EY of Colored Perovskite BIPVs and Partial Shading Analysis

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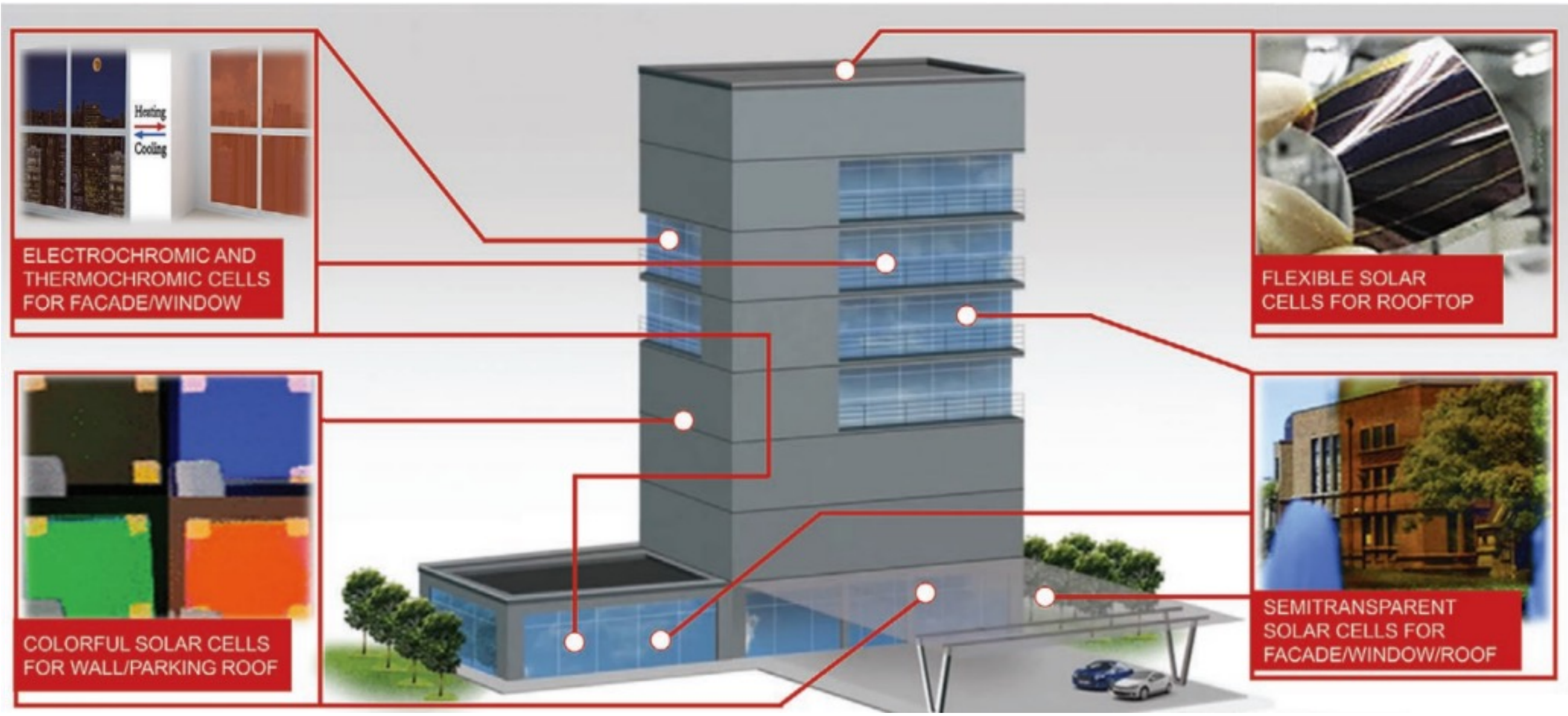
Colored Solar Cells: Why are they Important?

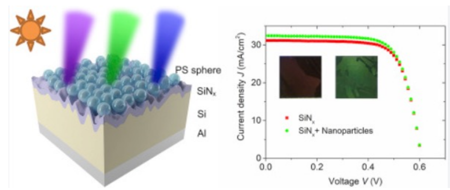


- Traditional (c-Si) solar cells are used only on rooftops, due to poor aesthetics and installation constraints
- Colorful perovskite solar cells (PSCs) enables good aesthetic while being efficient

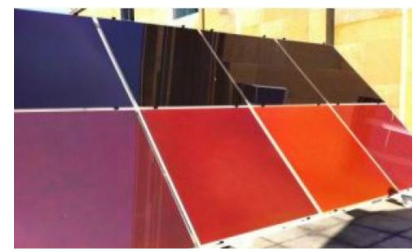
External Methods for Colored PVs

- Automotive paints on glass
- Ceramic inks on glass

- Scattering EVA foils

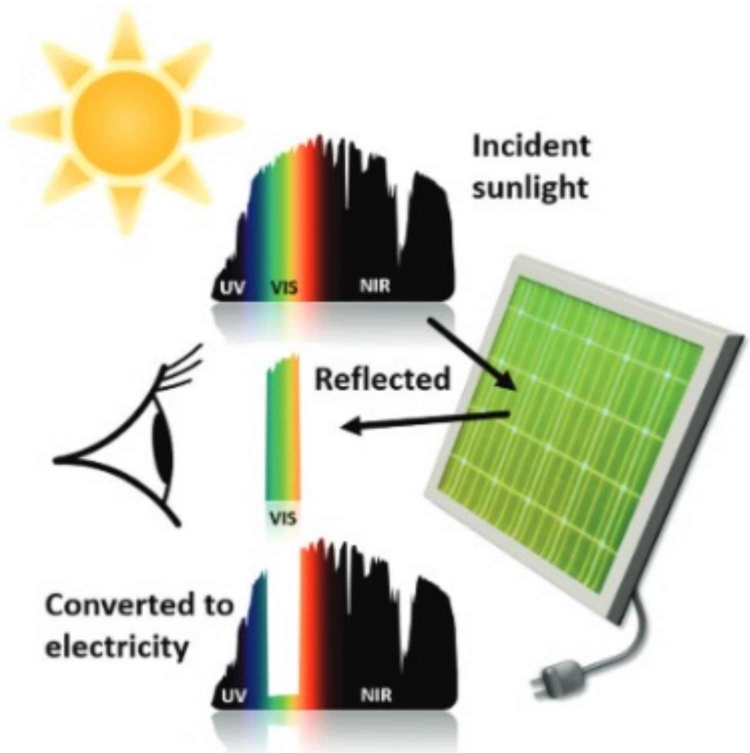


- Dielectric resonant nano scatters



- Color filters
  - Applicable on both cells and glass
  - Color purity
  - Limited PV performance losses

Efficiency Limit of a Colored Solar Cell

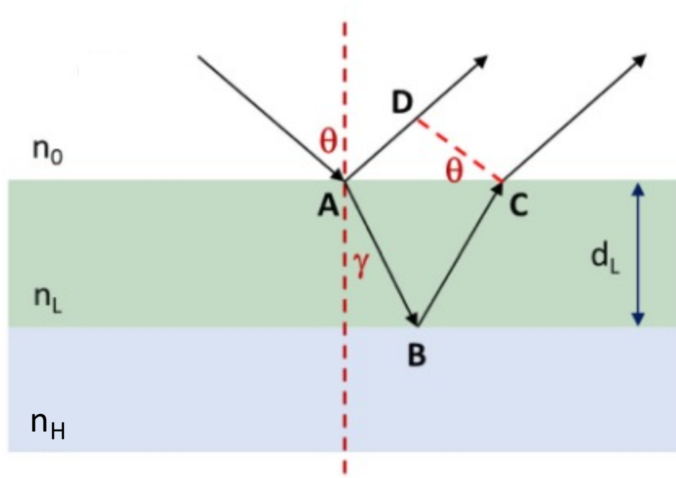


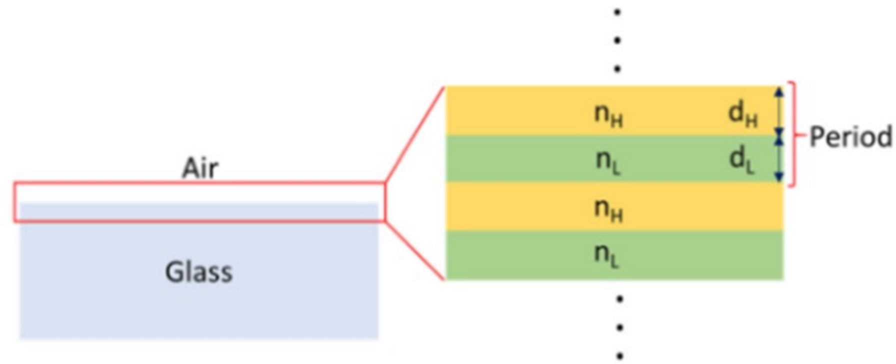
Performance loss depends on:

- Hue (λ)
- Brightness (Luminosity or AVR)
- Color Purity (FWHM)

J. Halme et al., *Energy Environ. Sci.*, 2019, 12, 1274–1285

Working Principles of a Color Filter





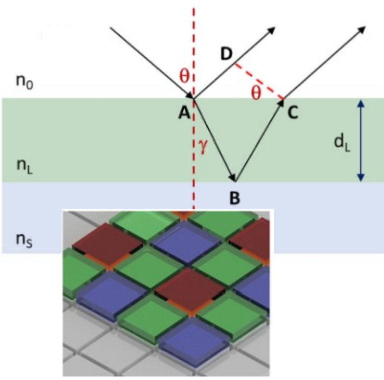
$$R = \left(\frac{1 - \left(\frac{n_H}{n_L}\right)^{2p} \cdot \frac{n_H^2}{n_s}}{1 + \left(\frac{n_H}{n_L}\right)^{2p} \cdot \frac{n_H^2}{n_s}} \right)^2$$

