NIST/UL Workshop on Photovoltaic Materials Durability

Corrosion-induced AC Impedance Elevation in Crystalline Silicon Photovoltaic Cells/Modules

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Gaithersburg, Maryland, USA

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This work was supported by the New Energy and Industrial Technology Development Organization (NEDO), Japan.

Final Destination: Service Lifetime Prediction

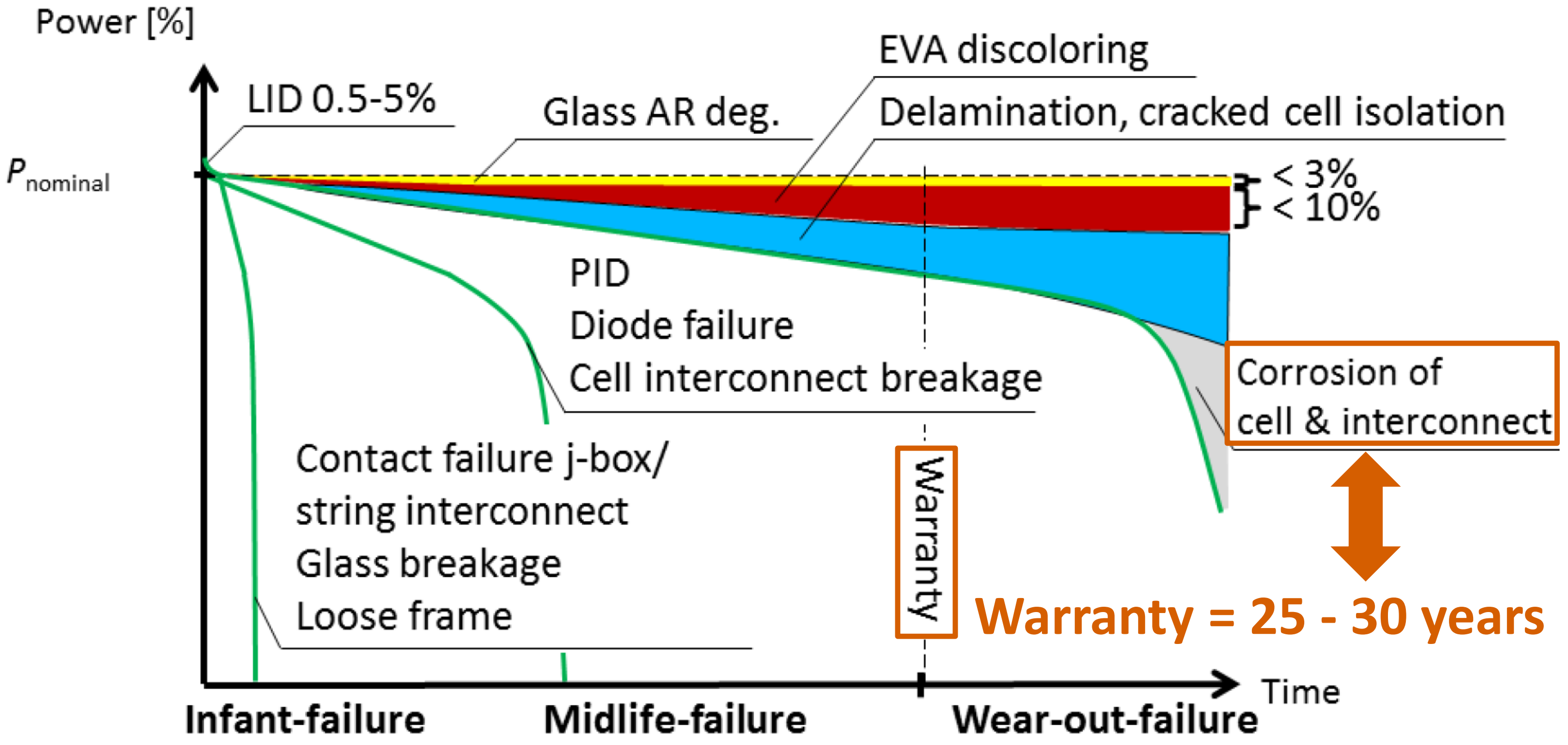
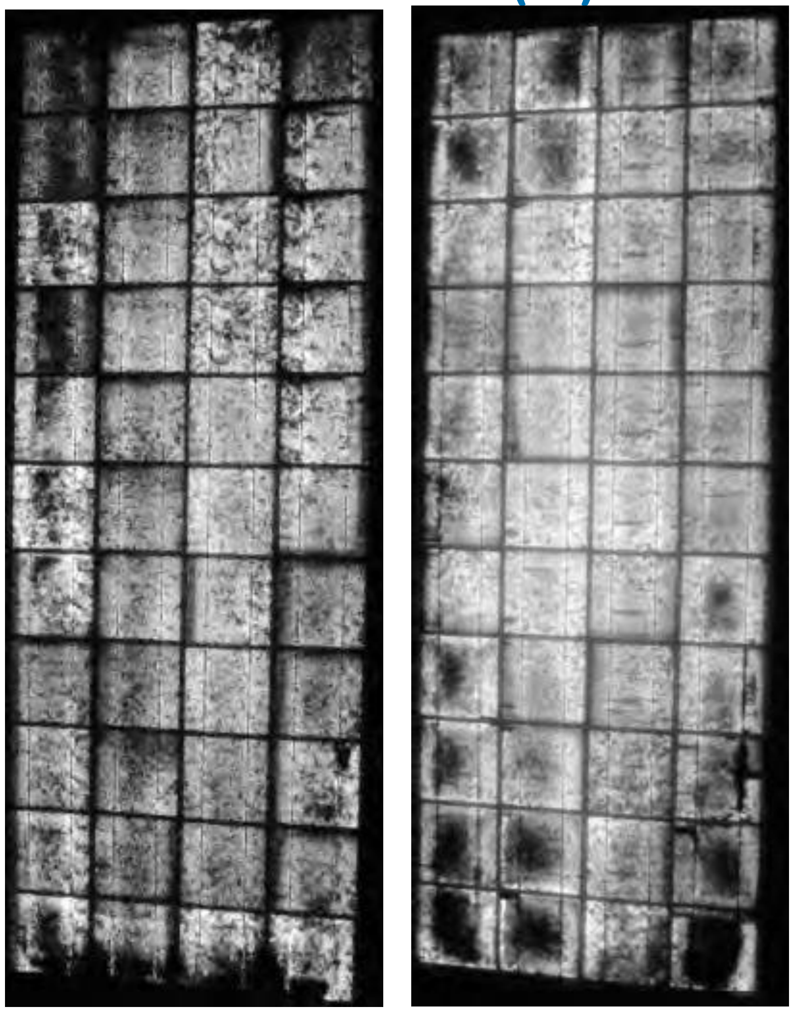


Fig. 3.1: Three typical failure scenarios for wafer-based crystalline photovoltaic modules are shown. Definition of the used abbreviations: LID – light-induced degradation, PID – potential induced degradation, EVA – ethylene vinyl acetate, j-box – junction box.

IEA-PVPS Task13 Team, "Review of Failures of Photovoltaic Modules." Paris: International Energy Agency, 2014.

PV Modules exposed for 21 years in Cfa climate (JP)

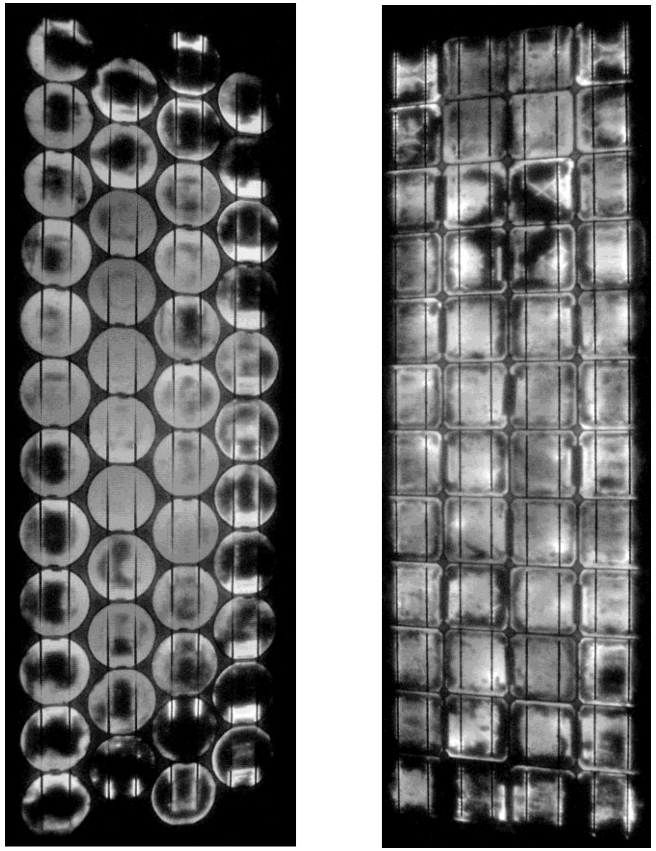


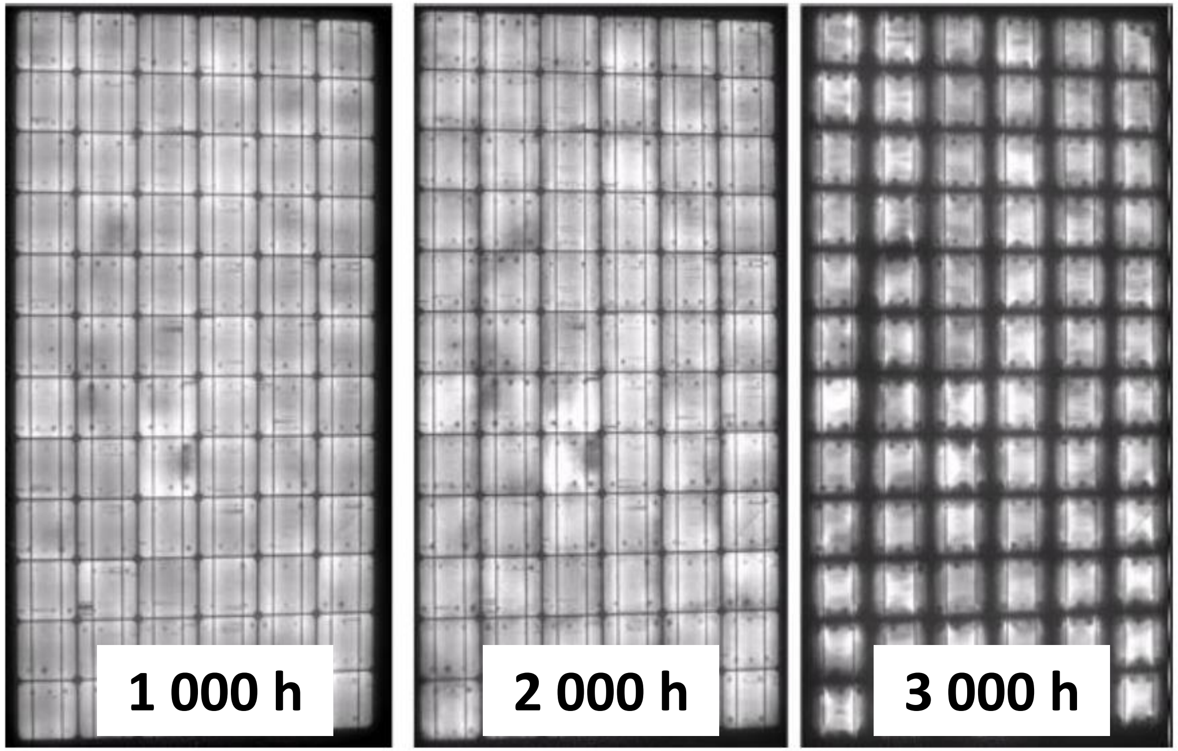
Different EL appearances

There is no evidence that the failure mode observed after extended 85/85 exposure ever occurs in fielded modules.

J. H. Wohlgemuth and M. D. Kempe in *Proc. 2013 IEEE 39th Photovolt. Spec. Conf.*, 2013, pp. 0126–0131.

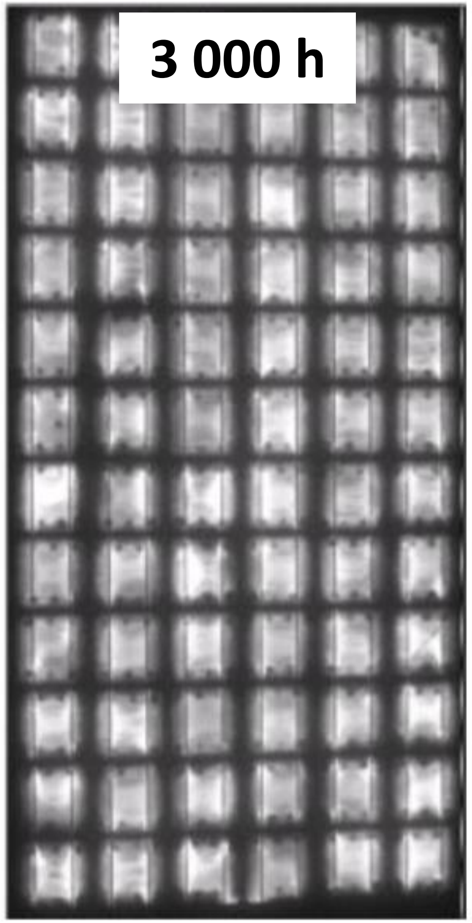
Exposed in a *Field* for ca. 30 Years ⟷ **under *DH Stress Conditions***





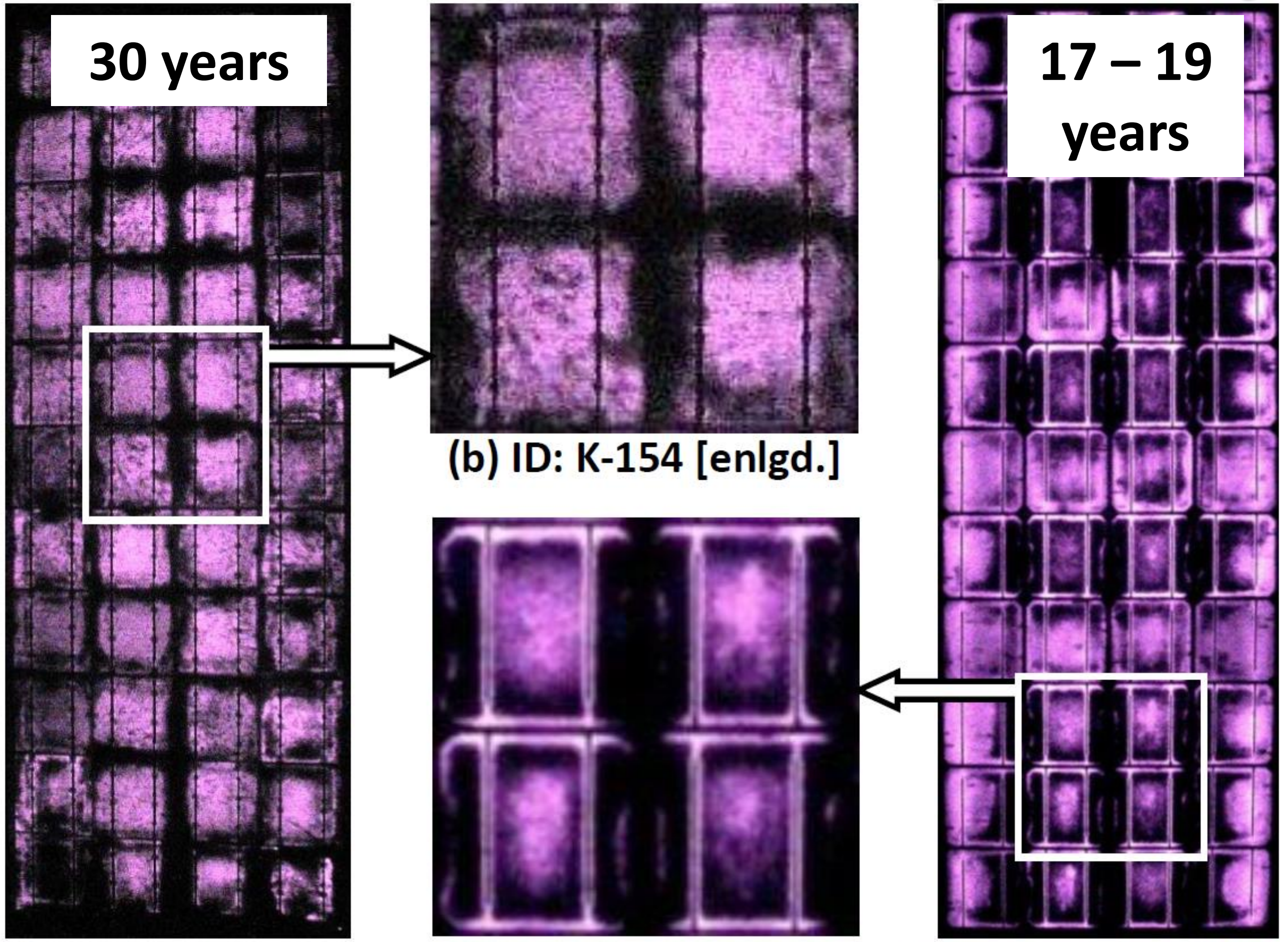
N. Bogdanski and W. Herrmann, in *Proc. 26th Eur. Photovolt. Sol. Energy Conf. Exhib.*, 2011, pp. 3093–3096.

