3G rule for attending in person lectures at KIT:

- ***geimpft*** **– vaccinated**
- ***genesen*** **– recovered**
- ***getestet*** **– tested**

Karlsruher Institut für Technologie

“Solar Energy” WS 2021/2022

Lecture 9: Organic and Perovskite Thin-film Solar Cells

Tenure-Track-Prof. Dr. Ulrich W. Paetzold

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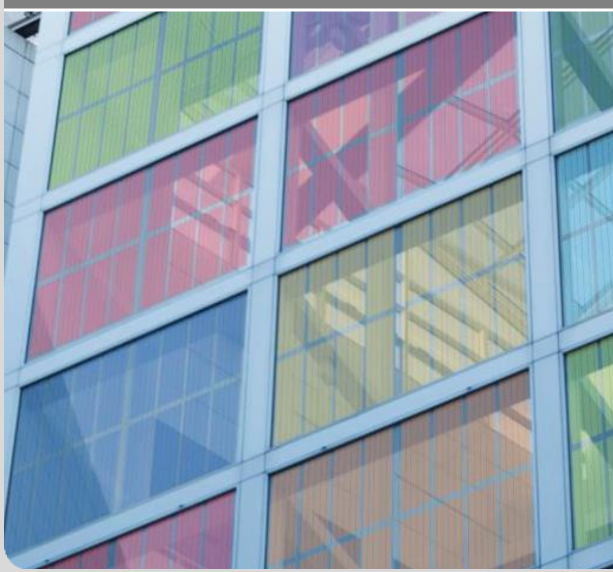
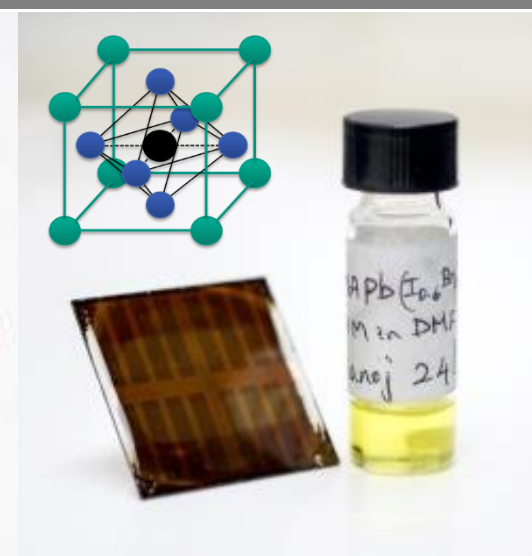
Light Technology Institute (LTI), Engesserstrasse 13, Building 30.34, 76131 Karlsruhe

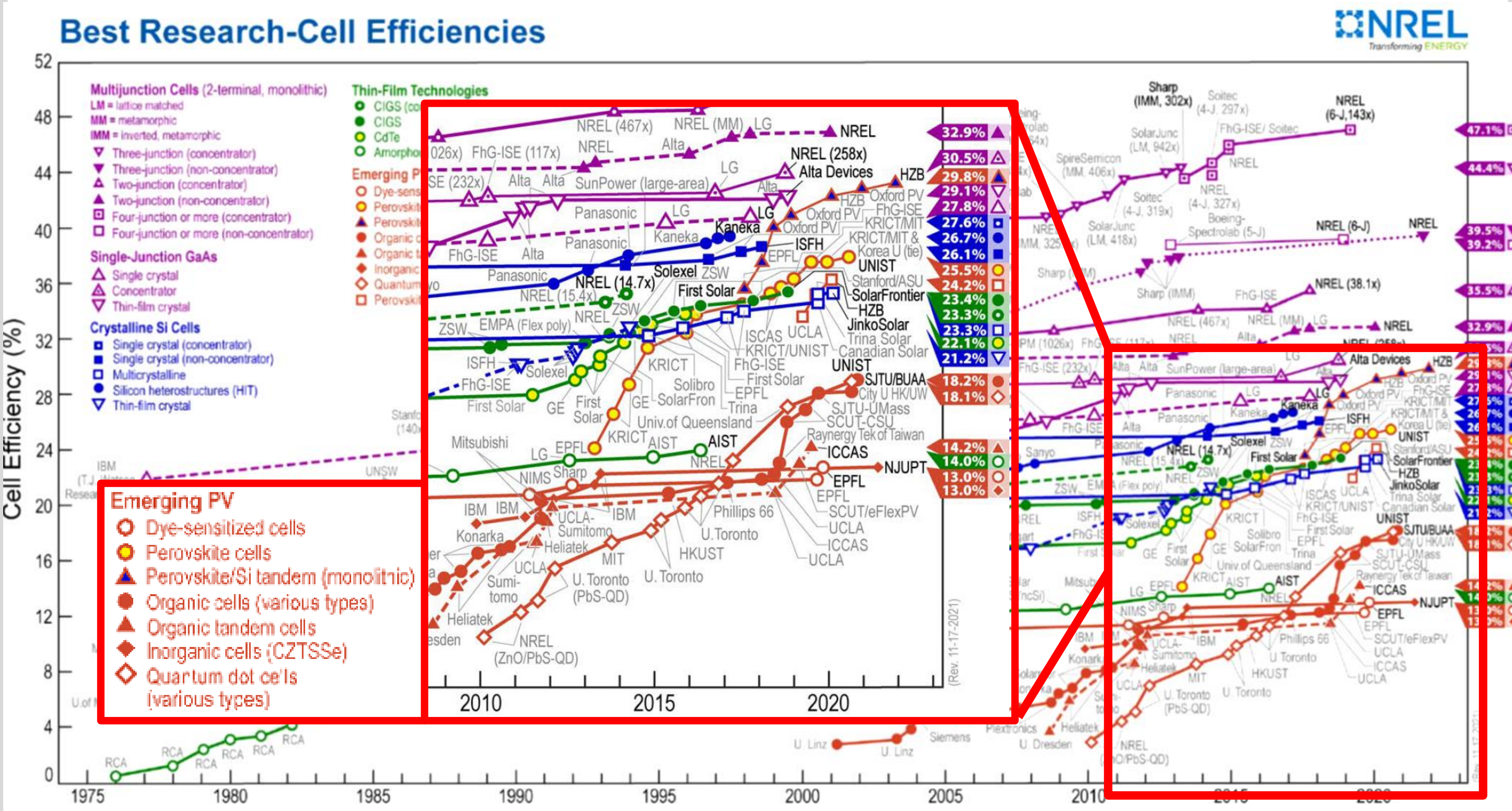
KIT Focus Optics & Photonics





Parts of the material used here have been kindly provided by Prof. T. Kirchartz, and Dr. D. Cheyns.

Why organic or perovskite PV?



Source: https://www.nrel.gov/pv/cell-efficiency.html

PART 1 - ORGANIC PHOTOVOLTAICS

Part 1: Organic Photovoltaics

Karlsruher Institut für Technologie

- **Material properties**
- Inorganic vs. organic semiconductor
- Working principle organic solar cells
- Fabrication of organic solar cells / device architecture
- Major Challenges of the technology
- Applications

What is organic about OPV

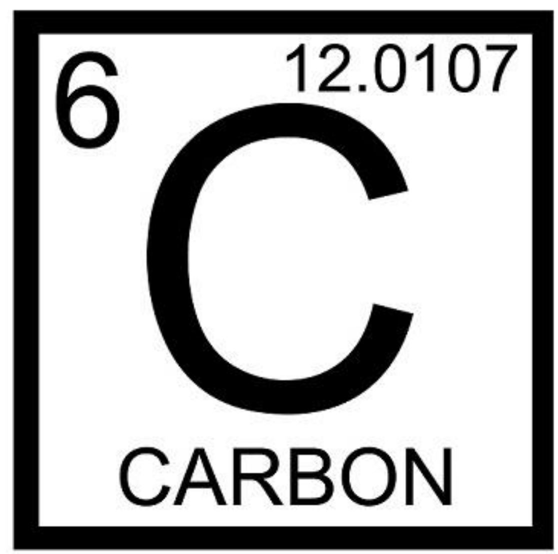
How the plants works…?
Can we mimic the nature?!!

... greenhouses ?

... artificial leaves?

Belectric

... maybe ... but the point is that we use organic materials, in its various forms that contain carbon atoms!



Sources: belectric
Courtesy to Barry Rand & David Cheyns

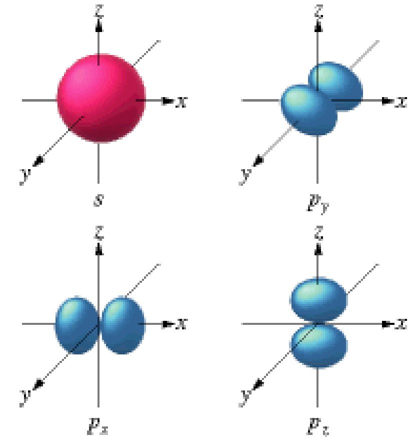
Carbon Hybridization

Atomic carbon (6th electrons)

$1s^2$ $2s^2$ $2p^2$

↑↓   ↑↓   ↑   ↑   —

($1s^2$ $2s^2$ $2p_x^1$ $2p_y^1$ $2p_z^0$)

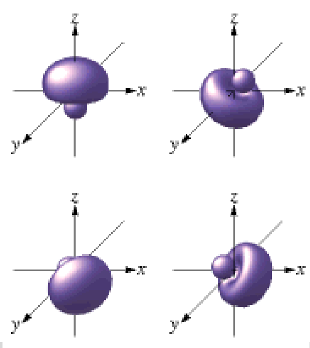


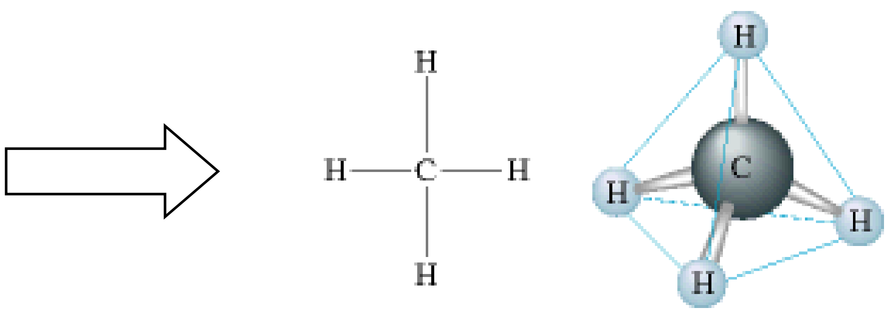
- <u>sp^3 hybridization</u>

Mixing the 2s and *three* 2p orbitals

↑↓   ↑   ↑   ↑   ↑

$1s^2$ sp^3 sp^3 sp^3 sp^3





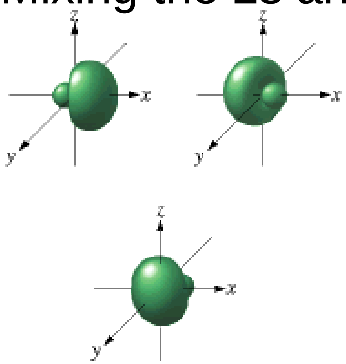
Methane

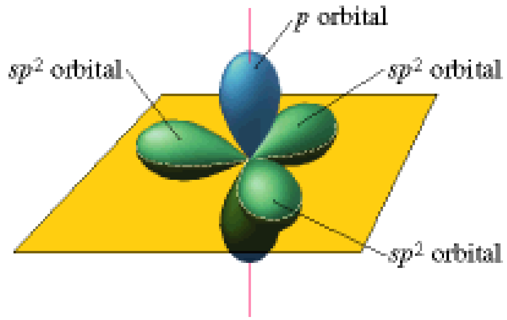
Carbon Hybridization

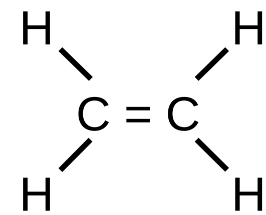
sp² hybridization

Mixing the 2s and *two* 2p orbitals

↑↓	↑	↑	↑	↑
$1s^2$	sp^2	sp^2	sp^2	$2p_z^1$





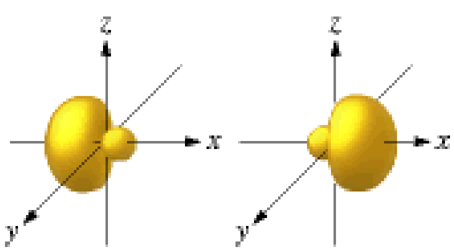


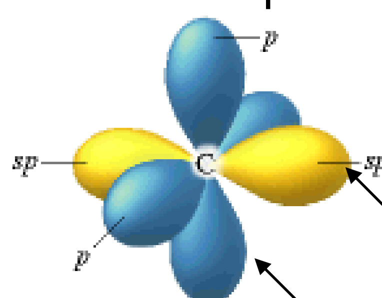
Ethene

sp hybridization

Mixing the 2s and *one* 2p orbital

↑↓	↑	↑	↑	↑
$1s^2$	sp	sp	$2p_y^1$	$2p_z^1$





H - C ≡ C - H

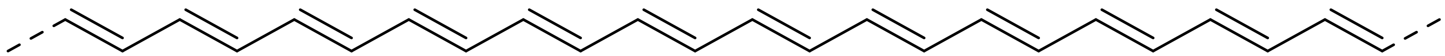
Ethyne

σ – bond → strong

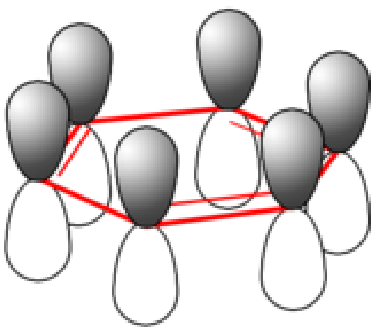
π – bond → weak

Conjugated Polymers

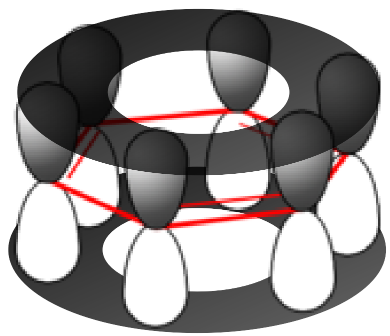
An organic compound with alternating single and multiple (e.g. double) bonds
More specifically: each atom in a chain must posses a *p-orbital*



Example: benzene – connecting a conjugated polymer of sp hybridized C atoms in a ring



6 p-orbitals



Delocalization

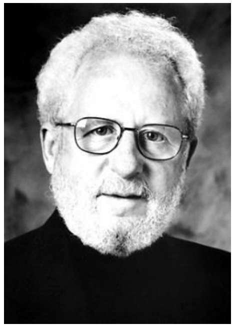
1. **Increase stability**/Lower overall energy of the molecule due to delocalized states
2. **General delocalization** of the electrons across all adjacent parallel aligned p-orbitals

-> electrons can move “freely” which **gives rise to conductivity**

Conjugated Polymers

Nobel Prize in Chemistry 2000

Awarded jointly to Alan J. Heeger, Alan G. MacDiarmid and Hideki Shirakawa "*for the discovery and development of conductive polymers*"



Conjugated Polymers

An organic compound with alternating single and multiple (e.g. double) bonds
More specifically: each atom in a chain must posses a *p-orbital*

<u>**Polyacenes as 2D examples**</u>

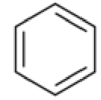
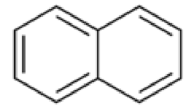
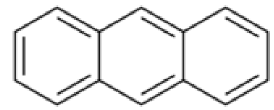
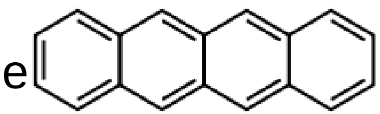
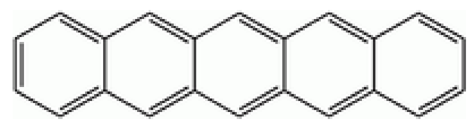
Color:

With every double bond added, the system absorbs photons of longer wavelength

Stability

General formula: $C_{4n+2}H_{2n+4}$ where n is the number of rings

Stability decreases as n increases

Benzene		2550 Å
Naphthalene		3150 Å
Anthracene		3800 Å
Naphthacene		4800 Å
Pentacene		5800 Å

Conjugation in cyclic structures results in *aromaticity*

Types of organic materials

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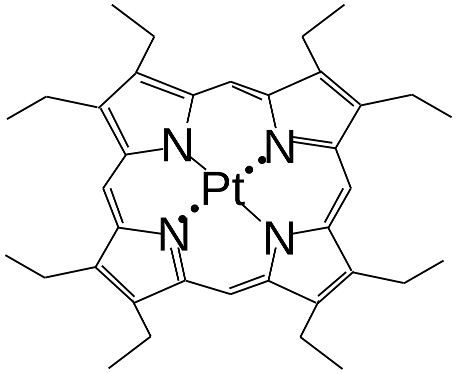
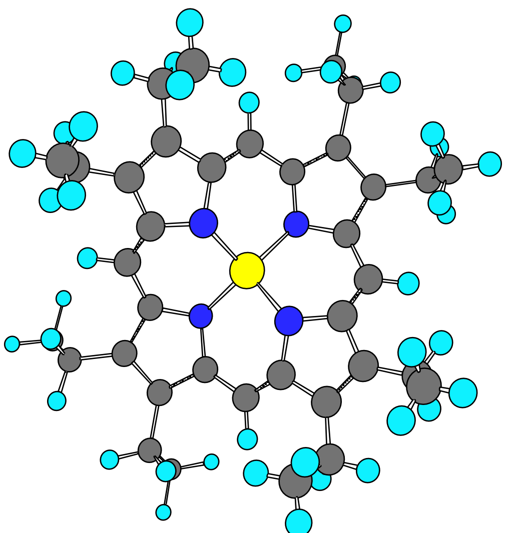
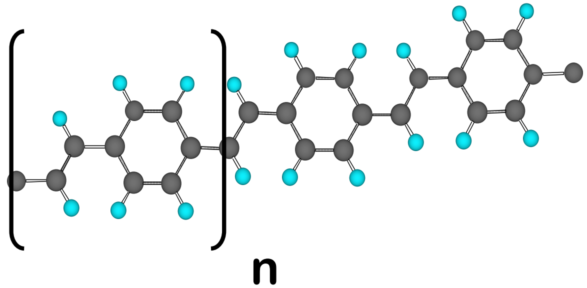
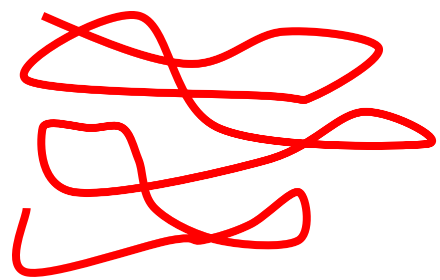
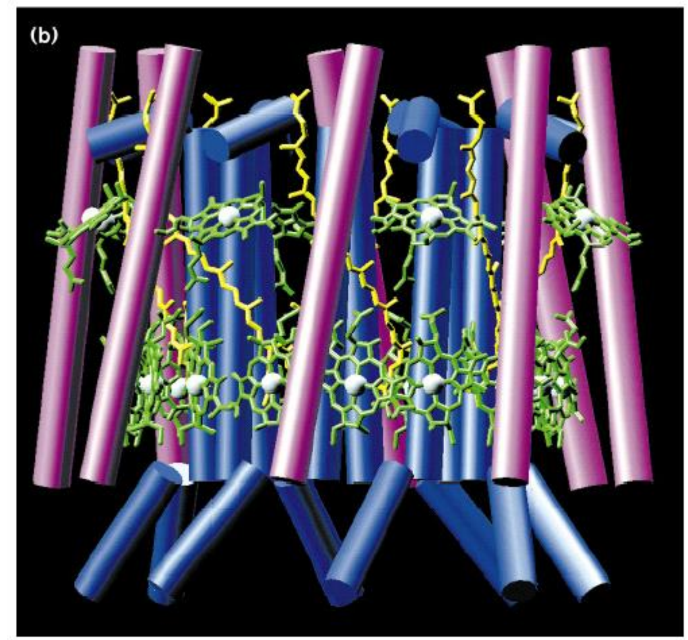










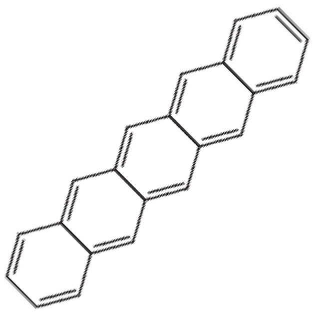
Koepke *et al*. Structure **4**, 581 (1996)

Monomers **Polymers** **Biological Molecules**

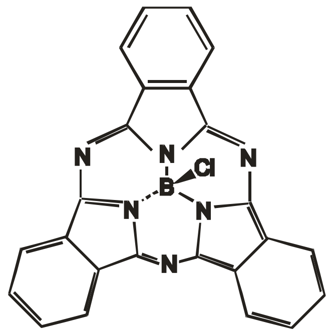
Structural Complexity →

Typical small molecules

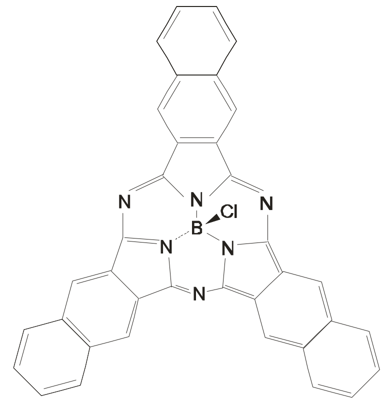
- Donors:



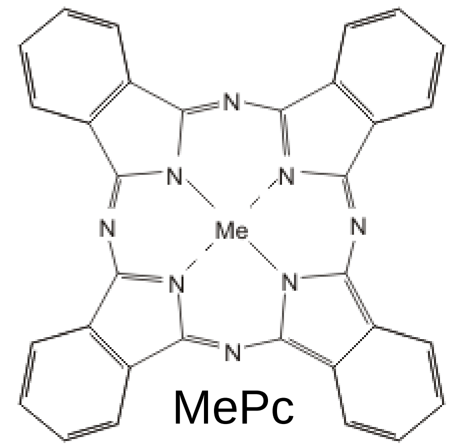
pentacene



SubPc

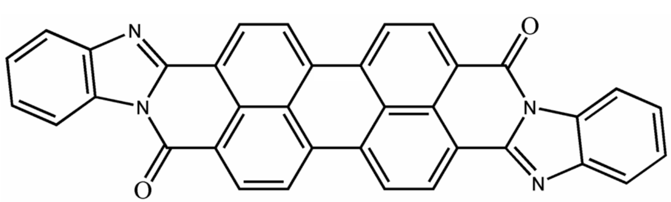


SubNc

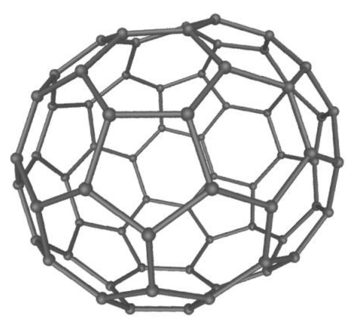


MePc

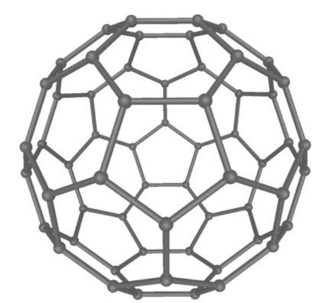
- Acceptors: perylene derivatives, fullerenes



