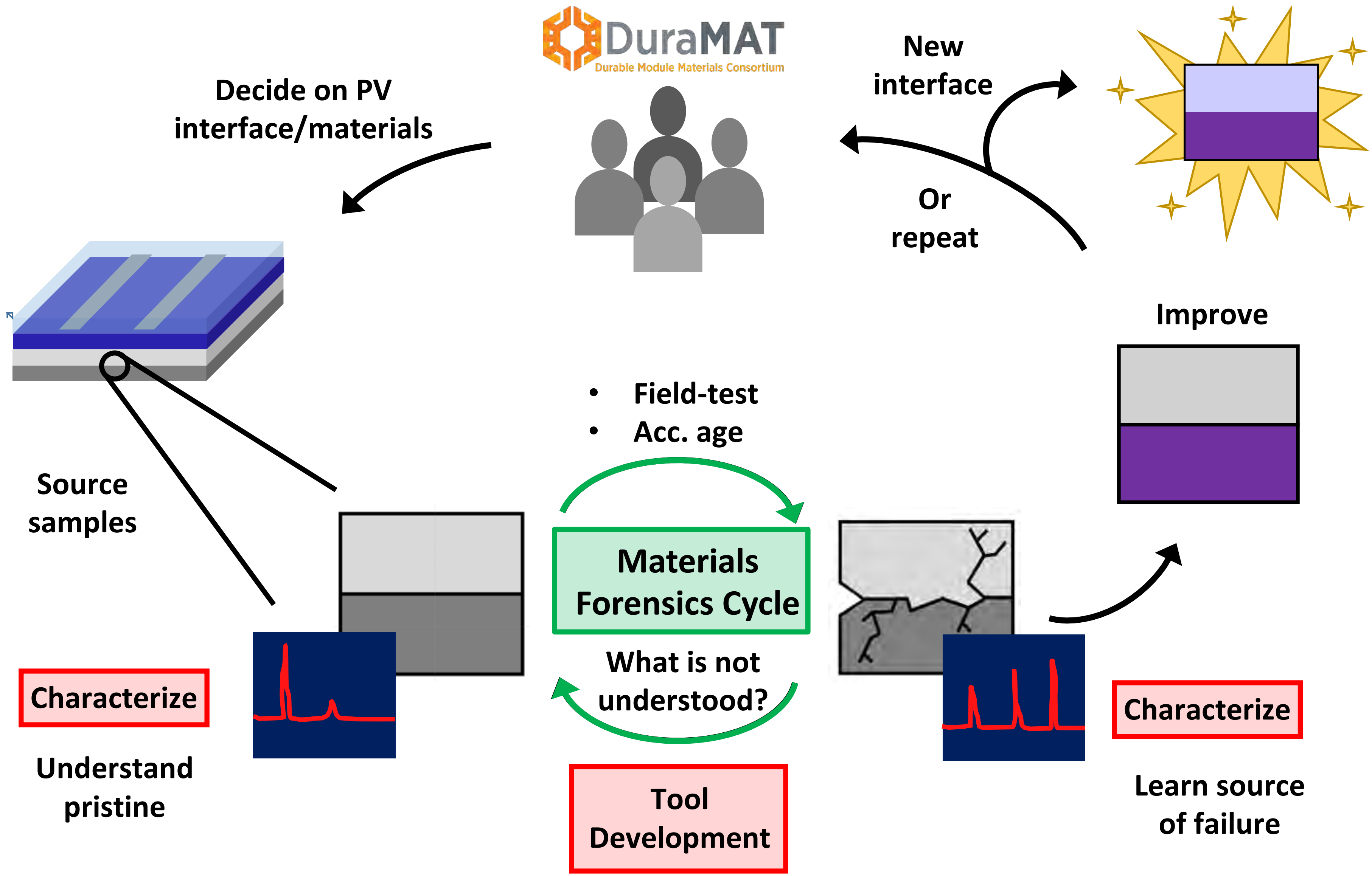
Materials forensics for understanding PV module material durability

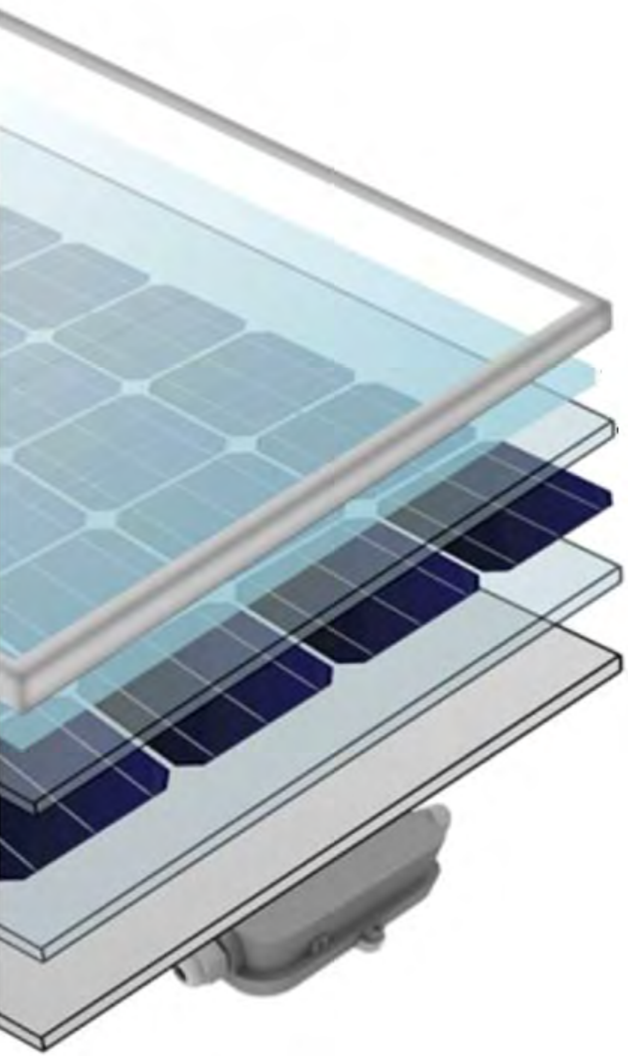
Laura T. Schelhas
SLAC National Accelerator Laboratory

What is materials forensics?

And how can it help PV reliability?



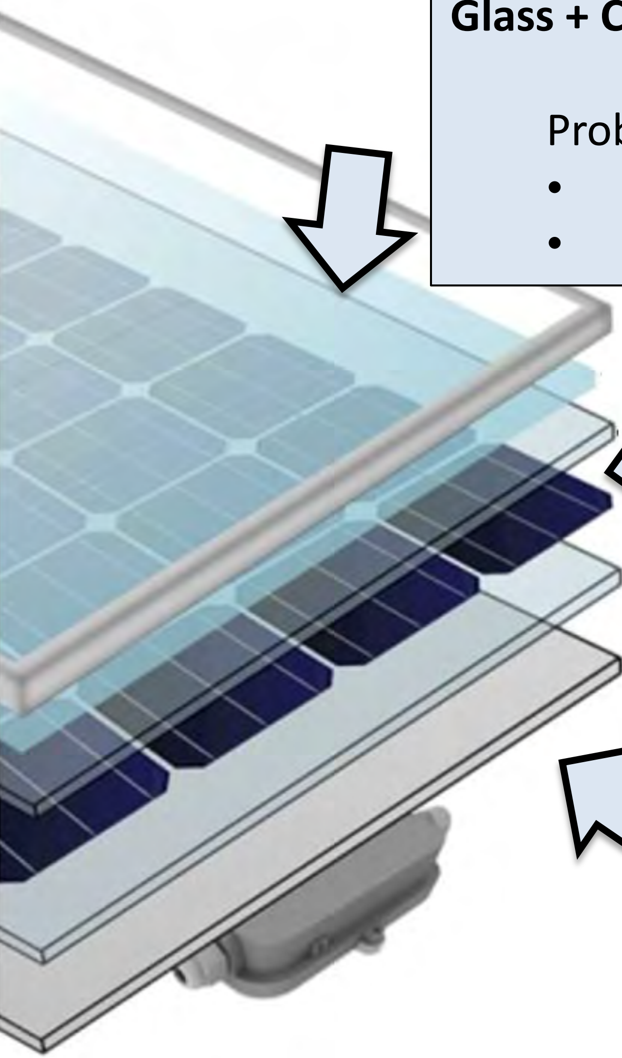
Interfaces & surfaces common failure points



1. Identify which interfaces are the biggest concern

2. Develop methods for understanding failure mechanisms
- Chemistry
- Morphology
- Functional mechanical properties (e.g. adhesion)

Interfaces & surfaces common failure points



Glass + Coating + Soil

Problem areas:

- Durability
- Functionality

Encapsulant + Metallization

Problem areas:

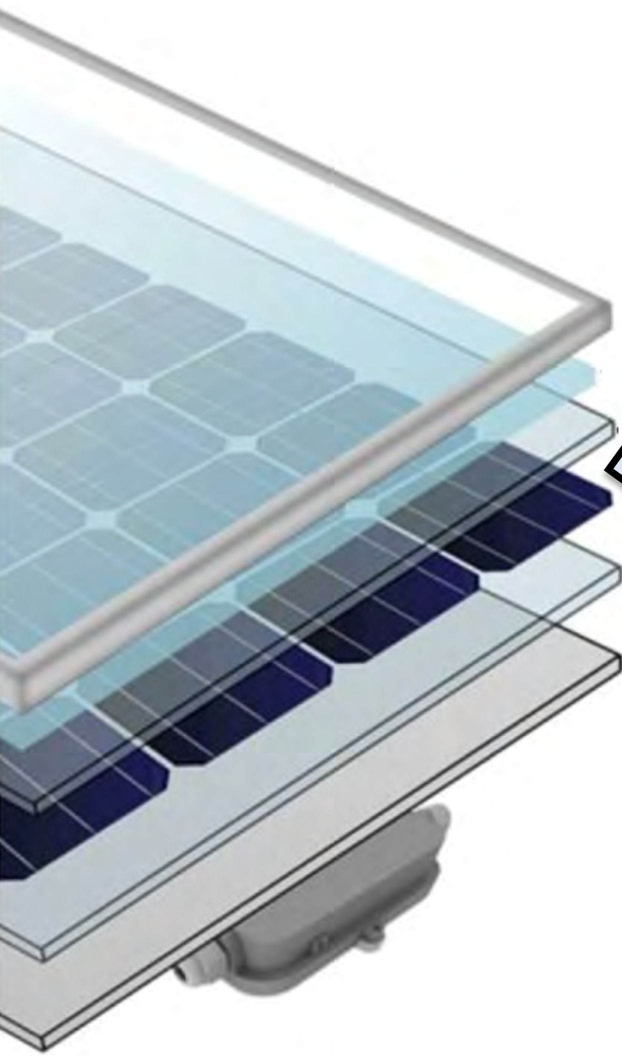
- Delamination
- Corrosion

Backsheets (layered polymers)

Problem areas:

- Cracking
- Delamination

Interfaces & surfaces common failure points



1. Encapsulant + Metallization

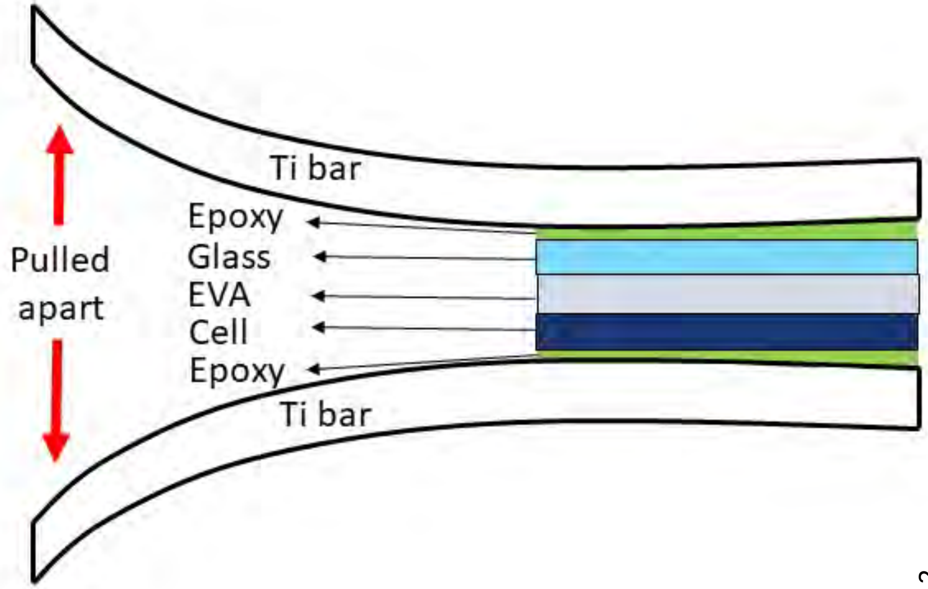
Problem areas:

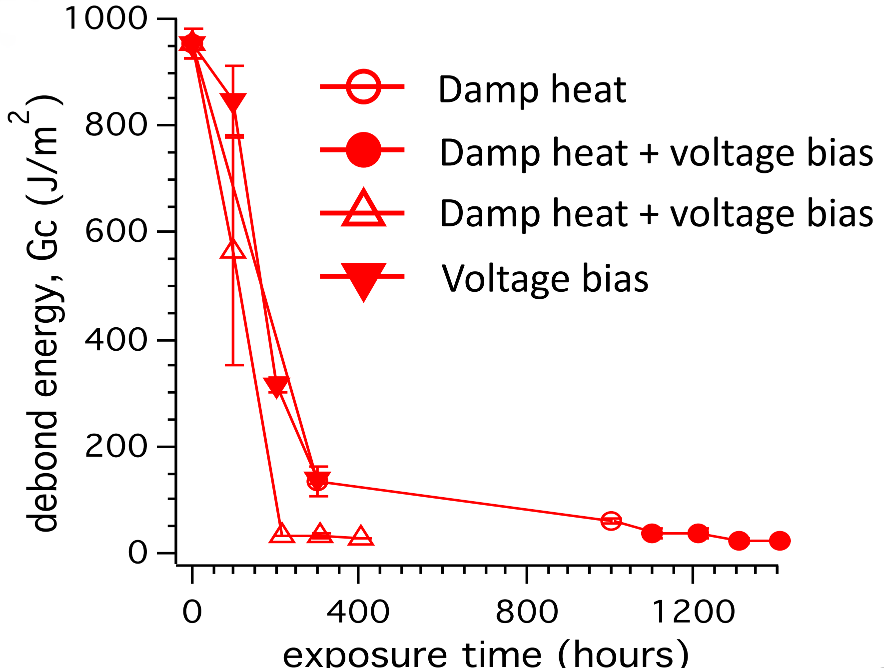
- Delamination
- Corrosion

Can we determine the interfacial chemistry responsible for delamination?

