Low-Cost, Crack-Tolerant Metallization: Materials Engineering Solution to Module Reliability

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DOE DuraMAT (RGJ-7-70325 and RGJ-8-8224)
DOE CINT (2019AU0023) and NMSBA

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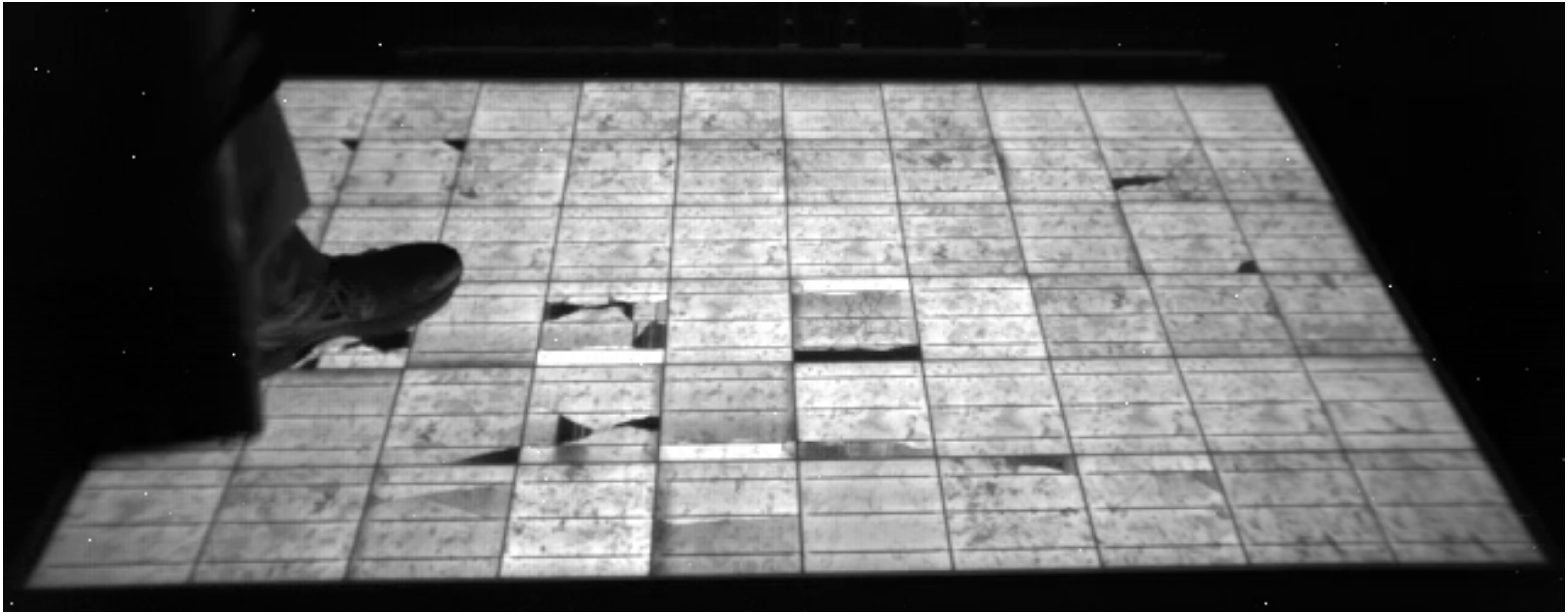
Cell Cracks – What Can Happen?



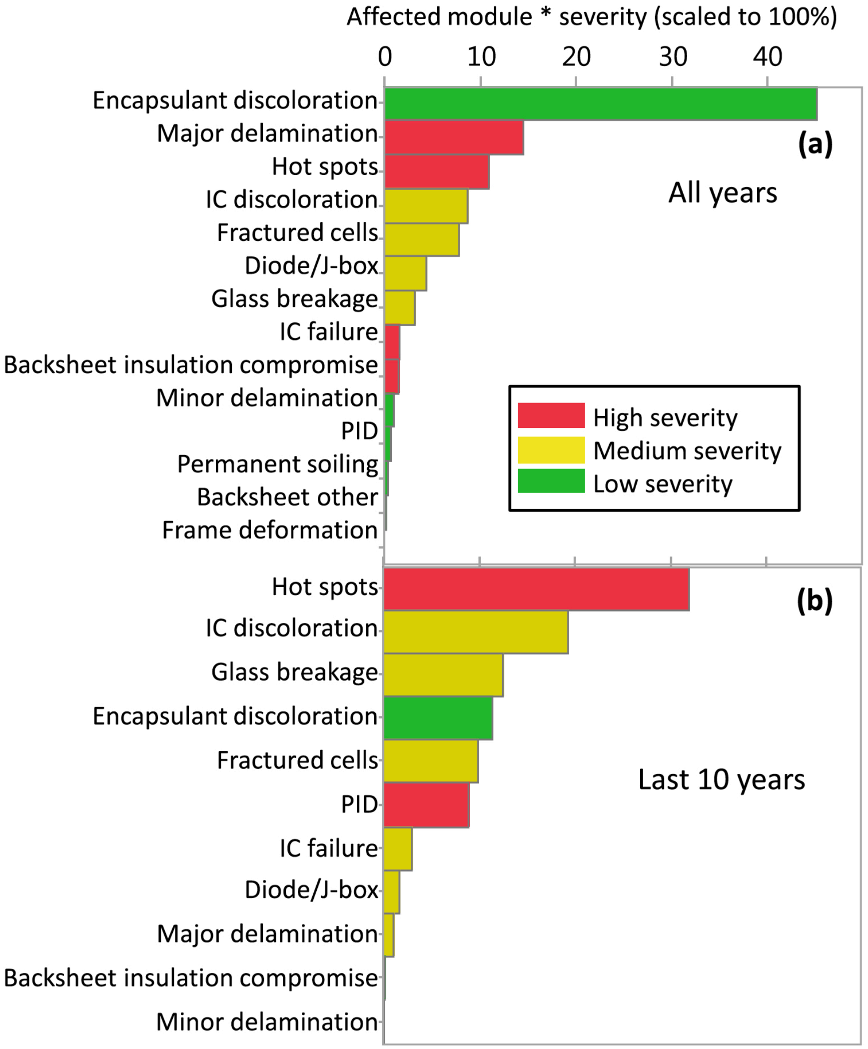
Electroluminescence video by T. Silverman, https://www.youtube.com/watch?v=-qdyxIybmoc (2017).

500 mm

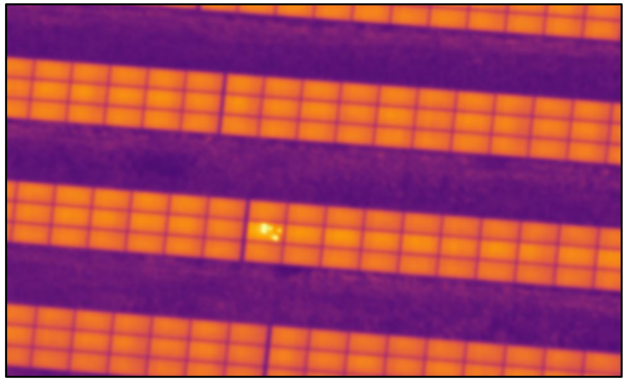
The module continues working even after major cell breakage, but…
cracks eventually lead to power loss over time.

This could happen to you!

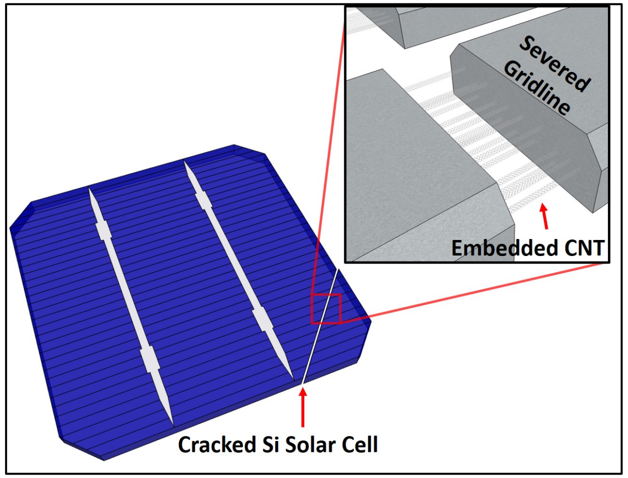
Degradation due to Hot Spots and Cell Cracks in Terrestrial PV Cells



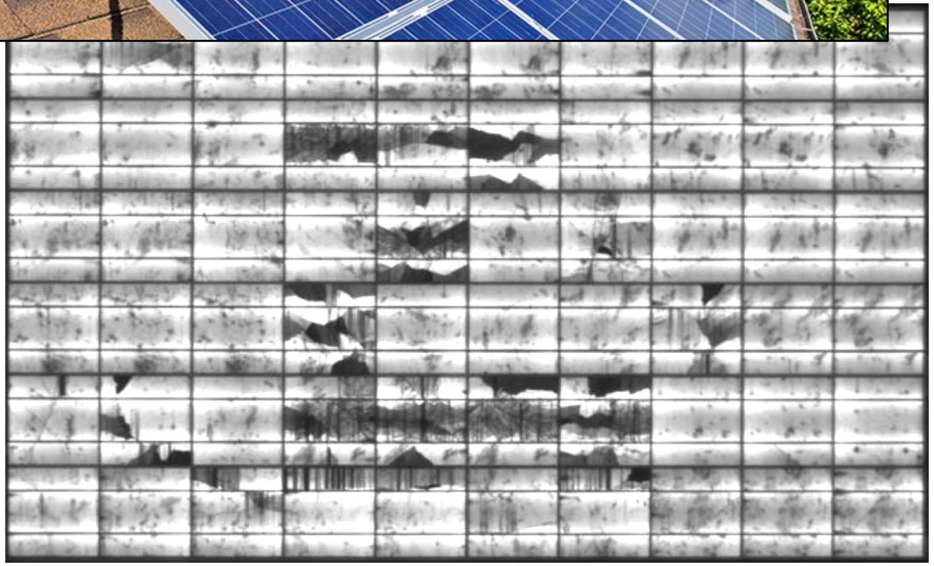
Jordan *et al.*, *Prog. Photovolt. Res. Appl.* **25**, 318-326 (2017).



R. Andrews, 2018 NREL PV Reliability Workshop, Lakewood, CO (2018).



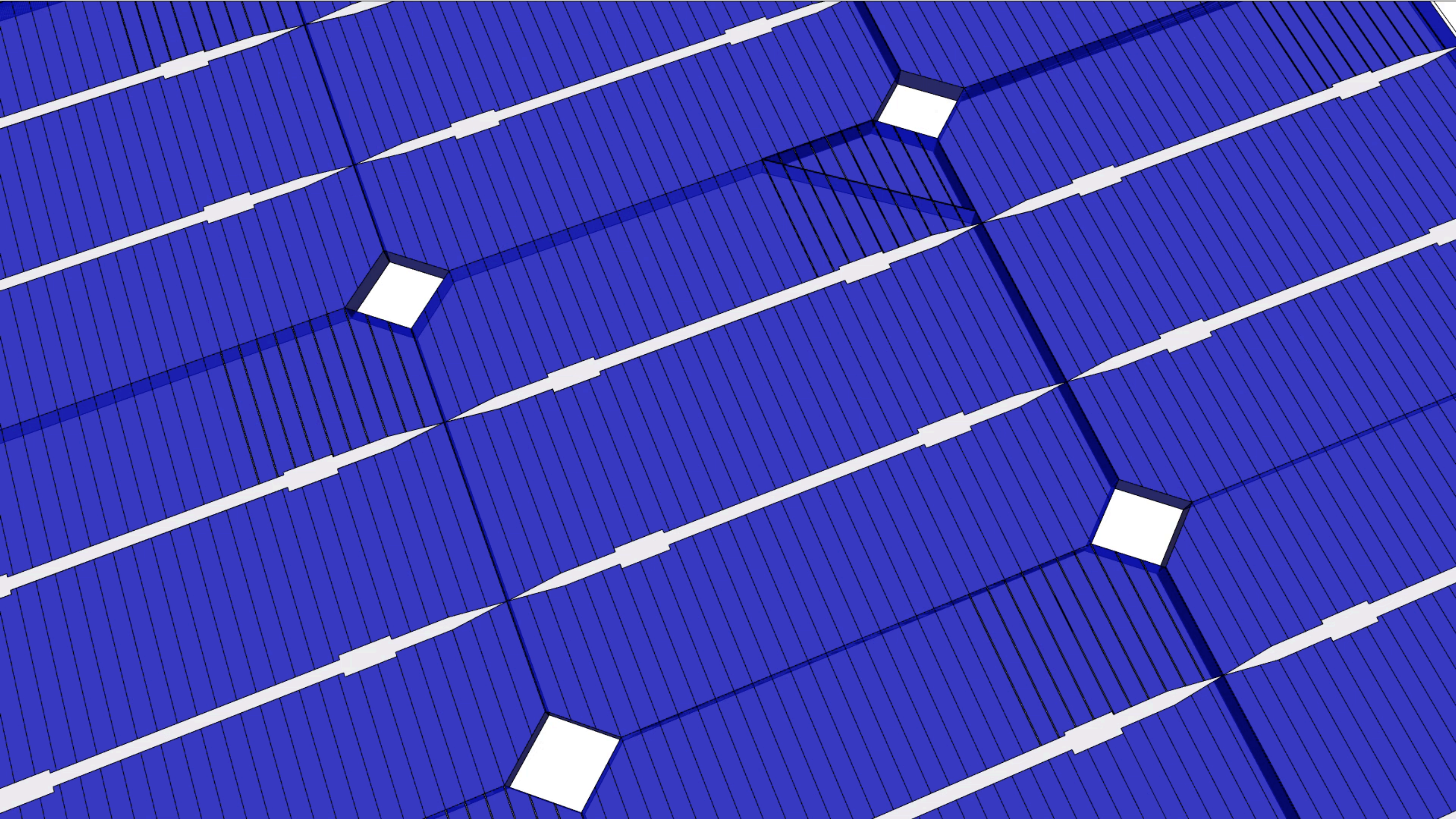
http://energyinformative.org/best-solar-panel-monocrystalline-polycrystalline-thin-film/



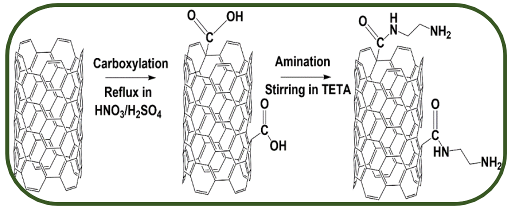
Könges *et al.*, 26th EU PVSEC, 3290-3294 (2011).

