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Local nm-Scale imaging of Electrical Contact for Series Resistance Degradation of Silicon Solar Cells

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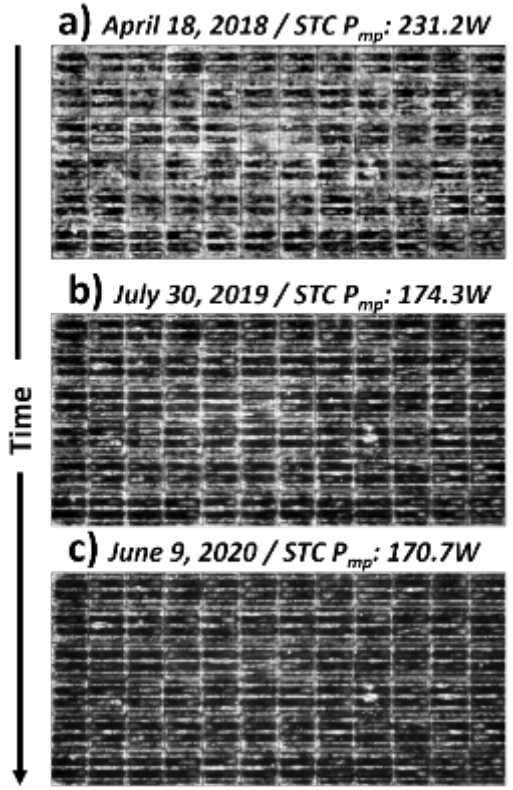
Outline

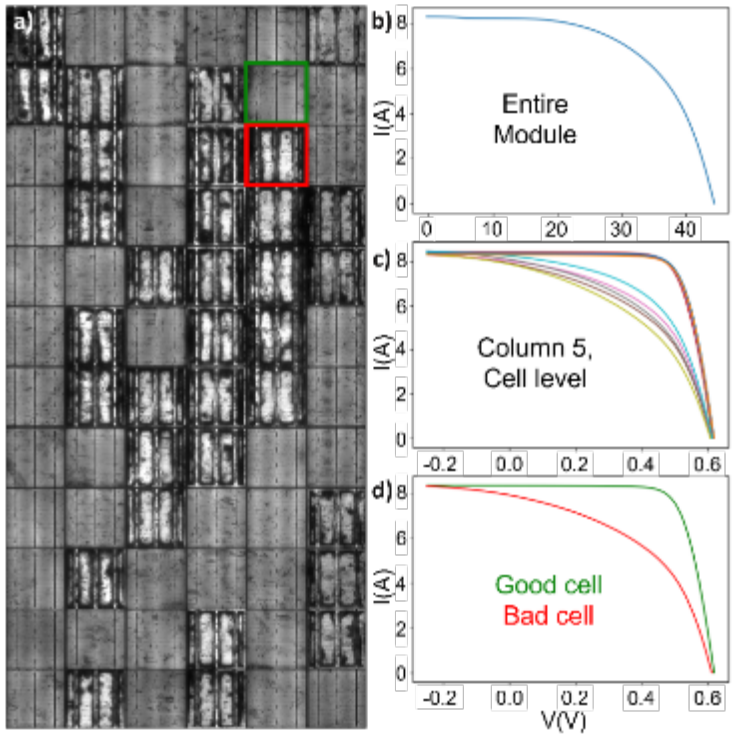
- Introduction to series resistance degradation observed in utility scale solar farm
- Introduction to scanning spreading resistance microscopy (SSRM) local resistance imaging
- SSRM imaging on unaffected cell, degraded and less degraded areas of affected cell
- Discussions of structural change and associated grid chemistry
- Summary

