Quantifying Primary Arc-induced Degradation of Perovskite Solar Cells

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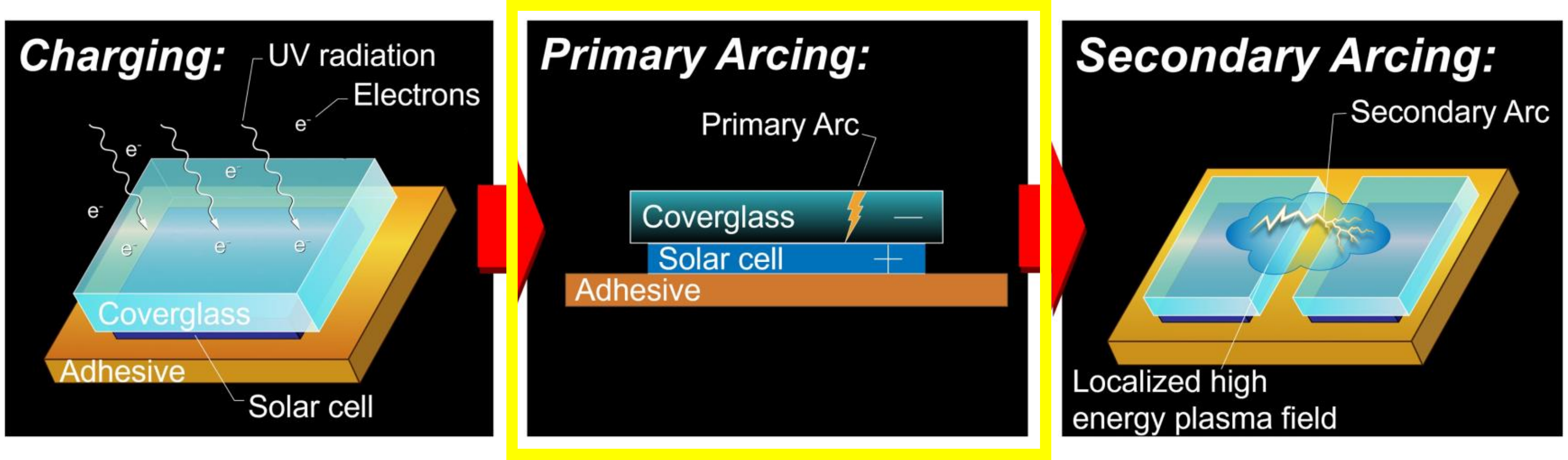
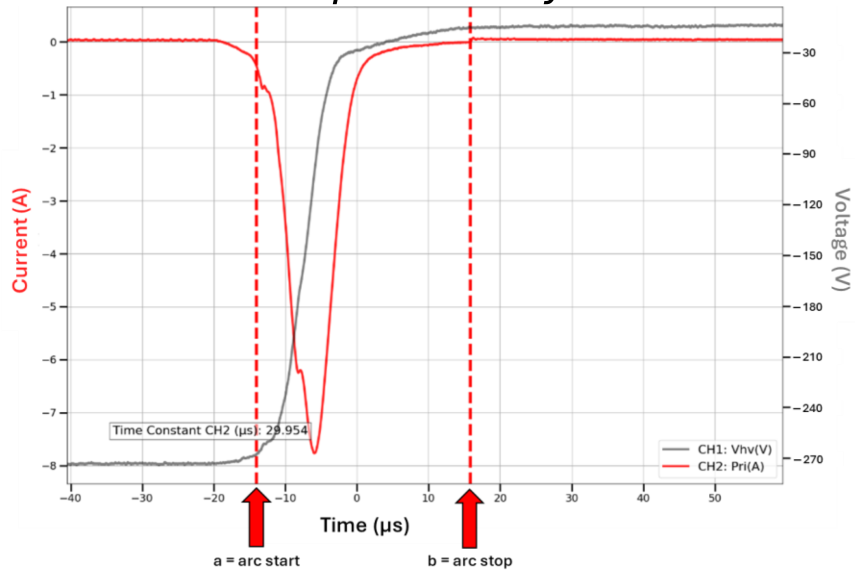
Intro to Spacecraft Charging

- Operation in the space environment exposes solar cells to charged particles, which can induce electrostatic discharges on the cell.
- **Due to their very thin architecture, preliminary research indicates that perovskite solar cells may be especially susceptible to damage via primary arcing.**
- We aim to characterize perovskites' vulnerability to primary arcing to best inform protecting them.

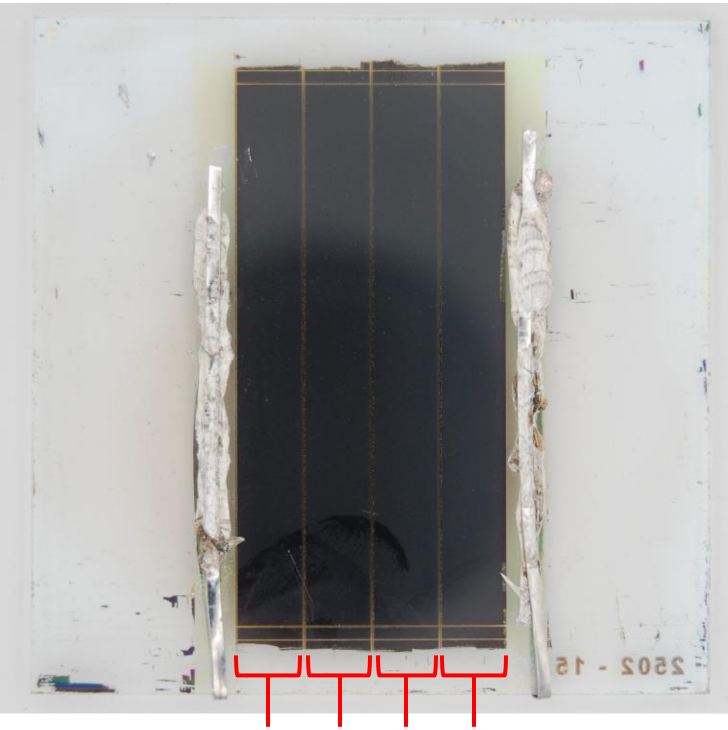


Example Primary Arc



Experimental Setup

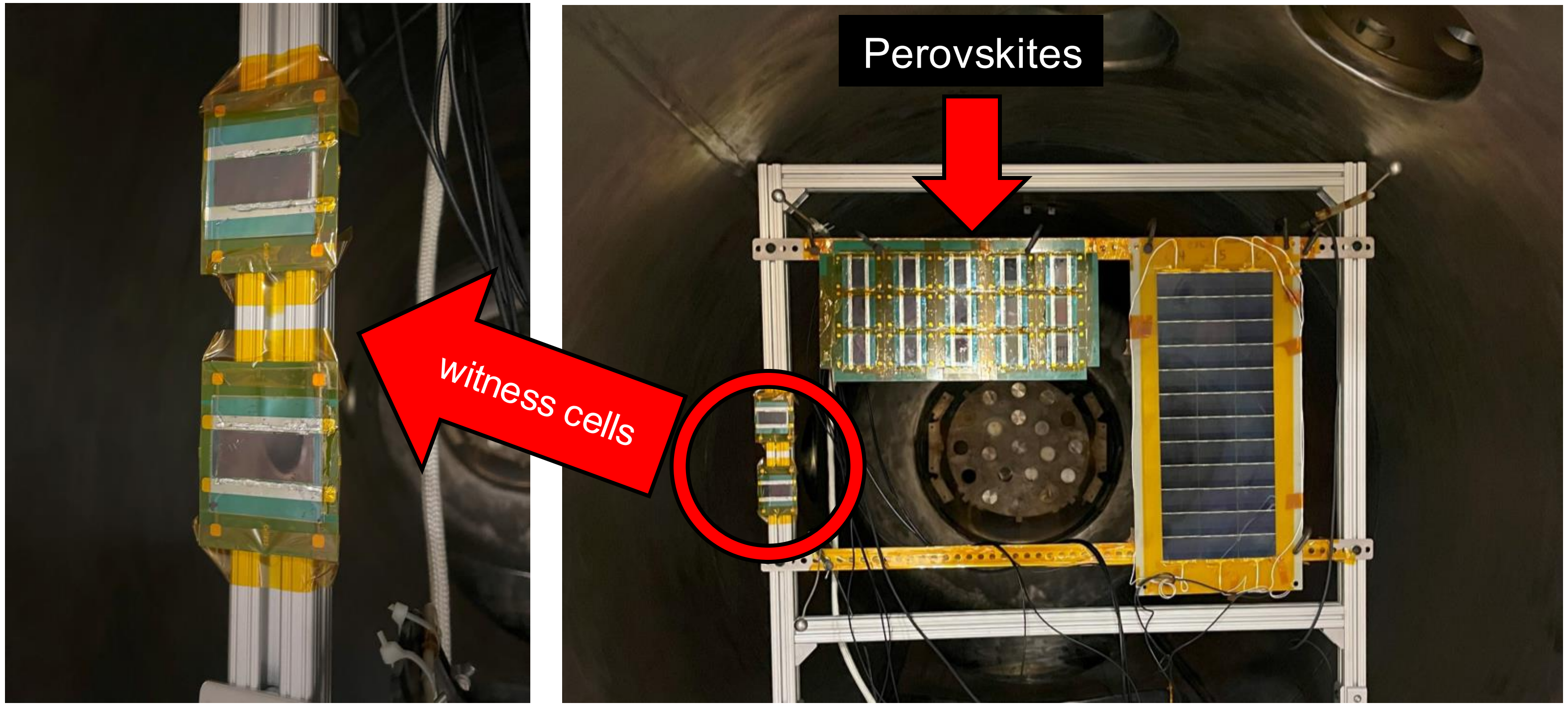
"Mini-module" from NLR



4 individual subcells in series

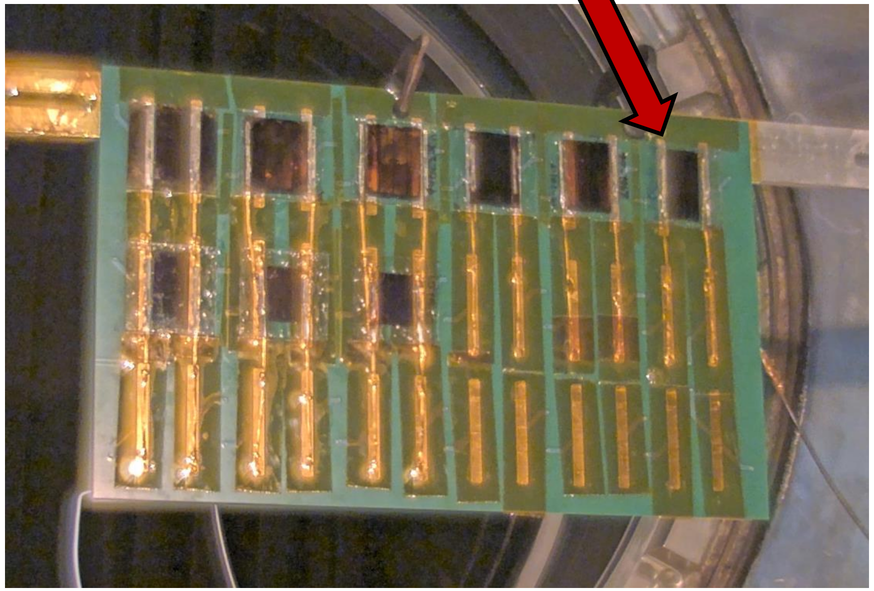
For clarity, I will be referring to each mini-module as a "cell" throughout this presentation; all 4 subcells are characterized together.

Inside the vacuum test facility, cells are divided into three strings of five cells each; two witness cells are included that will undergo high vacuum but *no primary arcing*.