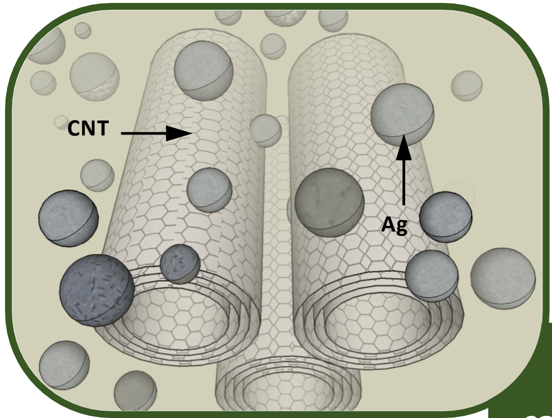
✓ Solder bond failures and cracked cells are suspect for hot spots.[1]

[1]Jordan *et al.*, *Prog. Photovolt. Res. Appl.* and **25**, 318-326 (2017) and **25**, 583-591 (2017).



Osazda's Approach to Crack-Induced PV Degradation





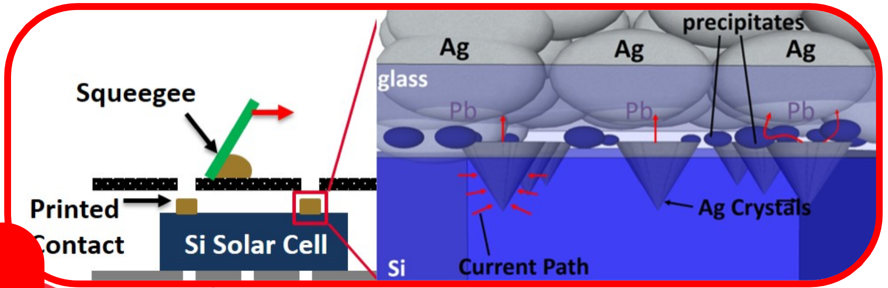
Goal 1: Commercial MMC Paste Product

Step 1: Materials Engineering
- MMC Paste Formulation

carboxylation vs. amination, μ, wt.%, etc.

Step 2: Processing
- Screen Printing & Firing

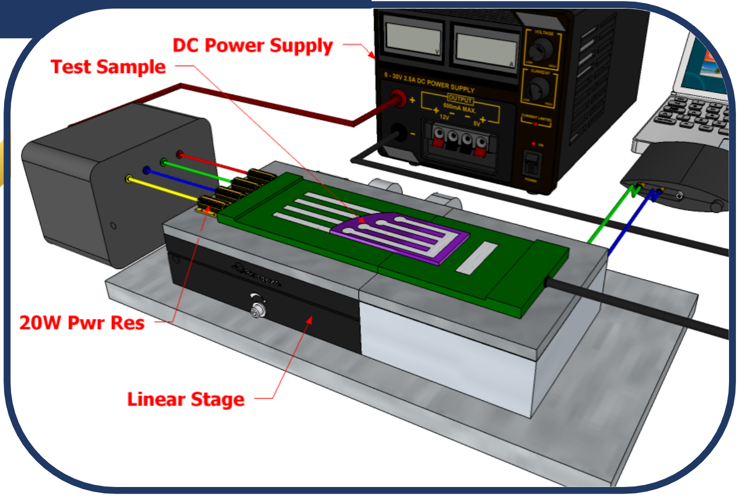
σ_C, R_{sq}, r_c, etc.



Goal 2: Proprietary Integration Processing Recipes

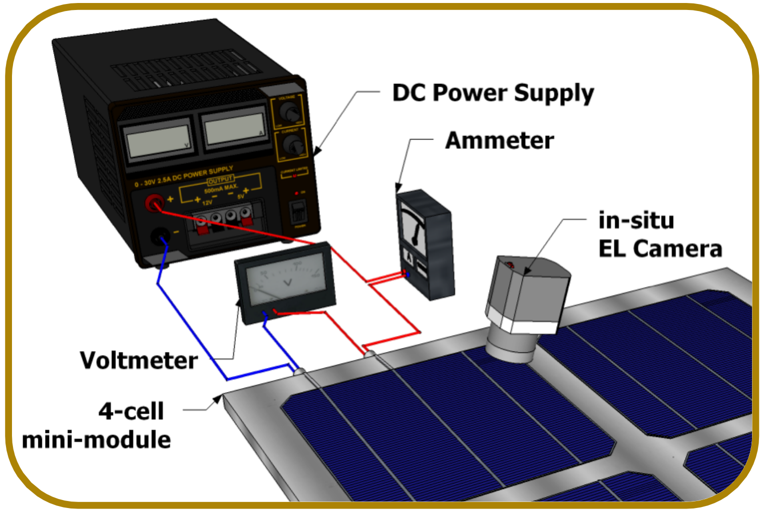
Step 3: Materials Characterization
- RACK & DMA

E, σ_{YS}, ρ_{ε}, S-N, etc.



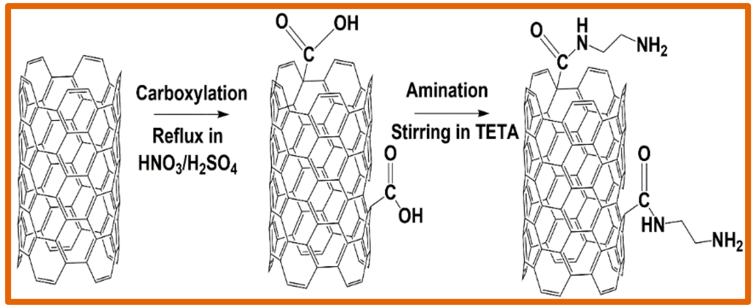
Step 4: Integration
- Cell and Mini-Module Testing

V_{oc}, J_{sc}, FF, η, accumulated damage, equivalent year thermal cycles, etc.



Goal 3: Predictable Module Performance & Degradation

Paste Formulation (Osazda)

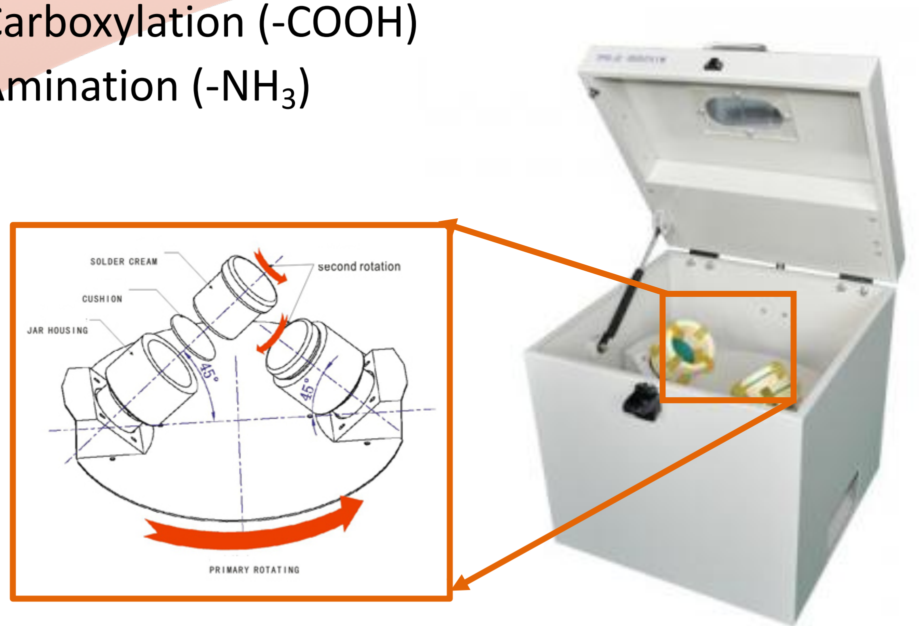


Surface functionalization

- Carboxylation (-COOH)
- Amination ($-NH_3$)

