Transient PL Spectroscopy for the Characterisation of Silicon

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UNSW Seminar

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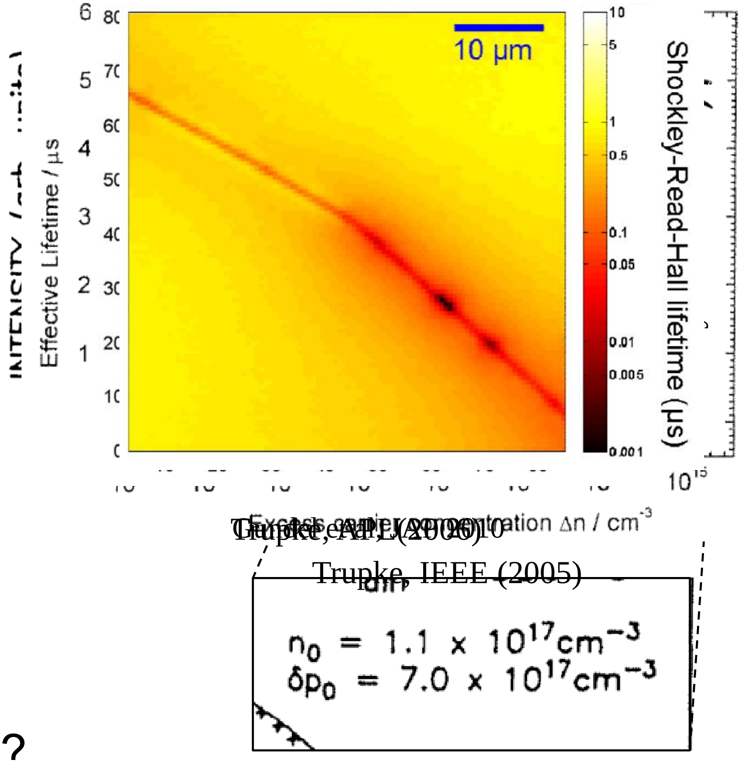
Motivation
Photoluminescence Probing of Silicon

- Photoluminescence (PL) emission
  - Direct measure of carrier density
  - Silicon: low emission
  - Early investigations: integral measurement[1]
- New detectors, new approaches
  - Diodes: Injection dependent[2]
  - Si-CCDs: PL Imaging[3]
  - InGaAs-LineCCDs: µPL Mapping[4]
- There’s still problems in quantification, why?
- Highest sensitivity: time correlated single photon counting



Trupke, APL (2006)

Gundel, et al, JAP 2010

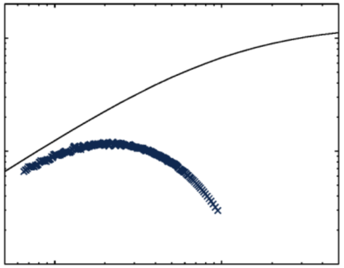
Trupke, IEEE (2005)

[1] Hangleiter PRB (1987)
[2] Trupke et al, IEEE (2005)
[3] Trupke et al, APL (2006)
[4] Gundel, Heinz et al, JAP (2010)

Agenda – Transient PL Spectroscopy

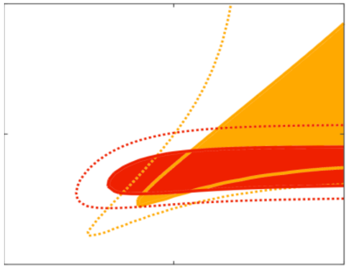
1. Experimental advance

   Interpretation and evaluation:
   The problem of diffusion and weighting



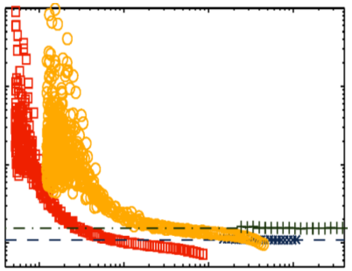
2. Micro-Photoluminescence Mapping

3. Measurement of surface recombination



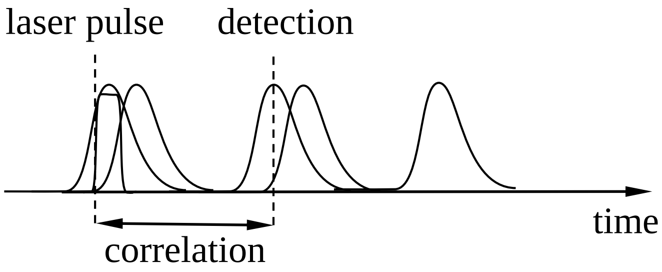
4. Transients on p-type Cz silicon

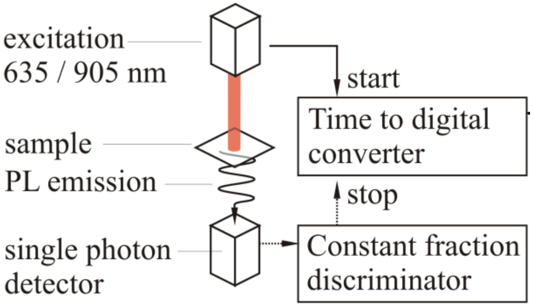
   Evidence for charge carrier capture and emission from trap states



