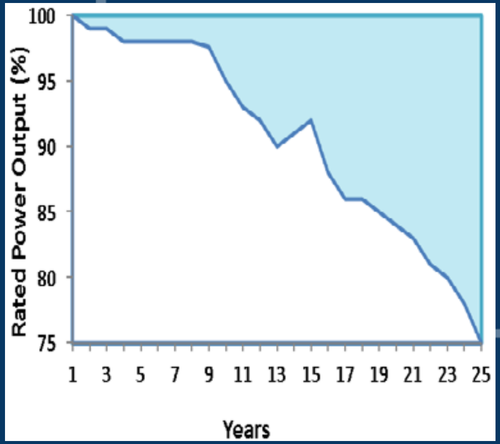
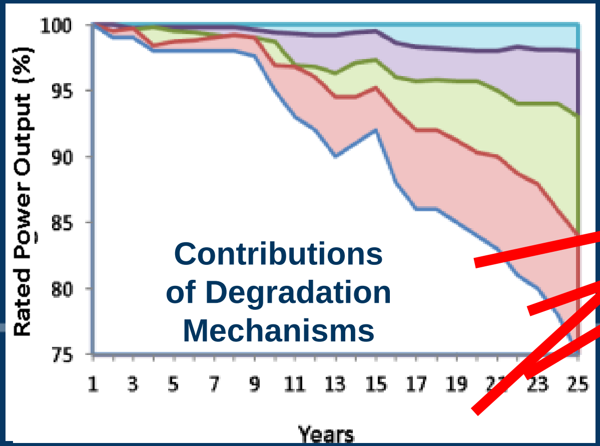
Degradation Science of PERC Technology:
Mechanistic Investigation with Advanced Characterization

Laura S. Bruckman
Jennifer L. Braid, Alexandra J. Longacre, Justin S. Fada, Trey D. Wager, Bryan D. Huey, Roger H. French





Partners

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FLORIDA SOLAR ENERGY CENTER®
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CanadianSolar

CYBRID backsheet

Outline

- **Data Science Approach to Lifetime Prediction**
- **PERC and Al-BSF mono-Si solar cells**
- **Degradation Science of PERC: <Stress|Mechanisms|Response>**
- **Characterization techniques and preliminary data**
- **PERC Bare Cell Preliminary Pilot Study**

Degradation Science Approach to Lifetime Prediction with Data Science

Elements of the Degradation Science Methodology

< Stress | Mechanism | Response > Framework

Population based studies
- Of systems, components, materials

Study protocols: exposure, evaluations
- Many stressor types, levels & cycles
- Exercising multiple degradation modes

Multiple responses measured per step
- Determine quantitative degradation rates

Cross-correlation of stress & response
- To produce system technology models
- Lifetime predictions by degradation modes
- Translational predictions for stress conditions

Population Based Studies
Sample Sets
Baseline, Steps 1,2,3,4…

Studies
System Level
Component Level
Materials

Degradation
Modes
Mechanisms
Quantitative Rates

Exposures
(Stresses)

Real Time
Accelerated

Single, Multi-Factor
Cyclic, Sequential

Evaluations
(Responses)

Sequential ⇨
Quantitative Rates

Performance
Canary: Precursor

Degradation Pathway Network Models
Physical & Statistical Sub-models
Stress | Response Cross Correlation
Lifetime Prediction by Modes

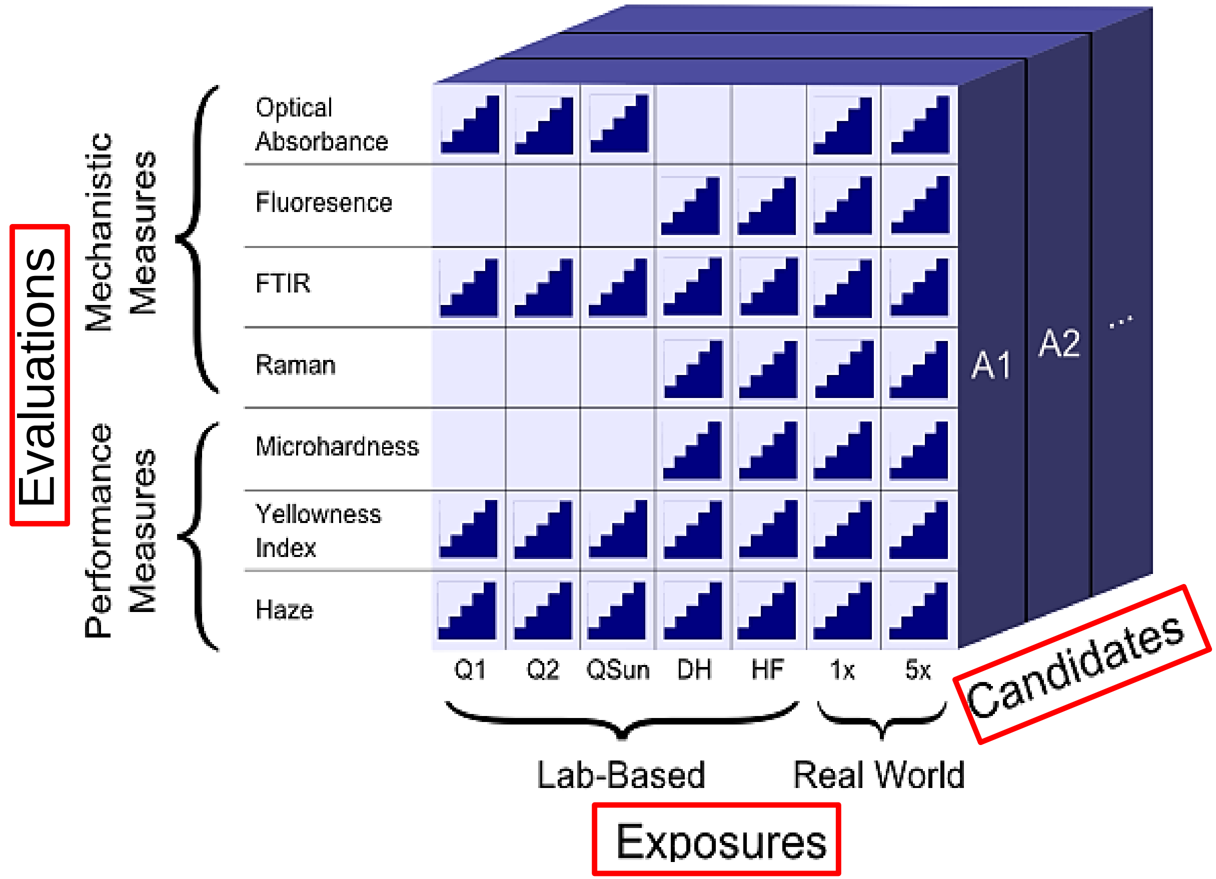
Degradation Science "Data Block" For Statistical Analytics

Using a < Stress | Mechanism | Response > Framework

Multiple Datatypes
- "Point" values
- Spectra
- Images
- Hyper-spectral Images

Basis in Physics and Chemistry
- Stressors: Heat, Moisture, Irradiance, etc.
- Responses: Yellowness Index, Gloss, Haze, Power output, etc.

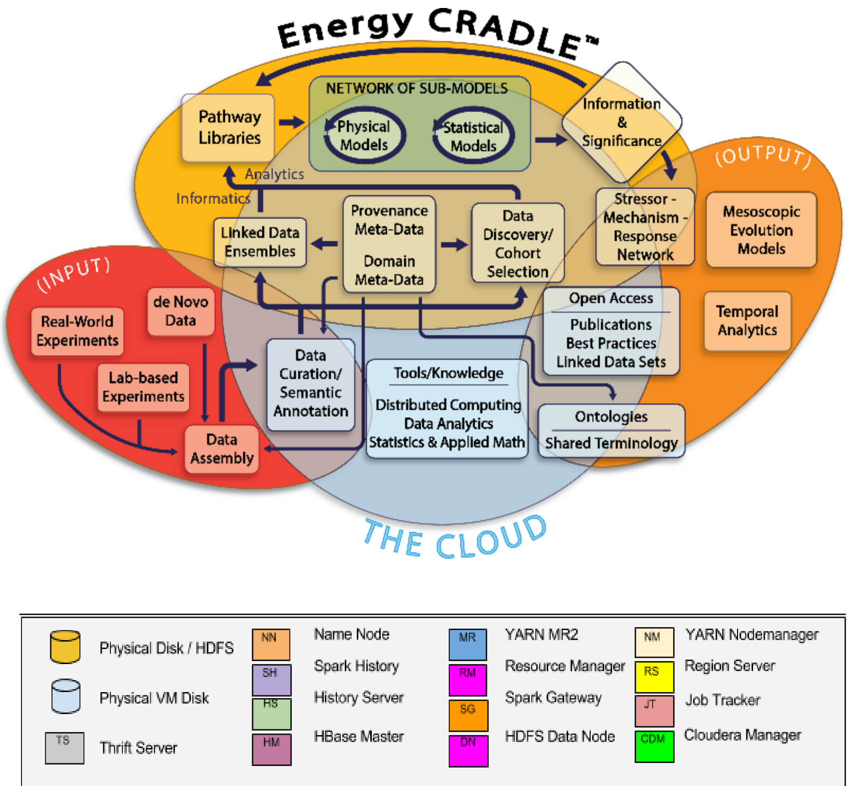
Statistically Informed Study
- Large Volume of Samples
- Diverse Exposures
  - Real-world & Lab Base
  - Accelerated & Real-time
- Many Evaluations
  - Mechanistic & Performance

