Fourth generation solar cells based on halide perovskites: poking them with ultrafast light

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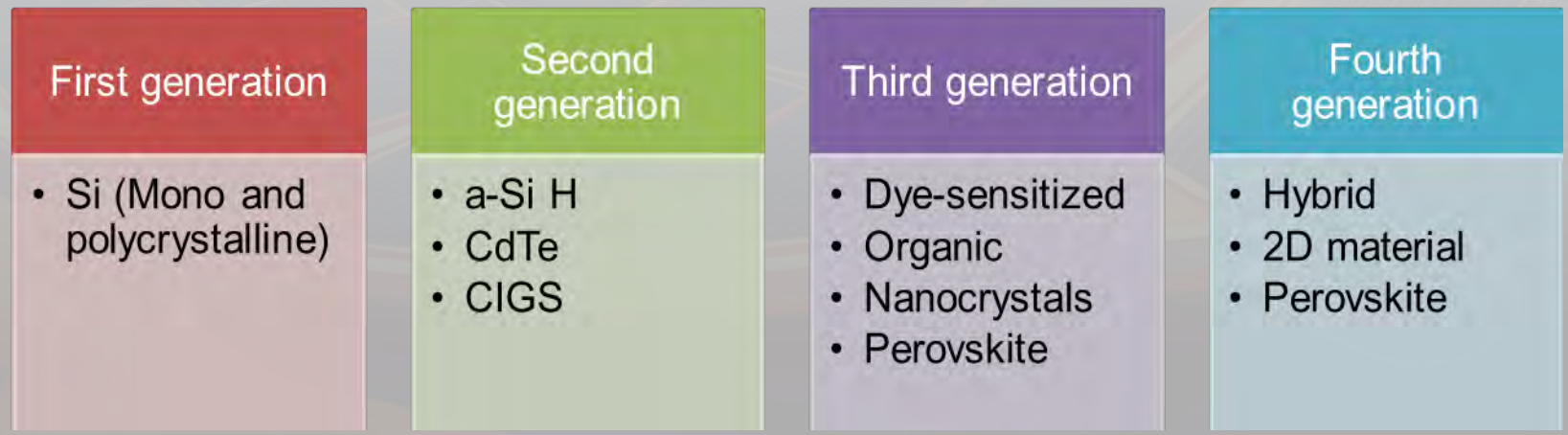
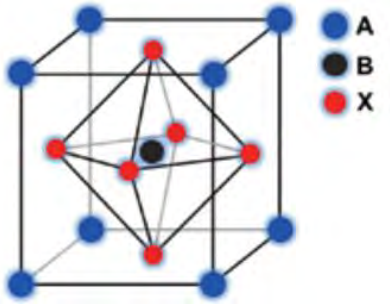
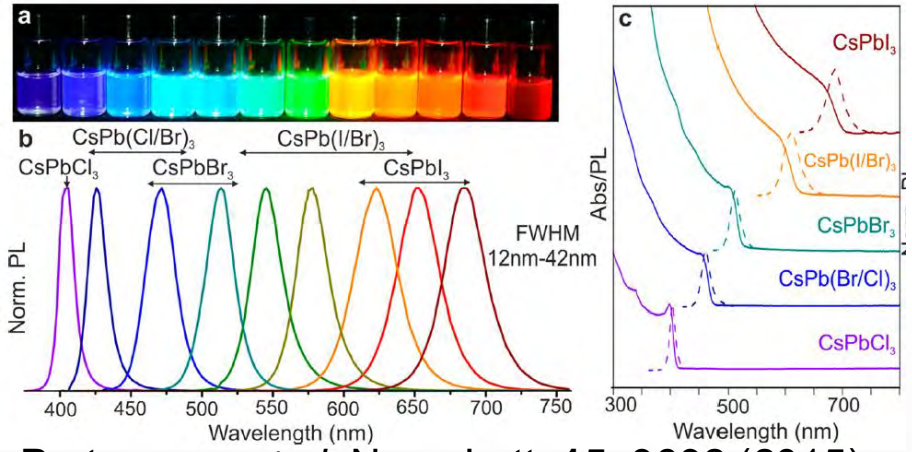


Metal halide perovskites are (not) new



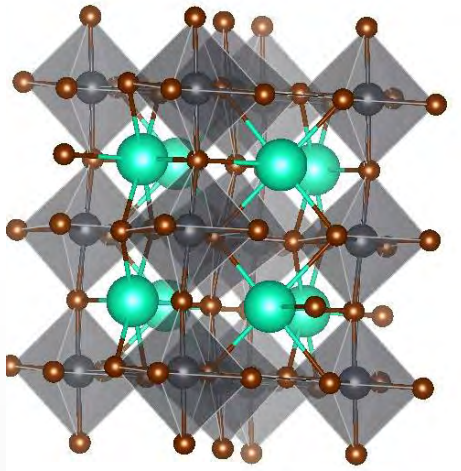
ABX_3

cations Anion



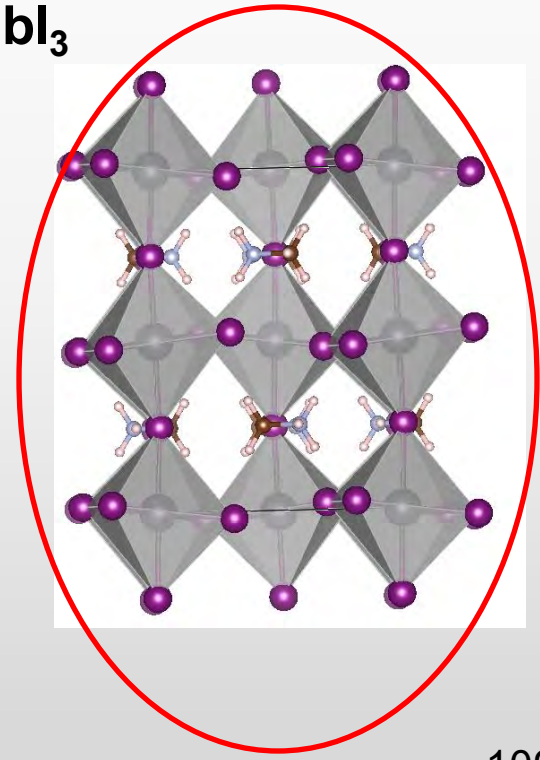
Protesescu *et al*. Nano Lett. **15**, 3692 (2015).

$CsPbBr_3$



- all-inorganic metal halide perovskites (IHPs)
- organic-inorganic metal halide perovskites (OIHPs)

