Origin of microsecond charge carrier lifetimes in polycrystalline CdTe solar cells

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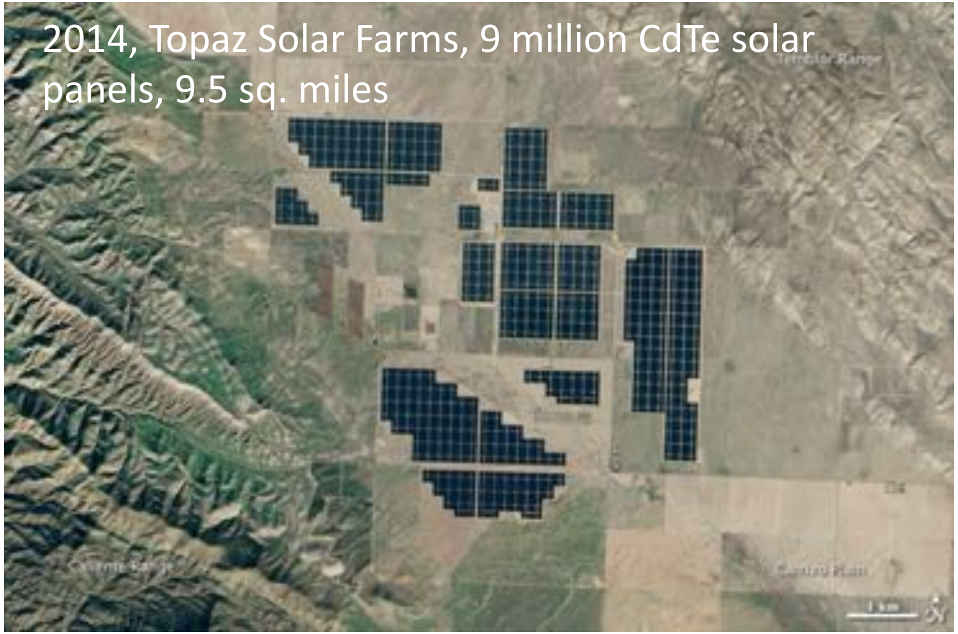
Chungho Lee

Virtual Chalcogenide PV Conference 2020
May 26th, 2020

Thin film PV



https://pv-magazine-usa.com/2020/04/23/fitch-rates-550-mw-first-solar-installed-topaz-project-notes-at-c-despite-superb-performance/

2020 thin film PV capacity:
~8 GW_{pp} – CdTe
~2 GW_{pp} - CIGS

Annual primary energy installations ~100 GW

Higher solar cell efficiency reduces PV cost and is necessary for competition with other energy technologies

Some current efforts to make CdTe solar cells more efficient (and reliable)

Group-V doping:

Metzger et al, Nature Energy 4, 837 (2019); McCandless et al, Sci. Rep. 8, 14519 (2018); Kartopu et al, Sol. Energ. Mat. Sol. Cells, 194, 259 (2019)

Front contacts:

Ablekim et al, ACS Energy Letters 5, 892 (2020)

Back contacts:

Liyanage et al., ACS App. Energy Materials 2, 5419 (2019), T. Song et al, IEEE J. Photovolt. 8, 293 (2018)

Interface chemistry:

Perkins et al, ACS Appl. Mat. Interf. 11, 13003 (2019)

Defect analysis:

Fiducia et al, Nature Energy 4, 504 (2019); Guo et al, Appl. Phys. Lett. 115, 153901 (2019); Moseley et al, J. Appl. Phys. 124, 113104 (2018)

Model systems (single crystals, epitaxial, polycrystalline heterostructures):

Nagaoka et al, Appl. Phys. Lett. 116, 132102 (2020), Kephart et al IEEE J.Photovolt., 8, 587 (2018); Zhao et al, IEEE J. Photovolt. 7, 690 (2017)

This talk is about one characteristic – minority carrier lifetime – which is impacted by and helps improve many of above efforts

Origin of μs lifetimes in CdSeTe

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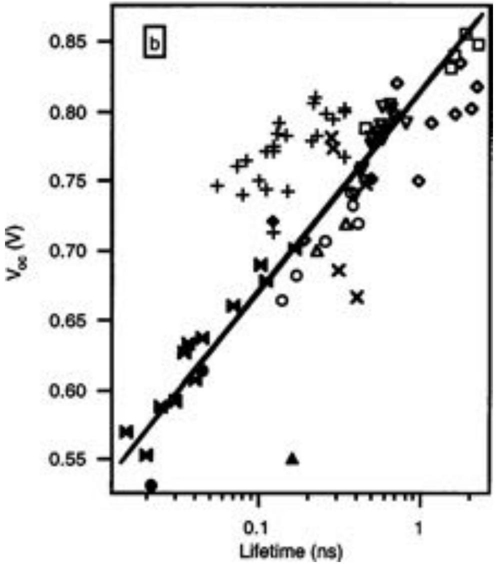
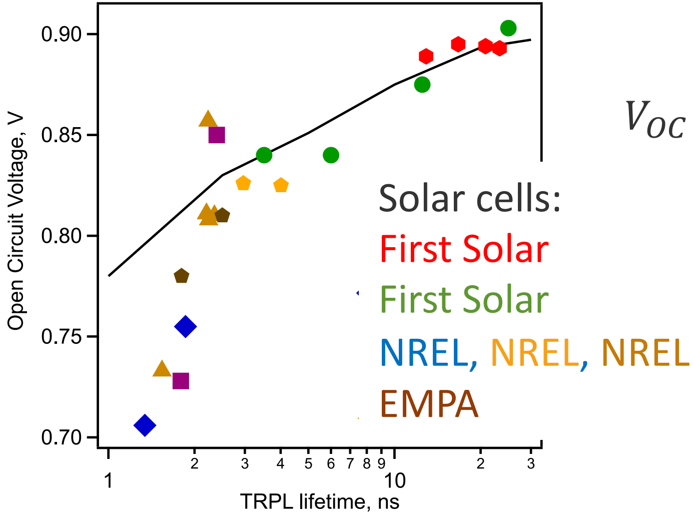
Charge Carrier Lifetimes

- Reduced SRH recombination is indicated by longer recombination lifetimes;
- Long-standing metric for improvements in V_{OC} in CdTe;
- Analysis is more complicated in current “graded” CdSeTe/CdTe absorbers



Metzger et al, J. Appl. Phys. 94, 3459 (2003)



DK et al, IEEE J. Photovolt. 6, 313 (2016)

$$V_{OC} = \frac{2kT}{q} ln\left(\frac{\tau J_L}{q n_i}\sqrt{\frac{2qN_A}{\varepsilon V_{bi}}}\right)$$