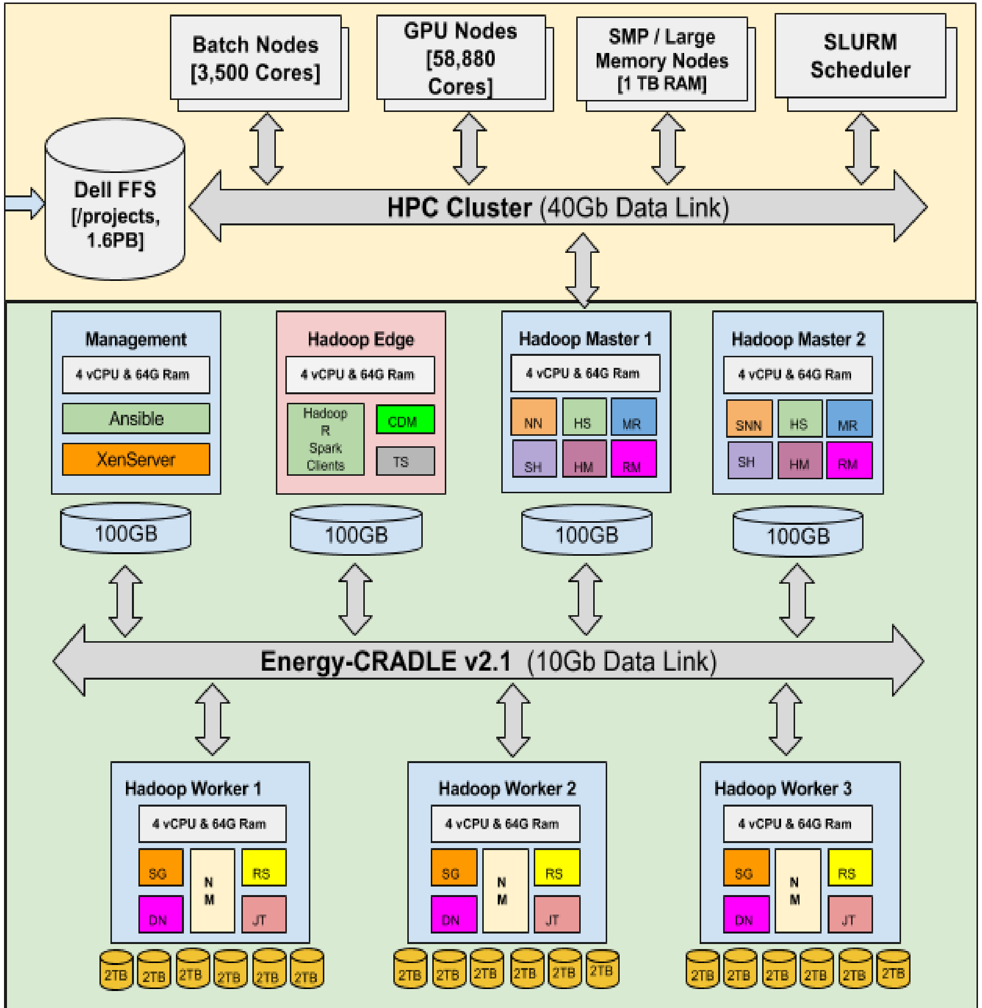


Energy-CRADLE v2.1 Architecture: Petabyte and Petaflop Computing

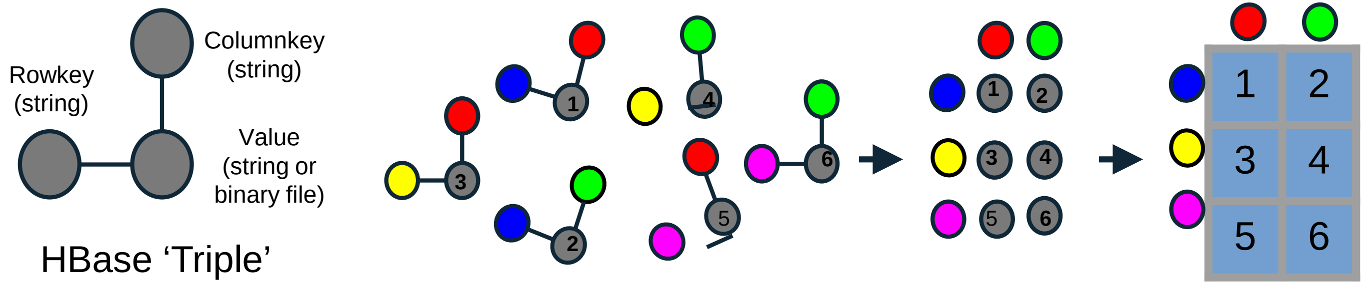
National Strategic Computing Initiative 2015

Hadoop/Hbase/MapReduce/Spark Based on Cloudera CDH5 distribution





Energy-CRADLE: Hadoop/Hbase Schema & NoSQL DB Abstraction



Combines Lab data (Spectra, Images etc.) With Time-series Data (PV Power Plant Data)

High Performance PV Data Analytics: Petabyte Data Warehouse In A Petaflop HPC Environment

- In-place Analytics: Distributed R-analytics in Hadoop/HDFS
- In-memory Data Extraction: To Separate HPC Compute Nodes

IEEE JPV

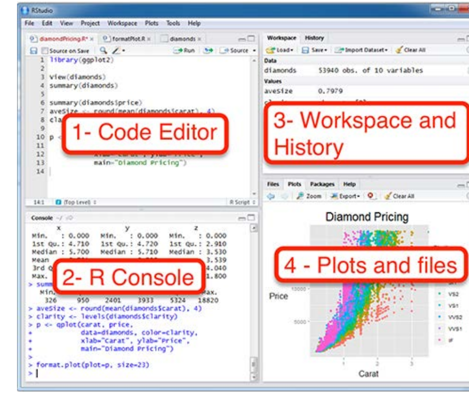
A non-relational data warehouse for the analysis of field and laboratory data from multiple heterogeneous photovoltaic test sites

Yang Hu, *Member, IEEE,* Venkat Yashwanth Gunapati, Pei Zhao, Devin Gordon, Nicholas R. Wheeler, Mohammad A. Hossain, *Member, IEEE,* Timothy J. Peshek, *Member, IEEE,* Laura S. Bruckman, Guo-Qiang Zhang, *Member, IEEE,* and Roger H. French, *Member, IEEE*

Hu, Y., V. Y. Gunapati, P. Zhao, D. Gordon, N. R. Wheeler, M. A. Hossain, T. J. Peshek, L. S. Bruckman, G. Q. Zhang, R. H. French. "A Nonrelational Data Warehouse for the Analysis of Field and Laboratory Data From Multiple Heterogeneous Photovoltaic Test Sites." IEEE Journal of Photovoltaics 7, no. 1 (January 2017): 230–36. doi:10.1109/JPHOTOV.2016.2626919.

Open Data Science Tool Chain

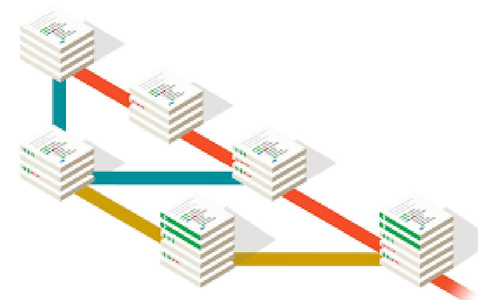
Using Open-source tools



Reproducible Research

- Using Rmarkdown reports
- Python Jupyter Notebooks
- Add new data
- Recompile your report
- All new figures and report!
- Well Documented Code/Reports

High Level Scripting Languages: R, Python



Rstudio Integrated Development Environment

- Commercially Supported

Git Repositories for Code Version Control

- Share code scripts with colleagues
- Share project data and reports with others

Github, BitBucket, GitLab for Collaboration

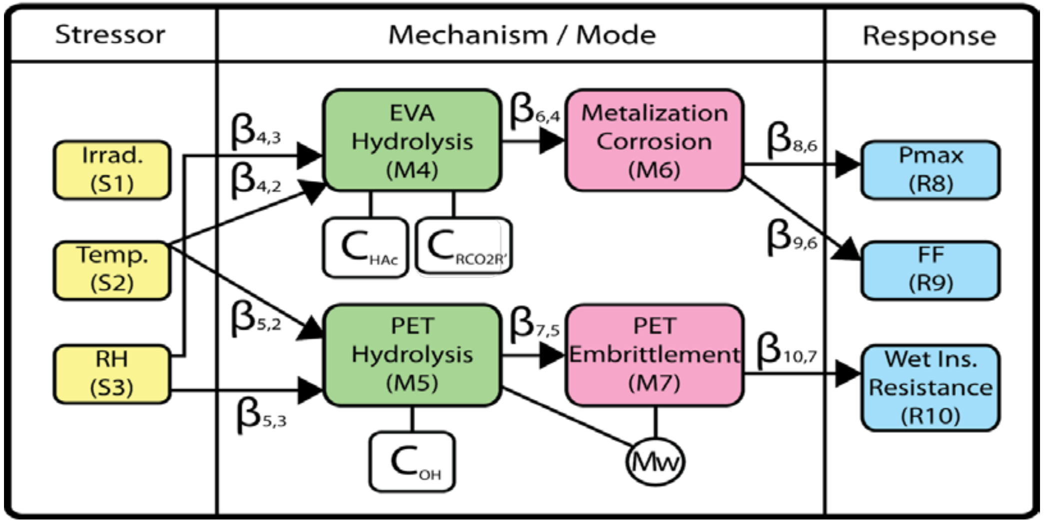
- Website hosting your Code Repositories

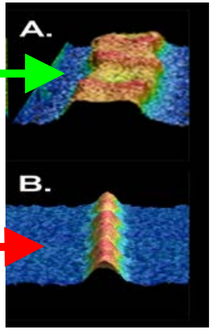
<Stress|Mechanism| Response> Network Models: Integrate Multiple Data Streams

They form Prediction Models for Complex Systems

With Network Equations
- Functional Forms
- Coefficients for Each Component

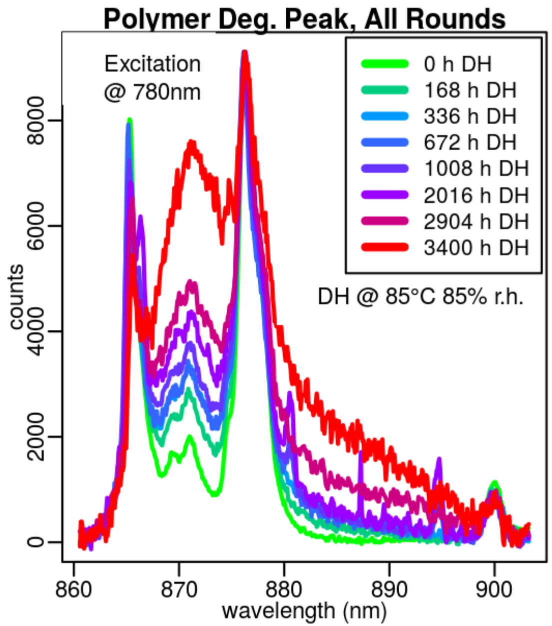
Metallization Corrosion
- Corrosion of screen printed Ag gridlines
- I-V, EL, Raman Confocal Microscopy
- Damp Heat Exposures

