



Review of observed degradation modes and mechanisms from fielded modules

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Lifetime prediction requires field experience

Reliability tests need to address the correct modes and accelerate the correct mechanisms

We need to know what field failure looks like

Collecting field failures

Locations and climates

Sacramento, California (warm temperate/summer dry/hot summer)

Cocoa and Marin County, Florida (warm temperate/fully humid/hot summer)

Springerville, Arizona (warm temperate/summer dry/warm summer)

Tucson, Arizona (arid/steppe/hot arid)

Toledo and Perrysburg, Ohio (snow/fully humid/hot summer)

Technologies

mono-Si, poly-Si, HIT, EFG Si

a-Si, CIGS, CdTe

Failure types

Chemical breakdown

Mechanical breakdown

Organizing observations

Crystalline silicon modules

Chemical breakdown

- Discoloration

- Corrosion

Mechanical breakdown

- Delamination

- Interconnect failure

- Cell cracking

Thin-film modules

Chemical breakdown

- Corrosion

Mechanical breakdown

- Edge seal deformation

- Interconnect failure

Crystalline silicon

Chemical breakdown

Discoloration

Yellowing of encapsulant

Driven by UV and heat

Corrosion

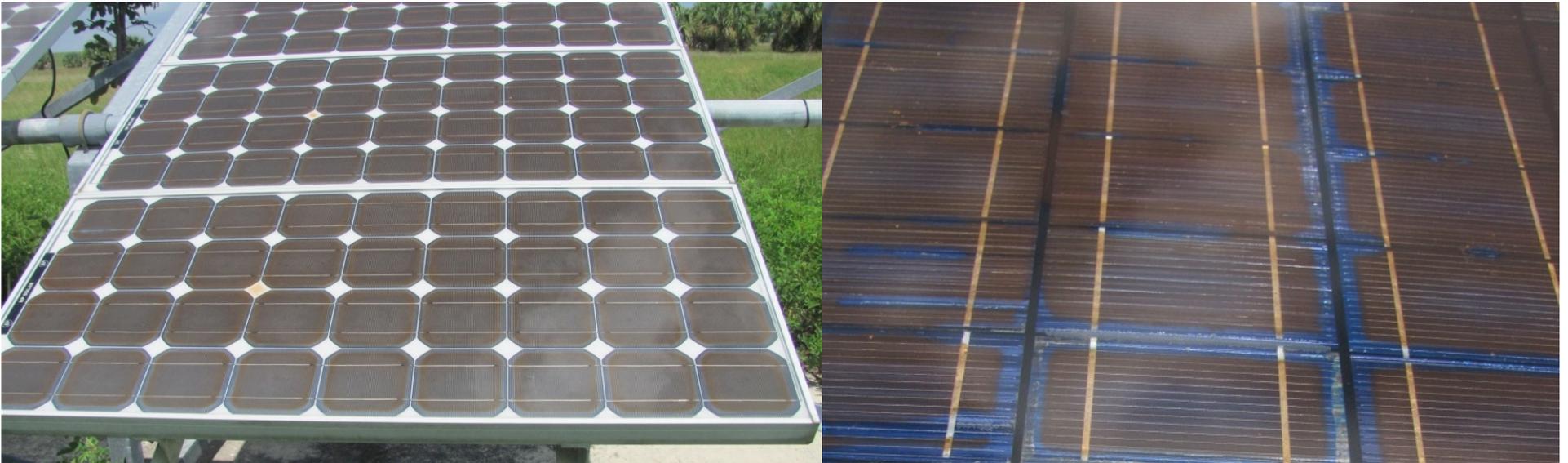
Oxidation of metal components

Driven by reaction with moisture and oxygen

Often coincident with delamination

Crystalline silicon: Chemical breakdown

Discoloration

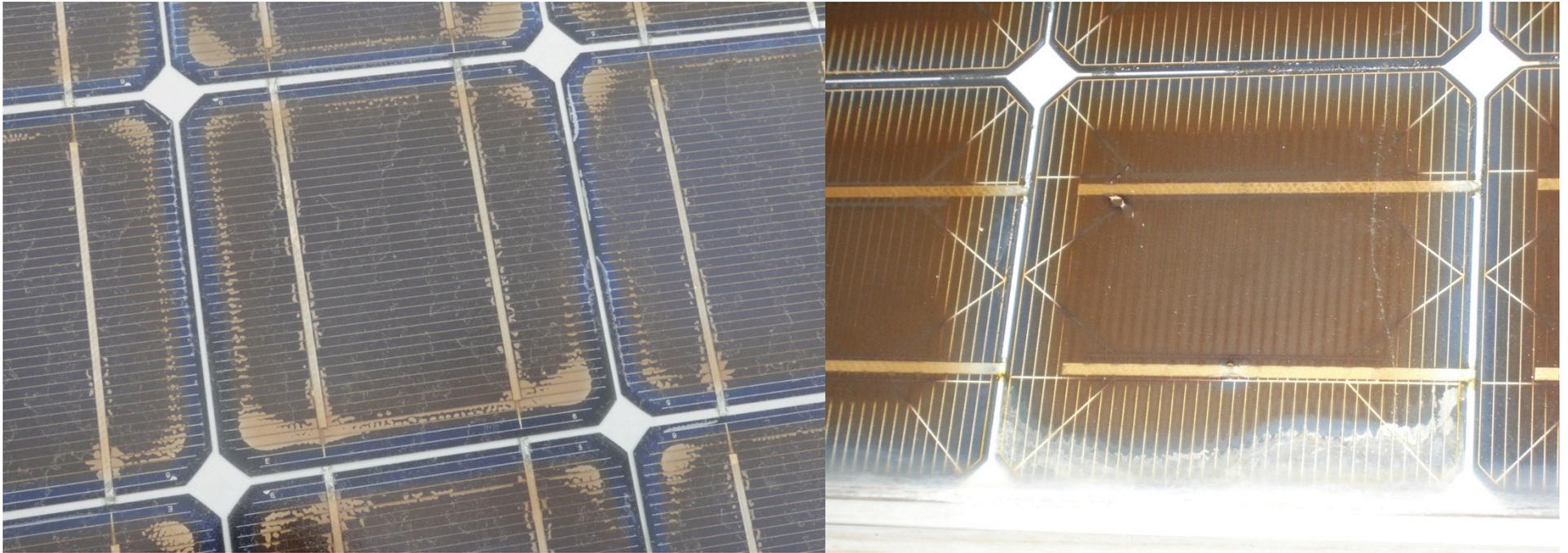


mono-Si (left) and EFG Si (right) after 23 years in Marin County, Florida (warm temperate/fully humid/hot summer)