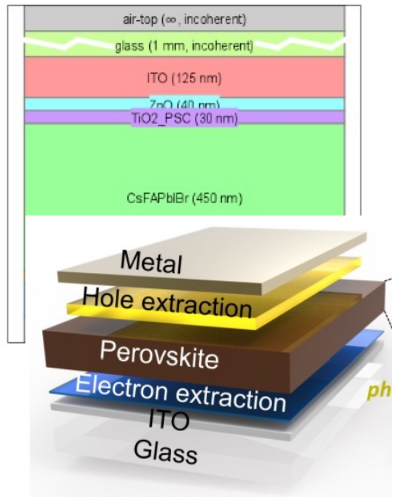
$$\text{FWHM} = \frac{4}{\pi} \cdot \sin^{-1}\left(\frac{n_H - n_L}{n_H + n_L}\right)$$

- $n_0 < n_L < n_H$
- Light interference between reflection in A and C
- Constructive interference if $2 n_L d_L \cos(\gamma) = m\lambda$

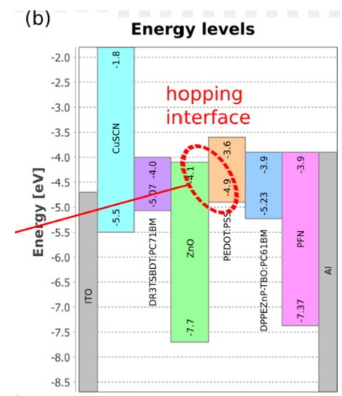
J. C. Ortiz Lizcano *et al.*, *Progress in Photovoltaics*, 2022, 30, 401–435

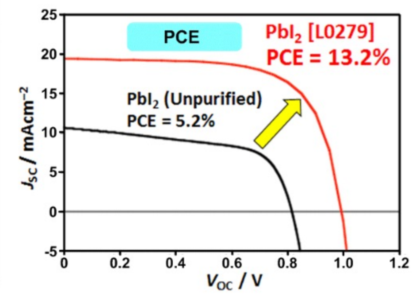
Combined Electro-Optical Simulation of Perovskite PVs





Initial Optical simulation of Filters and the stack in the PSC





Electrical + optical simulation of the Colored PSC

Simulations of PSC with a Narrow-bandwidth Filter

Emission

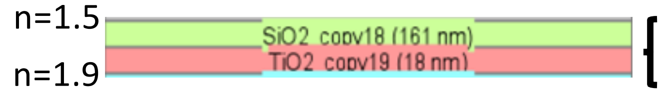
Drift-Diffusion

Advanced Optics

Absorption

Simulation software for opto-electrical modeling

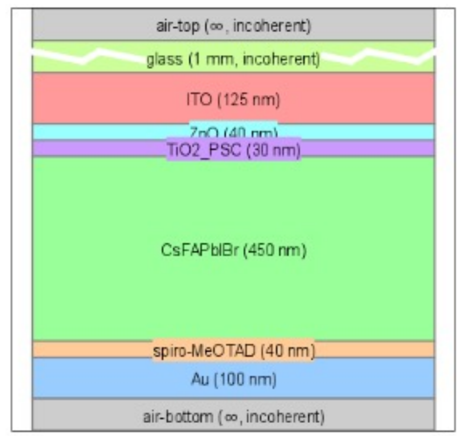
Period



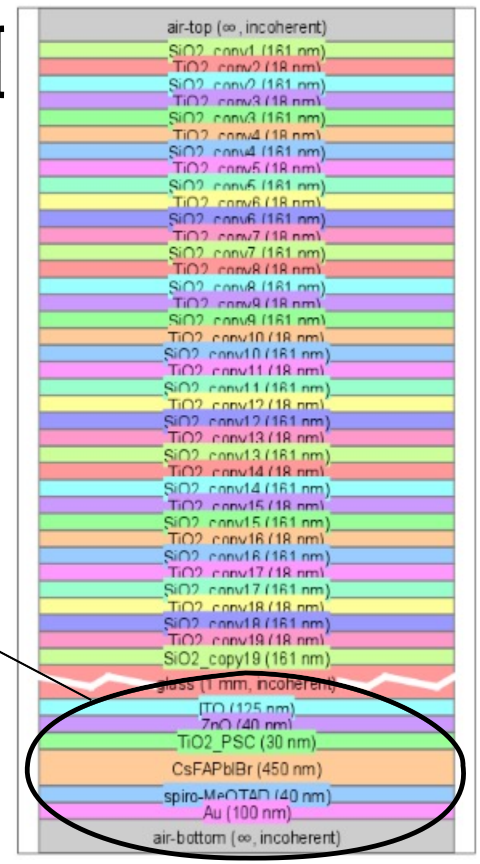
Filter-less solar cell with 20% PCE

Bandgap = 1.61 eV

Narrow-band reflective filter (NBRF)



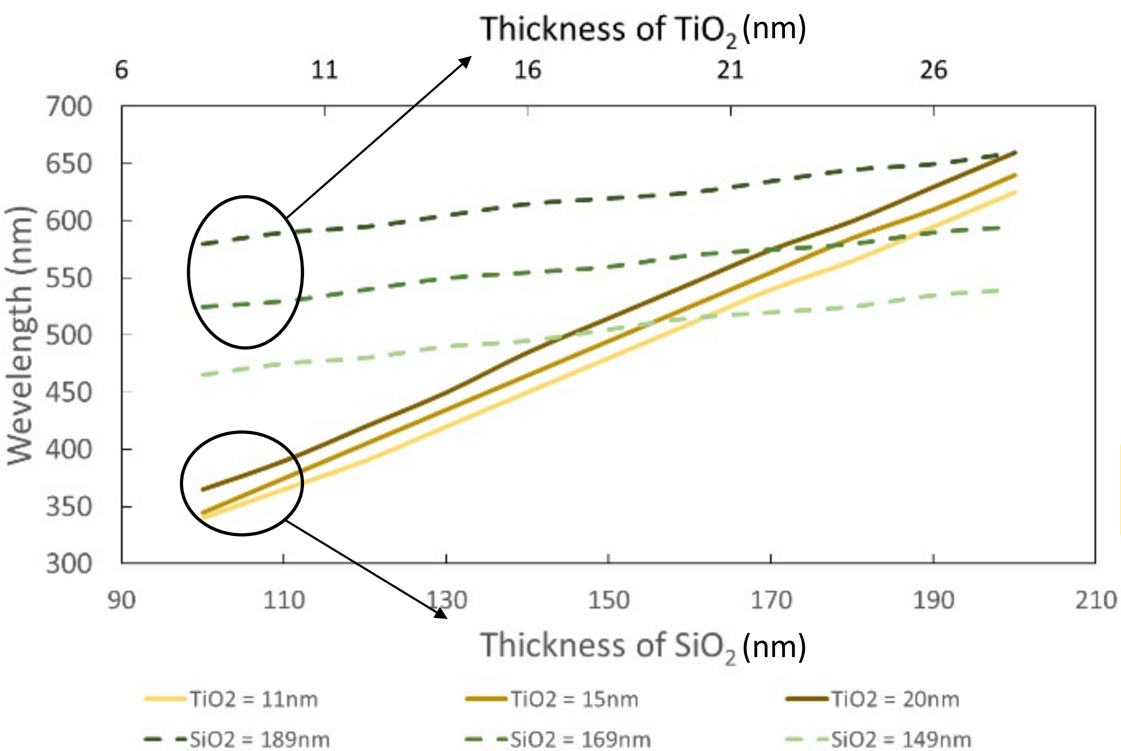
Layer structure

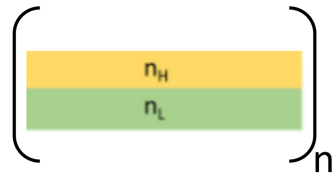


G. Y. Yoo *et al.*, *ACS Nano*, 2019, 13, 10129–10139 (experiments)

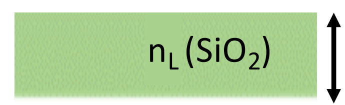
Design of the Optical Filter (λ)