Adhesion degradation at encapsulant/metallization interface

NATIONAL RENEWABLE ENERGY LABORATORY
Nick Bosco



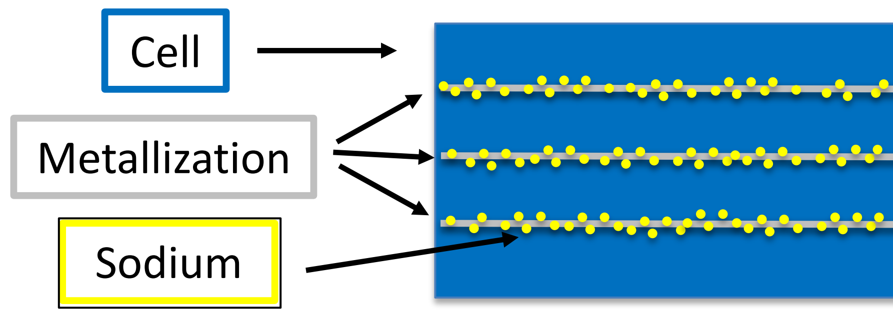


Debonding energy of encapsulant/metallization interface drops off when exposed to damp heat and/or high voltage

Negative voltage bias induces sodium migration

X-ray photoelectron spectroscopy → Provides chemical information at a material surface

- 400 hours
- Damp heat
- Voltage bias



N. Bosco, S. L. Moffitt, L. T. Schelhas, "Mechanisms of Adhesion Degradation at the Photovoltaic Module's Cell Metallization-Encapsulant Interface," *Progress in Photovoltaics*, (2018)

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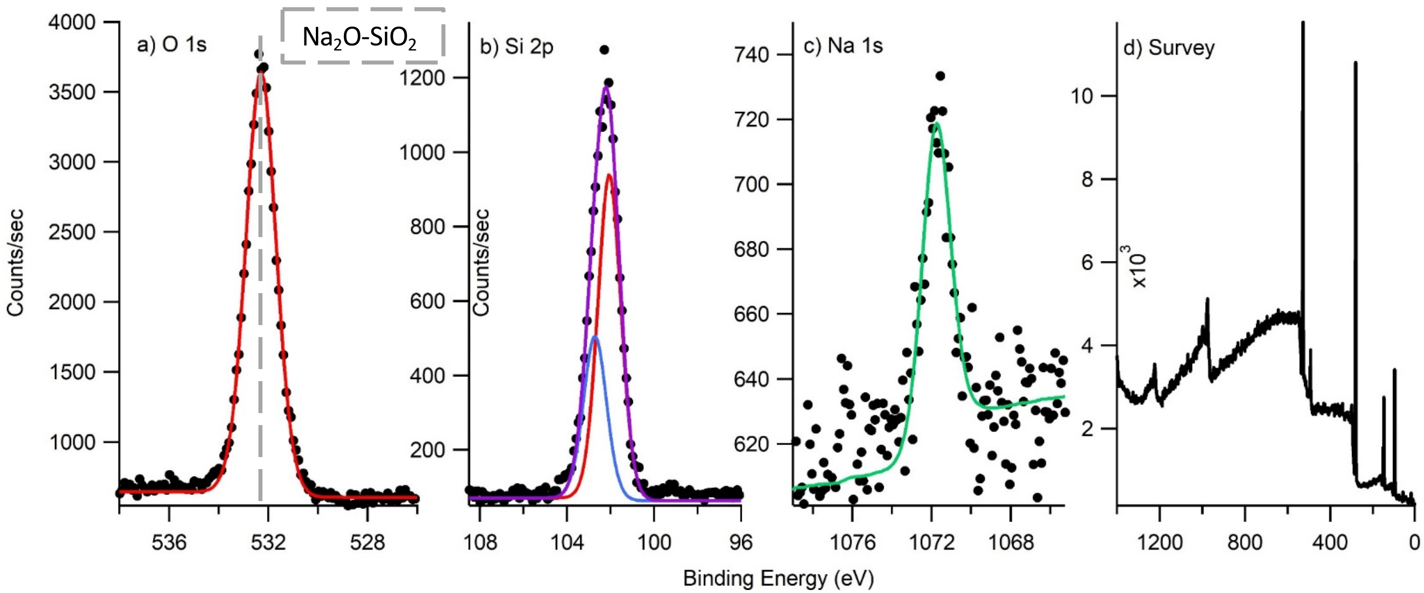


Hypothesis: Sodium Silicate (Na_2O-SiO_2) is forming at gridlines
Evidence: Chemical state of Na, Si, and O consistent with Na_2O-SiO_2

N. Bosco, S. L. Moffitt, L. T. Schelhas, "Mechanisms of Adhesion Degradation at the Photovoltaic Module's Cell Metallization-Encapsulant Interface," *Progress in Photovoltaics*, (2018)

Positive voltage bias:

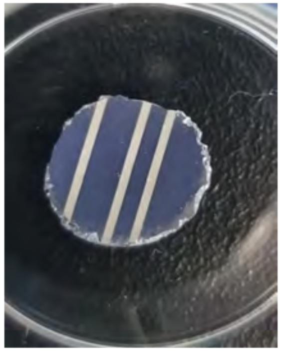
Different mechanism than negative bias?

NREL
NATIONAL RENEWABLE ENERGY LABORATORY
Peter Hacke, Dave Miller, Harry Qian, Katie Hurst

Positive Bias Testing and Coring

Encapsulated cell strip aged under DH (85oC/85% RH) and +1000V

#M1610-0012



Extracted cell piece

#M1610-0012A

Extracted EVA piece

#M1610-0012A-FE

Proposed mechanisms

EVA/Ag grid interface

Migration of Ag+ ions from grid into EVA → affecting resistivity and transparency of EVA

Ag gridline surface/bulk

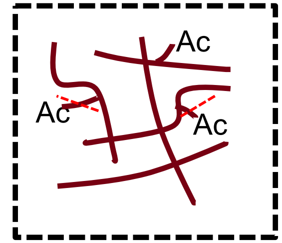
Corrosion of silver gridlines

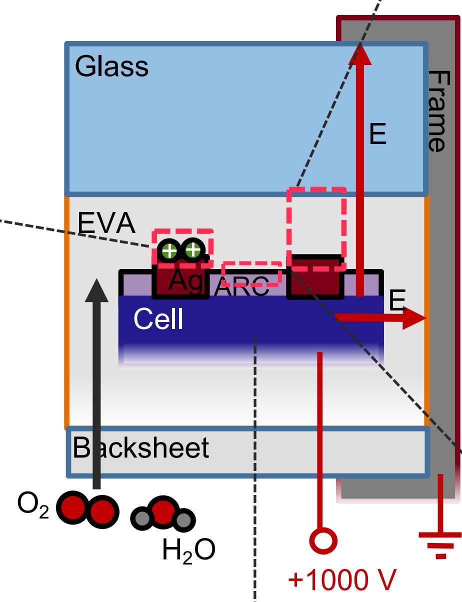
$Ag \rightarrow Ag^{+} + e^{-}$

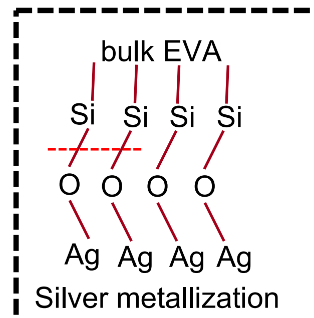
$2Ag^{+} + H_2O/\ O_2 \rightarrow Ag_2O + 2H^{+}$
$2Ag^{+} + H_2S? \rightarrow Ag_2S + 2H^{+}$

Glass/EVA interface, EVA bulk and EVA/cell interface

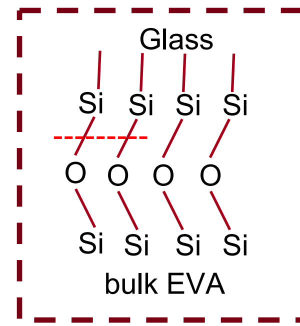
EVA decomposition → Acetic acid production







EVA/Ag grid interface



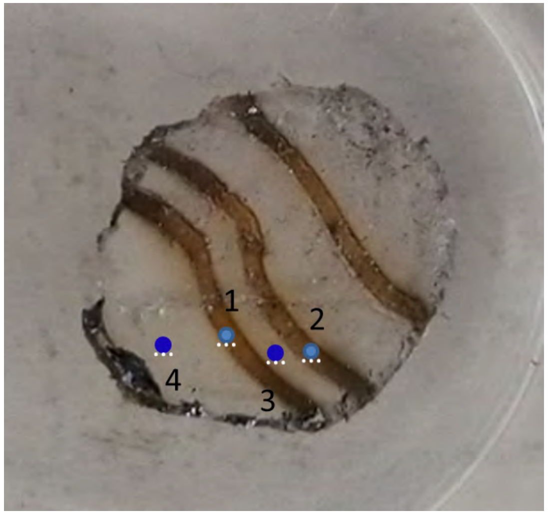
Glass/EVA interface

Siloxane bond dissociation
→ Delamination at interface

EVA/ ARC interface

Thinning of ARC layer → Change in S/N ratio → Change in refractive index → optical loss

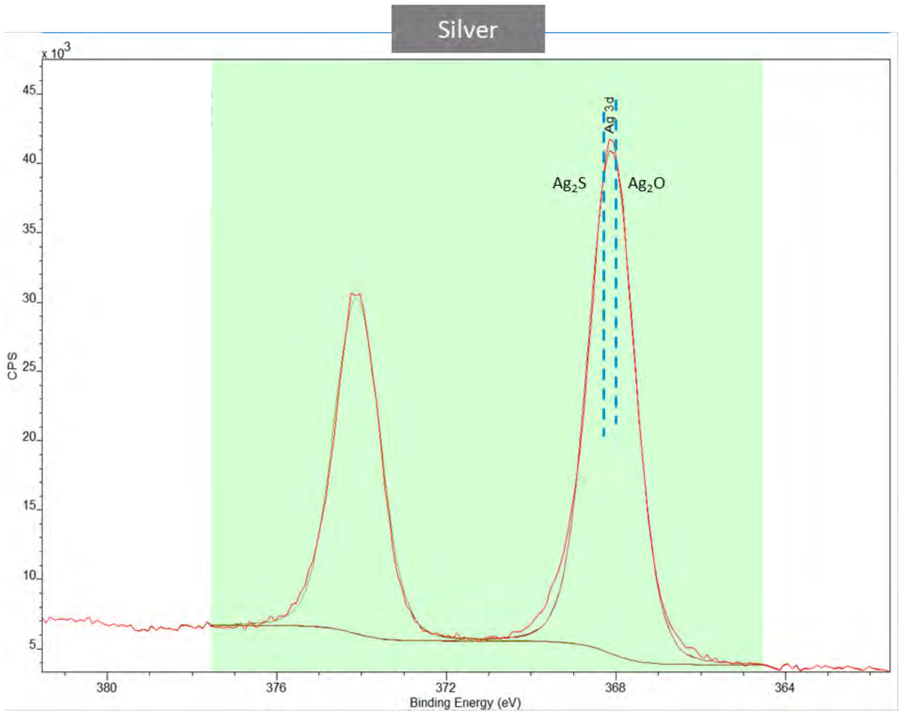
Positive bias: Ag not Na migration

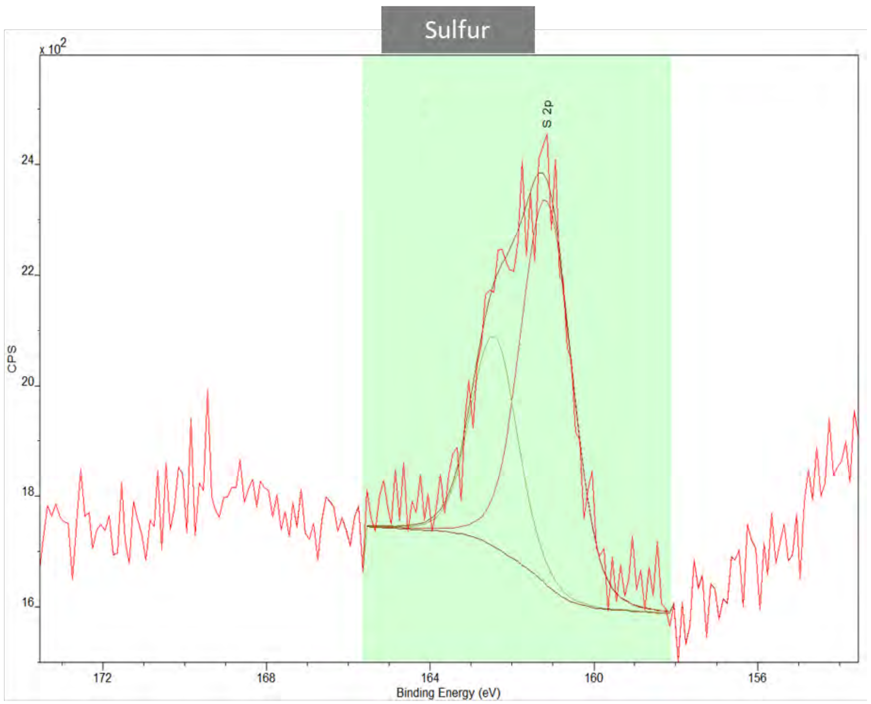


	1 – Grid	2 - Grid	3 - between	4 – Far off
C 1s	✔	✔	✔	✔
O 1s	✔	✔	✔	✔
Si 2p	✔	✔	✔	✔
Ag 3d	✔	✔	✔	X
S 2p	✔	✔	✔	X

- A halo of brown discoloration is observed around the gridline
- Limited diffusion of Ag+ ions in lateral direction
- No signature peaks of Ag and S in far away region

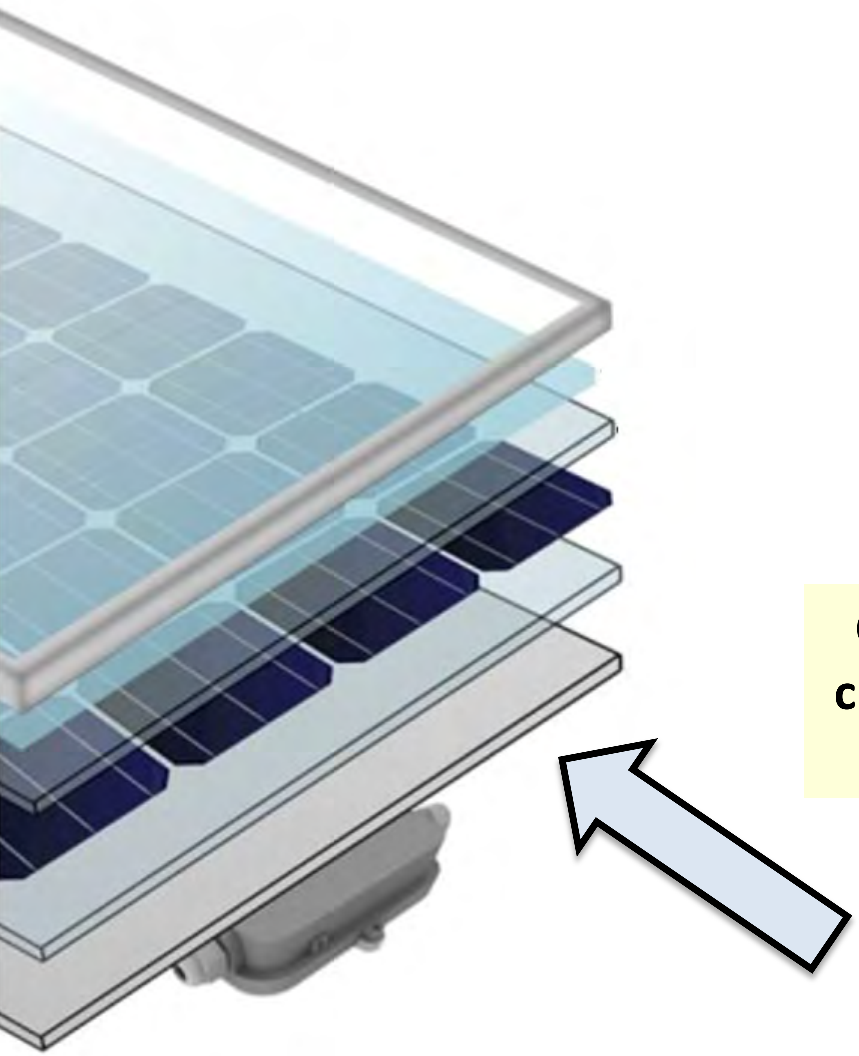
Identifying the source of browning





- Ag_2S & Ag_2O are likely responsible for brown discoloration
- Discoloration -> I_{sc} loss