Encapsulant can get very dark, reducing short-circuit current

Crystalline silicon: Chemical breakdown

Discoloration

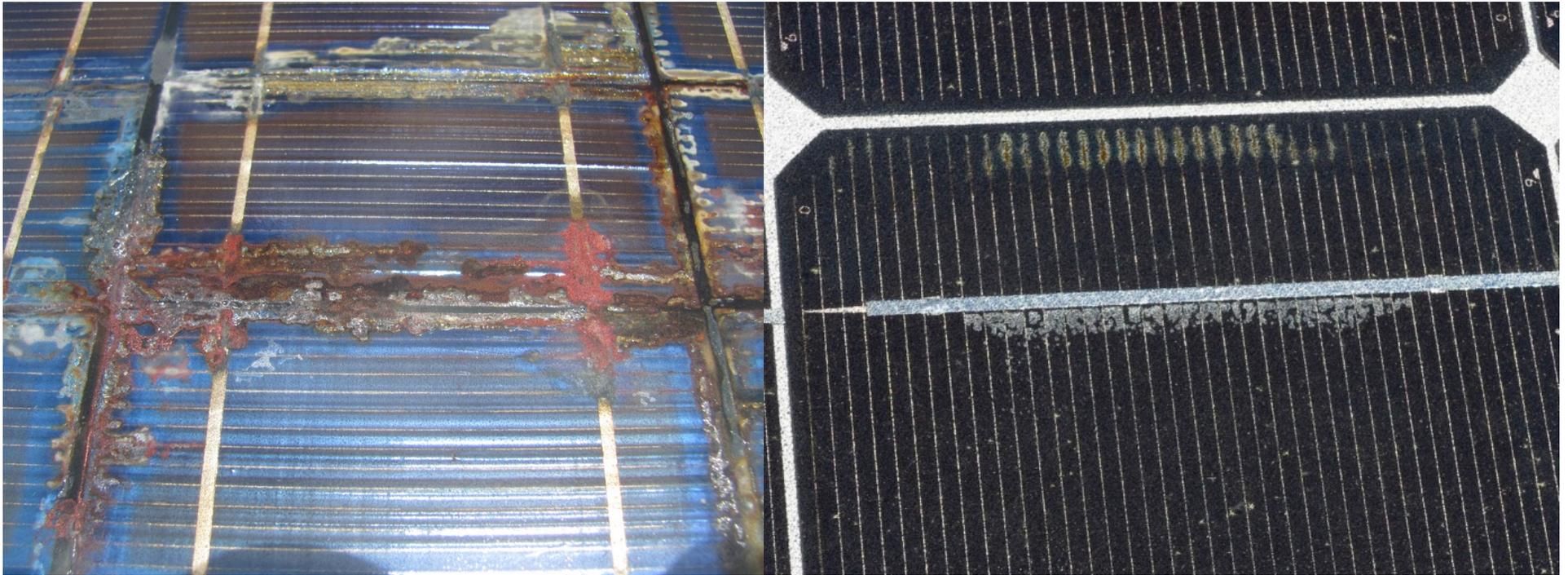


mono-Si after 18 years (left) and 27 years (right) in Sacramento (warm temperate/
summer dry/hot summer)

Delamination can accompany discoloration

Crystalline silicon: Chemical breakdown

Corrosion



EFG Si after 23 years in Marin County, Florida

mono-Si after 15 years in Cocoa, Florida

Delamination can let in moisture, causing corrosion, but some corrosion occurs without delamination

Crystalline silicon

Mechanical breakdown

Delamination

Caused by inadequate adhesion or loss of adhesion between layers

Driven by moisture, mechanical stress and UV

Interconnect failure

Thermomechanical fatigue of ribbons or solder bonds

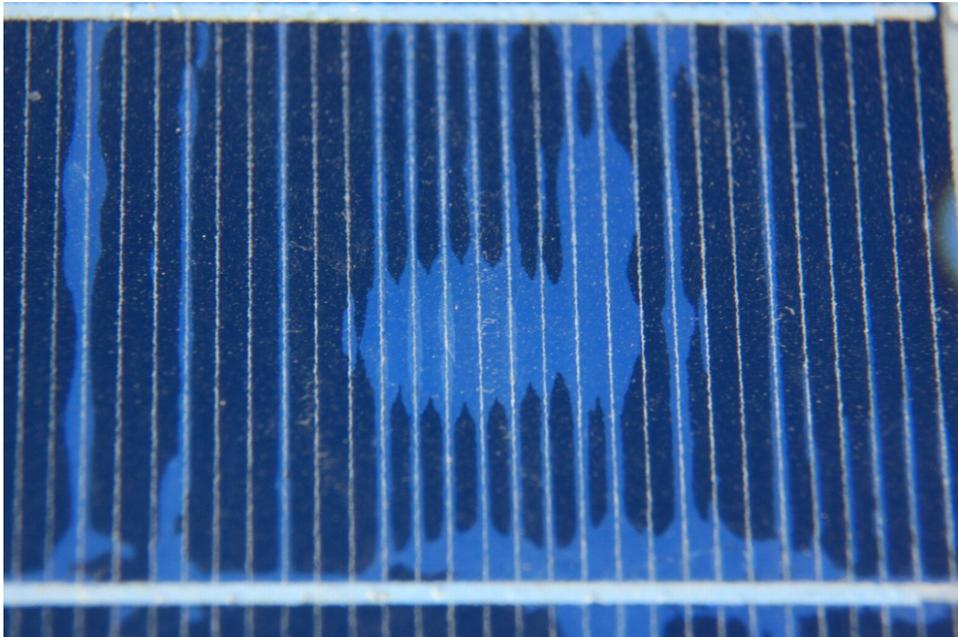
Driven by thermal cycling

Cell cracking

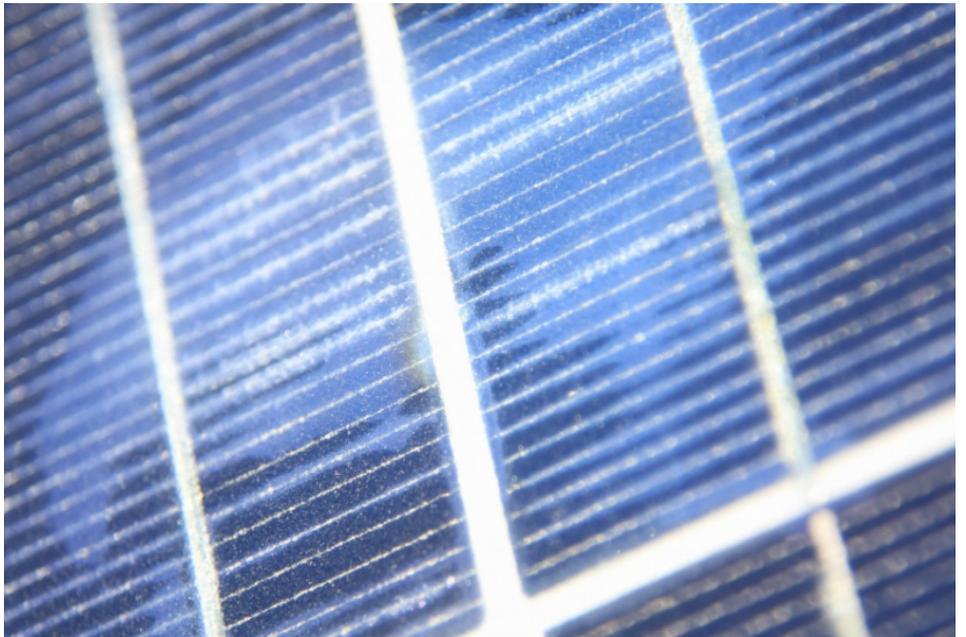
Driven by one-time application of stress

