2nd ATLAS/NIST Workshop, Nov. 13-14, 2013

An End-to-End (cell-to-module) Reliability of Thin Film Photovoltaics

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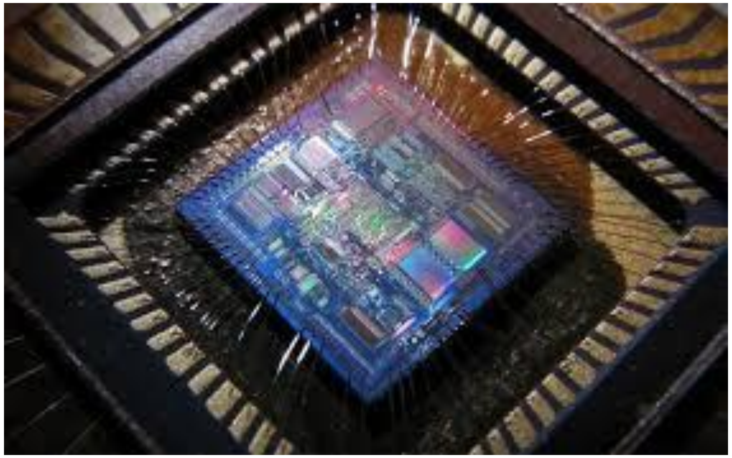
A Perspective from IC Reliability



Reliability is **Hierarchical** – End-to-end modeling is essential

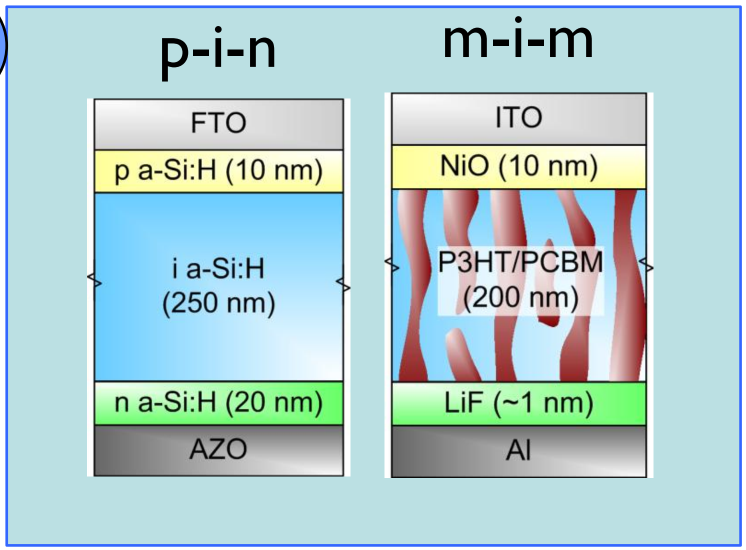
Reliability is **Physical/Universal**– Despite changes in material

Reliability is **correlated** – Embedded in software, such as RelExert

Hierarchy of Thin Film solar cells

Cell | Module | Panel

1



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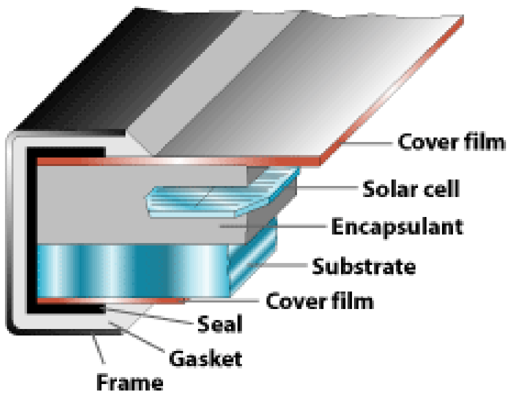

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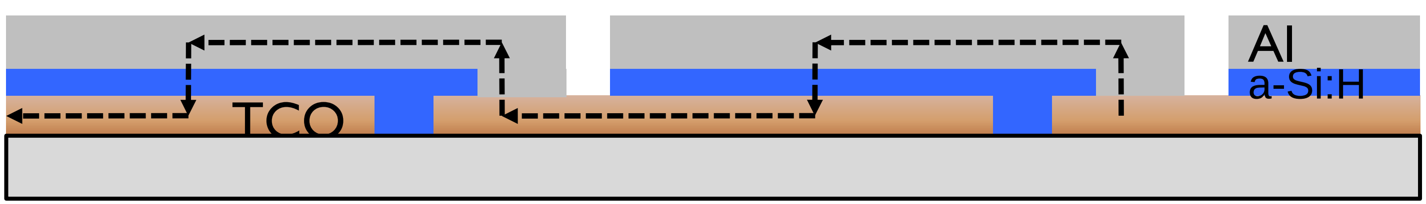
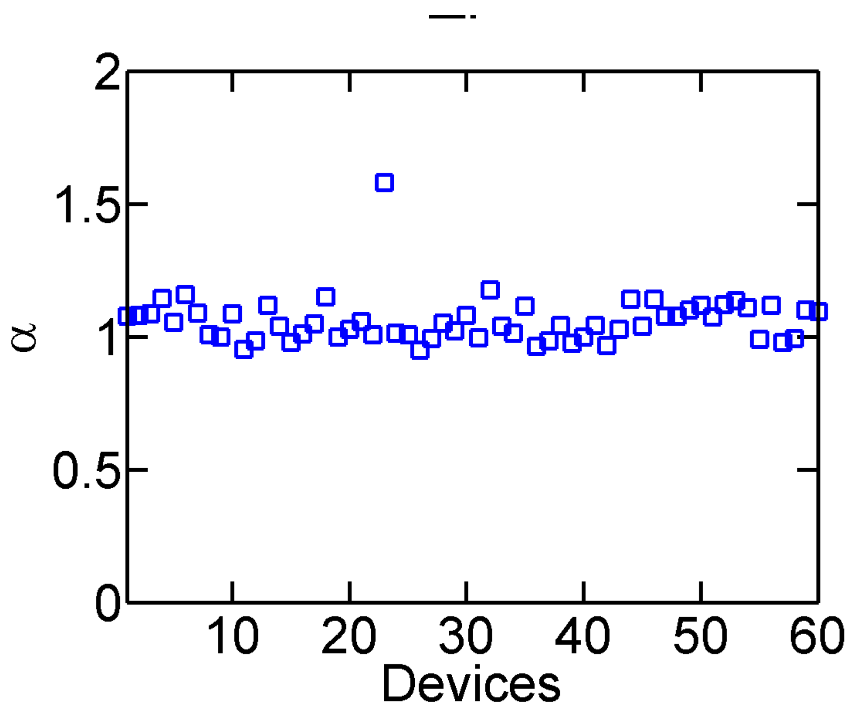
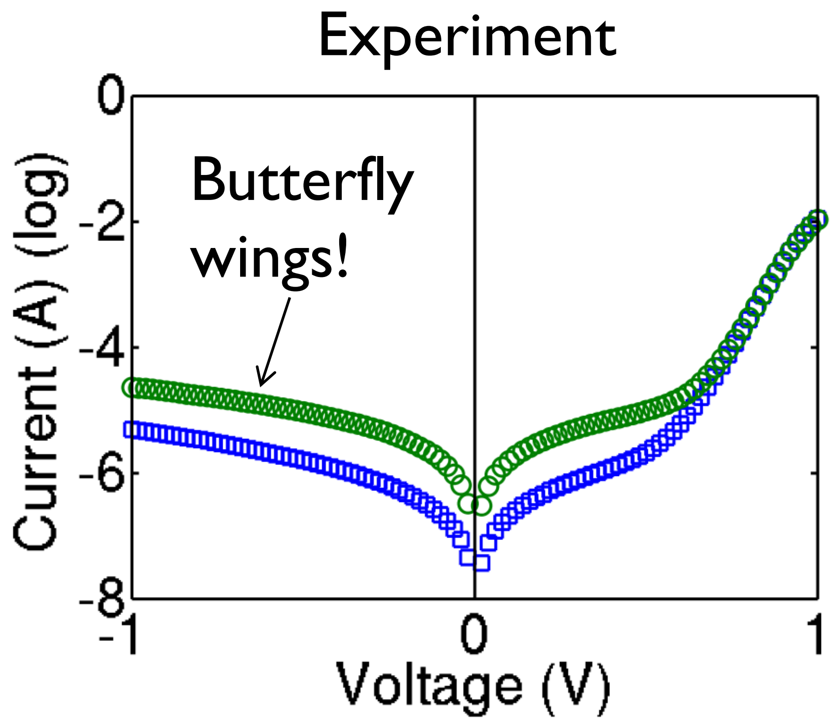


Many features are universal…

*Google Images

Theory & practice of thin film dark IV

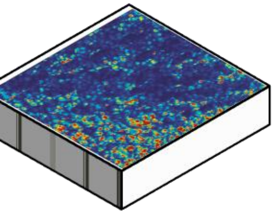


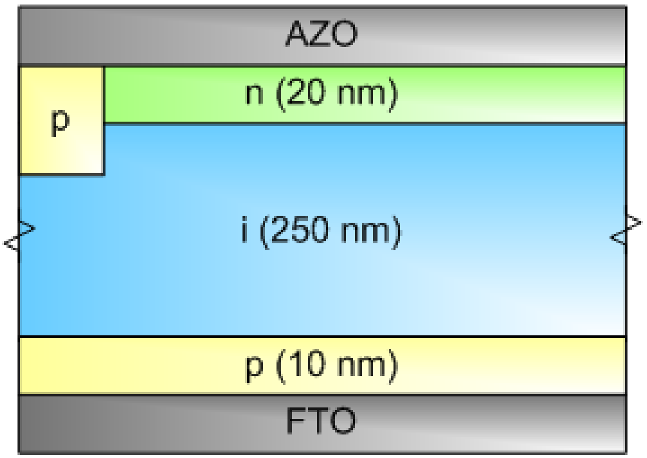


A real solar cell IV seldom looks like textbook IV!