However, we found *"DH-induced Degradation"-like EL appearance* in some *PV modules exposed in fields*.



"DH-induced Degradation"

N. Bogdanski and W. Herrmann, in *Proc. 26th Eur. Photovolt. Sol. Energy Conf. Exhib.*, 2011, pp. 3093–3096.



(a) ID: K-154 Module (d) ID: C2-11P [enlgd.] (c) ID: C2-11P Module

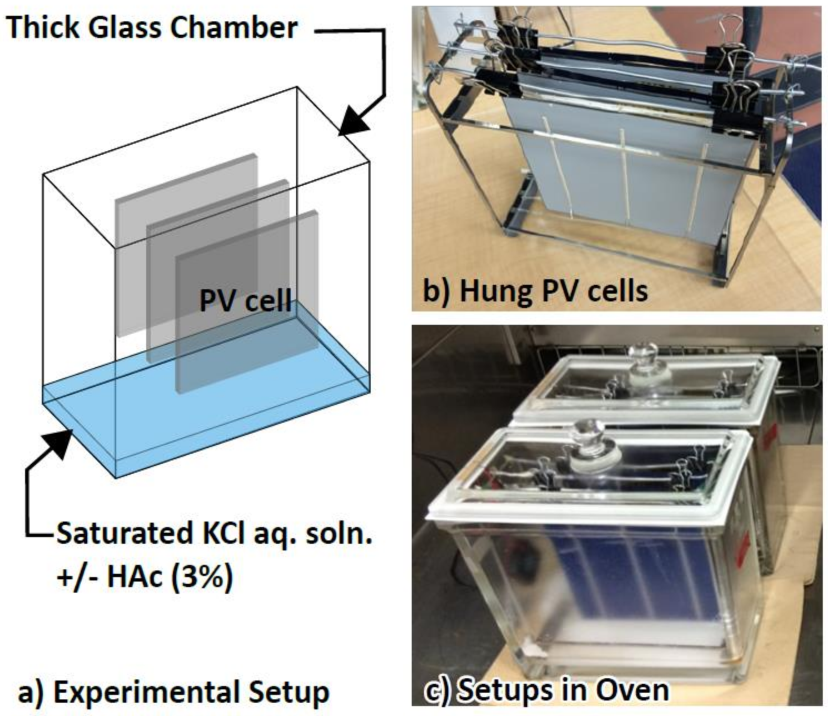
T. Tanahashi, Y. Hara, and A. Masuda, in *Proc. 33rd Eur. Photovolt. Sol. Energy Conf. Exhib.*, 2017, pp. 1462–1465.

Question?

These different EL appearances are induced by a common corrosion mechanism or not?

We have 3 Experimental Procedures on Corrosion (HAc = Acetic Acid)

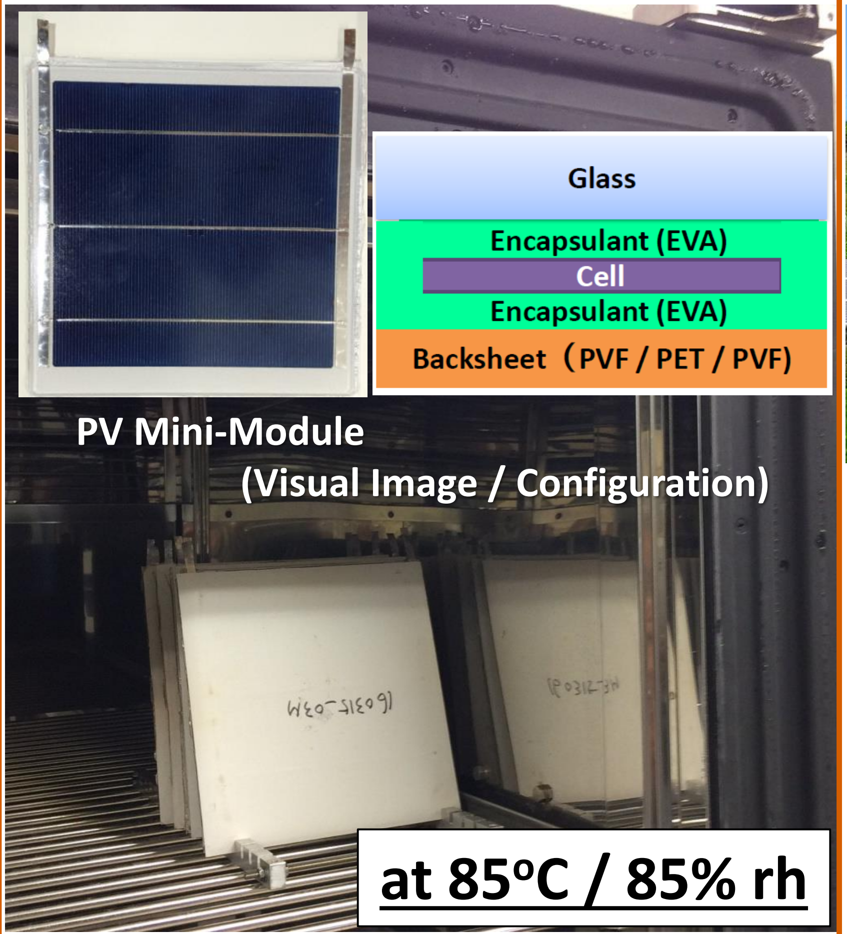
HAc-Vapor Exposure of Bare PV Cells



at 85°C/ 80% rh

T. Tanahashi et al., "Localization and characterization of a degraded site in crystalline silicon photovoltaic cells exposed to acetic acid vapor," *IEEE J. Photovolt.*, vol. 8, no. 4, pp. 997–1004, Jul. 2018.

DH Stress Test of PV Modules



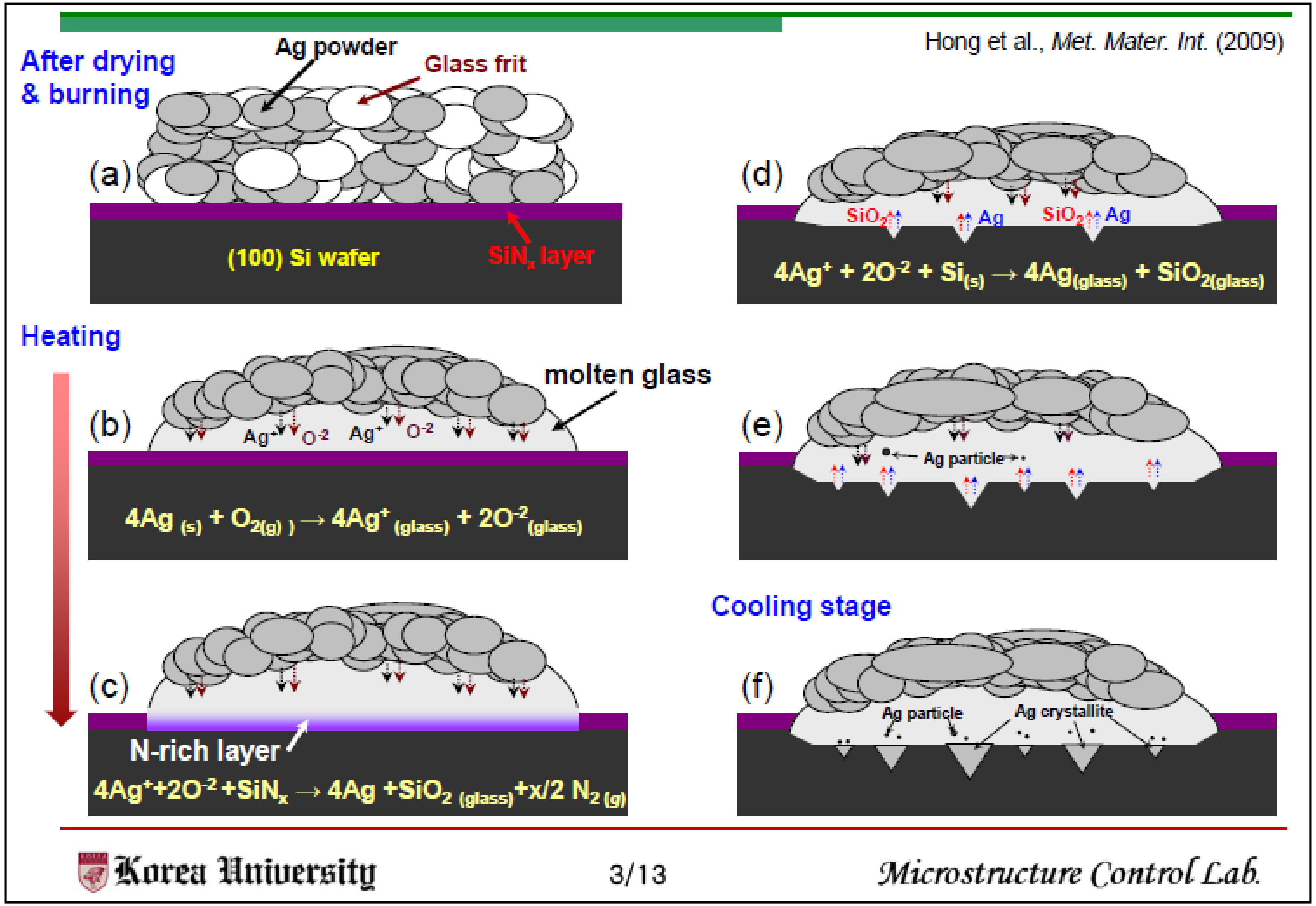
This Presentation

Outdoor Exposure

Ex. Outdoor Exposed PV Module from 1994 in Cfa Climate

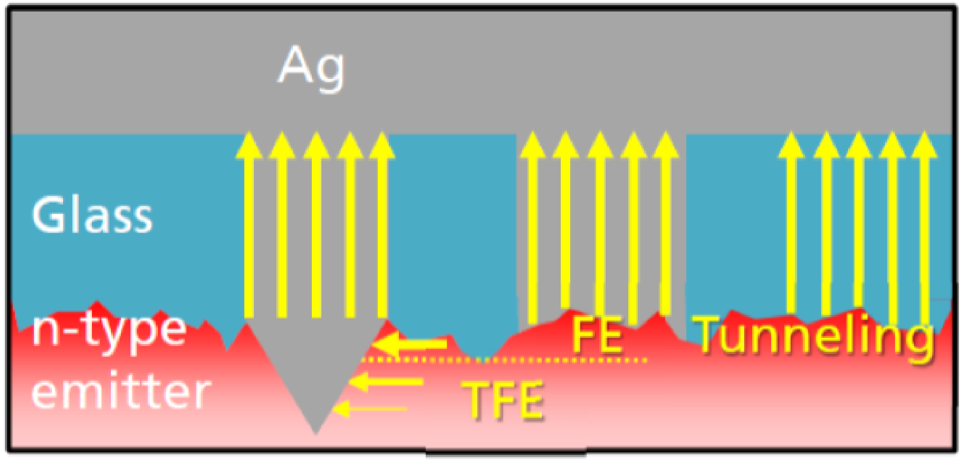
T. Tanahashi et al., "Corrosion-induced AC impedance elevation in front electrodes of crystalline silicon photovoltaic cells within field-aged photovoltaic modules," *IEEE J. Photovolt.*, vol. 9, no. 3, pp. 741–751, 2019.