PTCBI

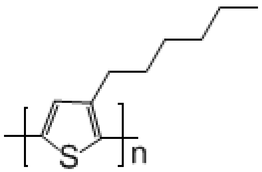


C_{70}

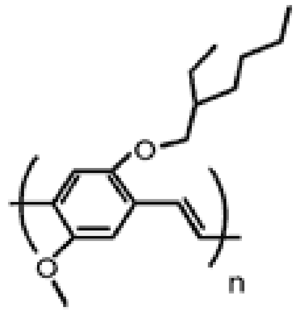


C_{60}

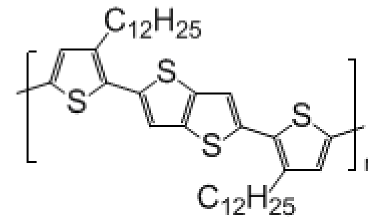
Typical polymers



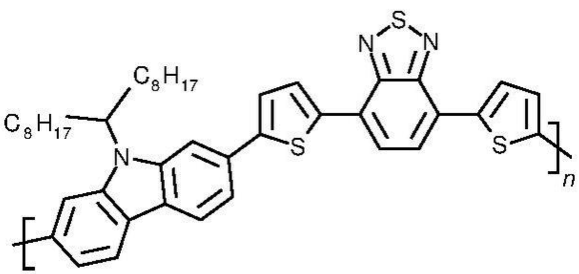
P3HT



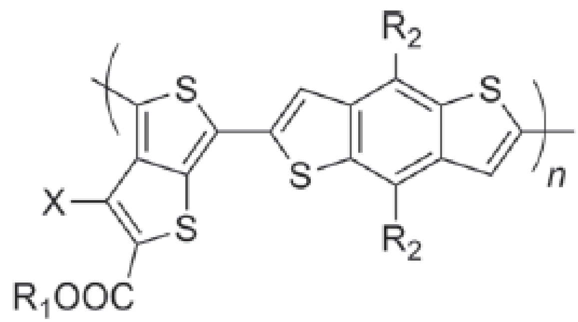
MEH-PPV



PBTTT-C_{12}



PCDTBT



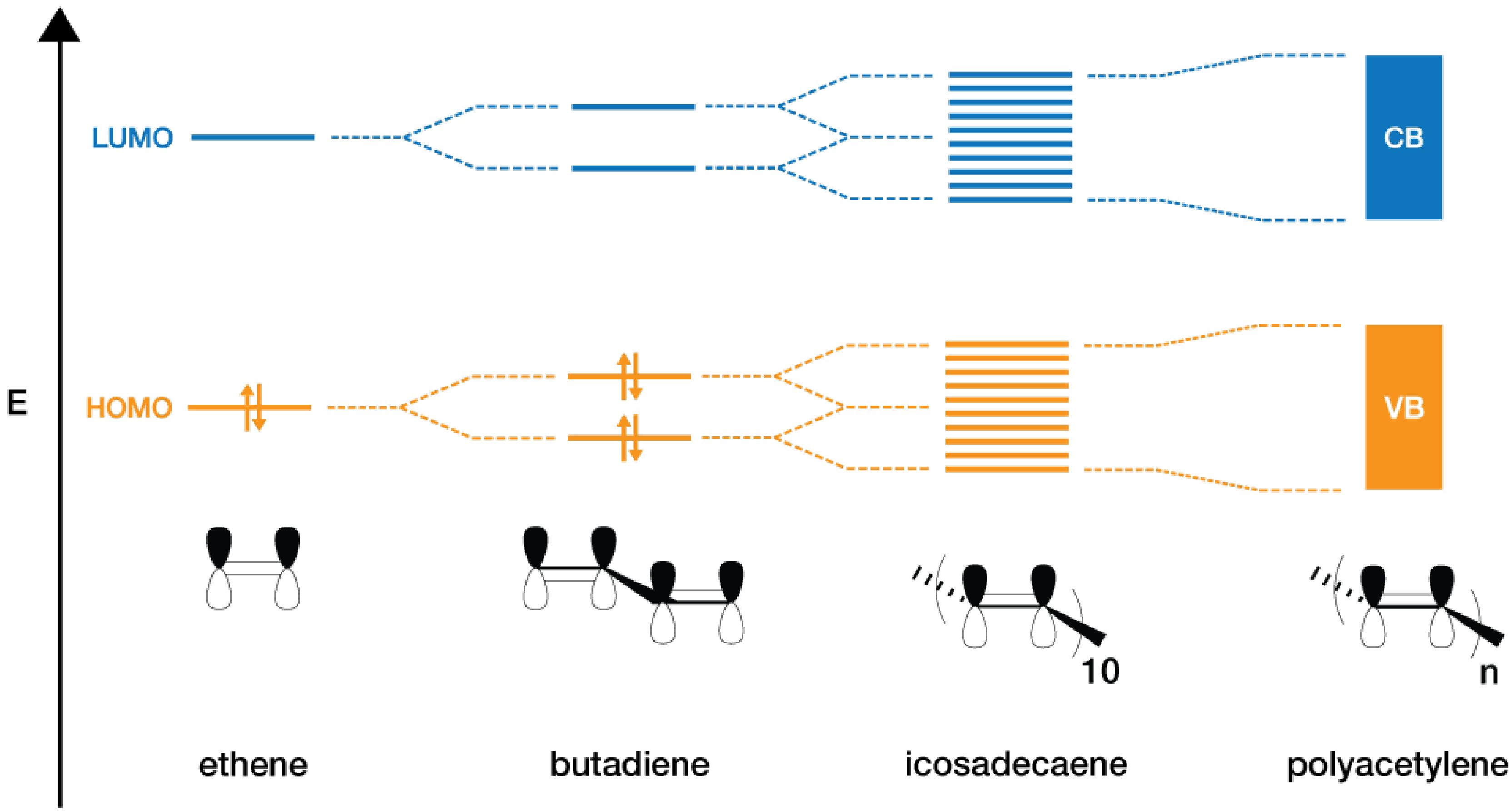
PTB1: X = H, R_1 = dodecyl, R_2 = octyloxy
PTB3: X = H, R_1 = 2-ethylhexyl, R_2 = octyl
PTB4: X = F, R_1 = octyl, R_2 = 2-ethylhexyloxy
PTB7: X = F, R_1 = 2-ethylhexyl, R_2 = 2-ethylhexyloxy
PTB9: X = H, R_1 = 2-ethylhexyl, R_2 = 2-ethylhexyloxy

Part 1: Organic Photovoltaics

Karlsruher Institut für Technologie

- Material properties
- **Inorganic vs. organic semiconductor**
- Working principle organic solar cells
- Fabrication of organic solar cells / device architecture
- Major Challenges of the technology
- Applications

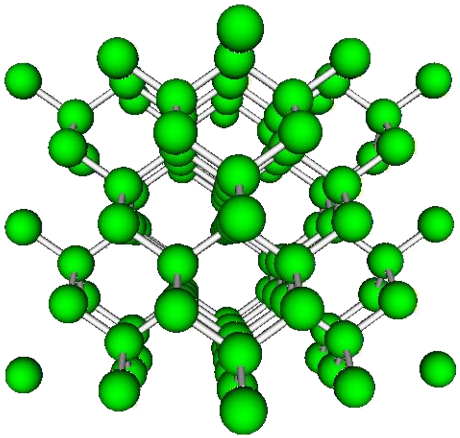
Organic Semiconductors

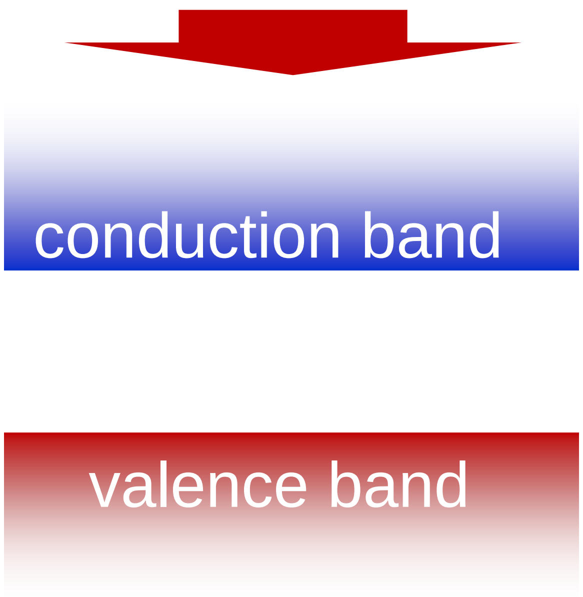


However, real bands are rare to observe because of disorder in relevant polymers.

Source: Courtesy of Thomas Kirchartz, Forschungszentrum Juelich

Inorganic vs. organic semiconductor

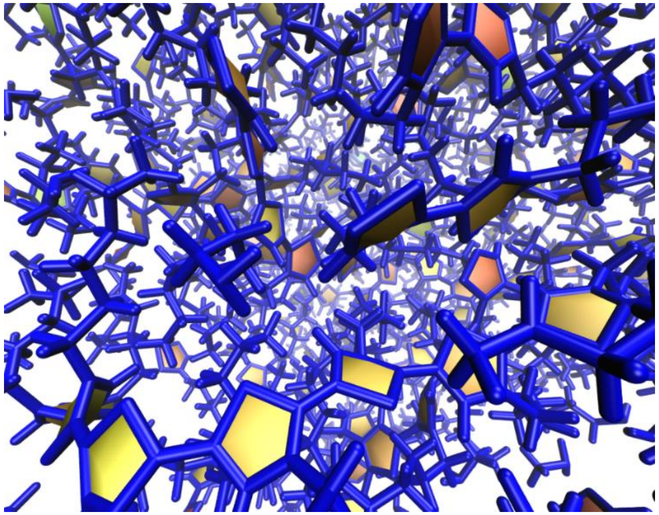




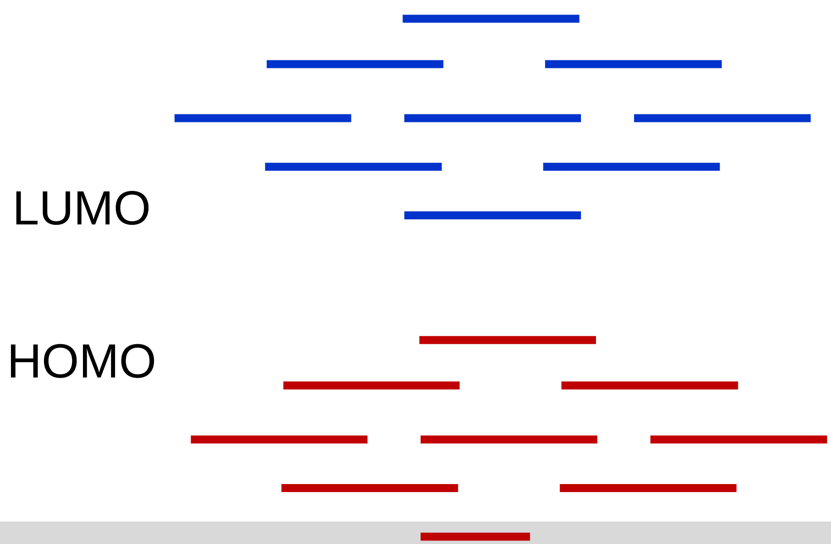
http://www.iue.tuwien.ac.at/phd/hoessinger/node26.html

inorganic

organic

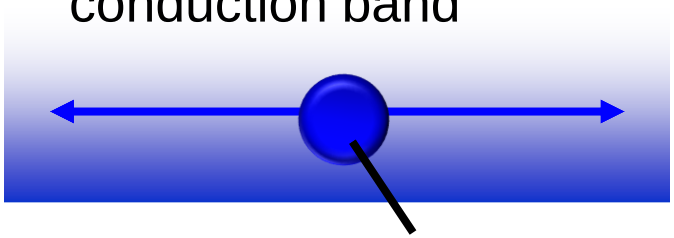


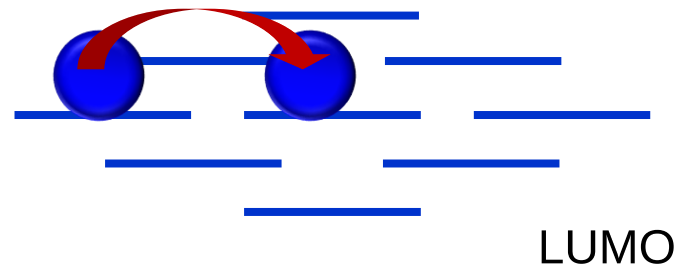
© Anne Guilbert, Imperial College London



Source: Courtesy of Thomas Kirchartz, Forschungszentrum Juelich

Transport

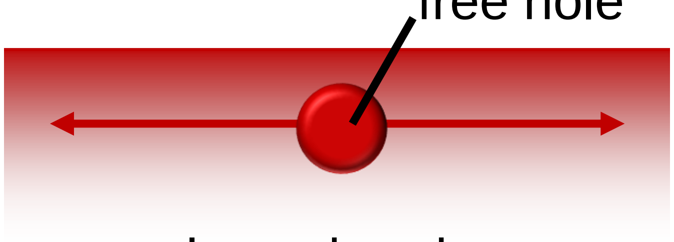


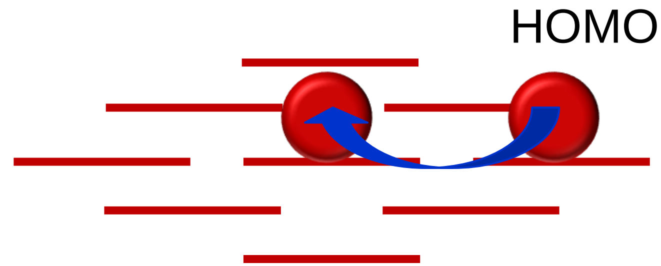


inorganic | organic

mobility:
μ = 1 to 10^4 cm^2/Vs

mobility:
$\mu \approx 10^{-4}$ cm^2/Vs



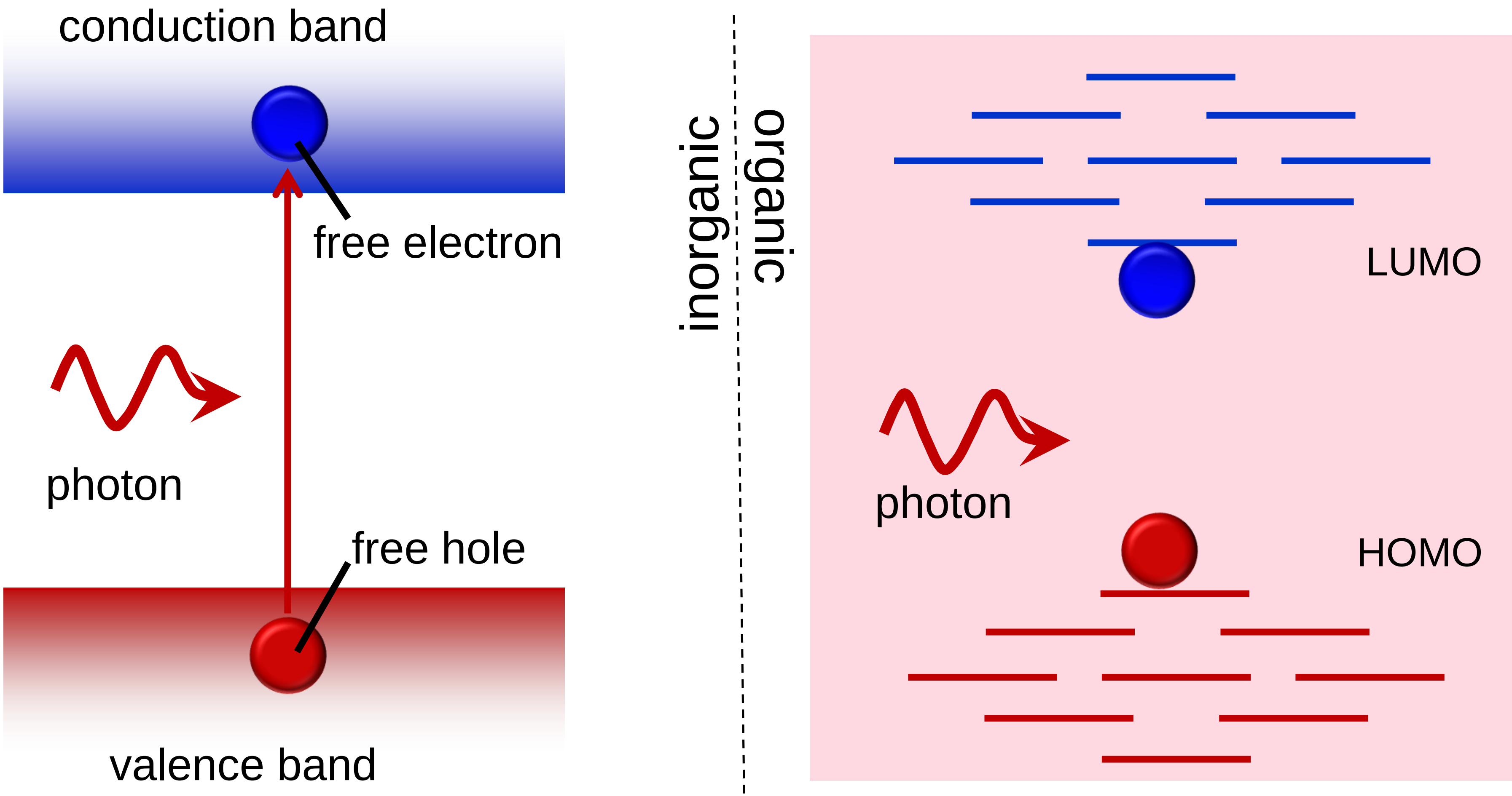


band transport

Transport via hopping

Source: Courtesy of Thomas Kirchartz, Forschungszentrum Juelich

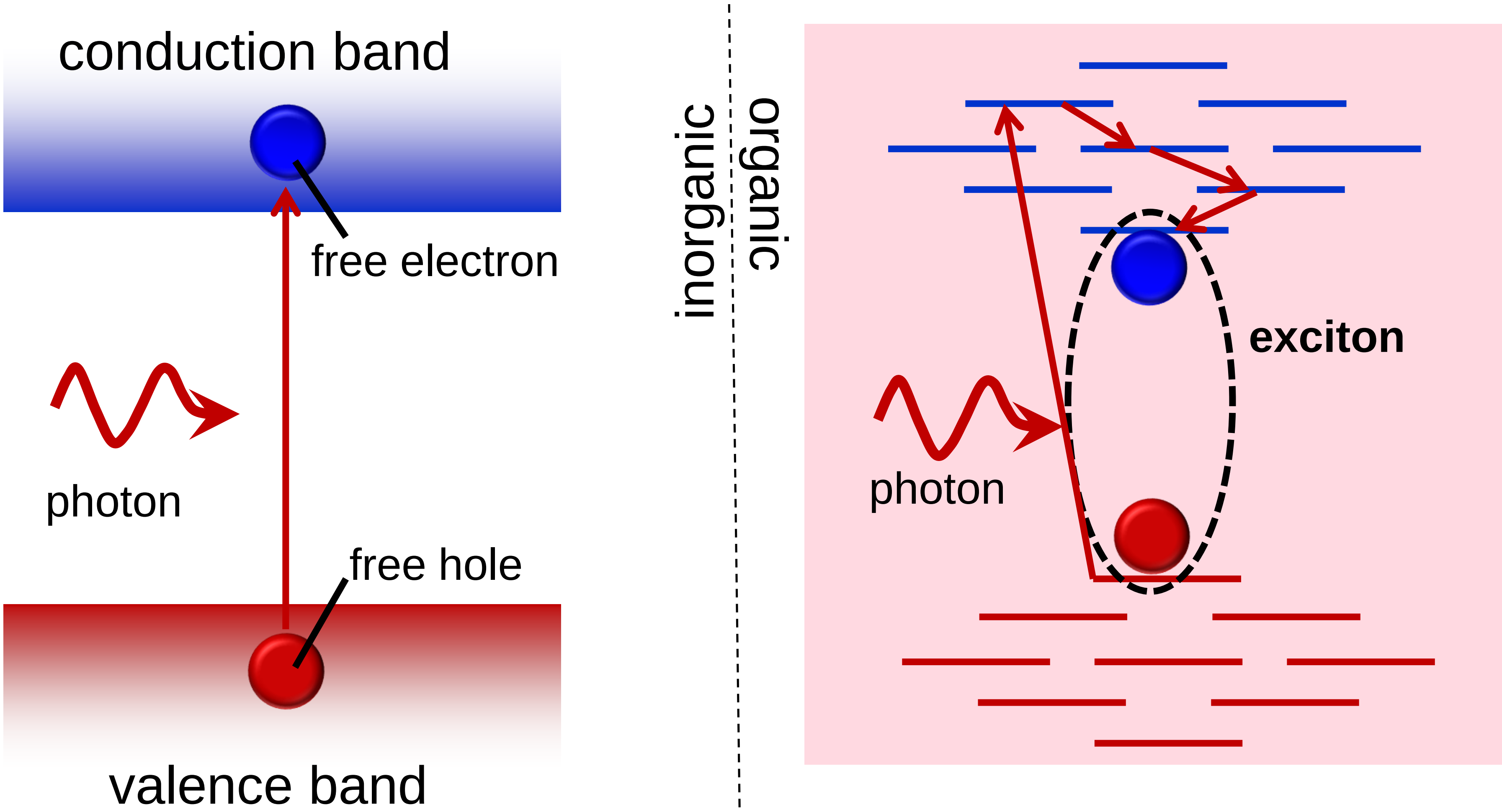
Photoexcitation / Absorption



dielectric constant $\varepsilon_r > 10$

Source: Courtesy of Thomas Kirchartz, Forschungszentrum Juelich

Photoexcitation / Absorption



dielectric constant $\varepsilon_r > 10$

Source: Courtesy of Thomas Kirchartz, Forschungszentrum Juelich

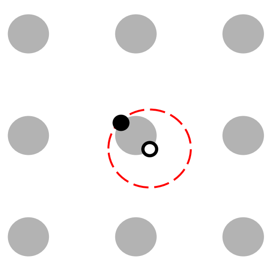
Photoexcitation / Absorption

conduction band

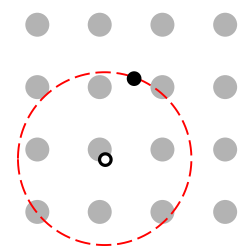
Types of excitons

- Absorption results in exciton creation
  - Bound electron-hole pair
  - Chargeless quasiparticle
  - Obeys boson statistics
  - Exciton radius depends sensitively on dielectric environment → screening