Green Solar Cell

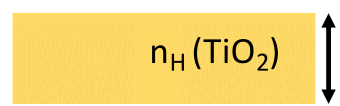




$\# \, periods \rightarrow no \, effect$

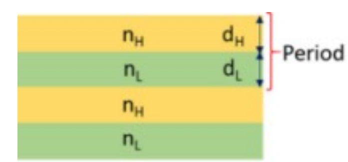


$increase \; d_L \propto \lambda$

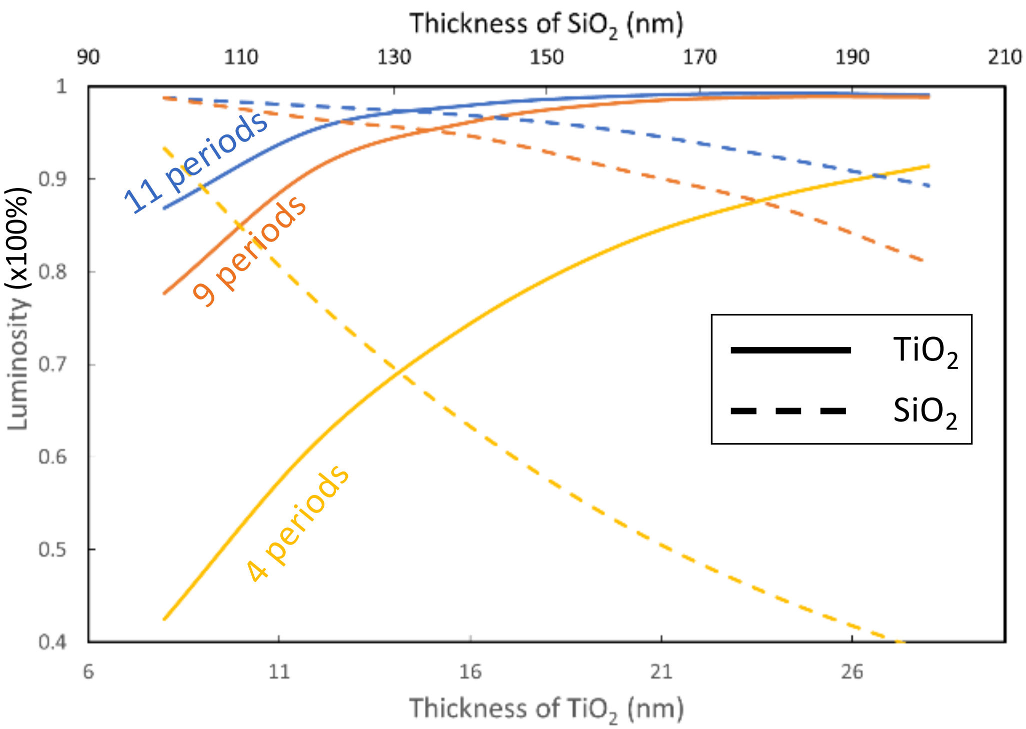


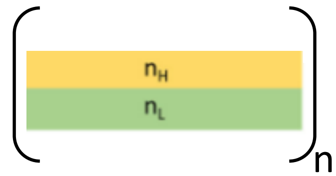
$increase \; d_H \propto \lambda$

Absorption

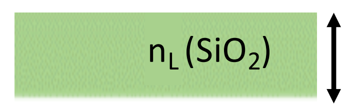


Design of the Optical Filter (Luminosity)

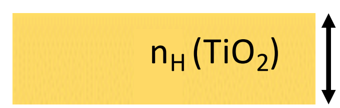




$$\# \, periods \propto luminosity$$

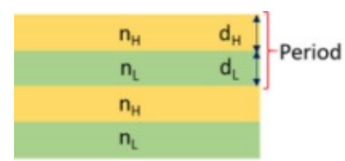


$$increase \; d_L \propto \frac{1}{luminosity}$$

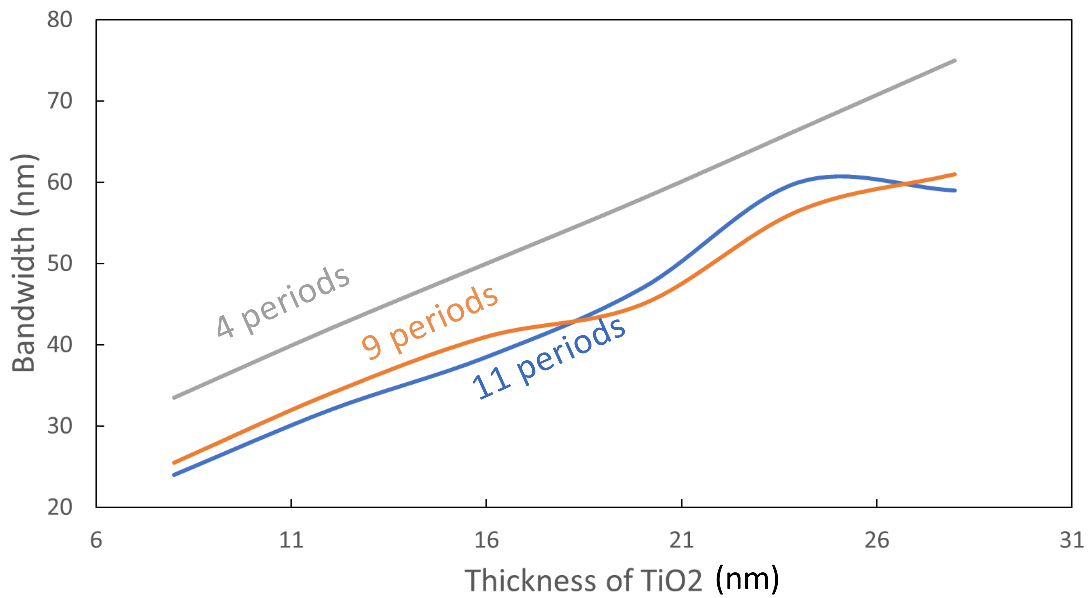


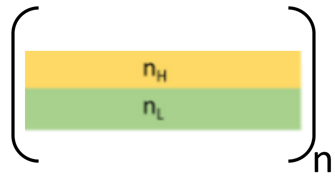
$$increase \; d_H \propto luminosity$$

Absorption

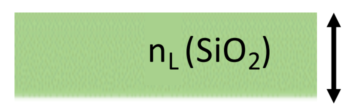


Design of the Optical Filter (FWHM)

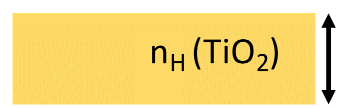




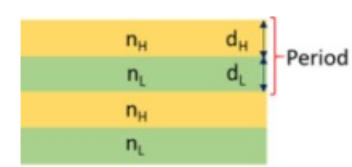
$$\#\, periods \propto \frac{1}{FWHM}$$



$$increase\ d_L \rightarrow no\ effect$$

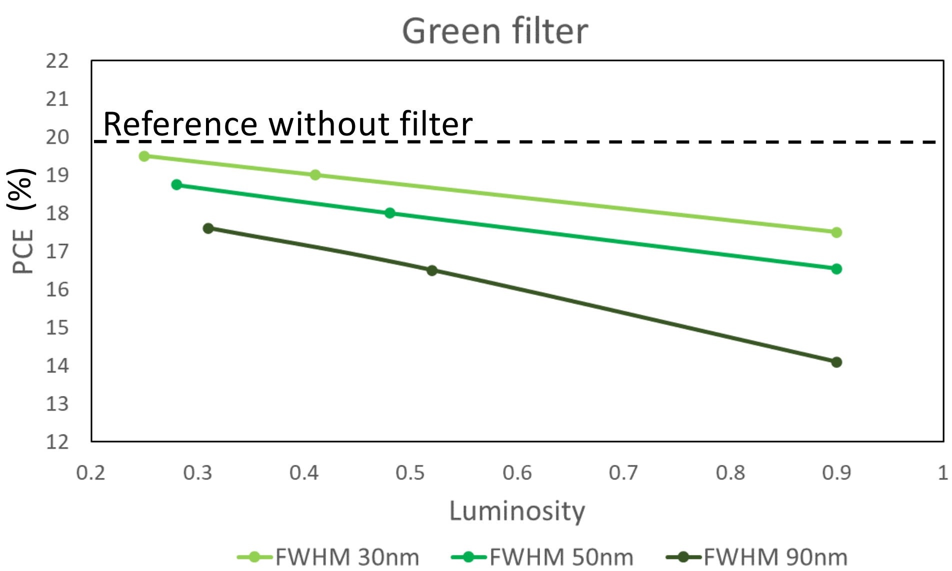


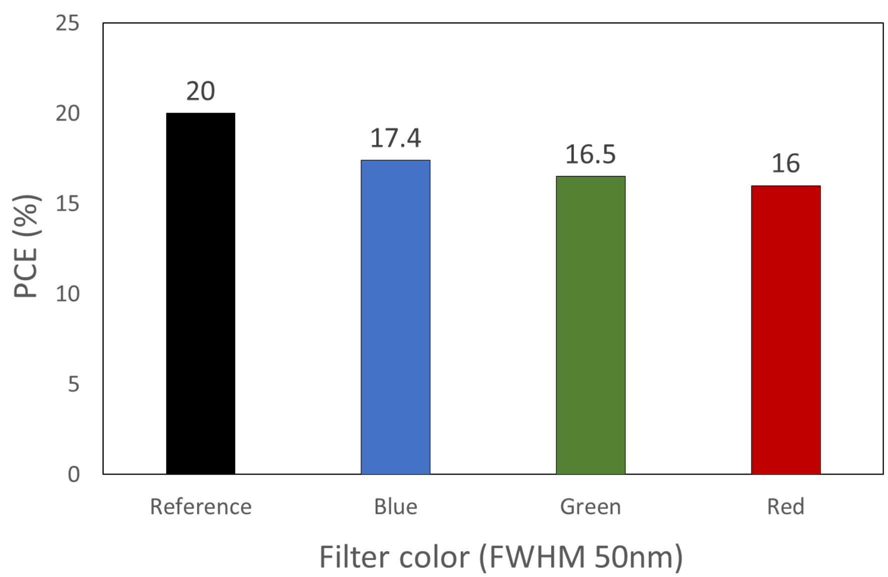
$$increase\ d_H \propto FWHM$$



Absorption

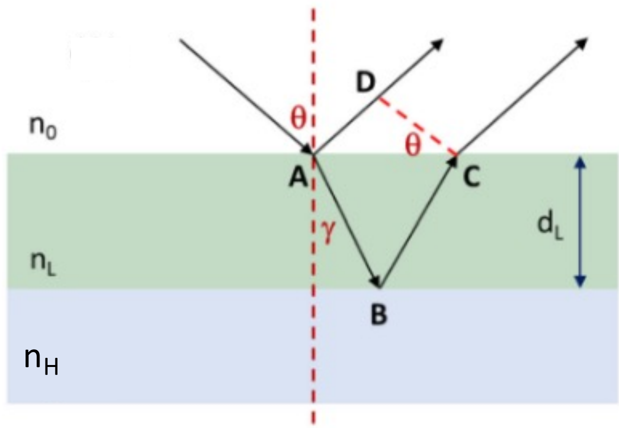
Impact of FWHM, Color and Luminosity on the PSC Efficiency



