June 11, 2018, City U Hong Kong

# Lead Halide Perovskite: Photovoltaics and Beyond

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Perovskite

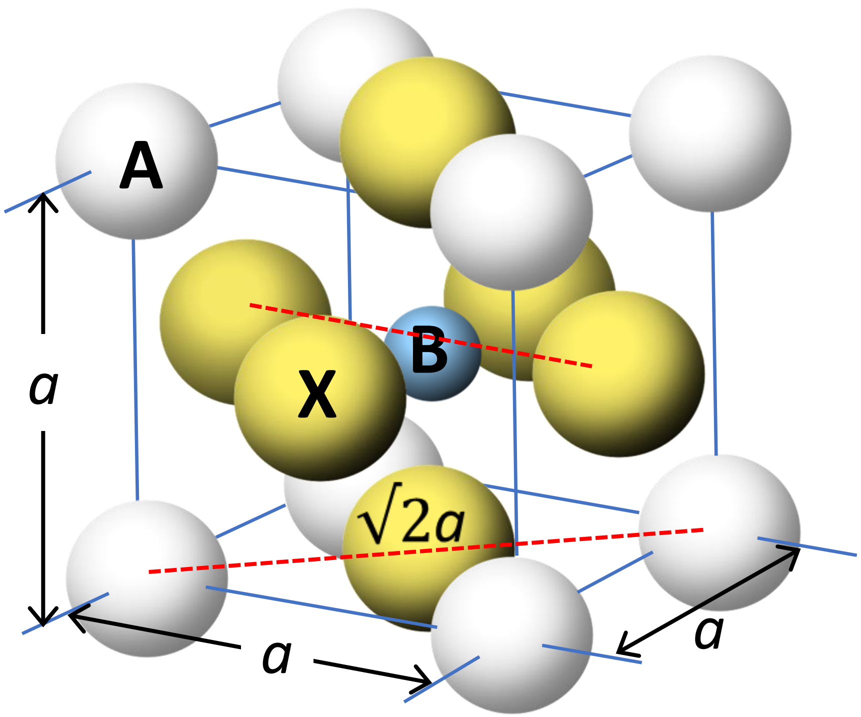
Conventional Oxide Perovskite

vs

Organic-inorganic Halide Perovskite

# $ABX_3$

$$a = 2(r_B + r_X)$$




$$\sqrt{2}a = 2(r_A + r_X)$$

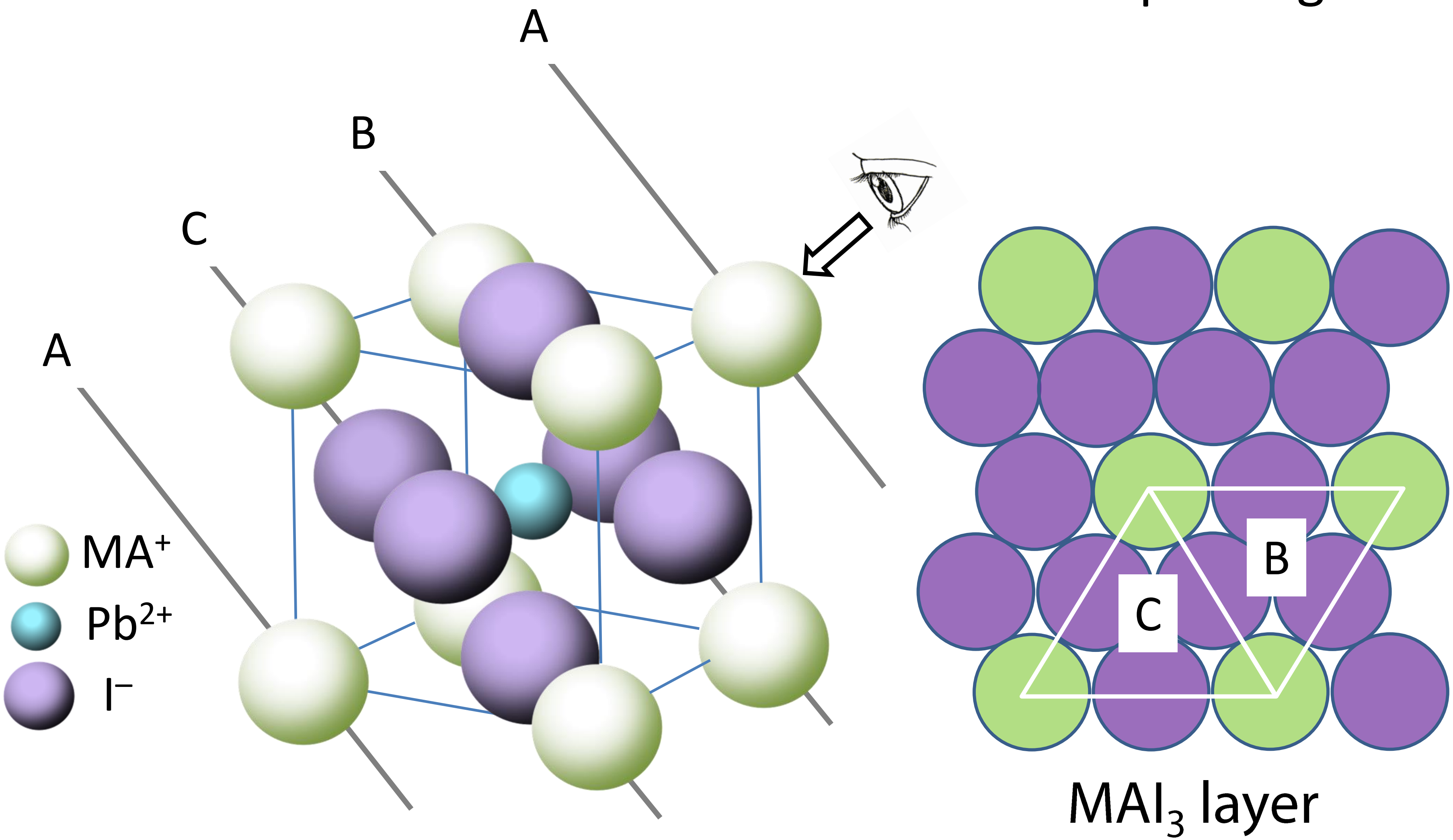
$$a = 2(r_B + r_X) = \sqrt{2}\,(r_A + r_X)$$

$$(r_A + r_X) = \sqrt{2}\,(r_B + r_X)$$

$$t = \frac{(r_A + r_X)}{\sqrt{2}(r_B + r_X)}$$

Ideal cubic : $t = 1$

# Cubic close packing




$$I^{-} = \frac{1}{2} \times 6 = 3$$

$$MA^{+} = \frac{1}{8} \times 8 = 1$$

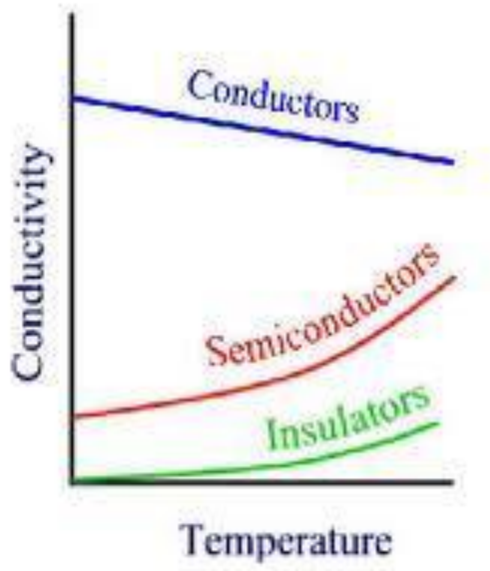
**$MAPbI_3$**

**One layer: $I^{-}$: 75%, $MA^{+}$: 25%**

**CONVENTIONAL SEMICONDUCTORS**

♠Electrical conductivity increases with temperature (because of excitation of electrons to conduction band by thermal energy)
*Metal: electrical conductivity decreases with temperature (because of electron-phonon interaction, electron is scattered by phonon vibration at high T)

♠ Uv-vis spectra (Exciton binding energy measurement): Band gap decreases with temperature



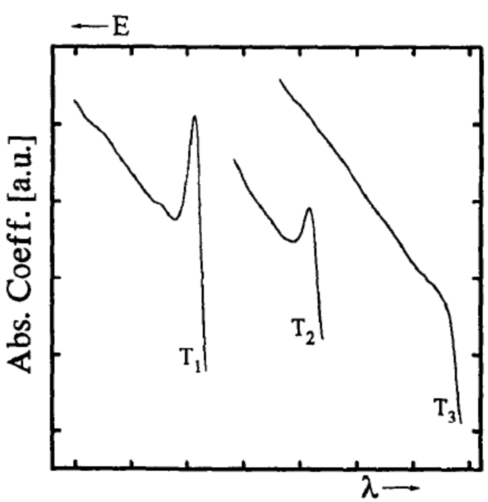
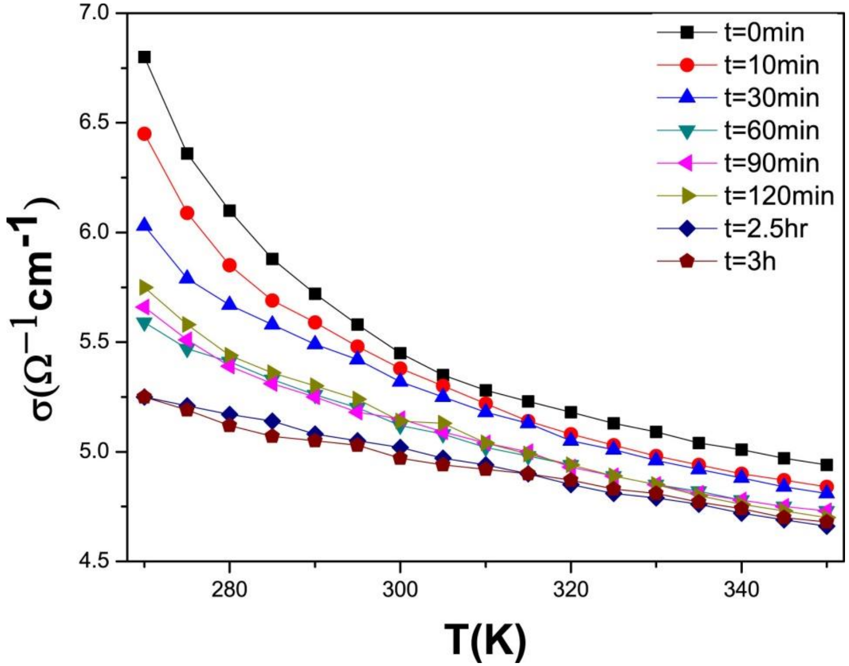
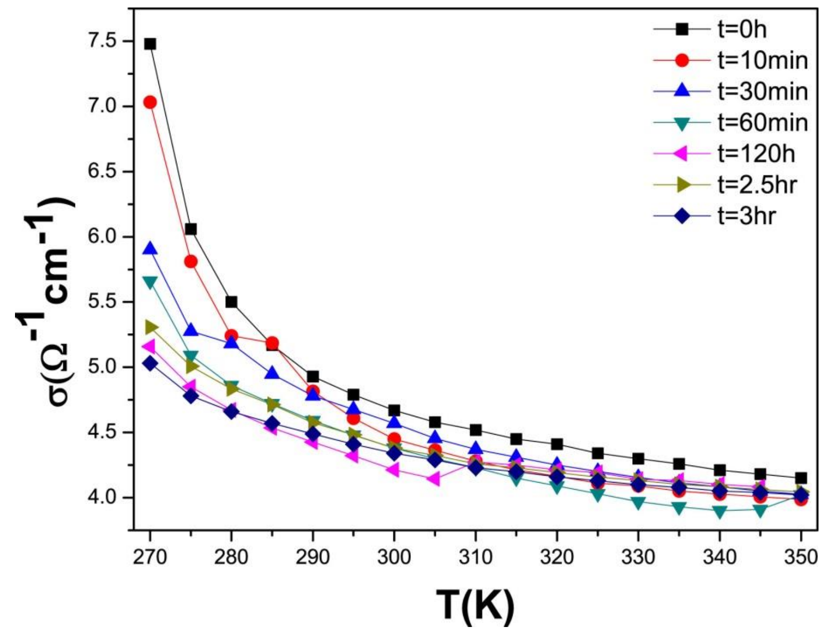




Figure 2.5. Illustration of the temperature dependence of experimental absorption spectrum (at the fundamental absorption edge) ($T_1<T_2<T_3$).

**$E_g$ decreases with temp.**

# How about organic-inorganic halide perovskite ($MAPbI_3$)?



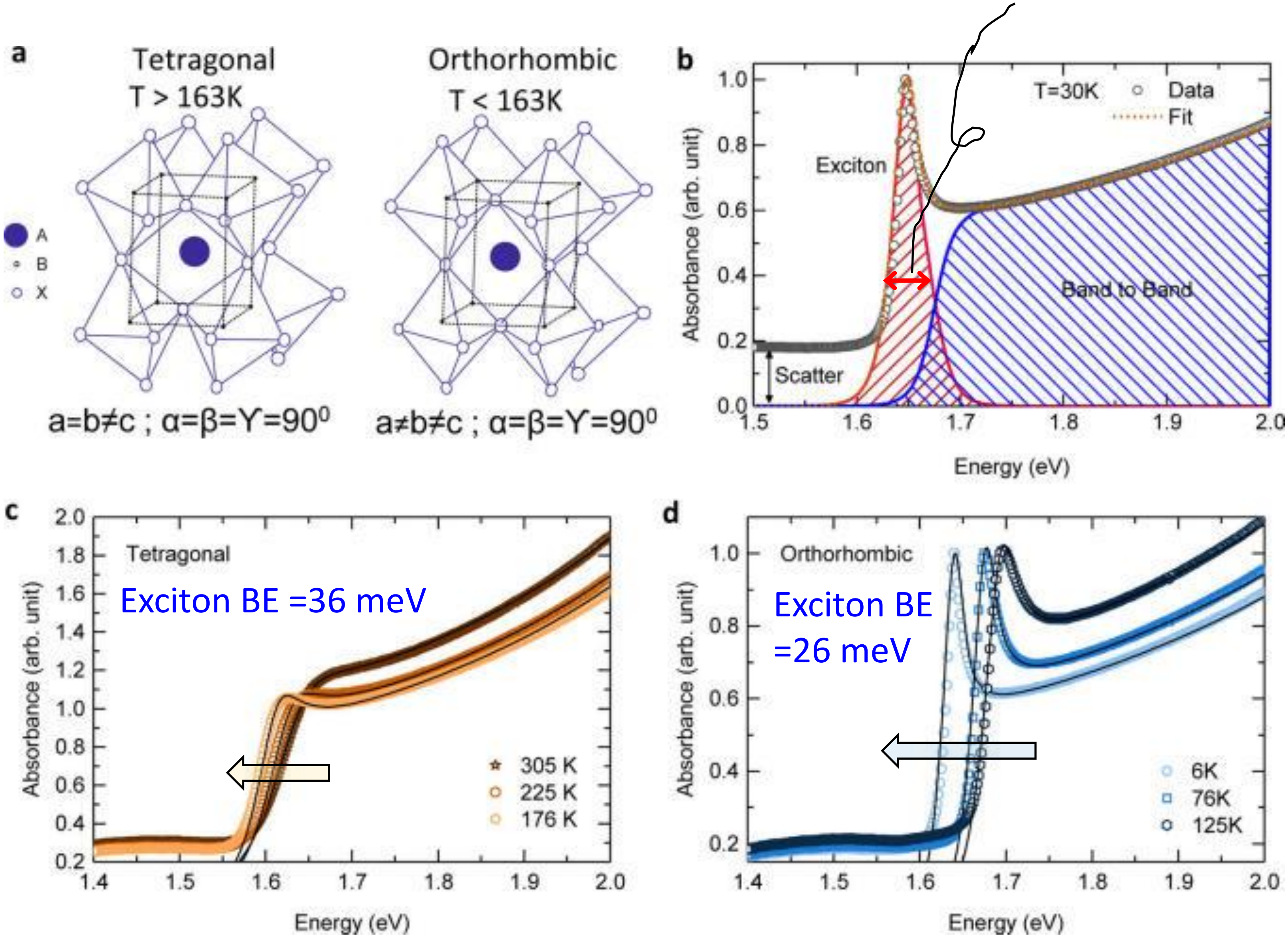

Electrical conductivity as a function of temperature for different age of the sample which was exposed to one sun illumination (left) and was stored in the dark (right).

Bizuneh Gebremichael et al., Physica B: Condensed Matter, 514, 2017, 85-88

**Conductivity decreases with temperature (different behavior from convectional semiconductor). Then, $MAPbI_3$ is metallic? Electron may be scattered by phonon vibration due to organic molecular motion.**

# Phase dependent exciton BE of $MAPbI_3$

FWHM = exciton BE (related to disorder)



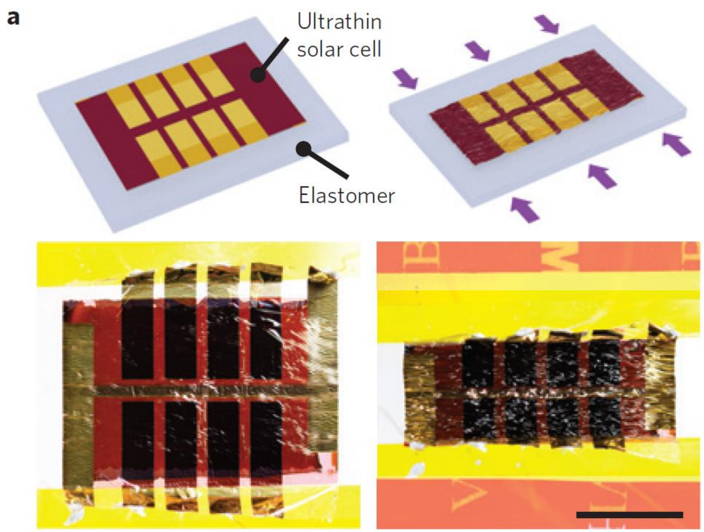

$E_g$ increases with temp: contrary to conventional semiconductor

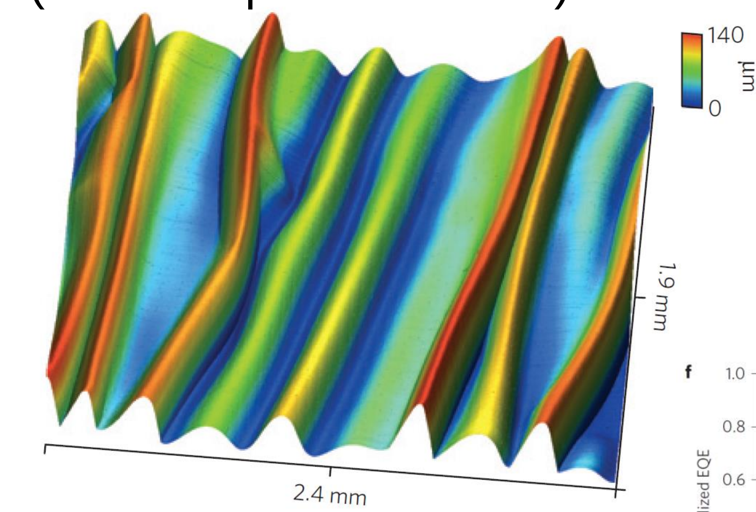
(Shivam Singh et al., J. Phys. Chem. Lett. 2016, 7, 3014−3021)

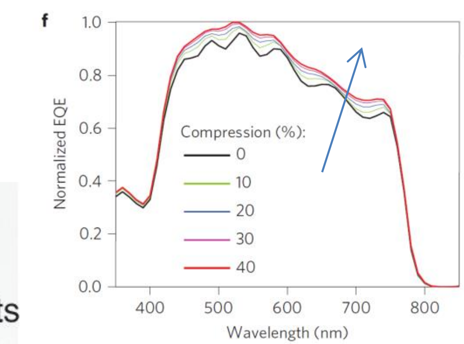
# Compression strain: better EQE?

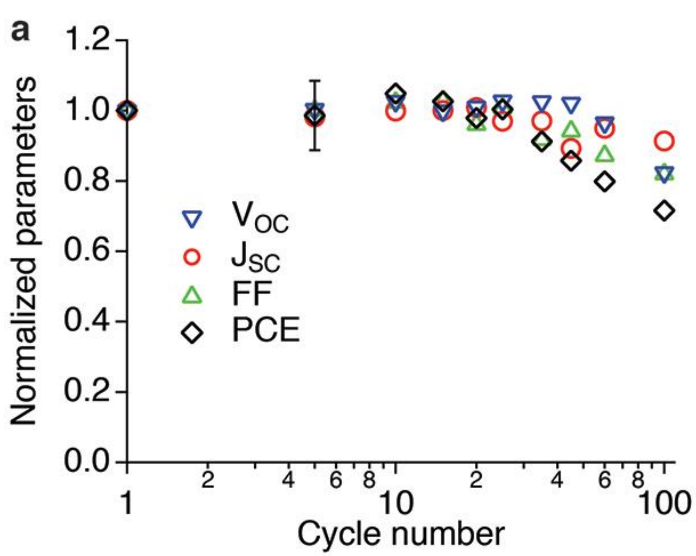
NATURE MATERIALS | VOL 14 | OCTOBER 2015

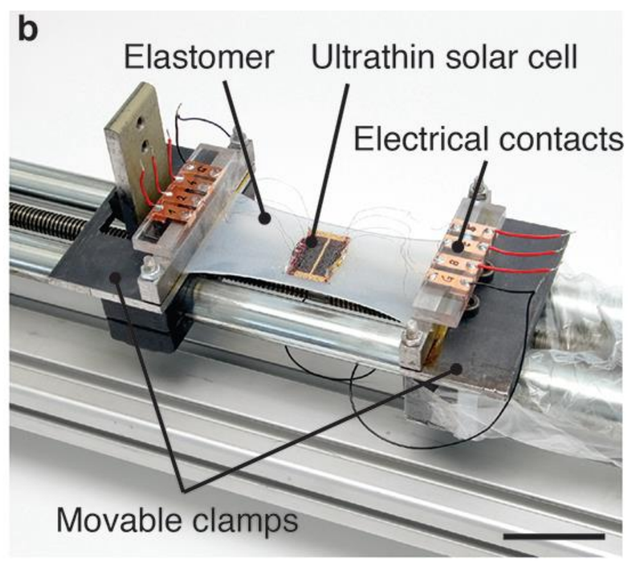
► 3-D map of the wrinkle morphology (40% compressive strain).



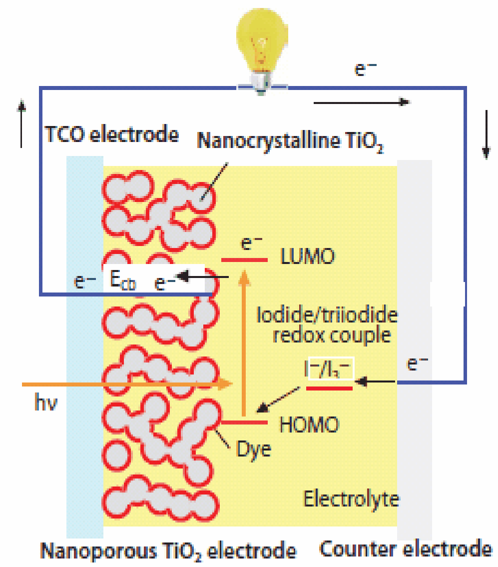



History

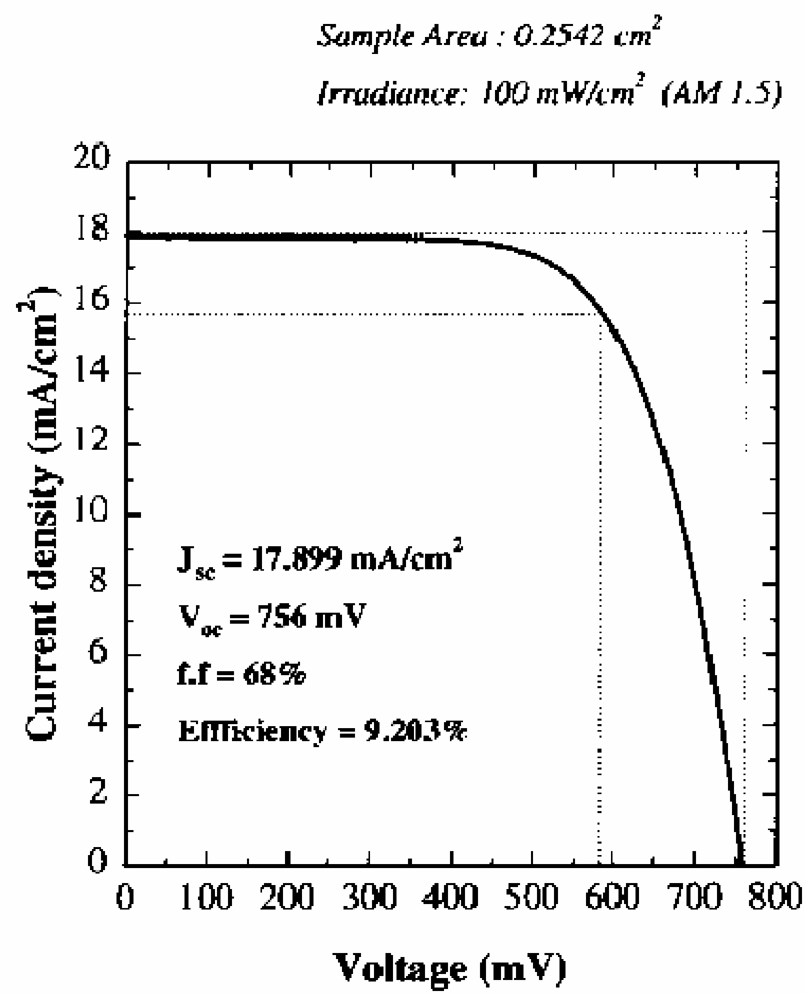
Genesis of Perovskite Solar Cell

# Solar Cell Work, since 1997

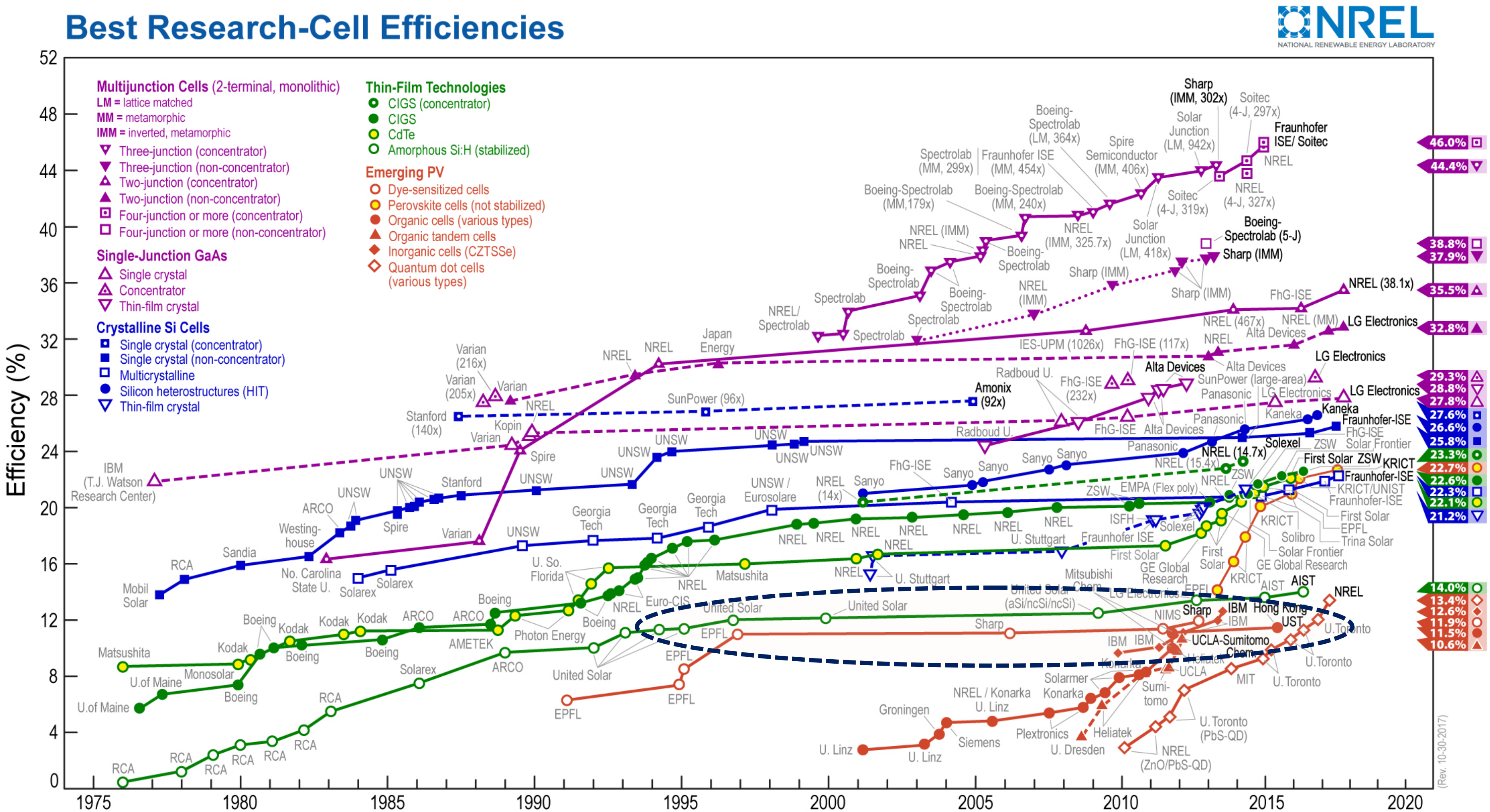
**Dr. Arthur Frank**





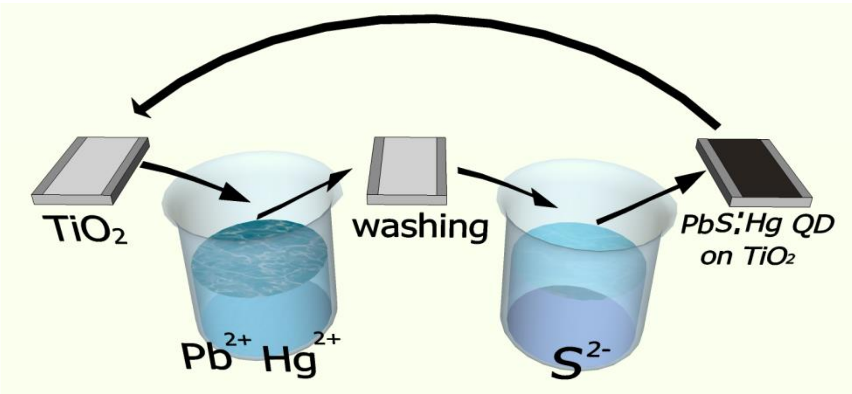


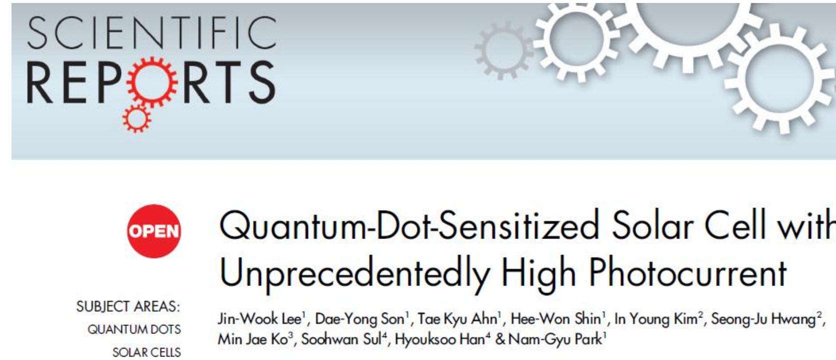
# DSSCs stop growing: Efficiency of ~ 12% since 1997