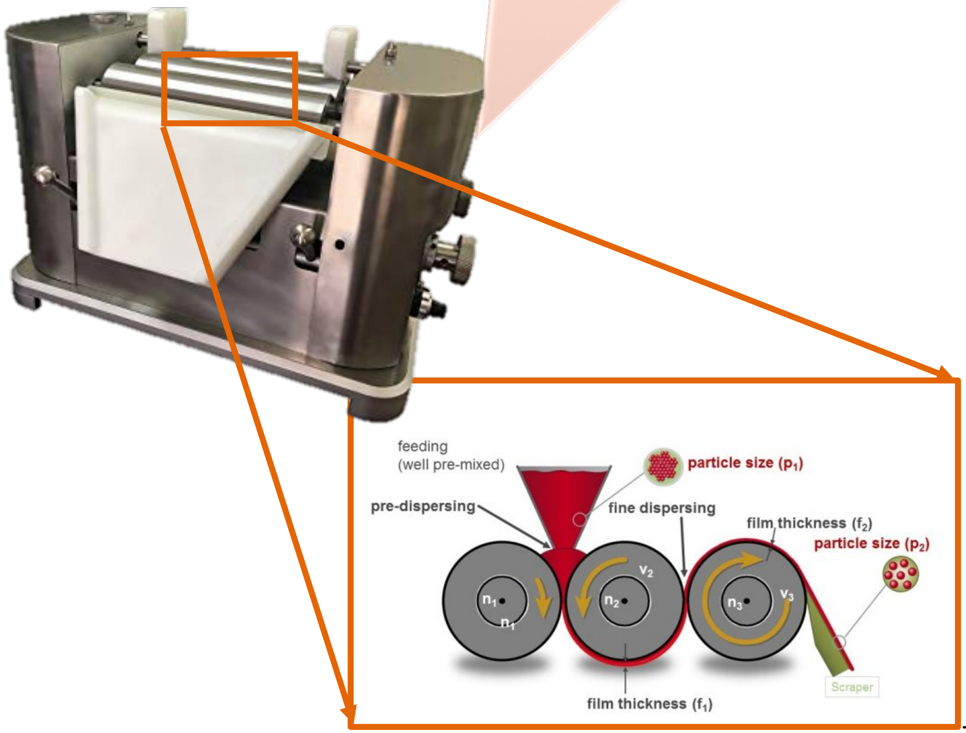
Mixing into Ag paste

- Using a planetary centrifugal mixer

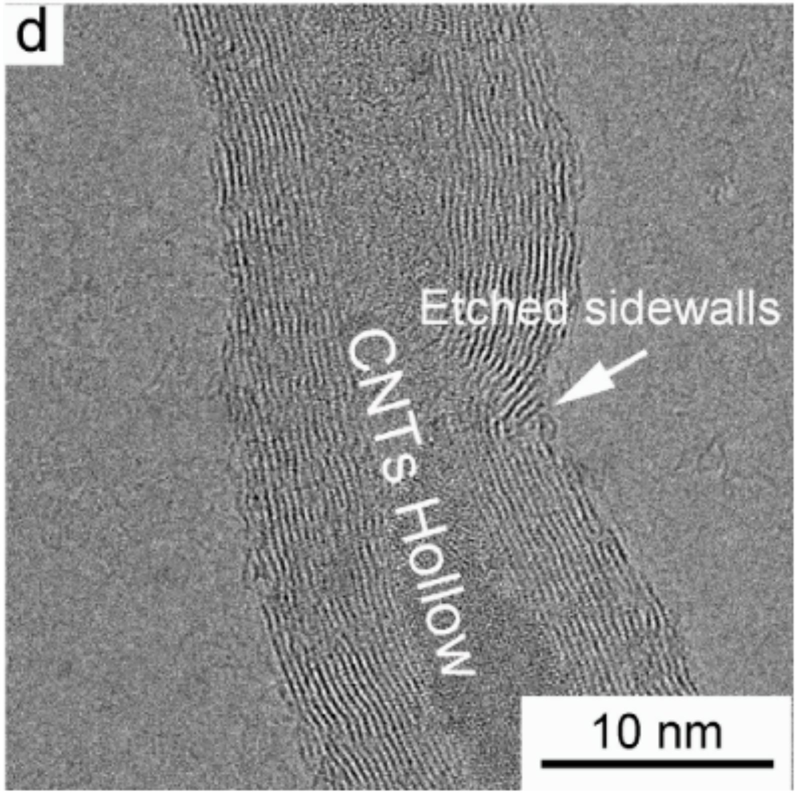


Milling CNT agglomerations

- Using a three-roll-mill



Multi-Walled Carbon Nanotube (MWNT) Functionalization



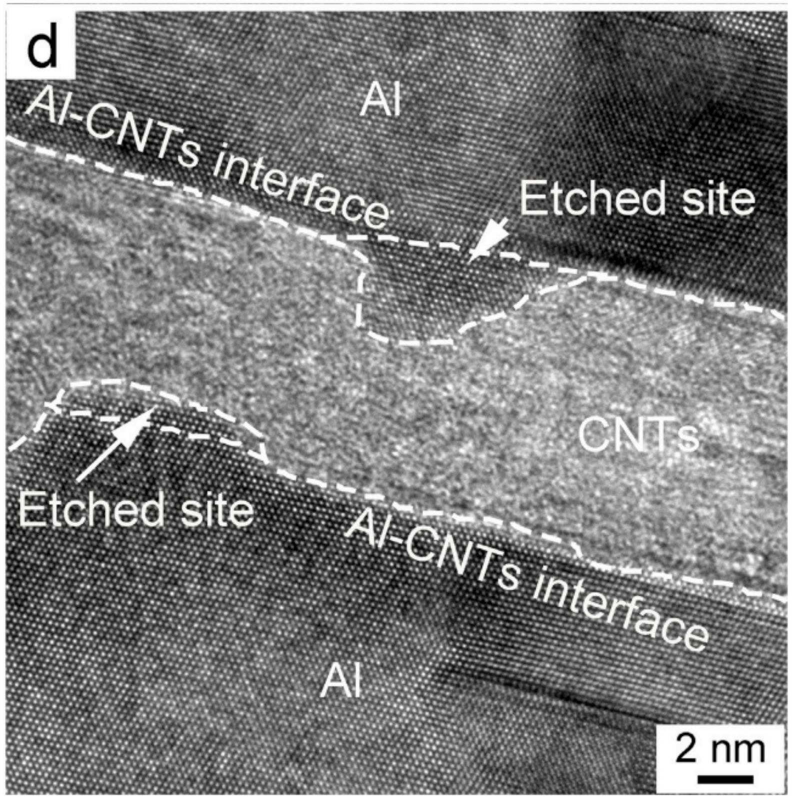


Figure 1: HRTEM image of etched sidewalls from HNO3 H2SO4 treatment, From: "Enhanced Mechanical Properties of Aluminum Based Composites Reinforced by Chemically Oxidized Carbon Nanotubes" by Guo, B., Zhang, X., Cen, X., Chen, B., Wang, X., Song, M., Ni, S., Yi, J., Shen, T., Du, Y., 2018, Reprinted with Permission

Figure 2: HRTEM image of etched sidewalls from HNO3 H2SO4 treatment, now combined with aluminum, From: "Enhanced Mechanical Properties of Aluminum Based Composites Reinforced by Chemically Oxidized Carbon Nanotubes" by Guo, B., Zhang, X., Cen, X., Chen, B., Wang, X., Song, M., Ni, S., Yi, J., Shen, T., Du, Y., 2018, Reprinted with Permission

BALANCING LOAD TRANSFER AND FRAGMENTATION

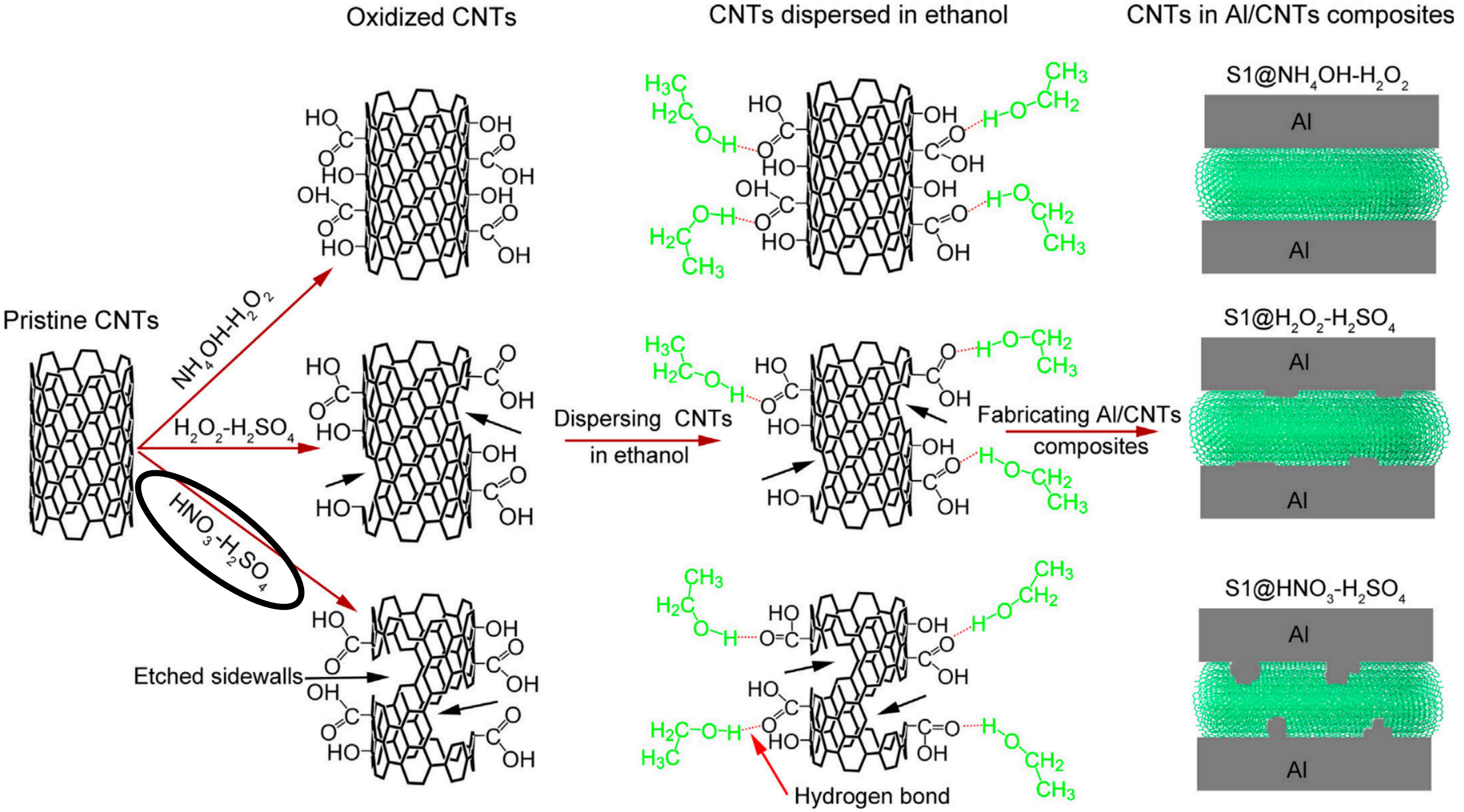


Figure 3: Displaying various mechanisms for functionalizing carbon nanotubes and the resulting features, From: "Enhanced Mechanical Properties of Aluminum Based Composites Reinforced by Chemically Oxidized Carbon Nanotubes" by Guo, B., Zhang, X., Cen, X., Chen, B., Wang, X., Song, M., Ni, S., Yi, J., Shen, T., Du, Y., 2018, Reprinted with Permission

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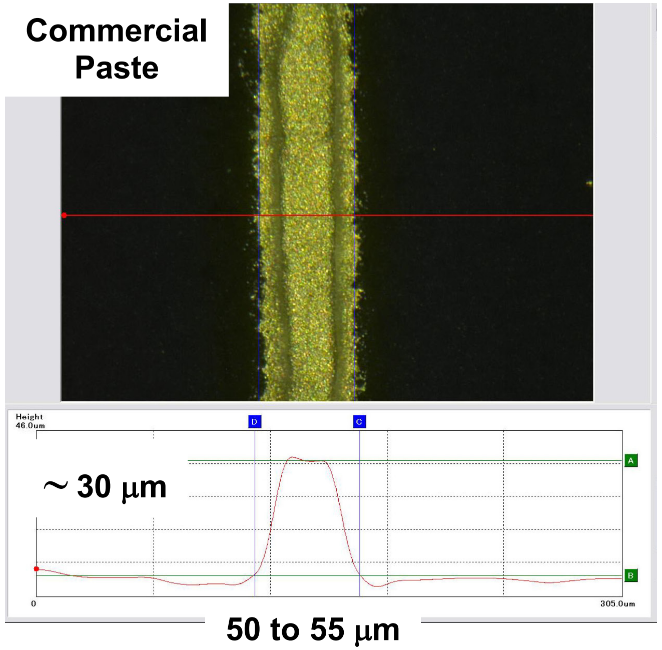
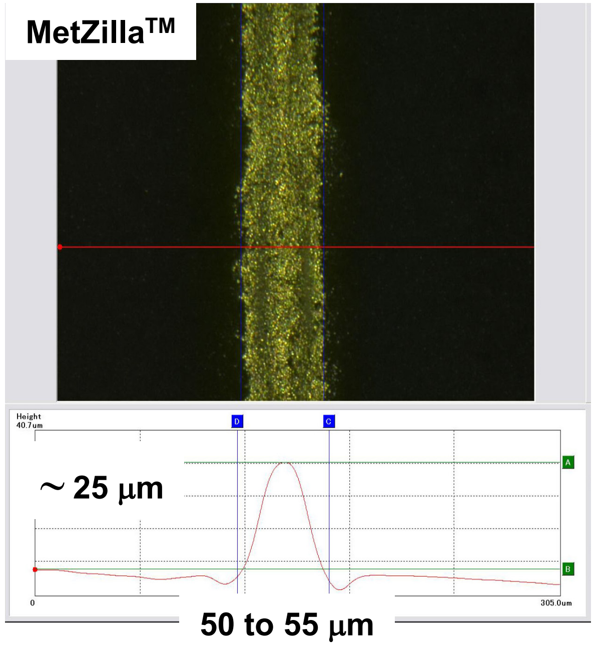
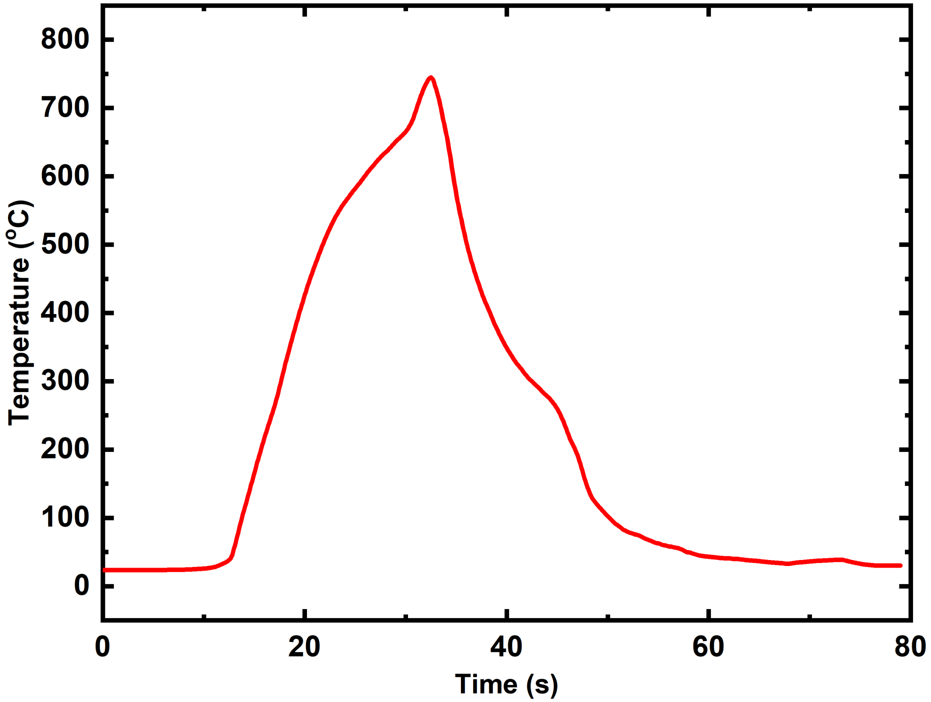
Screen Printing and Firing (Georgia Tech)