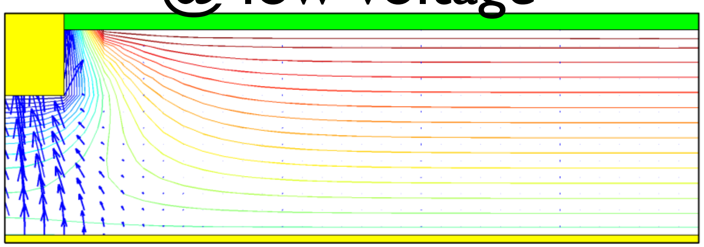
Dongaonkar and Alam, JAP, 2010

Physics of shunt leakage

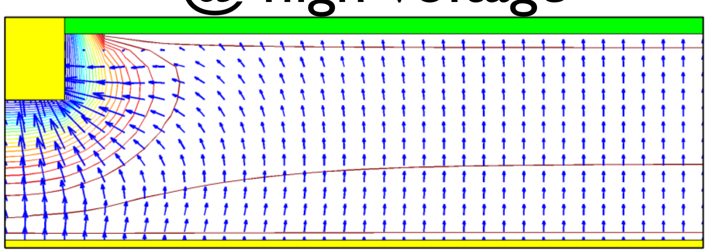


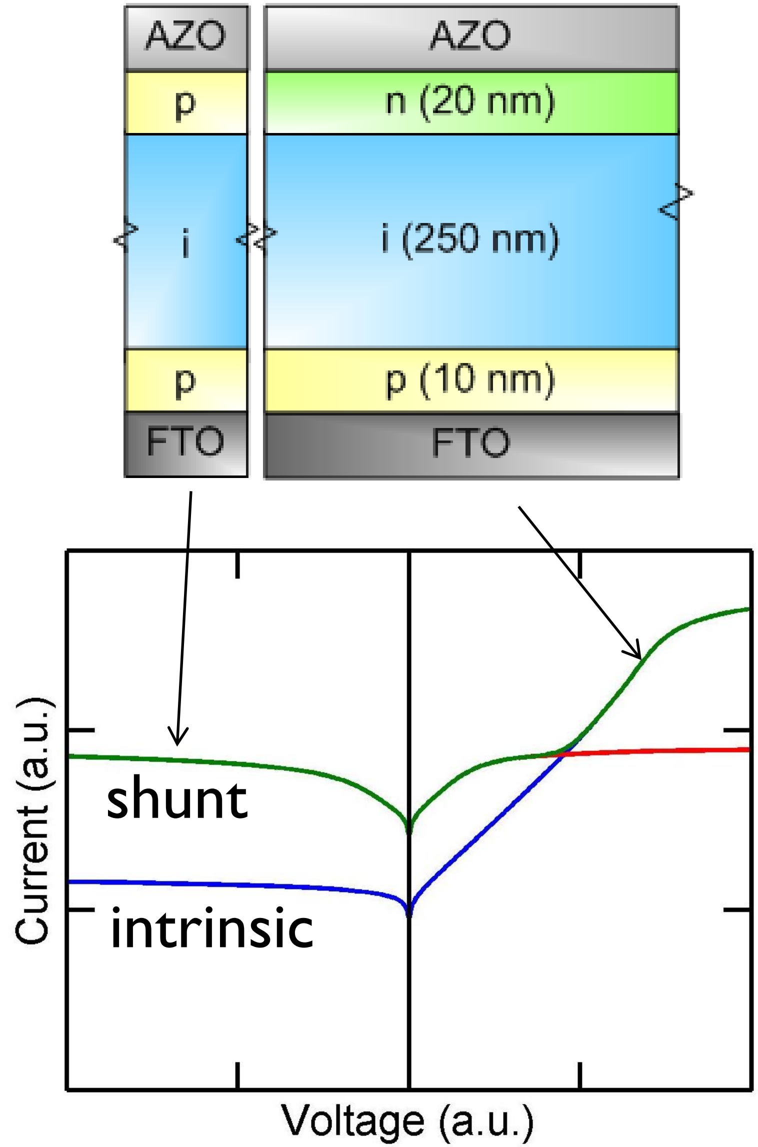


@ low voltage



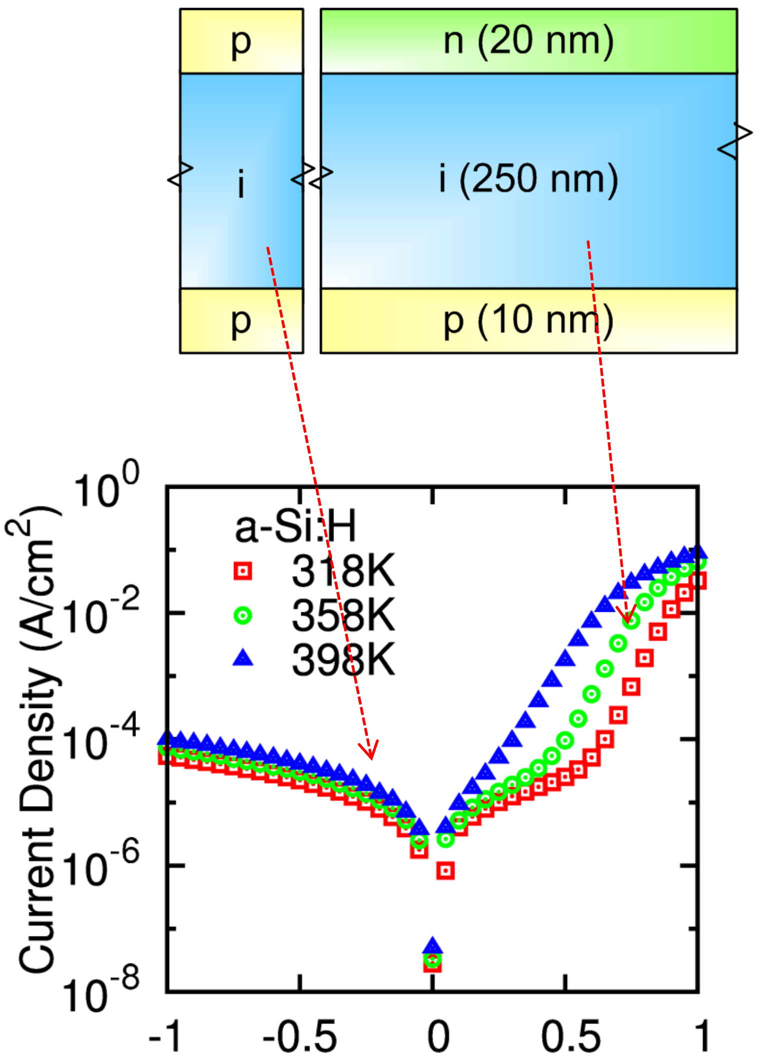
@ high voltage

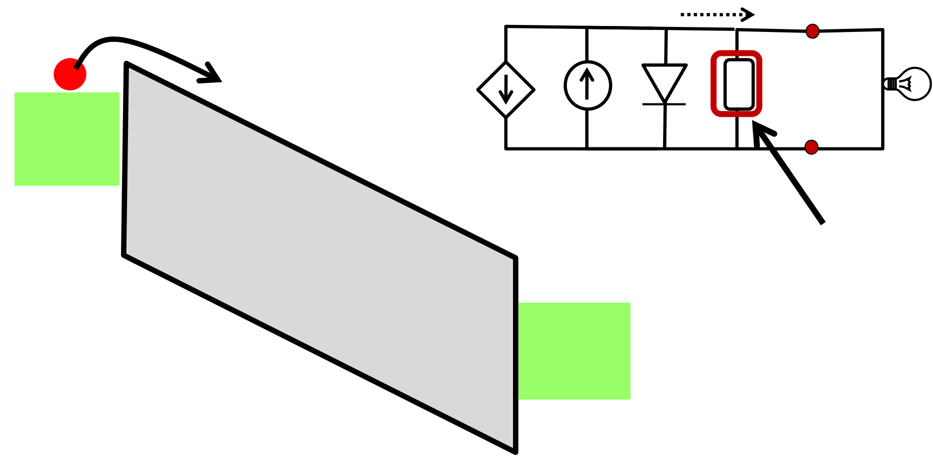




Dongaonkar and Alam JAP, 2010

Interpretation of ‘shunt’ leakage





$$J_n = qn\mu_n\mathcal{E}$$

$$\frac{d\mathcal{E}}{dx} = \frac{qn}{\kappa\varepsilon_0}$$

$$V_a = \frac{2}{3}\sqrt{\frac{2J_n}{\kappa\varepsilon_0\mu_n}}L^{3/2}$$

$$J \quad V_a = \frac{9\kappa\varepsilon_0\mu_n}{8L^3}V_a^2$$

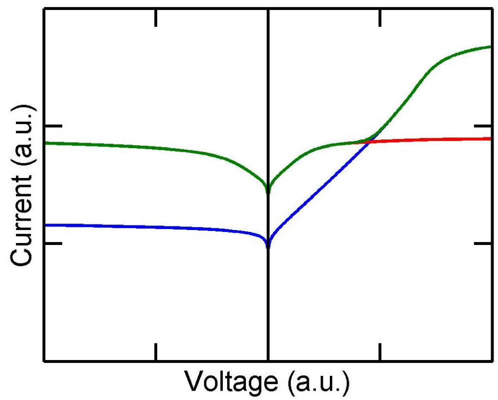
$$I_{shunt} = A\mu\frac{V^{\delta+1}}{L^{2\delta+1}}\;*$$

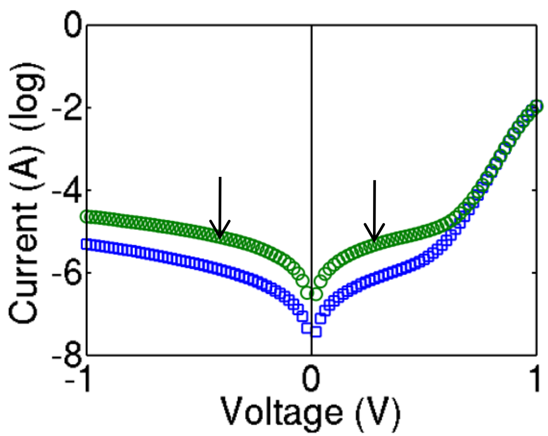
$$\gamma = \frac{E_A}{kT}$$

* G. Paasch et al., JAP 106, 084502 (2009)

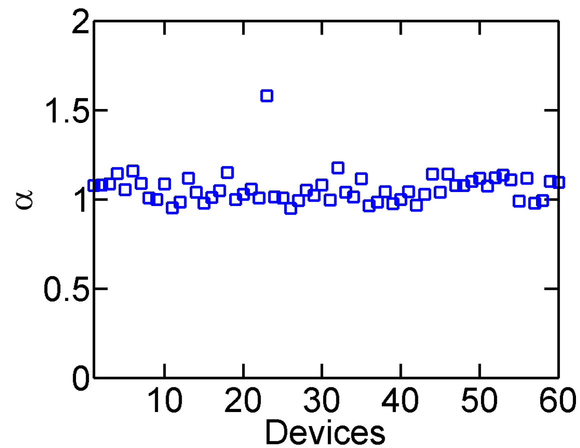
Features of shunt leakage

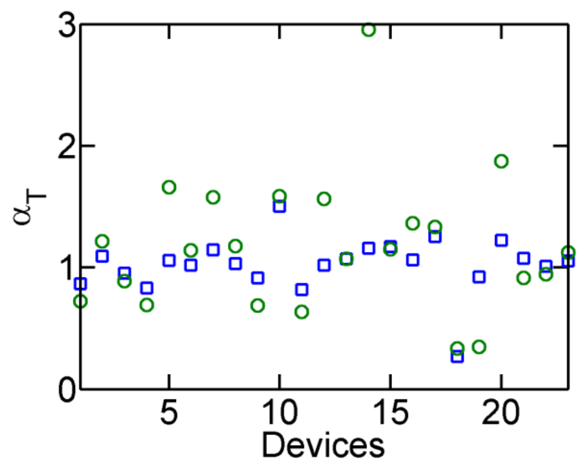
$$I_{shunt} = A\mu \frac{V^{\delta+1}}{L^{2\delta+1}}$$