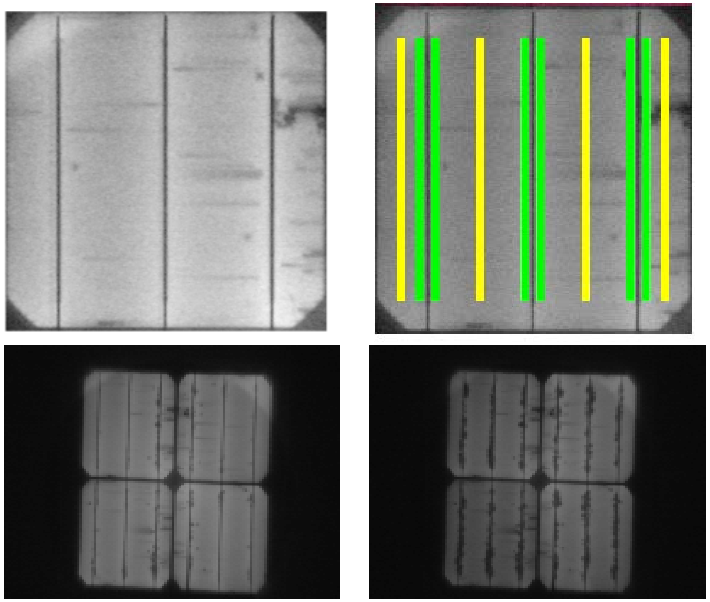


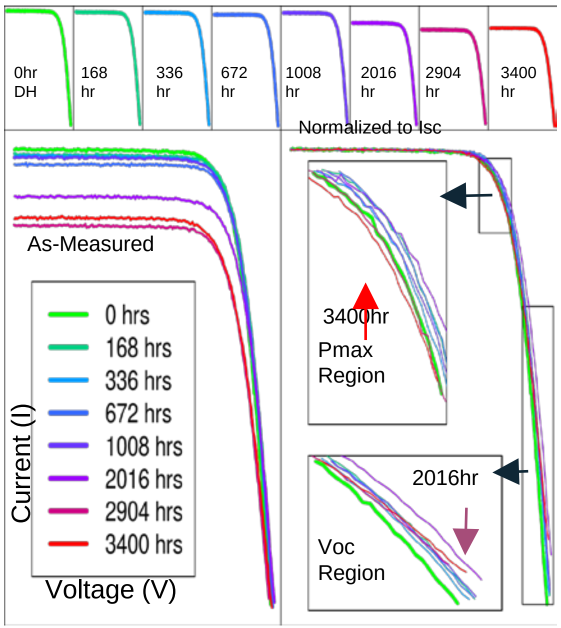


BAPVC-funded Mini-module Study of Degradation

Data Integration: Non-Aggressive & Aggressive Al-BSF Modules



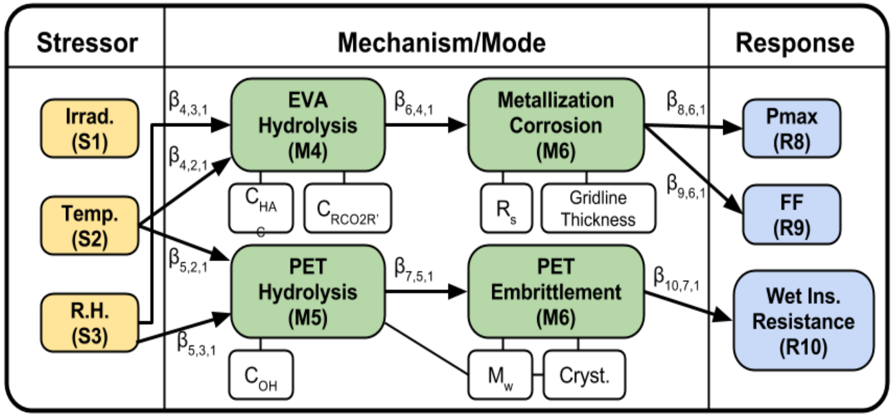




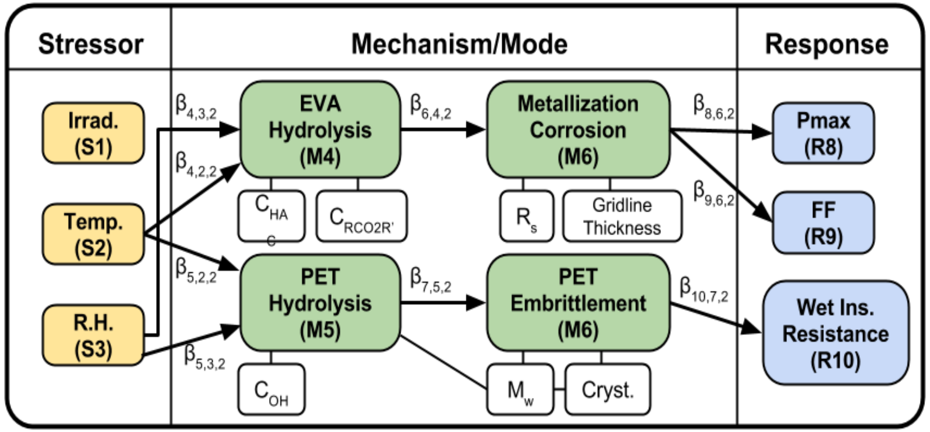
Combining Confocal Raman, Electroluminescence and I-V => System Level Power Loss

<S|M|R> Model for Aggressive and Non-Aggressive Gridline Geometries

Aggressive Geometry



Non-Aggressive Geometry



Mechanism & Pathway Equation

$$PMax \sim intC + CC * (intB + CB * (intA + IA * (hrsDH^2)) + IB * ((intA + IA * (hrsDH^2))^2)) + IC * ((intB + CB * (intA + IA * (hrsDH^2)) + IB * ((intA + IA * (hrsDH^2))^2))^2)$$

Coefficients For

Agg

$$PMax \sim 0.46 - 3.10e-06 * hrsDH^2 + 1.13e-05 * hrsDH^4 - 6.20e-12 * hrsDH^6 - 1.03e-05 * hrsDH^8$$

NAgg

$$PMax \sim -0.28 - 1.51e-06 * hrsDH^2 + 7.41e-06 * hrsDH^4 - 1.59e-12 * hrsDH^6 - 9.12e-06 * hrsDH^8$$

Durability of PERC and Al-BSF mono-Si Solar Cells

PERC Cells: Reliability?

Cell efficiencies of ~22%

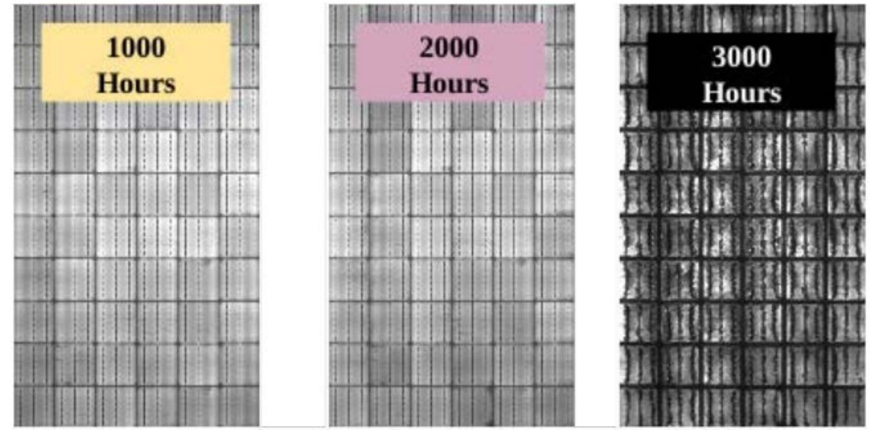
- Monocrystalline cells

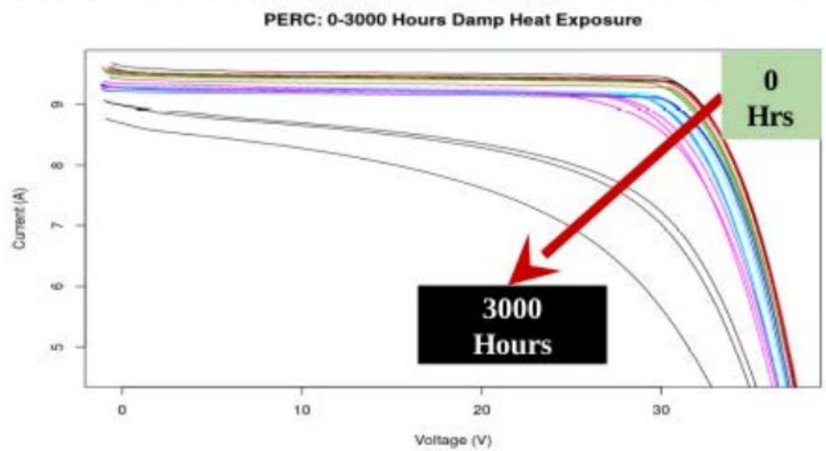
Projected to have 35% market share

- Increased efficiency and reduced LCOE

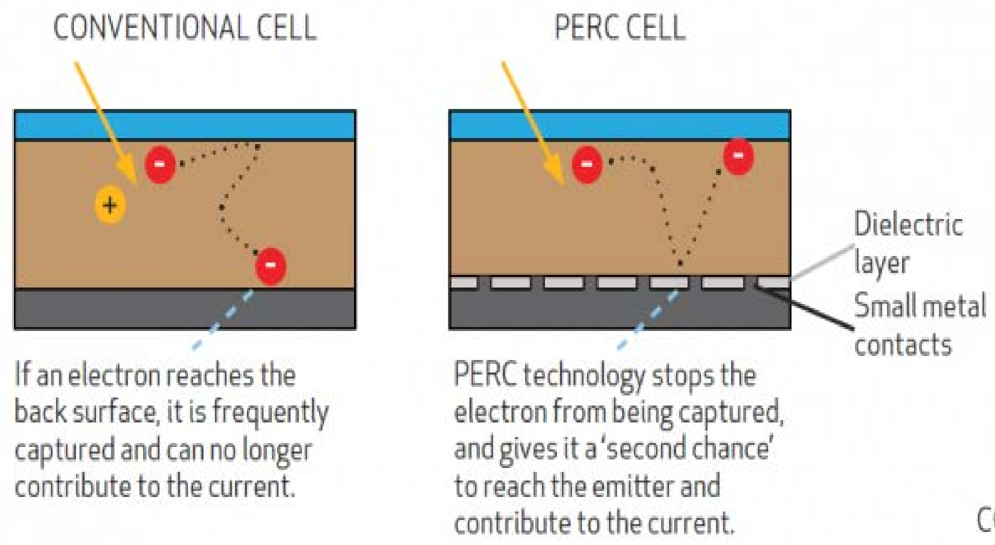
Added complexity of these cells impact reliability?

- Need predictive models of lifetime
- Need to understand additional degradation mechanisms
- How long does the oxide passivation layer last?

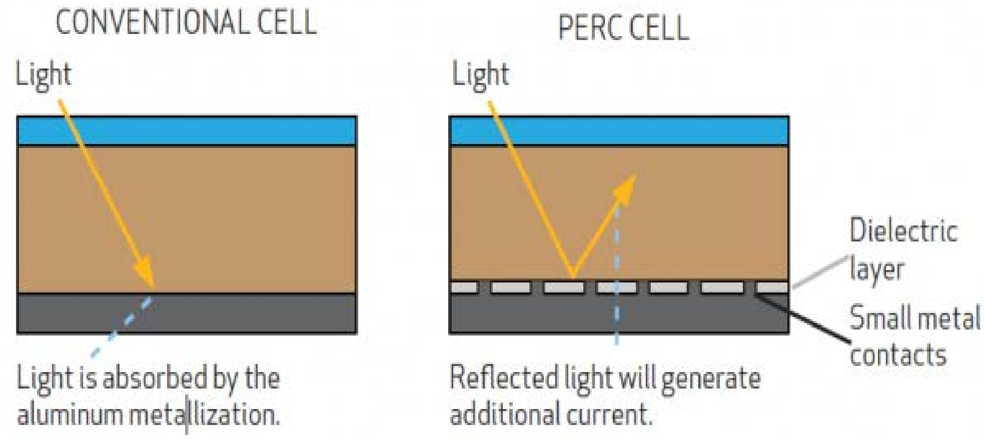




Al-BSF vs. PERC Operation

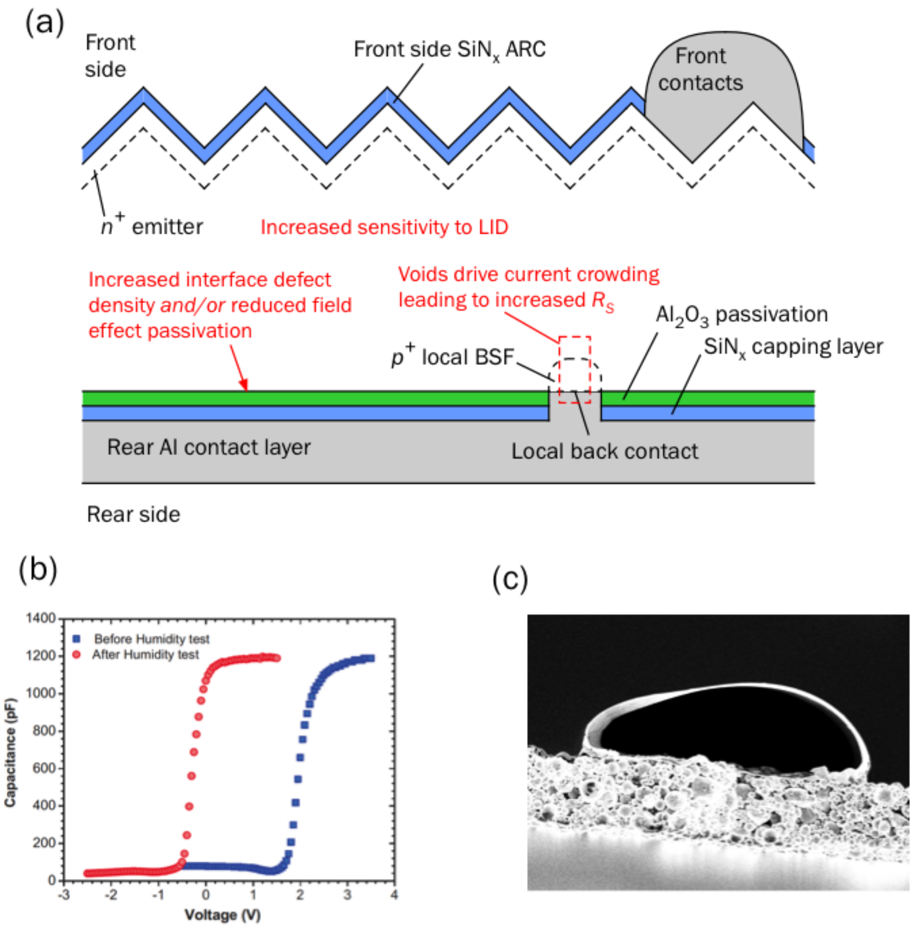


PERC decreases diffusion current recombination losses (J_{01}) by reducing the total BSF area



The dielectric oxide passivation layer acts as an optical reflector to increase the photocurrent (I_{sc}).