Due to low absorption coefficient of N719

# Scientists struggle for finding good sensitizers like QD with high α



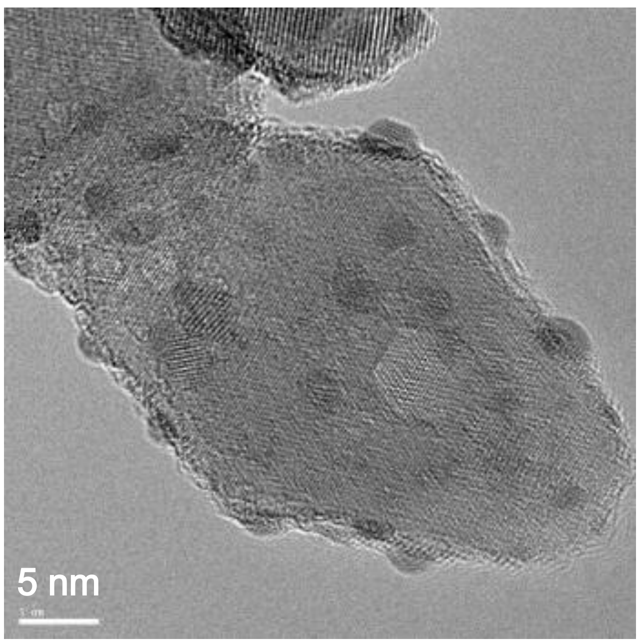


SCIENTIFIC REPORTS

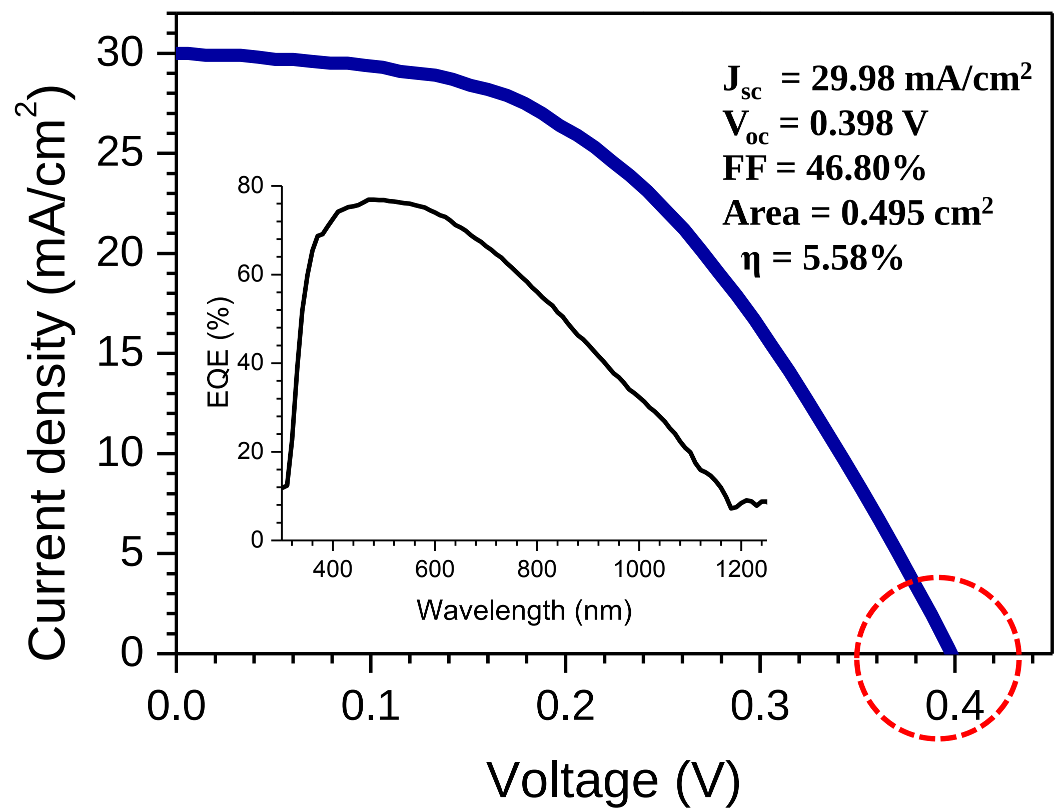
OPEN

SUBJECT AREAS:
QUANTUM DOTS
SOLAR CELLS

Quantum-Dot-Sensitized Solar Cell with Unprecedentedly High Photocurrent

Jin-Wook Lee[1], Dae-Yong Son[1], Tae Kyu Ahn[1], Hee-Won Shin[1], In Young Kim[2], Seong-Ju Hwang[2], Min Jae Ko[3], Soohwan Sul[4], Hyouksoo Han[4] & Nam-Gyu Park[1]



# NanoEuro2007 Conference

## September 11-14, 2007, St-Gallen, Switzerland
## (Organized by DyeSol)

# Program

Thursday, 13th September 2007

| | New technology and products |
|---|---|
| 09.00 - 09.25 | **DSC production – putting roll-to-roll to work**<br>Kevin Tabor, G24i, United Kingdom |
| 09.25 - 09.50 | **PVT – a tandem application for solar heat and power using DSC**<br>Henrik Soerensen, Esbensen Consulting Engineers, Denmark |
| 09.50 - 10.15 | **New DSC solutions**<br>TBC |
| 10.15 - 10.40 | **DSC appearance – multicoloured and stable panels**<br>Andreas Hinsch, Fraunhofer Institute for Solar Energy Systems (ISE), Germany |

**"Perovskite-sensitized DSSC" Talk given by T. Miyasaka**

**Efficiency of $MAPbI_3$ sensitized liquid DSSC was about ~2%**

# Motivated by the term "Perovskite"

**M.S. Thesis,** *Seoul National Univ., 1992*
"Preparation and Physico-chemical Properties of the Perovskite Type Oxides $A_2(CeTa)O_6$ (A=Ca, Ba)"

**Ph. D. Thesis**, *Seoul National Univ., 1995*
"Synthesis and Physico-chemical Properties of 2-dimensional Inorganic Solids and Their Intercalation Compounds"

**(Layered Superconducting Perovskite)**

# We started perovskite work since then

I asked Dr. Song Rim Jang (my first postdoc in my lab at KIST) to try to make perovskite film and solar cell

# Report on Perovskite Exp. (Jun. 7, 2008)

By Song Rim Jang (postdoc in 2008)

## Inorganic-organic perovskite-type quantum-well crystal

▶ **실험 목적**

일반적으로 사용하는 Ru계 염료 대신 색을 띄는 perovskite-type의 $CH_3NH_3PbBr_3$와 $CH_3NH_3PbI_3$를 사용하여, DSSCs에 적용하고 그 효능을 알아본다.

▶ **실험 방법**

- $CH_3NH_3PbBr_3$의 합성 과정

1. 21.81 mL $CH_3NH_2$와 28.28 mL HBr을 섞는다 ($CH_3NH_2$ : HBr = 1 : 1).
2. 무색의 이 용액을 evaporation하여 흰색 powder인 $CH_3NH_3Br$을 얻는다.
3. 0.0280 g $CH_3NH_3Br$과 0.0918 g $PbBr_2$를 5 mL DMF에 녹여 50 mM $CH_3NH_3PbBr_3$ 용액을 만든다 ($CH_3NH_3Br$ : $PbBr_2$ = 1 : 1). (Figure 1)
4. DMF를 증발시켜 제거하면 orange색의 $CH_3NH_3PbBr_3$ powder가 생성된다.

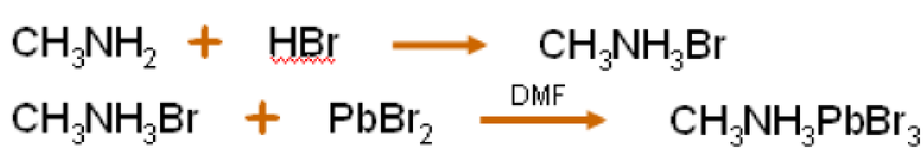



Figure 1. $CH_3NH_3PbBr_3$ 합성 과정4

# Report on Perovskite Exp. (Jun. 7, 2008)

\- $CH_3NH_3PbI_3$의 합성 과정

1. 21.81 mL $CH_3NH_2$와 45.36 mL HI를 섞는다 ($CH_3NH_2$ : HI = 1 : 1).
2. 무색의 이 용액을 evaporation하여 흰색 powder인 $CH_3NH_3I$를 얻는다.
3. 0.0397 g $CH_3NH_3I$와 0.1154 g $PbI_2$를 5 mL aceton에 넣고 40 °C에서 녹여 밝은 노랑색의 50 mM $CH_3NH_3PbI_3$ 용액을 만든다 ($CH_3NH_3I$ : $PbI_2$ = 1 : 1). (**Figure 2**)
4. Aceton를 증발시켜 제거하면 검은색의 $CH_3NH_3PbI_3$ powder가 생성된다.

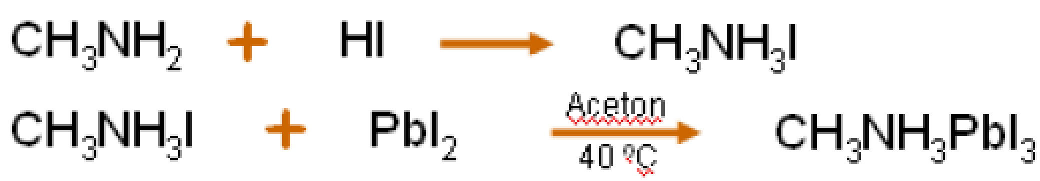
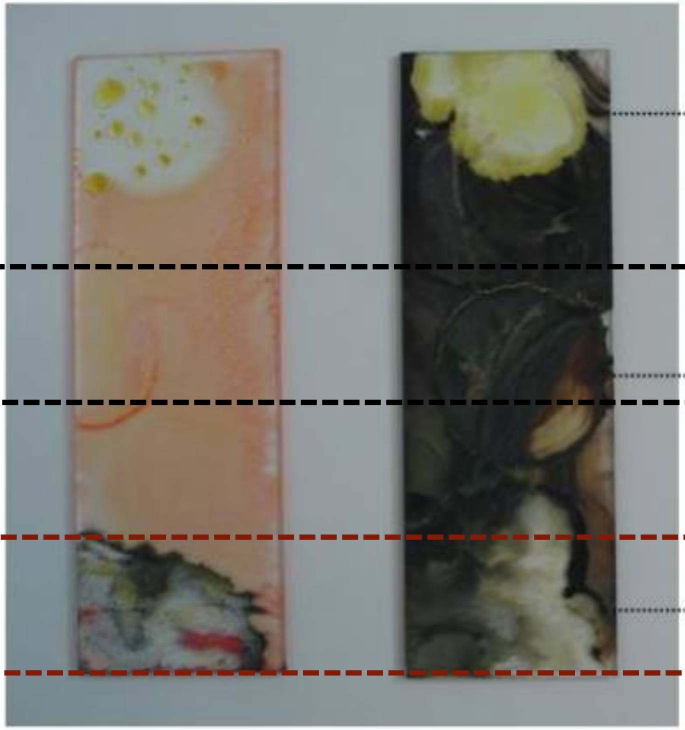



**Figure 2.** $CH_3NH_3PbI_3$ 합성 과정4

# Report on Perovskite Exp. (Jun. 7, 2008)

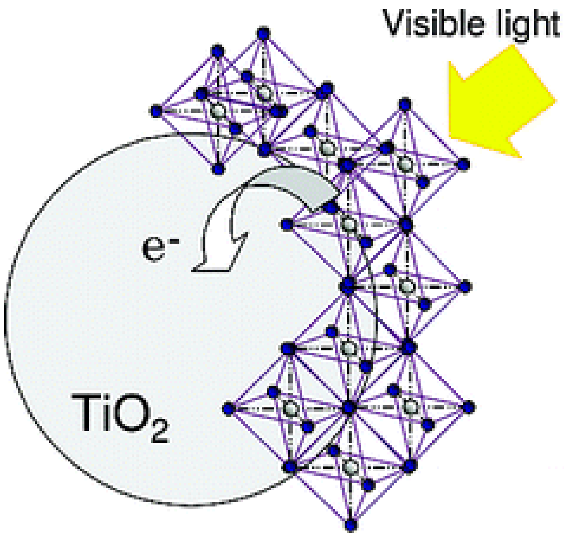
▶ 실험 결과

Slideglass 위에 합성한 perovskite-type의 $CH_3NH_3PbBr_3$ 용액을 뿌리고, solvent인 DMF를 증발시켜 제거하면 오렌지색의 powder가 생성된다. 마찬가로 $CH_3NH_3PbI_3$ 용액을 뿌린 후 aceton을 증발시켜 제거하면 검은색의 powder가 생성된다. 그러나 이들은 전해질에 녹는 문제가 발생하여 DSSC에 적용해 볼 수가 없었다. 그래서 우선 그 원인을 찾아보기 위해 전해질의 solvent인 acetonitrile를 떨어뜨려 보았으나, 아무런 변화가 없었다. 그러므로 acetonitrile 때문은 아님을 알 수 있었다. 이번에는 LiI와 $I_2$만으로 만들어진 전해질을 떨어뜨려 보았다. 그런데 오렌지색의 $CH_3NH_3PbBr_3$의 경우 검은색으로 바뀌는 것을 관찰할 수 있었다.

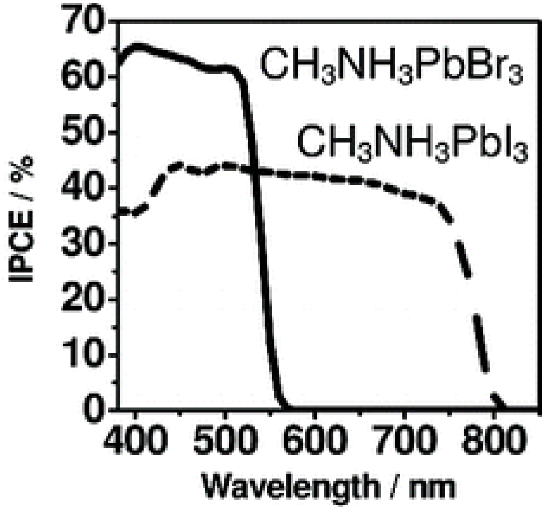


# 1st Report on Perovskite-sensitized Solar Cell (2009)

**[Precursor] ~ 8 wt%**
**$TiO_2$ thickness ~ 8 μm**



Perovskite nanocrystalline sensitizers




**Prof. T. Miyasaka**

J. AM. CHEM. SOC. 2009, *131*, 6050–6051

***Table 1.*** Photovoltaic Characteristics of Perovskite-Based Cells[a]

| perovskite sensitizer on $TiO_2$ | $J_{sc}$ (mA/cm$^2$) | $V_{oc}$ (V) | FF | $\eta$ (%) |
|---|---|---|---|---|
| $CH_3NH_3PbBr_3$ | 5.57 | 0.96 | 0.59 | 3.13 |
| $CH_3NH_3PbI_3$ | 11.0 | 0.61 | 0.57 | 3.81 |

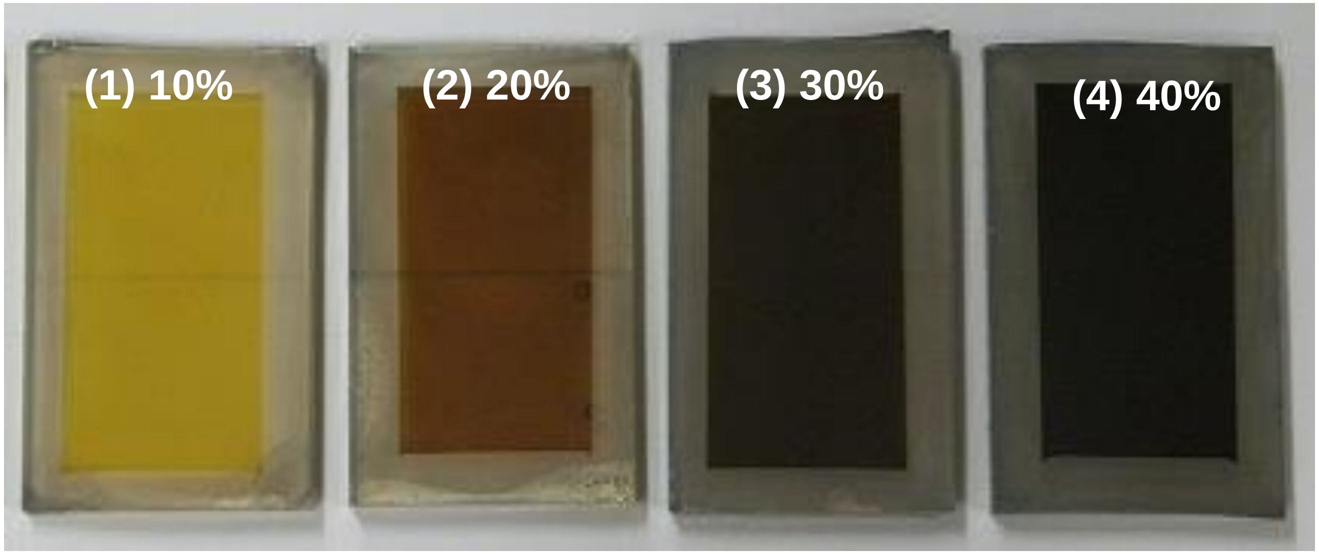
[a] Measured with an effective incident area of 0.24 cm$^2$ under 100 mW/cm$^2$ AM 1.5 simulated sunlight irradiation.

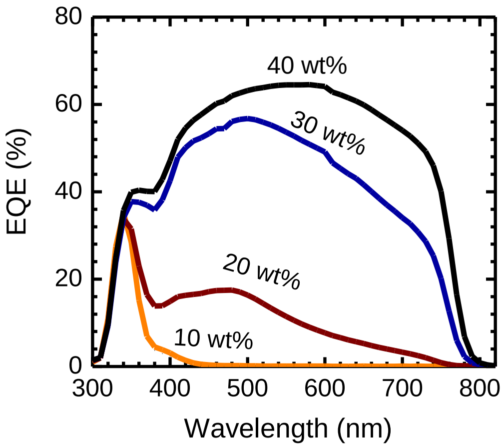
# 2nd Report on Perovskite solar cell: 6.5% (2011)

*Jeong-Hyeok Im*

40 wt% in GBL (~ 1.2 M)

$$CH_3NH_3I + PbI_2 \rightarrow (CH_3NH_3)PbI_3$$



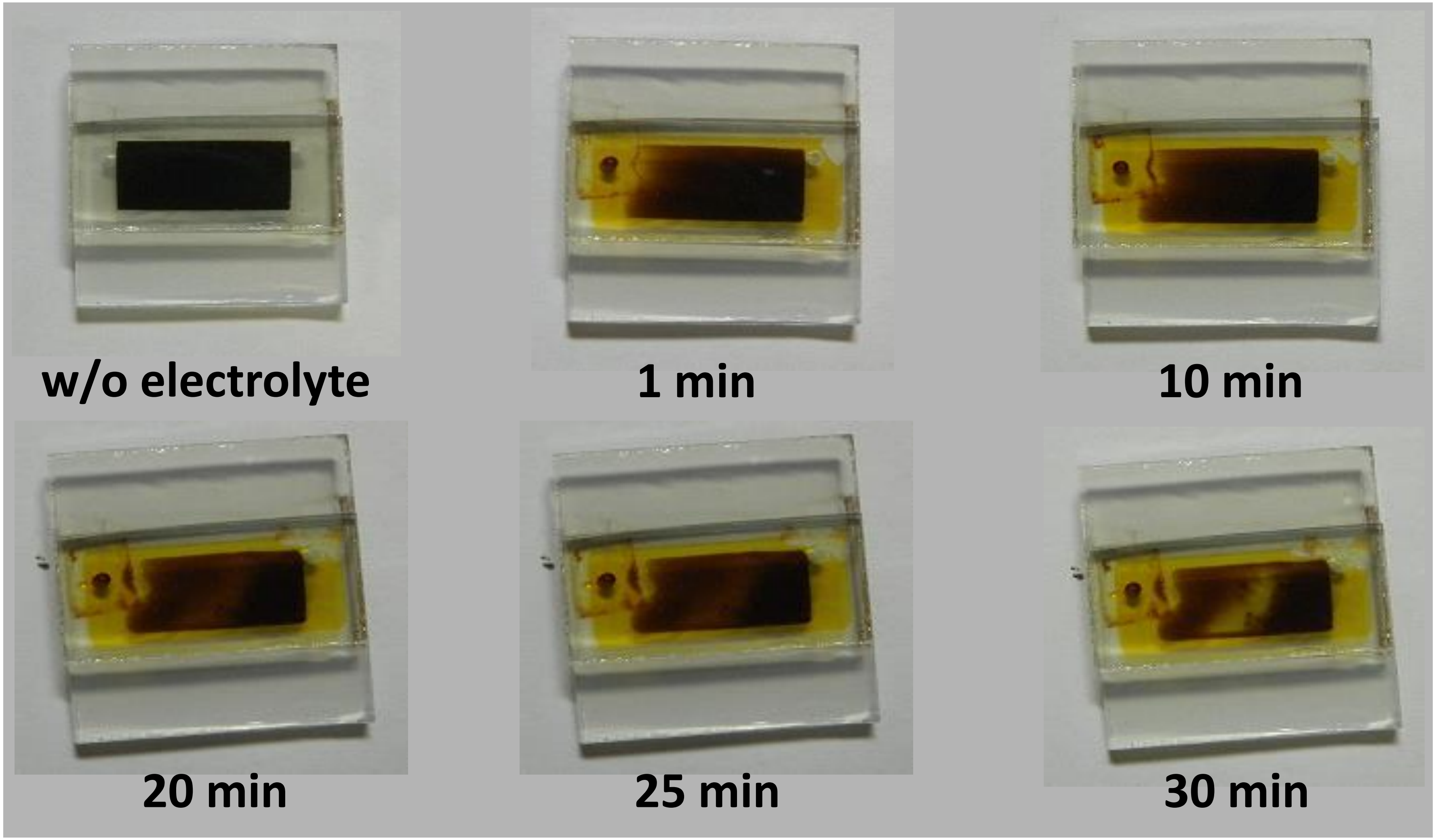




| | $J_{SC}$ (mA/cm²) | $V_{OC}$ (V) | FF | η (%) | Thickness |
|---|---|---|---|---|---|
| w/o surface treatment | 15.99 | 0.629 | 0.617 | 6.20 | **3.6 μm** |
| w/ surface treatment | 15.82 | 0.706 | 0.586 | **6.54** | |

J.-H. Im, N.-G. Park et al., ***Nanoscale***, 3, 4088 (2011)

Important message: Ion-ion interaction vs ion-solvent (solvation) interaction, critical in forming perovskite phase.

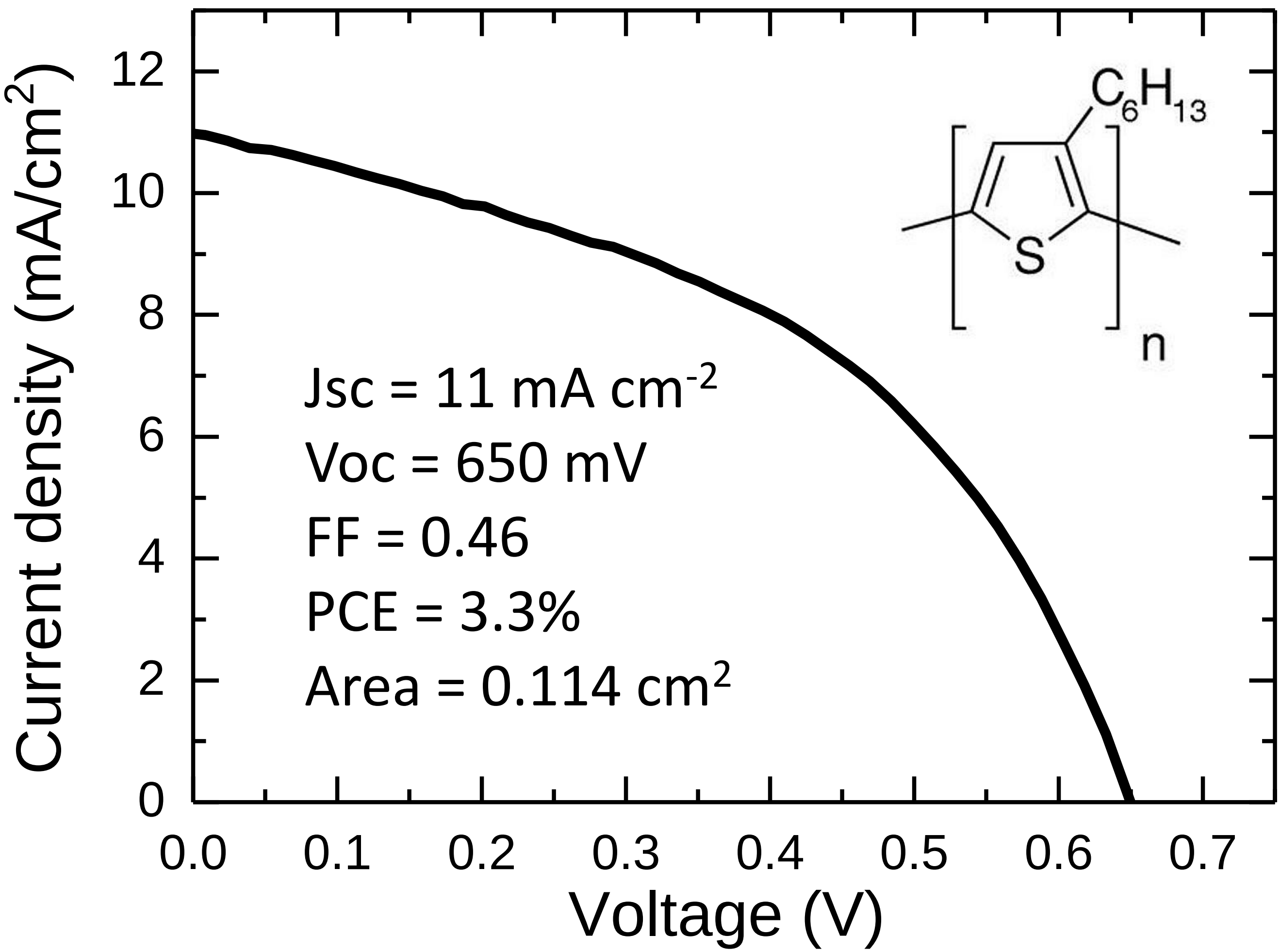
# Dissolution of $MAPbI_3$ in Liquid Electrolyte



# First Attempt with P3HT

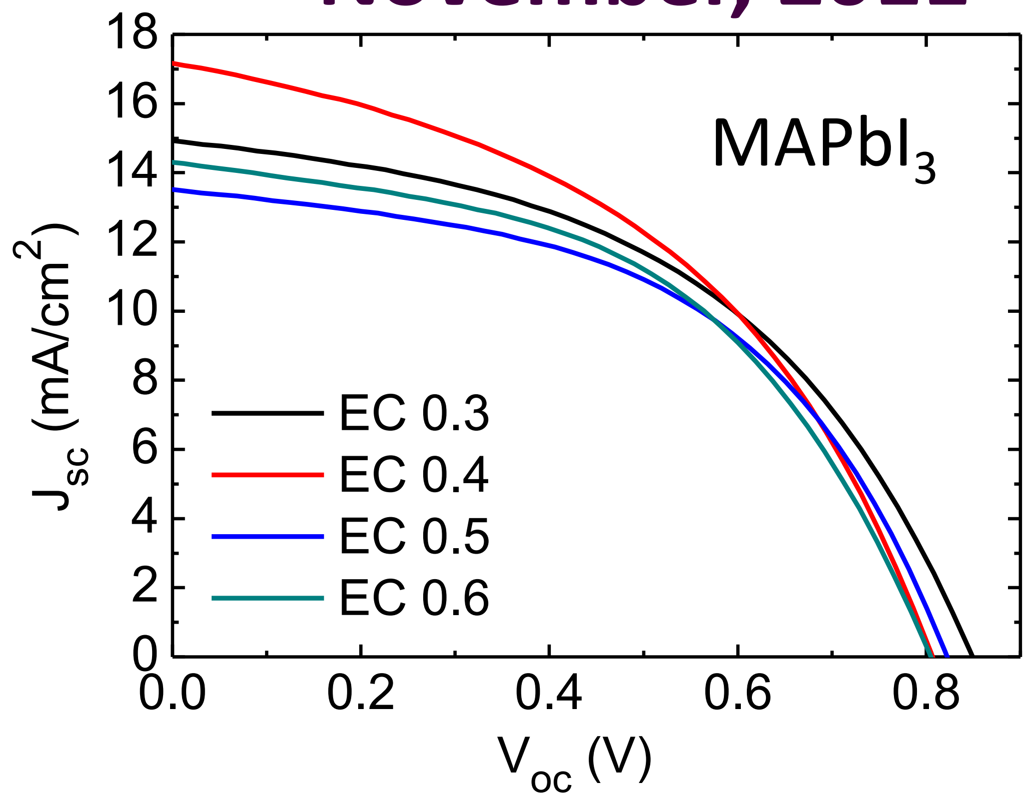
## July, 2011

12 mg P3HT in 1 mL Toluene; 1.5 µm thick mp-$TiO_2$



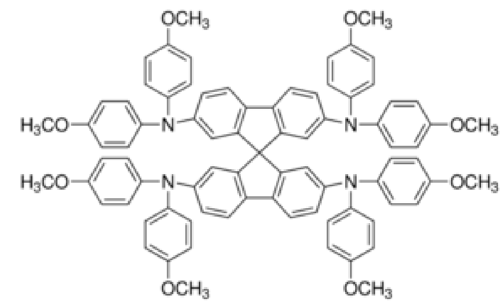
# Second Attempt with Spiro-MeOTAD

## November, 2011




***Hui-Seon Kim***

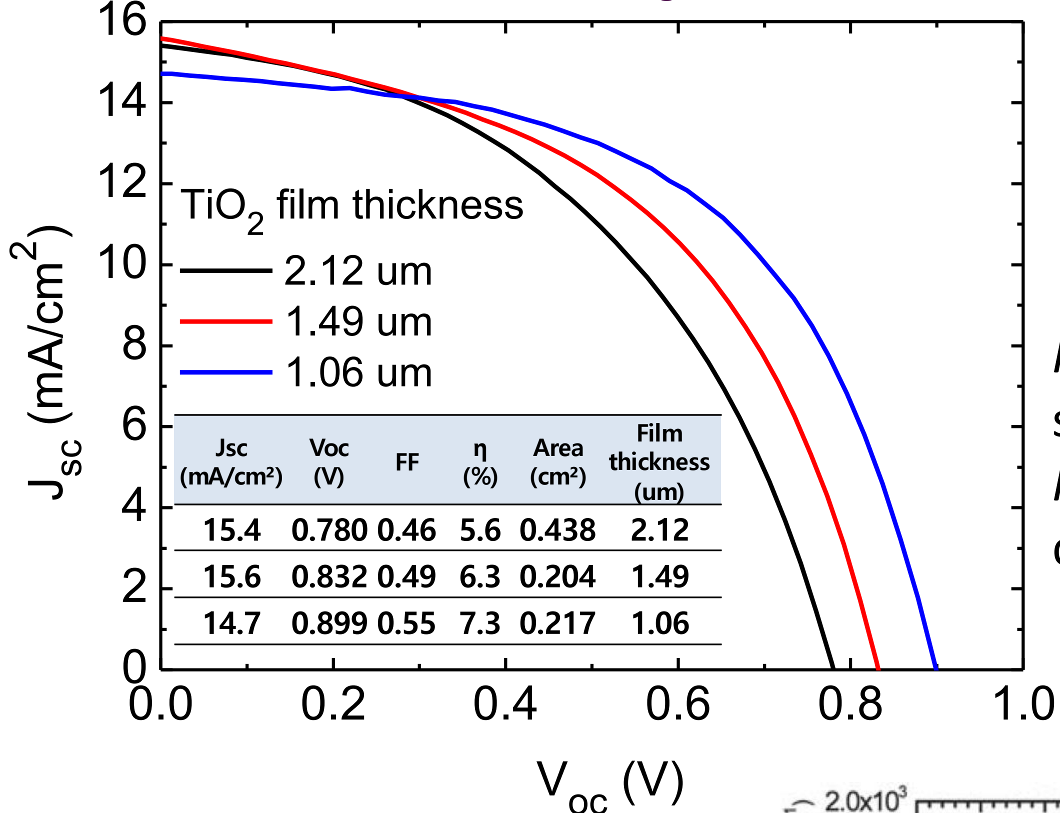
joined




| Sensitizer | TiO2 : TP : <u>EC</u> : LA =1.25 : 6 : x : 0.1 | Jsc (mA/cm²) | Voc (V) | FF | PCE (%) | A (cm²) | t (μm) |
|---|---|---|---|---|---|---|---|
| Perovskite | 0.3 | 14.9 | 0.849 | 0.47 | **6.0** | 0.226 | **1.25** |
| | 0.4 | 17.2 | 0.807 | 0.45 | **6.2** | 0.209 | **1.71** |
| | 0.5 | 13.5 | 0.822 | 0.50 | **5.6** | 0.244 | **1.83** |
| | 0.6 | 14.3 | 0.805 | 0.49 | **5.7** | 0.219 | **1.84** |