Crystalline silicon: Mechanical breakdown

Delamination



EFG Si after 11 years in Springerville

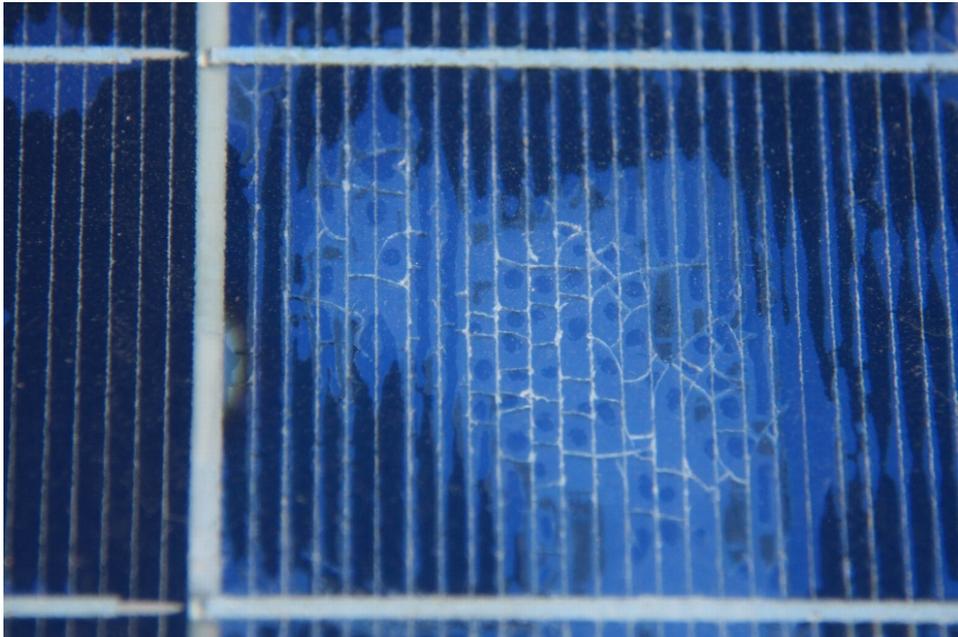


EFG Si after 13 years in Tucson

An ionomer encapsulant showed delamination along fingers at two sites

Crystalline silicon: Mechanical breakdown

Delamination



EFG Si after 11 years in Springerville

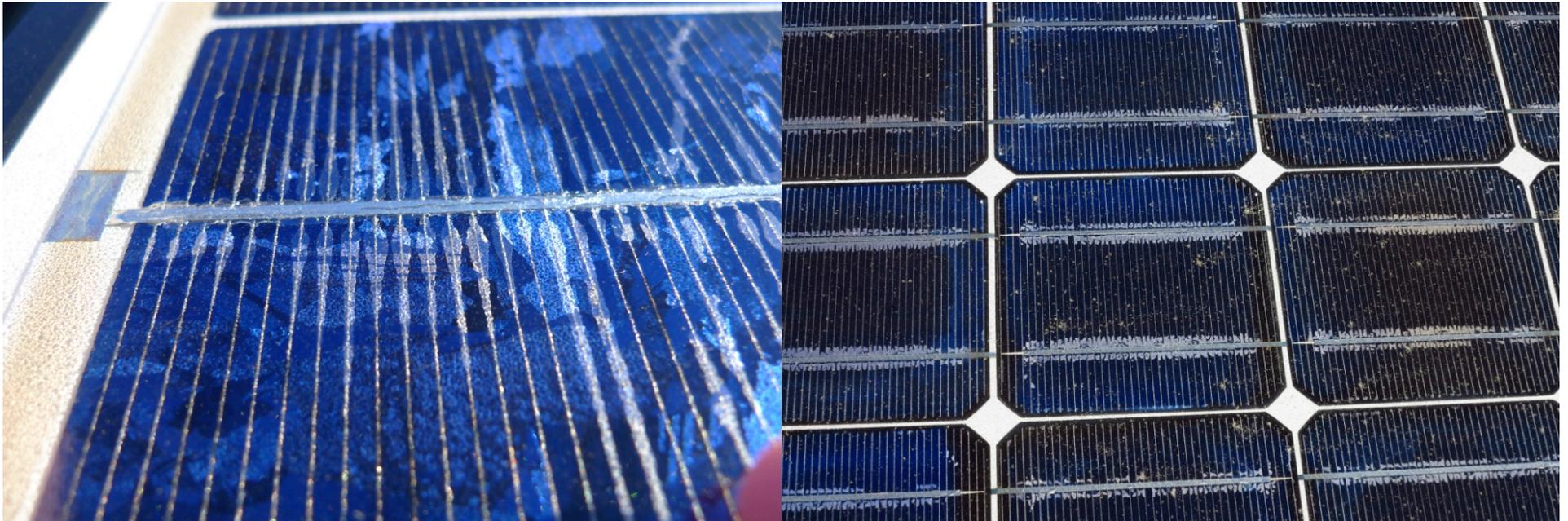
EFG Si after 13 years in Tucson

At the junction box, it showed cohesive failure, too

This was fixed with a reformulation of the ionomer

Crystalline silicon: Mechanical breakdown

Delamination



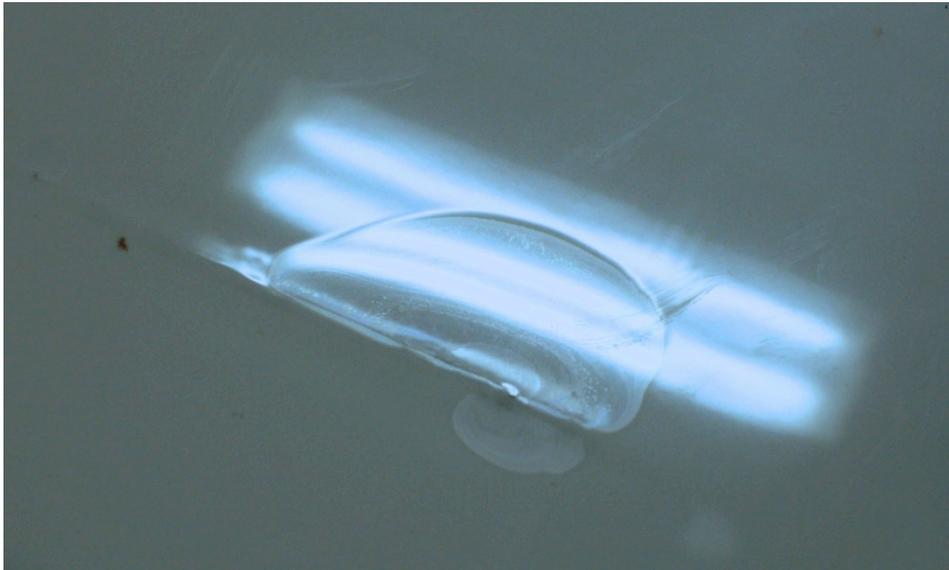
multi-Si after 10 years in Perrysburg, Ohio

mono-Si after 15 years in Cocoa, Florida

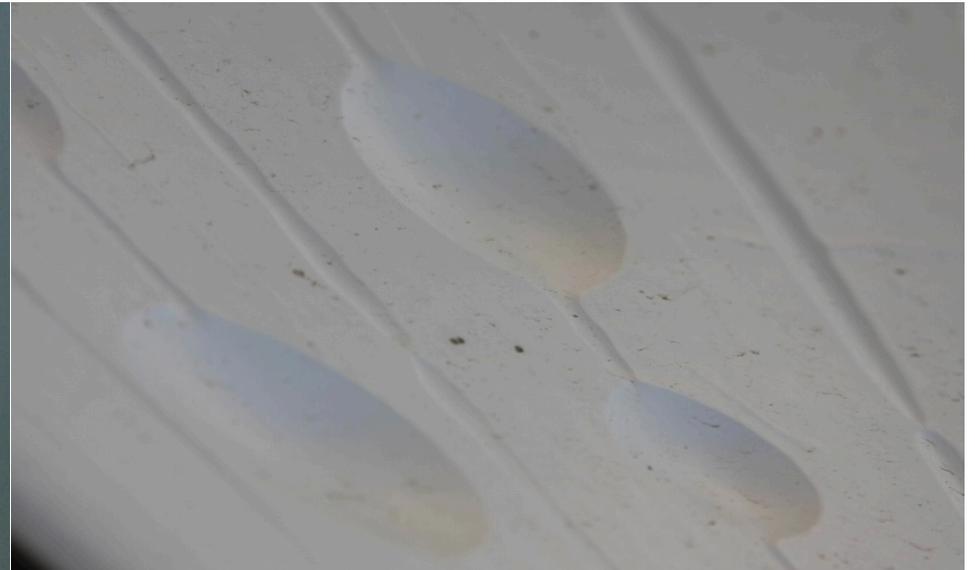
Delamination at the encapsulant-cell interface often follows ribbons and grid fingers