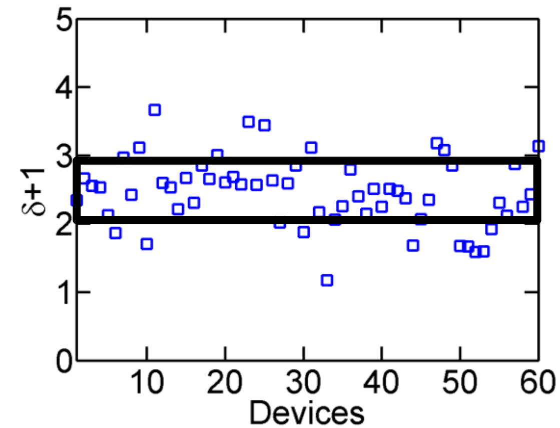


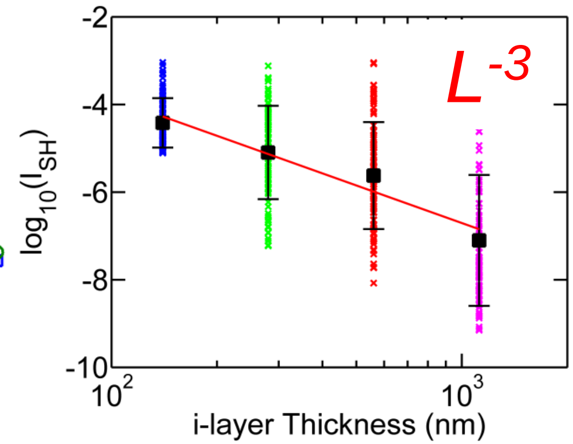
Symmetry





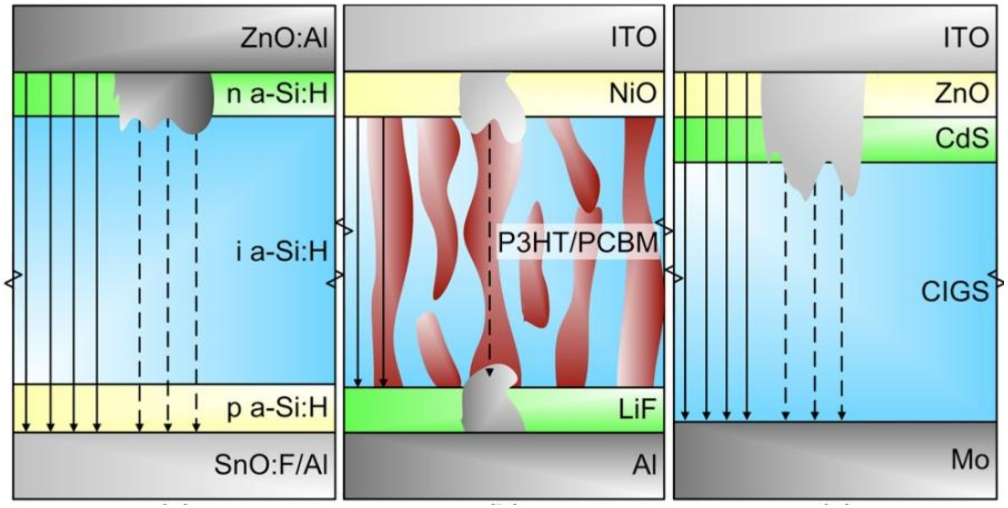
Exponents

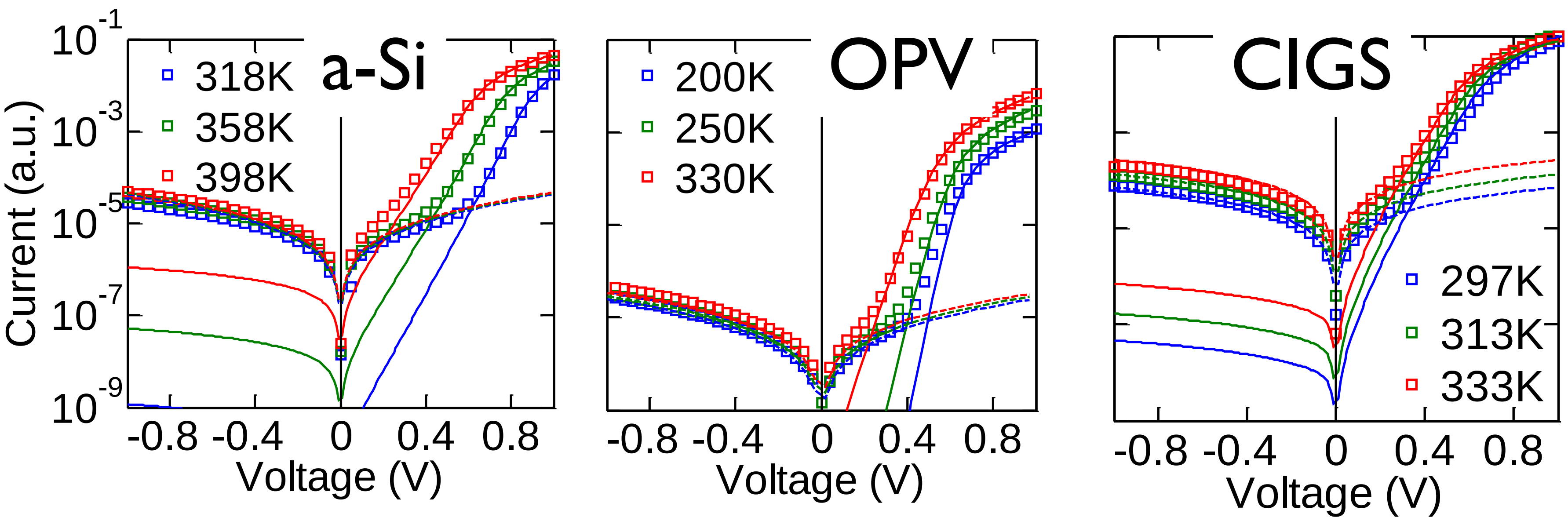




Dongaonkar and Alam, EDL, 2010; JAP 2011, JPV 2012

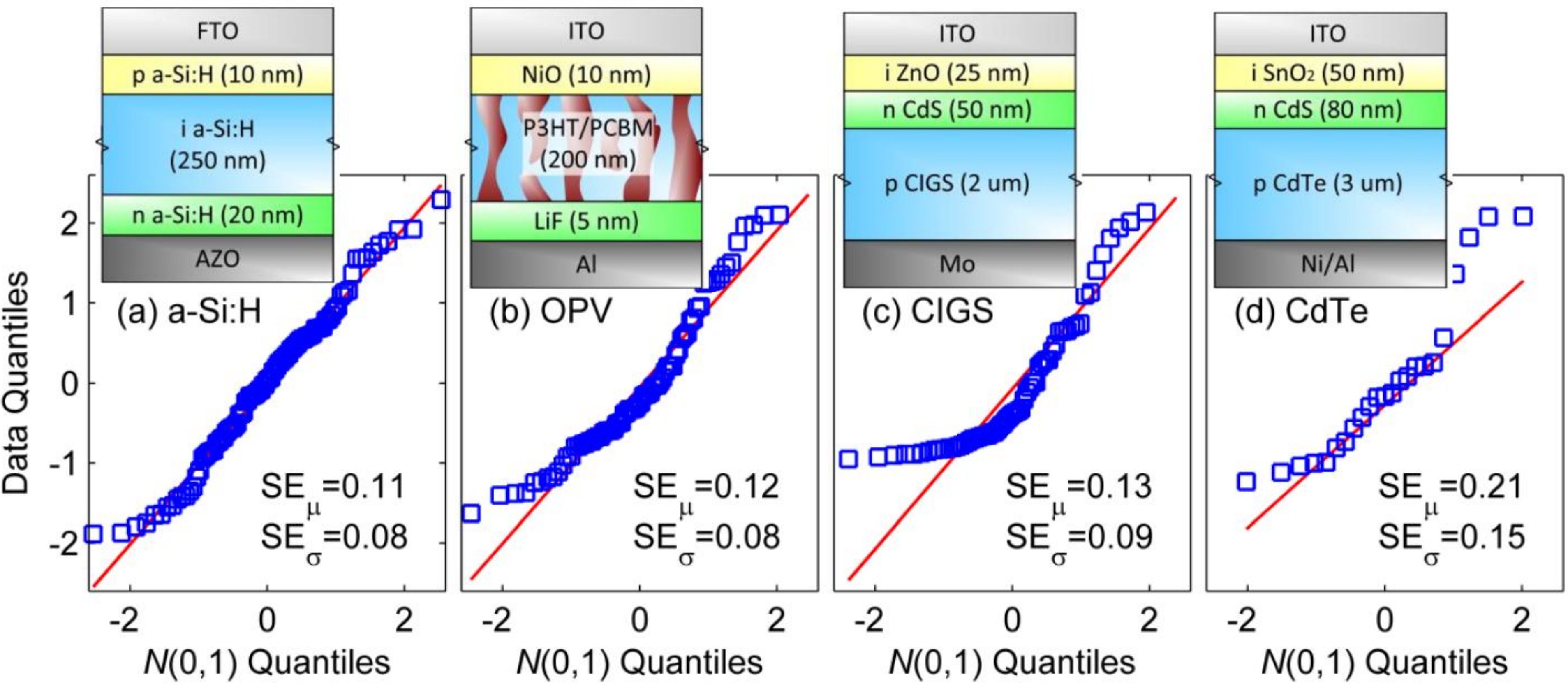
Universality of shunt conduction





Dongaonkar and Alam, JAP, 2011

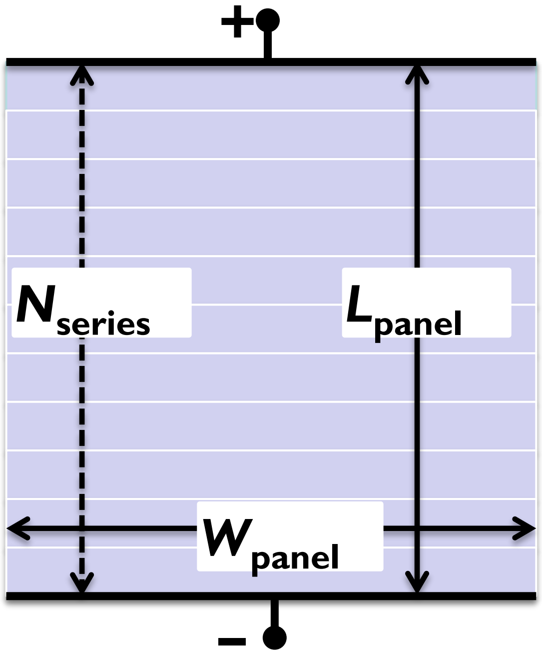
Universality of shunt statistics

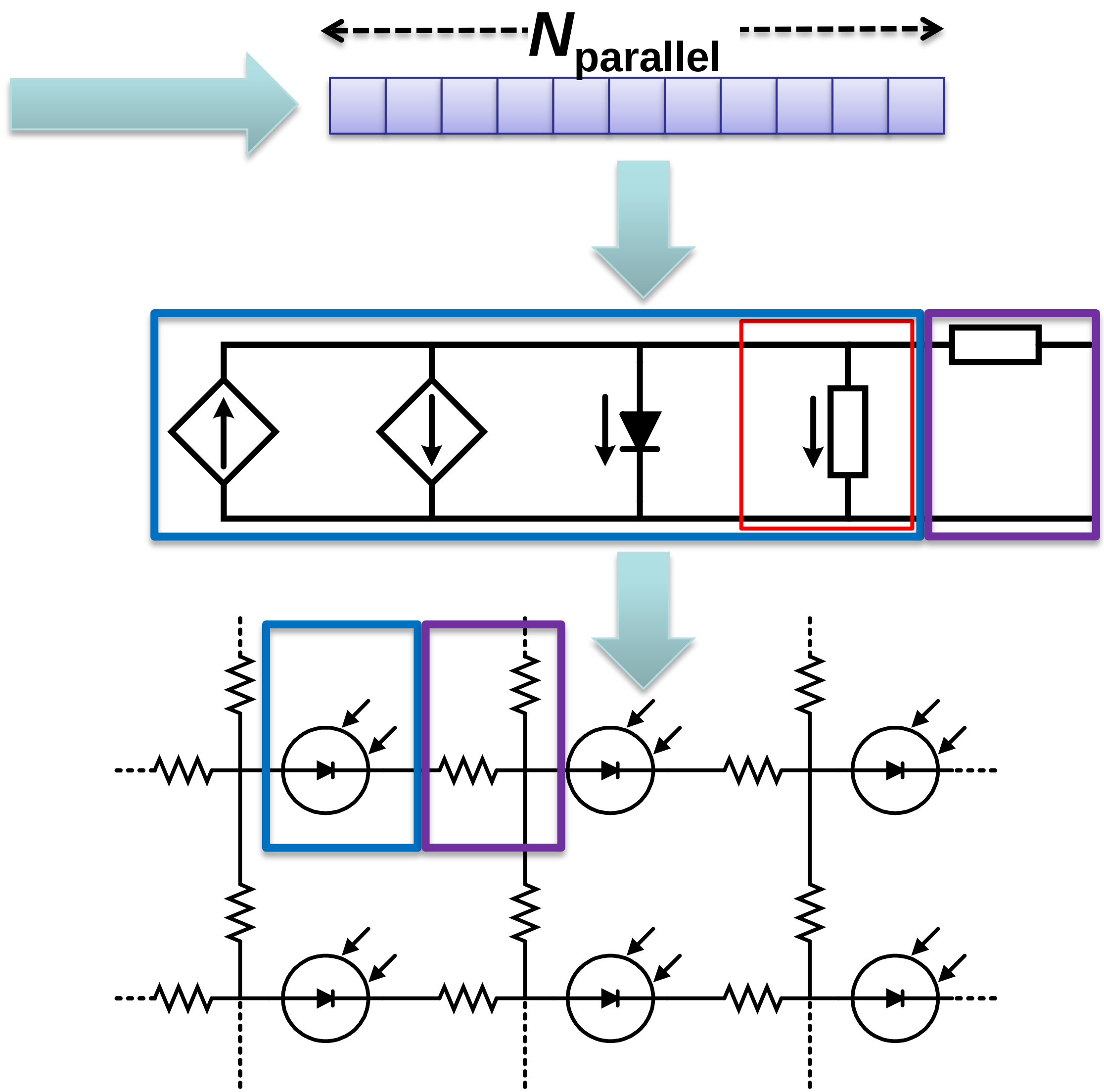


Log-normal distribution, bad cells are rare

Dongaonkar/Alam, EES, 2013

Variability, **Correlation** & performance: SPICE framework





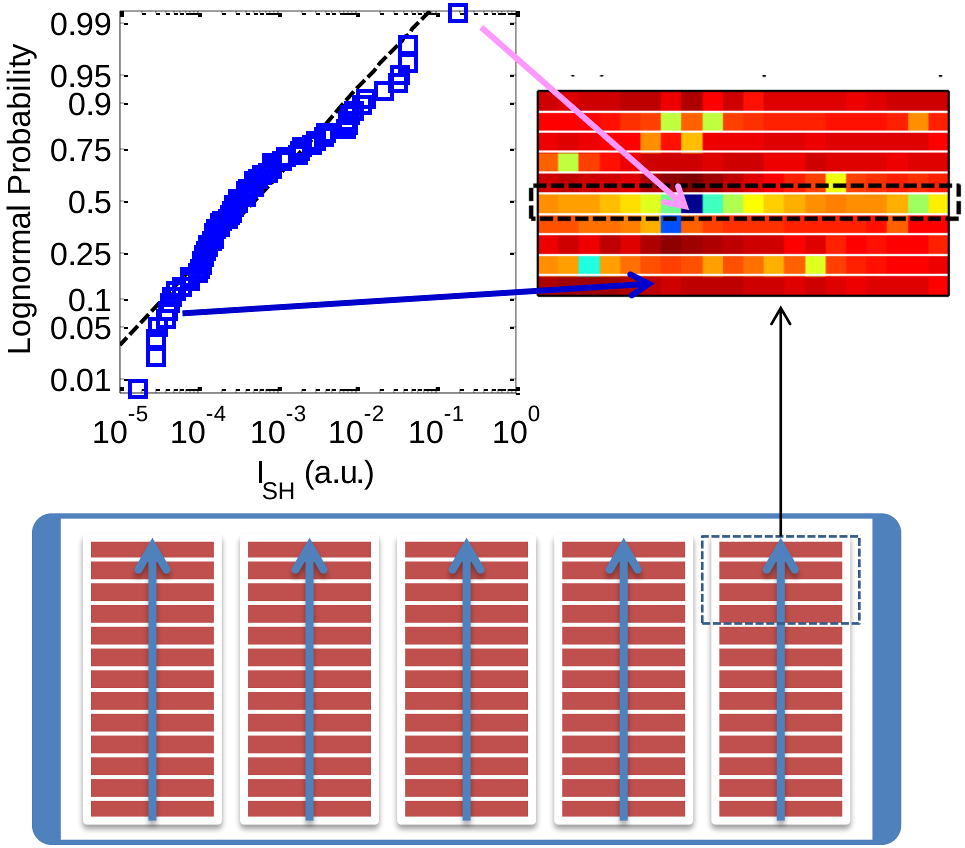
Compact Model

$I_{Shunt} \sim \ln N \quad \mu, \sigma^2$

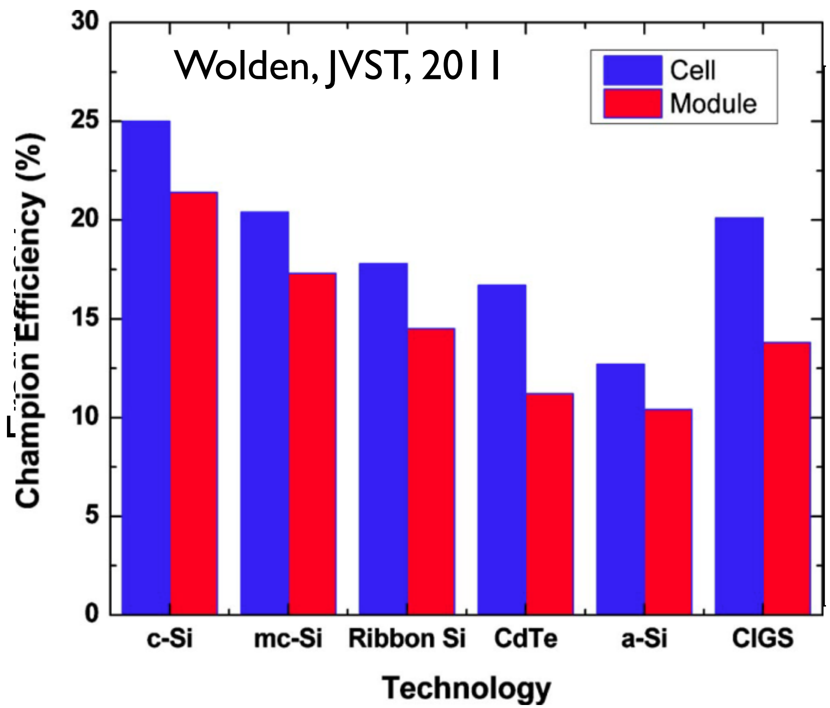
Sheet resistance

Panel vs. Cell Efficiency Gap Universal ?!

Shunts distributed within module