Introduction: Series resistance degradation in a utility-scale solar farm

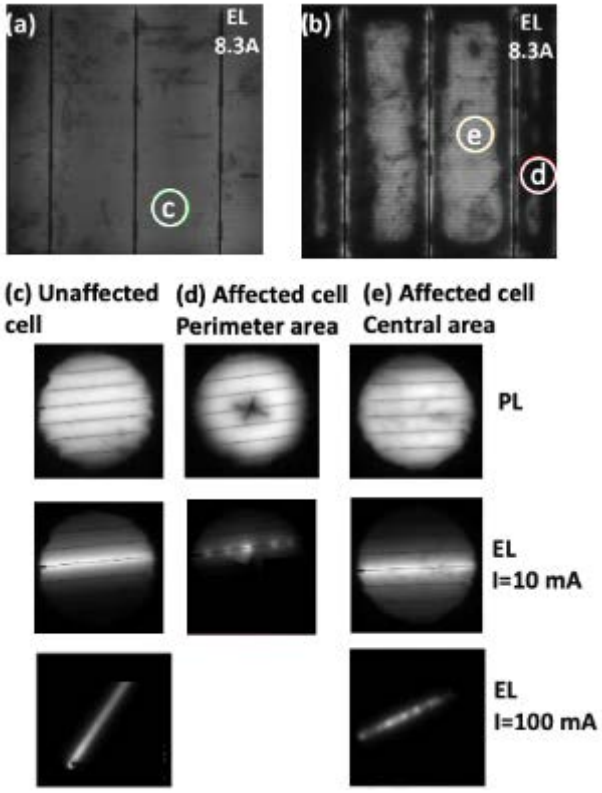
EL on modules of power loss with servicing years



Modules mixed with degraded and unaffected cells, I-V of individual cells



EL of degraded and unaffected cells, PL and EL of cored pieces

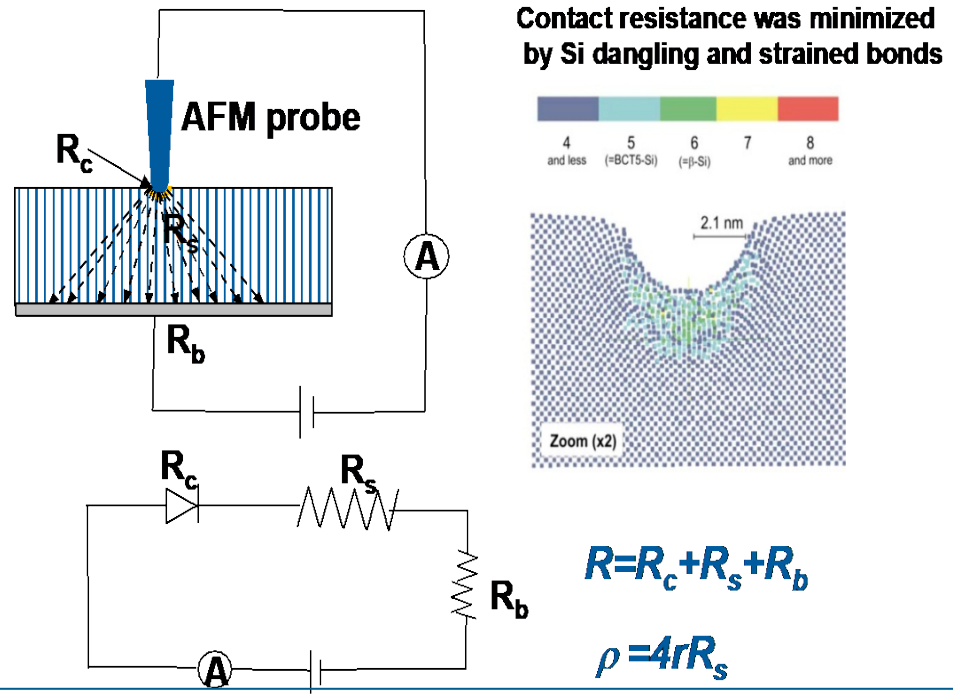


E.A. Gaulding et al, IEEE J. Photovoltaics 12, 690 (2022)

- I-V of degraded cell demonstrates FF degradation, caused by Rs
- Bead-pattern EL indicates Rs degradation of Ag finger/Si interface
- Degraded cell has perimeter area more degraded (bead pattern EL at 10 mA), and less degraded central area (continuous EL at smaller 10 mA current but bead pattern at larger 100 mA)

