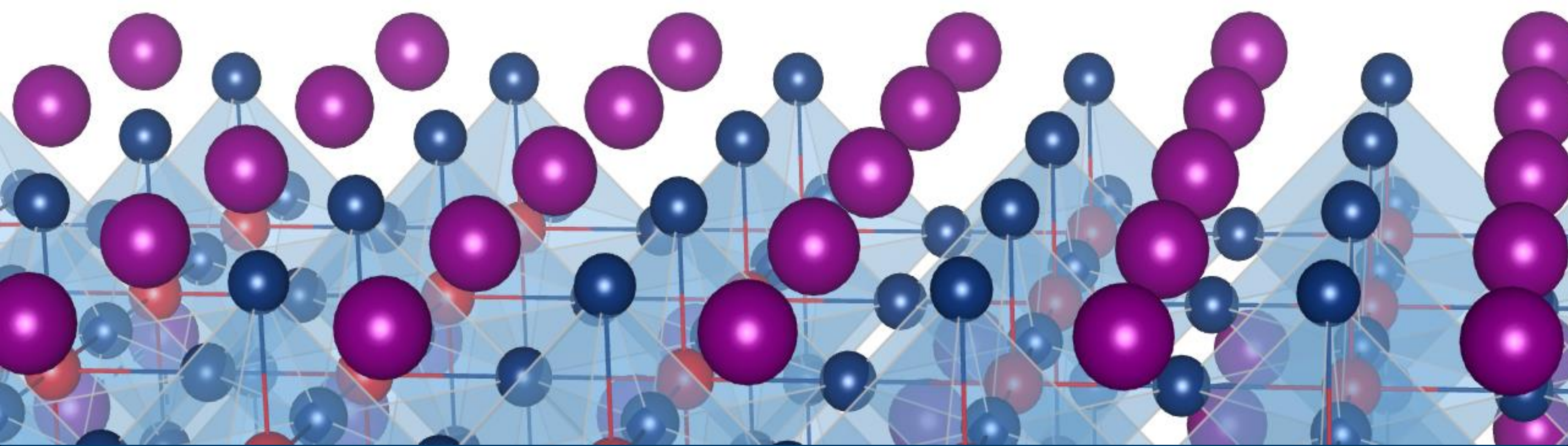


SOLUTION PROCESSABLE PHOTOVOLTAICS

Thomas Kirchartz

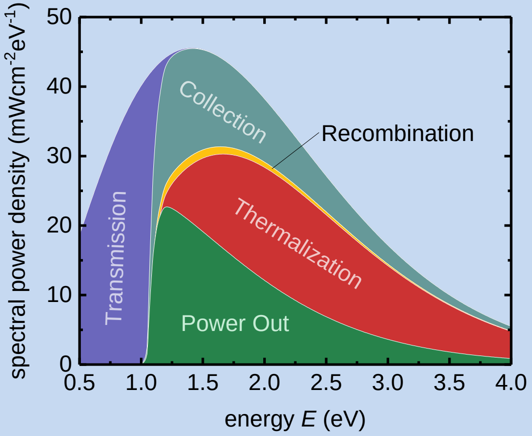
[1]IEK-5 Photovoltaik, Forschungszentrum Jülich,

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

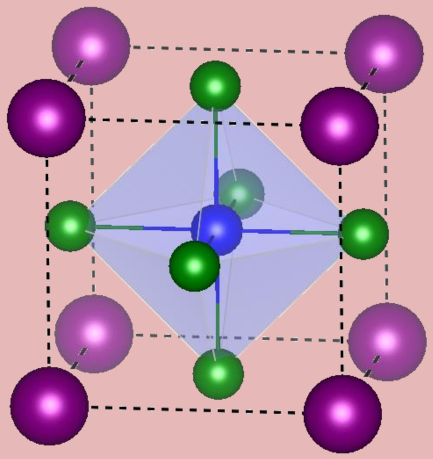
JÜLICH Forschungszentrum

Outline

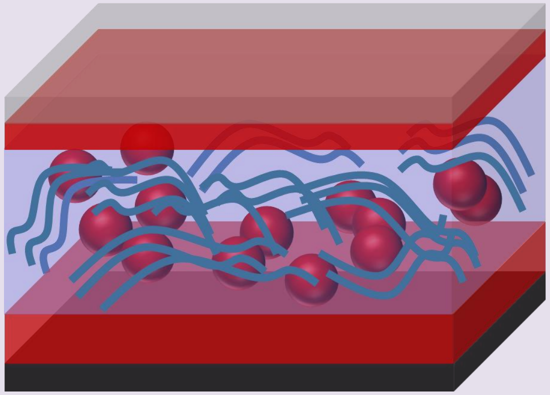
Functionality of Solar Cells – Main Losses



Perovskite Solar Cells

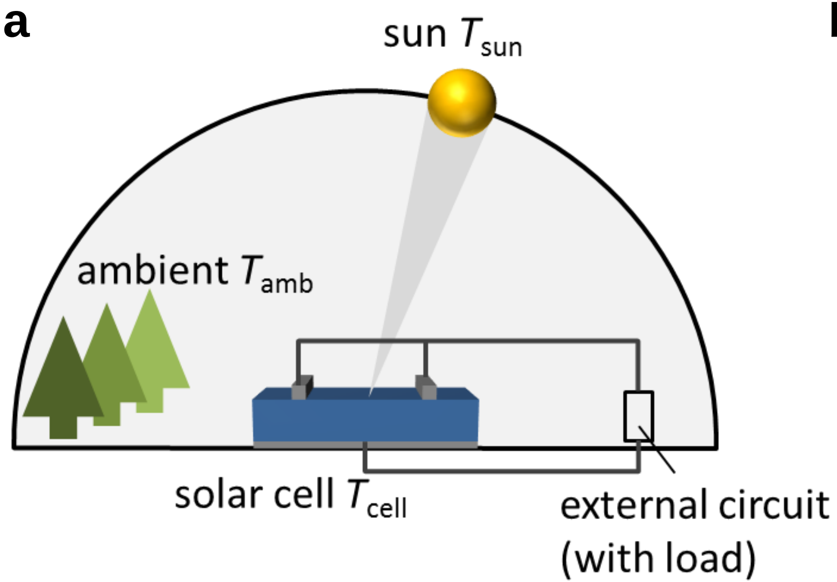


Organic Solar Cells

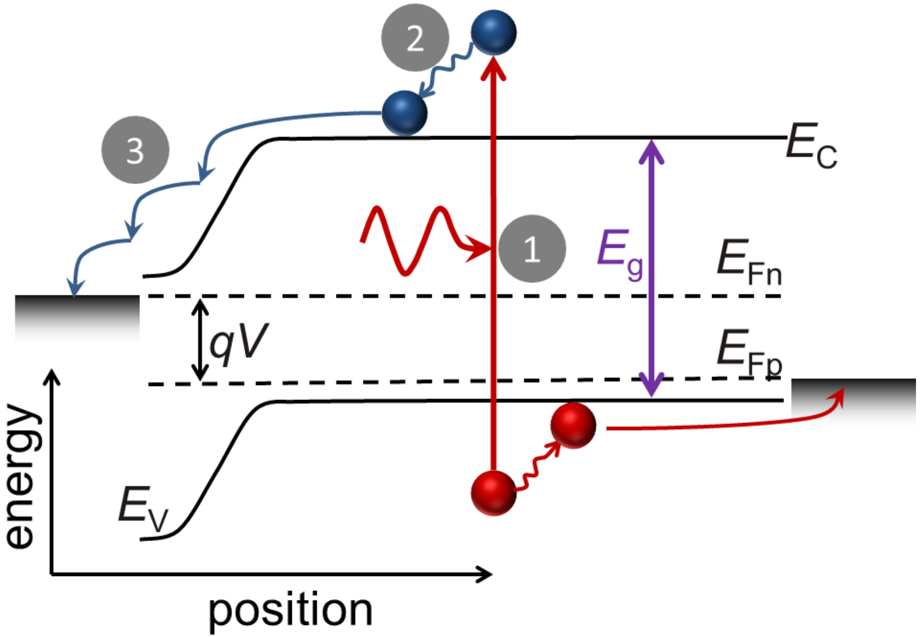


Photovoltaic Mechanism

a



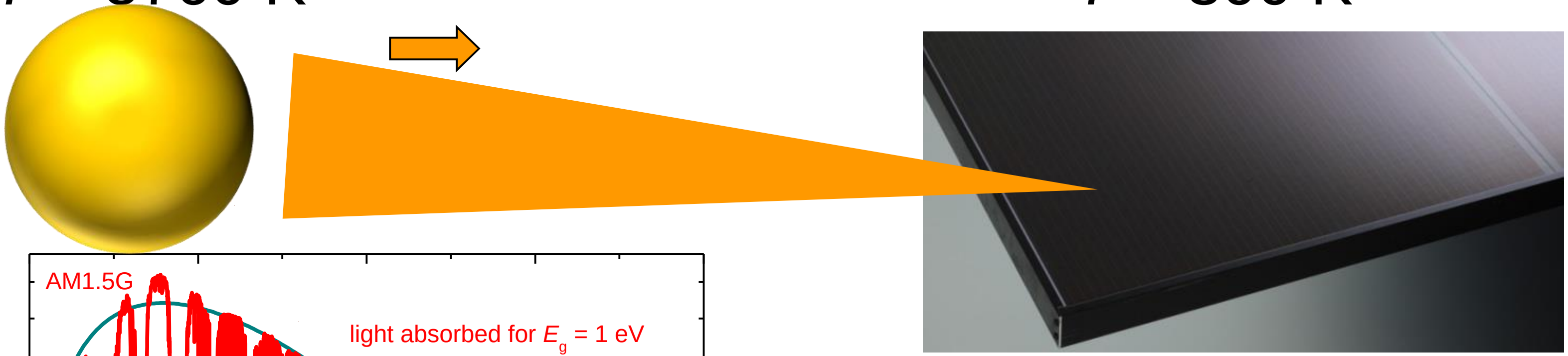
b

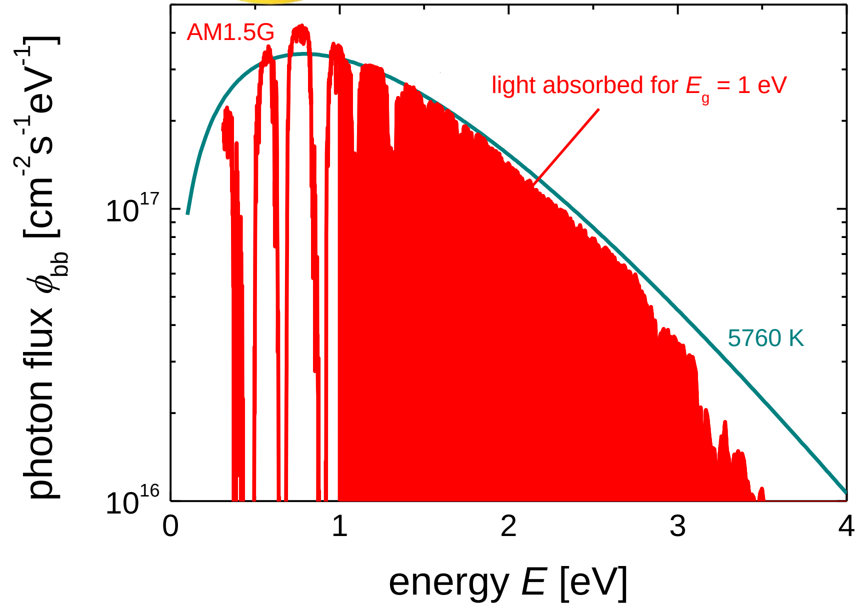


Step-Function Like Absorptance

T = 5760 K

T = 300 K





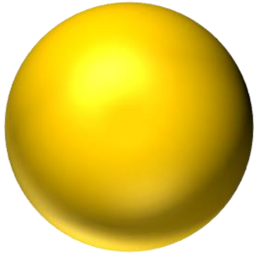
$$J_{sc} = q\int a(E)\phi_{sun}(E)dE$$

solar spectrum $\phi_{sun}(E)$

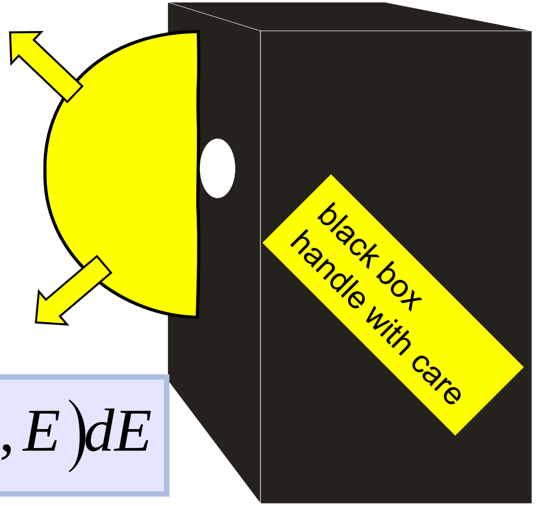
absorptance $a(E)$

Solar cell → Sun

T = 5760 K



T = 300 K



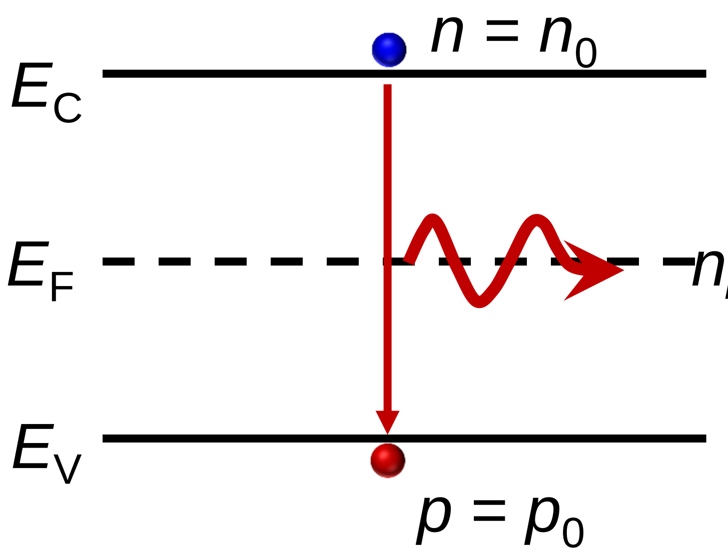
$$J_{0,\mathrm{em}} = q\int a(E)\,\phi_{\mathrm{bb}}(T_{\mathrm{sc}}, E)\,dE$$

Elementary charge q

Black body spectrum $\phi_{\mathrm{bb}}(E)$

absorptance $a(E)$ = emissivity $e(E)$

Radiative Recombination

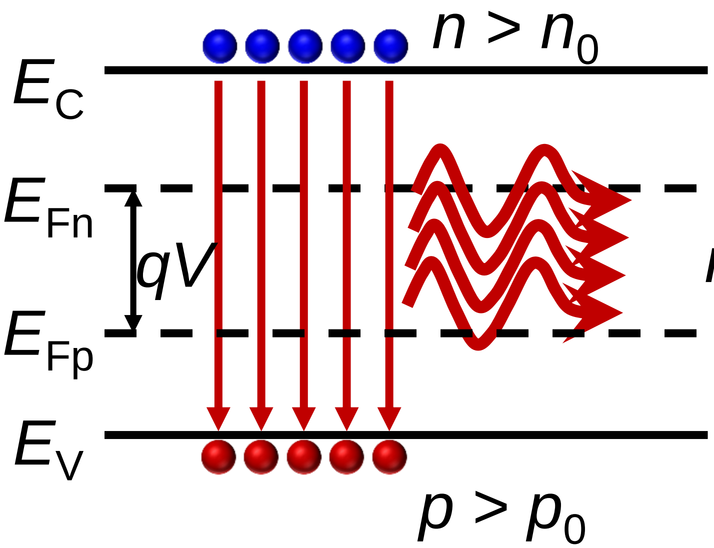


$np = n_0 p_0 = n_i^2$

$$\boxed{\phi(E) = a(E)\phi_{bb}(E)}$$

equilibrium

Radiative Recombination

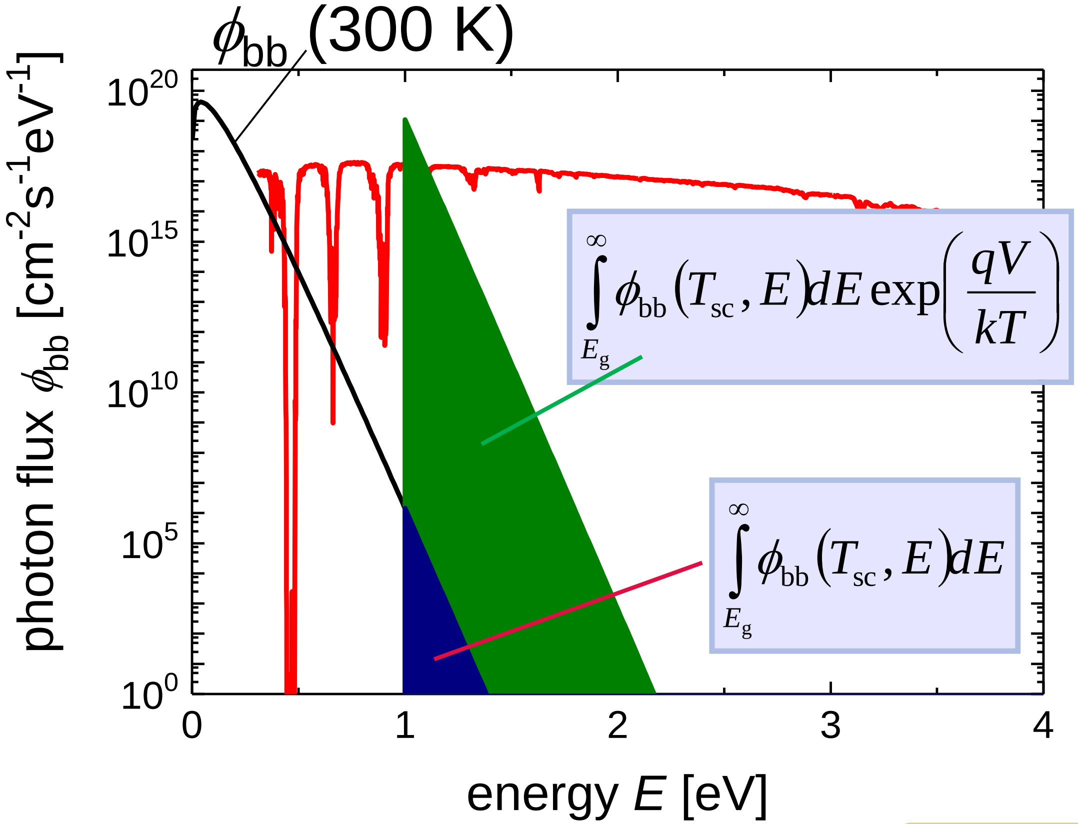


$$np = n_i^2 \exp(qV/kT)$$

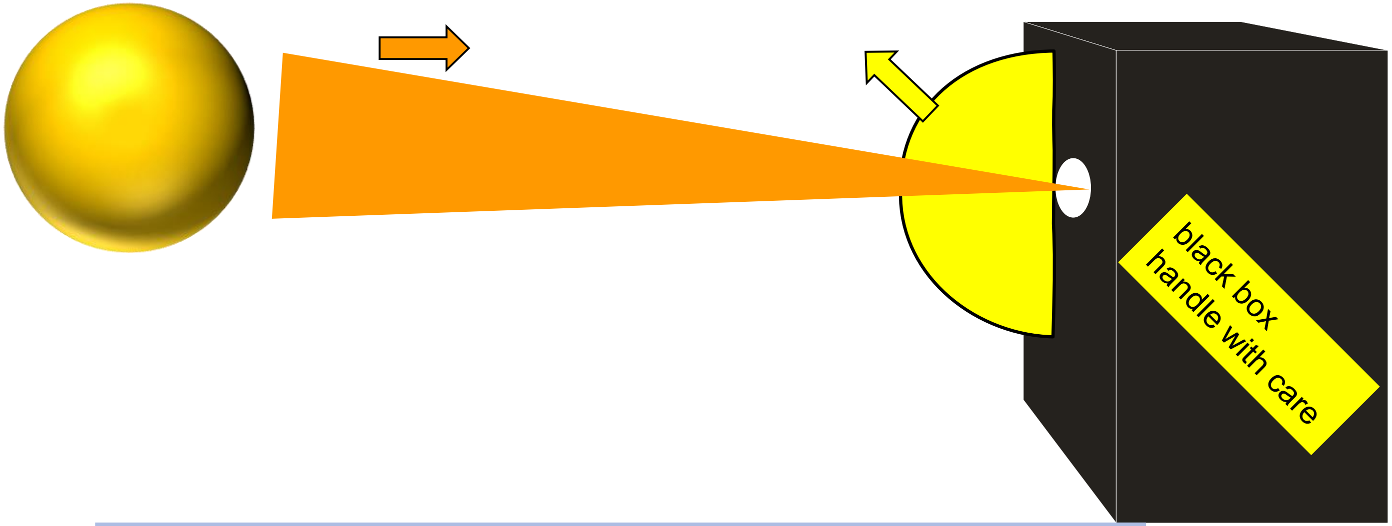
$$\boxed{\phi(E) = a(E)\phi_{bb}(E)e^{qV/kT}}$$