# Decrease in mp-$TiO_2$ thickness?

## April, 28, 2012




| Jsc (mA/cm²) | Voc (V) | FF | η (%) | Area (cm²) | Film thickness (um) |
|---|---|---|---|---|---|
| 15.4 | 0.780 | 0.46 | 5.6 | 0.438 | 2.12 |
| 15.6 | 0.832 | 0.49 | 6.3 | 0.204 | 1.49 |
| 14.7 | 0.899 | 0.55 | 7.3 | 0.217 | 1.06 |

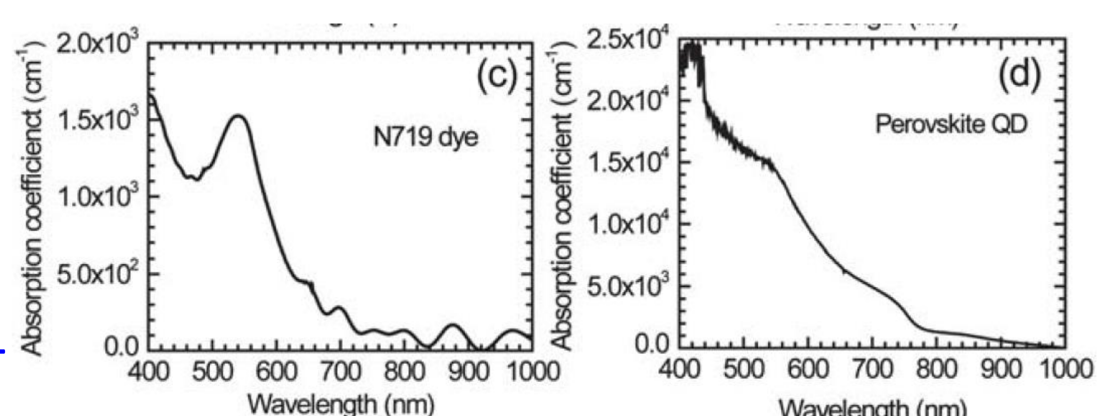
$$F(x) = F(x_0)e^{-\alpha(x-x_0)}$$

*F(x):* intensity at a point *x* below the surface of a semiconductor

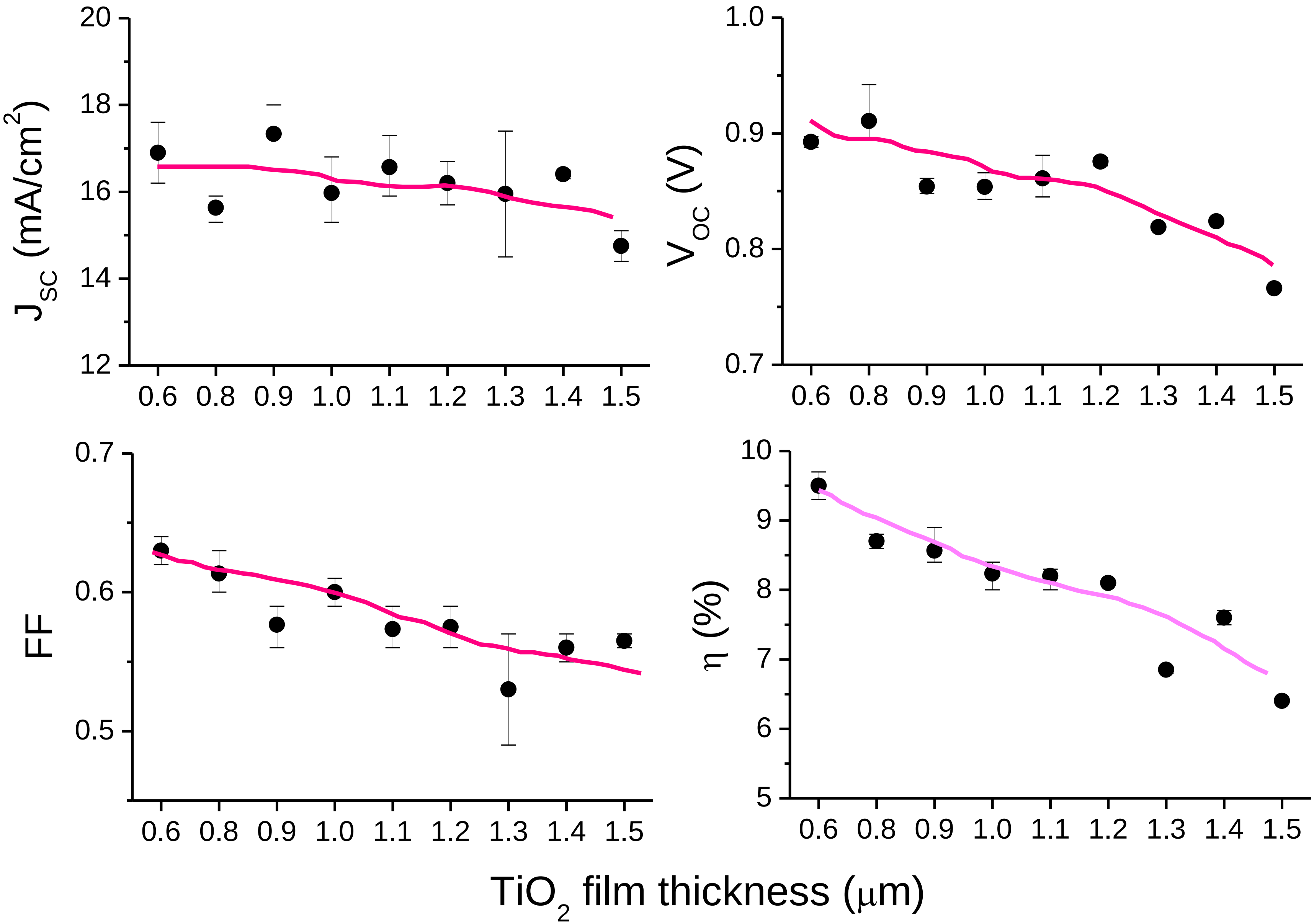
*$F(x_0)$:* intensity at a surface point $x_0$

α: absorption coefficient

N.-G. Park, Nanoscale, 2011

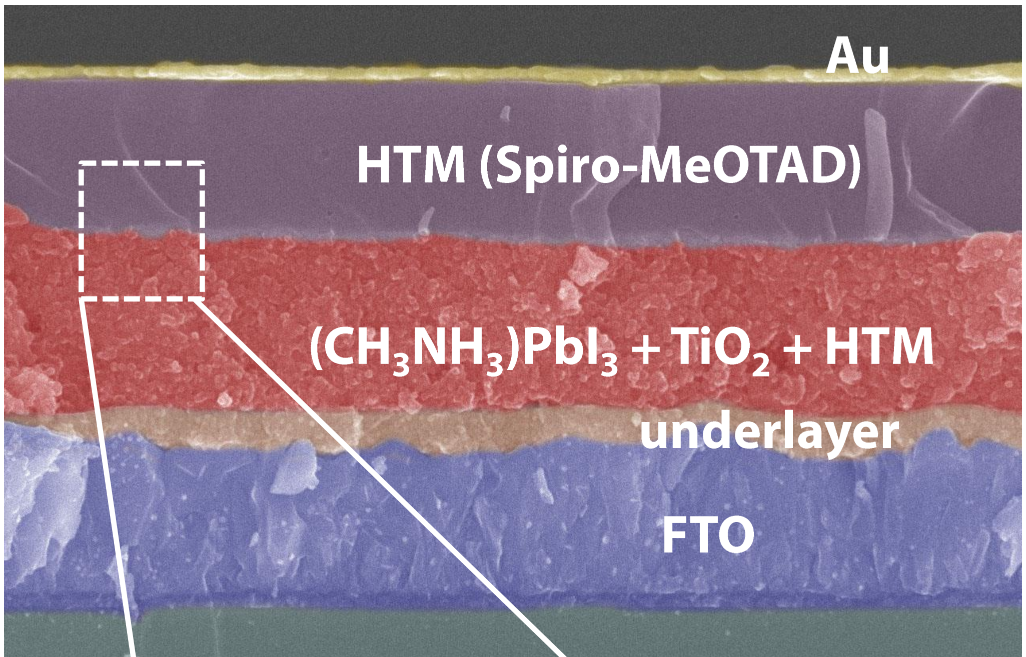


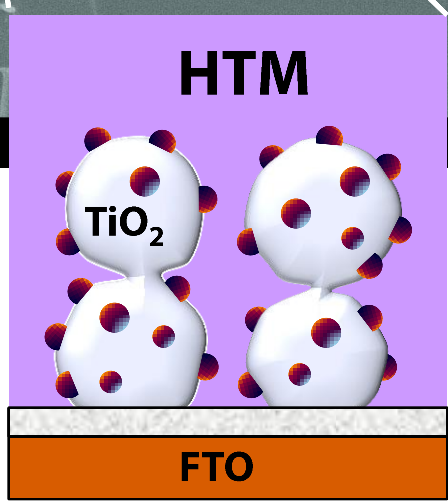
# PV Performance increased as thickness decreased

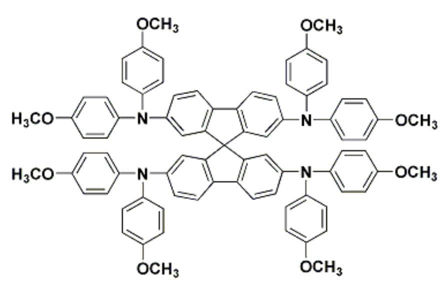


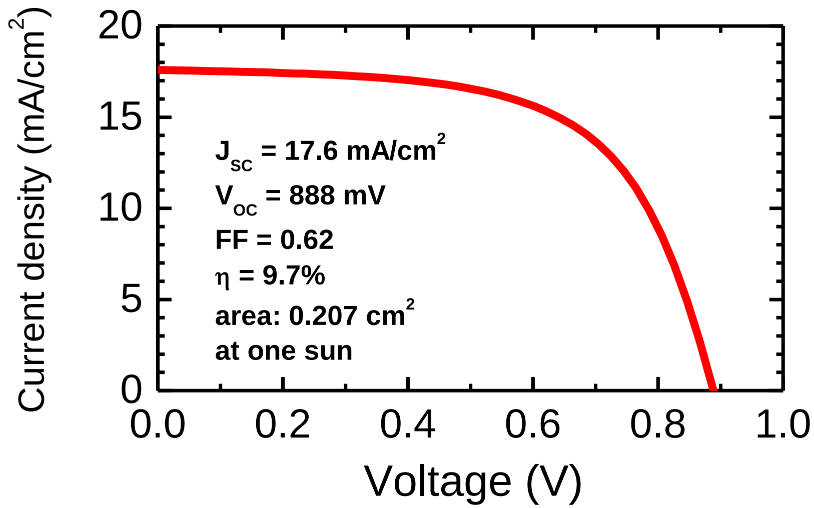
# 1st Report on SS-Perovskite Solar Cell (2012)

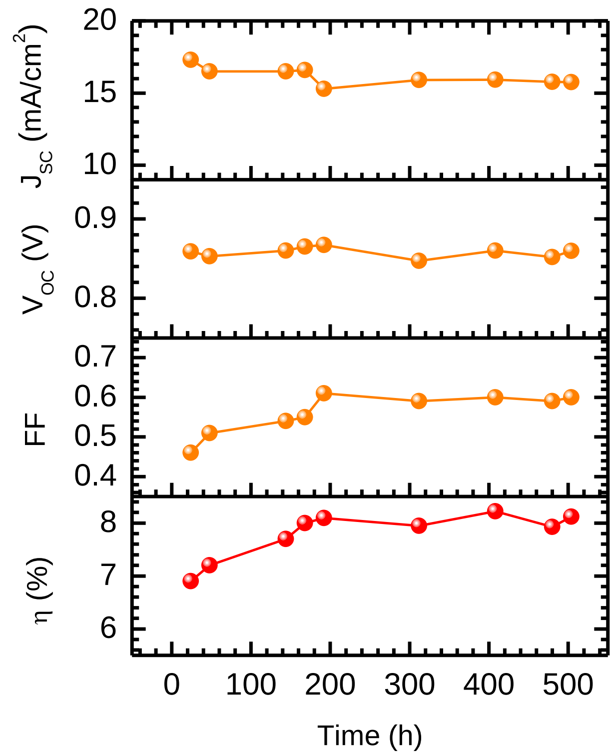
## with a PCE of 9.7% & stability



SCIENTIFIC REPORTS

"The First Report on Stable, High Efficiency Solid-State Perovskite Solar Cell"

OPEN

# Lead Iodide Perovskite Sensitized All-Solid-State Submicron Thin Film Mesoscopic Solar Cell with Efficiency Exceeding 9%

SUBJECT AREAS:
NANOPHOTONICS
OPTICAL MATERIALS AND DEVICES
INORGANIC CHEMISTRY
APPLIED PHYSICS

Hui-Seon Kim[1], Chang-Ryul Lee[1], Jeong-Hyeok Im[1], Ki-Beom Lee[1], Thomas Moehl[2], Arianna Marchioro[2], Soo-Jin Moon[2], Robin Humphry-Baker[2], Jun-Ho Yum[2], Jacques E. Moser[2], Michael Grätzel[2] & Nam-Gyu Park[1]

Received
5 July 2012

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6 August 2012

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21 August 2012

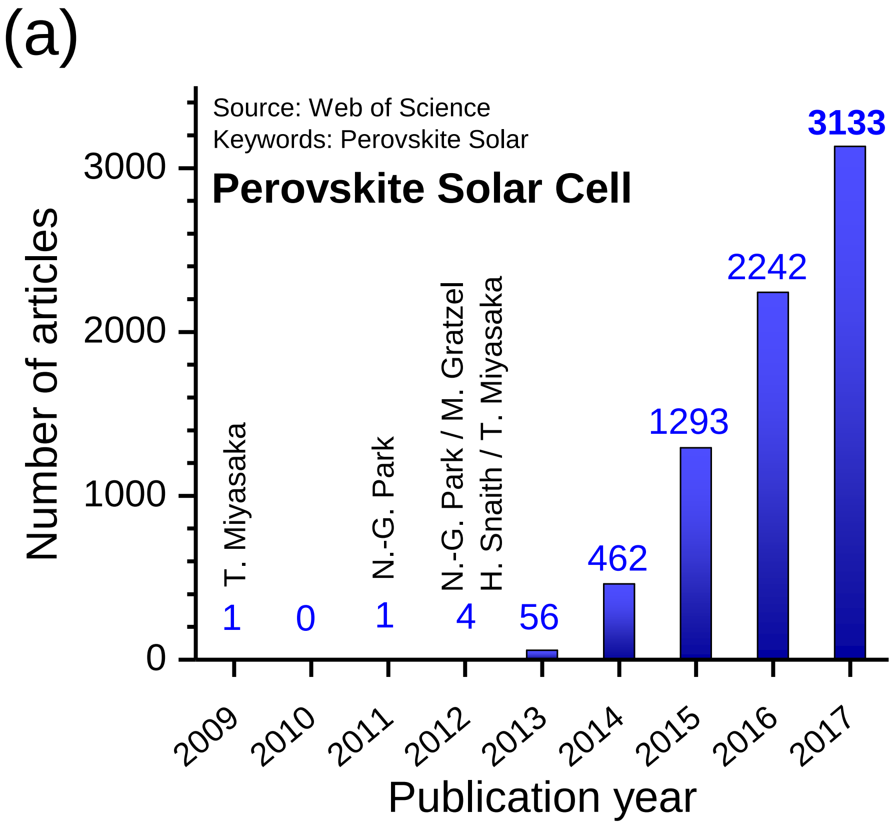
[1]School of Chemical Engineering and Department of Energy Science, Sungkyunkwan University, Suwon 440-746, Korea, [2]Laboratory for Photonics and Interfaces, Institute of Chemical Sciences and Engineering, School of Basic Sciences, Ecole Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, Switzerland.

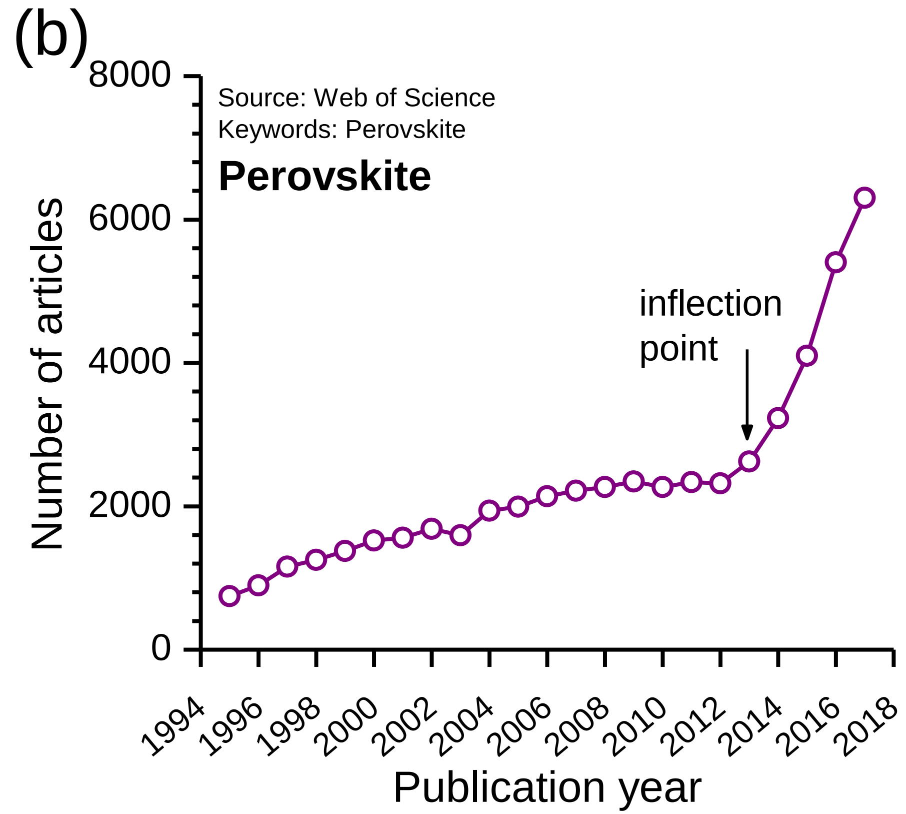
**~3,800 times cited as of May, 2018**

We report on solid-state mesoscopic heterojunction solar cells employing nanoparticles (NPs) of methyl ammonium lead iodide $(CH_3NH_3)PbI_3$ as light harvesters. The perovskite NPs were produced by reaction of methylammonium iodide with $PbI_2$ and deposited onto a submicron-thick mesoscopic $TiO_2$ film, whose pores were infiltrated with the hole-conductor *spiro*-MeOTAD. Illumination with standard AM-1.5 sunlight generated large photocurrents ($J_{SC}$) exceeding 17 mA/cm$^2$, an open circuit photovoltage ($V_{OC}$) of 0.888 V and a fill factor (FF) of 0.62 yielding a power conversion efficiency (PCE) of 9.7%, the highest reported to

Correspondence and requests for materials should be addressed to

# PSC research activities seen from publications



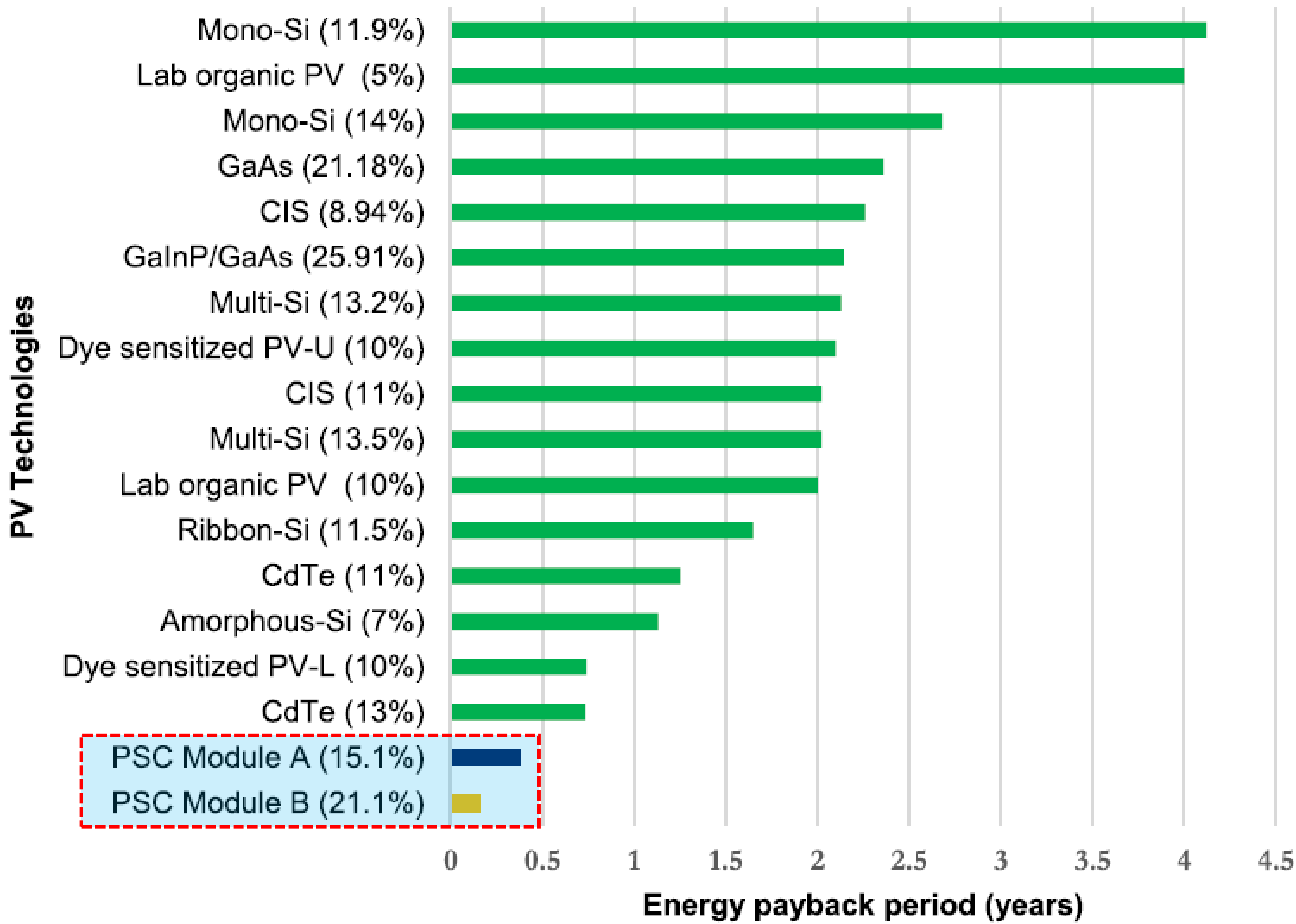




keyword "Perovskite Solar"

keyword "Perovskite"

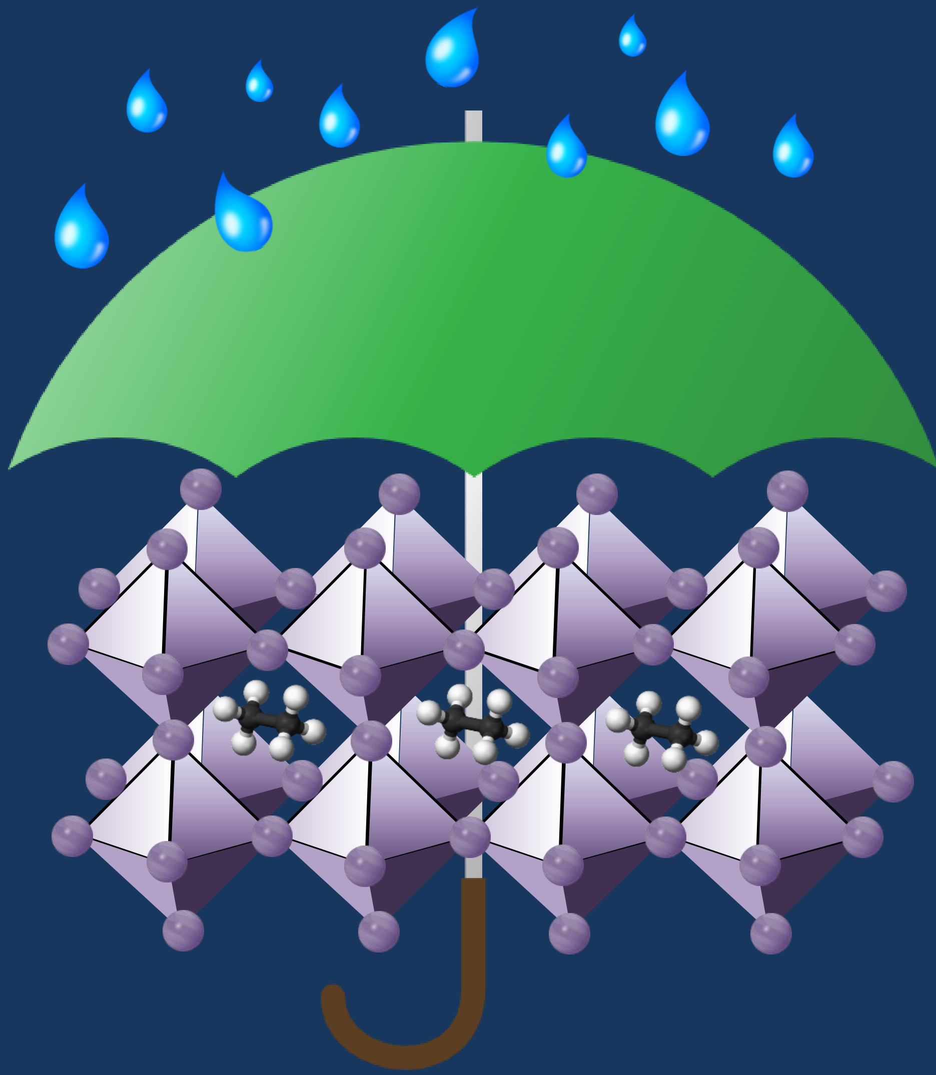
#**1,424** released in 2018 (more than 4,000 papers expected)

# Energy Payback Time




*Renewable and Sustainable Energy Reviews 80 (2017) 1321–1344*

# Toward Hysteresis-free, Stable PSC



# On the I-V Hysteresis

## Severe hysteresis leads to poor stability

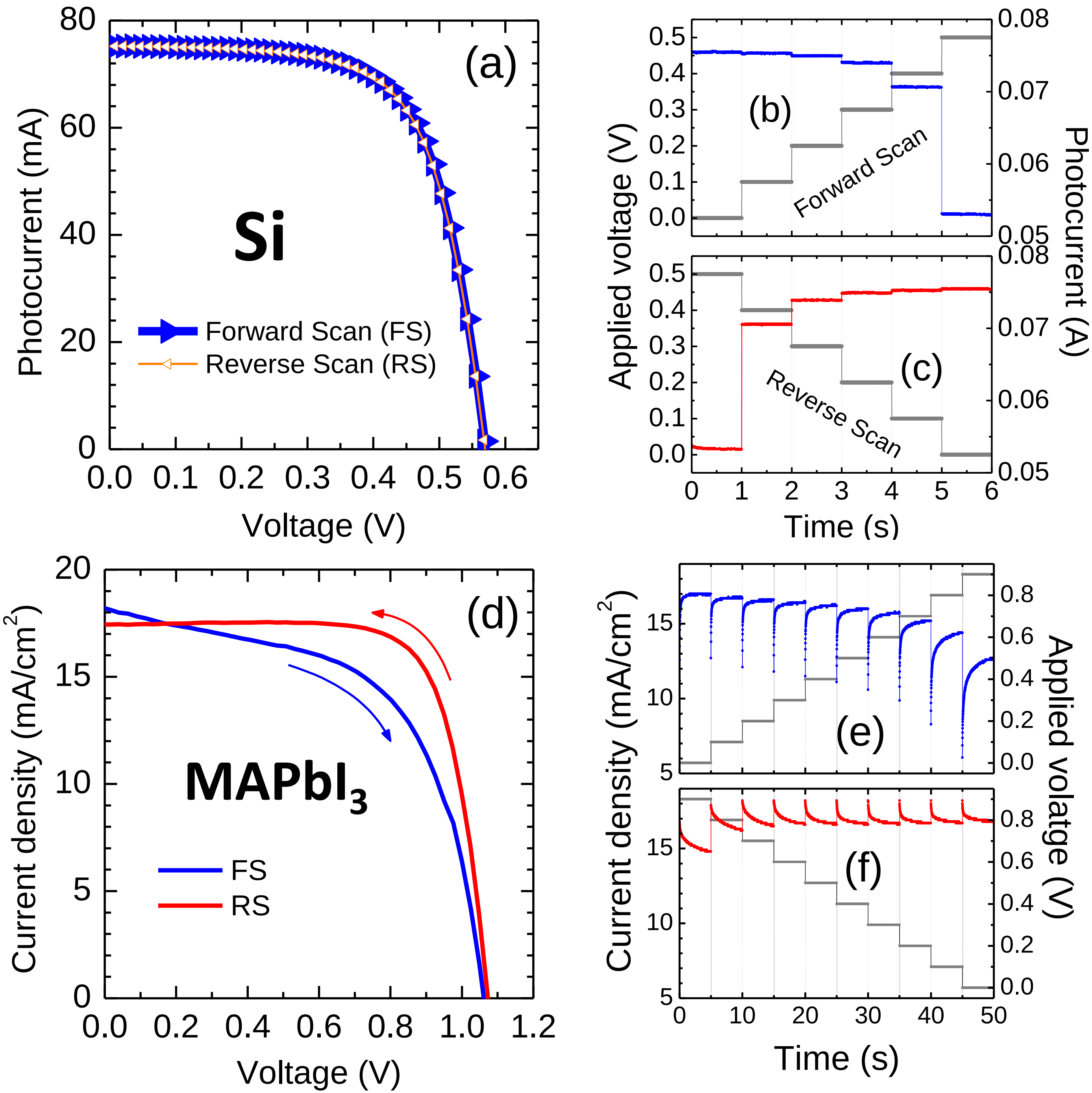
nature energy

PERSPECTIVE

PUBLISHED: 17 OCTOBER 2016 | ARTICLE NUMBER: 16152 | DOI: 10.1038/NENERGY.2016.152

**Towards stable and commercially available perovskite solar cells**

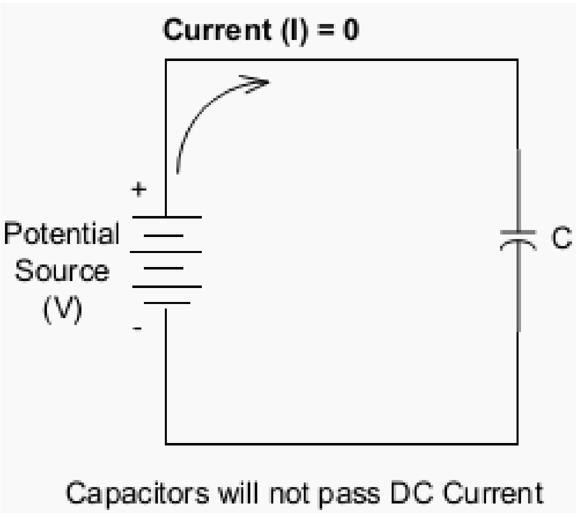
Nam-Gyu Park[1*], Michael Grätzel[2], Tsutomu Miyasaka[3], Kai Zhu[4] and Keith Emery[4]