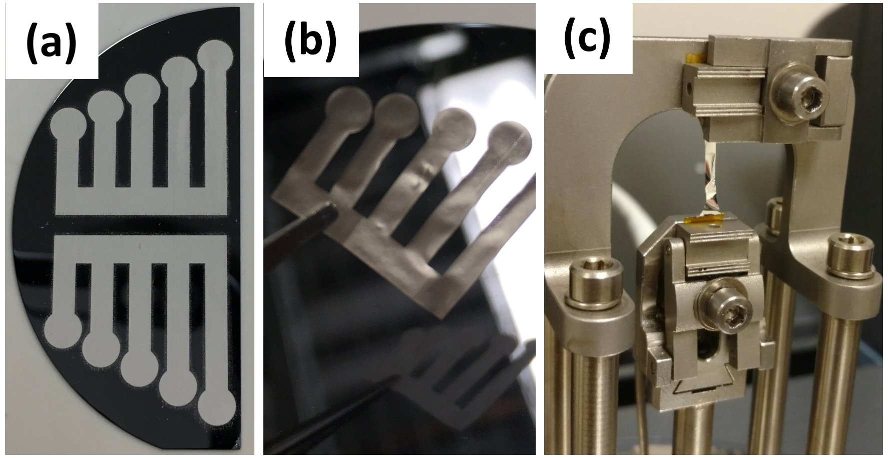


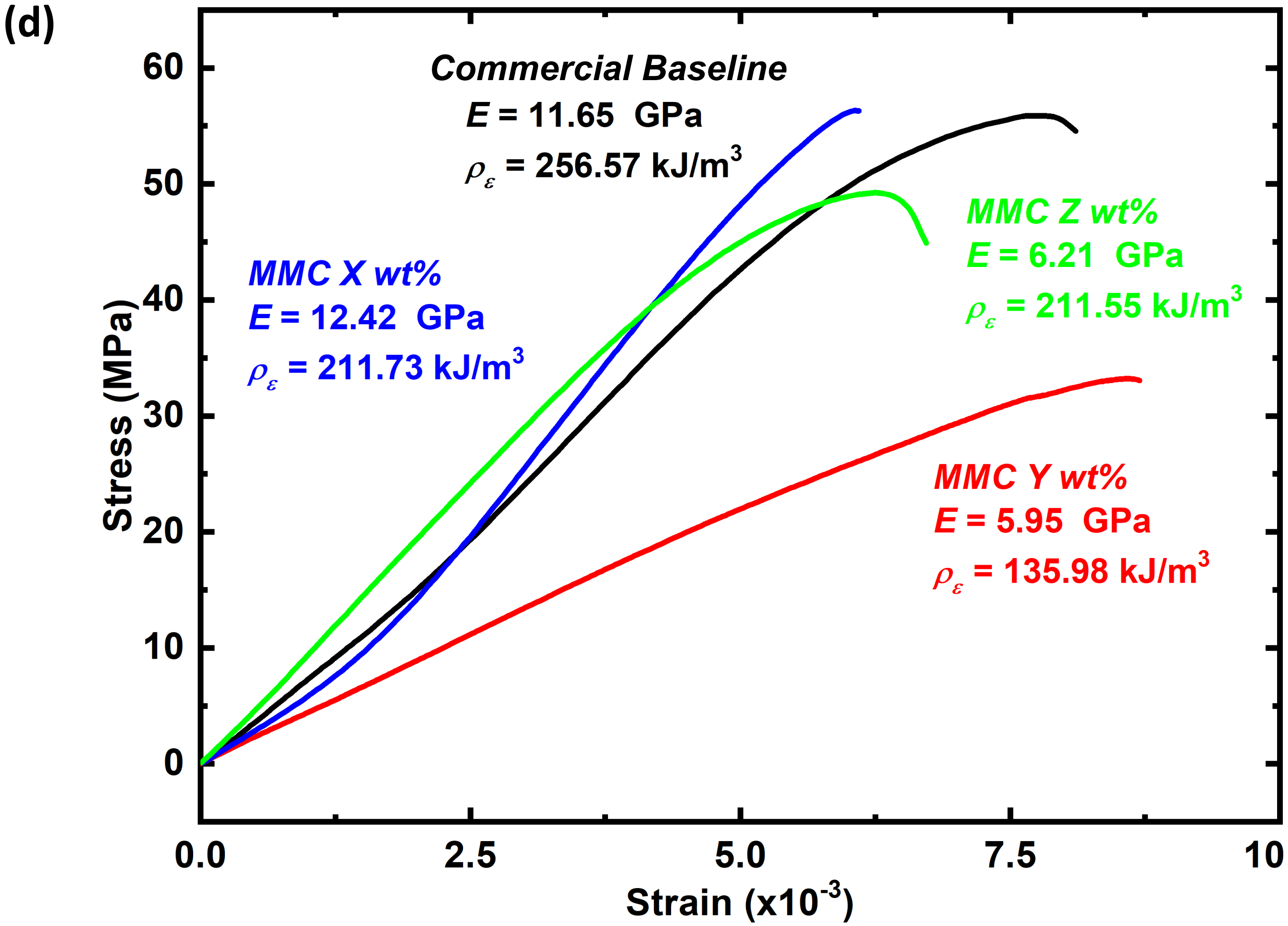


	R_c ($\Omega.cm^2$)	$R_{bus\text{-}to\text{-}bus}$ ($\Omega.cm^2$)	Laydown Weight Wet (g)	Laydown Weight Dry (g)
Commercial Paste	7.800	0.041	0.161	0.130
MetZilla™ Paste	8.700	0.056	0.151	0.115 – 0.125

- Plug-in solution to a standard industrial process
- Line uniformity, laydown weight, contact and bus-to-bus resistance need improvement

DYNAMIC MECHANICAL ANALYSIS (UNM)





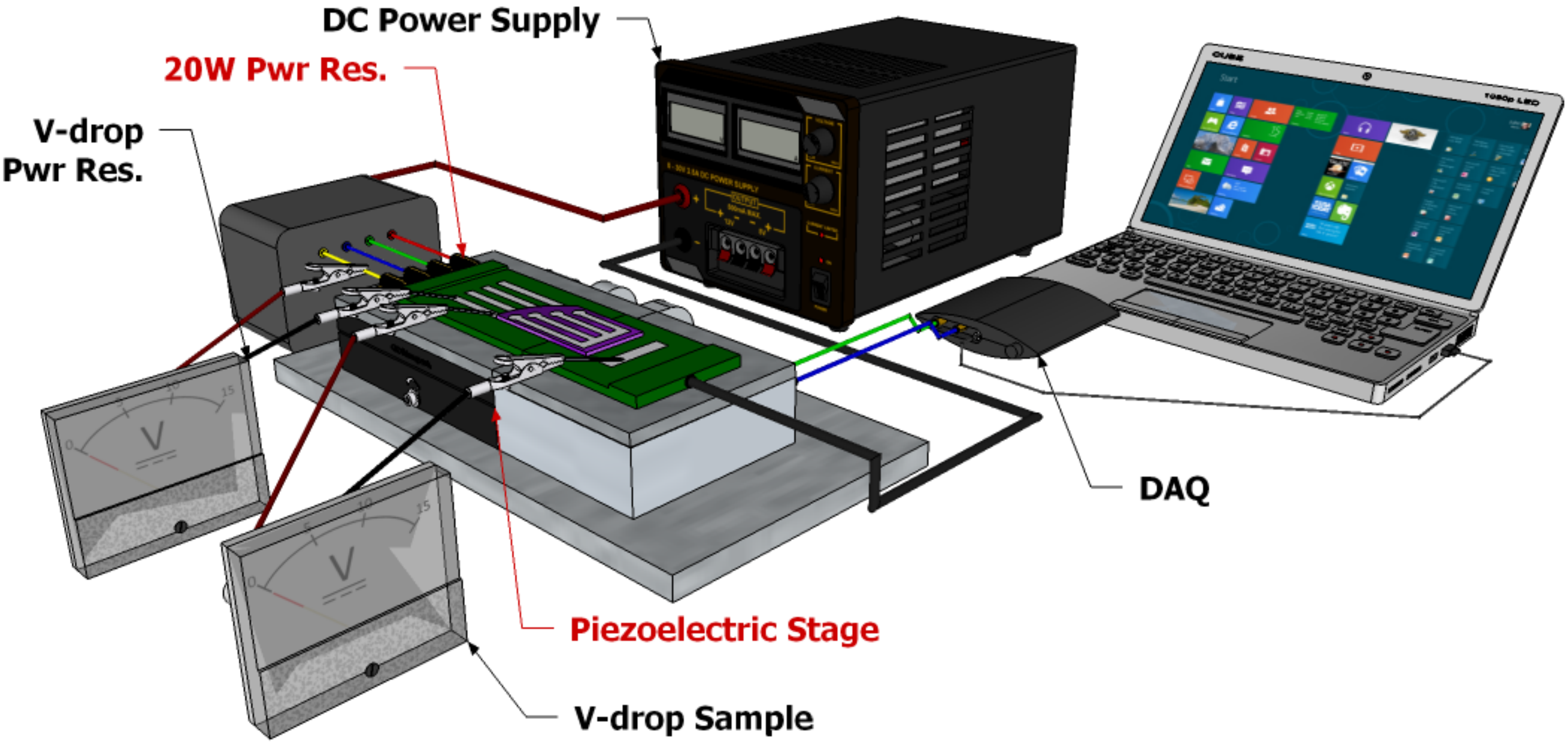
MetZilla™ for Al-BSF cells –

- 4% decrease in elastic modulus
- 16% increase in modulus of toughness
- Increase in ductility

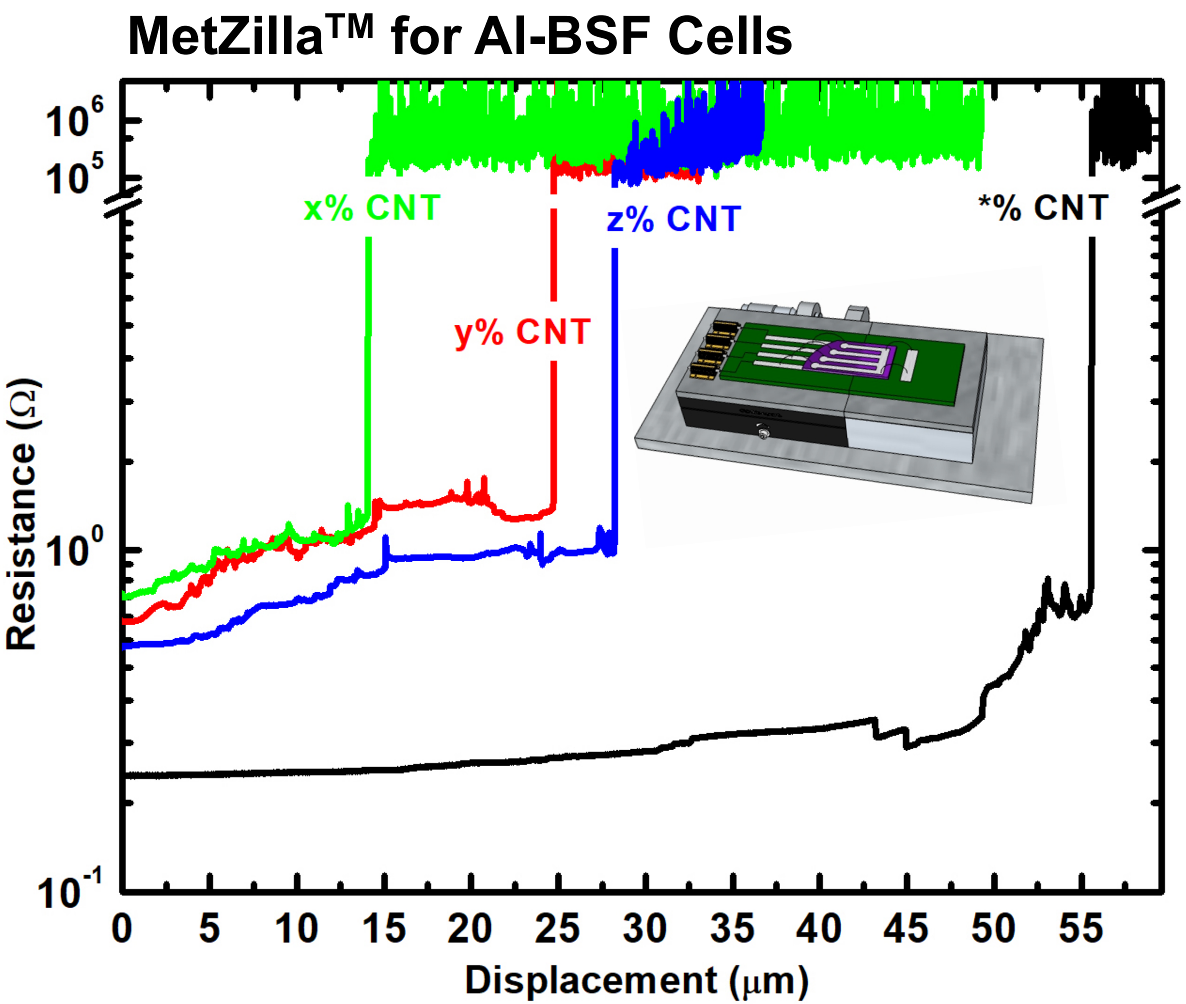
MetZilla™ for PERC cells – in progress

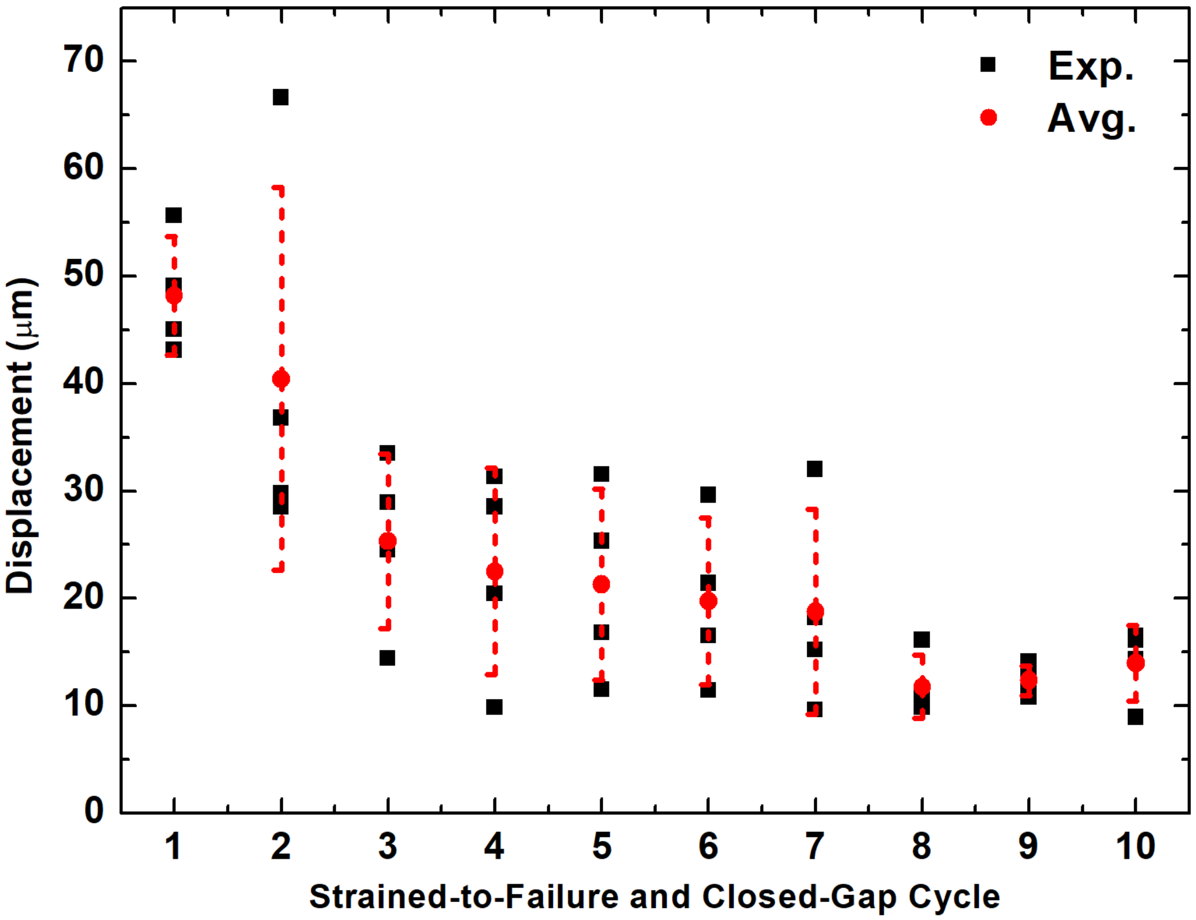
- Elastic modulus control is possible
- Ductility control is possible
- CNT wt% optimization is needed to Increase modulus of toughness