$CH_3NH_3PbI_3$



$CH_3NH_3PbX_3$, ein Pb(II)-System mit kubischer Perowskitstruktur

$CH_3NH_3PbX_3$, a Pb(II)-System with Cubic Perovskite Structure

Dieter Weber

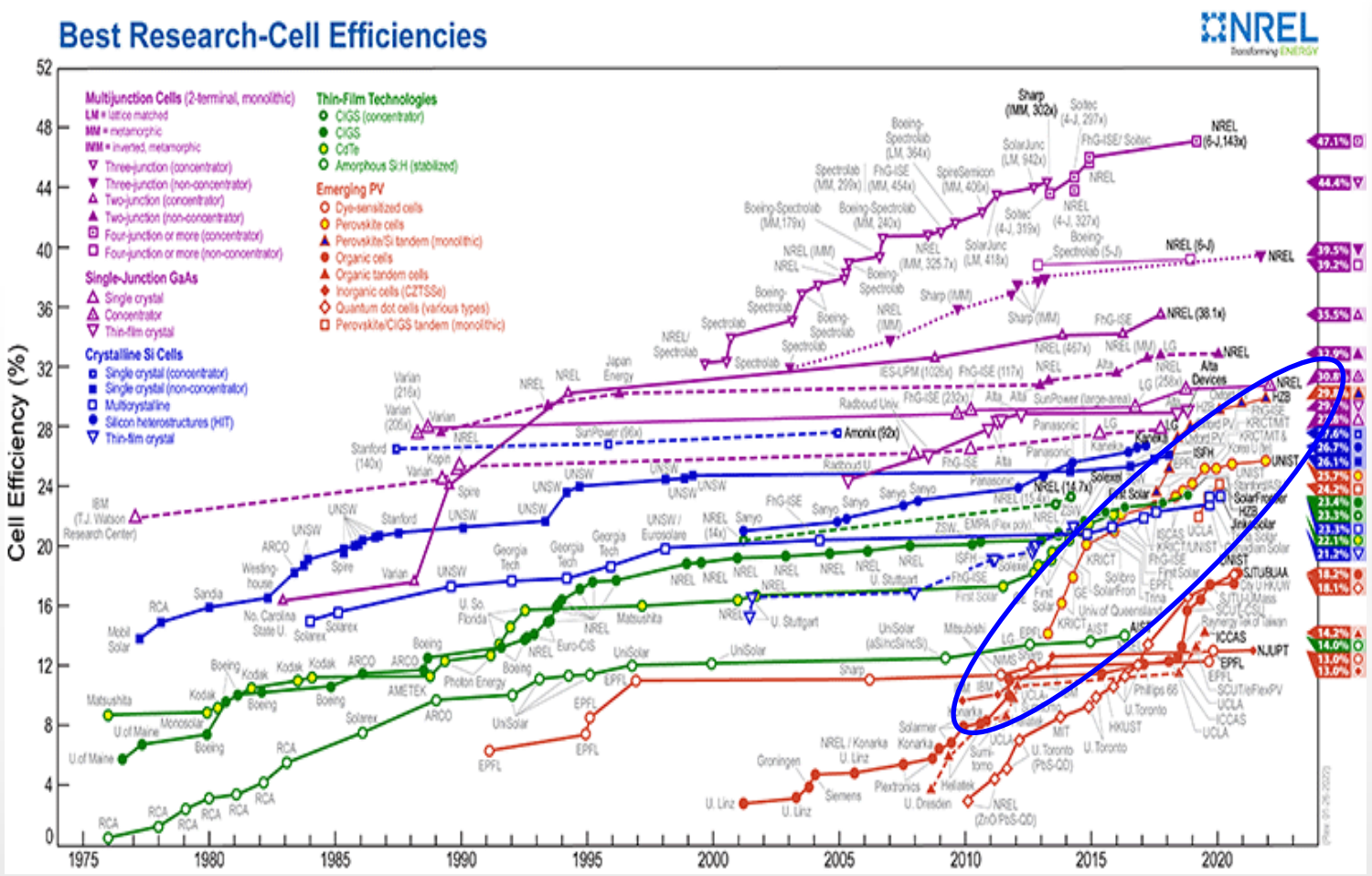
Institut für Anorganische Chemie der Universität Stuttgart

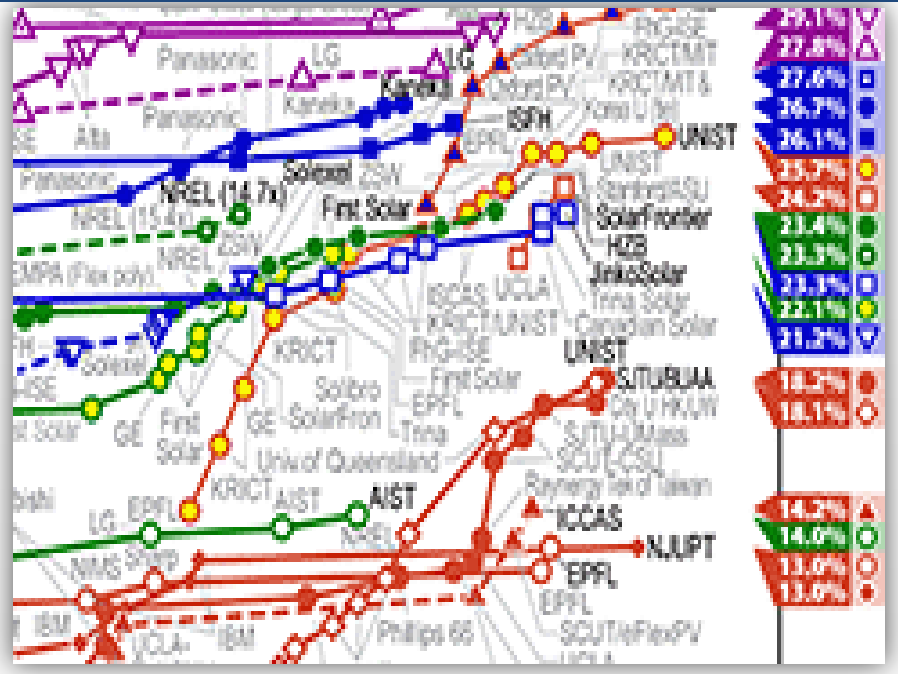
Z. Naturforsch. **33 b**, 1443–1445 (1978); eingegangen am 21. August 1978

Synthesis, X-ray

$CH_3NH_3PbX_3$ (X = Cl, Br, I) has the cubic perovskite structure with the unit cell parameters a = 5,68 Å (X = Cl), a = 5,92 Å (X = Br) and a = 6,27 Å (X = I). With exception of $CH_3NH_3PbCl_3$ the compounds show intense colour, but there is no significant conductivity under normal conditions. The properties of the system are explained by a "p-resonance-bonding". The synthesis is described.