Non-equilibrium

Balance Between Generation and Recombination



The Current-Voltage Curve



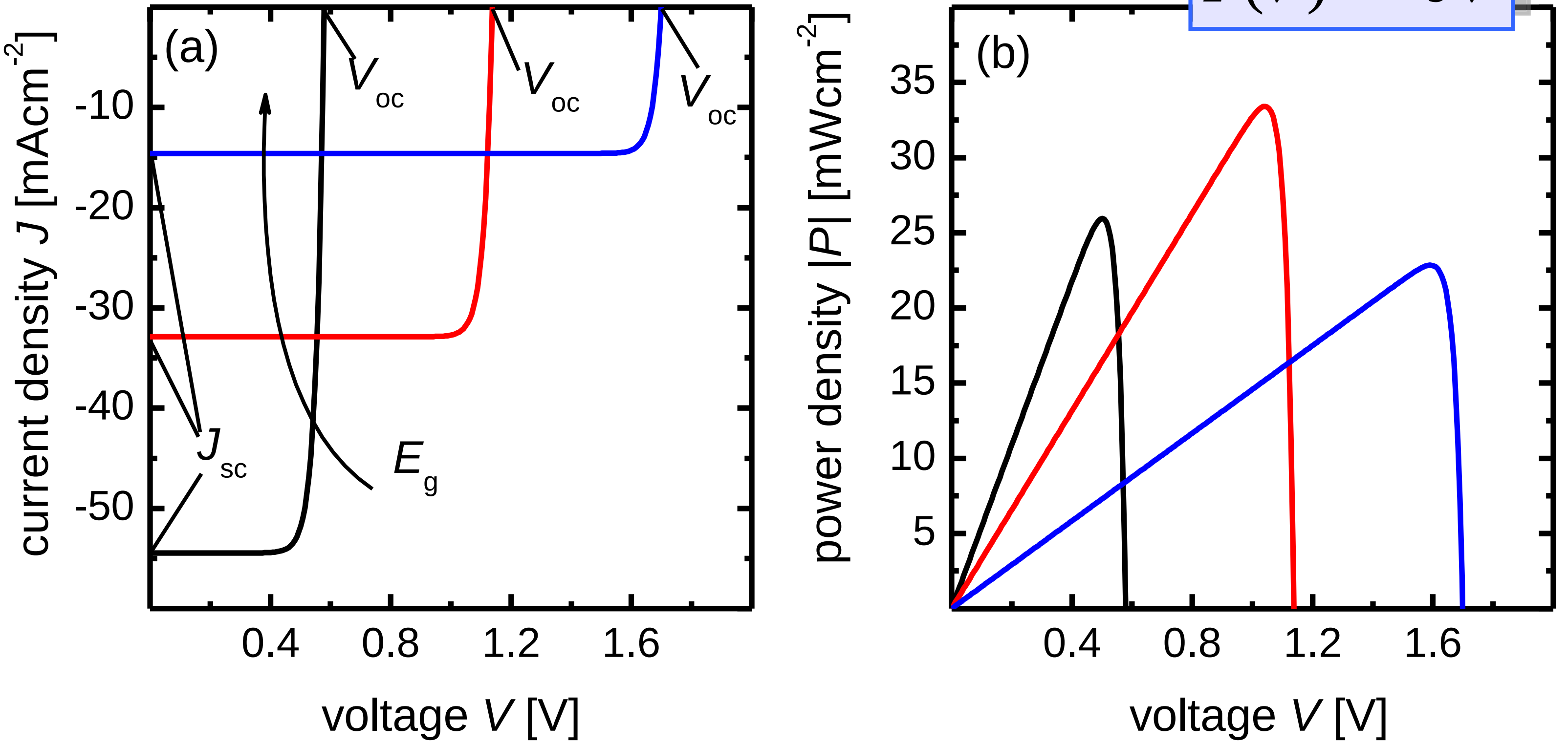
$$J = J_{\mathrm{d}} - J_{\mathrm{sc}}$$

$$= q\int a(E)\phi_{\mathrm{bb}}(T_{\mathrm{sc}}, E)dE\left[\exp\left(\frac{qV}{kT}\right) - 1\right] - J_{\mathrm{sc}}$$

Current Density and Power Density

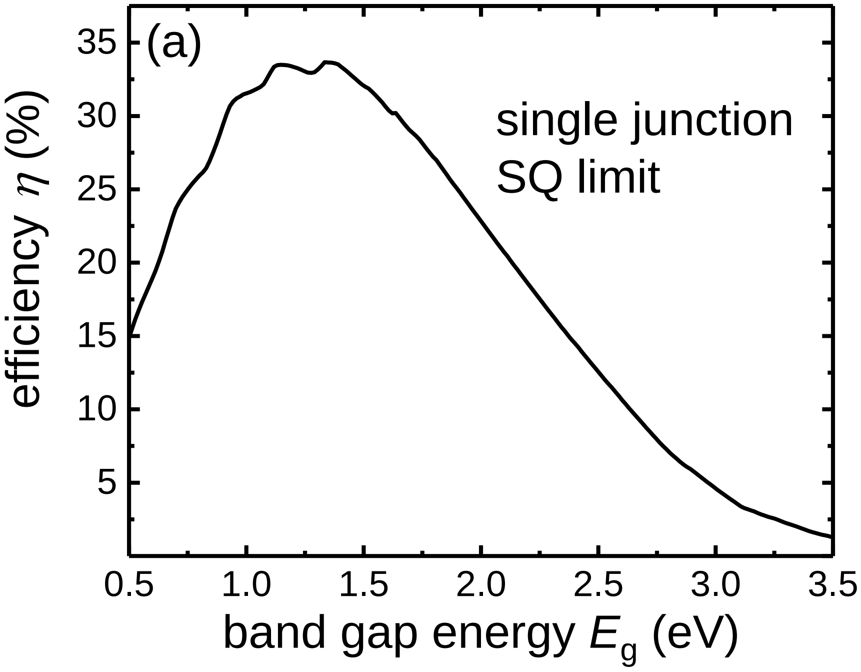
vs. Voltage

$$P(V) = -JV$$

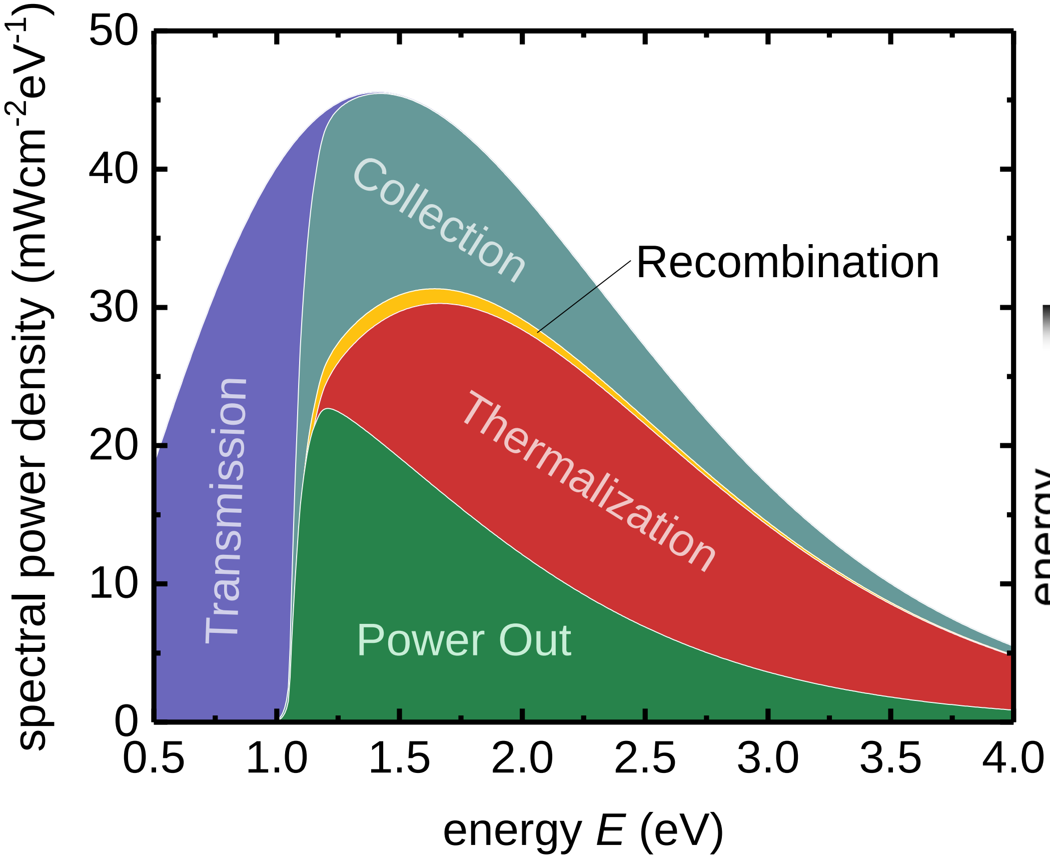


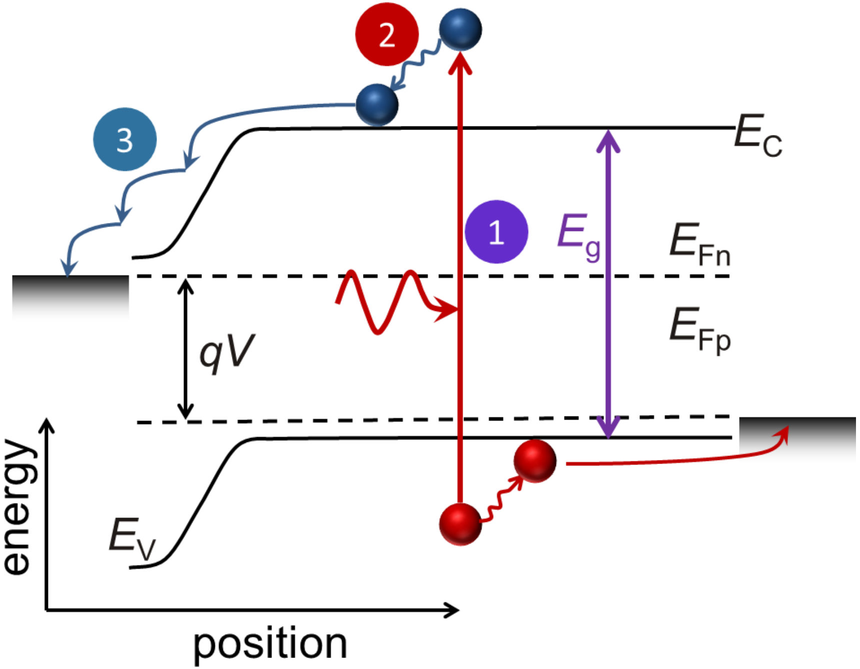
Shockley-Queisser Limit

Shockley and Queisser, J. Appl. Phys. (1961)

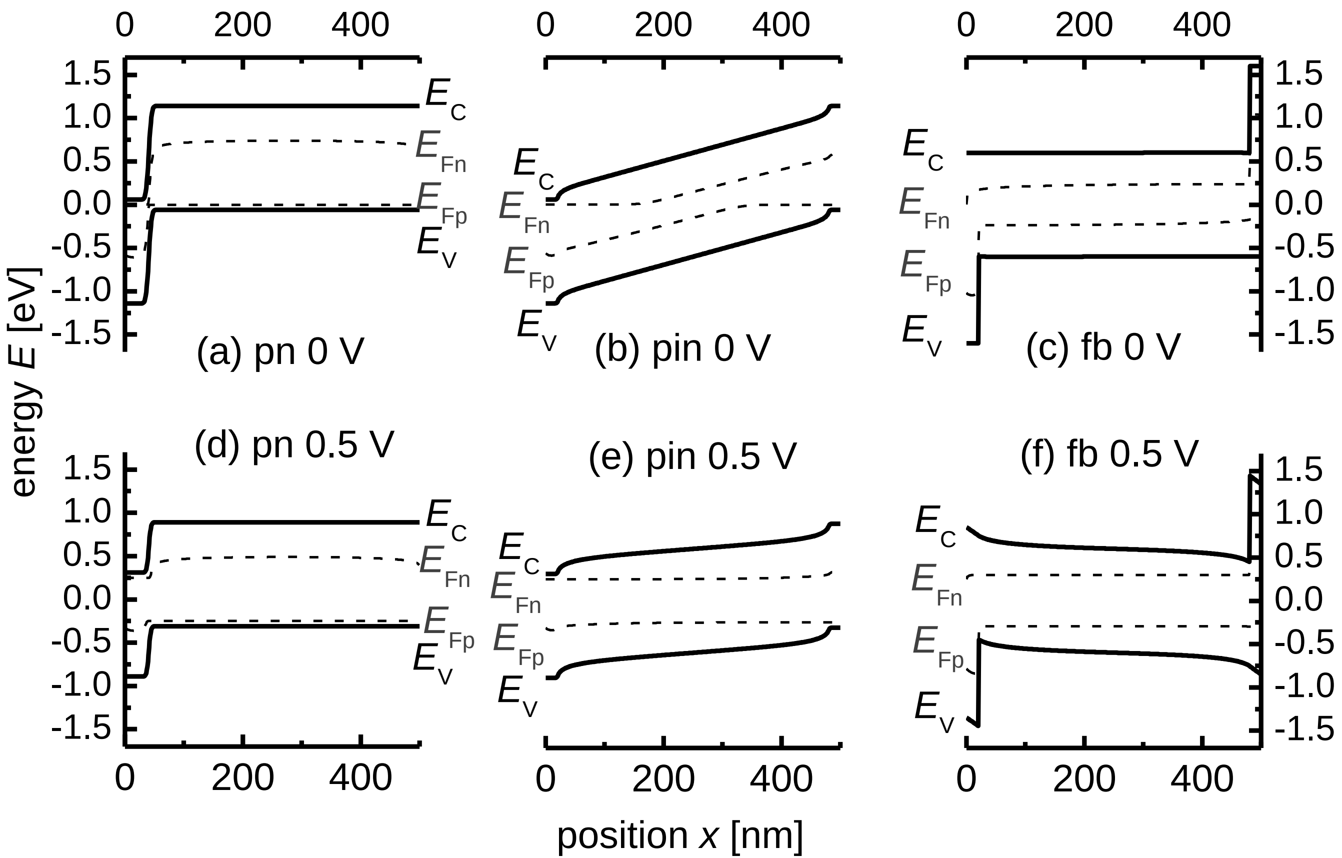


Losses in Silicon Solar Cell ($\eta \approx 27$ %)



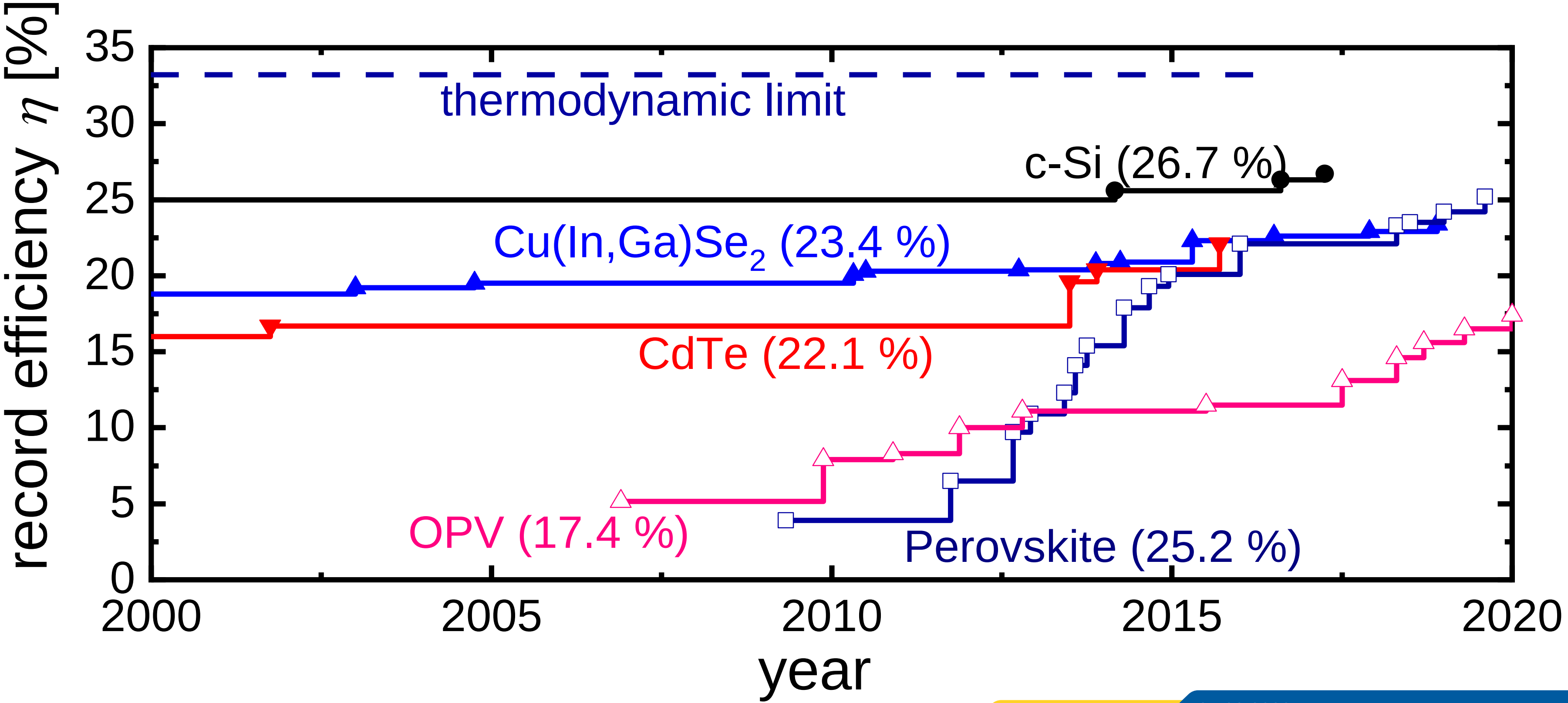


Which band diagram is a bad idea?



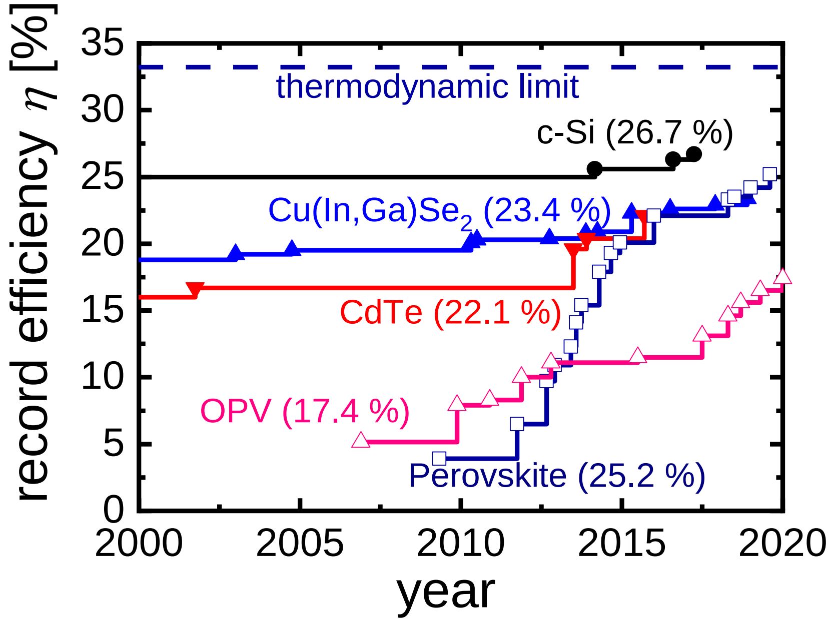
Do we need a pn-junction to make a solar cell?

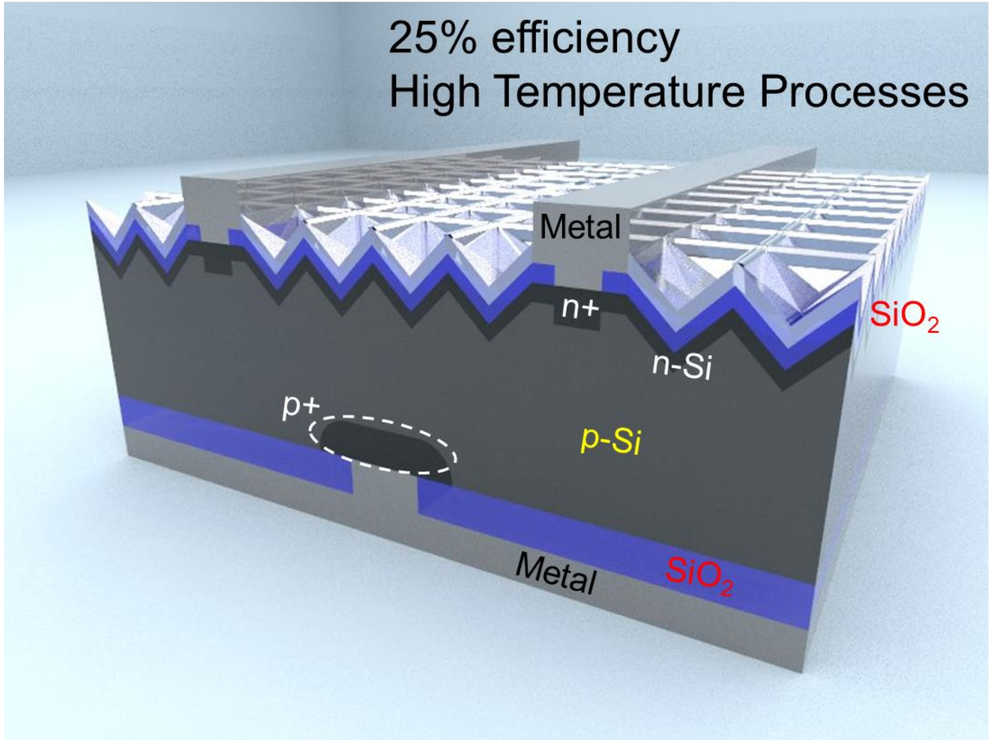
Efficiency trends for different PV technologies



