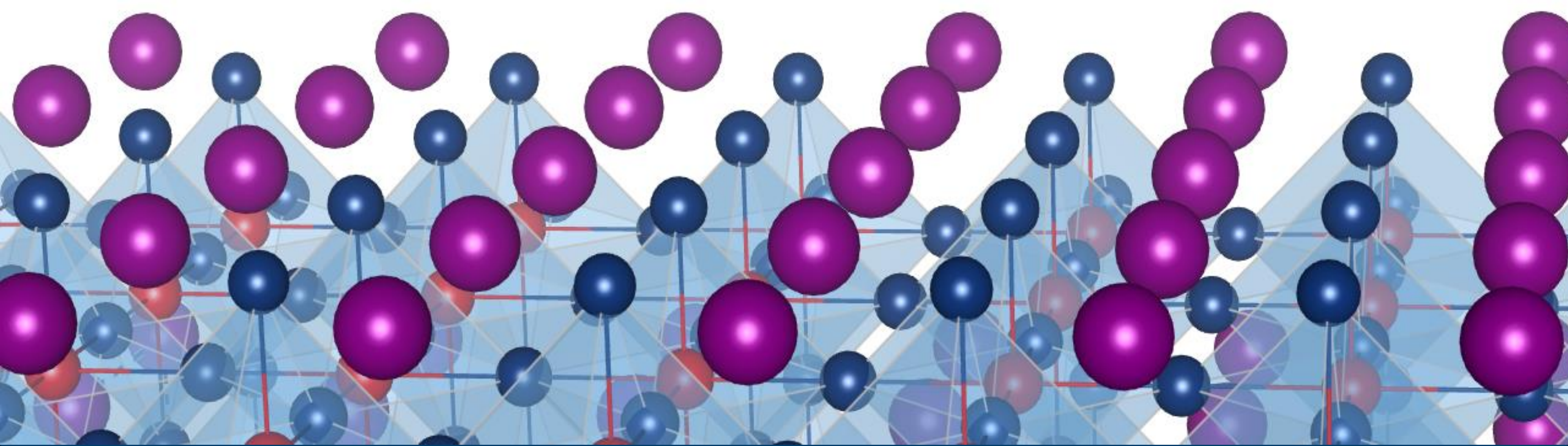


RECOMBINATION IN LEAD-HALIDE PEROVSKITE SOLAR CELLS

Thomas Kirchartz[1,2], Zhifa Liu[1], Lisa Krückemeier[1], Uwe Rau[1]

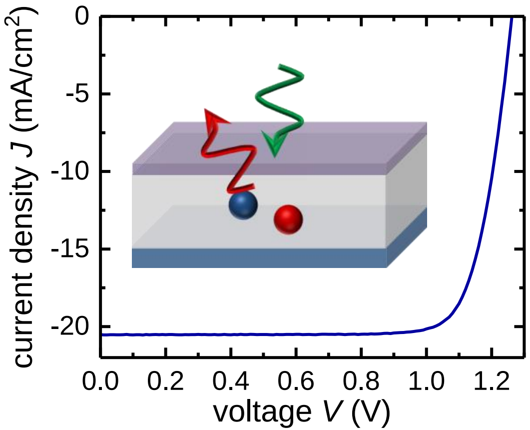
[1]IEK-5 Photovoltaik, Forschungszentrum Jülich,

[2]NST and CENIDE, Universität Duisburg-Essen

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

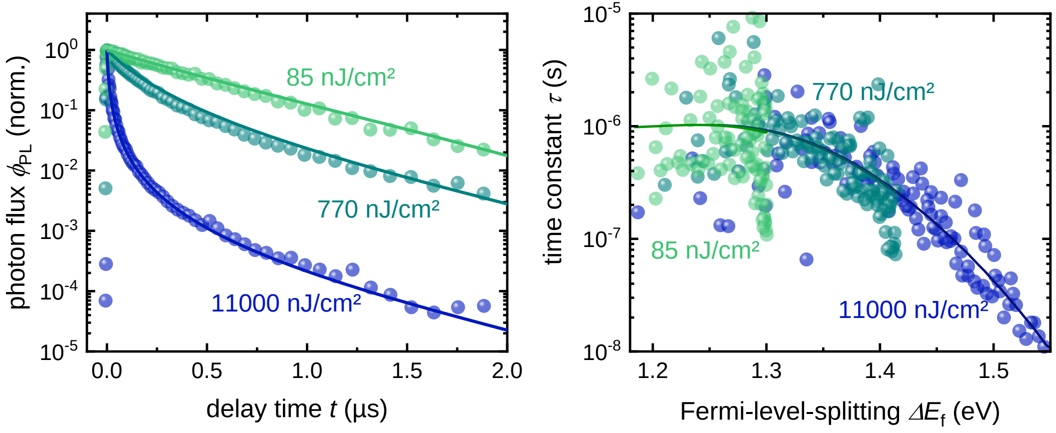
JÜLICH Forschungszentrum

Outline

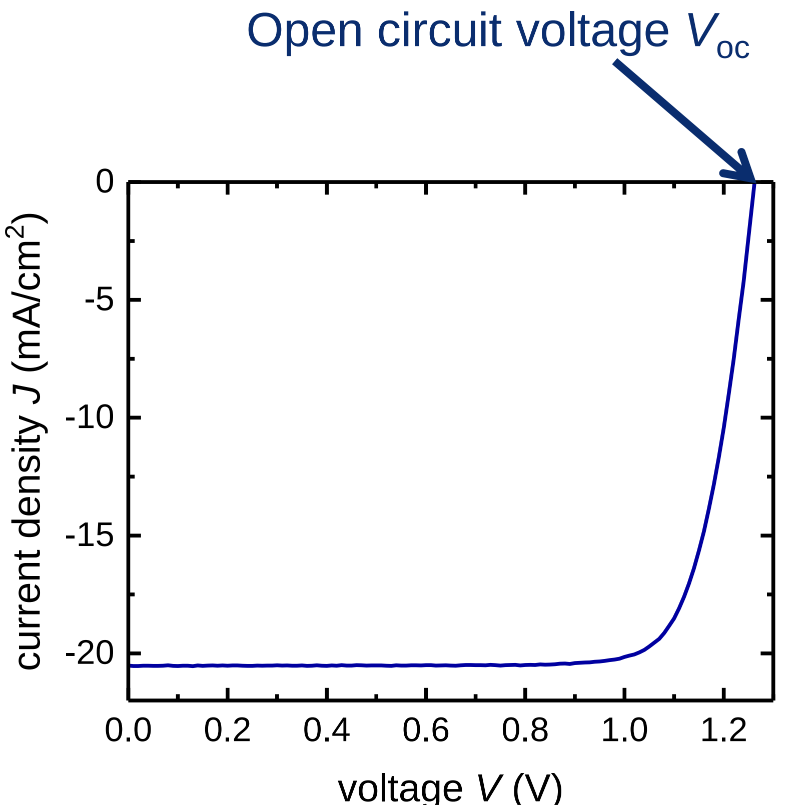


1) Luminescence efficiency and open-circuit voltage

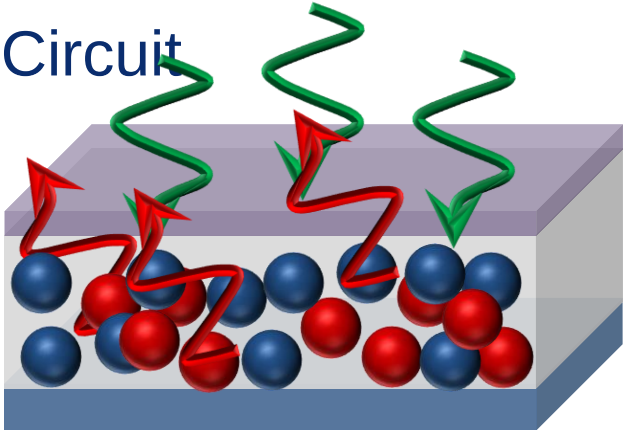
2) Measuring charge-carrier lifetimes



Solar Cell Basics



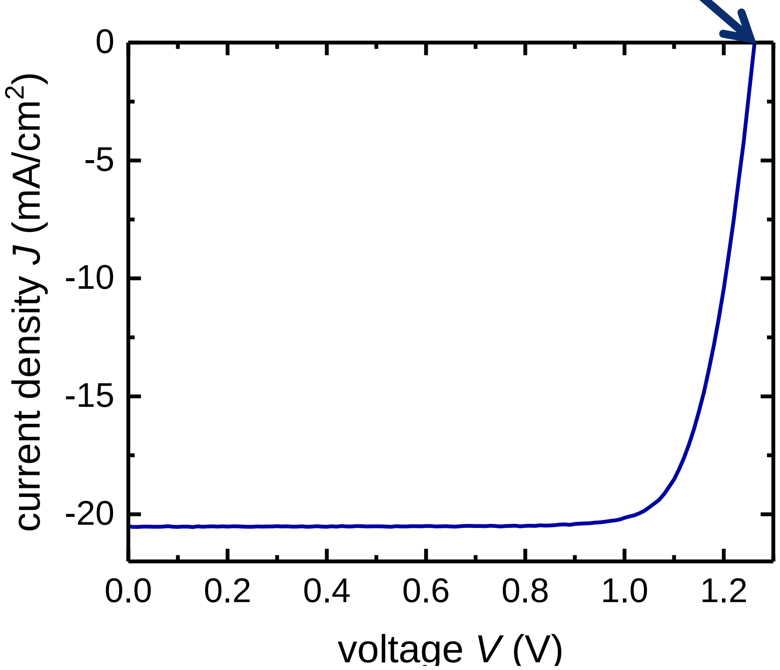
Open Circuit



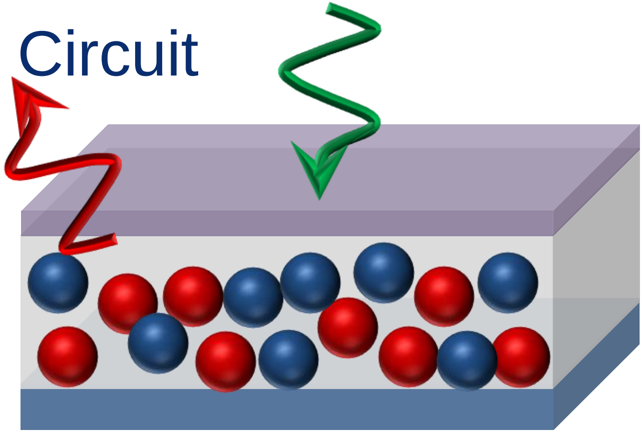
Open circuit voltage is controlled by recombination (radiative or non-radiative)

Solar Cell Basics

Open circuit voltage V_{oc}



Open Circuit



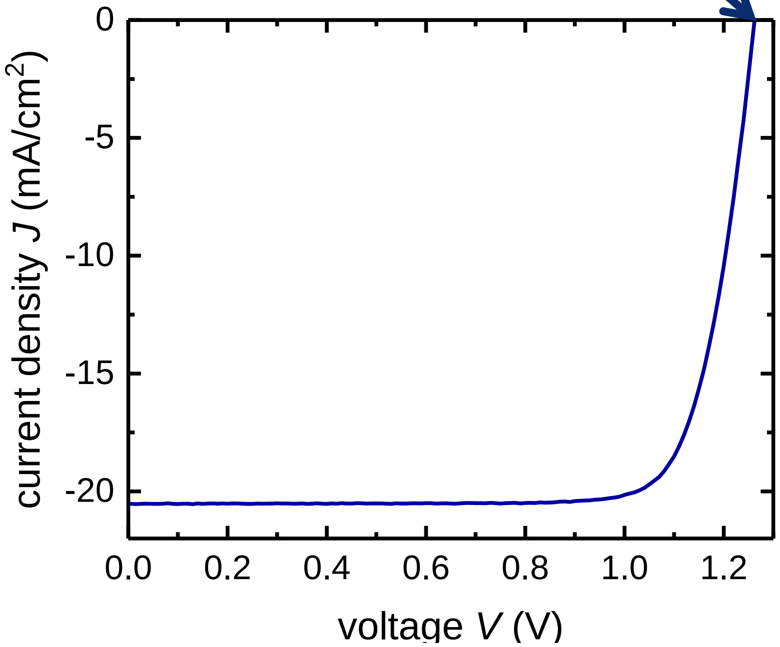
Ideal case: Only radiative recombination