Crystalline silicon: Mechanical breakdown

Delamination



multi-Si after 10 years in Perrysburg

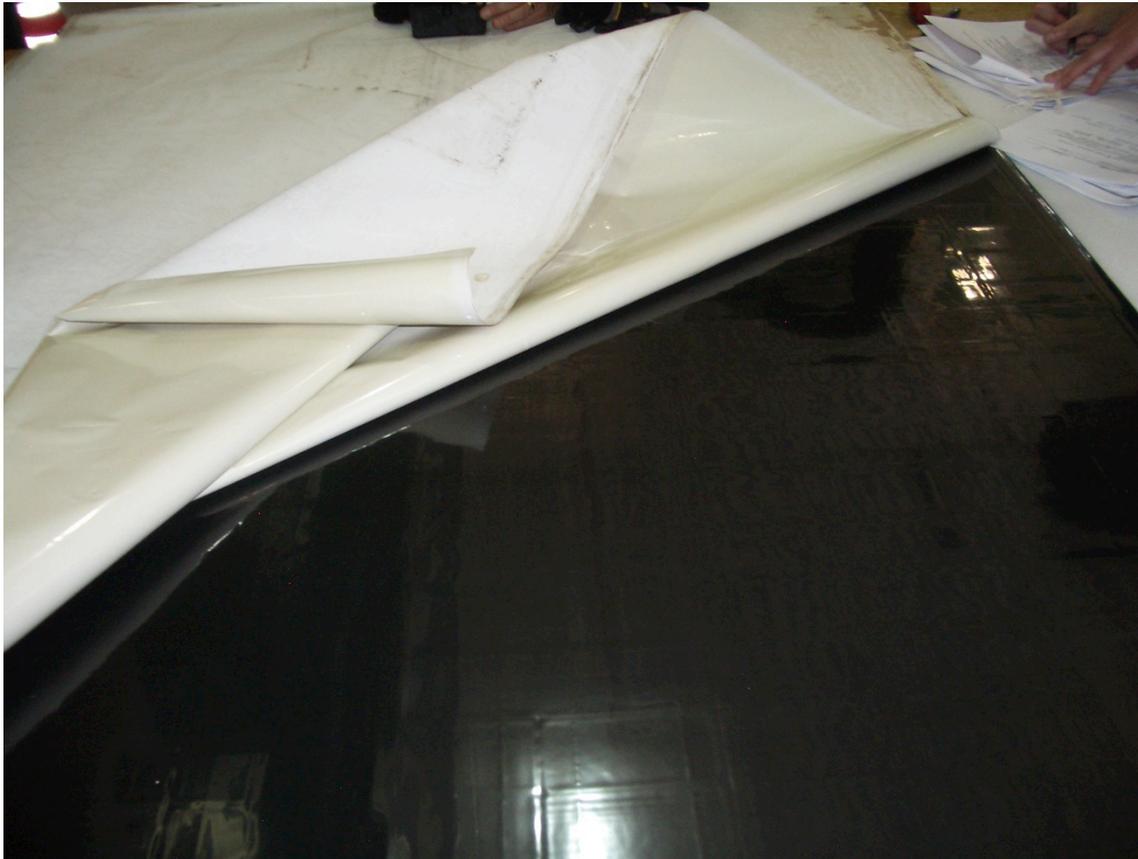


HIT after 10 years in Tucson
Al-containing backsheet traps outgassing

Backsheet layers can separate from each other or from the encapsulant

Crystalline silicon: Mechanical breakdown

Delamination

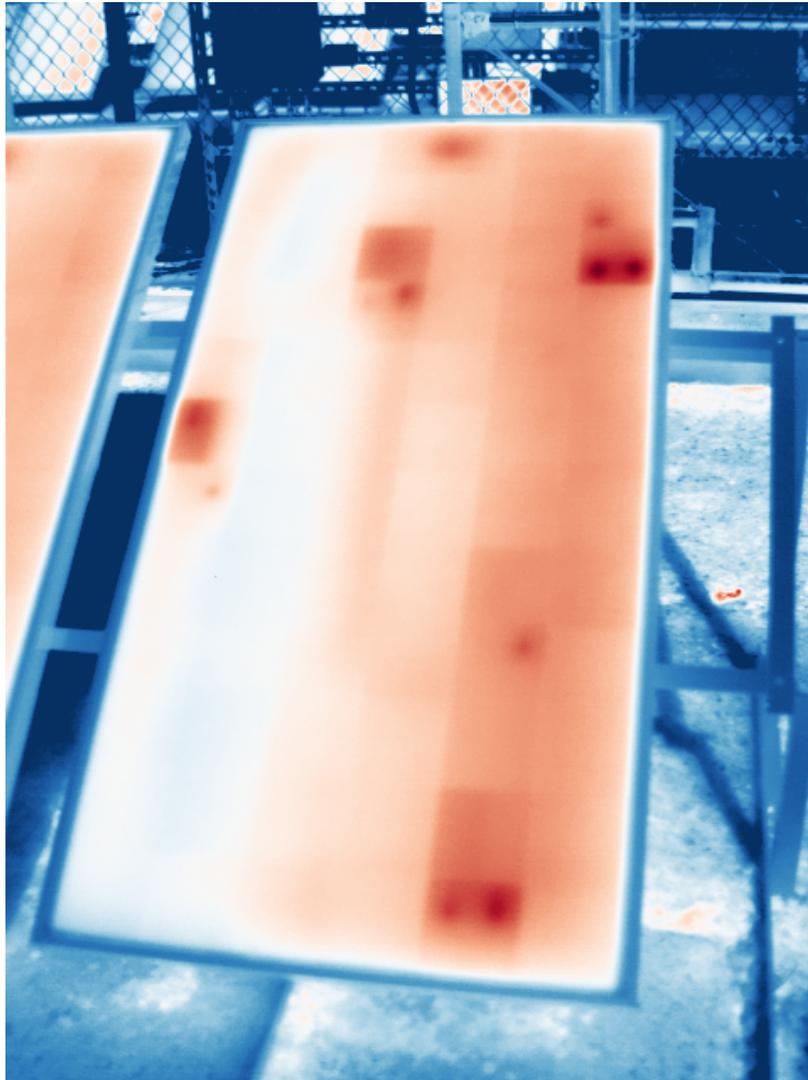


Or they can
flee the module
entirely

EFG Si after 27 years in Sacramento

Crystalline silicon: Mechanical breakdown

Interconnect degradation



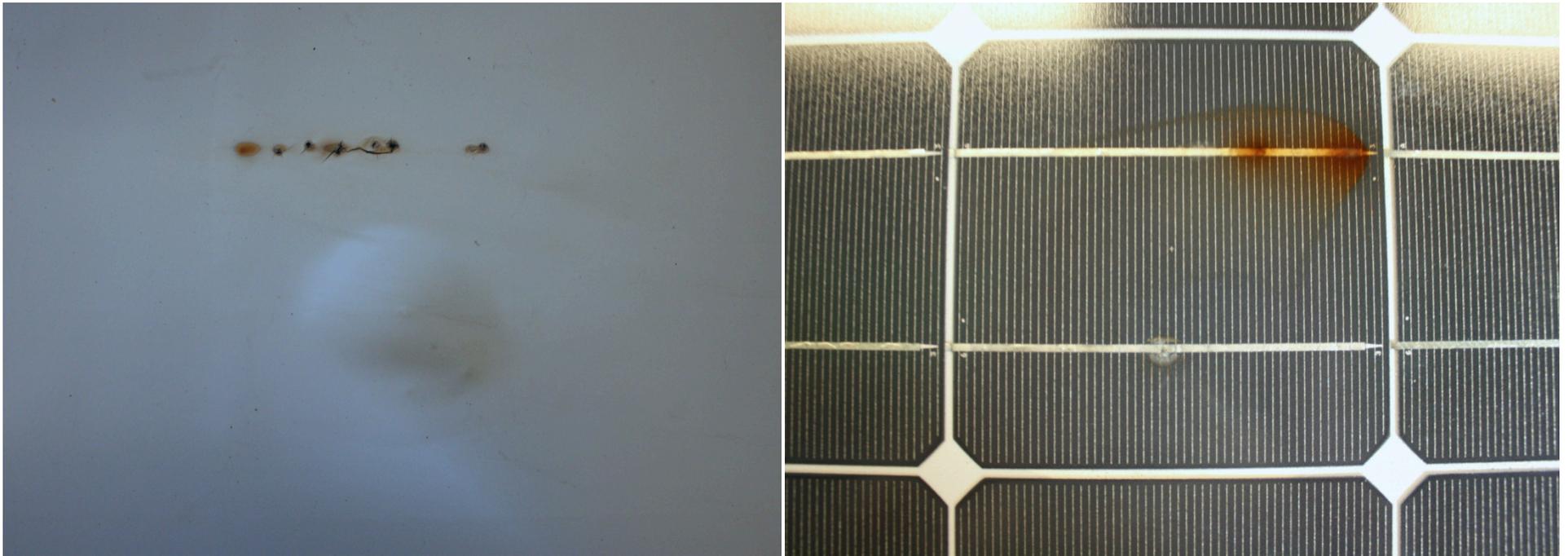
Broken solder bonds lead to high series resistance and loss of FF