Scanning spreading resistance microscopy (SSRM) local nm resistance imaging

Scanning spreading resistance microscopy (SSRM) resistivity imaging by probing local spreading resistance

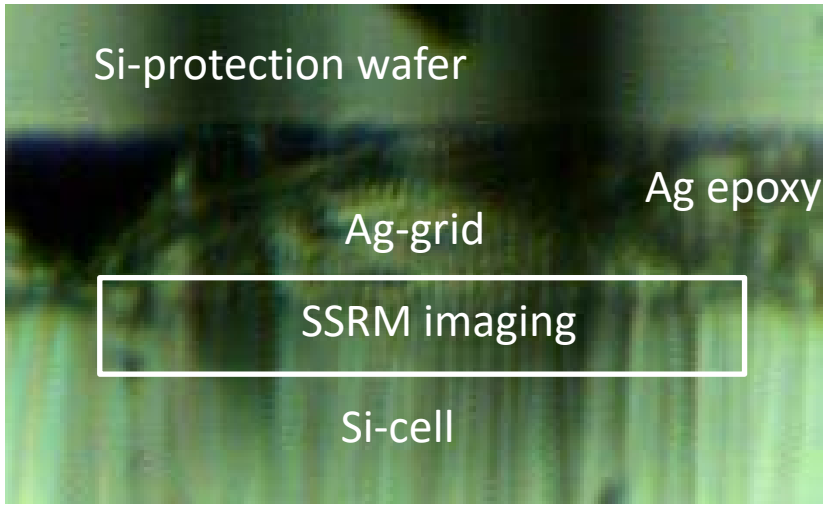


Contact resistance was minimized by Si dangling and strained bonds

$R=R_c+R_s+R_b$

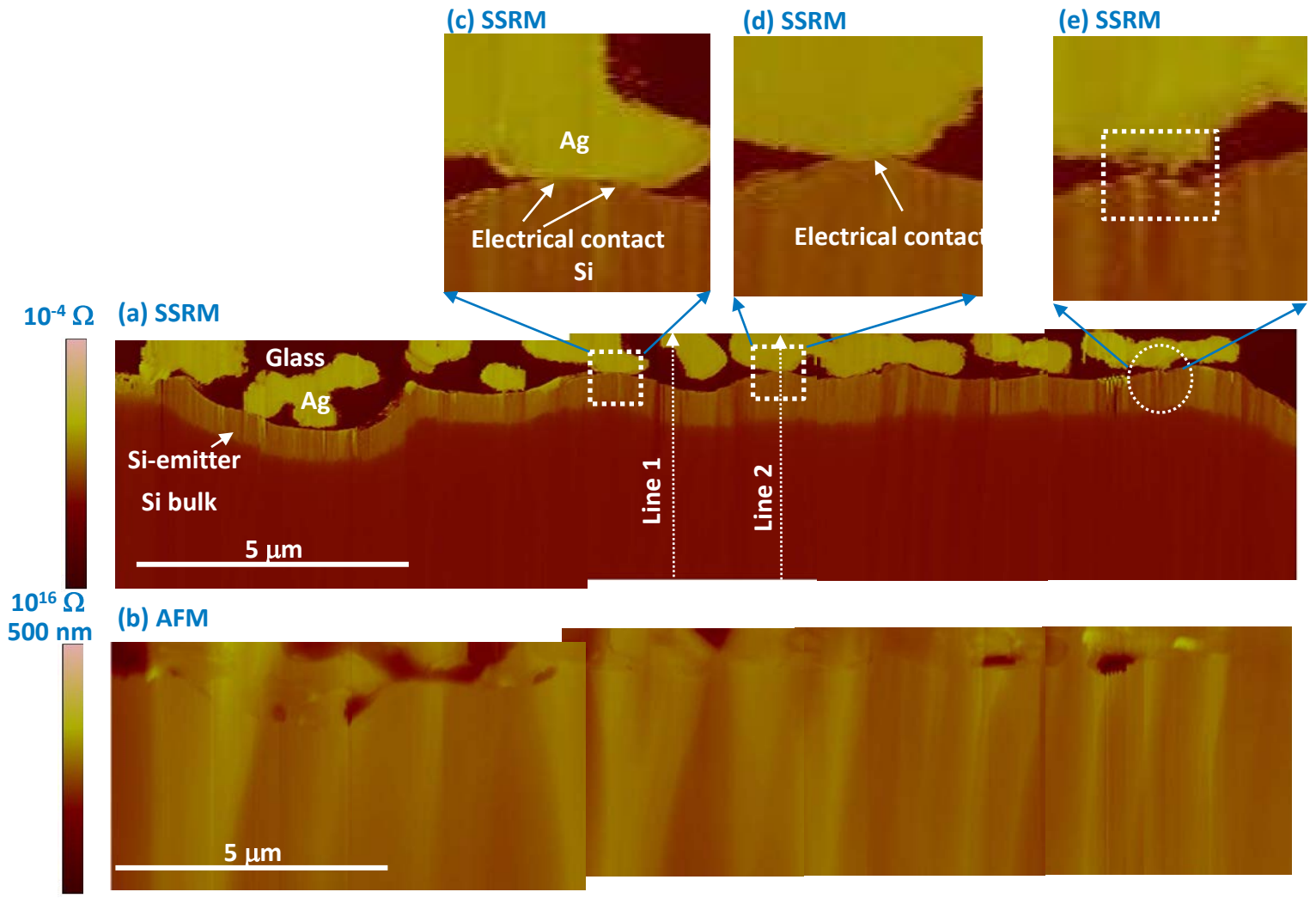
$\rho=4rR_s$

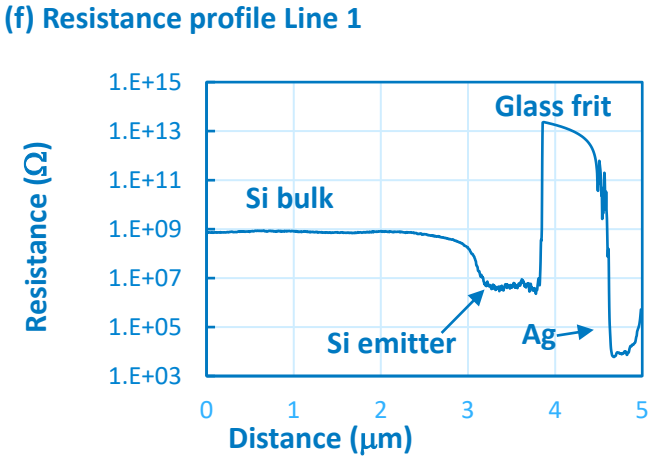
Optical view of cross-section sample preparation

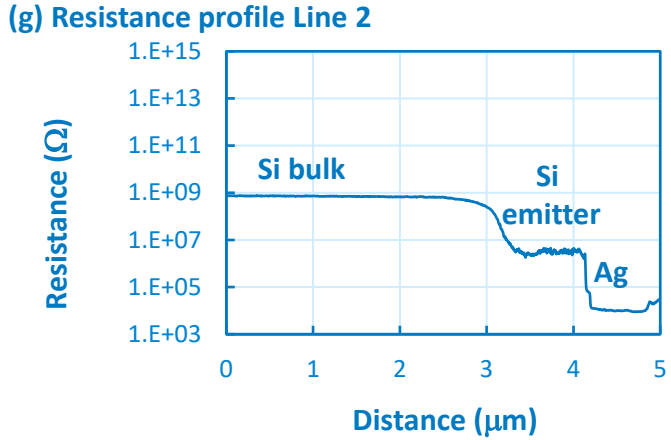


- SSRM: AFM-based local nm-resolution resistance imaging
- Two-terminal measurement, R dominated by the resistivity of local nm-volume of sample beneath the probe, spreading resistance drops quickly with distancing away from the probe-area
- Contact resistance between probe/sample is minimized by pressing the probe hard to the sample and applying a bias voltage Vs>3 V
- Back side contributes trivial resistance to the measured R
- Cross-sectional sample preparation: Sandwiching the Ag grid, cleaving cross-section, mechanical polishing, ion-milling polishing