Silver Contact Formation during “Fire-Through” Process



Chou, S.-B., et al. “Effect of forming gas annealing on screen-printed Ag metallization of silicon solar cells”, 5th Metallization Workshop (20-21 October. 2014)

Proposed Current Transport Mechanisms in Silver Contact[1)]



Field Emission (FE)

$$N_D \geq 10^{20}\ cm^{-3}$$

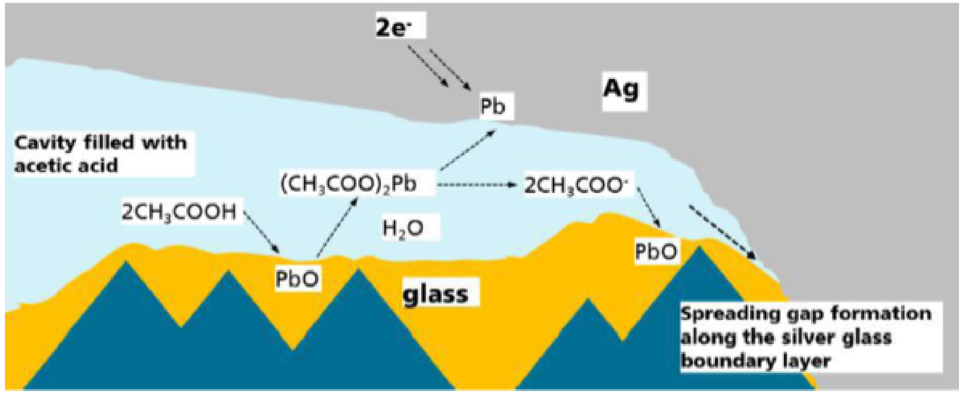
Thermionic Field Emission (TFE)

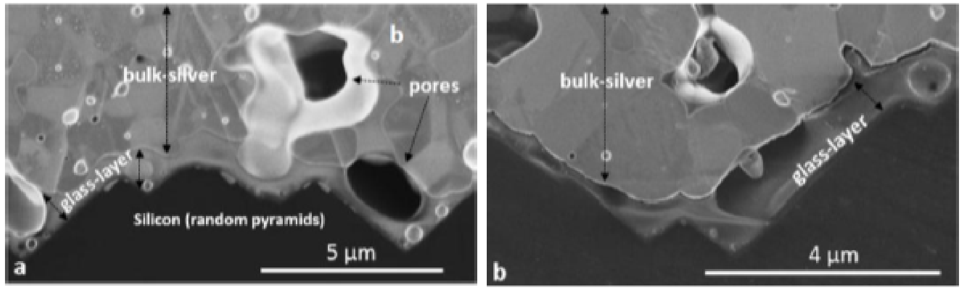
$$10^{17}\ cm^{-3} < N_D < 10^{20}\ cm^{-3}$$

Electron Tunneling

through glass layer
(directly or *via* nano-Ag colloids)

Dissolution of Glass-Silver Boundary Layer by Acetic Acid[2)]

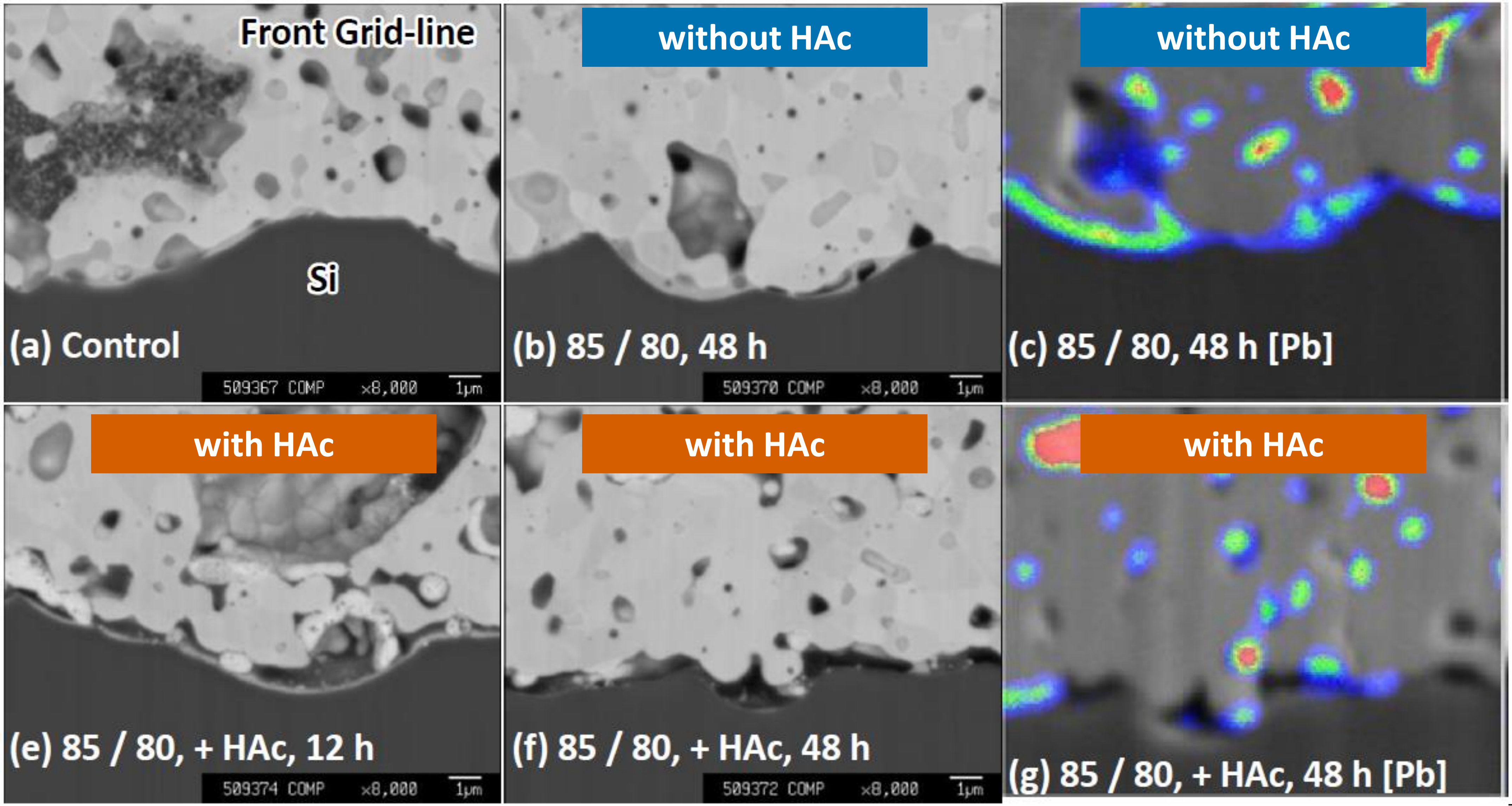




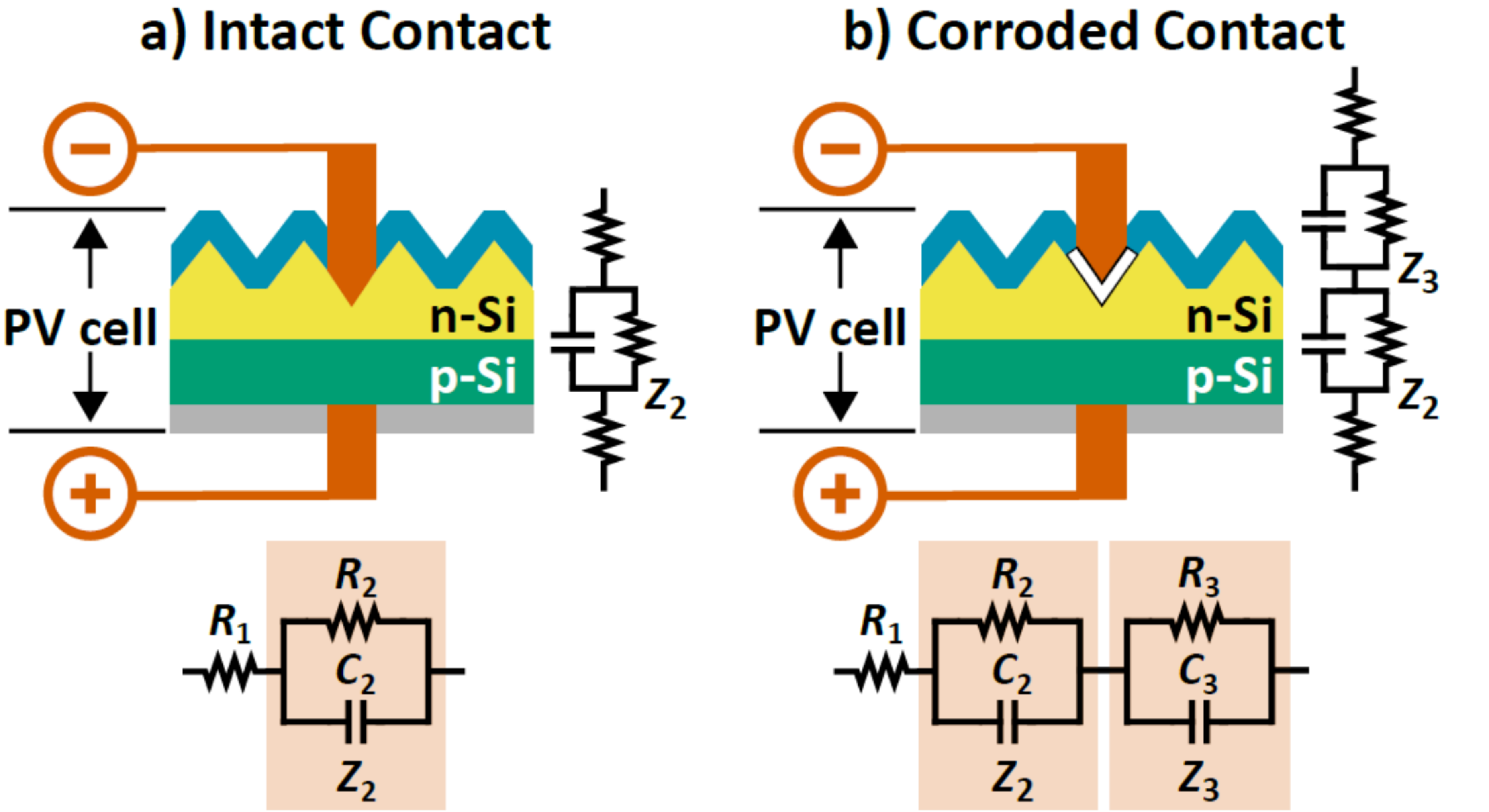
1) R. Hoenig et al., “Macroscopic and Microscopic Electrical Behavior of Screen Printed Silver Contacts to Phosphorus-Doped Emitters” , presented at 5th Metallization Workshop, 2014.

2) A. Kraft et al., “Investigation of Acetic Acid Corrosion Impact on Printed Solar Cell Contacts”, IEEE J. Photovolt. 5 (3): 736-743, 2015.

Evolution of Gap at Ag-Si Interface (HAc-Vapor Exposure)



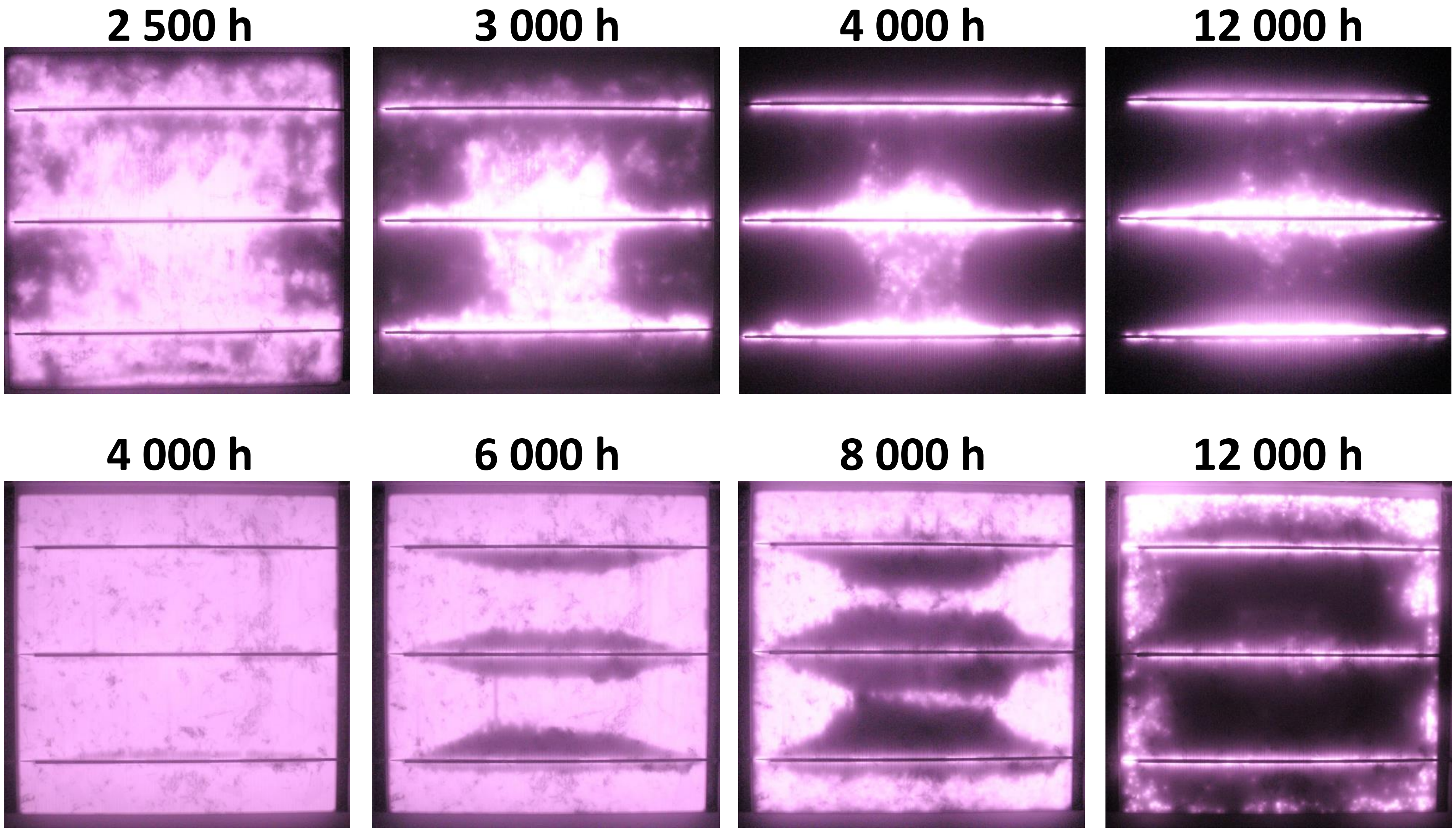
Detection of Corrosion-induced AC Impedance Elevation