They also result in highly localized dissipation of heat

mono-Si after 8 years in Tucson

Crystalline silicon: Mechanical breakdown

Interconnect degradation



mono-Si after 10 years in Perrysburg, Ohio

Highly localized heating from broken solder bonds damages adjacent materials

Crystalline silicon: Mechanical breakdown

Interconnect degradation



23 years in Marin County, Florida

16 years in Sacramento

Highly localized heating from broken solder bonds damages adjacent materials

Crystalline silicon: Mechanical breakdown

Broken cells



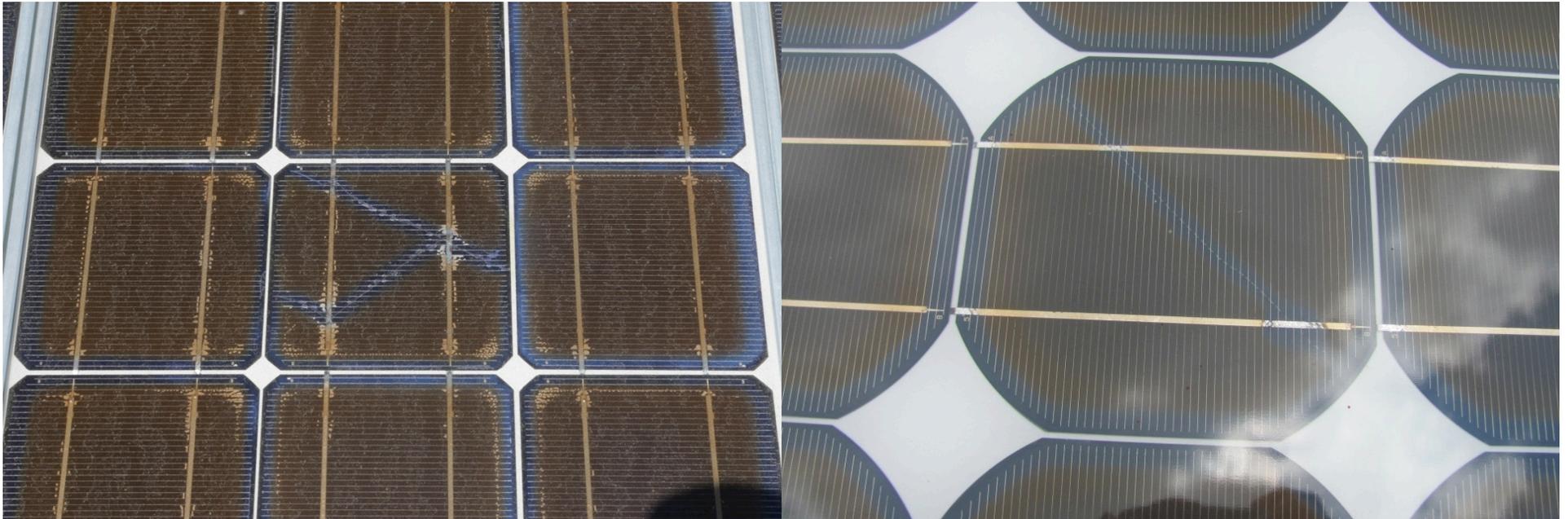
multi-Si after 10 years in Perrysburg

mono-Si after 15 years in Cocoa

Broken cells can become visible when they permit delamination along cracks

Crystalline silicon: Mechanical breakdown

Broken cells



mono-Si after 18 years in Sacramento

mono-Si after 23 years in Marin County, Florida

In modules with highly discolored encapsulant, the cracks permit photooxidative bleaching to occur