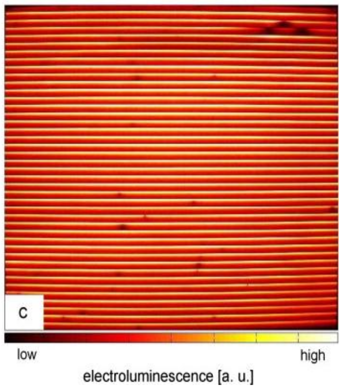


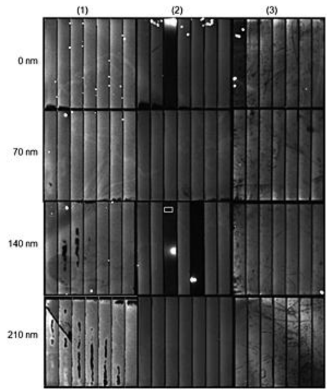
shunt and series resistance explain the gap

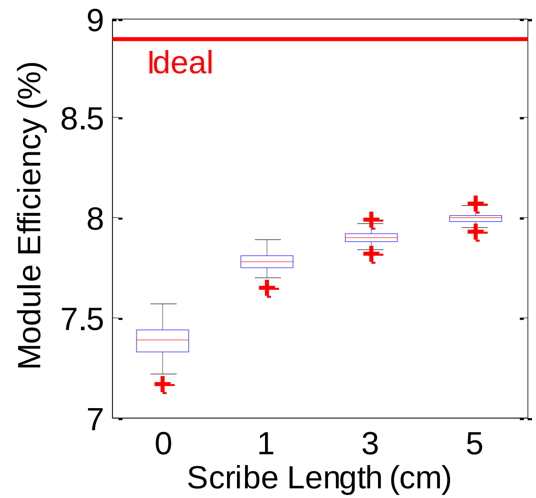


Cell/panel gap is essentially technology agnostic

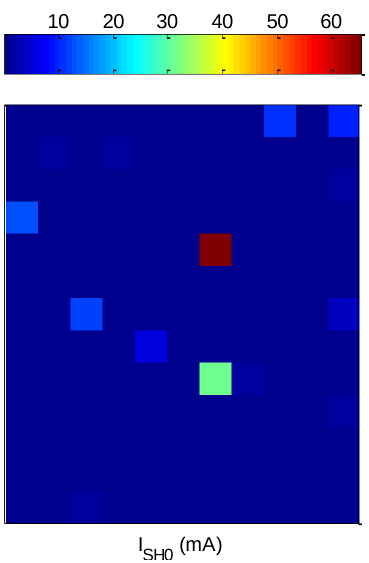
Efficiency recovery by local striping



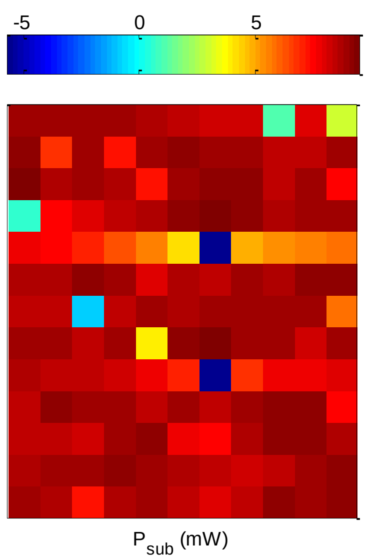


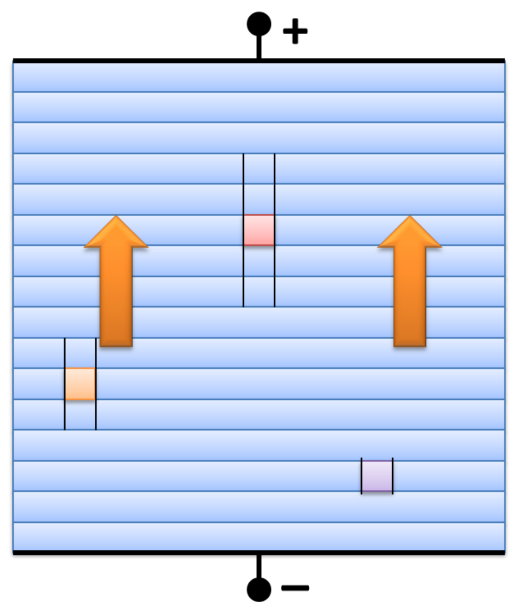


Current



Power



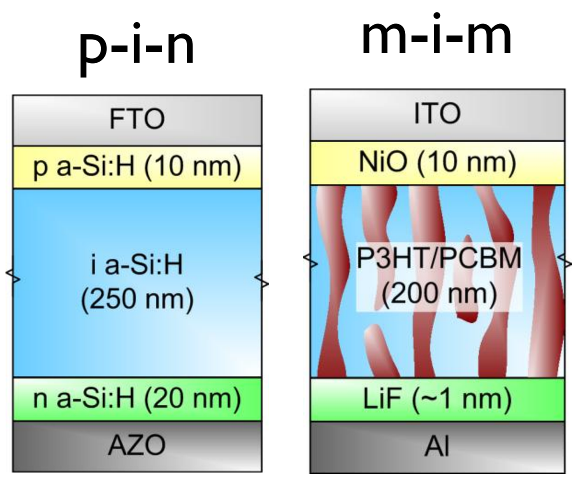


See S. Dogaonkar/Alam, IEEE J. Photovoltaics, 2013

Hierarchy of Thin Film solar cells

Cell → Module → Panel

1



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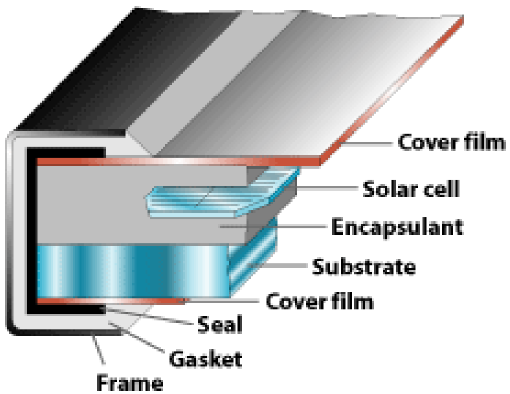

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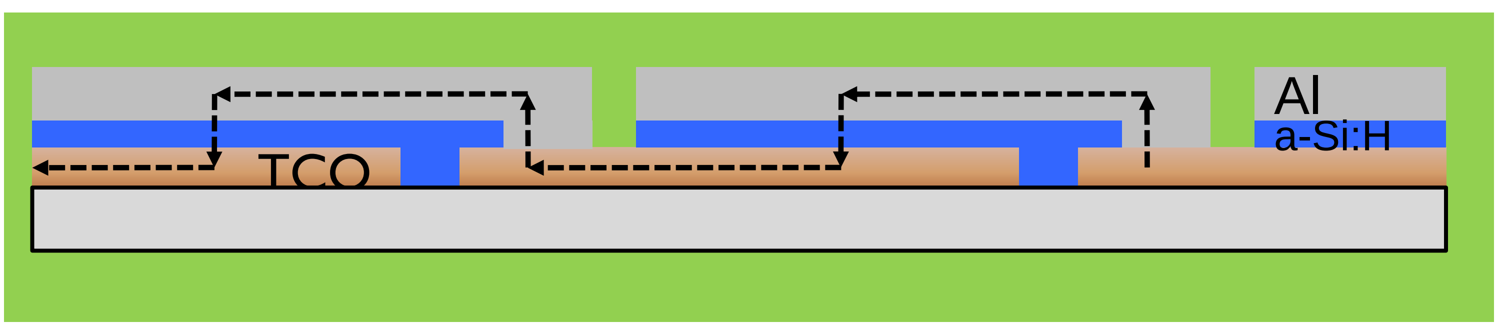
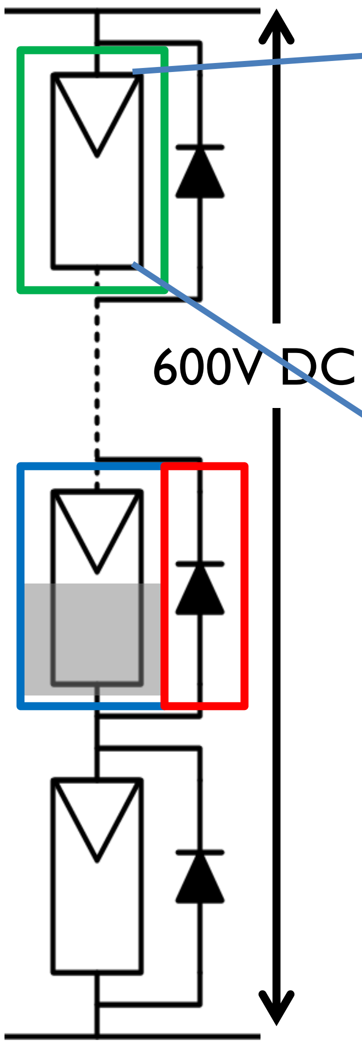
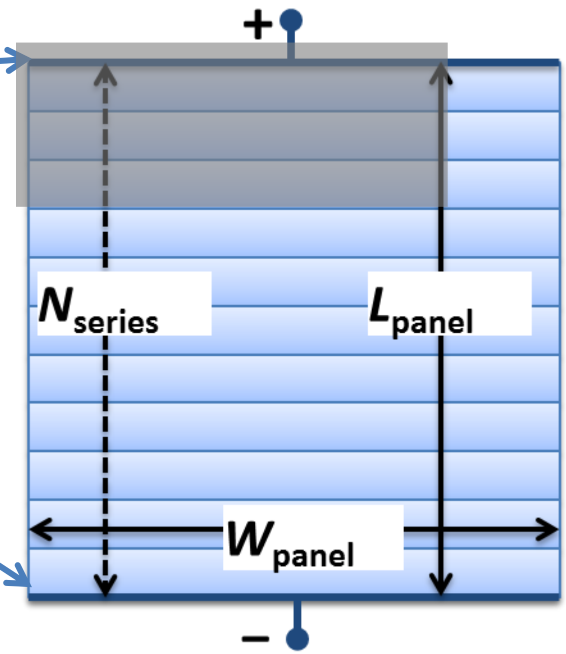