Frenkel exciton



Wannier-Mott exciton



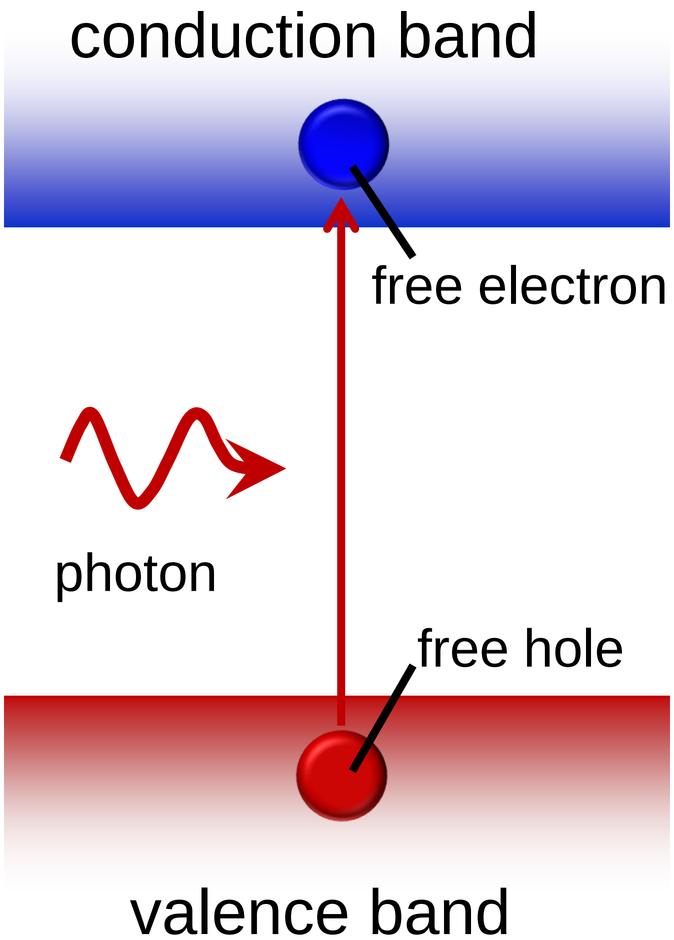
binding energy ~ 10 meV

Radius ~ 100 Å

Highly delocalized

Source: Courtesy of Thomas Kirchartz, Forschungszentrum Juelich

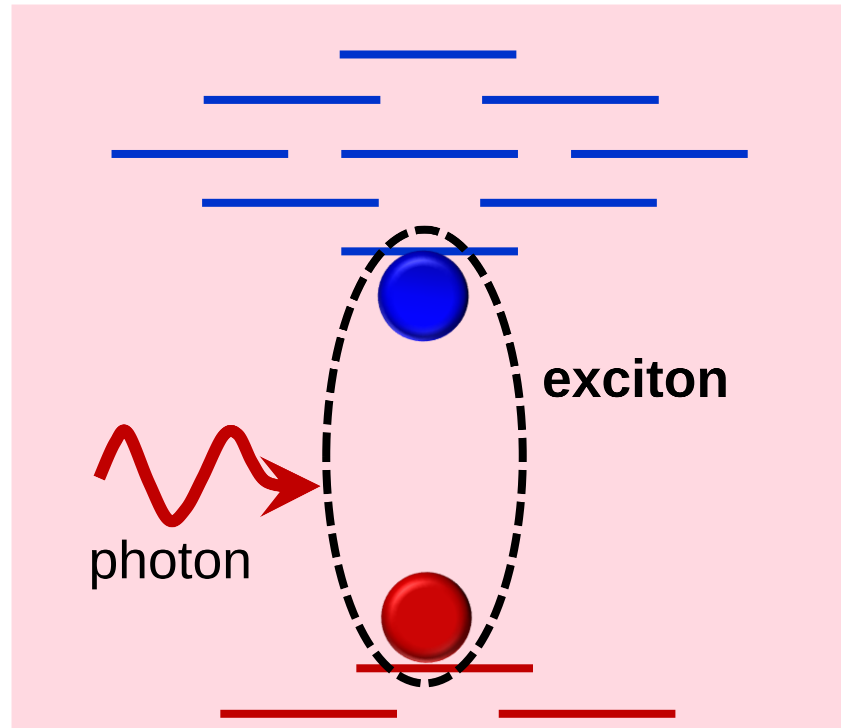
Photoexcitation / Absorption



dielectric constant $\varepsilon_r > 10$

inorganic

organic

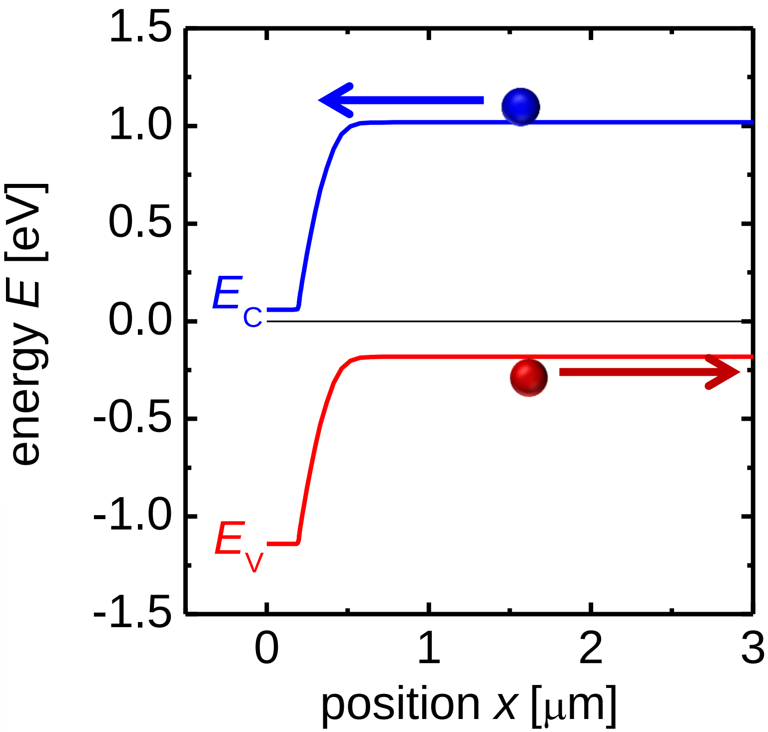


Coulomb binding of exciton:

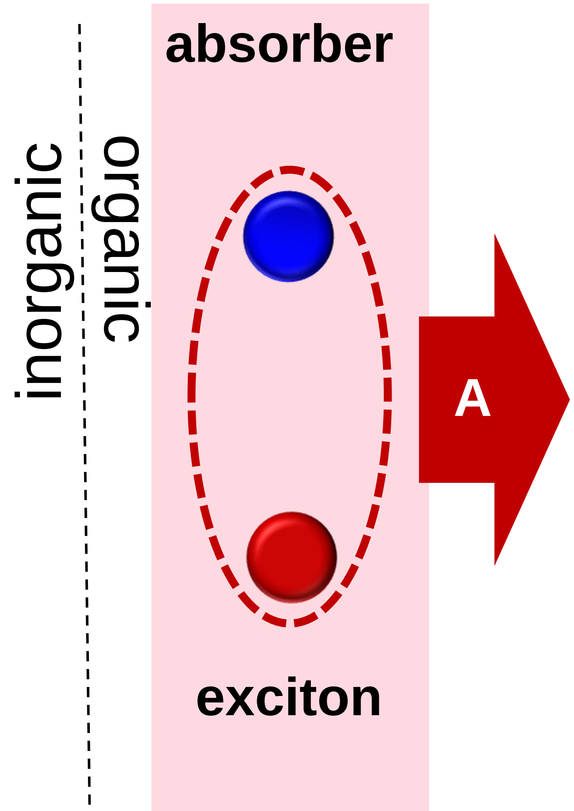
- dielectric constant $\varepsilon_r \approx 3 – 4$
- binding energy ~ 0.5 – 2 eV
- Radius ~ 5 Å, single molecule

Source: Courtesy of Thomas Kirchartz, Forschungszentrum Juelich

Charge separation



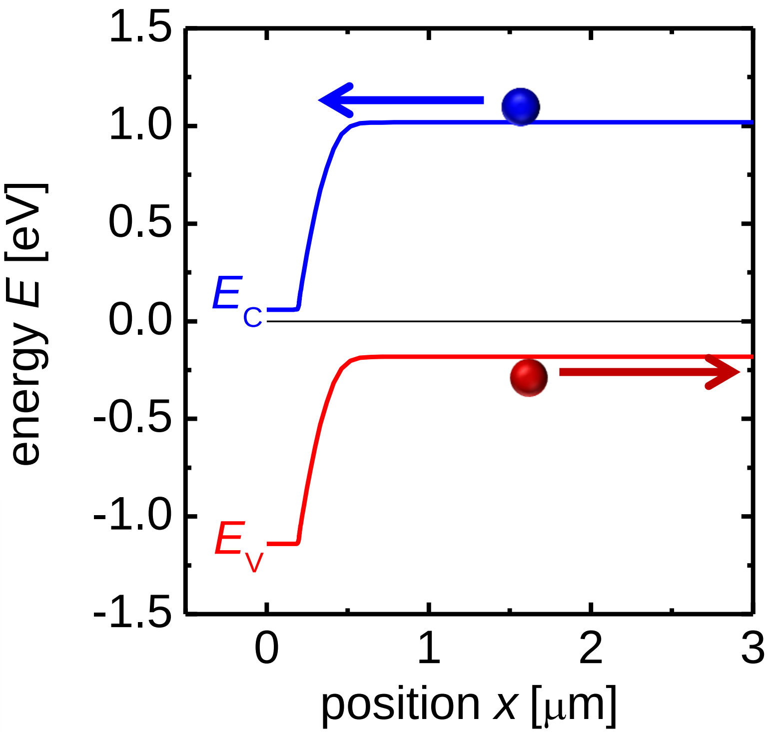
e.g. using a pn-junction



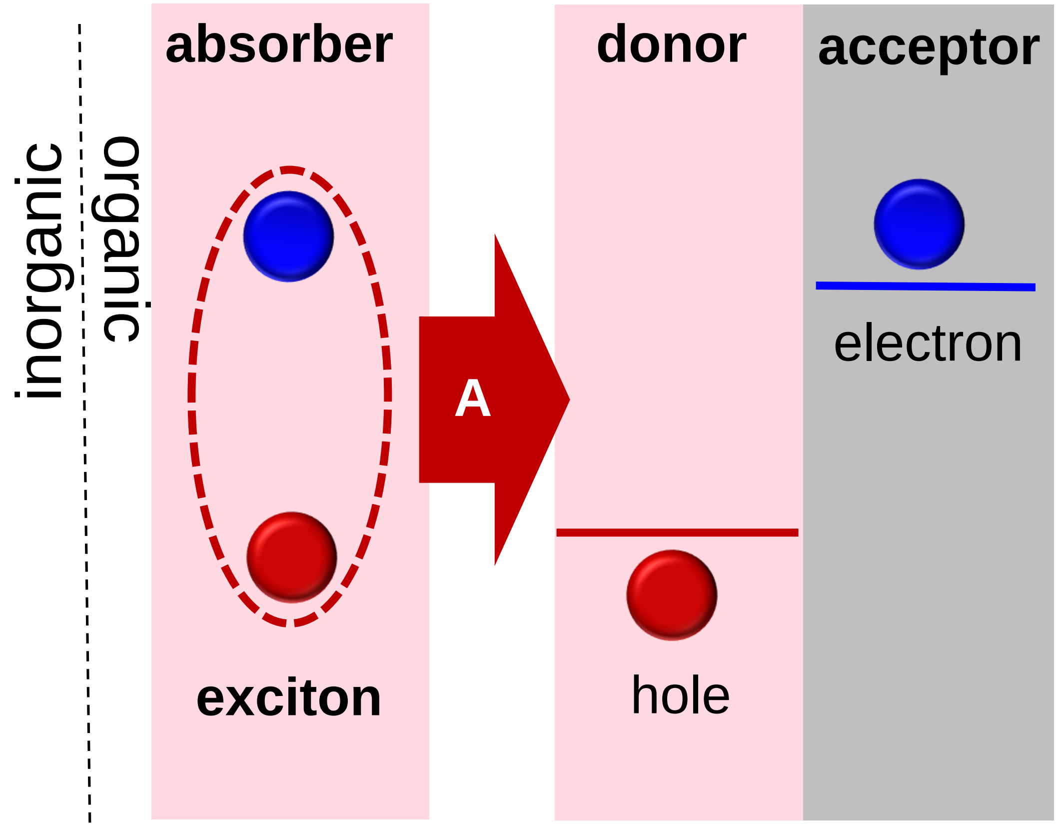
Exciton is localized to molecule
→ low diff. length ~ 10nm
→ dissociation interface needed

Source: Courtesy of Thomas Kirchartz, Forschungszentrum Juelich

Charge separation



e.g. using a pn-junction



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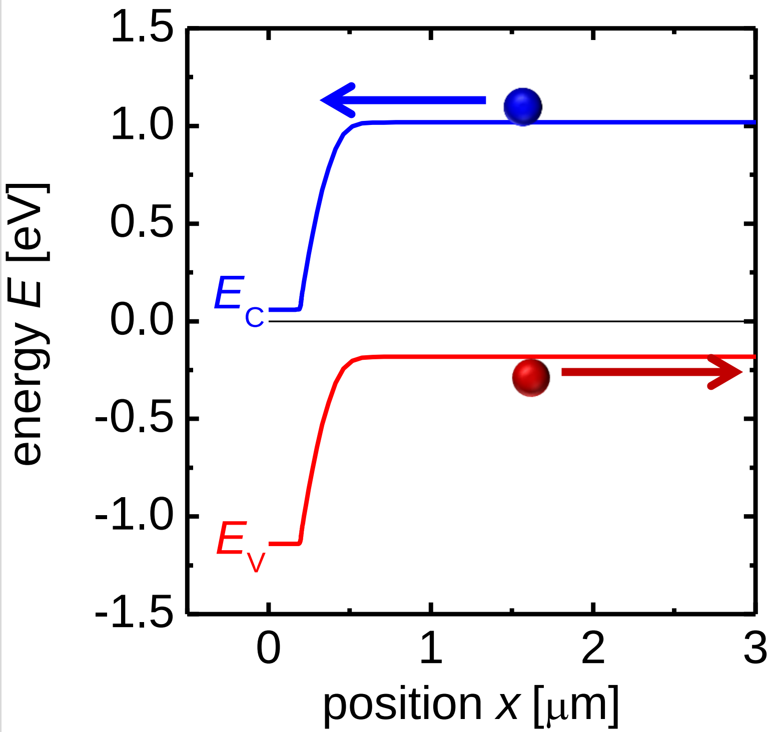
Charge separation



e.g. using a pn-junction

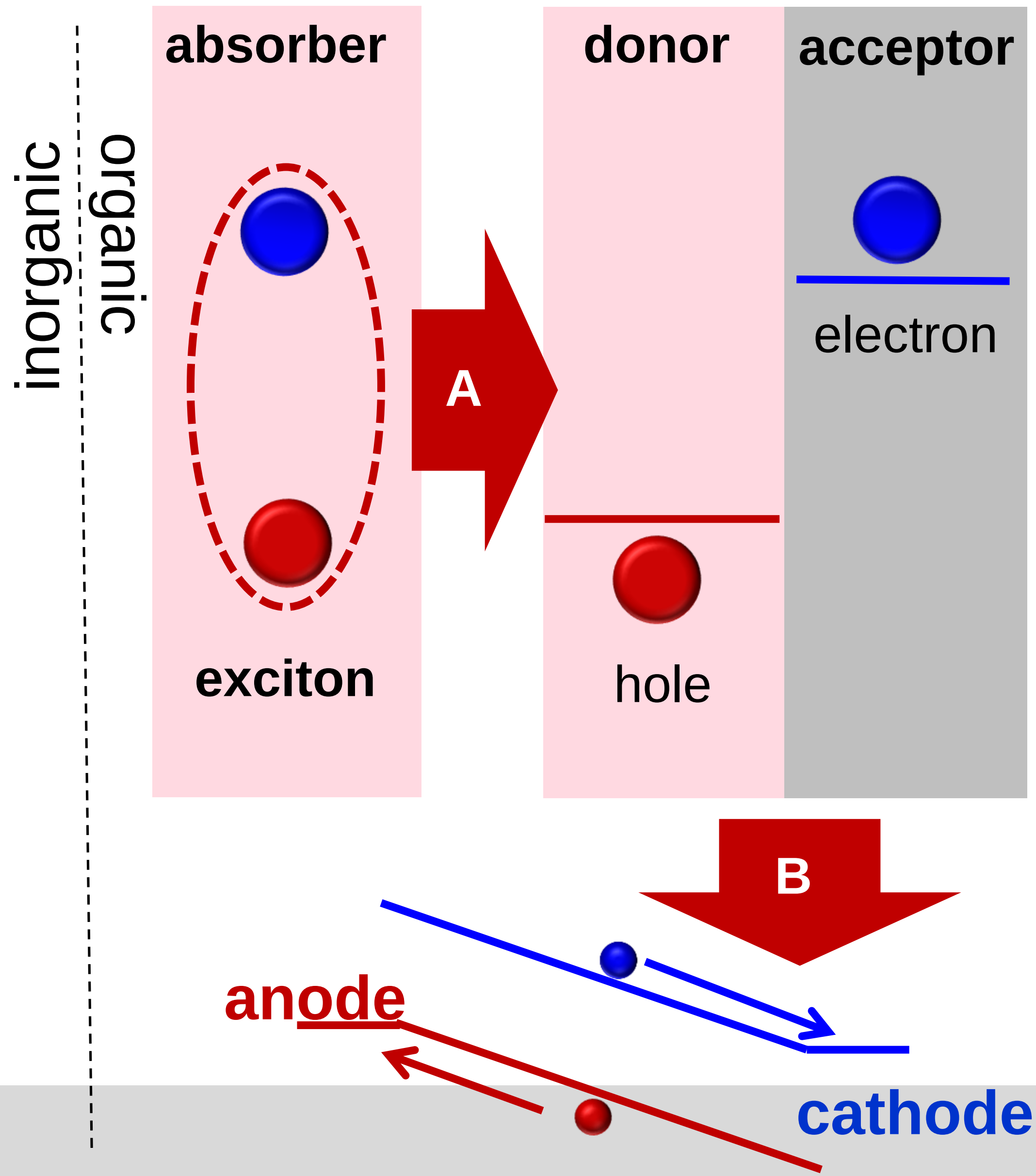


Illustration of energy levels

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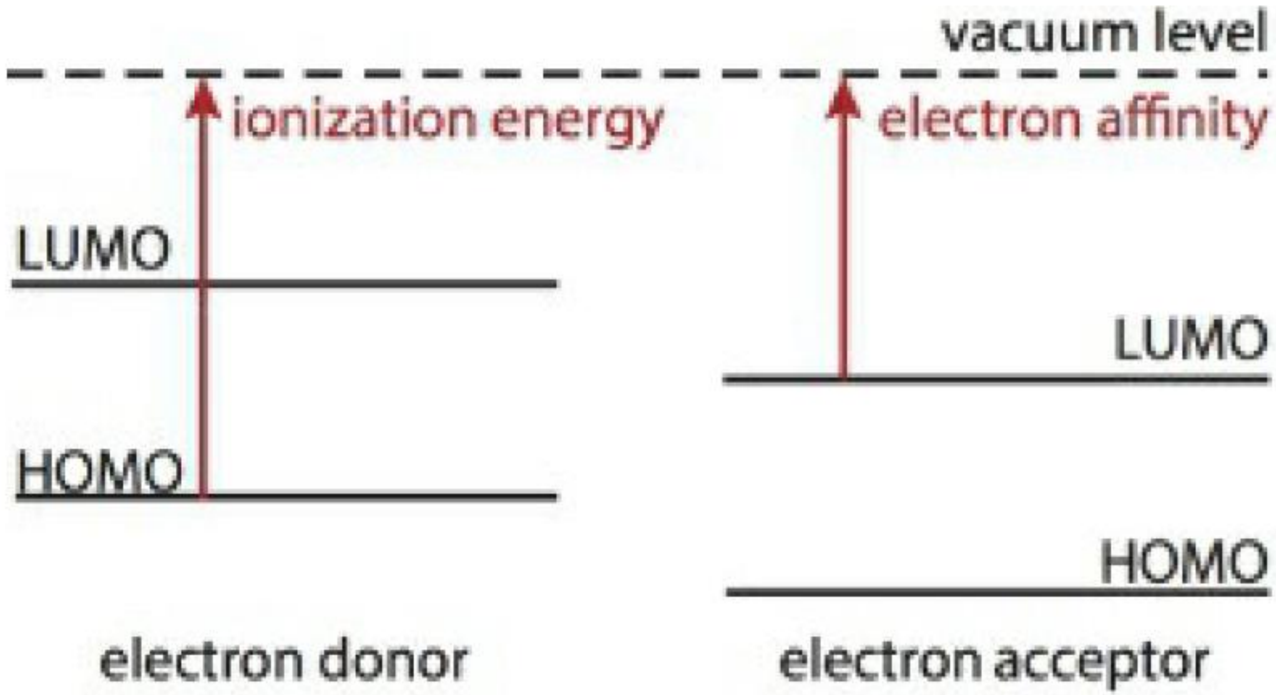
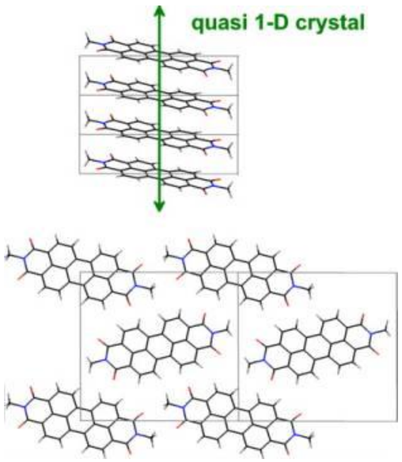


Source: textbook

Organic vs. inorganic semiconductors

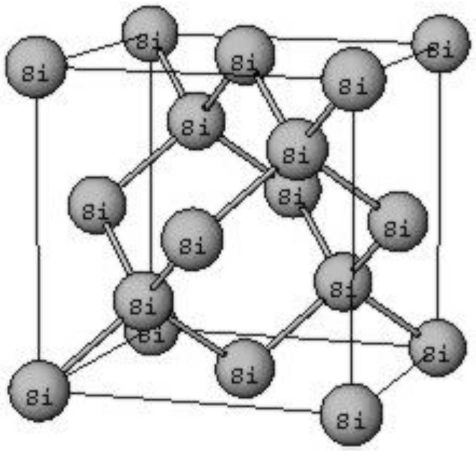
Organic

- Van der Waals interactions between polymers (E_{VdW} = 10^{-3} – 10^{-2} eV)
- Charge carrier and exciton localization
- High Eg → low mobility μ ≈ 1 cm^2/V s and mean free path *l* ≈ a_0 at room T
- Dissociation interface needed for solar cell devices (donor/acceptor blend)
- Soft, flexible



Inorganic

- Covalent-type interactions (E_{cov} = 2 – 4 eV)
- Charge carrier delocalization
- Higher μ and *l* ≈ 100 – 1000 a_0
- Hard, brittle



Part 1: Organic Photovoltaics

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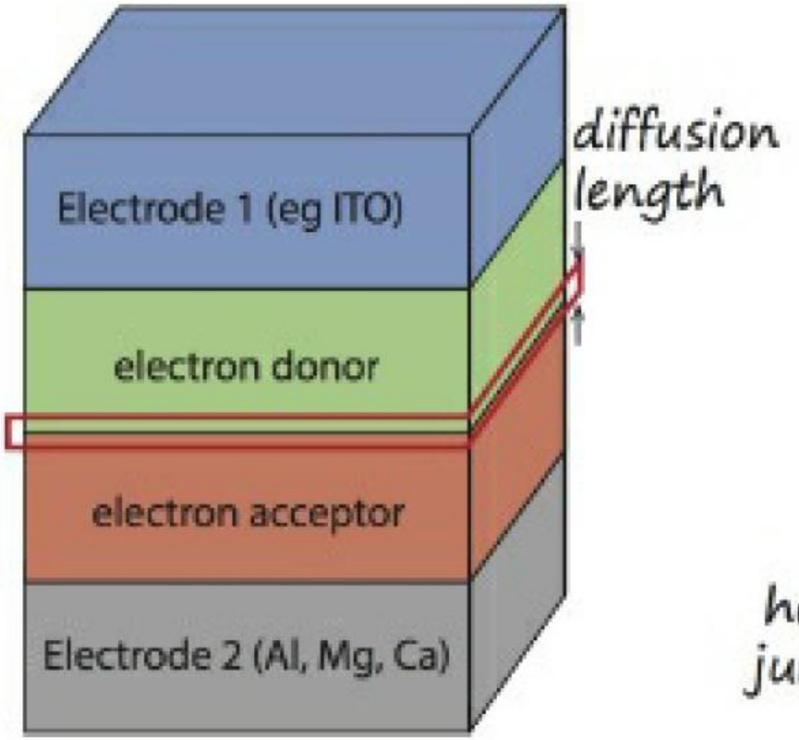
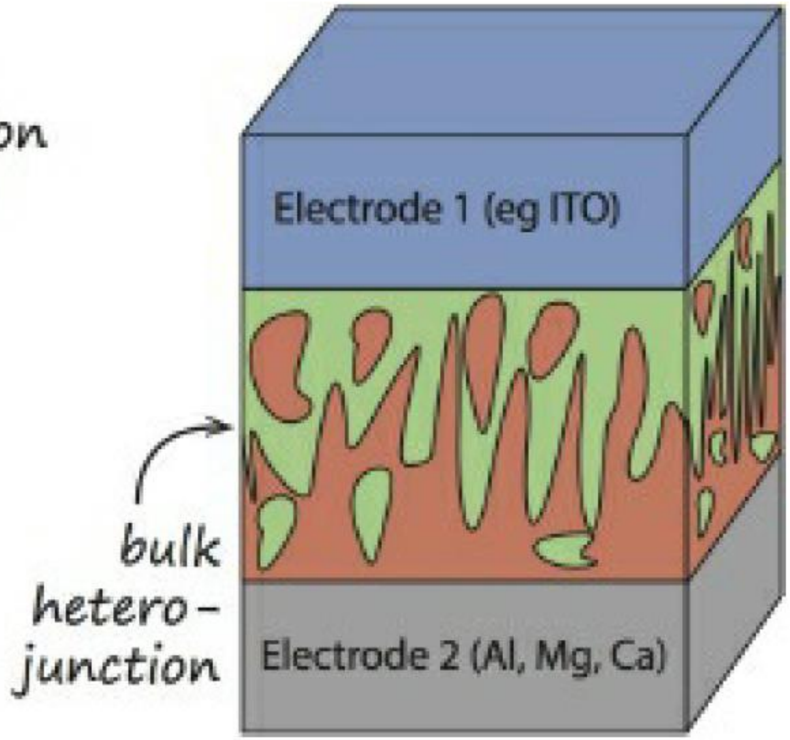
- Material properties
- Inorganic vs. organic semiconductor
- **Working principle organic solar cells**
- Fabrication of organic solar cells / device architecture
- Applications

How do organic solar cells work?