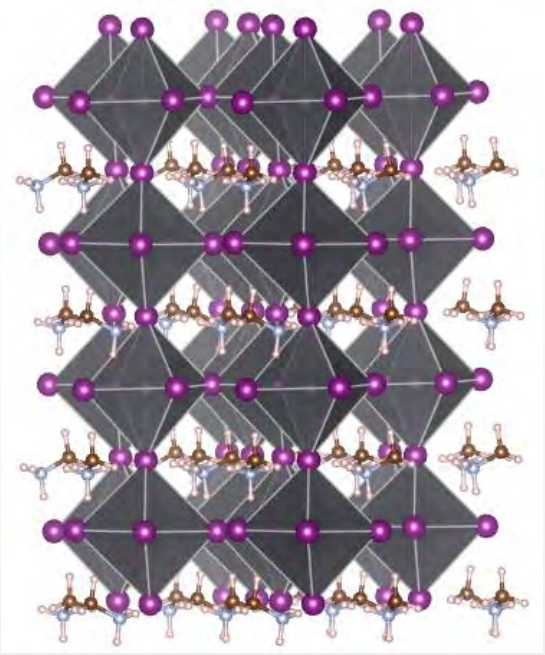
Solar cell efficiencies





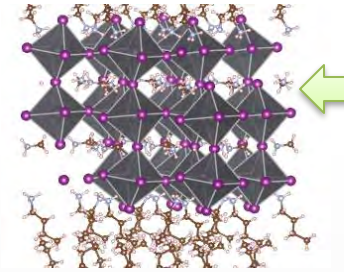
From 3D to low dimensional

ABX_3

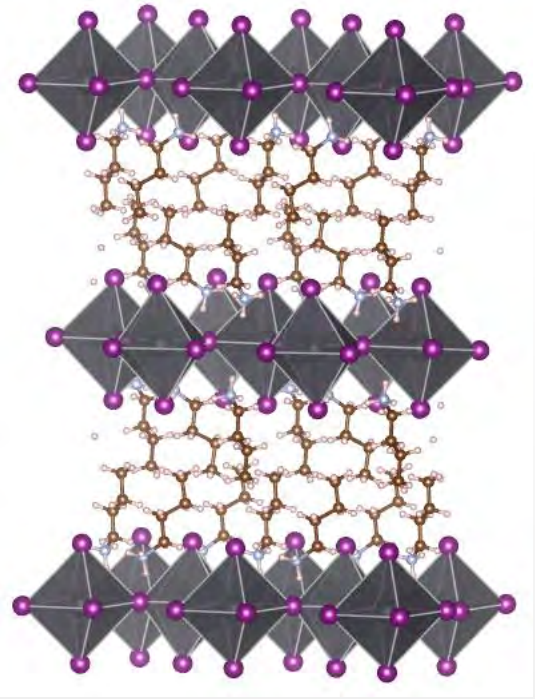


=∞

3D

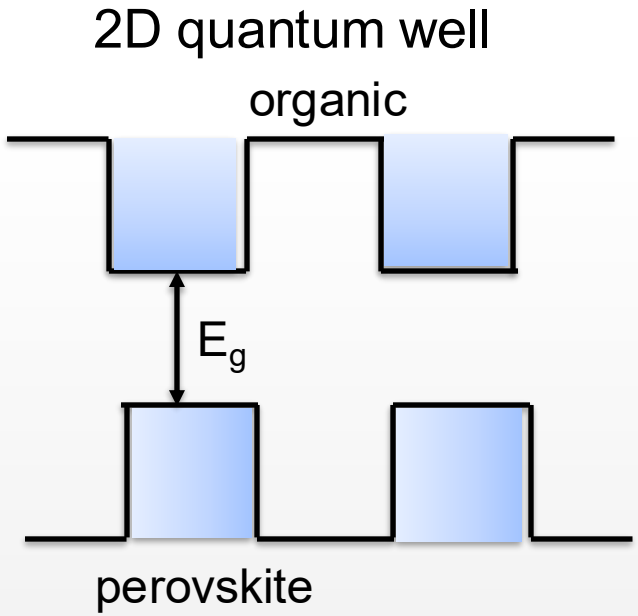


Quasi 2D



n=1

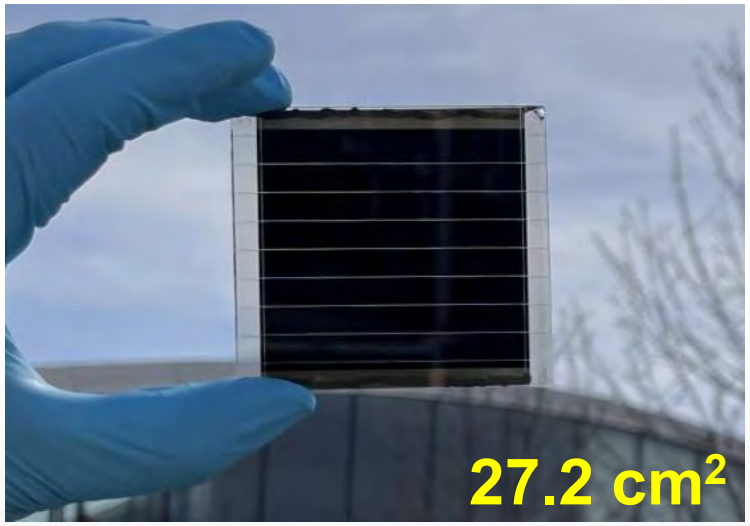
2D



Low D

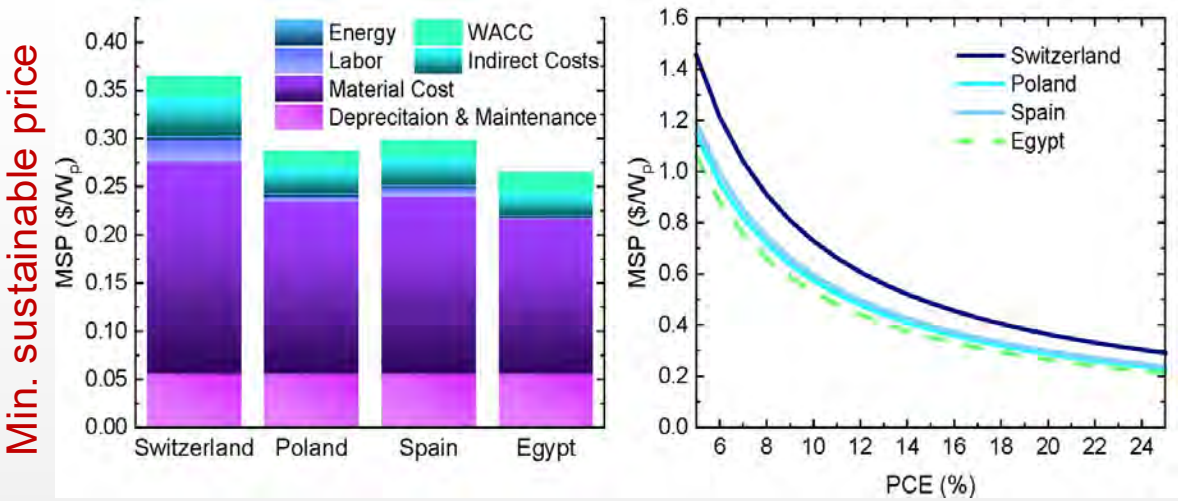
- Better solution processable and environmental stability
- Take advantage of quantum confinement

Perovskite solar modules



EPFL, May 2024
(3D/2D) 25.3%

Layer	Option 1	Option 2	Option 3	Option 4	Option 5
ETL 1	c-TiO_2	c-TiO_2	SnO_2	SnO_2	c-TiO_2
ETL 2	m-TiO_2	m-TiO_2			m-TiO_2
Perovskite	Perovskite	Perovskite	Perovskite	Perovskite	Perovskite
HTM	Spiro	Spiro	Spiro	Spiro	-
Electrode	Cr/Cu	Silver Ink	Cr/Cu	Silver Ink	C-Paste
Price/m2 (100 MW)	*$5.9*	*$6.6*	*$2.7*	*$3.4*	*$8.1*
Price/m2 (1 GW)	*$5.0*	*$5.1*	*$1.9*	*$2.0*	*$6.2*



Nazeeruddin *et al*. ACS Energy Lett. 2022, **7**, 9, 3039

Perovskite solar panels : 0.25 - 0.69 $/Wp
Si solar panels: 0.34 - 0.54 $/Wp

Halide perovskites – 21st century semiconductors

Article

Joint Forum on Halide Perovskite Materials and Devices for Energy and Electronic Applications

Suchismita Guha and Gerrit Boschloo

ACS Applied Energy Materials 2023, 6, 20, 10190-10192 **(Editorial)** Subscribed

Publication Date (Web): October 23, 2023

DOI: 10.1021/acsaem.3c02354

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ACS APPLIED ENERGY MATERIALS

Article

Joint Forum on Halide Perovskite Materials and Devices for Energy and Electronic Applications

Suchismita Guha and Gerrit Boschloo

ACS Applied Electronic Materials 2023, 5, 10, 5258-5260 **(Editorial)** Subscribed