Interfaces & surfaces common failure points



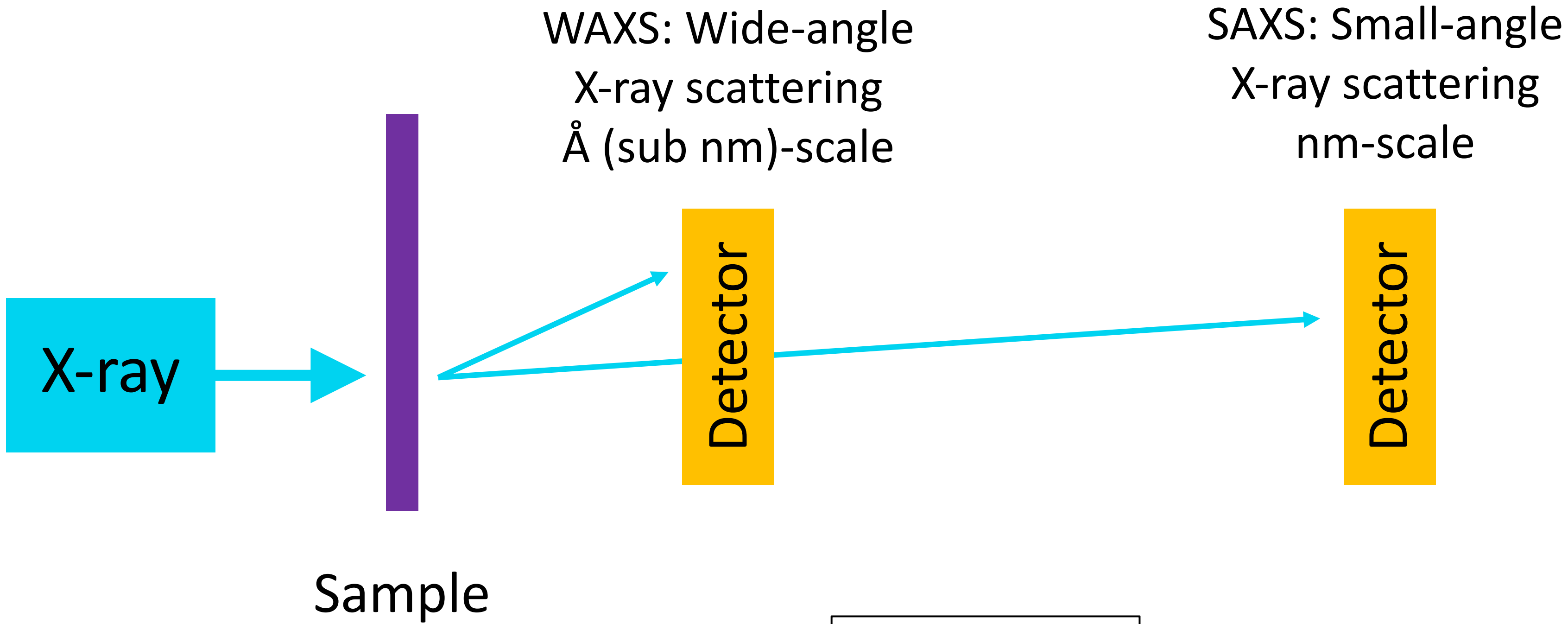
Can we determine the microstructural changes associated with the mechanical degradation?

2. Backsheets (layered polymers)

Problem areas:

- Cracking
- Delamination

WAXS and SAXS



X-rays scatter off of differences in electron density

Scattered X-rays record the structure in inverse-space ($Å^{-1}$)

$$Q = 2\pi/d$$

Scattering vector

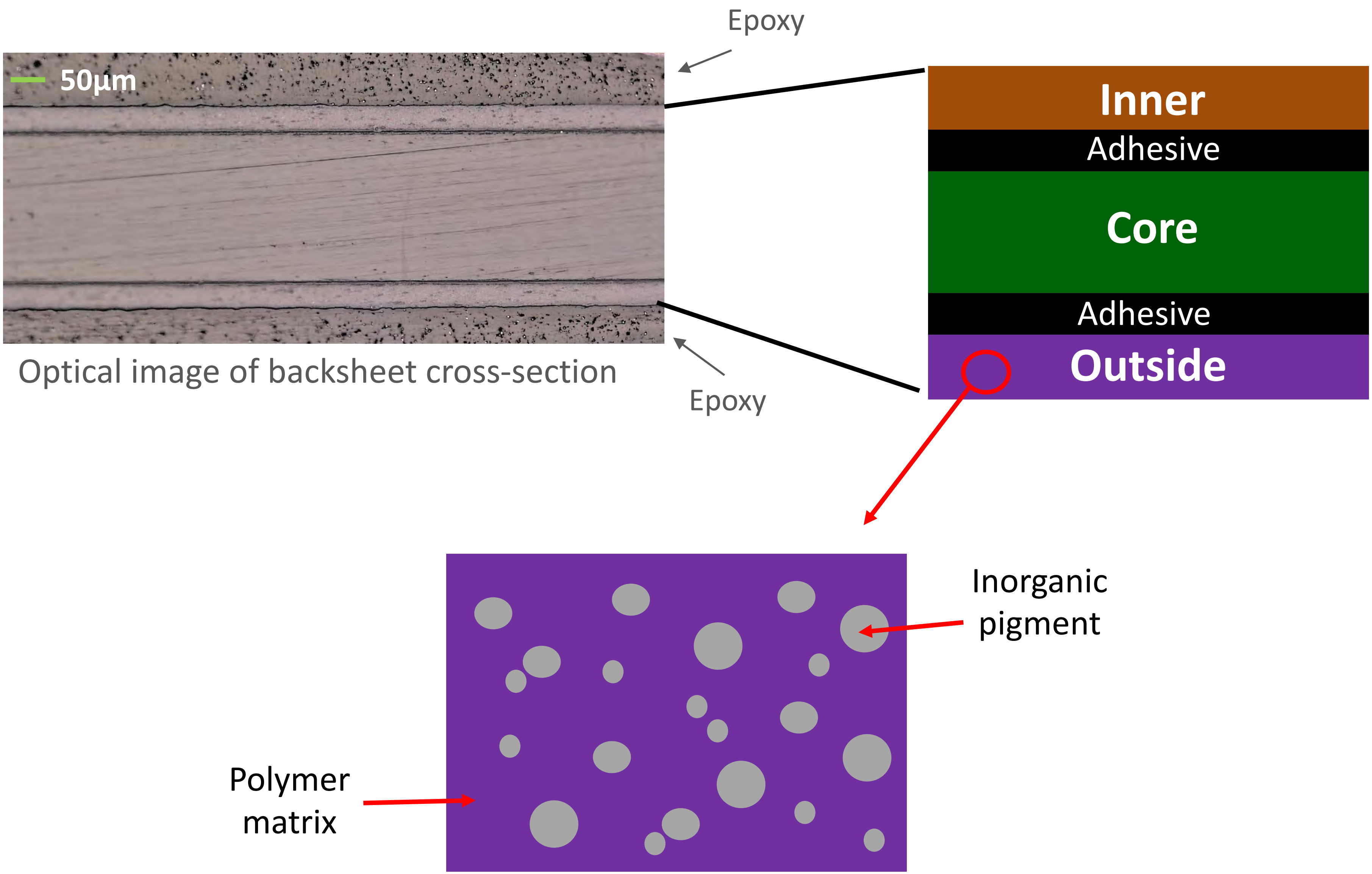
Feature size

$$Q = \left(\frac{4}{\lambda}\right) \sin\theta$$

Wavelength

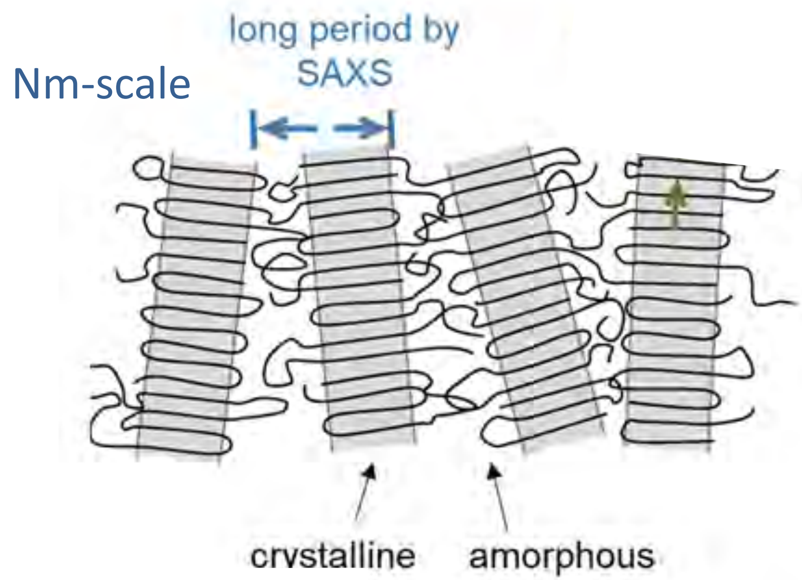
Scattering angle

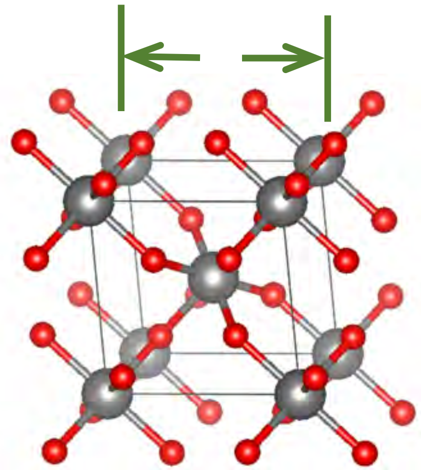
Backsheets are often layered, composite materials

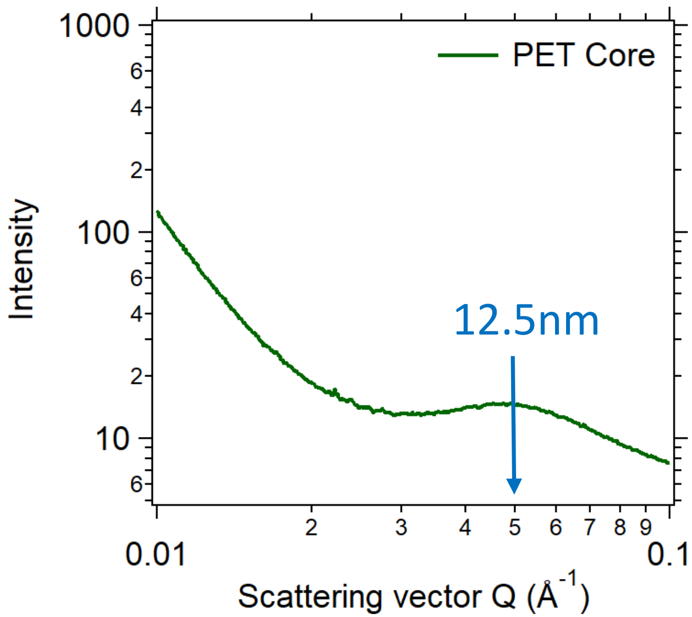


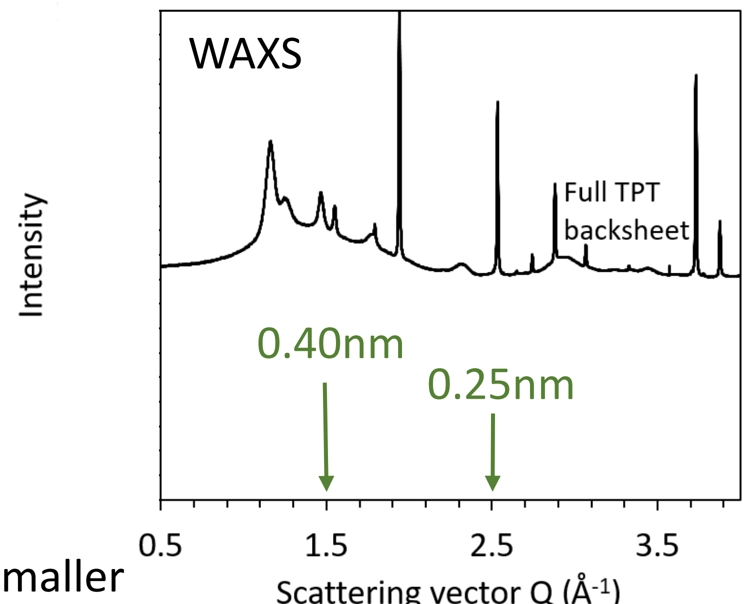
Optical image of backsheet cross-section