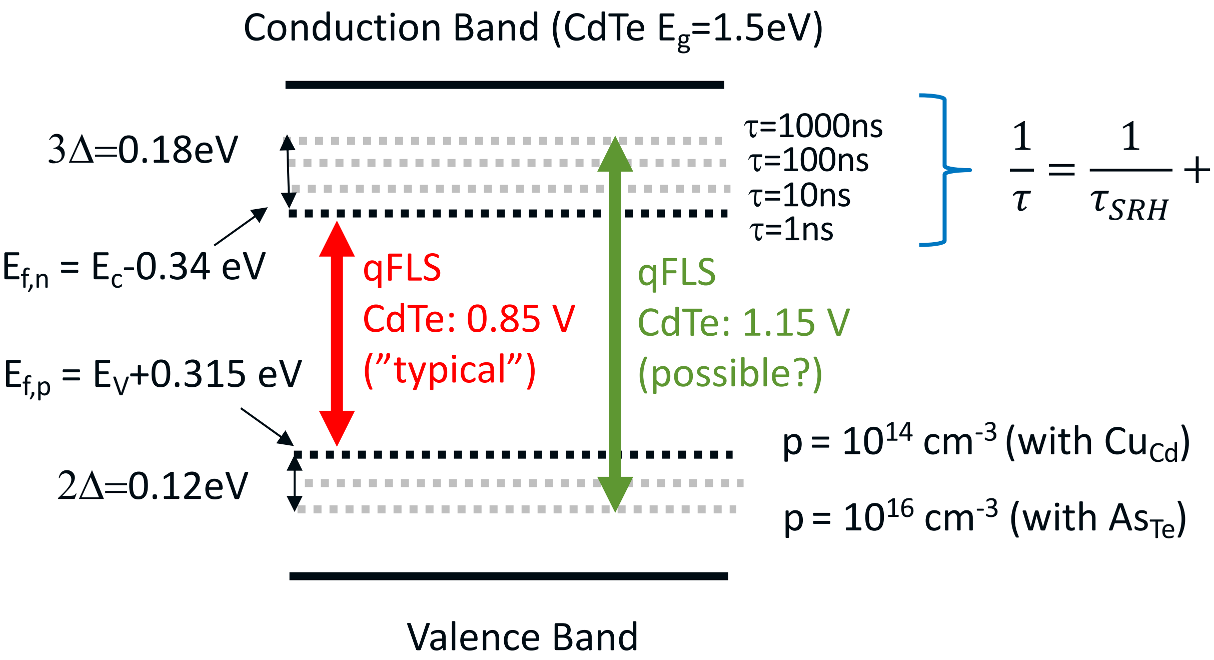
Lifetime as absorber qFLS metric

Electrons

$$E_{f,n} = E_C + kTln(n/N_C)$$

Holes

$$E_{f,p} = E_V - kTln(p/N_V)$$



$$\frac{1}{\tau} = \frac{1}{\tau_{SRH}} + \frac{1}{Bp}$$

Assumptions:
Holes: N_V=1.8×10^{19} cm^{-3}
Electrons: N_C=8×10^{17} cm^{-3}, 1 Sun, 1μm thick absorber

Lifetime as interface passivation metric

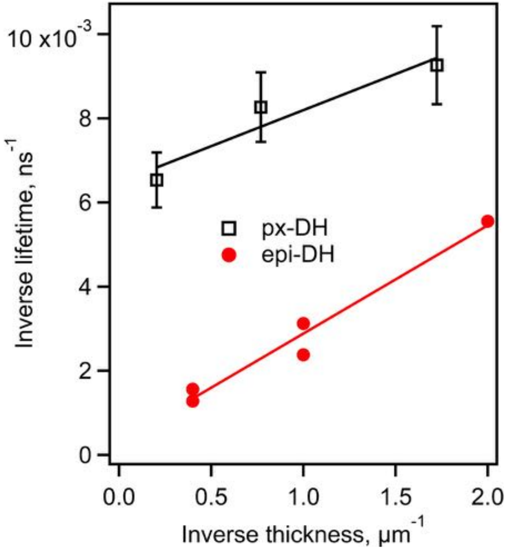
Passivated polycrystalline heterostructures

sputtered Al_2O_3 (alumina)

thickness d=0.6-4.9 μm

J. Kephart, Colorado State University

Interface recombination velocity
S = 100-200 cm/s for lattice-matched (epitaxial) and polycrystalline interfaces



Polycrystalline Al_2O_3/CdSeTe/Al_2O_3

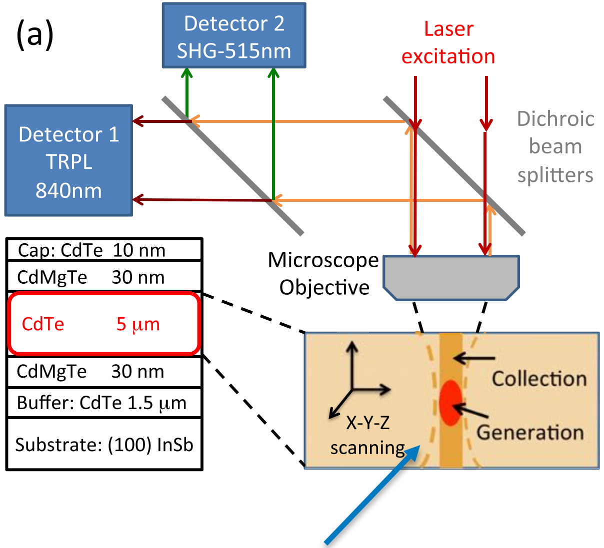
Epitaxial CdMgTe/CdTe/CdMgTe

T. Myers, Texas State University

$$\frac{1}{\tau_{TRPL}} = \frac{1}{\tau_B} + \frac{2S}{d}$$

DK, Kephart, et al, Appl. Phys. Lett. 112, 263901 (2018)

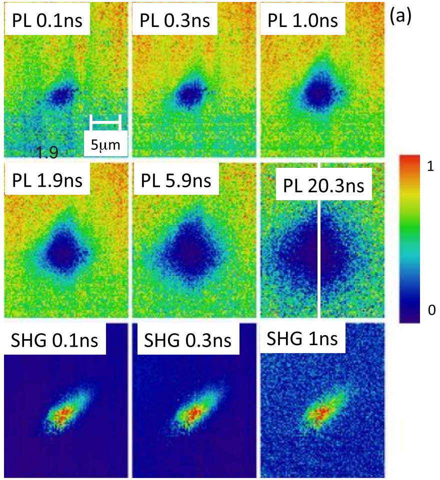
Lifetime as transport metric

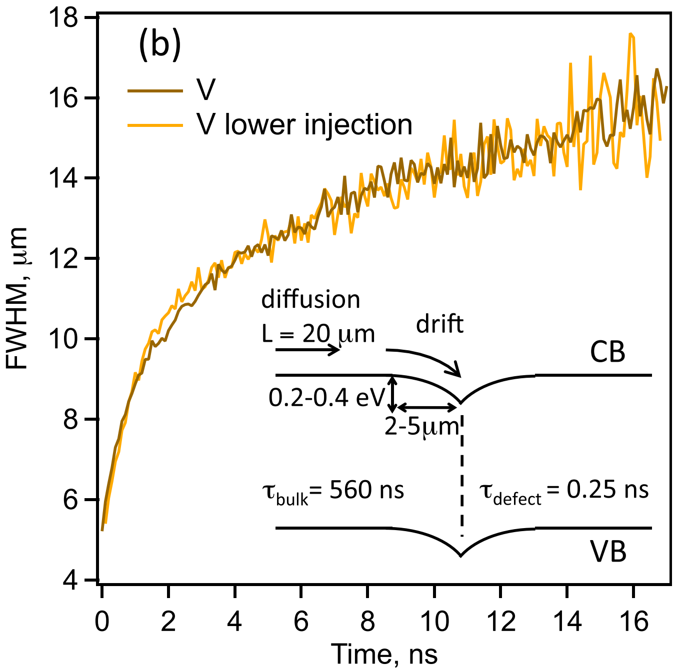


Carriers drift/diffuse from the generation volume

Single extended defect in epitaxial CdTe

Time-resolved PL imaging (TRPL microscopy)





DK, Myers, et al, Appl. Phys. Lett. 110, 083906 (2017)
DK, Farrell et al, J. Appl. Phys. 116, 123108 (2014)

SHG Second harmonics generation due to the space charge field; EFISH

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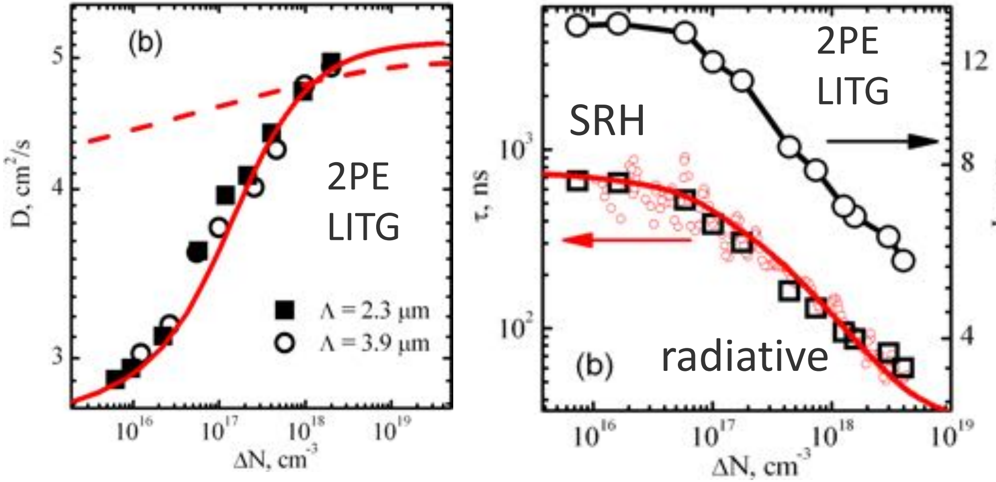
Lifetimes in single crystal CdTe

https://news.wsu.edu/2016/02/29/146010/

τ_B = 800 ns, L_D = 13 μm

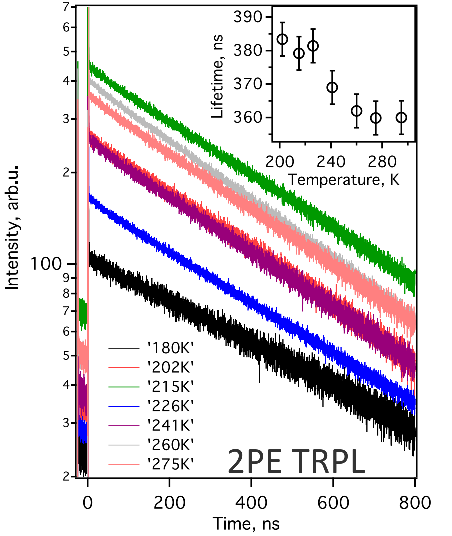
Single crystals: WSU, S. Swain and K. Lynn