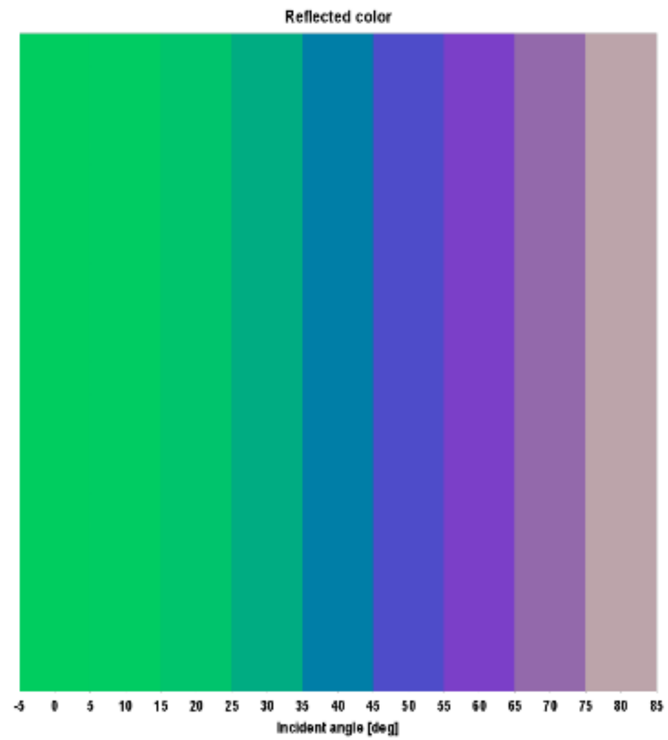


- Up to 30% PCE loss with FWHM 90nm green filter (Perovskite PV)
- 20% PCE loss between reference and red filter with FWHM of 50nm

Drawbacks: The Reflected Color has an "Angular Instability"



$$2n_L d_L \cos(\gamma) = m\lambda$$

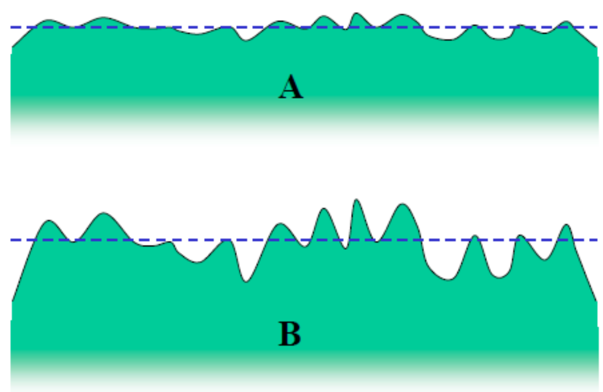


- Illumination wavelengths with constructive interference depends on incident angle
- Blue-shift of reflected color with increasing incident angle

The Roughness Modifies the Light Path

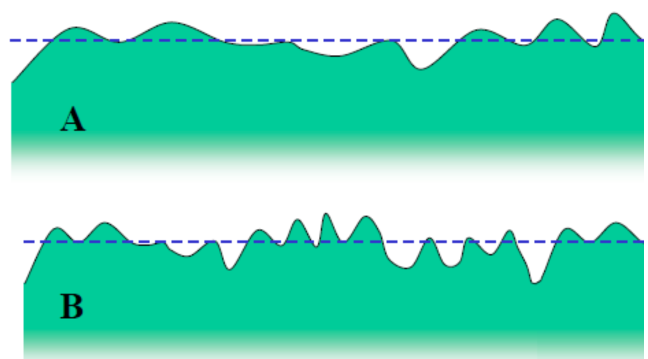
RMS = vertical roughness

RMS of B > RMS of A



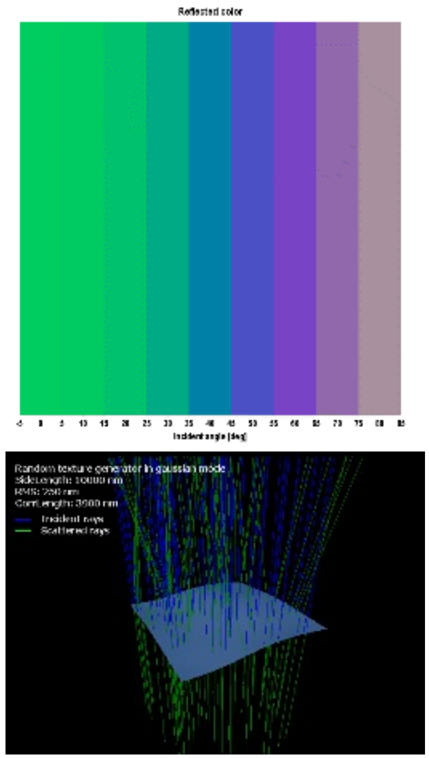
Correlation length = horizontal roughness

RMS(A) = RMS(B)
Corr. length of A is bigger than B

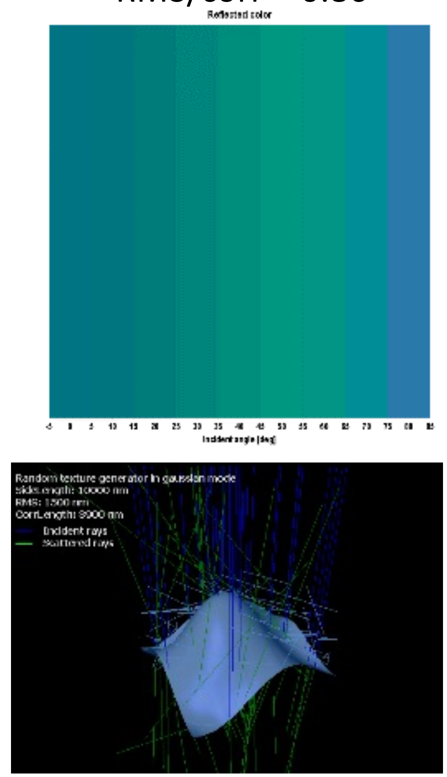


Impact of Scattering on Color Stability

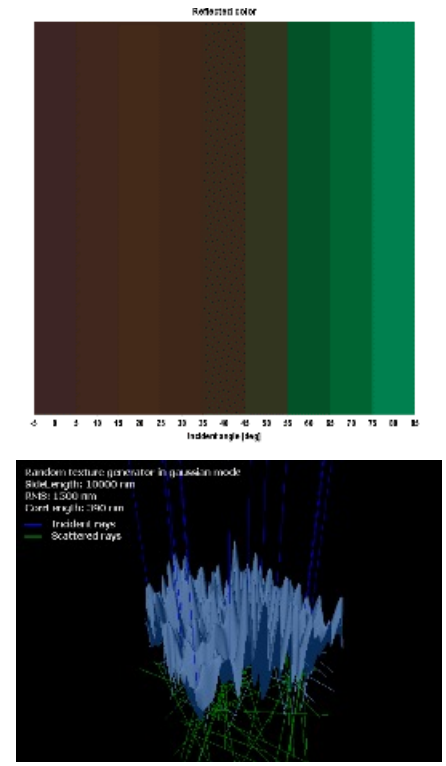
RMS/corr = 0.08

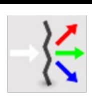


RMS/corr = 0.86



RMS/corr = 4.13





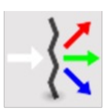
Advanced Optics

Absorption

- RMS/corr ≈ 1 reduces color-shift at all angles
- Reflection intensity is reduced

Which is the Energy Yield (EY) of a our Pero-PVs?

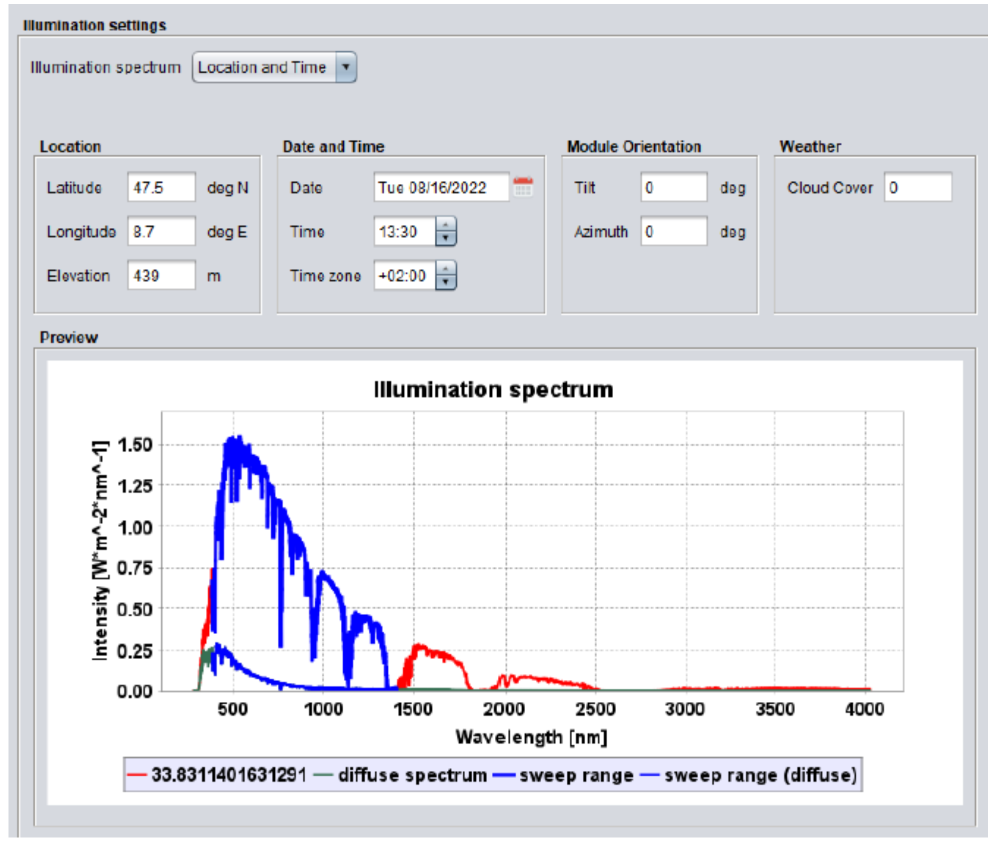
Simple Model for the Atmospheric Radiative Transfer of Sunshine (SMARTS)