(a) planar heterojunction

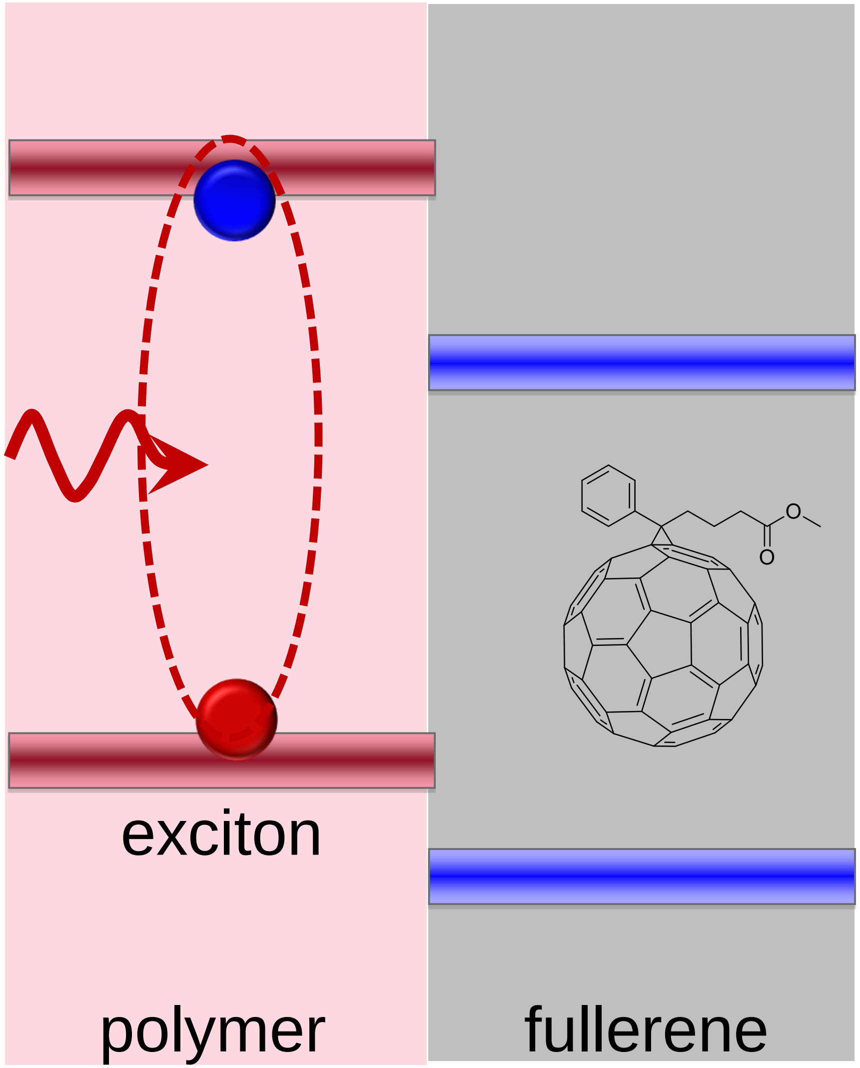
(b) bulk heterojunction



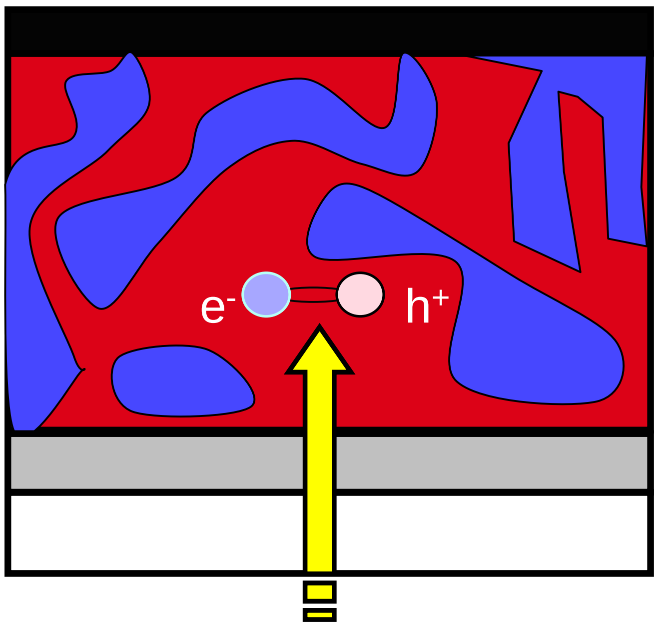


Source: textbook

Charge Separation

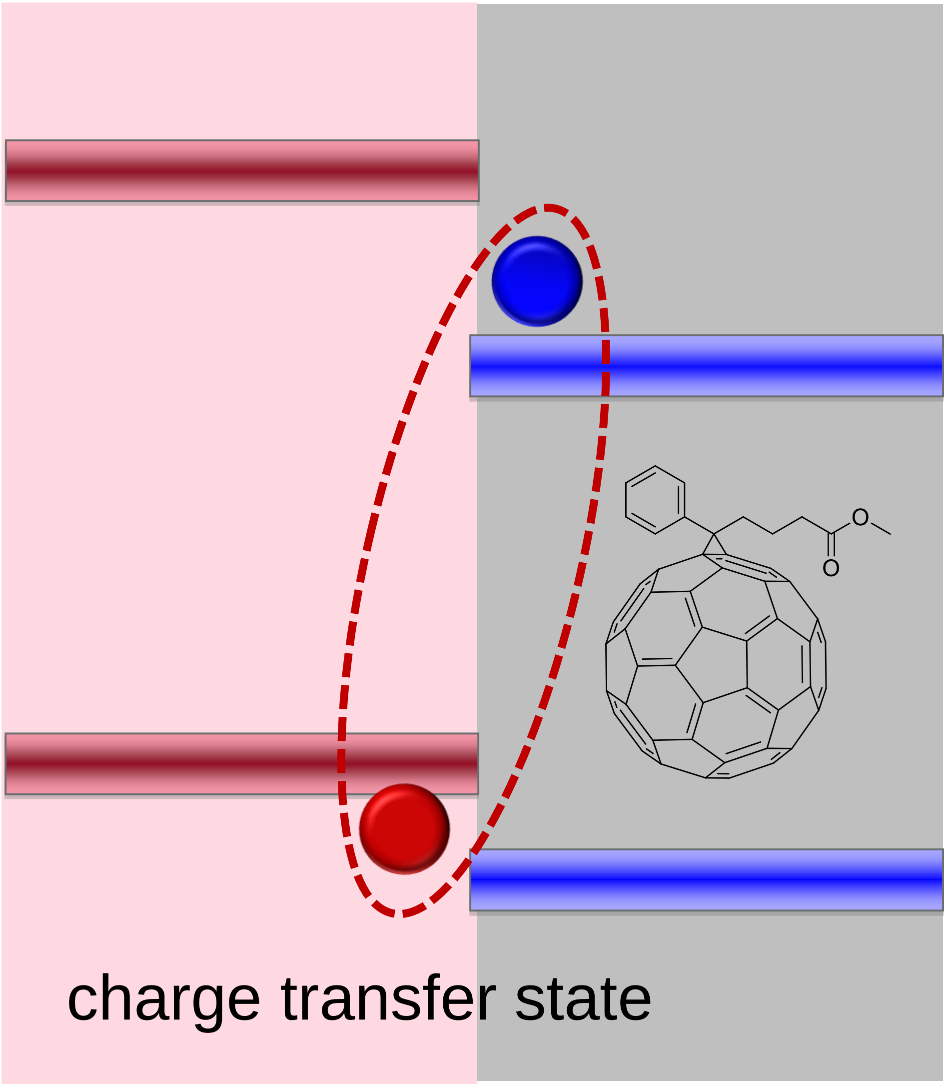


- Photon absorption
- Exciton generation
- Exciton diffusion

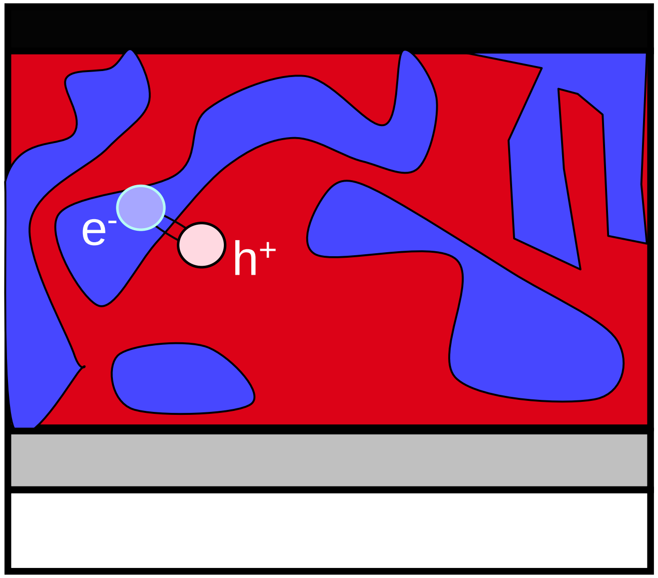


Source: Courtesy of Thomas Kirchartz, Forschungszentrum Juelich

Charge Separation

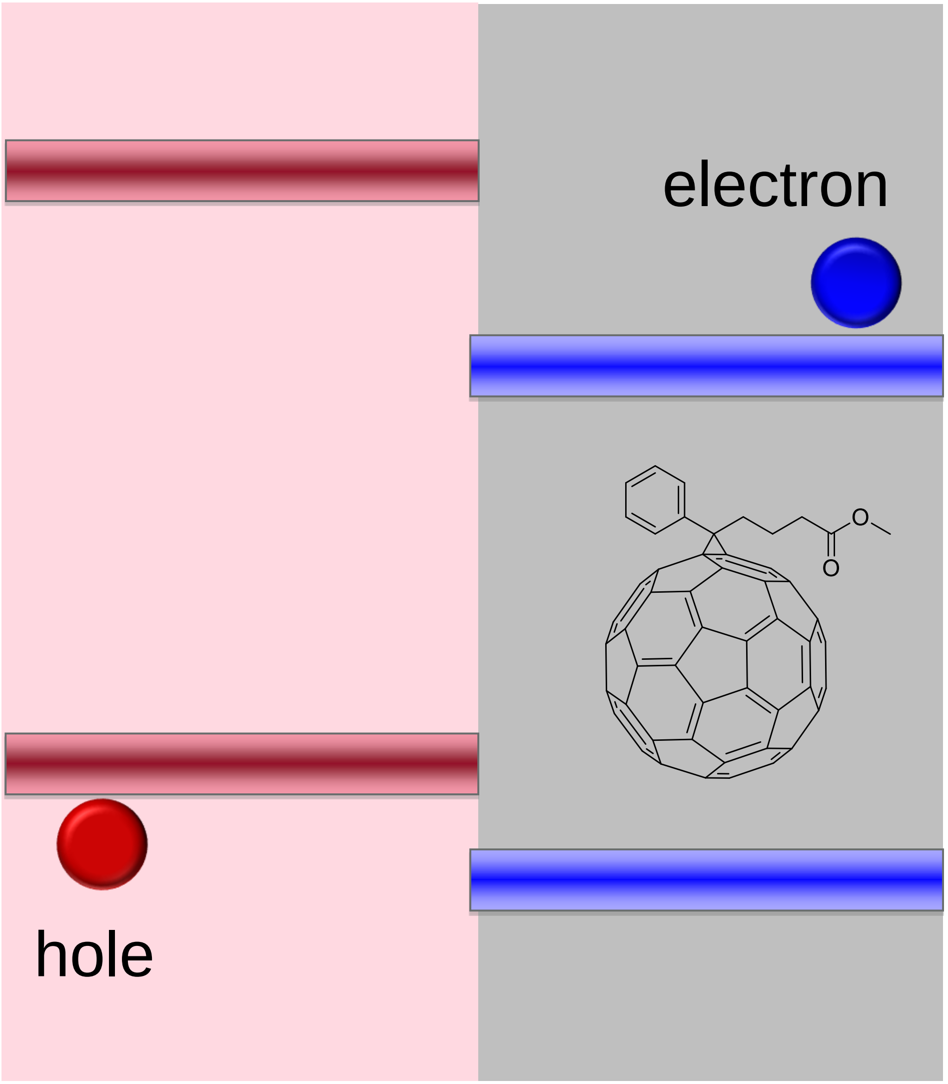


- Charge transfer

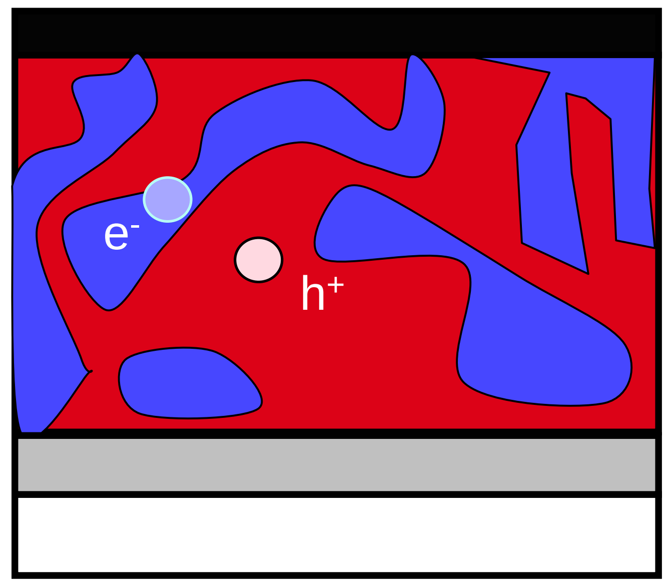


Source: Courtesy of Thomas Kirchartz, Forschungszentrum Juelich

Charge Separation

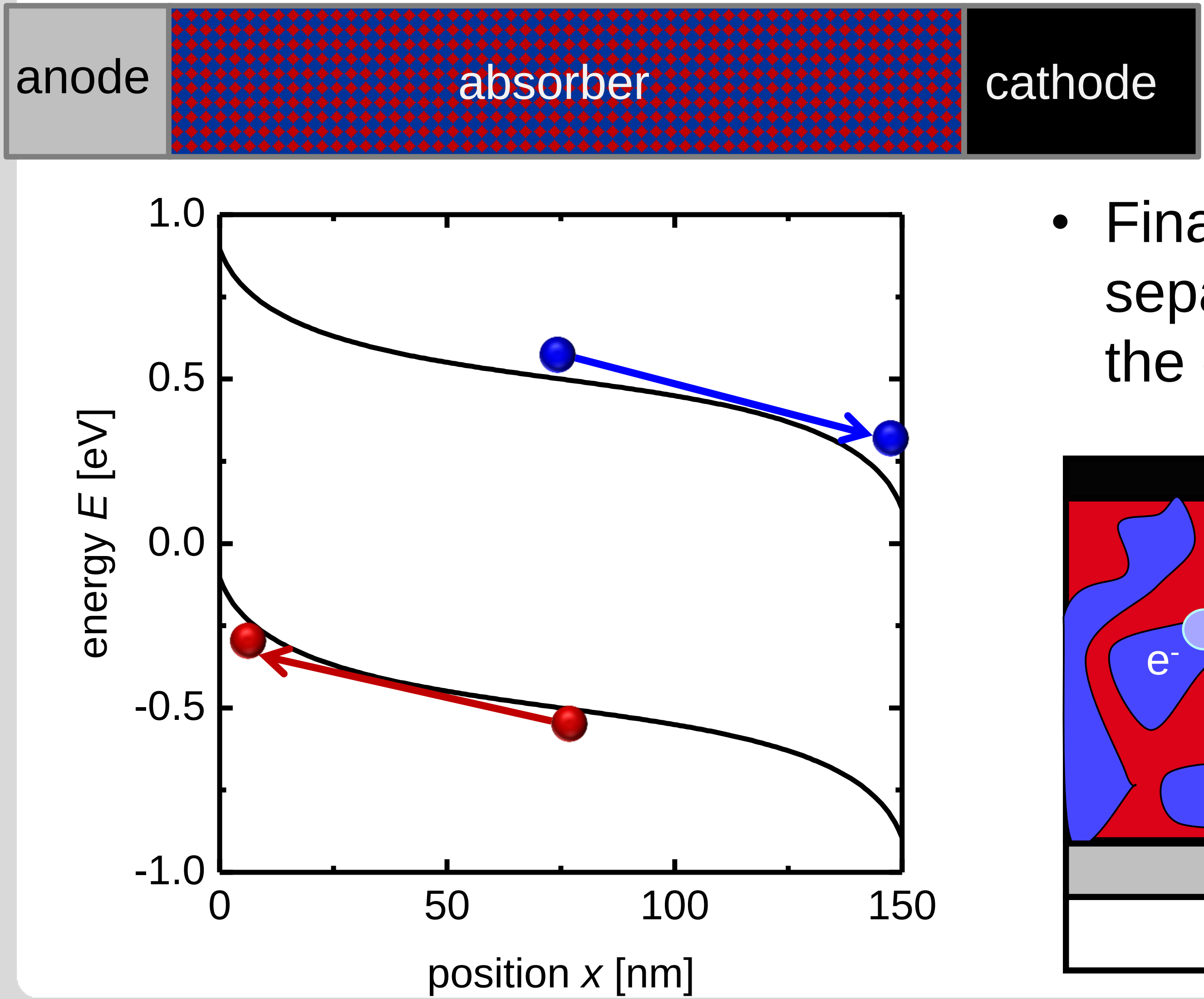


- Initial charge separation

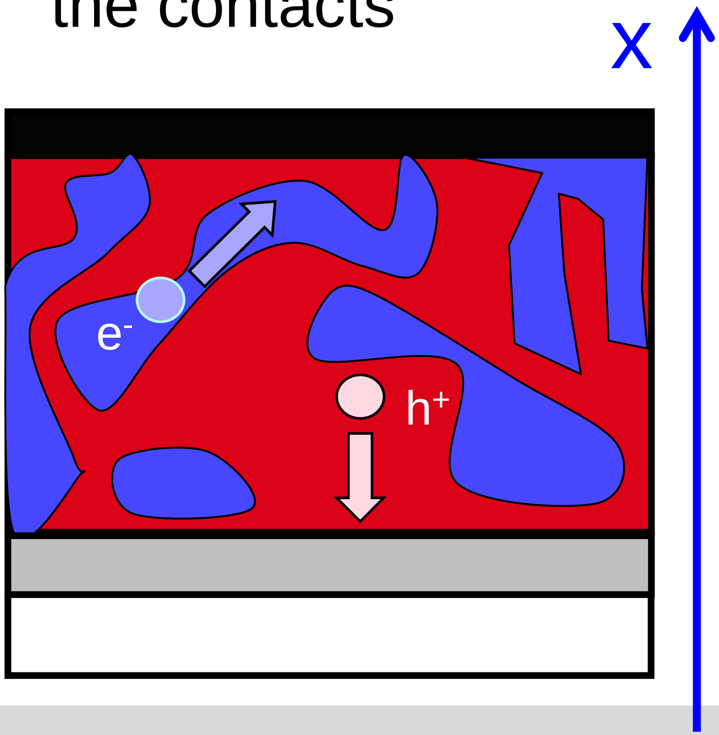


Source: Courtesy of Thomas Kirchartz, Forschungszentrum Juelich

Charge Separation



- Final charge separation towards the contacts

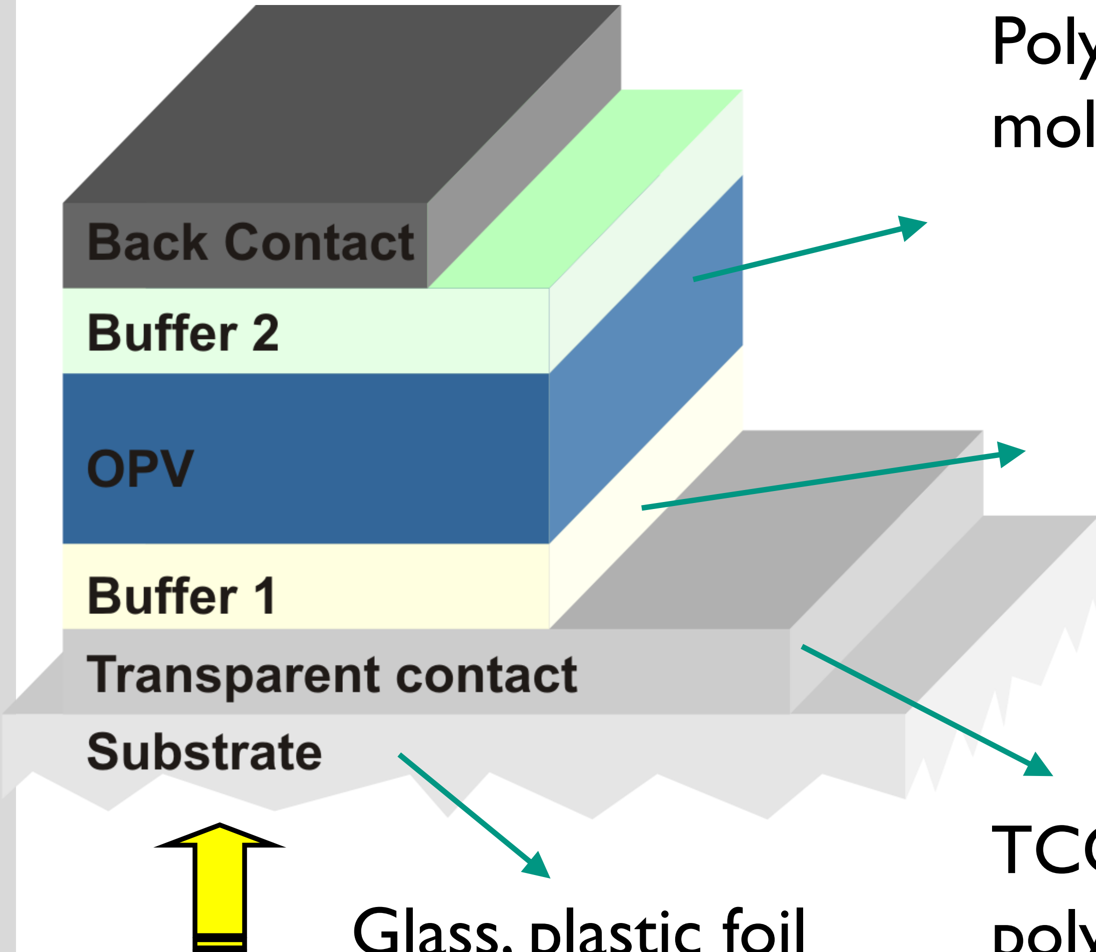


Source: Courtesy of Thomas Kirchartz, Forschungszentrum Juelich

Part 1: Organic Photovoltaics

- Material properties
- Inorganic vs. organic semiconductor
- Working principle organic solar cells
- **Fabrication of organic solar cells**
- Applications

Anatomy of a typical OPV cell



Polymer-based or small molecule-based

Doped organic films (PEDOT:PSS), metal oxides (TiO_x, ZnO, MoO_x, etc.)