PERC: Specific Degradation Concerns



(a) Light-induced degradation (LID)

- Carrier recombination is limited
- by bulk lifetime
- instead of surface recombination velocity

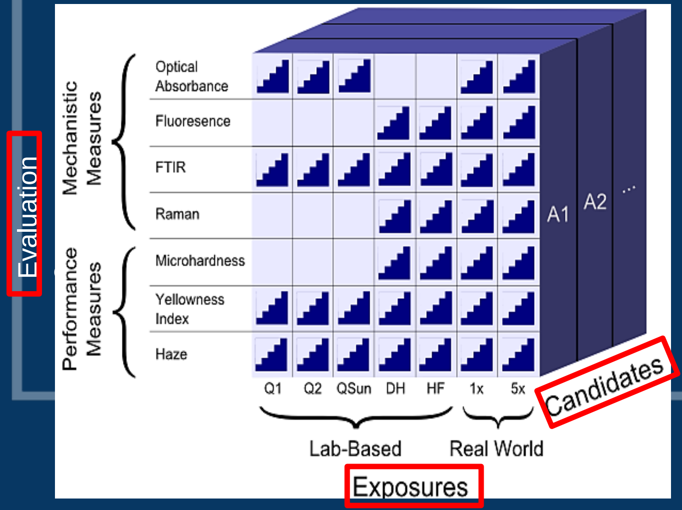
(b) Stability of Al_2O_3 passivation layer

- Reduction in field effect passivation
- in damp heat

(c) Void formation at local back contacts

- Current crowding
- Increased series resistance

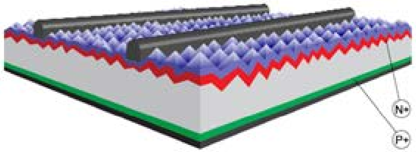
Degradation Science Approach to PERC Lifetime <Stress|Mechanism|Response>

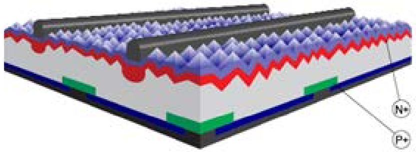


Sample Candidates and Stress

Sample Candidates: Al-BSF and PERC Cells

Mono-crystalline Cz-wafers	**Al-BSF**	**PERC**
Base Thickness (um)	179.3	169.3
Base Resistivity (Ohm-cm)	2.40	2.25
Emitter Thickness (um)	0.7	0.7
Emitter Sheet Resistance (Ohm/sq)	70-110	70-110
Front passivation	PECVD SiNx	PECVD SiNx
Front Grid	38um, 105 fingers, 1.1mm 4BB	38um, 105 fingers, 1.1mm 4BB
Gridline paste	PV19L Ag	PV19L Ag
Rear passivation	none	Al_2O_3
Rear contact paste	Monocrystal 1206 Al	PV36S Al





Bare cell exposures: Acetic acid and UV

Acetic acid concentration

- degraded module is 0.11-0.36% w/w to EVA*
- Corresponds 1.74-5.70 M aqueous solution

Aqueous acetic acid for uniform exposure

Q-Labs QUV Accelerated Weathering Tester

- UV stress and temperature/humidity

Two exposure types:

- Hot QUV:
  - 1.55 W/m^2 at 340 nm and 70° C
- Cyclic QUV:
  - 8 hours: 1.55 W/m^2 at 340 nm and 70° C
  - 4 hours: dark and 50° C with condensing humidity

*Barry Ketola and Ann Norris. "Degradation mechanism investigation of extended damp heat aged PV modules." *26th EUPVSEC* (2011).

Mini-Module Exposures: Damp Heat and Multi-factor

ZPH8 Environmental Test Chamber

- Controlled temperature and humidity conditions

Two standard exposures:

- Damp Heat:
    - 85° C, 85% RH
- Humidity Freeze:
    - 20 hrs: 70° C, 85% RH

SPHS-100 Environmental Test Chamber

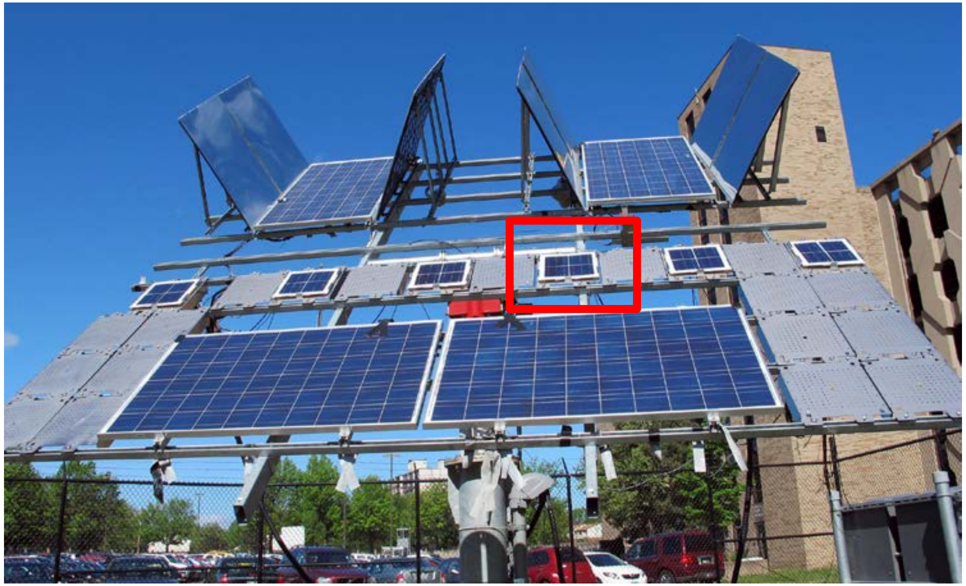
- Integrated with light and mini-module racks
- Controlled temperature, humidity, and UV conditions

Full multi-factor exposure: light + DH

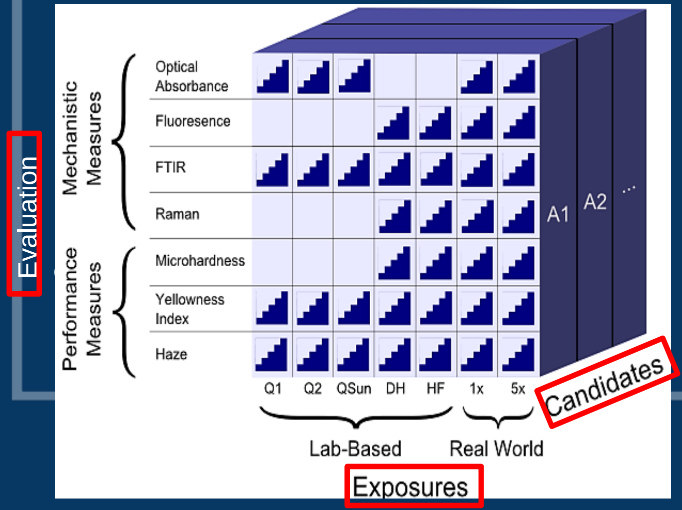
Mini-module exposures: Real-world

SDLE SunFarm - Cleveland, OH

- 2-axis trackers
- DayStar Multi-tracer for I-V
- Weather monitoring



Degradation Science Approach to PERC Lifetime
<Stress|Mechanism|Response>



Evaluations: Degradation Mechanisms

Measurement Approach: Cells and Mini-Modules

Cells are measured

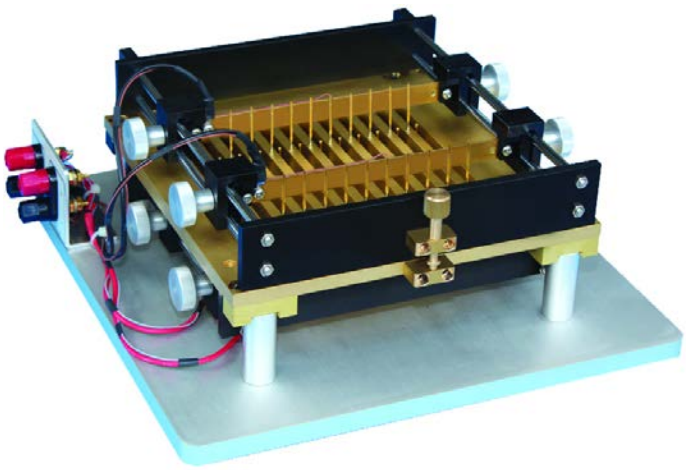
- in a cell test fixture
- to avoid soldering
- reduce variability in stringing and tabbing

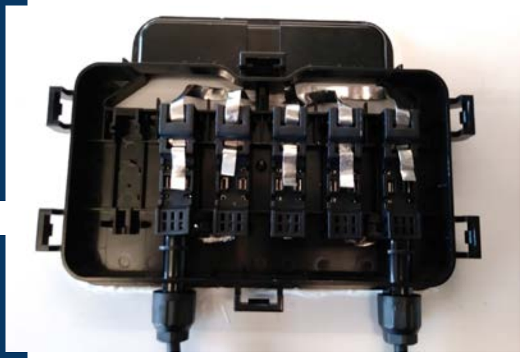
Cells are wired both:

- in series as in a traditional module
- individually for single- cell measurement

5-terminal junction box

- electrical access to each cell
- full module access
- via standard PV connectors