Light induced transient grating (LITG):
Mobility and lifetime in (compensated) bulk single crystals
Patrik Scajav, Vilnius University



Scajev et al, J. Appl. Phys. 123, 025704 (2018)

Time-resolved PL



DK et al, IEEE JPV 5, 366 (2015)

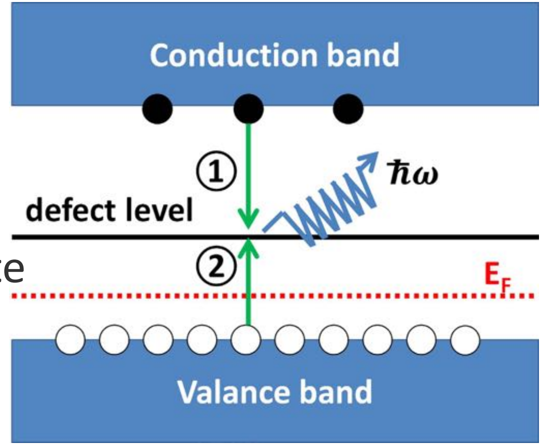
To date, bulk lifetimes in CdSeTe single crystals are <50 ns

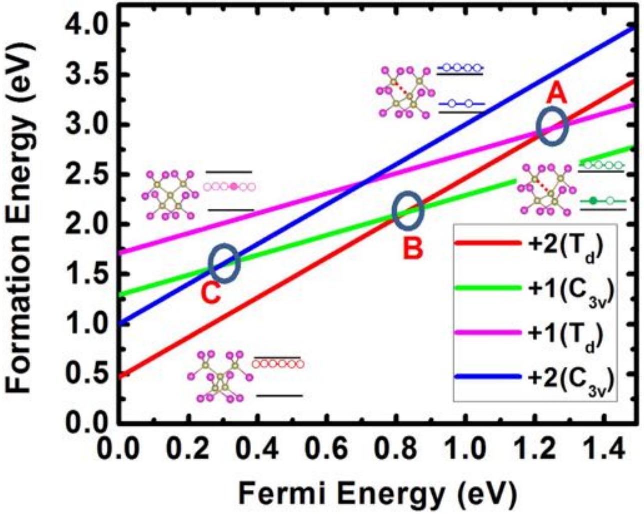
Accurate defect model in bulk CdTe

HSE06 calculated defect energies and hole density 2E14 cm^{-3}, bulk SRH lifetime 360 ns

V_{Cd} is also considered as SRH defect

Te_{Cd} antisite





J.-H. Yang, L. Shi, L.-W. Wang, S.-H. Wei, Sci. Rep. 6, 21712 (2016)

Te_{Cd} and V_{Cd} density can be changed by Cd partial pressure and CdTe growth temperature:

Ma et al, Phys. Rev. Lett. 111, 067402 (2013)

(no defect model in CdSeTe?)

(lifetimes <50 ns in single crystal CdSeTe?)

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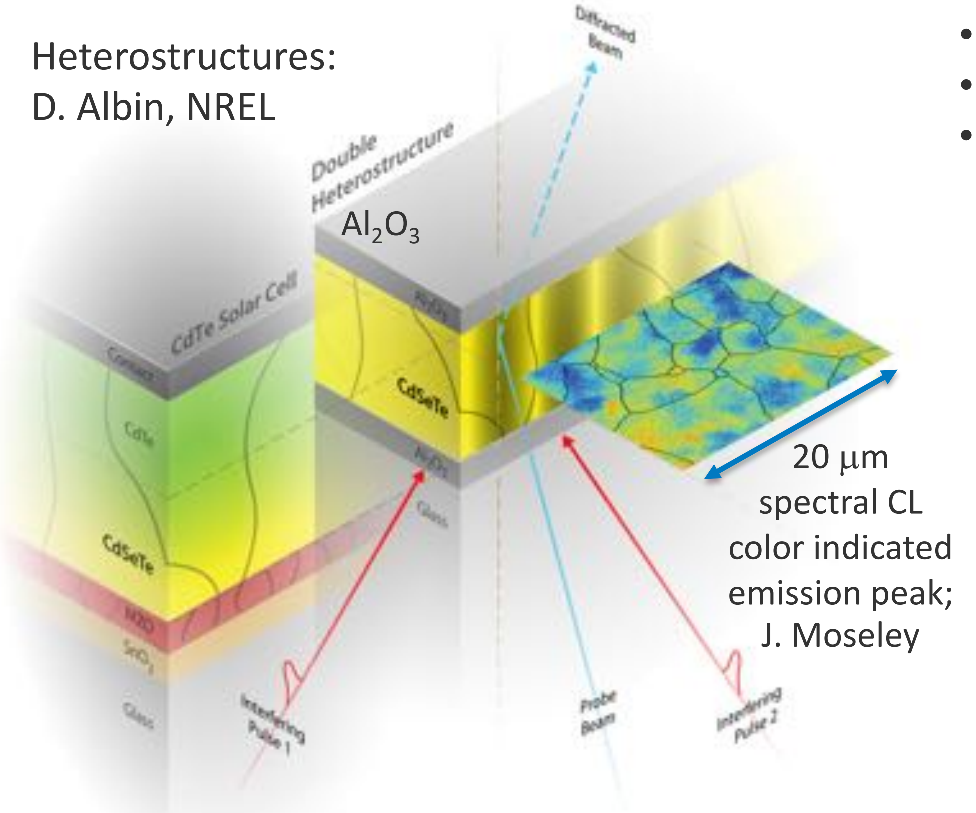
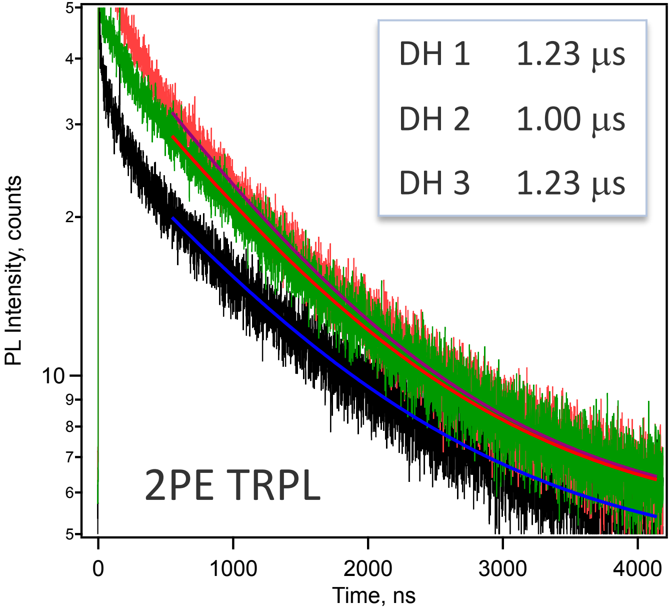
Polycrystalline heterostructures

Heterostructures:
D. Albin, NREL



- Alumina is used for passivation;
- Selenium is used in the absorber;
- Grains are large due to high temperature $CdCl_2$