Crystalline Si pn-junctions

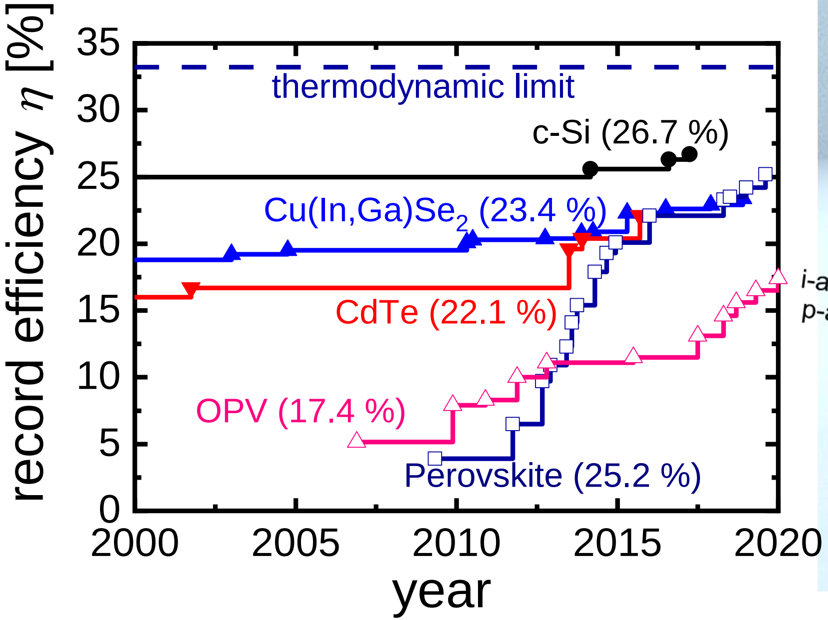
Diffused emitters





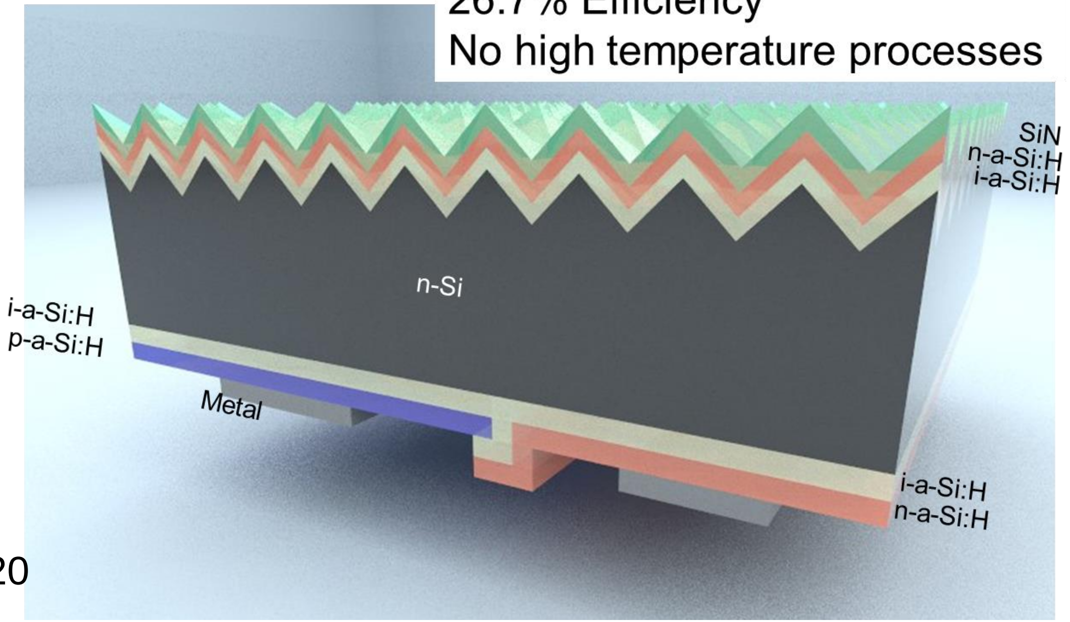
Crystalline Si solar cells

Heterojunction solar cells

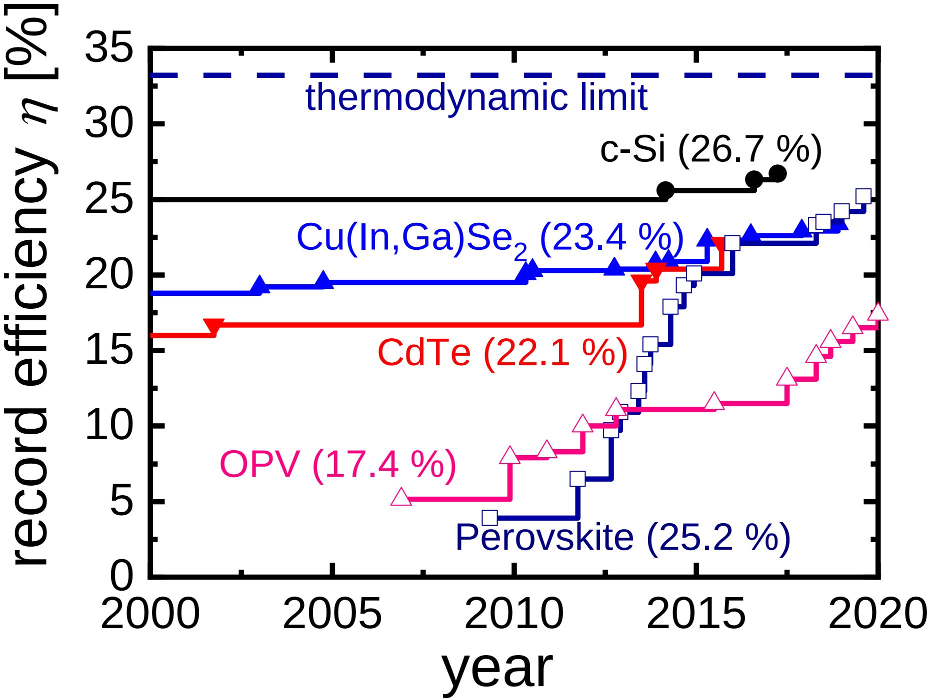


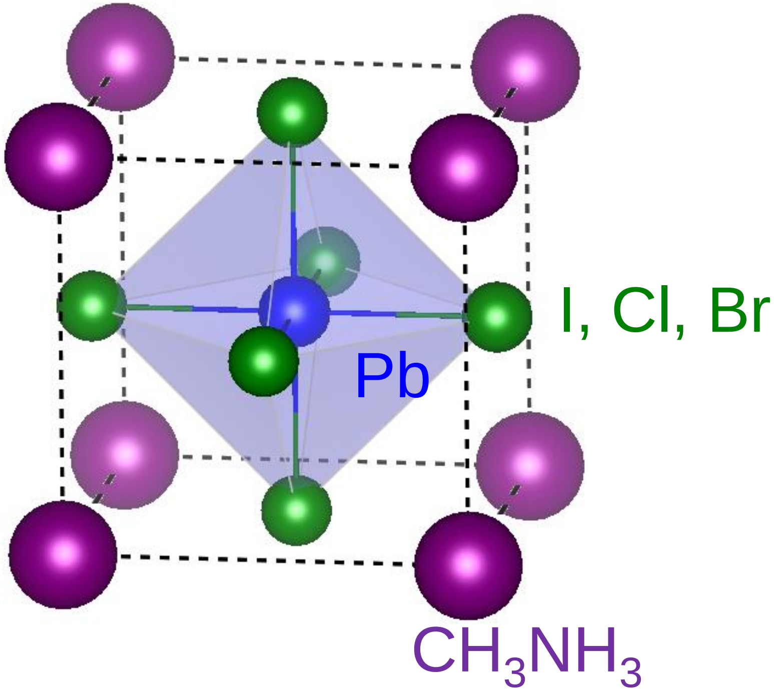
26.7% Efficiency

No high temperature processes



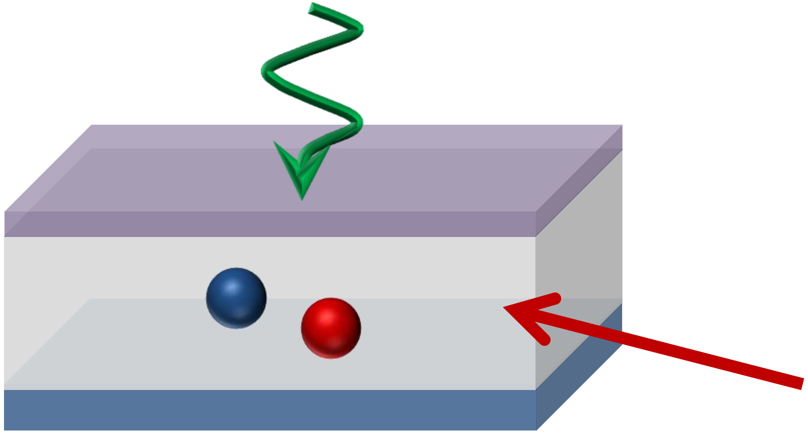
Halide-Perovskites

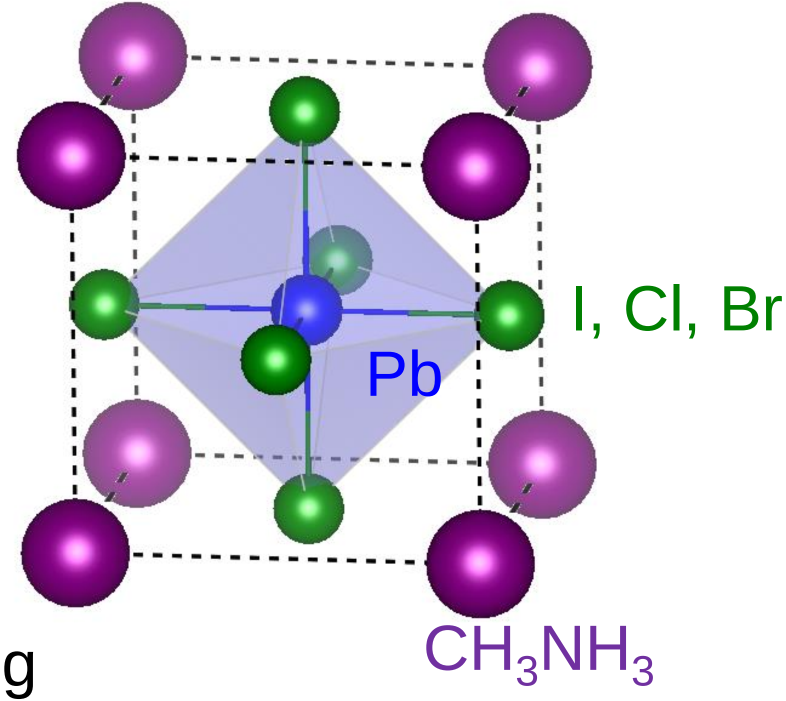




Halide-Perovskite Solar Cells

Absorber layer

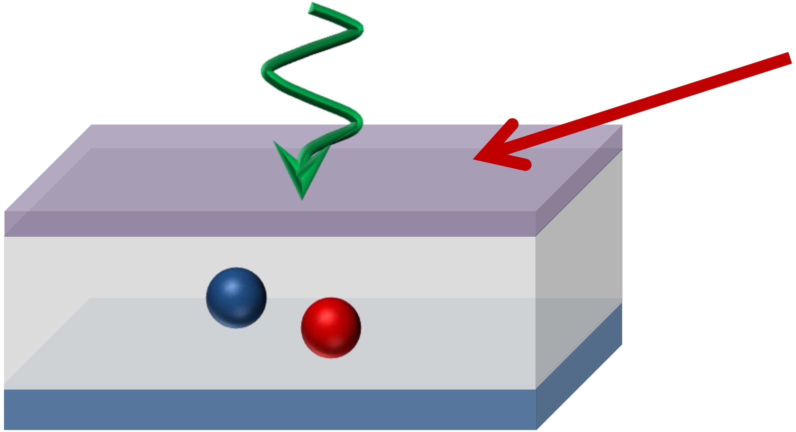


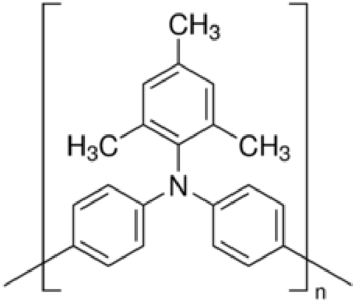


Fabricated e.g. by spin coating

Halide-Perovskite Solar Cells

Hole transport layer

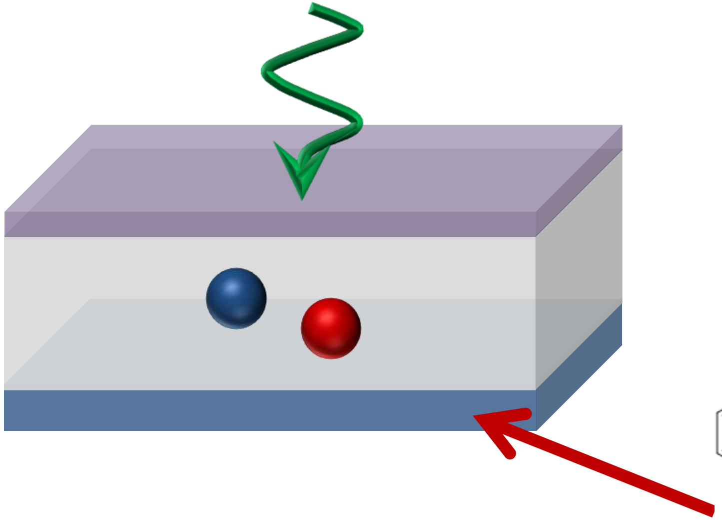


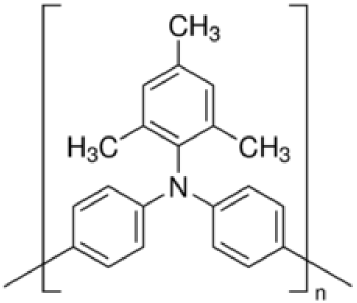


poly(triaryl amine)
called **PTAA**

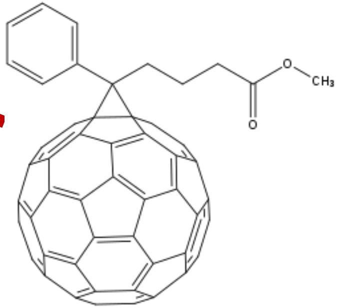
Halide-Perovskite Solar Cells

Electron transport layer





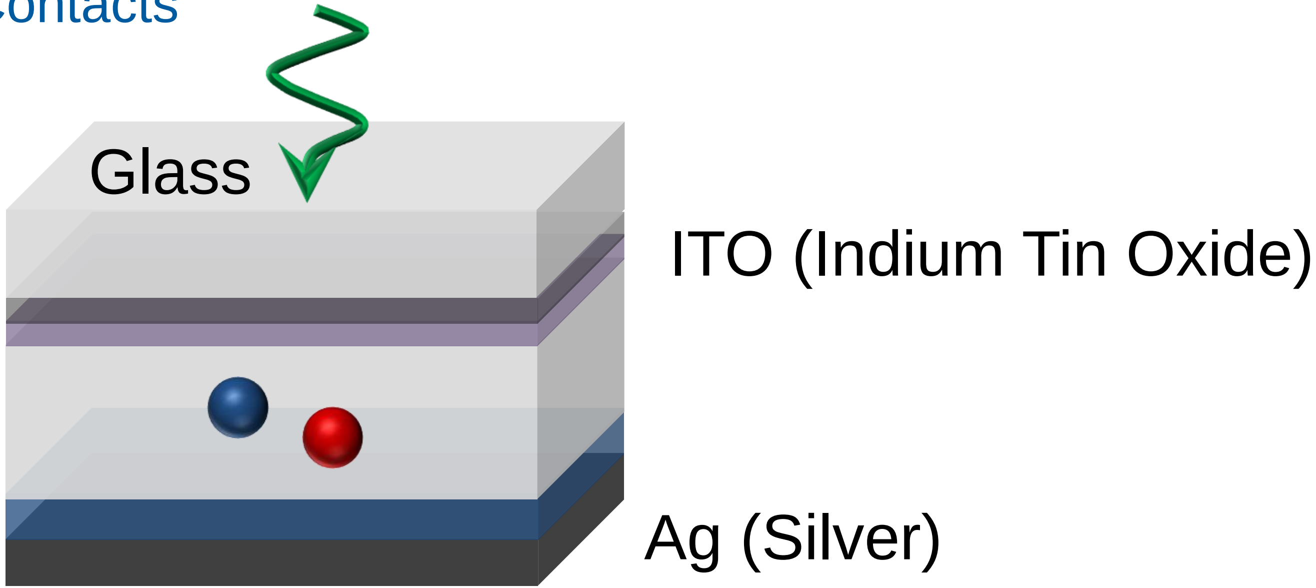
poly(triaryl amine) called **PTAA**



[6,6]-phenyl-C_{61}-butyric acid methyl ester called **PCBM**

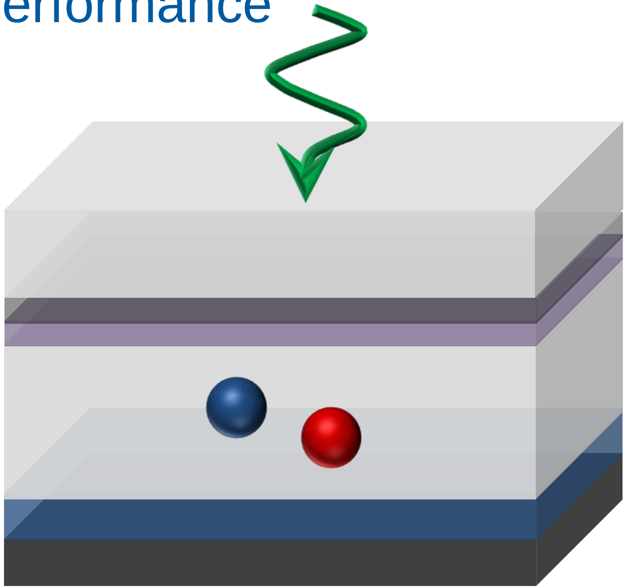
Halide-Perovskite Solar Cells

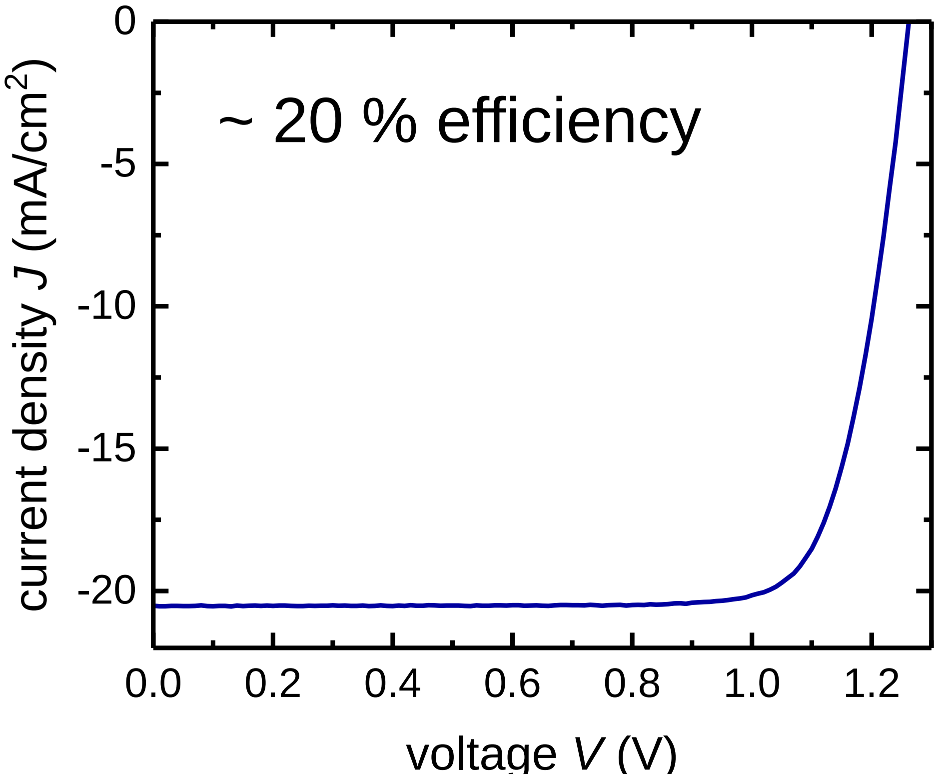
Contacts



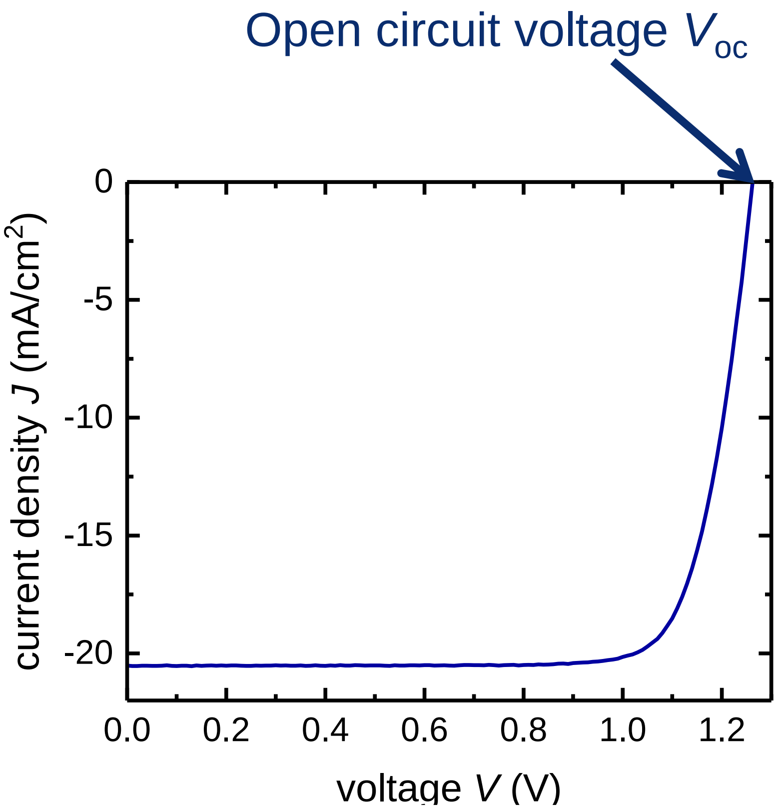
Halide-Perovskite Solar Cells

Performance

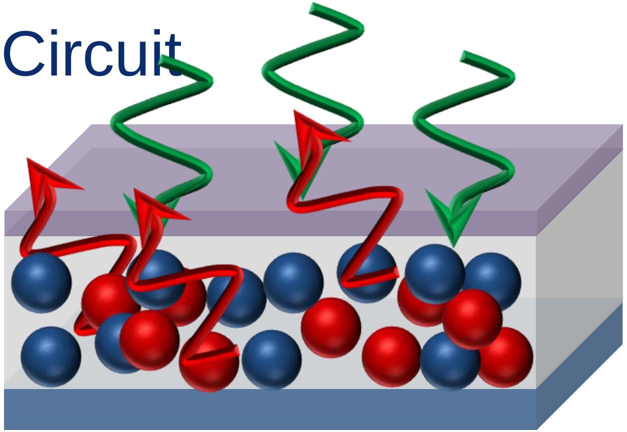




Solar Cell Basics



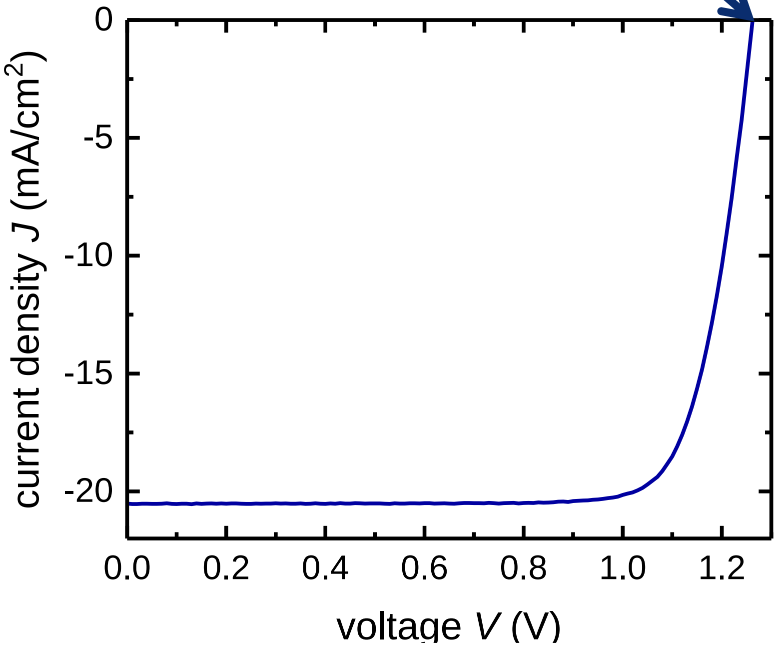
Open Circuit



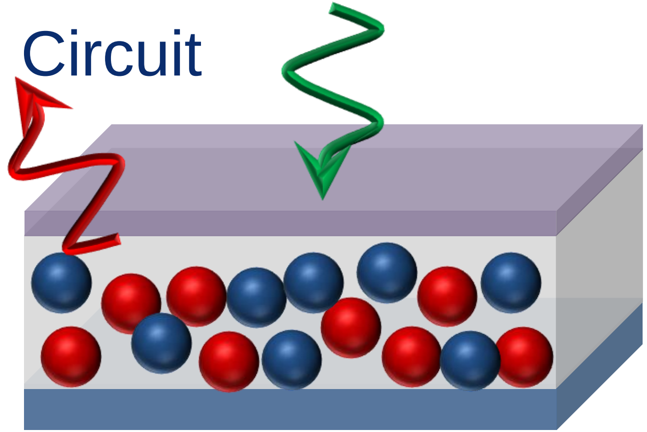
Open circuit voltage is controlled by recombination (radiative or non-radiative)