RACK (RESISTANCE ACROSS CLEAVES & CRACKS) MEASUREMENTS



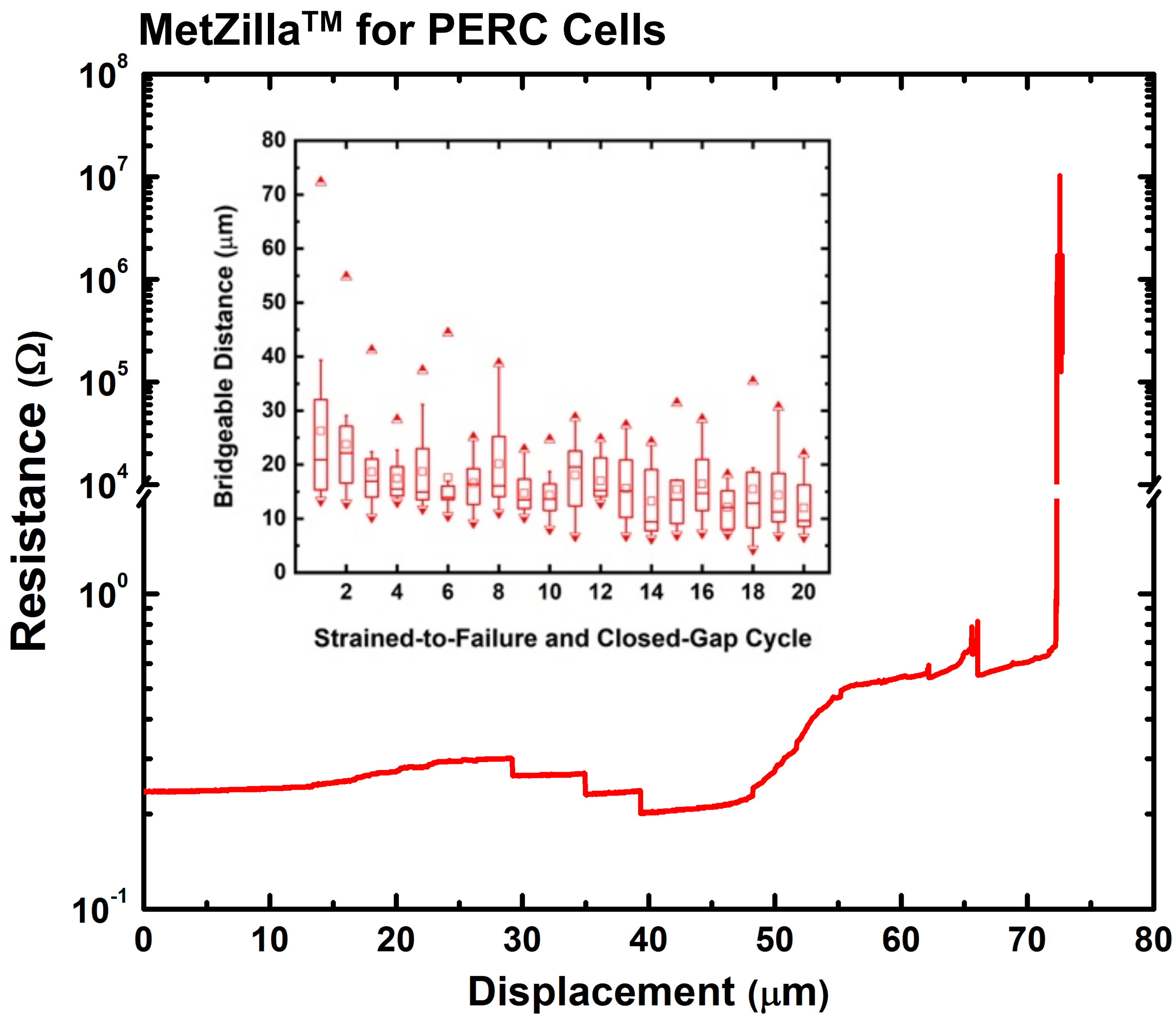
RACK (RESISTANCE ACROSS CLEAVES & CRACKS) – GAP BRIDGING & SELF-HEALING





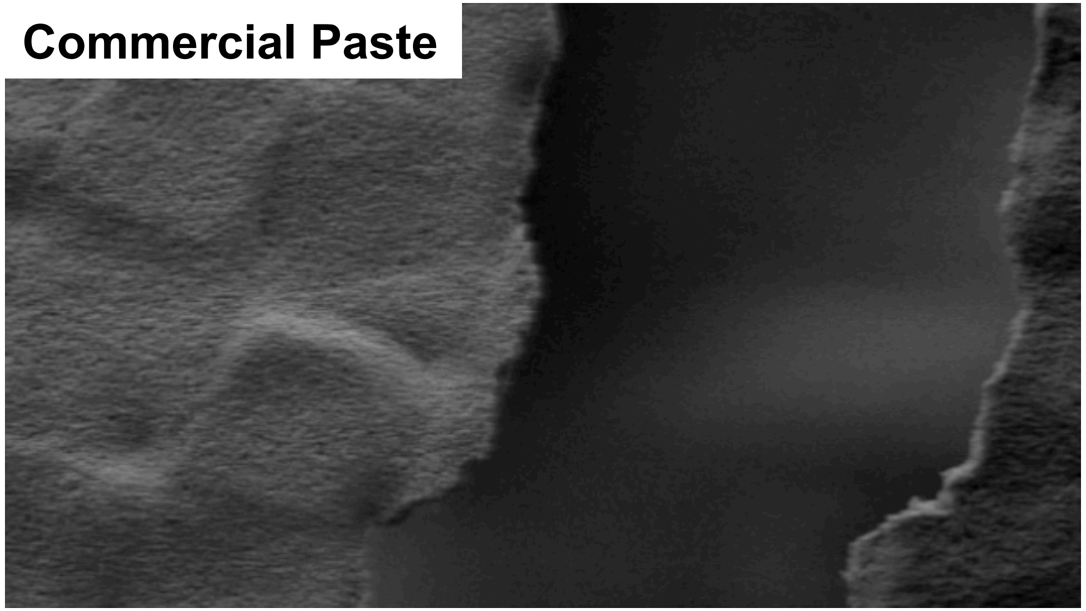
- **>50 μm** maximum bridgeable gap with optimum CNT loading
- "Self-healing" to bridge ~20 μm gaps repeatably

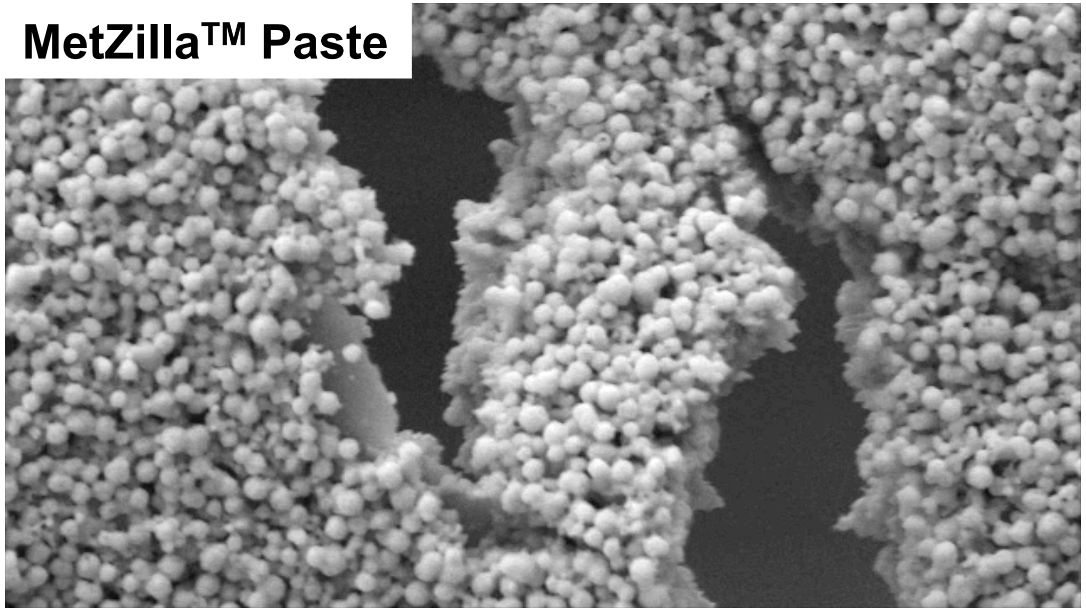
RACK (RESISTANCE ACROSS CLEAVES & CRACKS) – GAP BRIDGING & SELF-HEALING

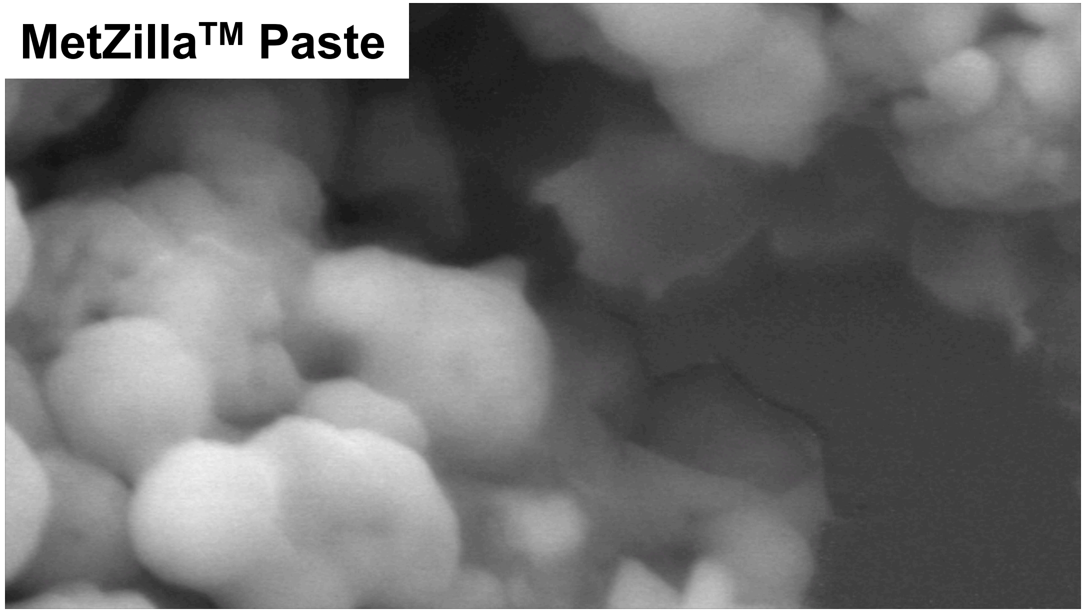


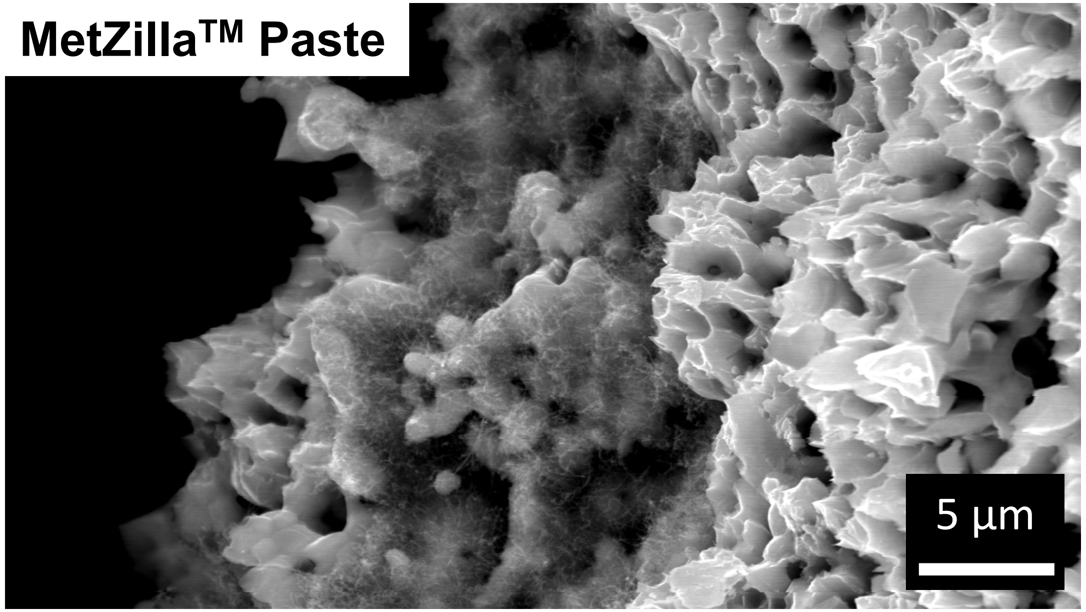
- **20 to 30 μm** average gap and **>70 μm** maximum bridgeable gap
- "Self-healing" to bridge ~10 to 20 μm gaps repeatably
- CNT wt% and firing schedule optimization needed