Thin-film PV

Chemical breakdown

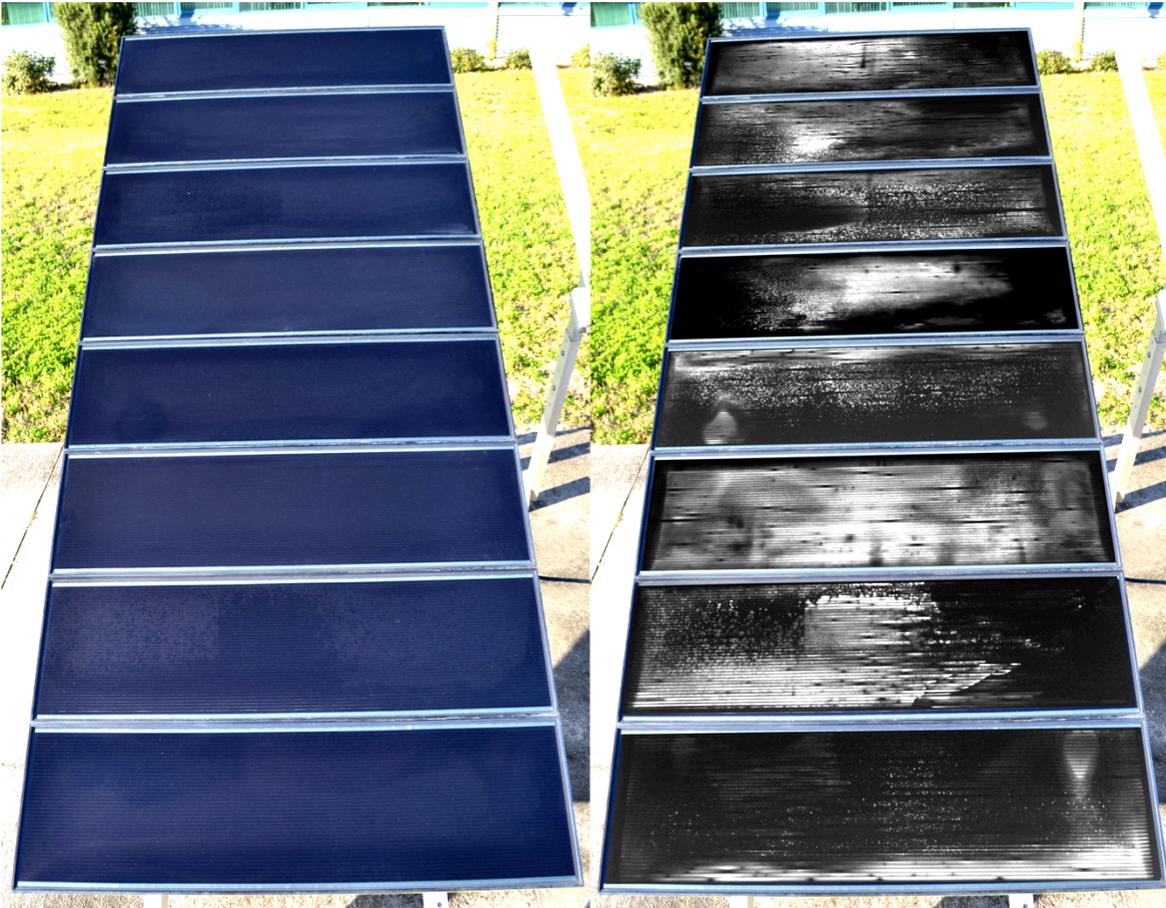
Corrosion

Decomposition of contact or absorber layers

Driven by moisture, heat and/or electric field

Thin-film PV: Chemical breakdown

Corrosion



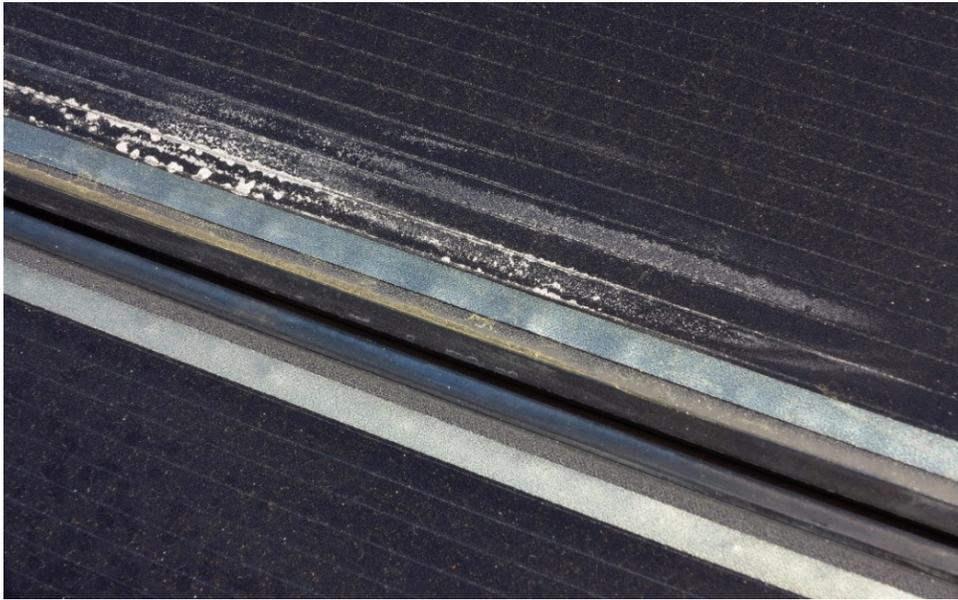
CIGS after 12 years in Cocoa (image courtesy FSEC)

TCO corrosion causes visible lightening and loss of emission in EL

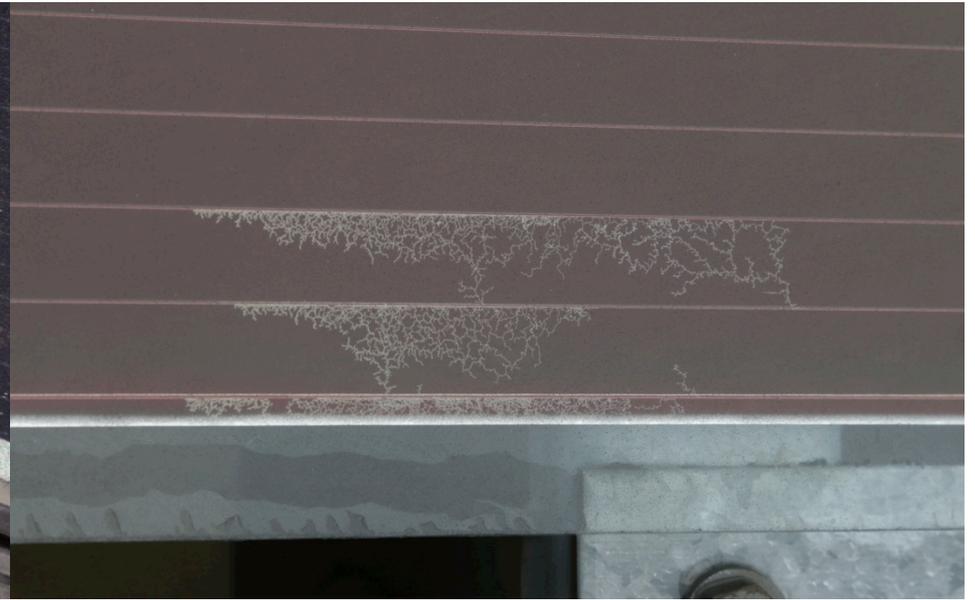
The increased series resistance is linked to loss of FF

Thin-film PV: Chemical breakdown

Corrosion



CIGS after 12 years in Cocoa



a-Si after 19 years in Sacramento

TCO/absorber corrosion can also interact with scribe lines

The dendritic form on the right is linked to voltage stress

Thin-film PV: Chemical breakdown

Corrosion



a-Si after 11–12 years in Springerville, Arizona

This TCO corrosion near the junction box appears to depend on polarity, suggesting an electric field mechanism