Solar Cell Basics

Open circuit voltage V_{oc}



Open Circuit

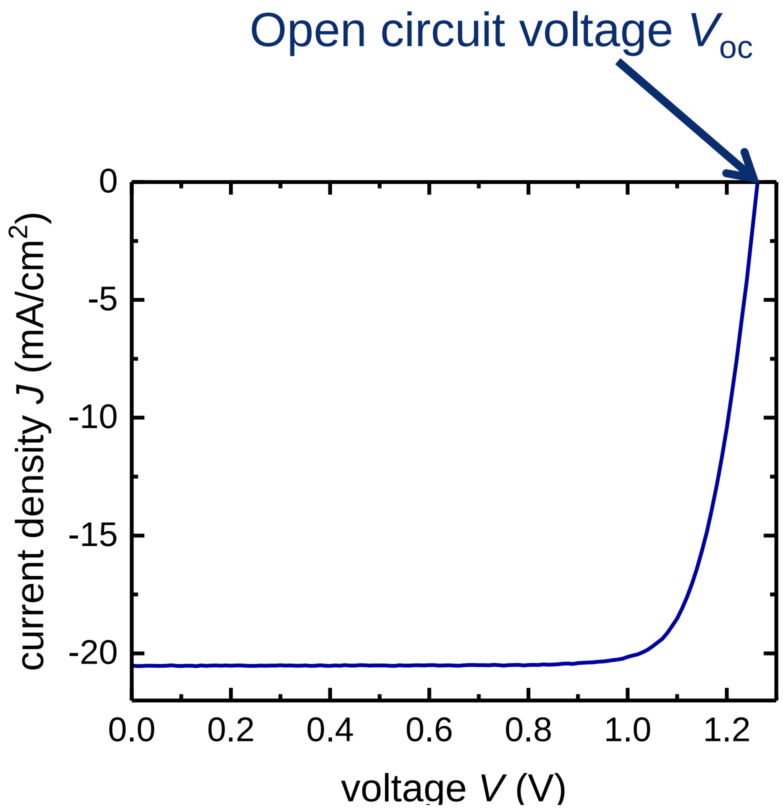


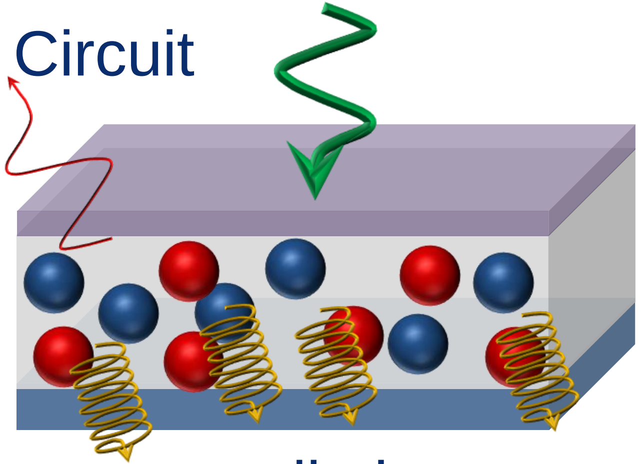
Ideal case: Only radiative recombination

$$V_{oc} = V_{oc}^{rad}$$

$$Q_e^{lum} = 1$$

Luminescence and open-circuit voltage





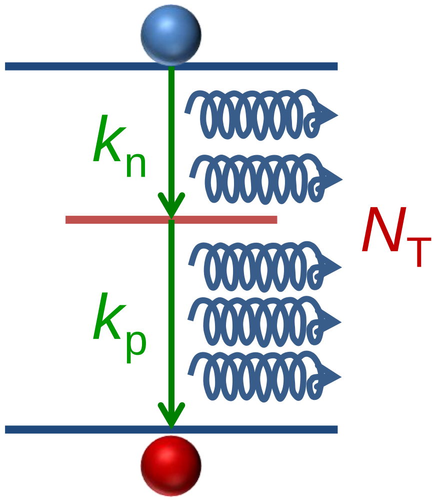
Real case: non-radiative recombination

$$V_{oc} = V_{oc}^{rad} - \frac{kT}{q}\left|\ln\left(Q_e^{lum}\right)\right|$$

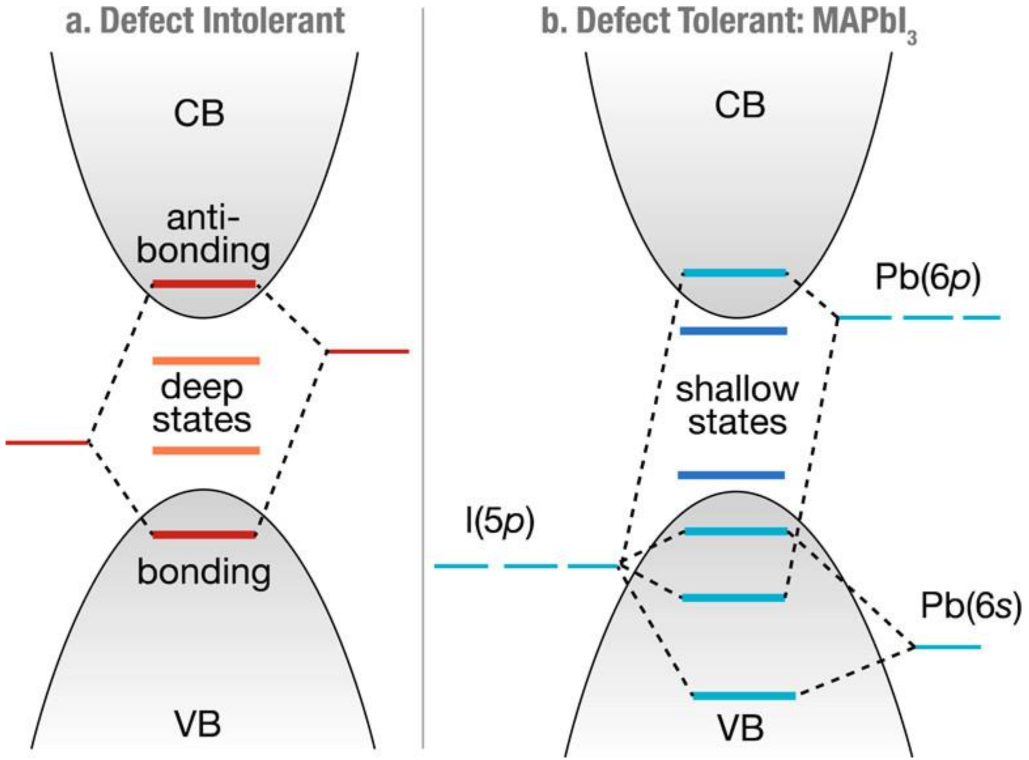
$$Q_e^{lum} < 1$$

Defect Positions

Antibonding valence bands

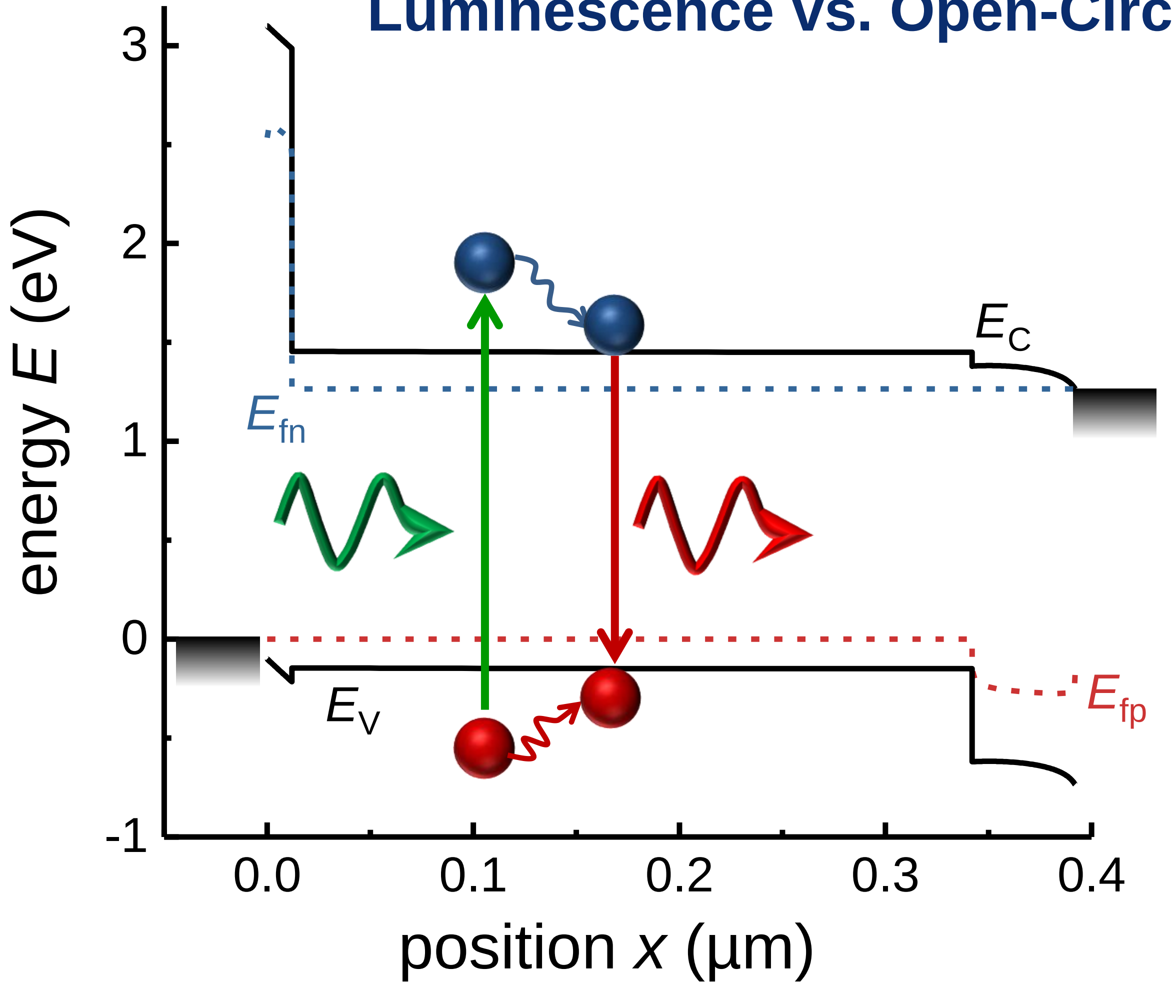


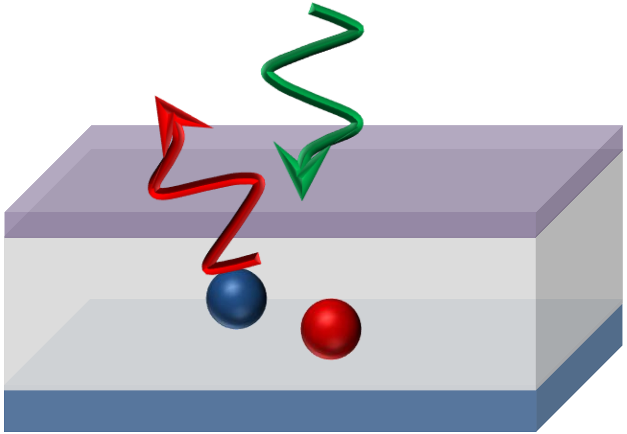
How many defects exist per volume?



Brandt et al., Chem. Mater. **29**, 4667 (2017)

Luminescence vs. Open-Circuit Voltage



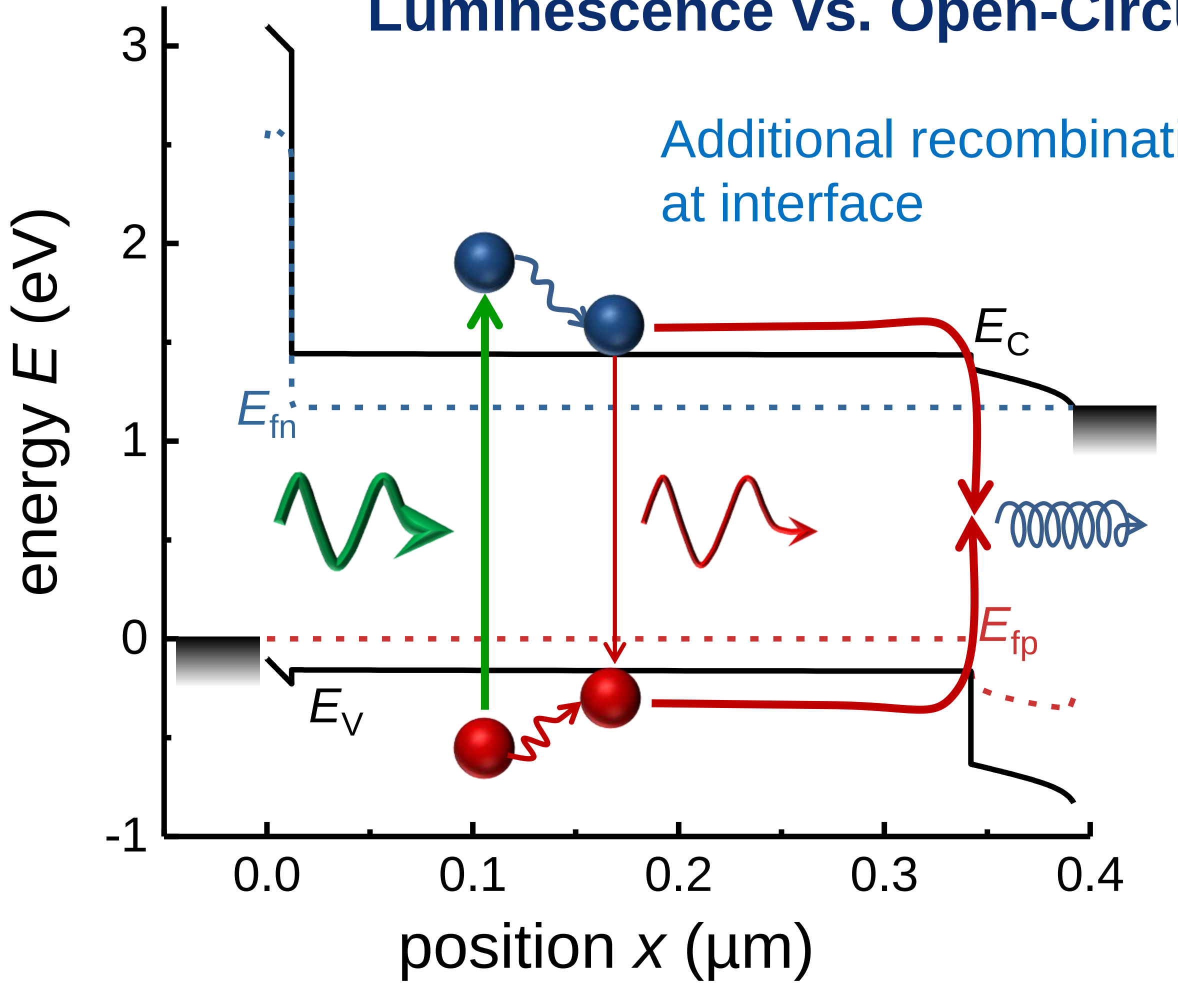


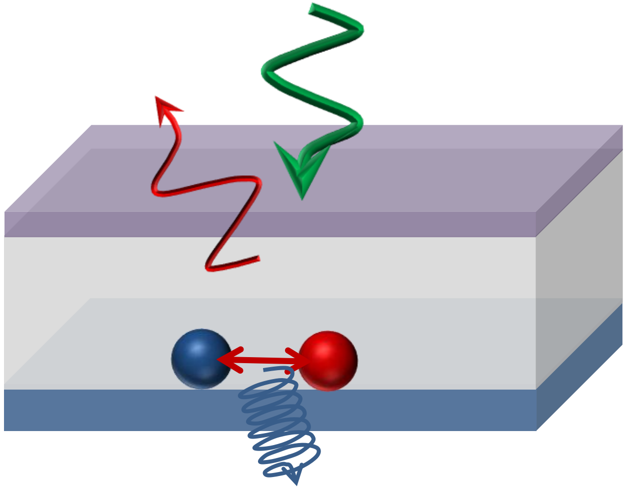
Radiative limit:

$$V_{oc} = V_{oc}^{rad}$$

$$Q_e^{lum} = 1$$

Luminescence vs. Open-Circuit Voltage





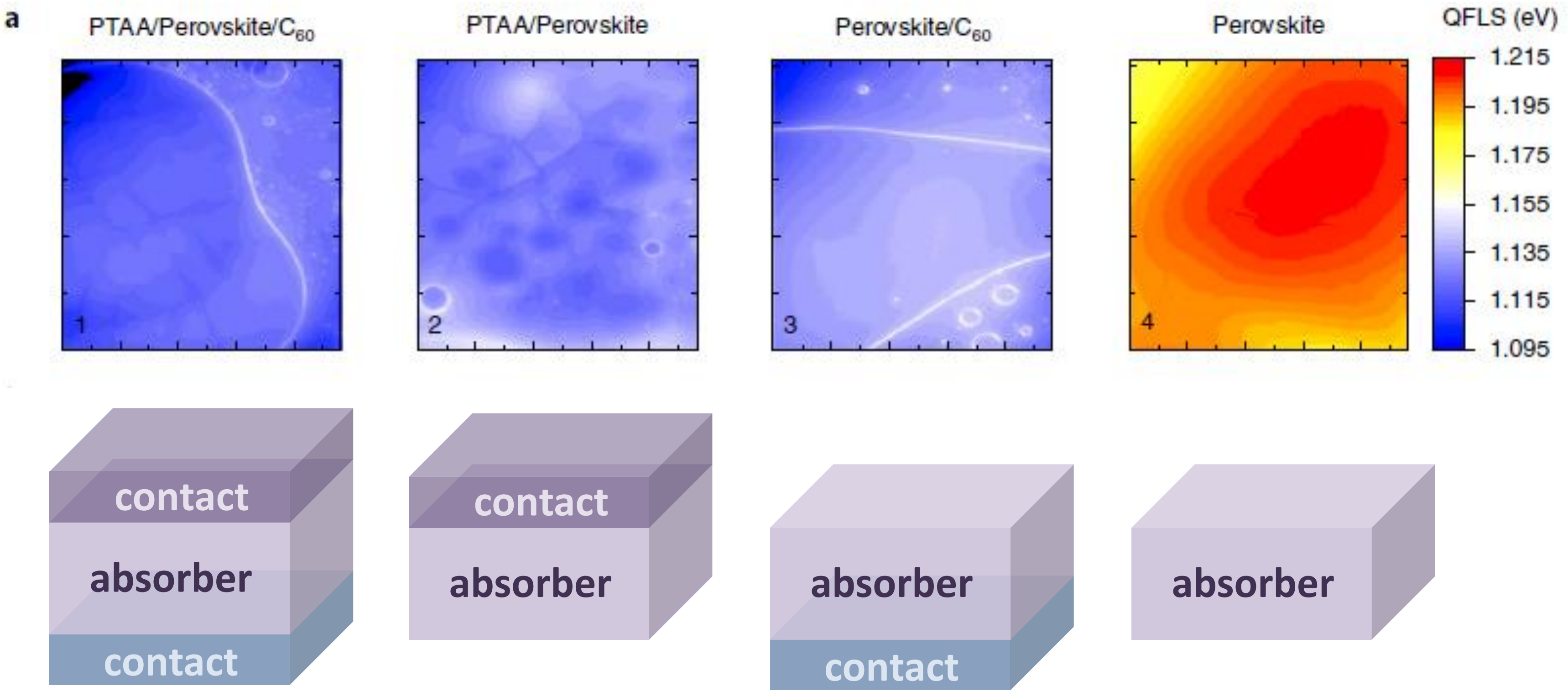
Non-radiative recombination:

$$V_{oc} = V_{oc}^{rad} + \frac{kT}{q} \ln\left(Q_e^{lum}\right)$$

$$Q_e^{lum} \ll 1$$

Steady-State PL

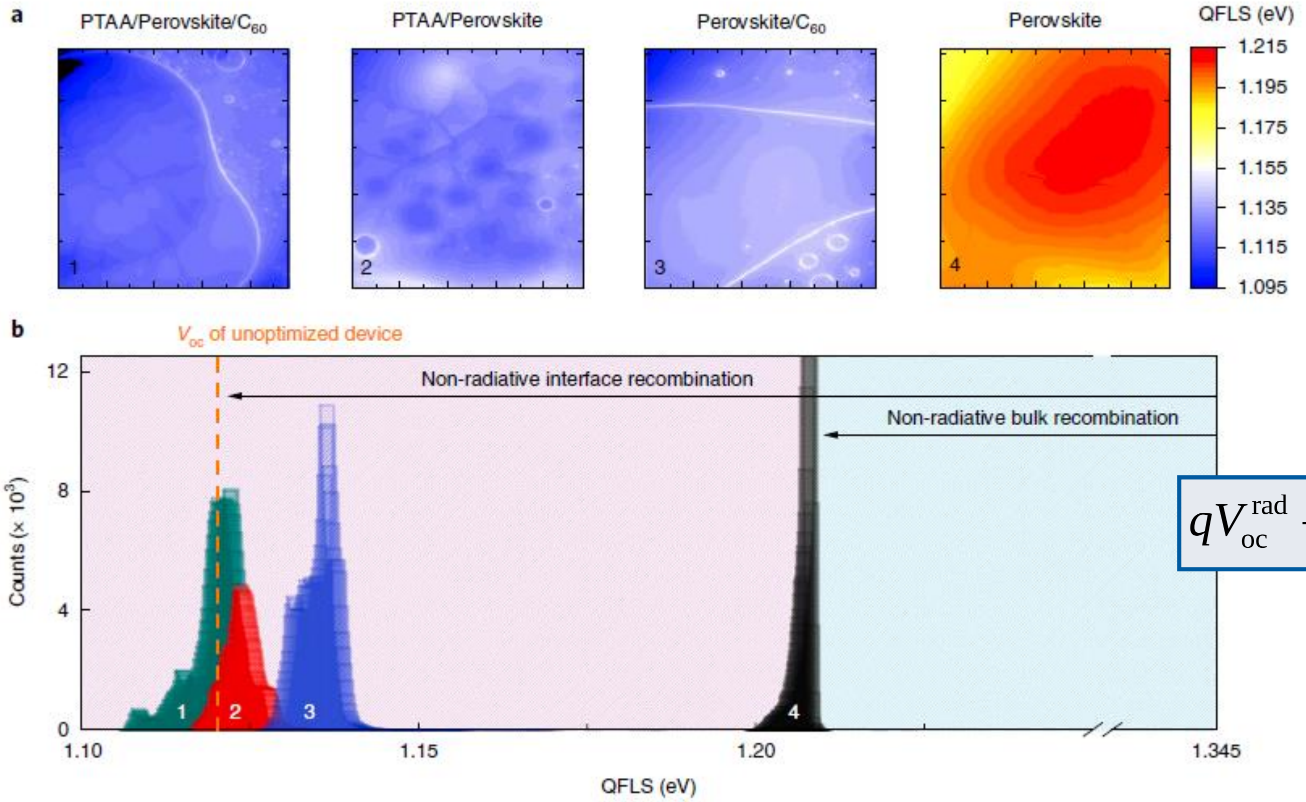
Measuring indirectly the quasi-Fermi-level splitting