1. Transient PL Spectroscopy
Experimental Advance

- Time correlated single photon counting
  - Low dark noise ~ 4 cps
  - Very sensitive
    (0.01 – 10^6 photons / s)
  - High time resolution < 1 ns
  - High dynamic bandwidth
    1 ns – 100 s



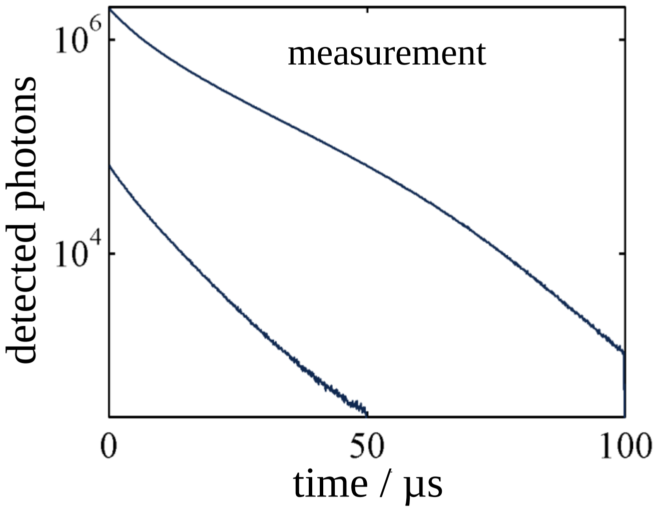


1. Transient PL Spectroscopy

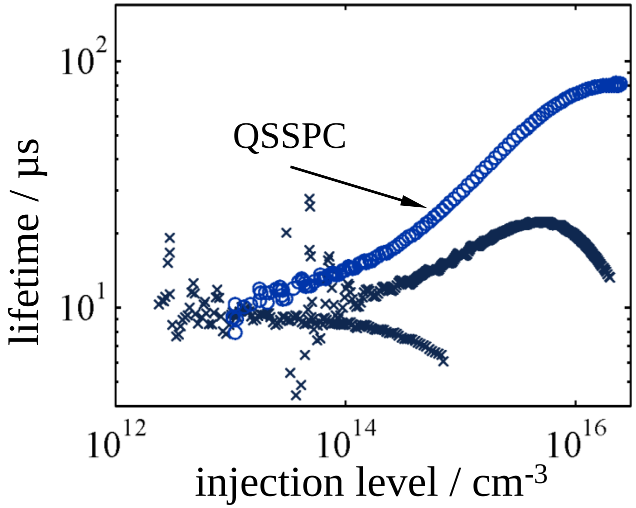
Lifetime measurement

- Proof of principle: excitation and detection area: ~ 50 µm half width
  - Inconsistency
  - Deviation from reference methods

Standard *p*-typ CZ silicon (1 Ωcm, thickness 180 µm, Al_2O_3)



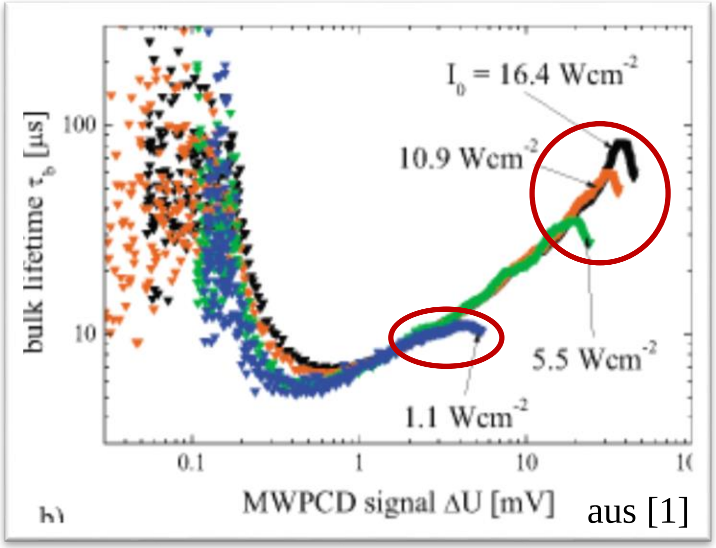
$$\tau(\Delta n) = -\frac{\Delta n(t)}{\frac{\mathrm{d}\Delta n(t)}{\mathrm{d}t}}$$



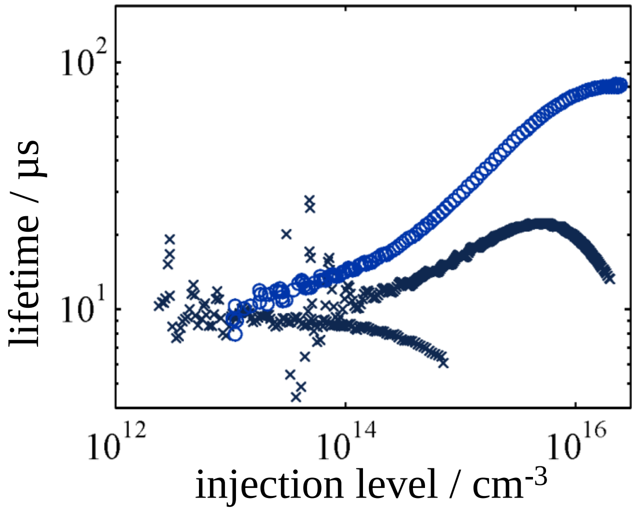
1. Transient PL Spectroscopy

Lifetime measurement

- Proof of principle:
  - Inconsistency
  - Deviation from reference methods
  - Comparison to literature, e.g. [1]



aus [1]