A cycle of damage:

Primary arc



Arc current **injects heat into cell**

Heating causes **damage** (material pyrolysis, shunting)

Surface defects can strengthen e-field and **increase primary arc probability at that point**

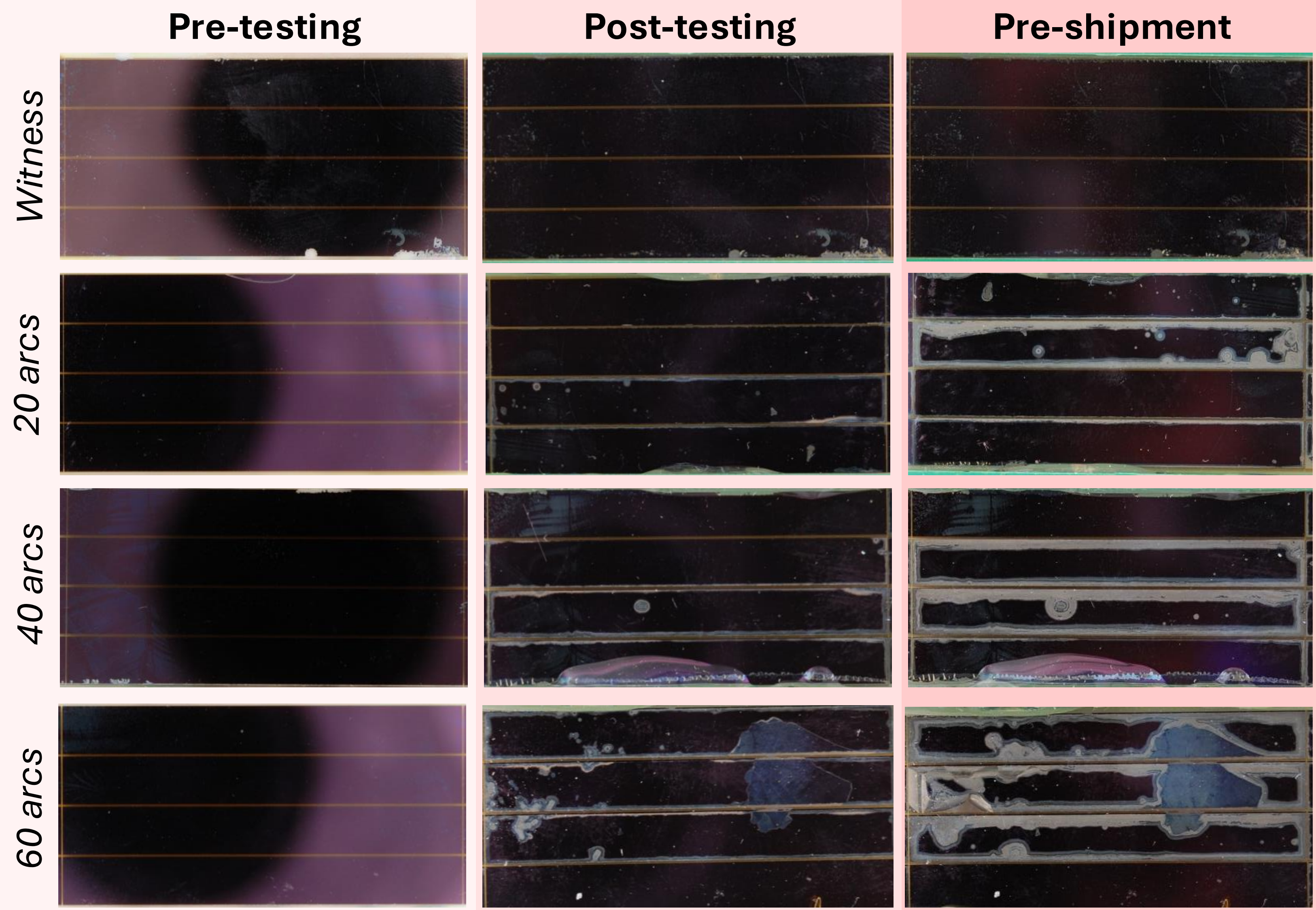
Shunts preferentially draw current during next arc, **increasing localized heating**

Increased primary arc rate and resulting thermal stress cause significant damage to cell

Physical Degradation

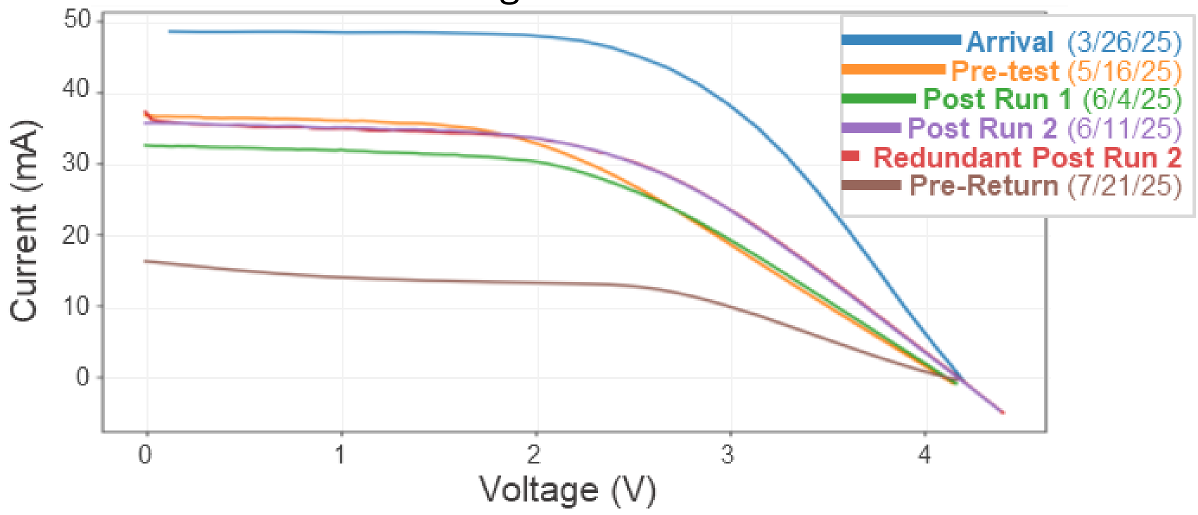
- Characterization, including LIV and visual inspection, was conducted before testing, after each ESD test run, and again before shipment back to NLR.
- When not actively under test or characterization, cells were kept in a nitrogen-purged environment.
- We noted that physical degradation of the cells that arced **did not halt when returned to safe environment.**

Takeaway: The stress of primary arcing induces a type of autocatalytic degradation of the perovskite cells.



Performance Degradation

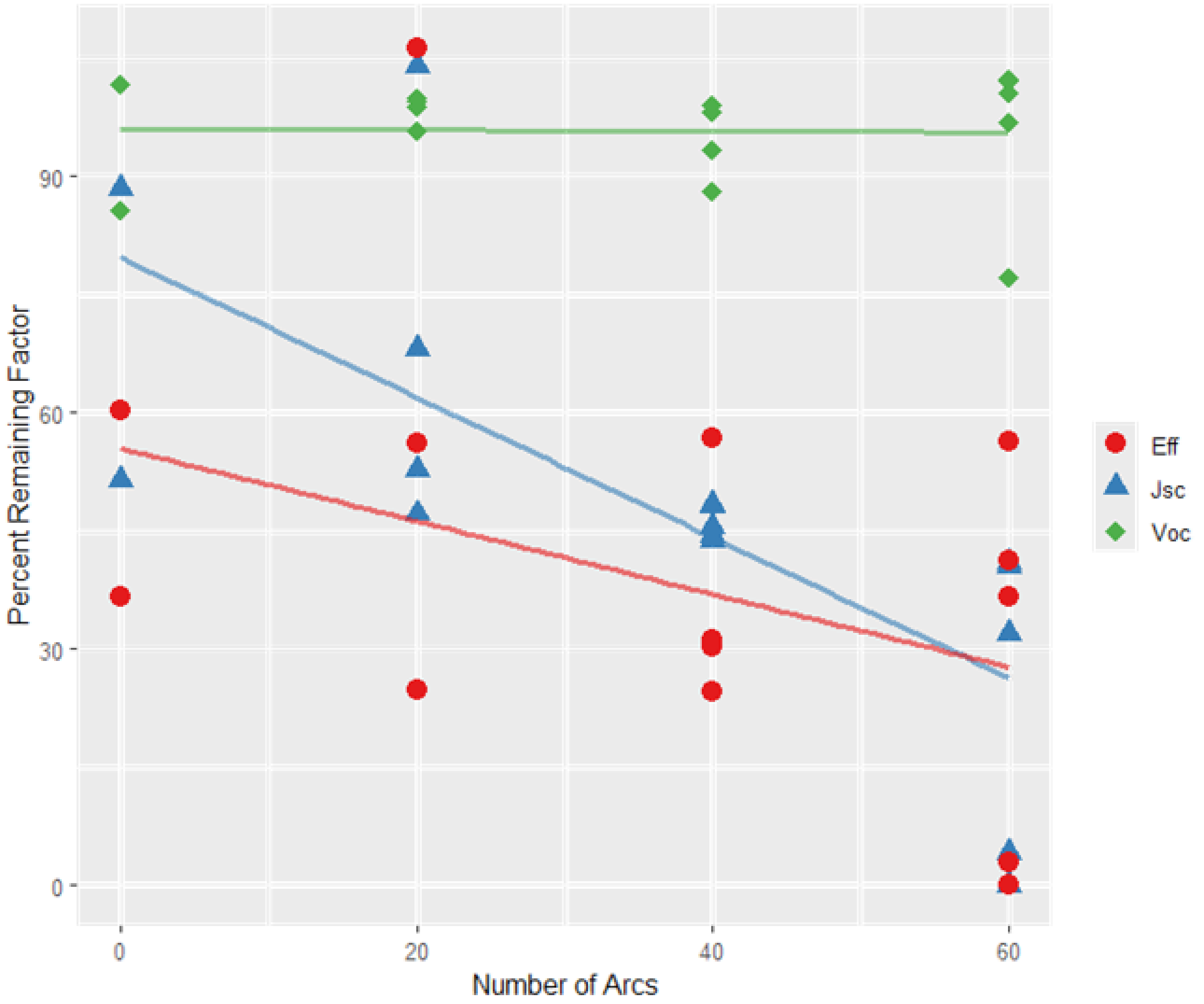
Demonstrative LIV Degradation



Takeaway: Isc and efficiency degradation begins after minimal amount of arcing and worsens significantly with increasing number of arcs.

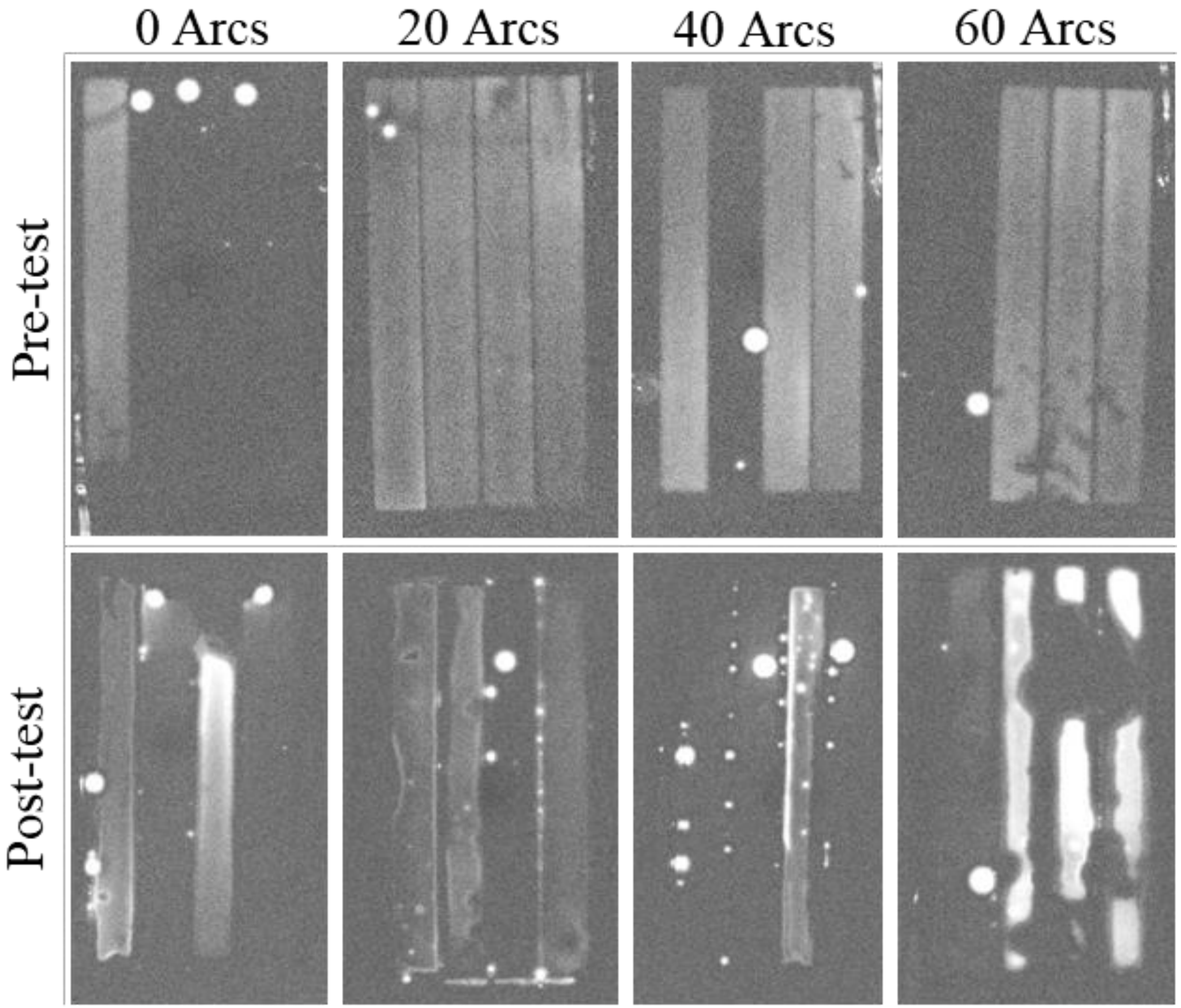
	#Arc	Voc	Eff	Jsc	FF
#Arcs	1.00	-0.02	-0.38	-0.73	0.28
Voc	-0.02	1.00	0.31	0.17	0.44
Eff	-0.38	0.31	1.00	0.86	0.63
Jsc	-0.73	0.17	0.86	1.00	0.24
FF	0.28	0.44	0.63	0.24	1.00

Cell Parameter Degradation



Dark Lock-in Thermography (DLIT)

- Since our hypothesis was that primary arcing would create shunts in the perovskite material, we took DLIT images before and after testing.
- All cells had at least one shunt upon arrival.
- For cells that experienced no arcing, shunts remained.
- For cells that *did* experience arcing, **visual degradation of the perovskite material often corresponded with a new or pre-existing shunt**.