Mechanical breakdown

Edge seal deformation

Caused by outgassing of packaging materials

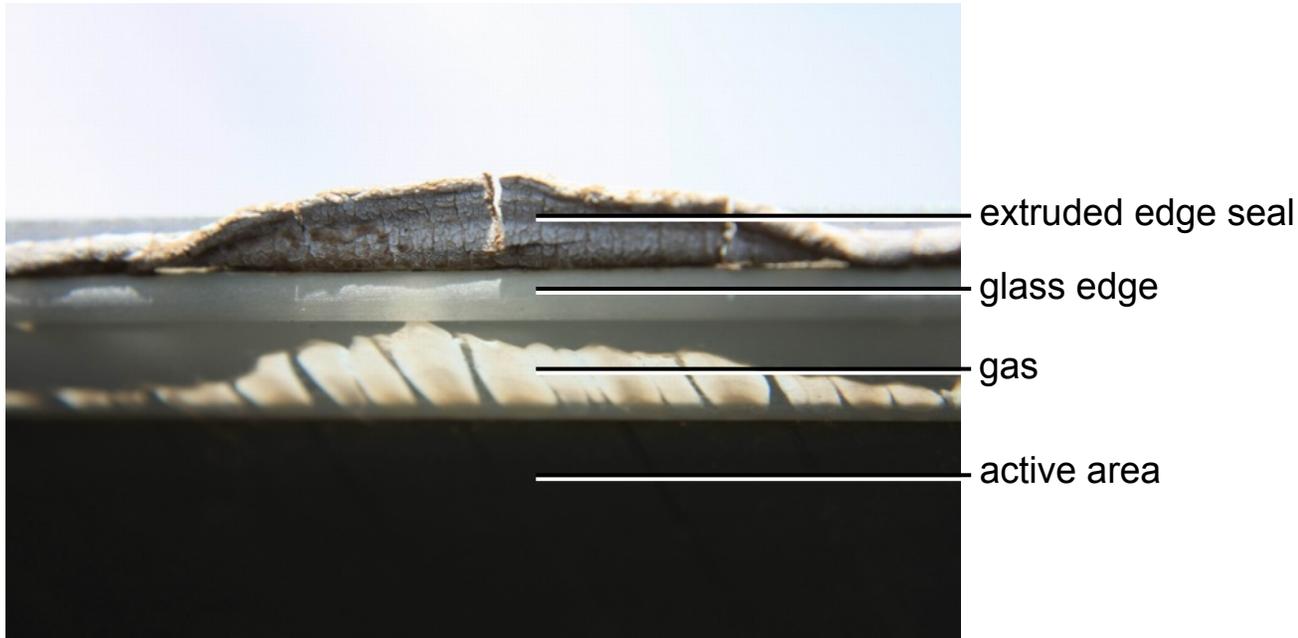
Interconnect failure

Actually a delamination caused by loss of adhesion

Driven by heat or thermal cycling

Thin-film PV: Mechanical breakdown

Seal deformation

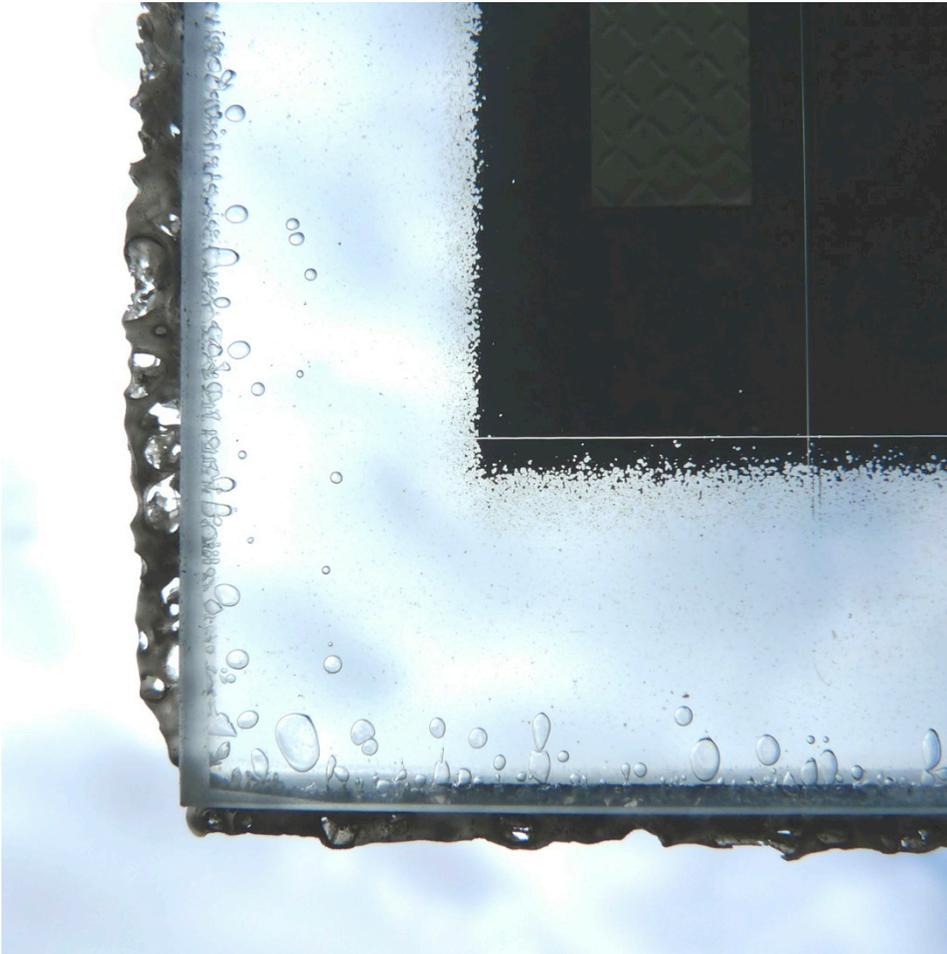


CdTe after 9–11 years in Springerville, Arizona

Internal pressure can push edge seals outward

Thin-film PV: Mechanical breakdown

Not seal deformation



CdTe after 8 years in Toledo, Ohio

A band of seal or encapsulant material can be pushed out during production

This extrusion is not a field failure

Thin-film PV: Mechanical breakdown

Interconnect degradation



8–11 years in Springerville, Arizona



8 years in Toledo, Ohio

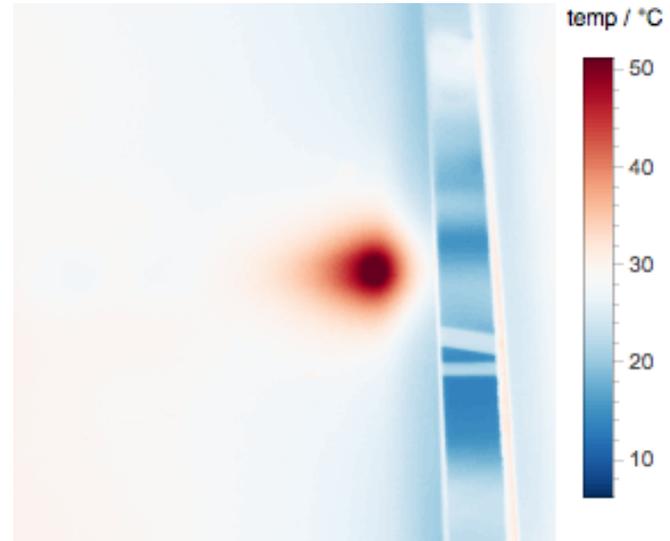
Delamination of the bus tape caused a partial failure of the interconnect

Thin-film PV: Mechanical breakdown

Interconnect degradation



8–11 years in Springerville, Arizona



8 years in Toledo, Ohio

The delamination causes an increase in series resistance, leading to lost power and increased heat dissipation



Conclusion

Lifetime prediction requires field experience

We displayed some of the chemical and mechanical breakdown modes we observed

- Discoloration

- Delamination

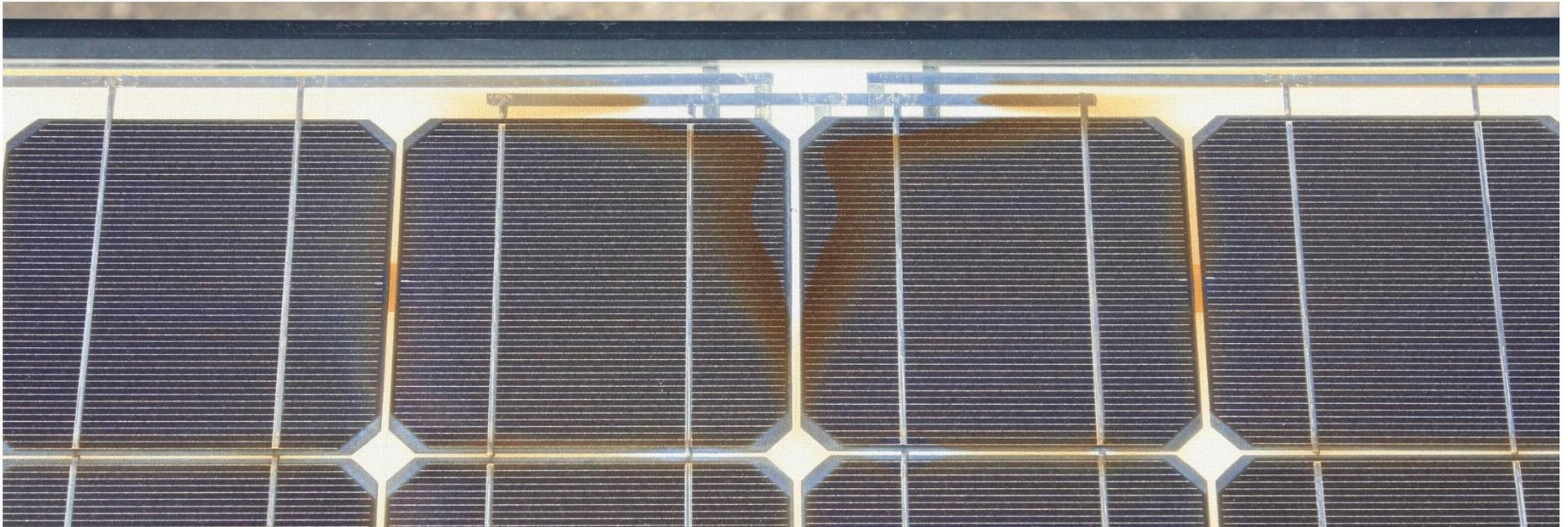
- Corrosion

- Interconnect degradation

Accelerated tests must address these failure modes

Crystalline silicon: Chemical breakdown

Discoloration



HIT after 10 years in Tucson (arid/steppe/hot arid)