DH Stress Test of PV Modules Evolution of EL Image

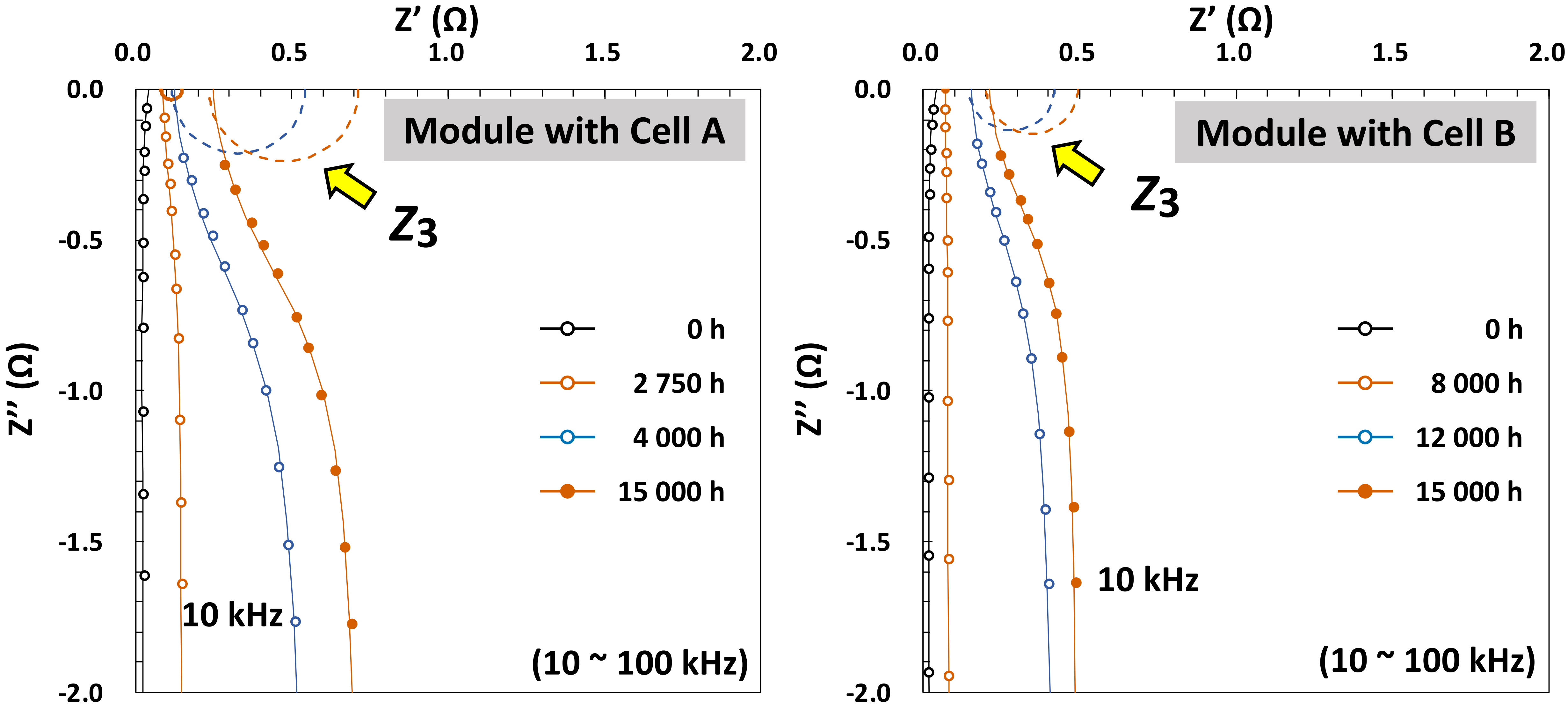
Module with Cell A

Module with Cell B



DH Stress Test of PV Modules

Emergent Incidence & Evolution of Z_3

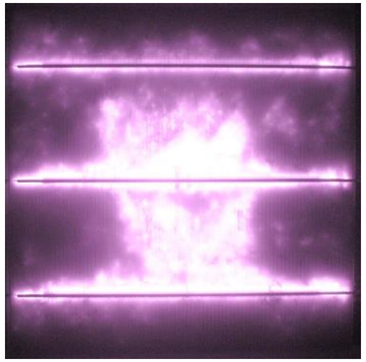


DH Stress Test of PV Modules

Evolution of Elec. Parameters

Module with Cell A

3 000 h

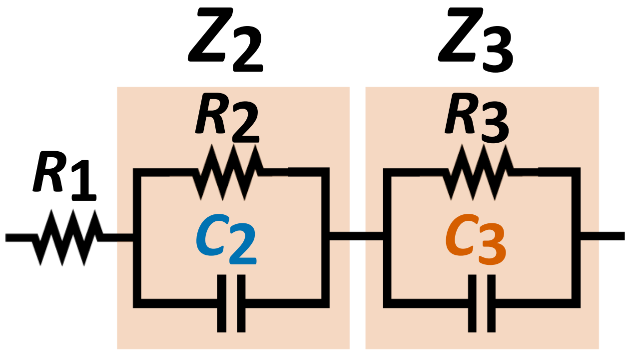


Synchronized Changes

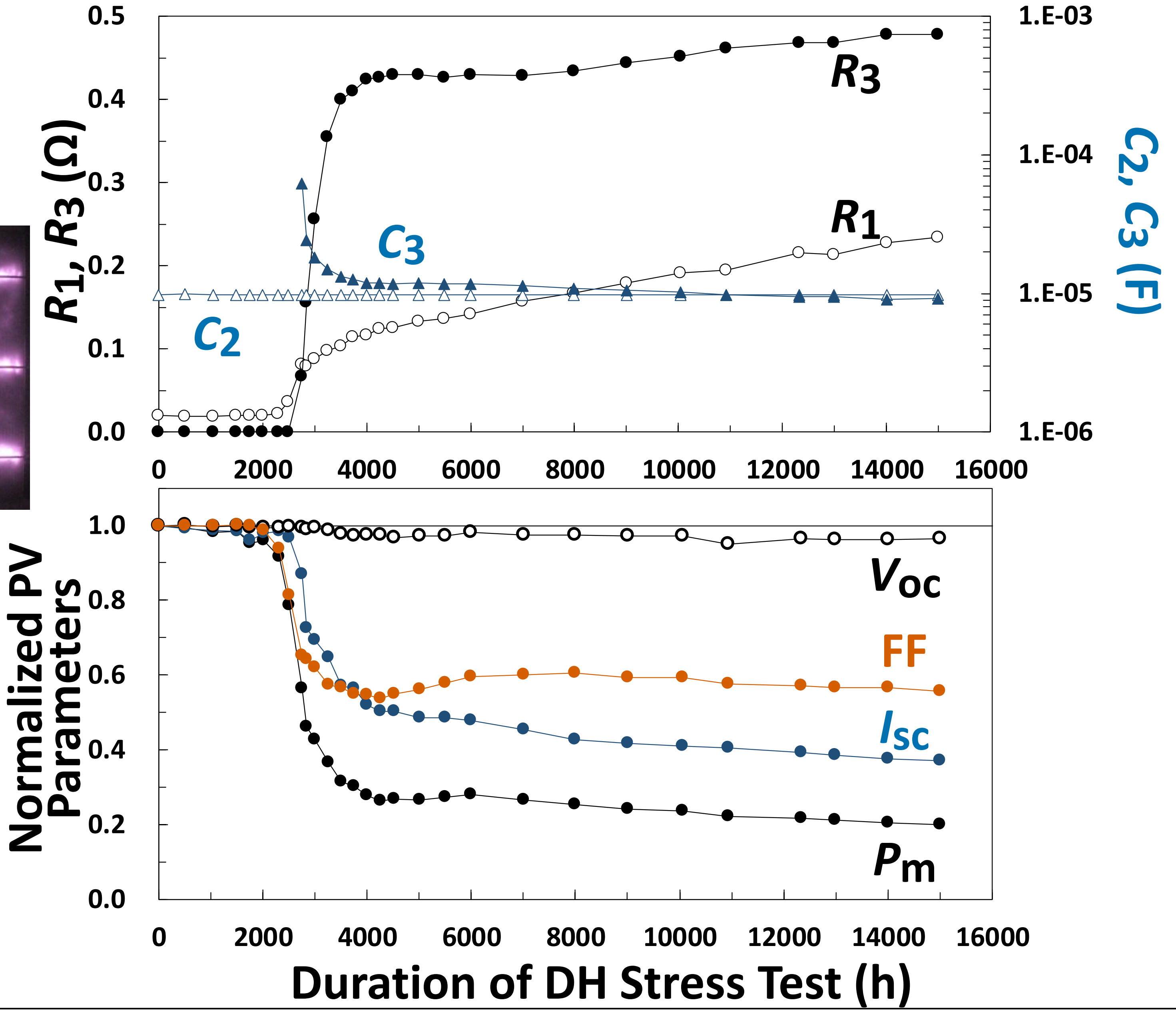
- FF / P_m: Reduction
- R_1 / R_3: Elevation
- C_3: Emergent Expression / Decay

Constant

- C_2



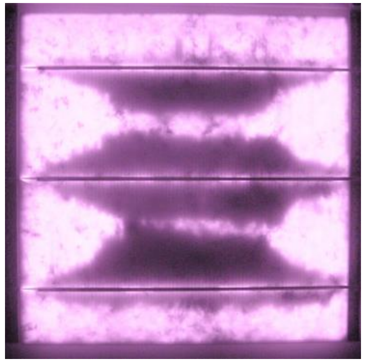
AC Equivalent Circuit



DH Stress Test of PV Modules

Evolution of Elec. Parameters

8 000 h



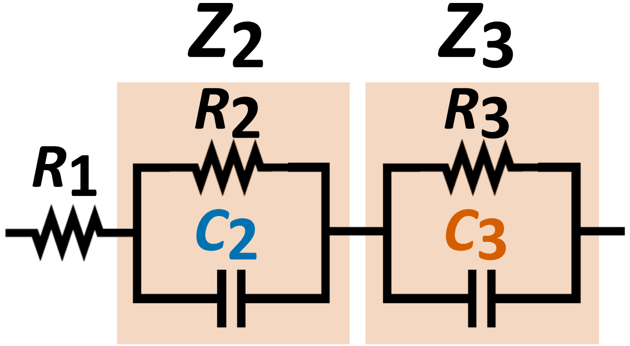
Module with Cell B

Synchronized Changes

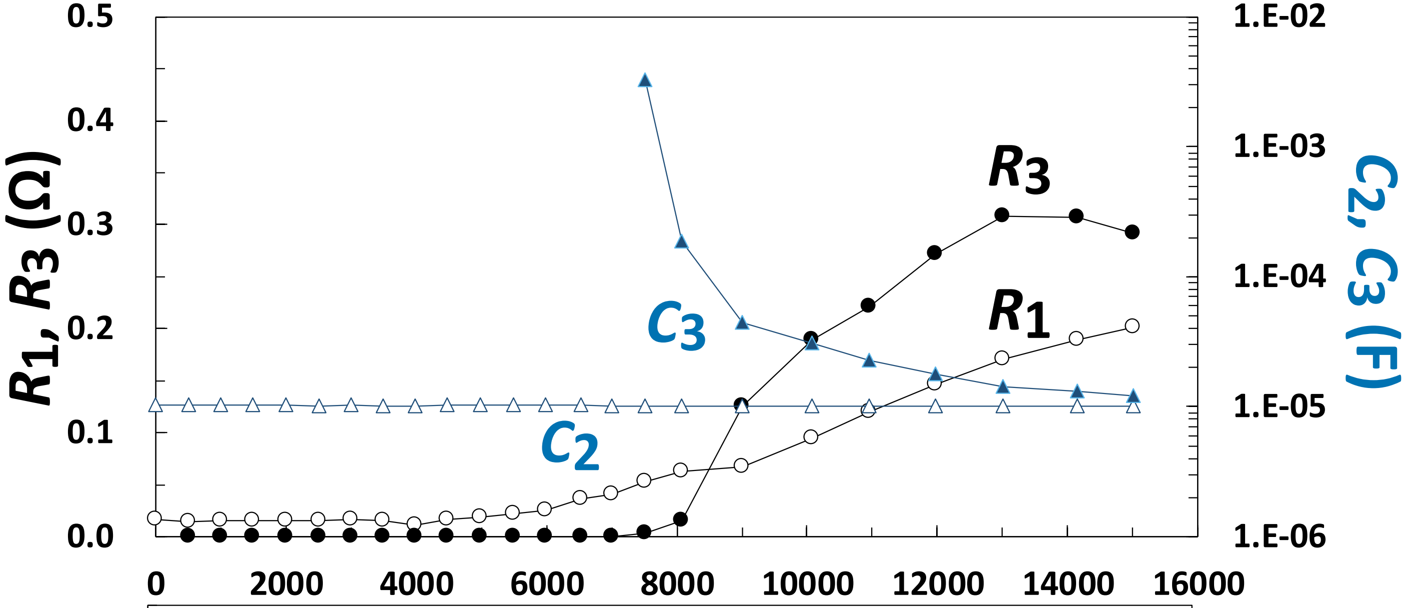
- FF / P_m: Reduction
- R_1 / R_3: Elevation
- C_3: Emergent Expression / Decay