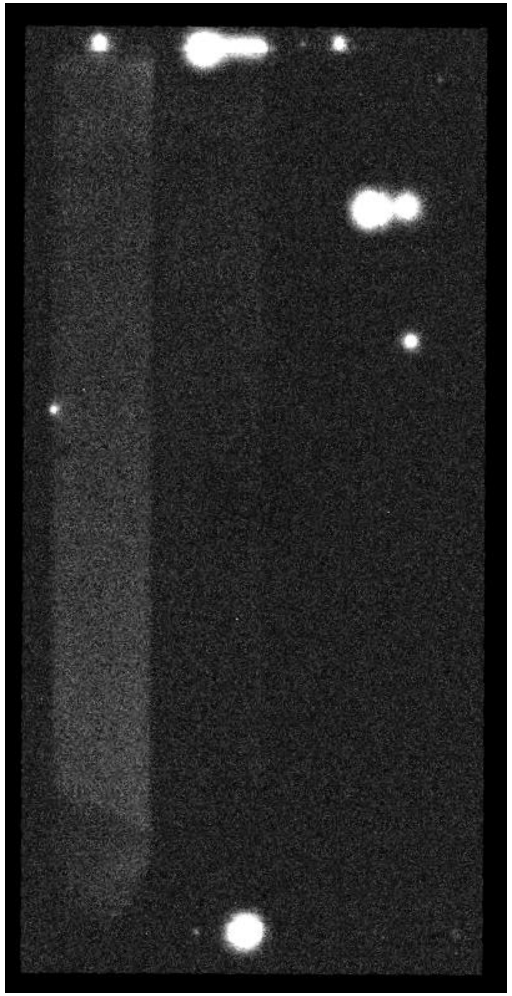


Takeaway: Shunts present at the start of testing may have served as higher likelihood arc locations, worsening damage in that area.