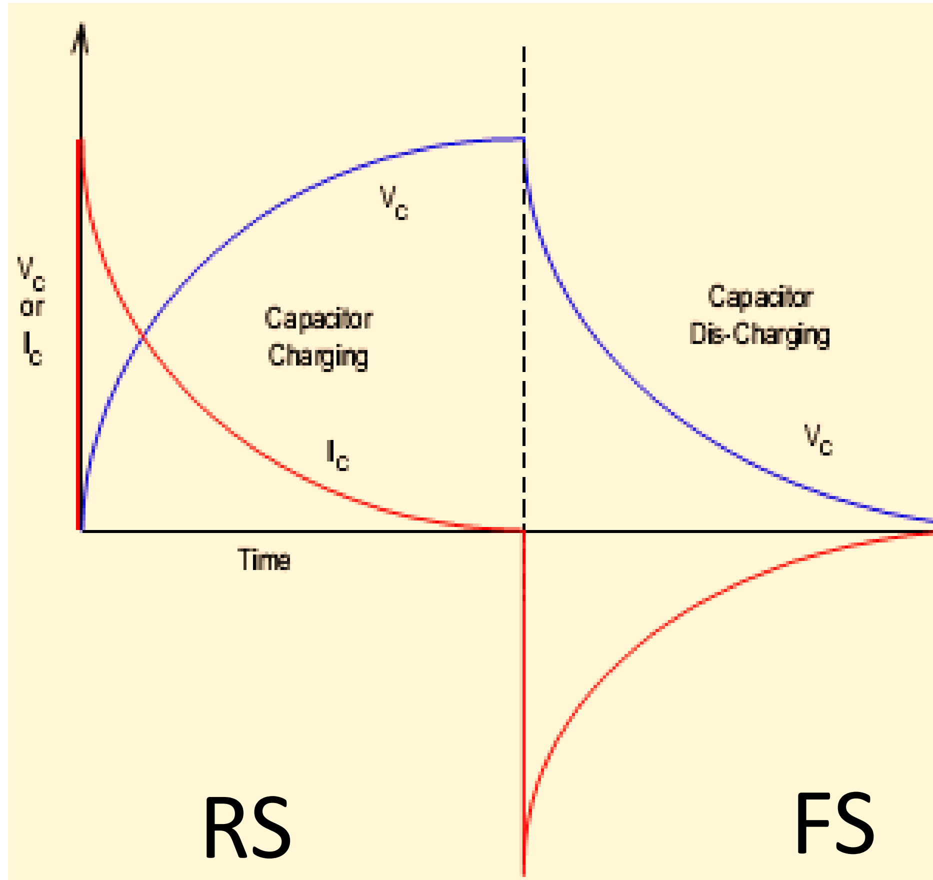


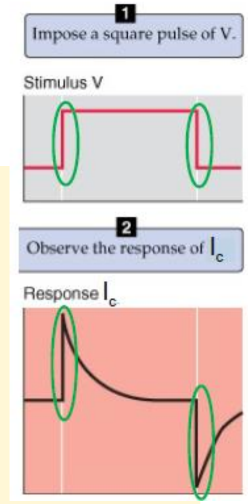
(a)
Si
Forward Scan (FS)
Reverse Scan (RS)
Photocurrent (mA)
Voltage (V)
(b)
Forward Scan
(c)
Reverse Scan
Applied voltage (V)
Photocurrent (A)
Time (s)
(d)
MAPbI3
FS
RS
Current density (mA/cm2)
Voltage (V)
(e)
(f)
Current density (mA/cm2)
Applied volatge (V)
Time (s)

# Capacitive Current

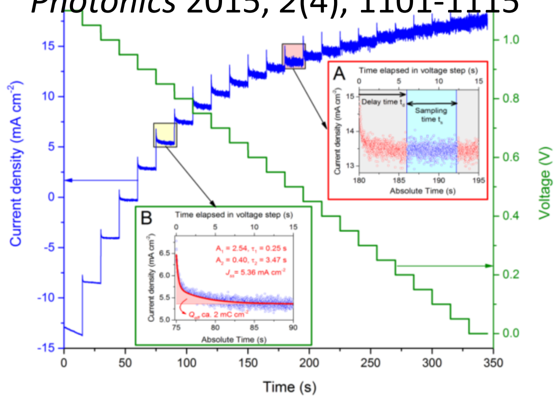
$$I = C\frac{dV}{dt}$$




*Photonics* 2015, *2*(4), 1101-1115




# Increases in Capacitance leads to Hysteresis

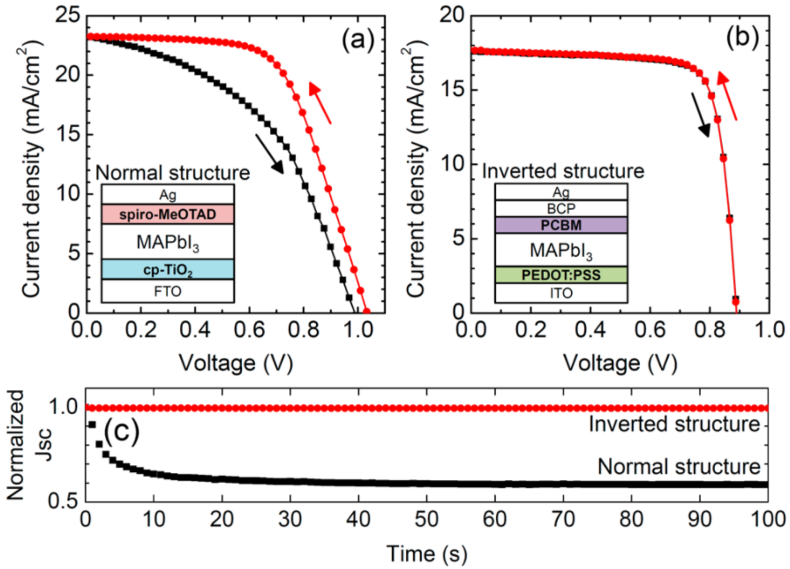
Management of Capacitor Component in PSC is important

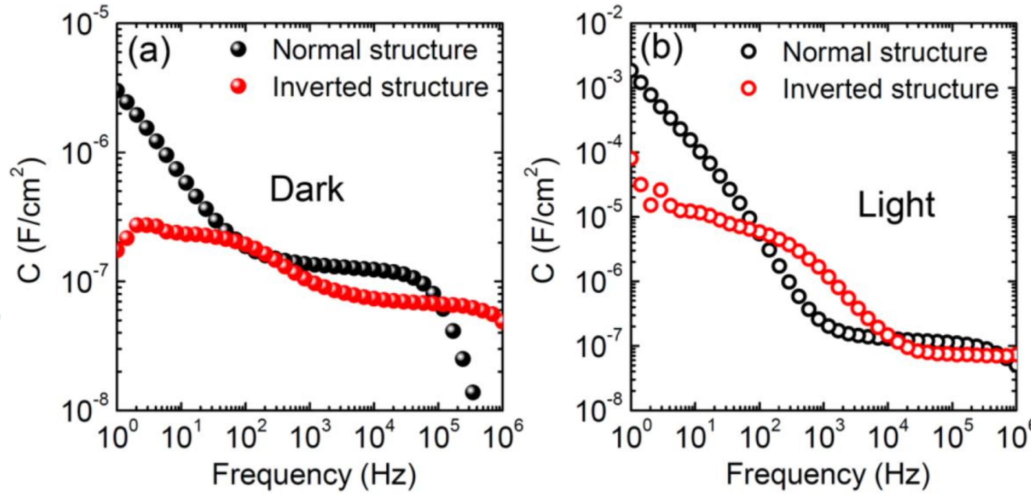
# ► Importance of Interface

(*J. Phys. Chem. Lett.* 2015, 6, 4633−4639)

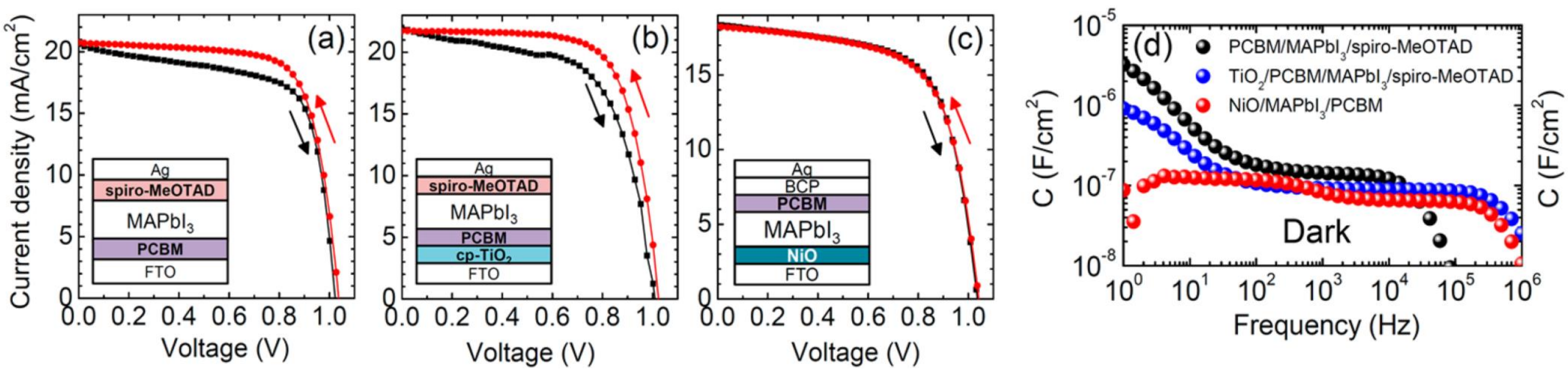
THE JOURNAL OF PHYSICAL CHEMISTRY Letters

- Hysteresis: normal vs inverted structure



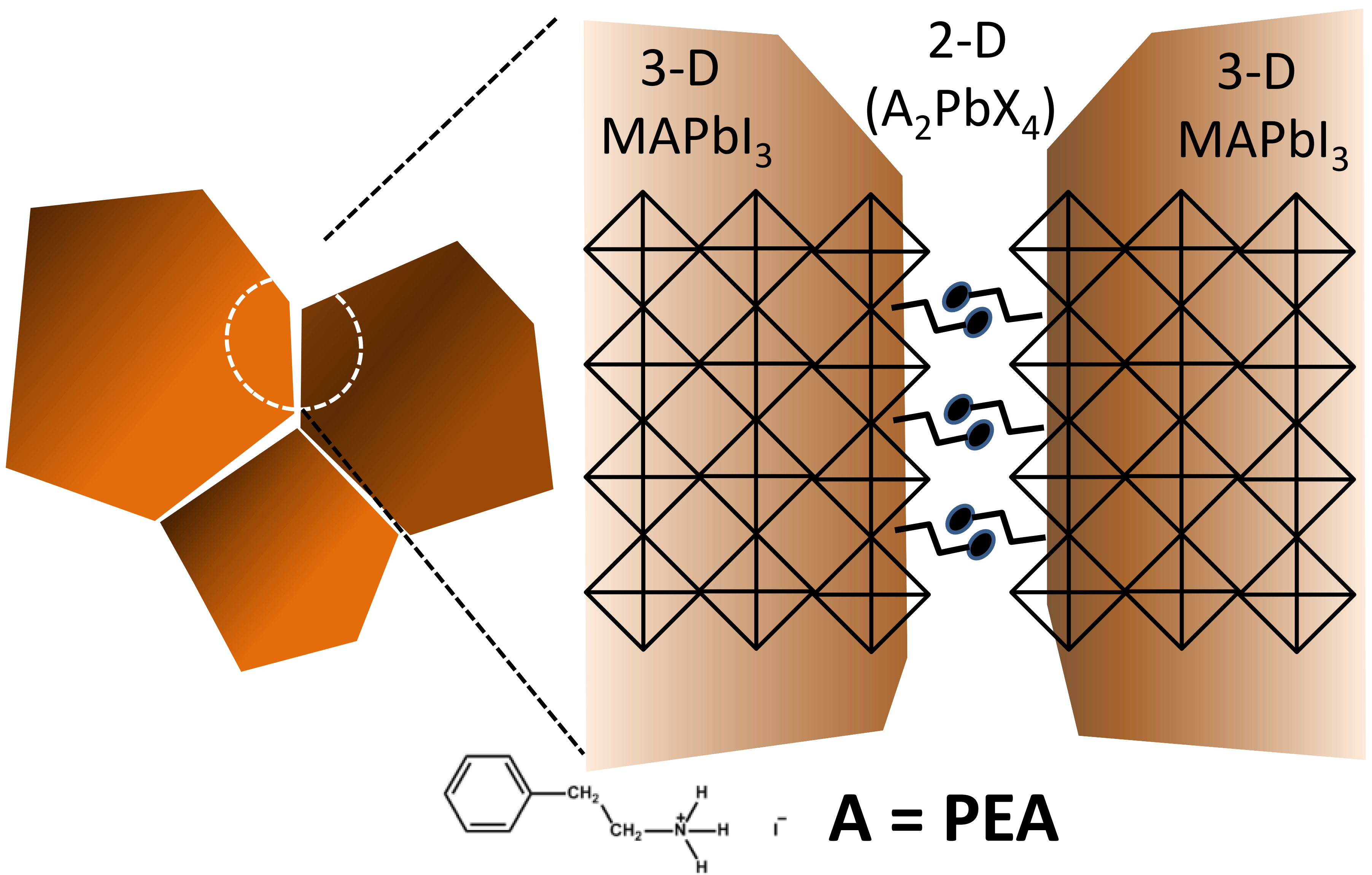

- Effect of selective contacts on hysteresis



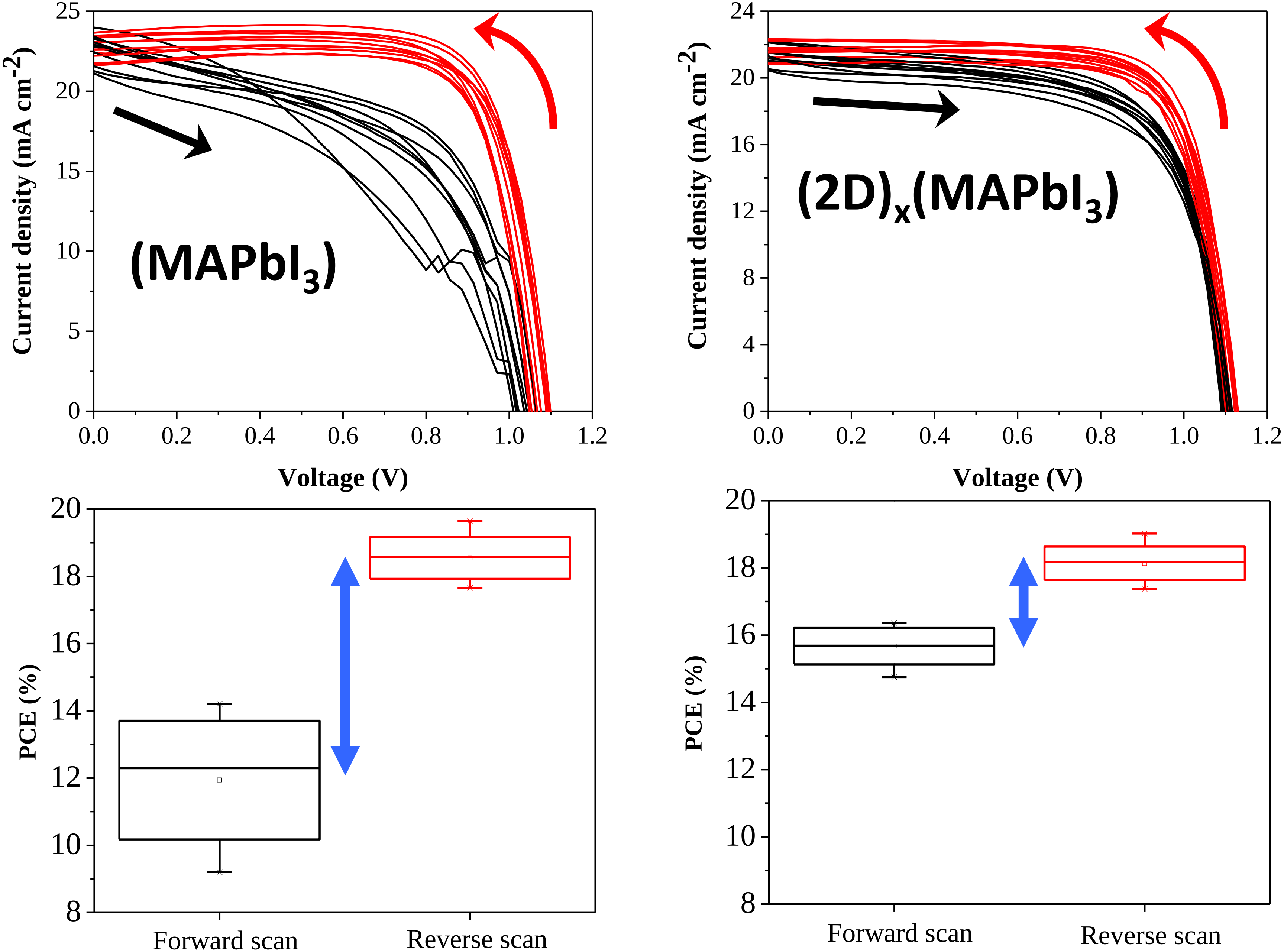
How to reduce or eliminate I-V hysteresis in normal structure with $TiO_2$?

(1) Interfacial engineering
(2) Bulk defect engineering

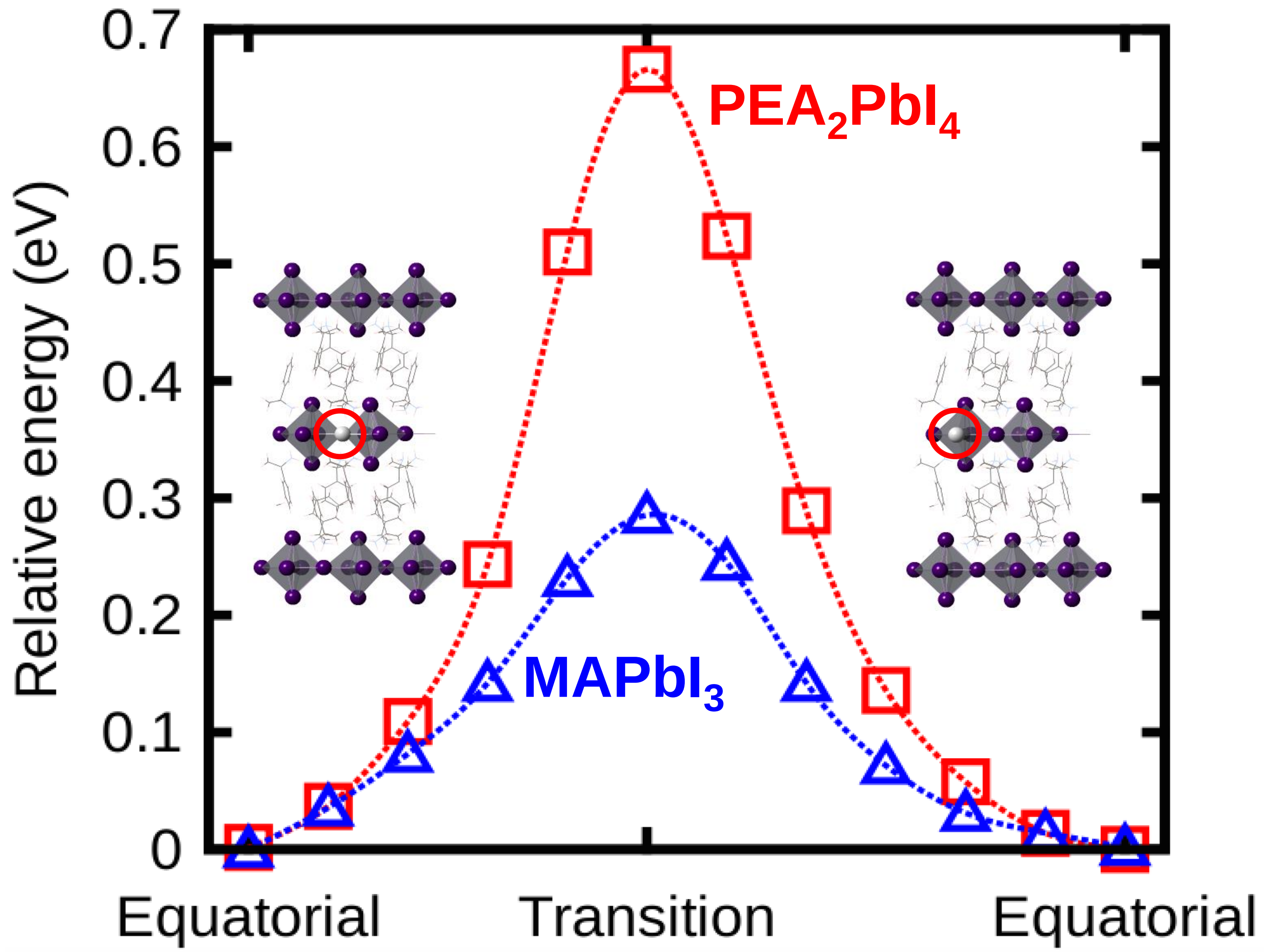
# Interfacial Engineering with 2D $(PEA)_2PbI_4$



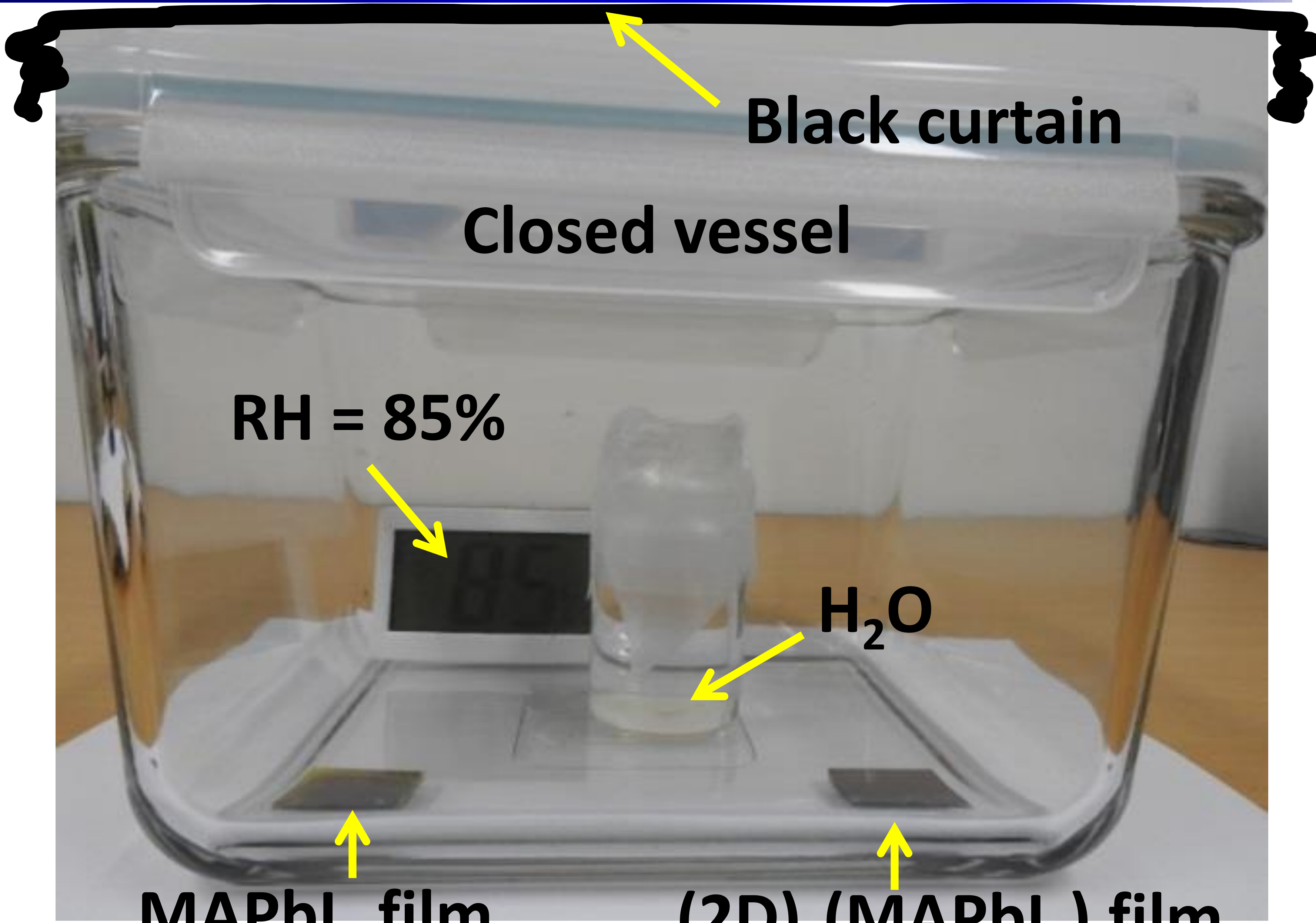
# Hysteresis reduced by modification with 2D



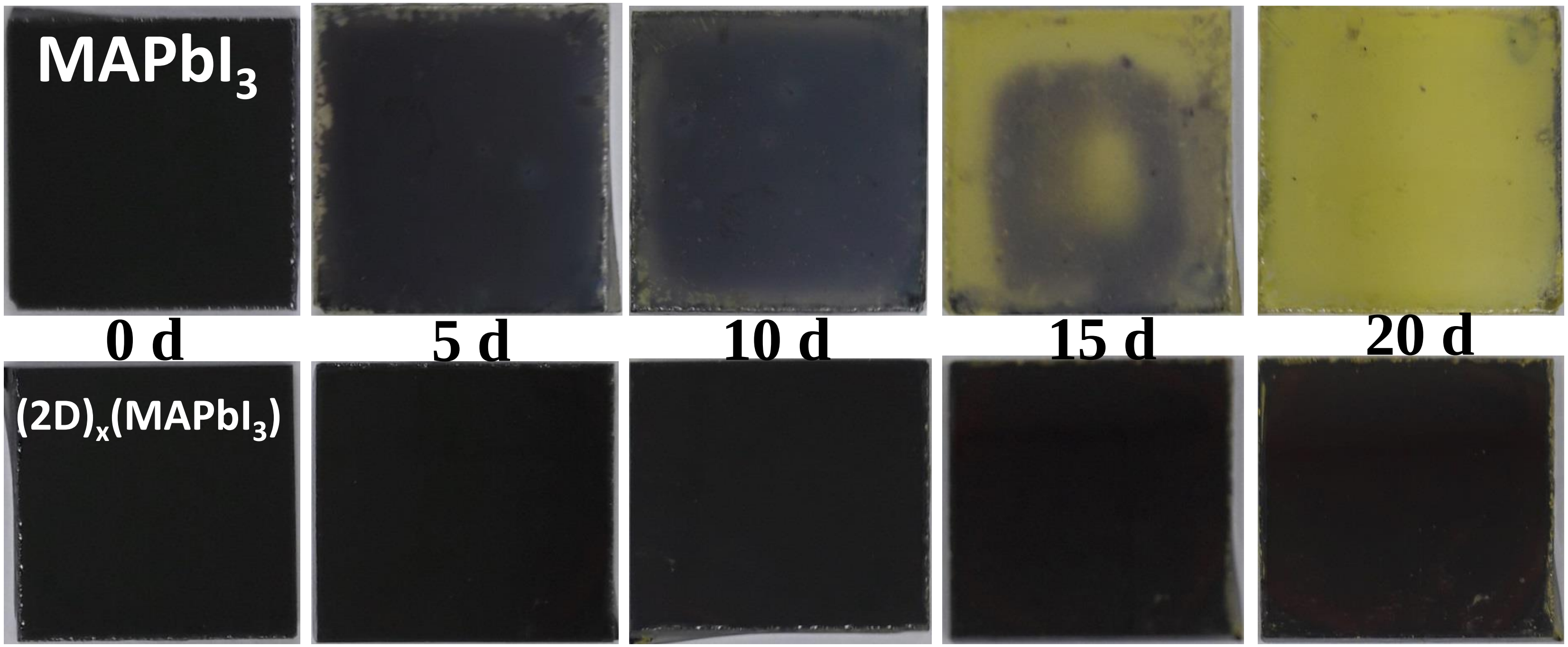
# Higher energy for iodide displacement in 2D than in 3D