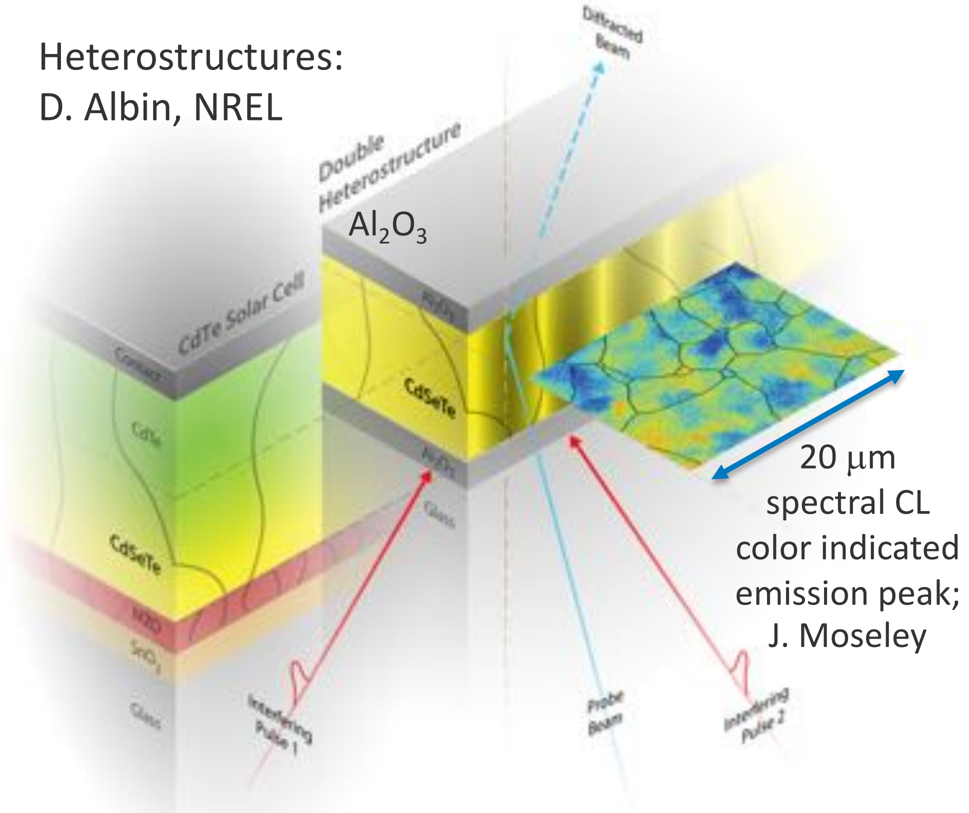


DK, Moseley, Scajev, Albin, pss-RRL 14, 1900606 (2020)
(cover illustration by A. Hicks)

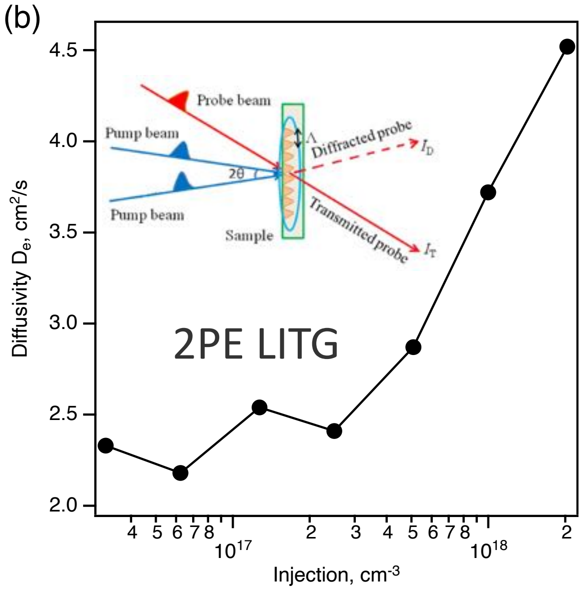
(Heterostructures without Se: τ = 30 ns)

Polycrystalline heterostructures

Heterostructures:
D. Albin, NREL



Light-induced transient grating
P. Scajev, Vilnius University

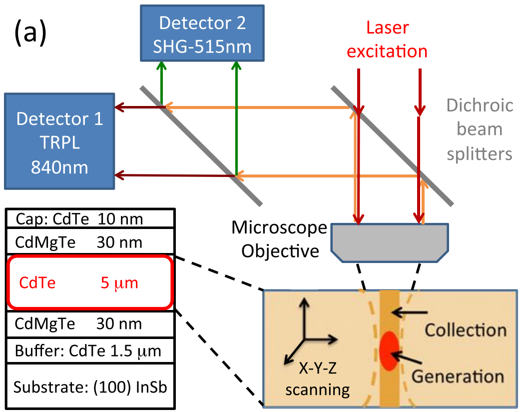


Mobility 100 cm^2/s
Diffusion length >10 μm

DK, Moseley, Scajev, Albin, pss-RRL 14, 1900606 (2020)
(cover illustration by A. Hicks)

Alumina passivation mechanism

SHG/EFISH: electric field induced second harmonics imaging (fs laser 1030nm, measure 515nm)



Images are cross-section measured with 2PE (no sample cross-sections)

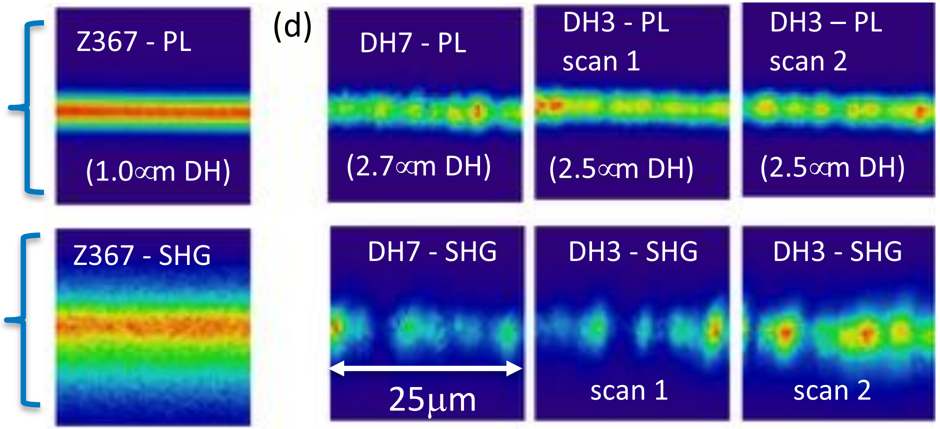
Lattice-matched passivation in single-crystal CdTe epilayers

no Al_2O_3 px-CdSeTe

Al_2O_3 passivation for polycrystalline CdSeTe

Two-photon excitation PL imaging

SHG/EFISH



very weak SHG, Interface defect passivation

strong interface electric field, field effect passivation?

But also see Perkins et al, IEEE J. Photovolt. 8, 1858 (2018)

DK, Kephart, et al Appl. Phys. Lett. 112, 263901 (2018)

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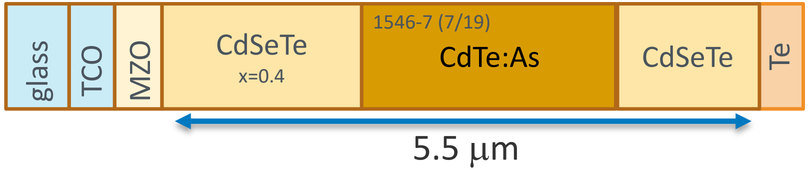
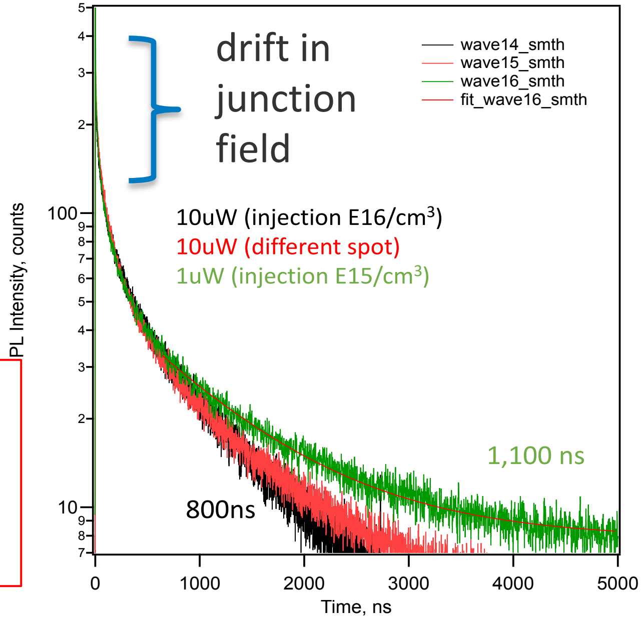
Lifetimes in CdSeTe/CdTe solar cells