SSRM local resistance imaging on Ag/Si interface of *unaffected cell*

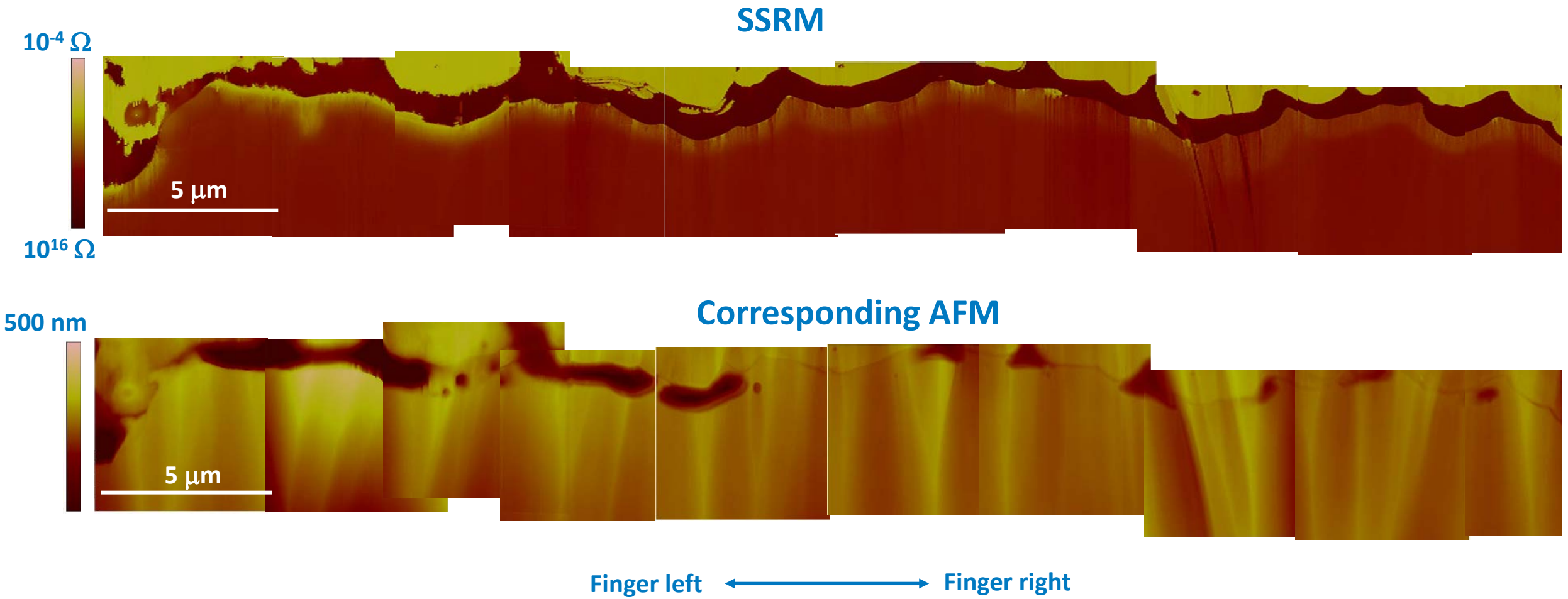






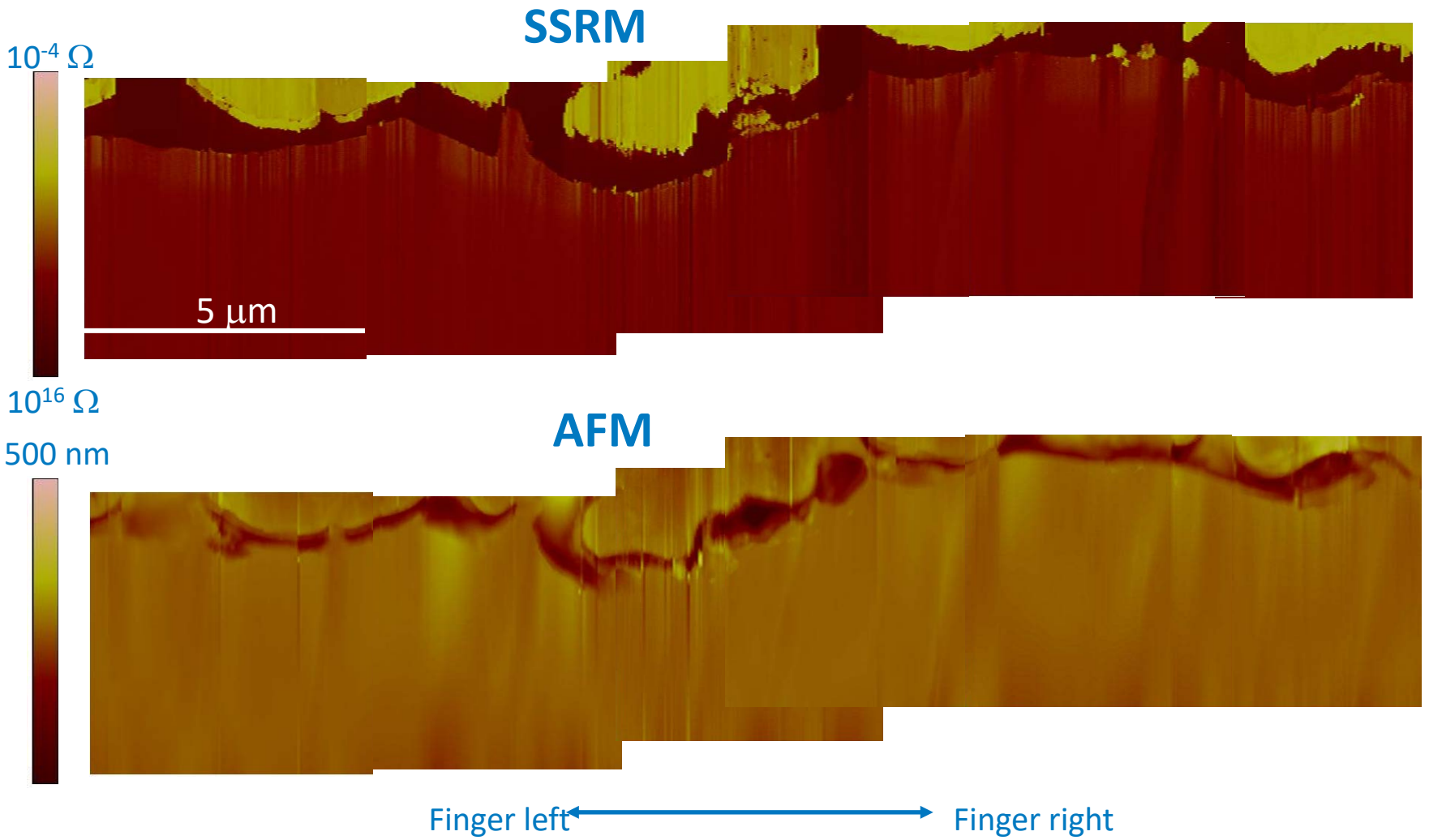
- Electrical conduction via Ag/Si point or small-area contact
- Ag-grid/Si-emitter interface: mixed conductive Ag particles in insulating glass frit matrix
- Glass frit holds adhesion of Ag with Si