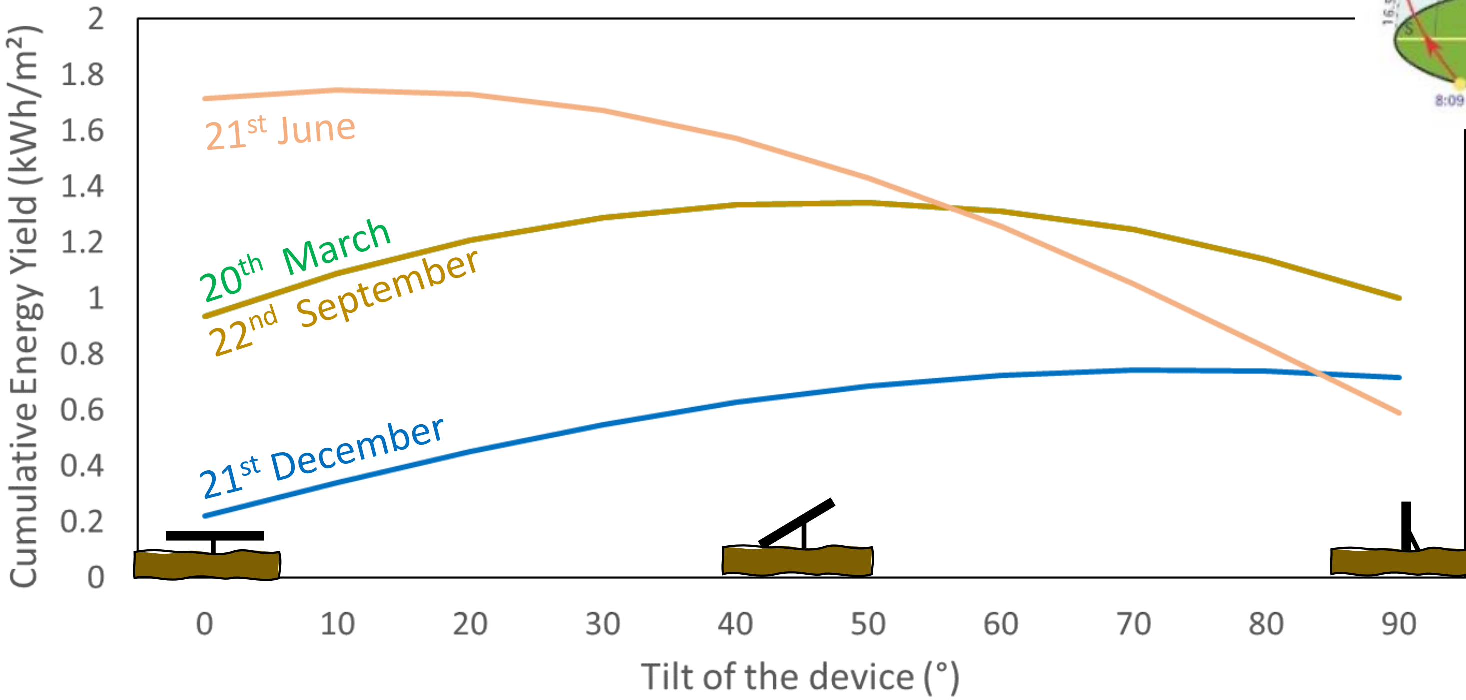
Advanced Optics

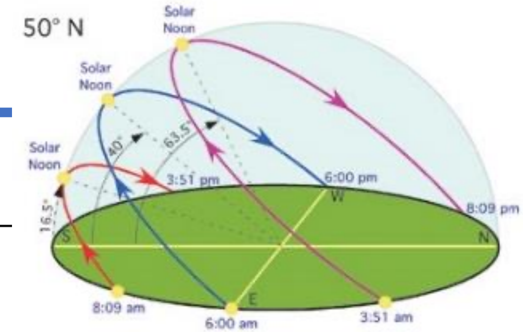
Drift-Diffusion

Absorption



EY vs Tilt Angle (PSC Facing South)

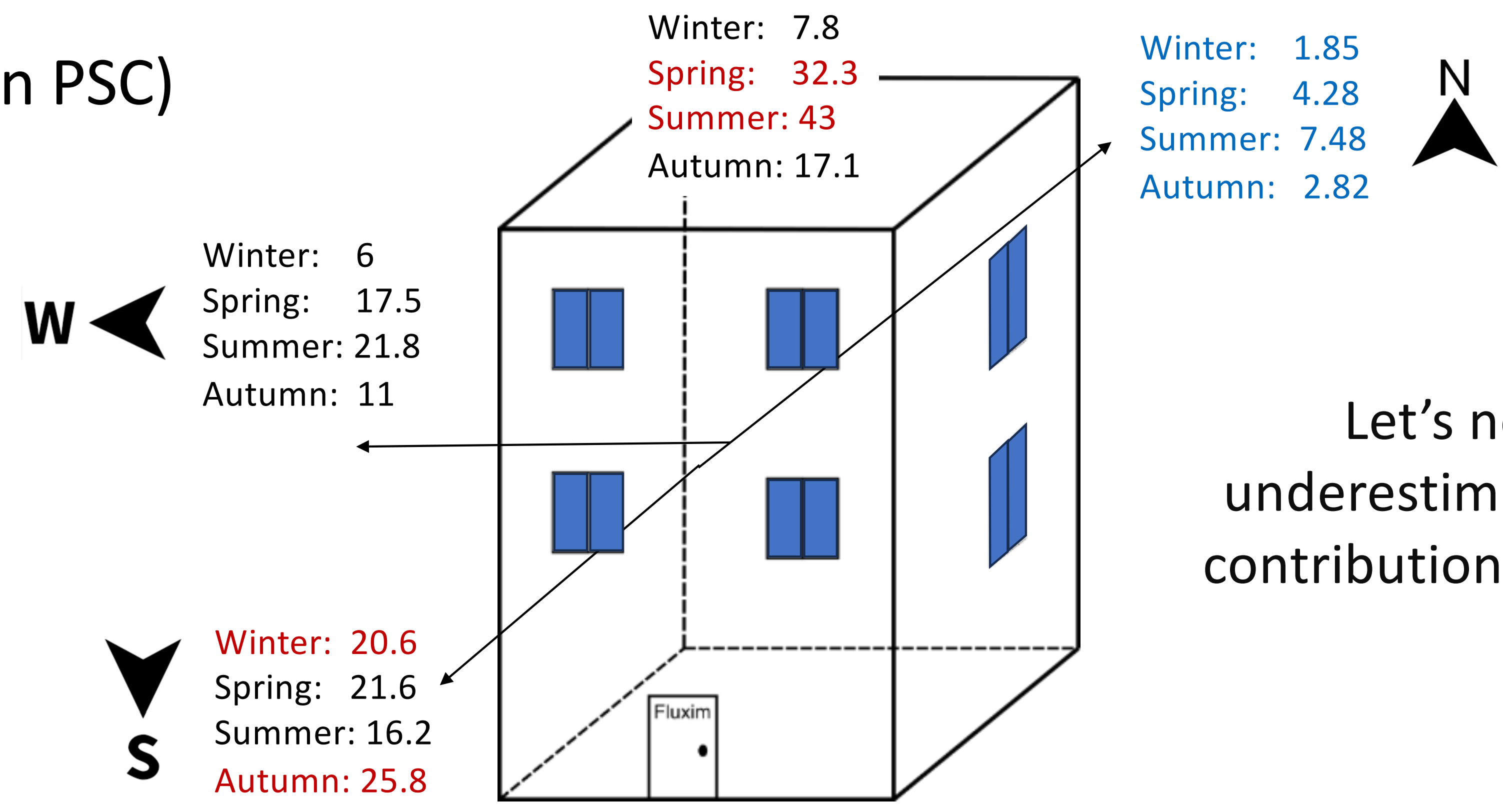




- Tilt angle to maximize the EY varies with the season
- Best tilt for summer is <20°
- Best tilt for winter is >70°

EY on the First Day of Each Season (kWh/m²)

(Green PSC)

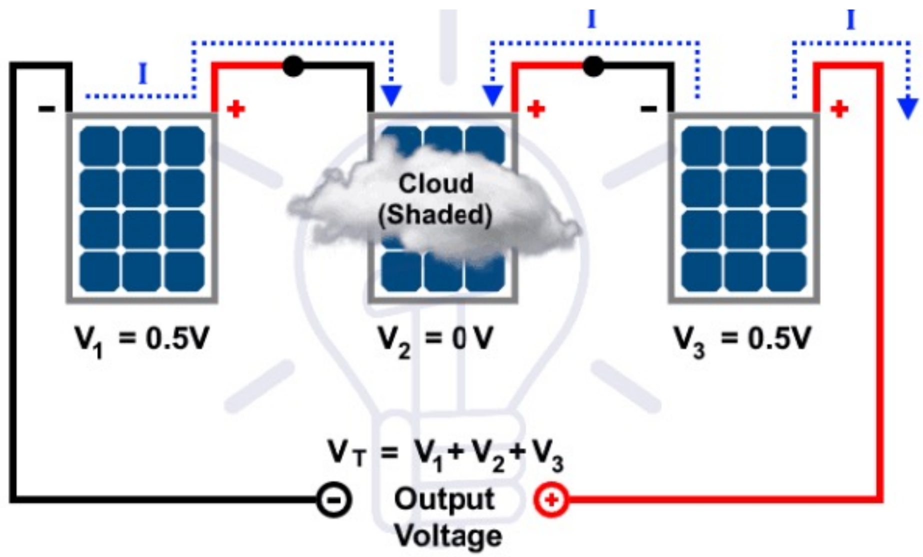


Let's not underestimate the contribution of BIPV

A **south façade** could be almost as efficient as a rooftop installation if we consider the **integral** during the year