As-doped devices, CSU



Devices:
A. Munshi,
A. Danielson,
C. Reich
W. Sampath



Radiative efficiency: talk by
A. Onno, ASU

- In sx-CdTe, carrier lifetimes ~1 μs explained by the point defect model;
- Equivalent τ_{TRPL} = 1 μs in undoped polycrystalline heterostructures with CdSeTe absorber (not CdTe) and Al_2O_3 passivation;
- In CdSeTe/CdTe devices, τ_{TRPL} = 0.3-1 μs with either Cu or As doping;
- **How does Se increase lifetimes in polycrystalline CdSeTe?**

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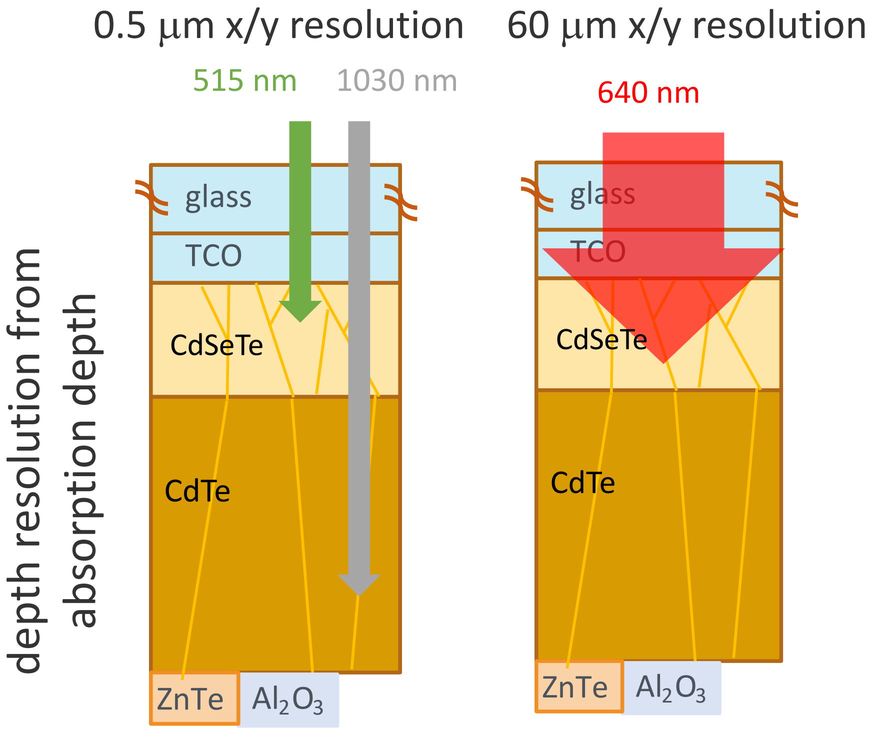
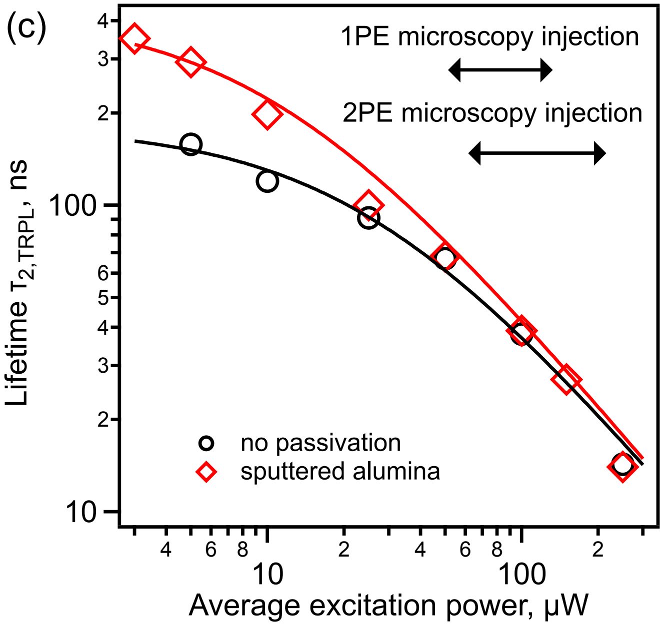
“Spectroscopic” lifetimes in CdSeTe/CdTe device

Cu-doped devices: C. Lee, First Solar

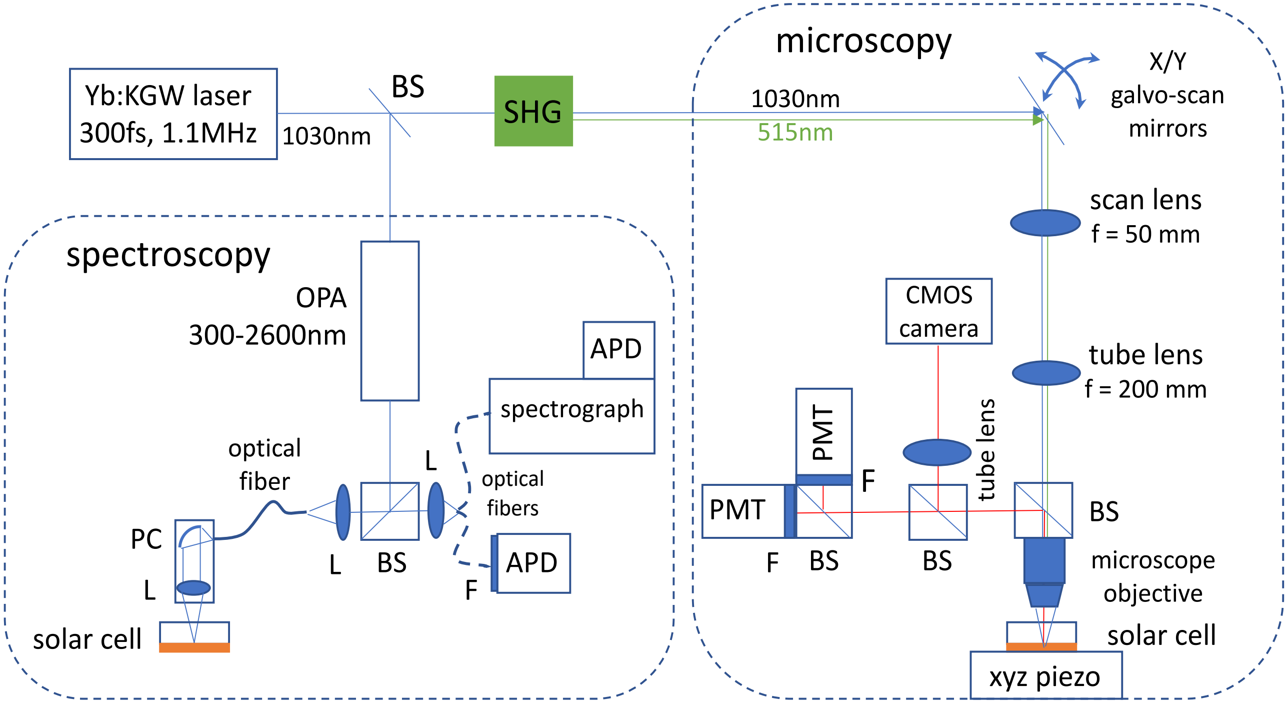


solid line is SRH + radiative fit

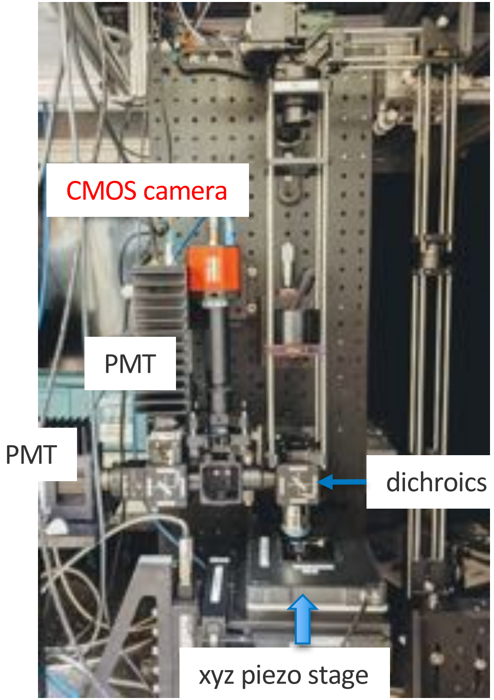
$$\frac{1}{\tau_{2,TRPL}} = \frac{1}{\tau_{SRH}} + \frac{1}{\tau_{rad}} = \frac{1}{\tau_{SRH}} + \mathrm{B}(\text{injection} + N_A)$$