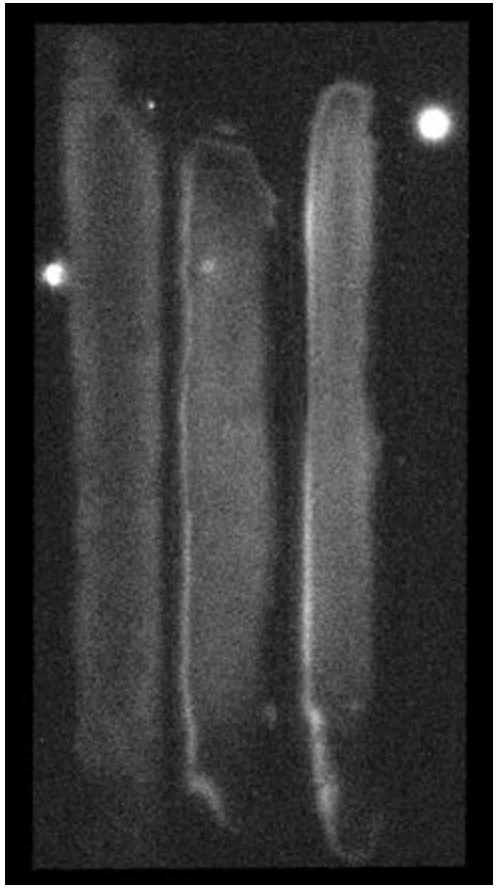
S_5305011: **40 arcs**

Post-test Visual

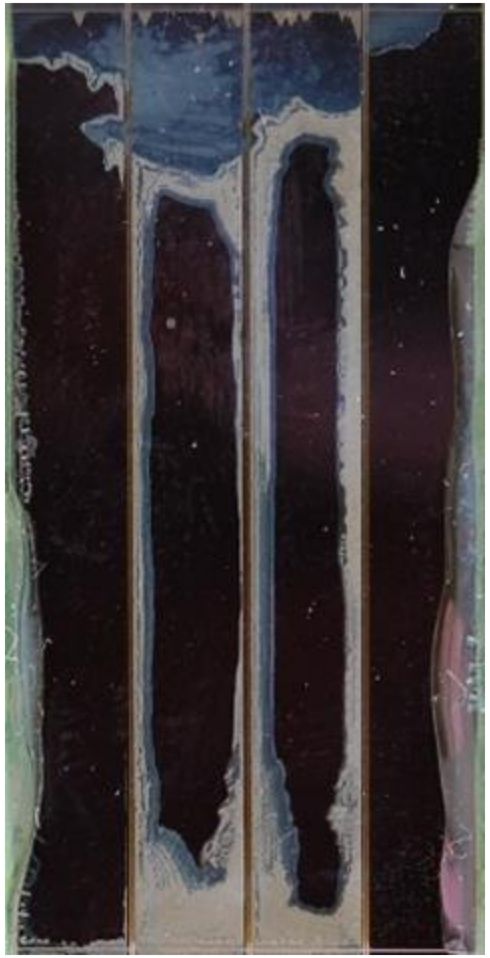
Pre-DLIT



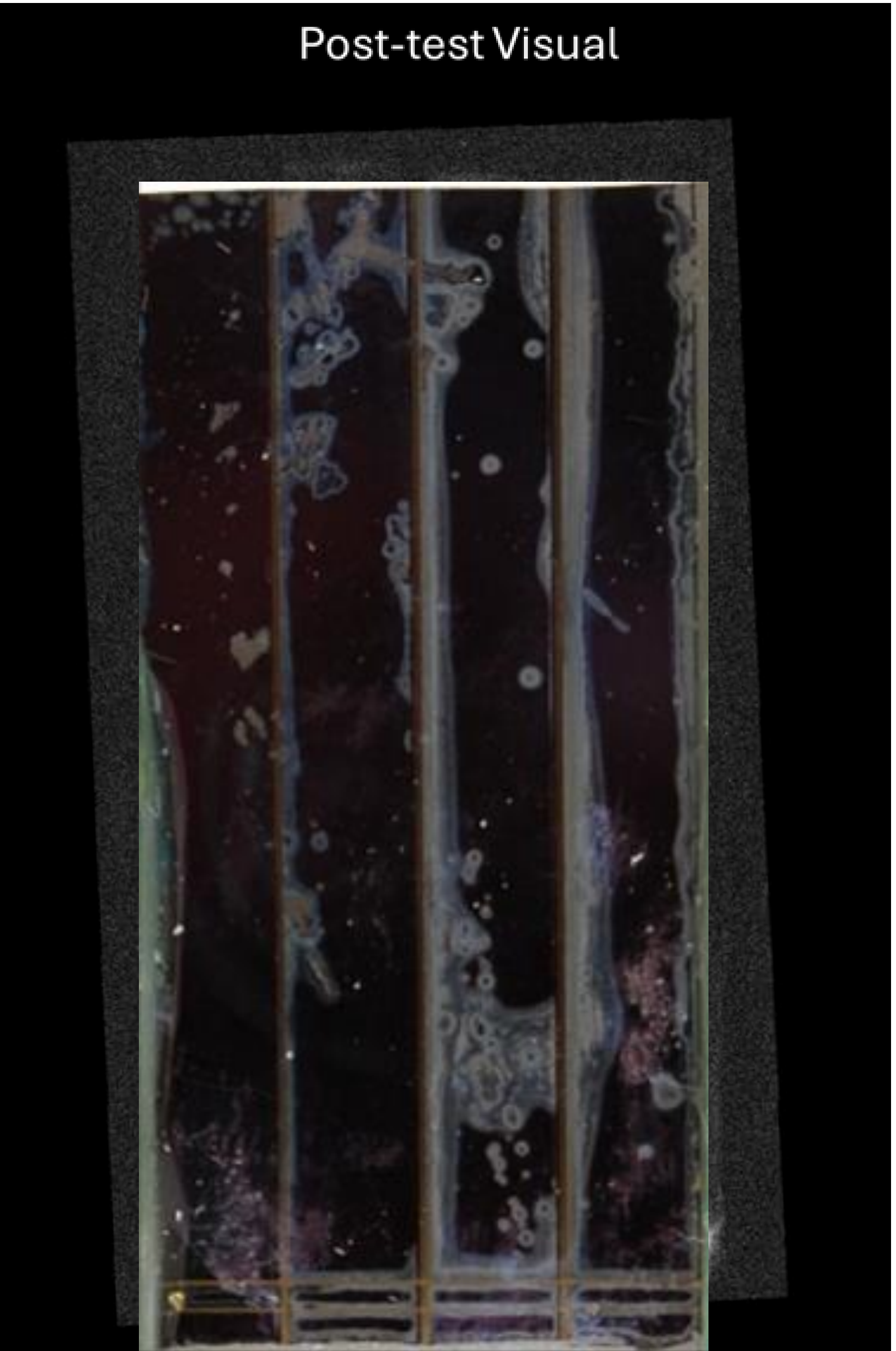
Post-DLIT



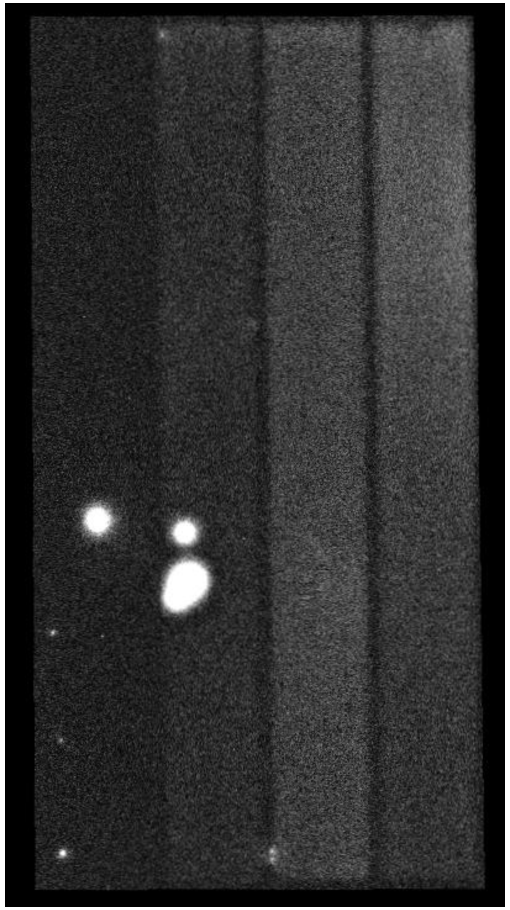
Post-Visual



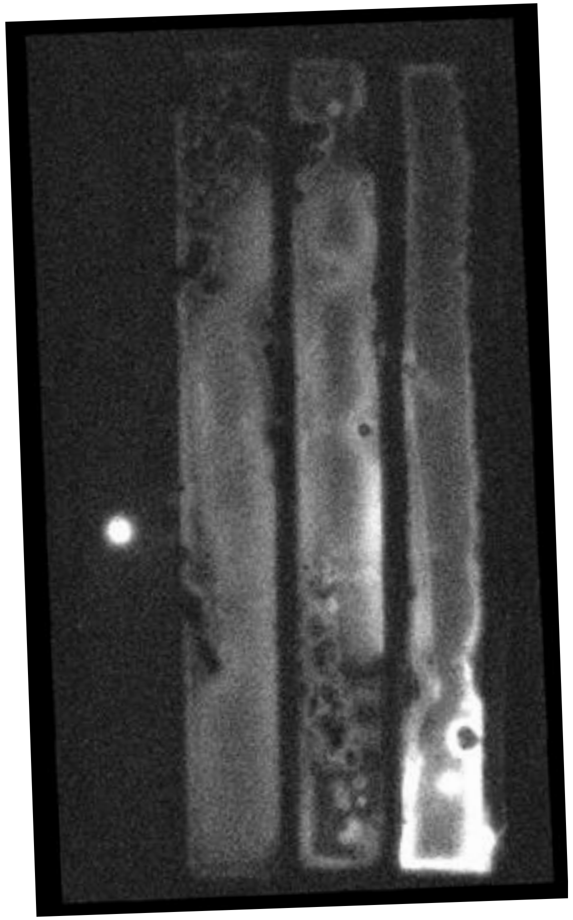
S_5305017: **40 arcs**



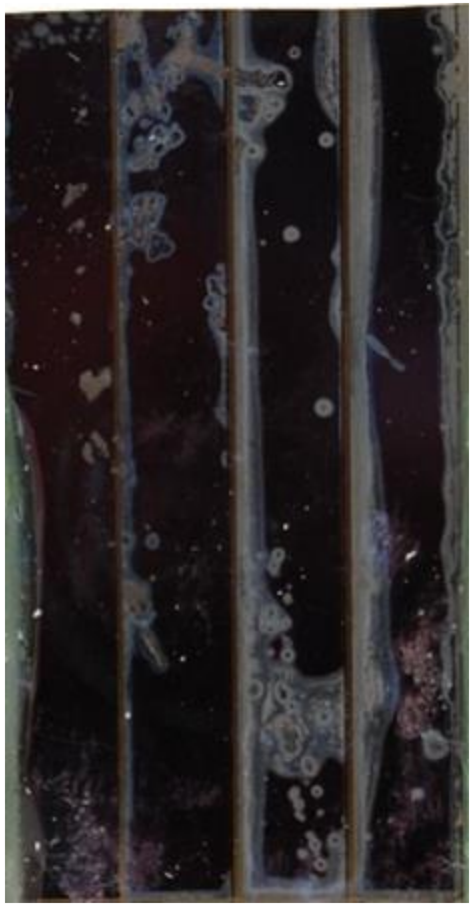
Pre-DLIT



Post-DLIT

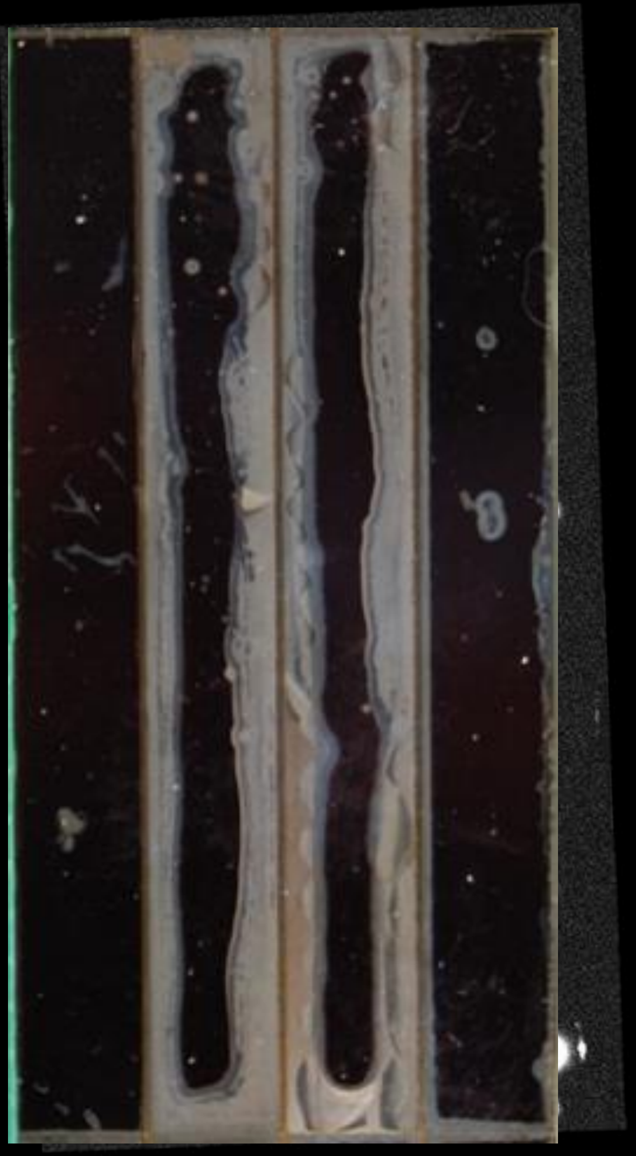


Post-Visual

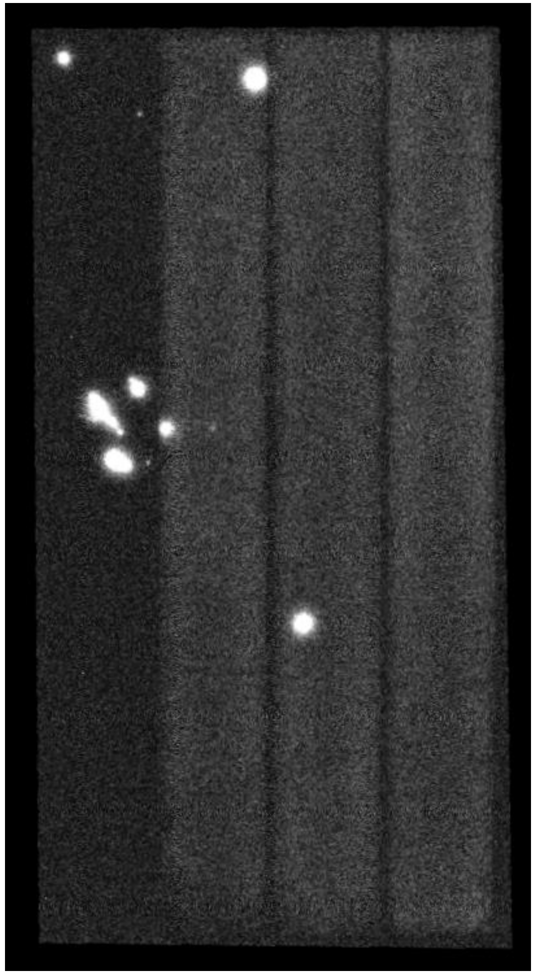


S_5305008: **60 arcs**

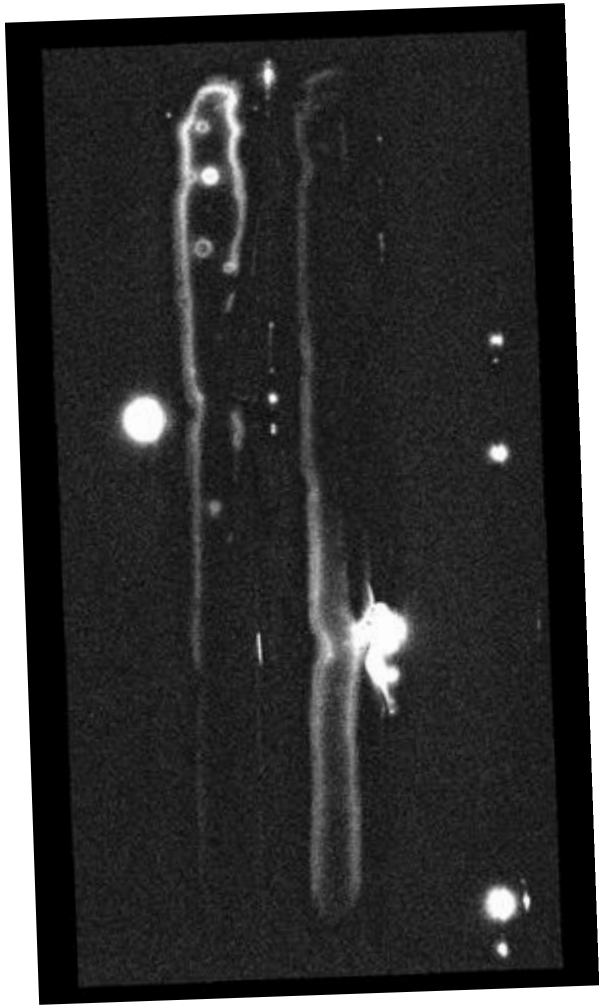
Post-test Visual



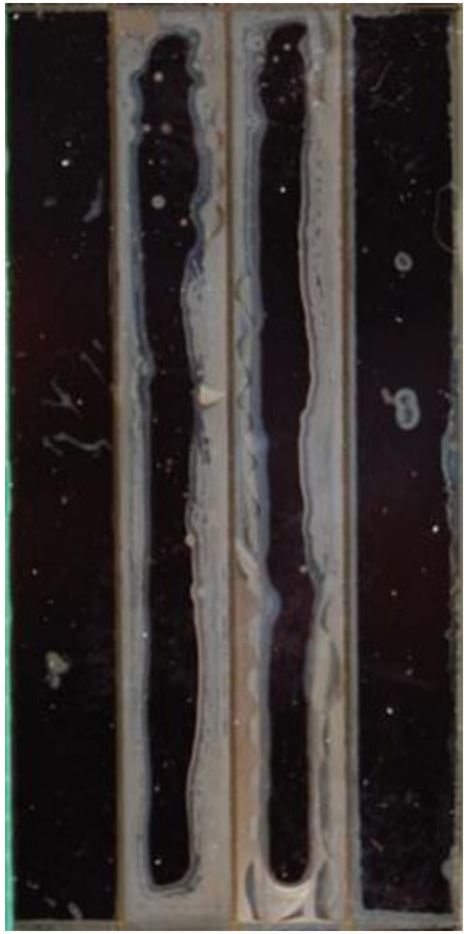
Pre-DLIT



Post-DLIT

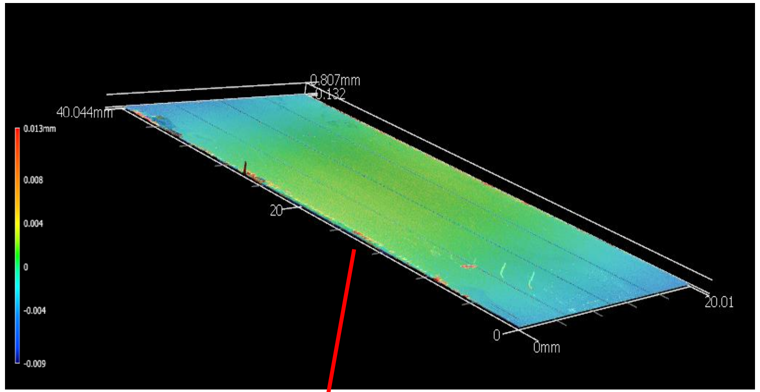


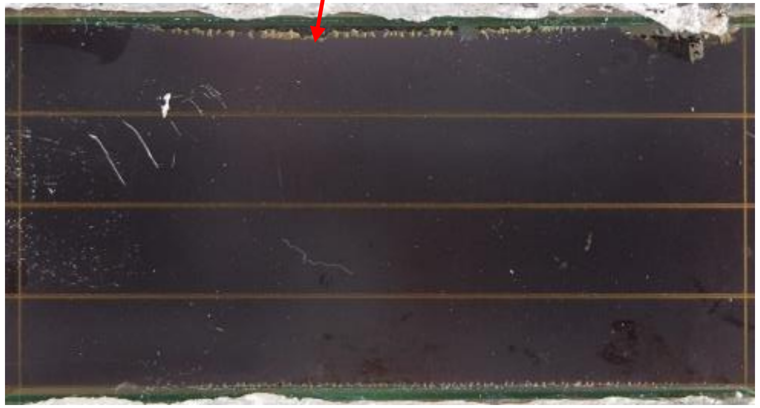
Post-Visual



Profilometry – Visual

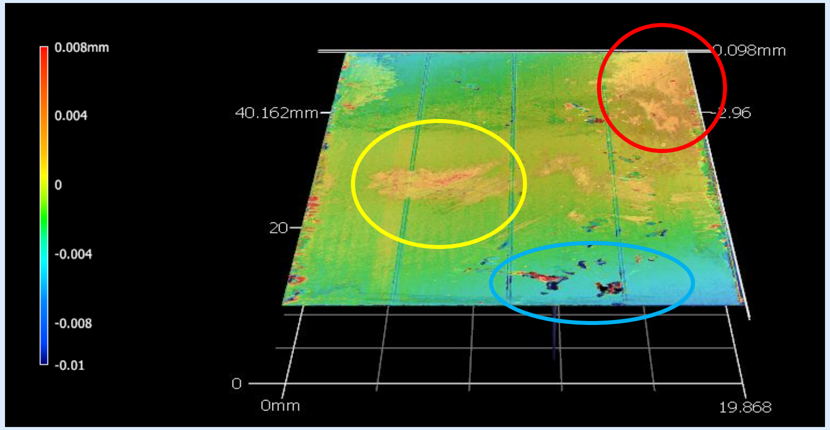
Witness Sample (#12)