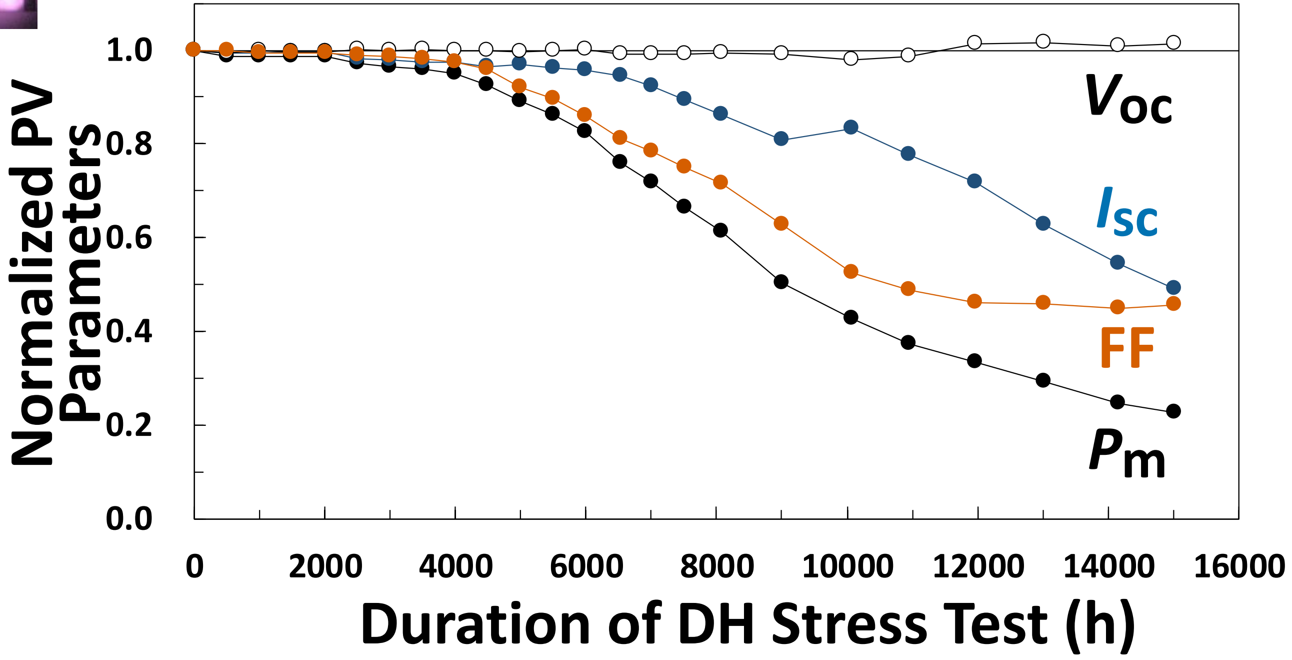
Constant

- C_2



AC Equivalent Circuit



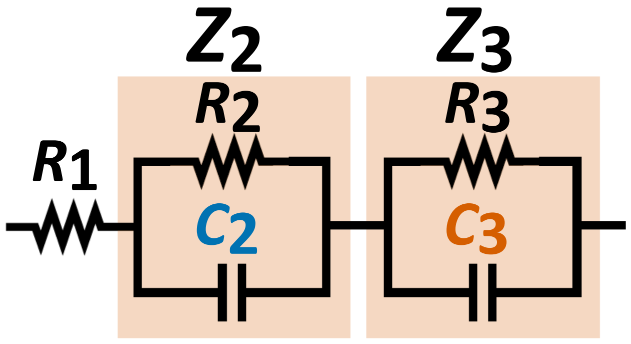


DH Stress Test

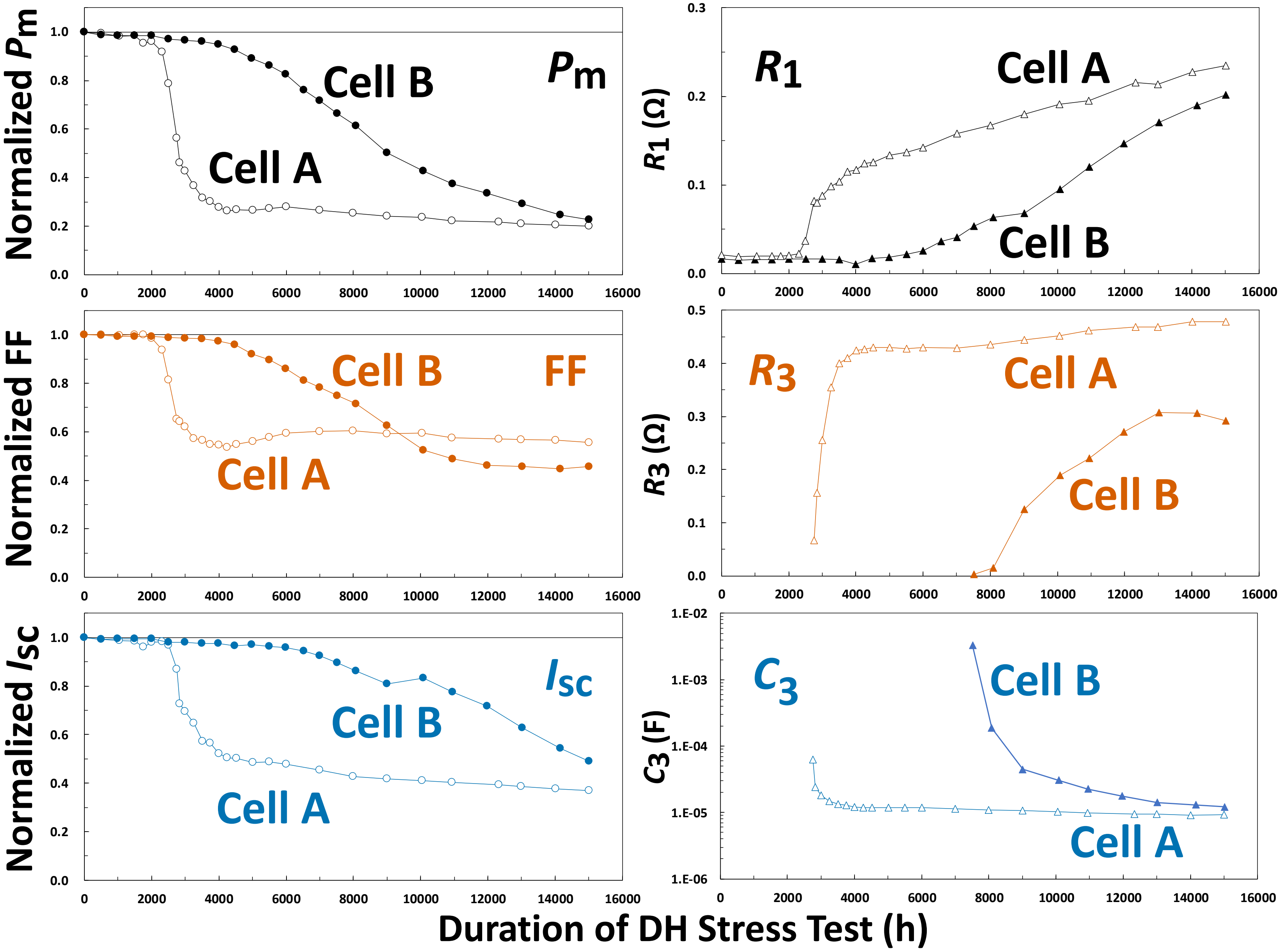
Module with Cell A

Module with Cell B

Complete Differences in Degradation Kinetics



AC Equivalent Circuit

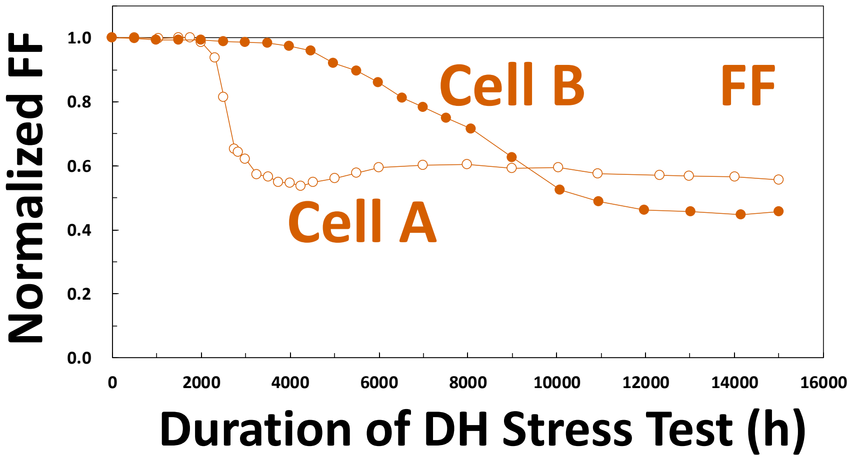


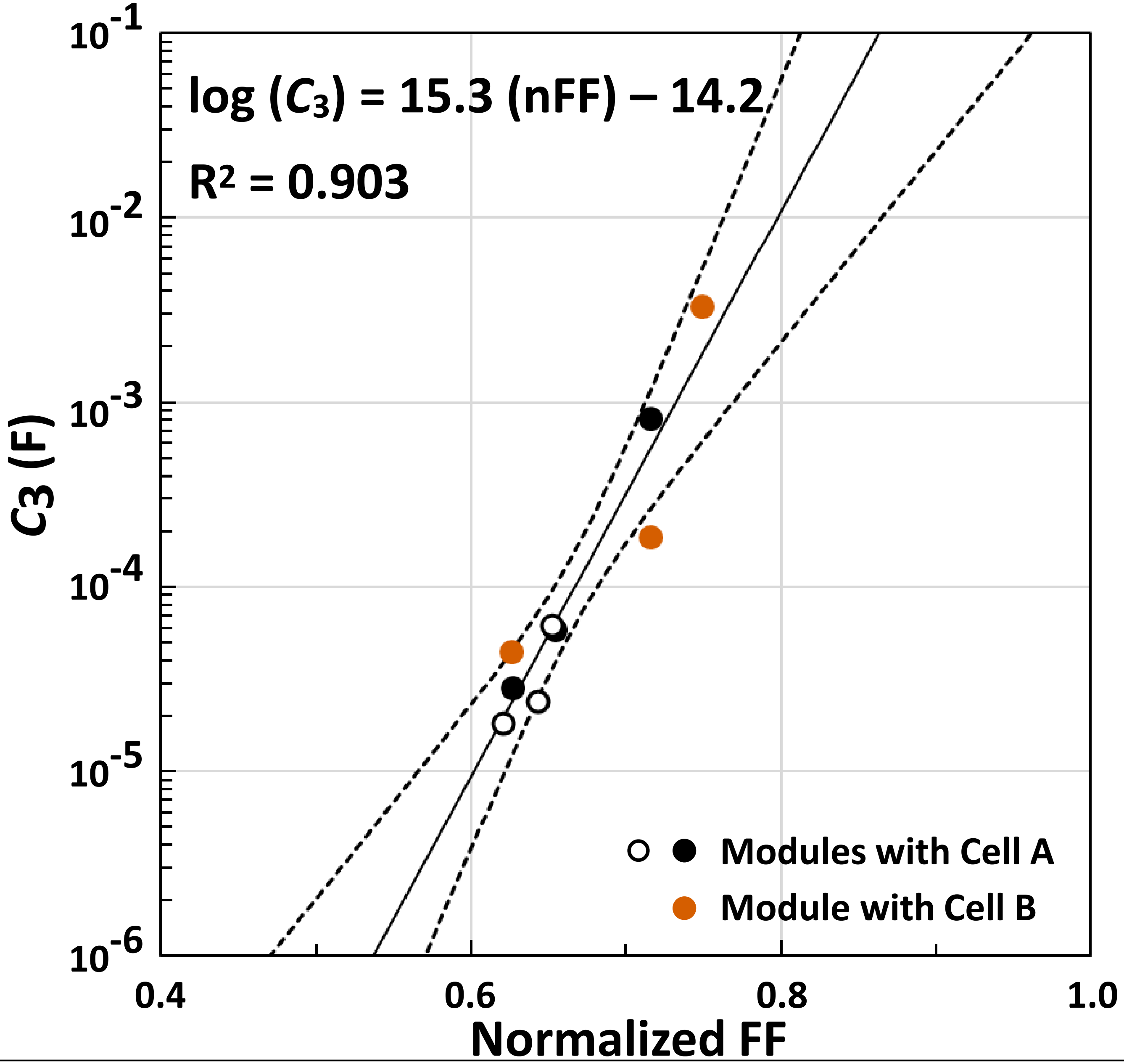
DH Stress Test of PV Modules

Correlation of C_3 with FF-Loss

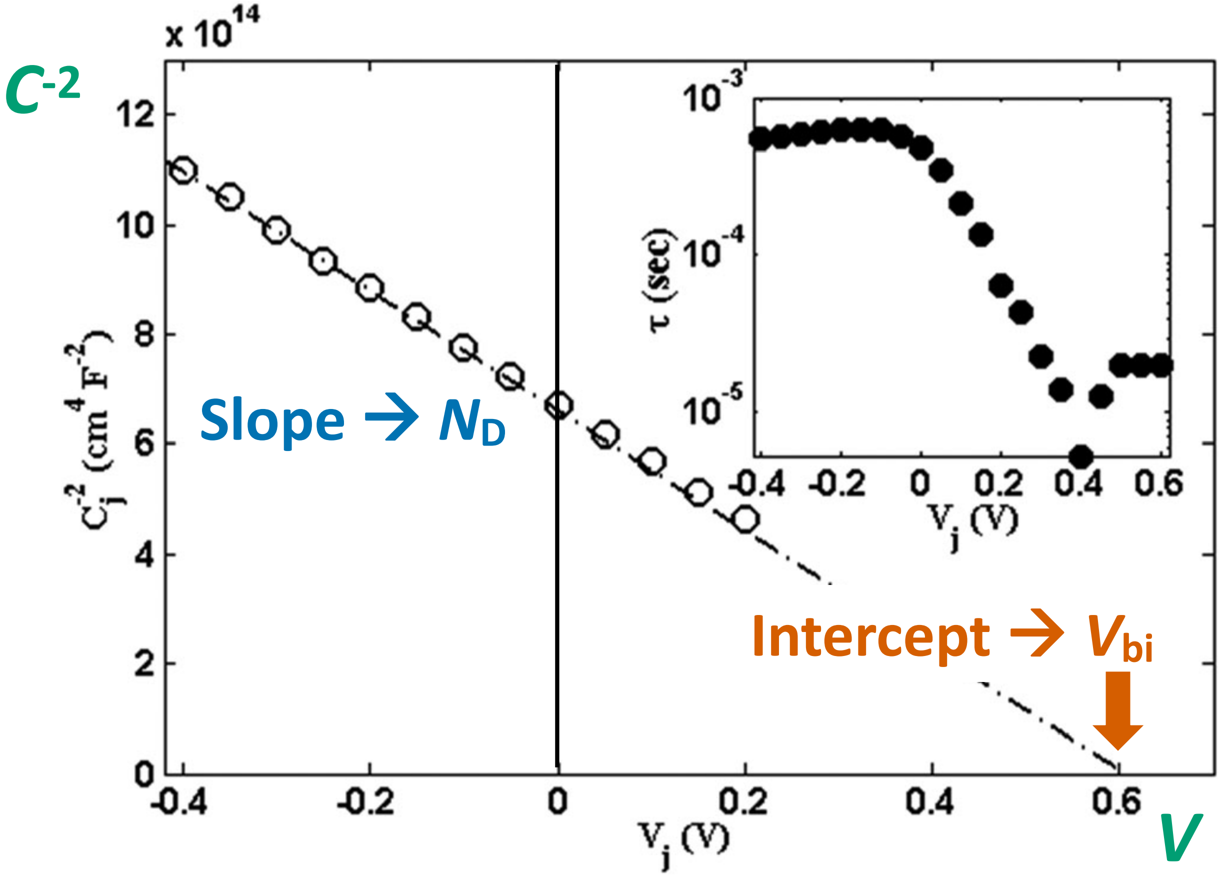
In both PV modules,
FF-loss depends on C_3 intensity

Capacitor Formation / Evolution
≈ Gap / Dielectric Formation
in Si-Metallization Interface





Mott-Schottky Plot



Mott–Schottky plot for a c- Si solar cell

The inset shows the variation of the minority carrier lifetime as a function of the applied bias.

P. Yadav et al., *Phys. Chem. Chem. Phys.*, 16 (29):15469–15476, 2014.

$$C^{-2} = \frac{2}{qA^2 \varepsilon N_D}(V + V_{\mathrm{bi}})$$

$$N_D = \frac{2}{q\varepsilon A^2 \left[\frac{dC^{-2}}{dV}\right]}$$

C: Capacitance

V: Applied DC Voltage

ε : Permittivity

q: Elementary Charge

N_D: Doping Density

V_{bi}: Build-in Potential

A: Area

DH Stress Test of PV Modules

Mott-Schottky Plots [C_2]

V_{bi} :

Cell A = 0.677 ± 0.005 V

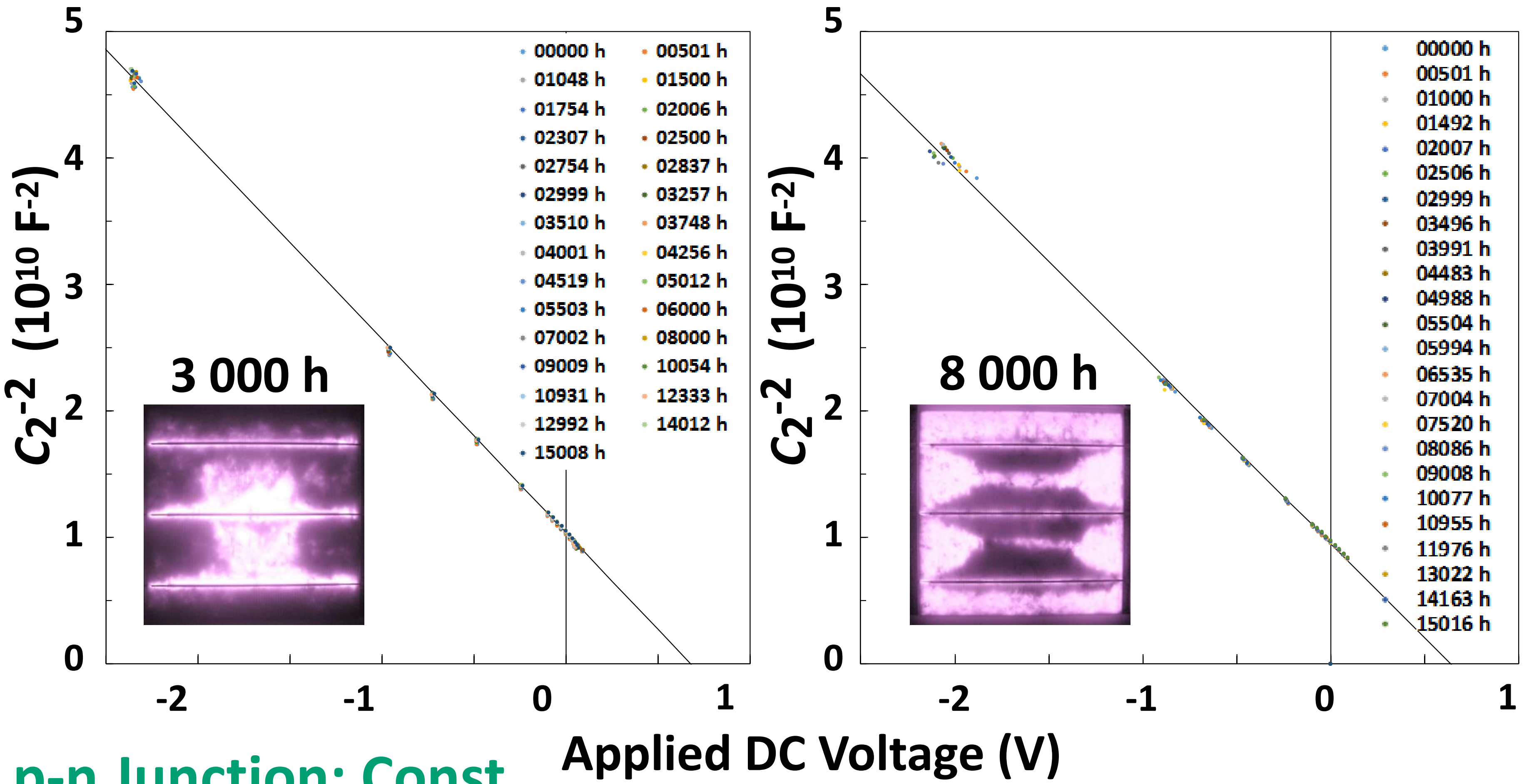
Cell B = 0.636 ± 0.021 V

N_D :

Cell A = 1.33×10^{16} cm^{-1}
(1.32 – 1.35 $\times 10^{16}$)

Cell B = 1.37×10^{16} cm^{-1}
(1.34 – 1.40 $\times 10^{16}$)

Module with Cell A | Module with Cell B



Elec. Characteristics in p-n Junction: Const.