*Google Images

Partial shading in string architecture



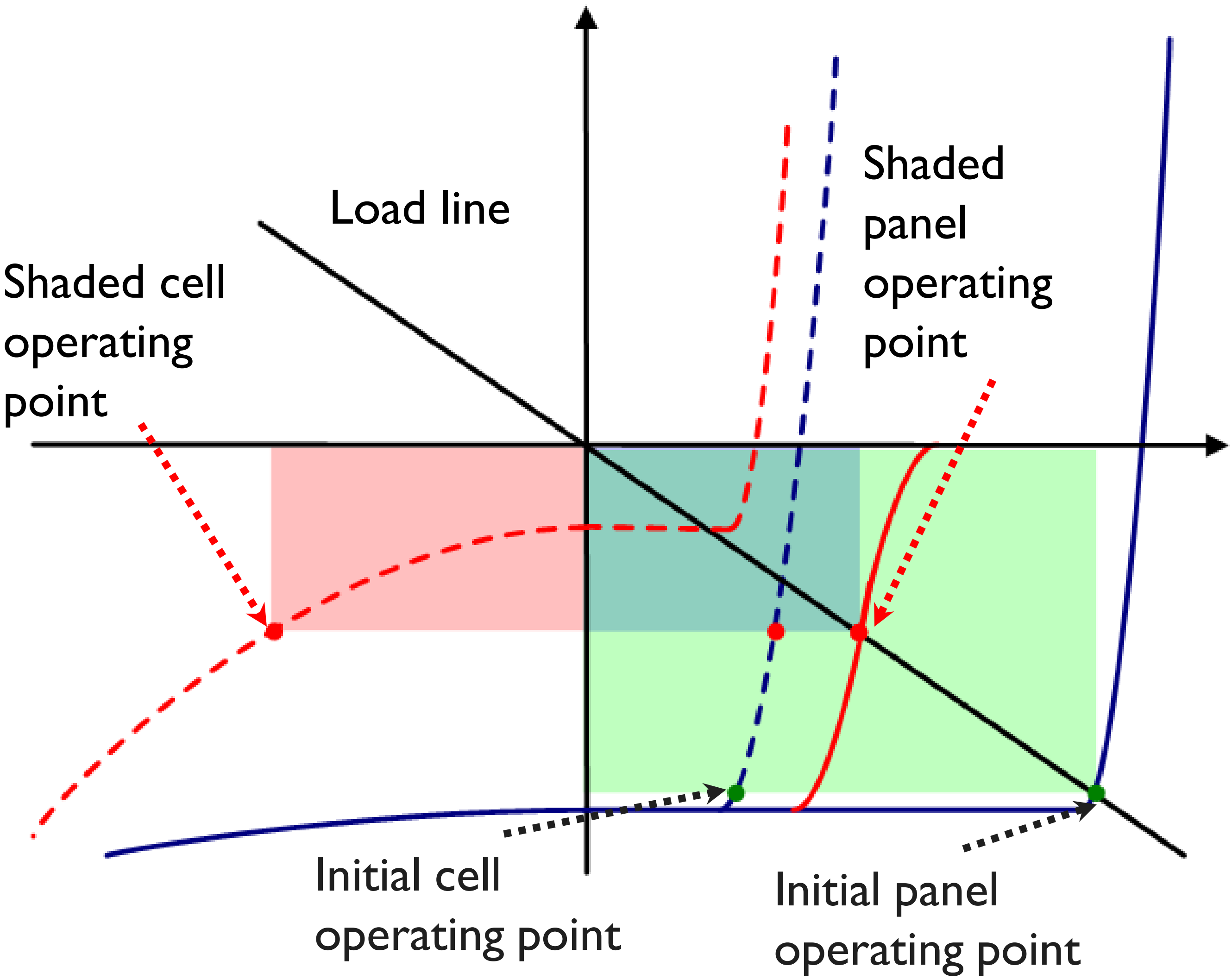


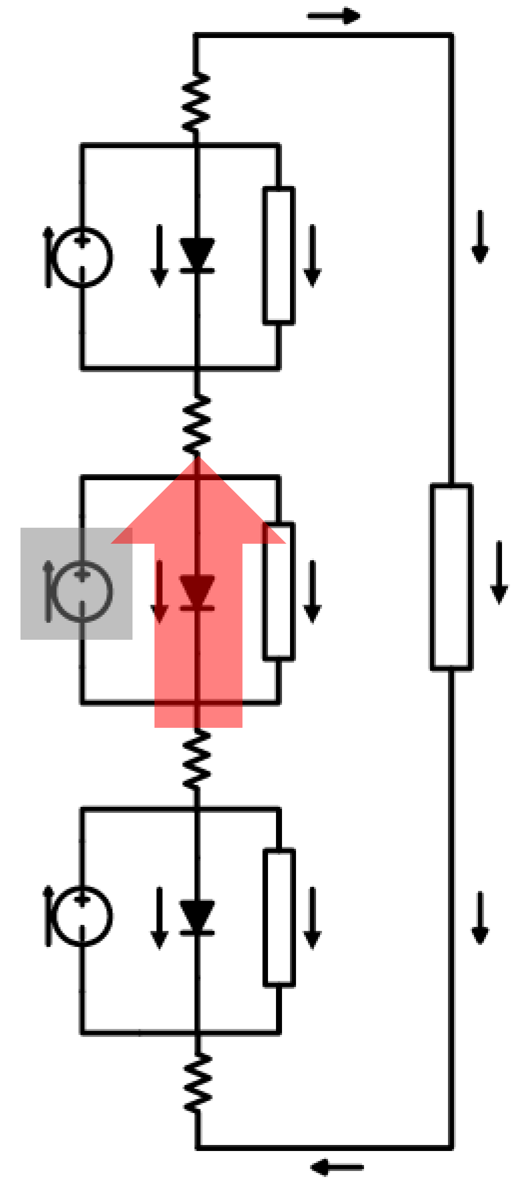
Typical large scale architecture

Only external bypass diodes

Cell shape/orientation are typically not considered

Being in shadow stresses the device

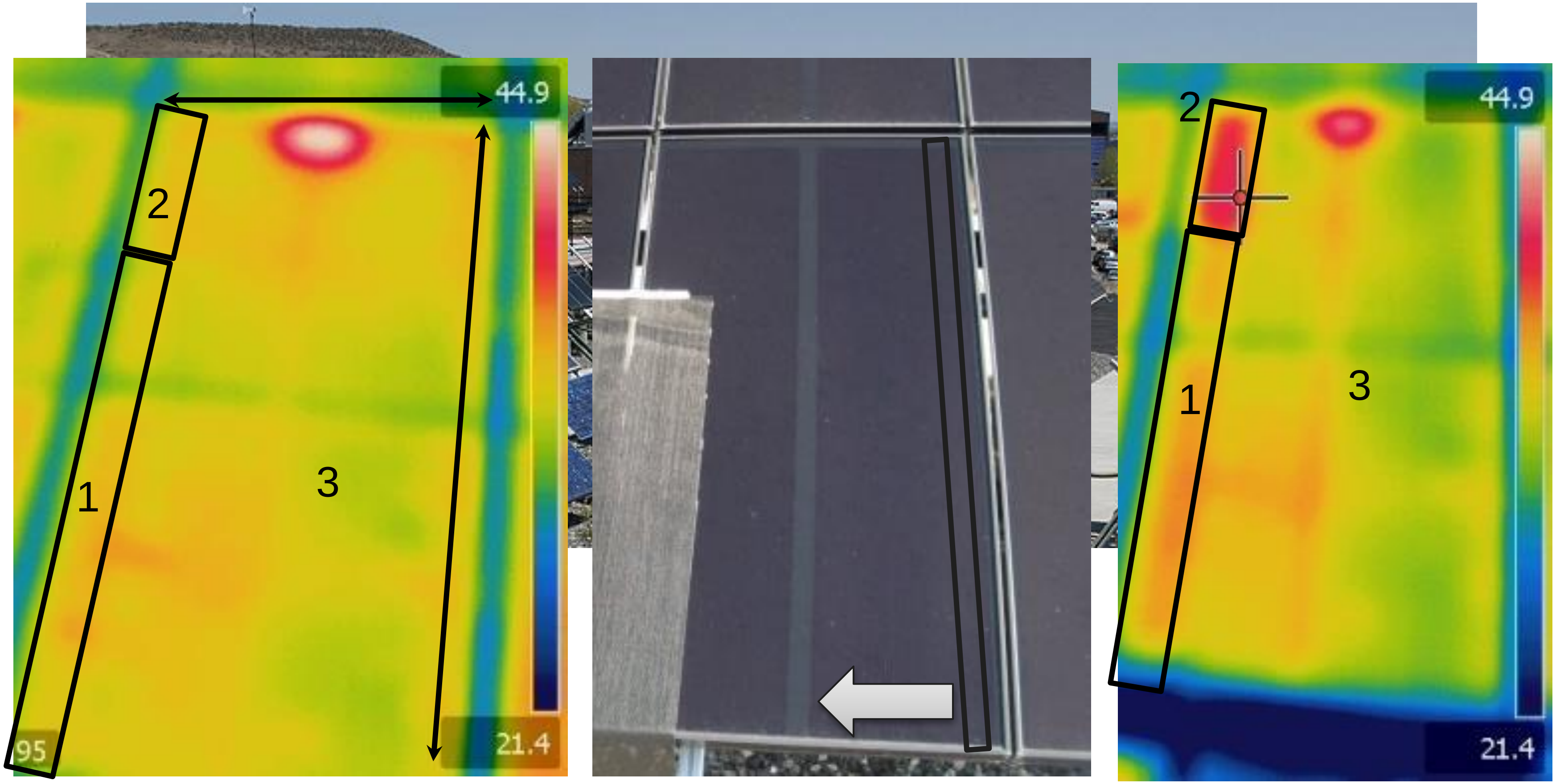




Shaded cells can get reverse biased!

