Rate of PID-p Progression in n-PERT Cells Depends on Encapsulant Resistivity and Irradiance

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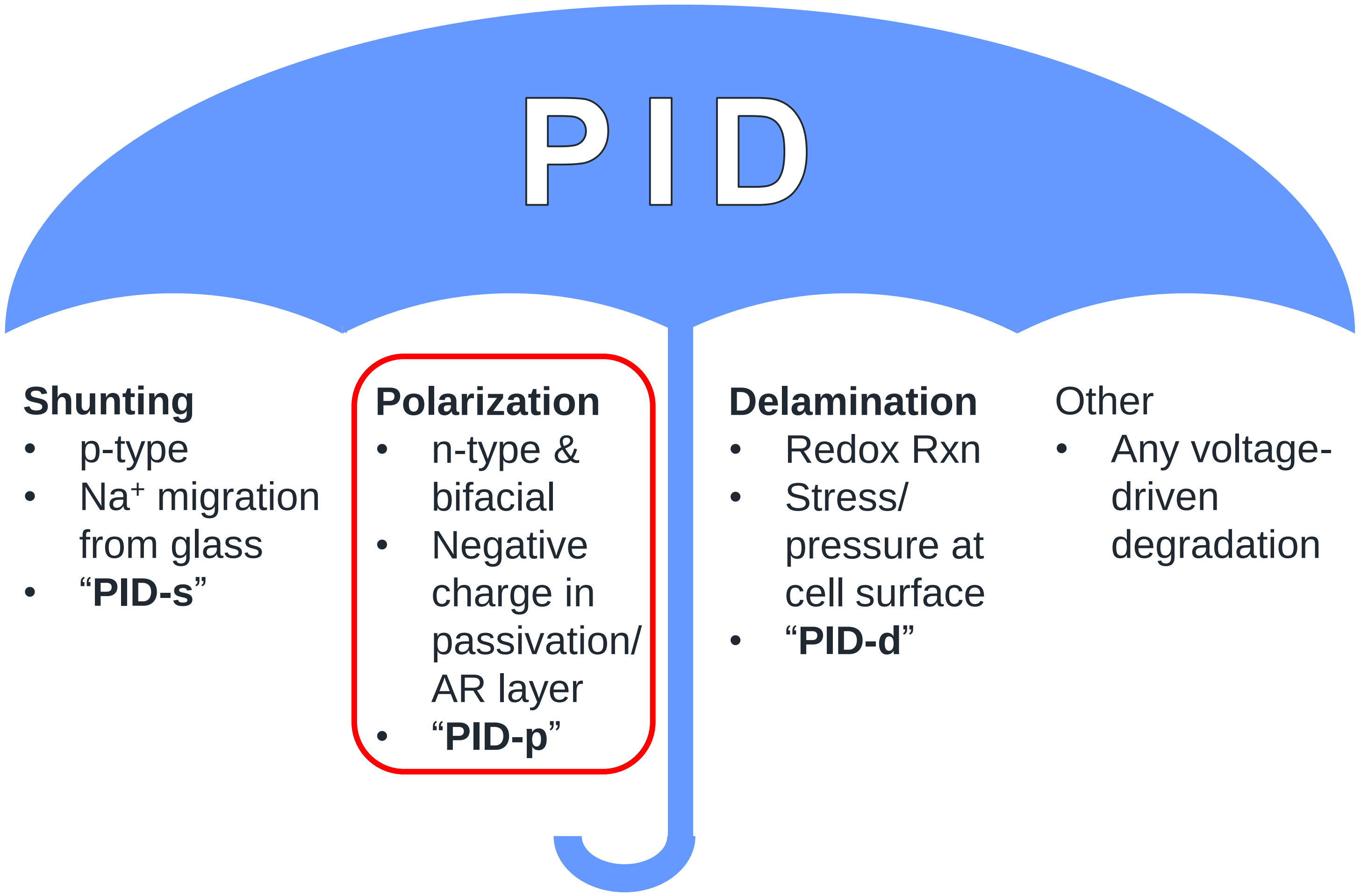
Potential-Induced Degradation



Outline

- **Background** on PID-p
- **Study**:
  - Controlled encapsulant resistivity
  - Time-dependence
  - Controlled light exposure
- **Conclusions:**
  - High resistivity slows PID-p progression
  - Light reverses PID-p in unstressed modules
  - Modules with low resistivity encapsulants are susceptible to PID-p even under 1 sun exposure

W. Luo, Y. S. Khoo, P. Hacke, V. Naumann, D. Lausch, S. P. Harvey, J. P. Singh, J. Chai, Y. Wang, and A. G. Aberle, Energy & Environmental Science, vol. 10, no. 1, pp. 43-68, 2017.

Potential-Induced Degradation

	PID-s	PID-p
Mechanism of power loss	Accumulation of Na+ ions in stacking faults reduces shunt resistance [1]	Increased surface recombination due to accumulation of charge [2]
Role of encapsulant	Na+ migration through encapsulant [3]	Non-specific charge migration through encapsulant [2]
Critical property of encapsulant	Na+ conductivity of encapsulant (difficult to measure, not well-correlated to resistivity) [4]	Total conductivity?

$$\sigma_{total} = \sigma_{e/h} + \sigma_{Na+} + \sigma_{K+} + \sigma_{H+} + \sigma_{OH-} + \cdots$$

1) Naumann, Volker, et al. *Solar Energy Materials and Solar Cells* 120 (2014)

2) Swanson, R., et al. In *15th PVSEC* (2005) Shanghai, China.

3) Kapur, Jane, et al. *IEEE Journal of Photovoltaics* 5.1 (2014)

4) Habersberger, B.M., et al. In *2018 IEEE 7th WCPEC (45th IEEE PVSC, 28th PVSEC & 34th EU PVSEC)*.

POTENTIAL-INDUCED DEGRADATION

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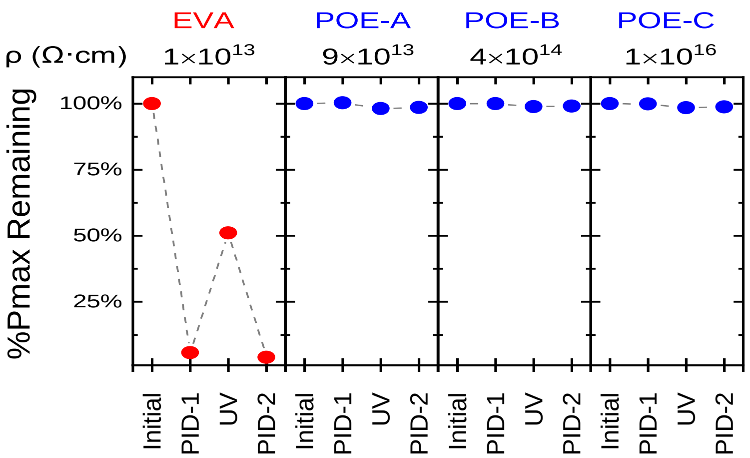

To our knowledge, no previous literature reports of the impact of encapsulant resistivity within a single material class where other factors are controlled