Stolterfoht et al. Nature Energy (2018)

Steady-State PL

Measuring indirectly the quasi-Fermi-level splitting



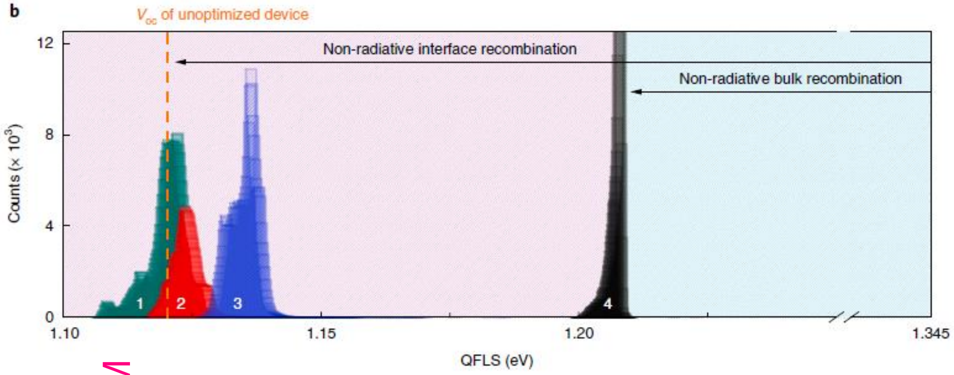
$$kT\ln(10) \approx 60\mathrm{meV}$$

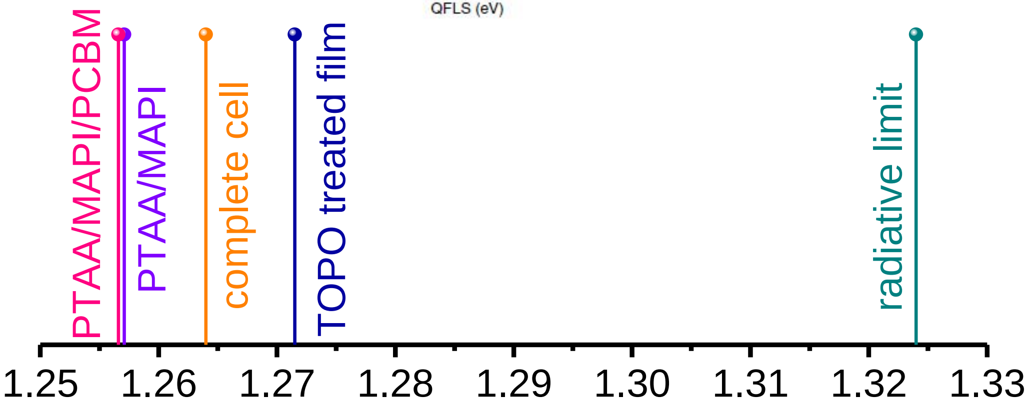
$$qV_{oc}^{rad} - qV_{oc} = -kT\ln\left(Q_e^{lum}\right) > 0$$

Stolterfoht et al. Nature Energy (2018)

Steady-State PL

Measuring indirectly the quasi-Fermi-level splitting





$$\boxed{kT\ln(10)\approx 60\mathrm{meV}}$$

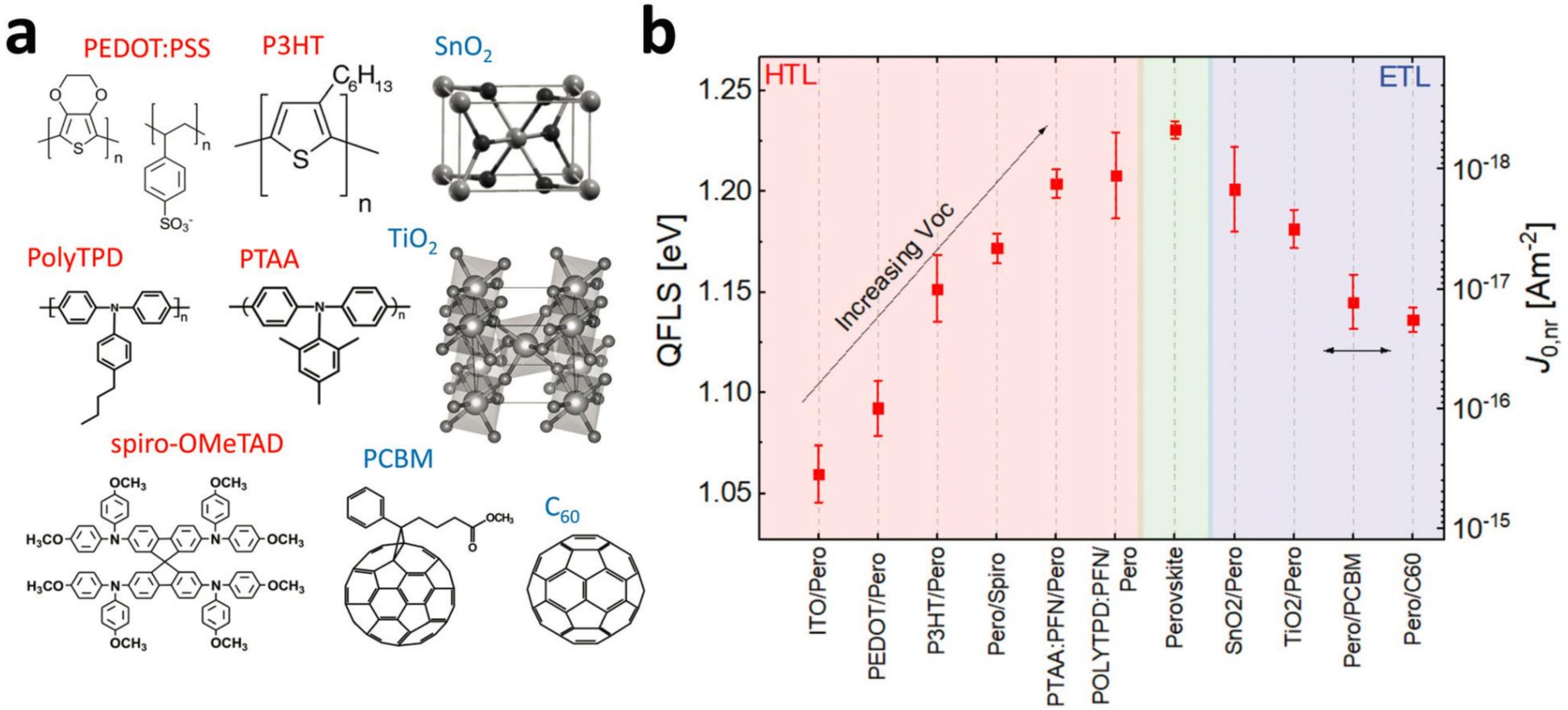
Stolterfoht et al. Nature Energy (2018)

$$\boxed{qV_{oc}^{rad}-qV_{oc}=-kT\ln\left(Q_e^{lum}\right)>0}$$

Liu et al., ACS Energy Lett. **4**, 110 (2019)

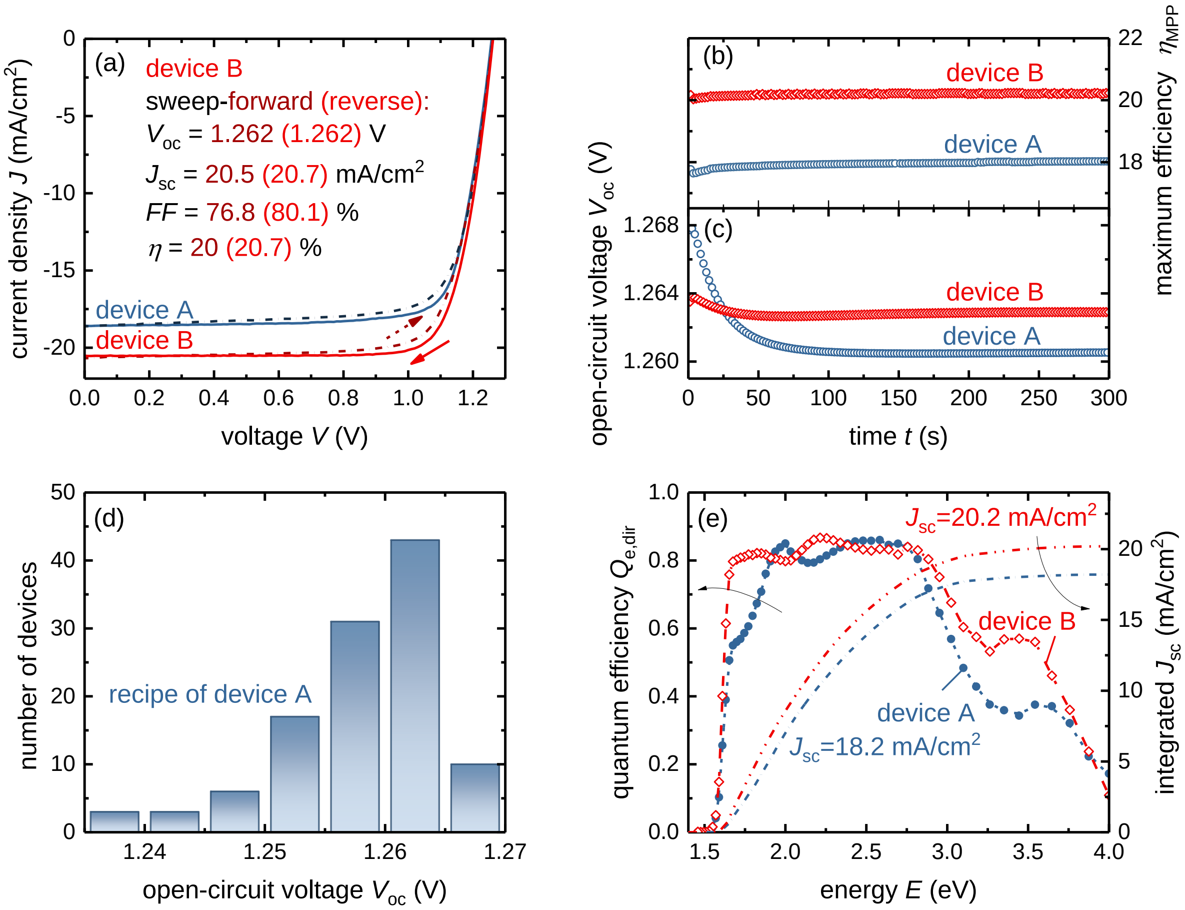
Screening of contact layers for high V_{oc}

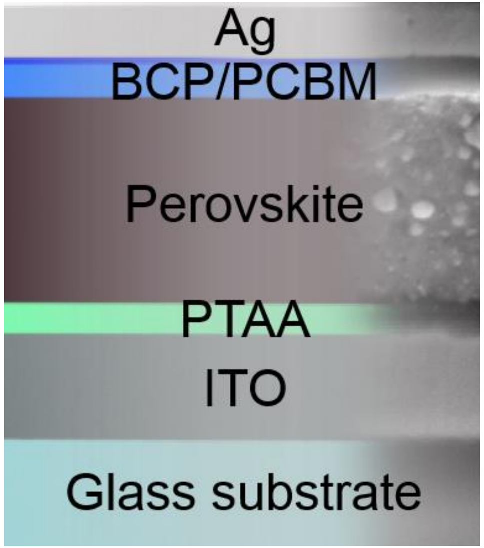
Triple cation recipe from Potsdam University



Stolterfoht et al. Energy Environ. Science (2019)

MAPI cells with $PbAc_2$ recipe

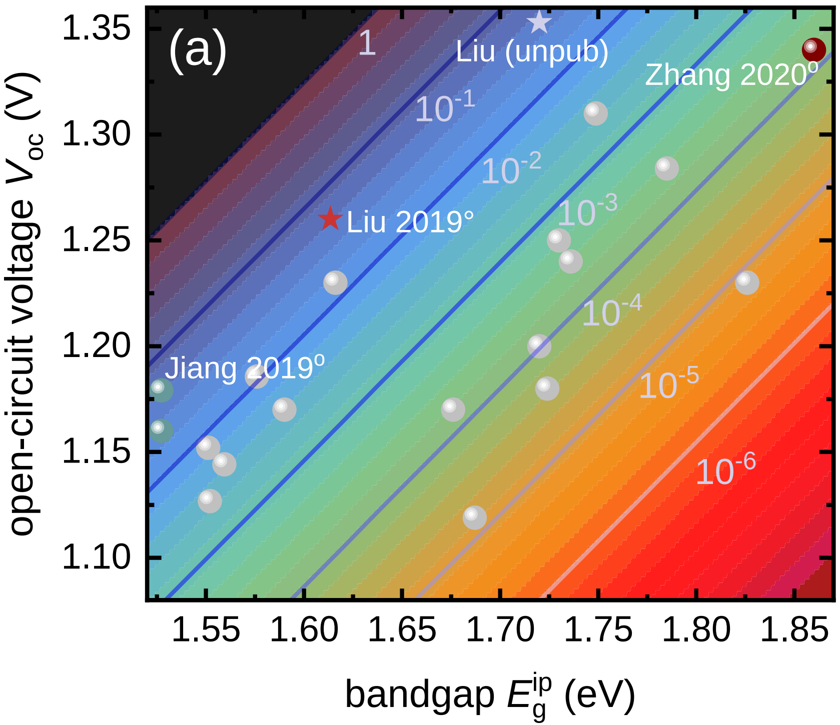


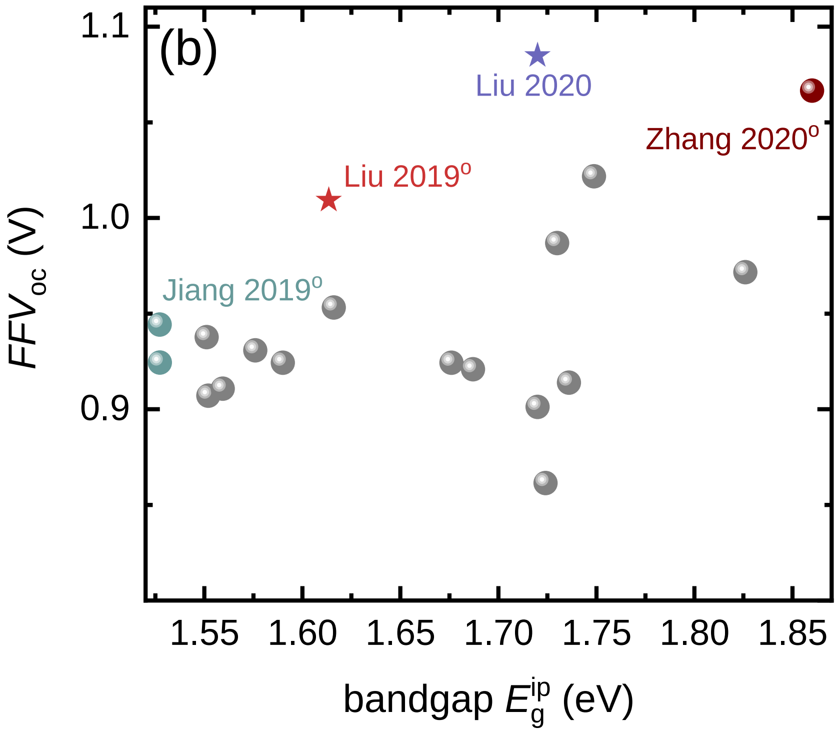


Liu et al., ACS Energy Lett. **4**, 110 (2019)

$CH_3NH_3Pb(I_{0.8}Br_{0.2})_3$ Solar Cells

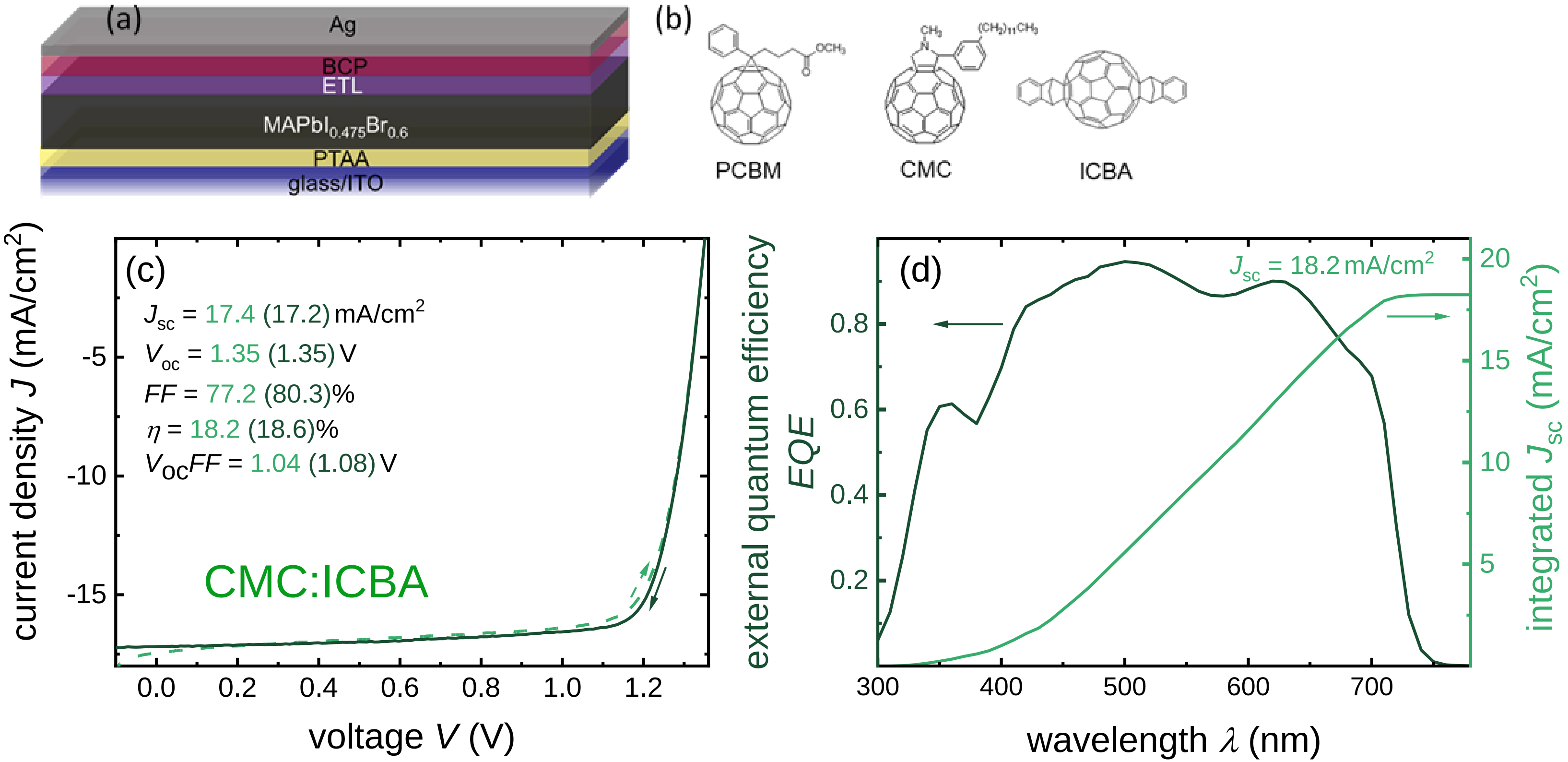
Difficulty of achieving E_g ~ 1.7 eV @ high V_{oc}