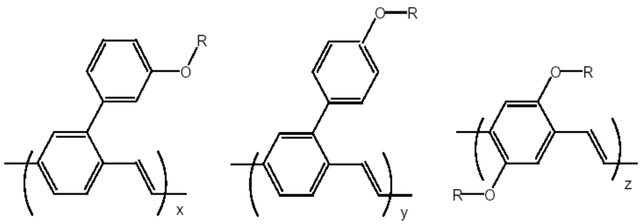
TCOs, thin metals, carbon, polymers, Ag nanowires

Glass, plastic foil

Materials for Organic Electronics

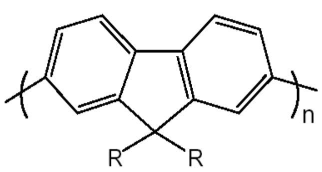
Two approaches lead to similar electronic properties

Conjugated polymers



R = $(CH_2)_3CH(Me)(CH_2)_2CHMe_2$

PPV co-polymers

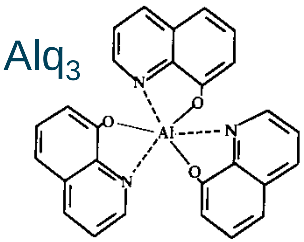


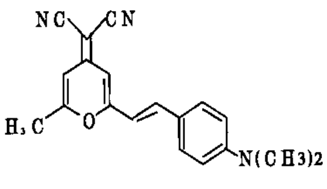
Polyfluorene

Cannot be evaporated

Small evaporated molecules

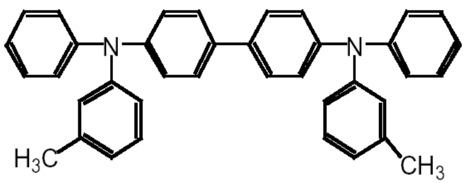
Alq_3



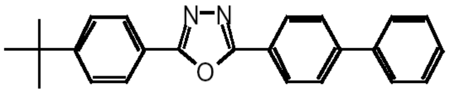


(DCM)

TPD



PBD



Can be evaporated

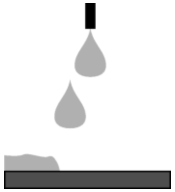
Organic Semiconductor Deposition

Solution processing/Coating/Printing

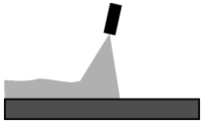
Spin coating
(not scalable)

Screen printing

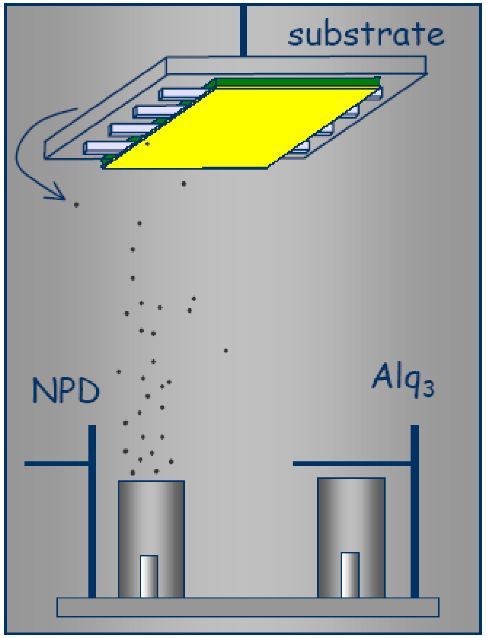
Inkjet printing



Spray-coating



Evaporation of small molecules



Vacuum Thermal Evaporation

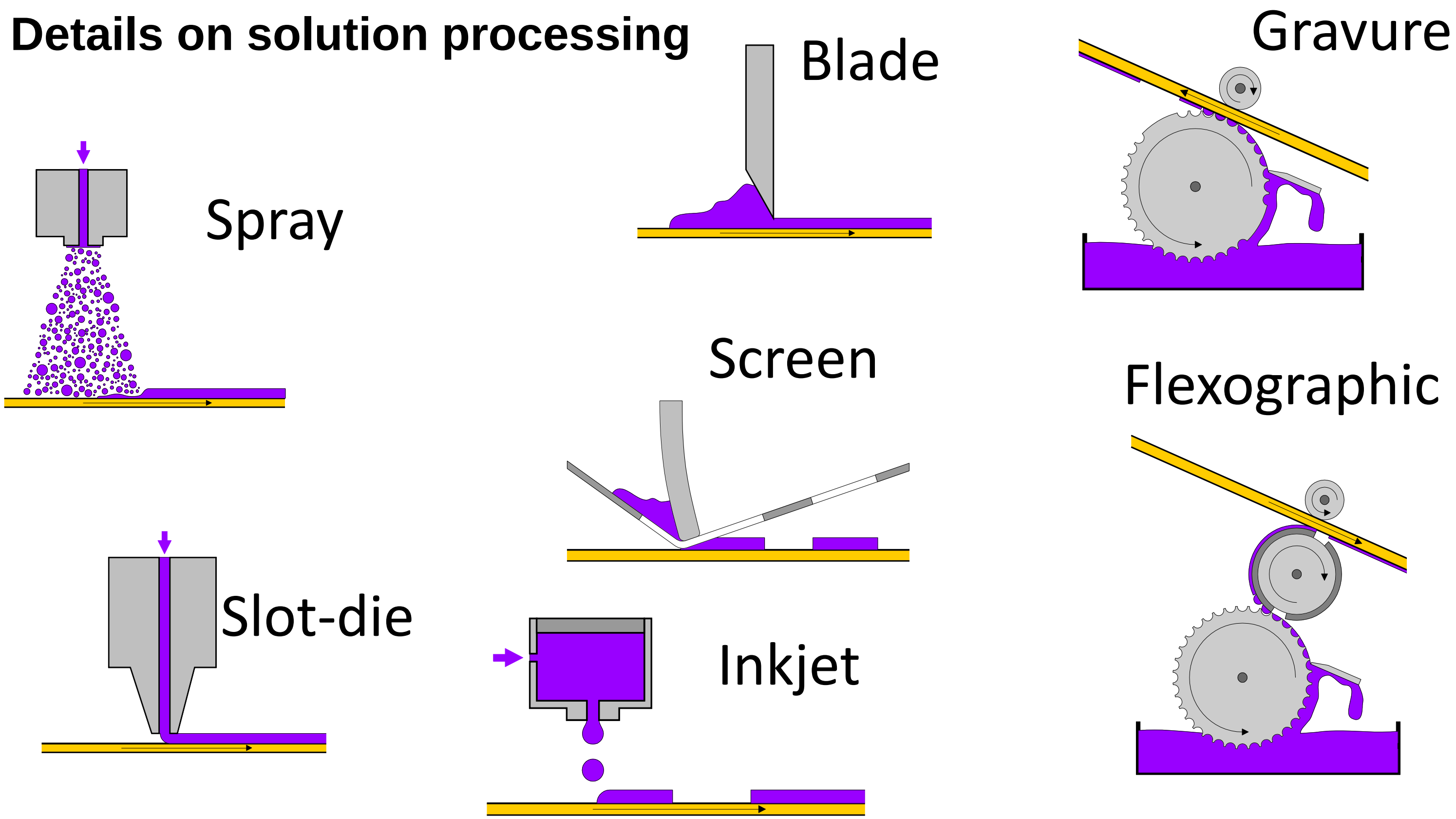
Organic Vapor Phase Deposition

Organic Semiconductor Deposition

Solution processing/Coating/Printing

Evaporation of small molecules

Details on solution processing



Organic Semiconductor Deposition

Karlsruher Institut für Technologie

Solution processing/Coating/Printing

Evaporation of small molecules

Competence Center Printing & Device Physics @ InnovationLab in Heidelberg

Mission
Lab-to-Fab

Partners BASF SE, Merck KGaA, KIT, TU Darmstadt

1 - Proof of concept

2 - Prototype

3 - Scale Up

Proof of concept

- Fluid < 10 ml
- Low material usage
- Direct feedback for material design and formulation development

Large-Area-Prototyping

- Fluid < 100 ml
- Lab-scale
- Up to letter-size substrates
- Targeted lateral resolution: < 10 µm

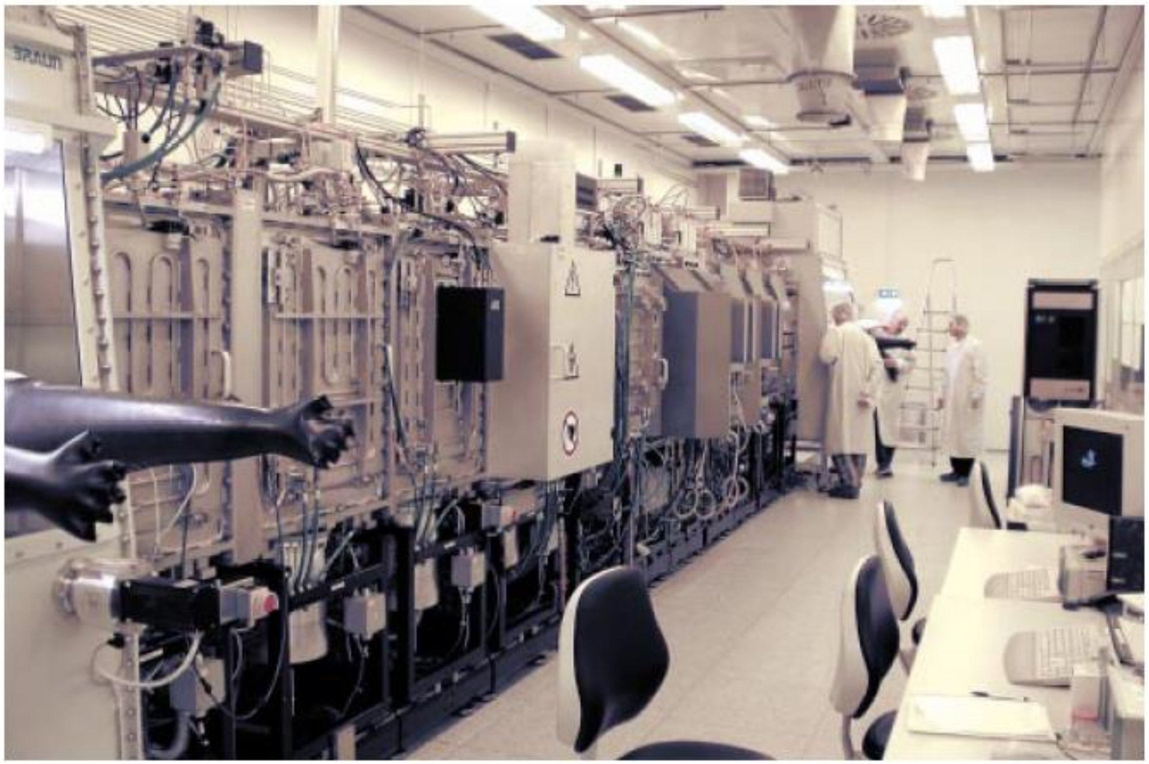
R2R R&D platform

- Fluid < 1 l
- R&D pilot line for production research
- Web width: 330 mm
- Web speed: up to 100 m/min

Organic Semiconductor Deposition

Solution processing/Coating/Printing

Evaporation of small molecules



11m long in-line evaporation equipment at Fraunhofer IPMS Dresden

Organic Photovoltaics

- Material properties
- Inorganic vs. organic semiconductor
- Working principle organic solar cells
- Fabrication of organic solar cells
- **Applications**

OPV in everyday applications

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Efficient operation at low light intensity

OPV in everyday applications

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Flexibility, aesthetic, light-weight and free-from

Source: Belectric

Semitransparent solar cells

e.g. for Building Integrated PV

Source: Heliatek

Organic Photovoltaics
from a product perspective

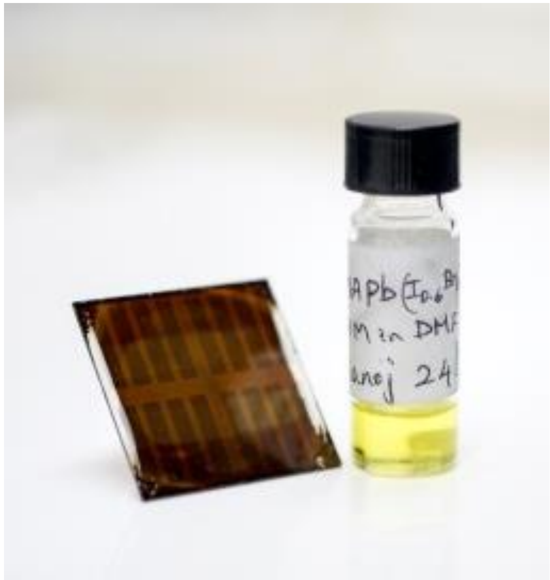
Pro	Con
Light-weight	Rather low efficiency (< 18%), especially too low for multijunction solar cells
Flexible and free-form	Long-term stability ?
Semitransparent	Material costs ?
Solution processable	However, best efficiency is reached with evaporation, which is more costly
Can be non-toxic	

→ At the current stage OPV is not competitive on the large volume for the standard solar modules PV market for residential rooftops and solar plants. However, special applications where flexible and semitransparent solar cells are needed could be a niche for OPV (e.g. indoor (low-light) or Building Integrated PV). Nowadays, Organic Electronics is more suitable for OLEDs and cheap sensors!

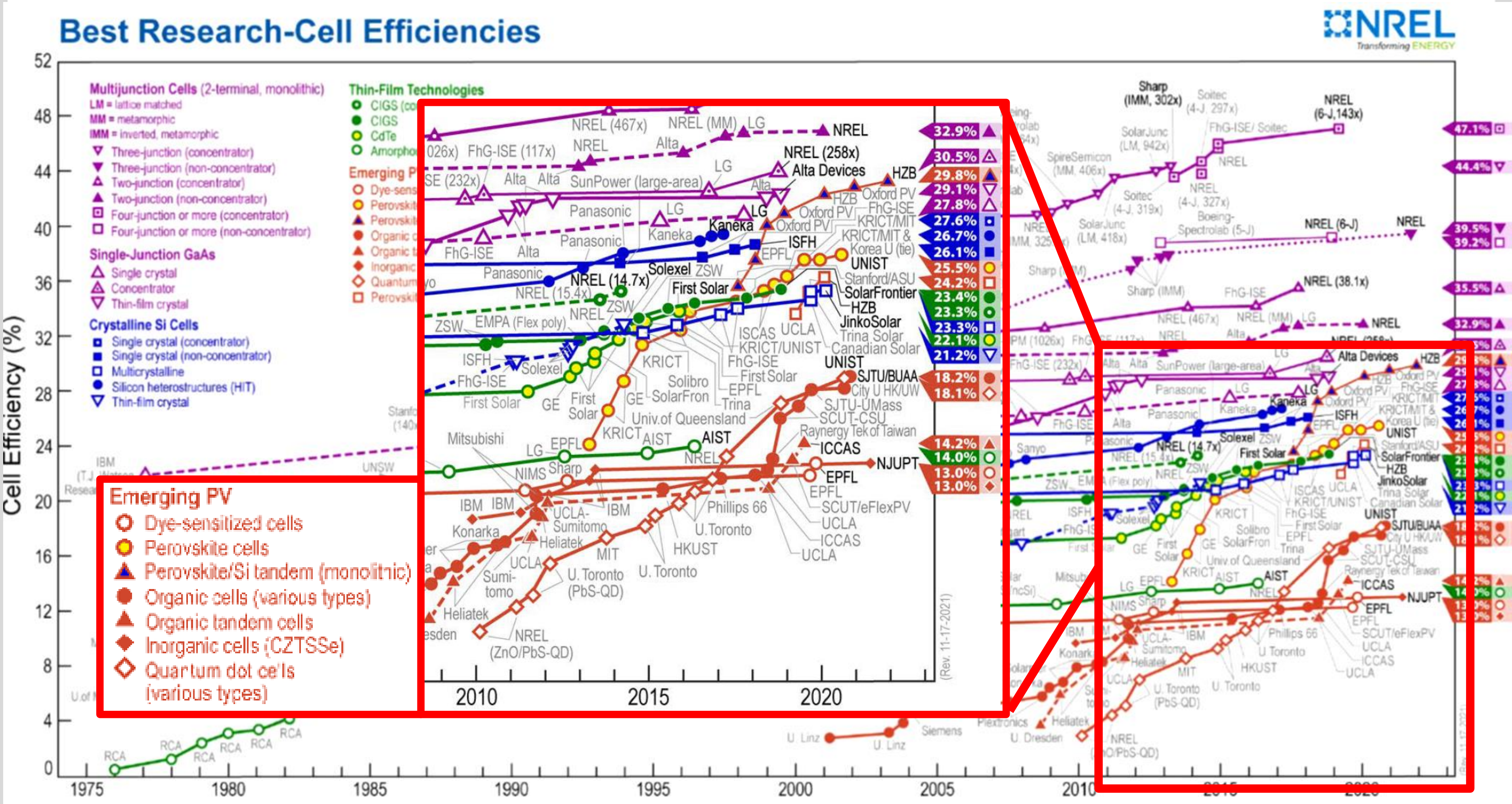
PART 1 - PEROVSKITE PHOTOVOLTAICS

Perovskite Photovoltaics

- **Why perovskite materials?**
- Fabrication of perovskite solar cells
- Challenges of perovskite PV
- Perovskite PV Research at KIT

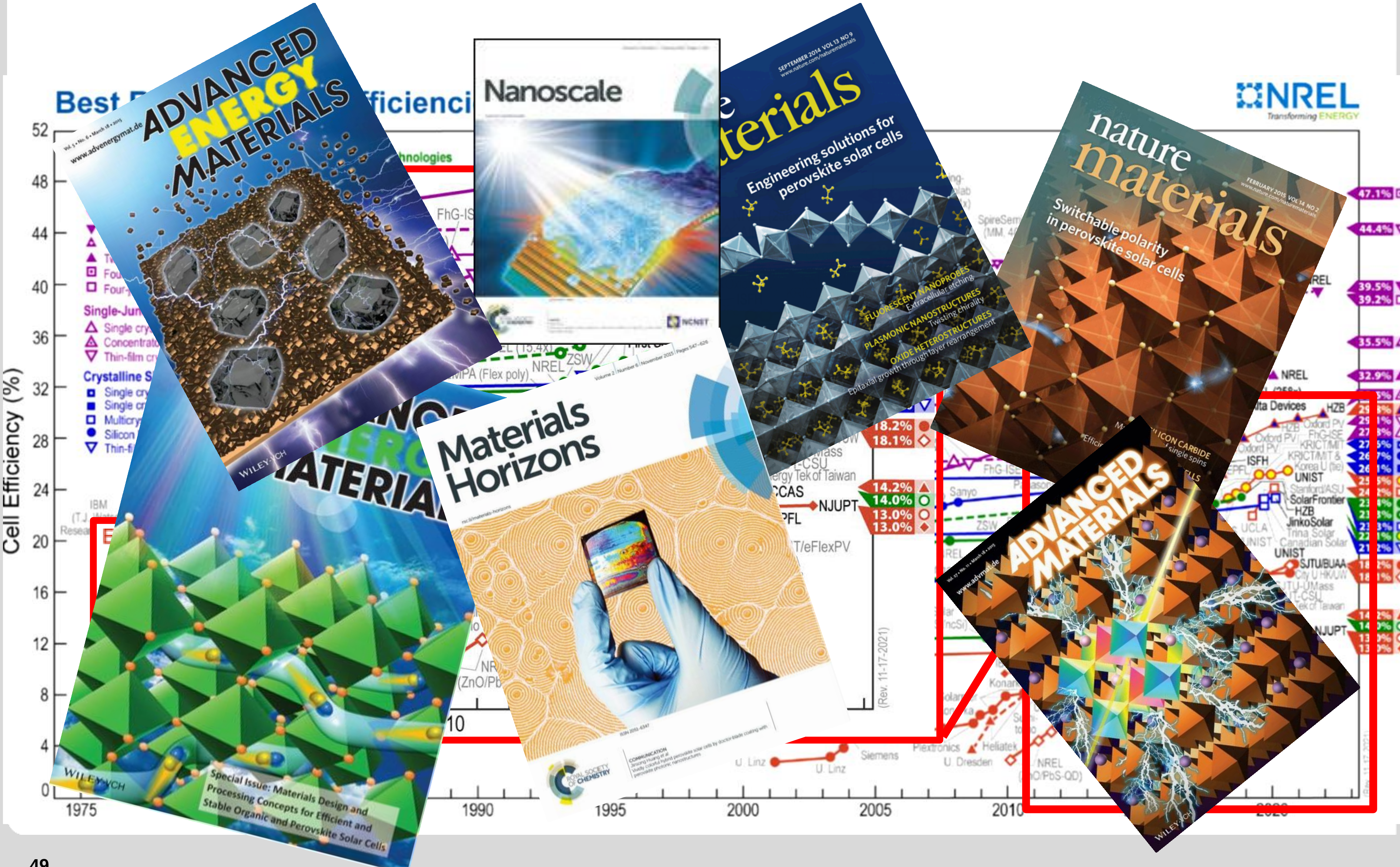


Why perovskite PV?



Source: https://www.nrel.gov/pv/cell-efficiency.html

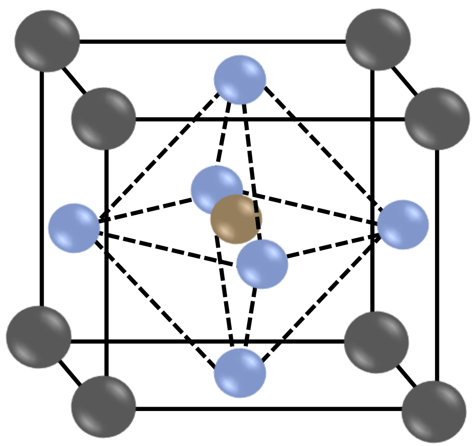
Why perovskite PV?



Source: https://www.nrel.gov/pv/cell-efficiency.html

What is a perovskite?