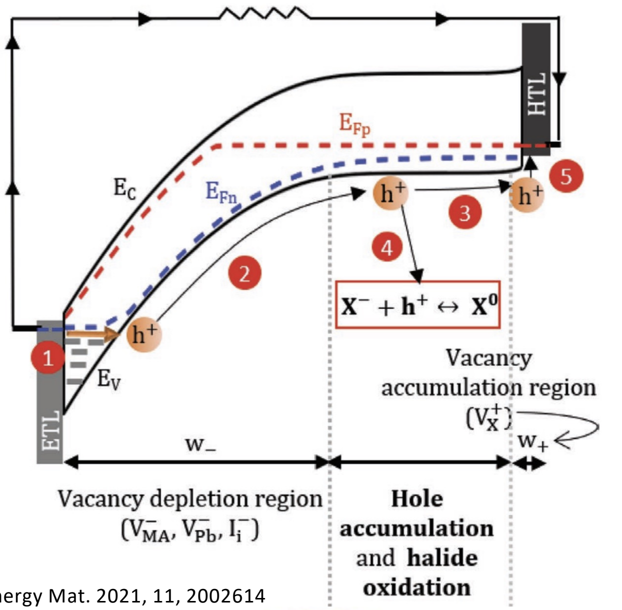
Shading in Perovskite Solar Modules

A shaded cell is going in **reverse bias** if there is no bypass diode



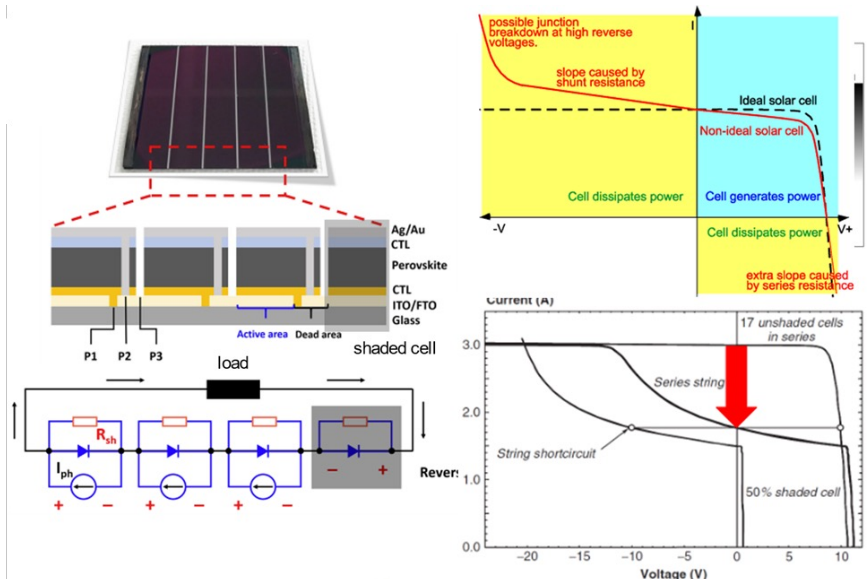
Understanding Reverse Bias Degradation in PSCs

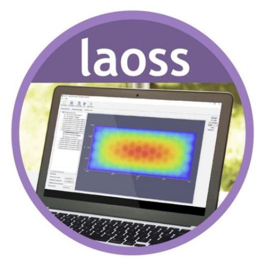
Single Perovskite Solar Cell



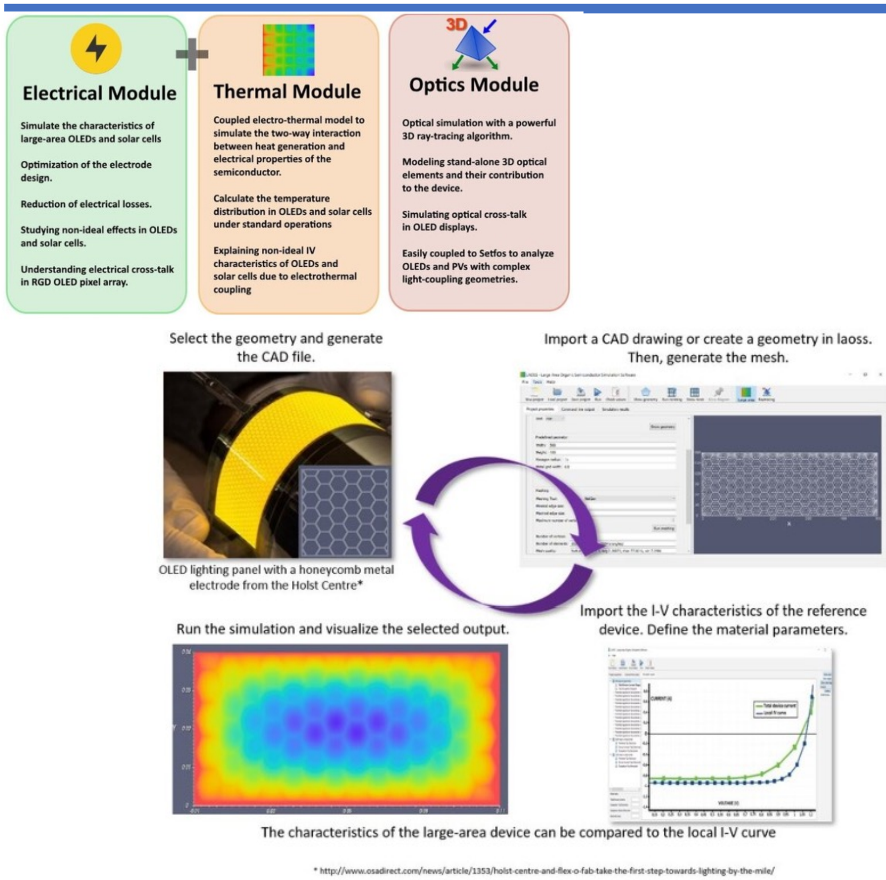
Adv. Energy Mat. 2021, 11, 2002614

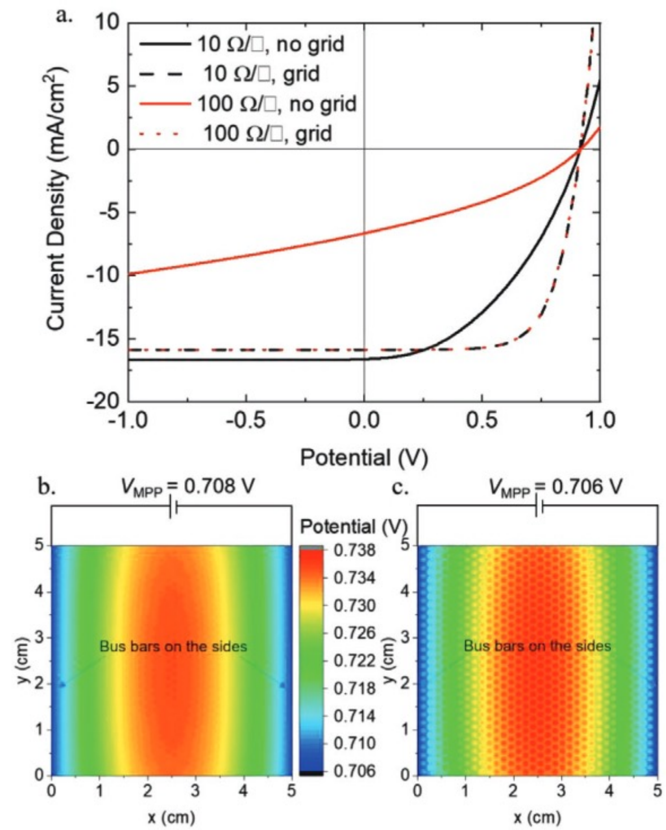
Perovskite PV Modules





What is LAOSS (FEM solver for thin-film PVs)





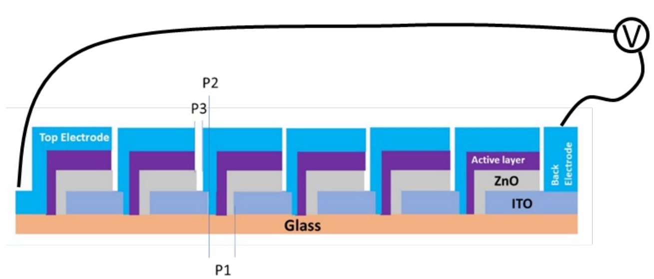
G. Burwell et al. “Parameterization of Metallic Grids on Transparent Conductive Electrodes for the Scaling of Organic Solar Cells”, Adv. Electron.Mater.2021, 7, 2100192
https://onlinelibrary.wiley.com/doi/10.1002/aelm.202100192