SSRM on Ag/Si interface in *perimeter area of degraded cell*



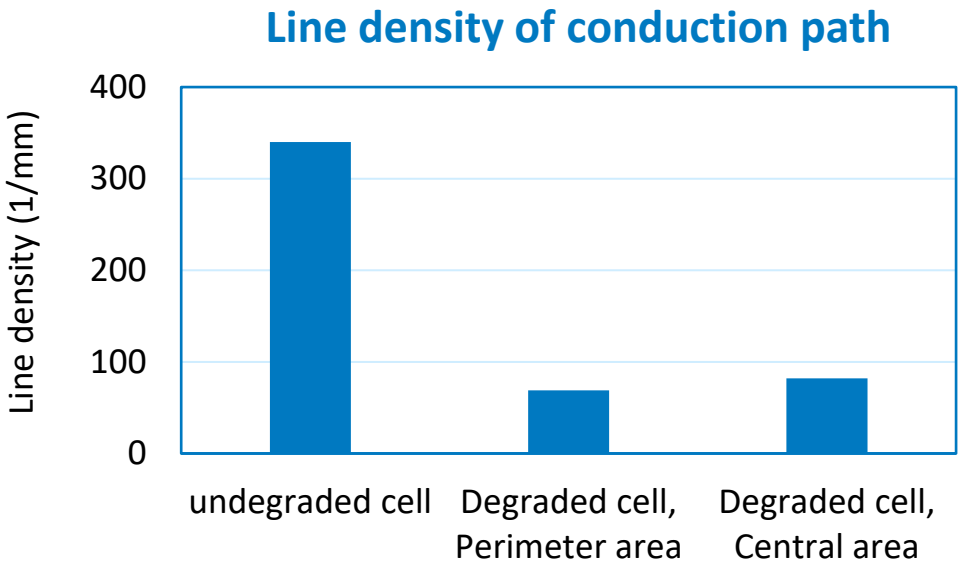
- Insulating "belt" with thickness of ~1 μm formed between Ag bulk and Si emitter
- Rs degradation mechanism: the insulating belt blocks electrical conduction pathway from emitter to Ag grid

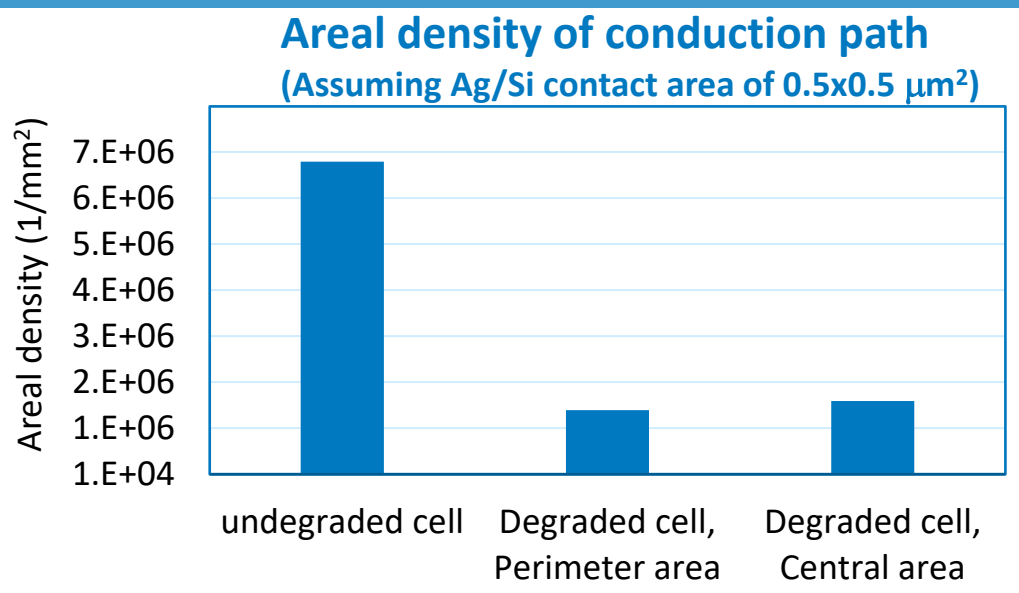
SSRM on Ag/Si interface in *central area of degraded cell*



Insulating "belt" with thickness of ~1 µm formed between Ag bulk and Si emitter, similar to the perimeter area

