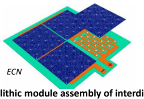
Meyer Burger

low-temperature solder wire interconnect solution for low temperature interconnection of HJT cells



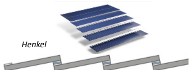
Hanwha Q-Cells

"zero gap" solution for close spacing of cells



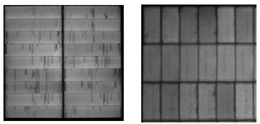
ECN

Foil for monolithic module assembly of interdigitated back-contact cells or metallization wrap-through cells



Henkel

Shingled cells

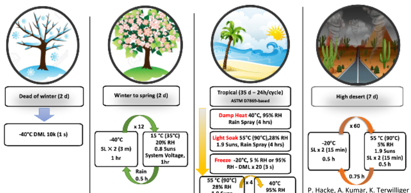


EL images of selected technologies in study: shingled (left) and low-temperature wire interconnect (right)

Surveyed 10 organizations (module makers, industrial partners, and research institutes) to gauge the interconnect market

Salient results:
- ***- Focus to <u>reduce cell-to-cell spacing</u> creating challenges and innovations on the interconnect level***
- ***- Interest in <u>low temperature interconnect</u> technologies (e.g., for heterojunction technology)***
- ***- <u>Most using multi-wire/multi-ribbon PbSn</u> and will make changes when the industry makes a jump away <u>based on needs</u> or <u>alternative solutions</u> become available to module manufacturers***

Combined-Accelerated Stress Testing: Shingled Cells with Electrically Conductive Adhesive

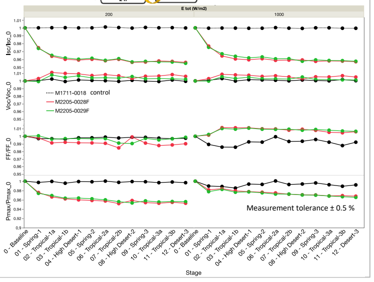


P. Hacke, A. Kumar, K. Terwilliger and coworkers *Progress in Photovoltaics Res. and App.* 2022

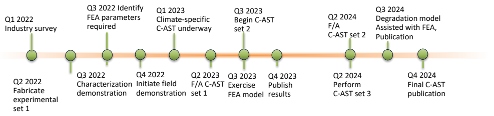
Flash test results during three cycles of C-AST for shingled Si HJT cells in glass/EVA/glass modules with new electrically conductive adhesive. 200 W/m² (left), 1000 W/m² (right) →

- **No loss in fill factor seen using 1000 W/m² (STC) indicating no interconnect failure**
- **Loss in I_{sc} (also seen in IEC 61215 TC 200 temperature cycling, -3%, but less in DH 1000, -1.5 ± 0.5 %) suggests some carrier-induced degradation of the n-base Si HJT cell.**

P. Hacke and D.C. Miller, for publication to *2023 EU-PVSEC (Lisbon)*



Timeline



- Q1 2022 Industry survey
- Q2 2022 Fabricate experimental set 1
- Q3 2022 Identify FEA parameters required
- Q3 2022 Characterization demonstration
- Q4 2022 Initiate field demonstration
- Q1 2023 Climate-specific C-AST underway
- Q2 2023 F/A C-AST set 1
- Q3 2023 Begin C-AST set 2
- Q3 2023 Exercise FEA model
- Q4 2023 Publish results
- Q2 2024 F/A C-AST set 2
- Q2 2024 Perform C-AST set 3
- Q3 2024 Degradation model Assisted with FEA, Publication
- Q4 2024 Final C-AST publication

Focus: low-temperature soldered wire interconnects

<u>Hypothesis</u>

Considering the lower temperature melting alloys used with low-temperature wire interconnects (as used with Si HJT cells), the degradation of such interconnects is NOT accelerated by thermal cycling in the same way as traditional Pb-based solder interconnects. Rather, the mechanical nature of their connection to the cell metallization may be degraded by mechanical wear [1,2].

<u>Approach</u>

- **A parallel experimental and modeling effort will elucidate if and how multi-wire interconnects are degraded by mechanical wear.**
- **The modeling effort will quantify ribbon to gridline movement under mechanical and thermal loading.**
- **The experimental effort will seek to induce mechanical wear of multi-wire interconnects with targeted mechanical cyclic load testing as with Remote Source Dynamic Mechanical Acceleration and extended IEC 61215 temperature cycling**

[1] L. Spinella and N. Bosco, "Thermomechanical fatigue resistance of low temperature solder for multiwire interconnects in photovoltaic modules," Sol. Energy Mater. Sol. Cells, vol. 225, no. January, p. 111054, 2021, doi:10.1016/j.solmat.2021.111054