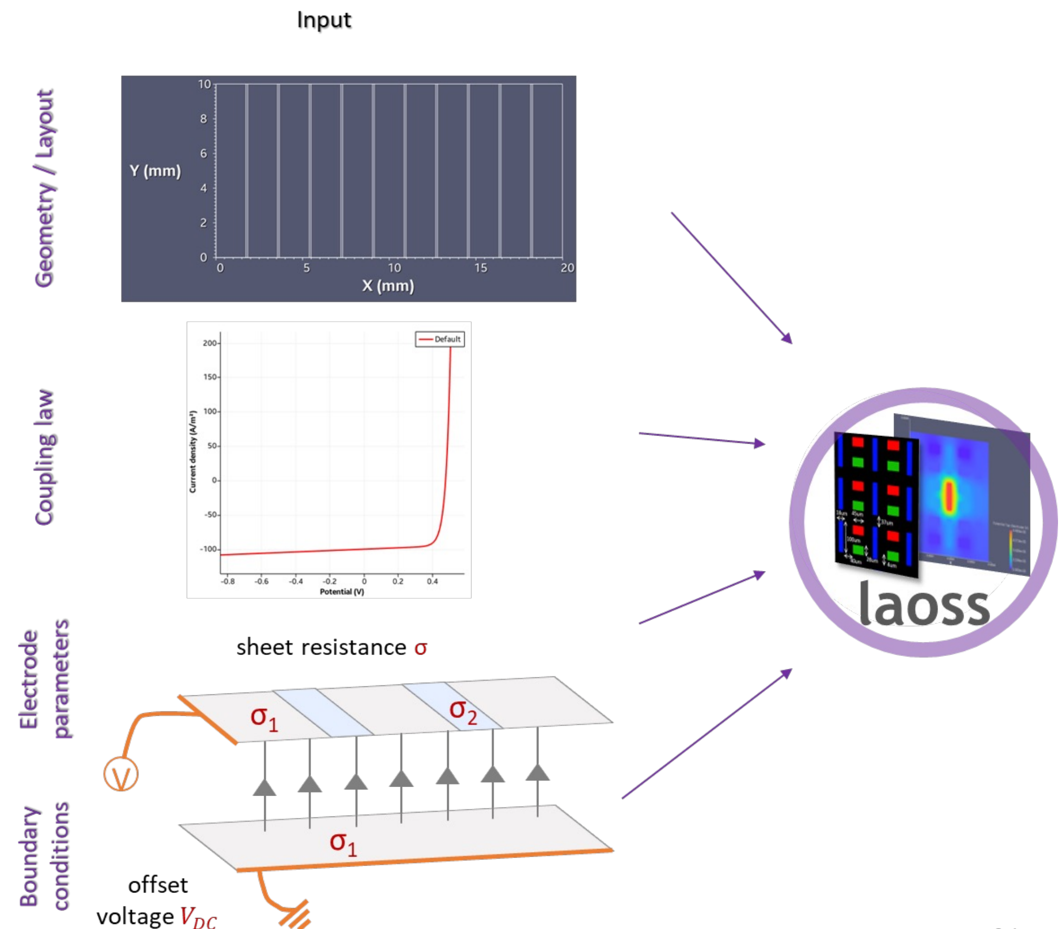
Simulation of a Perovskite Minimodule

- Simulation software **Laoss** (electrical module)
- FEM method in 2D+1D:
  - 2D in top/bottom electrodes (Ohm’s law)
  - 1D vertical coupling law (e.g. diode equation)

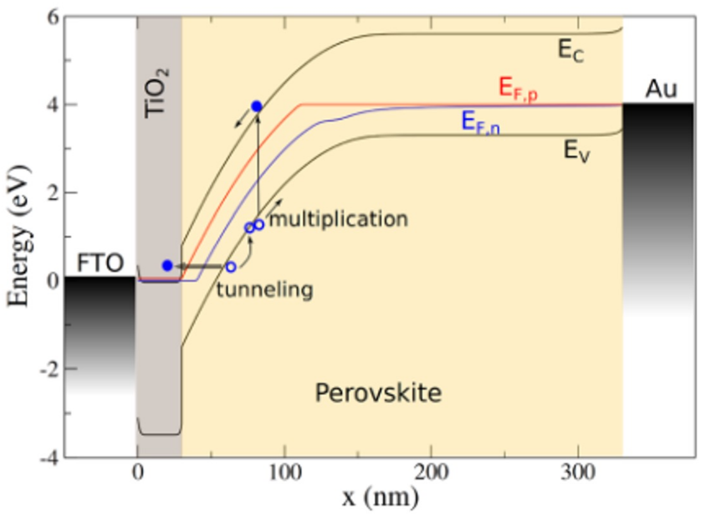
$$-\nabla\left({R_{sh}^{T/B}}^{-1}\nabla\varphi^{T/B}\right) = j(\varphi^{T},\varphi^{B})$$

- Calculate potential distribution, currents, losses, etc.



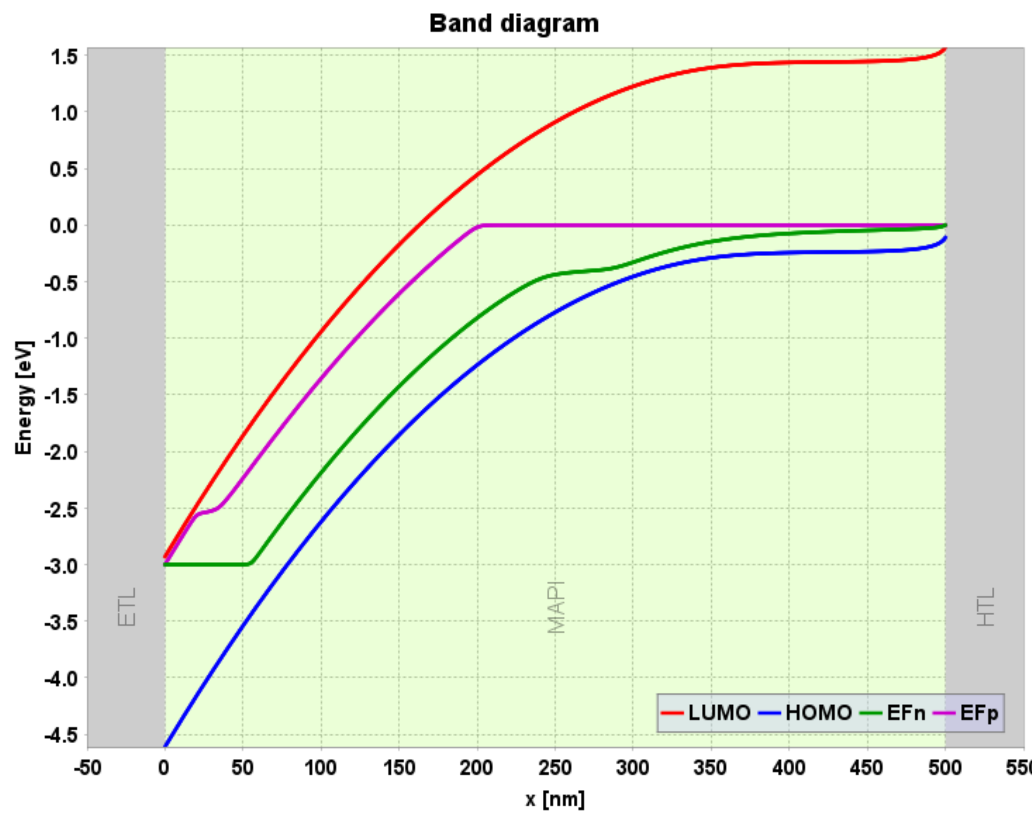


JV coupling law for PSCs in Reverse Bias



Appl. Phys. Lett 120, 113505, (2022)

WORK IN PROGRESS



Band bending in the active layer of a pero PV at V= -3V

Implementation of one fully shaded cell in LAOSS

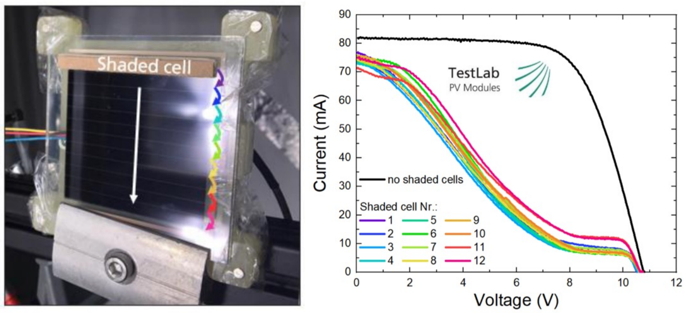
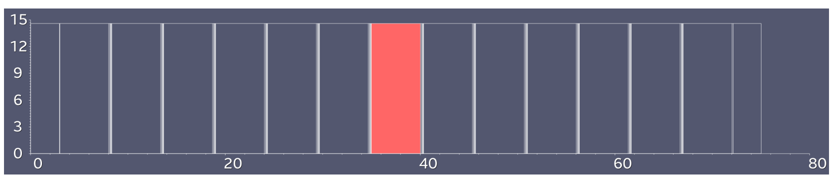
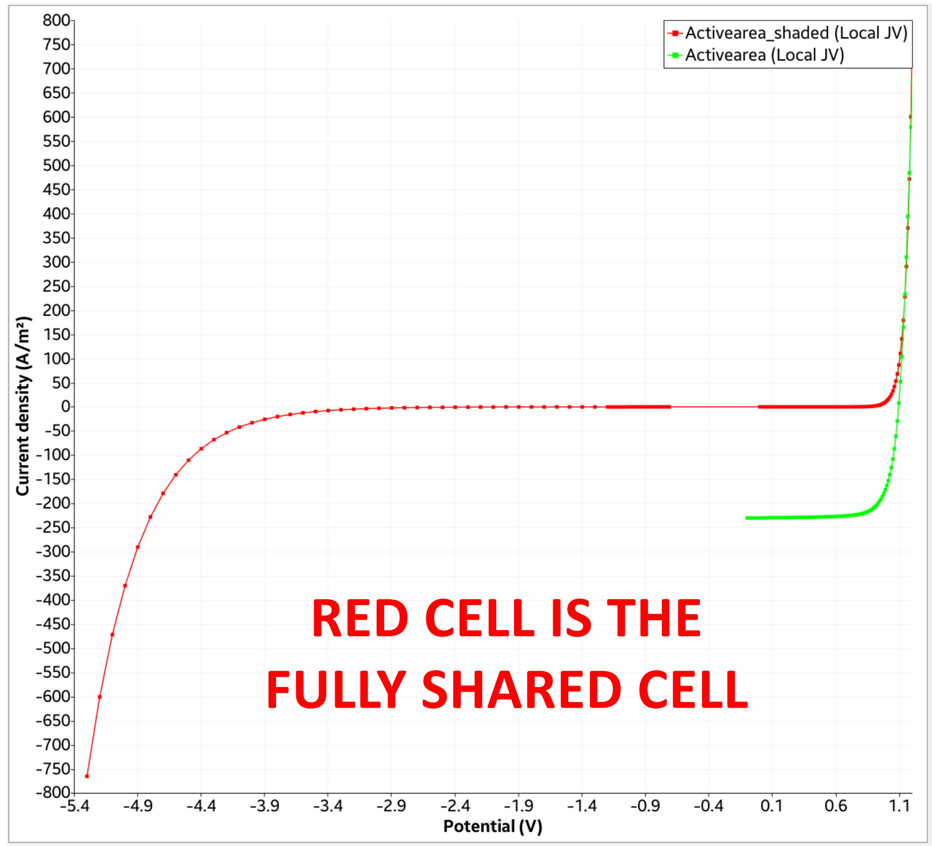