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

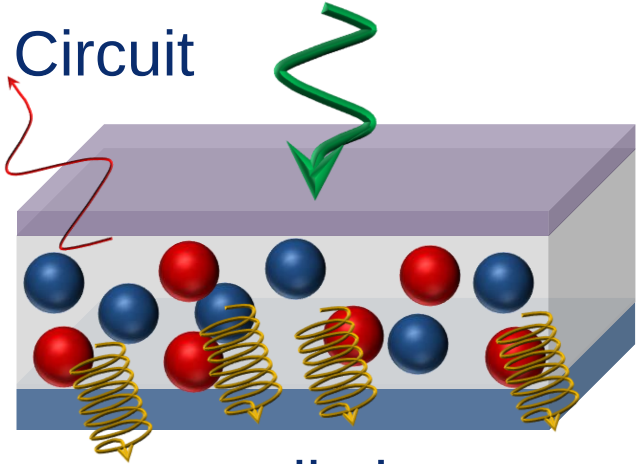
$$Q_e^{lum} = 1$$

Luminescence and open-circuit voltage

Open circuit voltage V_{oc}



Open Circuit

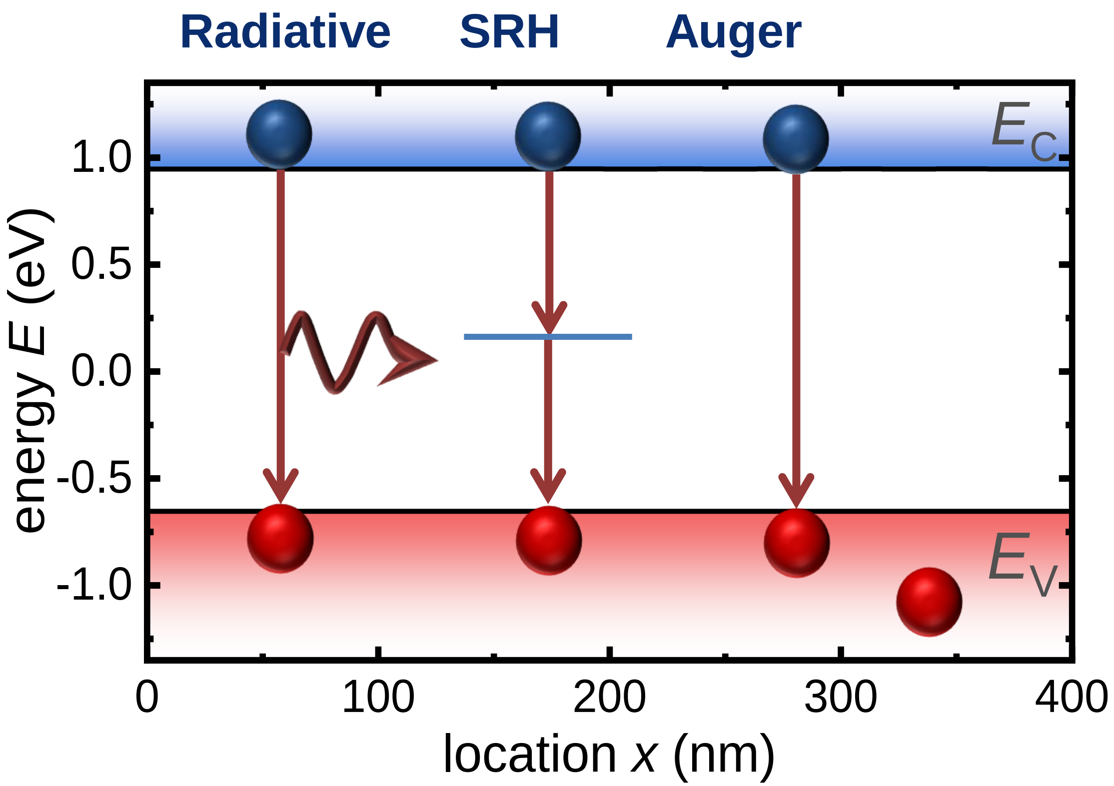


Real case: non-radiative recombination

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

$$Q_e^{lum} < 1$$

Different types of recombination

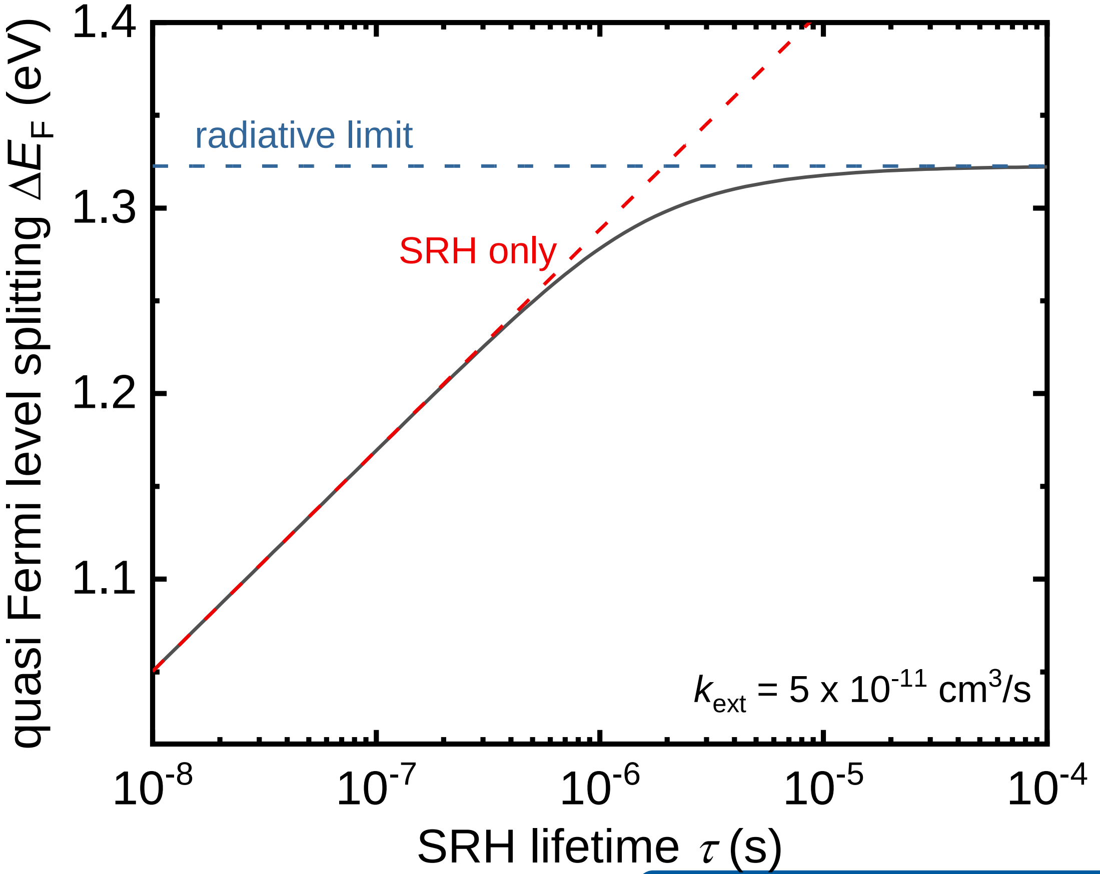


Why are charge carrier lifetimes relevant?

@ open circuit

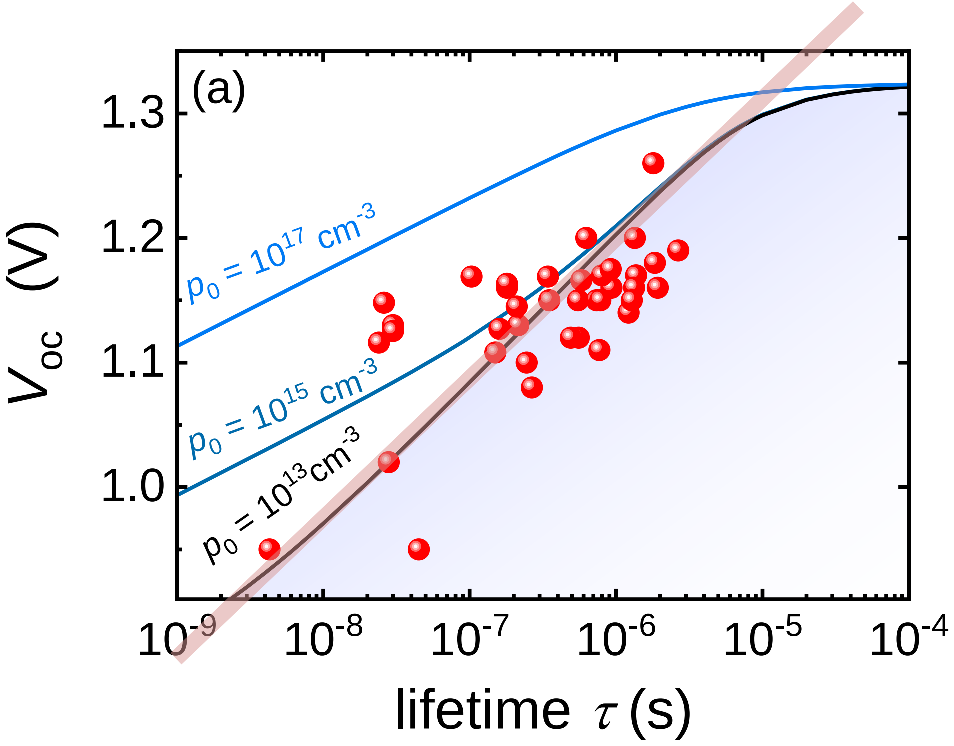
$$G = kn^2 + \frac{n}{\tau}$$

$$\Delta E_{\mathrm{F}} = kT \ln\left(\frac{n^2}{n_i^2}\right)$$



Kirchartz et al. Adv. Energy Mater. 2020

Why things are more difficult in reality than in theory?

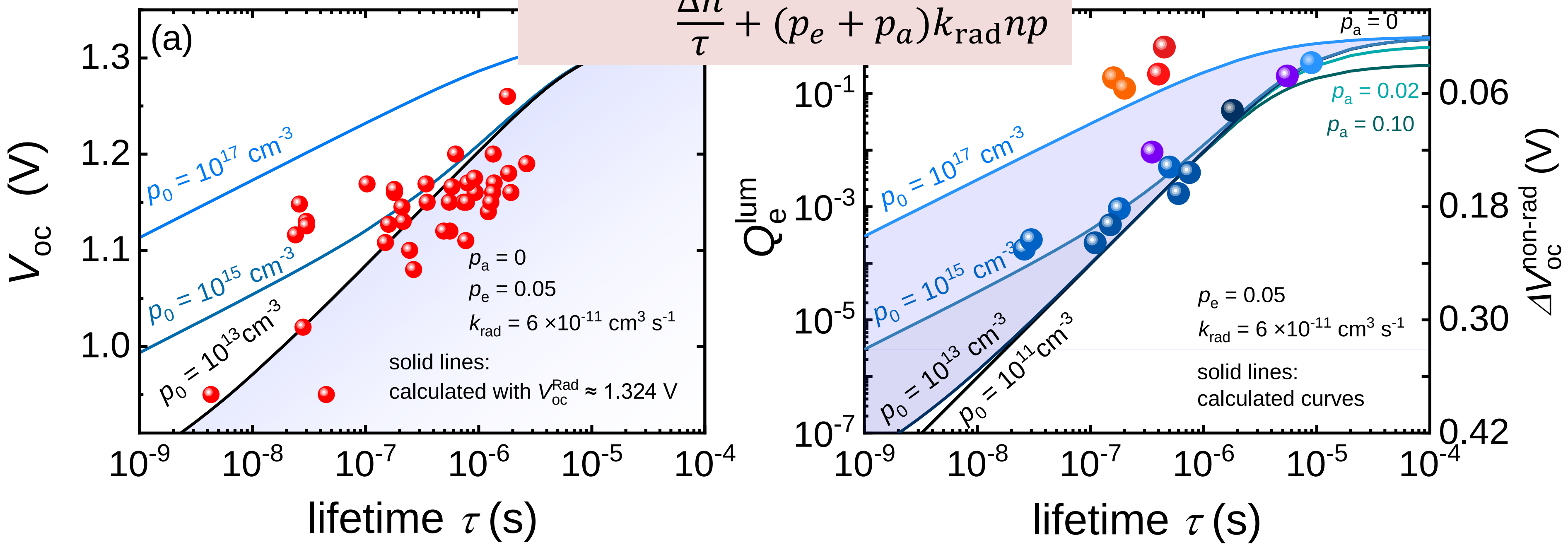


$$\Delta E_F = 2kT \ln\left(\frac{G\tau}{n_i}\right)$$

Kirchartz et al. Adv. Energy Mater. 2020

Why things are more difficult in reality than in theory?