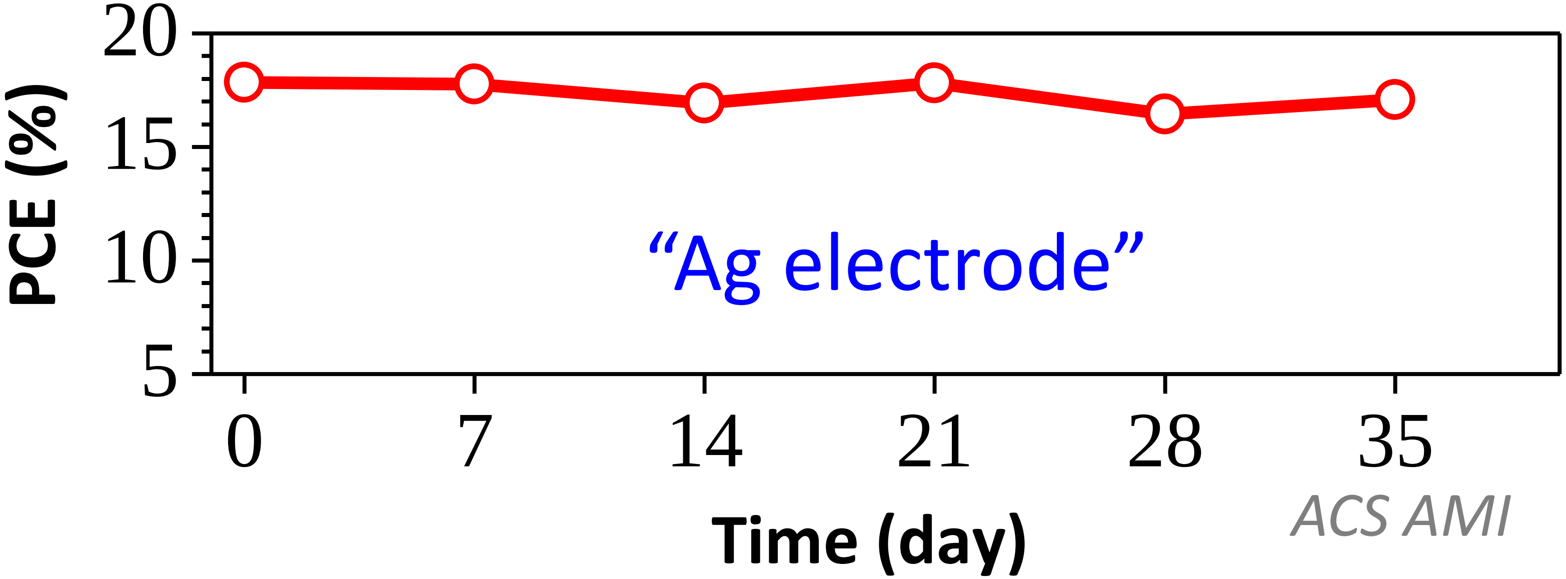


# Humidity Test

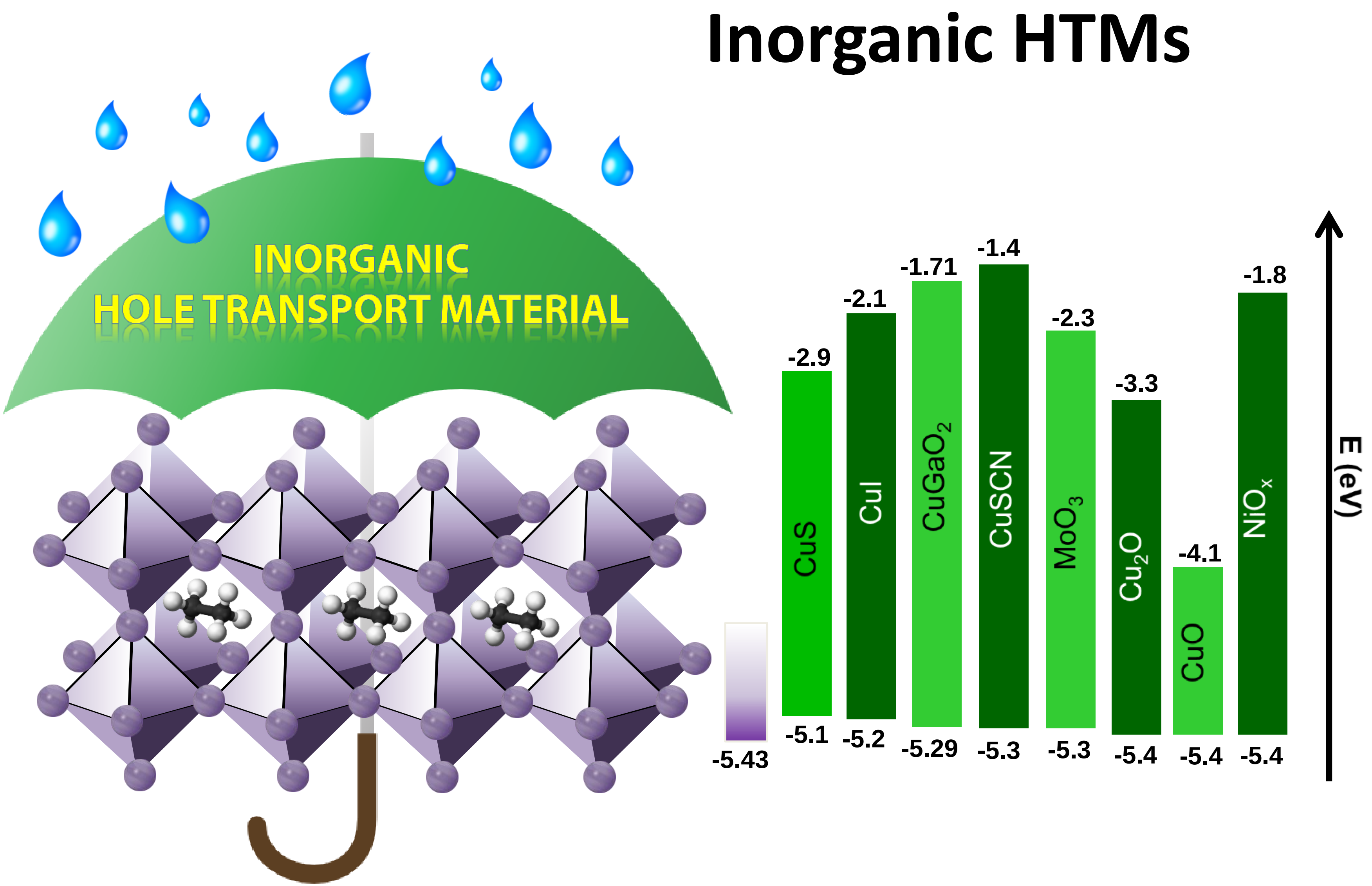


# Device stability of $(2D)_x(MAPbI_3)$ under R=85%



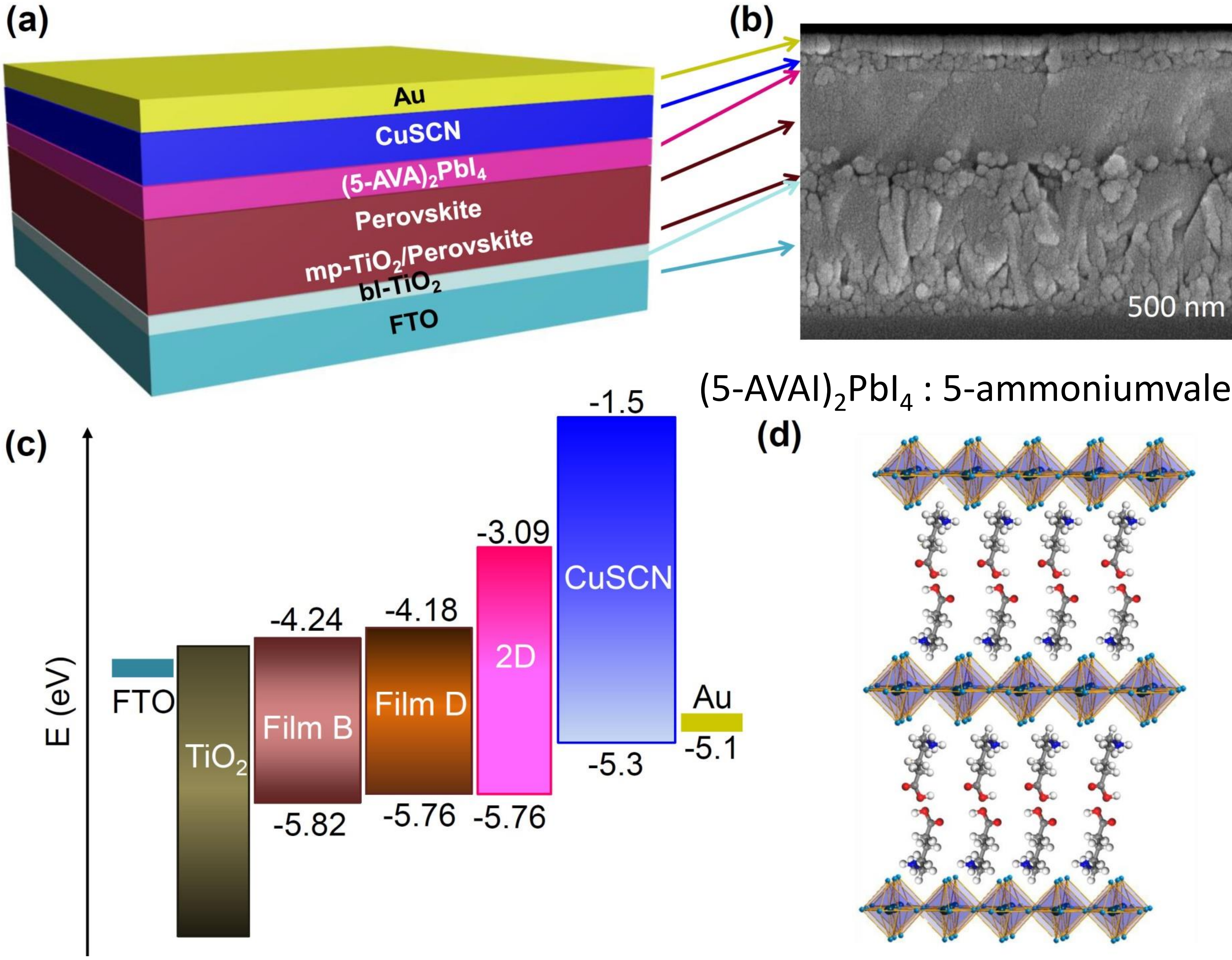

ACS AMI



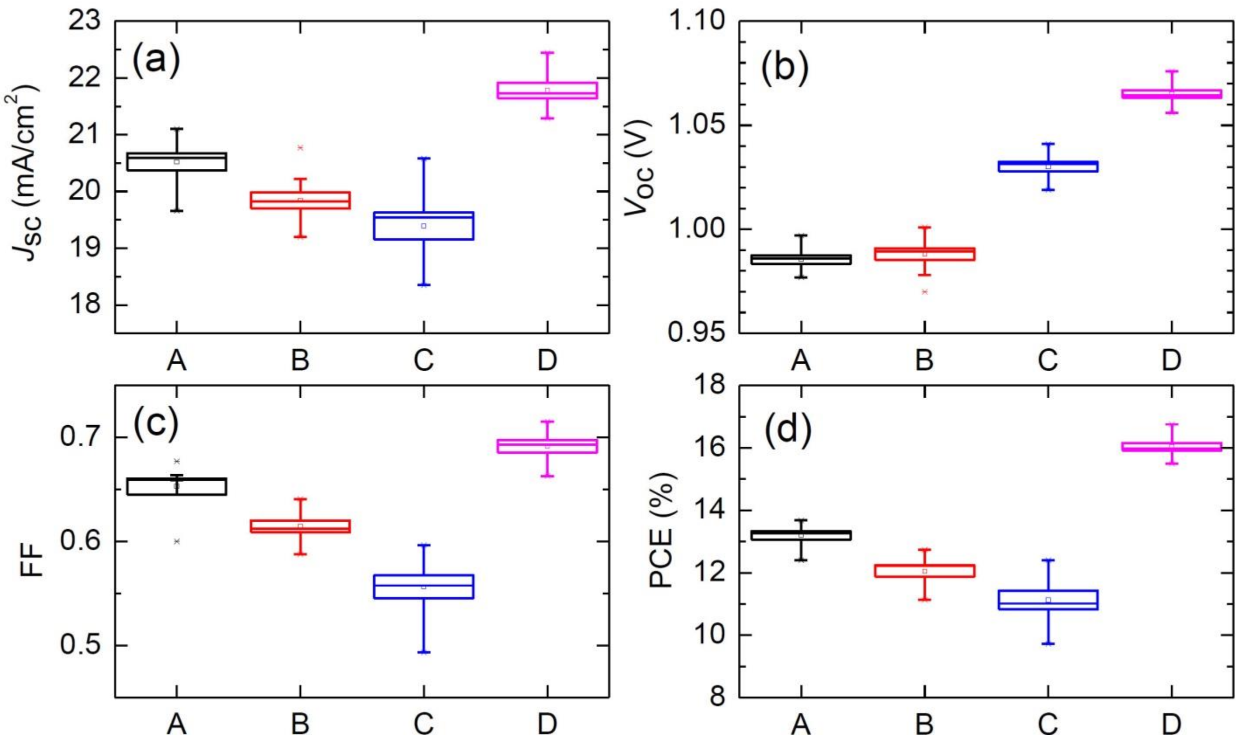
Inorganic HTMs
INORGANIC
HOLE TRANSPORT MATERIAL
-5.43
CuS
-2.9
-5.1
CuI
-2.1
-5.2
CuGaO2
-1.71
-5.29
CuSCN
-1.4
-5.3
MoO3
-2.3
-5.3
Cu2O
-3.3
-5.4
CuO
-4.1
-5.4
NiOx
-1.8
-5.4
E (eV)

# In-situ formation of 2D on perovskite surface

(5-AVAI)$_2$PbI$_4$ : 5-ammoniumvaleric acid



# Post-treatment of 5-AVAI on $PbI_2$ excess PSK

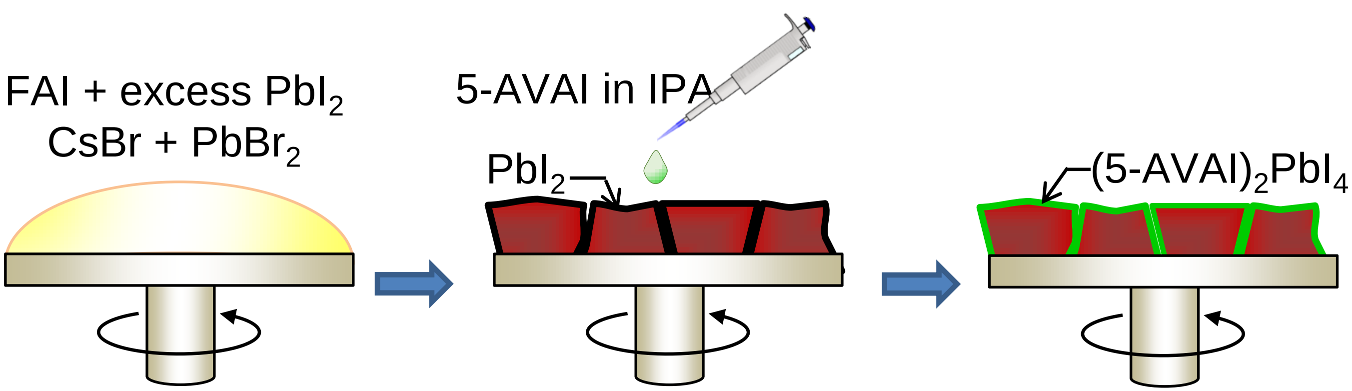



Device **A**: stoichiometric $(FAPbI_3)_{0.88}(CsPbBr_3)_{0.12}$

Device **B**: non-stoichiometric $(FAPbI_3)_{0.88}(CsPbBr_3)_{0.12}$ with excess 8 mol% $PbI_2$

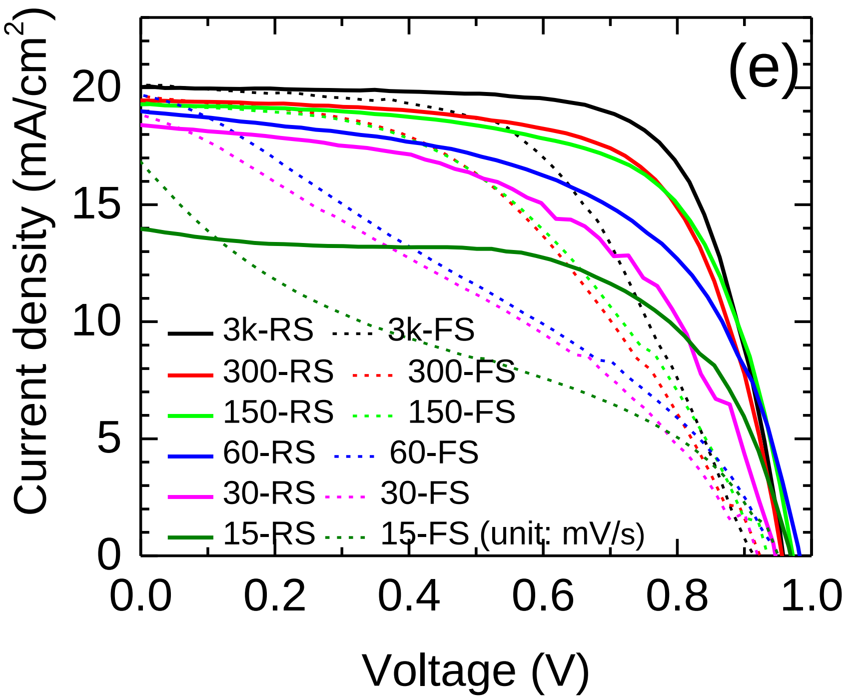
Device **C**: 5-AVAI post-treatment on A

Device **D**: 5-AVAI post-treatment on B

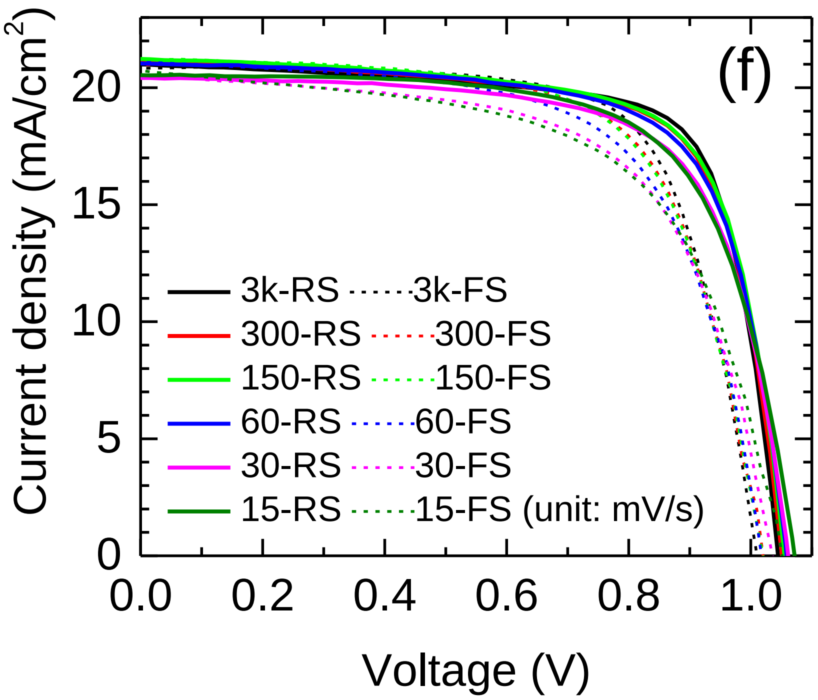


# Scan rate independent

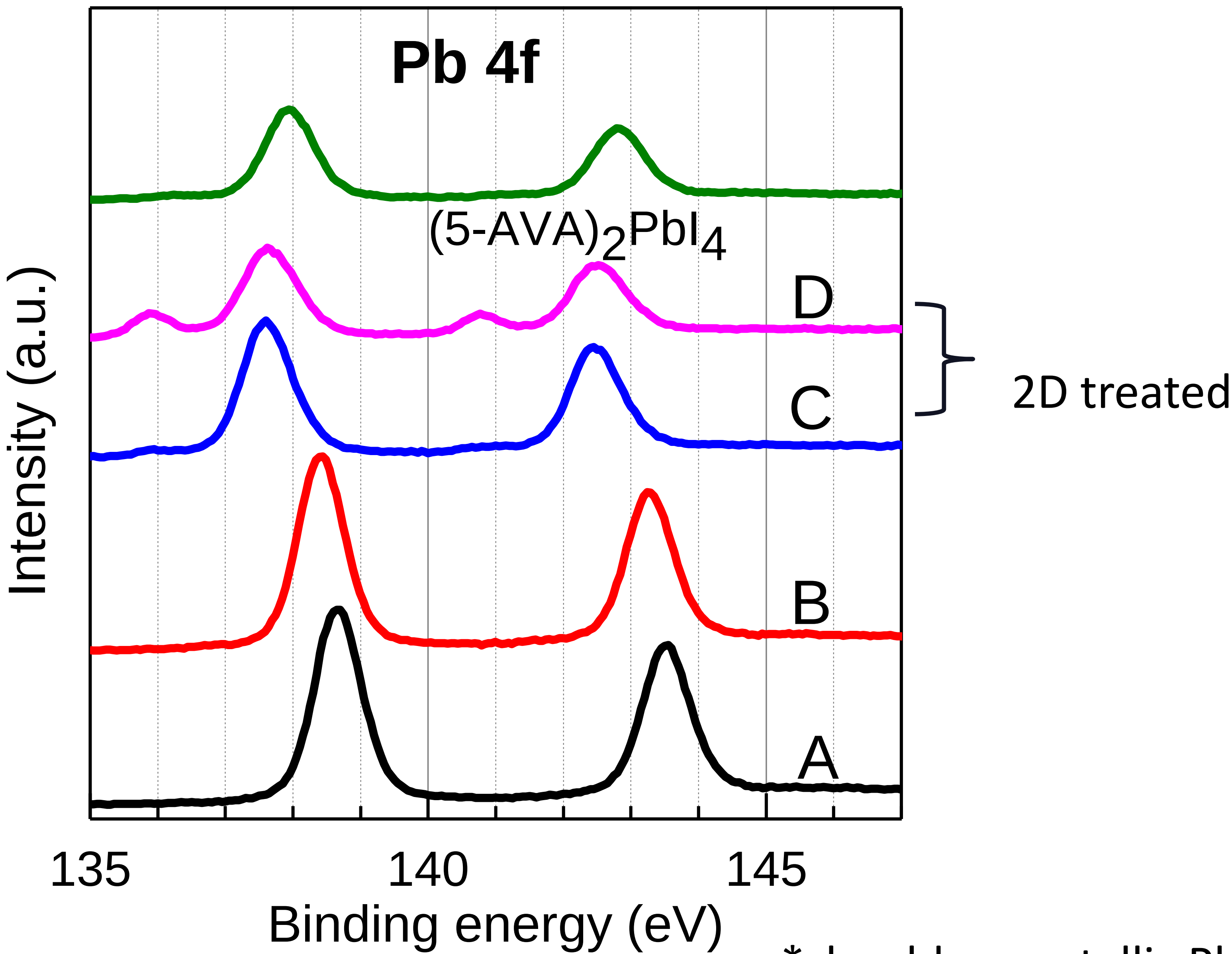
## Device A




## Device D

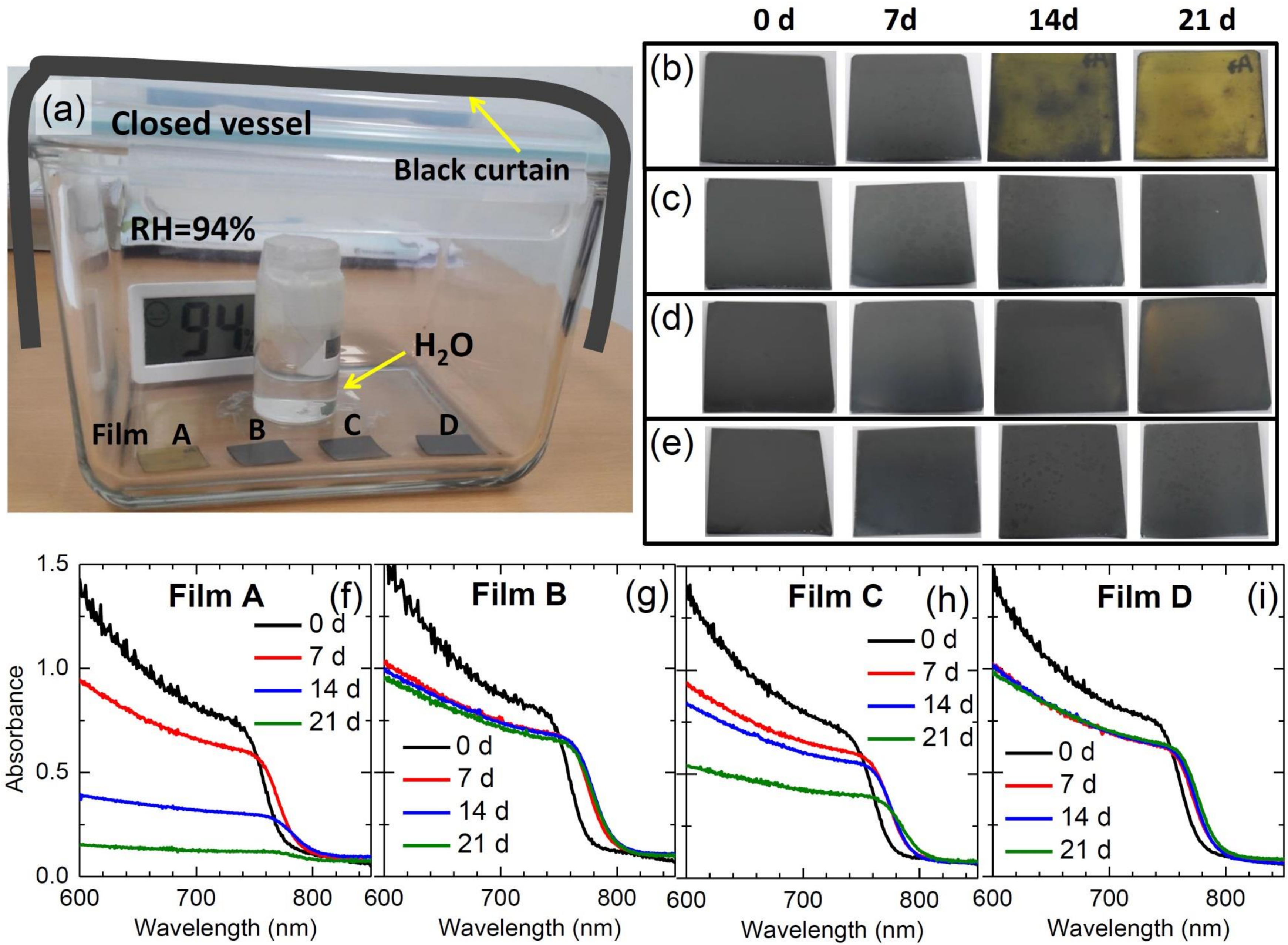


# Evidence of in-situ formed 2D

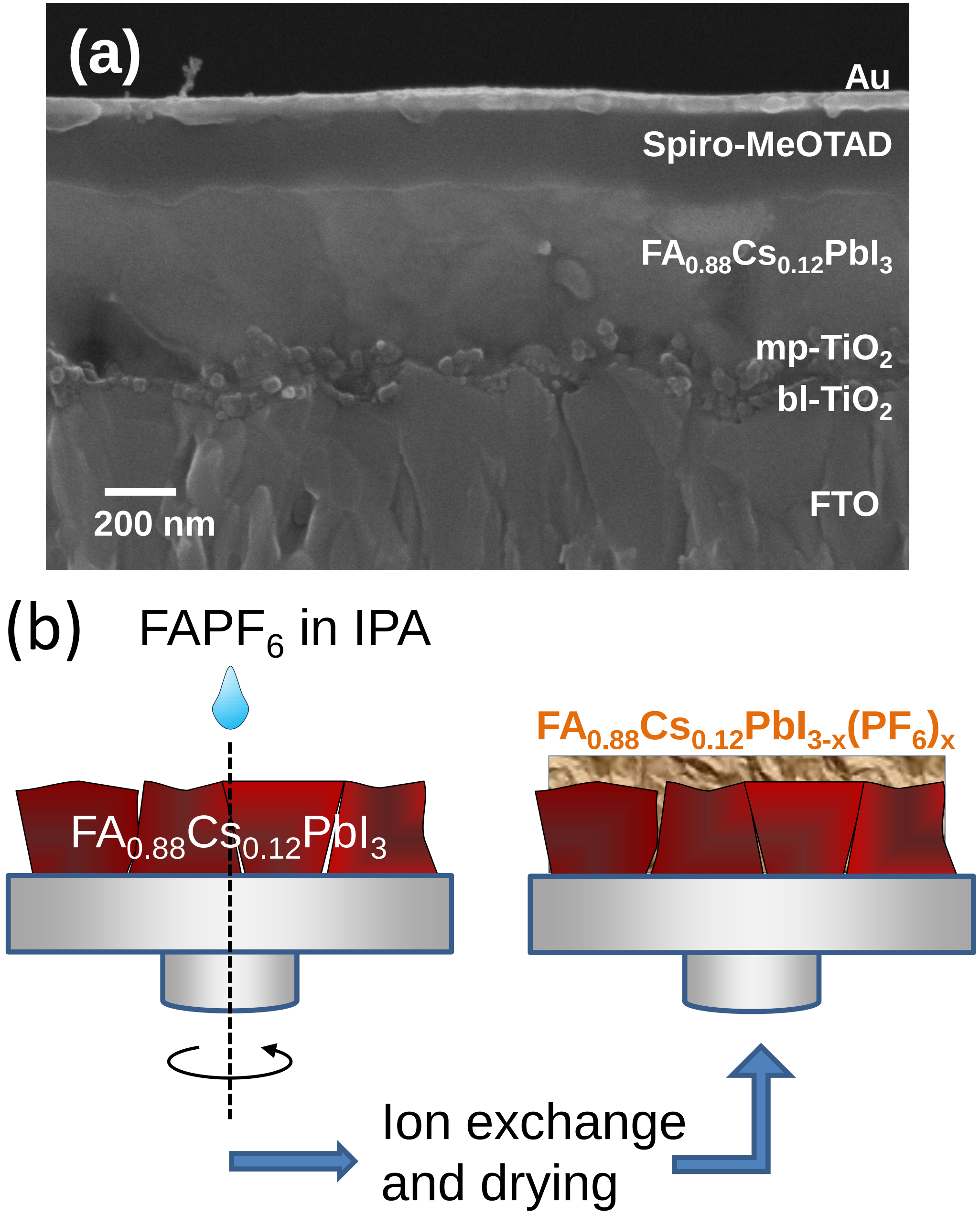



*shoulder: metallic Pb

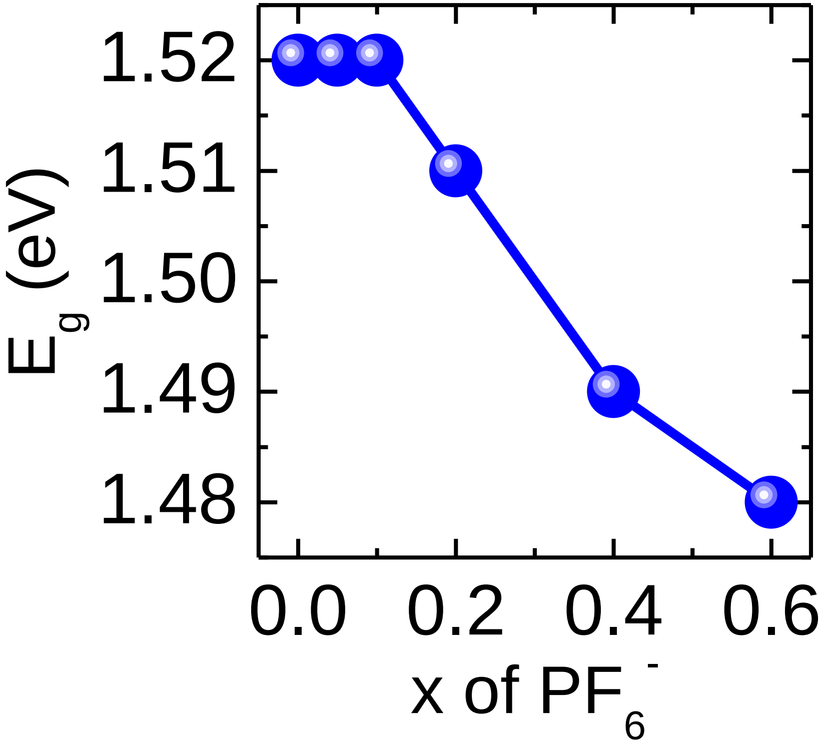
# Effect of In-situ formed 2D on stability

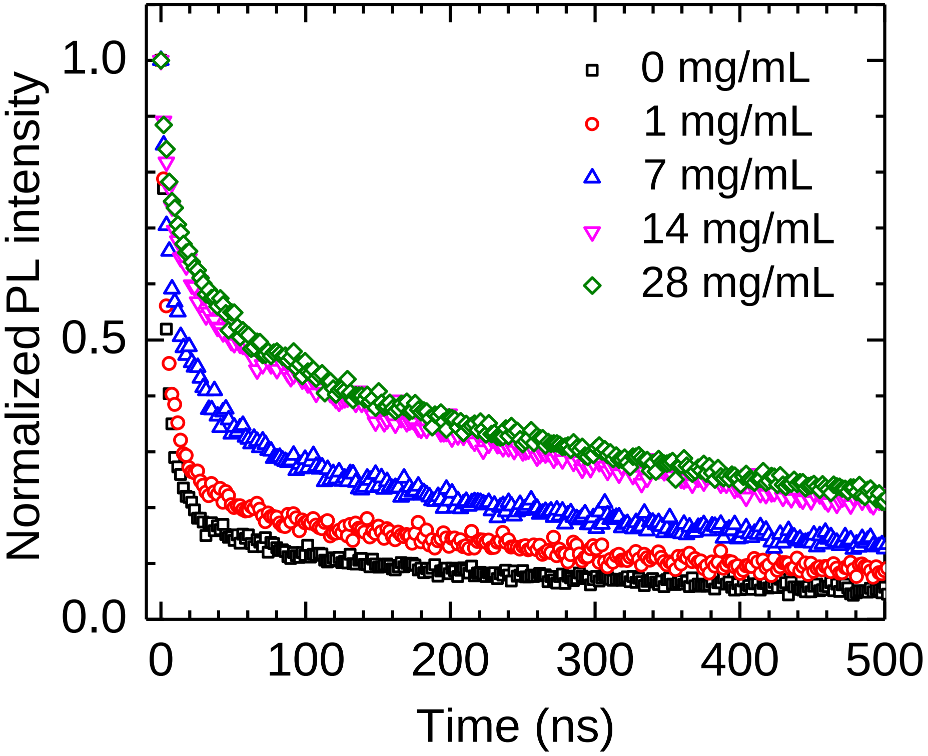


# Ion Exchange Reaction for Interfacial Engineering



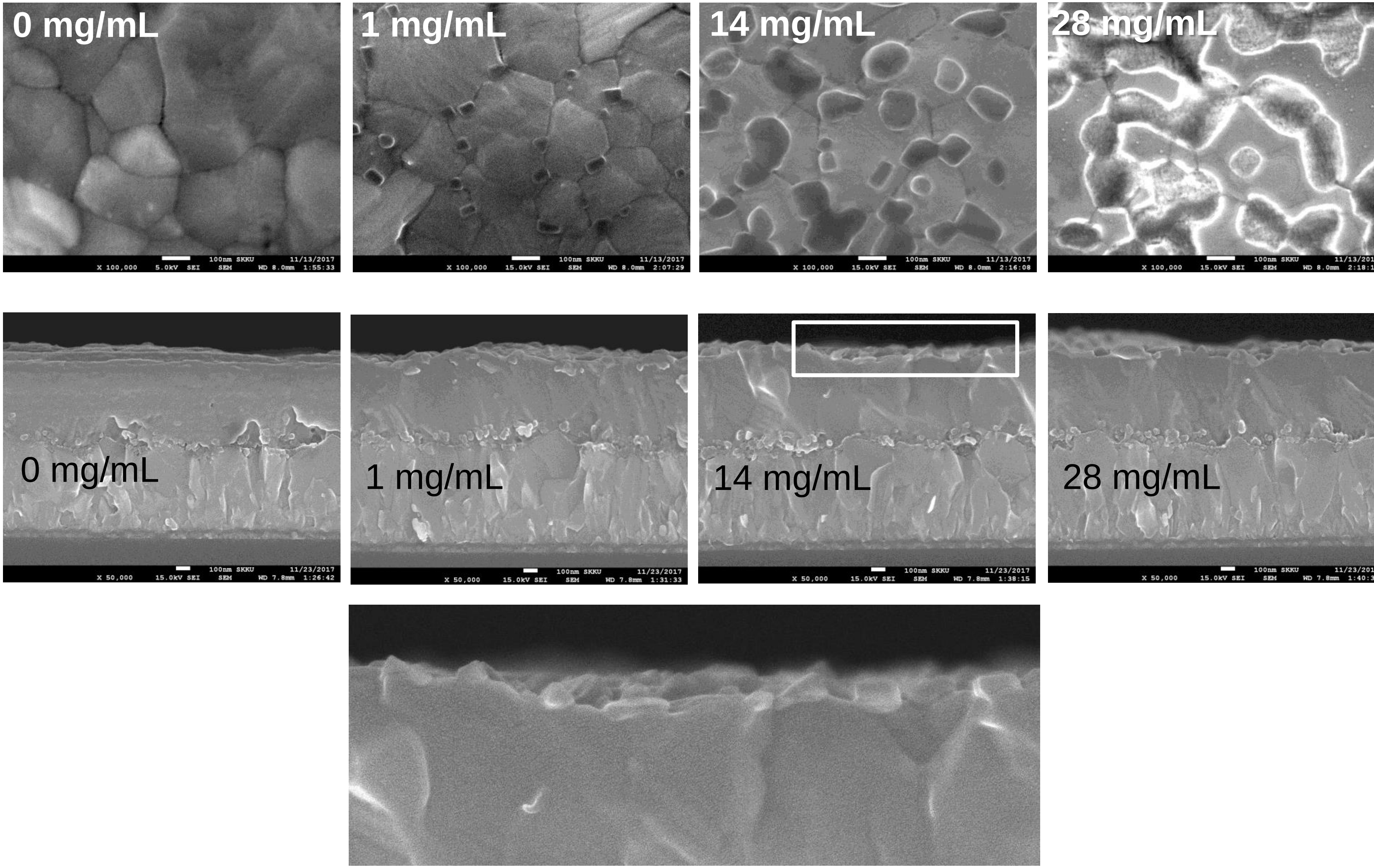
# Bang gap decreased, Carrier life time increased