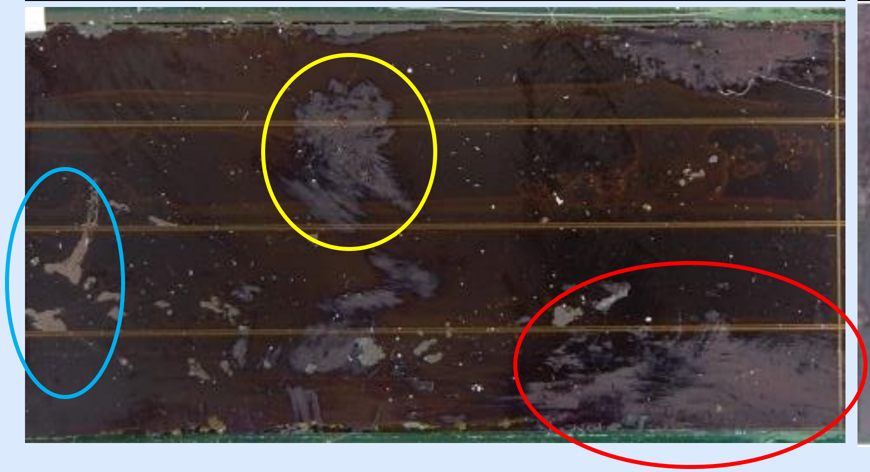




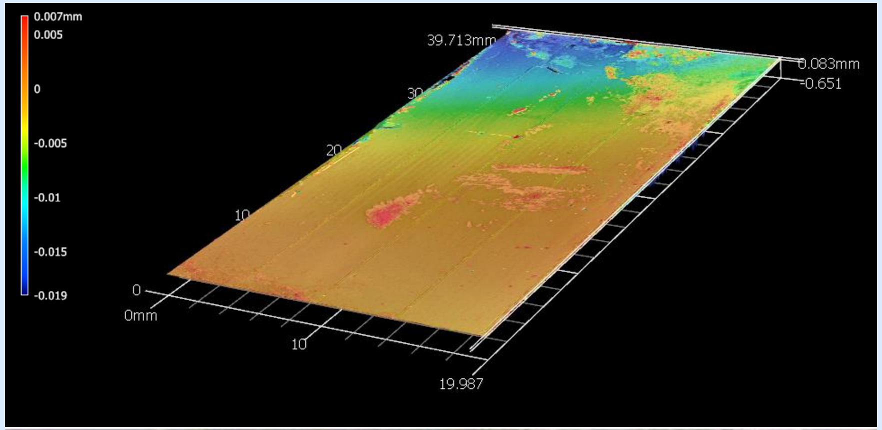
Defects largely constrained to scribe lines.

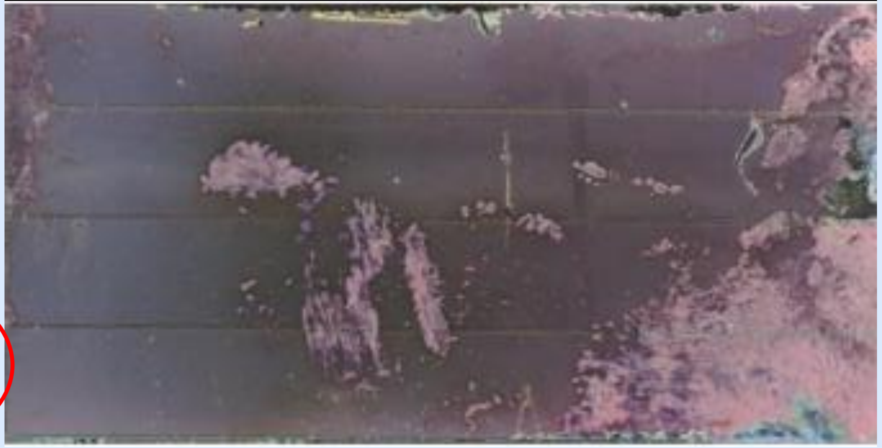
String 2 (40 arcs)





String 3 (60 arcs)

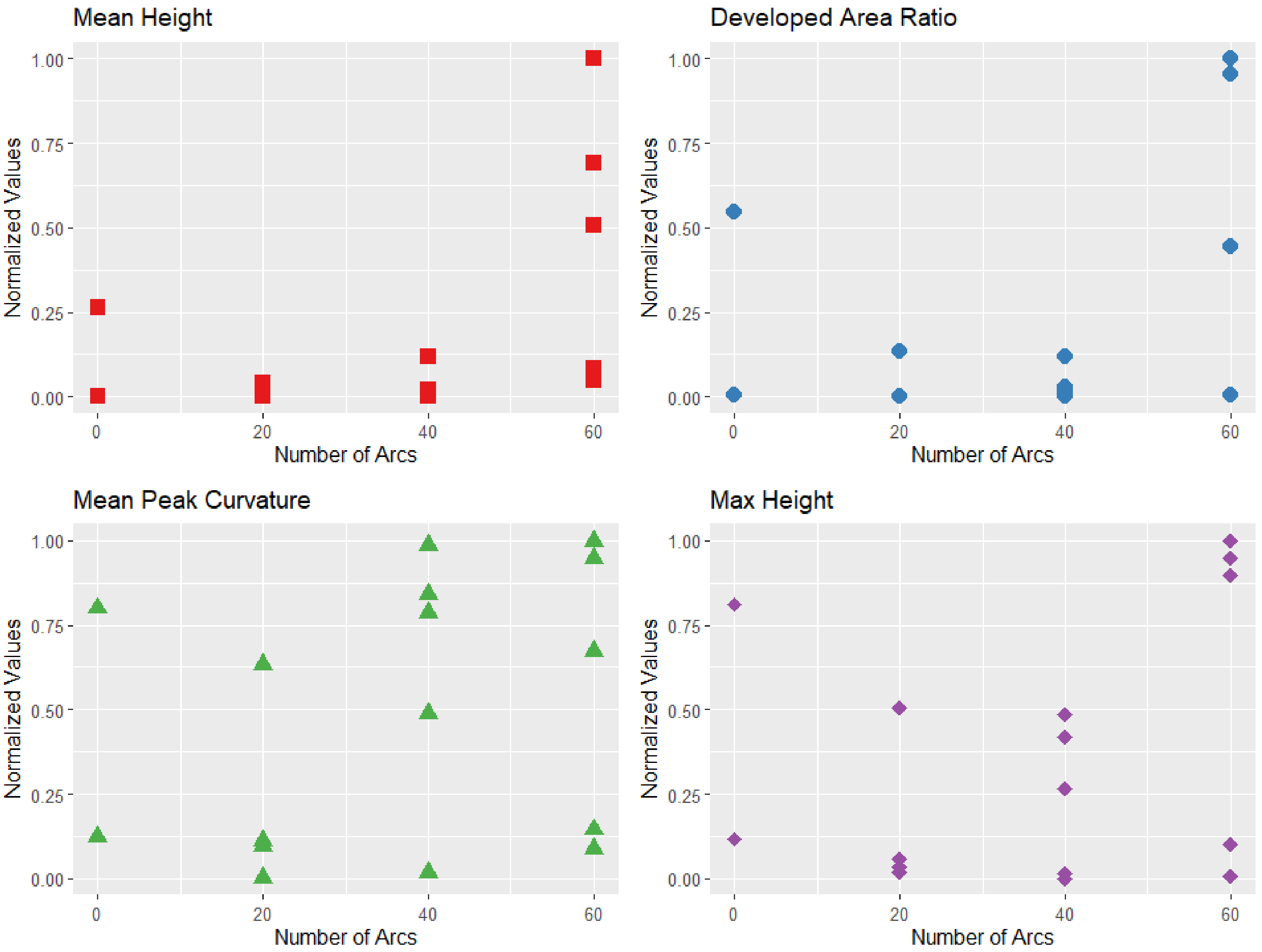




Defects in the module occurring at scribe lines **and across cells.**

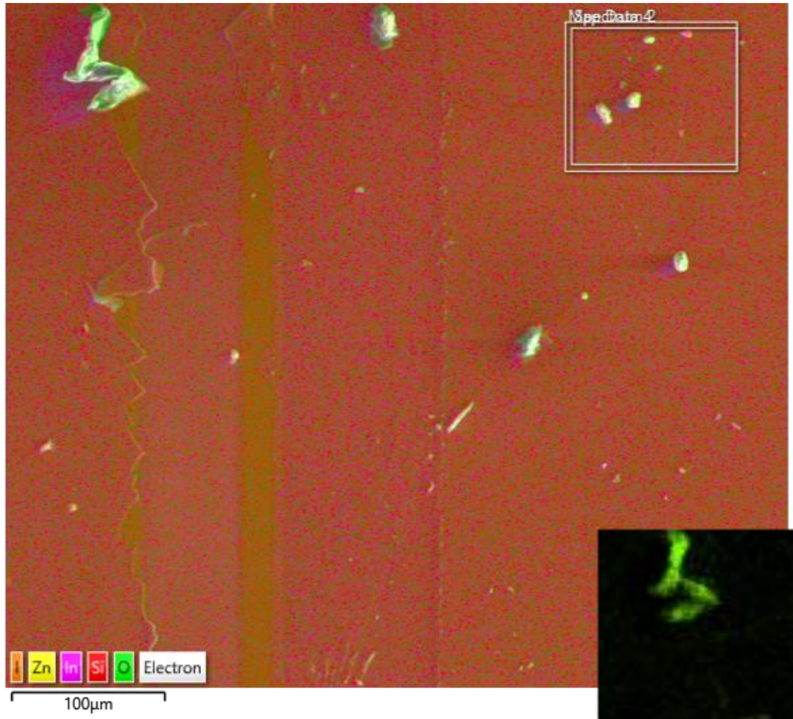
Profilometry – Quantitative

- Samples that experiences 60 arcs see an increase in **mean height** and **developed area ratio,** both of which indicate an increase in surface roughness and irregularity.
- No strong trend in mean peak curvature, indicating that curves are both round and sharp.



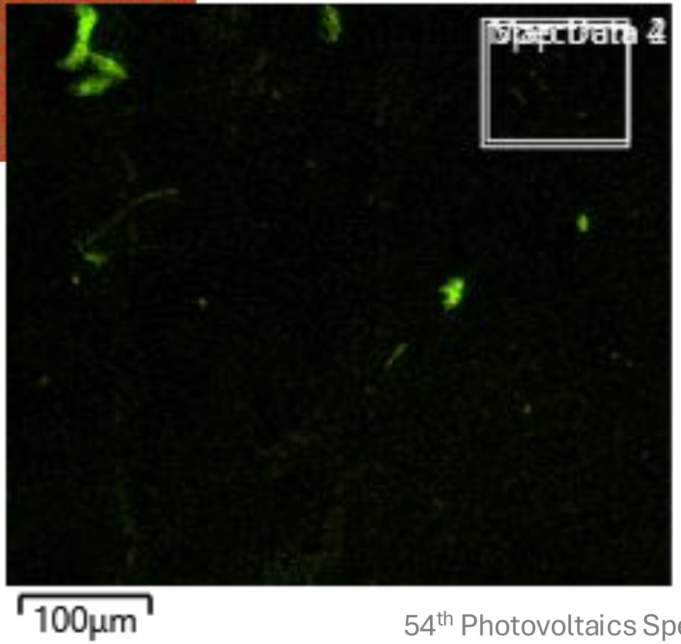
Takeaway: Arcing damage on the surface is increasing general surface roughness through material ablation and redeposition.