Experimental validation of shadow stress

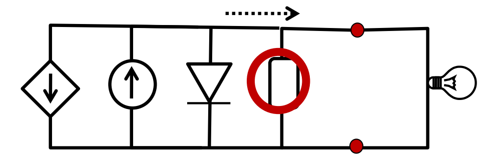
NREL outdoor test facility - Golden CO

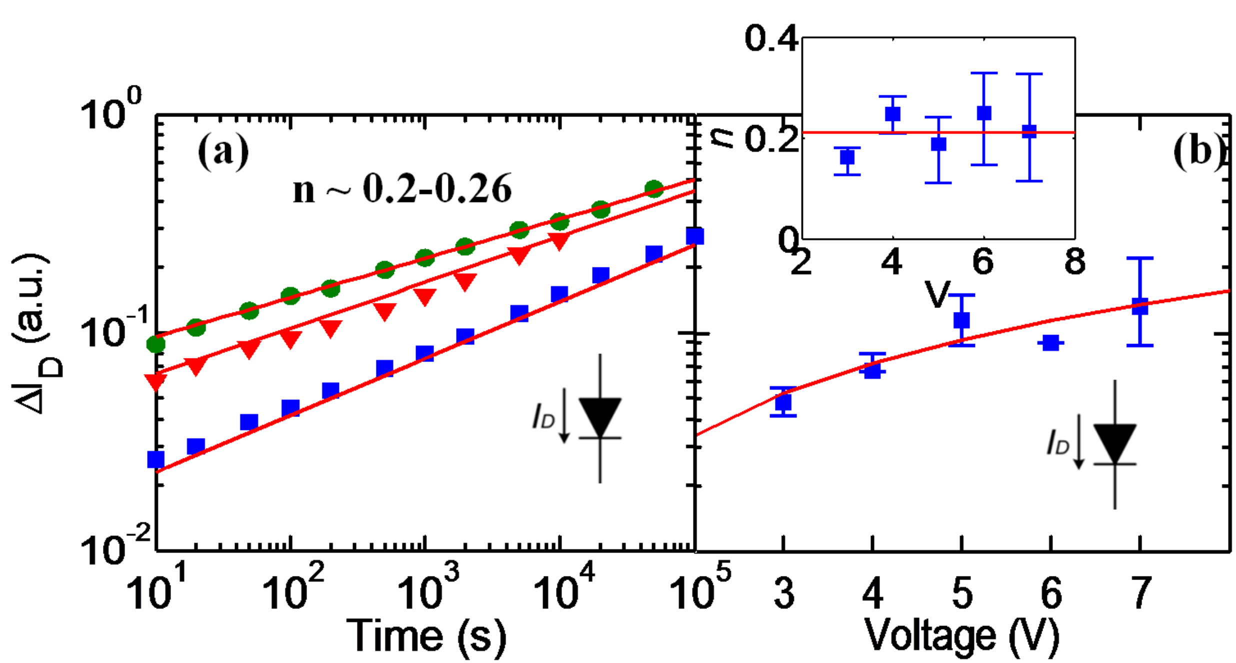


Current flow

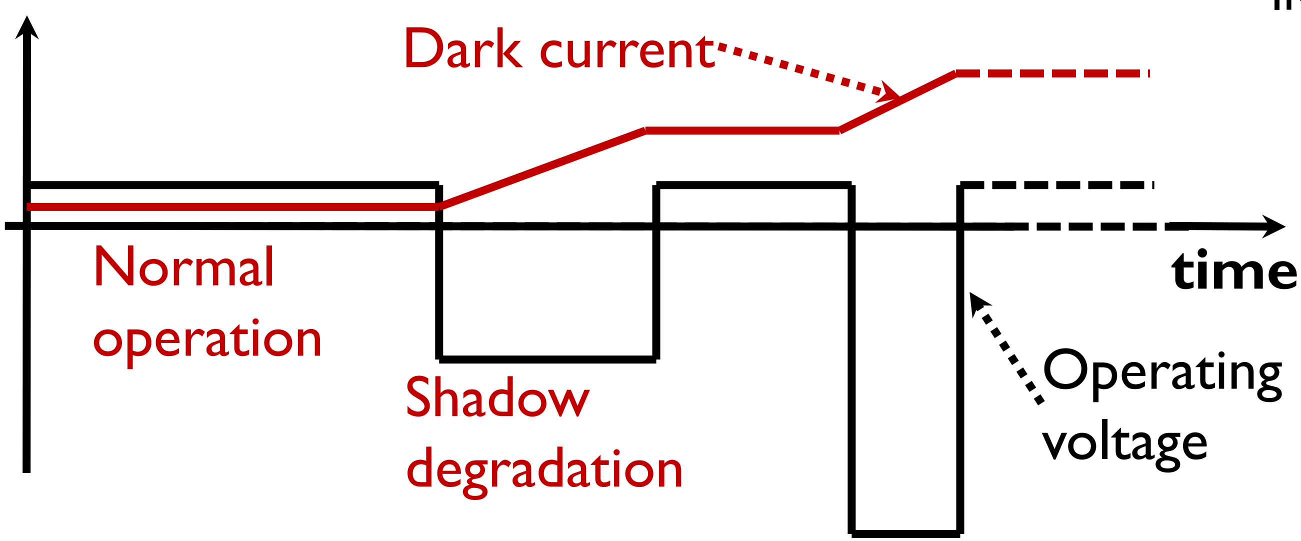
Asymmetric shadow stress confirmed by IR images of installed modules

Shadow degradation

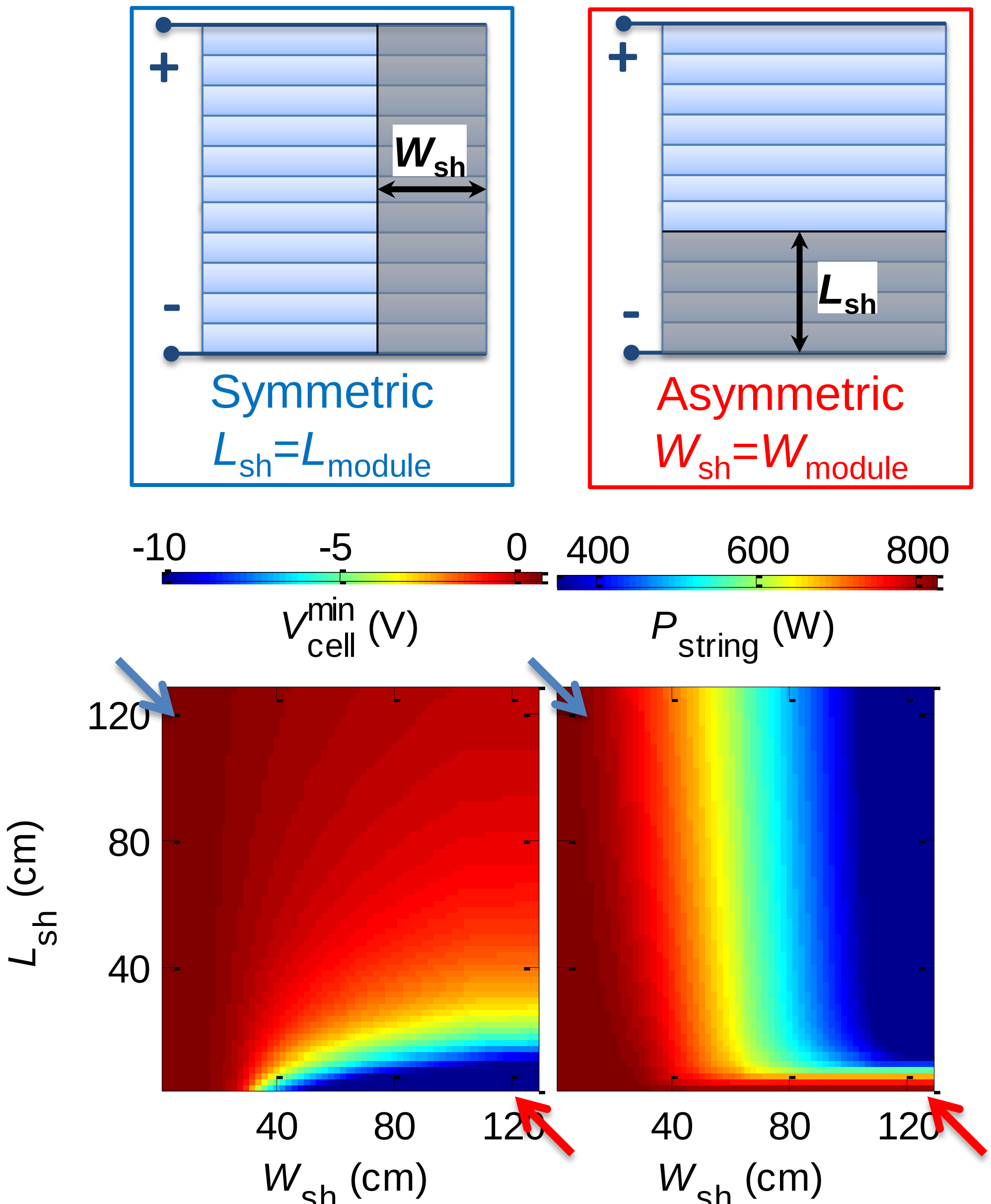




Dongaonkar et al.
IRPS 2011



Symmetry and Shadow in a TFPV



Partial shading can cause reverse breakdown

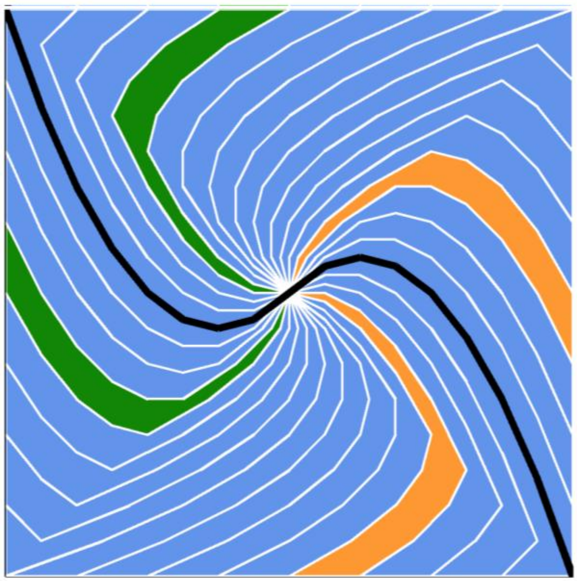
The power loss can be significant (30-40%) for large shadows

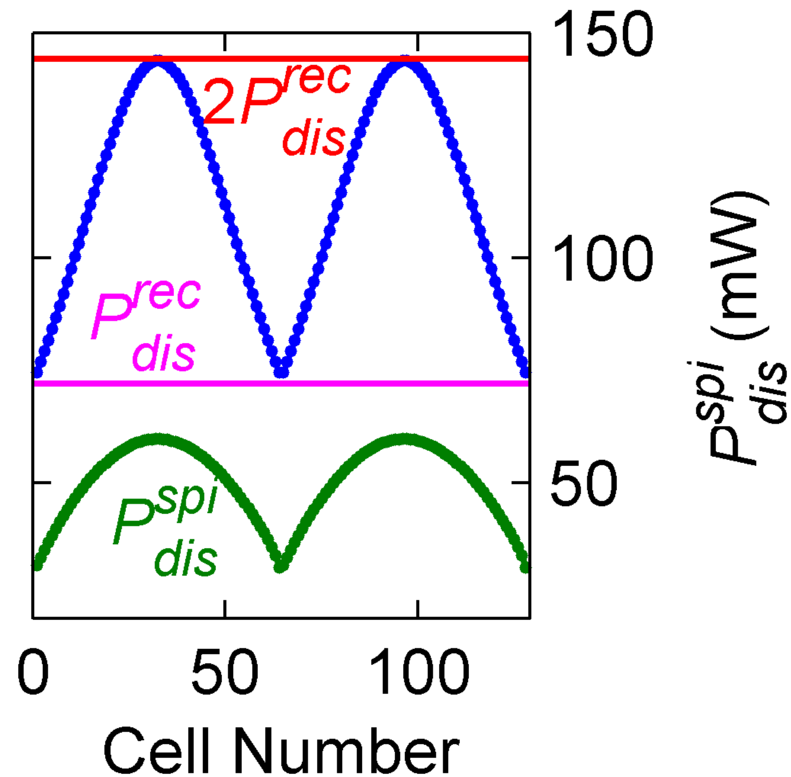
Symmetric shade does not cause reverse stress

Asymmetric case is most dangerous

External bypass is useless for cell protection

Shadow is rectangular, but cell need not be (exercise in constrained folding)





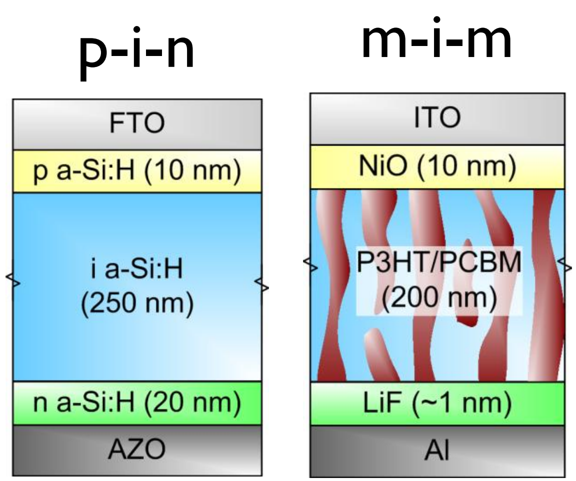
Better shade tolerance (fewer cases of reverse stress)
Significantly better power output under shading
No axis of rectilinear symmetry

Dongaonkar and Alam, Prog. in Photovoltaics, 2013.