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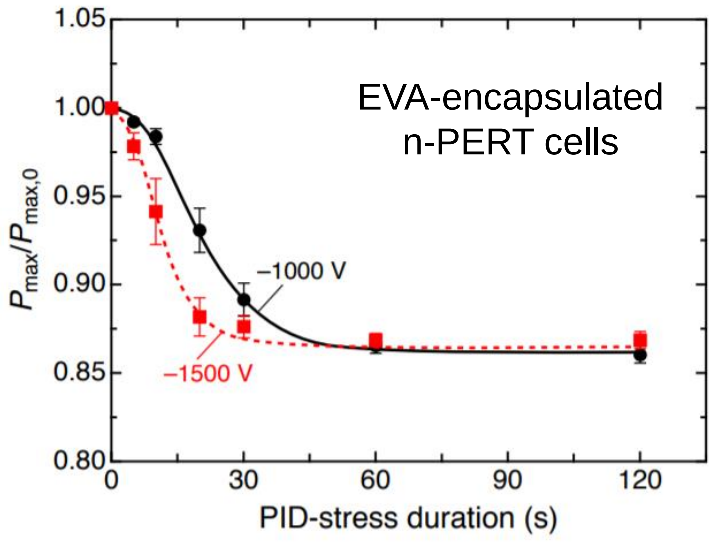
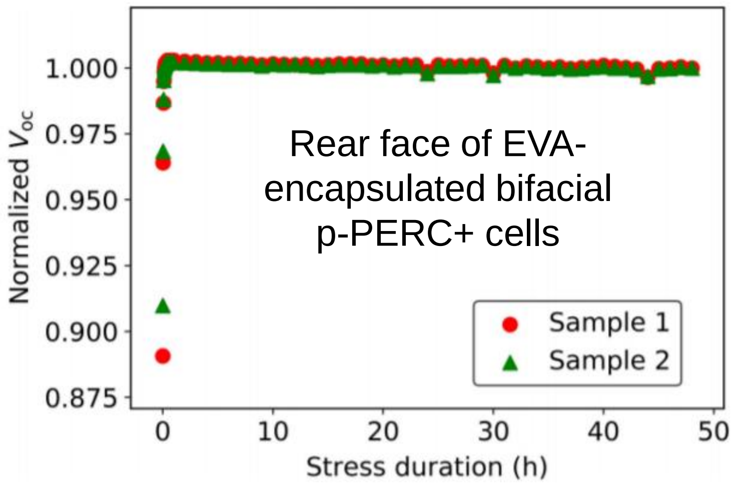
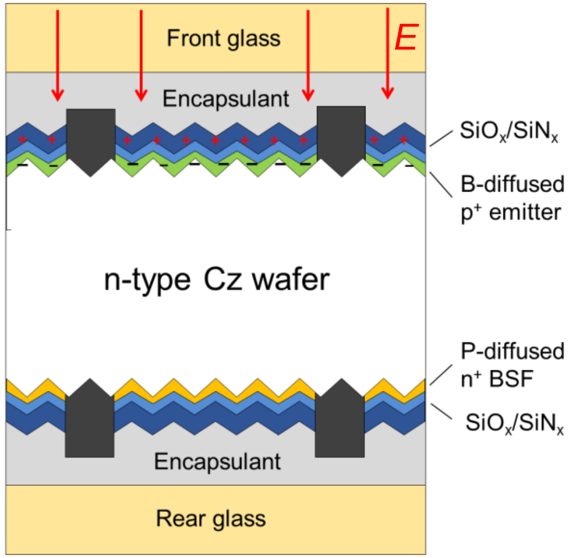
Key Background Work on PID-p



Time-dependent PID at -1000 and -1500 V stress [1]



Following dark PID, 40 W/m^2 irradiance at t = 0 causes recovery [2]



- PID-p occurs rapidly in low resistivity encapsulant (EVA)
- Rate of progression roughly proportional to voltage
- Typically saturates at ~12-15% power loss

- Rapid recovery under light exposure is typical
- In some (but not all) cases, simultaneous irradiance prevents PID-p progression

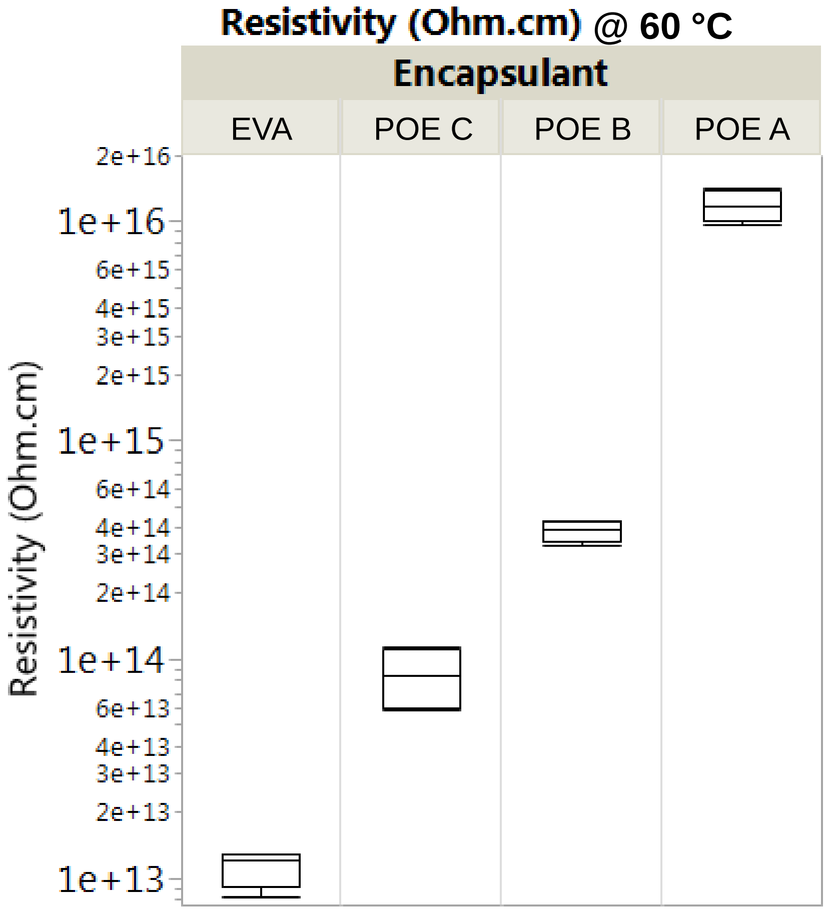
Key questions:

- How does encapsulant conductivity impact the rate of PID-p progression?
- Under what conditions does light prevent or mitigate PID-p?
- How do the opposing forces of encapsulant conductivity and irradiance interact?

[1] Yamaguchi, S., et al. (2018). *Japanese Journal of Applied Physics*, *57*(12), 122301.

[2] Luo, W., et al. (2018). *IEEE Journal of Photovoltaics*, *8*(5), 1168-1173.

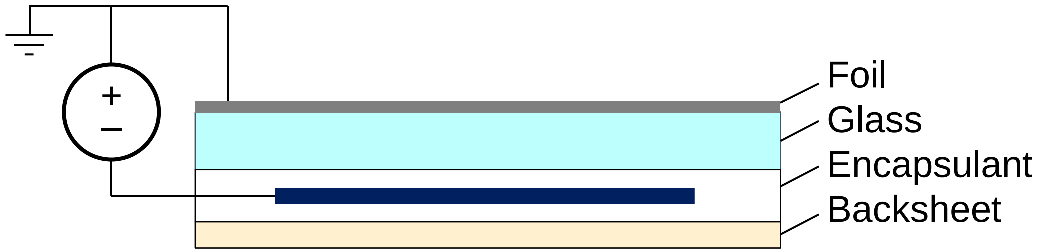
Experimental Setup



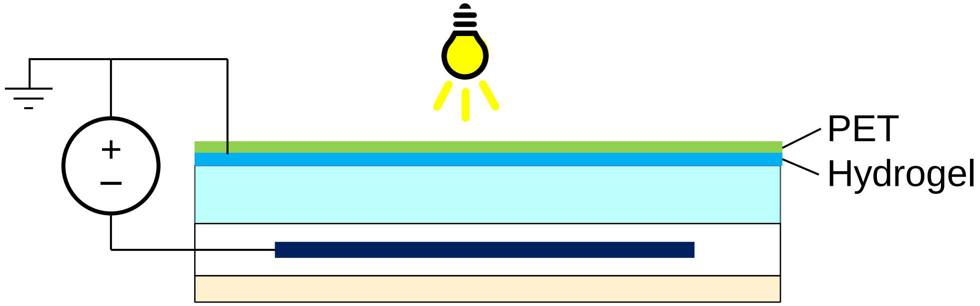
Materials and Experiments

- **Experimental encapsulants**
  - 3 POE resins, 1 EVA resin
  - POE resins have identical crystallinity and MW
  - All converted to film with same formulation and extruder
- **n-base PERT cells with a p+/n front junction**

Time-dependent dark PID experiments (60 °C)