Generic formula: ABX_3



A (In)organic cation (e.g. $CH_3NH_{3,}$)

B Inorganic cation (e.g. Pb)

X Anion (e.g. I)

Found in 1830 by Mr. Perovski in the Ural mountains

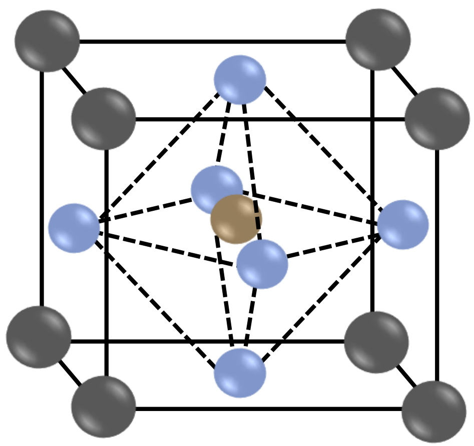
Calcium Titanium Oxide/Calcium Titanate:

$CaTiO_3$

Source: textbook

Perovskite - a class of crystals

Generic formula: ABX_3



A (In)organic cation (e.g. CH_3NH_3,)

B Inorganic cation (e.g. Pb)

X Anion (e.g. I)

Coarse guidelines for crystal formation

1. Goldschmidt's tolerance factor

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

$$0.8 \leq t \leq 1.1$$

2. Ratio of ionic radii

$$\mu = \frac{r_B}{r_X}$$

$$0.4 < \mu < 0.9$$

Source: textbook

Perovskite - a class of crystals

Prominent inorganic examples:

	t	μ
CaTiO3	0.97	0.43
SrTiO3	1.00	0.43
BaTiO3	1.06	0.43

Ba=1.61 Å;
Ca=1.34 Å;
Sr= 1,44 Å;
Ti=0.605 Å;
O=1.4 Å;

- Dielectric CaTiO3
- Ferroelectric BaTiO3
- Piezoelectric Pb(Ti,Zr)O3
- Superconducting SrTiO3
- Semiconducting SrTiO3

Only recently for Optoelectronics/PV:
Semiconducting and strongly absorbing
MAPbI3

Coarse guidelines for crystal formation

1. Goldschmidt's tolerance factor

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

$0.8 \leq t \leq 1.1$

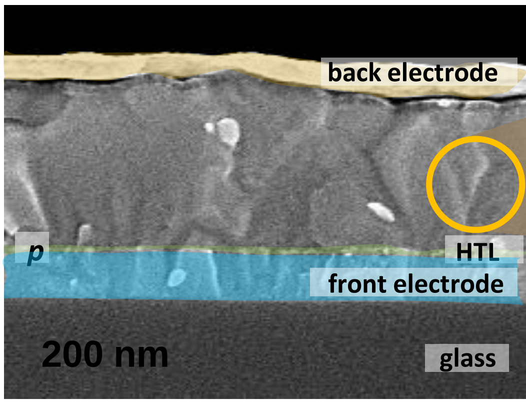
2. Ratio of ionic radii

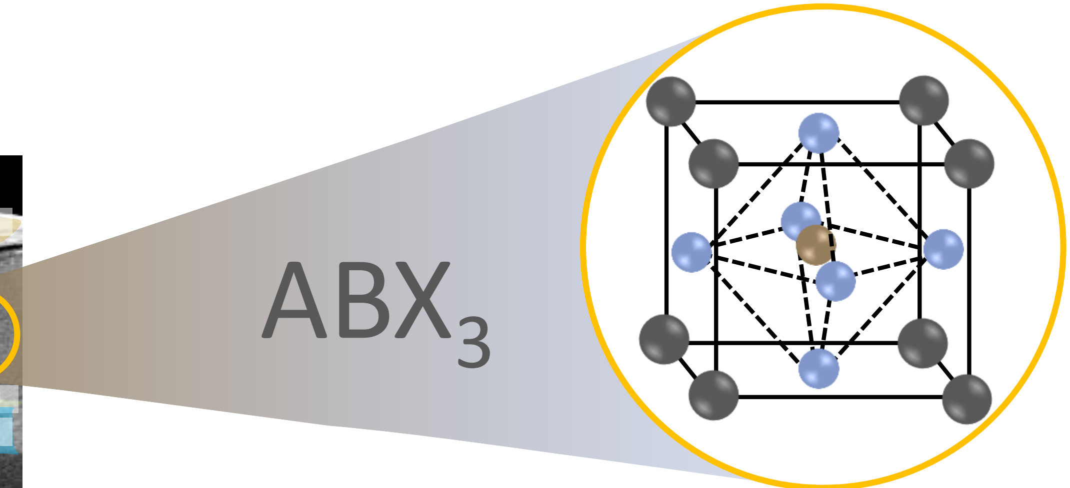
$$\mu = \frac{r_B}{r_X}$$

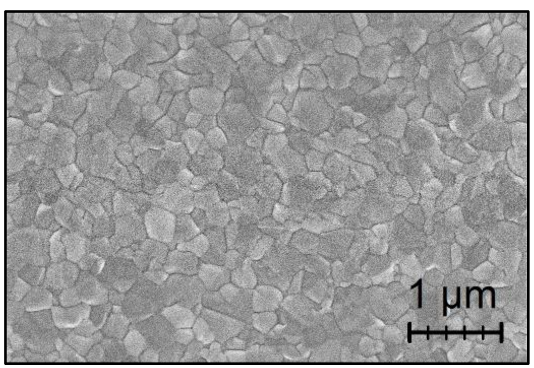
$0.4 < \mu < 0.9$

First reported for PV in 2009 (3.9%), however research only booming since 2012.., now up to 25.2%!!

Metal Halide Perovskite Thin Films







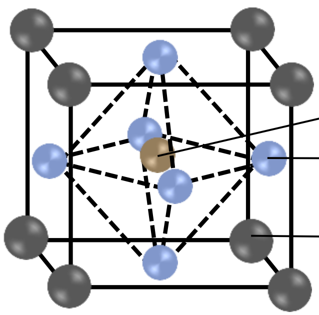
A (In)organic cation (e.g. $CH_3NH_3^-$, Cs^-)

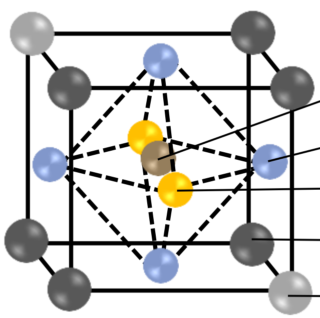
B Inorganic cation (e.g. Pb^-, Sn^-)

X Anion (e.g. I^+, Br^+)

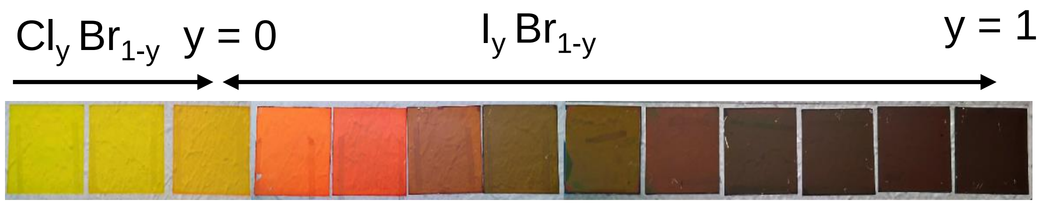
Tunable Bandgap of Multi-Cation Perovskite

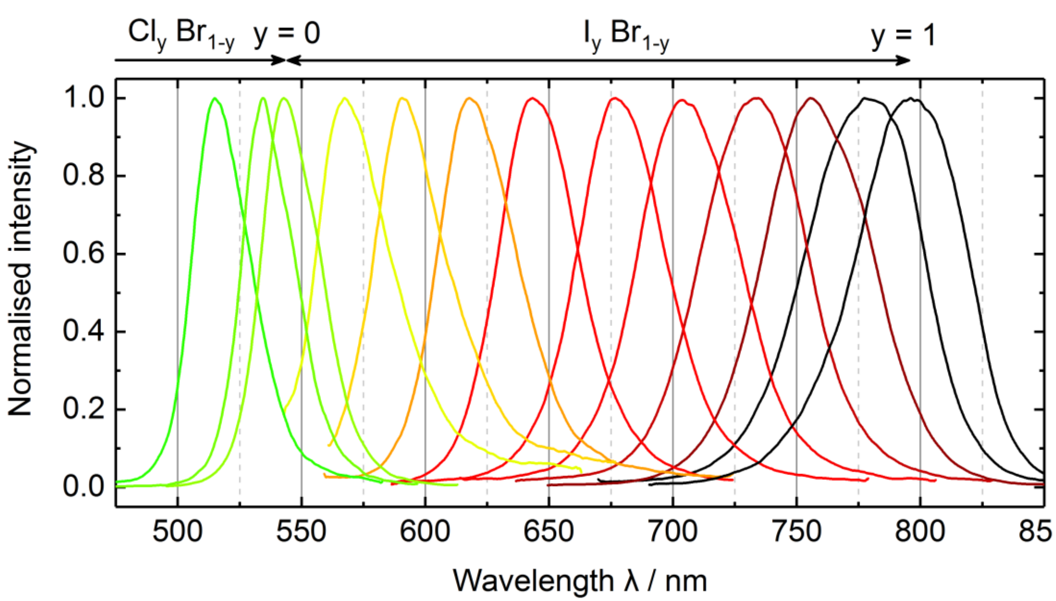
Compositional Engineering





Tunable photoluminescence





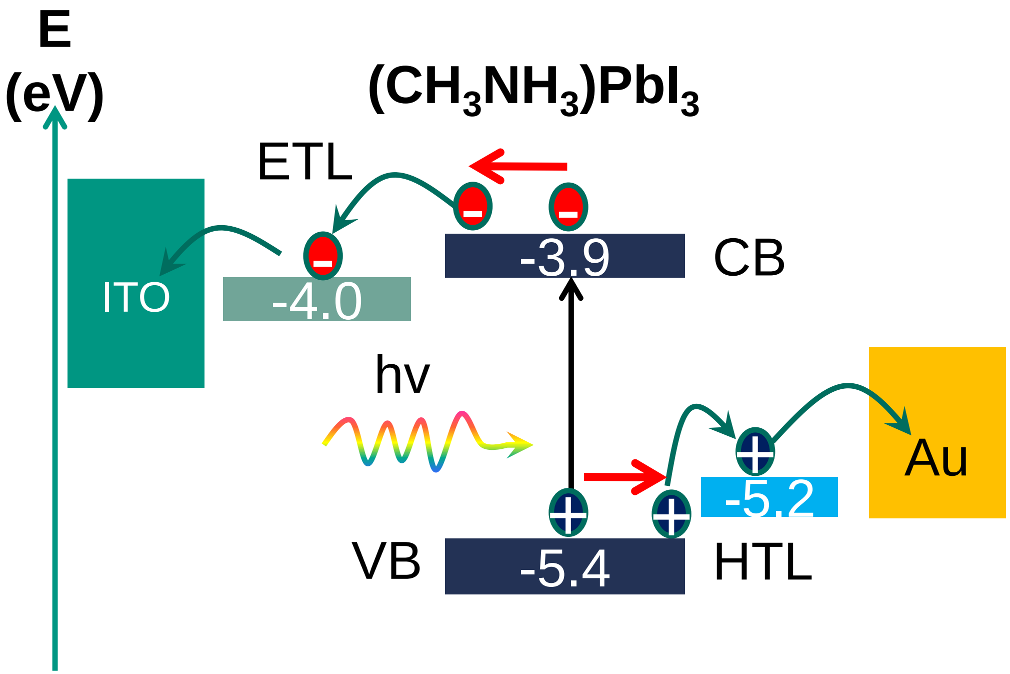
Brenner et. al, Optical Mat. Express. Vol. 7, 11, 4082-4094 (2017).

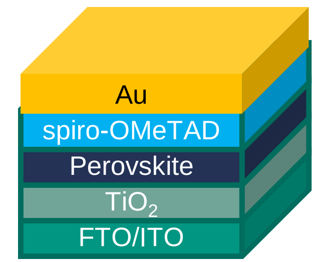
Perovskite Photovoltaics

Karlsruher Institut für Technologie

- Why perovskite materials?
- **Working principle of perovskite solar cells**
- Fabrication of perovskite solar cells
- Challenges and promises of perovskite PV
- Perovskite PV Research at KIT

Working Principle





<u>Steps:</u>

1. Light absorption
2. Excitation of **free charge carriers** (exciton binding energy < k_BT)
3. Diffusion to the charge selective transport layers (HTL and ETL)
4. Transport to the contacts

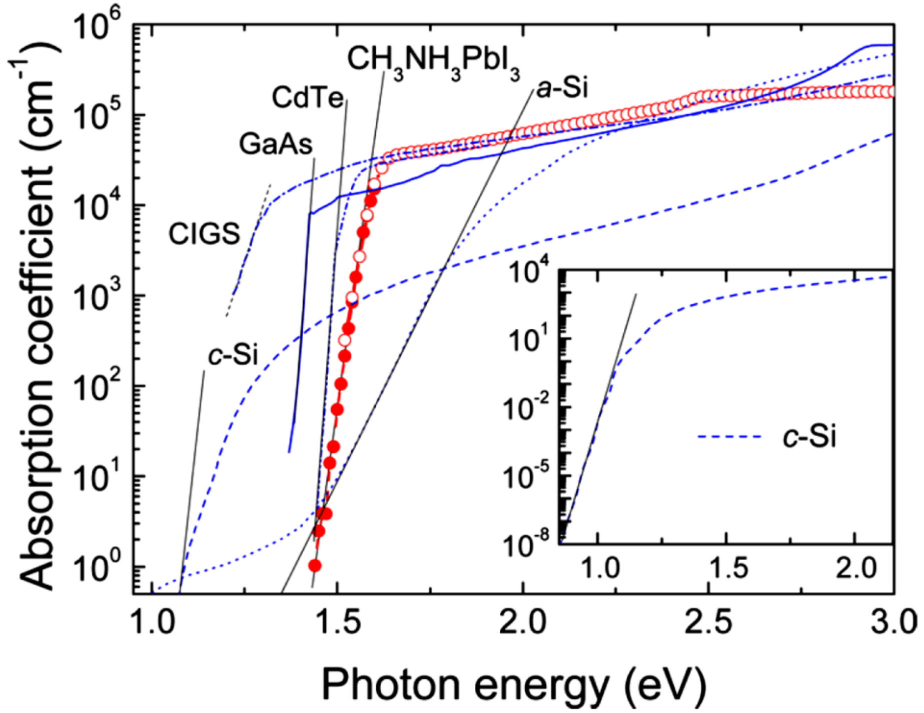
<u>Important intrinsic material requirements for PV</u>

1. high absorption coefficient (α)
2. large diffusion length (l_{diff})

Promises of Perovskite Photovoltaics

High absorption coefficient

- *High absorption coefficient*
  → abs. length 1/α < 0.3 µm
- *Direct band gap at ~1.6 eV*
- *Small Urbach tail (slope below Eg)*
  → low degree of disorder
- ***Even polycrystalline perovskite layers behave like monocrystalline materials!***

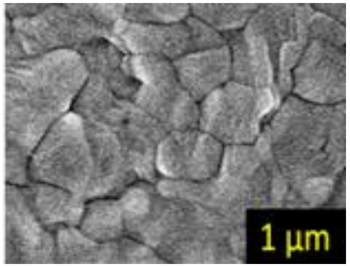


[1] S. Gharibzadeh et al., Adv. Energy Mater. 9(21), 1803699 (2019)
[2] V. Bermudez et al. **3**, 466–475 (2018)
[3] K. Yoshikawa et al., *Nat. Energy*, **2**, 17032 (2017).
[4] M. A. Green, *Prog. Photovoltaics* **20**, 472 (2012)

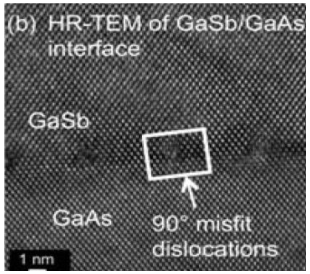
Excellent Optoelectronic Properties

- Low non-radiative recombination losses yield high open-circuit voltage.

	Perovskite *[1]*	***CIGS*** *[2]*	***Si*** *[3]*	***GaAs*** *[4]*
Max. V_{OC}	1.21 V / 1.31V	0.757 V	0.73 V	1.12V
E_G	1.62eV / 1.72eV	1.15eV	1.07eV	1.39eV
eV_{OC} / E_G	**74-76%**	**~65%**	**~68%**	**82%**



crystallinity



Polycrystalline perovskite thin films yield almost as high eV_{OC} / E_G as epitacially grown GaAs thin films.

[1] S. Gharibzadeh et al., Adv. Energy Mater. 9(21), 1803699 (2019)
[2] V. Bermudez et al. **3**, 466–475 (2018)
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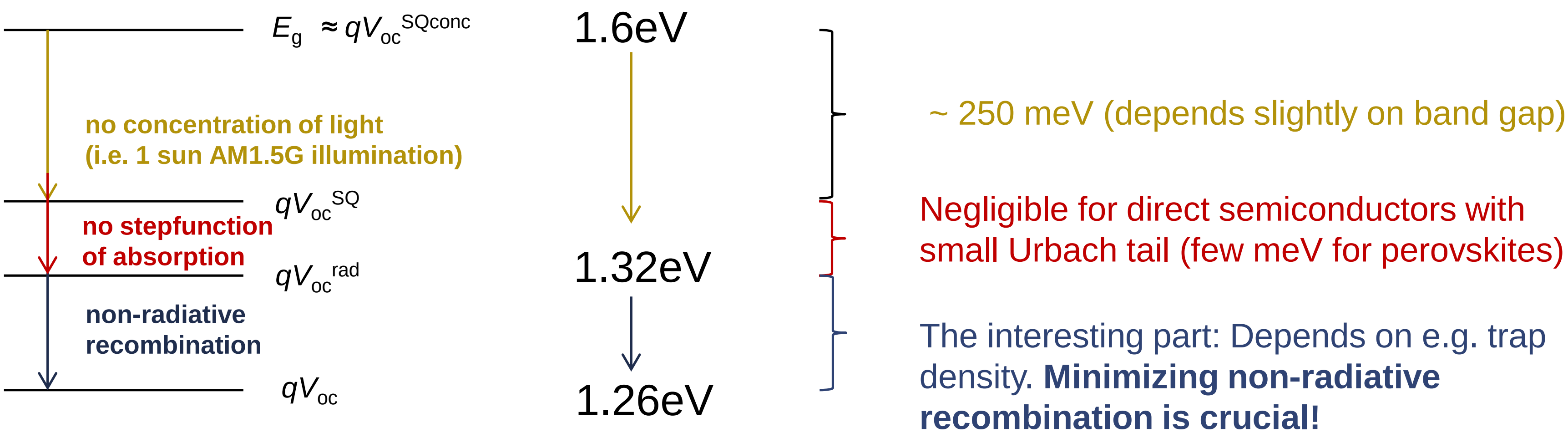
Promises of Perovskite Photovoltaics

High voltage

- Perovskites are typically polycrytalline layers but **almost as good** as the best known epitaxially grown semiconductors (GaAs)



Promises of Perovskite Photovoltaics

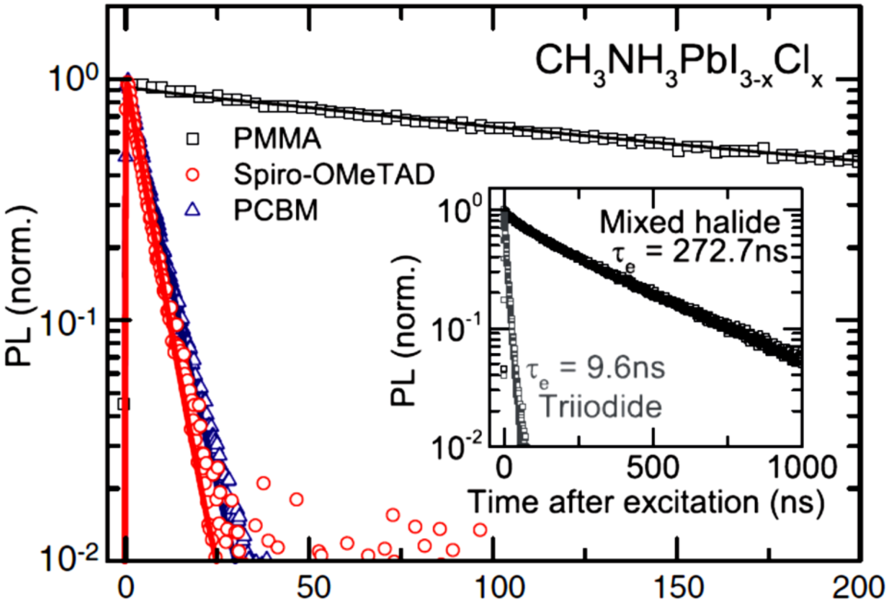
High absorption coefficient + long diffusion length

Transient Photoluminescence reveals minority charge carrier lifetime τ_{min}

<u>*For multicrystalline layers:*</u> τ_{min} ~ 0.2 – 0.8 µs

→ diff. length $l_{diff} = (\mu k_B T/e)^{1/2}$; τ_{min} ~ 0.5 µm

<u>*For single crystals:*</u> l_{diff} ~ 175 µm – 3 mm



high current generation

$l_{diff} > 1/\alpha$ => *We can use layer thickness where all light with $E > E_g$ is absorbed and all charge carriers can be collected.*

[1] S. Gharibzadeh et al., Adv. Energy Mater. 9(21), 1803699 (2019)
[2] V. Bermudez et al. **3**, 466–475 (2018)
[3] K. Yoshikawa et al., *Nat. Energy*, **2**, 17032 (2017).
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Karlsruher Institut für Technologie

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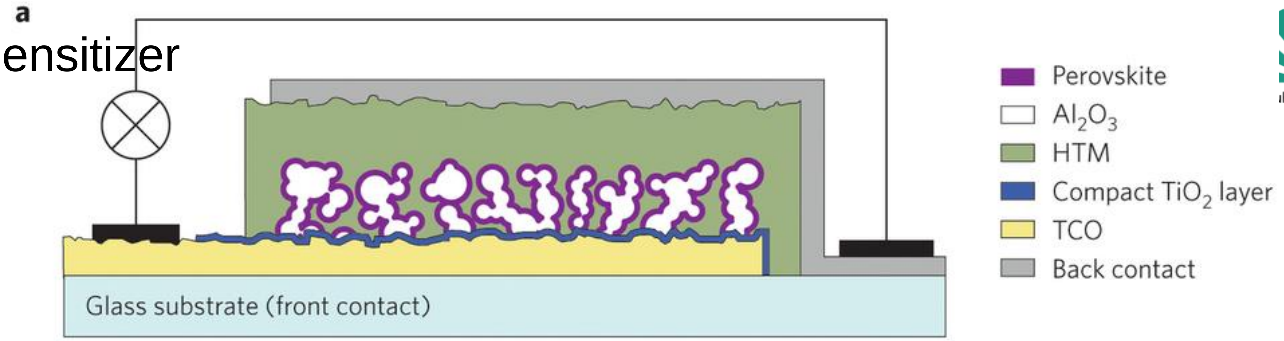
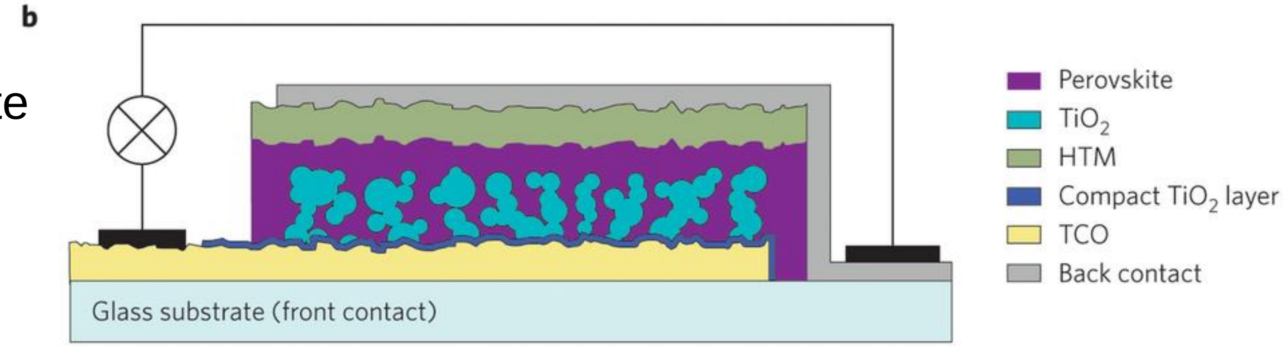
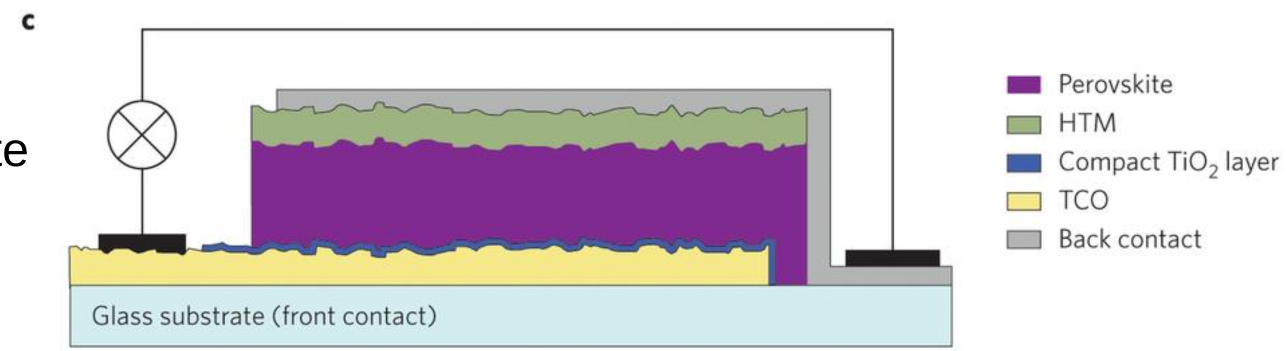
Mesoscopic,
Perovskite as sensitizer



Mesoscopic,
Thick perovskite

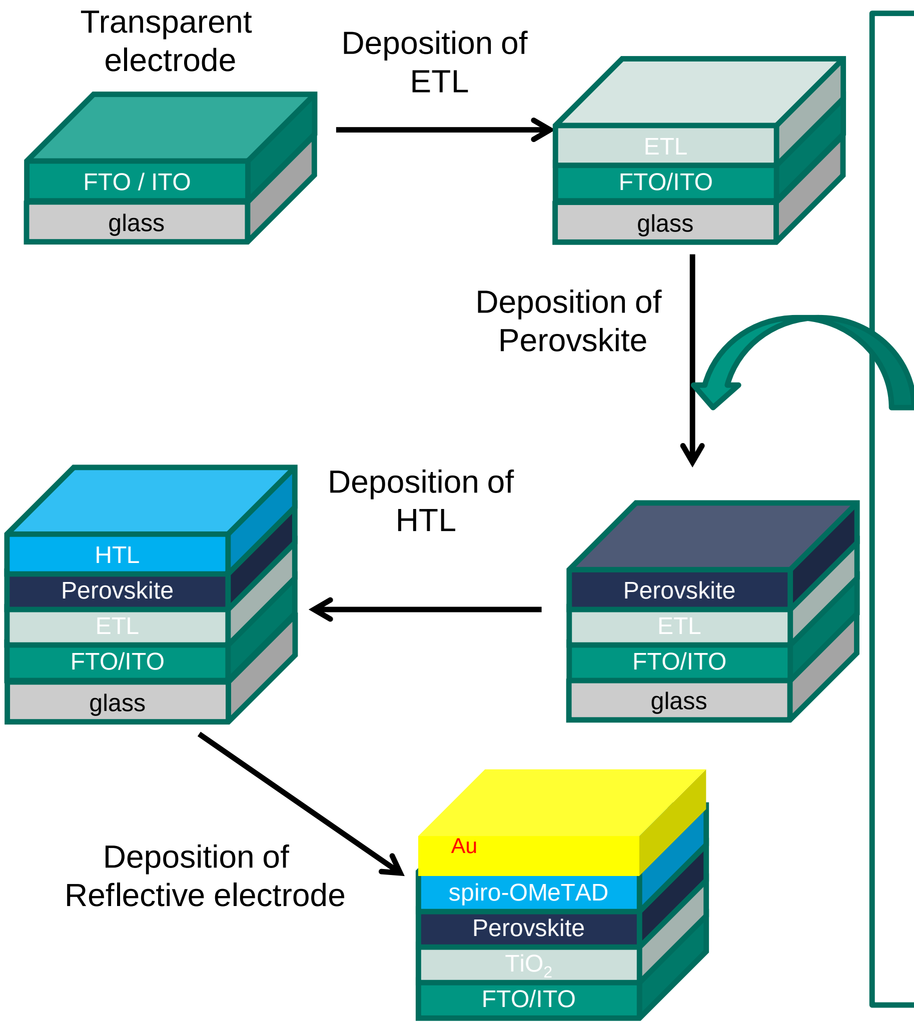


Planar,
Thick perovskite



Source: M. Grätzel, Nat. Mater. 13, 838–842 (2014).