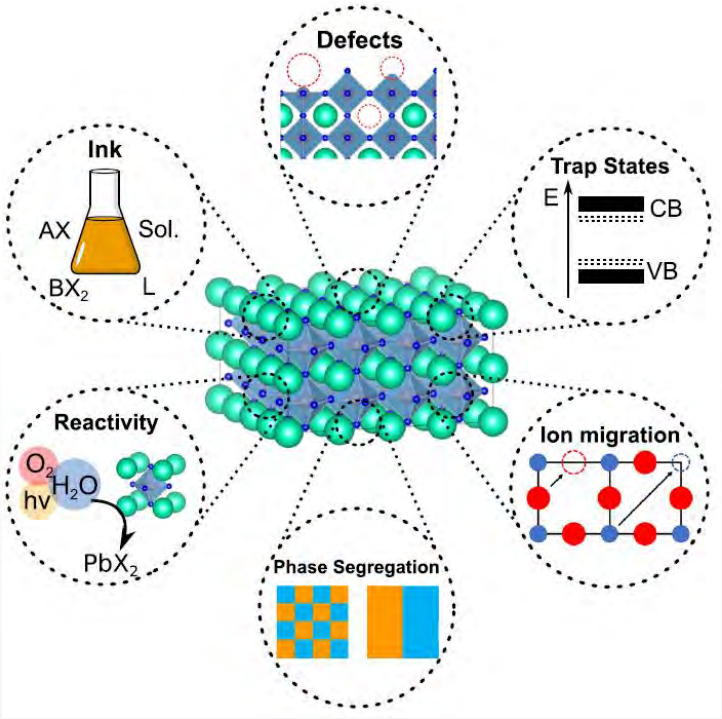
Publication Date (Web): October 24, 2023

DOI: 10.1021/acsaelm.3c01305

ACS APPLIED ELECTRONIC MATERIALS

"Interdisciplinary journal covering all aspects of electronic materials"

What are the challenges?



Schmidt-Mende *et al*. APL Mater. **9**, 109202 (2021).

We are pursuing a solvent-free synthesis of halide perovskite thin films.

Transient absorption techniques based on ultrafast laser techniques provide insights

Shockley-Queisser limit

JOURNAL OF APPLIED PHYSICS VOLUME 32, NUMBER 3 MARCH, 1961

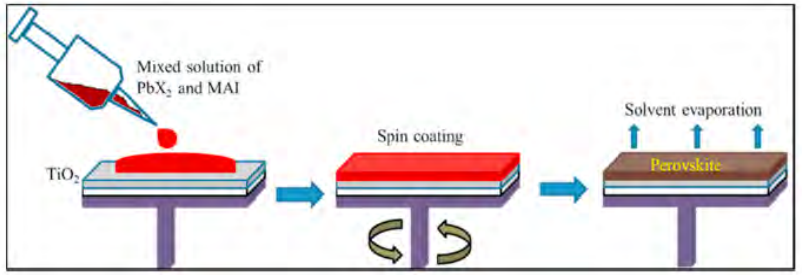
Detailed Balance Limit of Efficiency of *p-n* Junction Solar Cells*

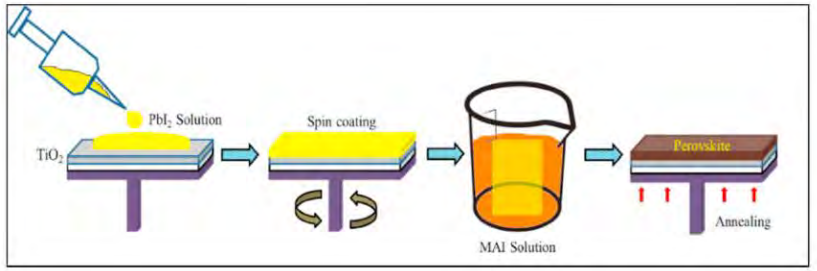
WILLIAM SHOCKLEY AND HANS J. QUEISSER
Shockley Transistor, Unit of Clevite Transistor, Palo Alto, California
(Received May 3, 1960; in final form October 31, 1960)

In order to find an upper theoretical limit for the efficiency of *p-n* junction solar energy converters, a limiting efficiency, called the *detailed balance limit* of efficiency, has been calculated for an ideal case in which the only recombination mechanism of hole-electron pairs is radiative as required by the principle of detailed balance. The efficiency is also calculated for the case in which radiative recombination is only a fixed fraction f_e of the total recombination, the rest being nonradiative. Efficiencies at the matched loads have been calculated with band gap and f_e as parameters, the sun and cell being assumed to be blackbodies with temperatures of 6000°K and 300°K, respectively. The maximum efficiency is found to be 30% for an energy gap of 1.1 ev and $f_e=1$. Actual junctions do not obey the predicted current-voltage relationship, and reasons for the difference and its relevance to efficiency are discussed.

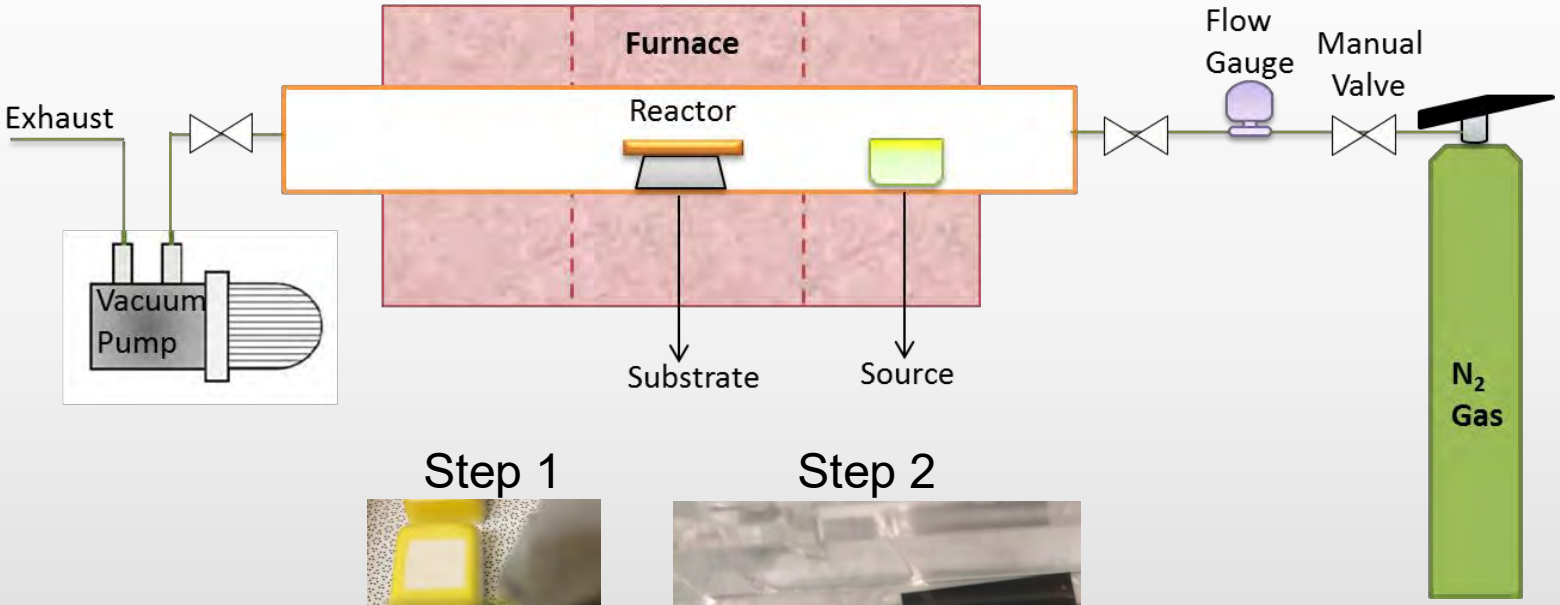
Carrier multiplication and hot carrier extraction are some pathways

CVD growth of halide perovskites ($MAPbI_3$)





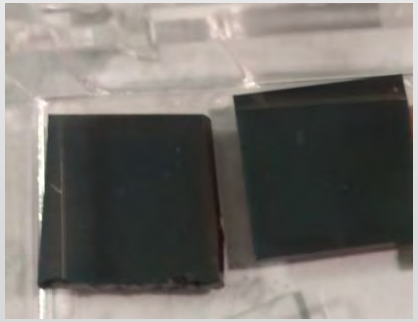
Jamal *et al*. Renew. Sustain. Energy Rev. **98** 469 (2018).