Hierarchy of Thin Film solar cells

Cell → Module → Panel

1



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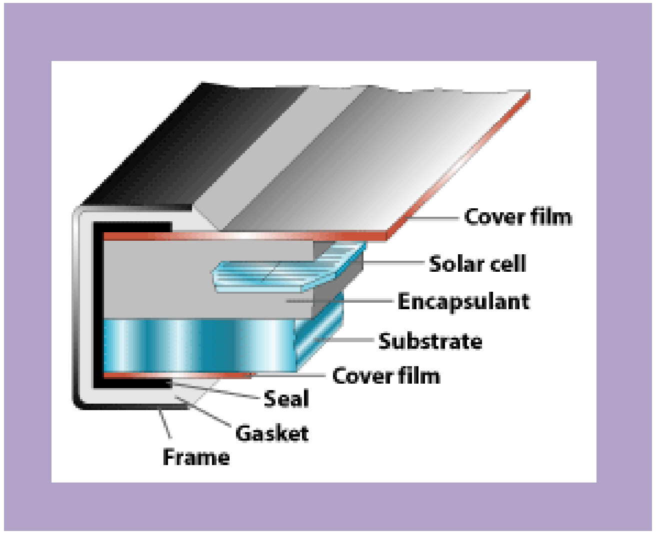

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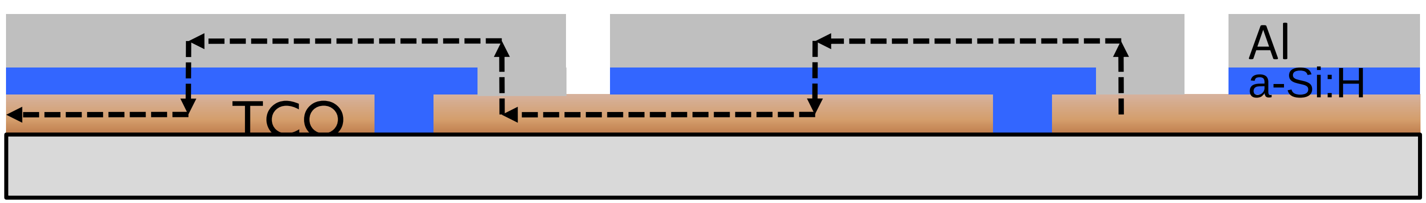
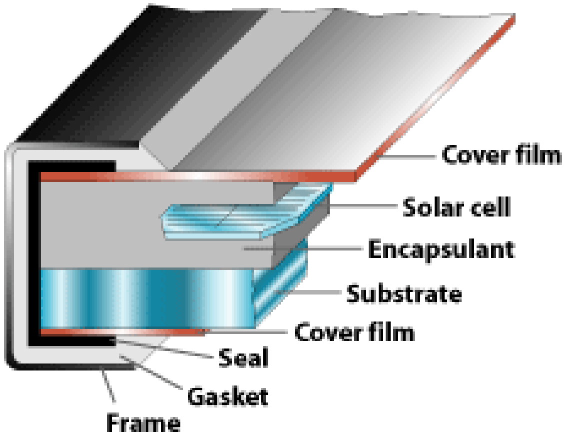


*Google Images

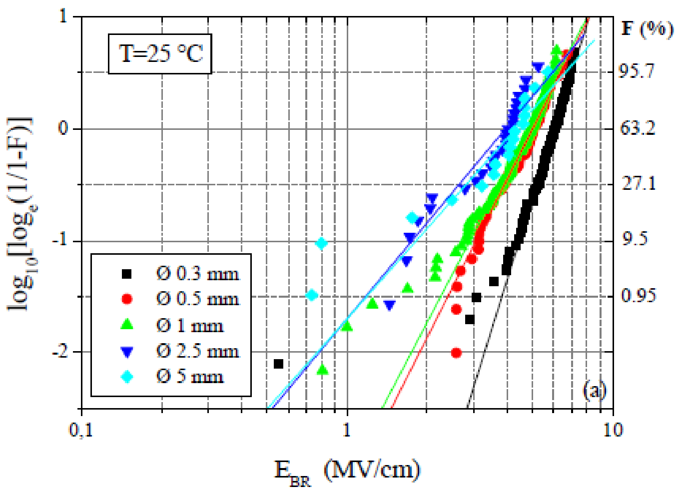
Reliability of polymers in solar cells

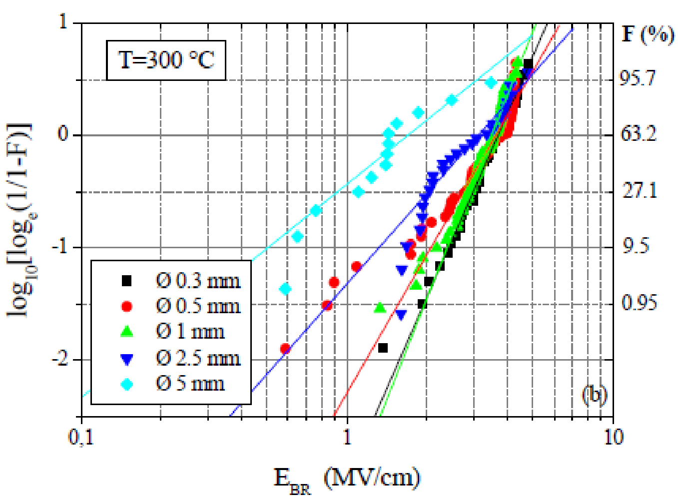


"*Even though polymers are a very promising material for the construction of PV modules, they are the reason of many failures and seem to be the weakest point of PV modules of our days.*" – Claudio Ferrara and Daniel Philip, Energy Procedia, 2012

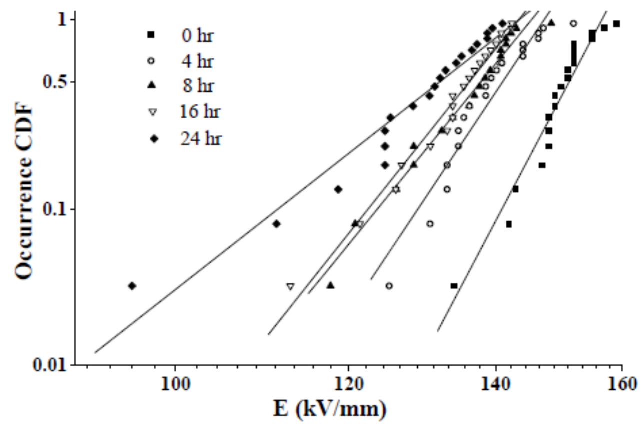
Review: Water treeing and Electrical breakdown of PI

E_{BR} Weibull for different thickness of dry PI at different temperatures. (Diaham et al., TDEI, 2010)

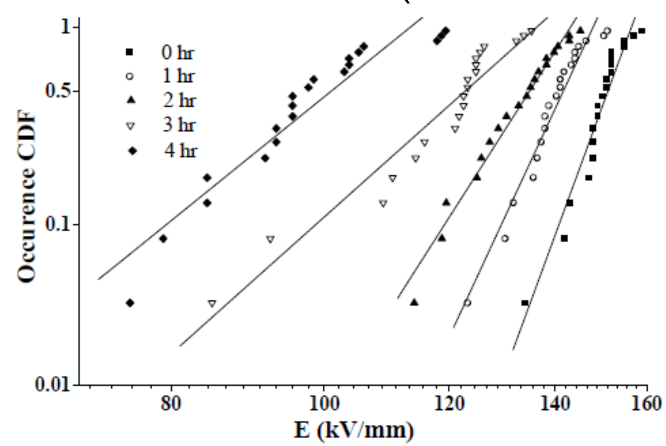




E_{BR} Weibull for varying times of PI water immersion. (Li et al., TDEI, 2011)



E_{BR} Weibull for varying times of PI heat treatment at 475^0C. (Li et al., TDEI, 2011)

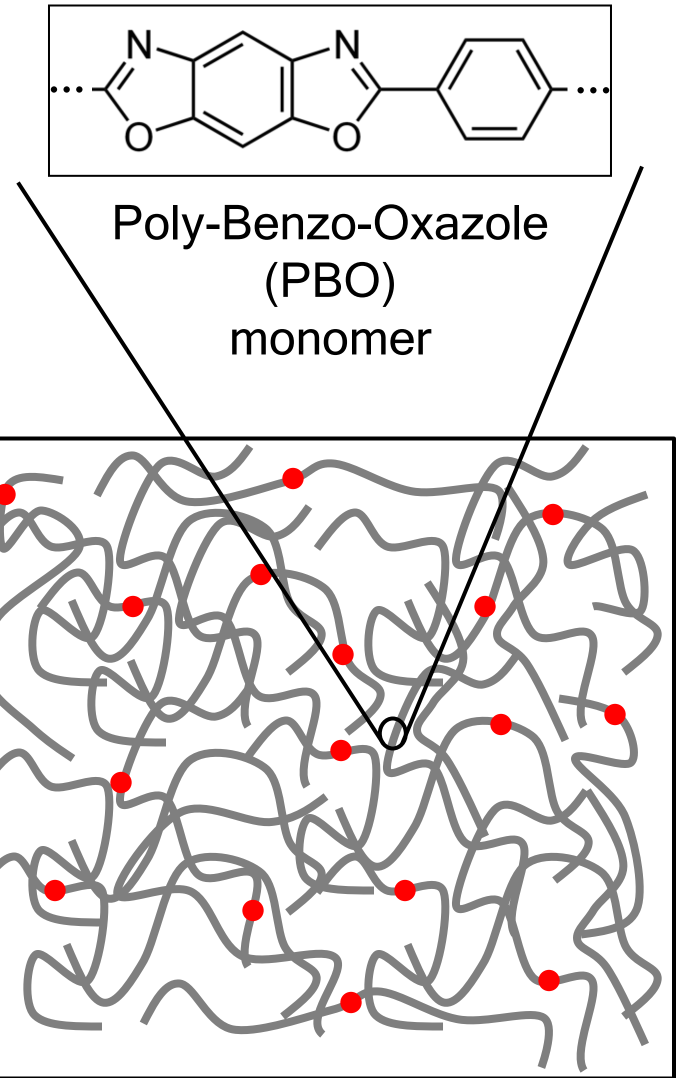


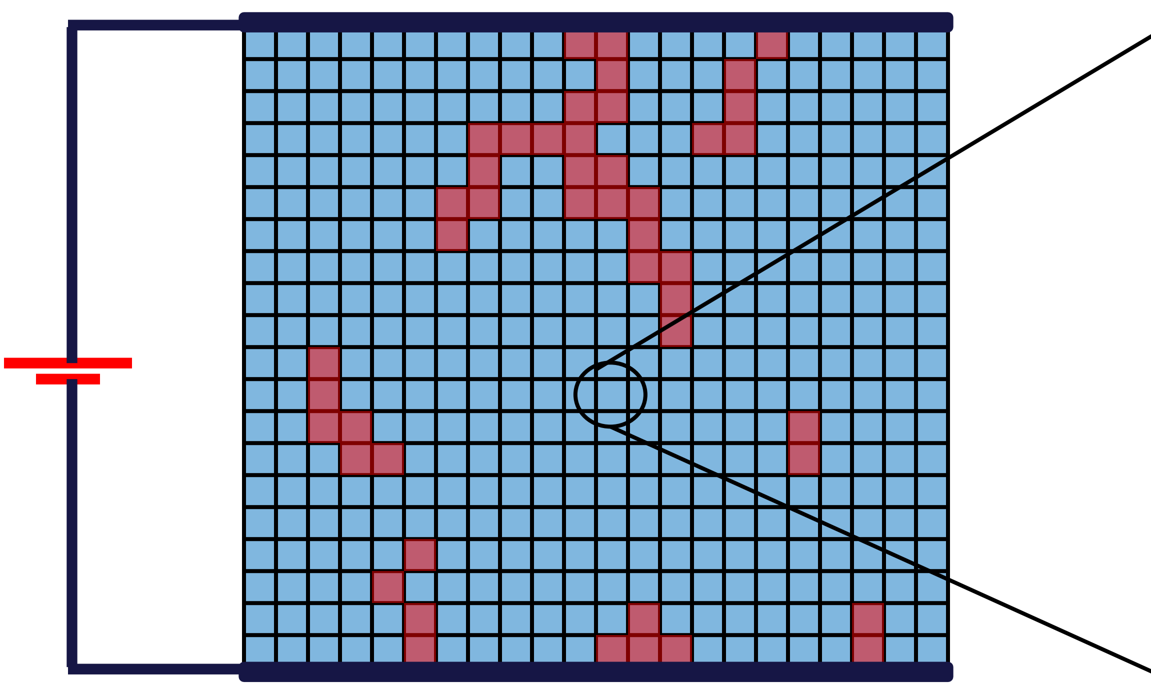
Thermo-chemical breakdown model

Breakdown kinetic equation

$$\frac{dN}{dt} = -N\frac{kT}{h}\exp\left(-\frac{\Delta H - aE}{kT}\right) = -k_{BD}N$$

