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

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Final Destination: Service Lifetime Prediction

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

Warranty = 25 - 30 years

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.

Different EL appearances

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

Exposure Conditions

Exposed in a Field for ca. 30 Years

under DH Stress Conditions


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


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

- a) Experimental Setup
  - Thick Glass Chamber
    - Saturated KCl aq. soln. +/- HAc (3%)
  - b) Hung PV cells
  - c) Setups in Oven

at 85°C / 80% rh

DH Stress Test of PV Modules

- Glass
- Encapsulant (EVA)
- Cell
- Encapsulant (EVA)
- Backsheet (PVF / PET / PVF)

PV Mini-Module
(Visual Image / Configuration)

at 85°C / 85% rh

Outdoor Exposure

Ex. Outdoor Exposed PV Module from 1994 in Cfa Climate


Silver Contact Formation during “Fire-Through” Process

Proposed Current Transport Mechanisms in Silver Contact

Field Emission (FE)
\[ N_D \geq 10^{20} \text{ cm}^{-3} \]

Thermionic Field Emission (TFE)
\[ 10^{17} \text{ cm}^{-3} < N_D < 10^{20} \text{ cm}^{-3} \]

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

Dissolution of Glass-Silver Boundary Layer by Acetic Acid


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

(a) Control without HAc

(b) 85 / 80, 48 h without HAc

(c) 85 / 80, 48 h [Pb] without HAc

(d) 85 / 80, + HAc, 12 h with HAc

(e) 85 / 80, + HAc, 48 h with HAc

(f) 85 / 80, + HAc, 48 h [Pb] with HAc
Detection of Corrosion-induced AC Impedance Elevation
DH Stress Test of PV Modules

Module with Cell A

Evolution of EL Image

Module with Cell B
DH Stress Test of PV Modules

Emergent Incidence & Evolution of $Z_3$

Module with Cell A

$Z_3$

Module with Cell B

$Z_3$

$Z'$ (Ω)

$Z''$ (Ω)

0 h

2 750 h

4 000 h

15 000 h

10 kHz

(10 ~ 100 kHz)

0 h

8 000 h

12 000 h

15 000 h

10 kHz

(10 ~ 100 kHz)
DH Stress Test of PV Modules

Evolution of Elec. Parameters

Module with Cell A

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

Constant
- $C_2$

AC Equivalent Circuit

Normalized PV Parameters

Duration of DH Stress Test (h)
DH Stress Test of PV Modules

Evolution of Elec. Parameters

Module with Cell B

Synchronized Changes
- FF / Pm: Reduction
- R1 / R3: Elevation
- C3: Emergent Expression / Decay

Constant
- C2

AC Equivalent Circuit

Normalized PV Parameters

Duration of DH Stress Test (h)

R1, R3 (Ω)

Z2

Z3

R2

R3

C2

C3

Voc

Isc

FF

Pm
DH Stress Test

Module with Cell A
Module with Cell B

Complete Differences in Degradation Kinetics

AC Equivalent Circuit

Normalized $P_m$

Normalized FF

Normalized $I_{sc}$

Duration of DH Stress Test (h)

$R_1$ (Ω)

$R_3$ (Ω)

$C_2$ (F)

$C_3$ (F)
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

$log (C_3) = 15.3 \text{ (nFF)} - 14.2$

$R^2 = 0.903$
Mott-Schottky Plot

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


\[ C^{-2} = \frac{2}{qA^2\varepsilon N_D} \quad (V + V_{bi}) \]

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

- **C**: Capacitance
- **V**: Applied DC Voltage
- **\varepsilon**: Permittivity
- **q**: Elementary Charge
- **N_D**: Doping Density
- **V_{bi}**: Build-in Potential
- **A**: Area
DH Stress Test of PV Modules

**Mott-Schottky Plots \([C_2]\)**

\[ \text{Module with Cell A} \]

\[ \text{Module with Cell B} \]

**\(V_{bi}\):**

- Cell A = 0.677 ± 0.005 V
- Cell B = 0.636 ± 0.021 V

**\(N_D\):**

- Cell A = \(1.33 \times 10^{16}\) cm\(^{-1}\) (1.32 – 1.35 \(\times 10^{16}\))
- Cell B = \(1.37 \times 10^{16}\) cm\(^{-1}\) (1.34 – 1.40 \(\times 10^{16}\))

**Elec. Characteristics in p-n Junction: Const.**
**Mott-Schottky Plots \([C_3]\)**

**DH Stress Test of PV Modules**

\(C_3: \text{non-Linear}\)

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

- \(\alpha: \text{Reduction}\)
- \(\beta: \text{nearly Const.}\)
- \(\gamma: \text{Elevation}\)

**\(V_{bi}\):**

- 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

$\log (C_3) = 8.24 \left( nP_m \right) - 8.47$

$R^2 = 0.881$
DH Stress Test of PV Modules

Correlation of Coeff. $\alpha \cdot \beta \cdot \gamma$ with $P_m$-Loss

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

- Coefficient $\alpha$
- Coefficient $\beta$
- Coefficient $\gamma$

Normalized $P_m$

Module with Cell A
Module with Cell B
DH Stress Test of PV Modules

Correlation of Coeff. $|\alpha| \cdot \gamma$ with $P_m$-Loss

Coefficient $|\alpha|$ $nP_m = 0.39 \exp[-1.30 \ (|\alpha|/10^{10})] + 0.19$ $R^2 = 0.934$

Coefficient $\gamma$ $nP_m = 0.40 \exp[-0.79 \ (\gamma/10^{10})] + 0.18$ $R^2 = 0.973$

Normalized $P_m$

Module with Cell A
Module with Cell B
Common Degradation Mechanism / Model in Both Modules

These degradations are simultaneously occurring within a cell.

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

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

Effect of moisture penetration...?
\[ \log(C_3) = p \, (nP_m) - q \]
\[ \rightarrow nP_m = \left[ \log(C_3) + q \right] / p \]

ca. 0.6 > nP_m > ca. 0.2:

\[ C_3^{-2} = \alpha \times \exp(-\beta \times V) + \gamma \]
\[ \rightarrow nP_m = r \exp(-s \cdot |\alpha|) + u \]
\[ \rightarrow nP_m = v \exp(-w \cdot \gamma) + x \]

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)

Mott-Schottky Plots \([C_2 \cdot C_3]\)

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

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

\(C_2 \): linear
\(C_3 \): non-linear

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

Thank you for your attention!

Backup
Approach

HAc Vapor Exposure

HAc Vapor / High-T / High-H

Constant Stresses

Isotropic Degradation

Fundamental Reaction(s)

DH Stress

High-T / High-H

Constant Stresses

Anisotropic Deg.

Complex Reactions
(+ Moisture Ingress / HAc Production)

Outdoor Exposure

Fluctuating T / H / UV...

Fluctuating Stresses

Anisotropic Deg.

More Complex Reactions
(+ Variable T / H / Irradiation / …)
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.