Liu, Siekmann et al. to be published

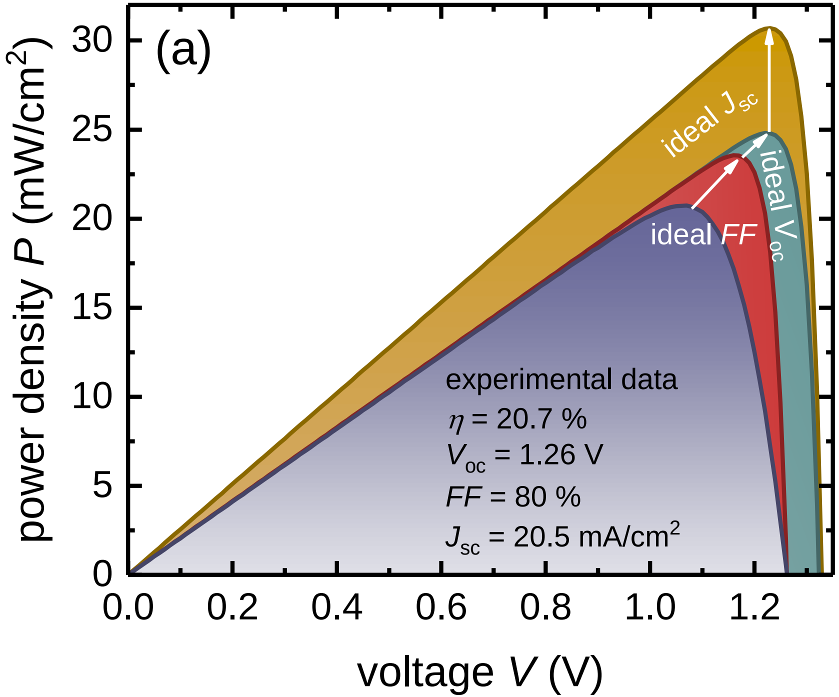
$CH_3NH_3Pb(I_{0.8}Br_{0.2})_3$ Solar Cells

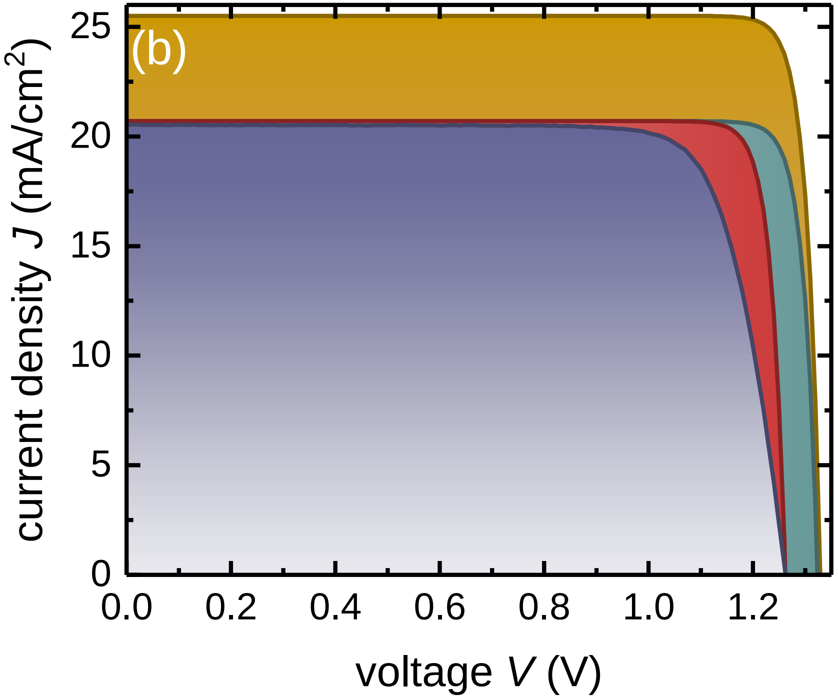


Liu, Siekmann et al. to be published

Loss Analysis

Comparison to the SQ model

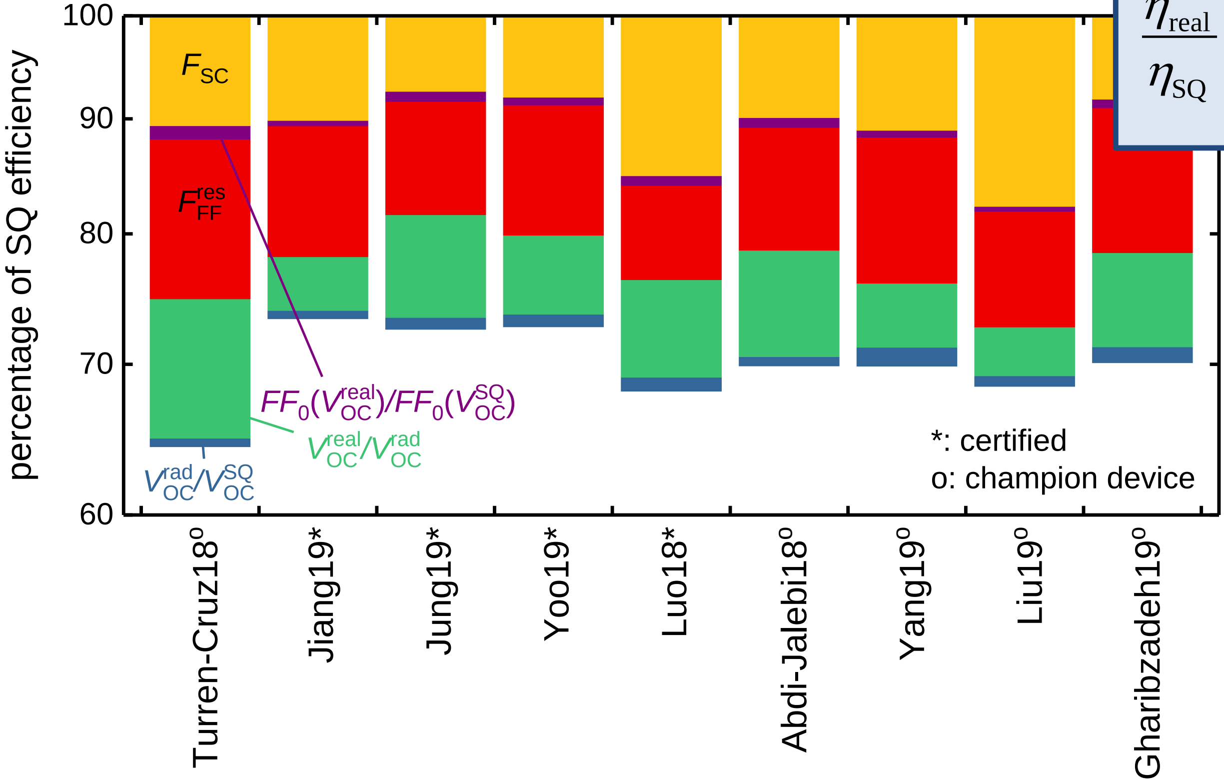




Development of perovskite solar cell efficiencies

…and associated losses

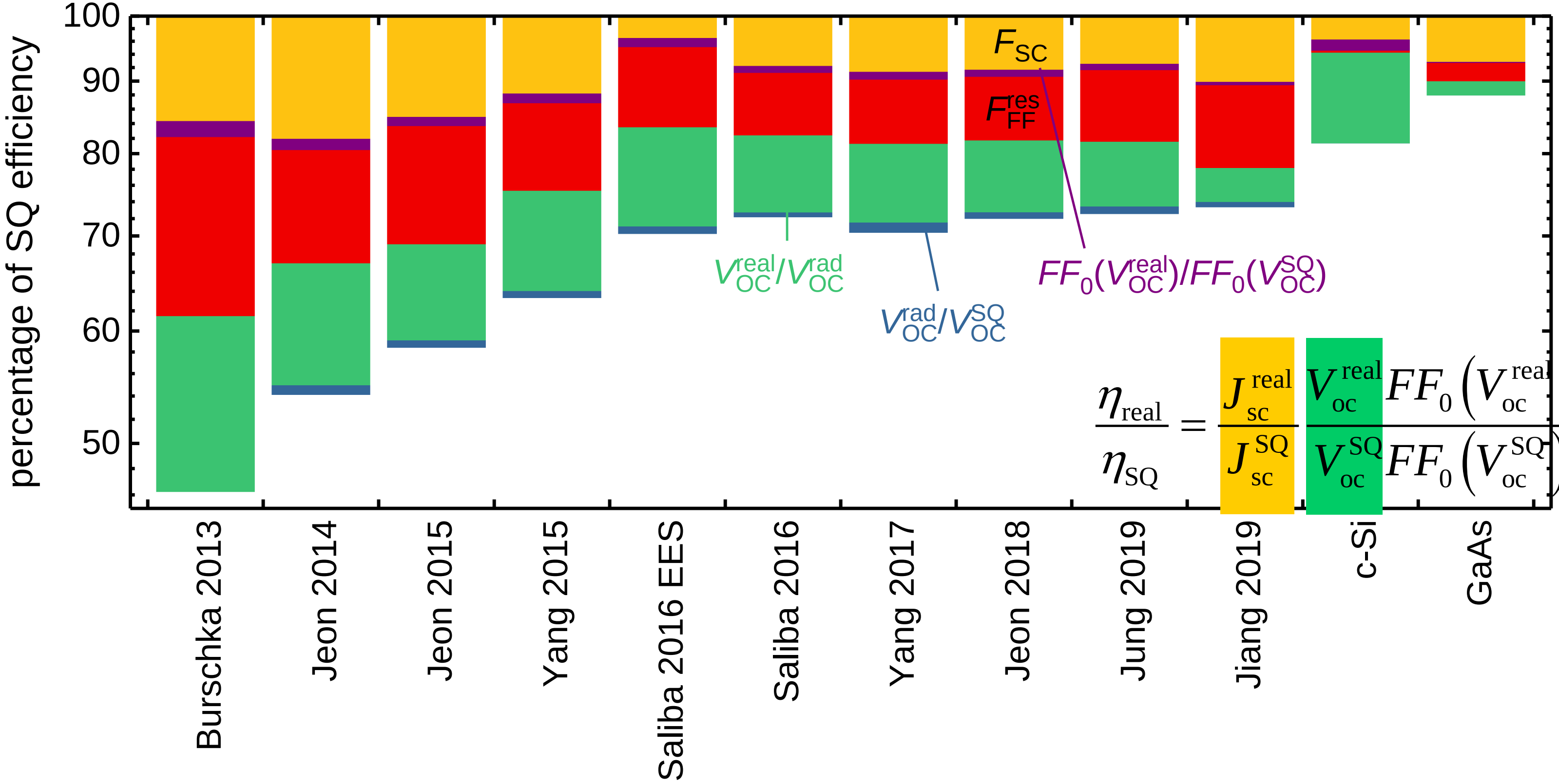
$$\frac{\eta_{\mathrm{real}}}{\eta_{\mathrm{SQ}}} = \frac{J_{\mathrm{sc}}^{\mathrm{real}}}{J_{\mathrm{sc}}^{\mathrm{SQ}}} \frac{V_{\mathrm{oc}}^{\mathrm{real}} FF_0\left(V_{\mathrm{oc}}^{\mathrm{real}}\right)}{V_{\mathrm{oc}}^{\mathrm{SQ}} FF_0\left(V_{\mathrm{oc}}^{\mathrm{SQ}}\right)} \frac{FF^{\mathrm{real}}}{FF_0\left(V_{\mathrm{oc}}^{\mathrm{real}}\right)}$$



Krückemeier et al. Adv. Energy Mater. 2020, Guillemoles et al. Nat. Photon. 2019

Development of perovskite solar cell efficiencies

…and associated losses



$$\frac{\eta_{real}}{\eta_{SQ}} = \frac{J_{sc}^{real}}{J_{sc}^{SQ}} \frac{V_{oc}^{real} FF_0\left(V_{oc}^{real}\right)}{V_{oc}^{SQ} FF_0\left(V_{oc}^{SQ}\right)} \frac{FF^{real}}{FF_0\left(V_{oc}^{real}\right)}$$

Krückemeier et al. Adv. Energy Mater. 2020, Guillemoles et al. Nat. Photon. 2019

Key remaining issues for perovskite PV

JÜLICH
Forschungszentrum

SOLAR CELLS

A piperidinium salt stabilizes efficient metal-halide perovskite solar cells

Yen-Hung Lin[1*], Nobuya Sakai[1], Peimei Da[1], Jiaying Wu[2], Harry C. Sansom[1], Alexandra J. Ramadan[1], Suhas Mahesh[1], Junliang Liu[3], Robert D. J. Oliver[1], Jongchul Lim[1†], Lee Aspitarte[4], Kshama Sharma[5], P. K. Madhu[5], Anna B. Morales-Vilches[6], Pabitra K. Nayak[1,5], Sai Bai[7], Feng Gao[7], Chris R. M. Grovenor[3], Michael B. Johnston[1], John G. Labram[4], James R. Durrant[2,8], James M. Ball[1], Bernard Wenger[1], Bernd Stannowski[6], Henry J. Snaith[1*]

nature sustainability
ARTICLES
https://doi.org/10.1038/s41893-020-0586-6

Check for updates

Sustainable lead management in halide perovskite solar cells

So Yeon Park[1,2,9], Ji-Sang Park[3,9], Byeong Jo Kim[1,4], Hyemin Lee[5], Aron Walsh[6,7], Kai Zhu[8], Dong Hoe Kim[5✉] and Hyun Suk Jung[1✉]

Lead (Pb)

SOLAR CELLS

Thermodynamically stabilized β-$CsPbI_3$–based perovskite solar cells with efficiencies >18%

Yong Wang[1], M. Ibrahim Dar[2*], Luis K. Ono[3], Taiyang Zhang[1], Miao Kan[1], Yawen Li[4], Lijun Zhang[4], Xingtao Wang[1], Yingguo Yang[5], Xingyu Gao[5], Yabing Qi[3*], Michael Grätzel[2*], Yixin Zhao[1,6*]

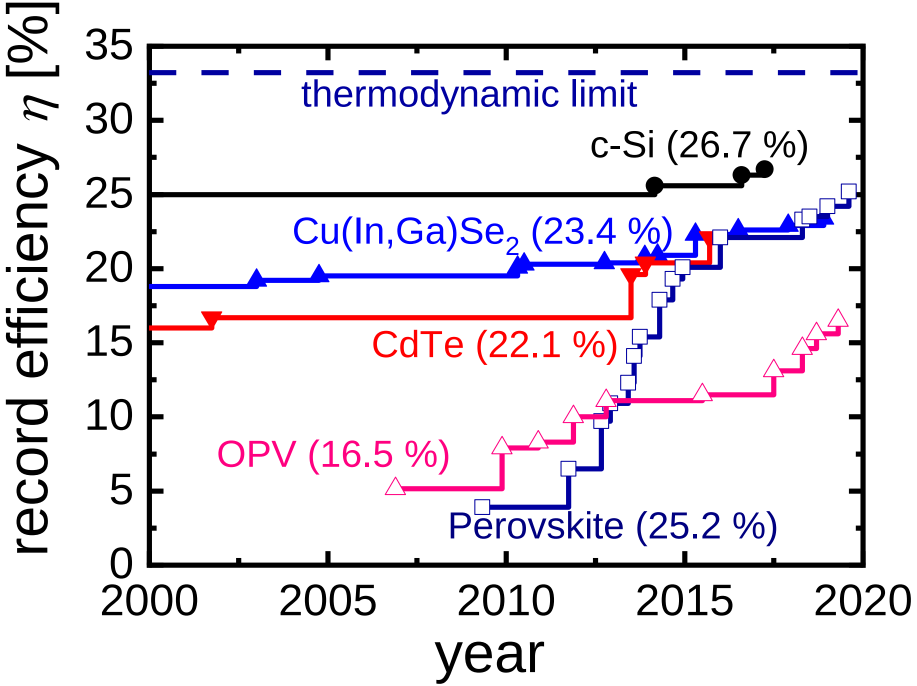
SOLAR CELLS

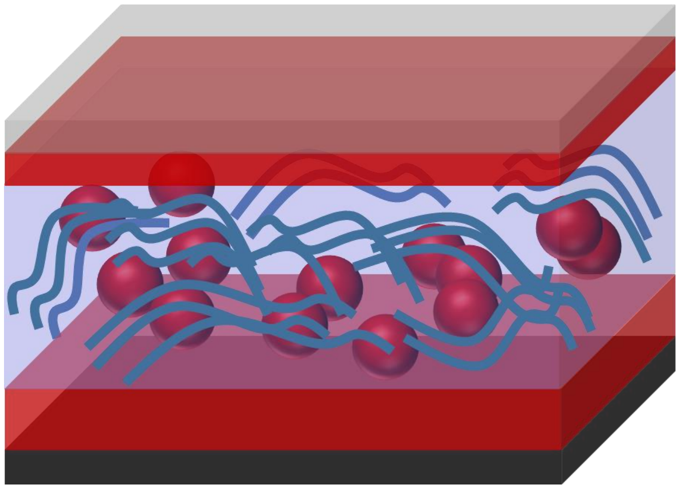
Stabilizing halide perovskite surfaces for solar cell operation with wide-bandgap lead oxysalts

Shuang Yang[1,2*], Shangshang Chen[1*], Edoardo Mosconi[3], Yanjun Fang[1,2], Xun Xiao[1], Congcong Wang[4], Yu Zhou[1], Zhenhua Yu[1], Jingjing Zhao[1,2], Yongli Gao[4], Filippo De Angelis[3,5,6], Jinsong Huang[1,2†]

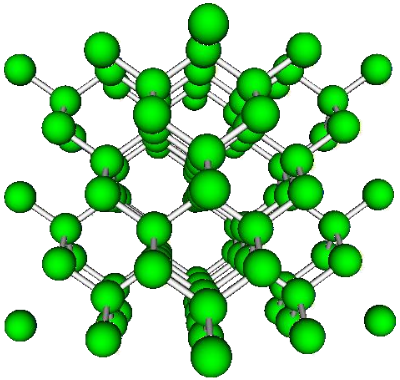
Stability

Organic Solar Cells

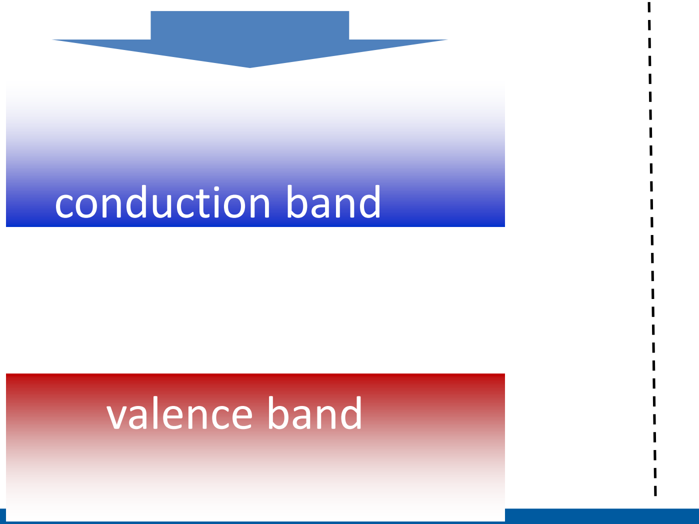




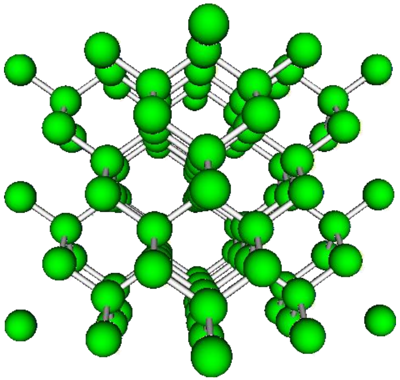
Inorganic vs. Organic semiconductors



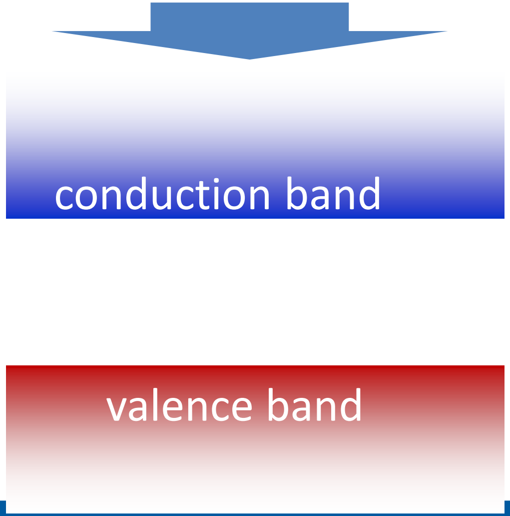
http://www.iue.tuwien.ac.at/phd/hoessinger/node26.html



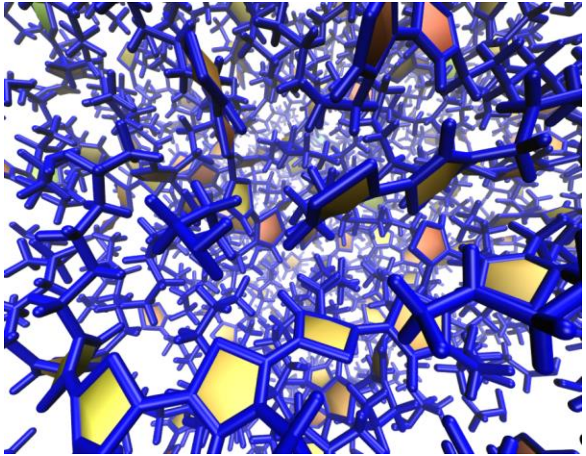
Inorganic vs. Organic semiconductors



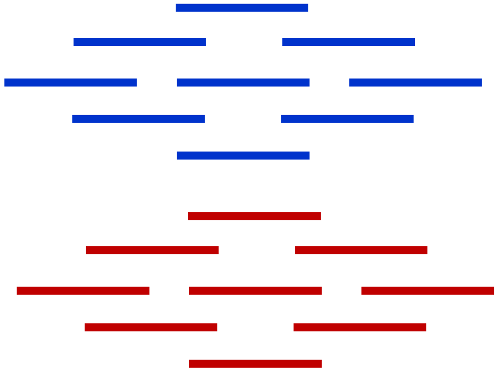
http://www.iue.tuwien.ac.at/phd/hoessinger/node26.html