DH Stress Test of PV Modules Mott-Schottky Plots [C_3]

C_3: <u>non-Linear</u>

$C_3^{-2} = \alpha \exp(-\beta V) + \gamma$

α: Reduction

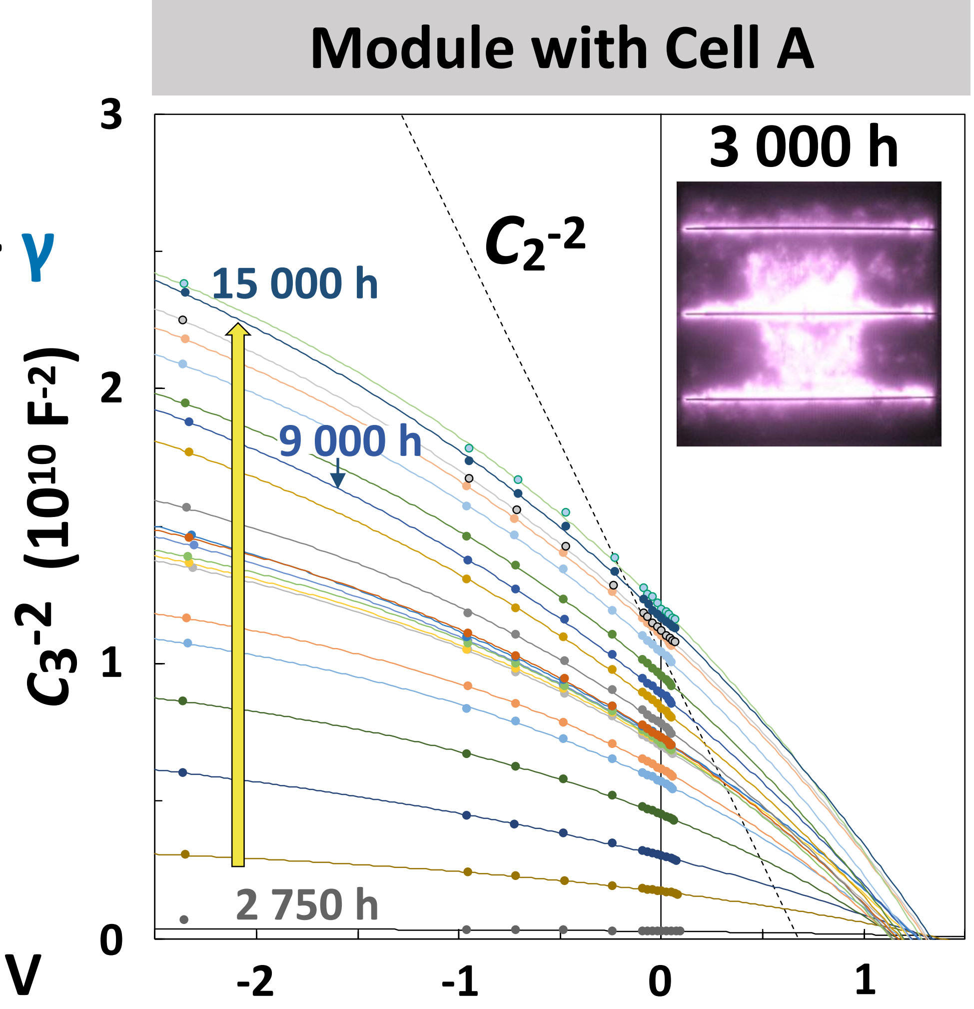
β: nearly Const.

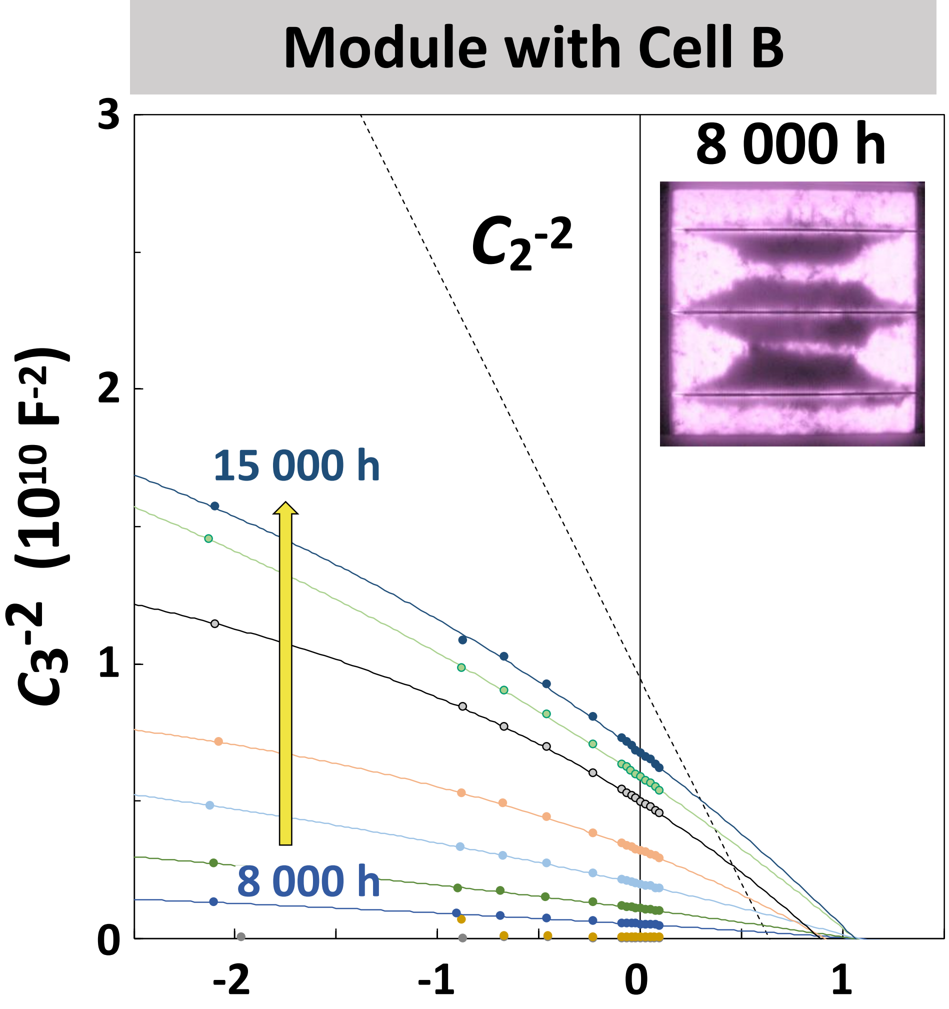
γ: Elevation

V_{bi} :