Fabrication of devices



Fabrication of Organometal Halide Perovskites from Precursors

Large variety of cheap precursors

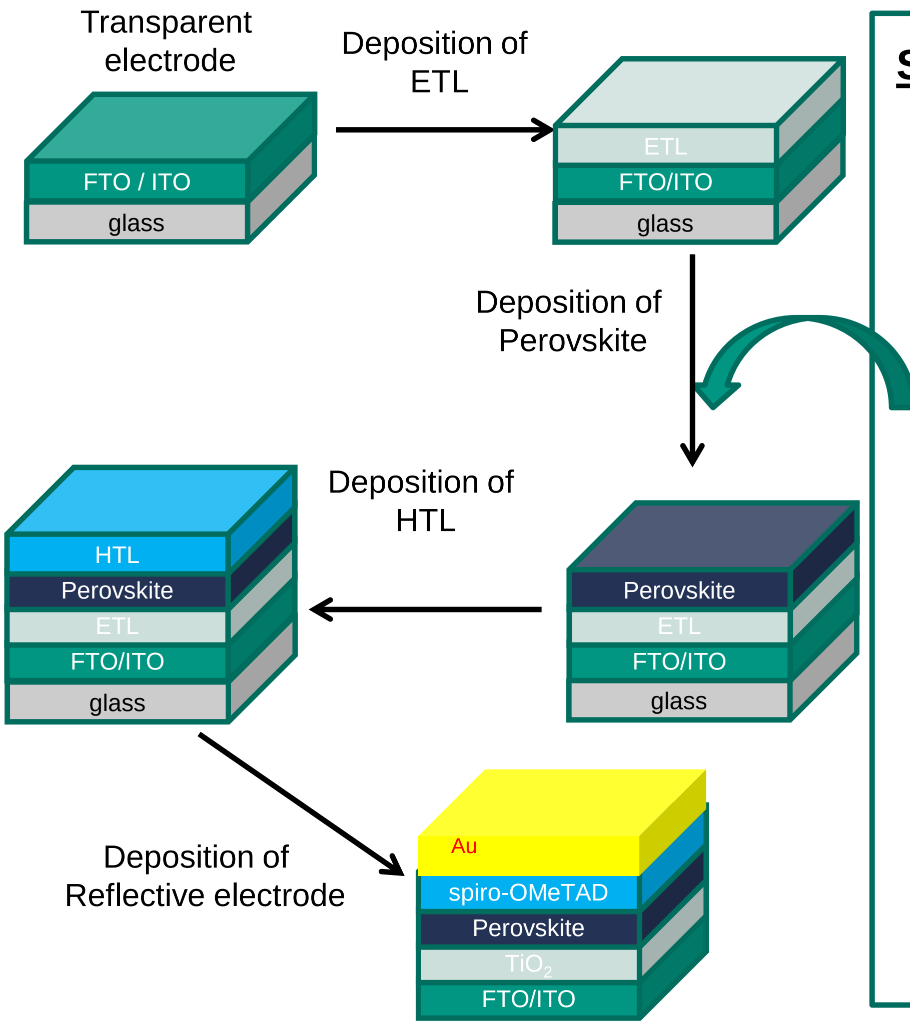
1. Precursor "providing" the small cation (PbI_2, $PbCl_2$, $Pb(CH_3COO)_2$, ...)
2. Precursor "providing" the large cation (CH_3NH_3I, CH_3NH_3Cl, CH_3NH_3Br, FAI)

Exemplary route for $CH_3NH_3PbI_3$

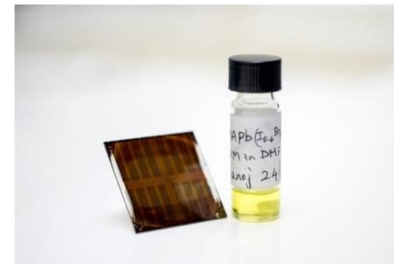
$$3\ CH_3NH_3I + PbCl_2 \rightarrow CH_3NH_3PbI_3 + Cl(\uparrow)$$

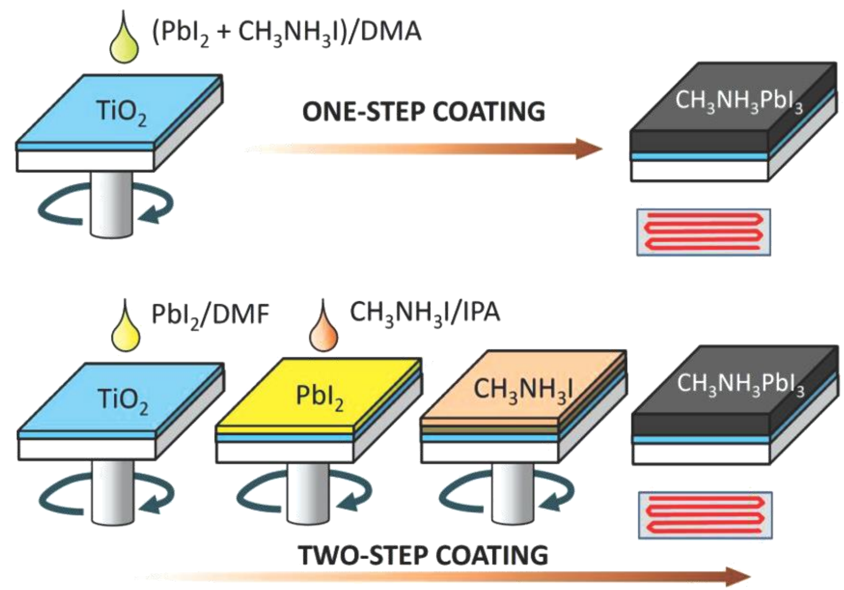
$$CH_3NH_3I + PbI_2 \rightarrow CH_3NH_3PbI_3$$

Fabrication of devices



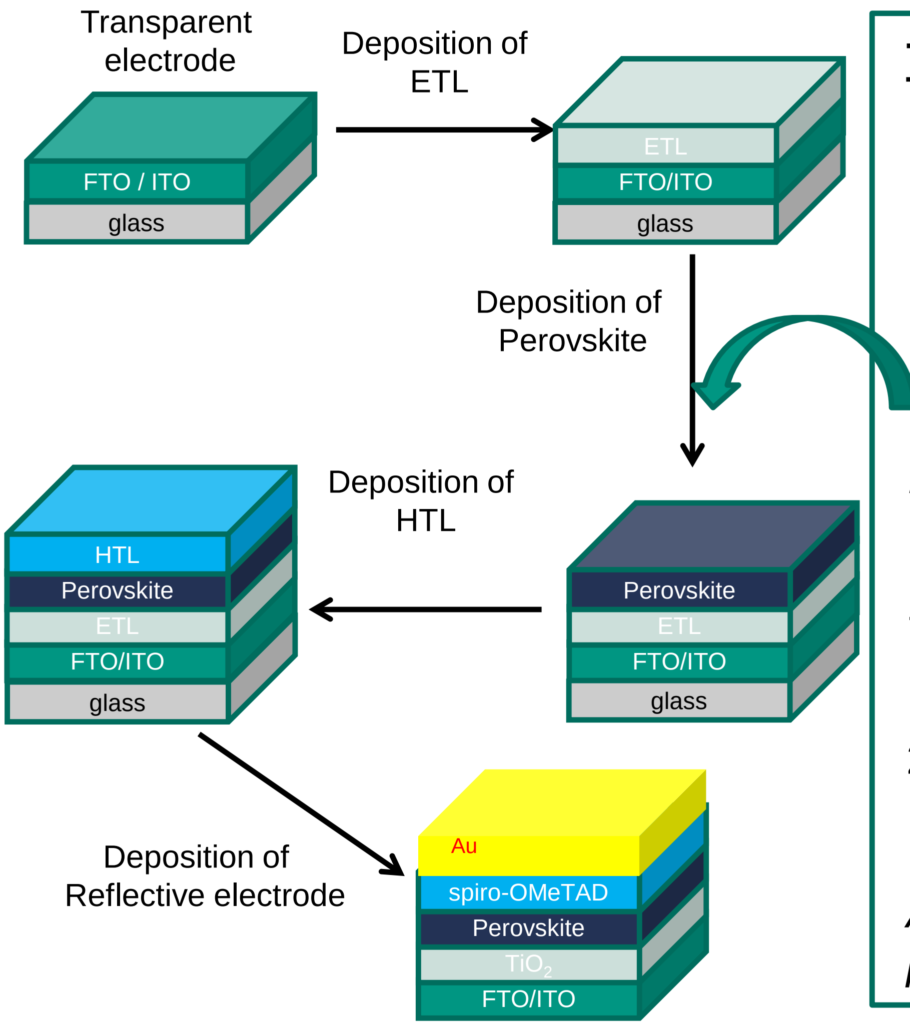
Solution processing



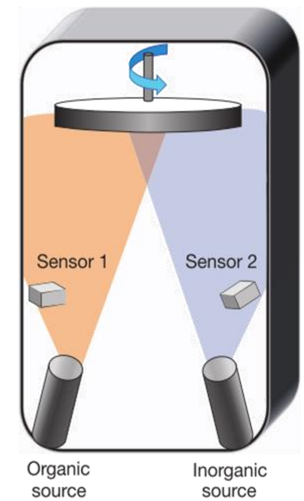


Source: J.-H. Im, H.-S. Kim, N.-G. Park, *APL Mater. 2, 081510 (2014).*

Fabrication of devices



Thermal (co-)evaporation



Two source needed:

1. Organic source (CH_3NH_3I)
   - moderate T
2. Inorganic source (e.g. Pb)
   - high T

Also, combination of evaporation and solution processing possible.

Source: M. Liu, M. B. Johnston, H. J. Snaith, *Nature 501, 395–398 (2013).*

Perovskite Photovoltaics

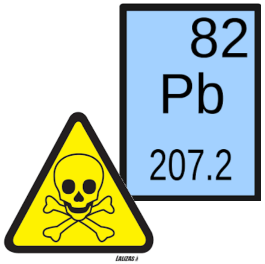
Karlsruher Institut für Technologie

- Why perovskite materials?
- Working principle of perovskite solar cells
- Fabrication of perovskite solar cells
- **Challenges and promises of perovskite PV**
- Perovskite PV Research at KIT

Challenges of Perovskite Photovoltaics

Karlsruher Institut für Technologie

Toxicity of Pb



“Lead is a highly poisonous metal (whether inhaled or swallowed), affecting almost every organ and system in the body”.

Today, all high efficient perovskite materials for PV contain Pb.

- one *m2 of perovskite solar cell contains ~1,4 g of lead.*

- a 75 kg person takes up 0.09 mg of lead by food per day.

Replacement for lead would be preferred.

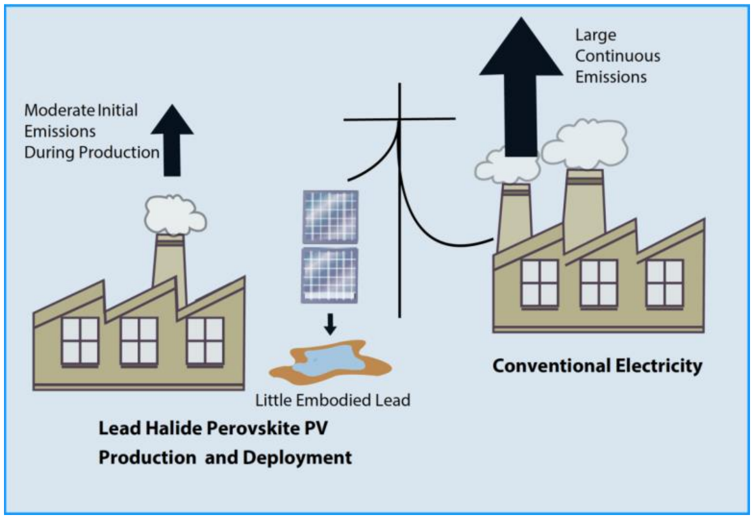
(Restriction of Hazardous Substances Directive 2002/95/EC)

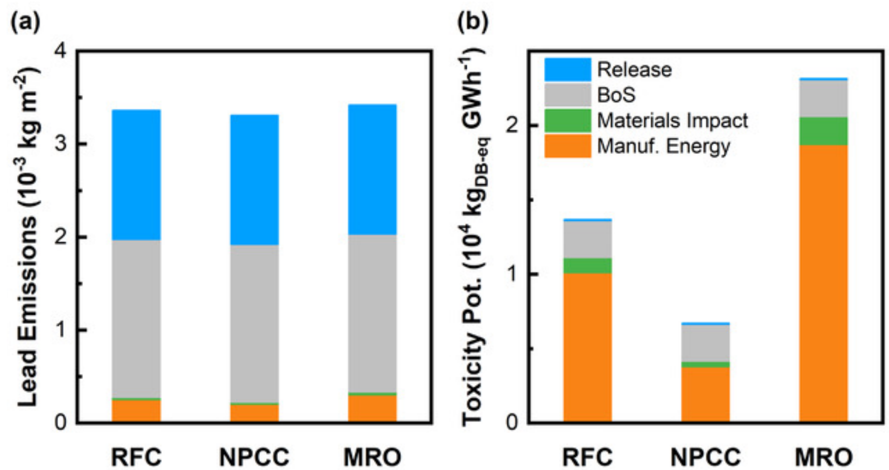
Source: Courtesy of Jonas Schwenzer

Challenges of Perovskite Photovoltaics

Toxicity of Pb

The discussion is complex: Compared to conventional electricity the emissions are low!





Lead missions associated with different categories of LHP-PV manufacturing and operation.

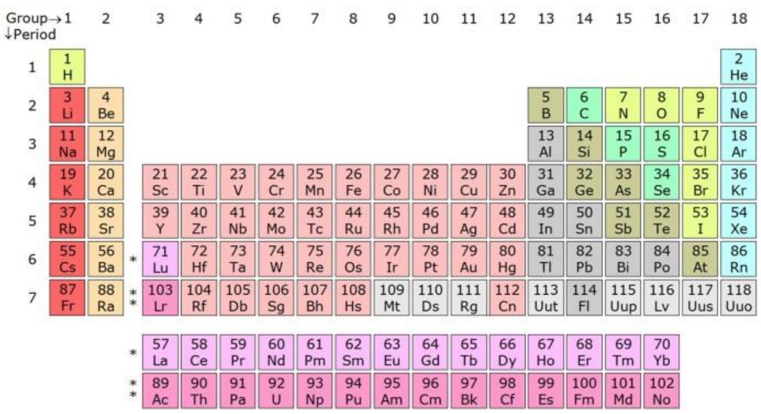
Looking at today energy mix, the majority of the emissions do not originate from the perovskite film, but the energy used during production.

Challenges of Perovskite Photovoltaics

Toxicity of Pb: Research on Pb-free perovskites

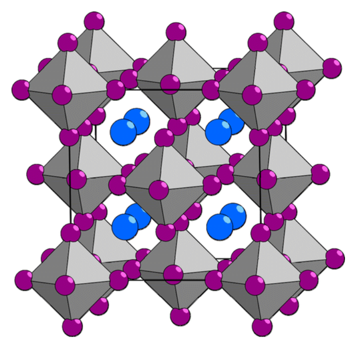
Sn / Ge based perovskites

- *Same main group as Pb*
- *Devices were fabricated with acceptable PCE*
- *Problem: Oxidization, Sn^{2+} => Sn^{4+}*



<u>*Double perovskites*</u>

- Very young field (< 3 year)
- Few devices reported only
- **$A_2BB'X_6$ with A^+, X^- and B^{+x}, B'^{+4-x}**
- Challenging thin-film deposition
- High stability
- High charge carrier lifetimes



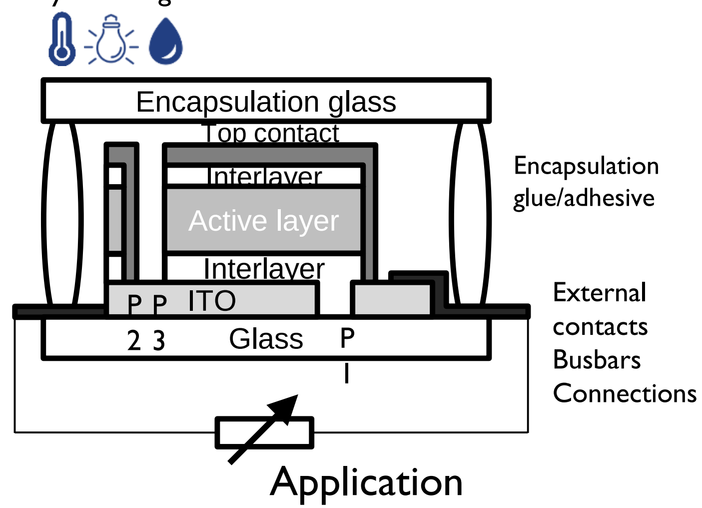
1. Billen, P. et al. Comparative evaluation of lead emissions and toxicity potential in the life cycle of lead halide perovskite photovoltaics. Energy 166, 1089–1096 (2019).

Challenges of Perovskite Photovoltaics

Karlsruher Institut für Technologie

Stability

A perovskite solar module is exposed to harsh outdoor conditions.



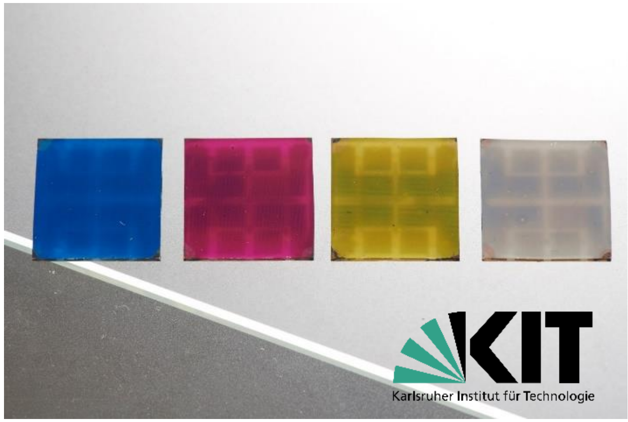
Key stress factors:

1. humidity/water
2. Light
3. Temperature

- **All of them are still critical today !**
- **Yet no complete understanding of degradation processes.**
- **Next to replacing Pb the stability is the major challenge for this technology.**

Promises of Perovskite Photovoltaics

Coloured Perovskite Photovoltaics



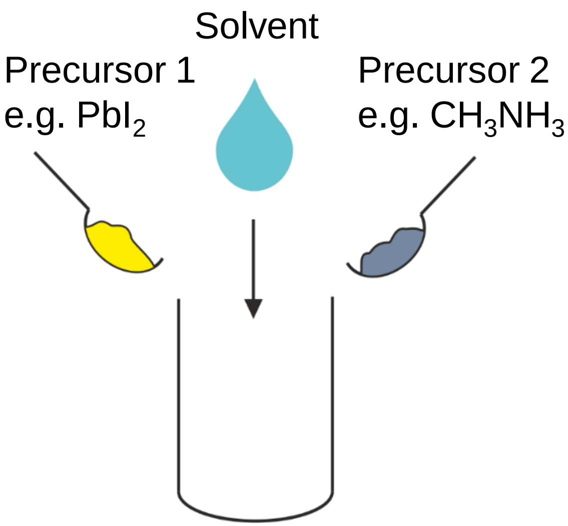
Promises of Perovskite Photovoltaics

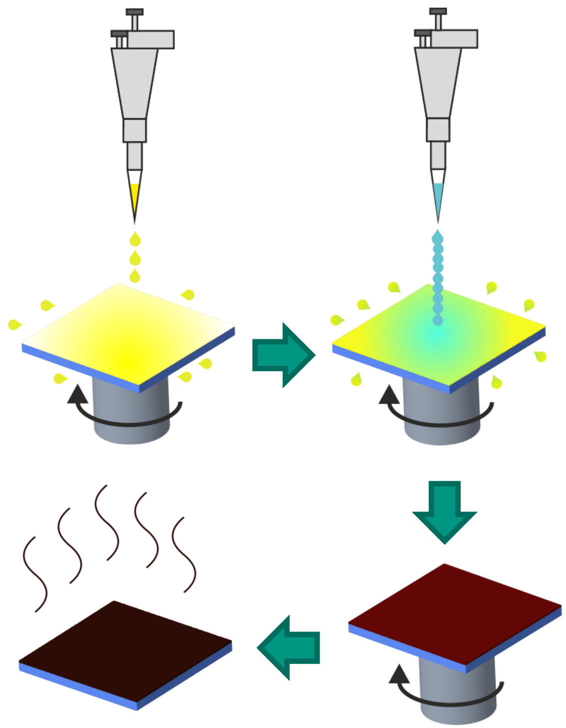
Facile Processing of Perovskite Thin Films