Encapsulant and “beauty strips” turned brown near the junction box due to elevated temperature

Climate zones

Springerville

Arizona

Csb

warm temperate/summer dry/warm summer

Toledo

Ohio

Dfa

snow/fully humid/hot summer

Tucson

Arizona

BSh

arid/steppe/hot arid

Sacramento

California

Csa

warm temperate/summer dry/hot summer

Ocala (Marin County)

Florida

Cfa

warm temperate/fully humid/hot summer

Cocoa

Florida

Cfa

warm temperate/fully humid/hot summer

Denver

Colorado

BSk

arid/steppe/cold arid

Crystalline silicon: Mechanical breakdown

Broken glass

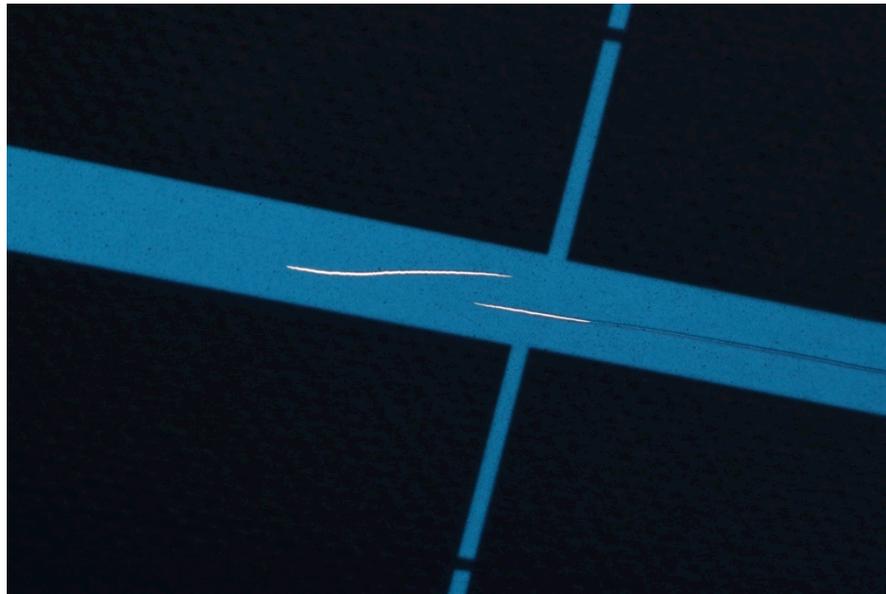


16 years in Sacramento
<1% affected

11 years in Springerville, 2%, mostly just back glass broken

Crystalline silicon: Mechanical breakdown

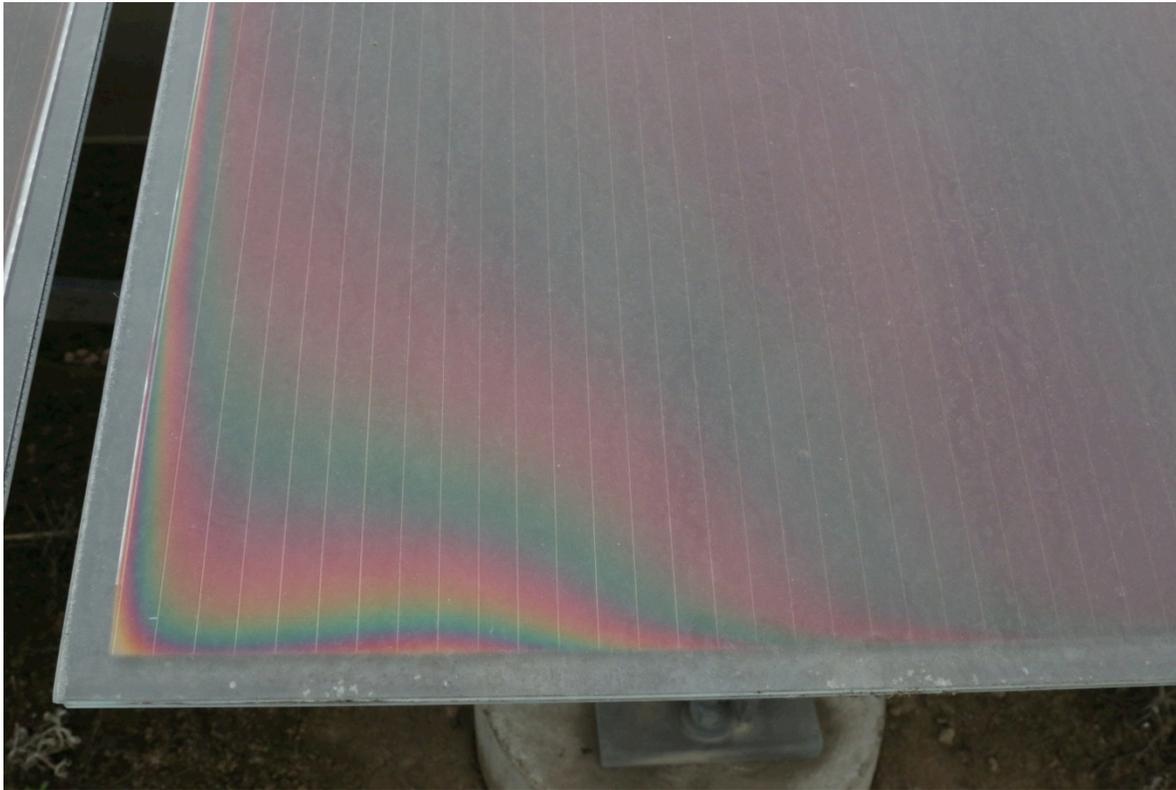
Broken backsheet



16 years in Sacramento

Thin-film PV: Chemical breakdown

Corrosion



Local TCO corrosion can appear as interference fringes

a-Si after 19 years in Sacramento

Thin-film PV: Mechanical breakdown

Broken glass

Main idea

8–11 years in Springerville, Arizona
(warm temperate/summer dry, warm)

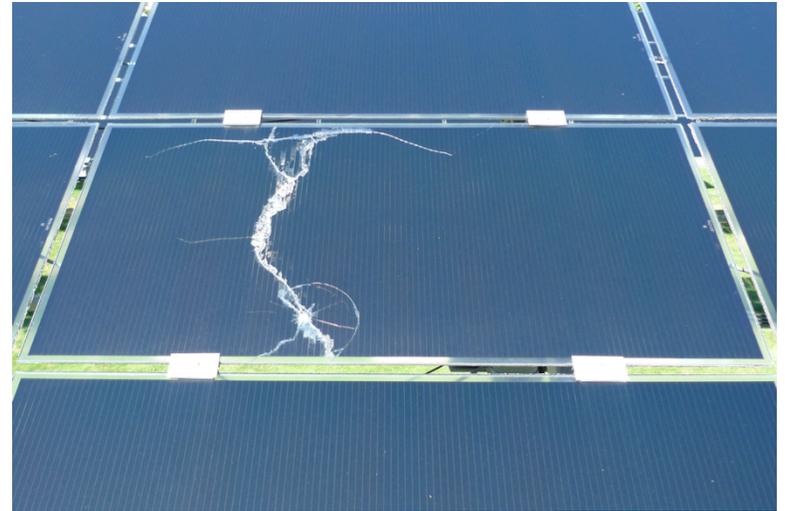


CdTe <1%



a-Si 5.5%

CdTe, 8 years in Toledo, Ohio
(snow/fully humid/hot summer)



1.4%