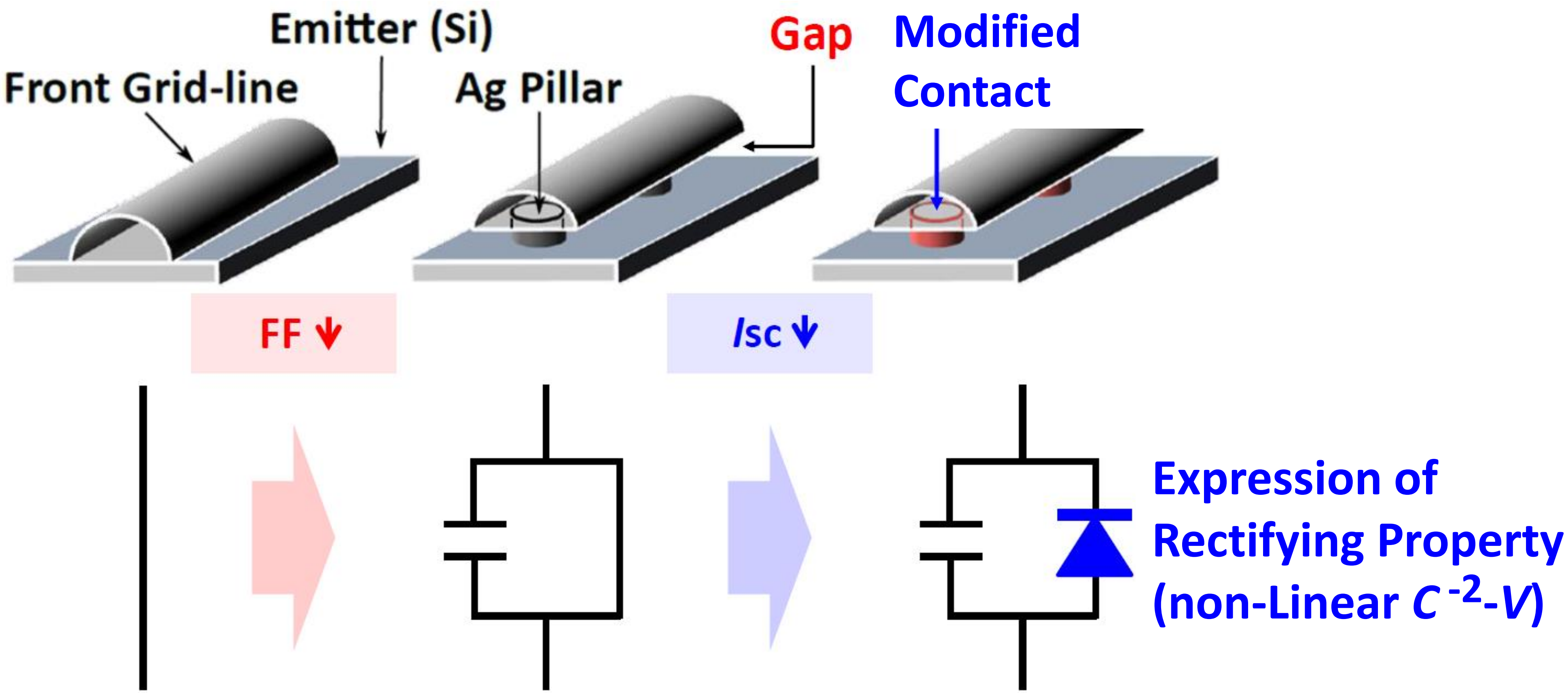
Cell A = 1.233 ± 0.072 V

Cell B = 1.010 ± 0.077 V





Degradation Mechanism / Model in Both Modules

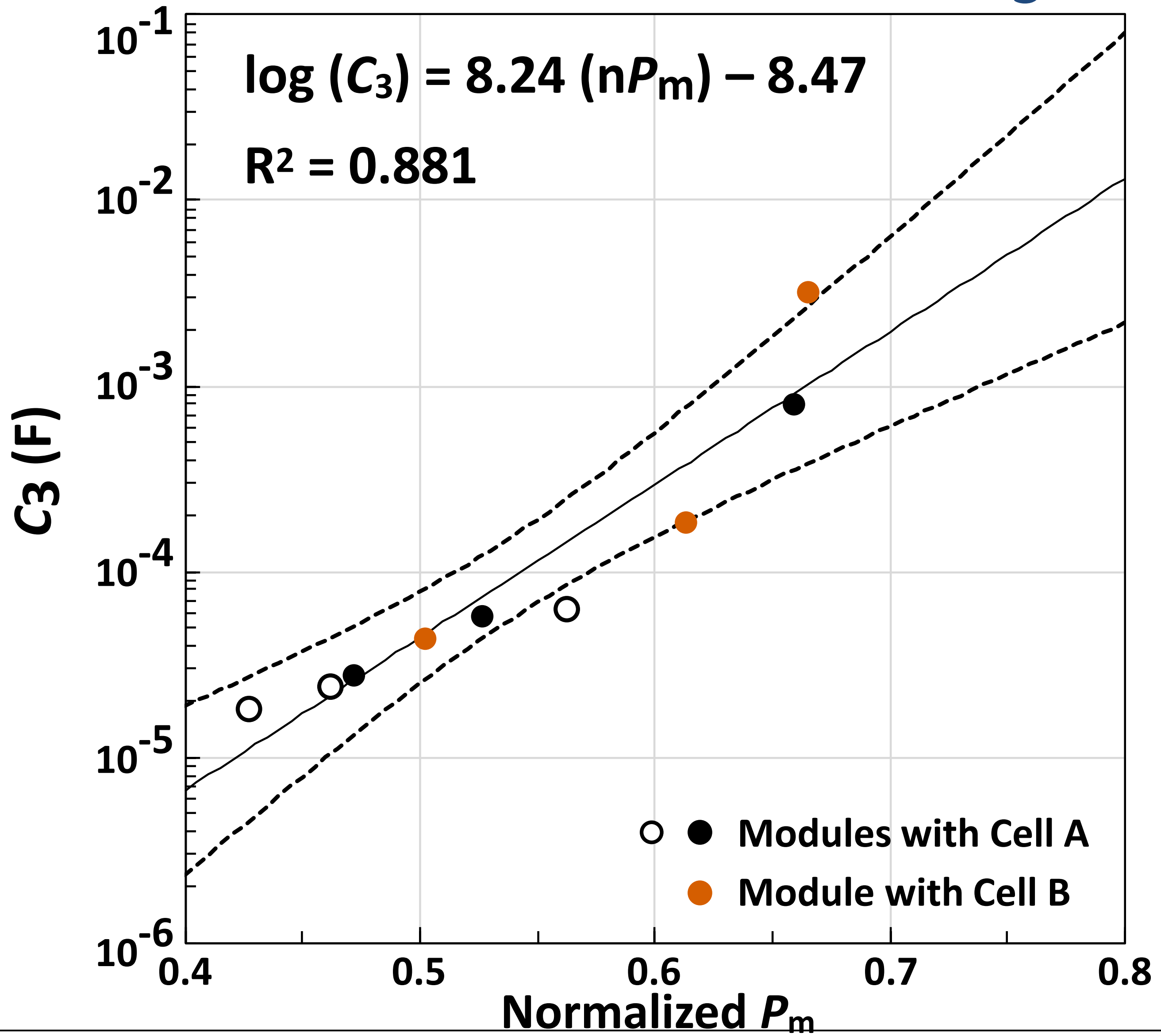


$$\log (C_3) = p\,(nFF) - q$$

$$C_3^{-2} = \alpha \exp(-\beta V) + \gamma$$

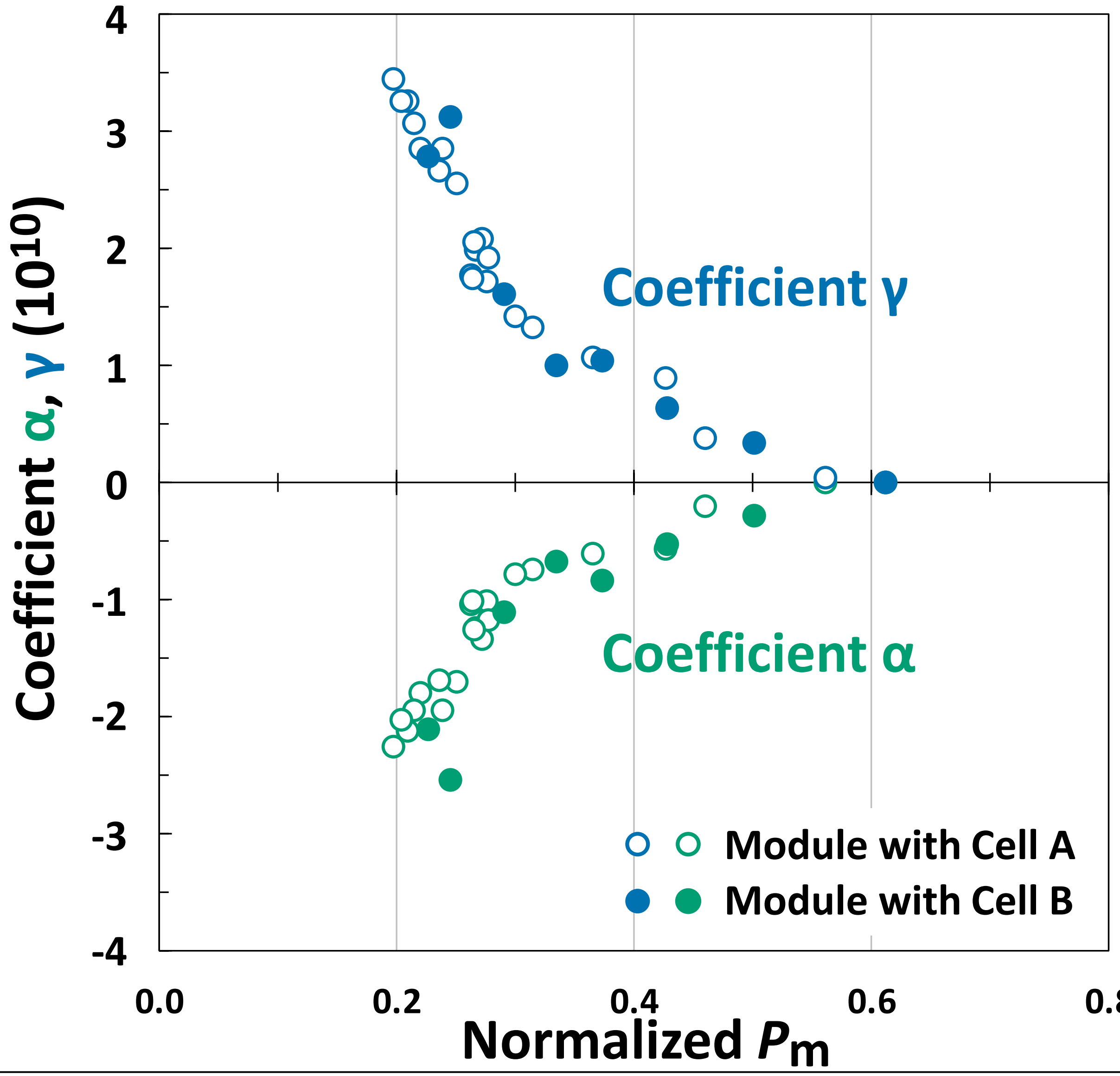
DH Stress Test of PV Modules

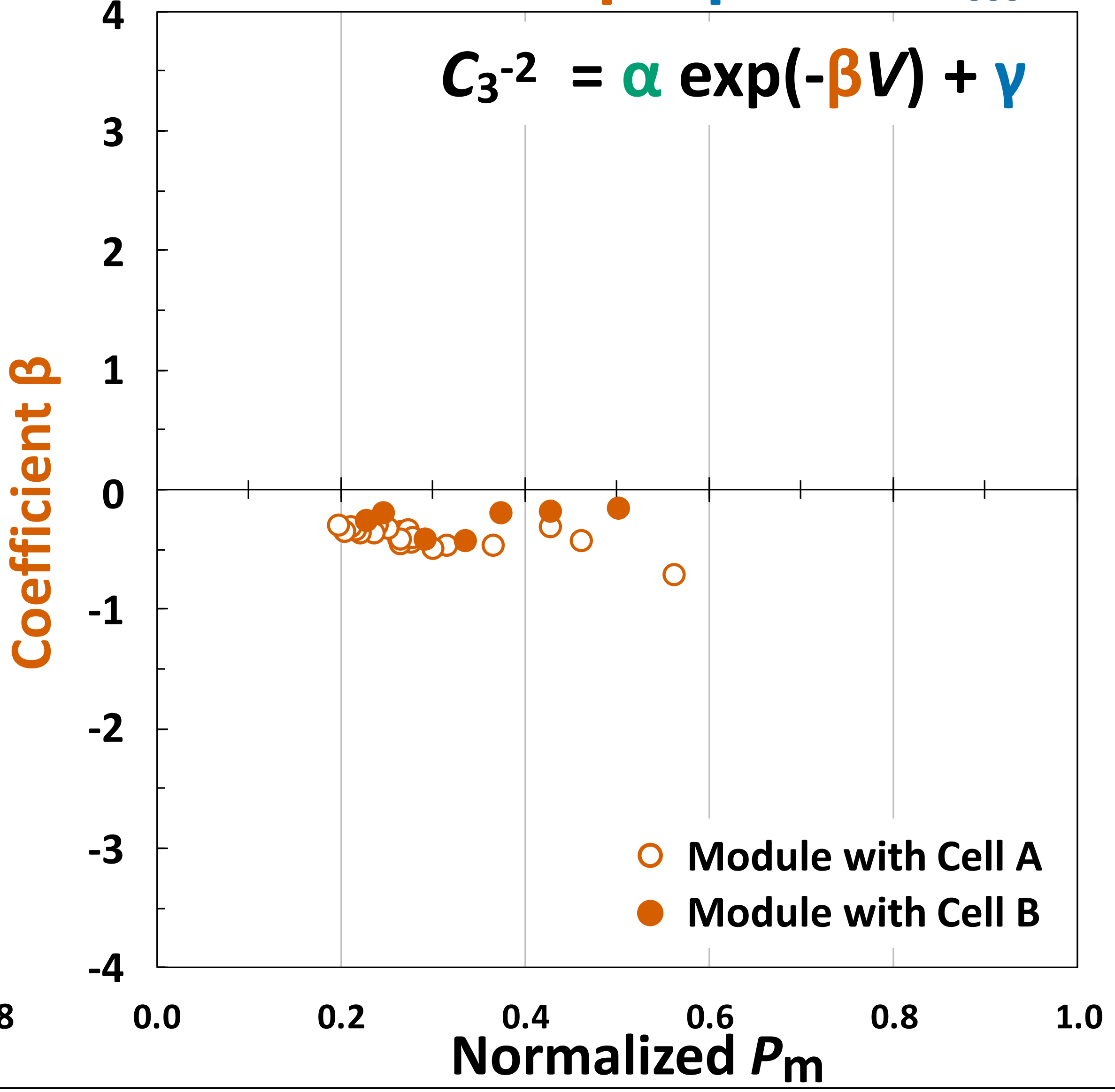
Correlation of C_3 with P_m-Loss



DH Stress Test of PV Modules

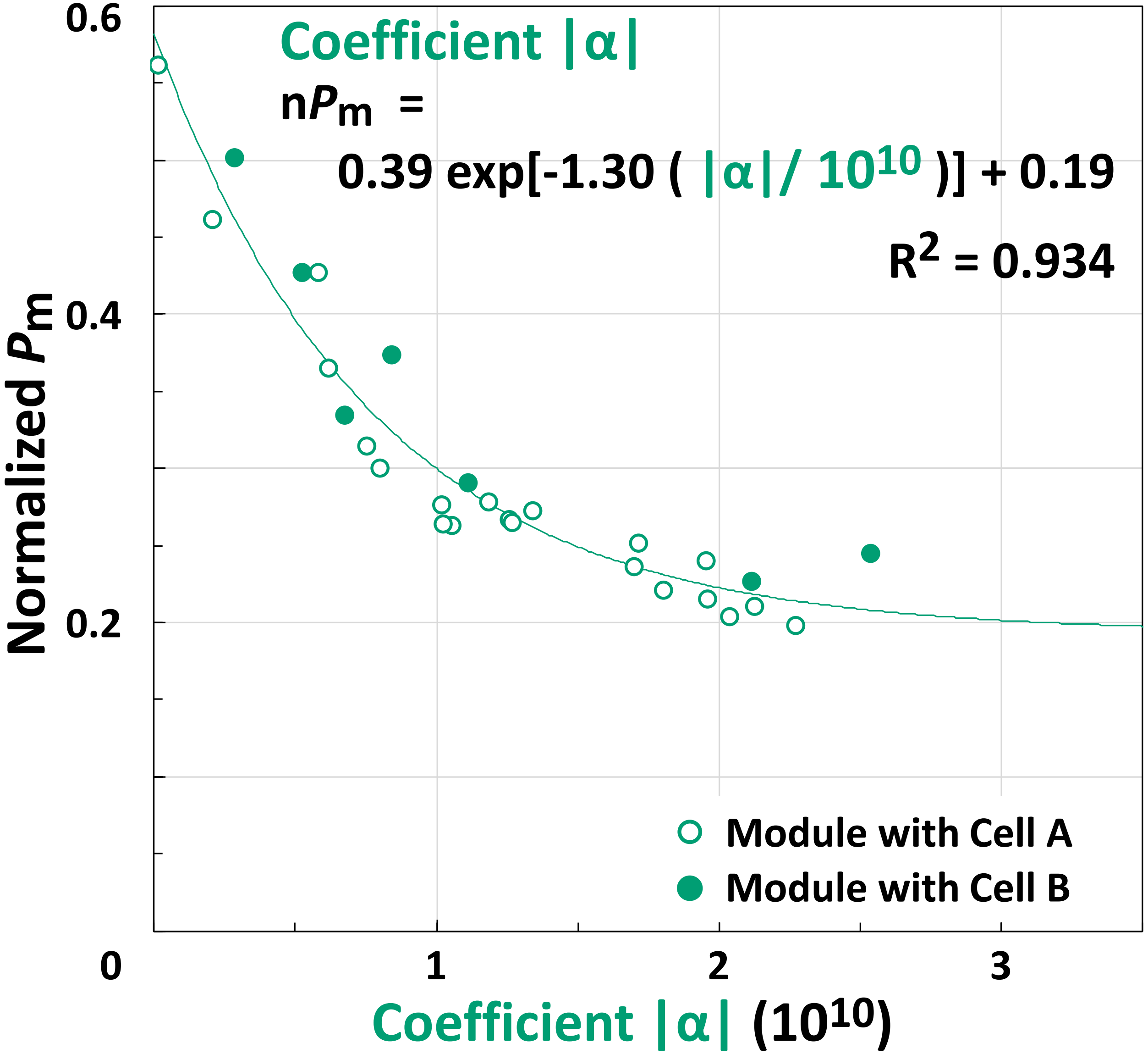
Correlation of Coeff. α · β · γ with P_m-Loss