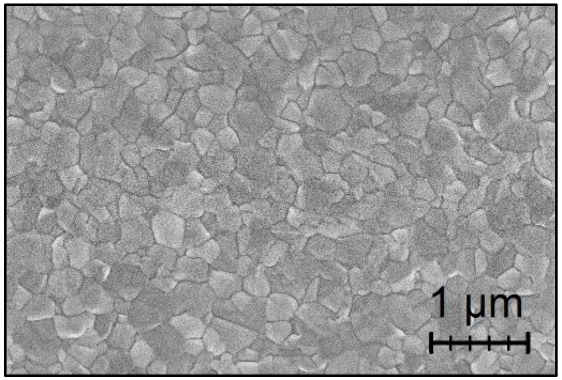
Solution preparation

Spin coating & annealing

Polycrystalline perovskite thin film

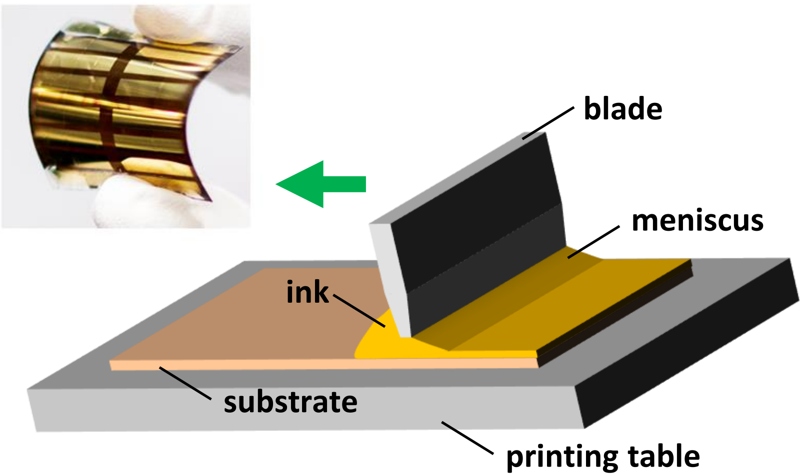


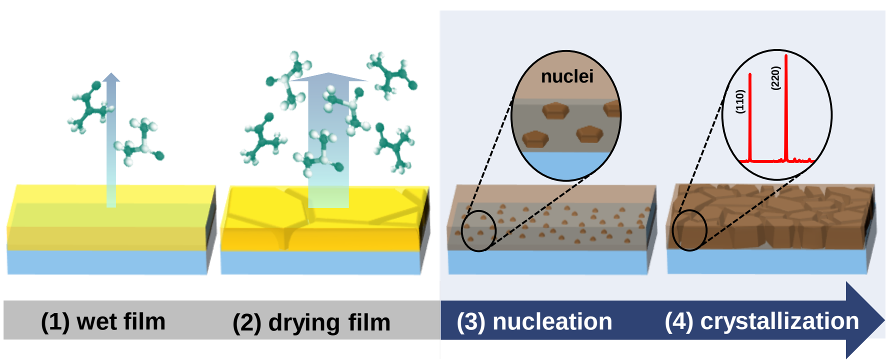




grain size: 100nm - 1µm

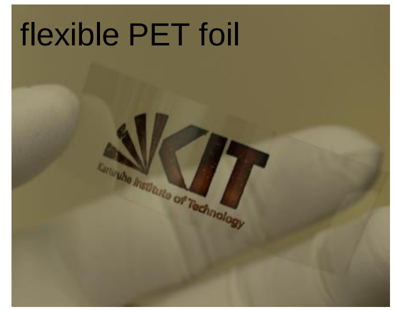
Promise: Coated and Printed Perovskite PV

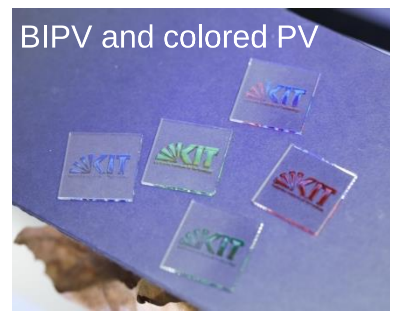




I. A. Howard et al. *Adv. Mater.* **31**(15), 1602807 (2019)

Inkjet-printed perovskite optoelectronics





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TECHNOLOGICAL EDUCATIONAL INSTITUTE of WESTERN GREECE

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SUNOVATION

Publications:

H. Eggers et al., *Adv. Energy Mater. – in press* (2019)

F. Mathies et al., *ACS Appl. Energy Mat.* **1**(5), 1833 (2019)

S. Schlißke et al., *ACS Appl. Energy Mat.* **2**(1), 764 (2019)

F. Mathies et al., *J. Phys. Chem. A* **4**(48), 994209 (2016)

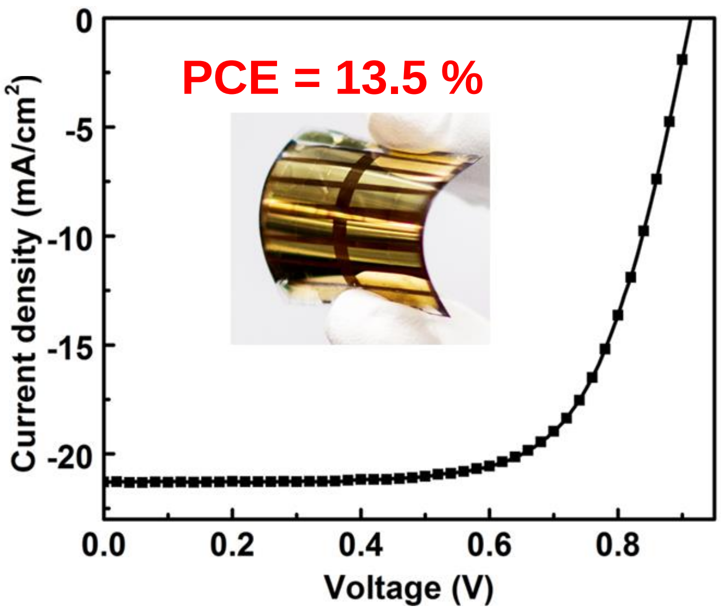
Promises of Perovskite Photovoltaics

Flexible and light weight

- Significant market for flexible and light weight solar cells
- Any application that does not allow for heavy „glass“

Promises of Perovskite Photovoltaics

Flexible and light weight



- All processes must be compatible with the process temperature of the flexible substrate
- Solar cells needs to withstand bending
- Deposition more complex
- Advantage:
  - New applications
  - R2R fabrication

After 50 bending cycles up to 90% of the initial performance can be maintained.

Source: Qiu, W., Paetzold, U. W., … Cheyns, D., J. Mater. Chem. A 2015, 3 (45), 22824–22829.

Perovskite Photovoltaics
from a product perspective

Pro	Con
High efficiency (>25%)	Material costs (perovskite is cheap, but what about the other layers?)
Flexible and light-weight	Long-term stability..?!
Can be semitransparent → Multijunction PV with >30% efficiency possible!	Pb based perovskites are toxic, Pb-free (e.g Sn based) perovskites still show much lower efficiency
Solution processable (i.e. printable → upscaling)	Upscalability and reproducibility still pose big challenge for mass production
Potentially cheap production!	

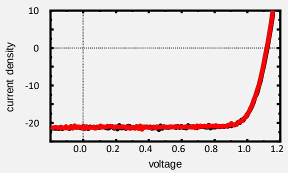
→ At the current stage, the most straight-forward application of perovskite PV is for multijunction solar cells (e.g. in combination with Si or CIGS), to push the efficiency beyond 30%. But research is still young and new details are discovered on a short timescale, hence other applications are realistic!

PEROVSKITE PHOTOVOLTAICS @KIT

Research on perovskite PV at KIT

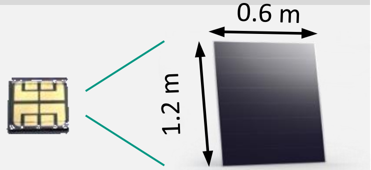
Taskforce Perovskite Photovoltaics

high efficiencies



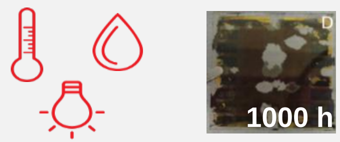
~28% ⇒ >33%

large areas



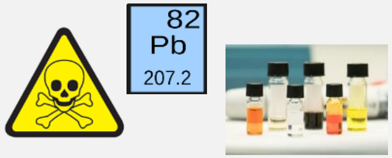
~1 cm² ⇒ >1 m²

stability



~1000 h ⇒ >25 years

toxicity



- **Pb-free**
- **non-toxic solvents**

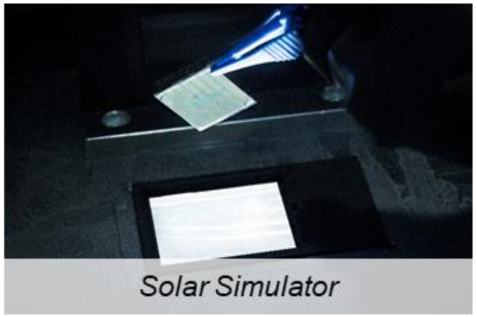
Mission: Advance the **stability** and **scalability** of perovskite-based tandem photovoltaics and advance the performance (*PCE* > 33%).

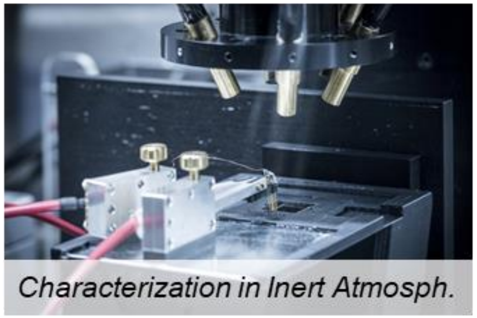
Perovskite PV Taskforce at KIT // 22 PhDs and Postdocs

Research on perovskite PV at KIT

Where to find us?

Thin-film Lab



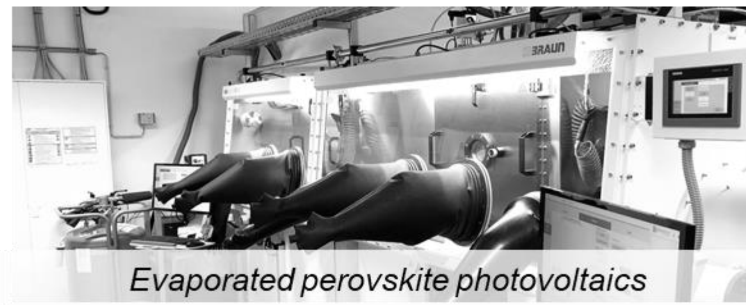


Research on perovskite PV at KIT

Karlsruher Institut für Technologie

Where to find us?

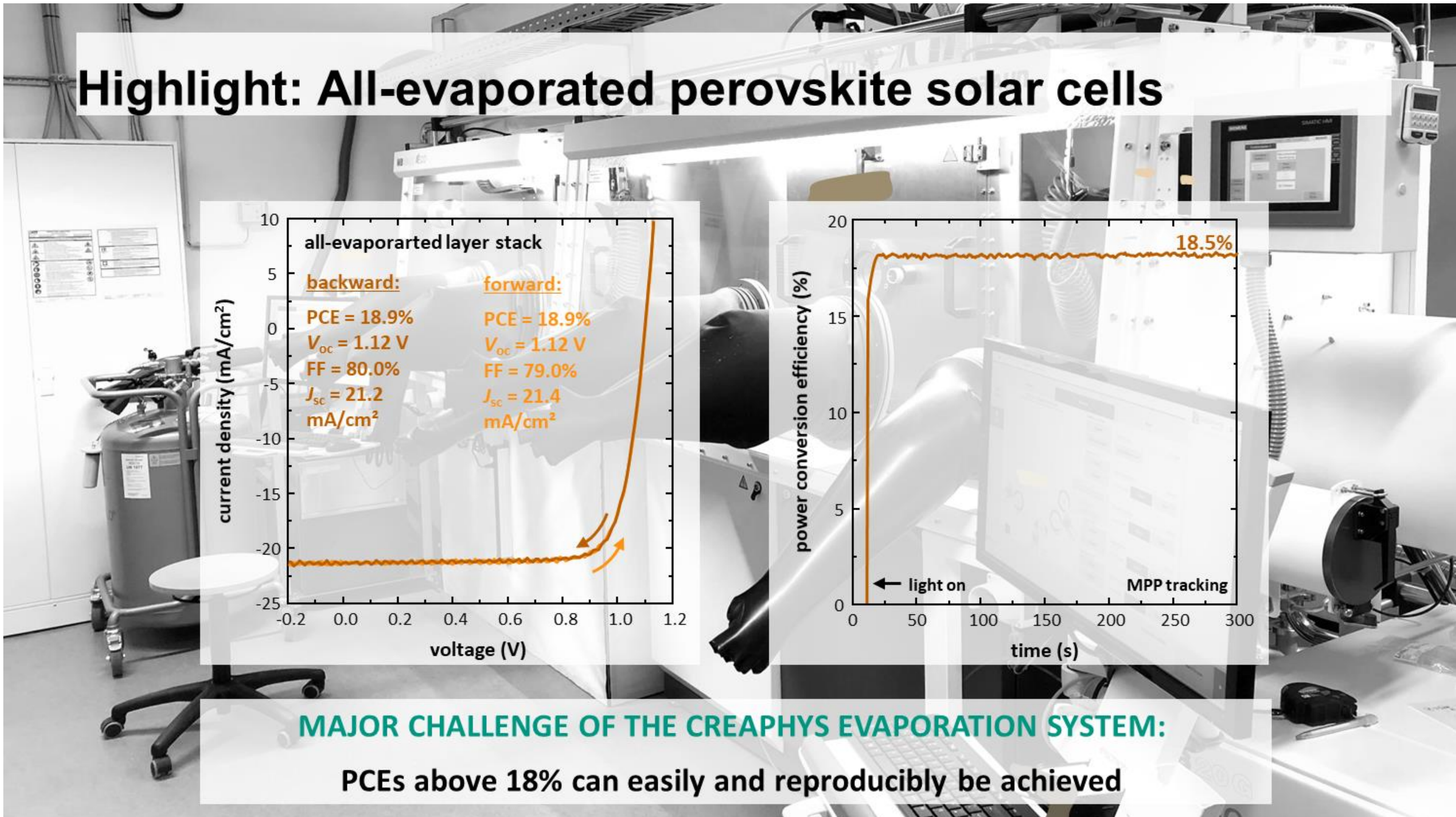
UPSCALING LAB



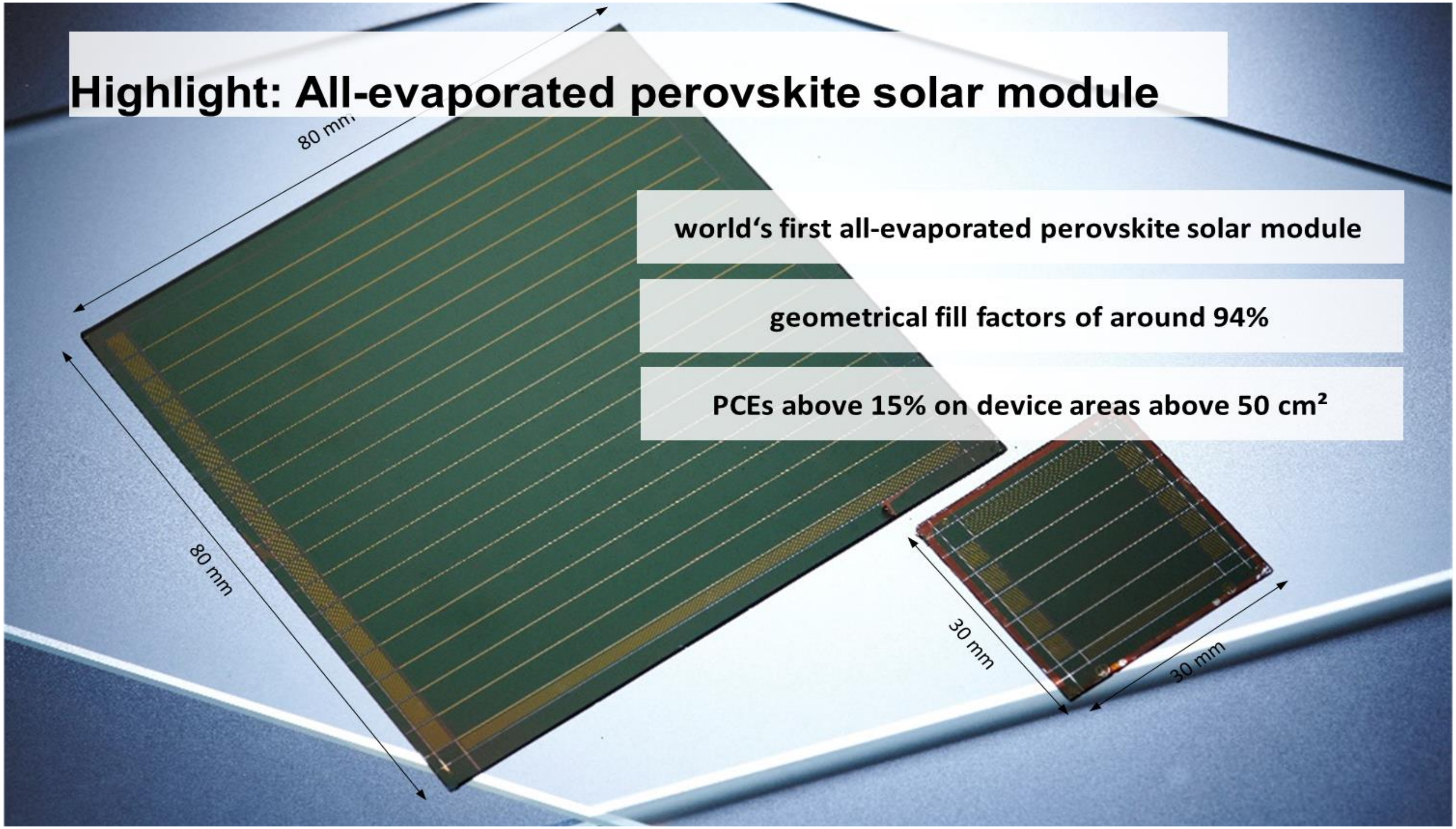
Evaporated perovskite photovoltaics

In Situ Characterization Platform

Research on perovskite PV at KIT



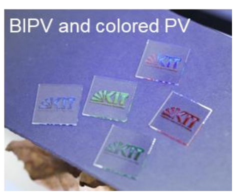
Research on perovskite PV at KIT

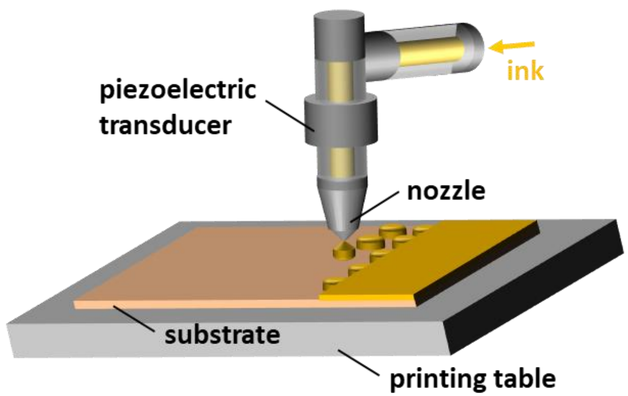


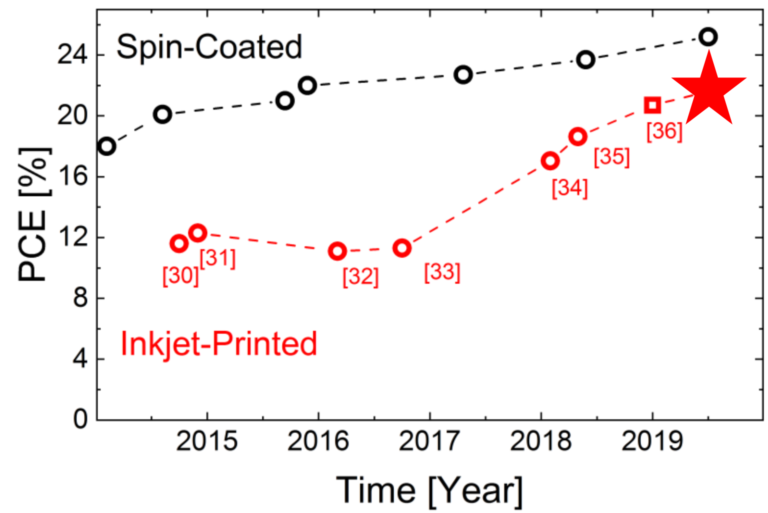
Research on perovskite PV at KIT

Highlights: Inkjet-Printed Perovskite Solar Cells

Focus KIT: Scalable deposition techniques (solution processed and evaporated)







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Technological Educational Institute of Western Greece

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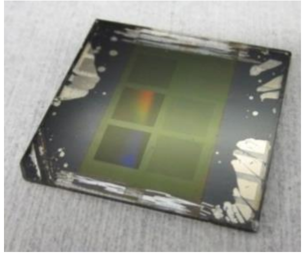
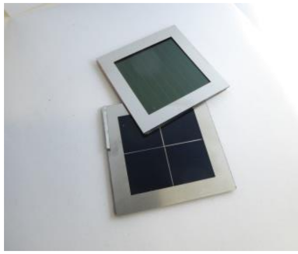
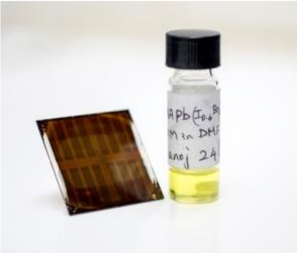
H. Eggers et al. *Advanced Energy Materials* 10(5) 1903184, 2020.

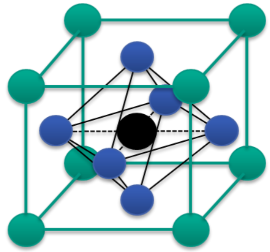
Perovskite Research at KIT

Karlsruher Institut für Technologie









- Highly dynamic and expanding field at LTI and IMT
- Cross stitute „Tasforce Perovskite PV“

  with PostDocs

OPEN Masterprojects !!!

Contact: ulrich.paetzold@kit.edu

Possible topics

- Lead-free & perovskites/ hadamzadeh)
- Perovskite Lasers (Yang Li)
- Evaporated perovskite PV (Tobias Abzieher, Thom
- Perovskite/Si tandem solar cells (Paul Faßl, Ihteaz Hossain)
- Optics/Photonics in perovskite PV (Fabrizio Gota)
- Inkjet-printed perovskites (Fabian Schackmar)
- Laminated perovskite PV (Julie Roger)
- Stability of perovskite materials and devices (Sara Moghadamzadeh, Roja Singh)

Summary

Requirements for any new PV material …

… wanting to compete with existing technologies:

- *It must be competitive in* ***(1) efficiency****,* ***(2) stability,*** *and* ***(3) yield****.*
- *It should be* ***abundant*** *and* ***non-toxic****.*
- *It shall offer* ***low-cost fabrication****.*
- *It would be nice to offer* ***extra features/added values****.*

Source: "Current and Future Cost of Solar Photovoltaics" Agora Energiewende 2015.

Requirements for any new PV material …

… wanting to compete with existing technologies:

Requirement	OPV	Perovskite PV
High-efficiency	17.4% (however, strong improvements recently)	>25%
Stability	Still needs to be investigated in more detail for new materials	Promising results in the last 1-2 years, but still the most pressing issue
High Yield	Moderate, good in low-light	Yes
Abundance	Depends on material	Yes
Non-toxic	Yes	No
Low-cost fabrication	Potentially, but depends on used material	Yes, but upscaling is still an issue
Flexible	Yes	To some extent
Tunability of Eg	To some extent	Yes

Questions ?

Self-Test

- What does „organic“ mean ?
- What are the main differences between an organic seminconductor and a classical semiconductor ?
- Name some unique features of organic solar cells ?
- What are the main features of perovskite PV to allow high efficiencies?
- What are the main issues with perovskite PV nowadays?
- What are the main requirements for any new PV material?