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[1] Lauer et al., JAP 104(10):104503, 2008

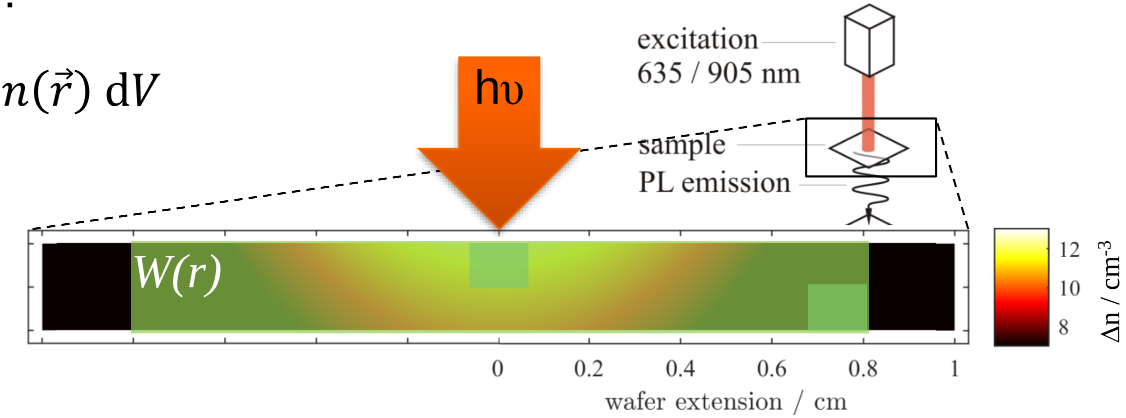
1. Transient PL Spectroscopy

Evaluation and Interpretation

$$I\mathrm{d}V \sim \Delta n(\Delta n + N)\mathrm{d}V$$

$$I \sim \overline{\Delta n}(\overline{\Delta n} + N)$$

- Integral measurement of $I = \int I(\vec{r})W(\vec{r})\mathrm{d}V$
- Diffusion
- Dual use of photoluminescence $I(\vec{r})\mathrm{d}V$
  - Measure of $\Delta n(\vec{r})\mathrm{d}V$
  - Detection probability $\frac{I(\vec{r})}{\int I(\vec{r})\,\mathrm{d}V}$ of $\Delta n(\vec{r})$
- Relevant avarage of Δn?
  - $\overline{\Delta n} = \int \qquad W(\vec{r})\Delta n(\vec{r})\,\mathrm{d}V$



Heinz et al., JAP 118(10):105706, 2015

1. Transient PL Spectroscopy

Evaluation and Interpretation

SPECIAL CASE 1

If in steady state
and if W ≪ extension of generation profile $\mathrm{G}(\vec{r})$
and if wafer thickness ≪ diffusion length, then

$$\frac{I(\vec{r})}{\int I(\vec{r})\,\mathrm{d}V} = 1$$

SPECIAL CASE 2

if diffusion length ≪ extension of generation profile $\mathrm{G}(\vec{r},t)$
and if $I \sim \Delta n$ (low injection), then

$$\frac{I(\vec{r},t)}{\int I(\vec{r},t)\,\mathrm{d}V} \approx \frac{G(\vec{r},t)}{\int G(\vec{r},t)\,\mathrm{d}V} = \frac{G(\vec{r},t)}{G_0}$$

Heinz et al., JAP 118(10):105706, 2015

1. Transient PL Spectroscopy

Evaluation and Interpretation

$$\overline{\Delta n} = \int \frac{I(\vec{r})}{\int I(\vec{r})\,\mathrm{d}V} W(\vec{r})\Delta n(\vec{r})\,\mathrm{d}V$$

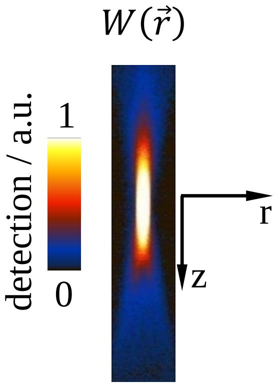
- Microscopic equation of continuity (transient)
  - $\frac{\partial \Delta n(\vec{r})}{\partial t} = -\frac{\Delta n(\vec{r})}{\tau} + \vec{\nabla}\left[D\vec{\nabla}\Delta n(\vec{r})\right]$
- Intensity weighting
  - $\frac{\mathrm{d}\overline{\Delta n}}{\mathrm{d}t} + \gamma = -\frac{\overline{\Delta n}}{\tau(\overline{\Delta n})} + \bar{D}$
    - $\bar{D}$ weighted diffusion
    - $\gamma = \frac{1}{\int I(\vec{r})\mathrm{d}V} \int \frac{\partial I(\vec{r})}{\partial t}\left(\overline{\Delta n} - \Delta n(\vec{r})\right)\mathrm{d}V$