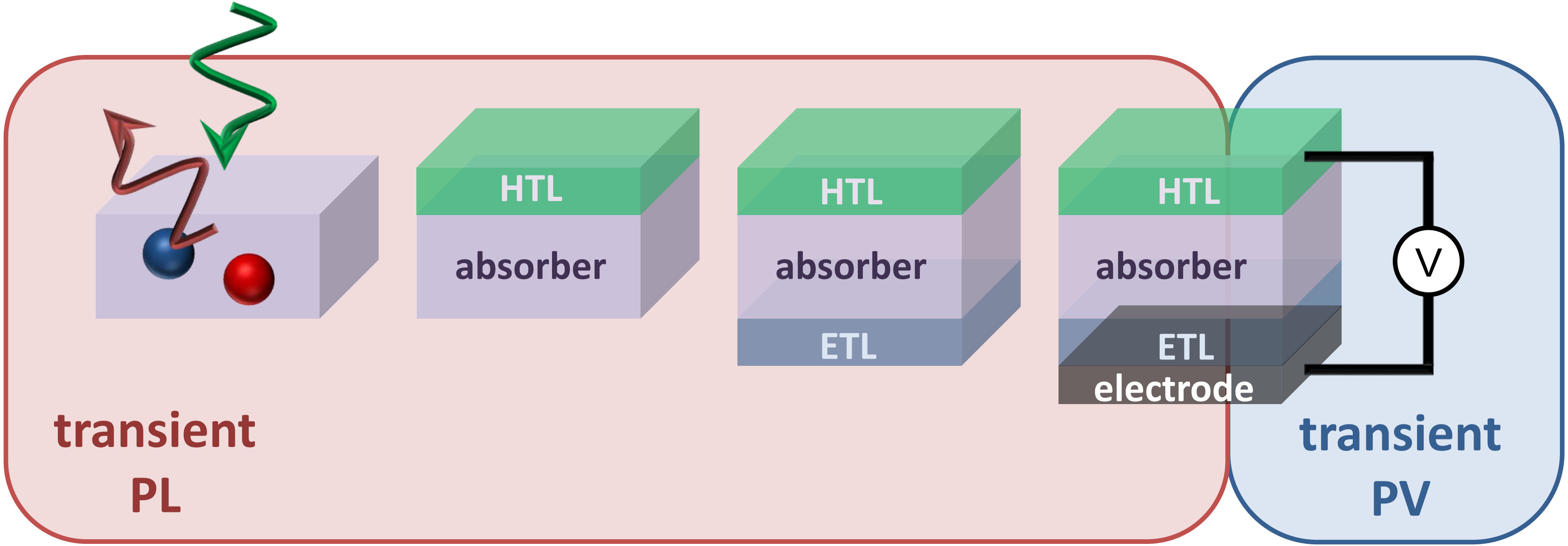
$$Q_e^{lum} = \frac{p_e k_{rad} np}{\frac{\Delta n}{\tau} + (p_e + p_a) k_{rad} np}$$



Kirchartz et al. Adv. Energy Mater. 2020

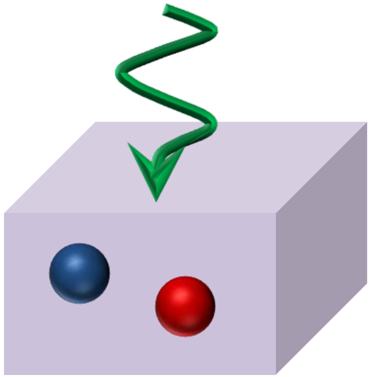
How can transient methods help…

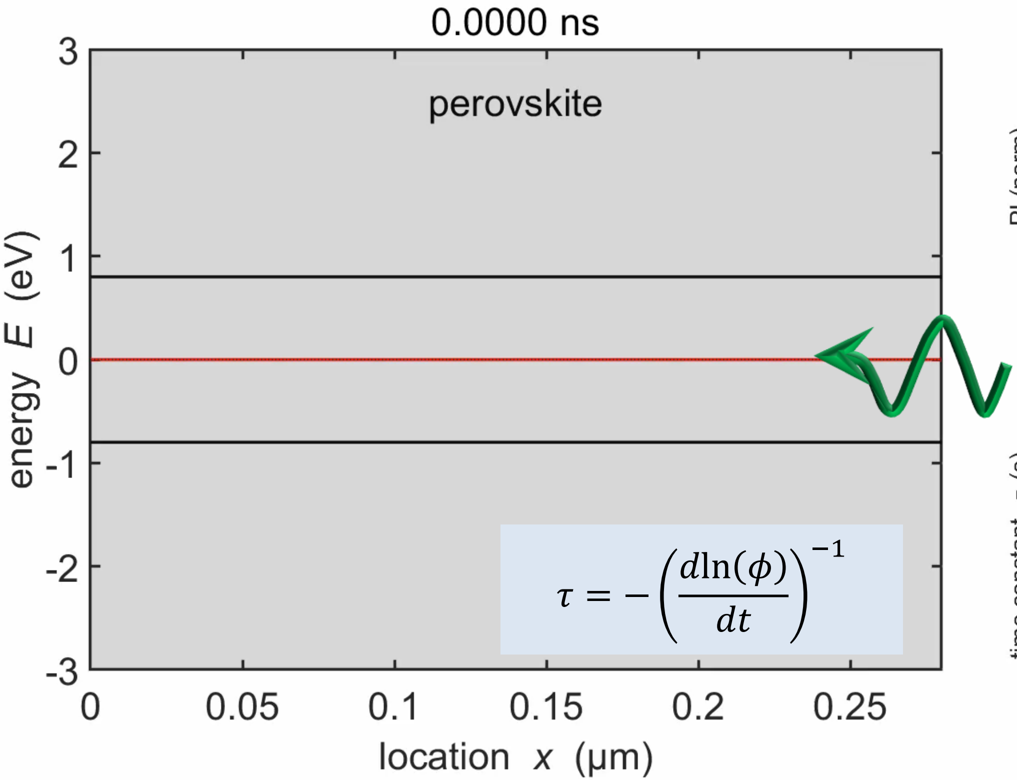
…to study recombination and voltage losses



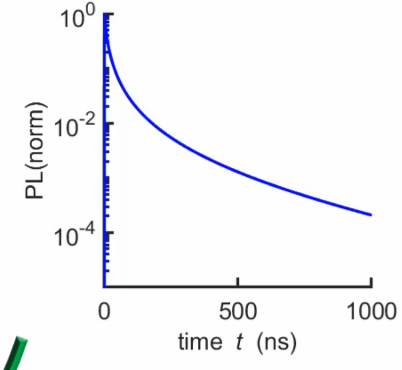
Transient Photoluminescence

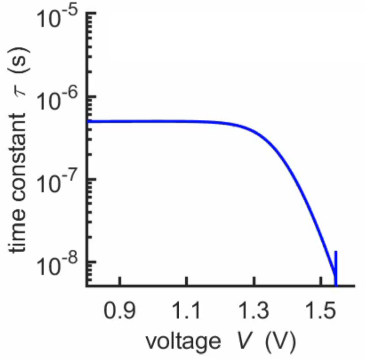
Layer on glass - Video





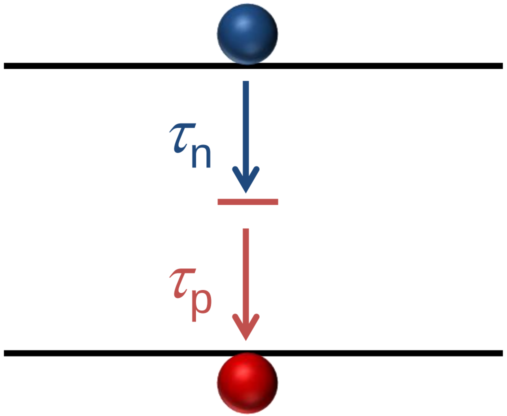
$$\tau = -\left(\frac{d\ln(\phi)}{dt}\right)^{-1}$$





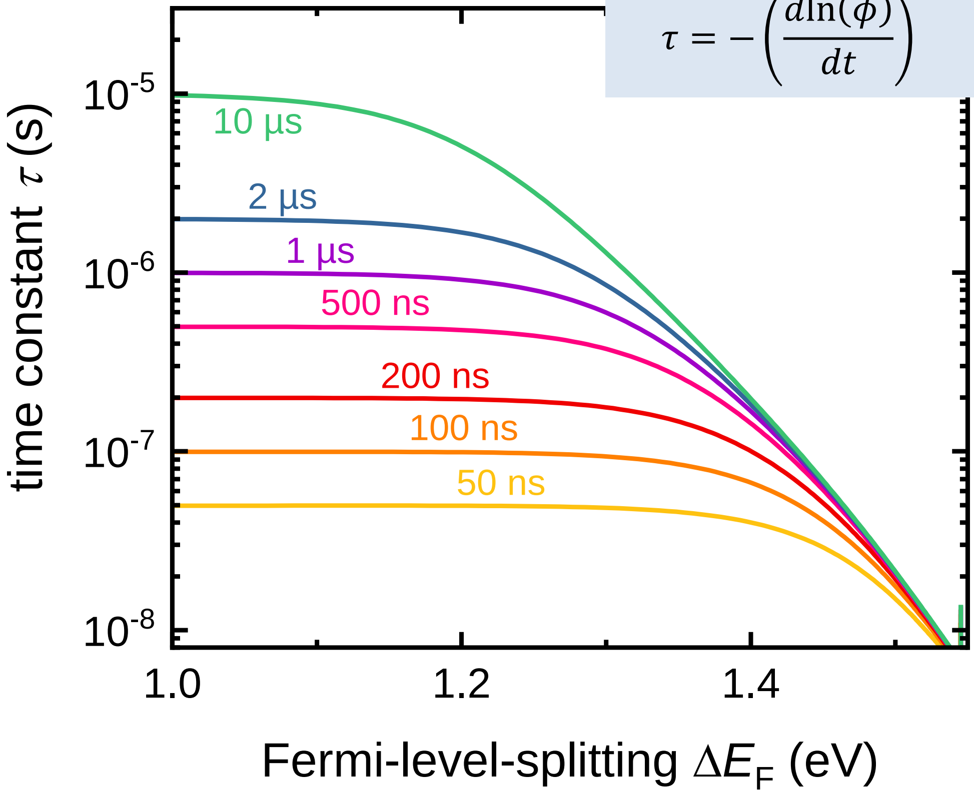
Transient Photoluminescence

Layer on glass – Bulk recombination



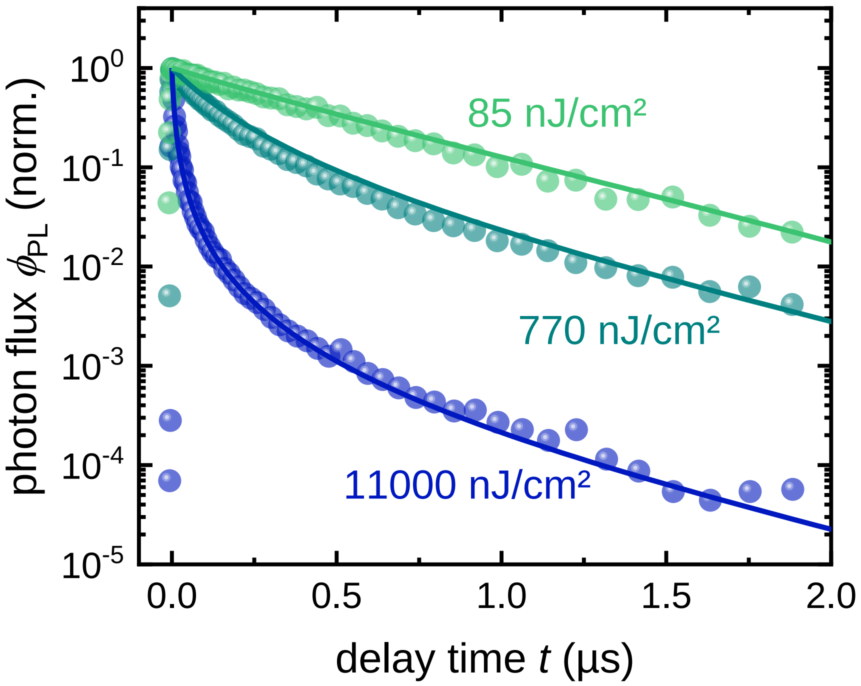
$$\frac{dn}{dt} = -knp - \frac{np}{\tau_p n + \tau_n p} - C(np^2 + n^2 p)$$

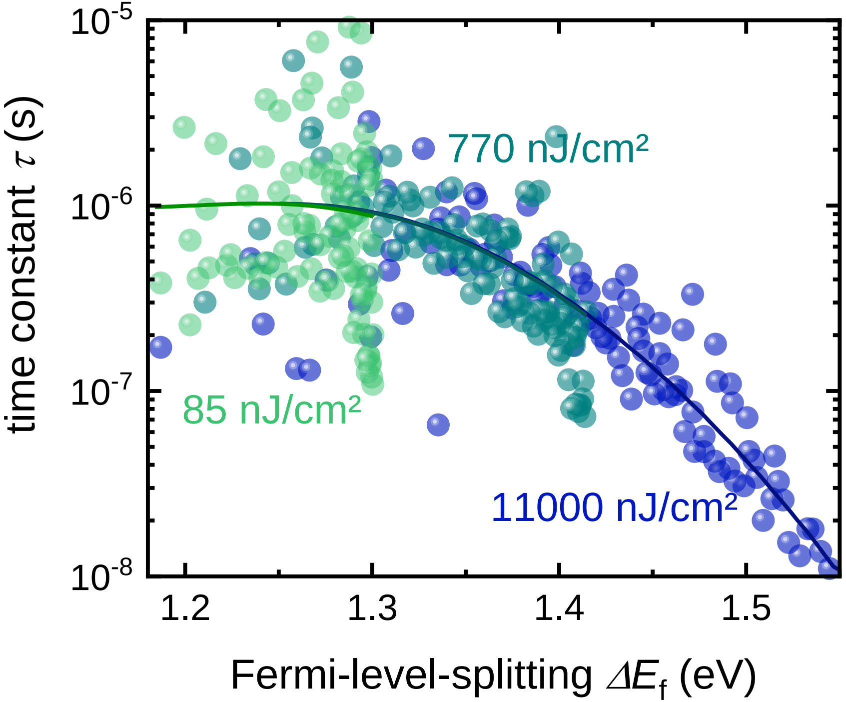
$$\tau = -\left(\frac{d\ln(\phi)}{dt}\right)^{-1}$$