- Two or three zone furnace
- The PbI_2 source is vaporized at 380 °C
- MAI is vaporized at 180 °C

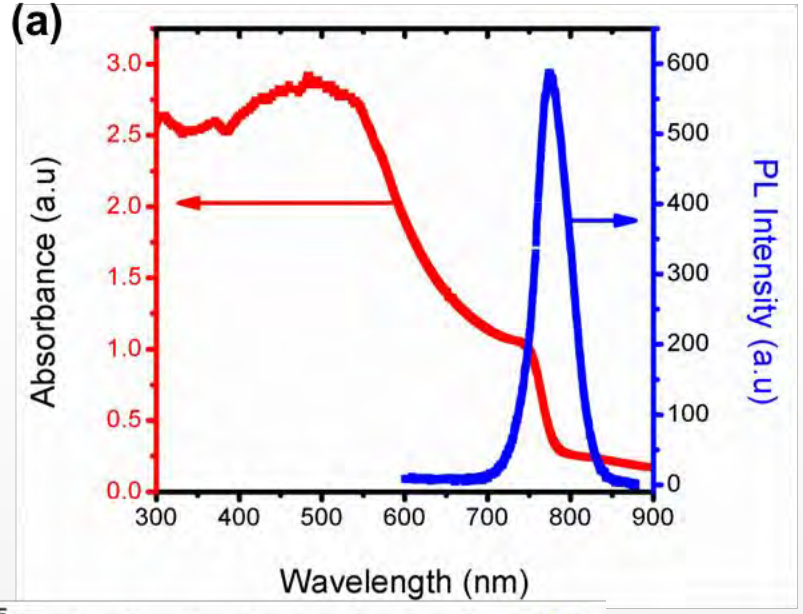
Step 1

Step 2

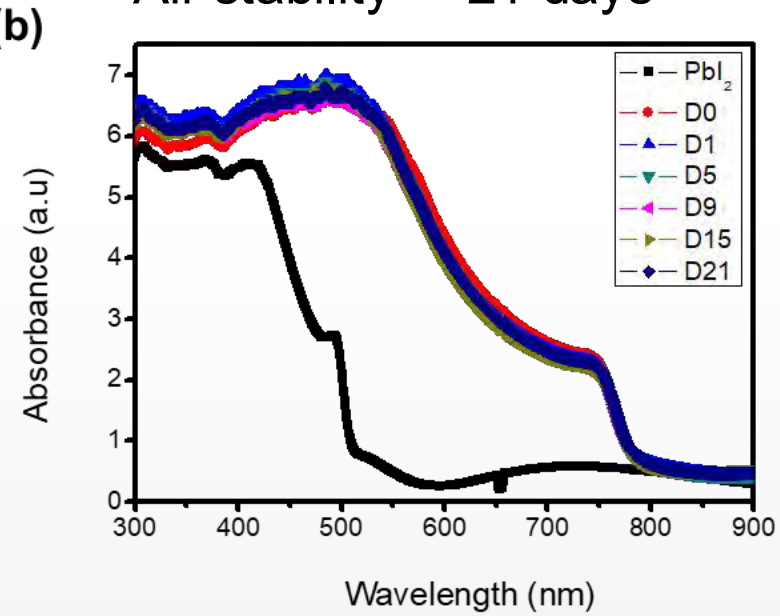


Optical and solar cell properties

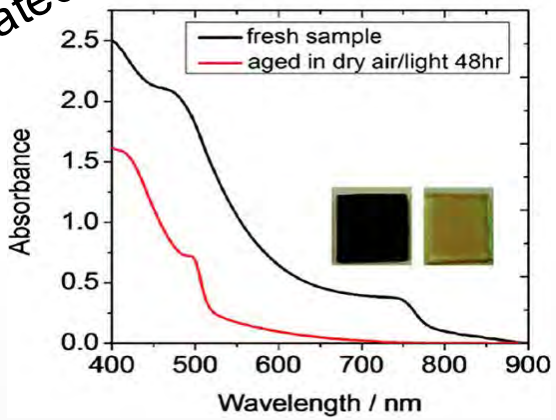
All measurements in air



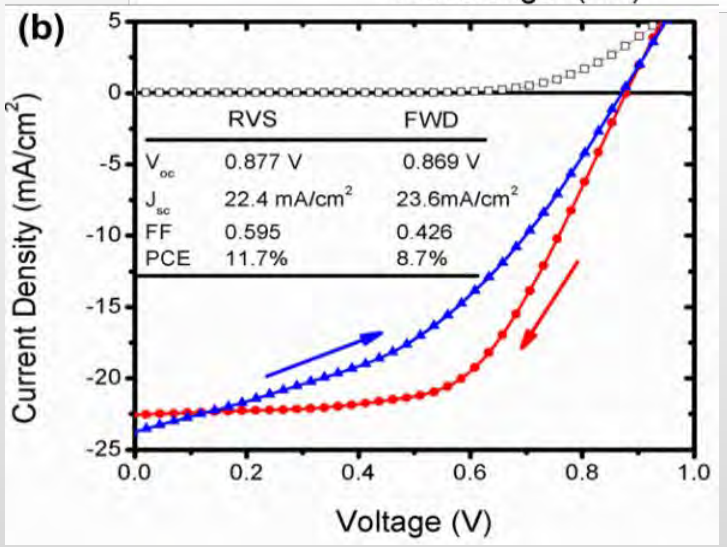
Air stability > 21 days



Spincoated films



Bryant *et al.* Energy Environ. Sci. **9**, 1655 (2016).

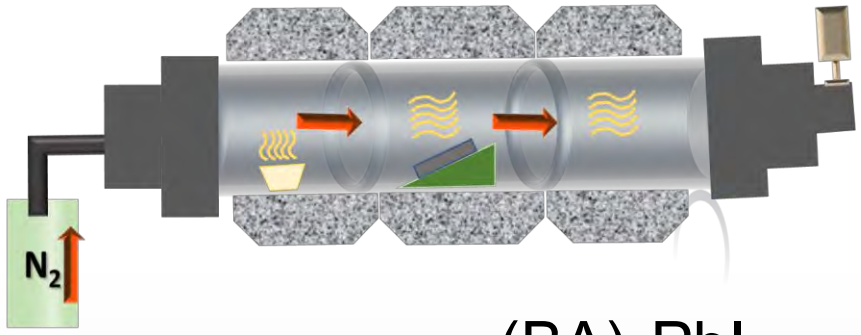


$$\eta = \frac{FF \times V_{OC} \times J_{SC}}{P_{in}}$$

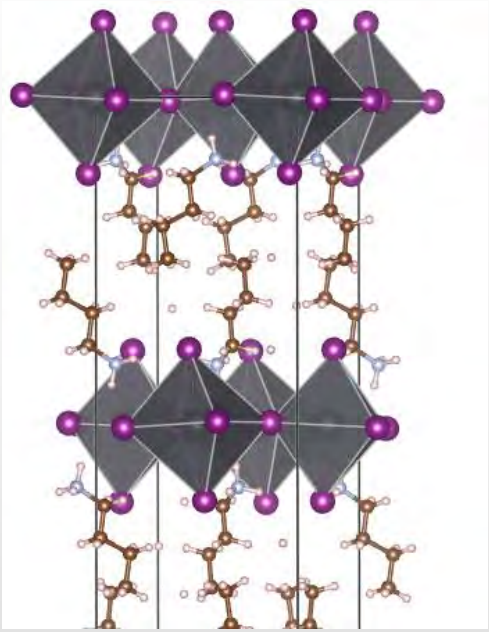
- Samples exposed to uncontrolled humidity (80%) and temperature up to 23 °C.
- Solar Cell PCE of 11.7%
- Maintains 85% of its PCE after 21 days in open air

Ngqoloda *et al*. ACS Appl. Energy Mater. **3**, 2350–2359 (2020).