Statistical analysis of Ag/Si point or small contact area conduction path

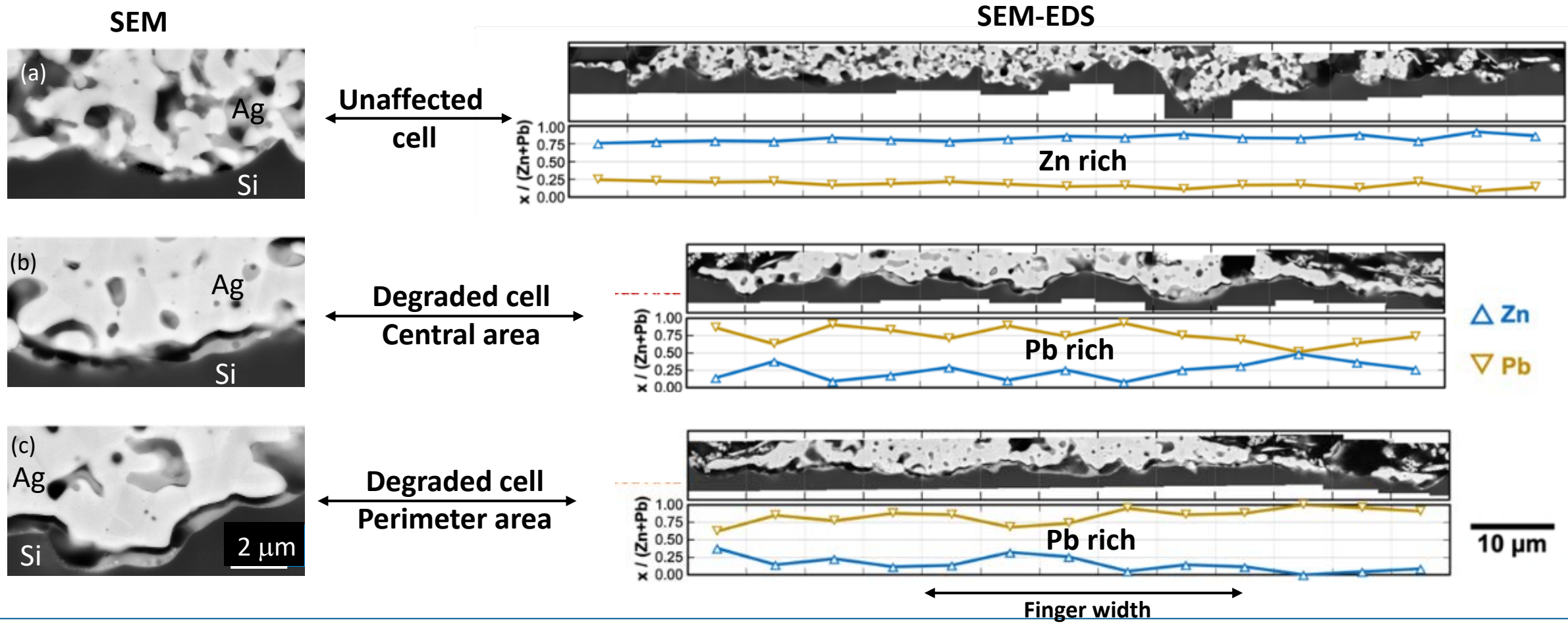




	Undegraded cell	Degraded cell Perimeter area	Degraded cell Central area
Scan length (mm)	172	287	291
Contact point numbers	58	13	24
Line contact density (1/mm)	340	69	82
Areal contact density ($1/mm^2$)	$6.8x10^6$	$1.4x10^6$	$1.6x10^6$

Rs degradation mechanism: electrical conduction path of Ag/Si contact decreased much in degraded cell, compared with undegraded cell.

What caused the electrical conduction blocking?
What is difference between degraded and unaffected cells?



- Unaffected cell – Porous mixture of Ag and ceramic; Affected cell-Ag solid bulk; Whether this difference existed before field service cannot be verified
- Ag contact degradation: Ag particle segregate away from Si emitter
- This structure change is caused by different suscetbility of glass frit : Zn rich in unaffected cell, Pb rich in degraded cell

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Summary

- Electrical conduction pathway --- point or small areal contact of Ag particle with Si emitter
- Rs degradation mechanism: substantial reduction of Ag/Si contact number
- Ag particle in contact with Si likely segregated away from Si emitter and an insulating glass frit belt is formed at Ag/Si interface
- This structural change during the long term filed service is caused by Pb rich in the Ag past, compared with Zn rich in the unaffected cell
- Our results showcase a multiscale and multimode characterization approach for understanding PV degradation mechanisms

Thank you

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