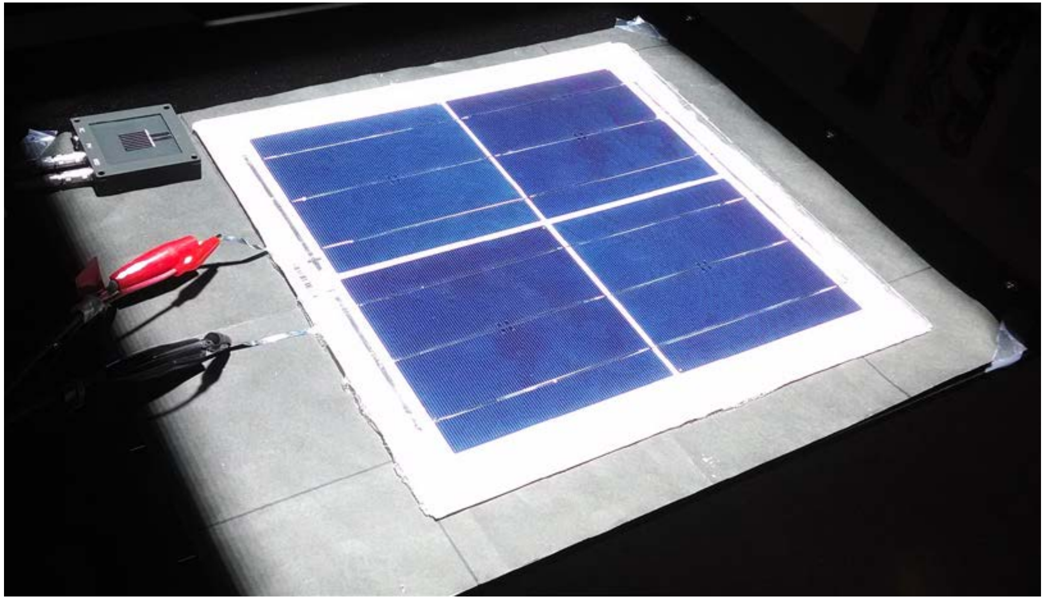


Current-Voltage Curve Tracing: Cells and Mini-Modules

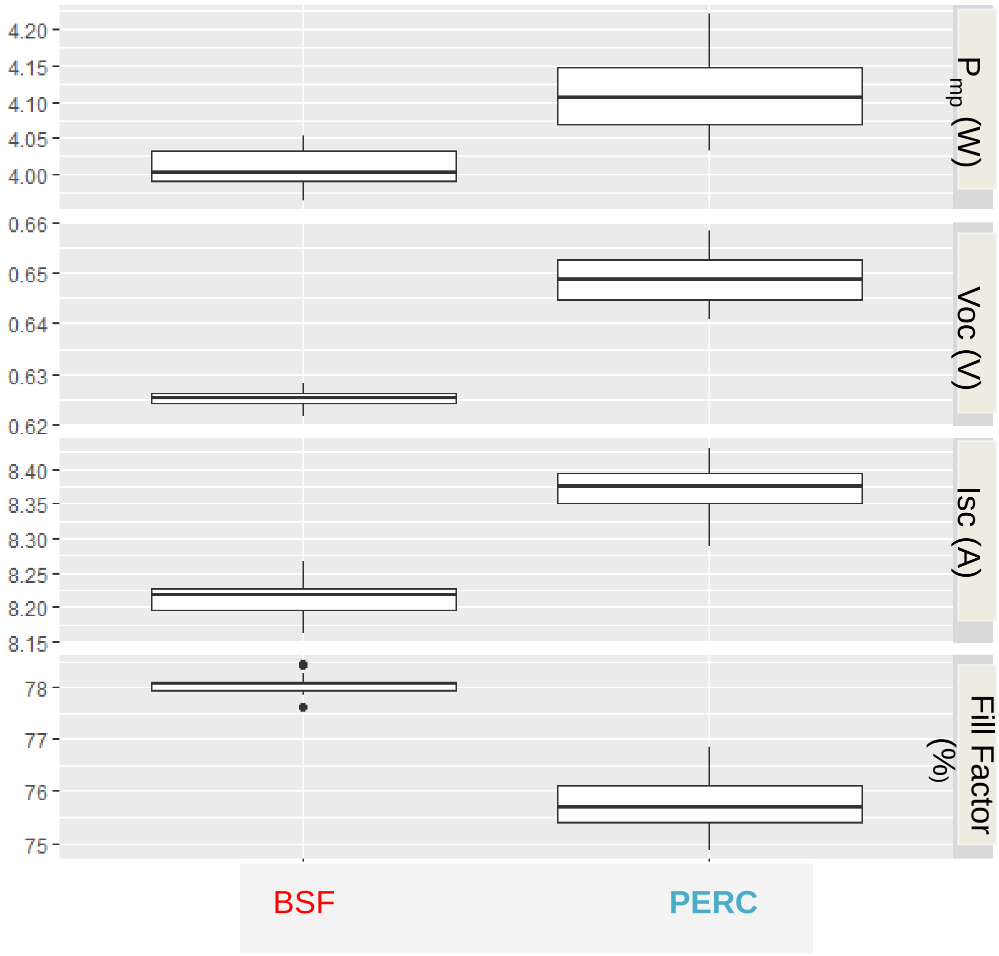
AllReal Class AAA Solar Simulator
DayStar Suitcase

Traditional I-V performance parameters:

- P_{mp}, Voc, Isc, FF, Ipeak, Vpeak



I-V Measured Parameters: Bare Cells



PERC cell architecture

- **higher power conversion efficiency**
  - Increased open circuit voltage because of reduced surface recombination
  - Increased current from light reflectance of rear dielectric

PERC shows reduced fill factor

- **expected due to local back contacts**

Suns-Voc: Cells and Mini-Modules

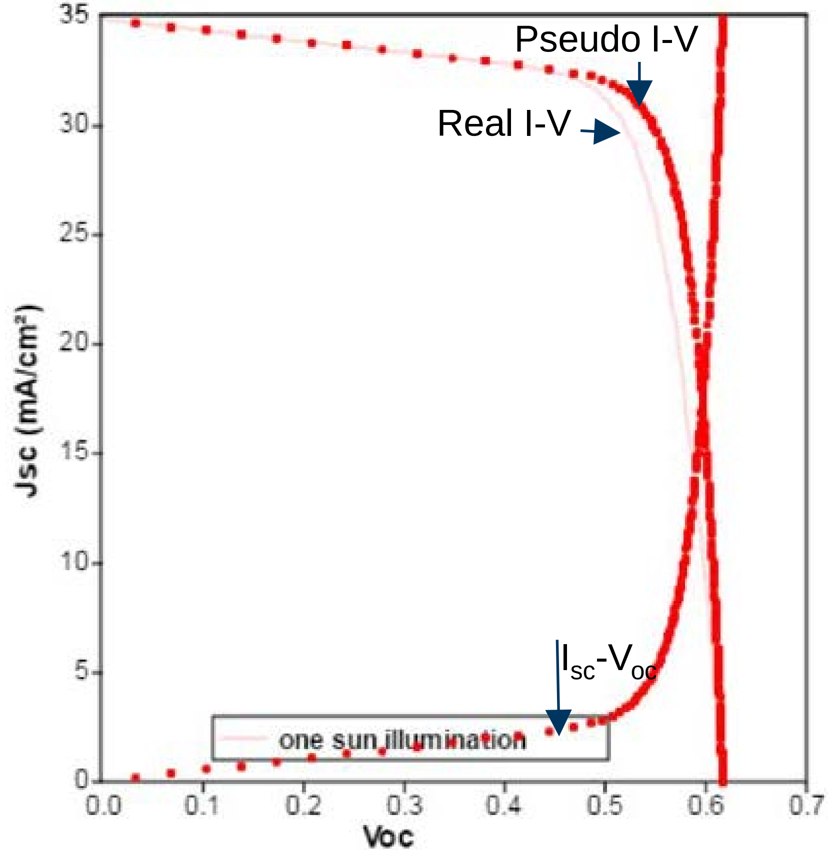
Sinton Suns-Voc-150

Isc-Voc: pseudo I-V curve

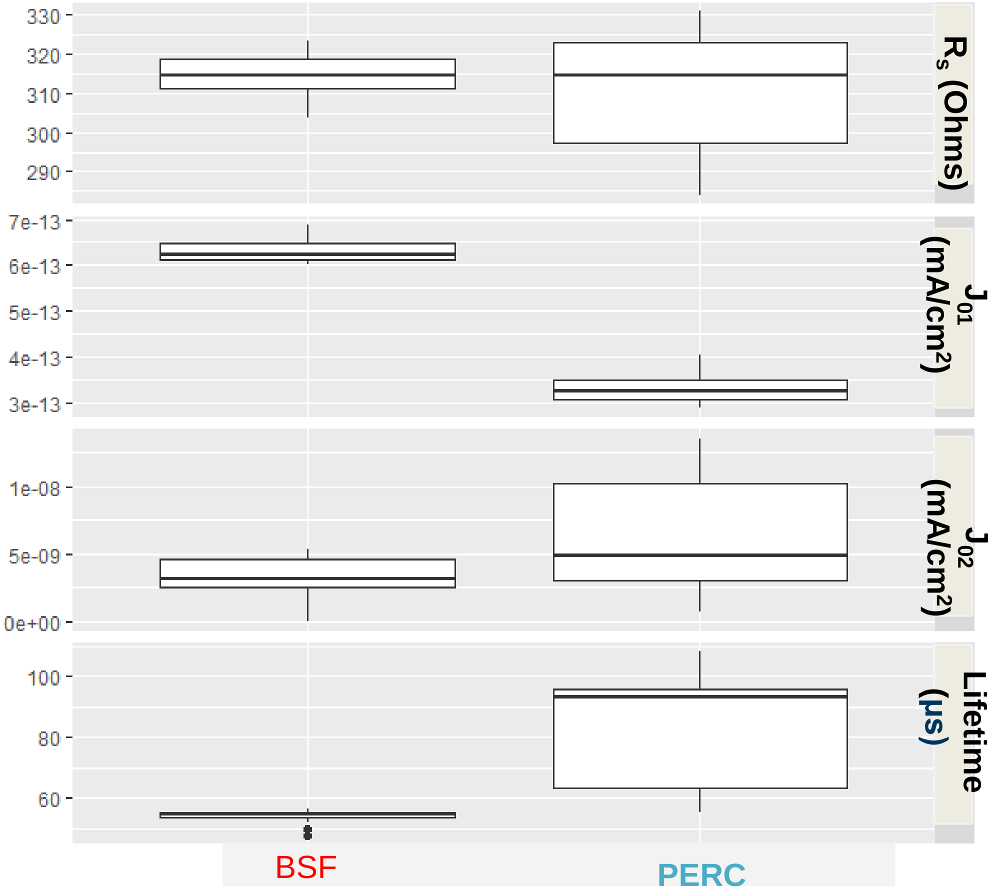
- from I-V statistics at various light intensities
-
- **I(V) = Isc(1sun) - Isc(Voc)**

The pseudo I-V curve

- does not include R_s, R_{sh}, J_{01}, J_{02}
- can be calculated by comparison with the 1-sun I-V curve
-
-