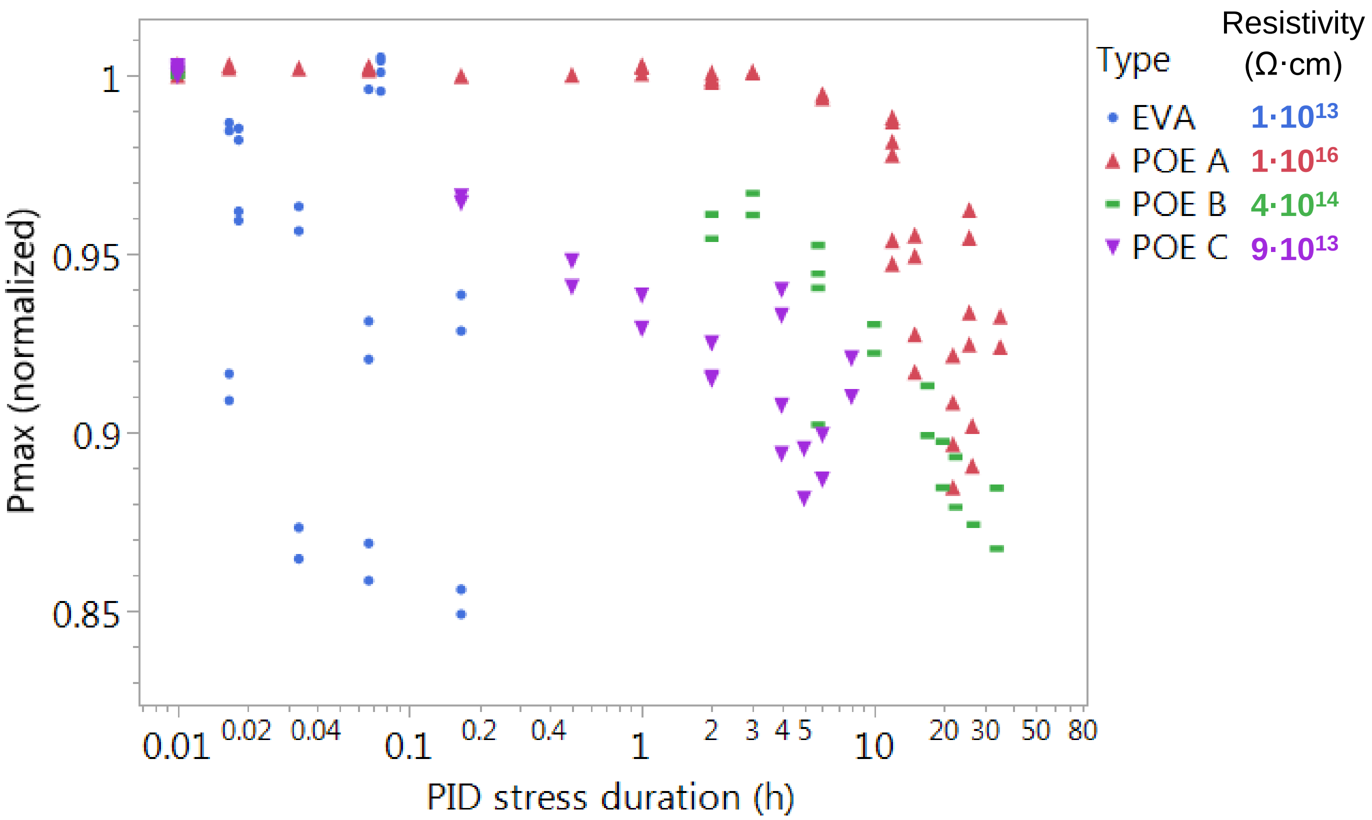


Time-dependent PID experiments w/ irradiance (60 °C)



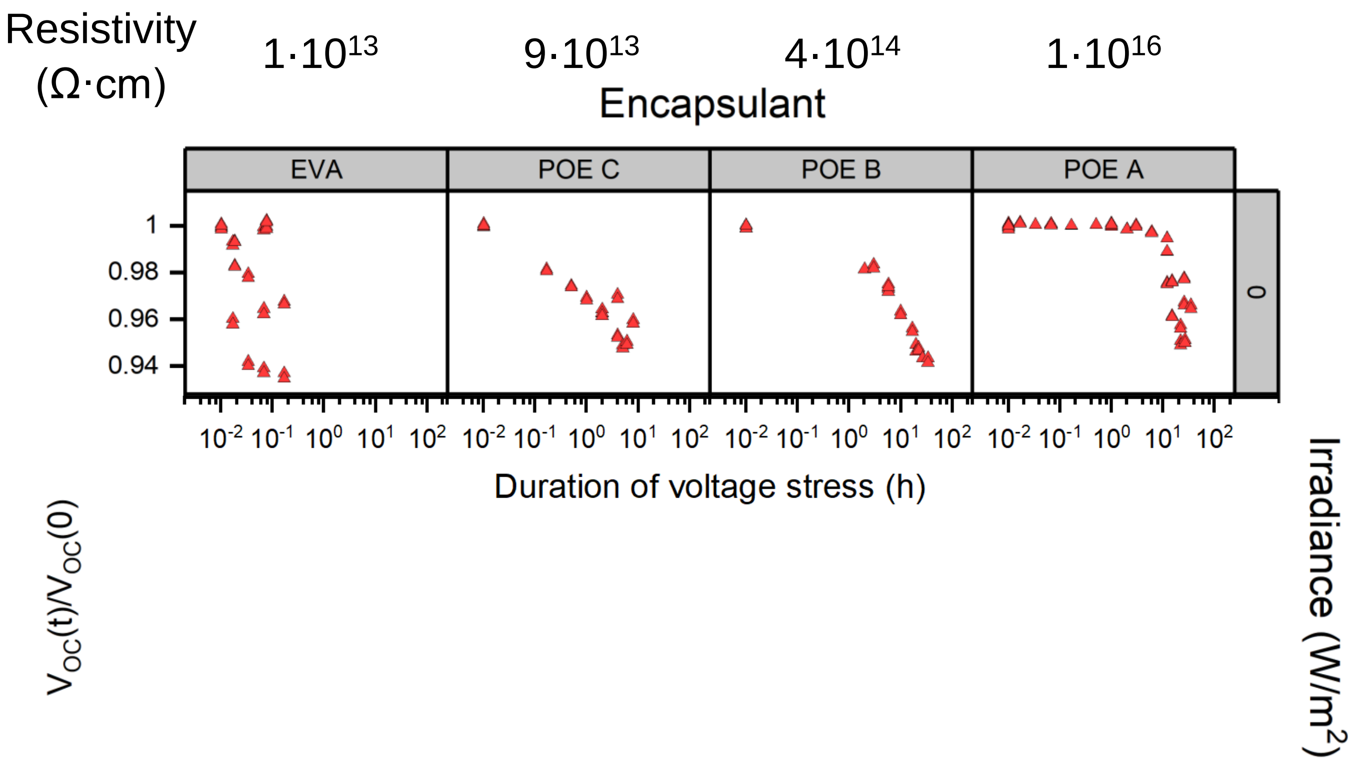
Illumination controlled via in-chamber small solar simulator equipped with neutral density filters to achieve 100, 300, or 1000 W/m^2 irradiance

RESULTS OF DARK PID EXPERIMENT



- Rapid power loss in EVA-encapsulated module, consistent with other work
- Higher resistivity encapsulants delay progression of power loss
- While POE A has 100x higher resistivity than POE C, power loss is only delayed by about 10x
  - Lab resistivity vs. in-device resistivity
  - Variation in sensitivity to different charged species
- Power loss was fully reversible with brief exposure to light in all cases

2^{ND} STUDY WITH NREL: PID + IRRADIANCE



V_{OC} is used as a proxy for power loss

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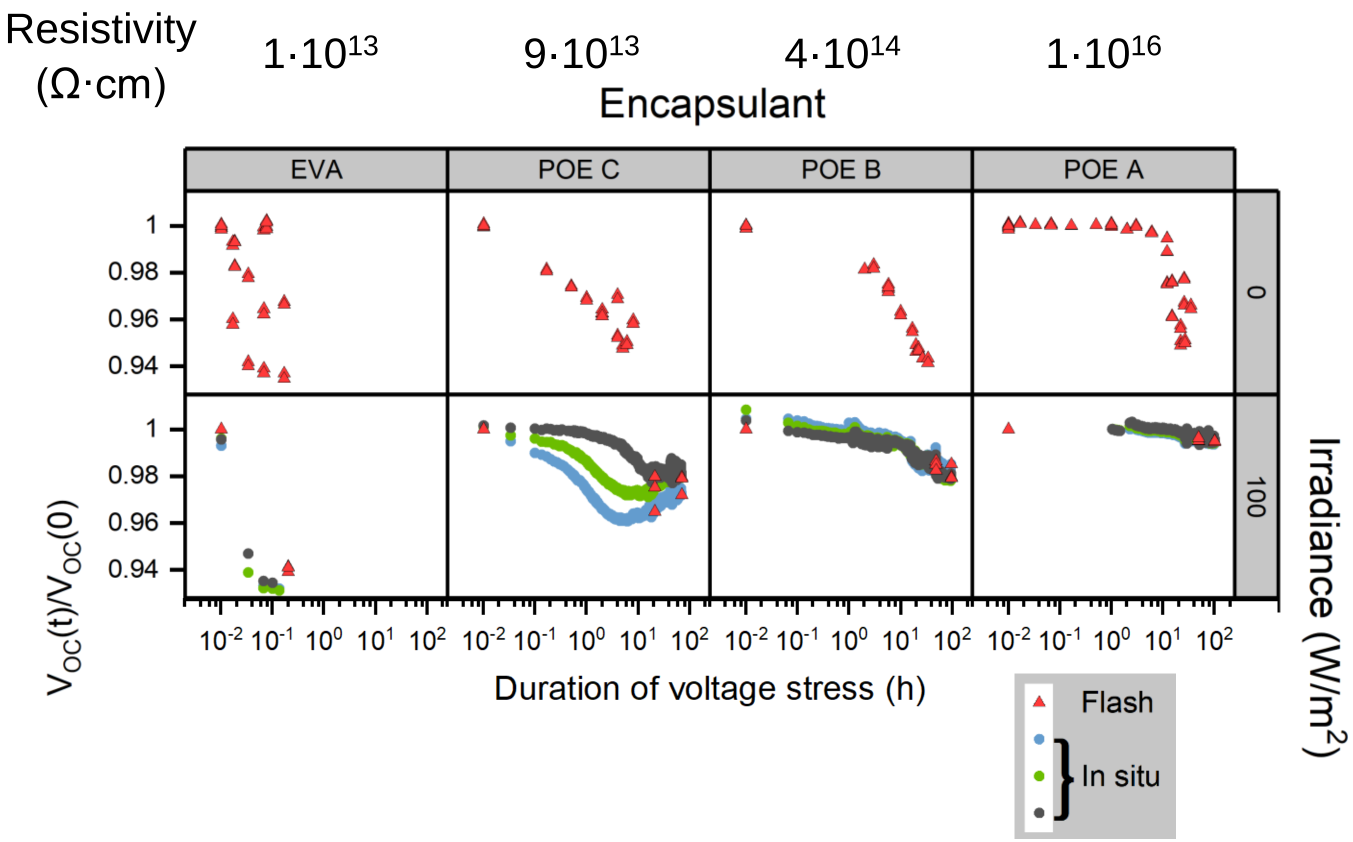