SAXS and WAXS of backsheets







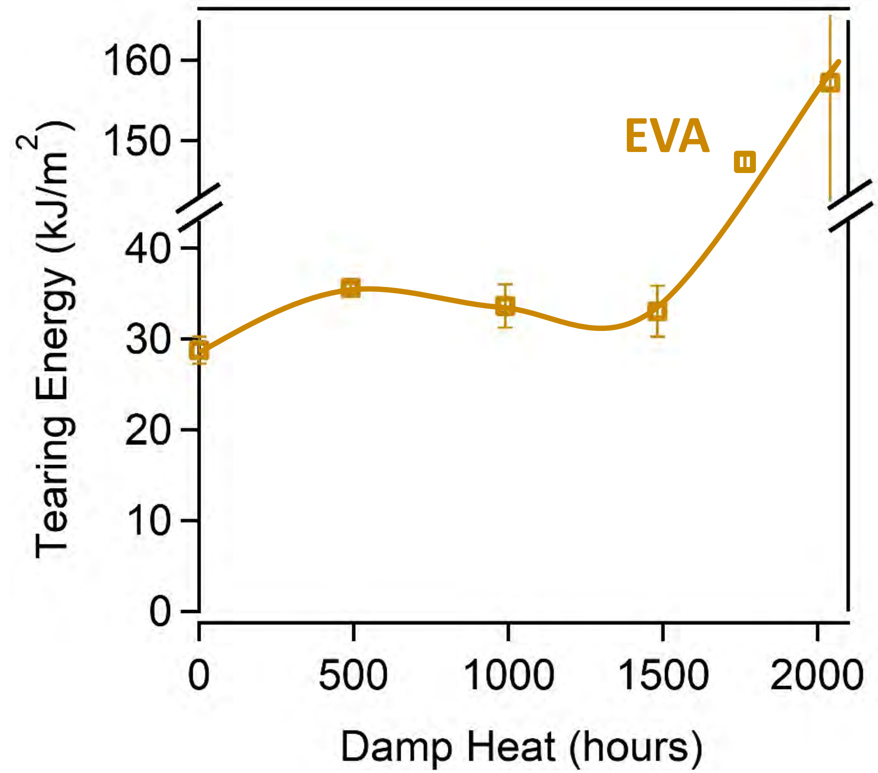


Larger to smaller

Damp heat-induced mechanical changes

85 %RH /85° C

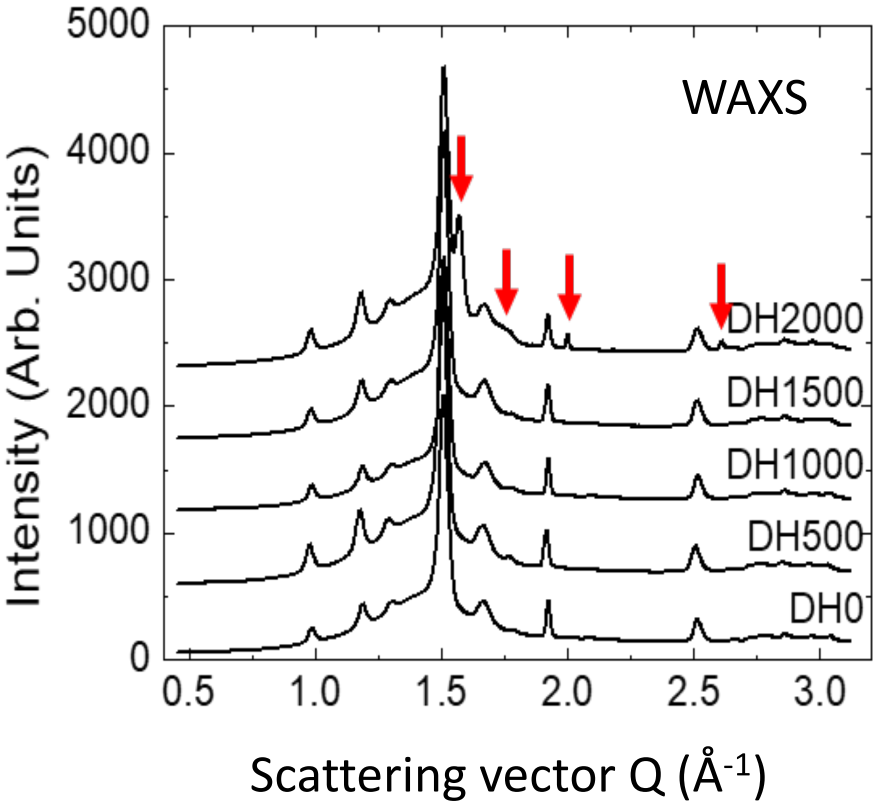
Damp heat (DH) =
85% humidity + 85° C



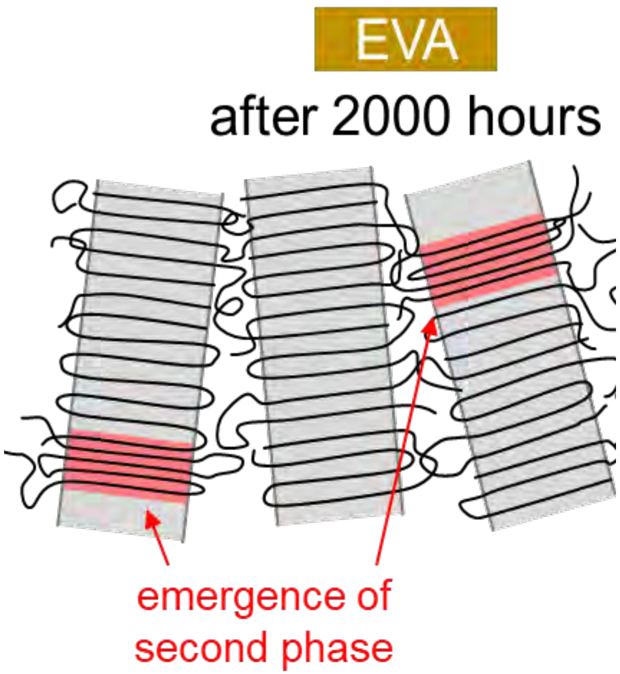
Dauskardt group

Pak Yan Yuen, Stephanie L. Moffitt, Fernando D. Novoa, Laura T. Schelhas, Reinhold H. Dauskardt, "Tearing and reliability of photovoltaic module backsheet structures," *Progress in PV*, 2019

Polymer packing change in EVA after damp heat

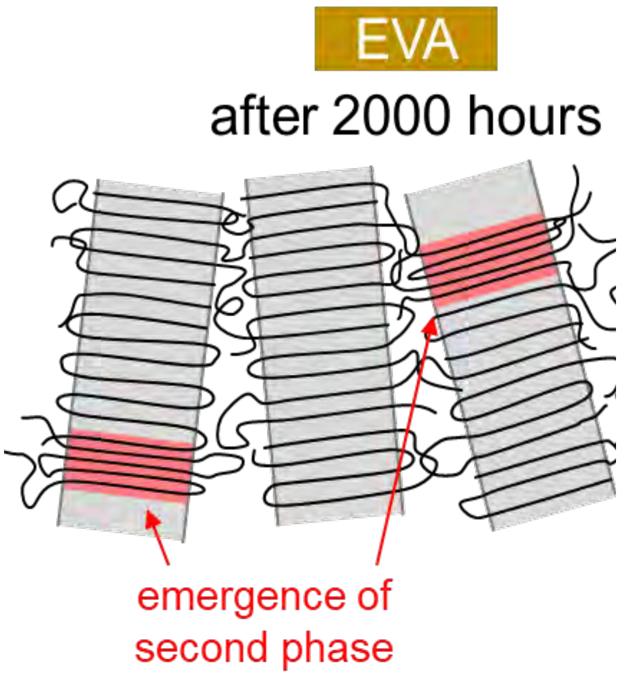


Damp heat (DH) =
85% humidity + 85° C

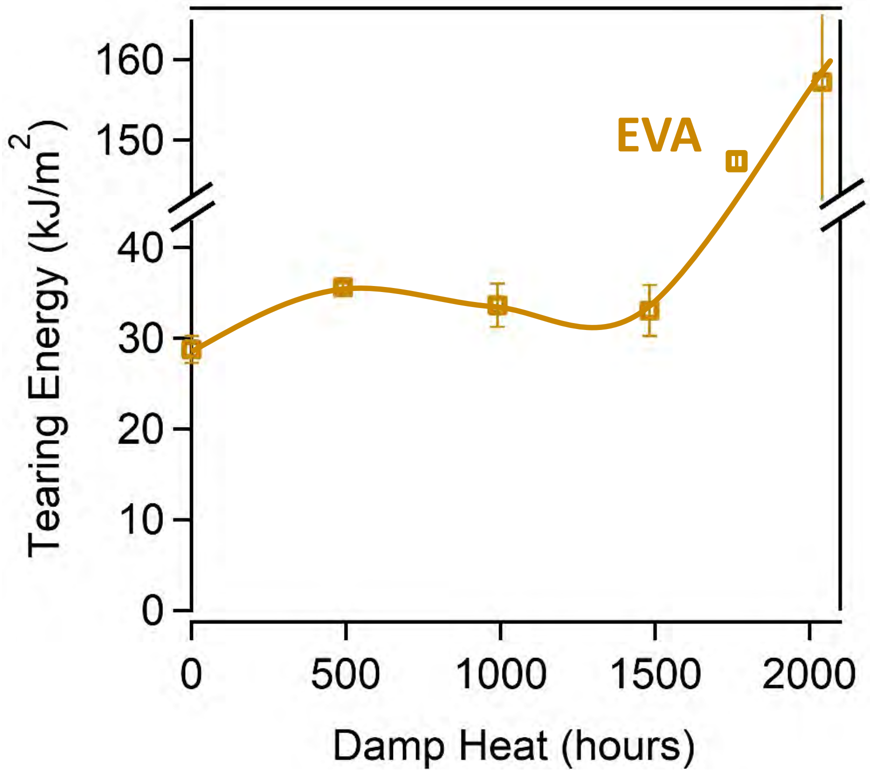


Pak Yan Yuen, Stephanie L. Moffitt, Fernando D. Novoa, Laura T. Schelhas, Reinhold H. Dauskardt, "Tearing and reliability of photovoltaic module backsheet structures," *Progress in PV*, 2019

Structure change linked to increased yield strength



New phase may further enable EVA to undergo plastic deformation (cold-drawing)

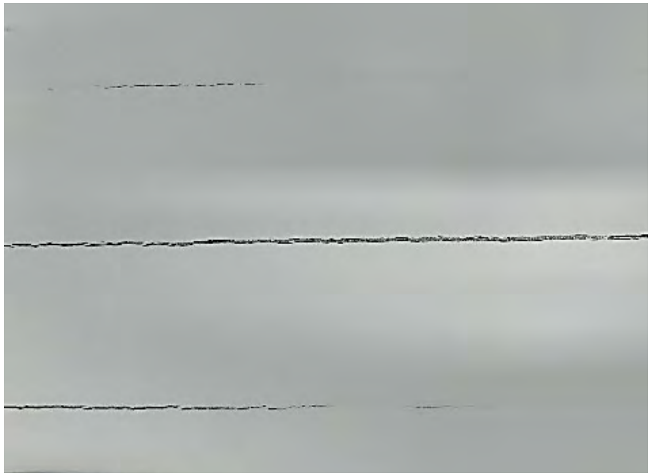


Pak Yan Yuen, Stephanie L. Moffitt, Fernando D. Novoa, Laura T. Schelhas, Reinhold H. Dauskardt, "Tearing and reliability of photovoltaic module backsheet structures," *Progress in PV*, 2019

CAST accelerated-aging of PA

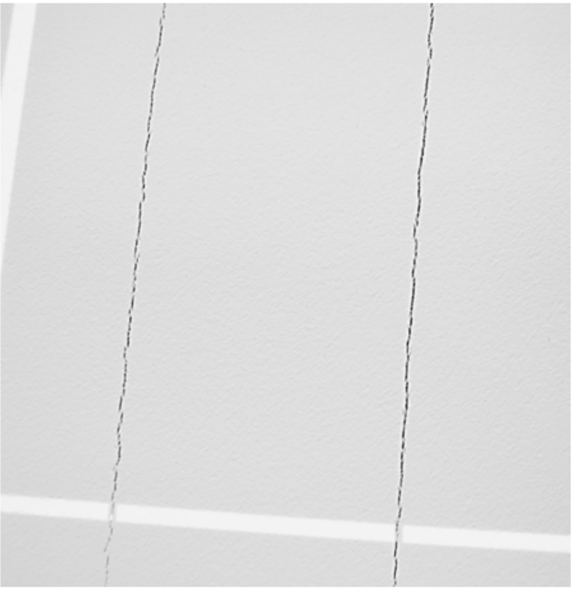
PA: poly-amide-based backsheet

CAST: Combined accelerated stress testing



PA

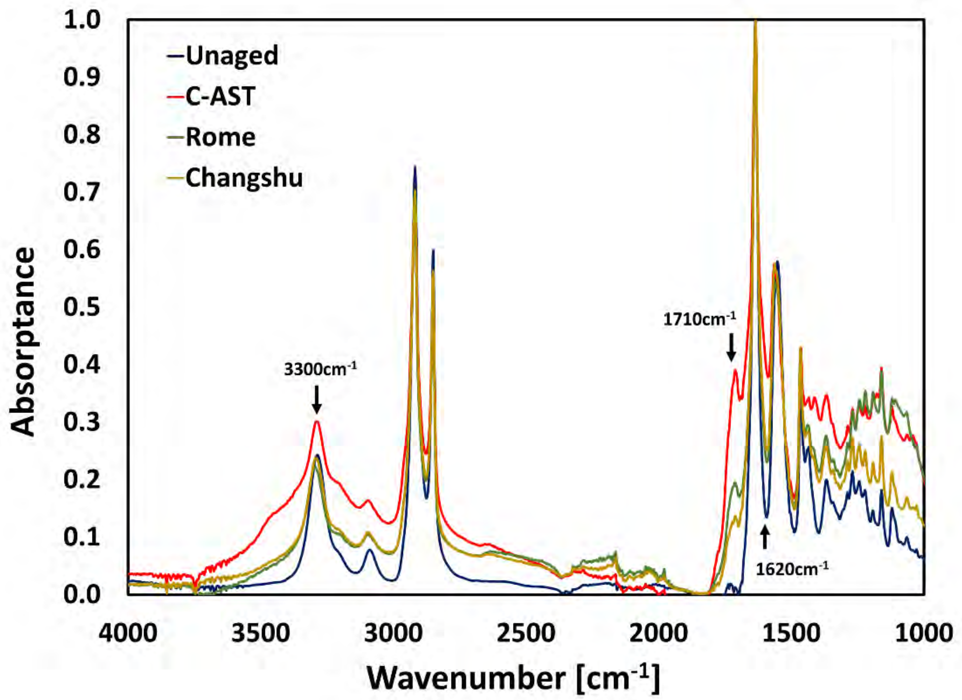
Field-deployed for 5 years



PA

Is the mechanism the same?