Suns-Voc Measured Parameters: Cells



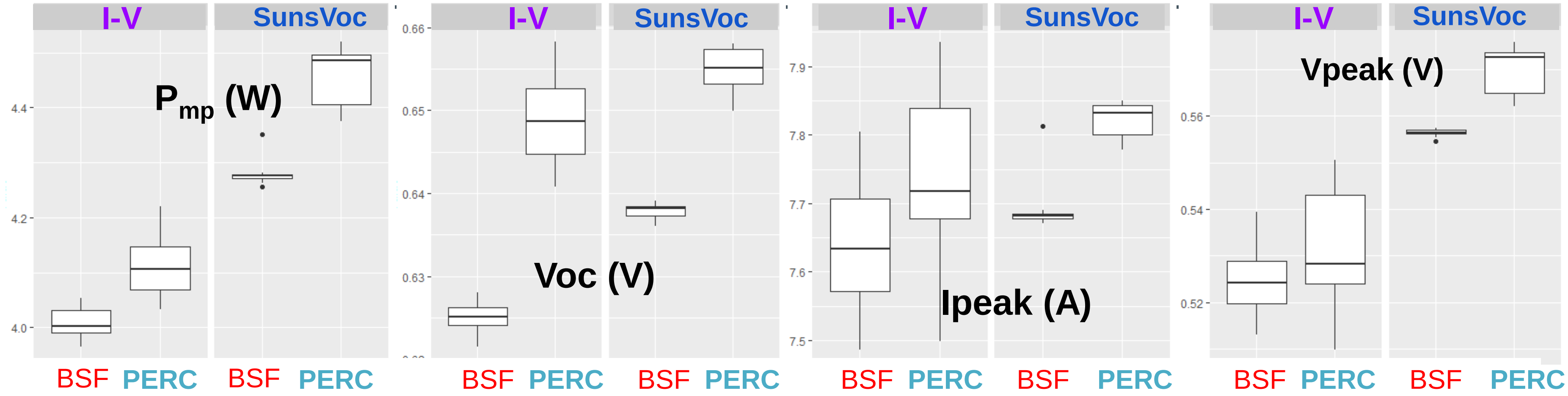
Similar series resistance
- PERC shows greater variability
- possible paste issue

PERC shows decreased J_{01}
- bulk and surface recombination
- due to the rear passivation layer

PERC has slightly greater J_{02}
- recombination in depletion region
- likely because of the generally higher current

Higher minority carrier lifetime in PERC
- decreased surface recombination velocity

Suns-Voc vs. I-V parameters - bare cells



P_{mp} difference between I-V and Suns-Voc curves

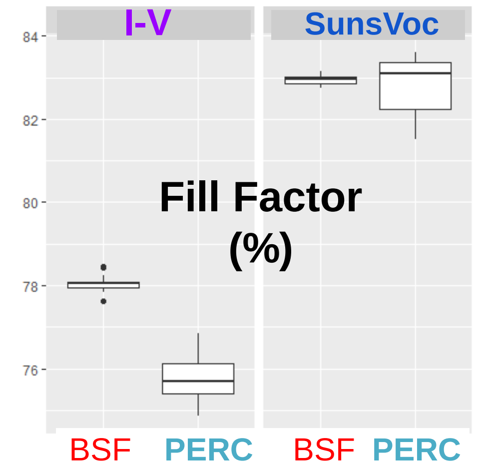
- difference in power generation
- resulting from R_s, R_{sh}, and recombination losses

Voc difference between I-V and Suns-Voc

- greater for BSF cells than PERC
- due to surface recombination

Fill factor is a comprehensive representation

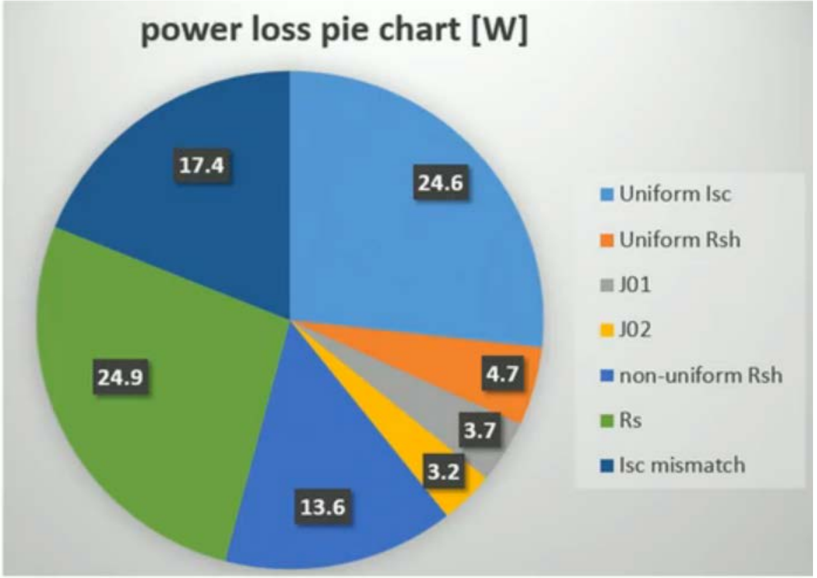
- resistive and recombination effects

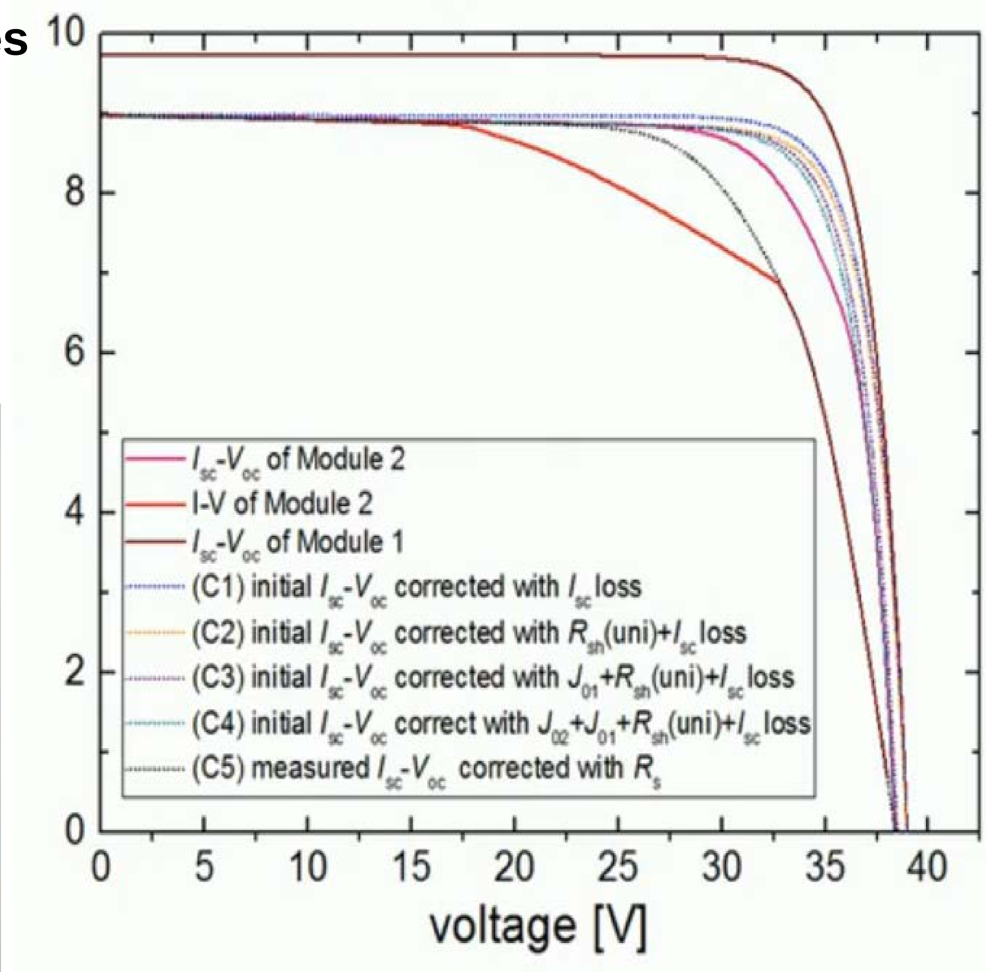


Suns-Voc & I-V analysis for new parameters

Comparison of I-V and Suns-Voc curves

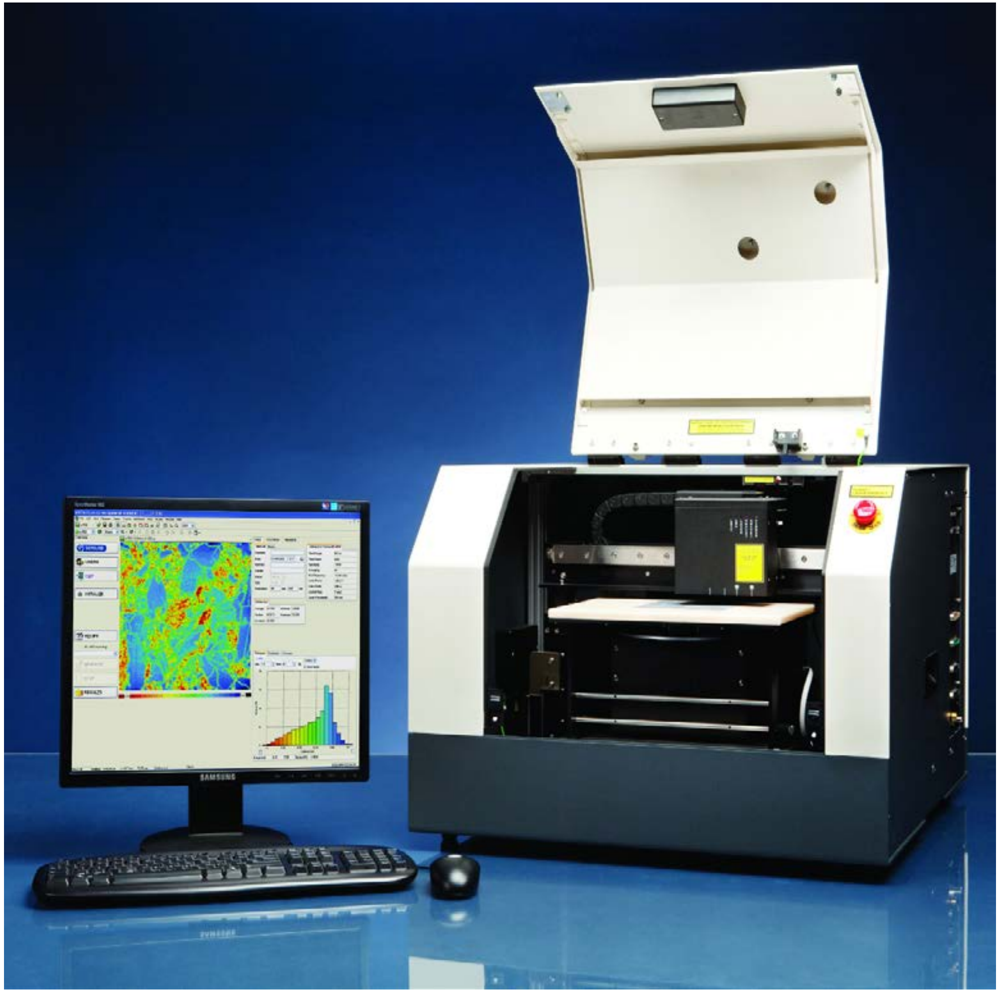
- baseline and exposed cells/modules
- to find losses due to:
  - Isc
  - Rsh
  - Rs
  - J_{01}
  - J_{02}
  - non-uniformity





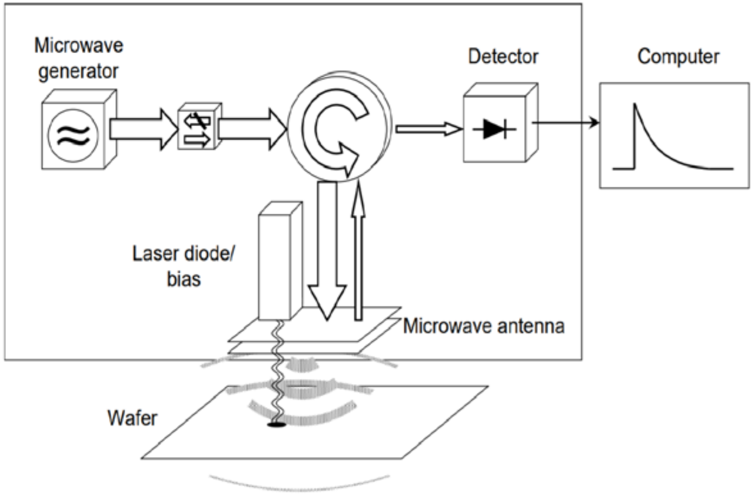
Guo, Siyu, et al. "Detecting loss mechanisms of c-Si PV modules in-situ IV measurement." *Reliability of Photovoltaic Cells, Modules, Components, and Systems IX*. Vol. 9938. International Society for Optics and Photonics, 2016.