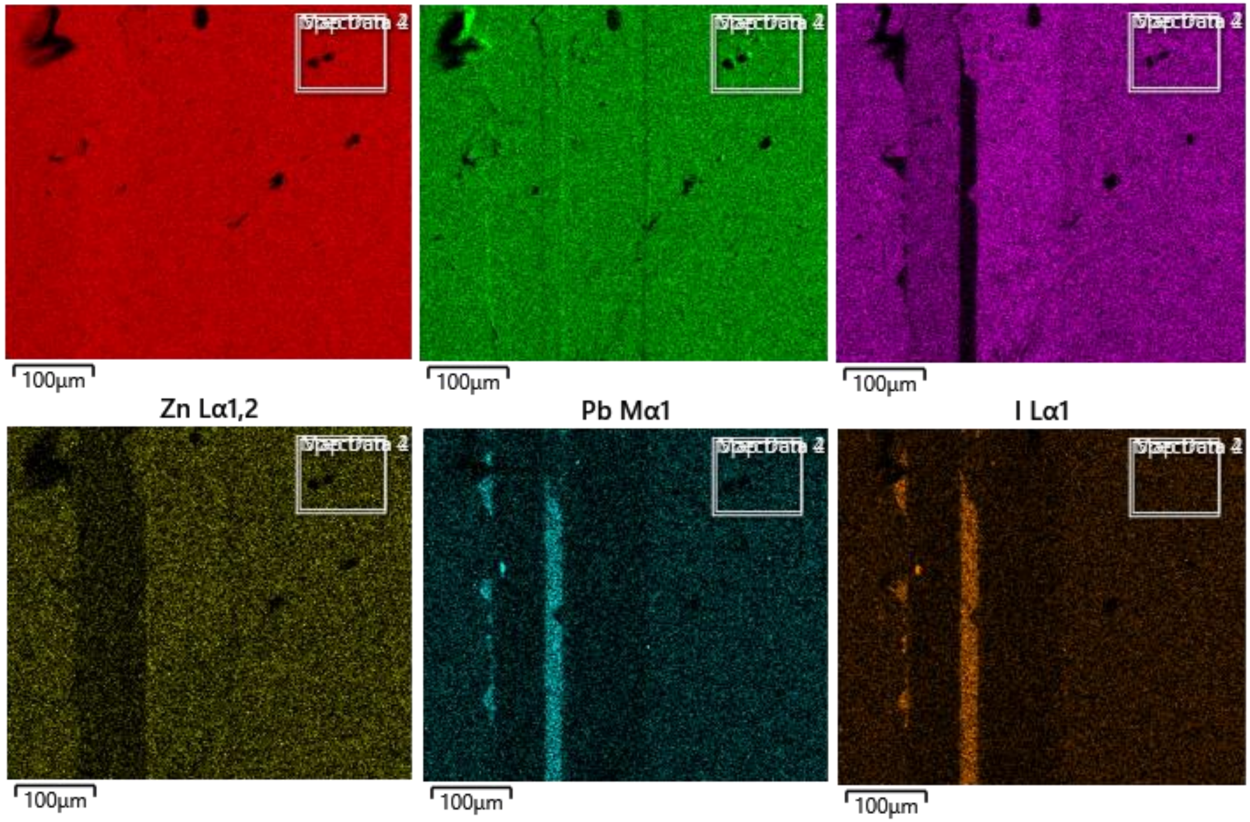
EDS on Arced Sample (60 arcs)



In addition to the expected materials making up perovskite and protective layers, **carbon deposits found on the surface of samples that experienced arcing.**

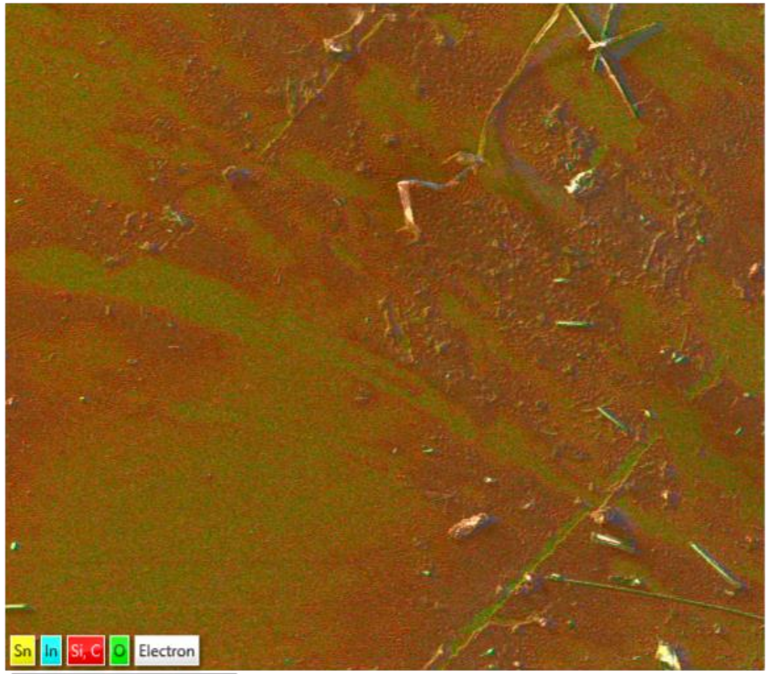
C Kα1,2



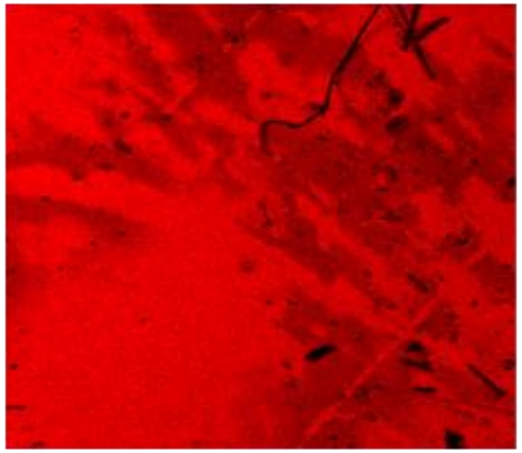


EDS on Arced Sample (40 arcs)