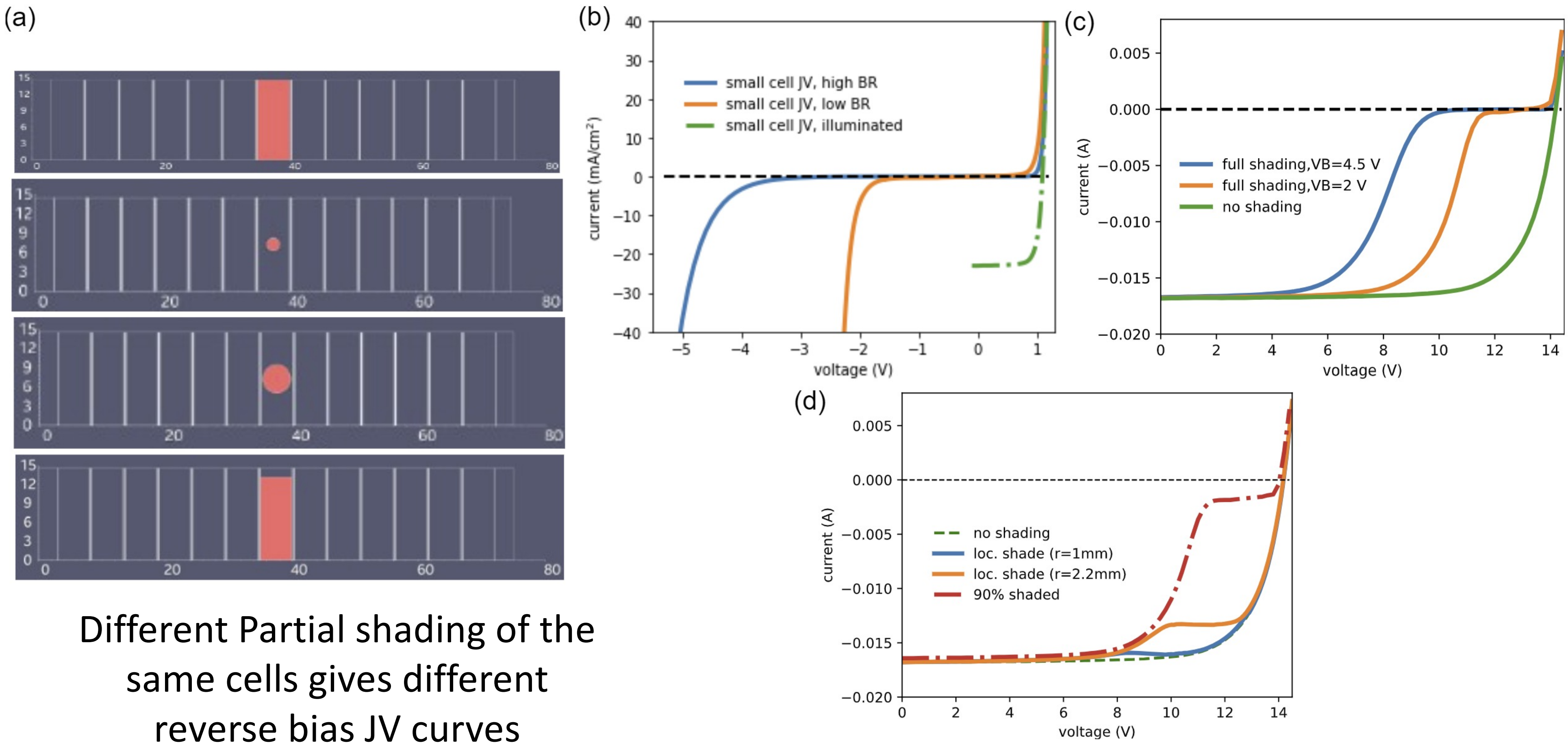
Figure S 16: Photograph of module illustrating the process of shading one individual sub-cell, acquisition of I-V curve of a module in this configuration, followed by shading the next sub-cell and conducting the same steps until the module I-V curves for each condition (when each sub-cell is shaded) are obtained.



Implementation of 30 sub-cell perovskite module in **LAOSS**

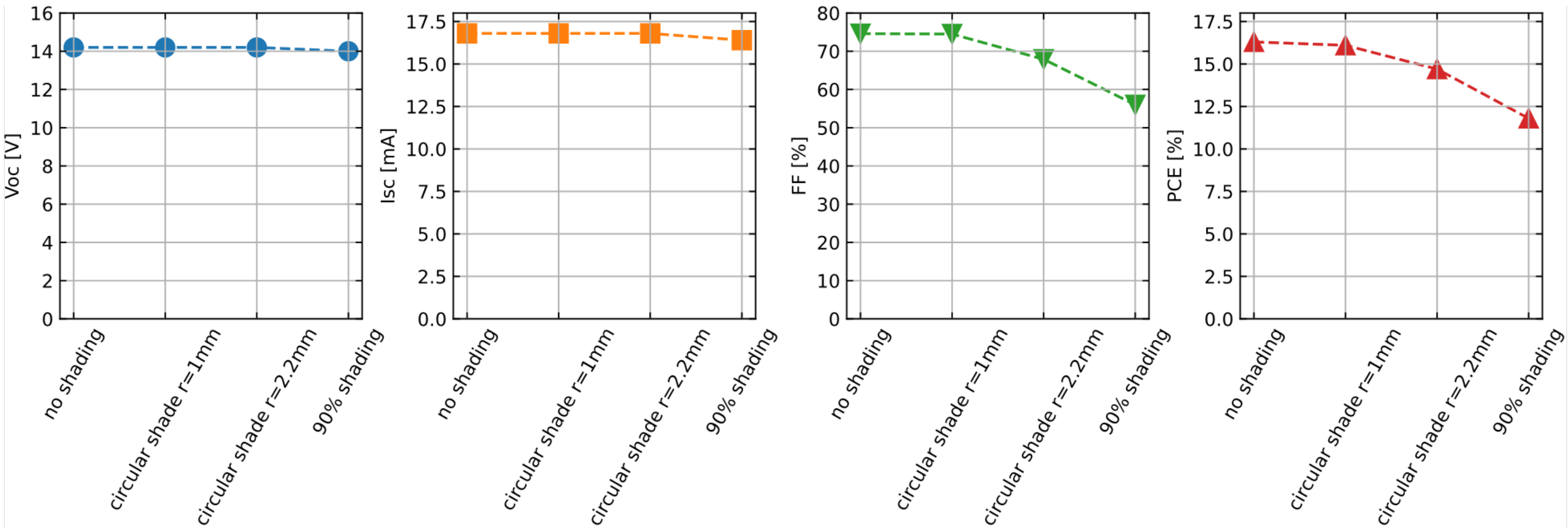


Perovskite Minimodule – JV Curves with Partial Shading



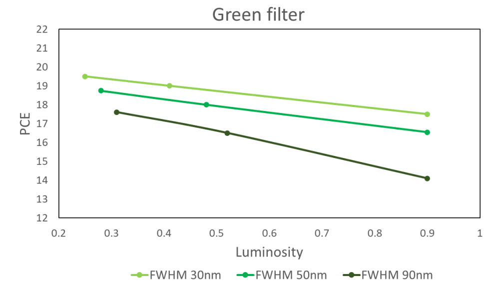
Different Partial shading of the same cells gives different reverse bias JV curves

Perovskite Minimodule – Device Parameters

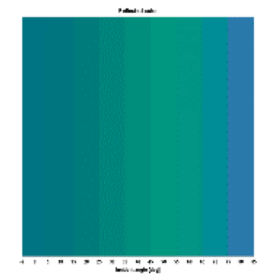


We would expect the voltage to remain high, but not the current. We speculate this is due to the low reverse breakdown voltage of the perovskite, which enables current conservation at the expense of voltage

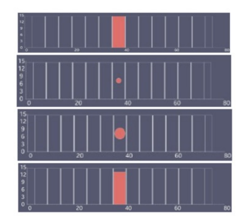
Conclusions



FWHM and luminosity have the strongest impact on PCE



Reflected color shifts with viewing angle. Scattering interfaces with RMS/corr≈1 minimize the shift



The integrated energy yield of a BIPV can be calculated. A rooftop solar cell is not the most efficient solution

We can estimate the effect of partial shading on the characteristics of a perovskite solar module

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