Microwave Photoconductive Decay (μPCD): Cells

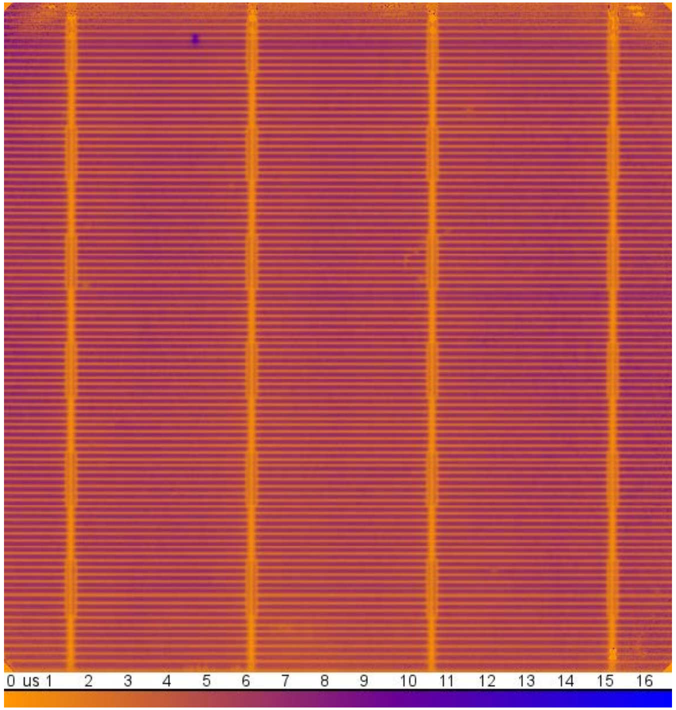


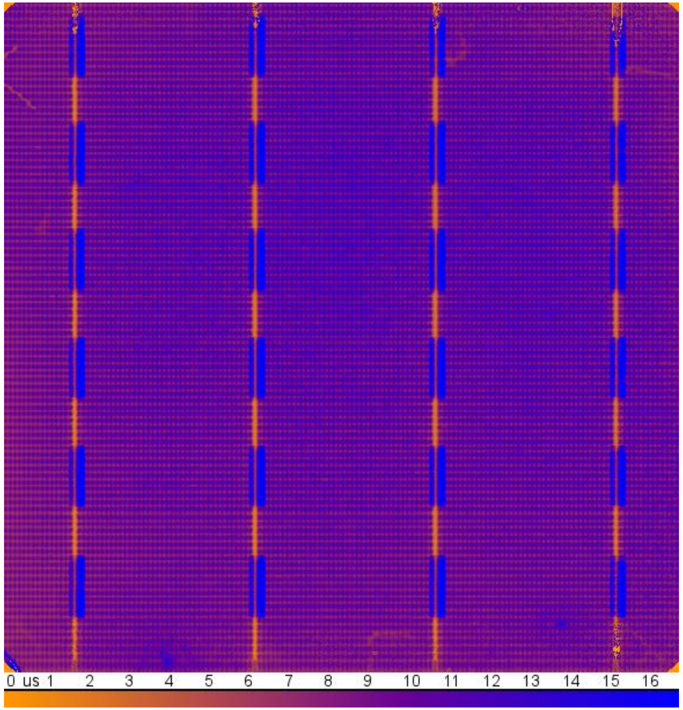
SemiLab WCT-2000PV

- Microwaves are reflected from the back surface or absorbed by free carriers
- Measures decay of excess charge carrier density to create a 2-D lifetime map



Minority Carrier Lifetime Maps (μPCD) : Al-BSF vs. PERC





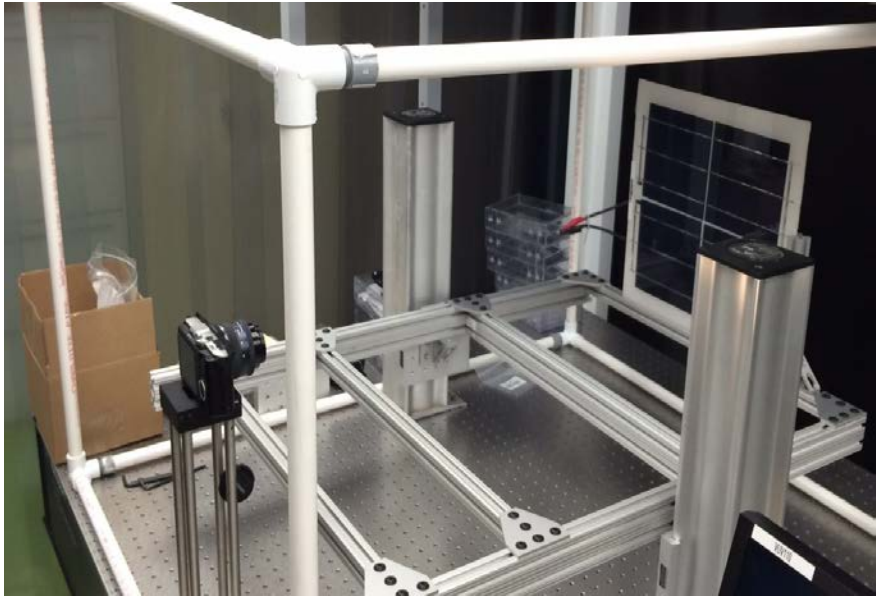
Al-BSF:

- Short lifetimes due to
- high back surface recombination

PERC:

- Longer lifetimes due to
- reduced rear surface recombination velocity
- resulting from passivation layer

Electroluminescence (EL): Cells and mini-modules

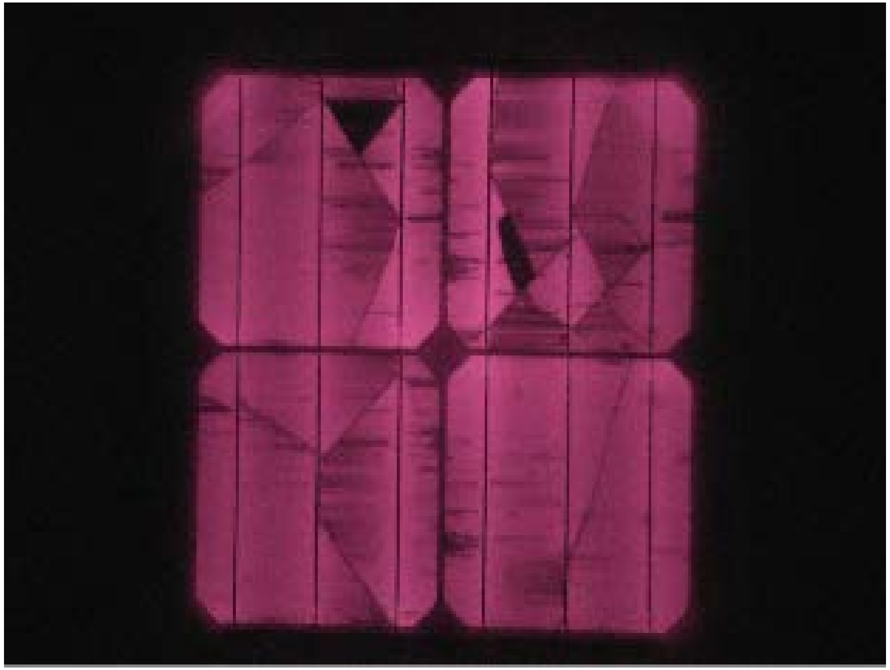


Power cell in forward bias
- **to produce IR electroluminescence**

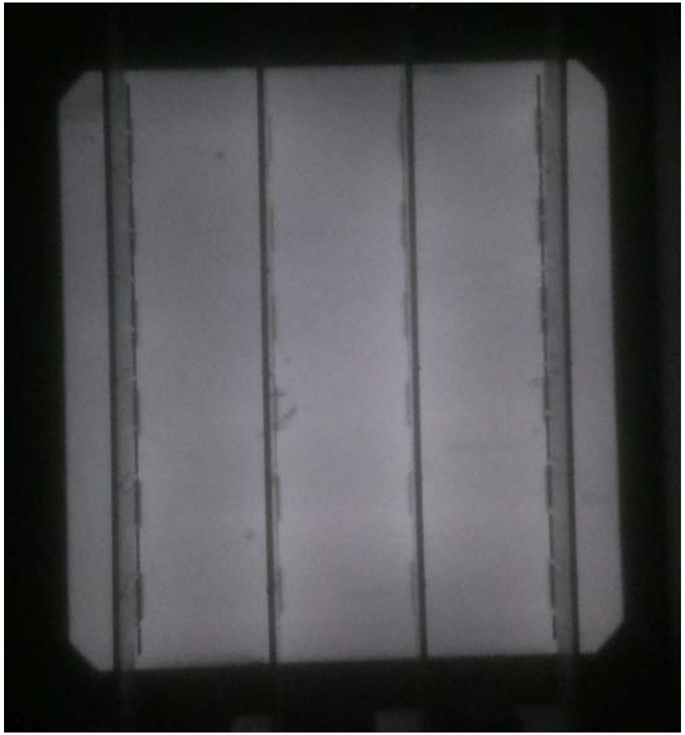
Electrical current proportional to
- **intensity of radiation**

Infrared camera
- **30 second exposures of the cell.**

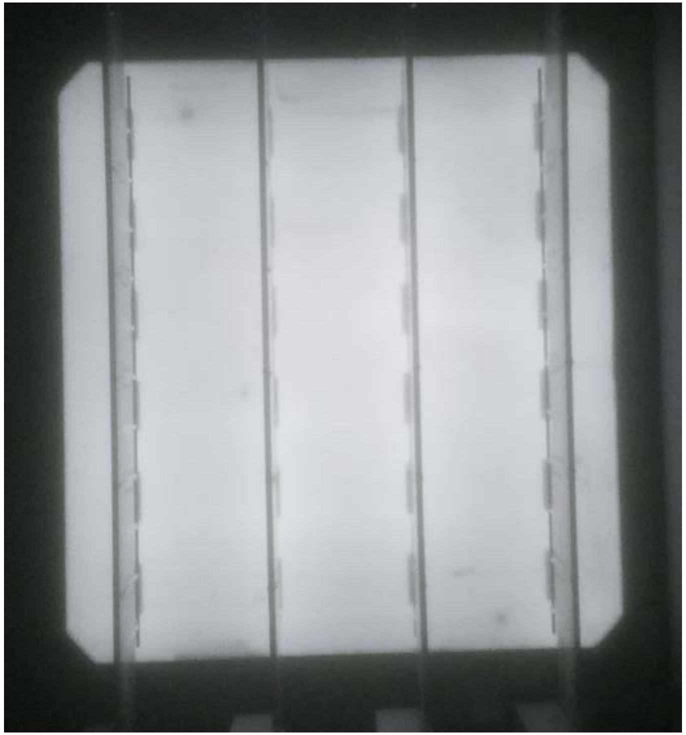
Reveals cracks, shunting, electrically active/inactive areas of the cell