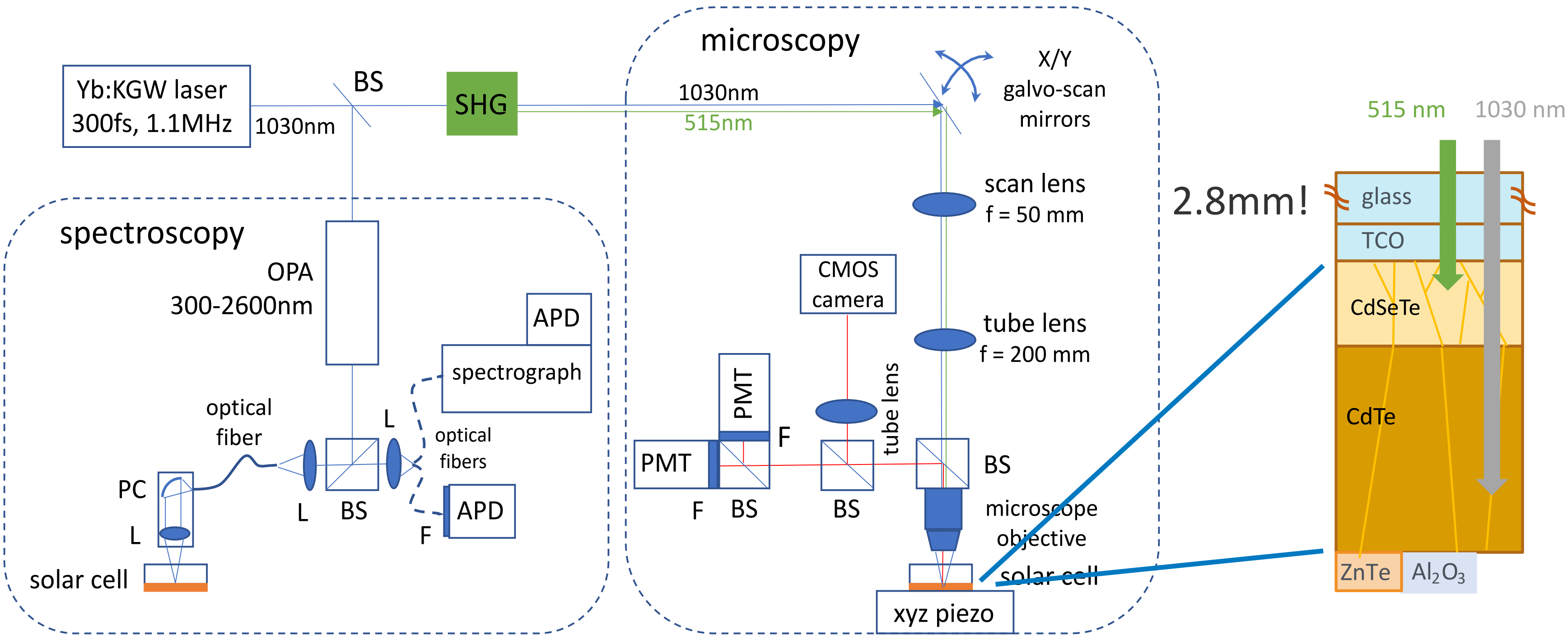
TRPL spectroscopy and microscopy



time-resolved laser scanning microscopy
with 1030 nm and 515nm excitation



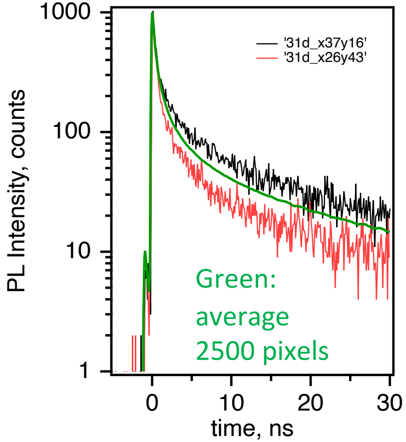
TRPL spectroscopy and microscopy



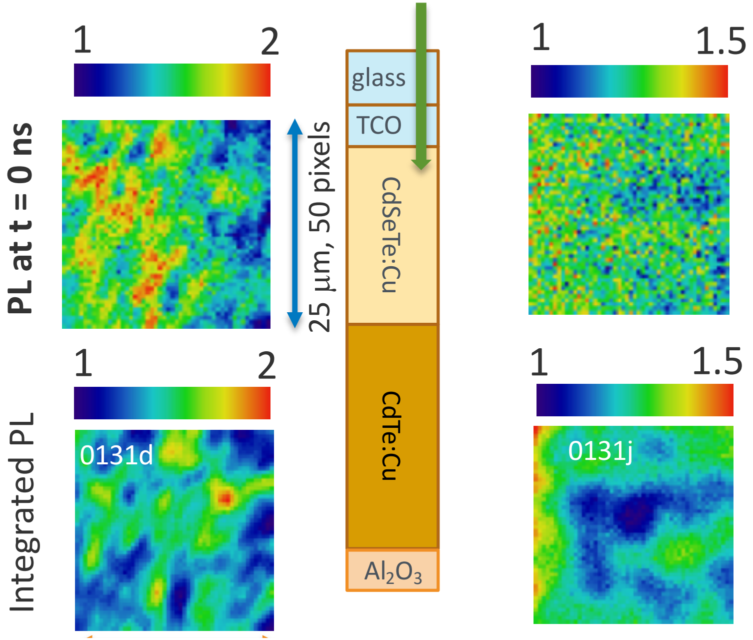
1PE lifetime microscopy in CdSeTe

lowest injection

Black/ red
Pixels with the most difference in lifetime

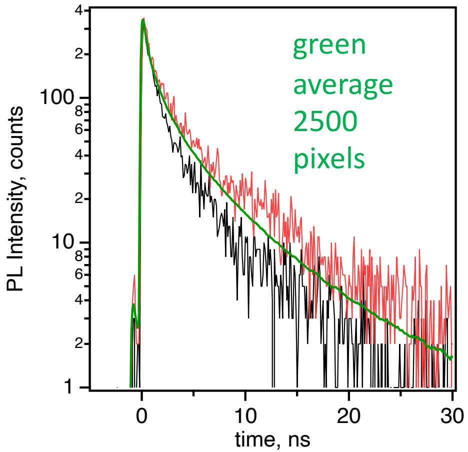


515nm



highest injection (100 times higher)

Black/ red
Pixels with the most difference in lifetime



- Data includes (A) amplitudes at t=0 and (B) lifetimes;
- Amplitudes and lifetimes are very uniform with CdSeTe excitation