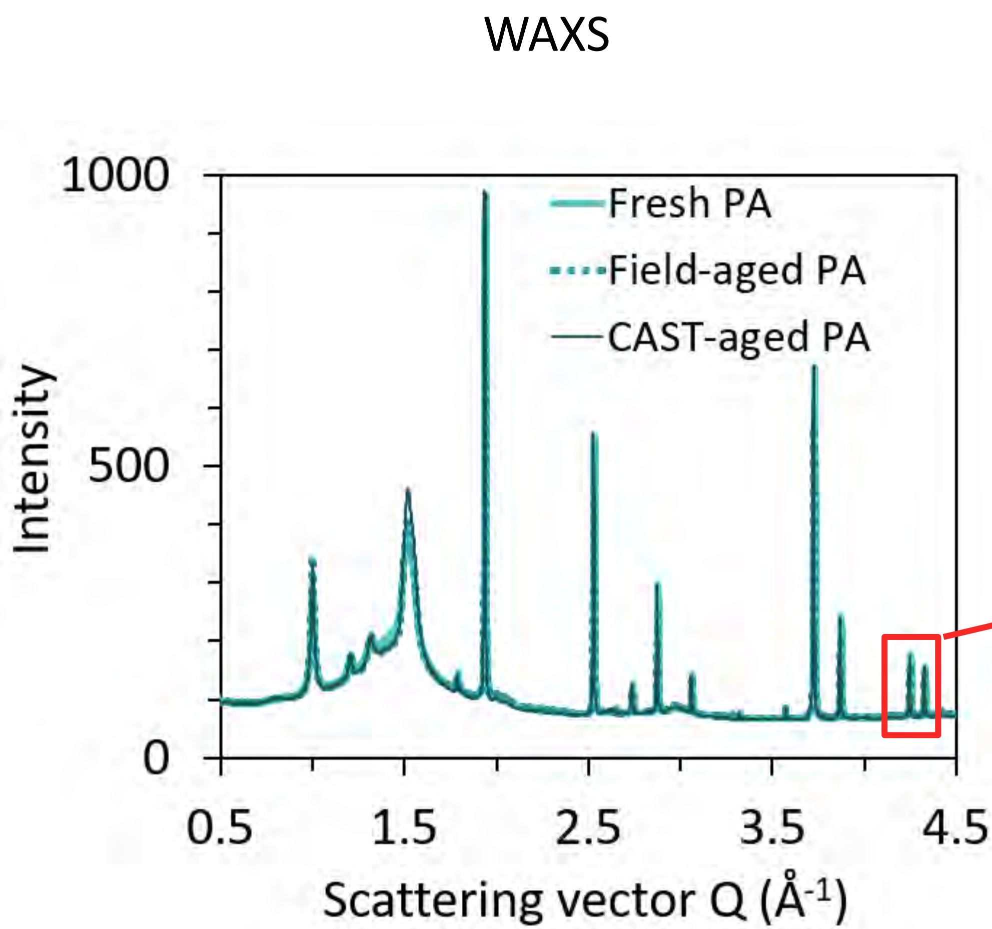
FTIR of field and C-AST aged PA

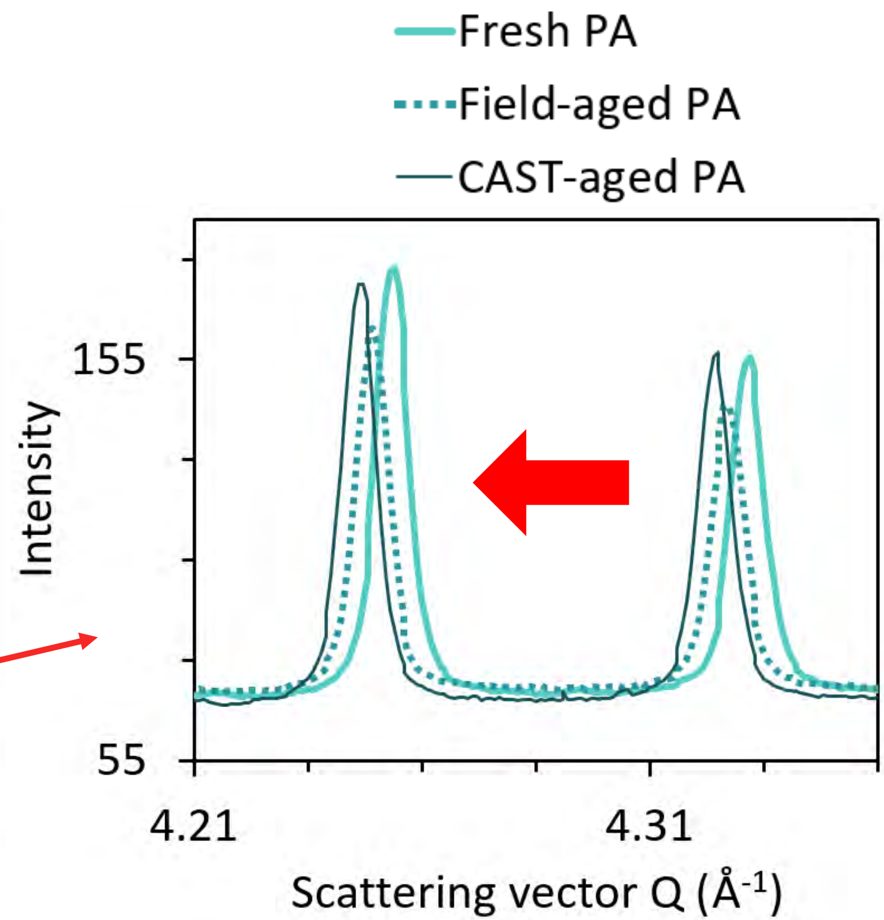


- Broadening of bands between 3200 and 3400 cm-1 is observable which suggests the formation of hydroxylated products and primary amines
- Increase in the peak at 1710 cm-1 suggests formation of carboxylic groups and C=C bonds which are associated with photo-oxidation*
- Peak changes in C-AST- and field-aged samples are same, suggesting relevant degradation mechanisms reproduced in C-AST

*Lyu et al "Degradation and Cracking Behavior of Polyamide-Based Backsheet Subjected to Sequential Fragmentation Test", IEEE JPV, 2018

Changes in pigment structure for aged PAs





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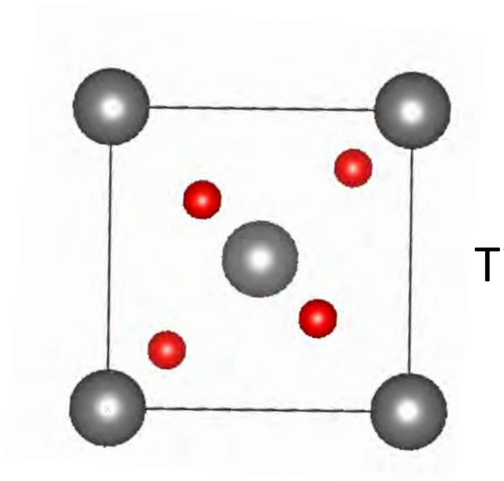
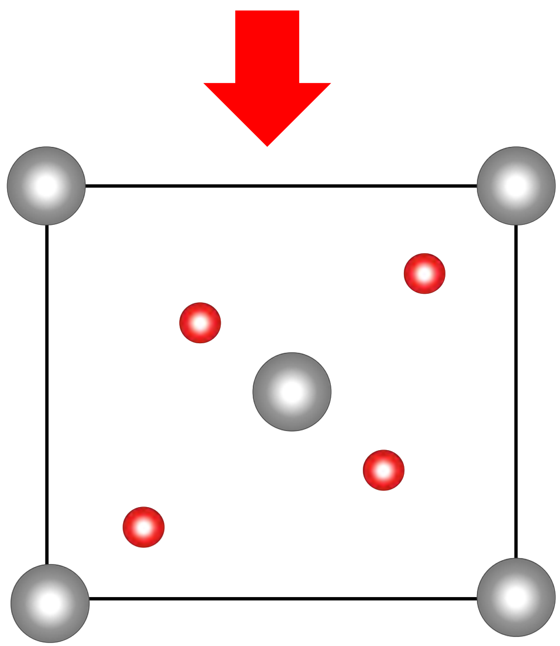
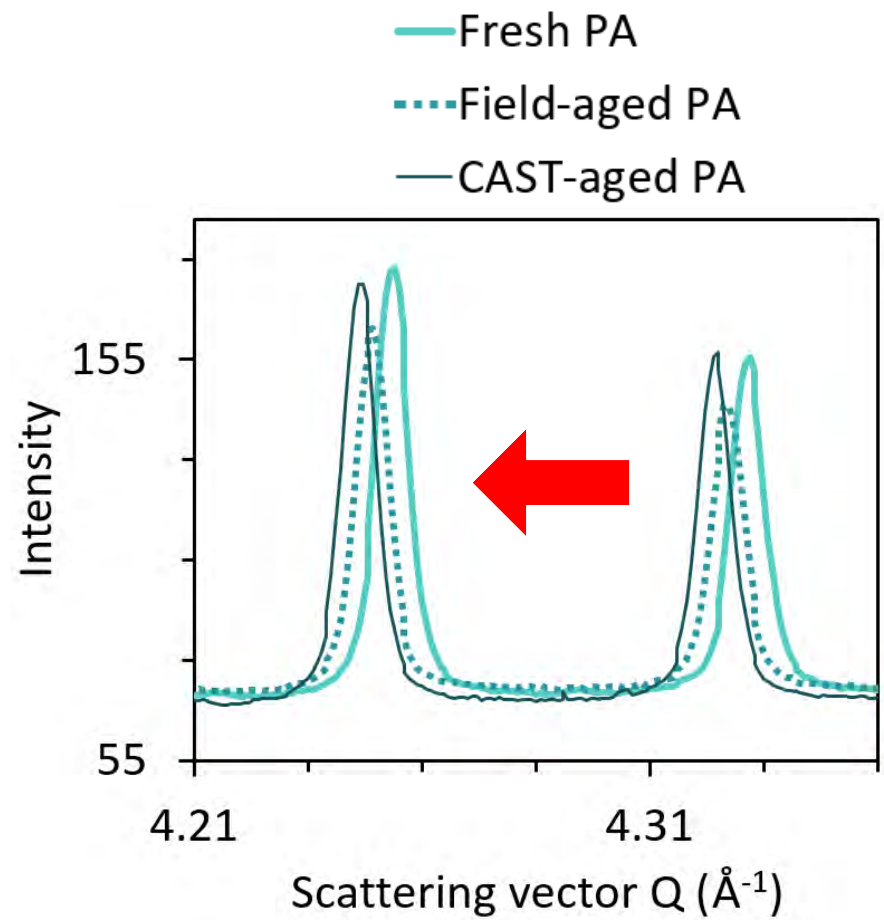


TiO_2

Expanding lattice

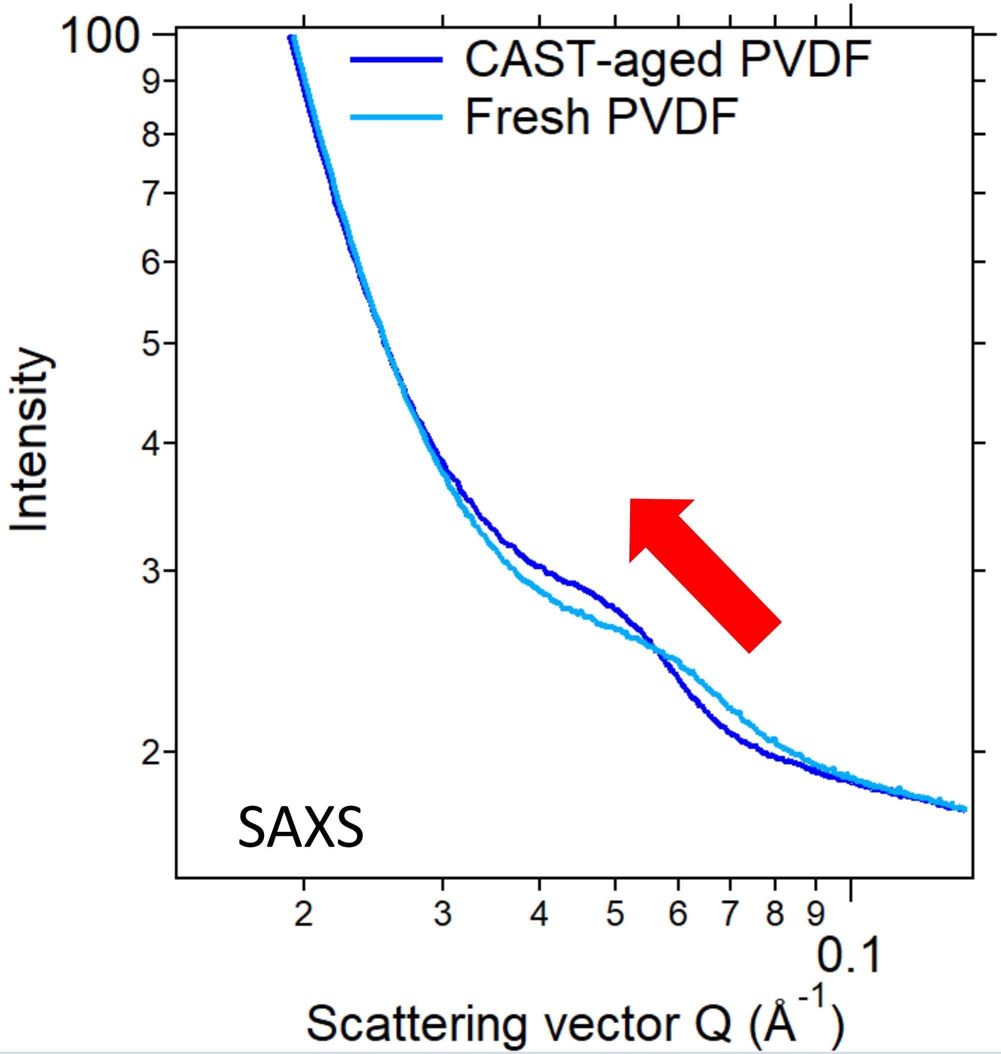


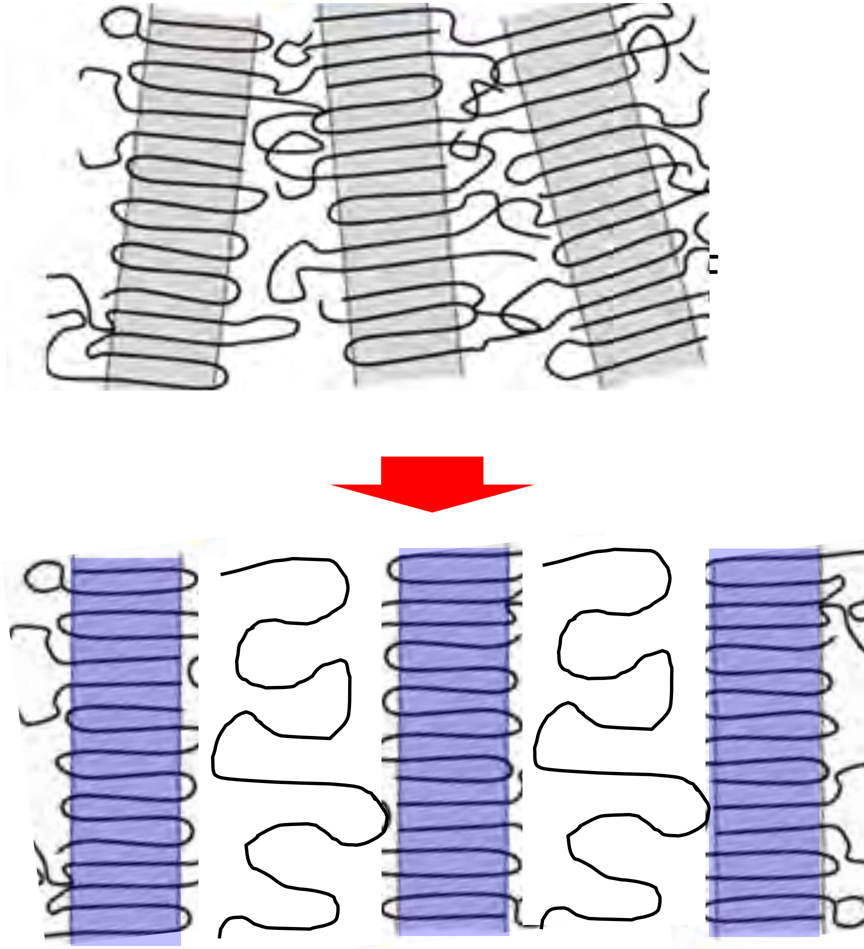


Lattice expansion is often seen in strained materials

Changes in pigment structure for CAST-aged PVDF

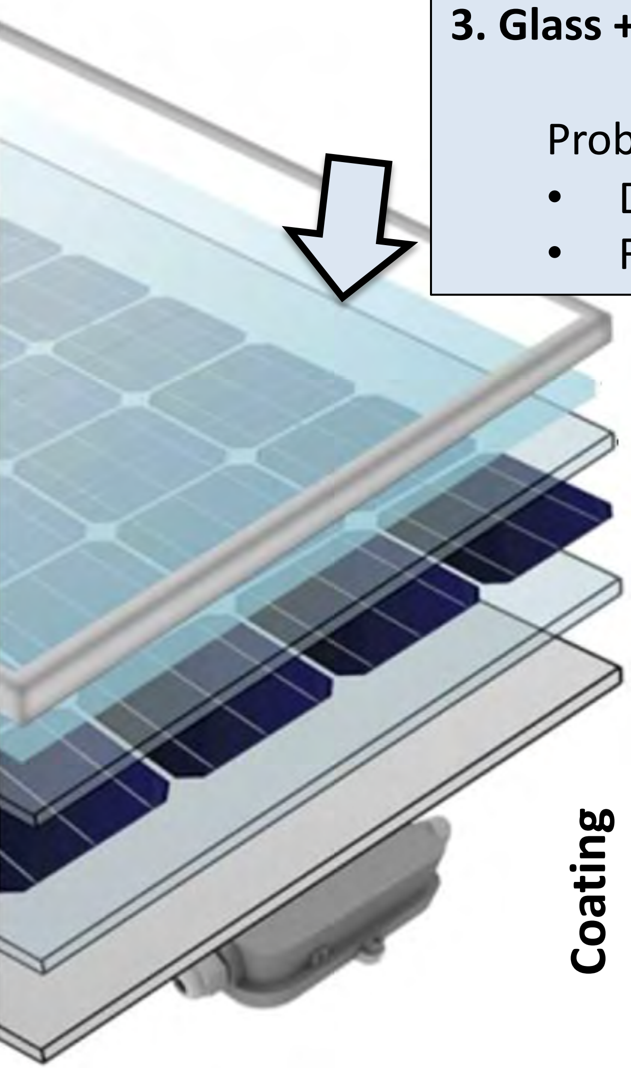
PVDF: Polyvinylidene fluoride-based backsheet





Is this the same for field-aged PVDF?