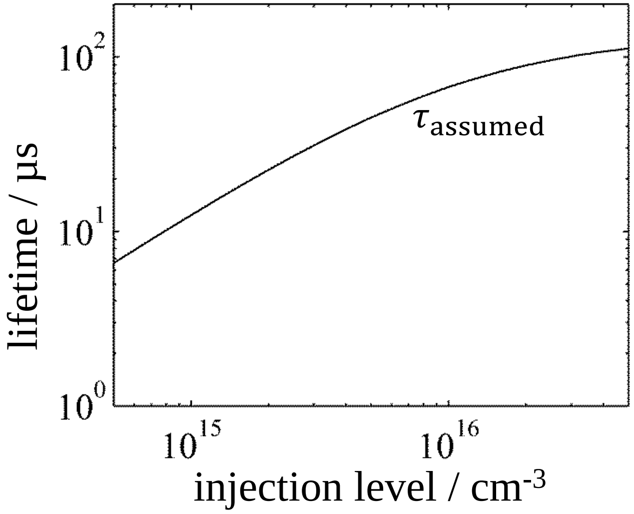
$$\tau(\overline{\Delta n}) = -\frac{\overline{\Delta n}(t)}{\frac{\mathrm{d}\overline{\Delta n}(t)}{\mathrm{d}t}}$$

Heinz et al., JAP 118(10):105706, 2015

2. Quantitative µPL Spectroscopy
Simulation of the Experiment

- Microscopic equation of continuity
  - $\frac{\partial \Delta n(\vec{r})}{\partial t} = -\frac{\Delta n(\vec{r})}{\tau_{\text{assumed}}} + \vec{\nabla}\left[D\vec{\nabla}\Delta n(\vec{r})\right]$
- PL intensity
  - $I\mathrm{d}V = B \cdot \Delta n(\Delta n + n_0)\mathrm{d}V$