[2] L. Spinella, K. Terwilliger, P. Walker, G. Perrin, C. . -S. Jiang and N. Bosco, "Reliability Implications of Solder in Multiwire Modules under Dynamic Mechanical Loading," *2021 IEEE 48th Photovoltaic Specialists Conference (PVSC)*, 2021, pp. 0108-0111, doi: 10.1109/PVSC43889.2021.9518566

Characterization of the low-temperature solder wire interconnects and modules

<u>Experimental</u>

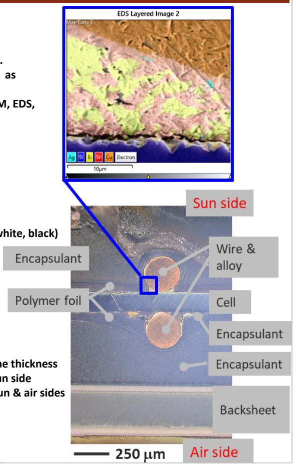
- **Samples: (4) module types examined**
- **Method: cores obtained for direct or cross-sectional examination (epoxy pot & polish).**
- **Encapsulants & backsheets were examined as extracted and after separation.**
- **Characterization by optical microscope, SEM, EDS, FTIR, DSC, TGA**

<u>Results</u>

- **SnBi (most recent) or SnIn (early) solder**
- **250 µm ∅ Cu wire (typical)**
- **50 µm x 25 µm (w x h) gridlines (typical).**
- **EVA and PO encapsulant observed (clear, white, black)**
- **PET backsheets observed (clear, white)**

<u>Observations</u>

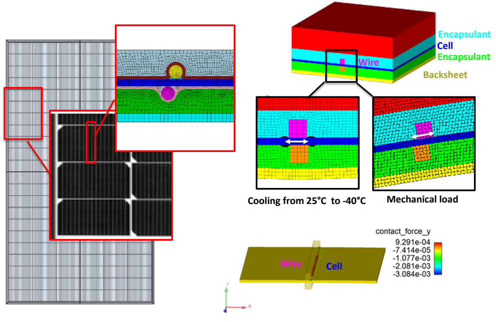
- **Cu wire diameter much greater than gridline thickness**
- **Conformality of polymer foil is better on sun side**
- **>1 encapsulant material may be present, sun & air sides**
- **Multi-layer backsheet**



Wire Interconnect Degradation Modeling Methodology

Full-module finite element modeling capabilities are used to derive expected glass and cell movements during thermal and mechanical cycling. Applying these movements to a detailed wire-scale model allows the propensity for wire separation vs. sustained contact to be examined.

Output metrics such as contact force, relative wire to cell displacement, and accumulated movement will serve as the basis for reliability predictions.



Full scale module models are invoked to derive boundary conditions for wire-level models

Conceptual models have demonstrated the propensity for wire movement under environmental changes and enable output of wire-to-cell contact metrics

Capability Development: Remote Source Dynamic Mechanical Acceleration (DMX)

<u>Experiment</u>

Modules will be exposed to isothermal, cyclic mechanical load testing as interconnect degradation is monitored. For this program, the next generation of DMX has been developed to allow for both:

- **Representative module mounting**
- **Loading in any environmental condition**

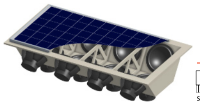
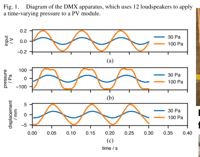


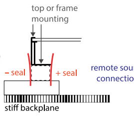
Fig. 1. Diagram of the DMX apparatus, which uses 12 loudspeakers to apply a time-varying pressure to a PV module.

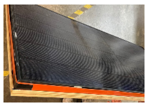


[1] T. J. Silverman, N. Bosco, M. Owen-Bellini, C. Libby and M. G. Deceglie, "Millions of Small Pressure Cycles Drive Damage in Cracked Solar Cells," in IEEE Journal of Photovoltaics, vol. 12, no. 4, pp. 1090-1093, July 2022

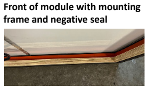
<u>Module mounting</u>

A double valve system has been developed that pneumatically seals the underside of the module without imposing any resistance to frame motion/displacement during loading.





Front of module with mounting frame and negative seal



Back of module with mounting frame and positive seal

DMX allows precise control over both pressure loading frequency and amplitude [1]

- **The first embodiment of DMX clamps down entire module frame perimeter**
- **Loading is also limited within ambient conditions**
- **For this program, the next generation of DMX has been developed to allow for both:**
  - **Representative module mounting**
  - **Loading in any environmental condition**

By separating the speaker enclosure from the module, and transmitting the induced pressure wave through a tube, the module may be placed within an environmental chamber while the speaker enclosure remains in ambient laboratory. A proof-of-concept successfully transmitted a 1 kPa peak-to-peak pressure wave through 1 m of tube.

U.S. DEPARTMENT OF ENERGY
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Sandia National Laboratories
BERKELEY LAB

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