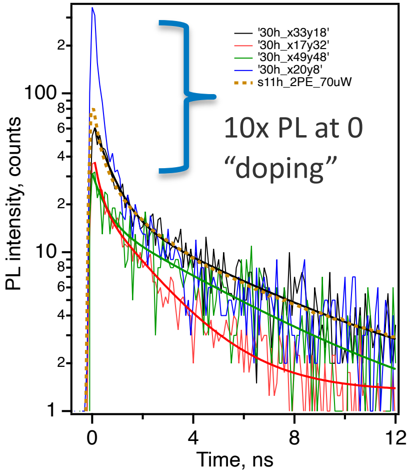
2PE Lifetime microscopy in CdTe

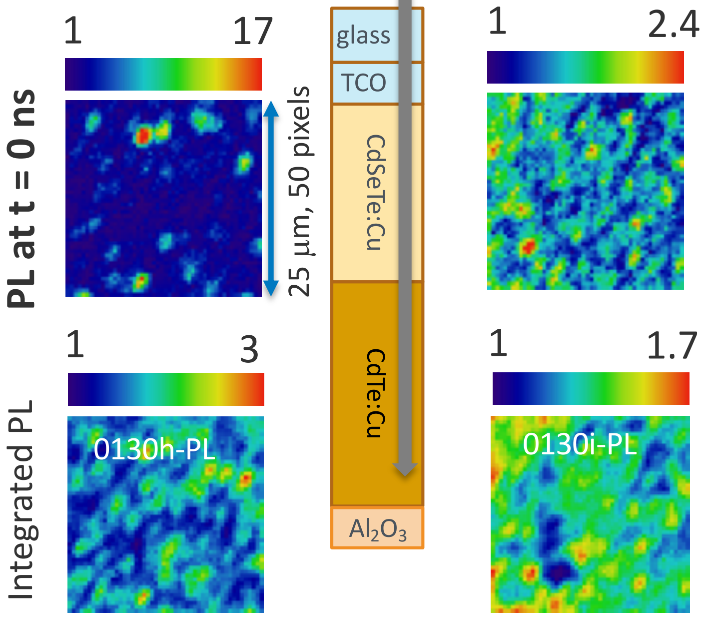
lowest injection

1030nm

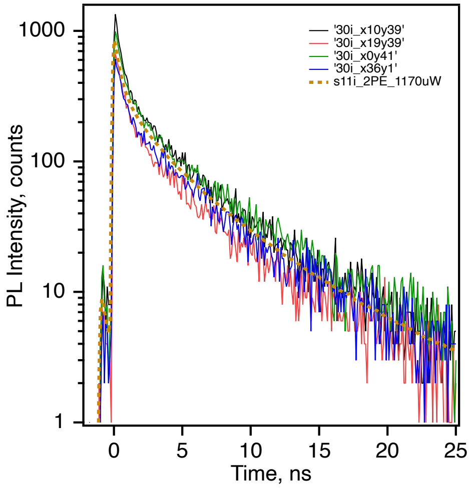
highest injection (280 times higher)

Single-pixel TRPL





Single-pixel TRPL



Pixel amplitudes and lifetimes differ with bulk CdTe excitation

Time-resolved microscopy data analysis
A: PL contrast before recombination (at t = 0)

$$PL(t,x,y) = Bn(\mathrm{t,x,y})\mathrm{p}(t,x,y)$$

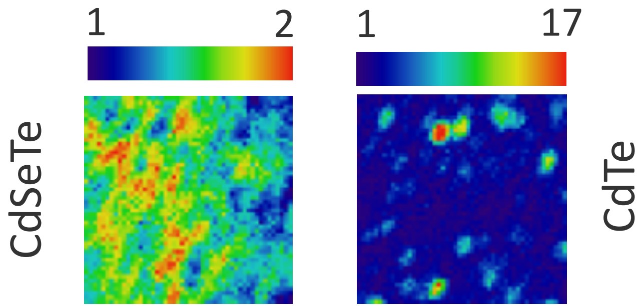
low injection, at t =0

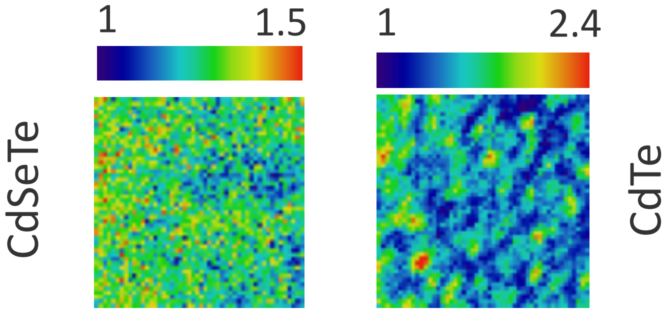
$$PL(t=0,x,y) = Bn(\mathrm{t}=0)N_A(x,y) = const\ N_A(x,y)$$

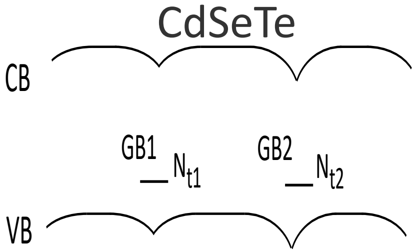
high injection, at t = 0

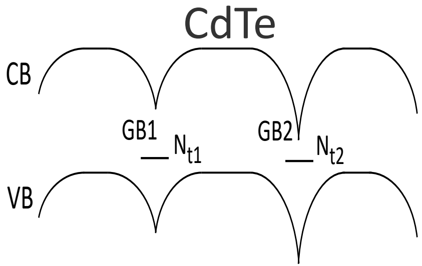
$$PL(t=0,x,y) = Bn^2(t=0) = const$$

All images at t=0



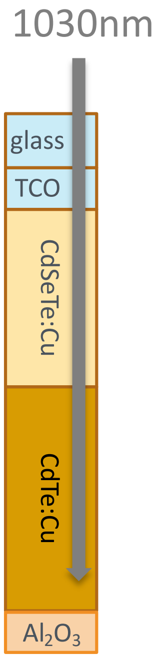


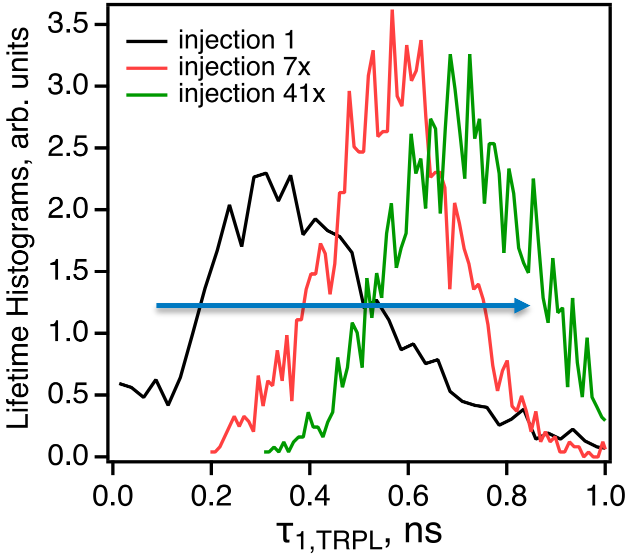


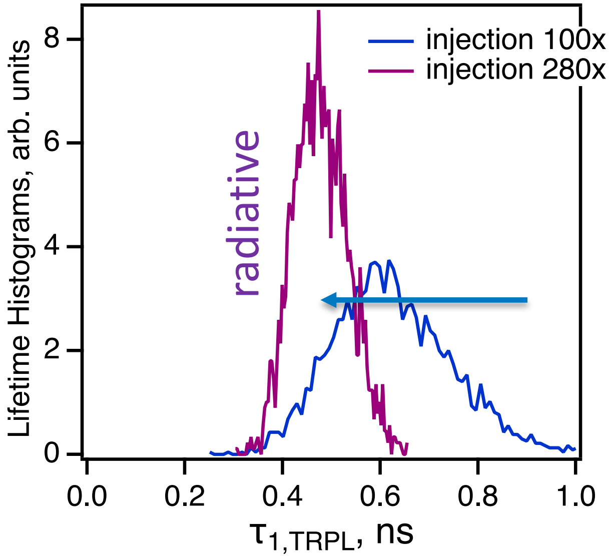


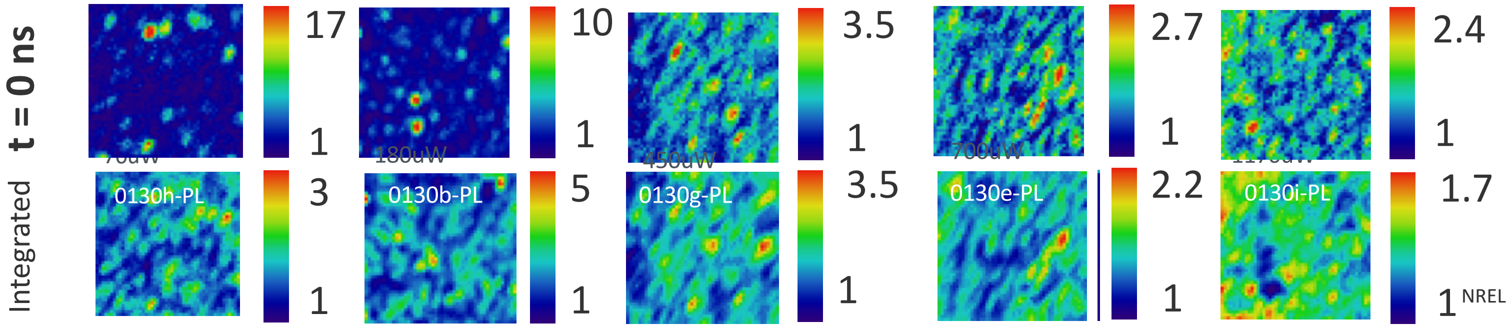
- Low injection: non-uniform N_A due to GB potentials, lower potentials in CdSeTe;
- GB space charge field screening at high injection