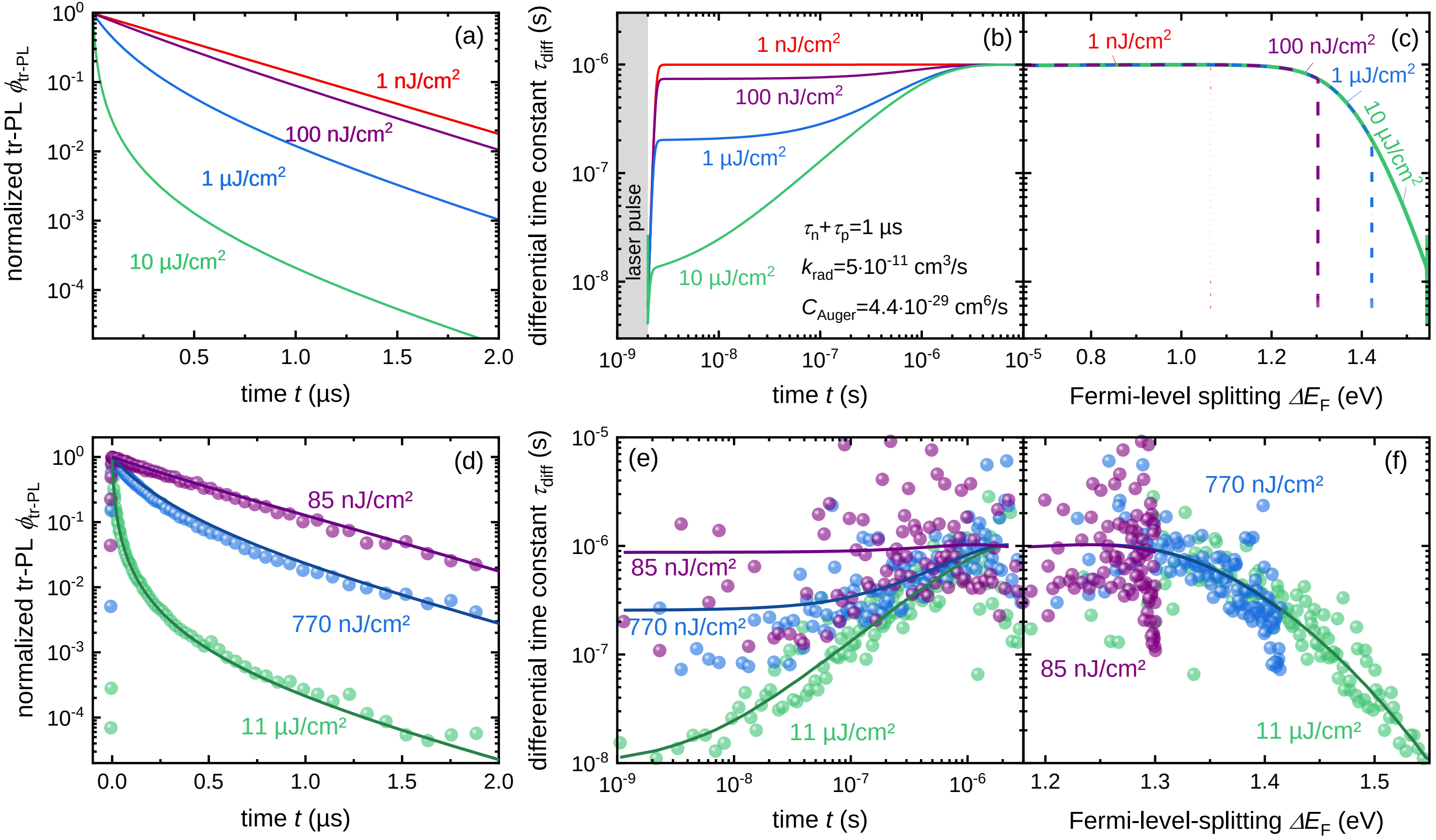
Layer on Glass

Experimental data



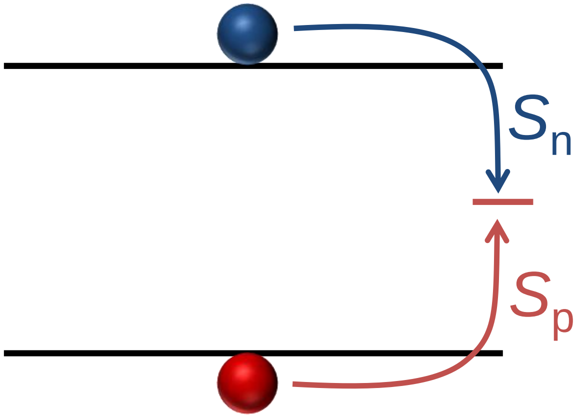


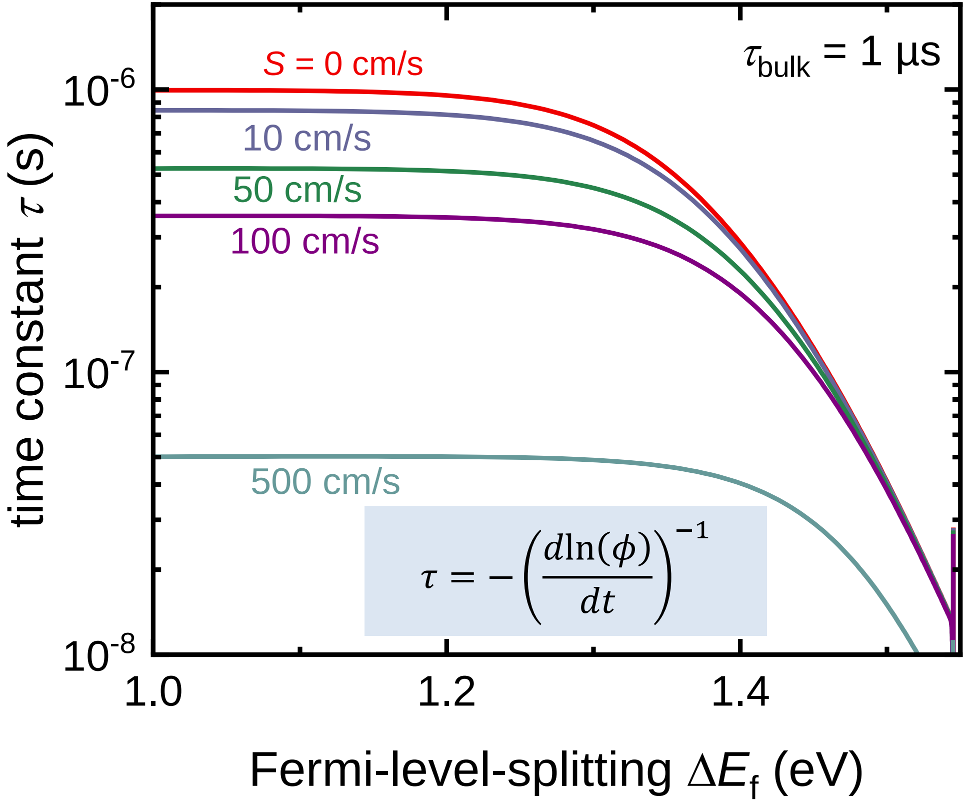
From time axis to QFLS axis



Transient Photoluminescence

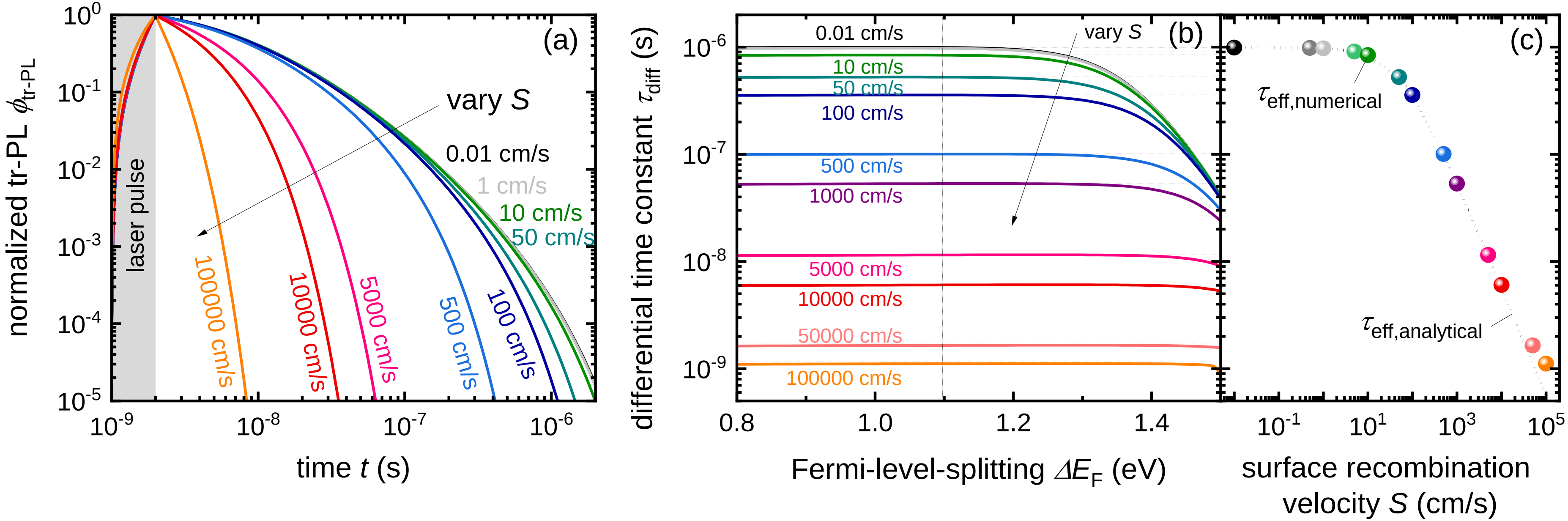
Layer on glass – Surface recombination





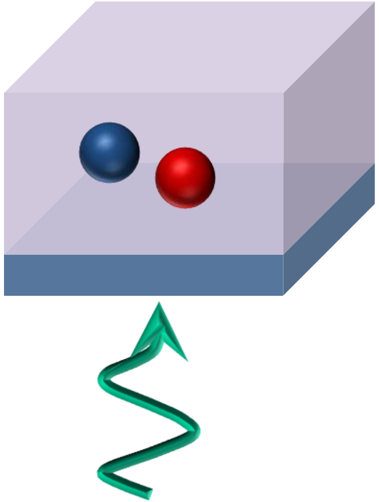
Transient Photoluminescence

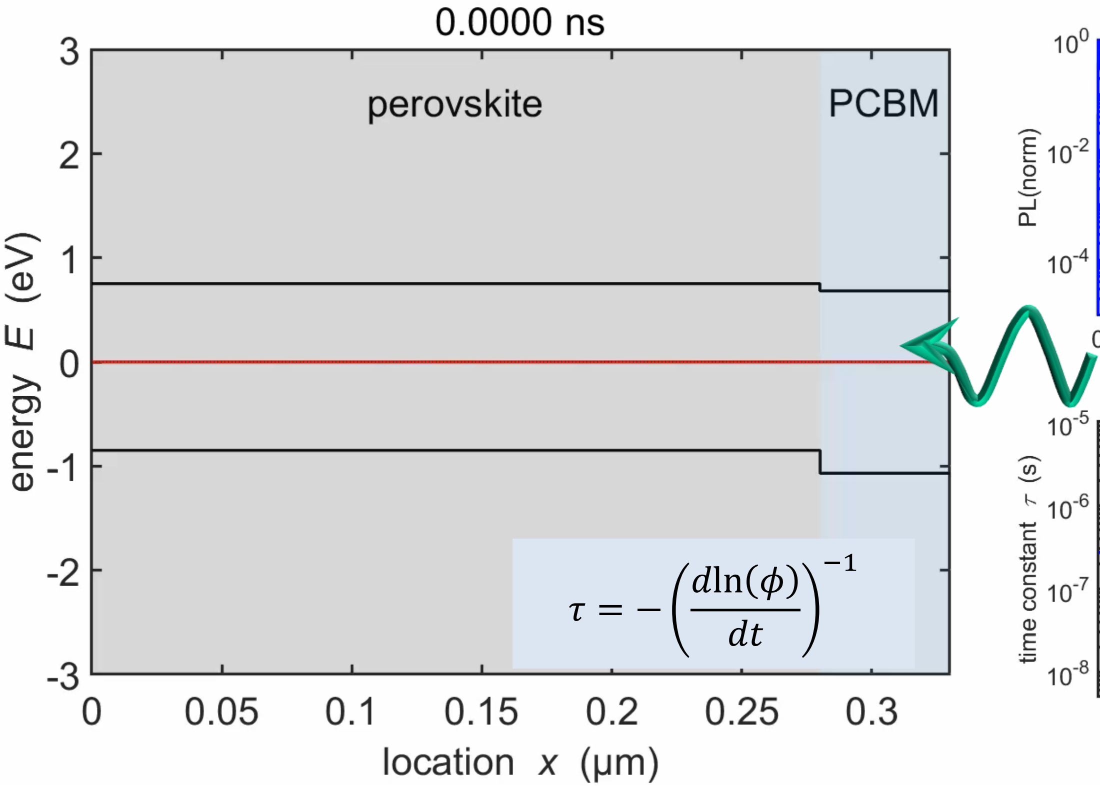
Layer on glass – Surface recombination



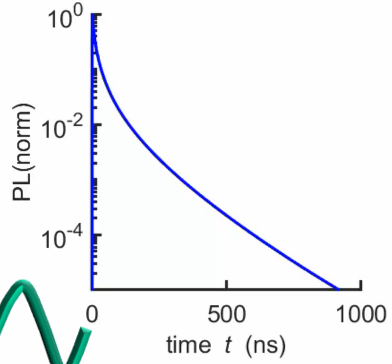
Charge transfer and recombination

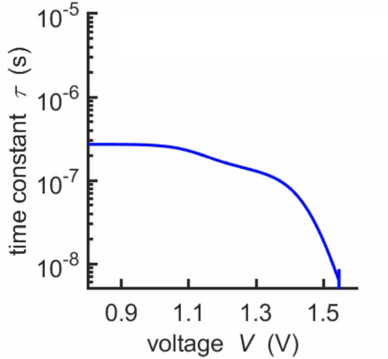