In Situ Scanning Electron Microscopy During Strain Test (CINT)

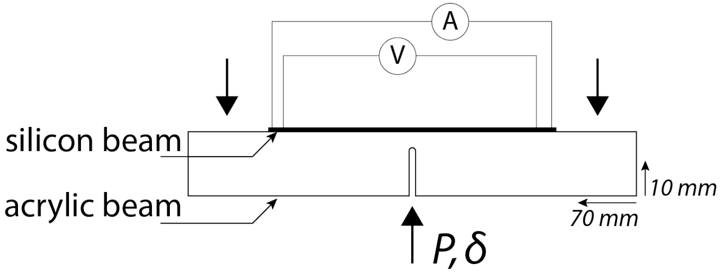


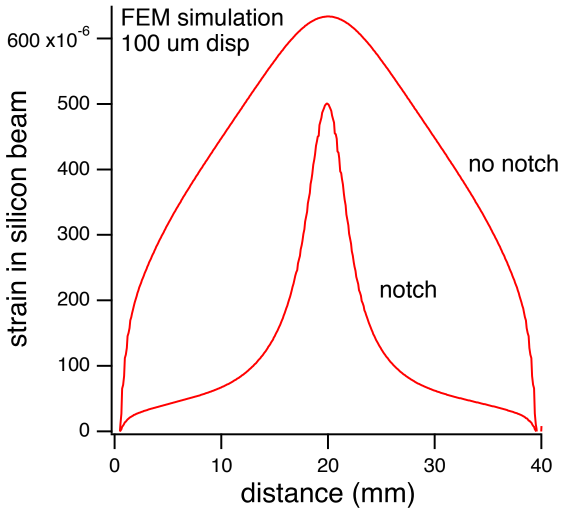


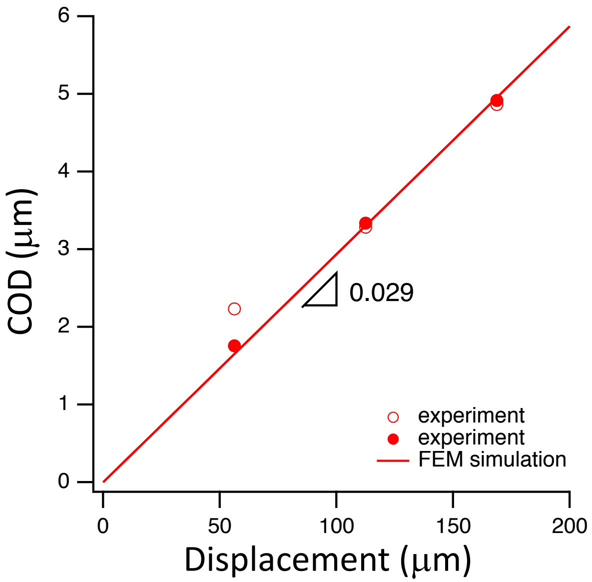


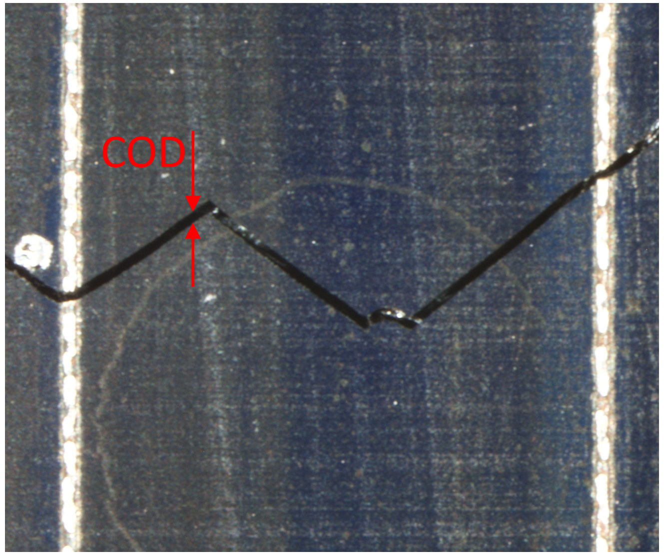


Three-Point Bending Test (NREL)





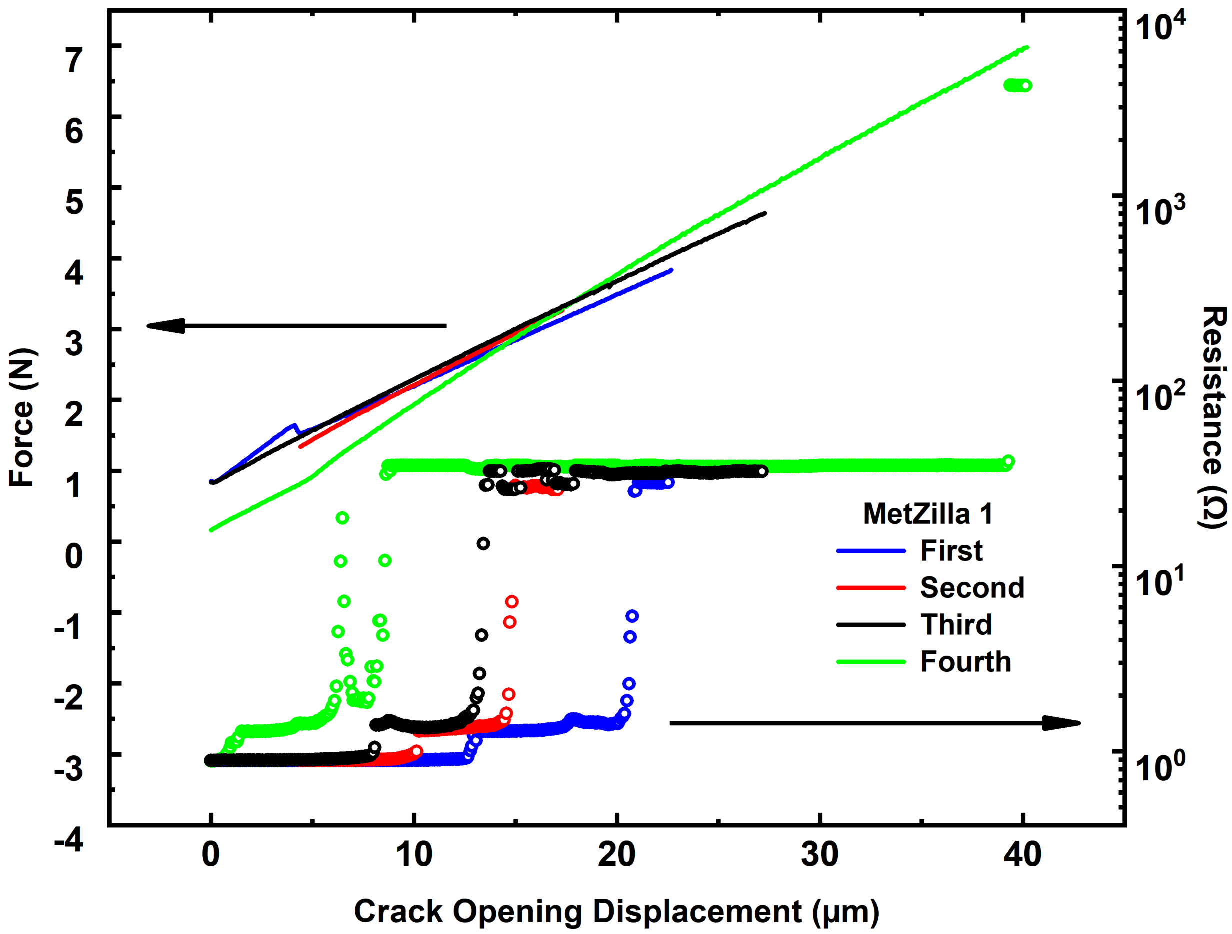




- Two gridlines between two bus bars on Si substrate.
- Si substrate on a notched acrylic beam.
- Concentrated strain at the center to induce a single crack.
- Acrylic beam supports the substrate and transfers strain to Si through 3-point bending.
- Bending load, displacement, and a 4-point electrical resistance across the gridlines are recorded.
- Further displacement after fracture causes the cracked faces of the Si to separate: crack opening displacement (COD).
- Bending displacement vs. COD has been simulated and experimentally verified through optical measurements of a cracked silicon beam.

Three-Point Bending Test (NREL) – Gap Bridging and Self-Healing

- Inflection point in loading force indicates crack formation.
- Baseline gridlines (DuPont paste) becomes electrically open upon crack formation.
- Resistance does not rise upon crack formation for composite gridlines (MetZilla™ paste) .
- Resistance eventually rises to 10s of Ω for MetZilla™ paste for > 20 μm COD.
- MetZilla™ gridlines likely self-heal before reversing back to the inflection point (crack formation).



Three-Point Bending Test – Predictive Degradation Model Development

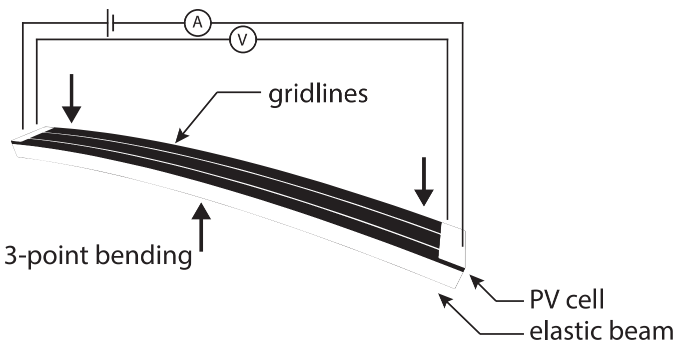
The fatigue life of composite-enhanced metallization is experimentally evaluated by novel cell-level measurements

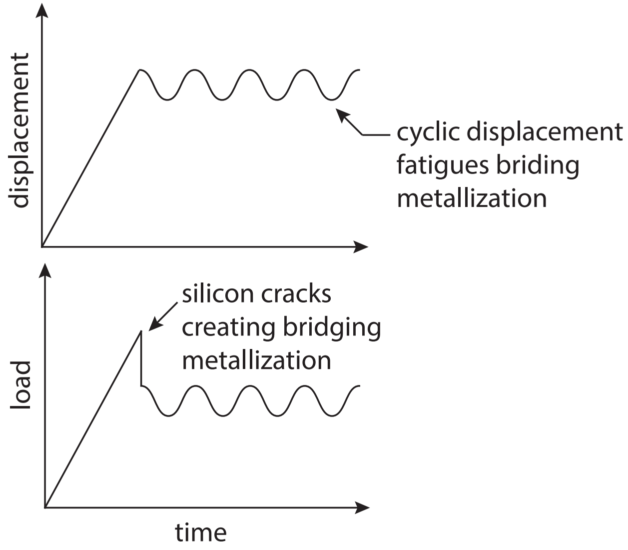
Sections of metallized PV cells are mounted on elastic substrates

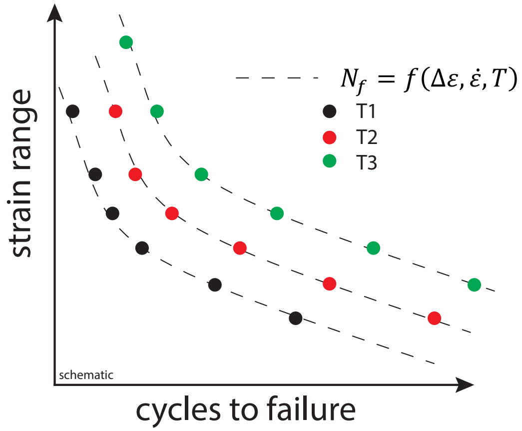
The composite beams are loaded in three-point bending to first crack the silicon and create the bridging metallization, then in a cyclic fashion

A four-point resistance measurement is made across the bridging metallization during cyclic loading