Time-resolved microscopy data analysis
B: Injection-dependent lifetime distribution in CdTe









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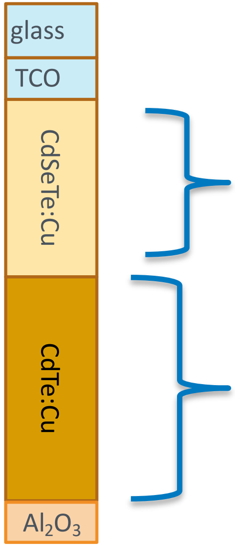
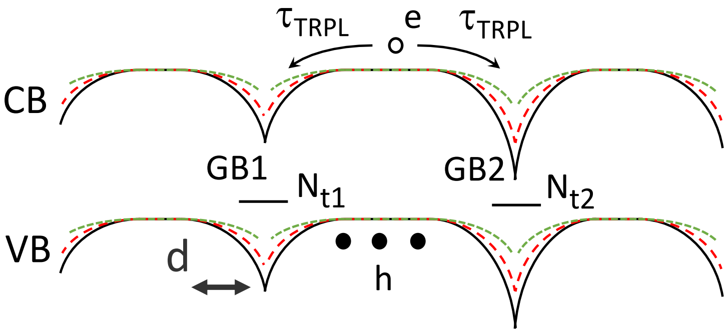
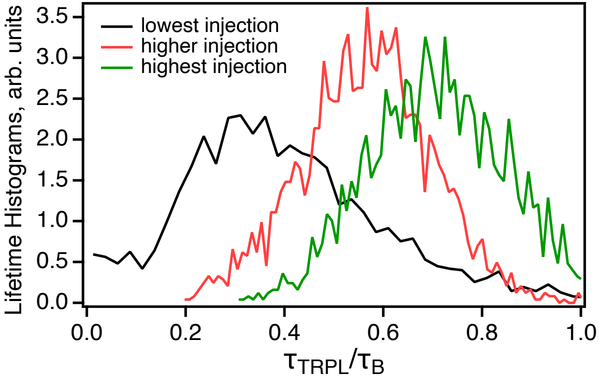
Origin of heterogeneous lifetimes in CdTe



Microscopic lifetimes are uniform in CdSeTe, indicating GB passivation



GB-defect mediated recombination



Grain Boundary barrier height

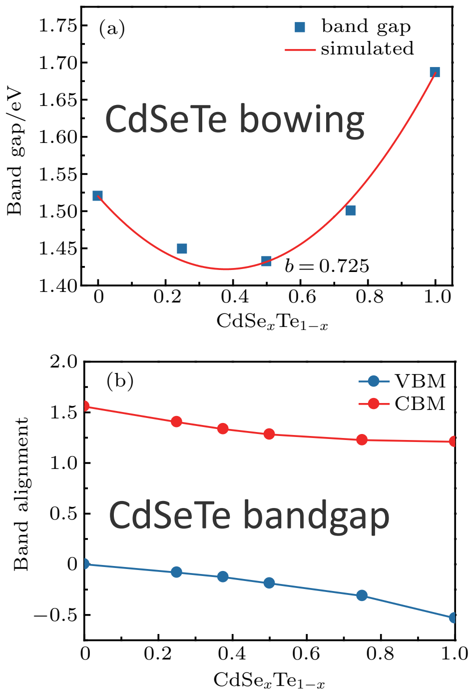
$$\Phi_B = \frac{eN_t^2[cm^2]}{8\epsilon\varepsilon_0 N_A}$$

GB trap density (distribution)

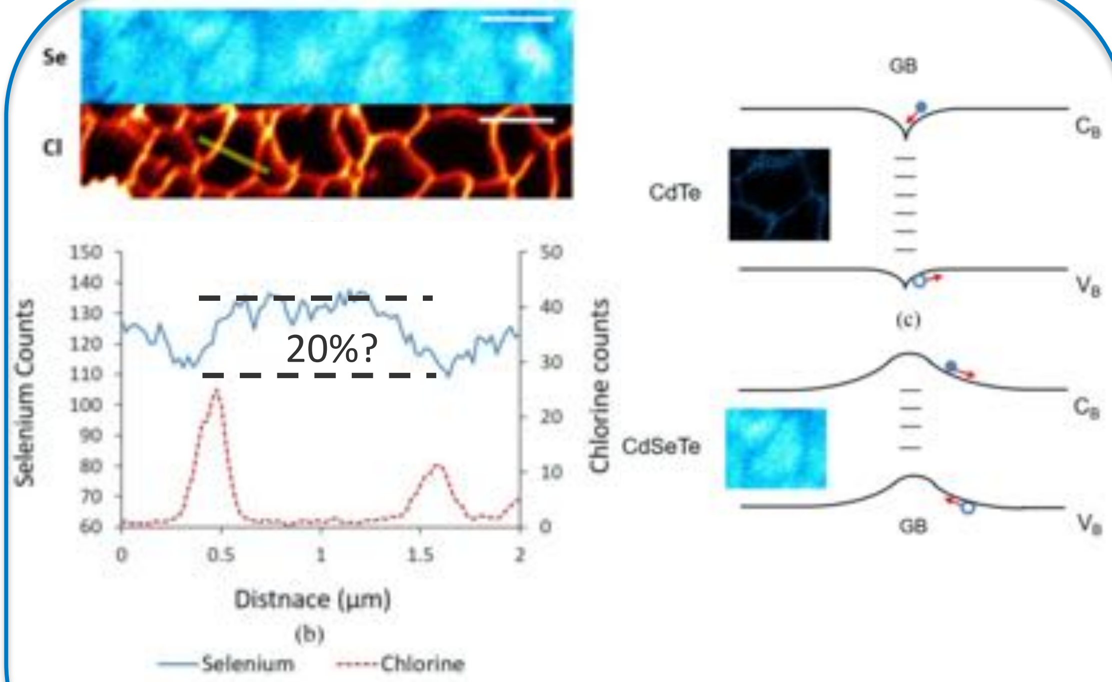
$$\tau_{TRPL} = \frac{d}{\mu E} = \frac{8\varepsilon\varepsilon_0 N_A d^2}{e\mu N_t^2[cm^2]}$$

Se composition, bandgap grading, and GB potentials

With Se GB potential change is limited to 100 meV?



J. Yang, S. Wei, Chinese Physics B 28, 086106 (2019)



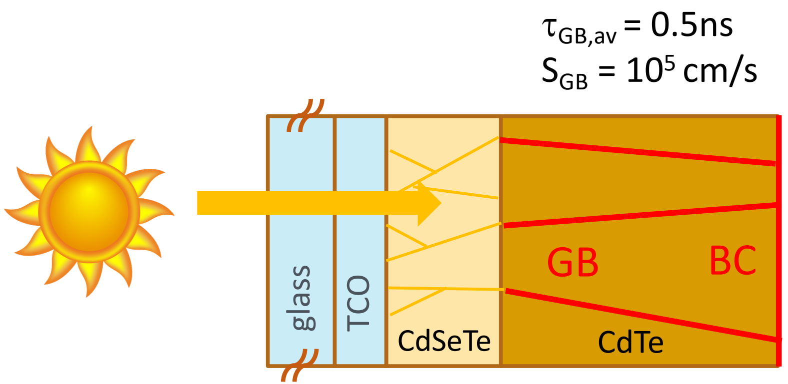
T.A.M. Fiducia, K. Li, A.H. Munshi, K. Barth, W.S. Sampath, C.R.M. Grovenor, and J.M. Walls, IEEE J. Photovoltaics **10**, 685 (2020).

Summary

- In polycrystalline CdSeTe absorbers, Se increases carrier lifetimes from <30 ns to >1000 ns due to GB passivation via space charge fields;
- Selenium GB diffusion is likely key aspect to control GB potentials and thus minority carrier lifetimes. Complex dependence on grain size, doping, $CdCl_2$ temperatures, etc.

τ_B = 170 ns
(no passivation)

τ_B = 350 ns
(Al_2O_3)



Red lines indicate device areas where recombination reduces carrier lifetimes

Thank you

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