Interfaces & surfaces common failure points



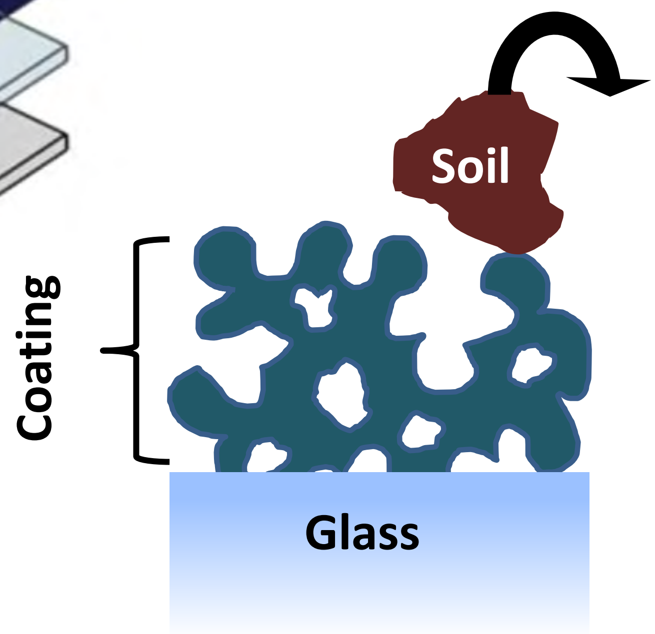
3. Glass + Coating + Soil

Problem areas:

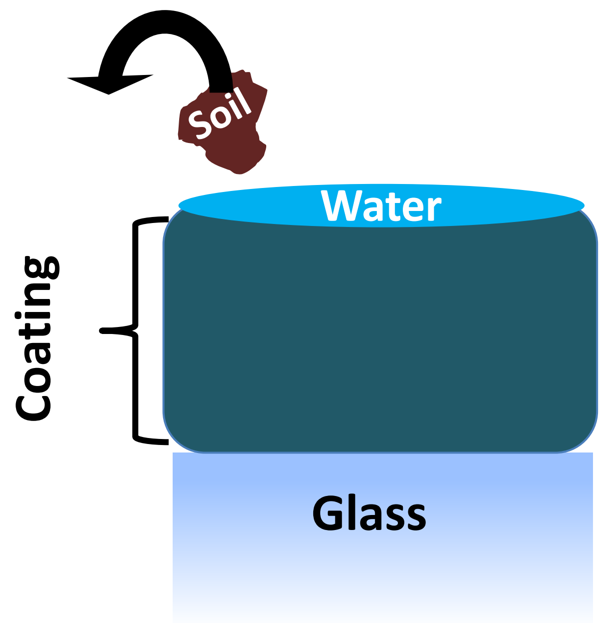
- Durability
- Functionality

WattGlass
Glass Coatings Perfected

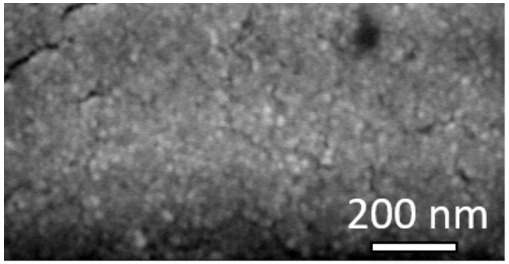
Coating morphology

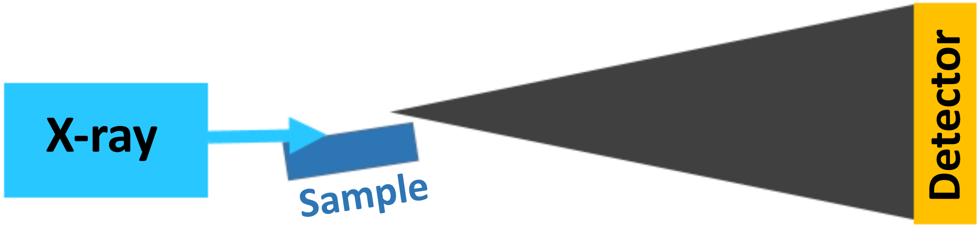


Coating chemistry



Characterization methods for coating morphology





Current technique:
Microscopy

- Limited to a vacuum chamber
- Unable to visualize coating below dirt layer
- Spot size is typically micron-scale

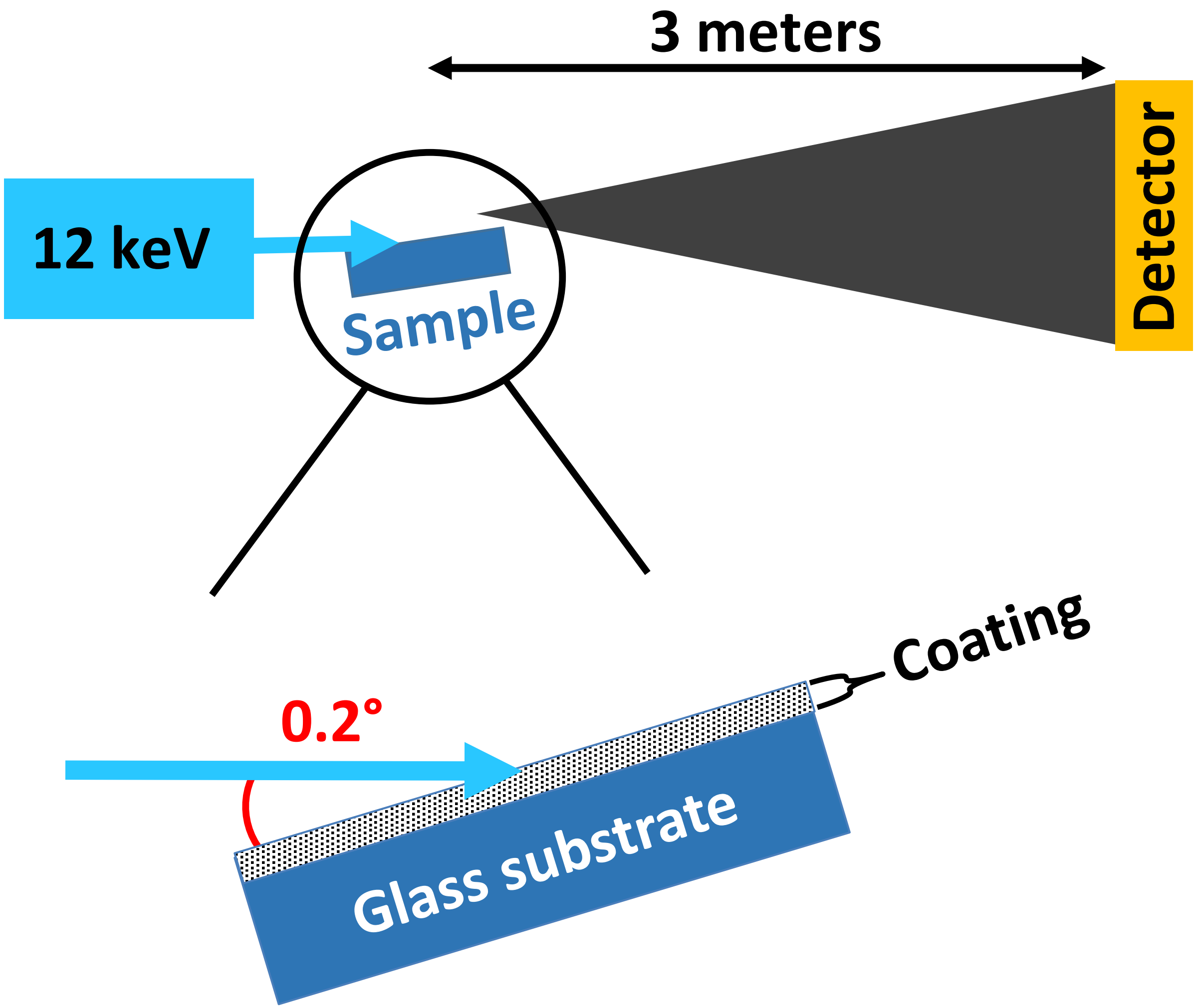
Vs.

New technique:
Small-angle X-ray scattering (SAXS)

- Performed under ambient conditions (including humidity)
- Can measure coating morphology despite the presence of surface dirt
- Spot size can be centimeter-sized