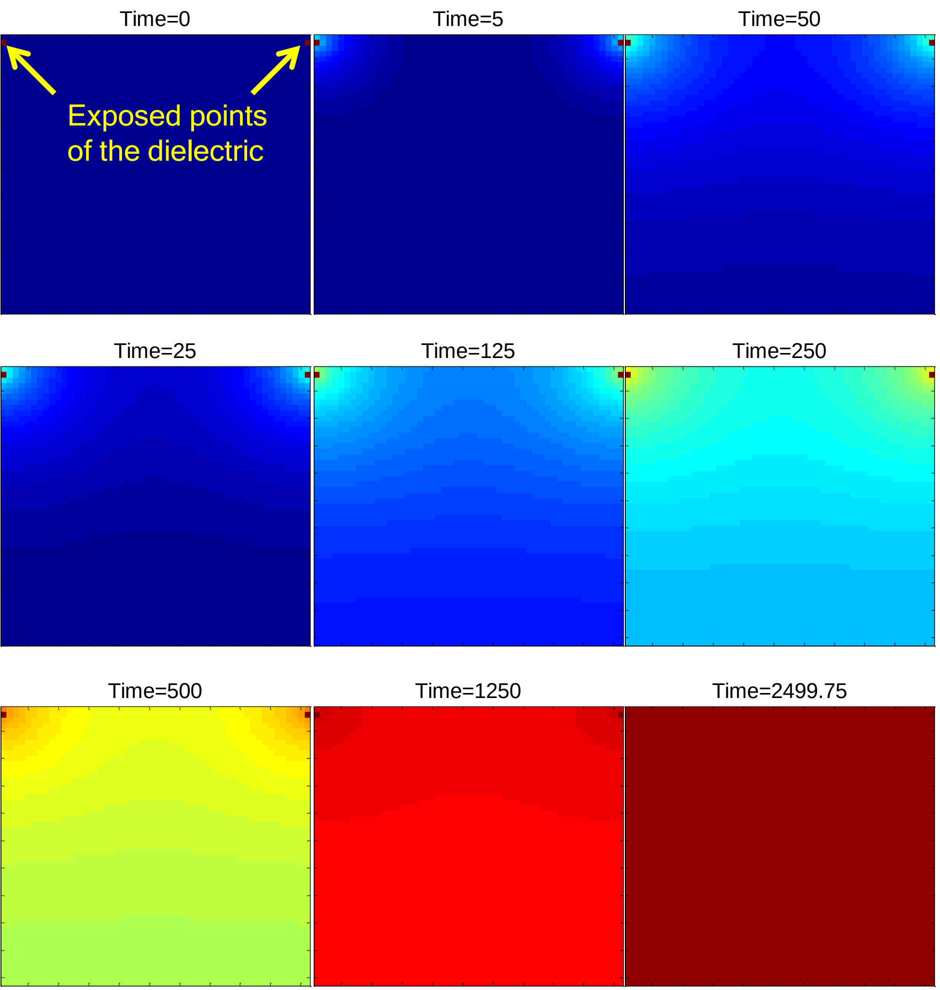
Breakdown of a grid-point occurs when: $\frac{N(t)}{N_0} = \eta = 0.5$



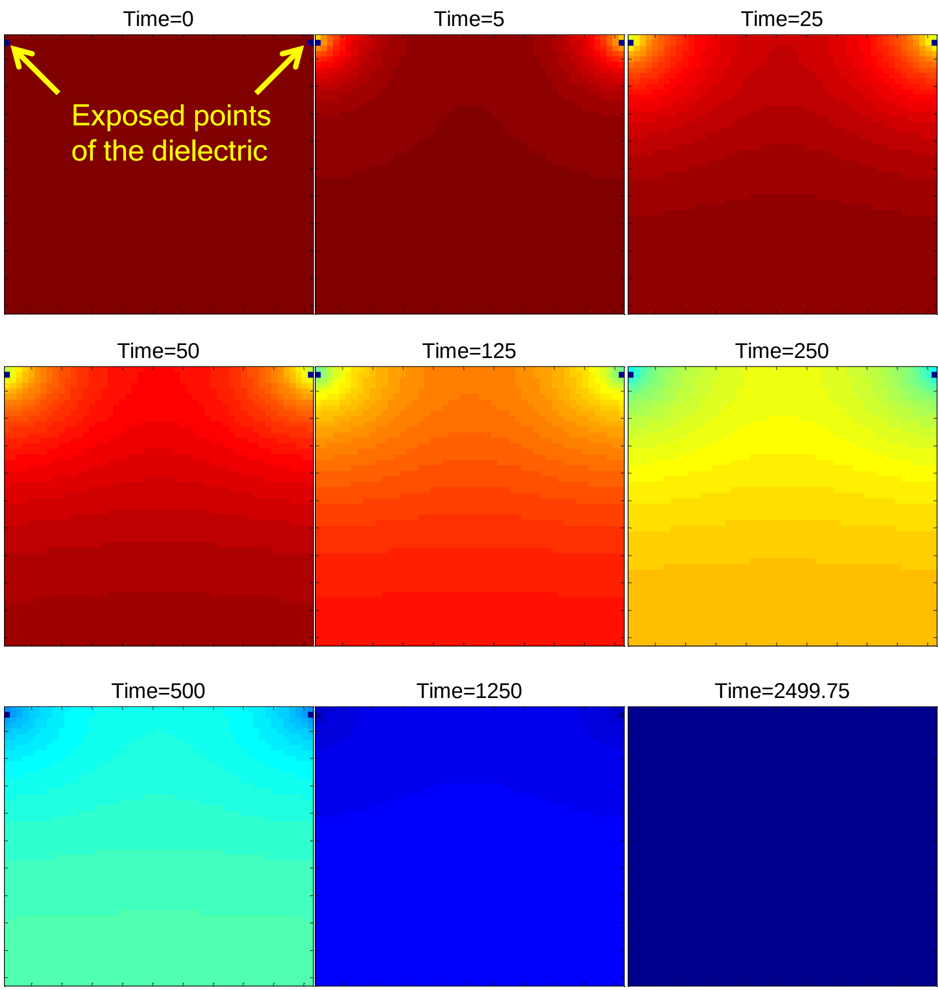


Water diffusion through polymers

Water uptake, initial PI is dry, ambient RH=100
$T_d = W = 5\text{mm}$, $D = 10^{-13}$



Water release, initial PI is wet, ambient RH=0
$T_d = W = 5\text{mm}$, $D = 10^{-13}$

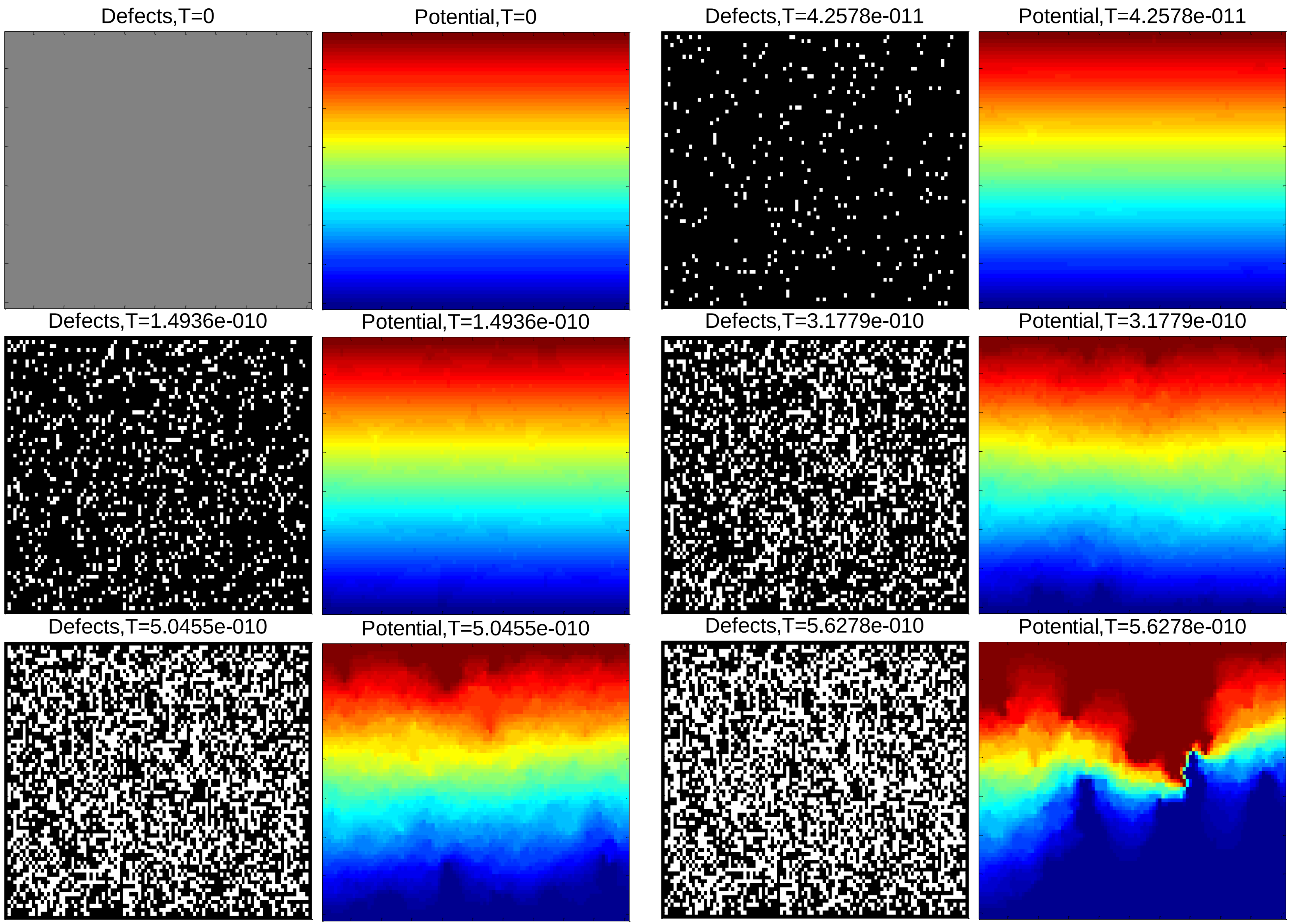


Breakdown simulations

Base dielectric:
W=100nm
T_d=70nm
V=70V

Left: Discharge pattern

Right: Potential profile



Conclusions: Complex need not be complicated

1. Energy output depends on panel efficiency and lifetime – there is an opportunity to develop physics based reliability models.
2. Shunt conduction and series resistances are key to solving the efficiency gap. Shadow, light, and thermal degradations limit lifetime. Offers opportunities for great contributions.
3. A software framework is necessary to interpreted correlated and hierarchical degradation effects. We are making progress.
4. A series of YouTube lectures on basics of solar cells. Also see https://sites.google.com/site/ece654solarcells/ for papers from our group and nanohub.org/resources/16560 for a course on Reliability.

Questions/comments: alam@purdue.edu

References from my group

For Dark current and shunt analysis, see

S. Dongaonkar, J. D. Servaites, G. M. Ford, S. Loser, J. Moore, R. M. Gelfand, H. Mohseni, H. W. Hillhouse, R. Agrawal, M. A. Ratner, T. J. Marks, M. S. Lundstrom, and M. A. Alam, "Universality of non-Ohmic shunt leakage in thin-film solar cells," Journal of Applied Physics, vol. 108, no. 12, p. 124509, 2010.

S. Dongaonkar, S. Loser, E. J. Sheets, K. Zaunbrecher, R. Agrawal, T. J. Marks, M. A. Alam, "Universal Statistics of Parasitic Shunt Formation in Solar Cells, and its Implications for Cell to Module Efficiency Gap," Energy & Environmental Science, 2013, 10.1039/C3EE24167J.

S. Dongaonkar, K. Y., S. Mahapatra, and M. A. Alam, "Physics and Statistics of Non-Ohmic Shunt Conduction and Metastability in Amorphous Silicon p–i–n Solar Cells," IEEE Journal of Photovoltaics, vol. 1, no. 2, pp. 111–117, Oct. 2011.

The effect of partial shading is discussed in

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