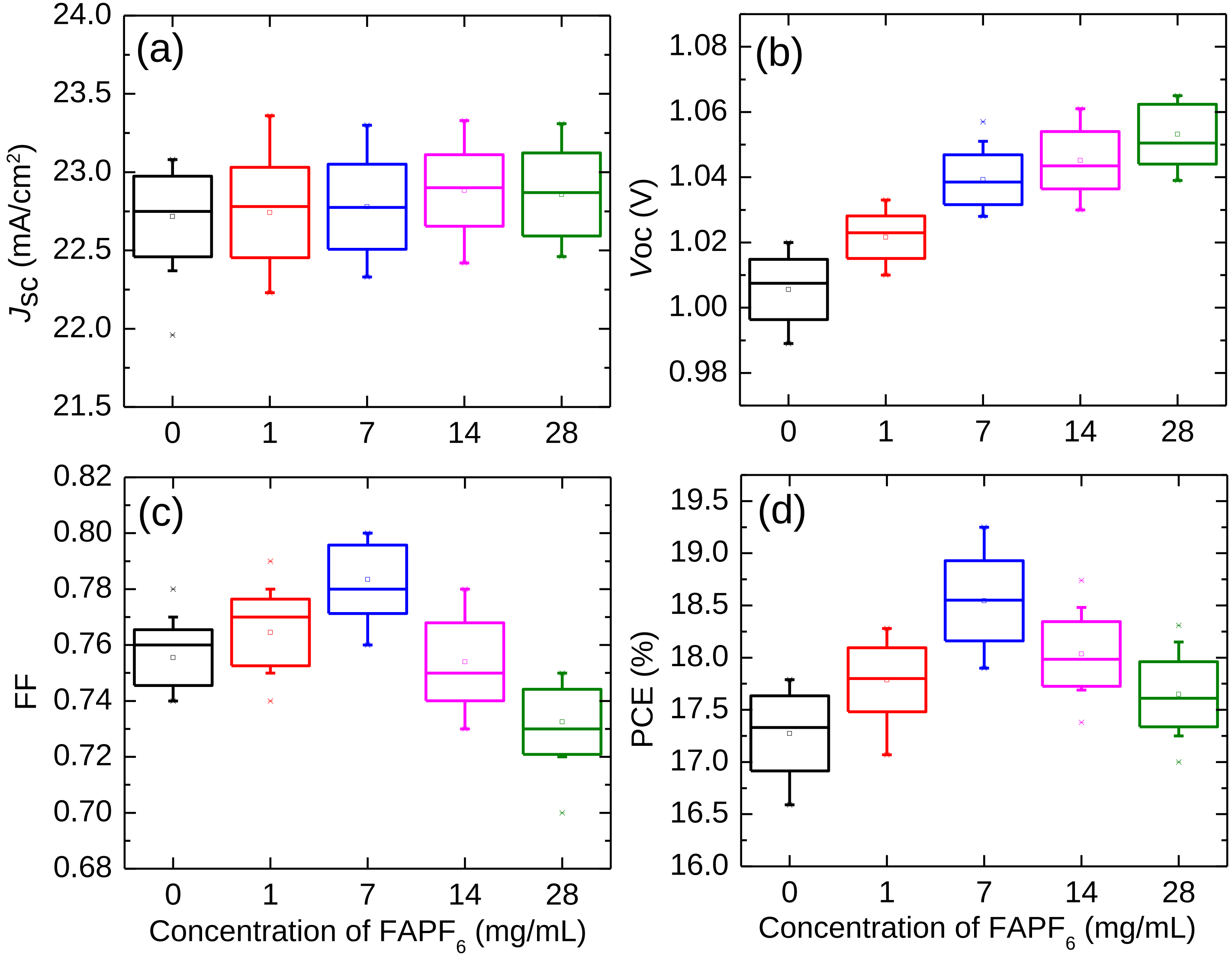



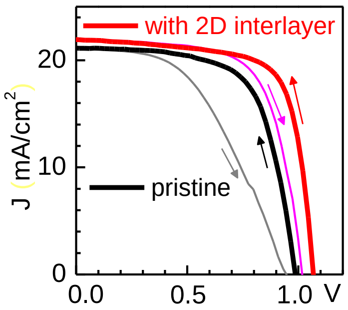

$PF_6^-$ (2.55 Å) is slightly larger than $I^-$ (2.20 Å)

# Evolution of $FA_{0.88}Cs_{0.12}PbI_{3-x}(PF_6)_x$ Layer

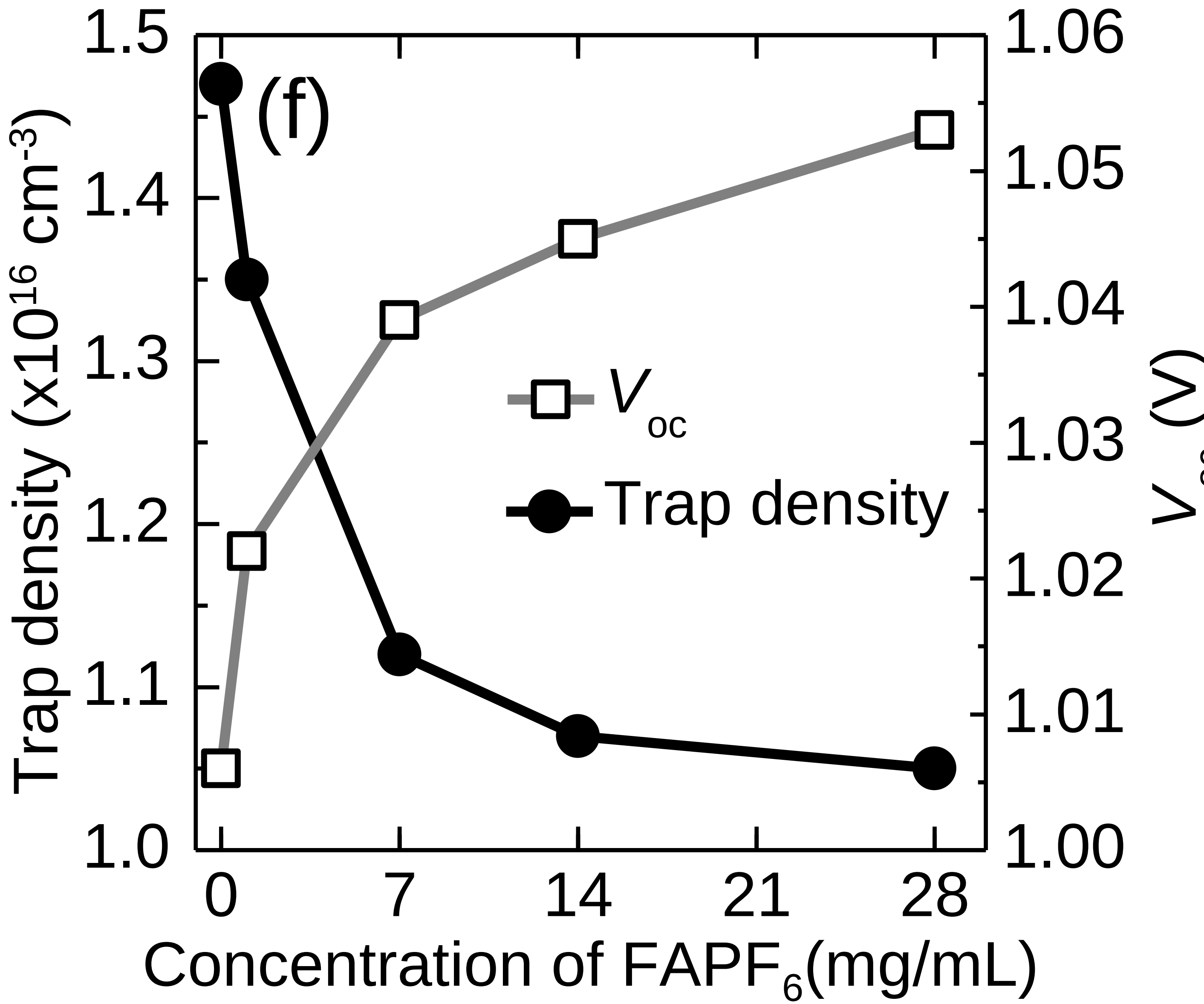


# Effect of Ion Exchange on PV Parameters



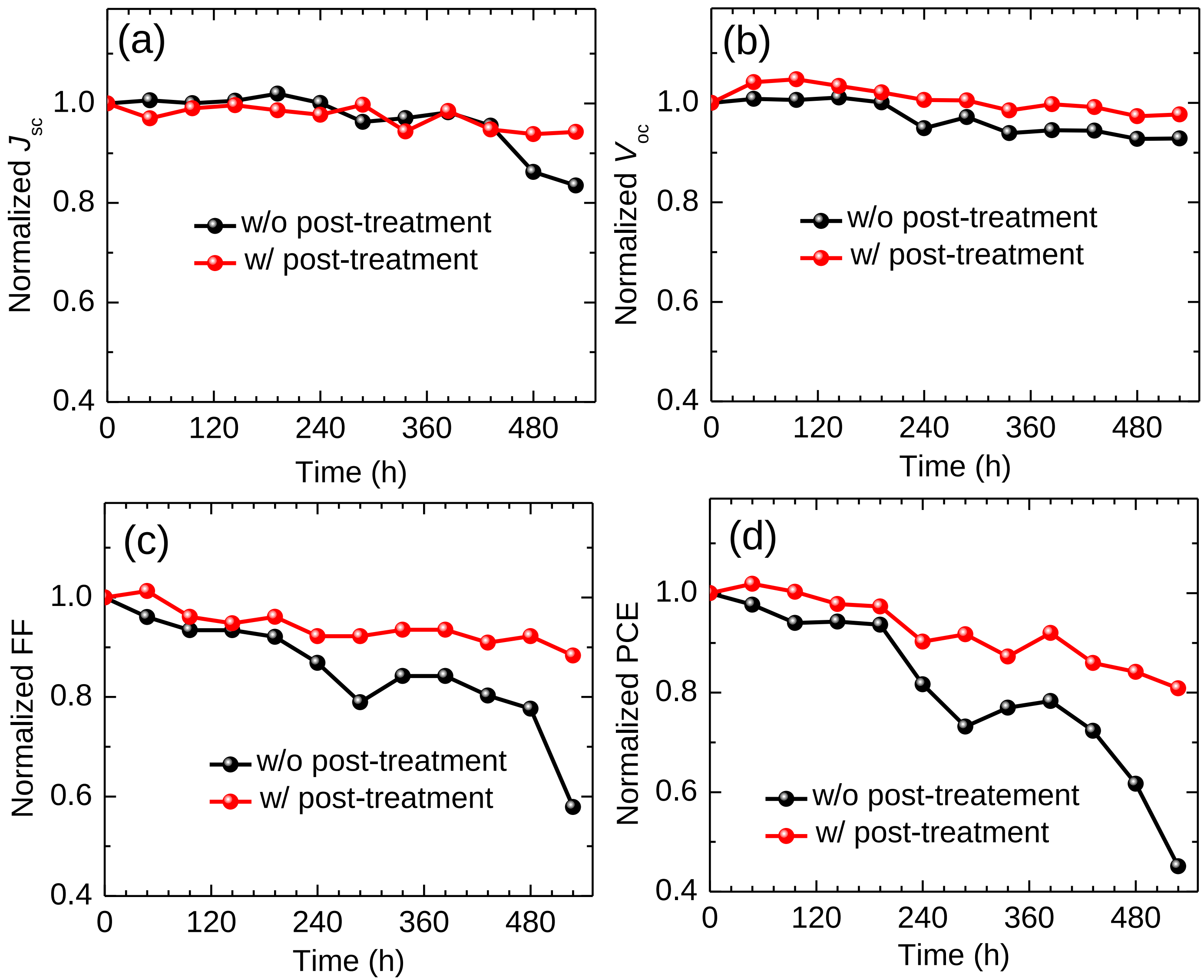




* Hysteresis was reduced by ion exchange reaction



(f)
1.5
1.4
1.3
1.2
1.1
1.0
Trap density (x10^16 cm^-3)
1.06
1.05
1.04
1.03
1.02
1.01
1.00
V_oc (V)
V_oc
Trap density
0
7
14
21
28
Concentration of FAPF_6(mg/mL)

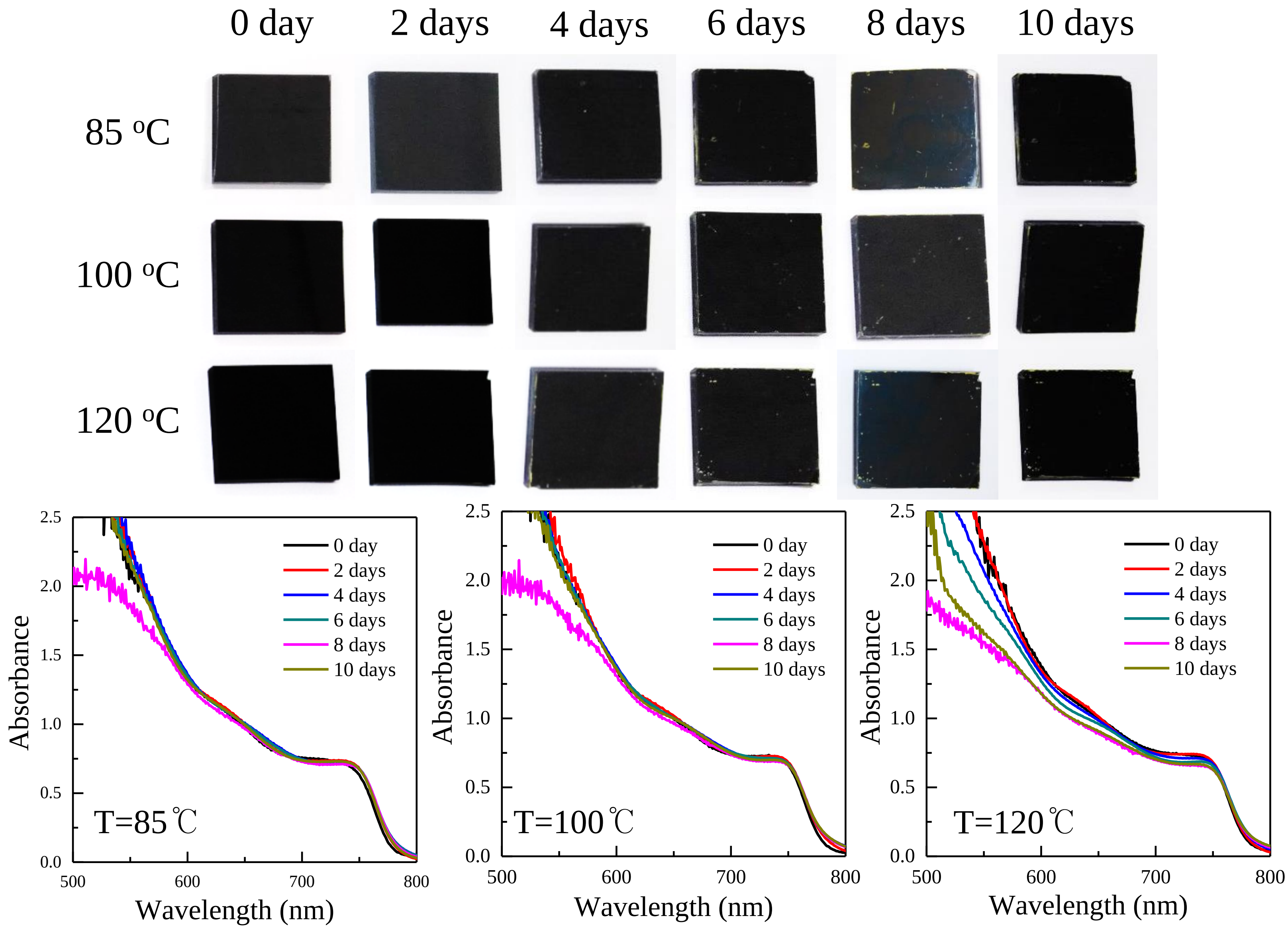
# Stability



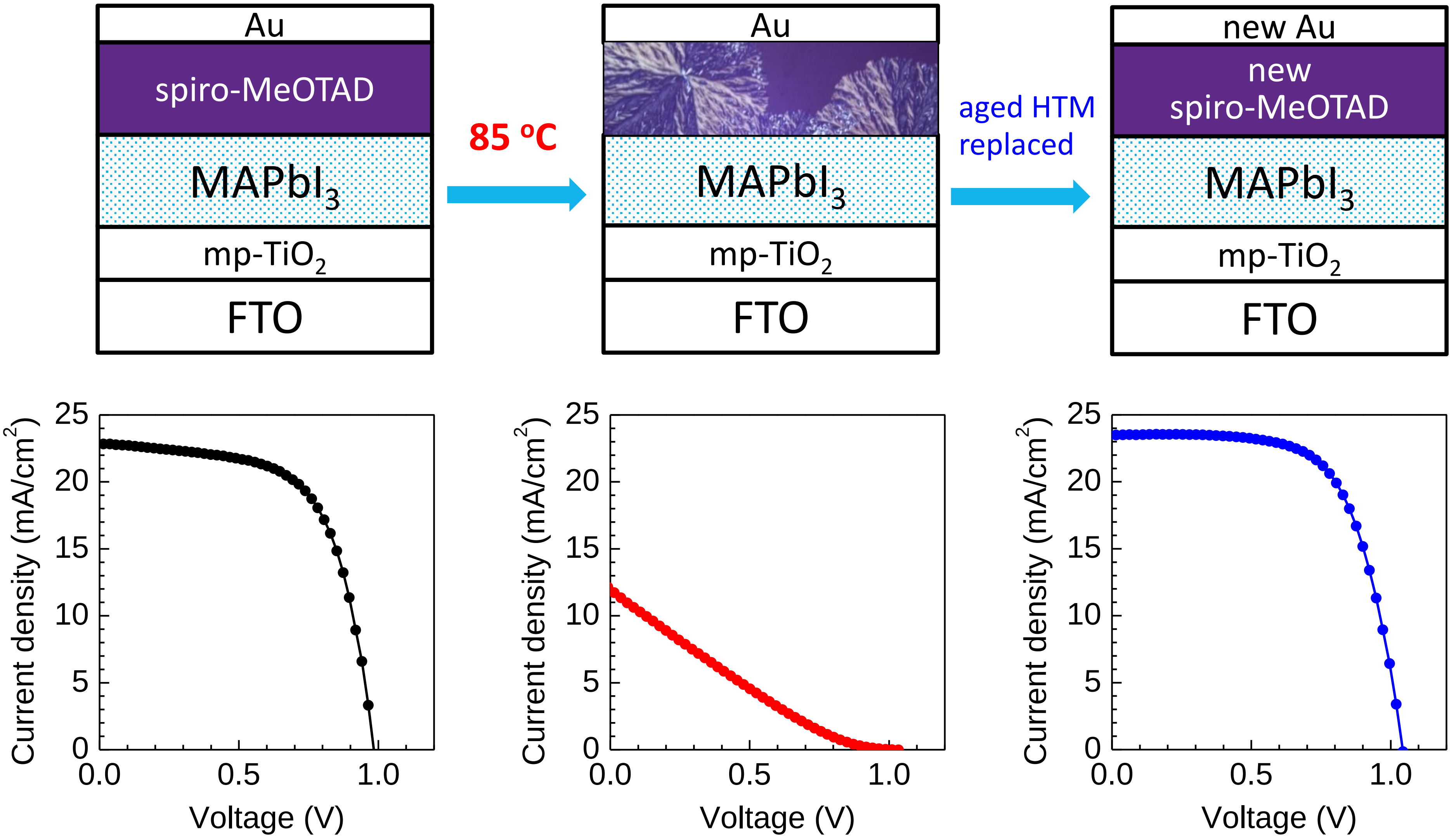

Under revision

# On the thermal stability

: $MAPbI_3$ film itself is thermally stable!



# In device with spiro-MeOTAD?

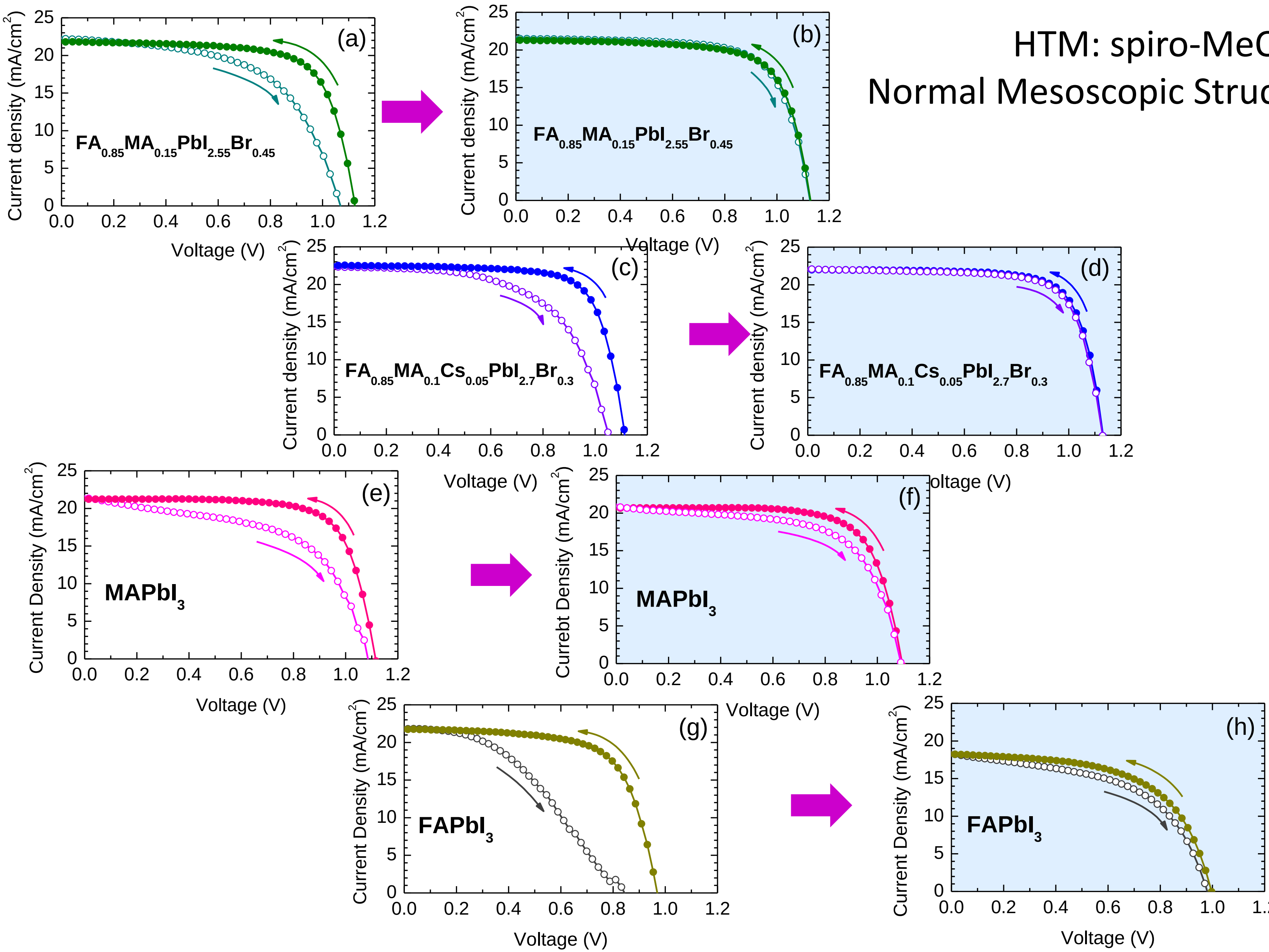



X. Zhao, N.-G. Park, *ACS Applied Materials & Interfaces*, 9, 7148-7153 (2017)

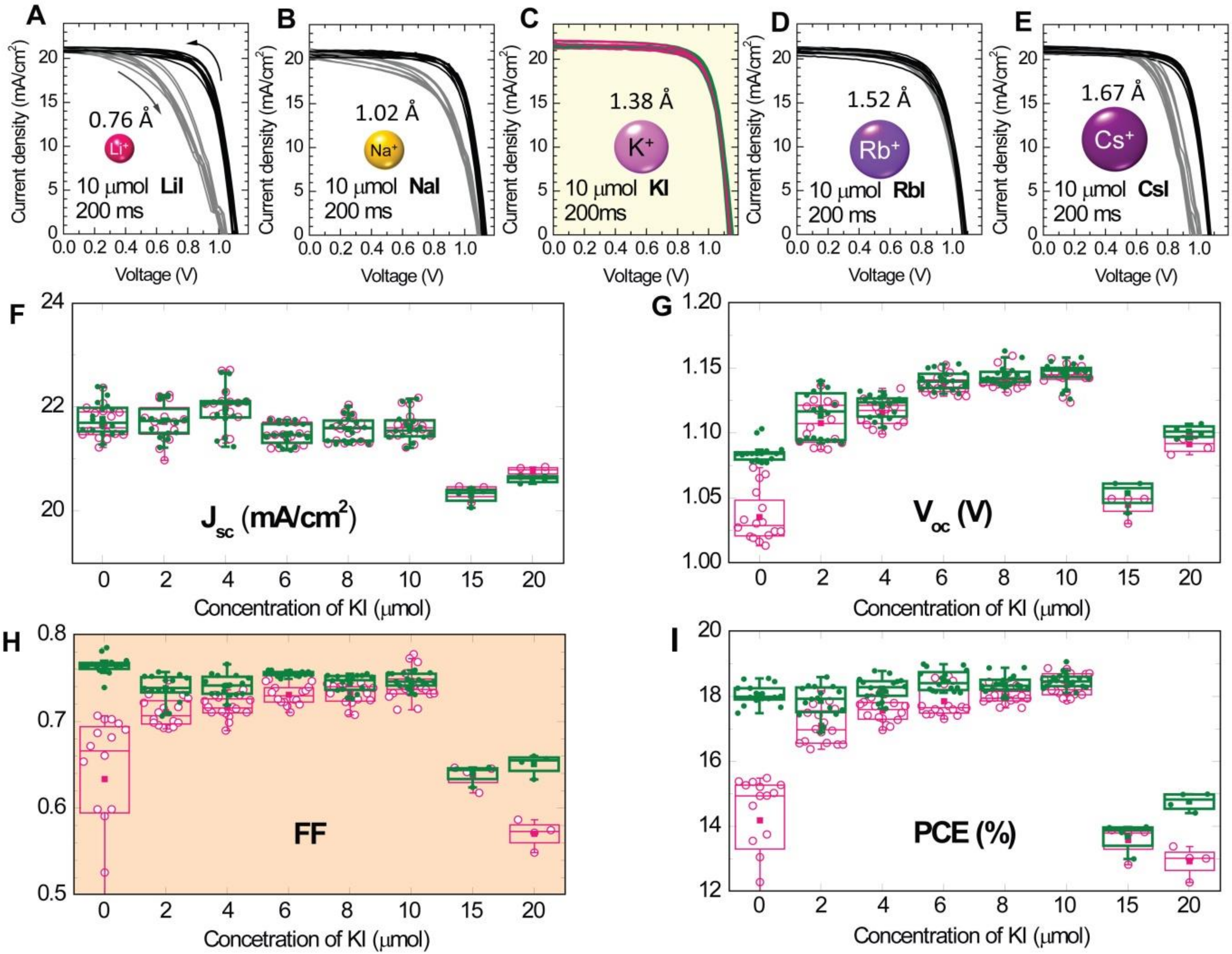
# Universal approach toward hysteresis-free PSC