Electroluminescense: Cells



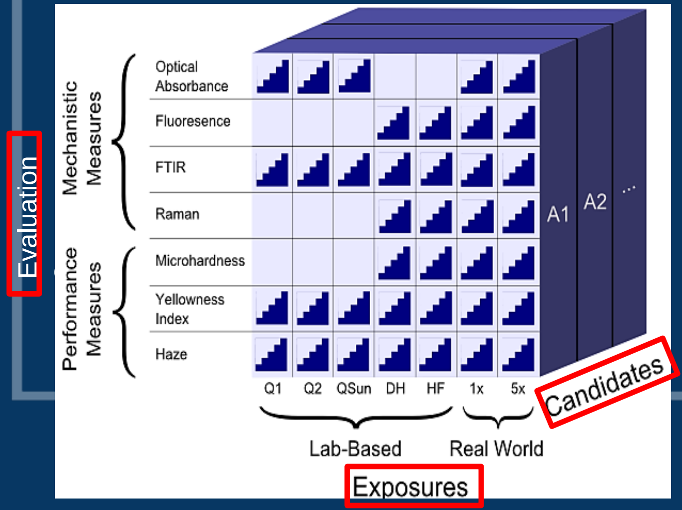
Al-BSF



PERC

Both images were taken at ~Isc for the same exposure time
Greater pixel intensity of PERC cell image indicates
- **greater radiative recombination from the band gap under reverse bias**

Pilot Study:
Bare Cell Acetic Acid Exposure



Acetic Acid Exposure on Bare Cells

PERC cells incorporated a different passivation layer (SiO_x)

- main phase of the project (Al_2O_3)

PERC and Al-BSF cells were fabricated

- with different pastes for front and back contacts

2.5 M aqueous acetic acid

- concentration in a degraded module

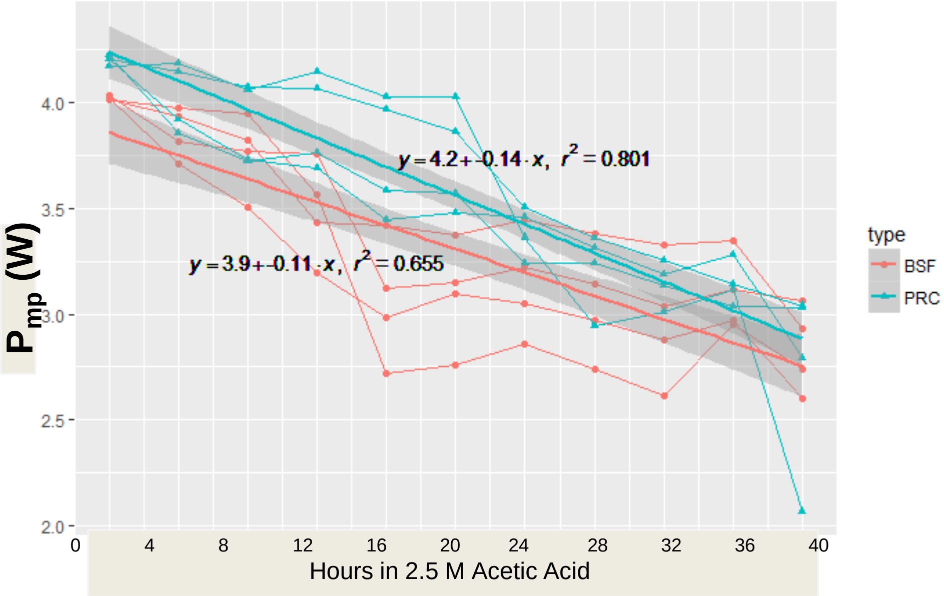
Equal exposure on front and back surfaces compared to vapor exposure.

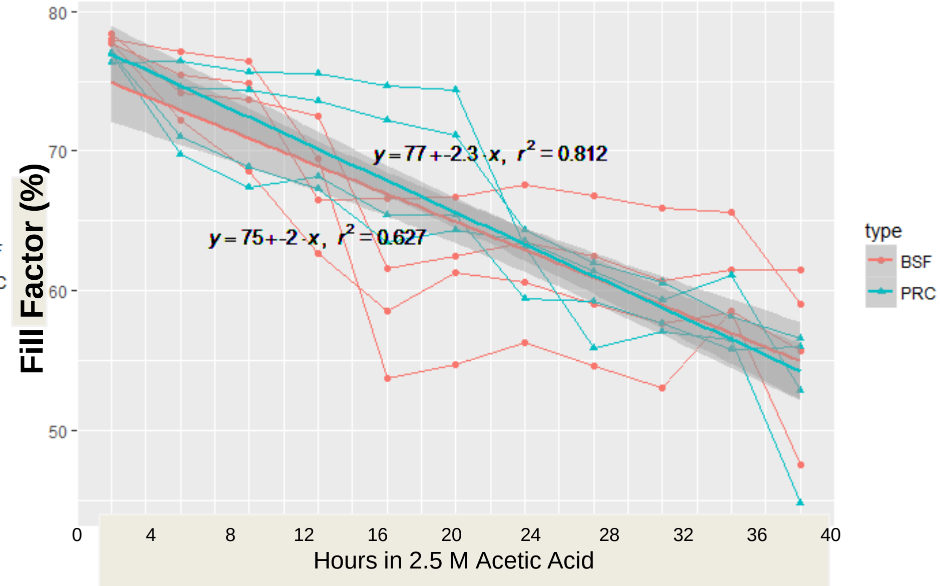
4 hour exposure steps, rinse, and dry before measurement

- Same sample exposed at each exposure step
- 4 samples were exposed
- 40 hours total exposure

I-V curve tracing in solar simulator

Preliminary Acetic Acid Results: P_{mp} and FF





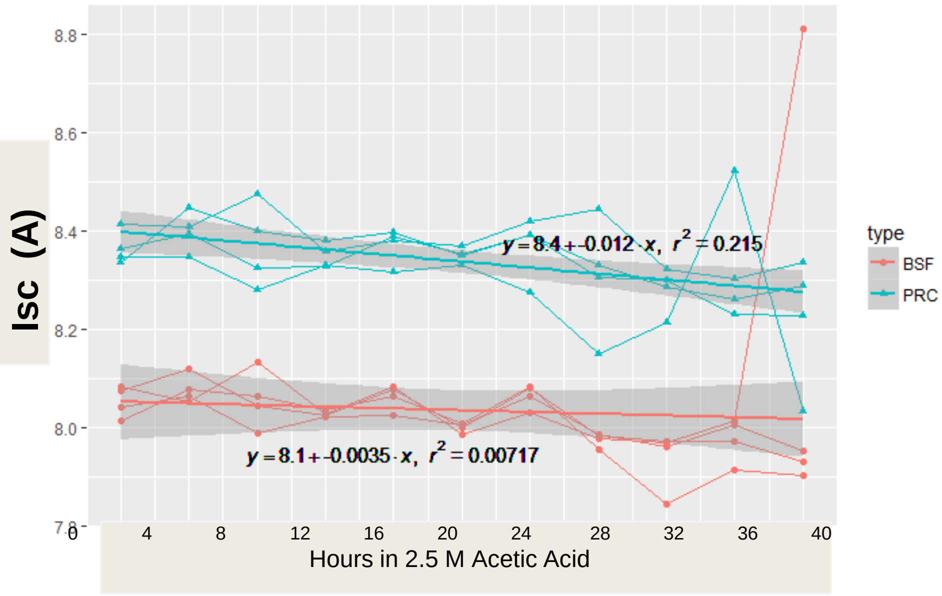
Similar degradation rates

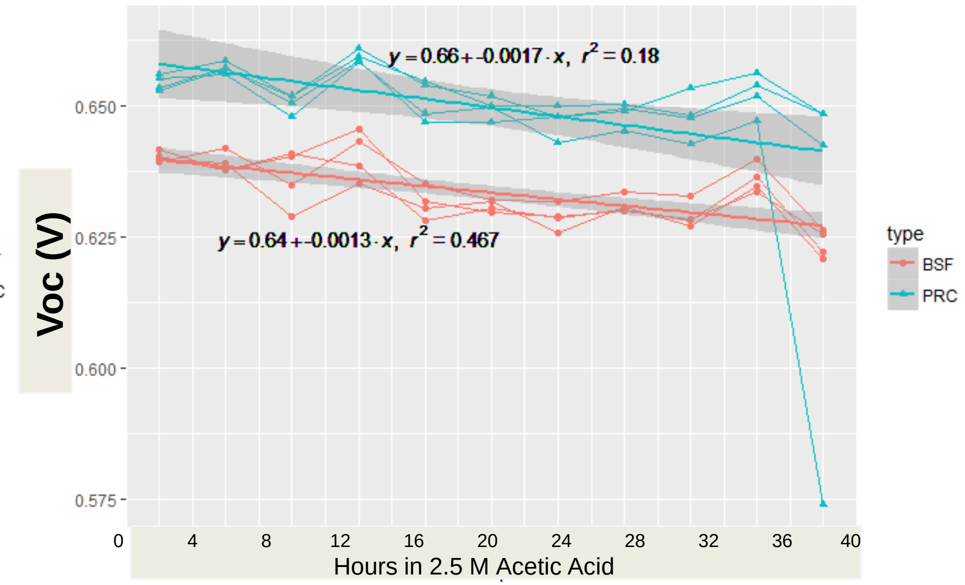
- between PERC and Al-BSF cells

Fill factor (FF) is reduced

- via increased series resistance (corrosion of contacts),
- slightly greater for PERC (possible paste issue)

Preliminary Acetic Acid Results: Isc and Voc





Short circuit current (Isc) and open circuit voltage (Voc)

- are relatively stable throughout the exposure
- unaffected by contact corrosion

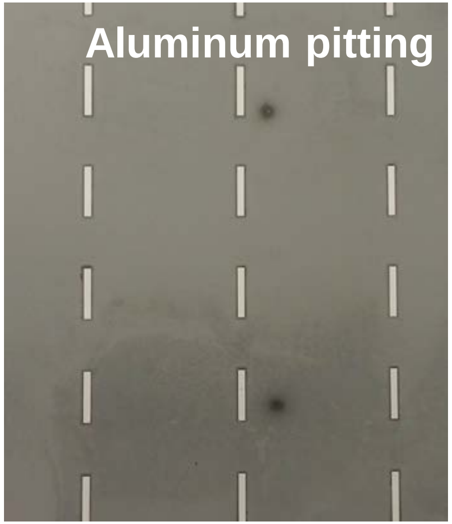
Preliminary Acetic Acid Exposure: Observations

Degradation of I-V parameters related to

- internal operation of bare cells (Isc and Voc)
- were similar for PERC and Al-BSF

Degradation of I-V parameters related to

- contact corrosion (FF and Vpeak)
- degraded faster for PERC than Al-BSF
- Potentially due to different pastes used for back contacts on PERC



Conclusions

Develop an understanding of PERC cell degradation mechanisms

- Light-induced degradation
- Passivation stability
- Localized contact issues

Develop a predictive model for PERC cell lifetime

- **<Stress|Mechanism|Response> framework**
  - Statistical analytics
  - Data Science Approach
- **Using bare cells and mini-modules**
  - Accelerated and Real-world **Stressors**
  - Multiple different evaluations for degradation **Mechanisms**
  - Overall power loss as a **Response**

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Questions