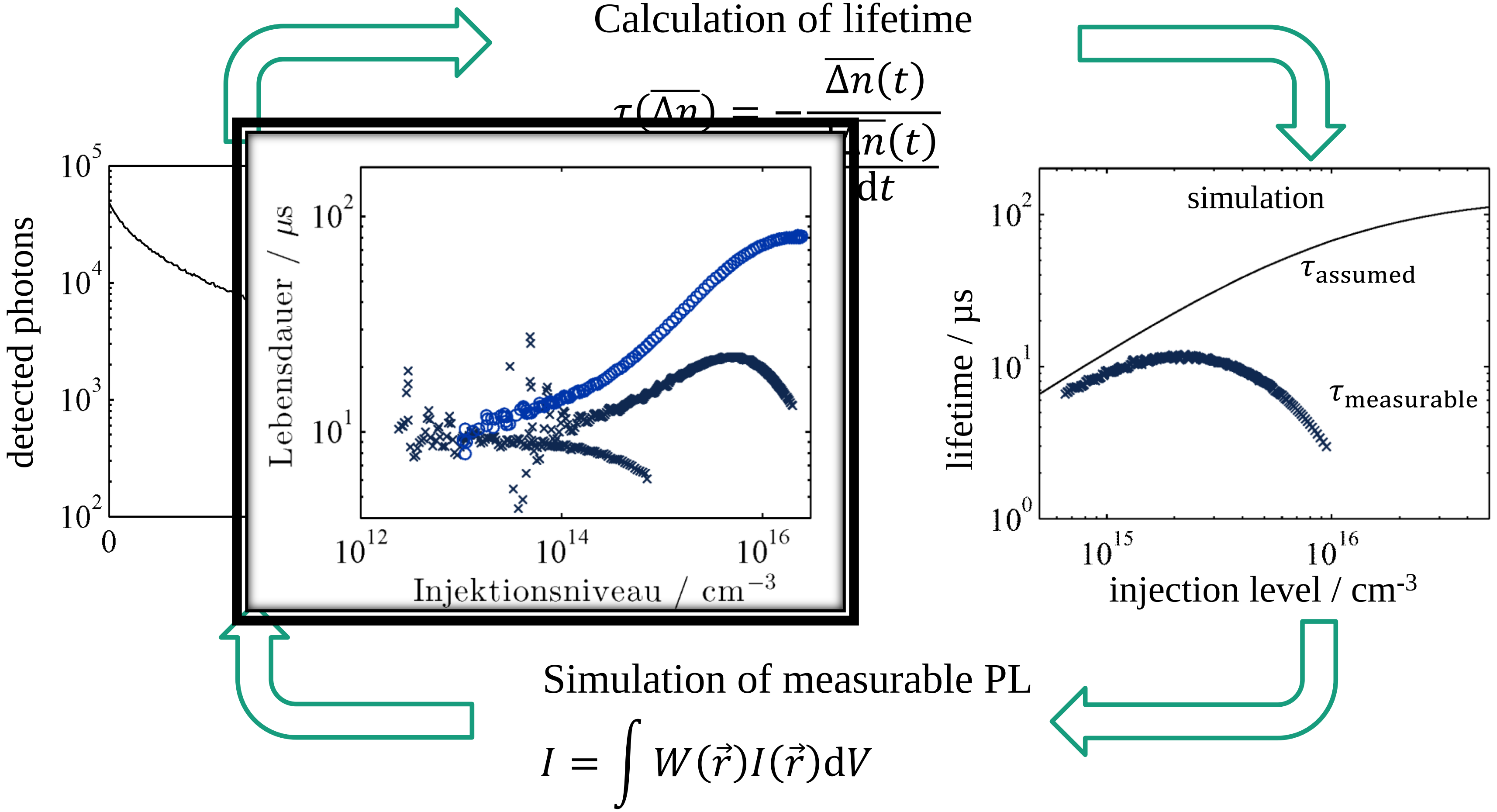


Simulation of measurable PL

$$I(t) = \int W(\vec{r}) I(\vec{r}, t)\mathrm{d}V$$

2. Quantitative µPL Spectroscopy

Simulation of the Experiment



Calculation of lifetime

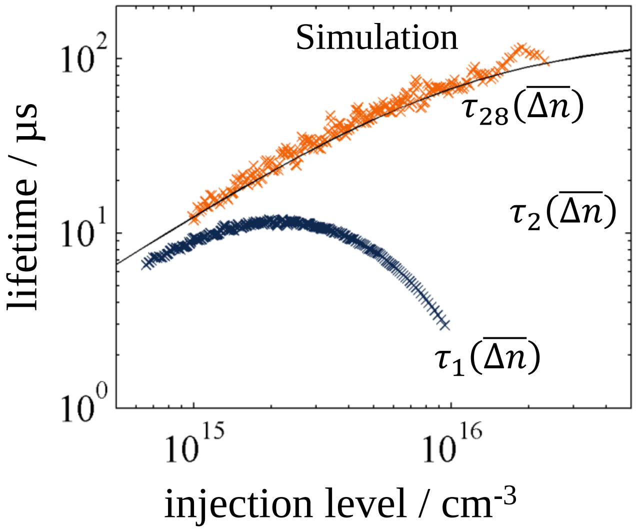
$$\tau(\overline{\Delta n}) = -\frac{\overline{\Delta n}(t)}{\frac{\mathrm{d}\overline{\Delta n}(t)}{\mathrm{d}t}}$$

Simulation of measurable PL

$$I = \int W(\vec{r}) I(\vec{r}) \mathrm{d}V$$

1. Transient PL Spectroscopy

Evaluation and Interpretation



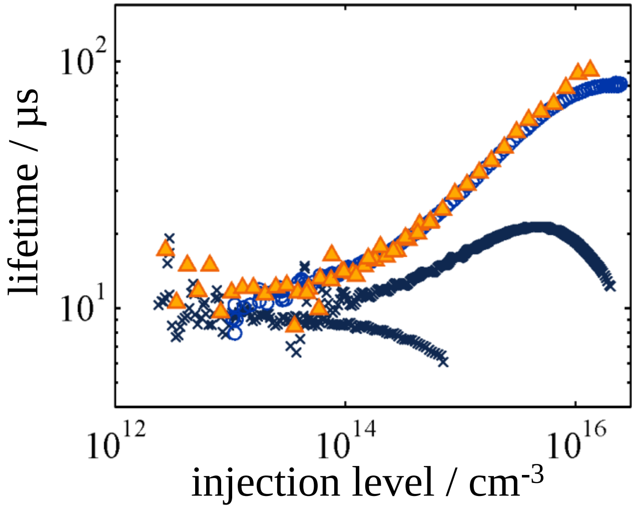
microscopic
equation

$\tau_{28}(\overline{\Delta n})$
$\approx \tau(\Delta n)$

Heinz et al., JAP 118(10):105706, 2015

1. Transient PL Spectroscopy
Proof of Principle & Implications

- Application to silicon[1]
  - Consistent data evaluation
  - Agreement with reference methods
- General importance?
    - Thick samples
      e.g. Ingots, cf. work Bowden[2]
  - MWPCD
    - Focussed excitation
  - Low lifetimes
    - Iron imaging



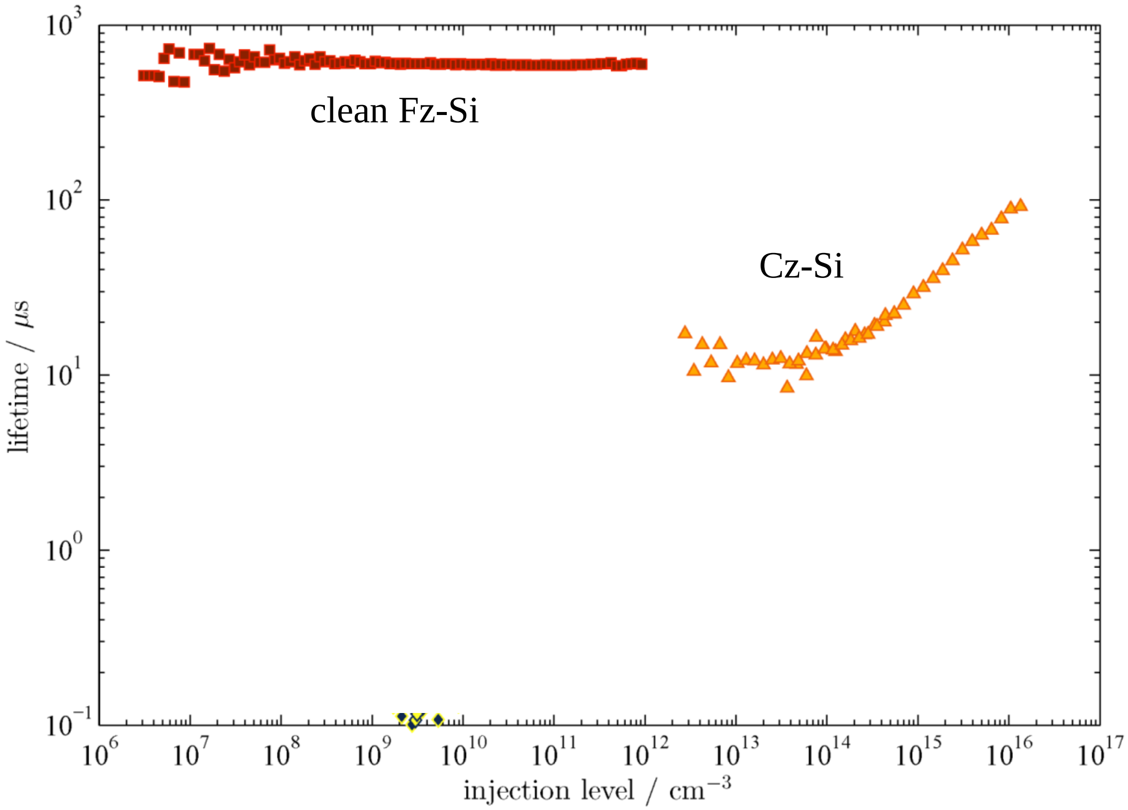
Standard *p*-typ CZ silicon
(1 Ωcm, thickness 180 µm,
Al_2O_3 passivation)