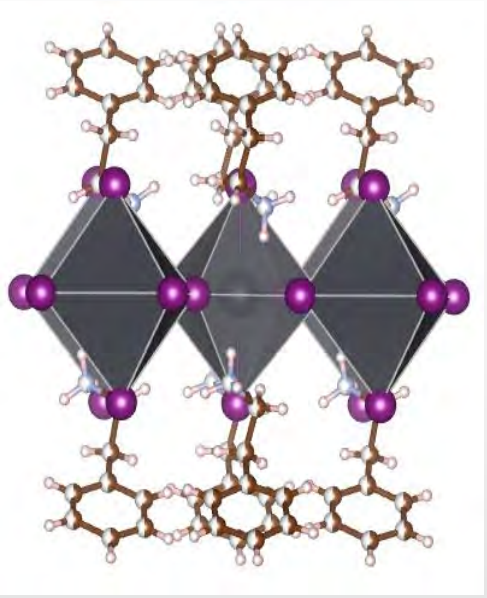
CVD growth of 2D perovskites

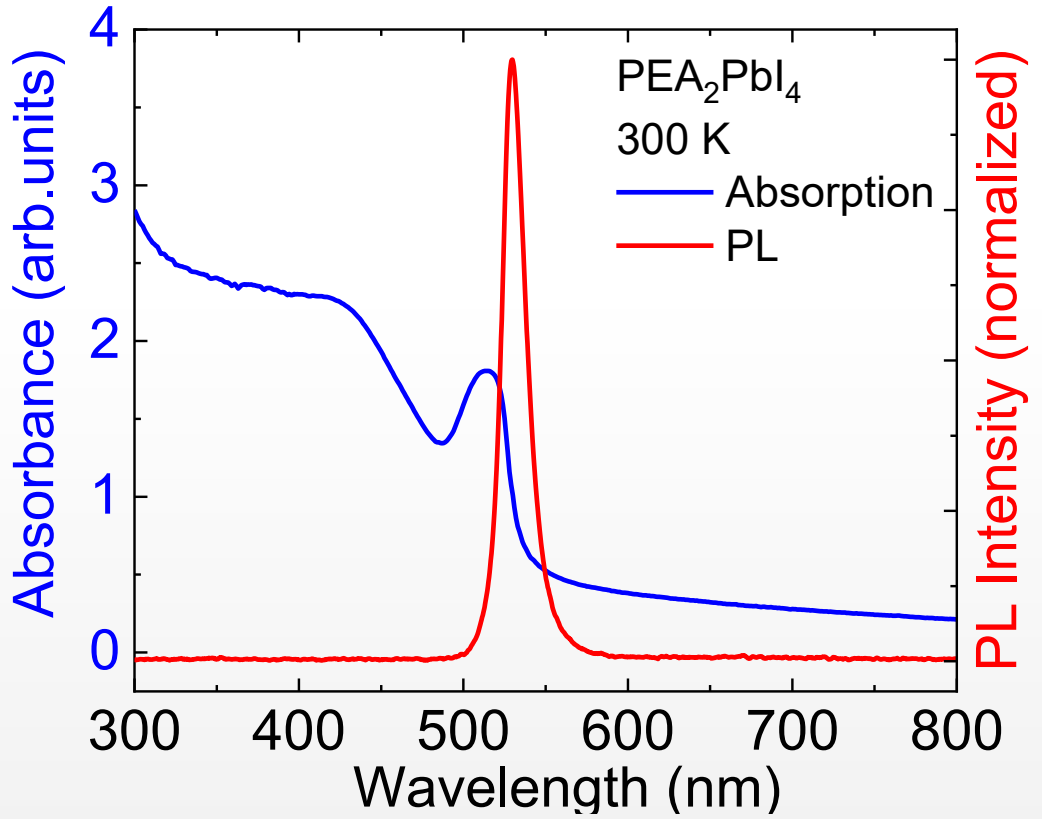


$(BA)_2PbI_4$



$(PEA)_2PbI_4$





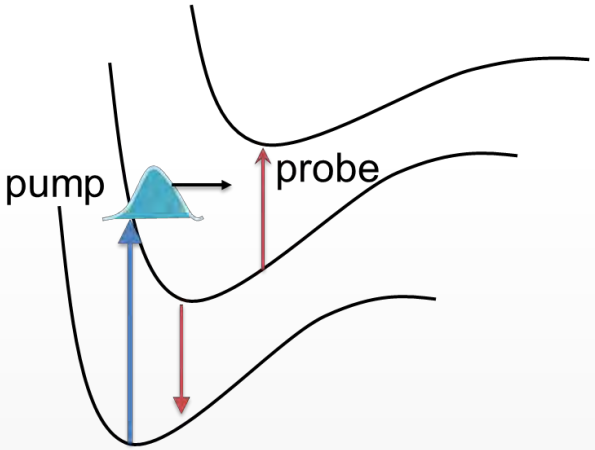
Strong excitonic features

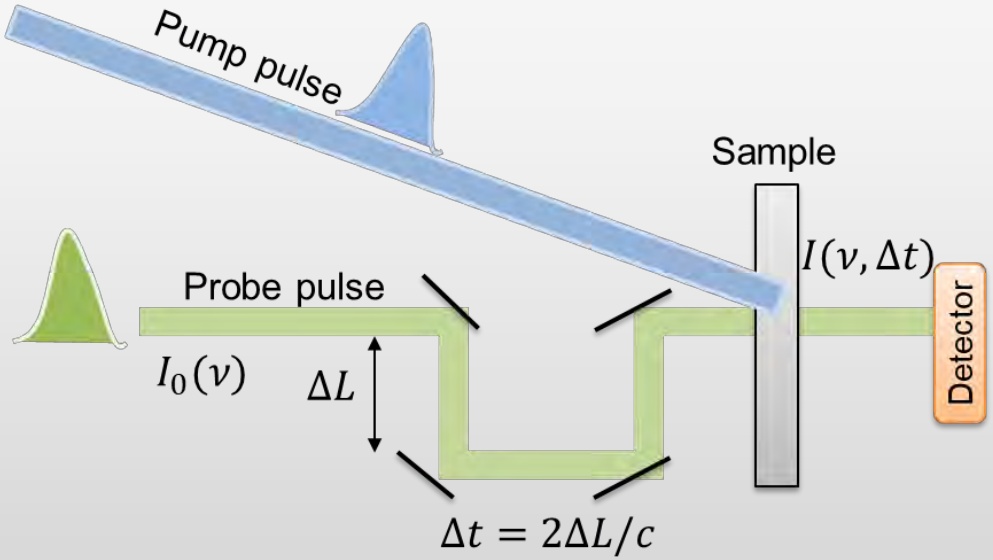
Arendse *et al.* ACS Appl. Mater. Interfaces **15**, 59055 (2023).