General idea





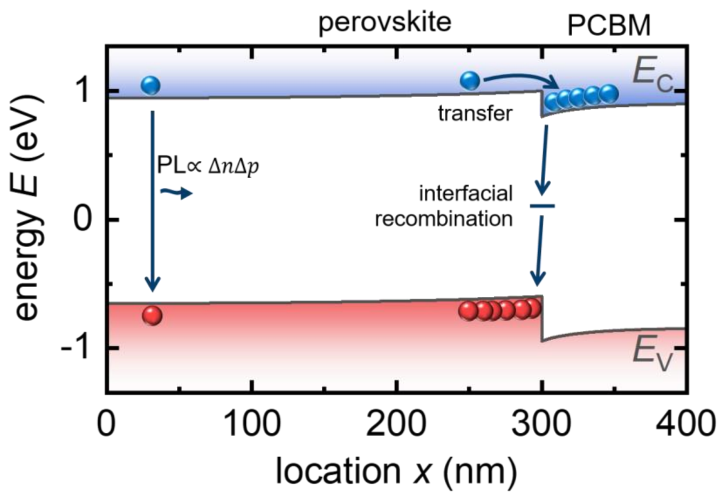
$$\tau = -\left(\frac{d\ln(\phi)}{dt}\right)^{-1}$$

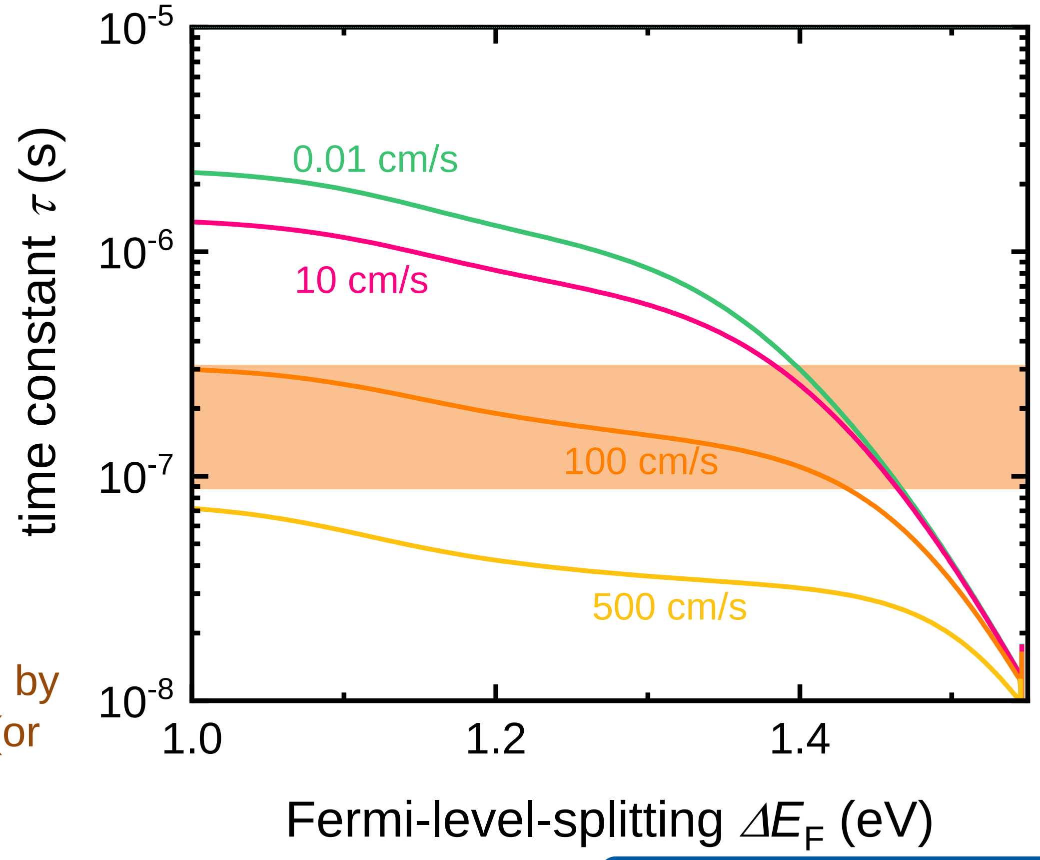




Charge transfer and recombination

Data

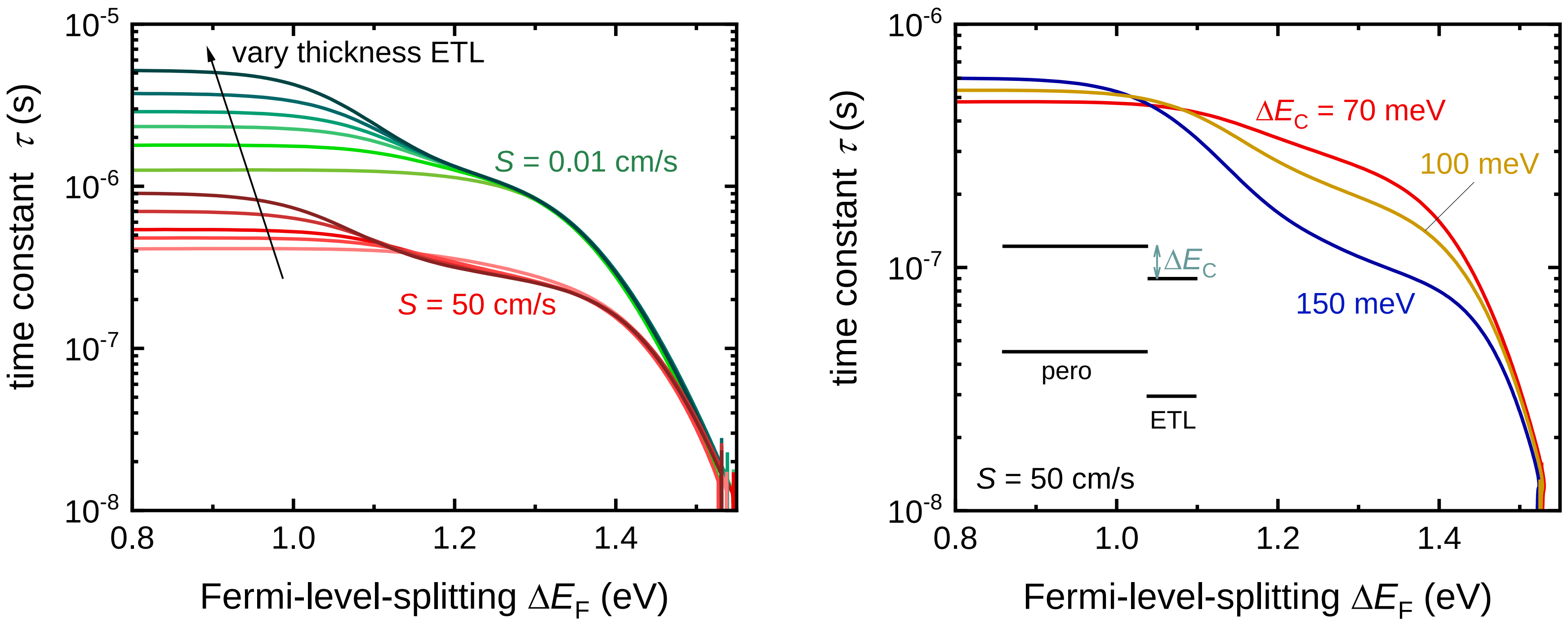




Time constant affected by band offsets and ETL (or HTL) thickness

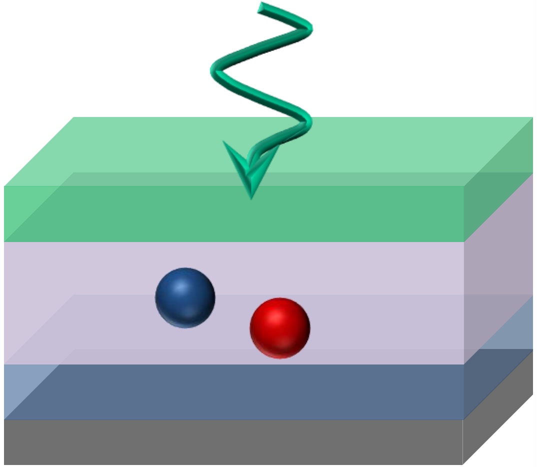
Charge transfer and recombination

Effect of ETL thickness and band offsets

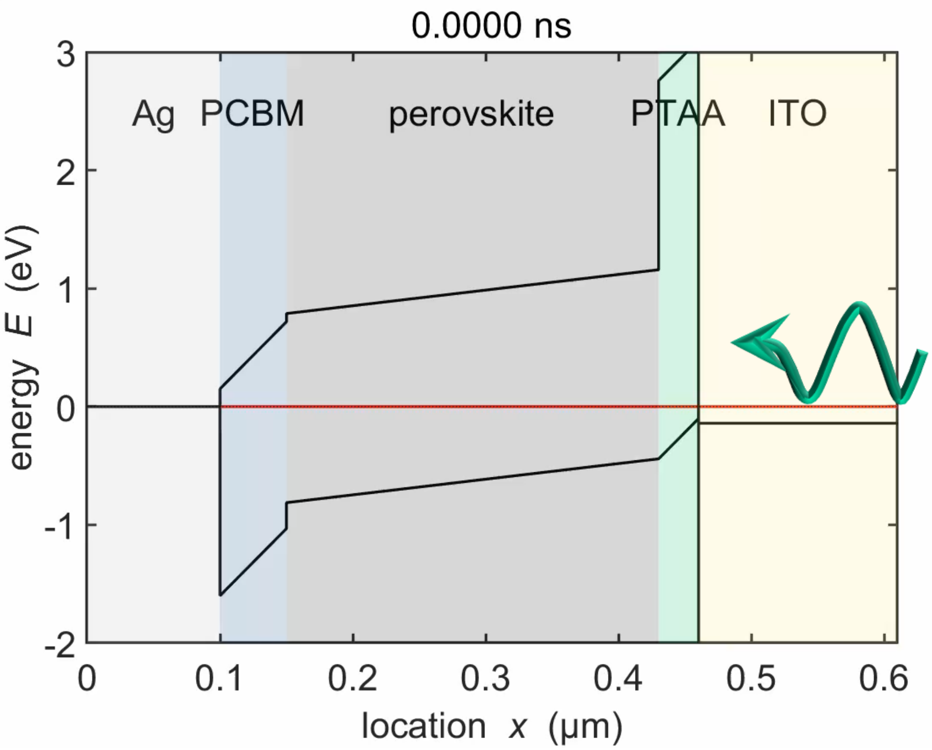


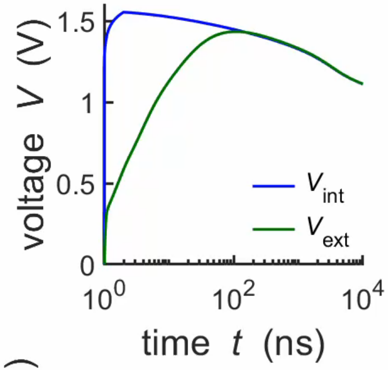
Transient Photoluminescence – Solar Cell