V_{OC} is used as a proxy for power loss

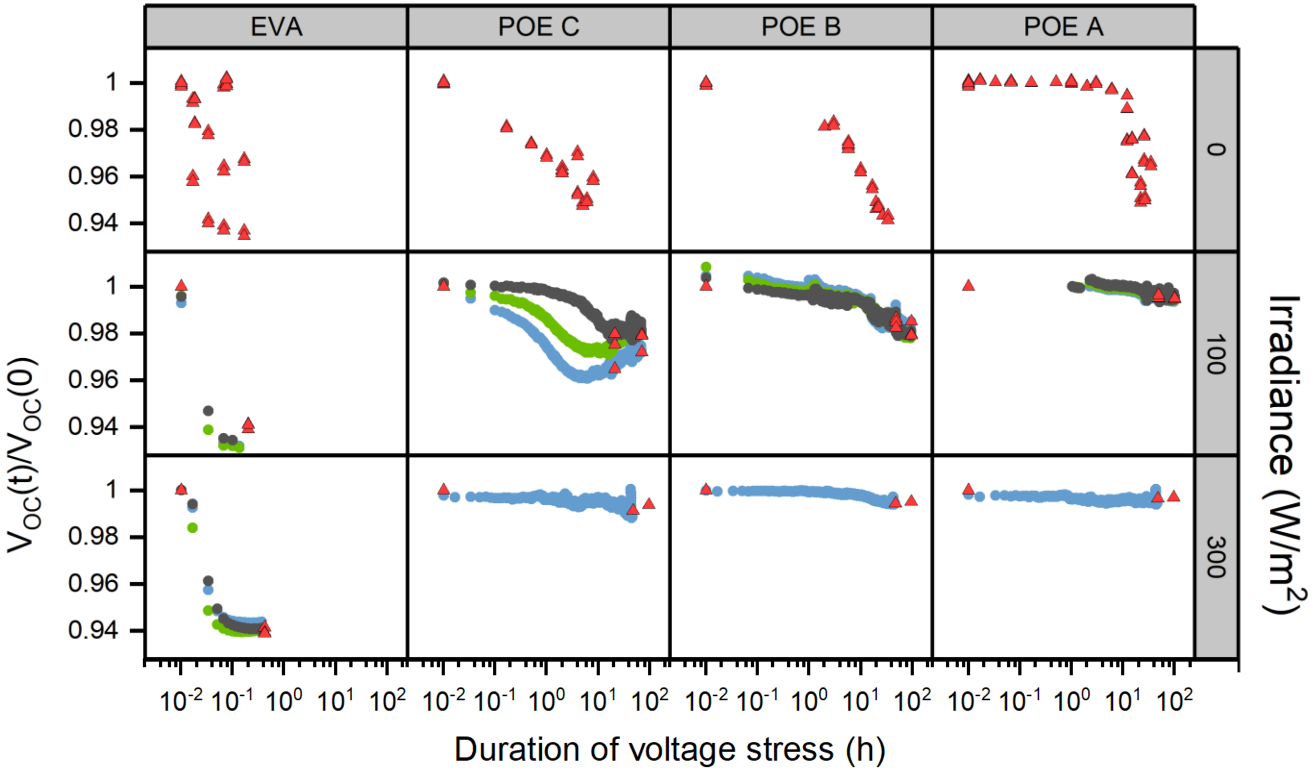
100 W/m^2

- EVA: Rapid loss to same extent as dark
- POE A: No evident loss
- POE B and C: Modest, slowed loss

2^{ND} STUDY WITH NREL: PID + IRRADIANCE

Resistivity (Ω·cm) | $1 \cdot 10^{13}$ | $9 \cdot 10^{13}$ | $4 \cdot 10^{14}$ | $1 \cdot 10^{16}$

Encapsulant



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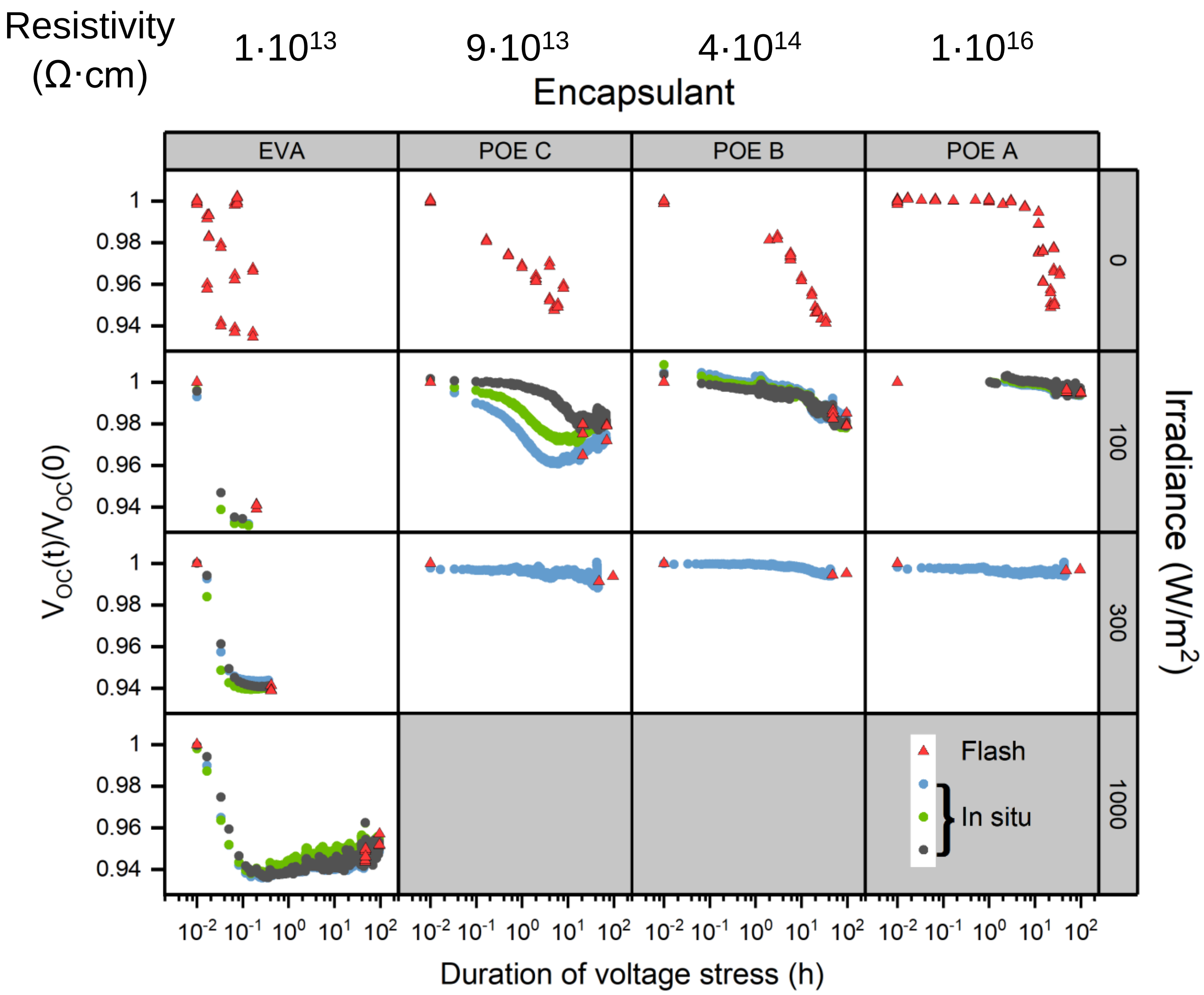
300 W/m^2
- EVA: Rapid loss to same extent as dark
- All POEs: Negligible loss