Full scanned image

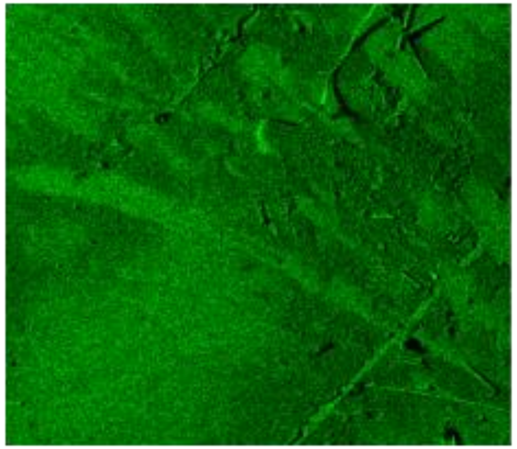


Si Kα1



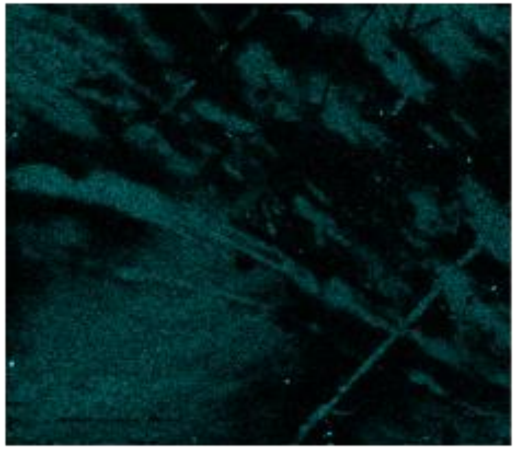
500μm

O Kα1



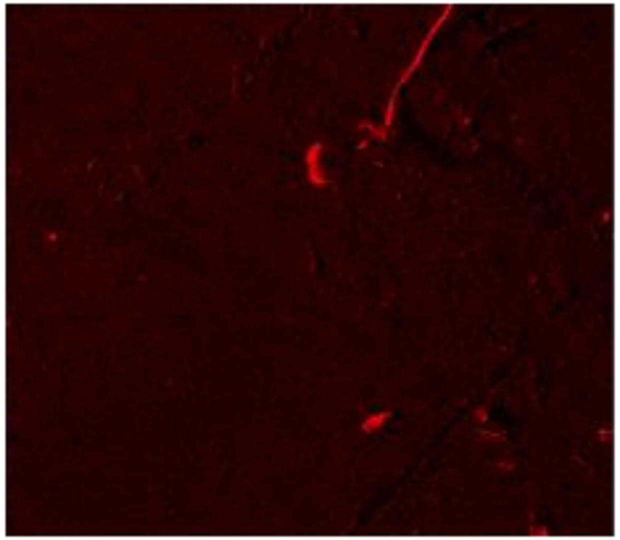
500μm

In Lα1



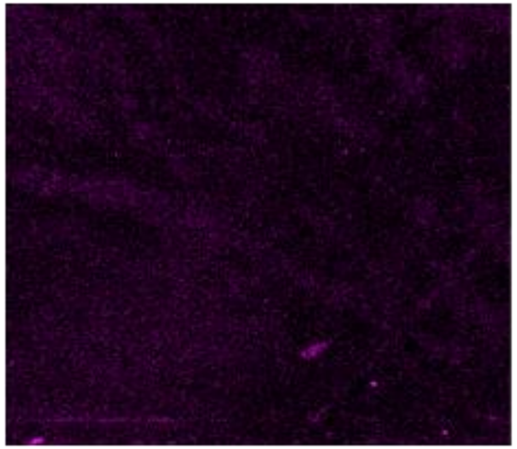
500μm

C Kα1,2



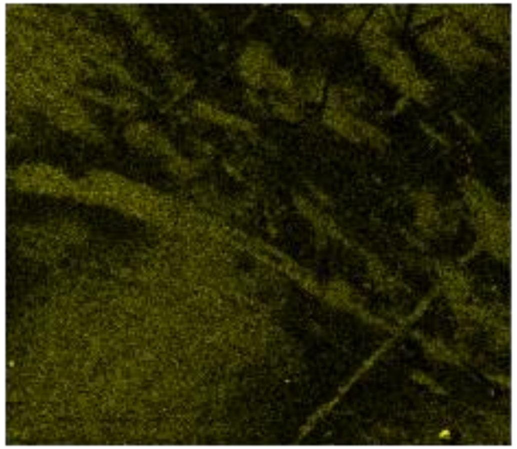
500μm

Pb Mα1



500μm

Sn Lα1

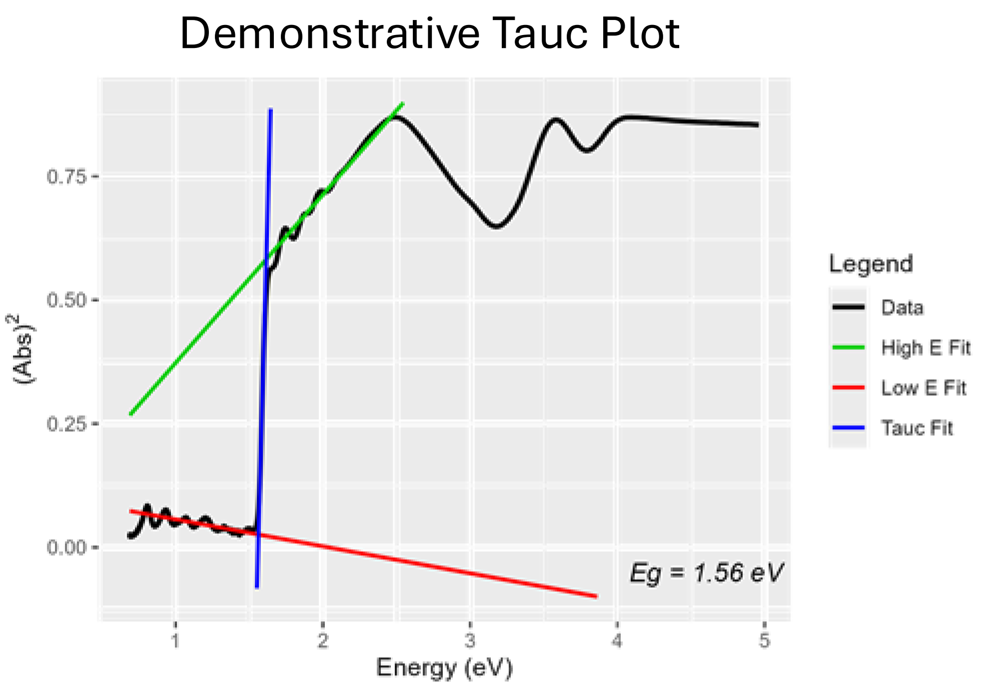


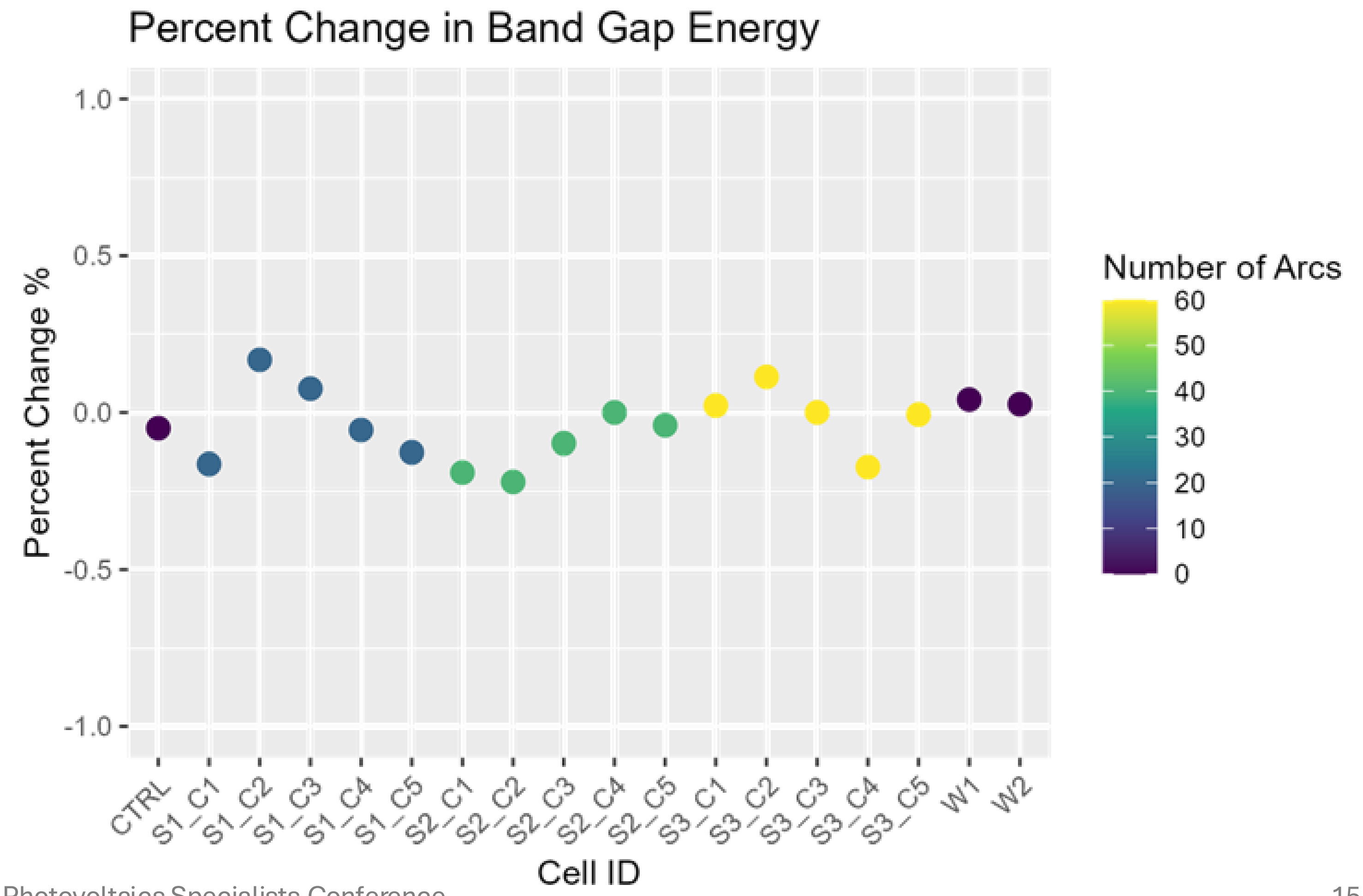
500μm

Takeaway: Cabon depositions on the surface consistent with contamination due to pyrolysis.

Spectrophotometry & Tauc Plots

- Spectrophotometry measured on a Lambda 950 UV/VIS.
- No significant changes in spectral performance due to primary arcing





Conclusion + Forward Work

Unprotected perovskite solar cells degrade readily when exposed to primary arcs, most likely due to the thermal stressors of these ESD events.

Primary arcs are not generally considered a risk to SOA space photovoltaics. **When assessing new solar cells for space, it's crucial that we thoroughly assess environmental factors and not just what is standard for traditional devices.**

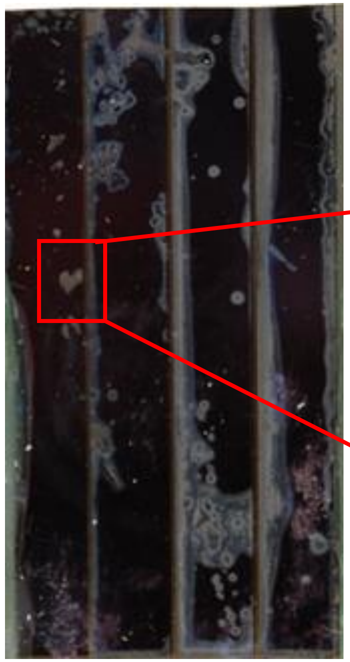
Forward Work:

1. More testing and characterization planned with a larger perovskite dataset (+ more witness and control samples) to improve statistics and deepen understanding.
2. Test more thin film technologies.
3. Exploring passive primary arc mitigation strategies to protect thin film cells from this damage mechanism.

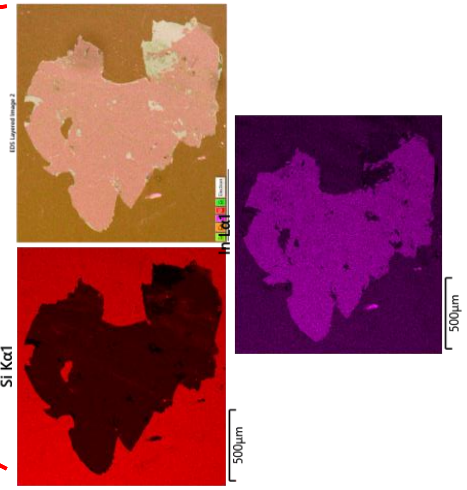
Thank you!

Thanks to NLR for letting us destroy your cells in the name of science & working with us on this characterization!

Interested in doing spacecraft charging testing on your solar cells/arrays? Reach out to the NASA GRC PV team!



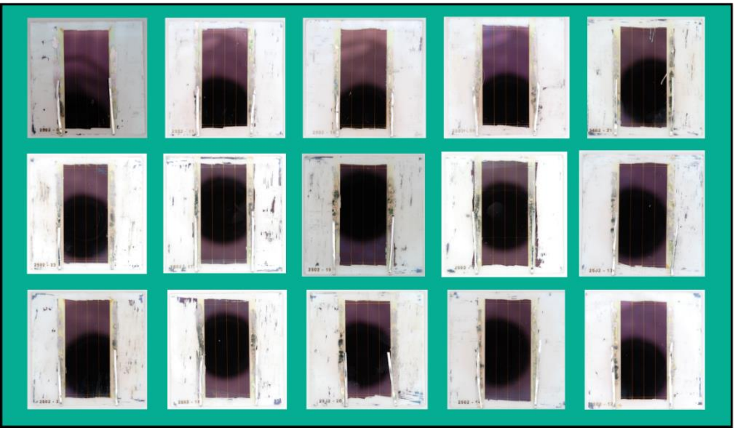
We



testing with external partners!

Backup

Pre ESD – Front Side

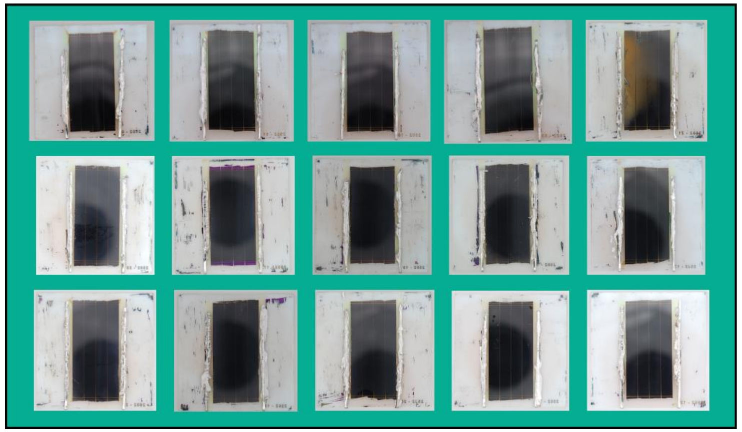


String 1

String 2

String 3

Pre ESD – Back Side

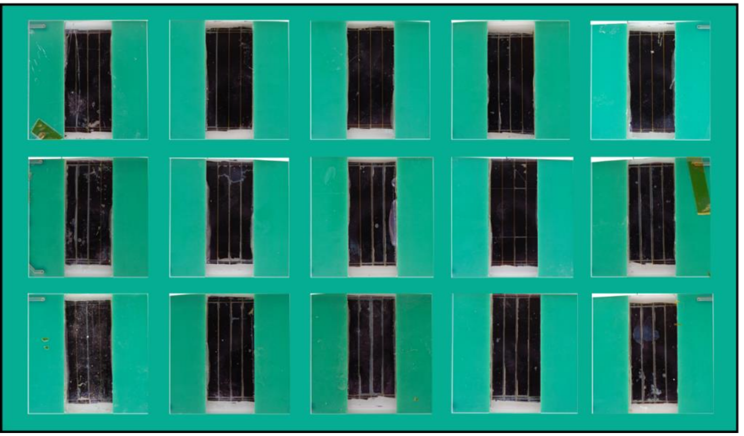


String 1

String 2

String 3

Post ESD – Front Side

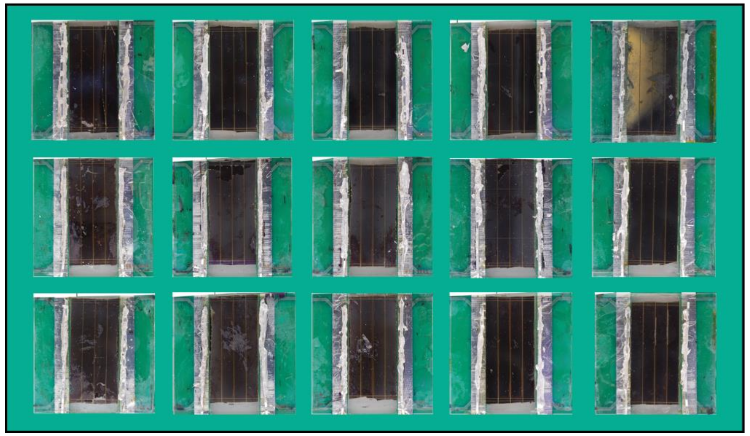


String 1 (20 arcs)

String 2 (40 arcs)

String 3 (60 arcs)

Post ESD – Back Side



String 1 (20 arcs)

String 2 (40 arcs)

String 3 (60 arcs)

Pre-Shipment – Front Side

String 1 (20 arcs)

String 2 (40 arcs)

String 3 (60 arcs)

Pre-Shipment– Back Side

String 1 (20 arcs)

String 2 (40 arcs)

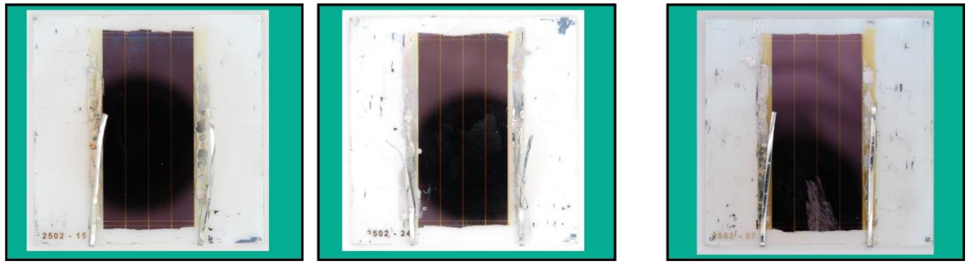
String 3 (60 arcs)

Witness and Controls Visual

Pre ESD – Front Side

Witness cells – exposed to high vacuum but not biased

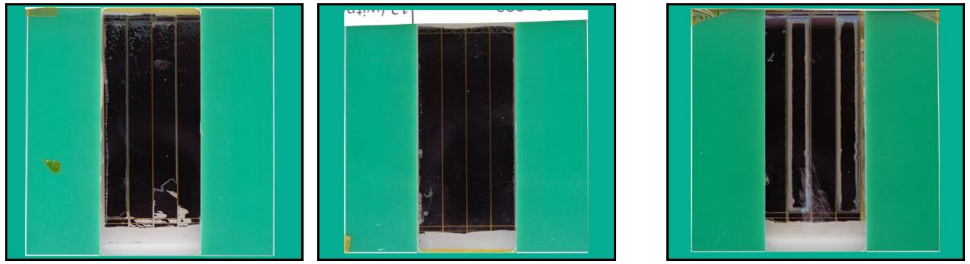
Control – cell remained in purged environment