[1] Heinz et al., APL **107**(12):122101, 2015
[2] Bowden, Sinton, JAP **102**:124501, 2007

1. Transient PL Spectroscopy

Lifetime and Injection Level Range

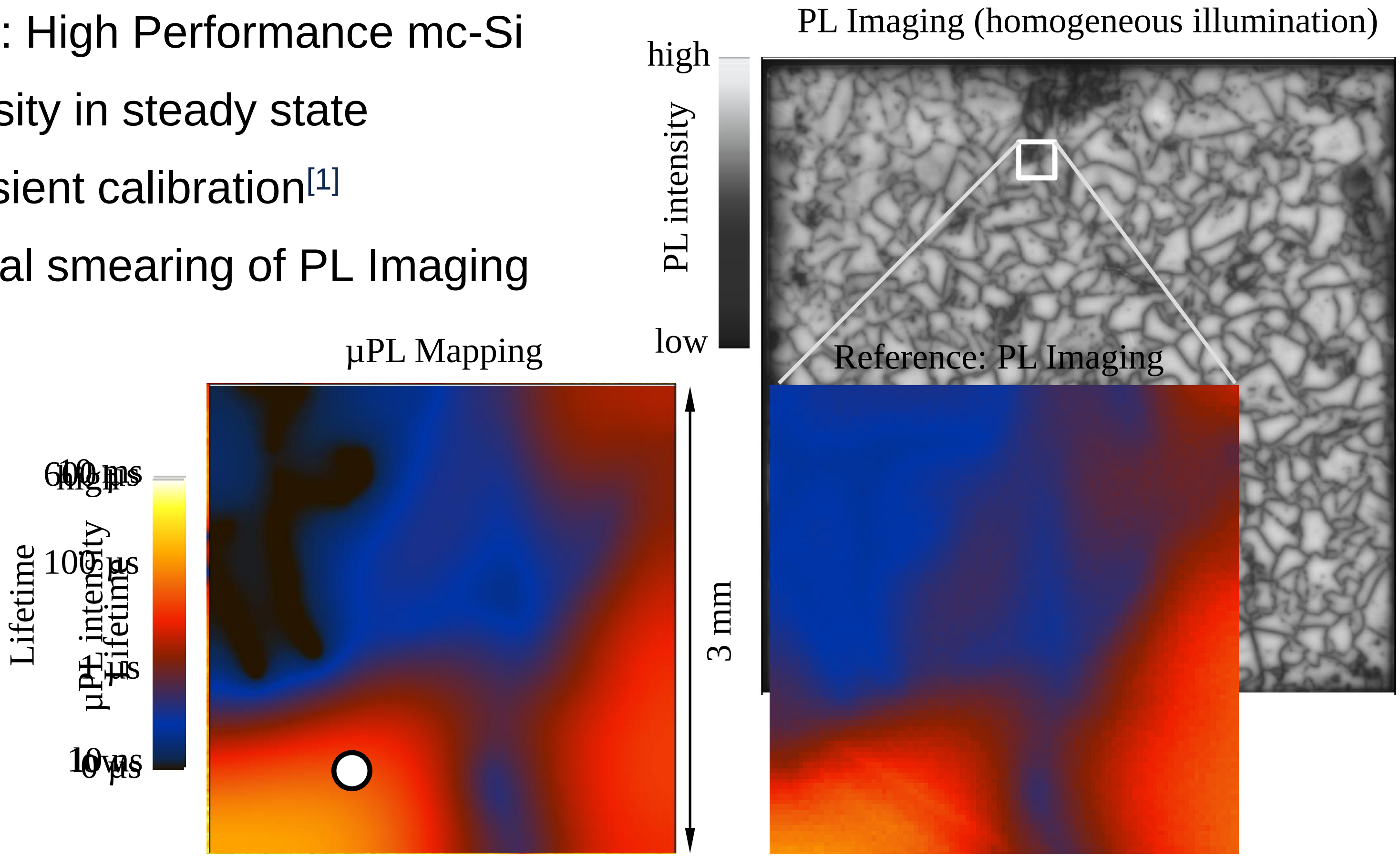
- Advances
  - Wide injection range
  - Wide lifetime range
  - measurement area ~ 50 µm diameter