# Defect Engineering: Universal Approach for Hysteresis-Free PSC

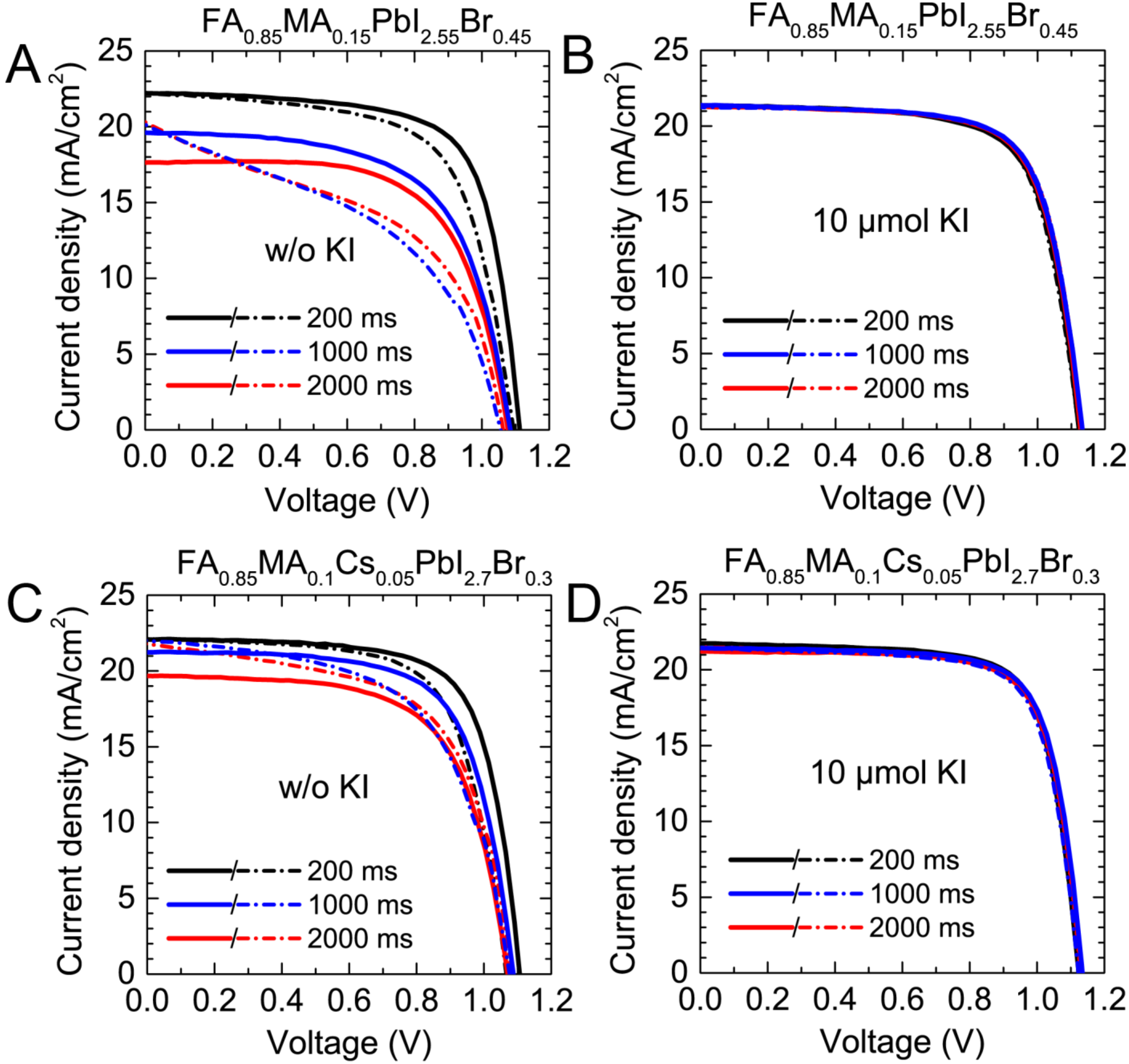
HTM: spiro-MeOTAD
Normal Mesoscopic Structure



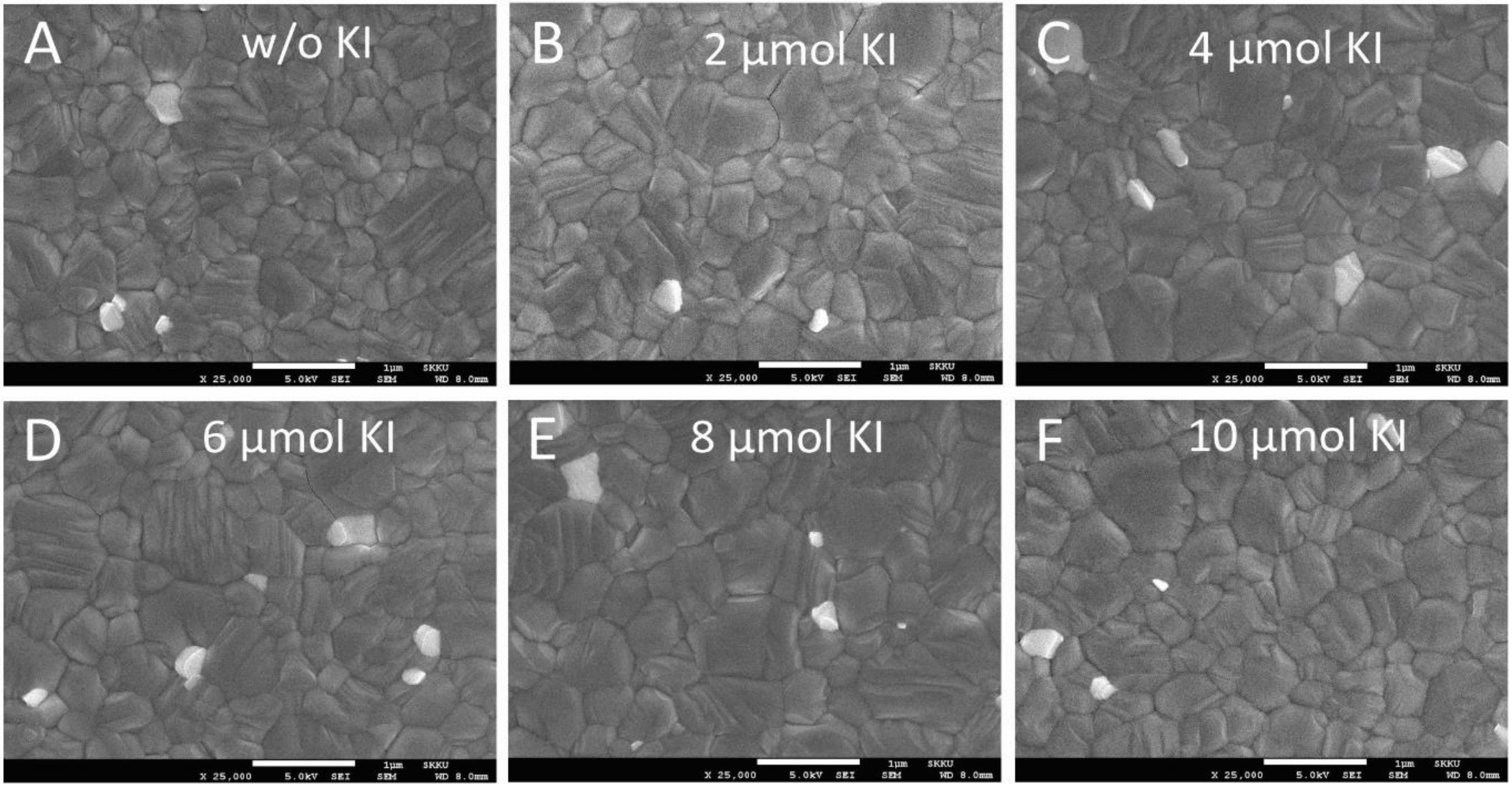
# Only KI? Other Alkali metal iodides?



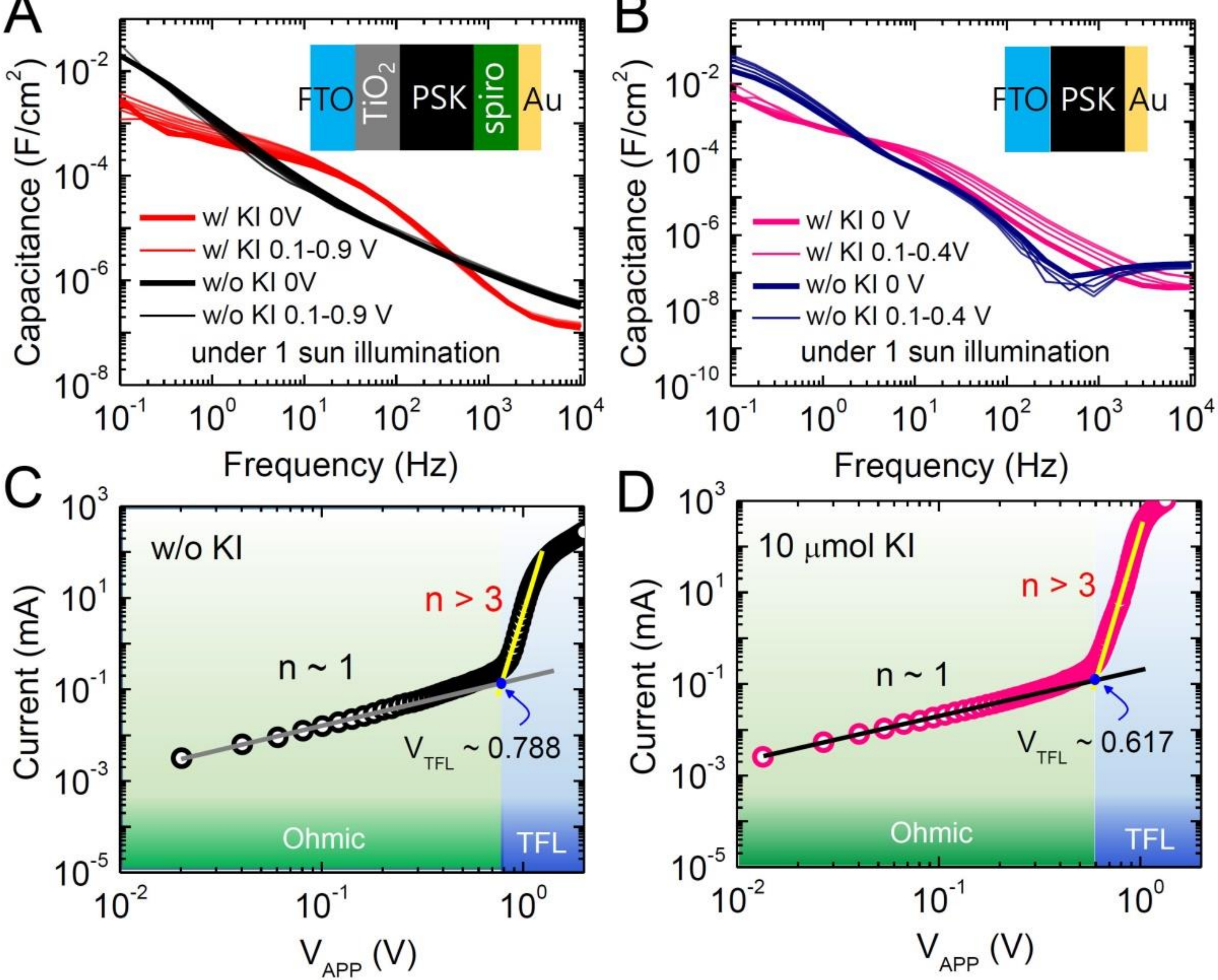
# Scan rate independent I-V behavior



# Morphology not affected by KI

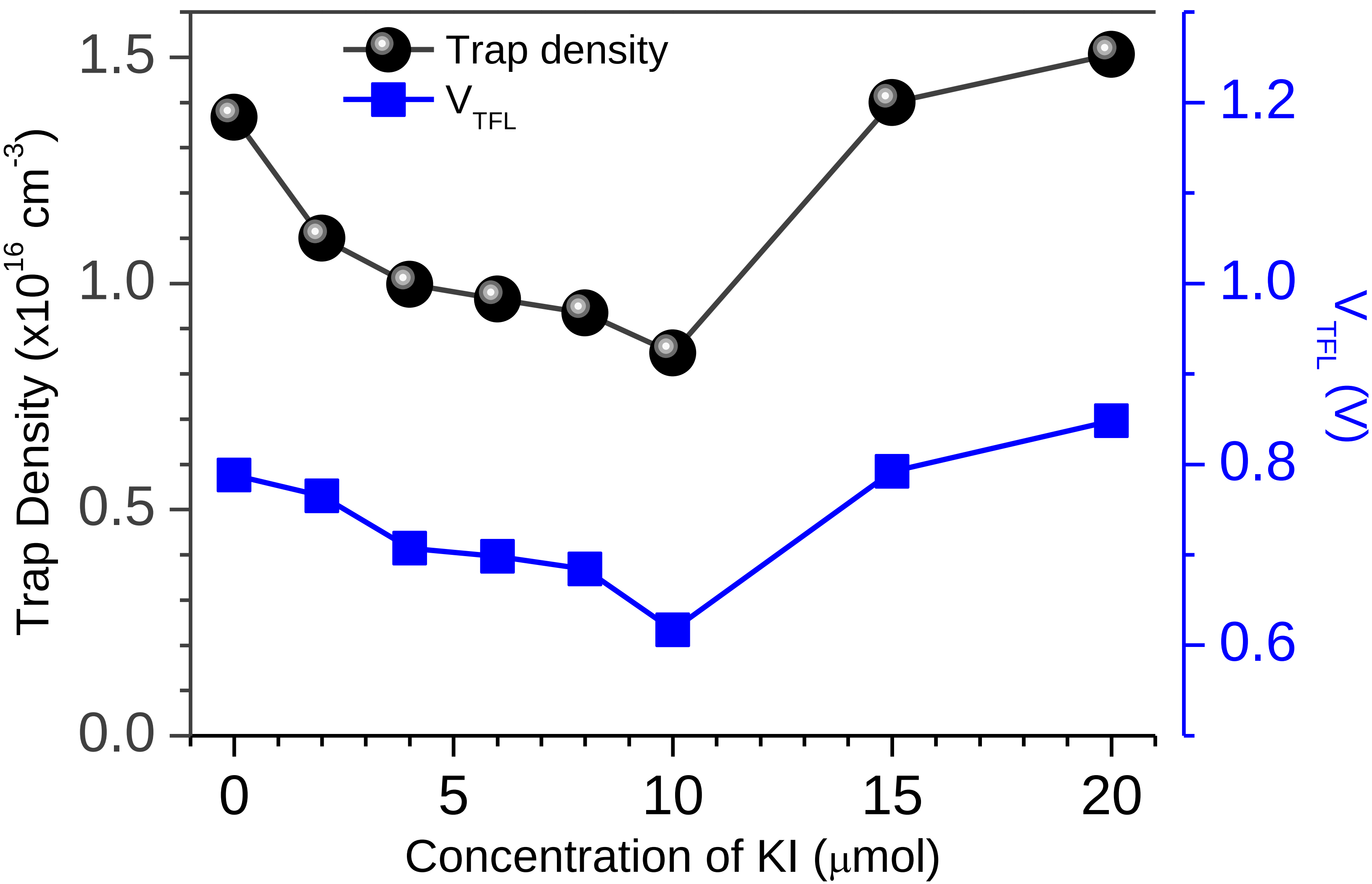



cf) Hysteresis can be affected by grain size

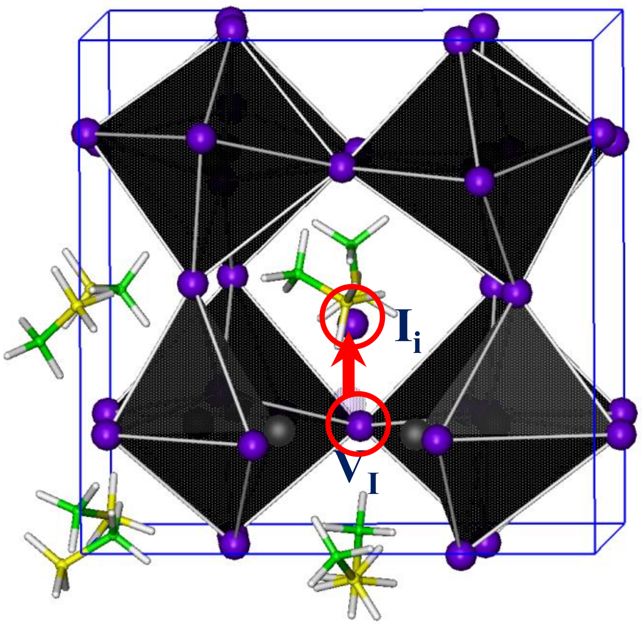


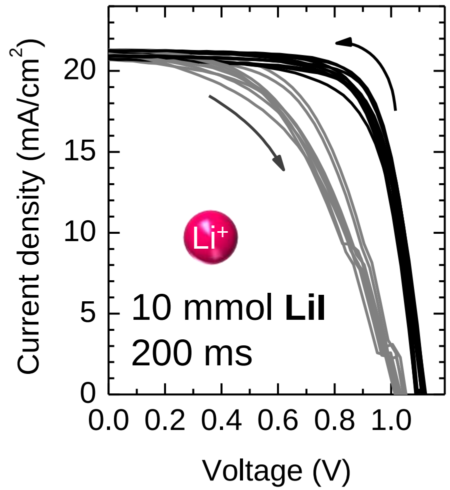

$$V_{TFL} = en_t d^2/2\varepsilon\varepsilon_0 \text{ } (n_t\text{: trap density})$$

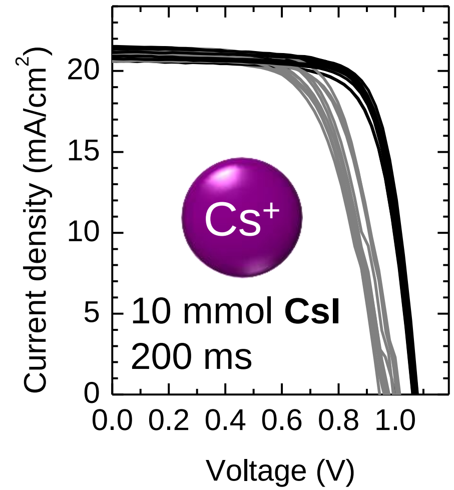
# Trap density as a function of [KI]



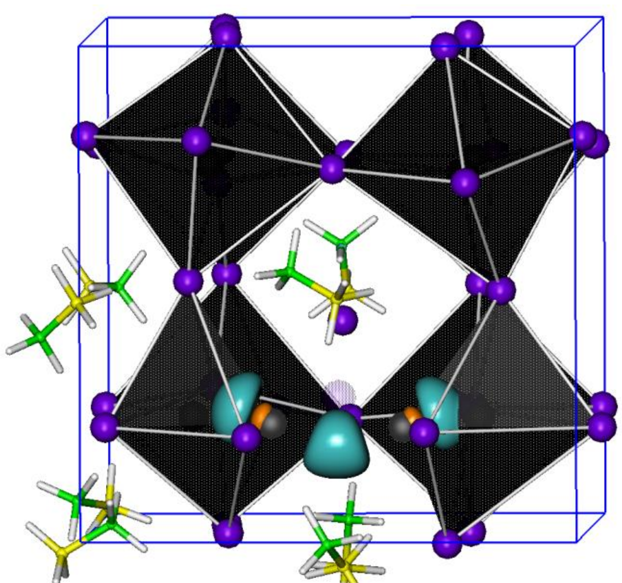
# Defect: Vacancy, Interstitial, Antisite, and Frenkel

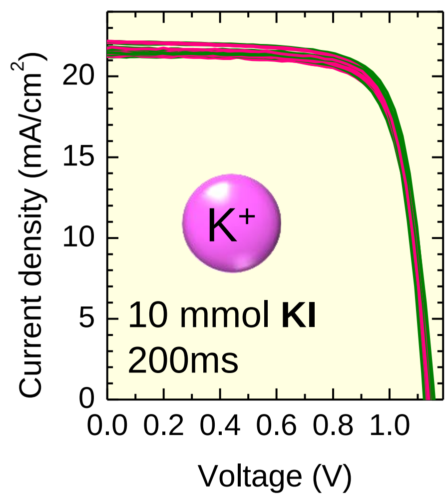


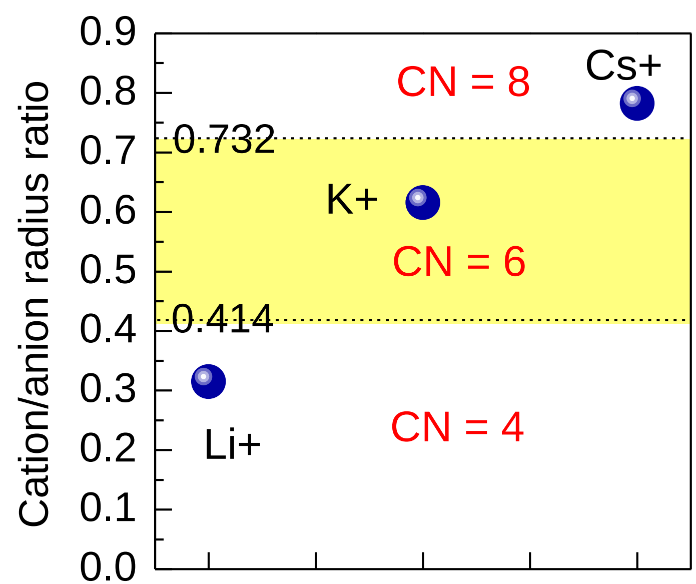




**J. Am. Chem. Soc., 140 (4),1358–1364 (2018)**



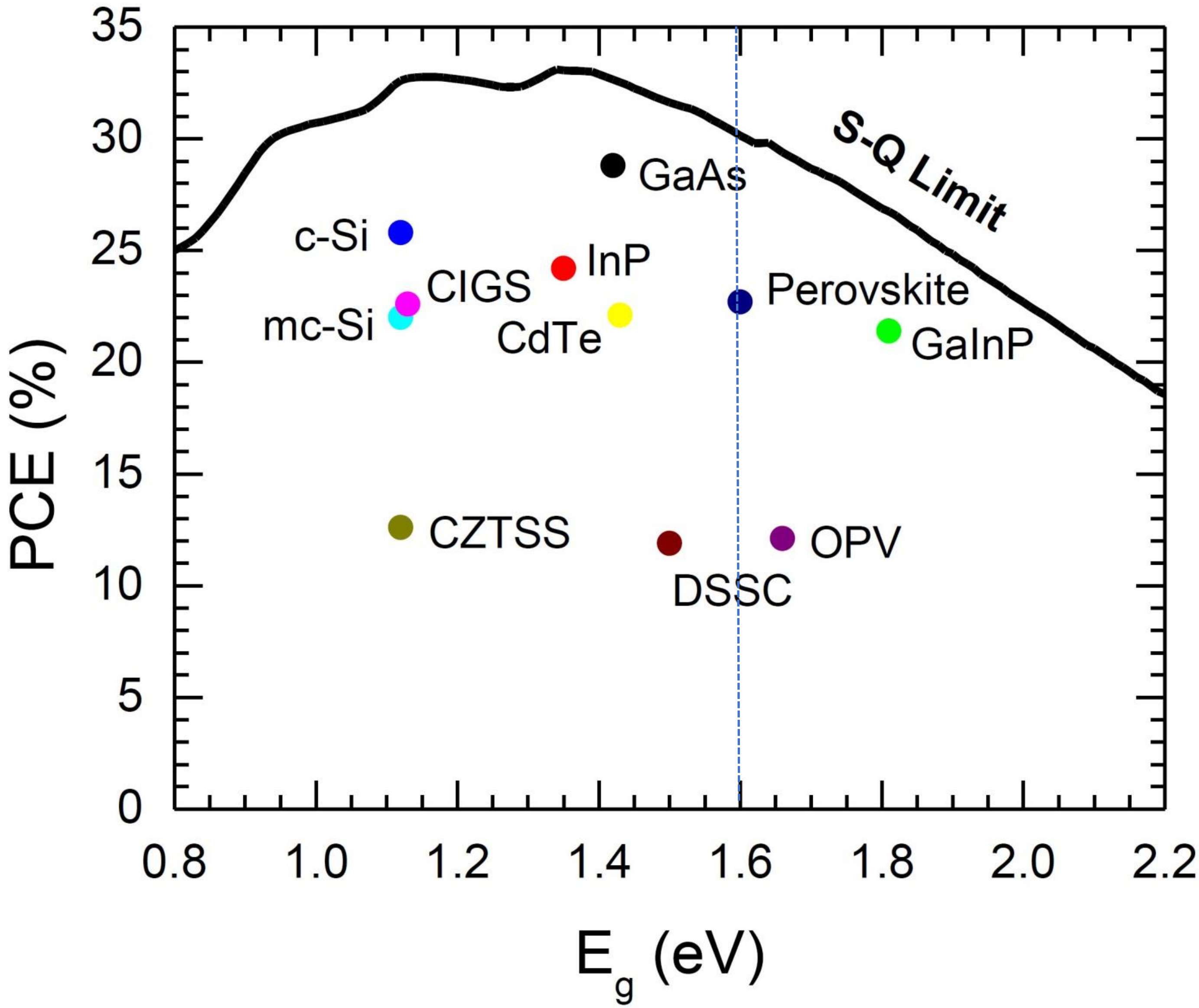


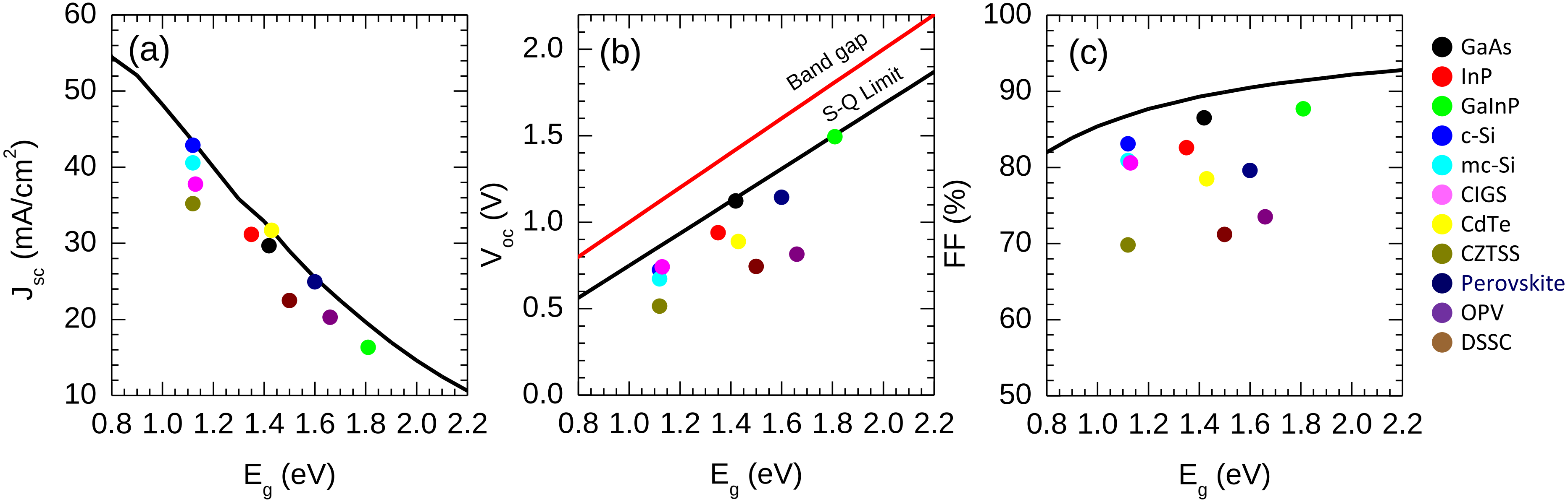



# Perspective

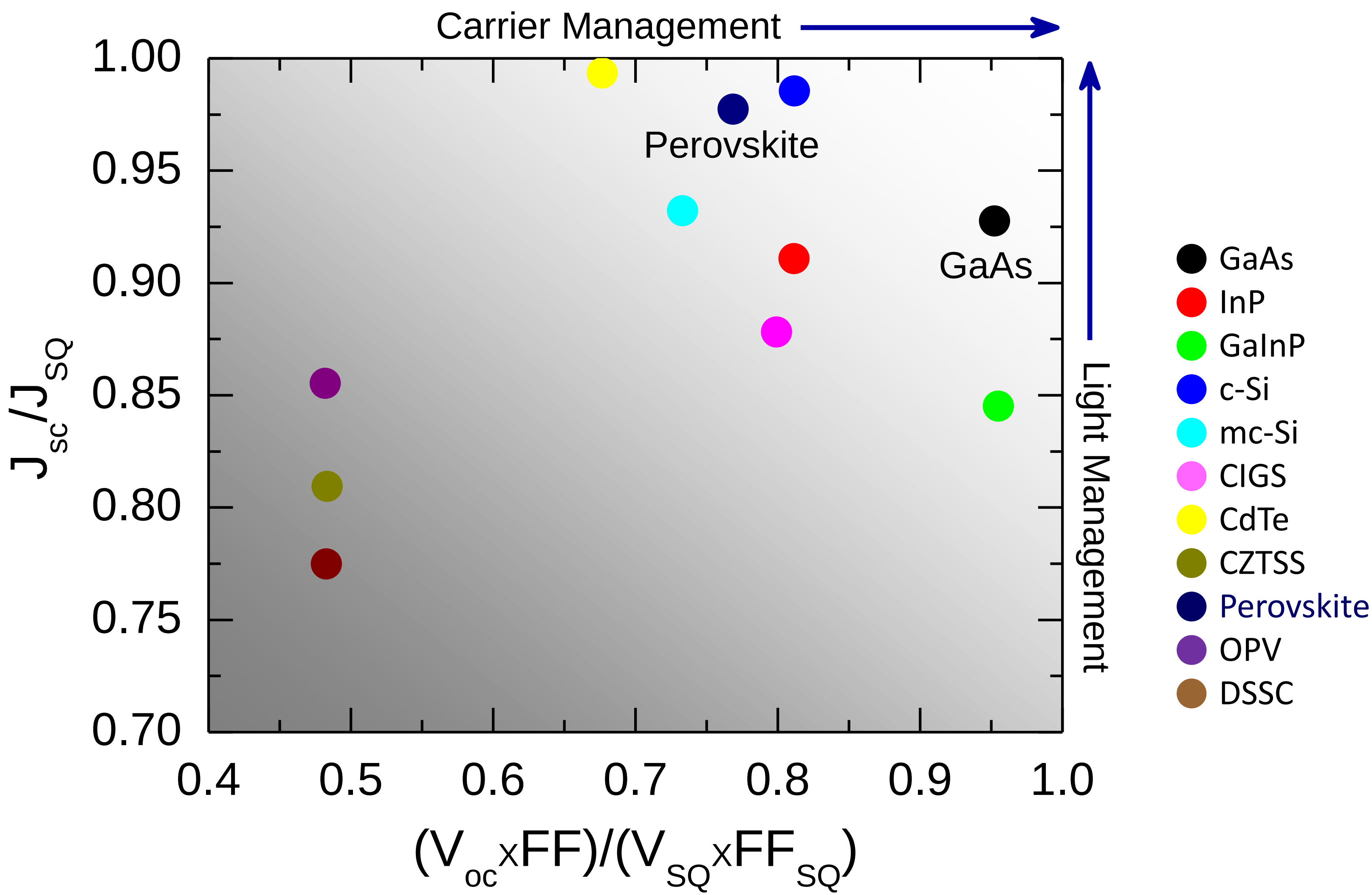
# Proposal of research direction of PSC toward S-Q limit

# PSC R&D Direction

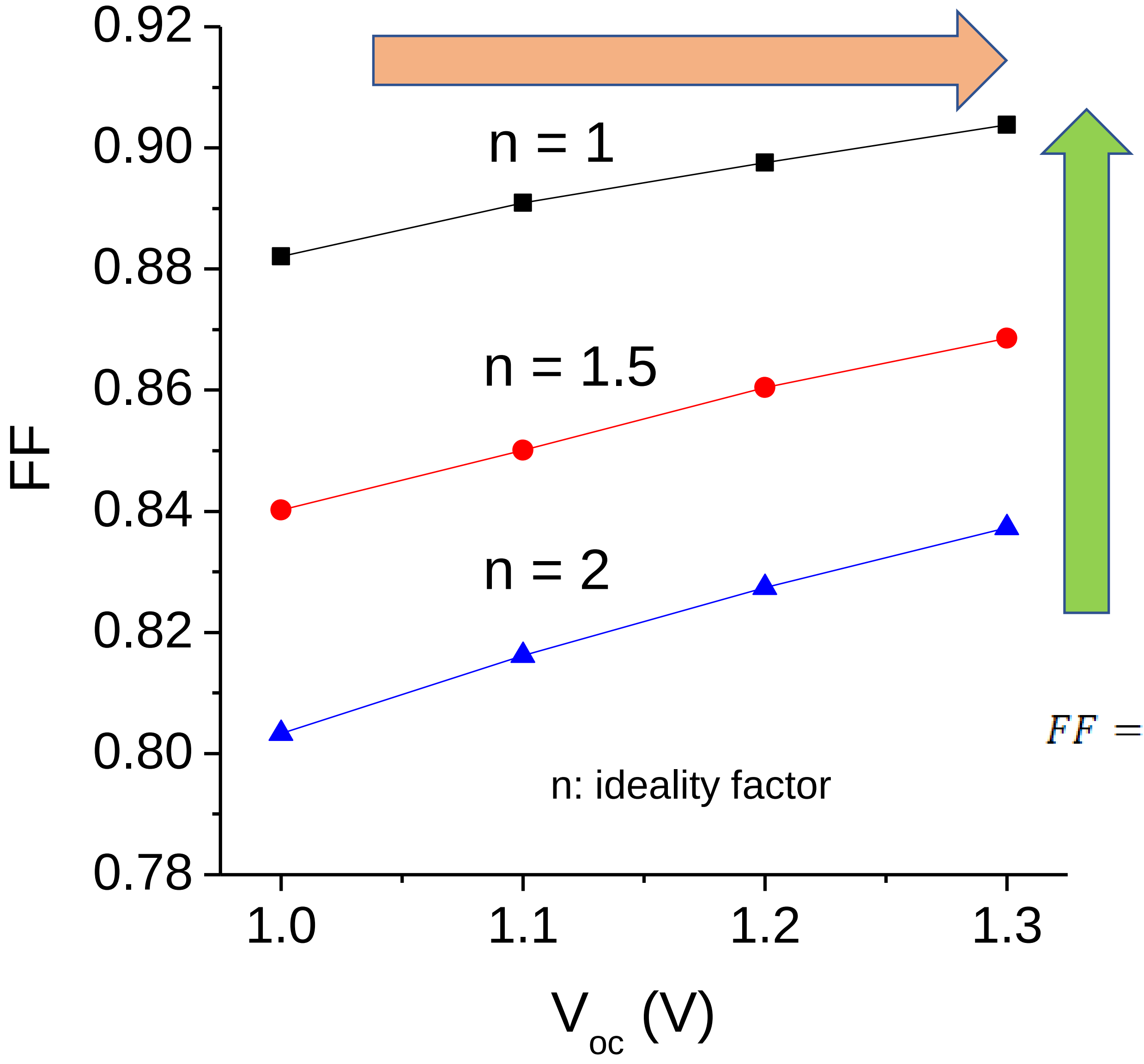




(a)
$J_{sc}$ (mA/cm$^2$)
60
50
40
30
20
10
0.8 1.0 1.2 1.4 1.6 1.8 2.0 2.2
$E_g$ (eV)
(b)
$V_{oc}$ (V)
Band gap
S-Q Limit
2.0
1.5
1.0
0.5
0.0
0.8 1.0 1.2 1.4 1.6 1.8 2.0 2.2
$E_g$ (eV)
(c)
FF (%)
100
90
80
70
60
50
0.8 1.0 1.2 1.4 1.6 1.8 2.0 2.2
$E_g$ (eV)
GaAs
InP
GaInP
c-Si
mc-Si
CIGS
CdTe
CZTSS
Perovskite
OPV
DSSC