2ND STUDY WITH NREL: PID + IRRADIANCE



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300 W/m^2

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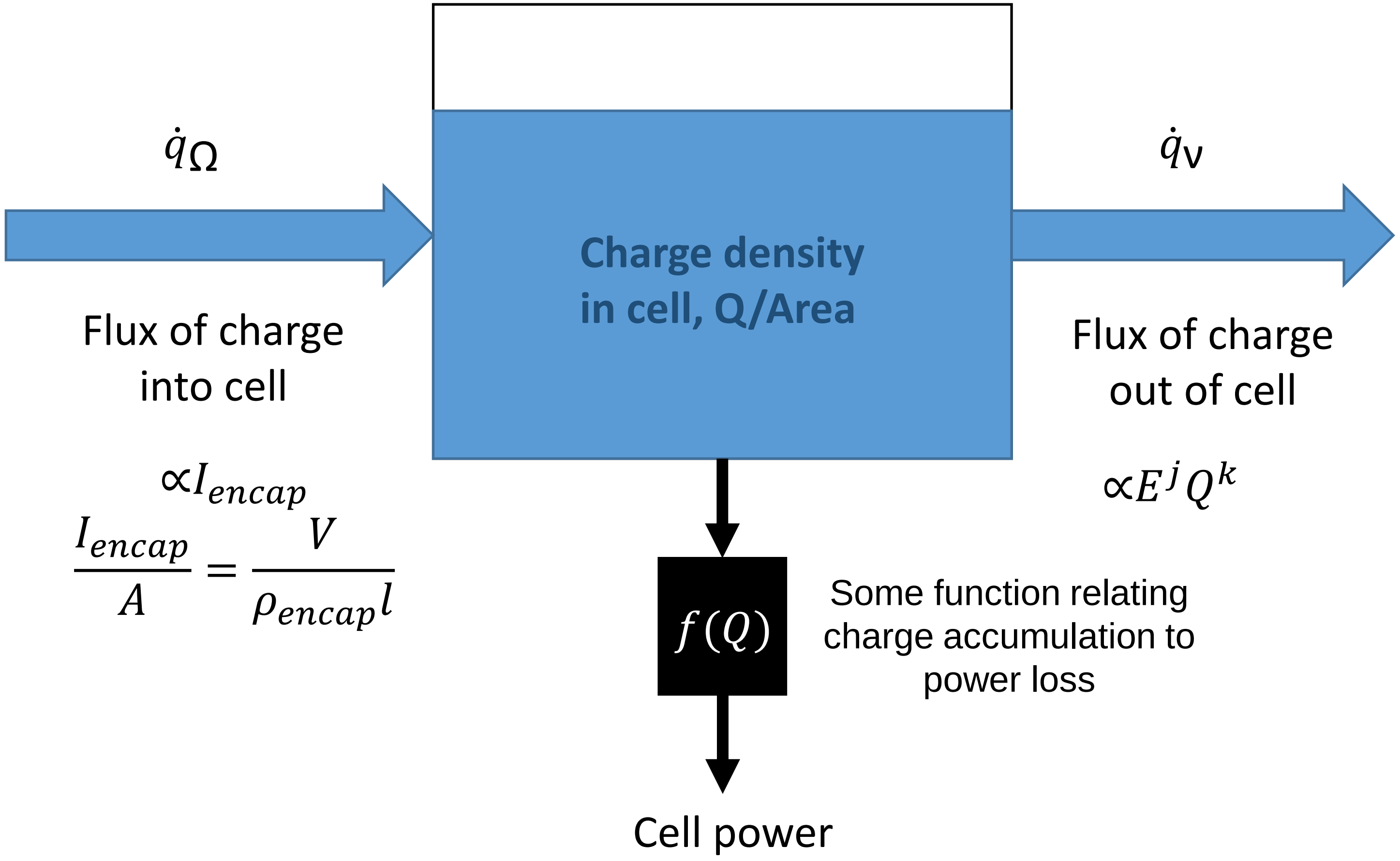
1000 W/m^2

- EVA: Rapid loss to same extent as dark

Habersberger, B.M, Hacke, P., Progress in Photovoltaics: Research and Applications. *In press.*

A Simple Model for Interpreting Results

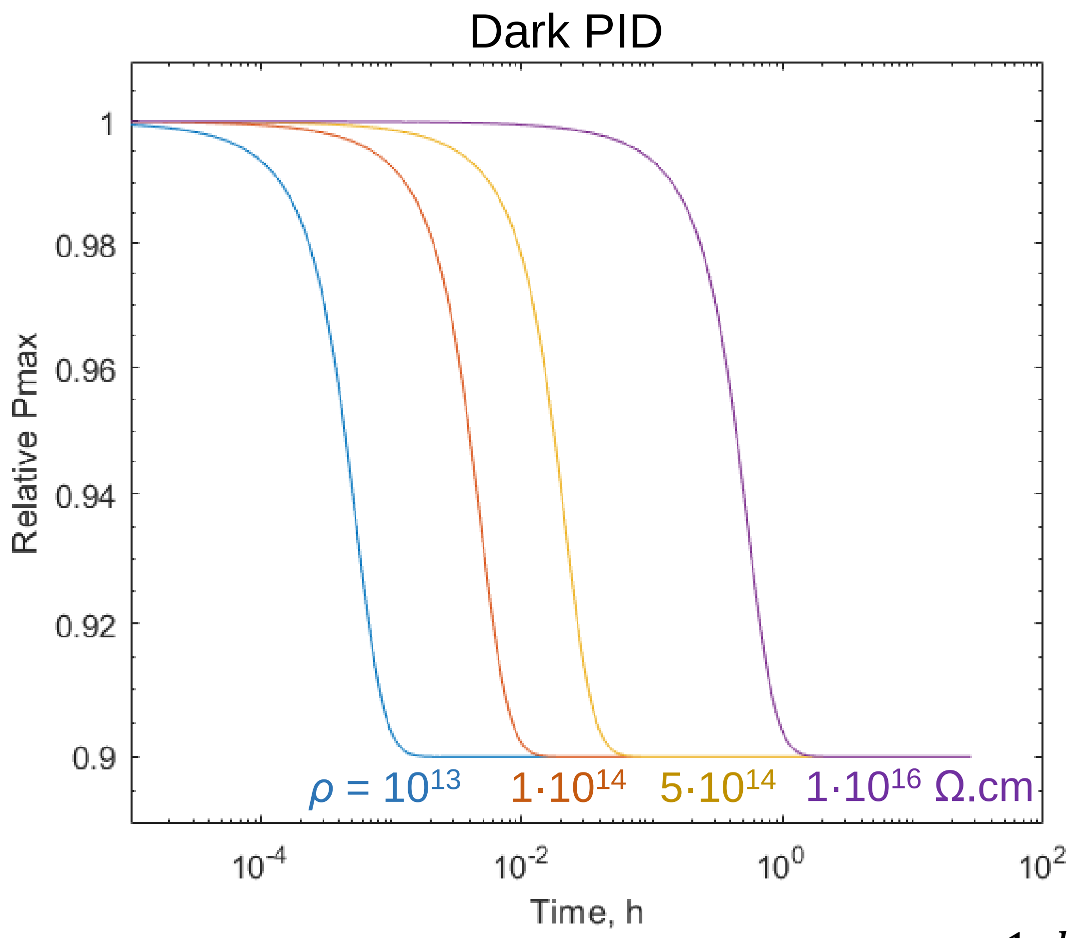


$$\frac{1}{A}\frac{dQ}{dt} = \dot{q}_\Omega + \dot{q}_V$$

"Stirred tank" model of PID-p

- Voltage causes a flux of charge into the cell surface
  - Inversely proportional to resistivity
- Irradiation relieves accumulated charge
  - Proportional to irradiance and current charge state
- Charge state determines cell power