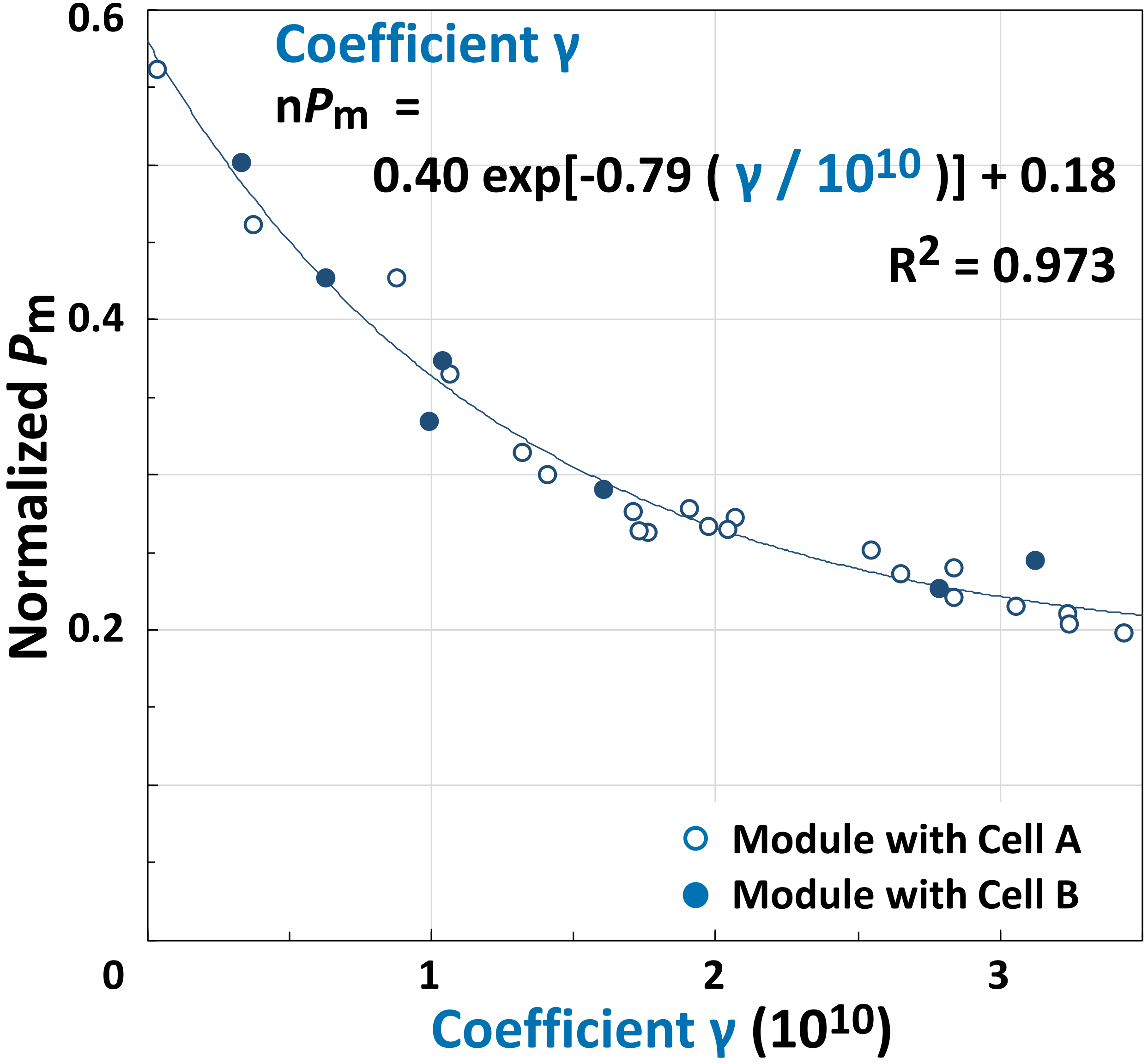




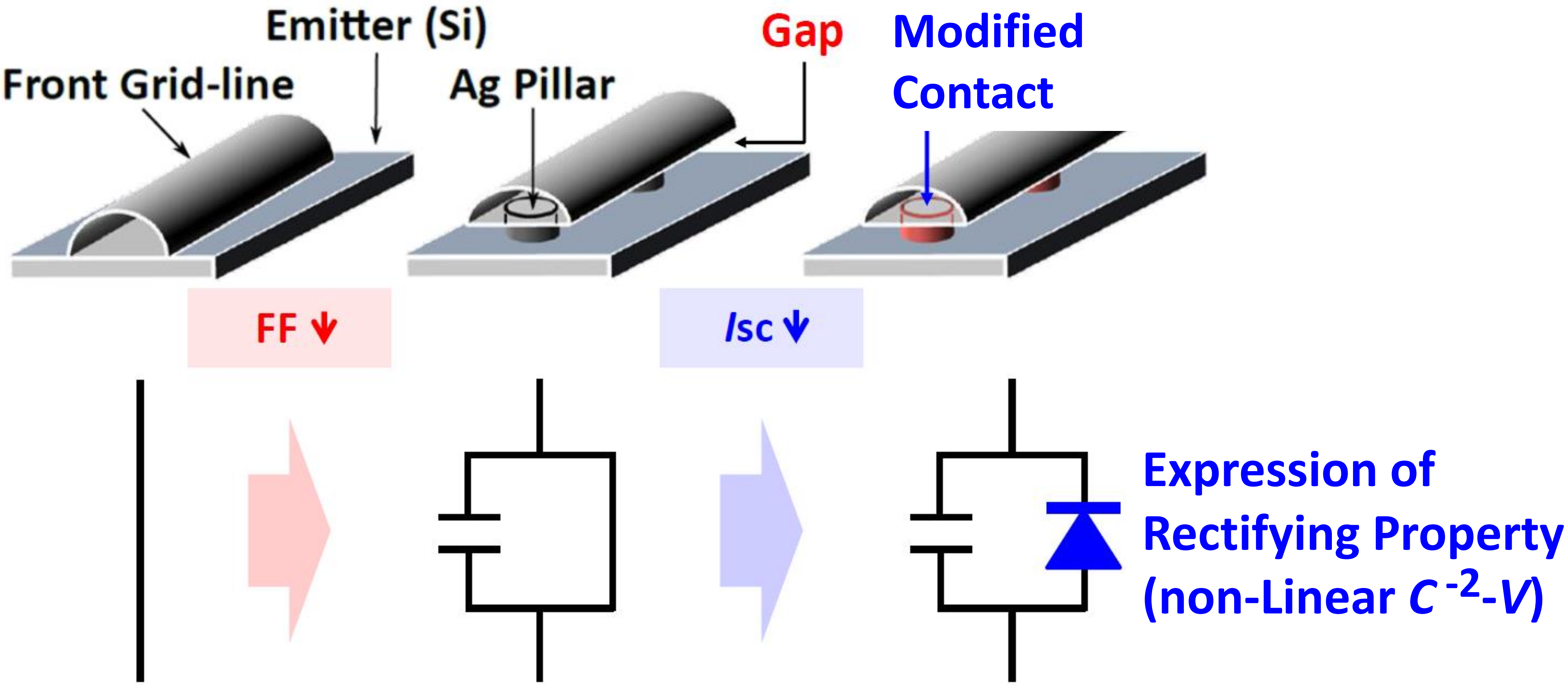
DH Stress Test of PV Modules

Correlation of Coeff. |α| · γ with P_m-Loss





Common Degradation Mechanism / Model in Both Modules



$P_m \leftarrow \log(C_3) = p\,(nFF) - q$

$P_m \leftarrow C_3^{-2} = \alpha \exp(-\beta V) + \gamma$

These degradations are simultaneously occurring within a cell.

→ Effect of moisture penetration…?

Summary:

$\mathrm{n}P_\mathrm{m}$ > ca. 0.4:

$$\log(C_3) = \mathrm{p}\,(\mathrm{n}P_\mathrm{m}) - \mathrm{q}$$

$$\rightarrow \mathrm{n}P_\mathrm{m} = [\log(C_3) + \mathrm{q}] / \mathrm{p}$$

ca. 0.6 > $\mathrm{n}P_\mathrm{m}$ > ca. 0.2:

$$C_3^{-2} = \alpha \times \exp(-\beta \times V) + \gamma$$

$$\rightarrow \mathrm{n}P_\mathrm{m} = \mathrm{r}\exp(-\mathrm{s} \cdot |\alpha|) + \mathrm{u}$$

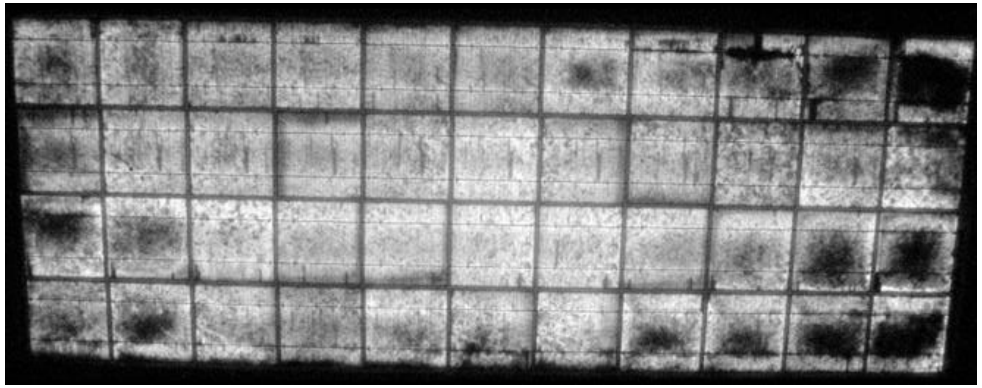
$$\rightarrow \mathrm{n}P_\mathrm{m} = \mathrm{v}\exp(-\mathrm{w} \cdot \gamma) + \mathrm{x}$$

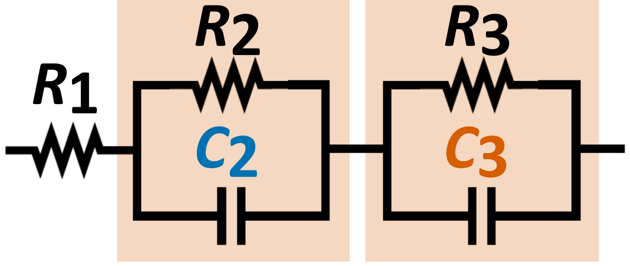
The parameters ($\alpha \cdot \beta \cdot \gamma$) from both PV modules were completely overlaid each other, as a function of power-loss.

These observations indicate that ***a common corrosion-mechanism works in both PV modules***, although the kinetics of corrosion occurring in the respective PV modules is extremely different.

Outdoor Exposure

K-64 PV Module (*21 Years in Field*)



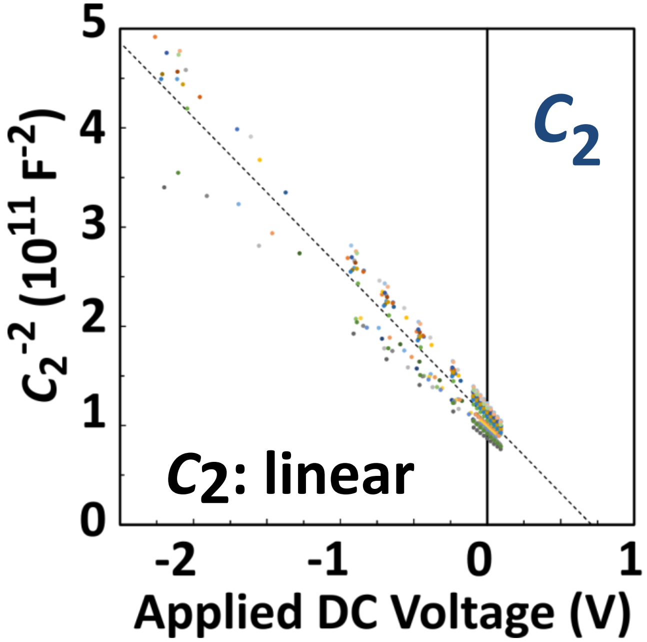


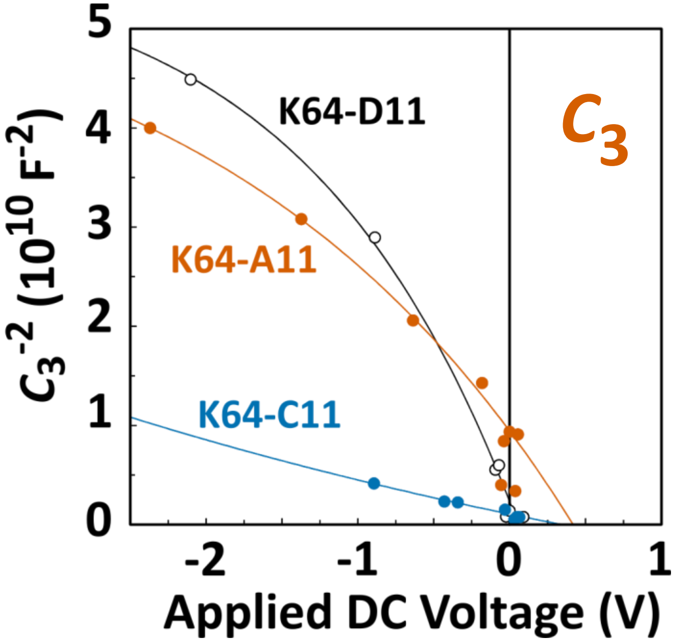
AC Equivalent Circuit

Mott-Schottky Plots [$C_2 \cdot C_3$]

$$C^{-2} = \frac{2}{qA^2 \varepsilon N_D}(V + V_{\mathrm{bi}})$$

C: Capacitance
V: Applied DC Voltage
ε : Permittivity
q: Elementary Charge
N_D: Doping Density
V_{bi}: Build-in Potential
A: Area





C_3: non-linear

$C_3^{-2} = \alpha \exp(-\beta V) + \gamma$

T. Tanahashi et al., *IEEE J. Photovolt.*, vol. 9, no. 3, pp. 741–751, 2019.

Thank you for your attention!

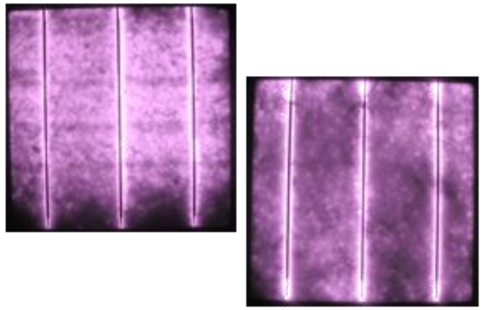
Backup

Approach

HAc Vapor Exposure	DH Stress	Outdoor Exposure

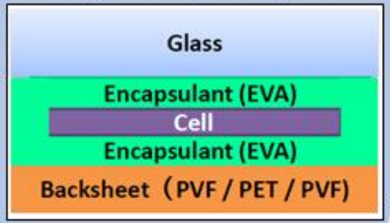
HAc Vapor / High-T / High-H

Constant Stresses

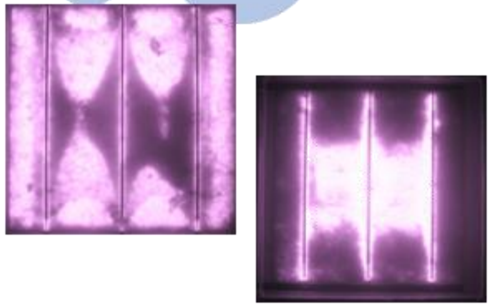


Isotropic Degradation

High-T / High-H

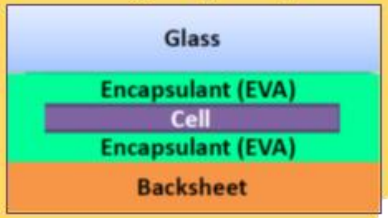


Constant Stresses

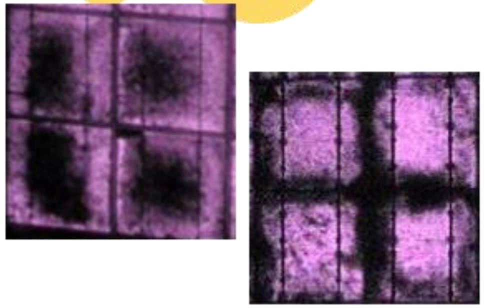


Anisotropic Deg.

Fluctuating T / H / UV…



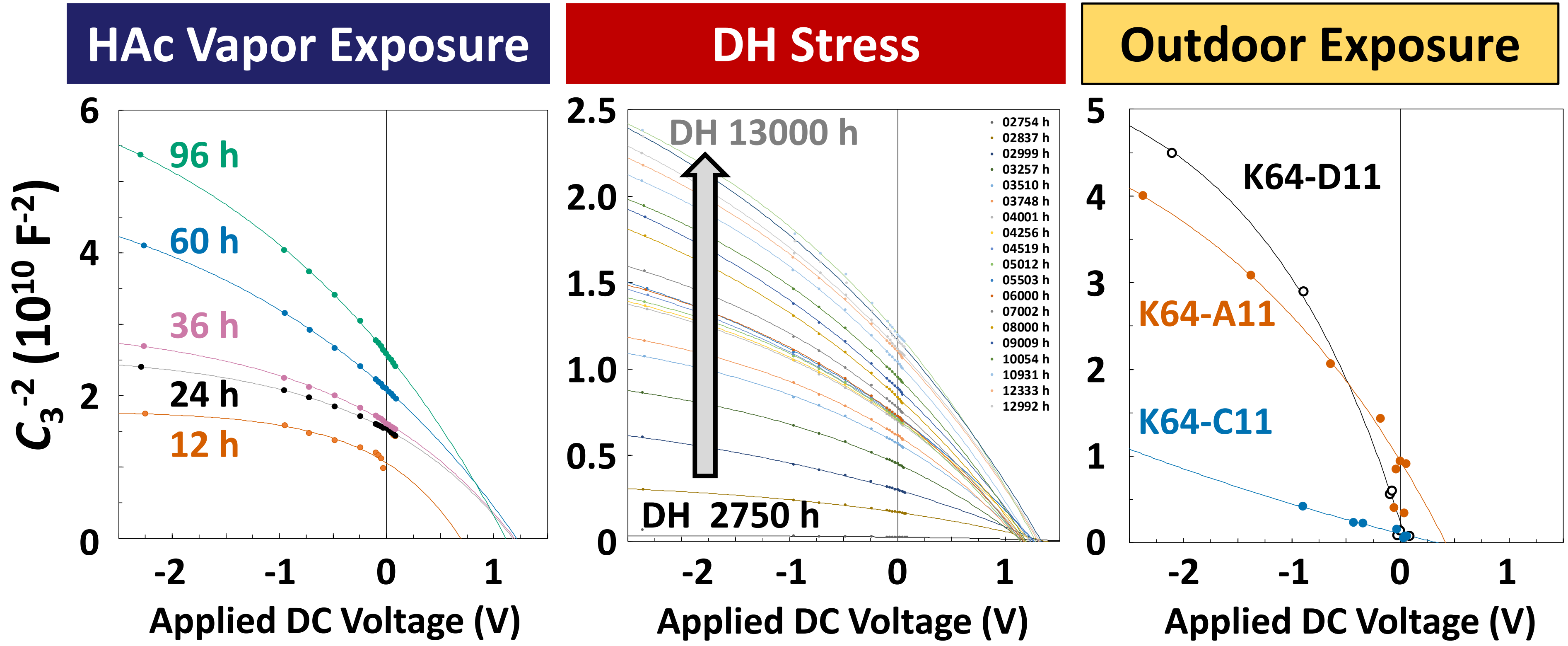
Fluctuating Stresses



Anisotropic Deg.

Fundamental Reaction(s)	Complex Reactions (+ Moisture Ingress / HAc Production)	More Complex Reactions (+ Variable T / H / Irradiation / …)

Mott-Schottky Plots [C_3]



Corrosion mechanisms are quite similar, regardless of whether the PV modules are degraded under field conditions over many years or under accelerated artificial corrosive stress test conditions.