Pushing $V_{oc}$ and FF up toward S-Q limit is important!




$$FF = \frac{v_{oc}\ \ln(v_{oc}\ 0.72)}{v_{oc}\ \cdot 1}$$

$$v_{oc} = \frac{q}{nkT} V_{oc}$$

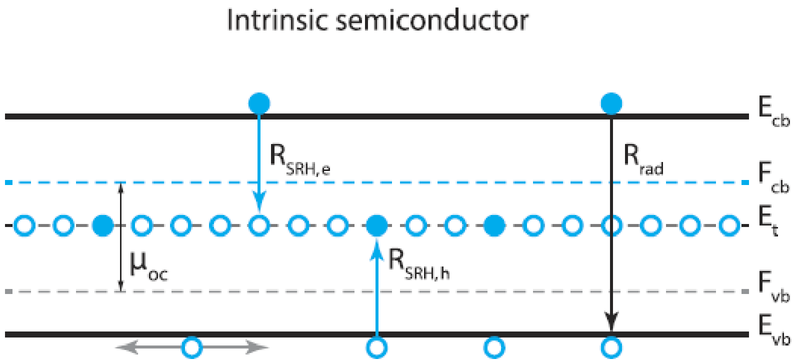
Ideal diode with high $V_{oc}$ will be best for $FF_{SQ}$

*Common issue to get S-Q limit $V_{oc}$ and FF*

# Recombination!

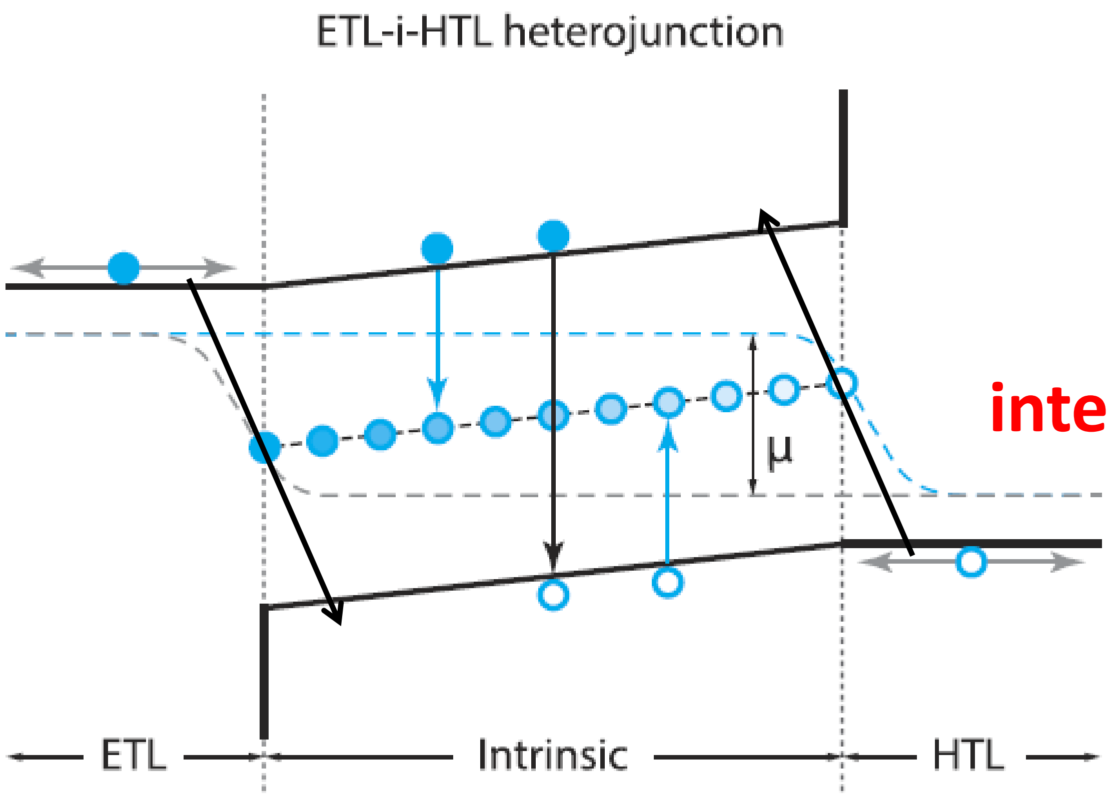
**Understanding "Recombination" is most important**

***in order to allow only band-to-band recombination***




**Radiative recombination**

**Shockley-Read-Hall (SRH) recombination (non-radiative)**




**interface**

# How to evaluate ideality ($n_{ID}$)factor

## 1. Light-intensity dependent $V_{oc}$ (reliable)

$$eV_{oc} = E_g - n_{ID}k_BT \ln \frac{I_0}{I}.$$

## 2. Dark JV (due to parasitic resistance)

$$J_{dark}(V) = J_0\left(\exp\frac{eV}{n_{ID}k_BT} - 1\right)$$

For PSC

$1.2 < n_{ID} < 5$?

## 3. Electroluminescence (due to parasitic resistance)

$$V_{oc} = \frac{k_BT}{e}\ln\left(EQE_{EL}\frac{J_{ph}}{J_{em,0}} + 1\right) \approx V_{oc,rad} - \frac{k_BT}{e}\ln\ EQE_{EL}$$

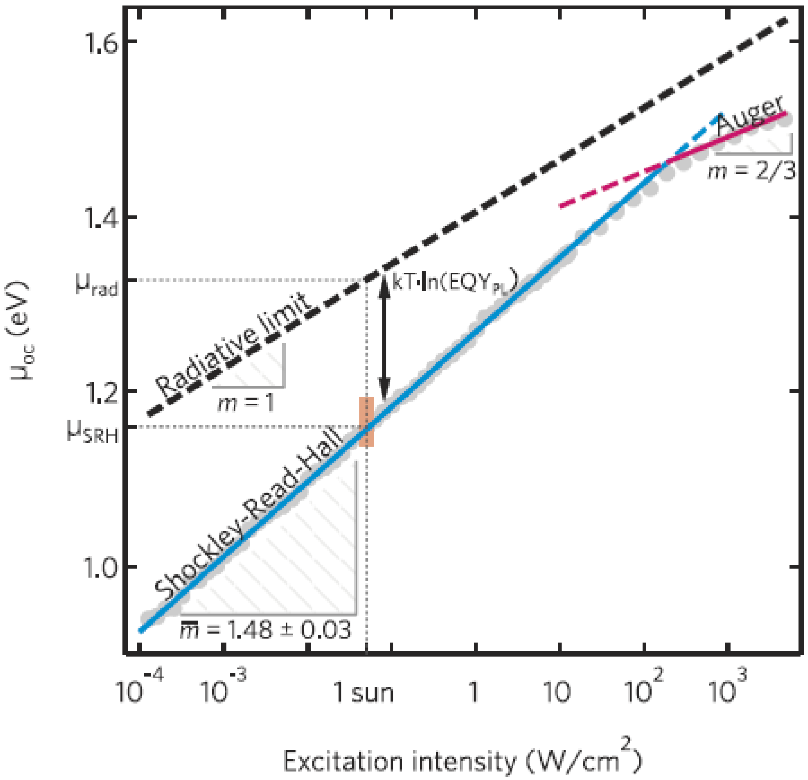
W. Tress et al., EES, DOI: 10.1039/c7ee02415k

# Optical determination of SRH and interface recombination using $EQY_{PL}$

* Similarly to $V_{oc}$-I, the free energy (chemical potential) of the electron-hole pairs ($\mu$) as a function of the intensity of the exciting light ($I_{ex}$), namely **the $\mu$-$I_{ex}$ characteristics**

$$\mu = kT \ln\left(\frac{J_{PL}}{J_{0,rad}}\right) = kT\left[\ln\left(\frac{J_{ex}}{J_{0,rad}}\right) + \ln(EQY_{PL})\right] = \mu_{oc,rad} + kT \ln(EQY_{PL})$$

$EQY_{PL} = 1$: only radiative recombination




m: ideality factor

**For Intrinsic $MAPbI_3$ film**

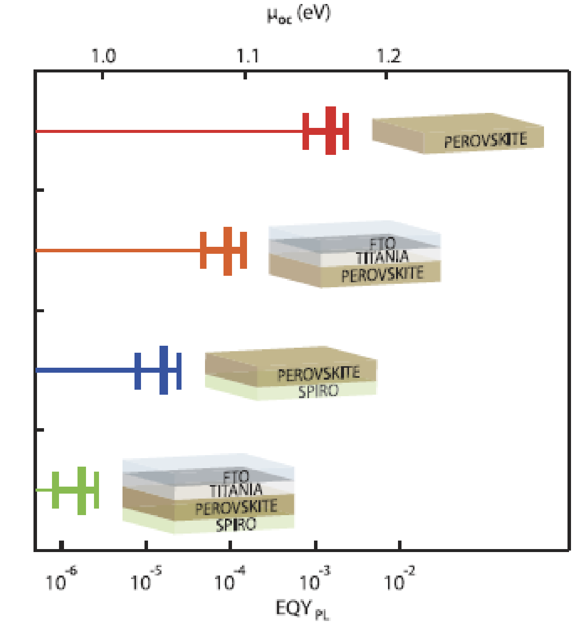
at 1sun

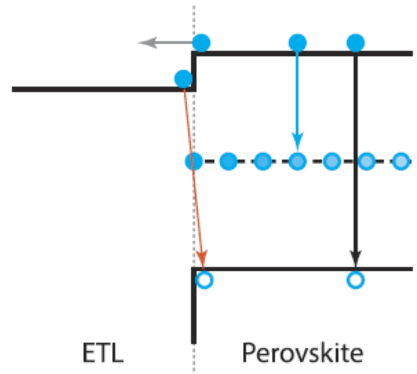
$\mu_{rad}$ = 1.33 eV ($V_{oc}$ = 1.33 V)

$\mu_{SRH}$ = 1.16 eV ($V_{oc}$ = 1.16 V)

Scientific **Reports** | 7:44629 | DOI: 10.1038/srep44629

# For heterojunction with ETL and HTL



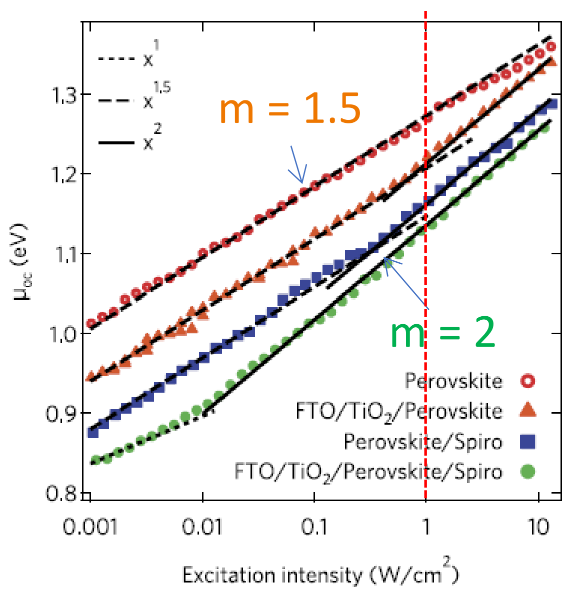



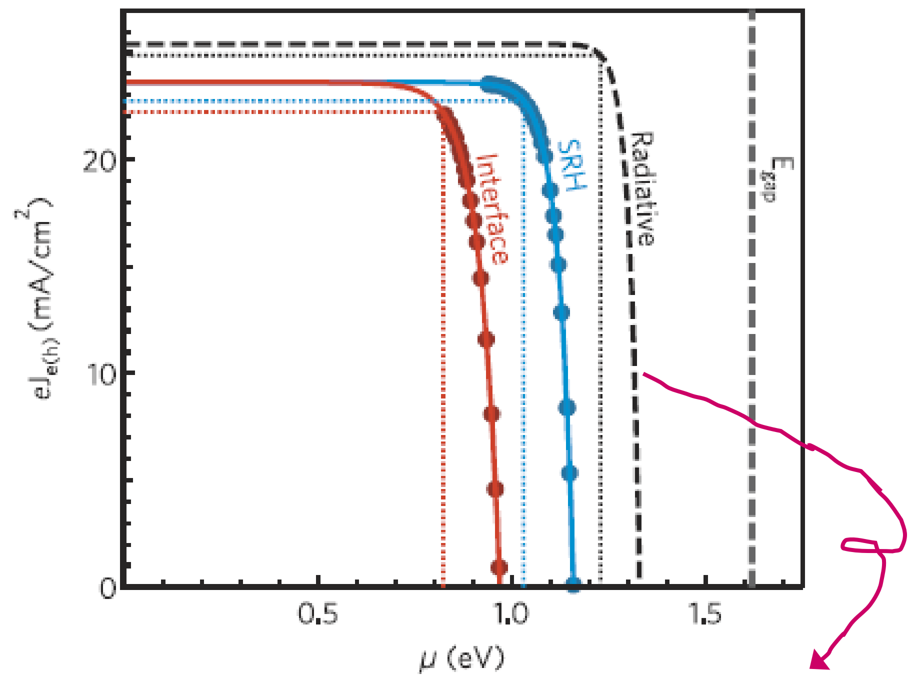

Three processes

**Radiative**

**SRH**

**Interface**




$V_{oc}$ = 1.33 V (ideality factor = 1) PCE$_{SQ}$ = 30.5%
($J_{sc}$ = 25.4 mA/cm$^2$, $FF$ = 0.91)

Scientific **Reports** | 7:44629 | DOI: 10.1038/srep44629

# Beyond PV:
# Highly sensitive X-ray photodetector

# Risk of medical X-ray radiation

**Repeated exposure to medical X-ray radiation can accumulate over time to substantial cancer-causing doses**

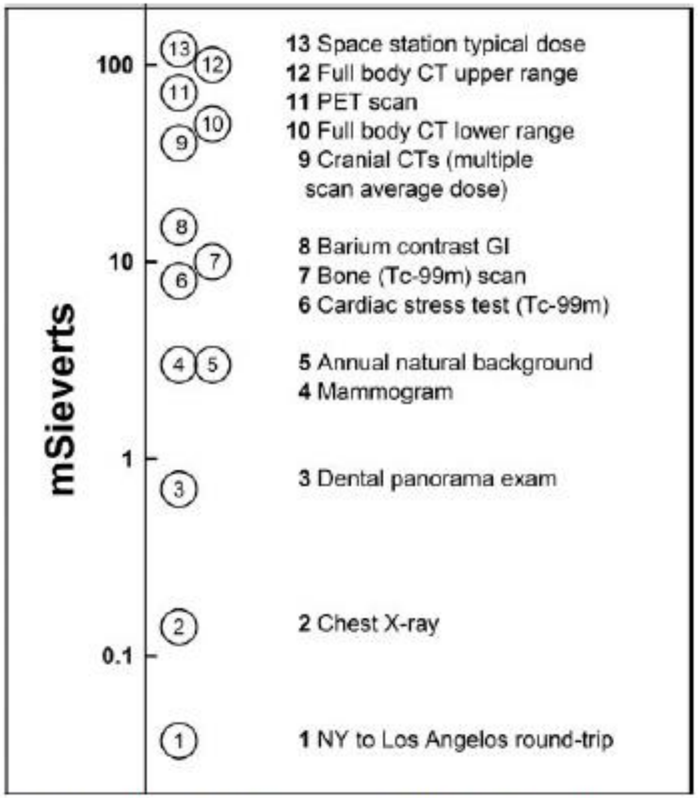



**FIG. 2.** Magnitude of radiation exposure from various sources. [Adapted from N. F. Metting: http://lowdose.energy.gov/imagegallery.aspx (32).] For cranial CT, the dose takes into account the multiple scans performed for the typical patient. GI, Gastrointestinal; PET, positron emission tomography.

**TABLE 1.** Units related to radiation safety used by the National Council on Radiation Protection and Measurements

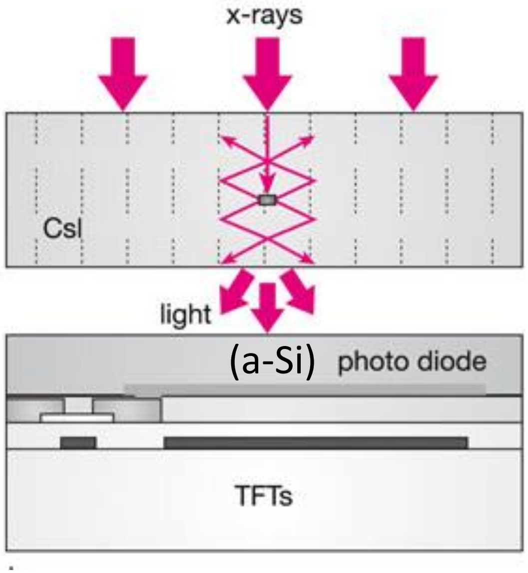
| |
|---|
| Absorbed dose |
| SI units: 1 gray (Gy) = 1000 mGy |
| Old units: 1 rad = 10 mGy |
| Effective dose |
| SI units: 1 sievert (Sv) = 100 rem; 1 rem = 10 mSv |
| Old units: 1 rad = 1 rem (for x-rays) |
| Amounts of radioactivity |
| 1 megabequerel (MBq; $10^6$Bq) = 0.027 mCi |
| 1 mCi = 37 MBq |
| 30 mCi = 1111 MBq |

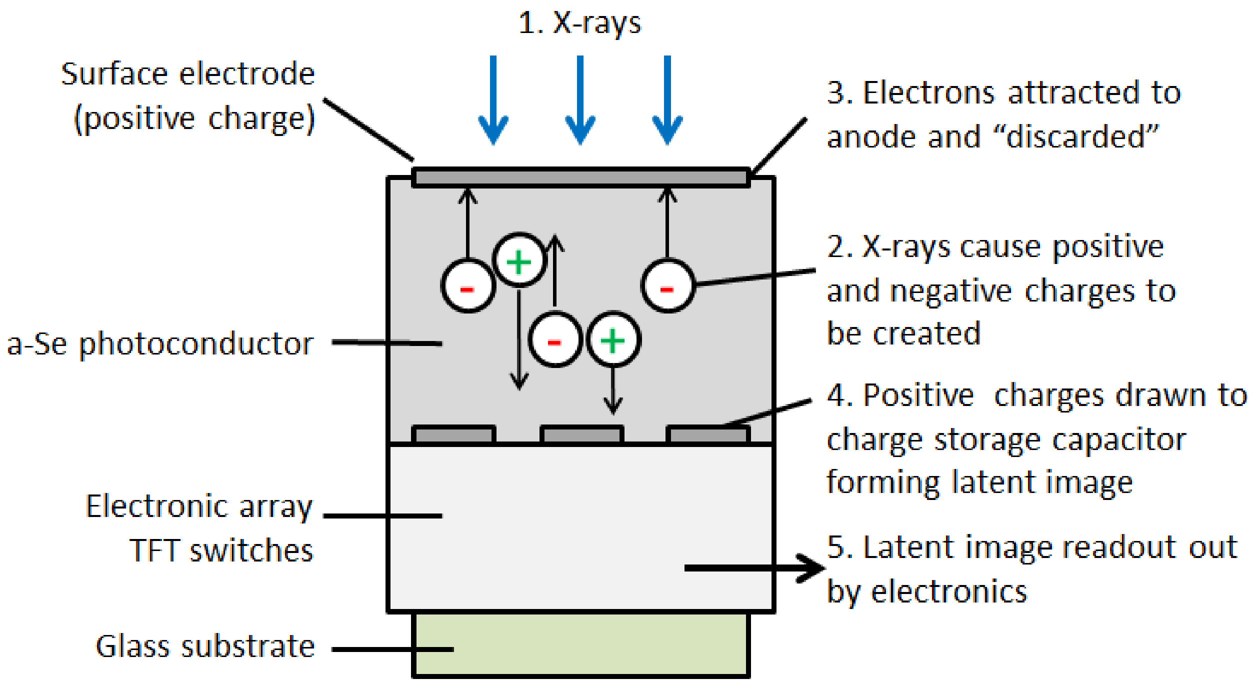
**Searching sensitive X-ray detector materials is a solution for this dose-risk problem.**

Endocrine Reviews, October 2010, 31(5):756–773

# Indirect and direct X-ray imaging

**Two flat detector technologies**
**Indirect method: thallium doped cesium iodide (CsI:Tl) scintillators**
**Direct method: amorphous selenium (a-Se) particularly suitable for mammography due to good X-ray conversion efficiency**

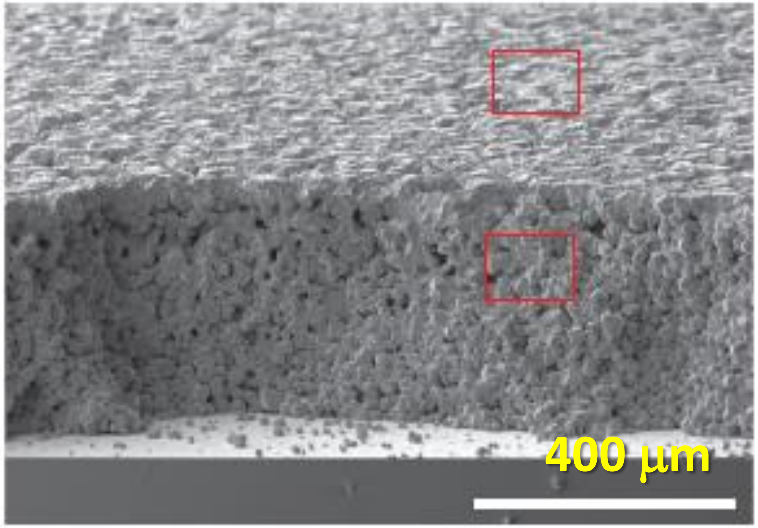


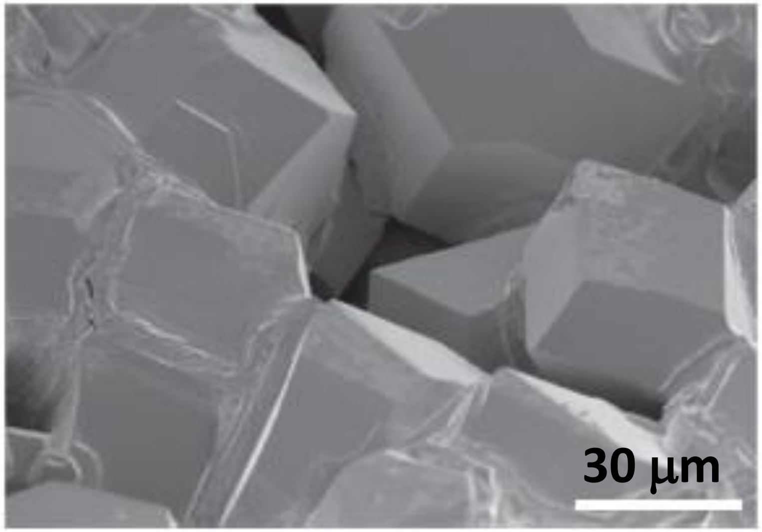



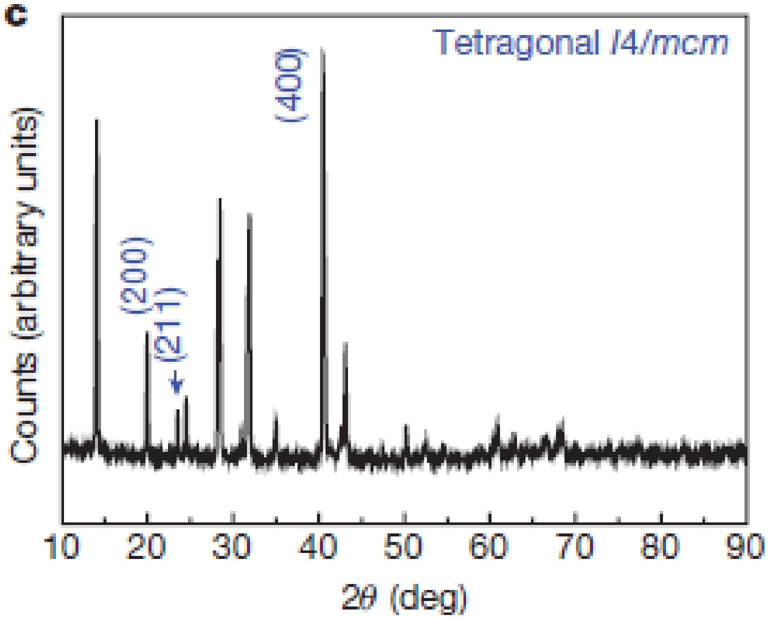

**Indirect (scintillator)**

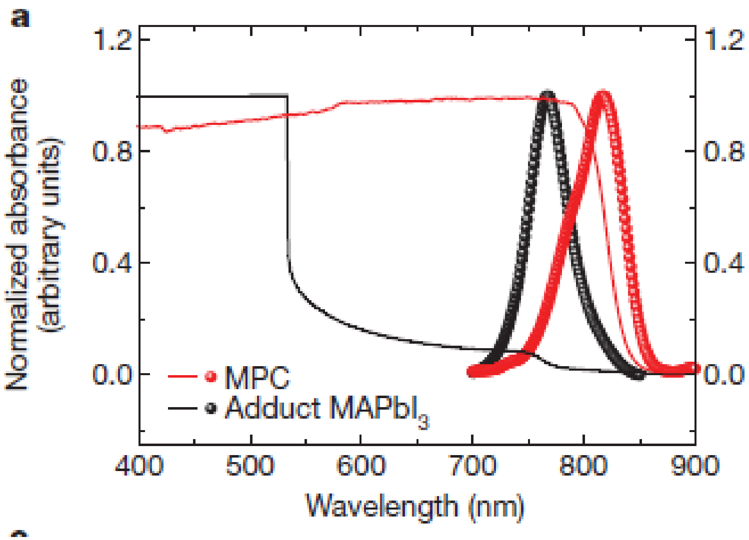
**direct**

# Multicrystalline Perovskite Crystal (MPC)

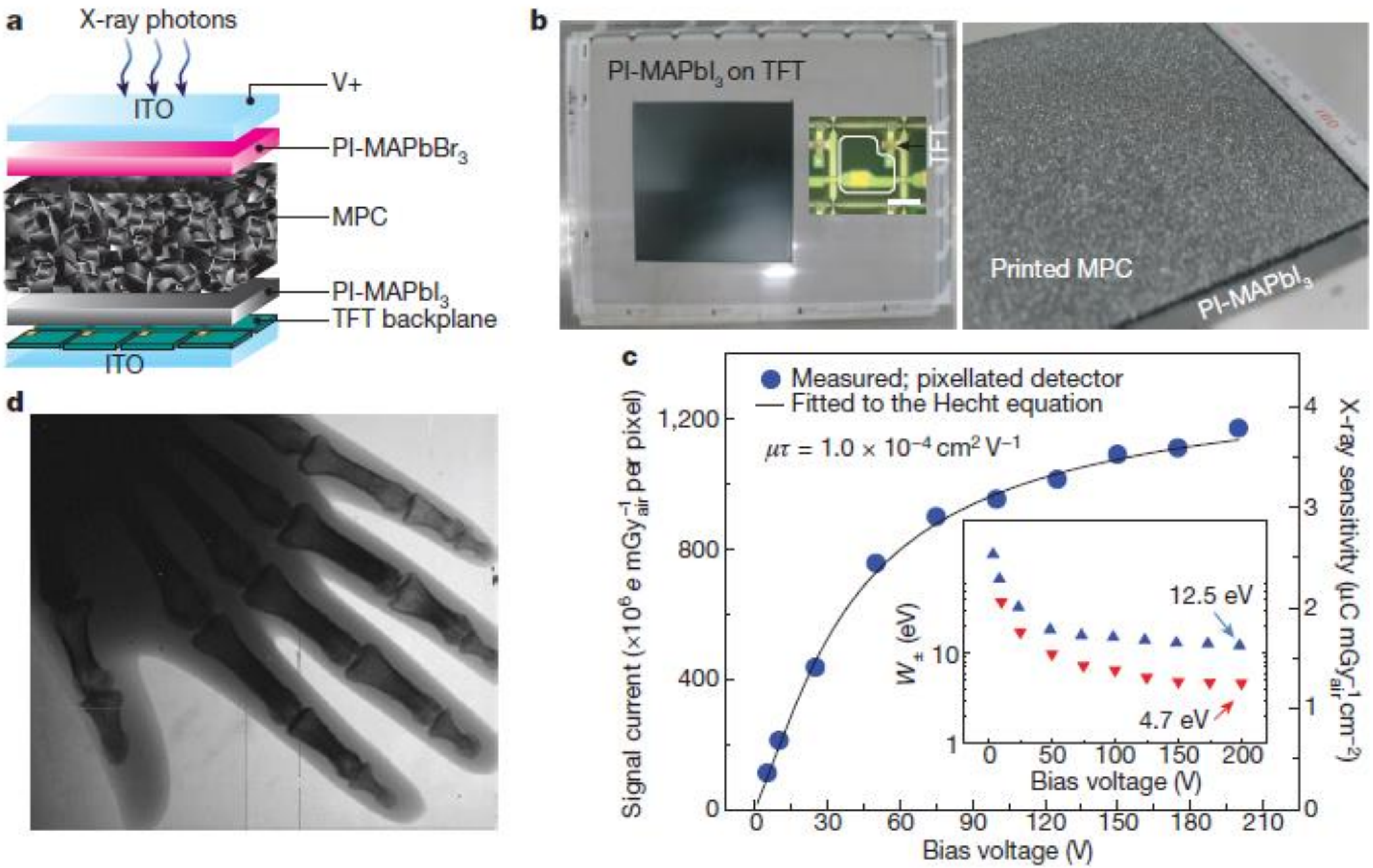


# Perovskite X-ray imaging




LETTER

**Printable organometallic perovskite enables large-area, low-dose X-ray imaging**

Nature, 550, 87-91, 2017

Yong Churl Kim[1], Kwang Hee Kim[1], Dae-Yong Son[2], Dong-Nyuk Jeong[2], Ja-Young Seo[2], Yeong Suk Choi[1], In Taek Han[1], Sang Yoon Lee[1] & Nam-Gyu Park[2]

10.1038/nature24032