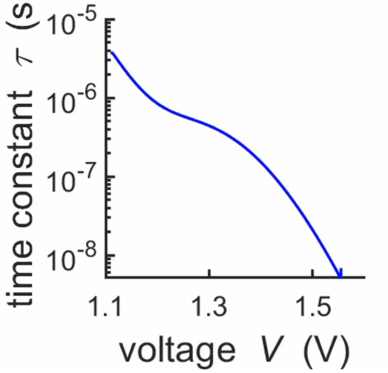
Video



$$-\frac{dn}{dt} = kn^2 + \frac{n}{\tau} + \frac{C}{qd}\frac{dV}{dt}$$

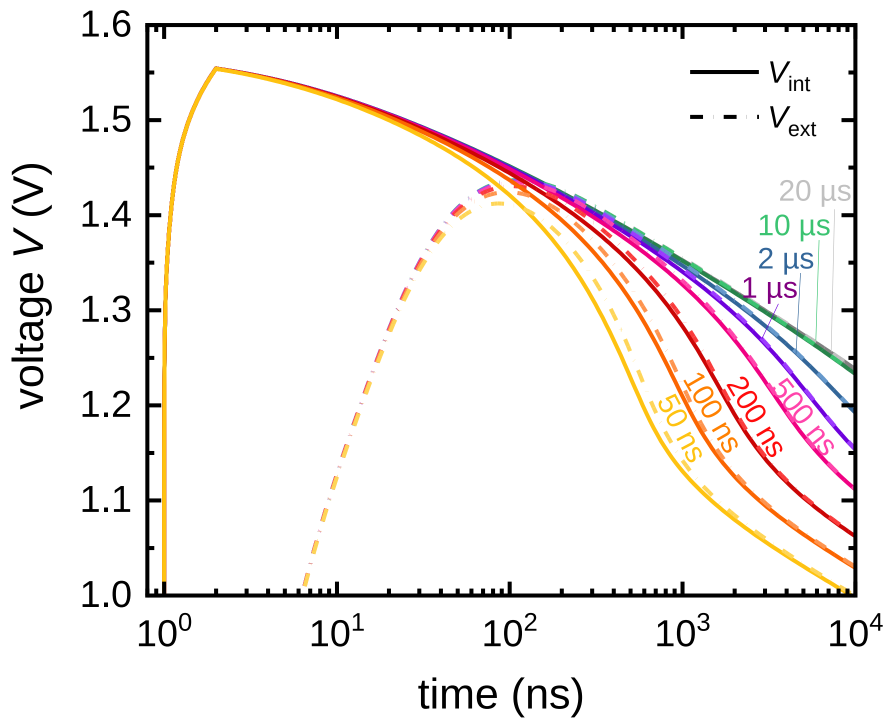


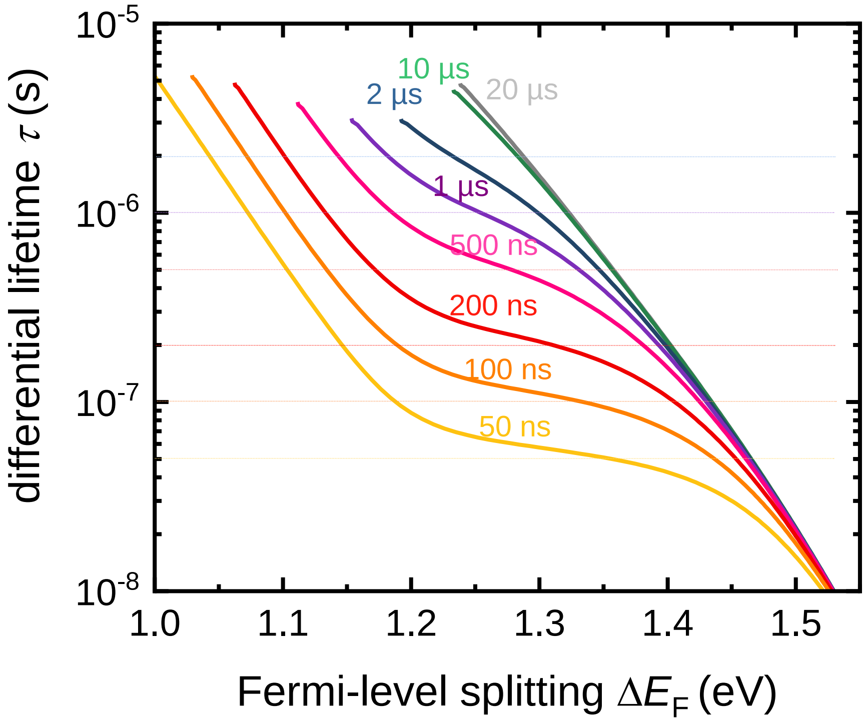




Large signal lifetime from TPL (wo bias)

Bulk lifetime variation, S=0.1 cm/s, laser fluence 10 µJ/cm^2





Comparison to V_{oc} decays (OCVD)

Energy & Environmental Science

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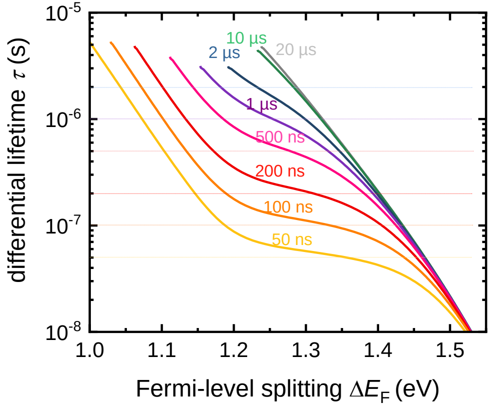
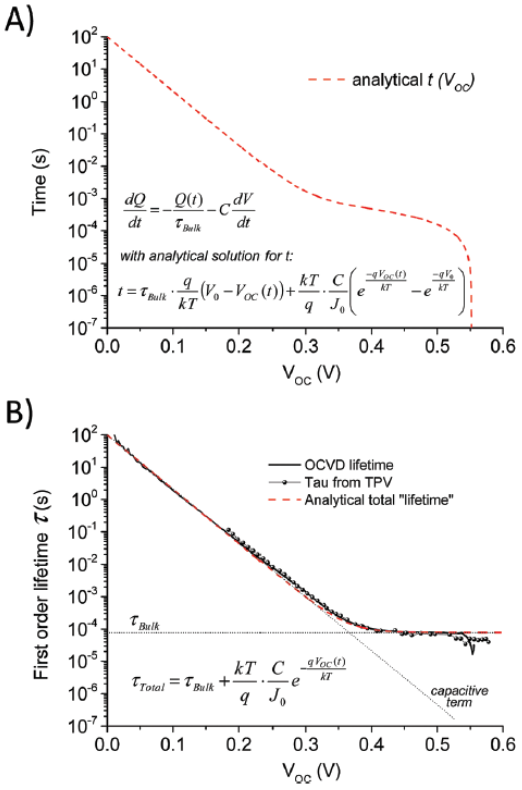
Revisiting lifetimes from transient electrical characterization of thin film solar cells; a capacitive concern evaluated for silicon, organic and perovskite devices†

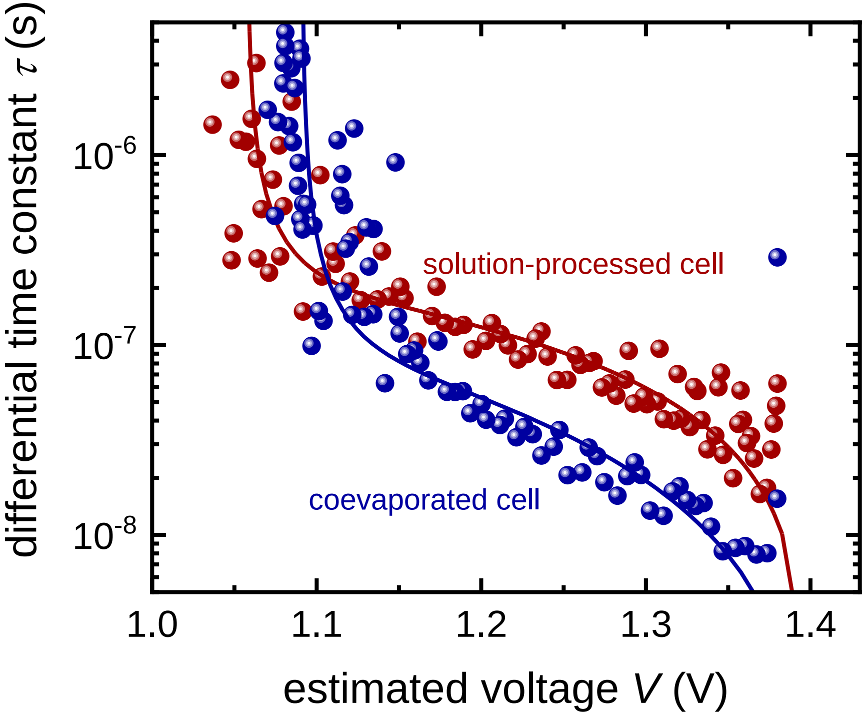
David Kiermasch,[a] Andreas Baumann,[b] Mathias Fischer,[a] Vladimir Dyakonov[ab] and Kristofer Tvingstedt*[a]

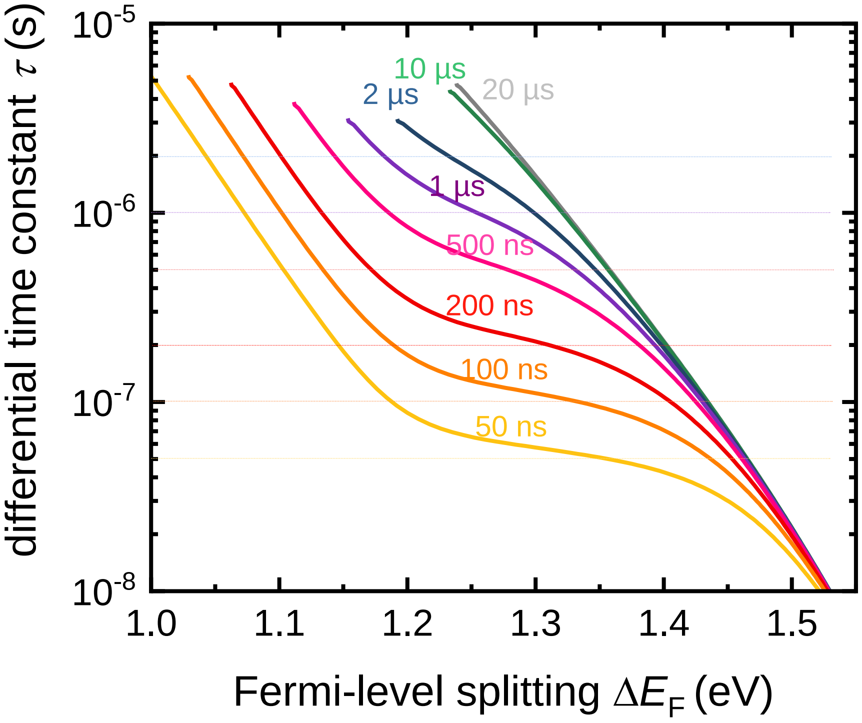




Large signal lifetime from TPL (wo bias)

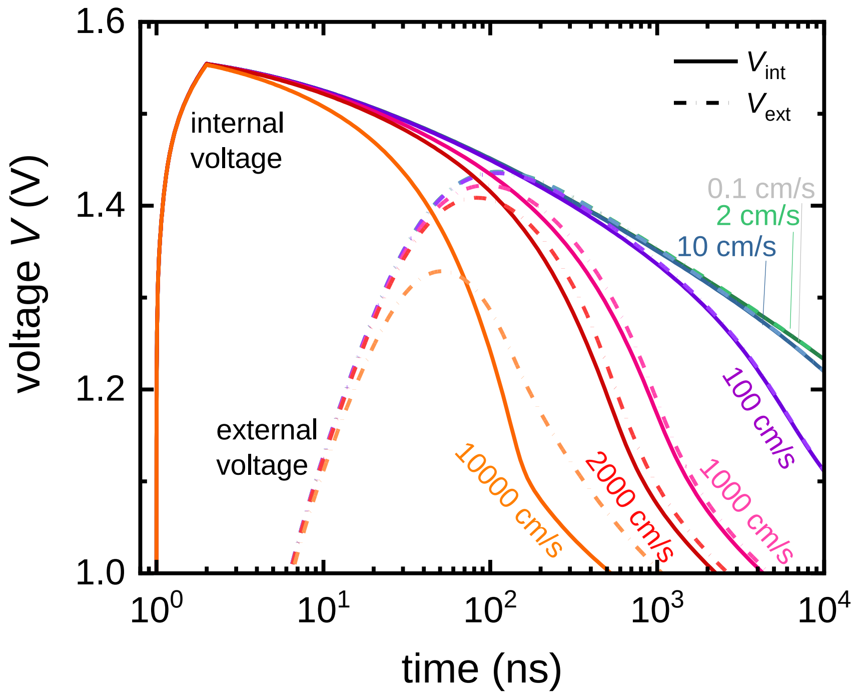
Experiment vs. Simulation

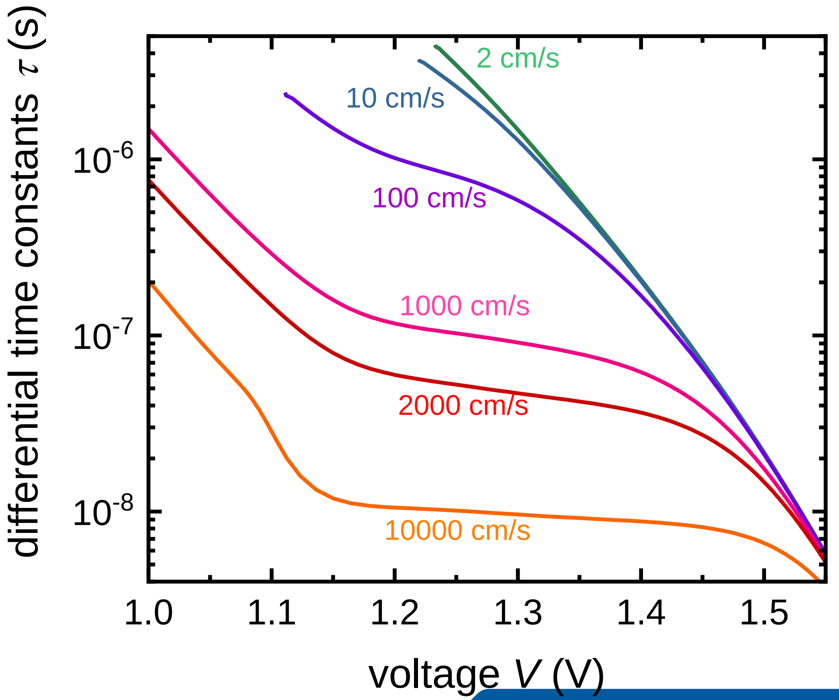




Large signal lifetime from TPL (wo bias)