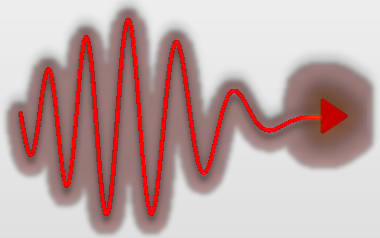
Spectroscopy with short pulses

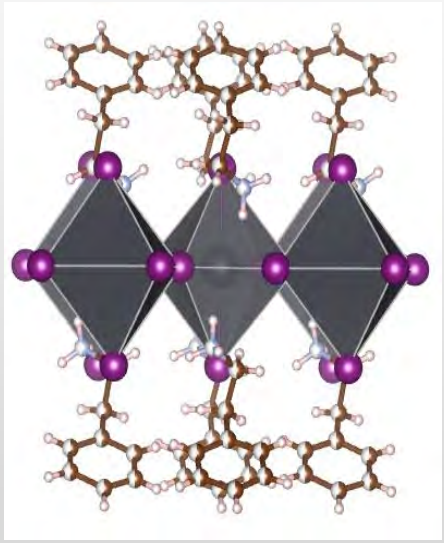
ECCS (MRI) 1827846

Pump-probe spectroscopy

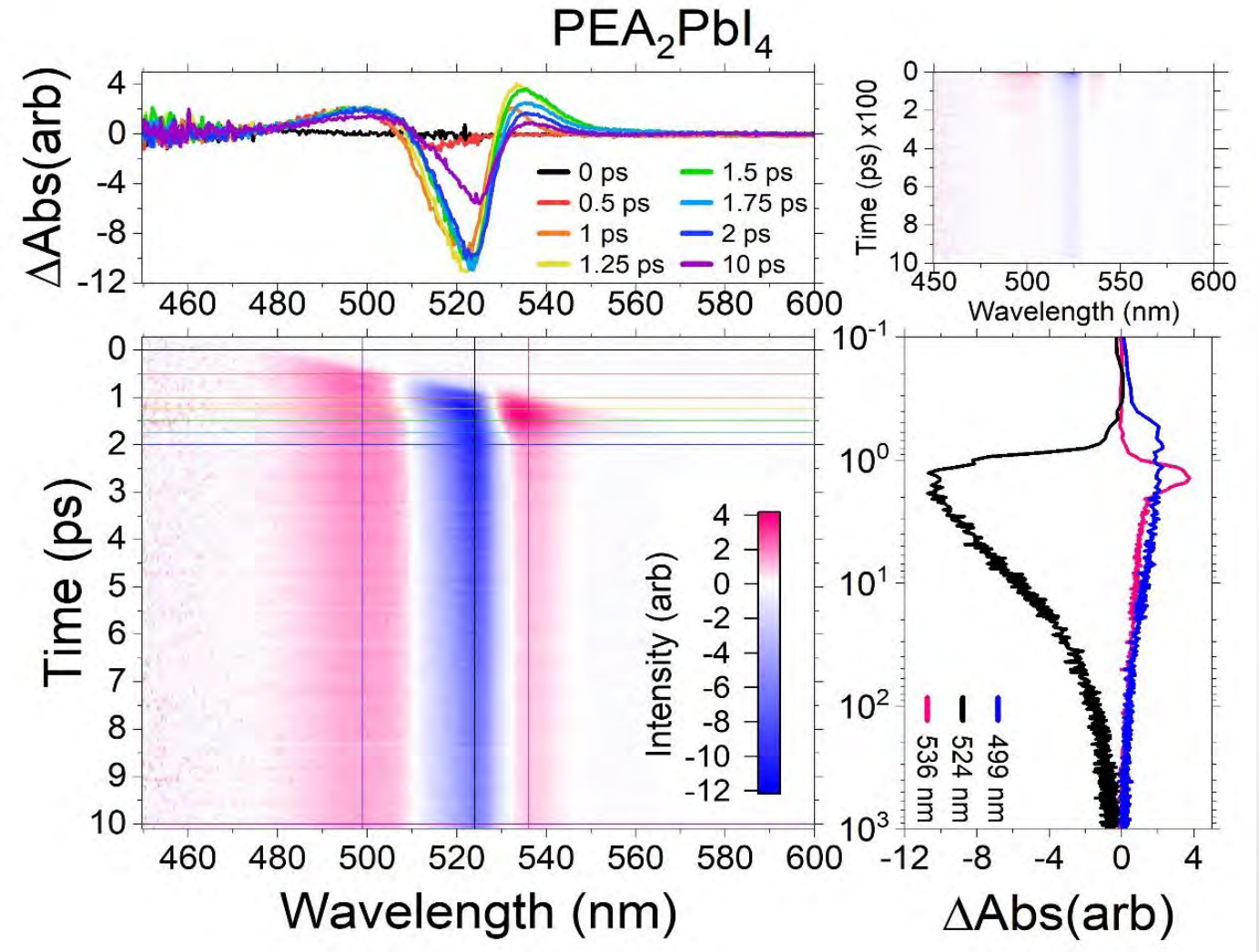








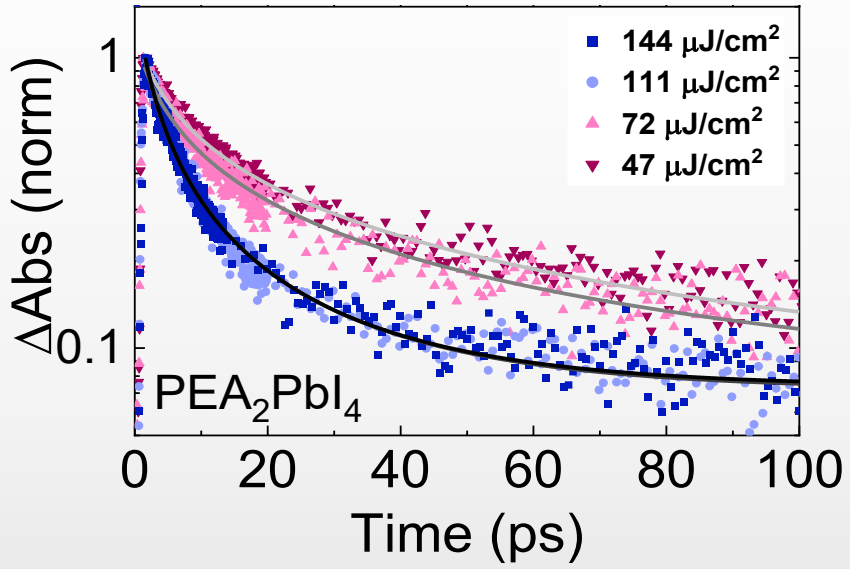
Typical transient absorption features – 2D perovskites