2. Spatially Resolved Lifetime

µ-PL Mapping

- Example: High Performance mc-Si
- PL Intensity in steady state
  - Transient calibration[1]
  - Lateral smearing of PL Imaging



[1] Heinz et al., (pss) RRL **107**(12):122101, 2015

2. Spatially Resolved Lifetime

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- Example: High Performance mc-Si
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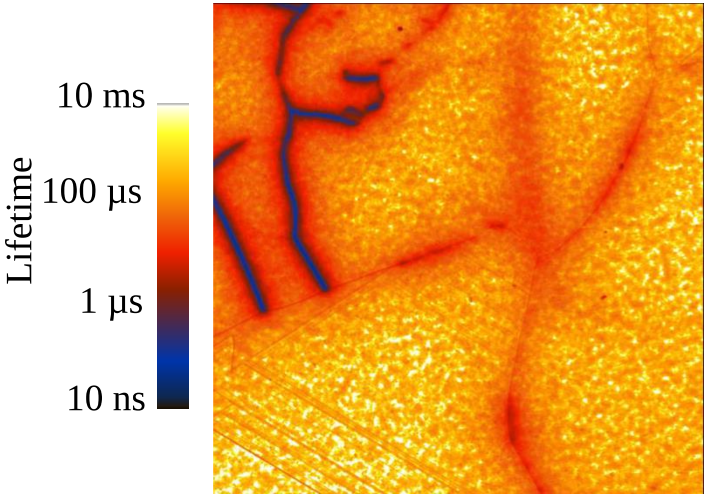
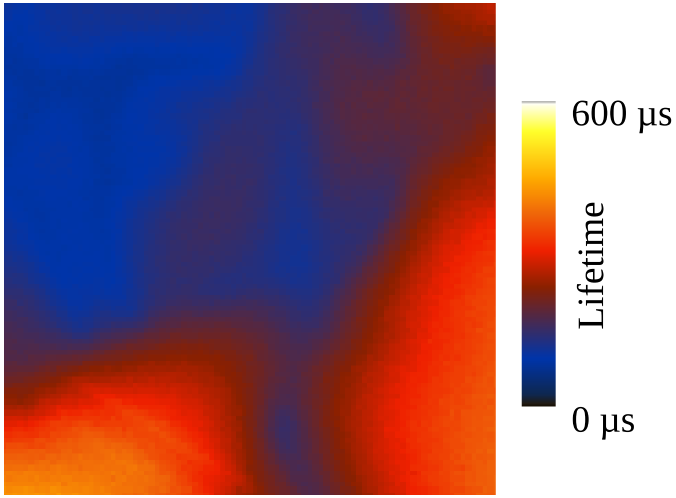
µPL Mapping



Reference: PL Imaging

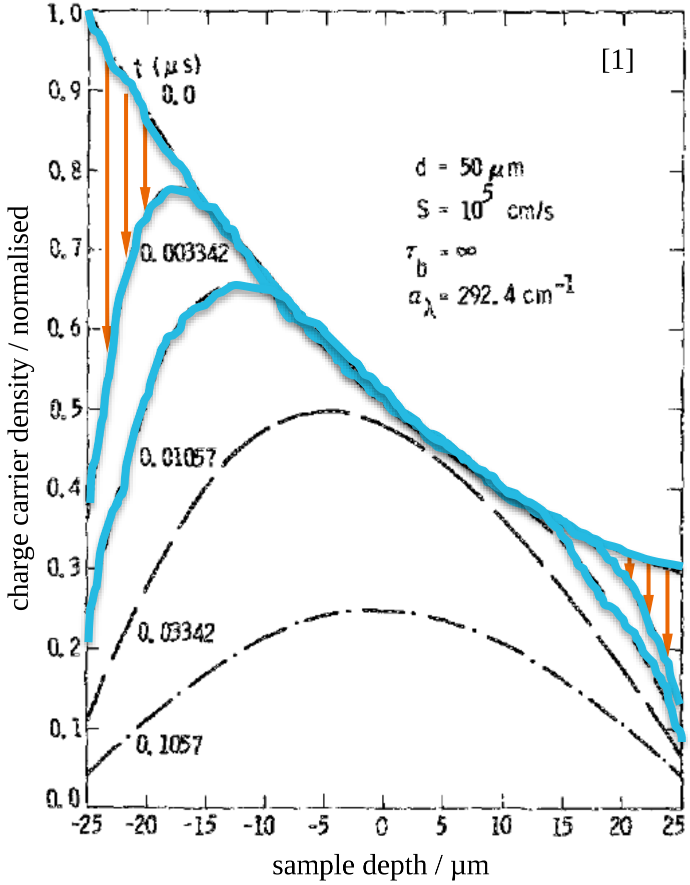


[1] Heinz et al., (pss) RRL **107**(12):122101, 2015

3. Recombination at Surfaces

Influence on Electron Density Decay

- Influence of surface recombination
  - Steady state: effective lifetime
  - Transient: Luke and Cheng[1]:
    Carriers near surface recombine fast