Bulk lifetime 10 µs, laser fluence 10 µJ/cm²



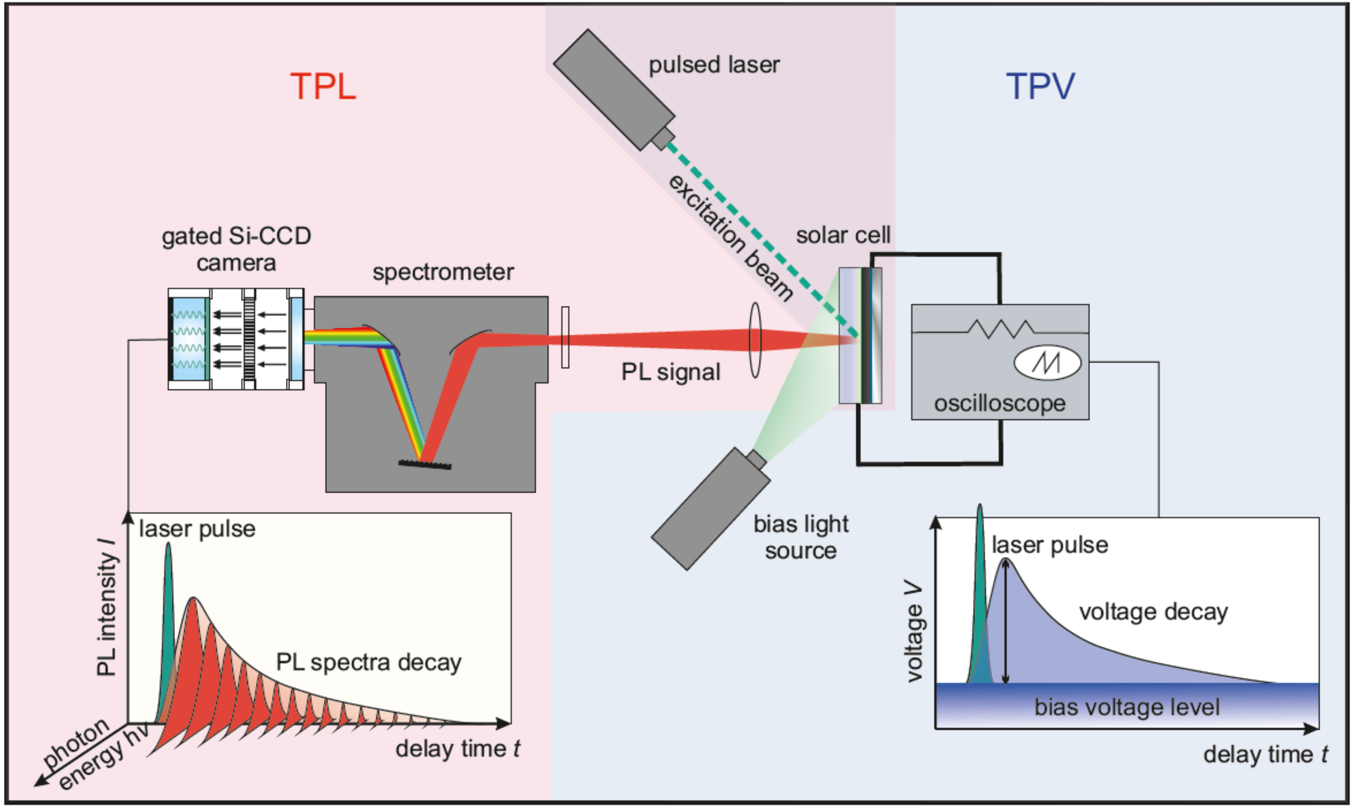


Transient Photoluminescence (TPL)

measures the luminescence decay

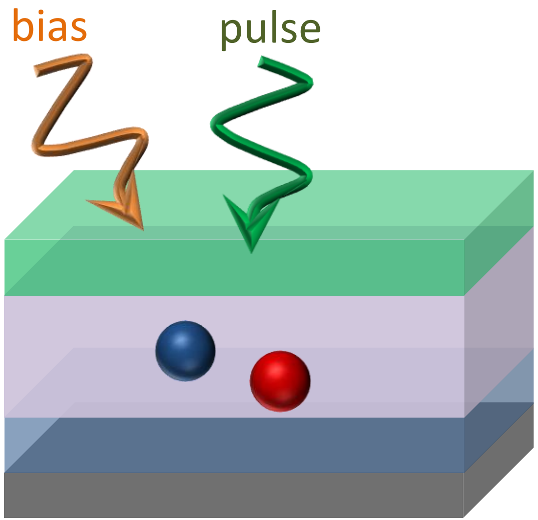
Transient Photovoltage (TPV)

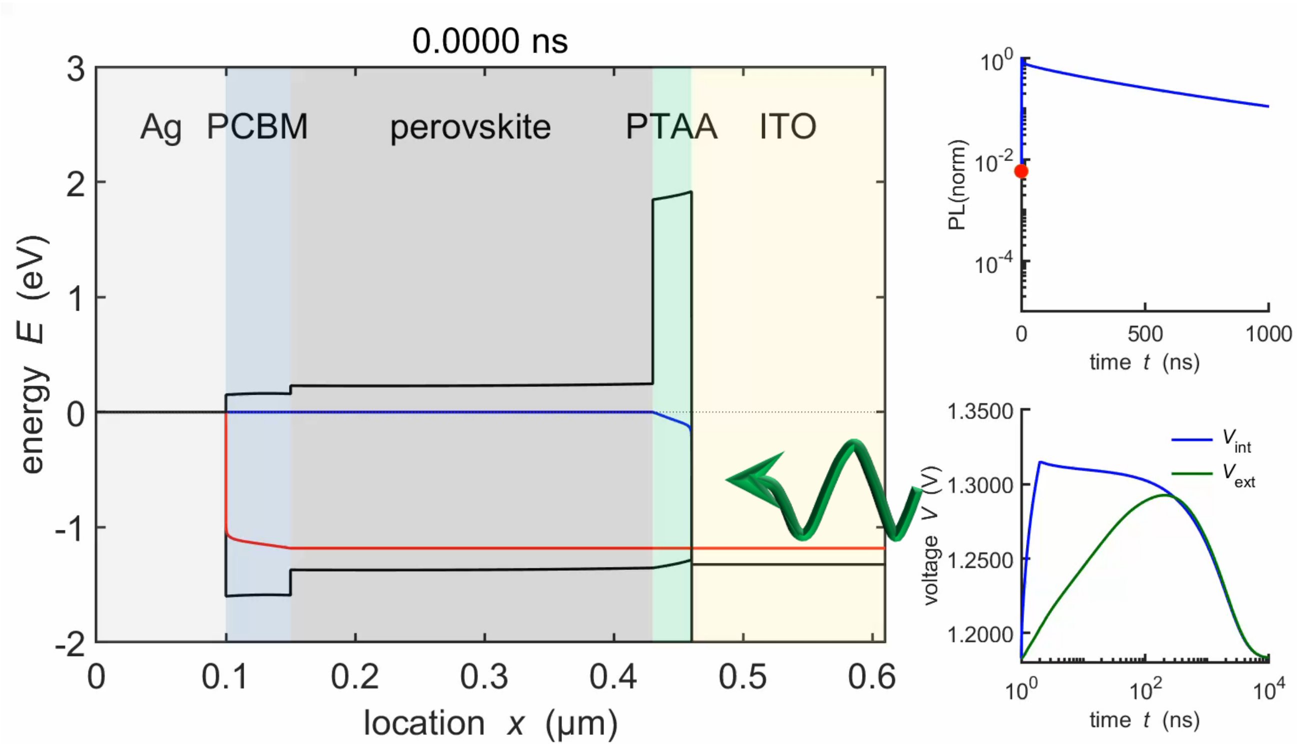
measures the decay of an external voltage