Qualitative Prediction using Tank Model

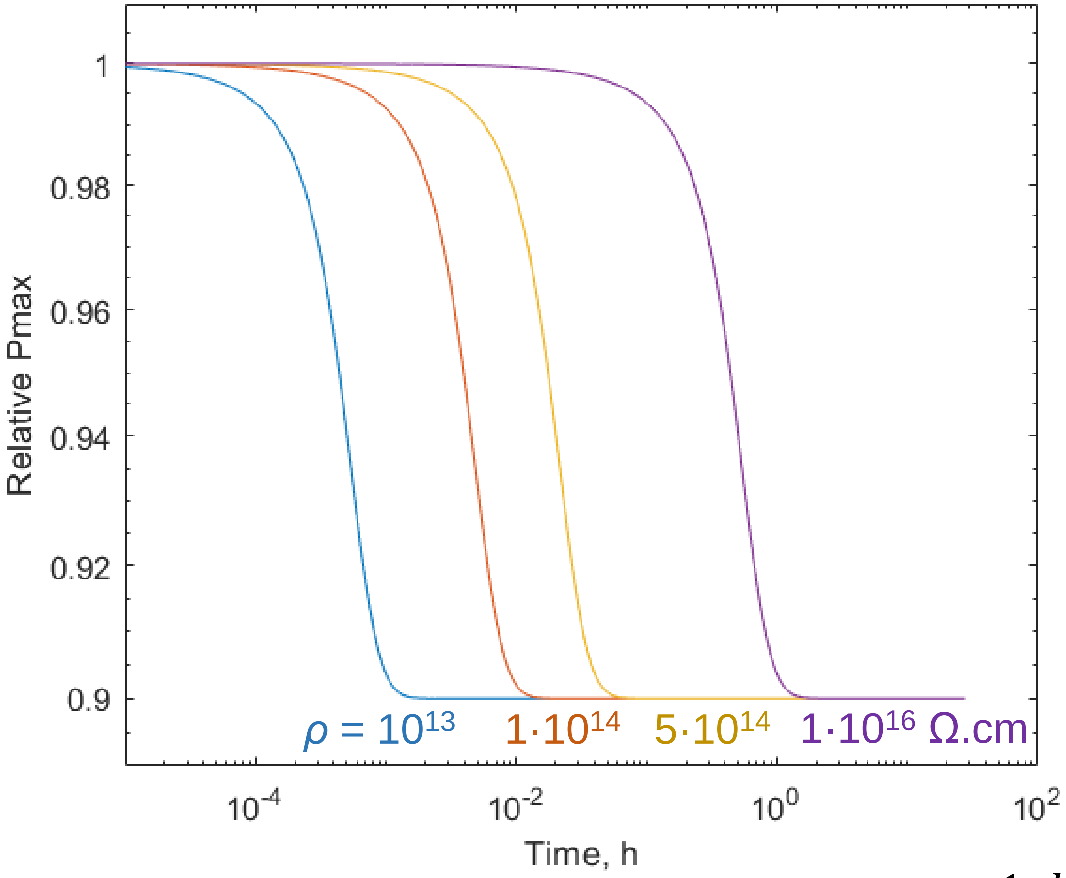


$$\frac{1}{A}\frac{dQ}{dt} = \frac{V}{\rho_{encap} l} - kEQ$$

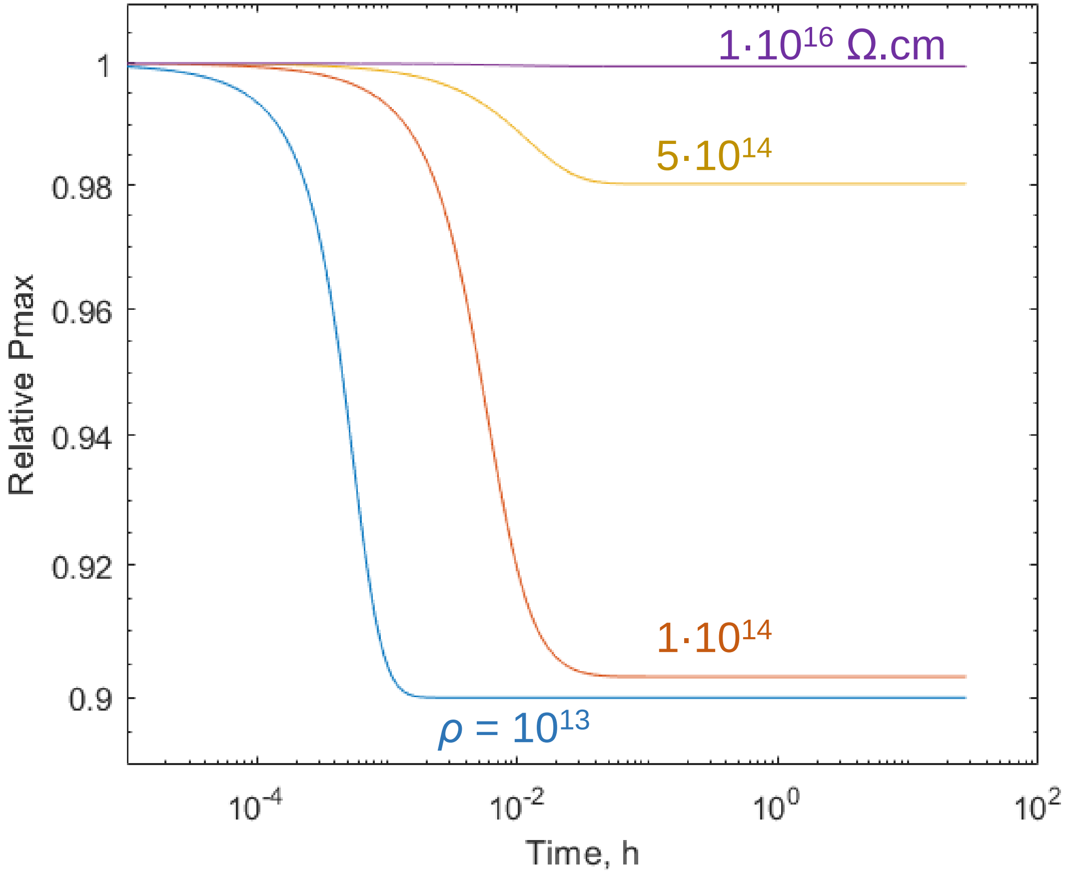
Very simple model qualitatively predicts results of PID-p with illumination

Qualitative Prediction using Tank Model

Dark PID



PID + 100 W/m^2



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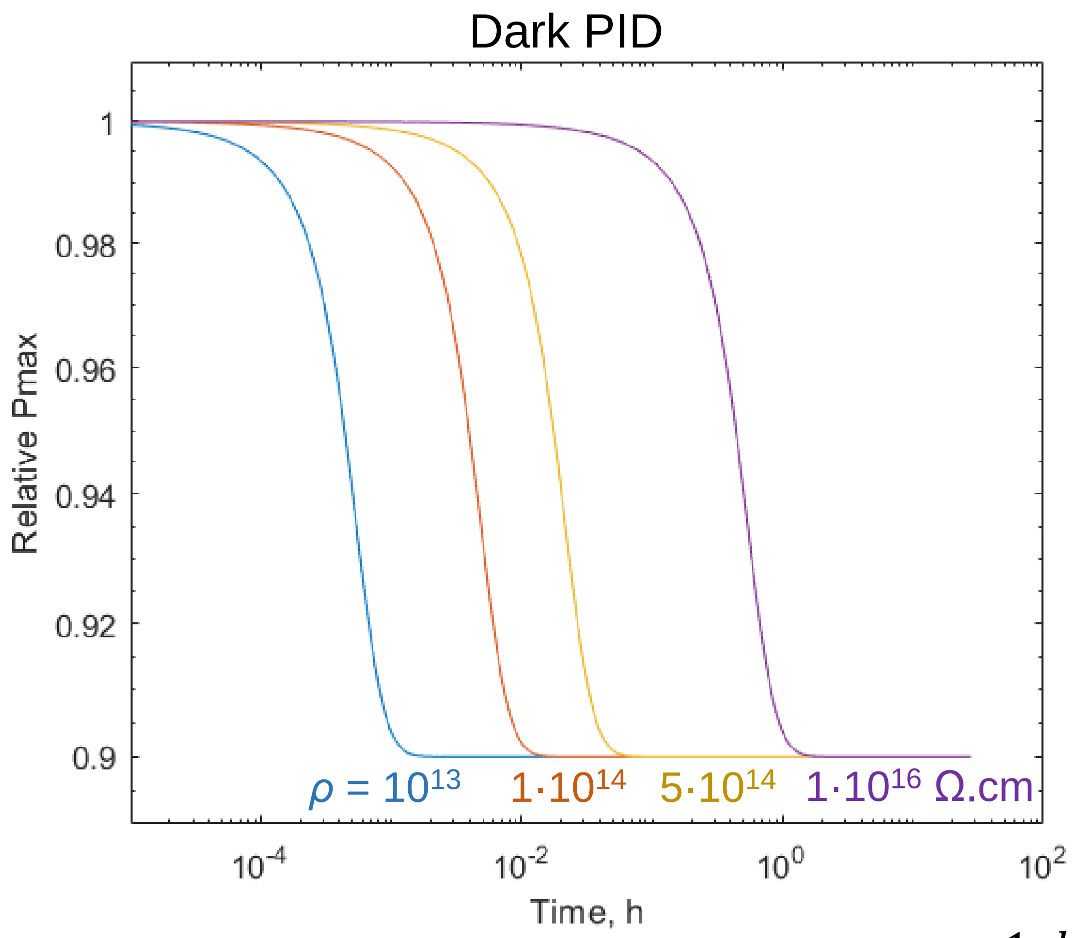