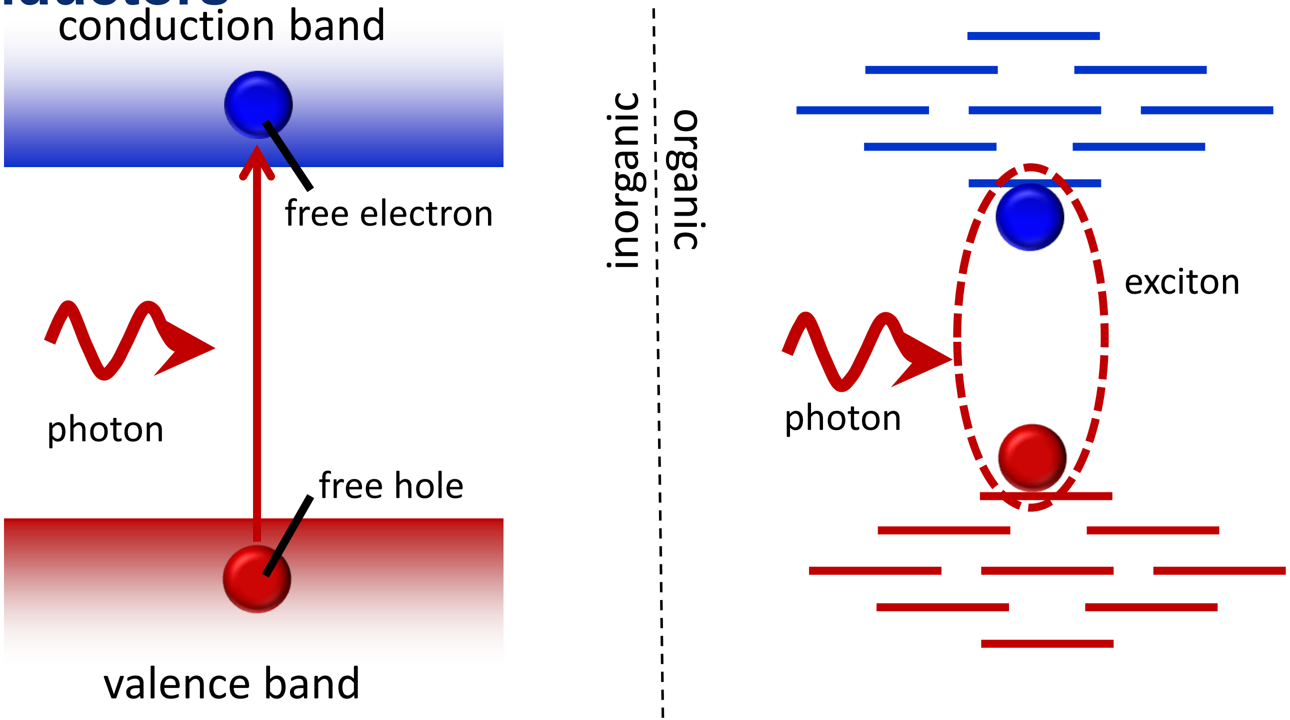
inorganic | organic



© Anne Guilbert, Imperial College London



Photoexcitation in inorganic vs. organic semiconductors

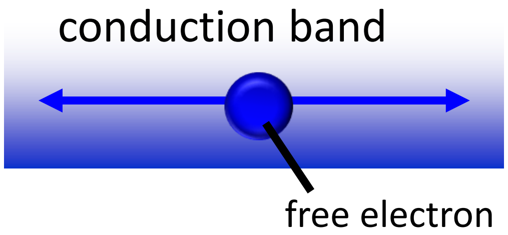


Coulomb binding of exciton

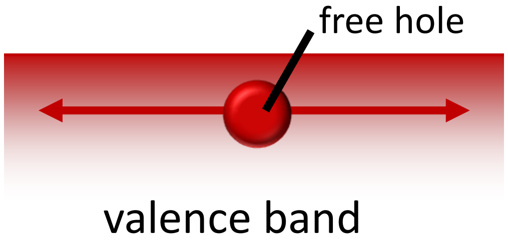
dielectric constant $\varepsilon_r > 10$

dielectric constant $\varepsilon_r \approx 3 - 4$

Charge Transport

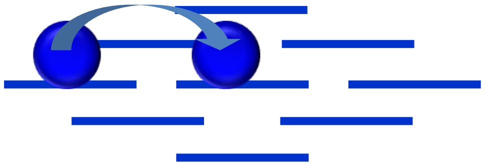


mobility:
μ = 1 to 10^4 cm^2/Vs

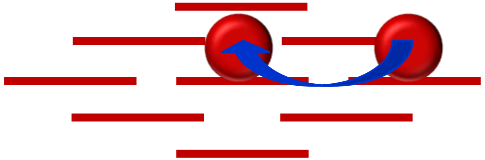


band transport

inorganic | organic

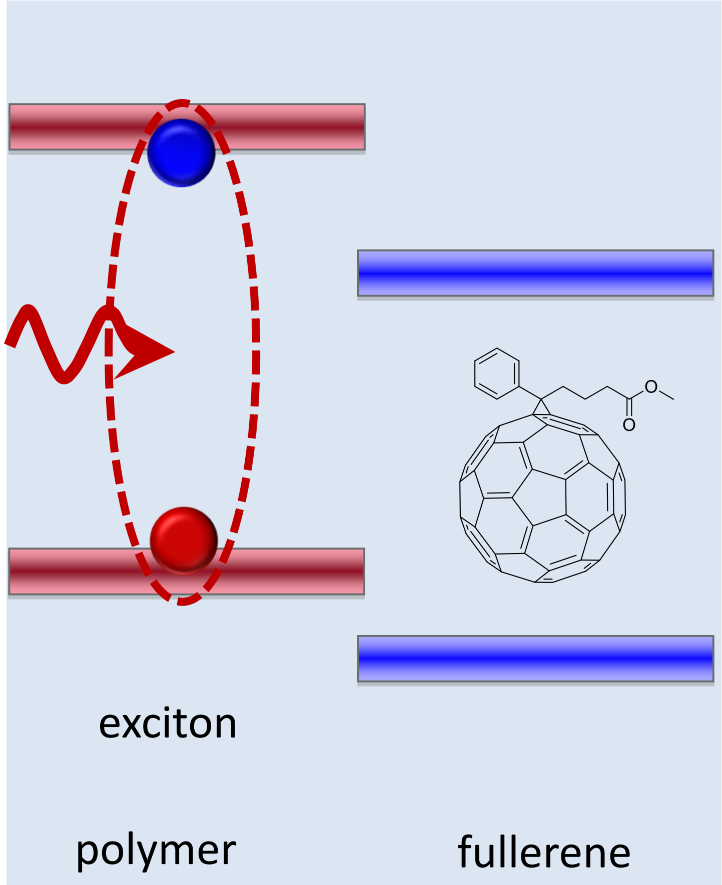


mobility:
$\mu \approx 10^{-4}$ cm^2/Vs

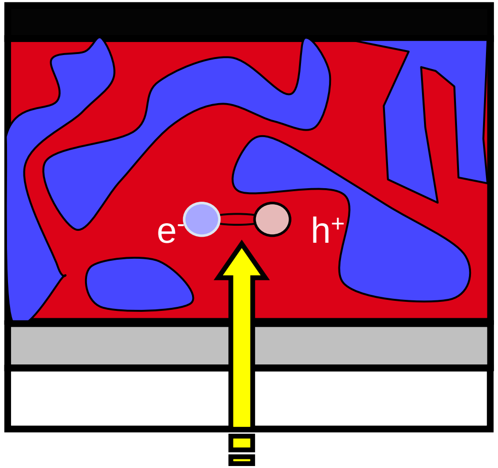


hopping

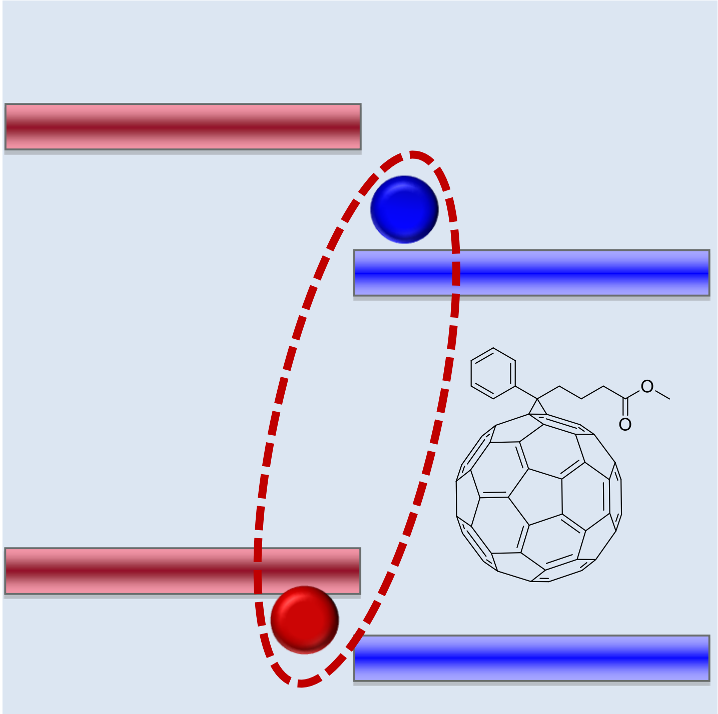
Photon absorption → Exciton generation



- Photon absorption
- Exciton generation
- Exciton diffusion

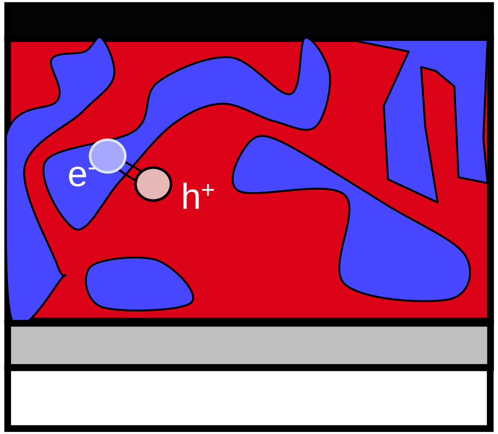


Charge Separation

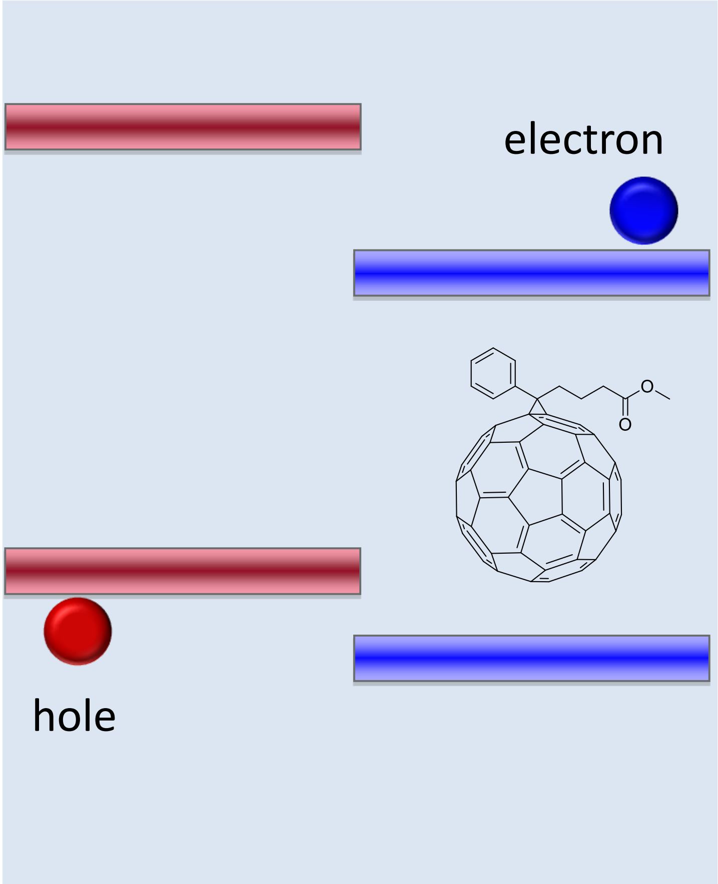


charge transfer state

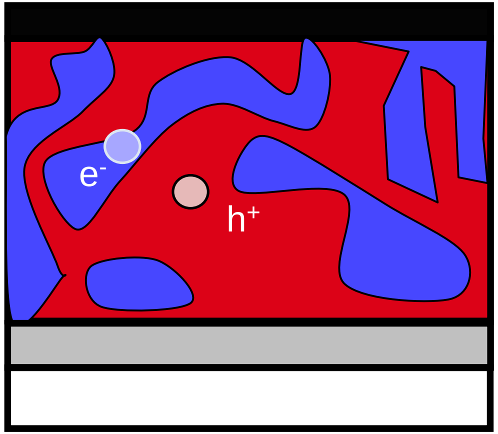
- Charge transfer



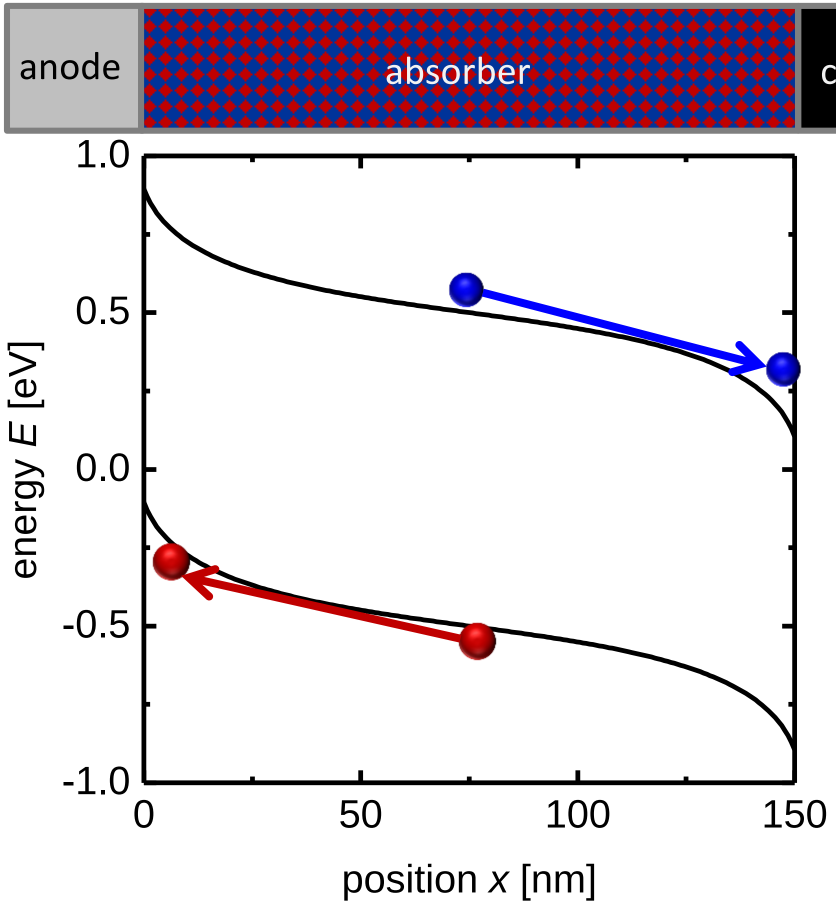
Charge Separation



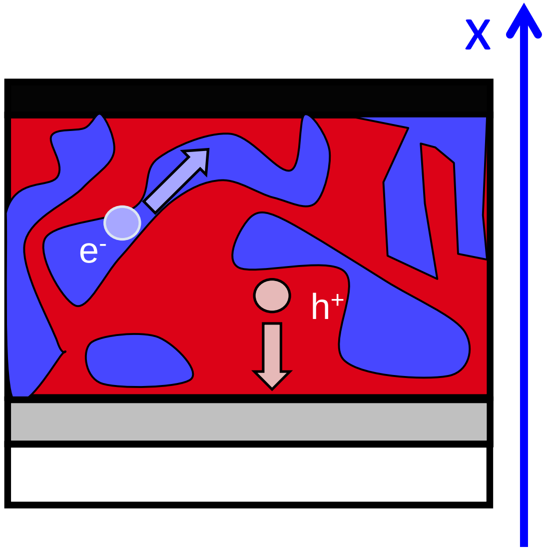
- Initial Charge separation



Charge Separation

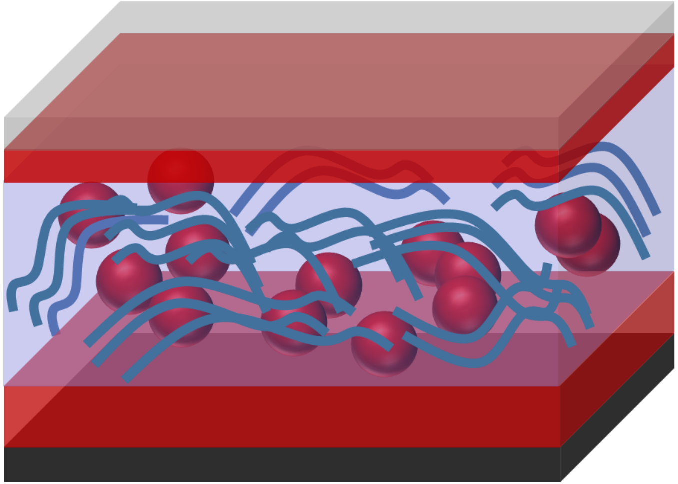


- Final Charge separation

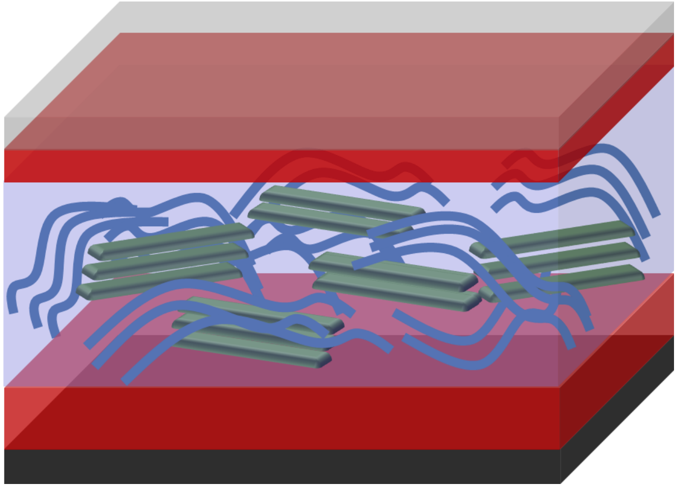


Recent trends in solution processable PV

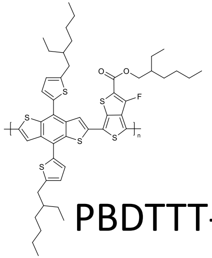
Non-Fullerene Acceptor Materials in Organic PV



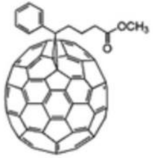
Polymer:Fullerene



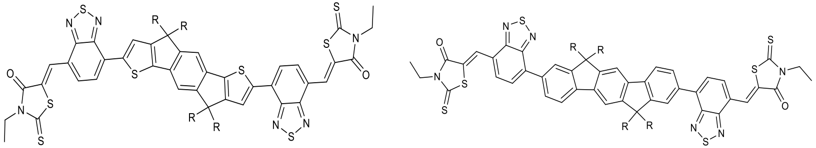
Polymer:NFA



PBDTTT-EFT

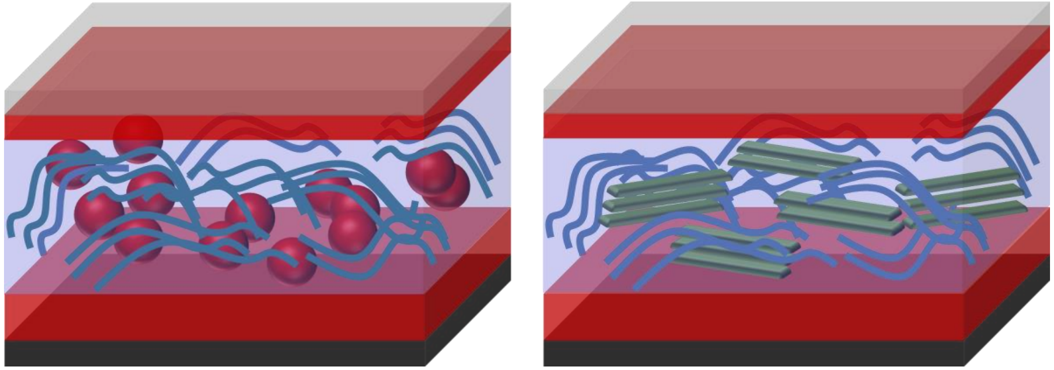


PCBM



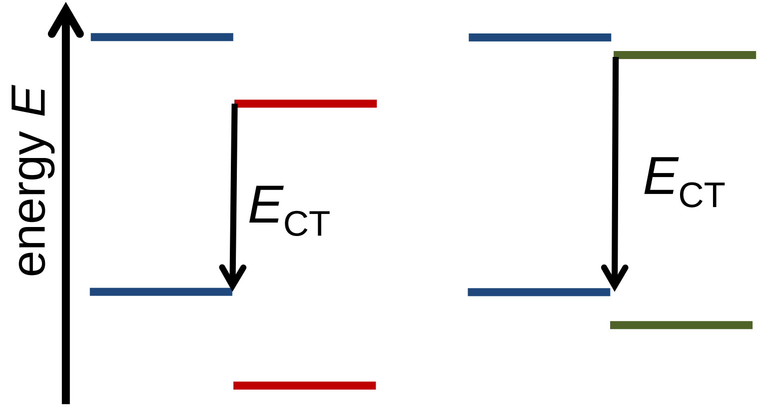
Novel acceptor materials (IDTBR, IDFBR)

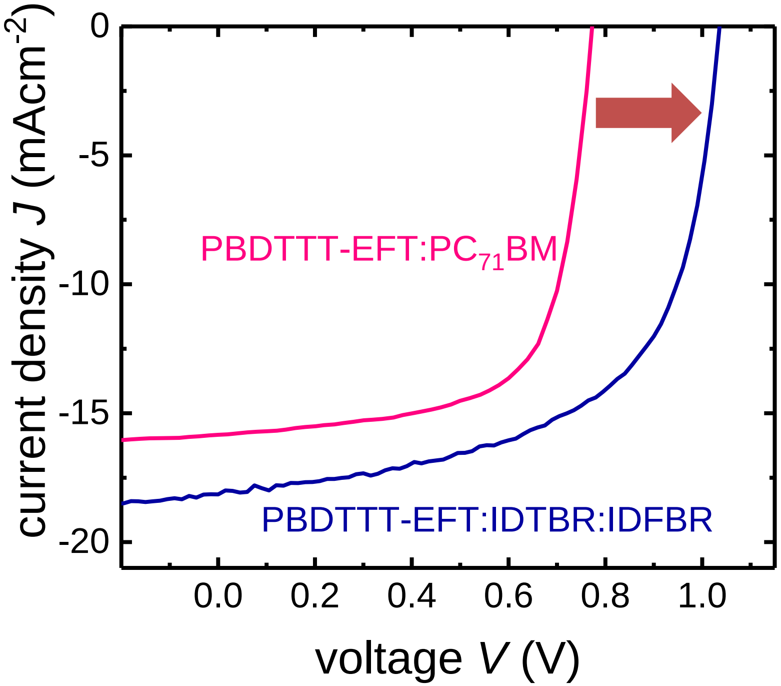
Non-Fullerene Acceptor Materials in Organic PV