Transients with bias light

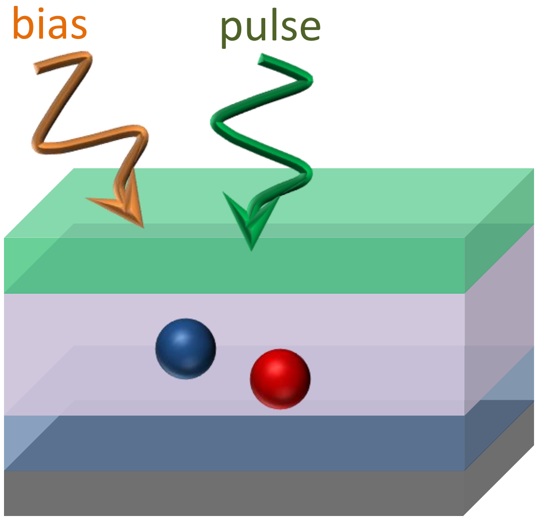
Video TPV vs. TPL



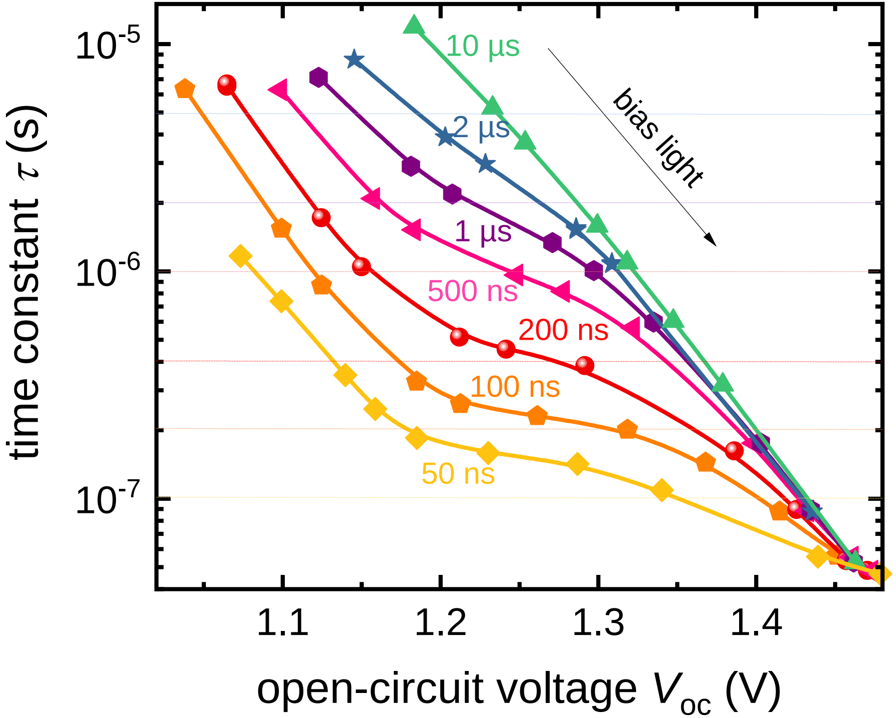


TPV Decay Constants

Small signal transients

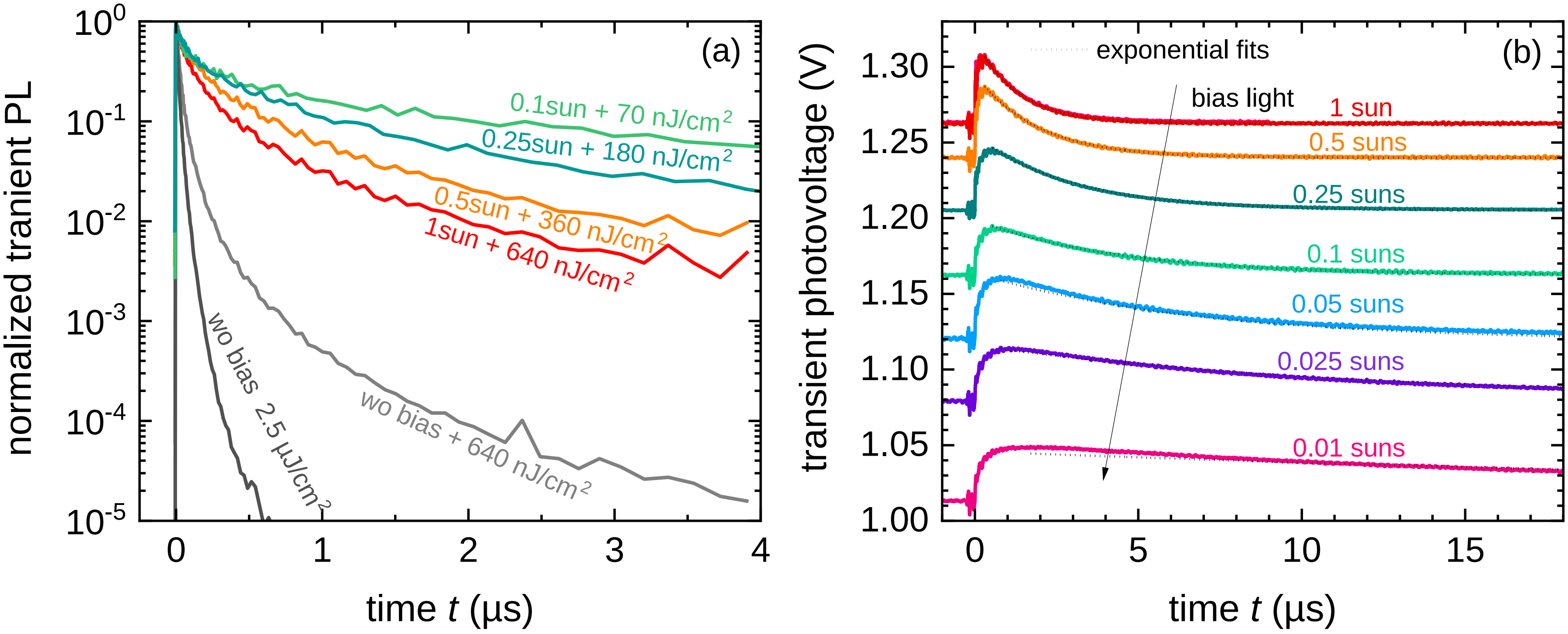


$$-\frac{dn}{dt} = kn^2 + \frac{n}{\tau} + \frac{C}{qd}\frac{dV}{dt} - G_{\text{bias}}$$

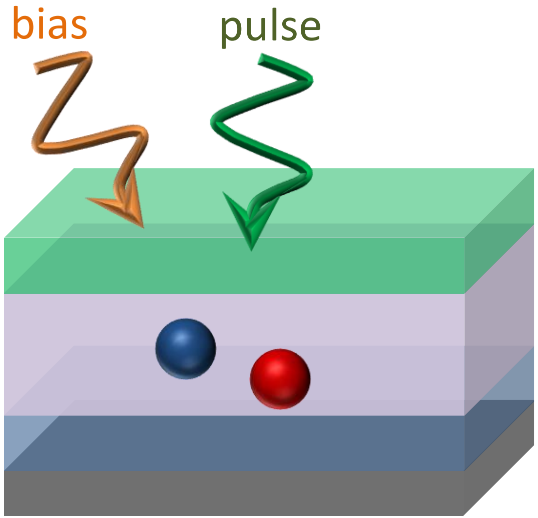


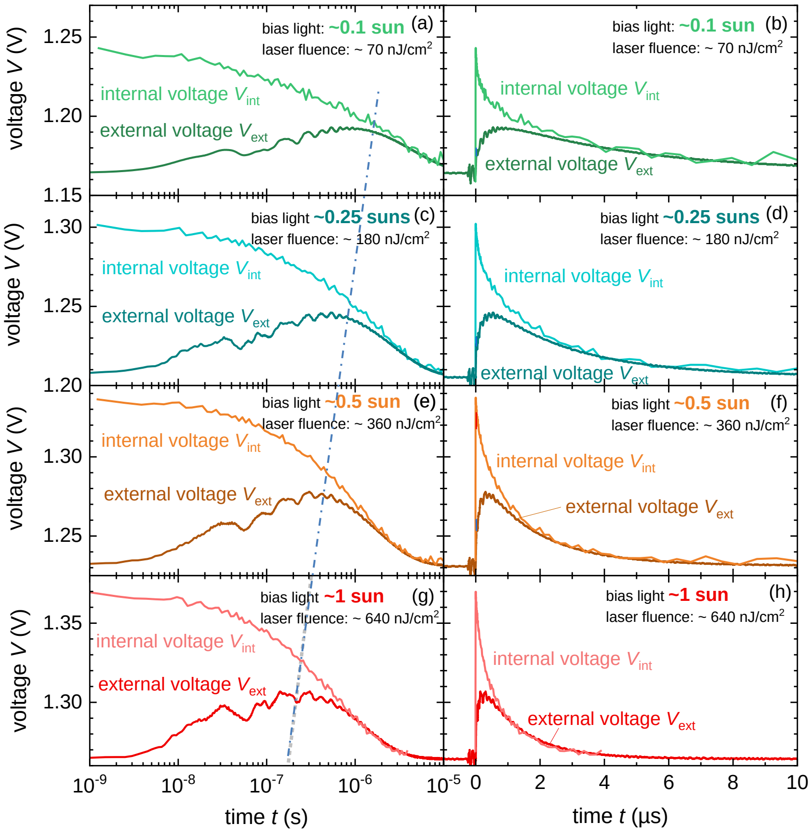
TPV vs. TPL Experimental Data

Selected TPL transients and TPV decays



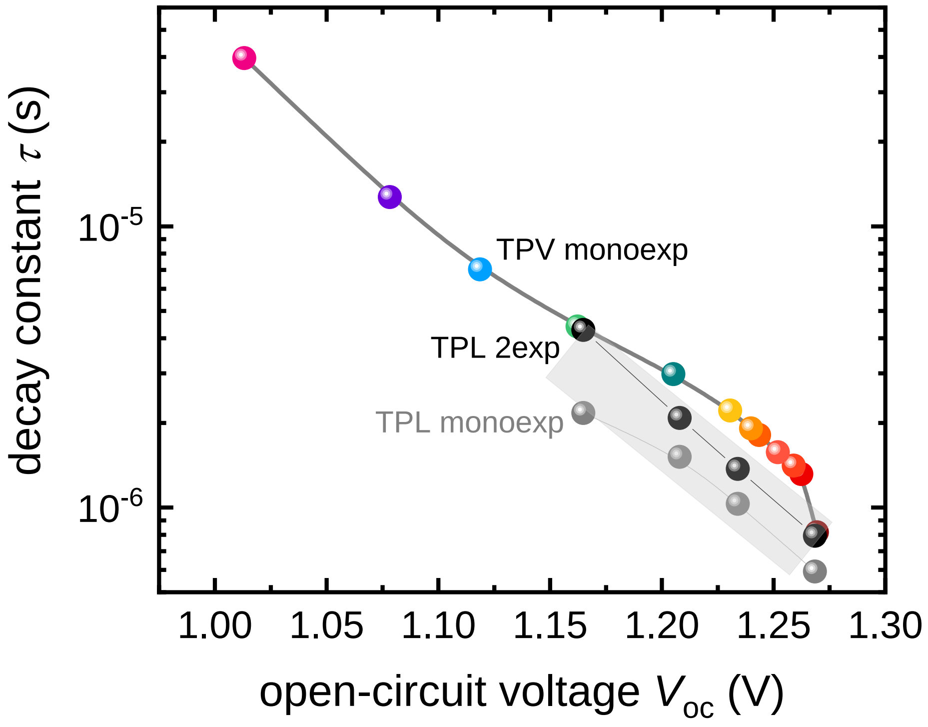
Experimental data – internal vs. external voltage

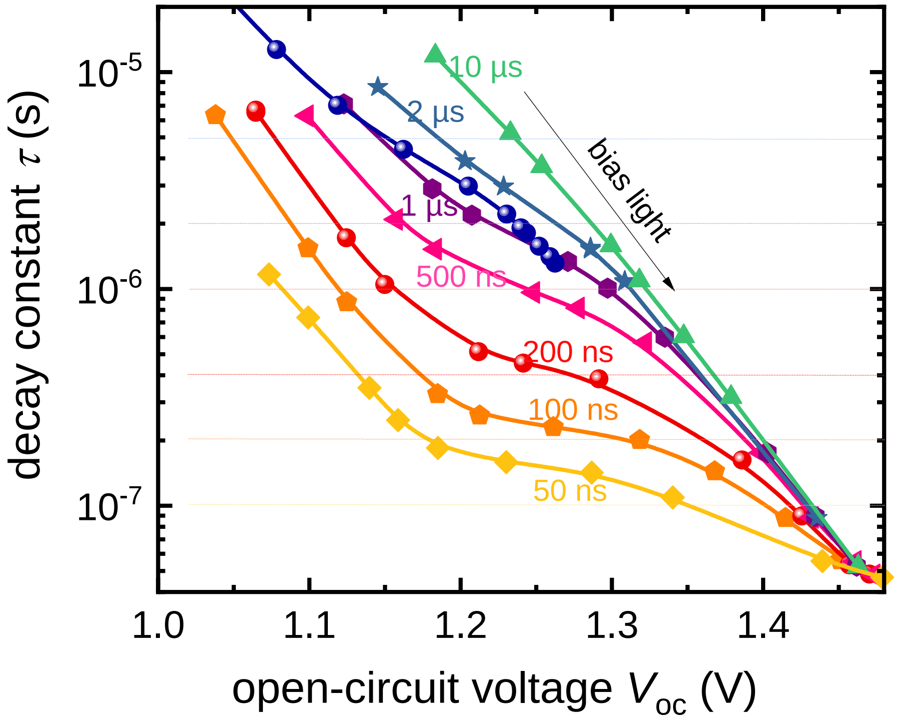




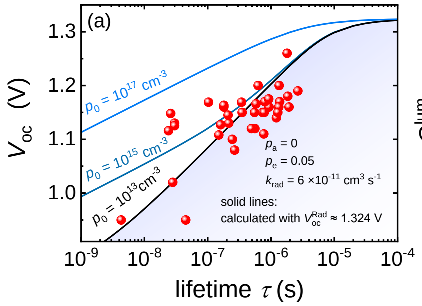
TPV Decay Constants

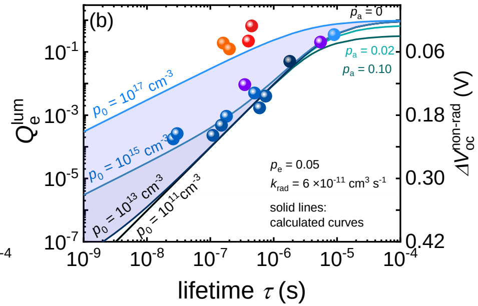
Experiment vs. Simulation





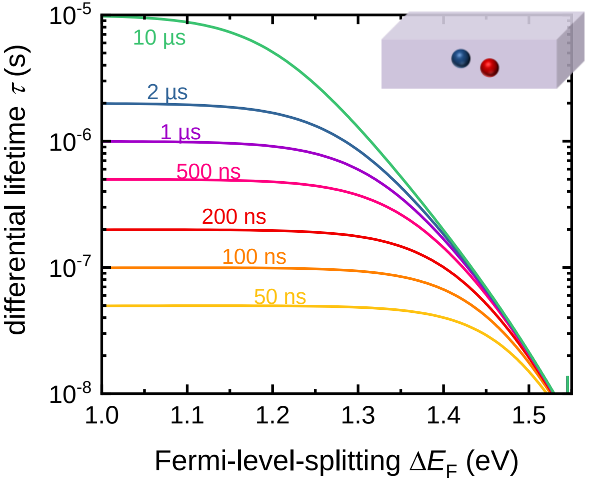
Summary

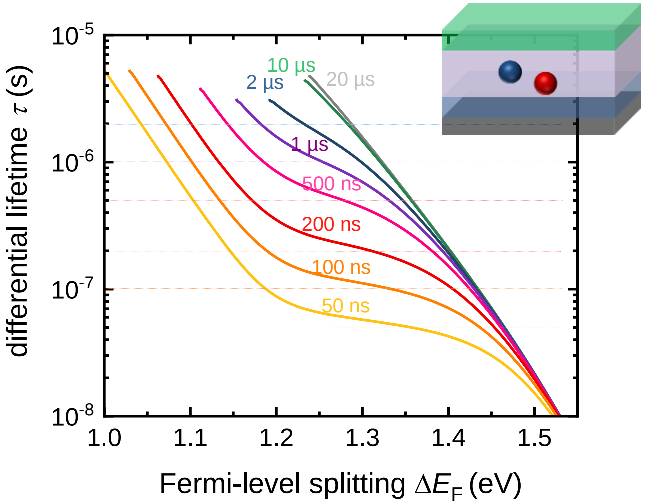




1) "Lifetimes" correlate with V_{oc} but not in an easy way

2) Interpretation of decay constants as a function of sample geometry





Thanks to
Thomas Unold
Jose Marquez
Martin Stolterfoht
Helmholtz Association for Funding

Thank you for your attention

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

JÜLICH Forschungszentrum