Decay Kinetics

$$\frac{dn}{dt} = G - k_1 n - k_2 n^2 - k_3 n^3$$

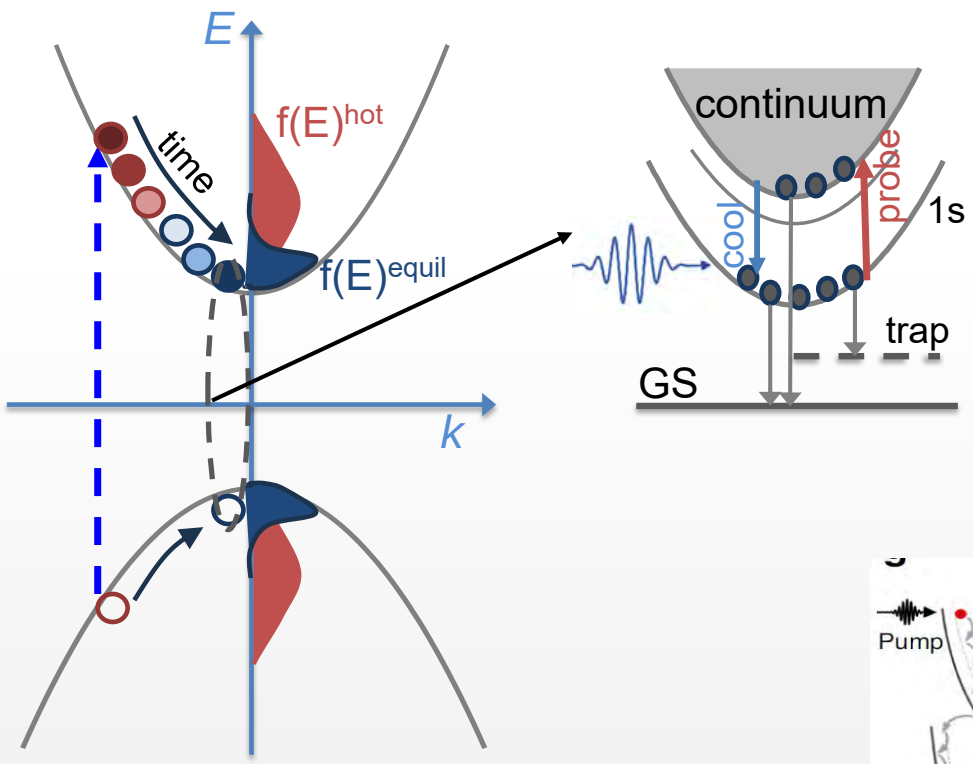
Auger recombination



k_3 dominates at early times
k_1 dominates at later times

(Babaian et al., under revision, 2024)

Relaxation and cooling dynamics



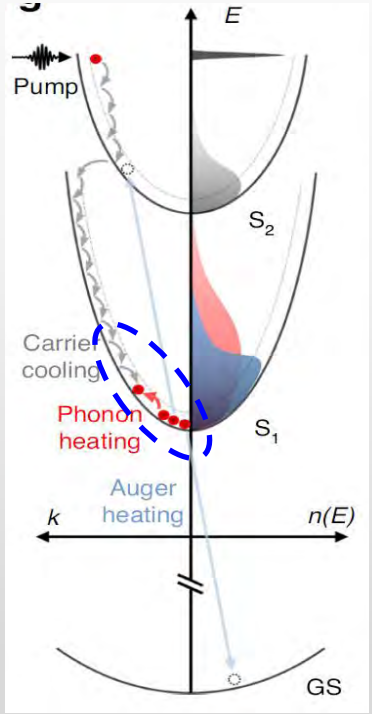
Strategy for increasing V_{OC}

Hot carrier extraction – harness the resonant

“ ”

Phonon bottleneck

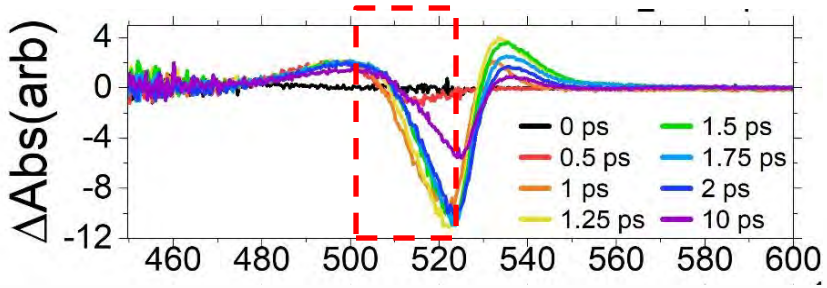
- Extended relaxation times (~ ps)
- Low carrier-phonon coupling



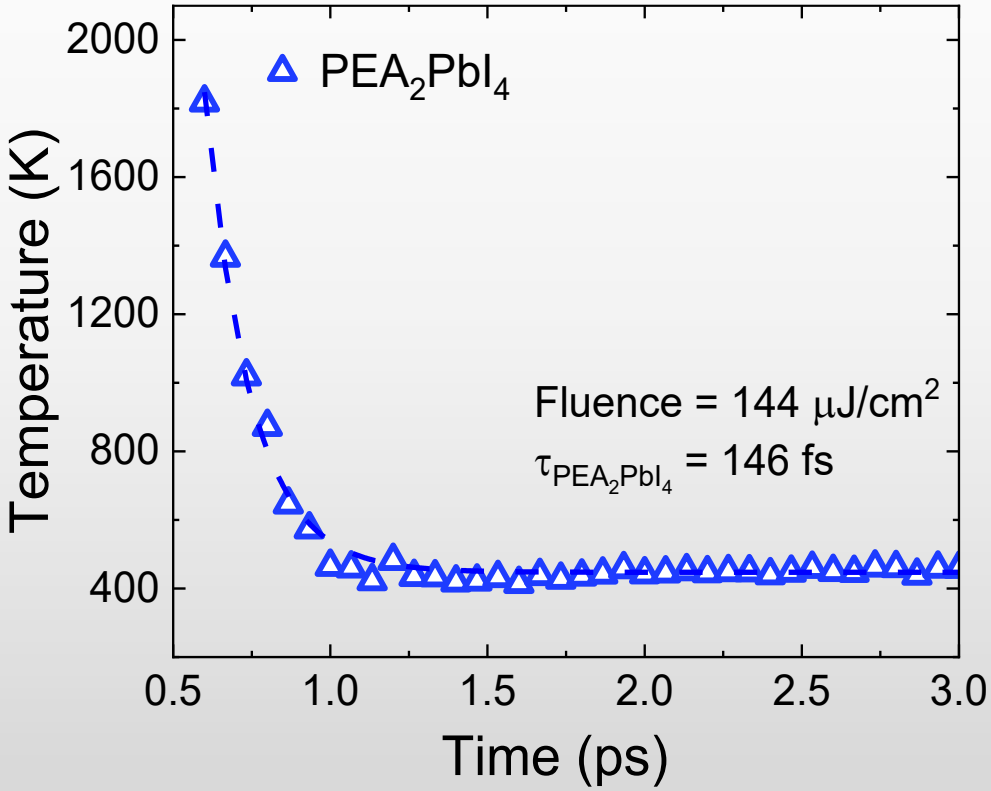
Dai *et al*. Light: Science & Applications (2023) **12**:208

“Not so good ne s for 2D perovskites” and ha t next?

$$\Delta A(\hbar\omega) \propto \exp(-\hbar\omega/(k_B T_e))$$



- Very fast cooling times (compared to 3D perovskites).
- Relaxation of carriers via Fröhlich interaction.
- Absence of a phonon bottleneck process.



What next?

- Mixed Pb-Sn perovskite nanocrystals show slow cooling times.
- Hetero-stacked perovskites with graphene and other 2D chalcogenides.
- “ ” supports a wide range of tunneling energy states.

Thank You!

Funding
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NSF ECCS (MRI) 1827846

Fourth generation solar cells based on halide perovskites: poking them with ultrafast light

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Randy Burns

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U. Western Cape

Prof. Chris Arendse

- Prof. Paul Miceli (MU)
- Dr. Daniel Hill (MU)
- Stephen Klue (MU)
- David Beckwitt (MU)
- Dr. Evguenia Karapetrova (Argonne National Lab)