When the bridge becomes open, a failure is recorded







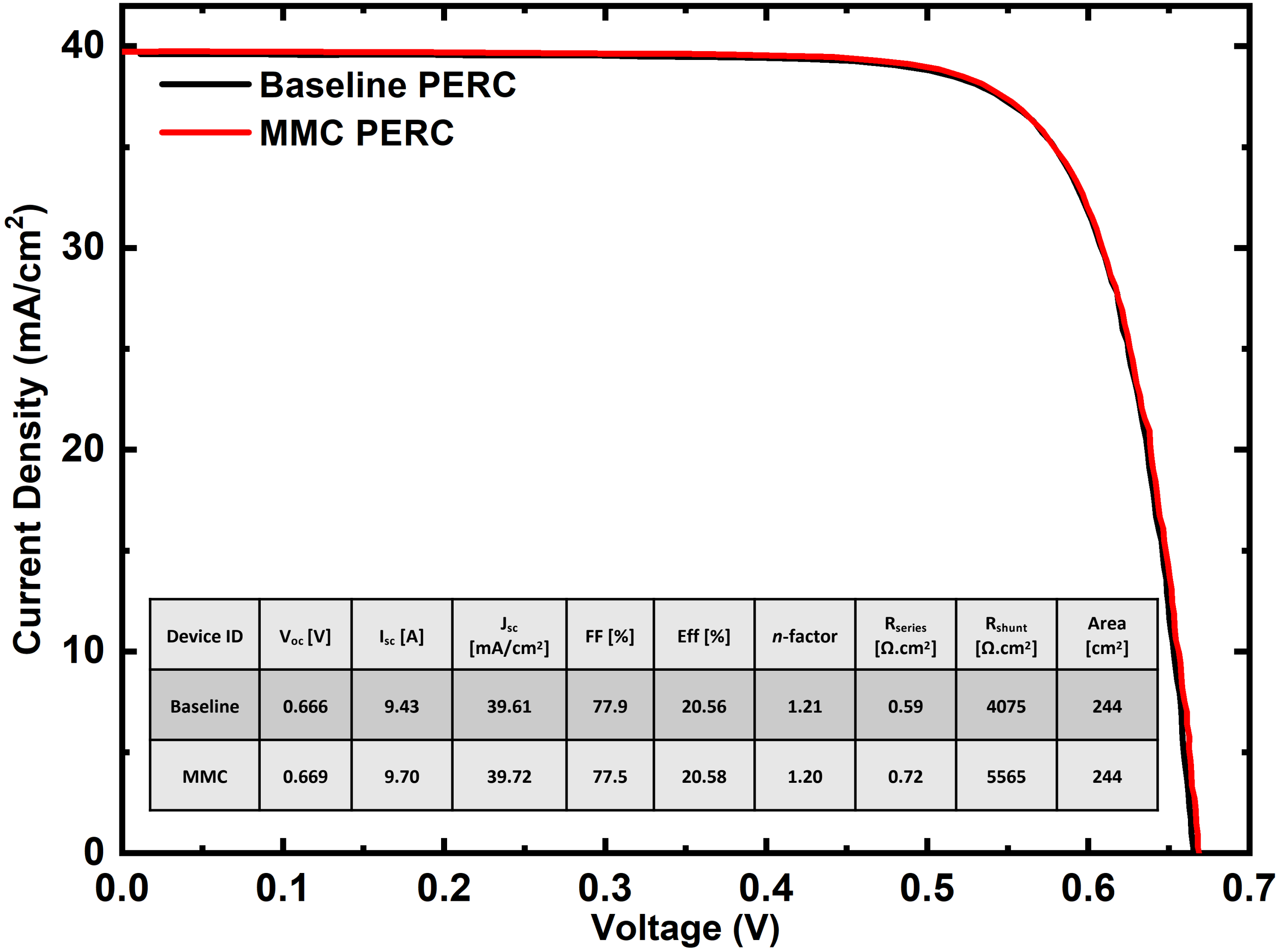
Repeating this measurement at a variety of strain ranges, rates and environmental conditions will describe fatigue life of the composite-enhanced metallization.

$$D = \sum_{i}^{n} \frac{1}{f(\Delta\varepsilon_i, \dot{\varepsilon}_i, T_i)}$$

Simplistically, a function that properly describes fatigue life may then be applied to on-sun module conditions by summing the incremental damage induced by each unique cycle. When *D=1*, failure will occur.

✓Independent verification of gap-bridging and self-healing.
✓*S-N* type measurements for predictive degradation model development.

Cell Performance – Silver Paste MMC



Device ID	V_{oc} [V]	I_{sc} [A]	J_{sc} [mA/cm²]	FF [%]	Eff [%]	*n*-factor	R_{series} [Ω.cm²]	R_{shunt} [Ω.cm²]	Area [cm²]
Baseline	0.666	9.43	39.61	77.9	20.56	1.21	0.59	4075	244
MMC	0.669	9.70	39.72	77.5	20.58	1.20	0.72	5565	244

✓ Similar cell performance with CNT incorporation

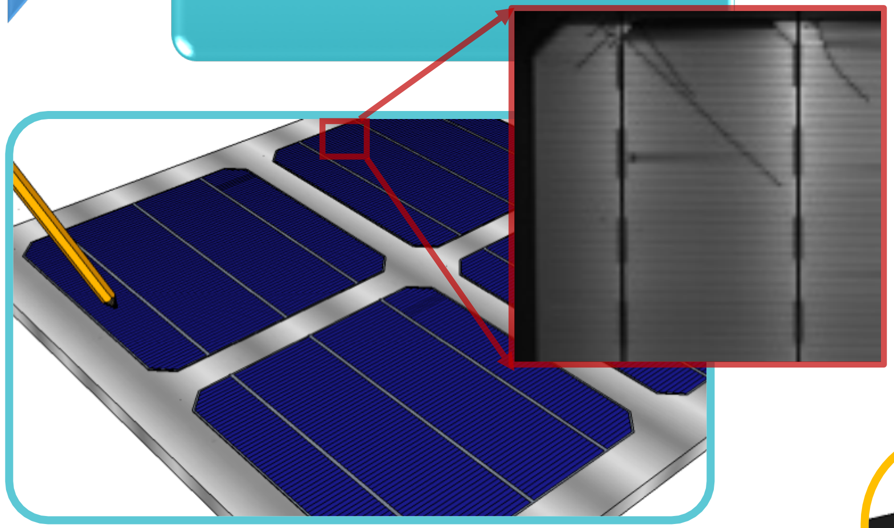
Description on Module Testing

Module Construction

- Physical layout
- Ribbon tabbing
- Bottom encapsulant

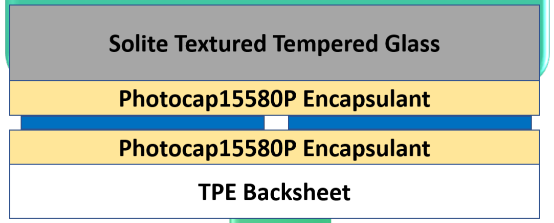
Initial Defects

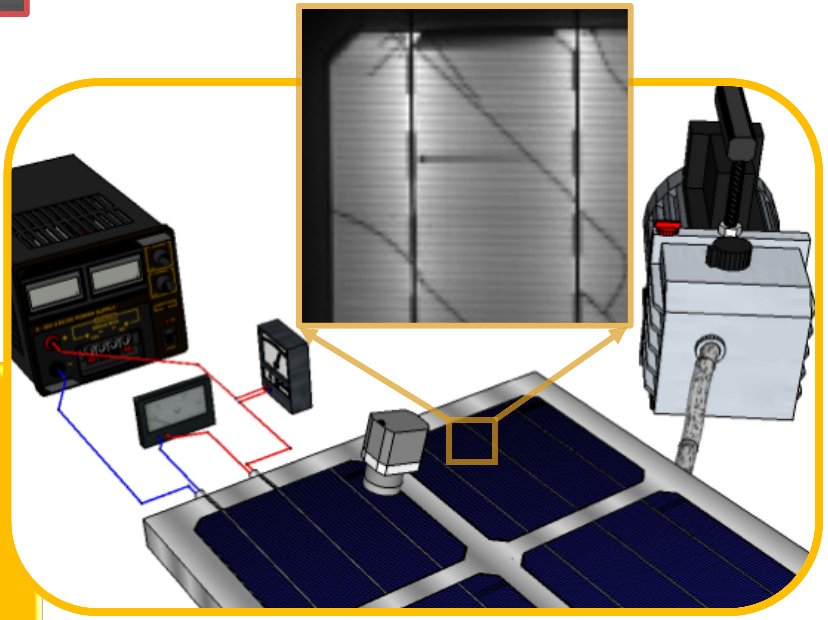
- Diamond scribe used to manually introduce cracks



Module Construction

- Top encapsulant
- Sample lamination



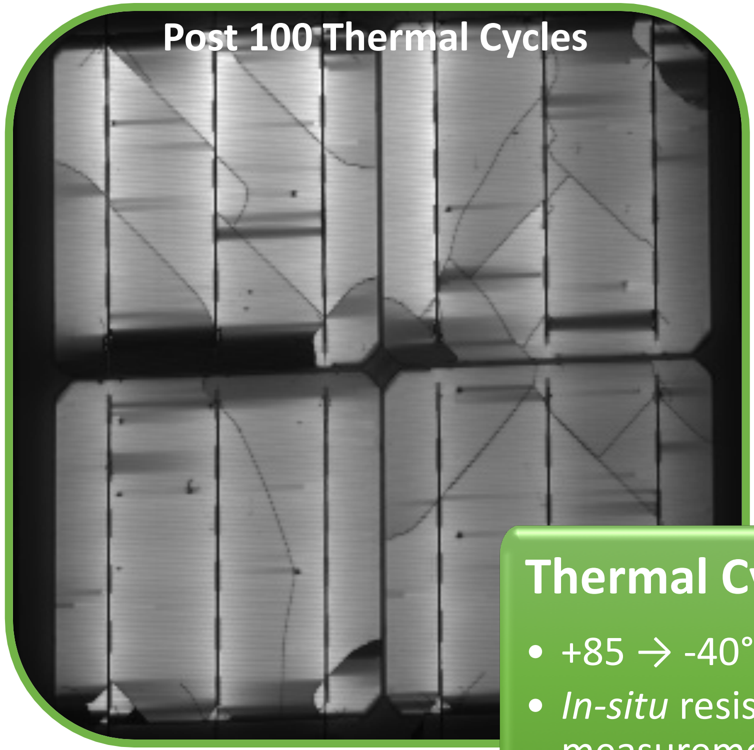


Vacuum Cracking

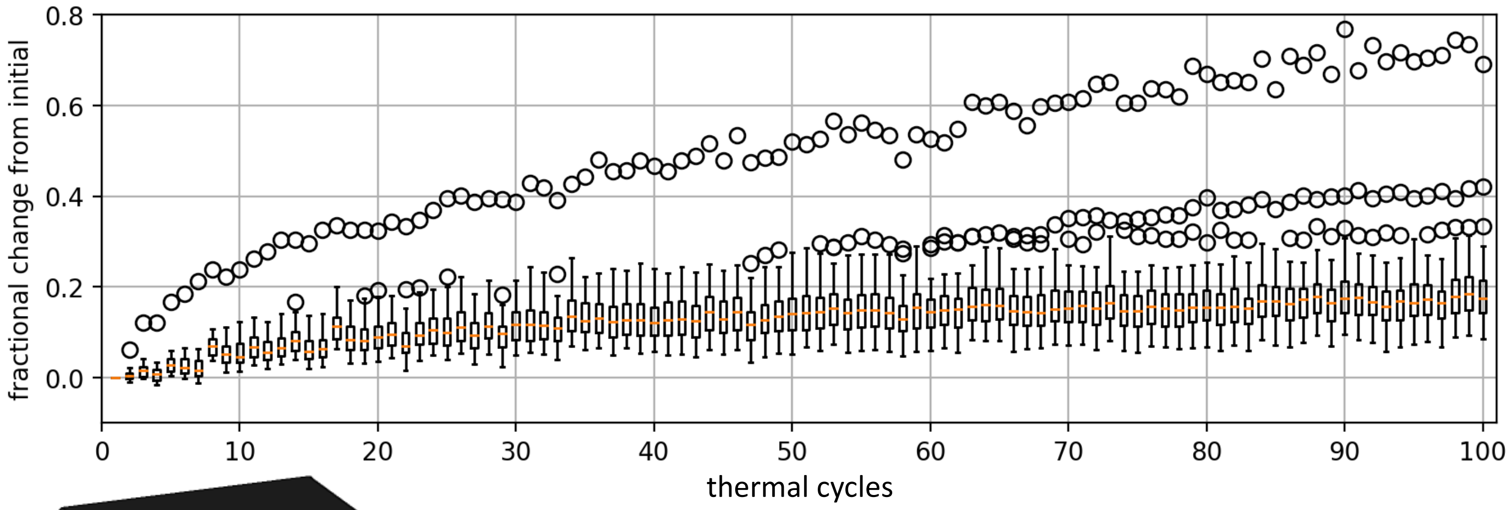
- Vacuum applied 0 – 15 kPa
- EL and resistance measurements post-crack