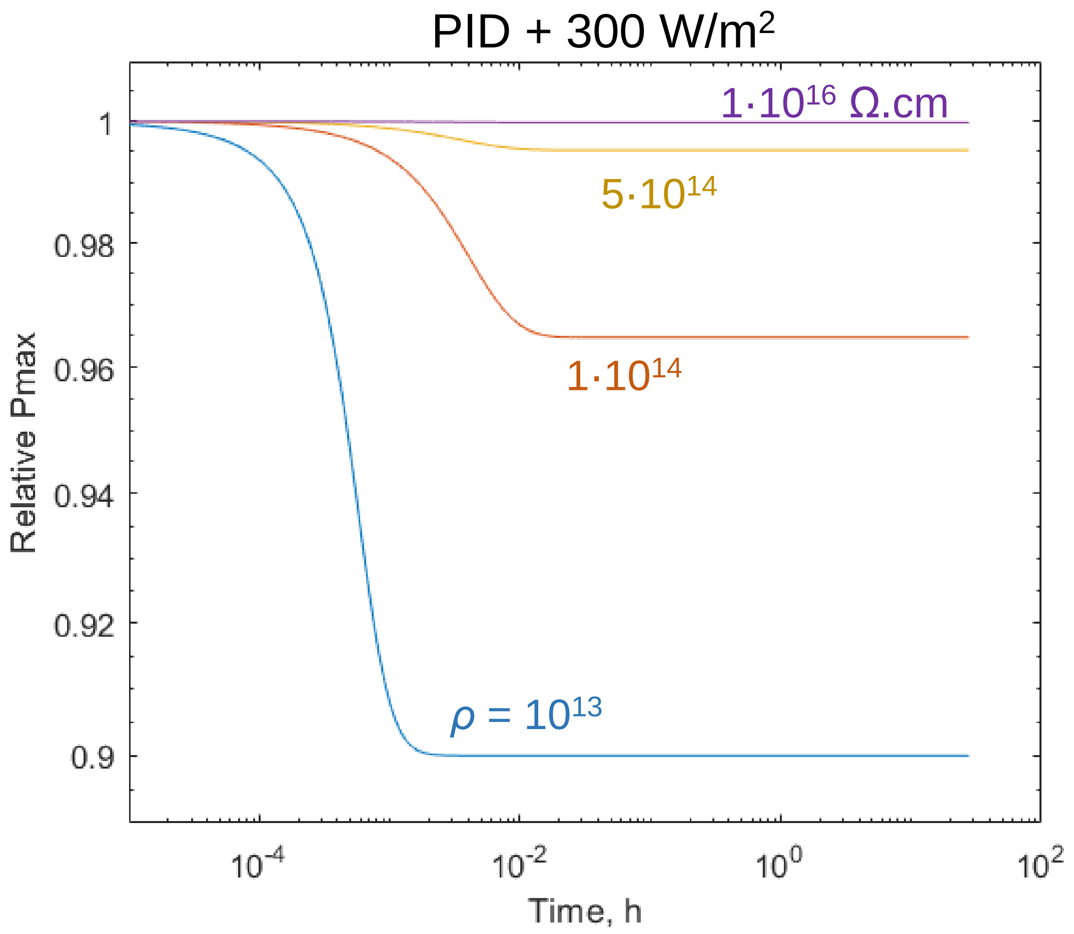

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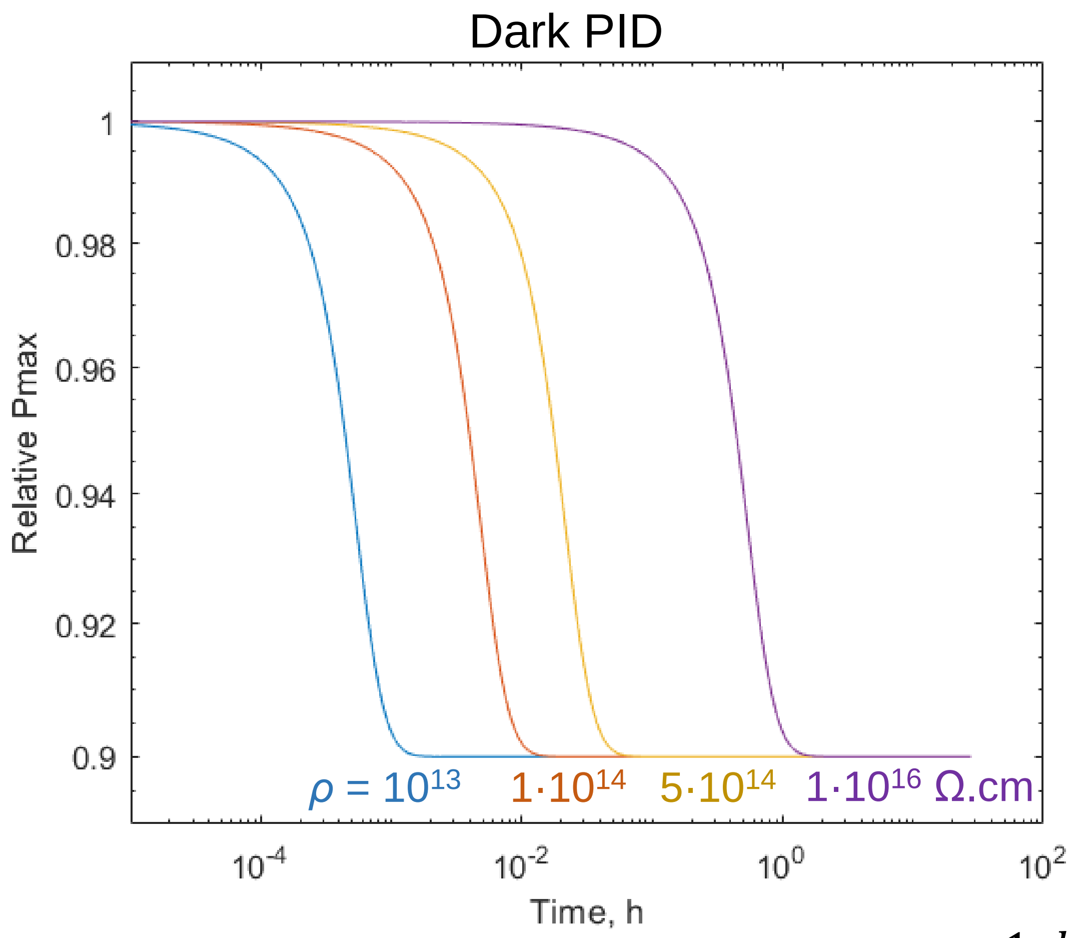