Post ESD – Front Side

Witness cells – exposed to high vacuum but not biased

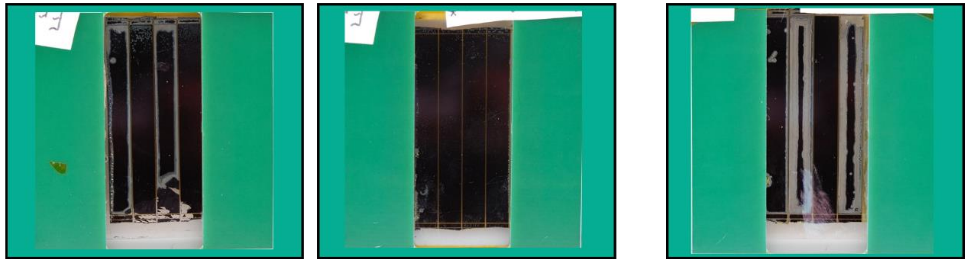
Control – cell remained in purged environment



Pre-Shipment – Front Side

Witness cells – exposed to high vacuum but not biased

Control – cell remained in purged environment



Pre ESD – Back Side

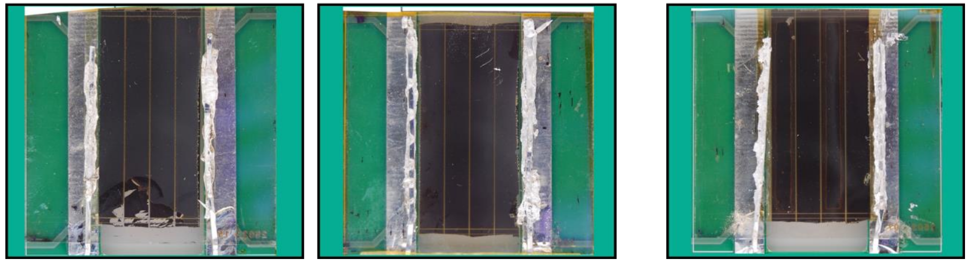
Witness cells – exposed to high vacuum but not biased

Control – cell remained in purged environment

Post ESD – Back Side

Witness cells – exposed to high vacuum but not biased

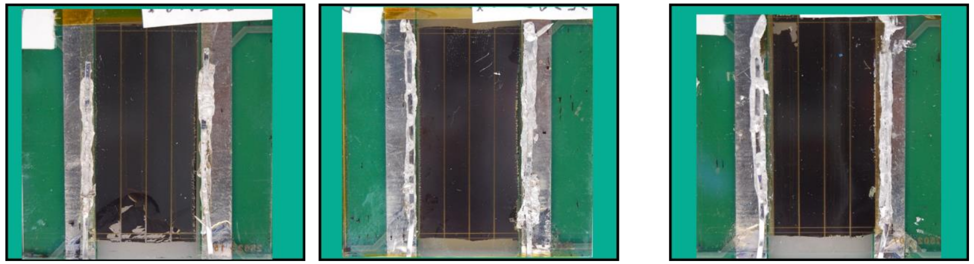
Control – cell remained in purged environment



Pre-Shipment – Back Side

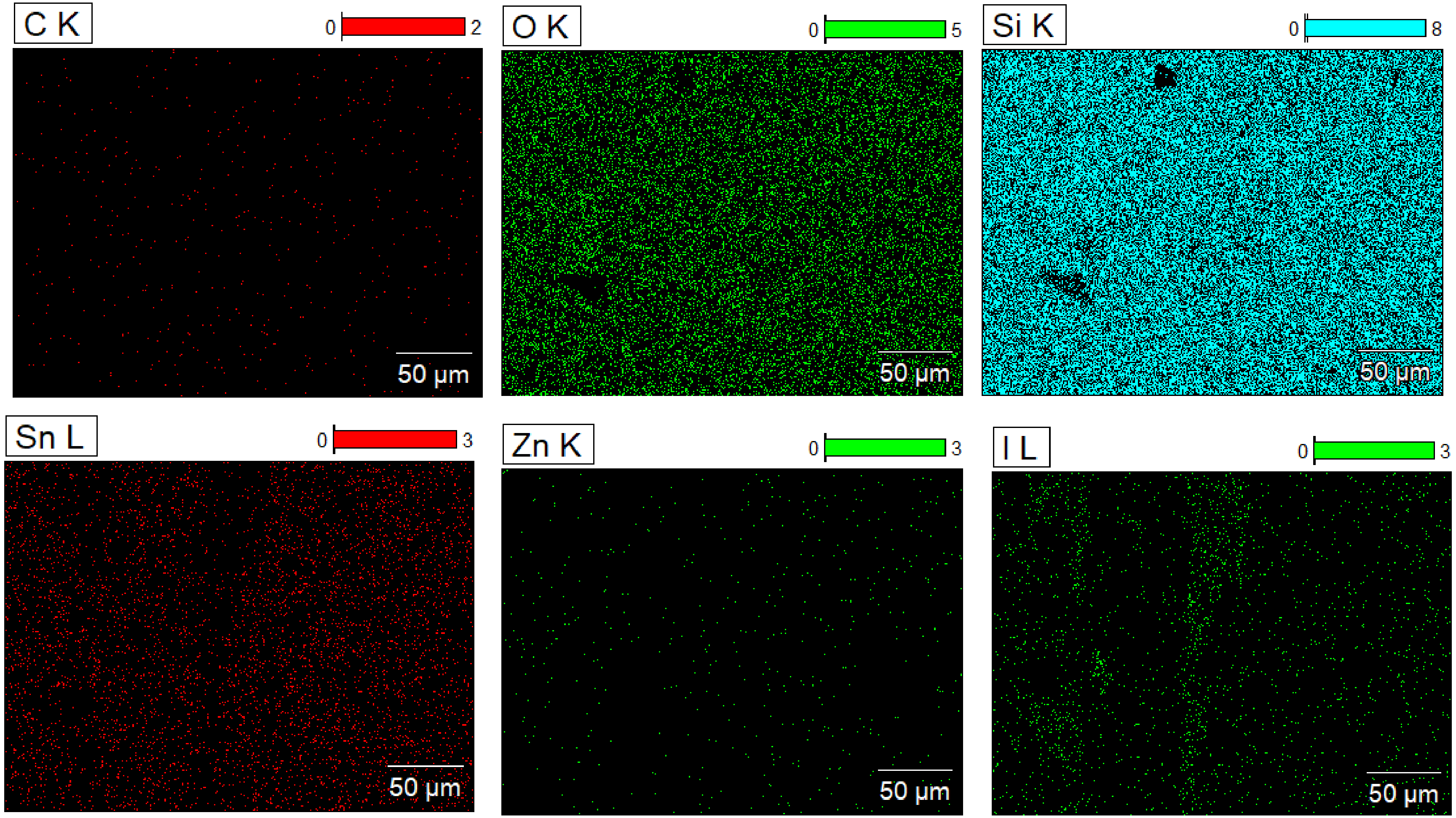
Witness cells – exposed to high vacuum but not biased

Control – cell remained in purged environment



EDS on Witness Samples

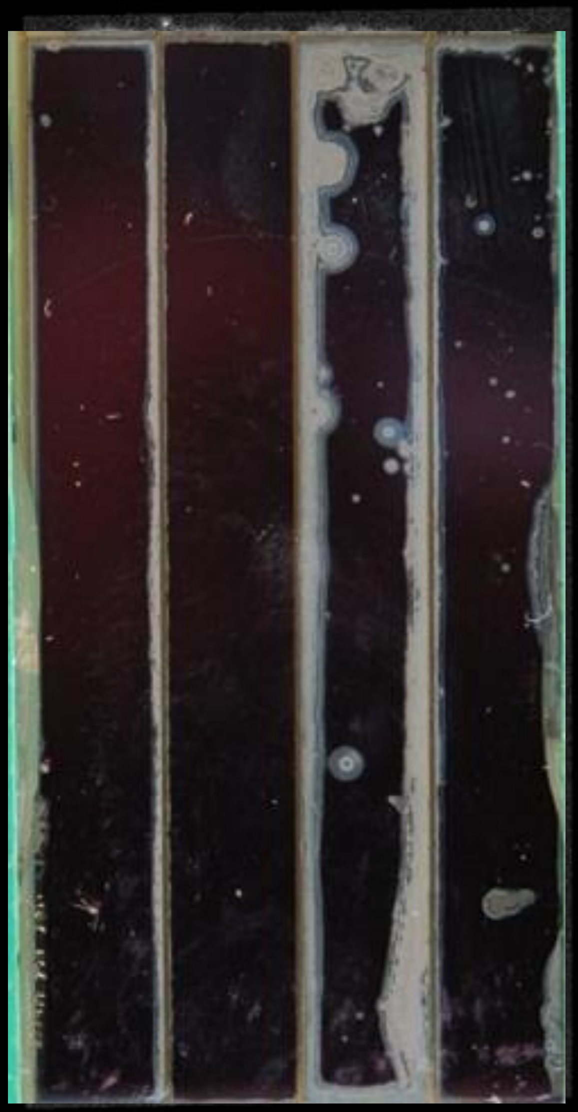
EDS on witness samples showed largely Si and O, consistent with the SiO top coating



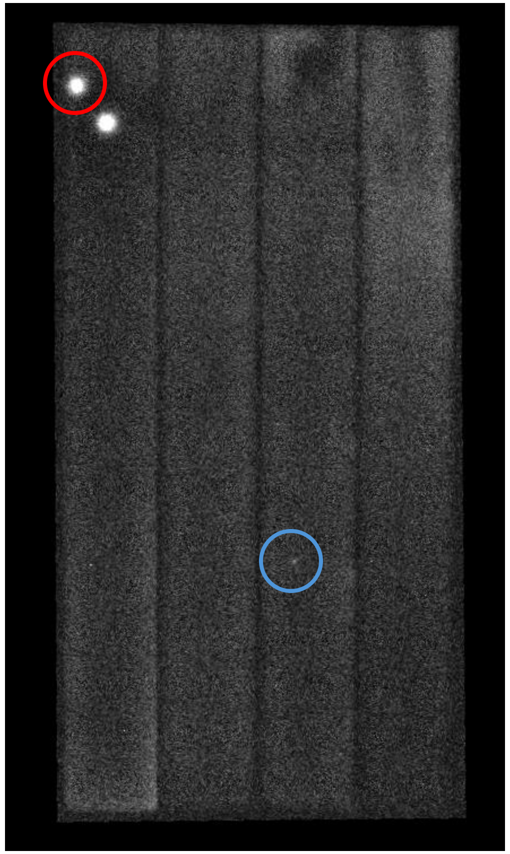
No Pb detected,
consistent with intact
barrier layers

S_5305003: **20 arcs**

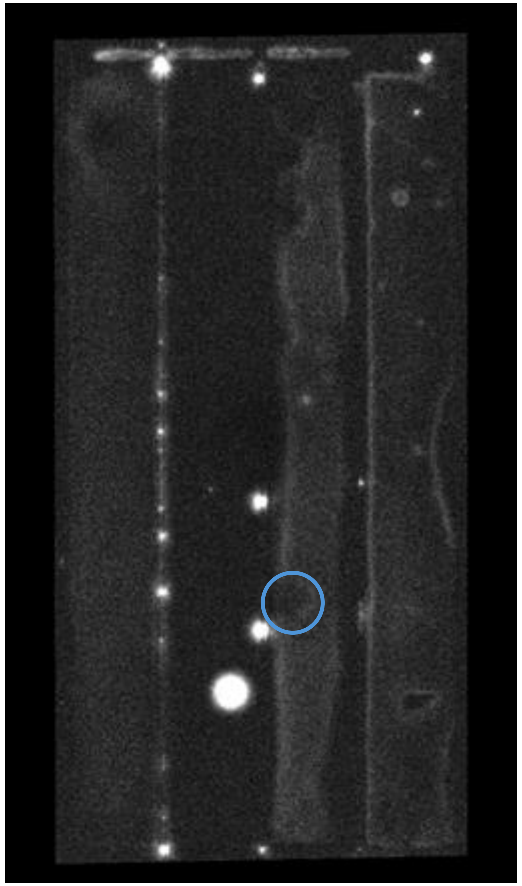
Post-test Visual



Pre-DLIT



Post-DLIT



Post-Visual