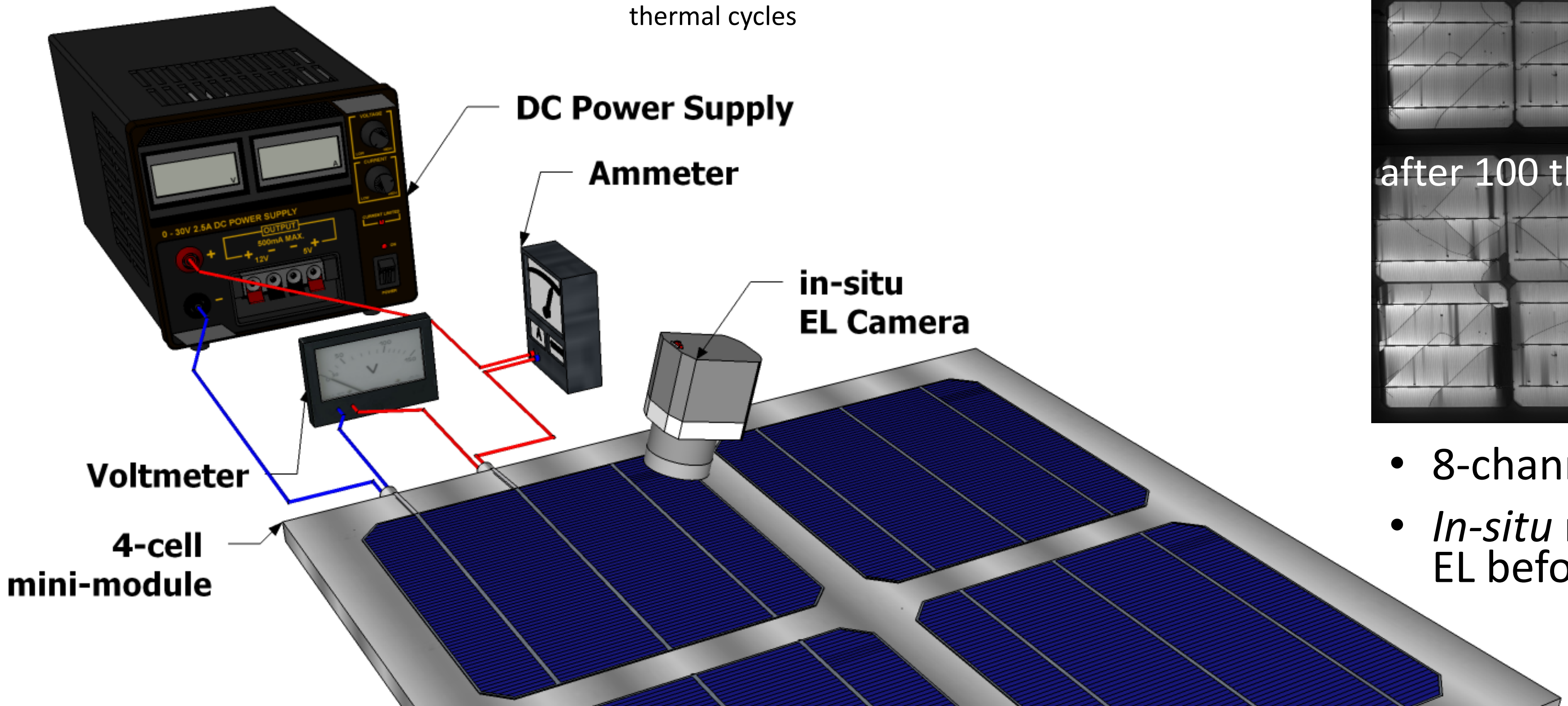
Thermal Cycling

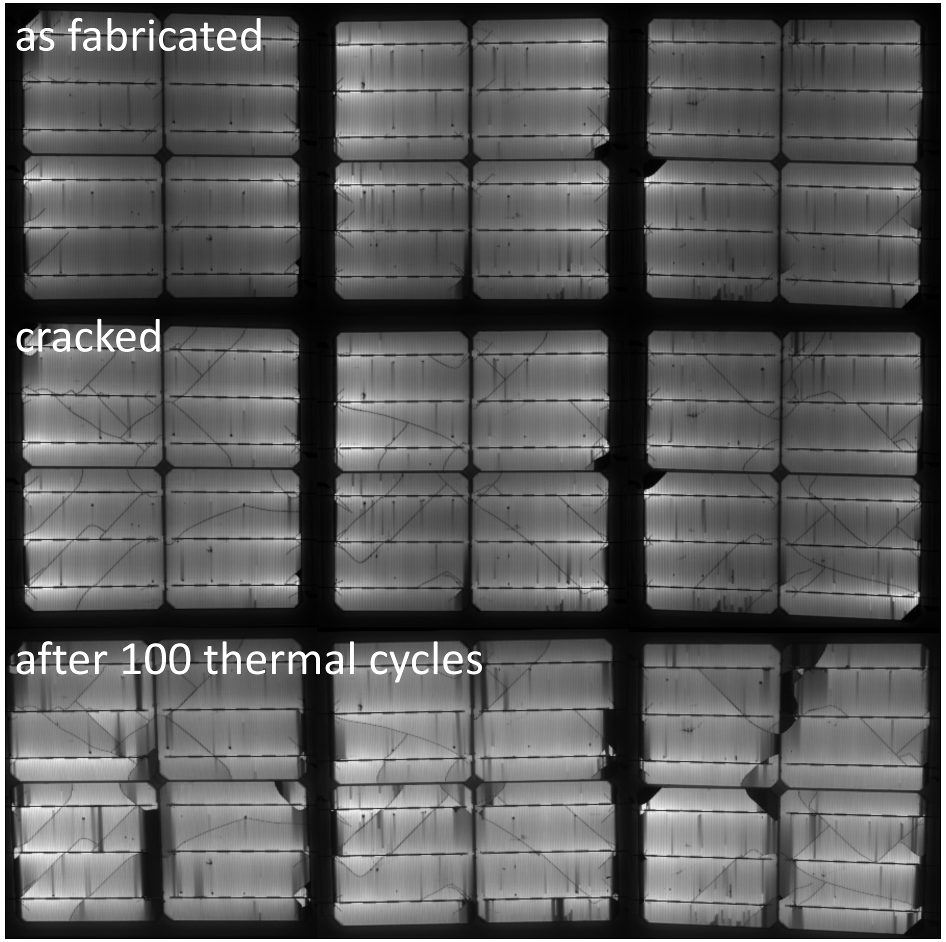
- +85 → -40°C
- *In-situ* resistance measurements



Baseline Module Testing

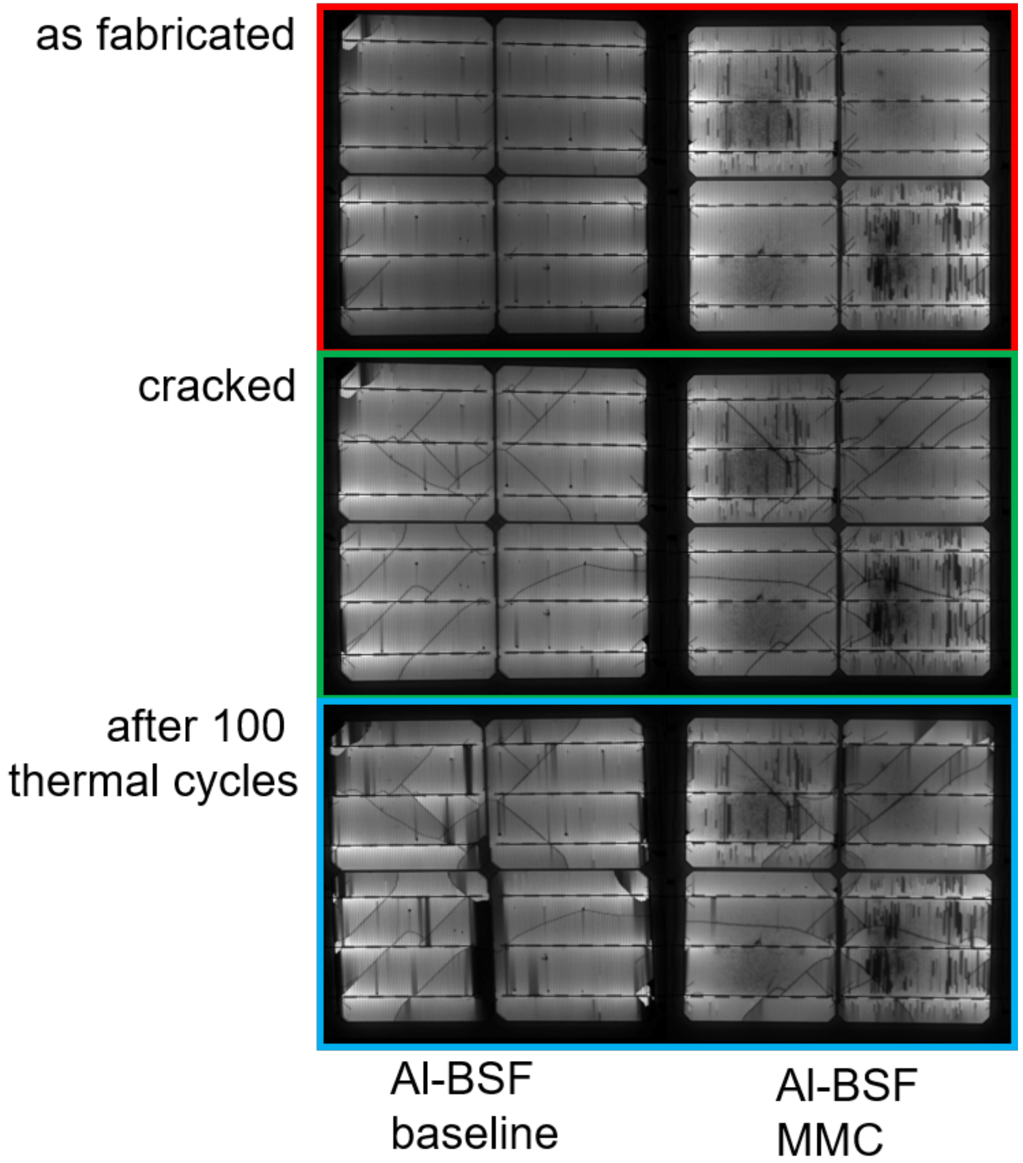


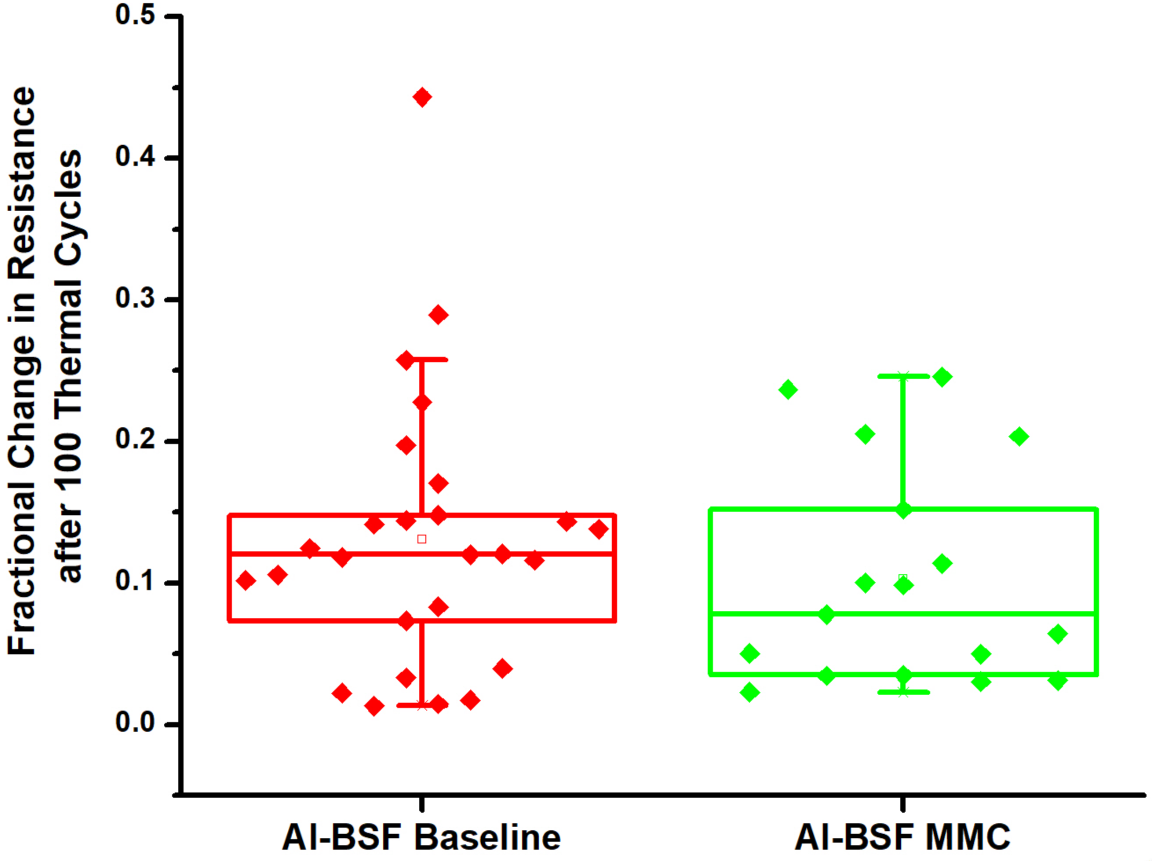




- 8-channels measurement per module
- *In-situ* resistance measurements and EL before and after thermal cycling

Module Integration – Accelerated Testing





- Commercial Ag paste as baseline
- MMC shows slower degradation
- Future testing with PERC

CONCLUSIONS

- Fracture toughness increases with CNT incorporation.
- MMC-enhanced metallization can provide > **50 µm** gap bridging capability.
- "Self-healing" occurs when the fractured composite gridlines are brought together.
- "Self-healing" is repeatable and settles at **10 to 20 µm**.
- Beginning-of-life cell performance is approximately the same with and without the MetZilla^{TM} integration.
- MetZilla^{TM}-enhanced Al-BSF modules degrade at a slower rate compared to baseline modules.
- Accelerated testing will be conducted on PERC mini-modules.

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Next DuraMAT Webinar

December 11, 2019

"Demonstrating New Concepts for Reliable Low-Cost Module Encapsulation and Moisture Barrier Technologies"

Presented by Reinhold Dauskardt of Stanford University

Register at duramat.org/webinars.html