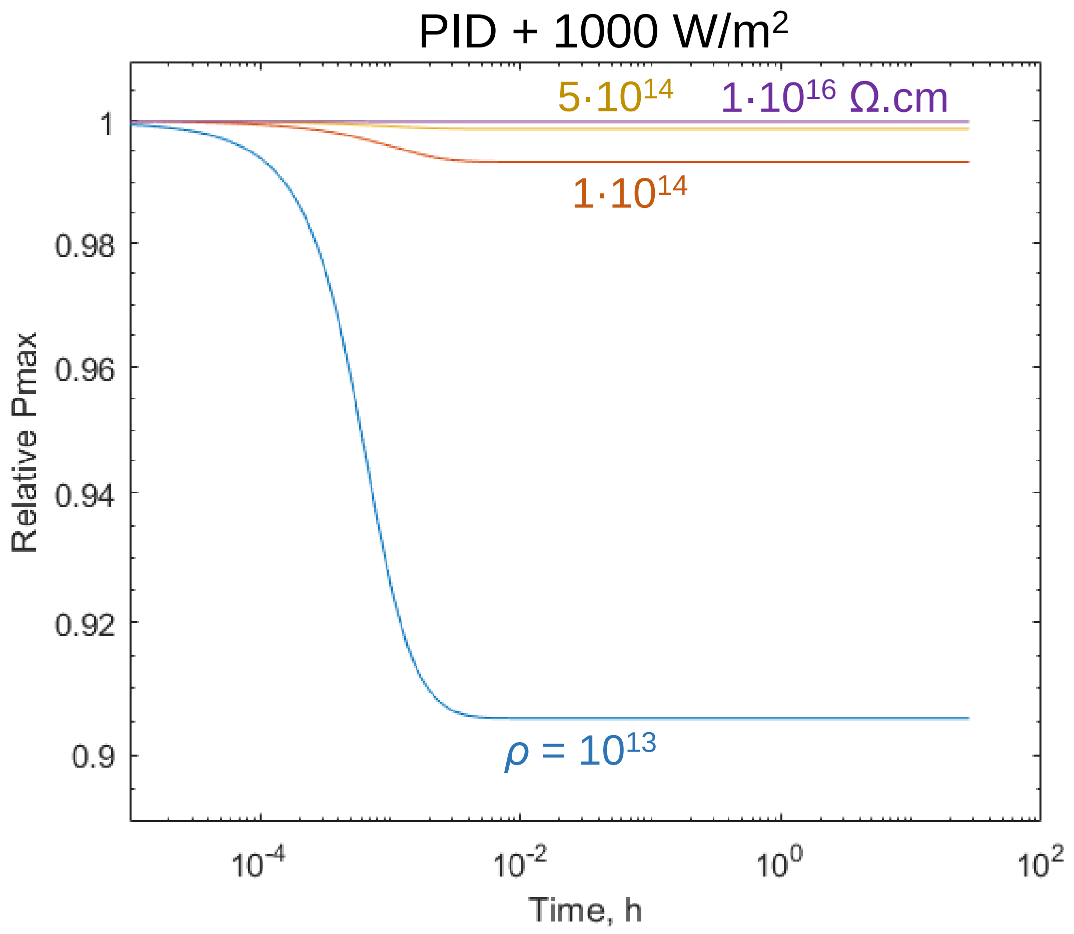

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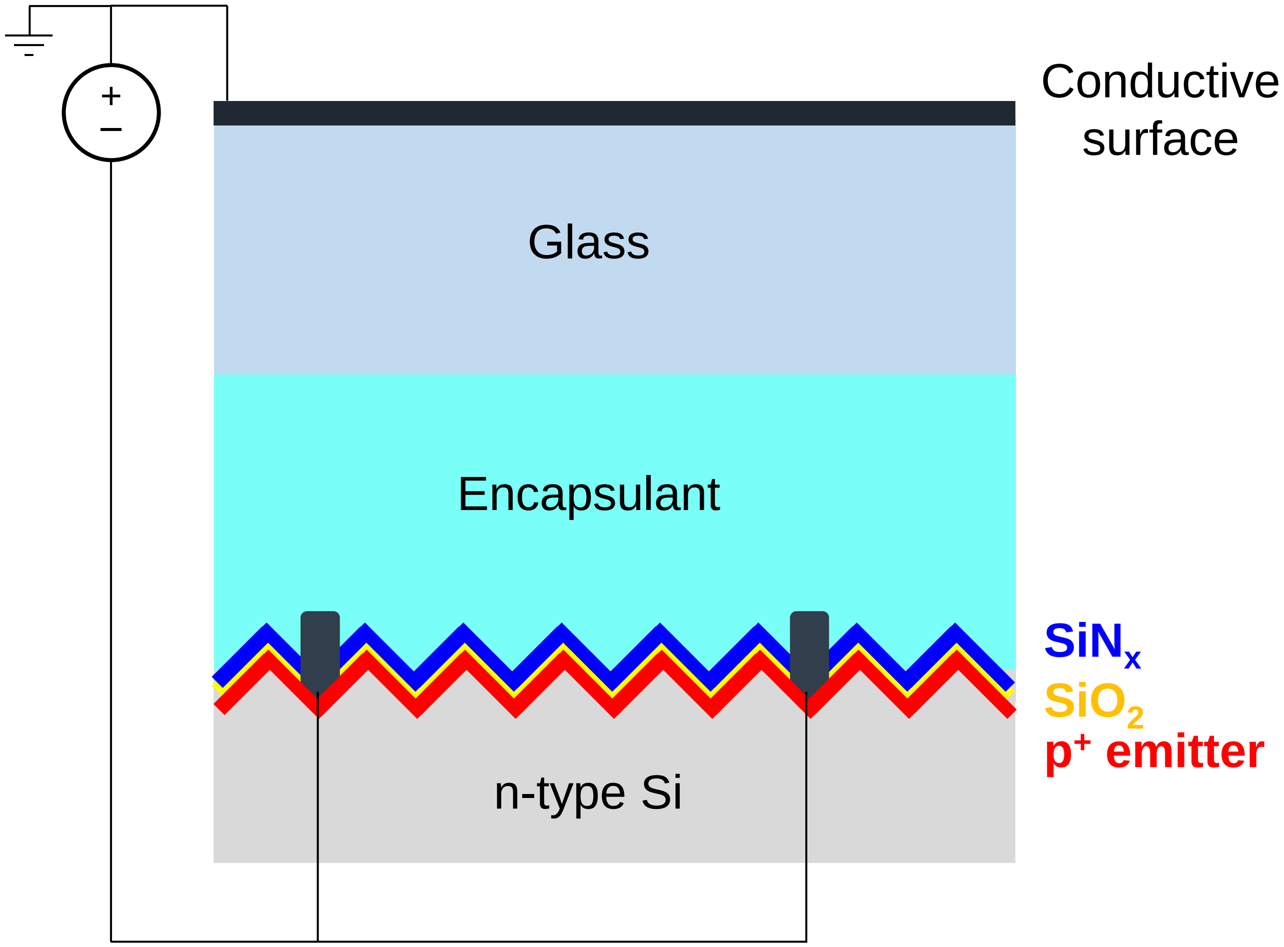
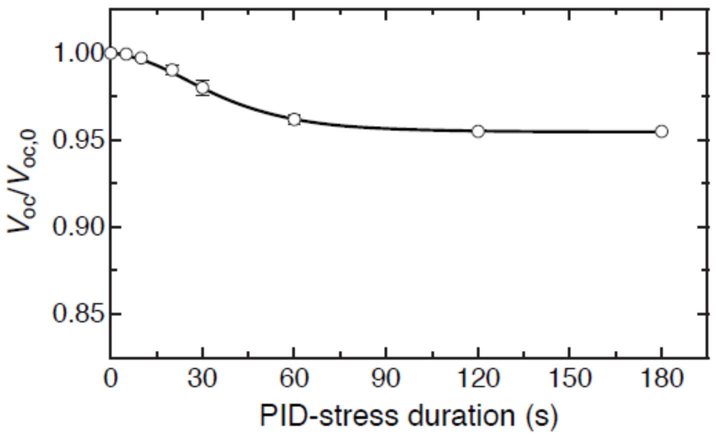
Connecting the Model to Device Physics



- PID-p is caused by charge accumulation on surface of cell
- A type of bond defect in silicon nitride, called a K^+ center, is believed to result in a charge trap
- Silicon nitride is photoconductive, so illumination enables elimination of trap and draining of charge through finger electrodes
- PID-p progression and recovery are due to the competing rates of charge accumulation (regulated by the encapsulant) and drainage (regulated by SiN_x conductivity)

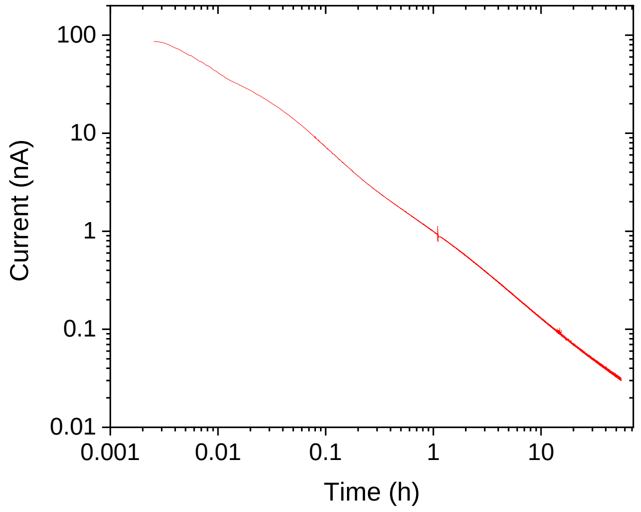
IMPROVEMENTS TO THE MODEL MAY ENABLE PID PREDICTIONS

$$\frac{1}{A}\frac{dQ}{dt} = \frac{V}{\rho_{encap} l} - kEQ$$



- Present model uses empirical P(Q) from measurements by Yamaguchi et al.
- Incorporate physics model relating local field to recombination rate

[1] Yamaguchi, S., et al. (2018). *Japanese Journal of Applied Physics*, *57*(12), 122301.



- Model uses lab-measured resistivity and treats as a fixed constant
- Resistivity decreases with time and depends on exposure to mobile ions in the device

Replace empirical constant k with physics-based description of photoconductivity in SiN_x

Photoconductivity as a function of
- Temperature
- Wavelength
- Intensity

Summary and Conclusions

Impact of encapsulant resistivity and simultaneous light exposure was explored in time-dependent PID experiments on n-PERT cells

Unlike PID-s, encapsulant resistivity is a critical factor in prevention of PID-p

Simultaneous light exposure was shown to mitigate PID-p, but only when combined with high resistivity encapsulants

A simple rate-based model qualitatively describes the observations, and improvements to this model could enable quantitative prediction of PID-p