Small-angle X-ray scattering

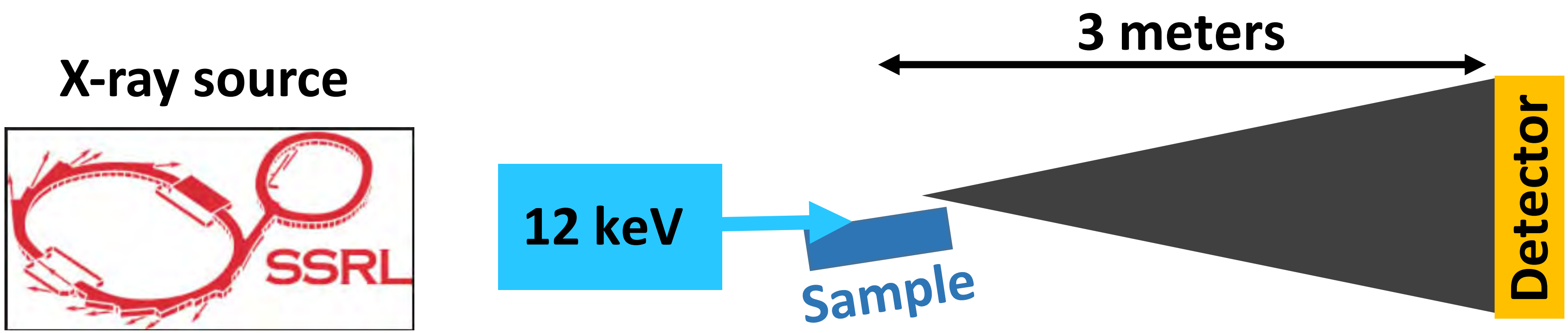
X-ray source



Grazing Incidence

X-ray path through the coating is maximized

Small-angle X-ray scattering



$$Q = 2\pi/d$$

Scattering vector

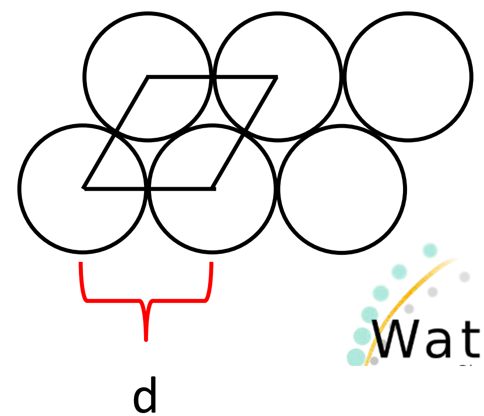
Feature size

$$Q = \left(\frac{4}{\lambda}\right) sin\theta$$

Wavelength

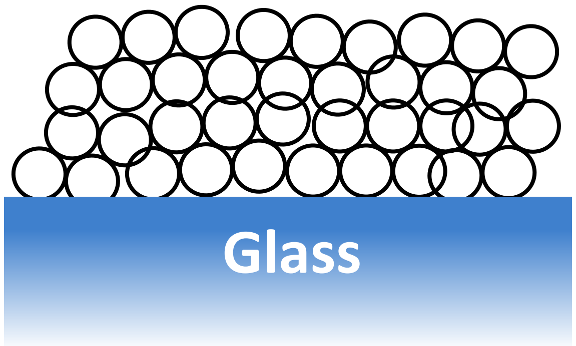
Scattering angle

Closed-packed SiO_2 spheres

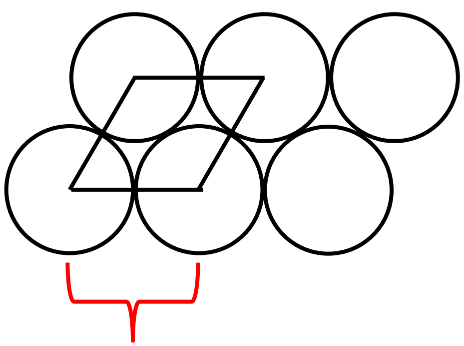


WattGlass

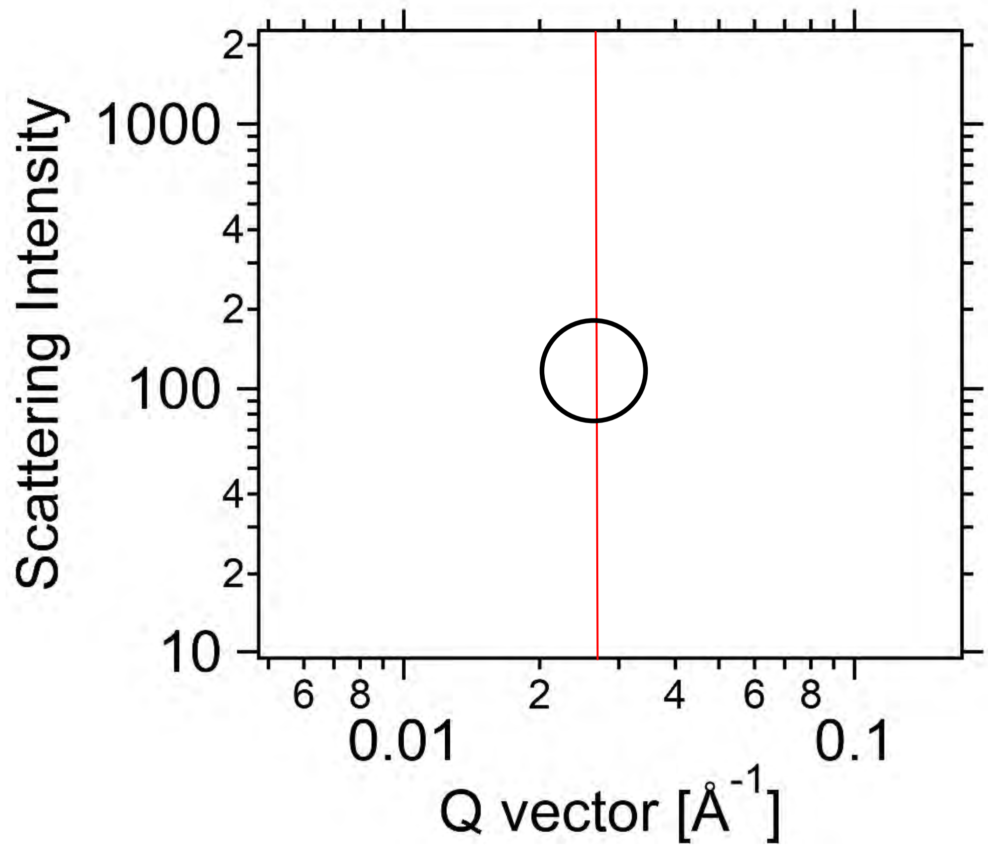
SAXS of WattGlass coating



Closed-packed
SiO_2 spheres



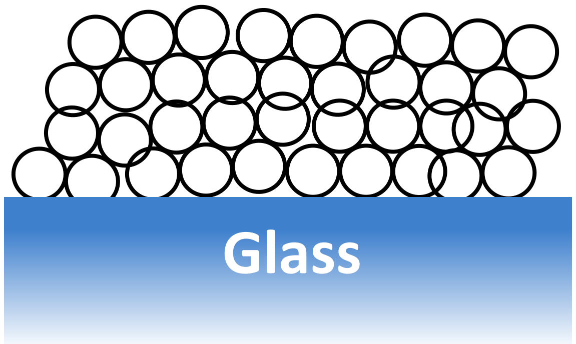
20-30nm

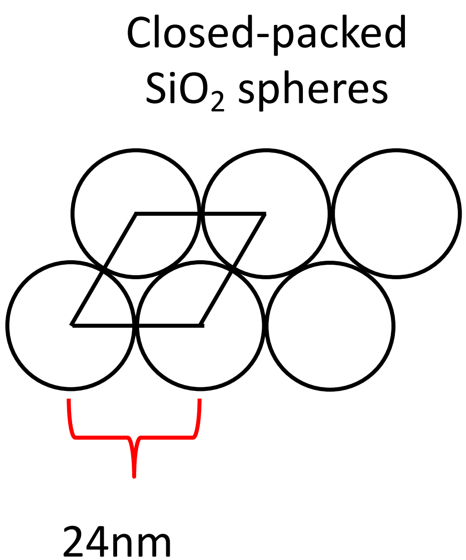


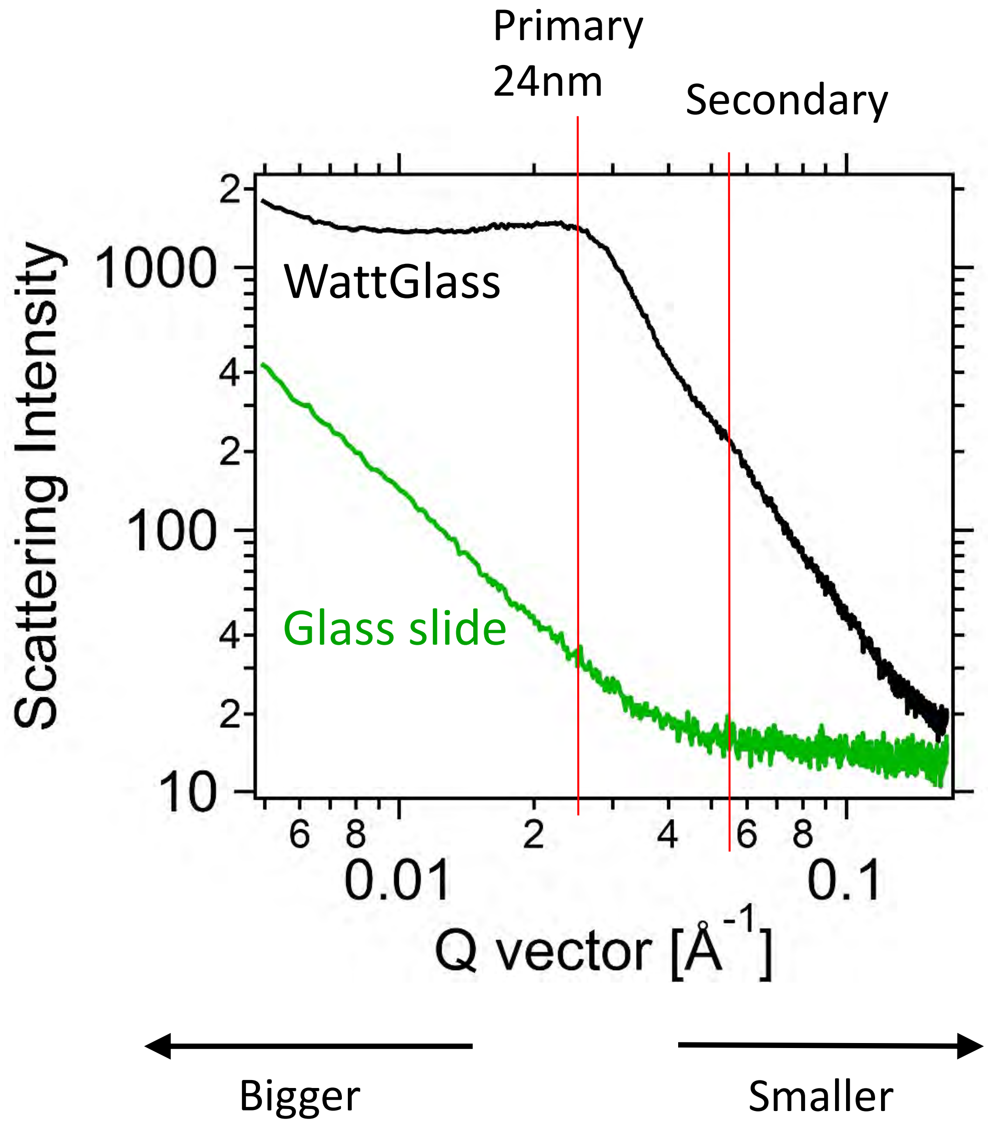
Bigger

Smaller

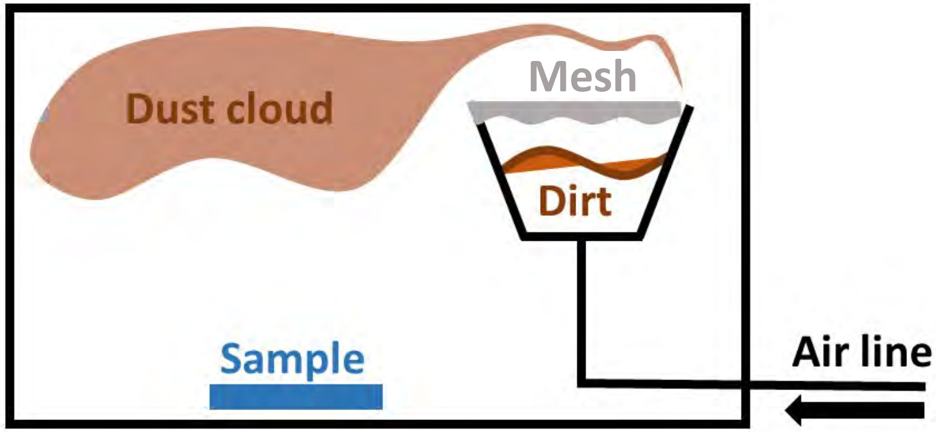
SAXS of WattGlass coating

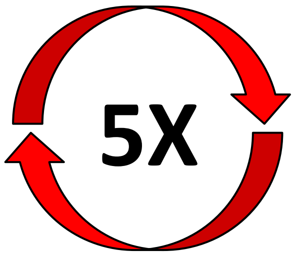


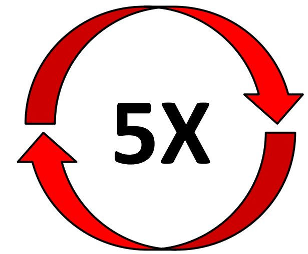


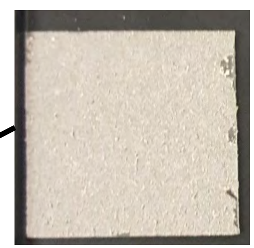


Soiling



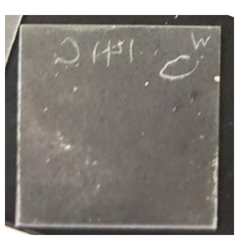






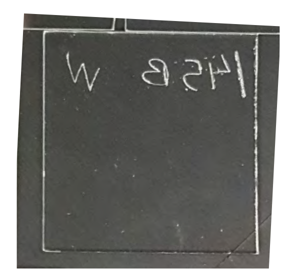
"dry-air" cleaning protocol

"water" cleaning protocol

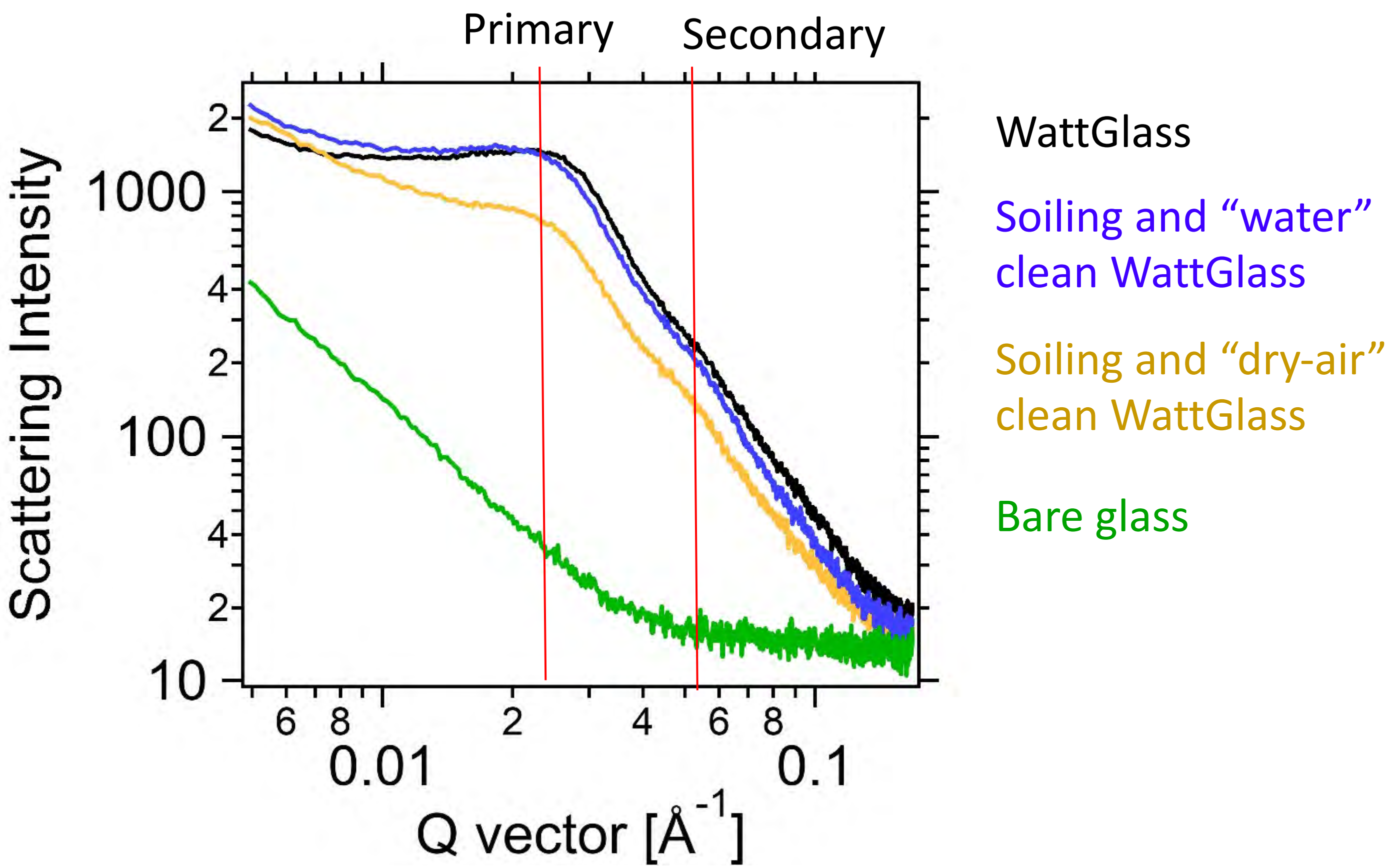


Compressed air with a low flow rate is blown over the sample surface

Distilled water is flowed over the sample from a squeeze bottle



Soiled WattGlass SAXS



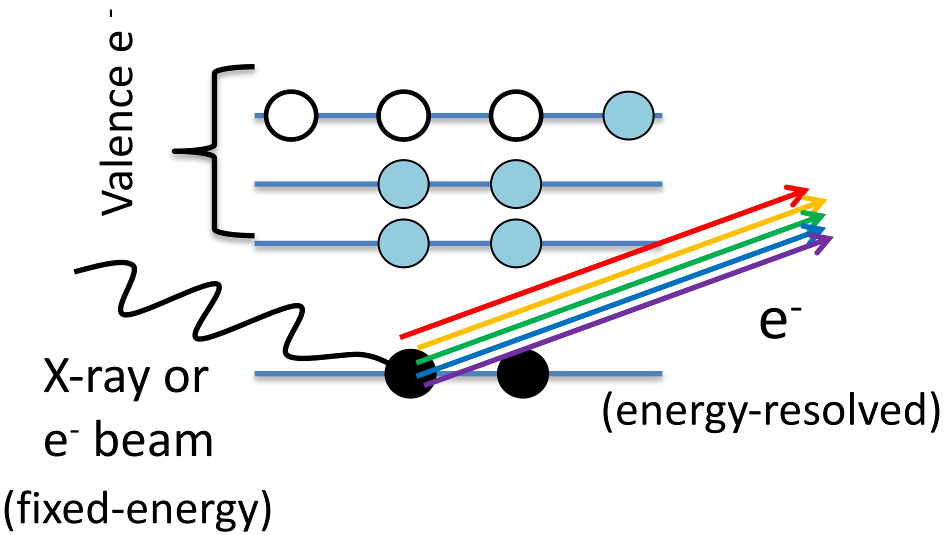
- Scattering features indicative of the coating morphology do not change
- Upturn in scattering intensity at small Q due to presence of μm-sized soil
- Slight damping of scattering intensity due to surface soil