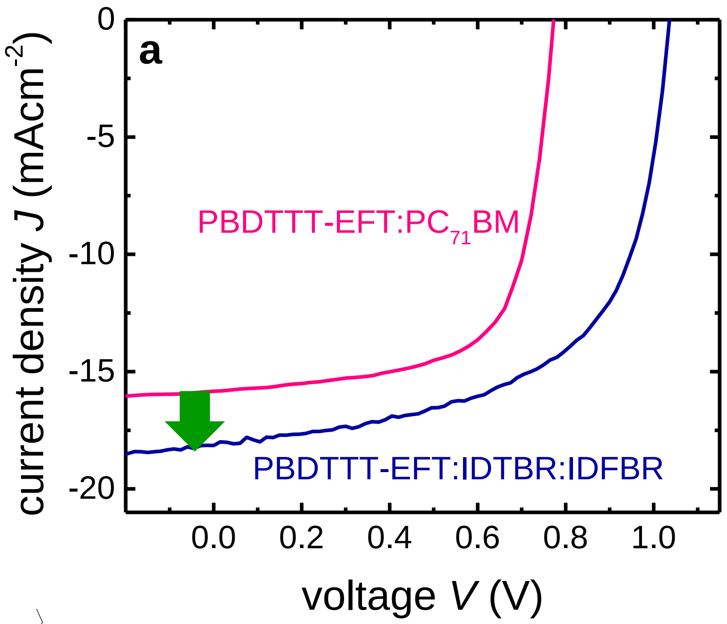
Polymer:Fullerene

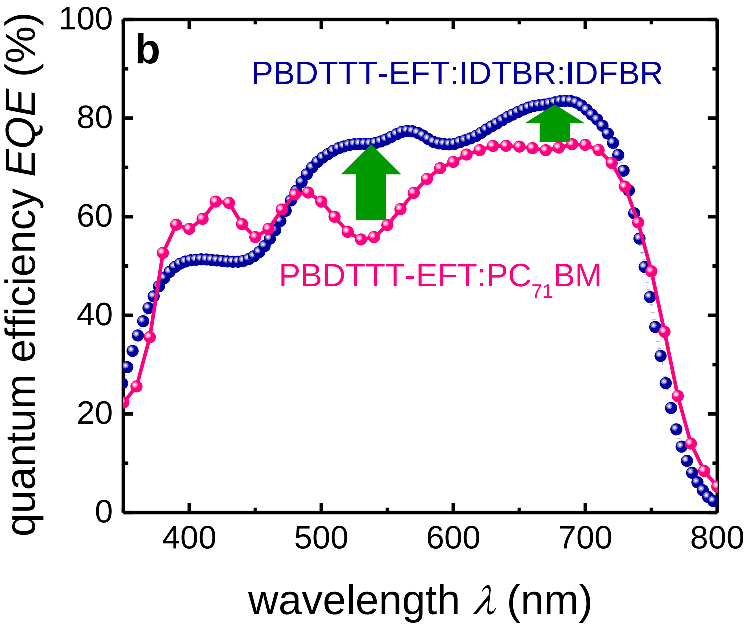
Polymer:NFA





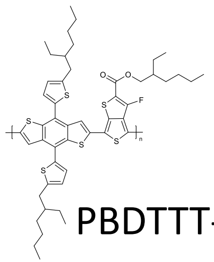
Non-Fullerene Acceptor Materials in Organic PV



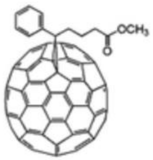


Baran et al. Nat. Mater. **16**, 363 (2017)

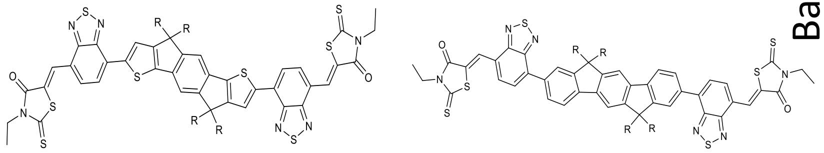
Baran et al. Energy & Environ. Science **9**, 3783 (2016)



PBDTTT-EFT

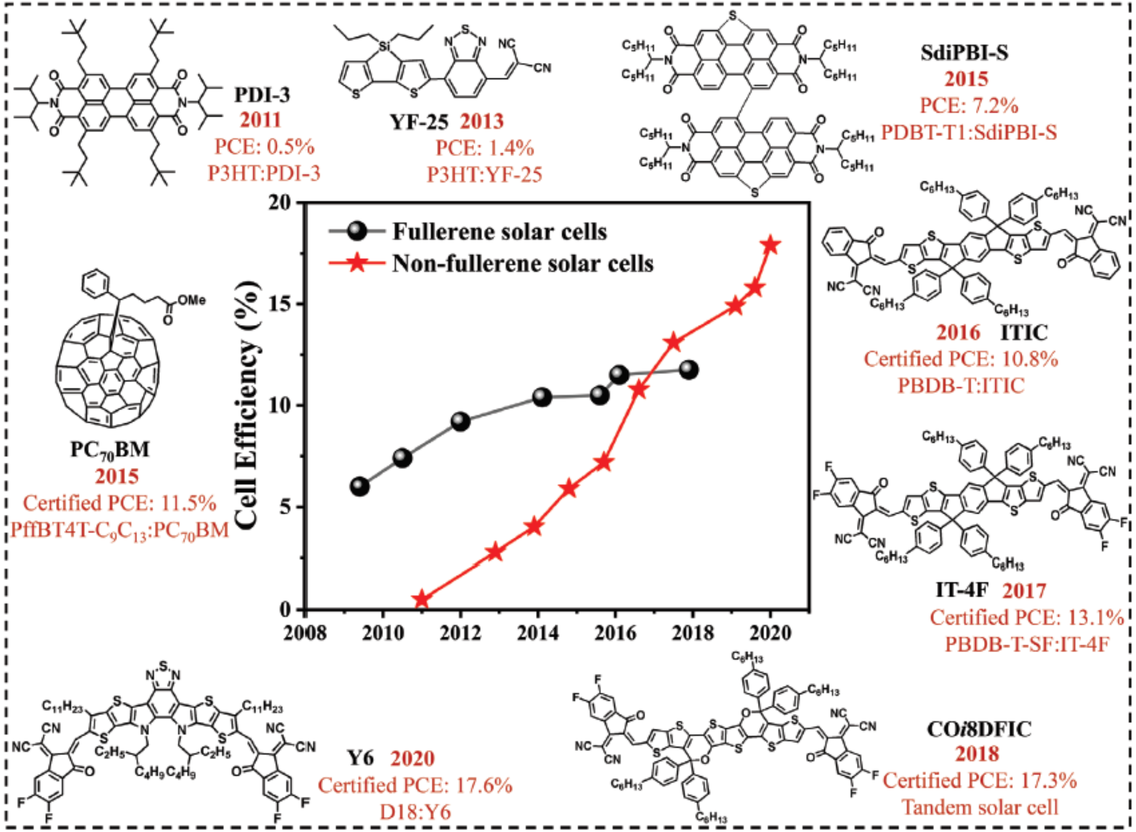


PCBM



Novel acceptor materials (IDTBR, IDFBR)

Fullerene based vs. NFA based organic PV



Meredith et al. Adv. Mater. 2001788 (2020)

Key open questions

1) Understanding the limits of V_{oc} vs. band gap

nature energy

ARTICLES

PUBLISHED: 10 APRIL 2017 | VOLUME: 2 | ARTICLE NUMBER: 17053

Intrinsic non-radiative voltage losses in fullerene-based organic solar cells

Johannes Benduhn[1]*, Kristofer Tvingstedt[2]*, Fortunato Piersimoni[3], Sascha Ullbrich[1], Yeli Fan[4†], Manuel Tropiano[5], Kathryn A. McGarry[6], Olaf Zeika[1], Moritz K. Riede[7], Christopher J. Douglas[6], Stephen Barlow[4], Seth R. Marder[4], Dieter Neher[3], Donato Spoltore[1] and Koen Vandewal[1]*

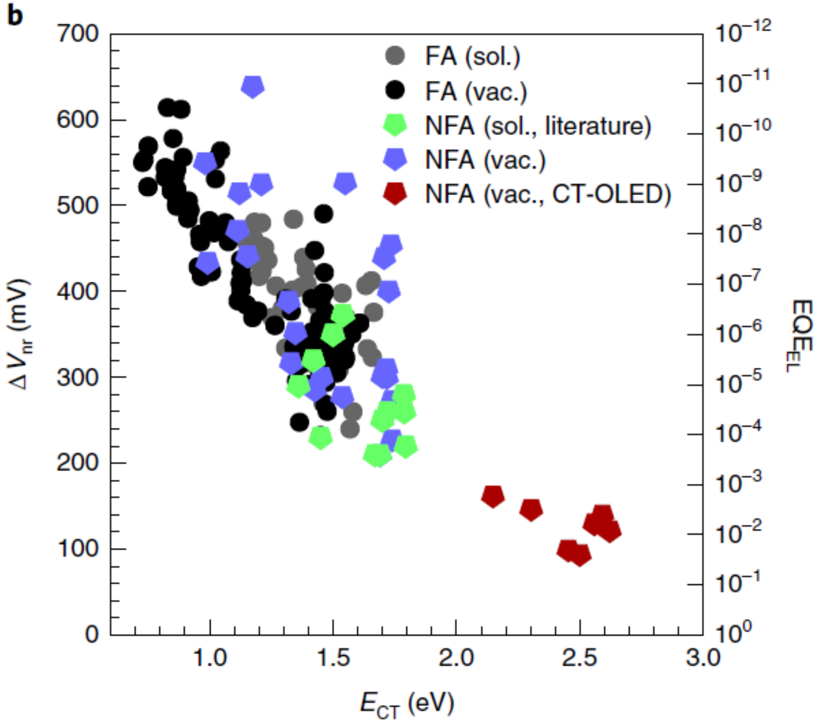
nature materials

LETTERS

https://doi.org/10.1038/s41563-019-0324-5

Emissive and charge-generating donor–acceptor interfaces for organic optoelectronics with low voltage losses

Sascha Ullbrich[1,5]*, Johannes Benduhn[1,5]*, Xiangkun Jia[1,5], Vasileios C. Nikolis[1], Kristofer Tvingstedt[2], Fortunato Piersimoni[3], Steffen Roland[3], Yuan Liu[1], Jinhan Wu[1], Axel Fischer[1], Dieter Neher[3], Sebastian Reineke[1], Donato Spoltore[1] and Koen Vandewal[1,4]*



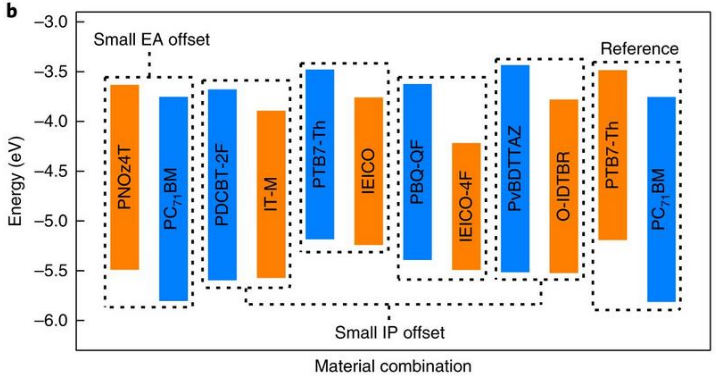
Key open questions

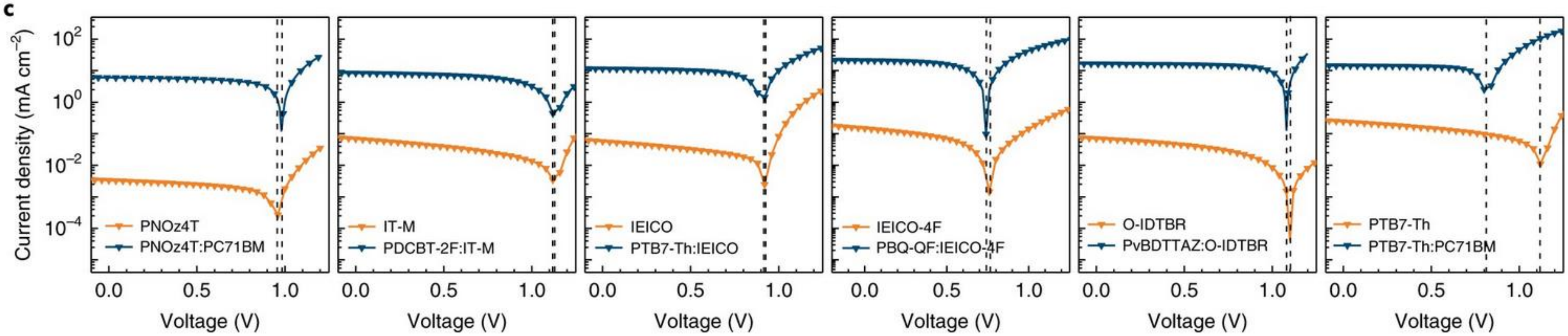
2) Why do we need two materials but hardly any offsets?

nature materials ARTICLES
https://doi.org/10.1038/s41563-018-0128-z

Design rules for minimizing voltage losses in high-efficiency organic solar cells

Deping Qian[1], Zilong Zheng[2], Huifeng Yao[3], Wolfgang Tress[4], Thomas R. Hopper[5], Shula Chen[1], Sunsun Li[3], Jing Liu[6], Shangshang Chen[6], Jiangbin Zhang[5,7], Xiao-Ke Liu[1], Bowei Gao[3], Liangqi Ouyang[1], Yingzhi Jin[1], Galia Pozina[1], Irina A. Buyanova[1], Weimin M. Chen[1], Olle Inganäs[1], Veaceslav Coropceanu[2]*, Jean-Luc Bredas[2], He Yan[6], Jianhui Hou[3], Fengling Zhang[1], Artem A. Bakulin[5]* and Feng Gao[1]*





Key open questions

3) Using „green“ (= non-halogenated) solvents

COMMUNICATION

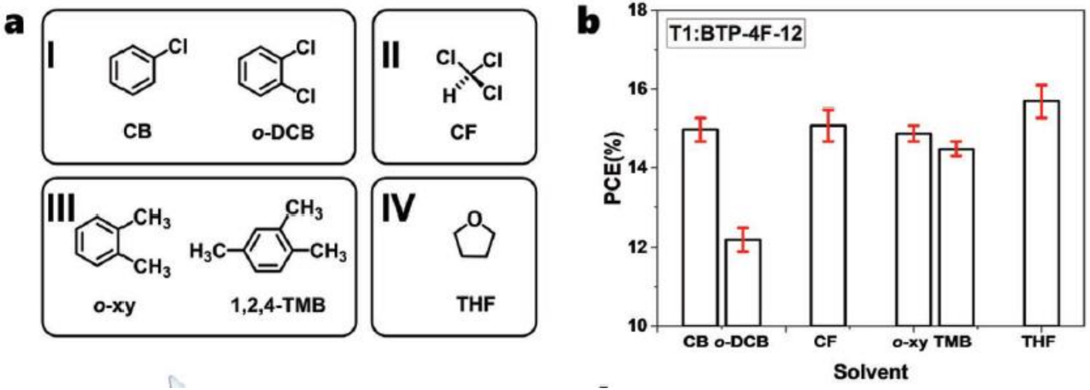
Organic Photovoltaics

ADVANCED MATERIALS
www.advmat.d

Check for updates

Eco-Compatible Solvent-Processed Organic Photovoltaic Cells with Over 16% Efficiency

Ling Hong, Huifeng Yao, Ziang Wu, Yong Cui, Tao Zhang, Ye Xu, Runnan Yu, Qing Liao, Bowei Gao, Kaihu Xian, Han Young Woo,* Ziyi Ge,* and Jianhui Hou**



Key open questions

4) Thicker films without efficiency losses

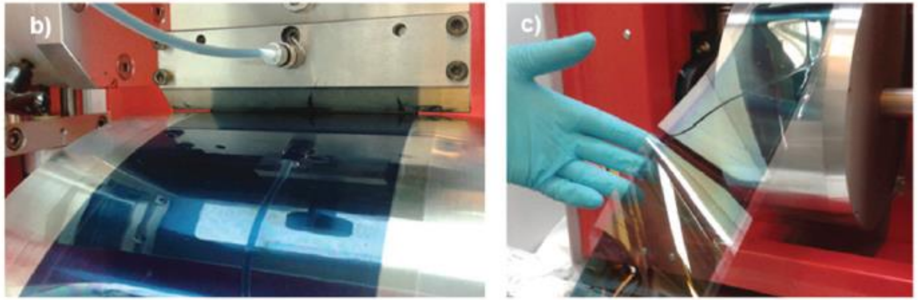
ACS APPLIED MATERIALS & INTERFACES

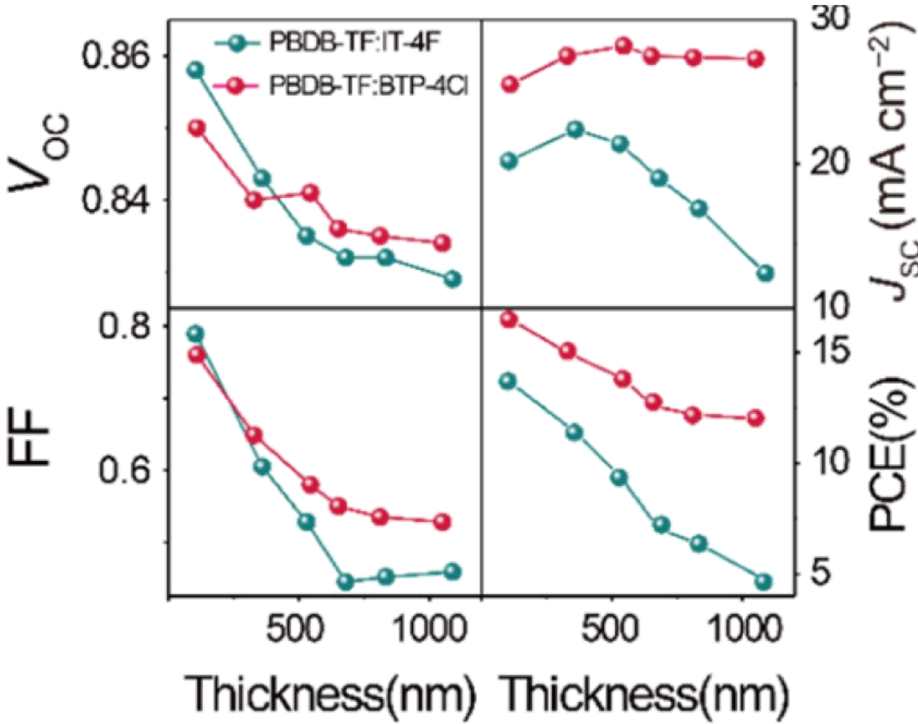
www.acsami.org Research Article

High-Efficiency Nonfullerene Organic Solar Cells Enabled by 1000 nm Thick Active Layers with a Low Trap-State Density

Lijiao Ma, Shaoqing Zhang,* Huifeng Yao, Ye Xu, Jingwen Wang, Yunfei Zu, and Jianhui Hou

Cite This: *ACS Appl. Mater. Interfaces* 2020, 12, 18777−18784 Read Online





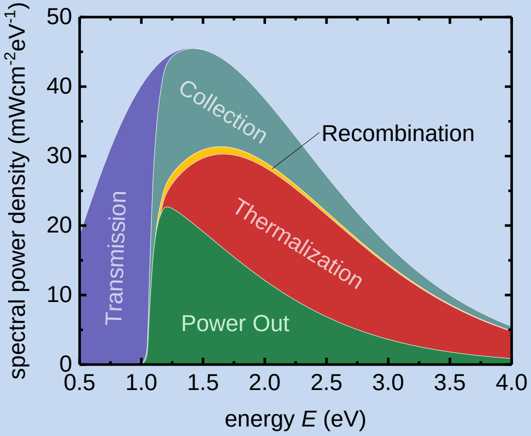
Important for industrial roll-to-roll production

Pic. From Lucera et al.Energy Environ. Sci (2016)

Summary

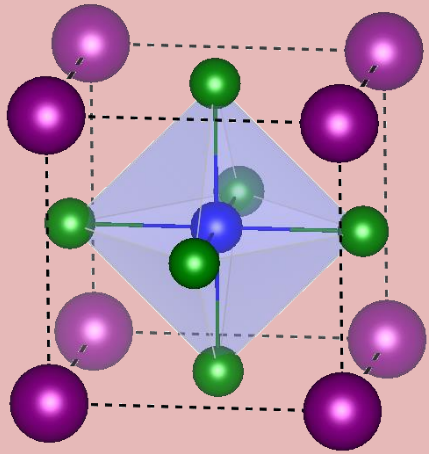
Functionality of Solar Cells – Main Losses

- $\eta < 33\%$
- Need some asymmetry to separate e and h



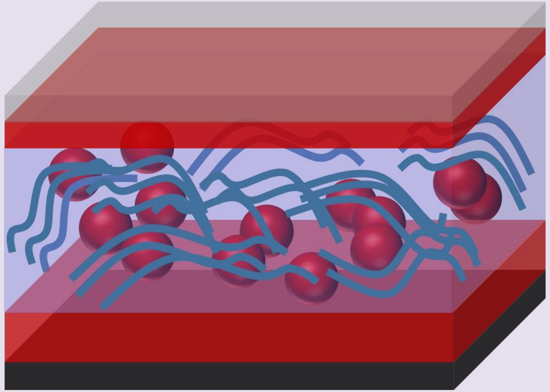
Perovskite Solar Cells

- Efficient, high Voc, highly luminescent
- Low stability
- Lead is an issue



Organic Solar Cells

- Efficiency increases rapidly during recent years
- Lead-free
- Poor charge transport



Thank you for your attention

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

JÜLICH Forschungszentrum