Characterization methods for coating chemistry

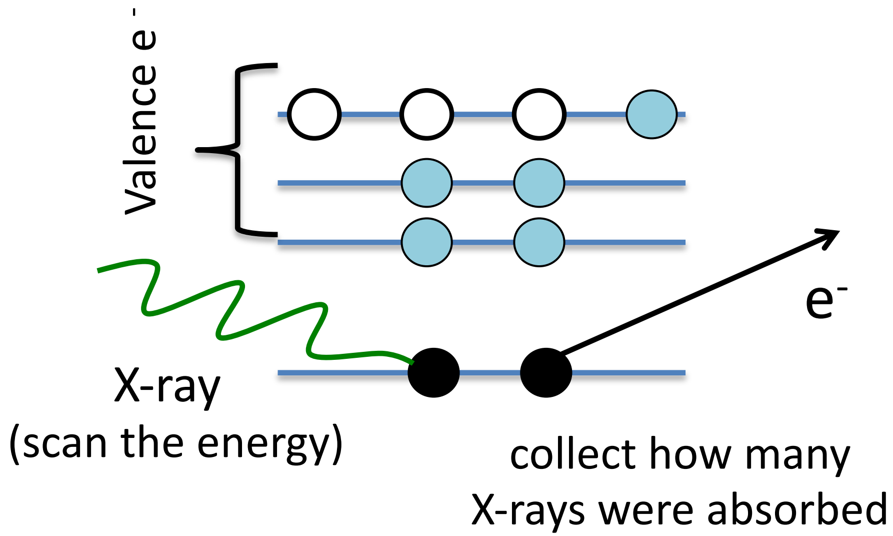
Current techniques: **Vs.** **New technique:**

X-ray photoelectron spectroscopy (XPS)

Energy dispersive spectroscopy (EDS)

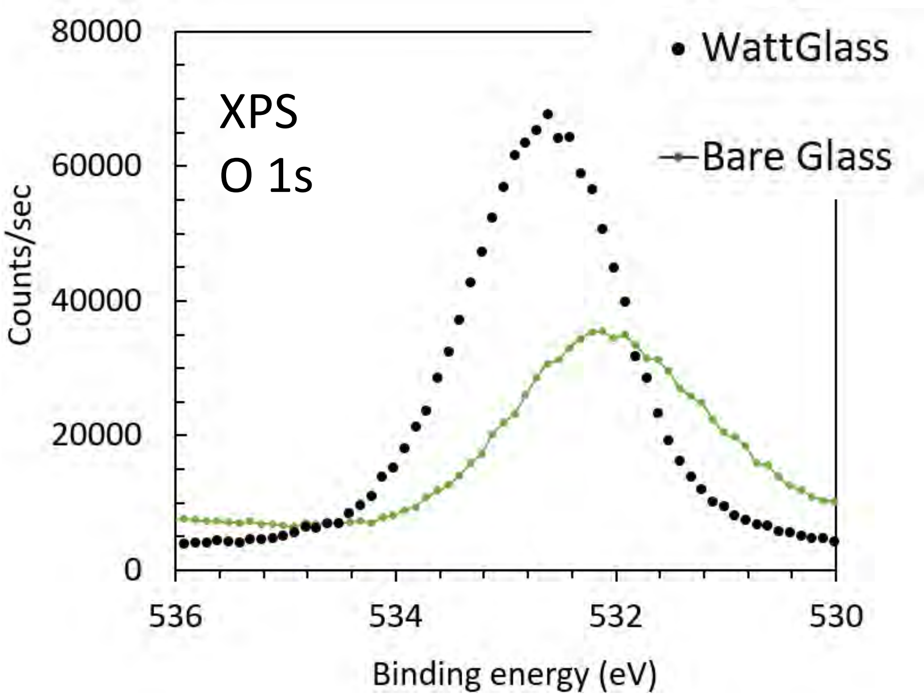


X-ray absorption spectroscopy (XAS)

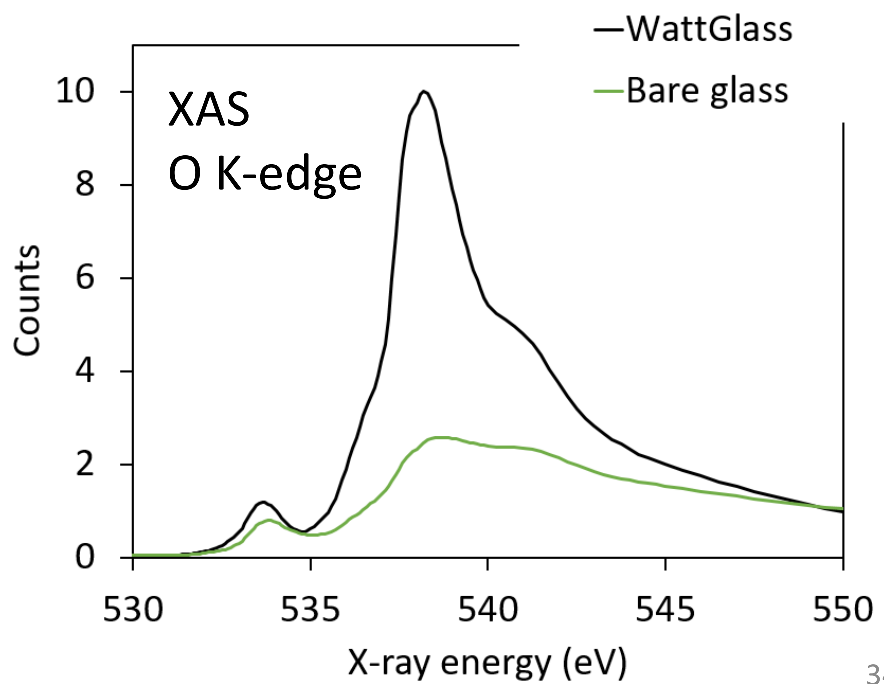


- Option for greater penetration depth
- Larger spot size
- More sensitive to chemistry changes

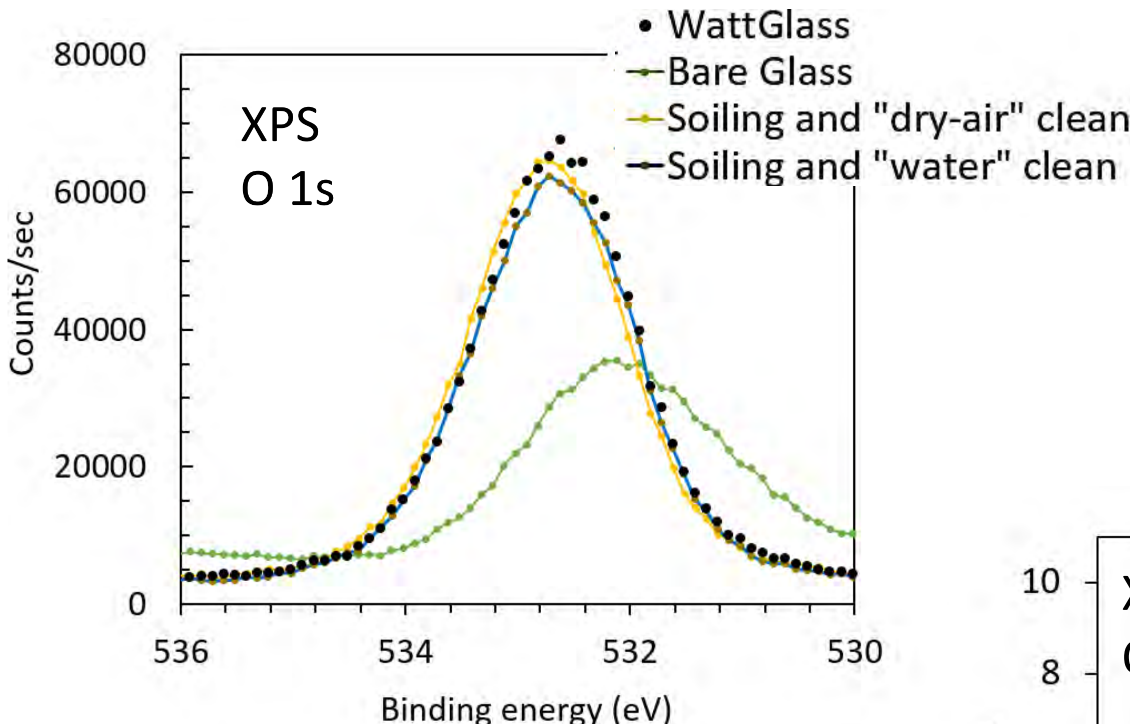
XAS and XPS of WattGlass coating O-chemistry



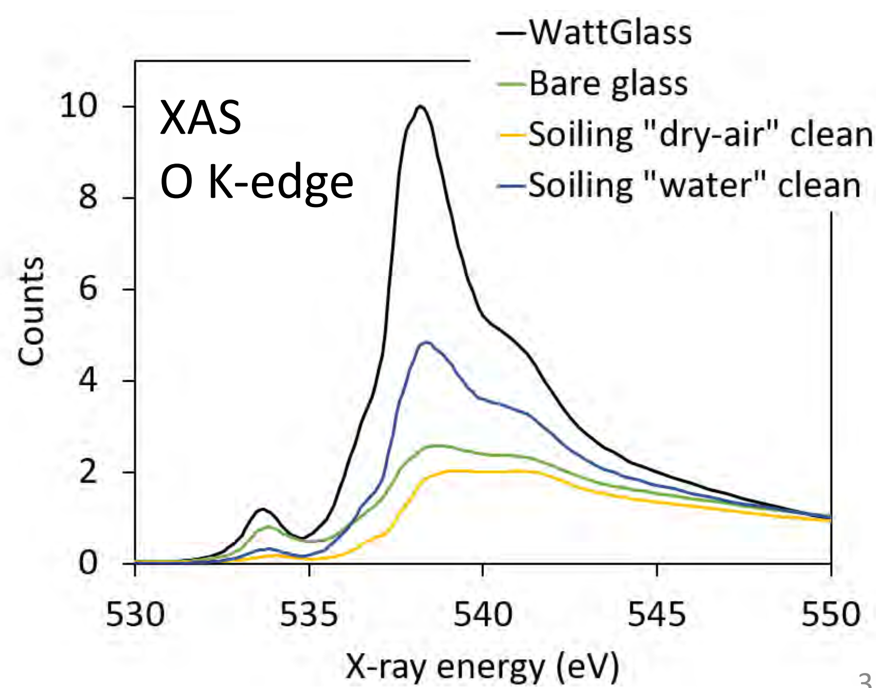
Coating is easily differentiated from bare glass by both techniques

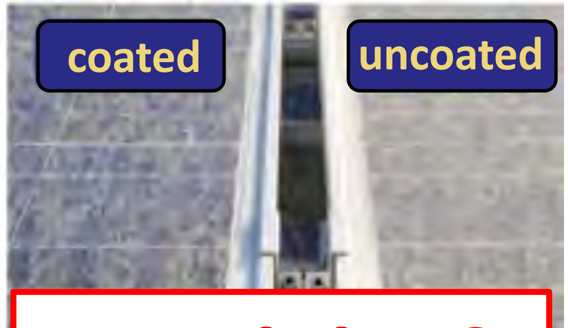


XAS and XPS of WattGlass coating O-chemistry



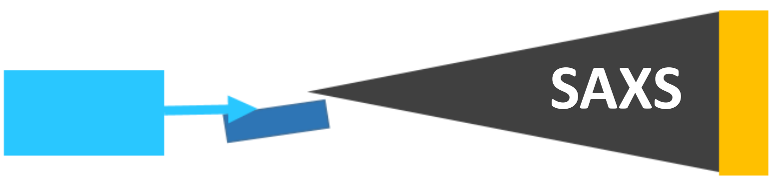
Changes in the coating O-chemistry after soiling can only be seen in XAS measurement





Durability?

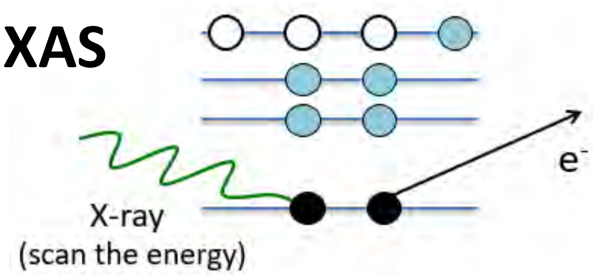
Morphology



Measure morphology under ambient conditions when soil is present

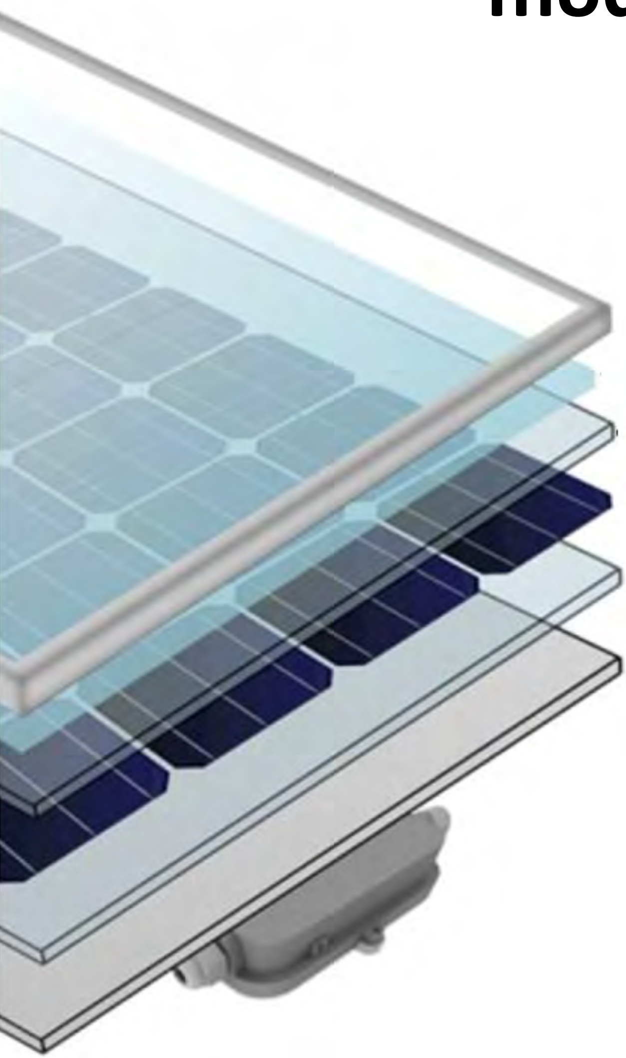
Chemistry

XAS



Higher sensitivity to subtle changes in coating chemistry

Materials forensics for understanding PV module material durability



- Tested methodologies to characterize interface degradation
- Focused on:
  - Chemistry
  - Morphology
  - Mechanical properties

- What's next for module forensics?
  - Fielded module testing
    - In-field testing
    - Forensics without the BOM
  - Validation of acceleration science

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Next Month’s Seminar – Save the date:

Monday, September 9 at 1:00 MT

"Testing at Scale: Methods and Challenges Associated with Curated, Grid-Tied PV System Research"

presented by Bruce King, Sandia