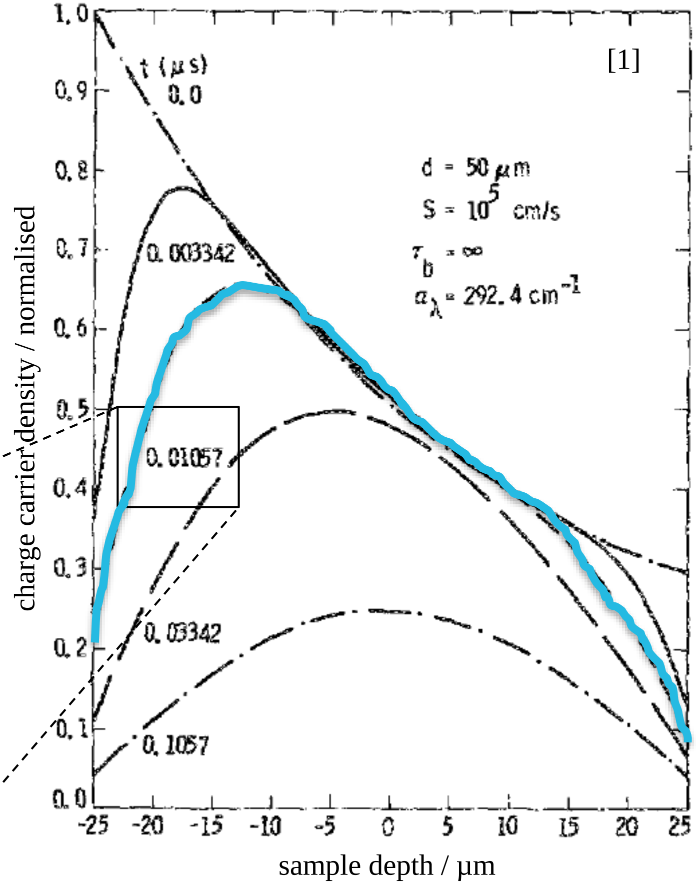


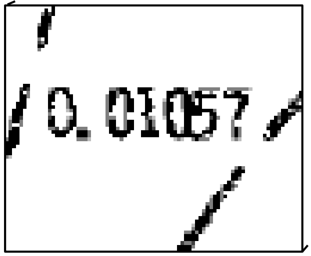
[1] Luke & Cheng, JAP **61**(6):2282-2293, 1987

3. Recombination at Surfaces

Influence on Electron Density Decay

- Influence of surface recombination
  - Steady state: effective lifetime
  - Transient: Luke and Cheng[1]:
    Carriers near surface recombine fast
- 1987: insufficient experimental equipment
- Approaches[2]:
  - Photoconductance
  - Reflectance
  - Induced current
  - Voltage





= 10.57 ns

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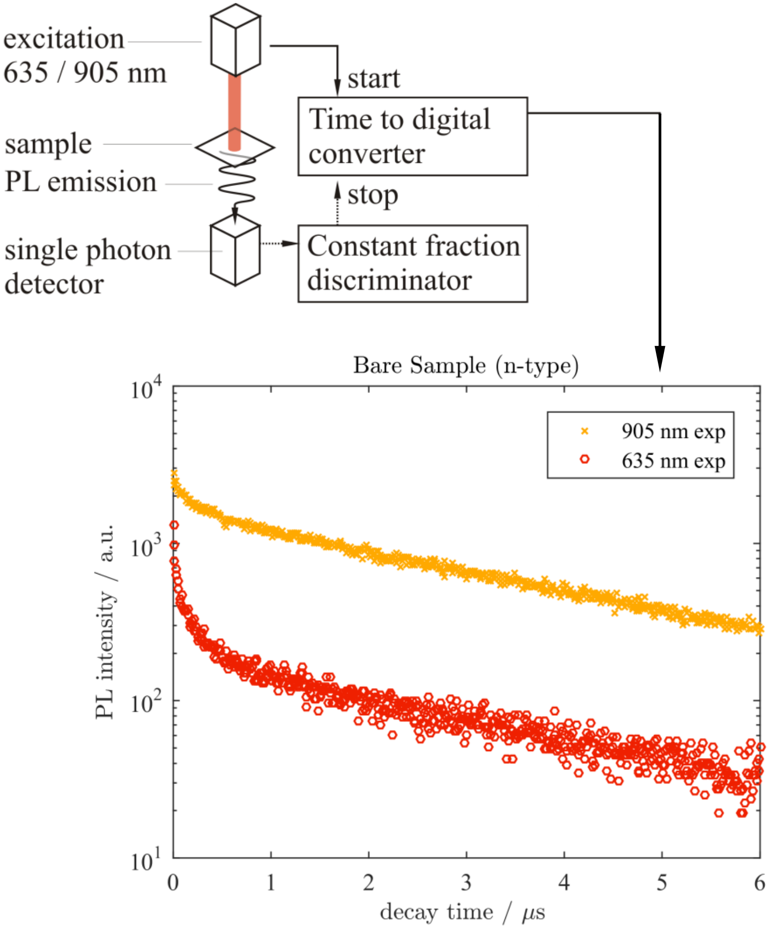
[1] Luke & Cheng, JAP **61**(6):2282-2293, 1987

[2] c.f. Refs. in Heinz et al., APL **110** (2017) 042105

3. Recombination at Surfaces
Influence on PL Decay

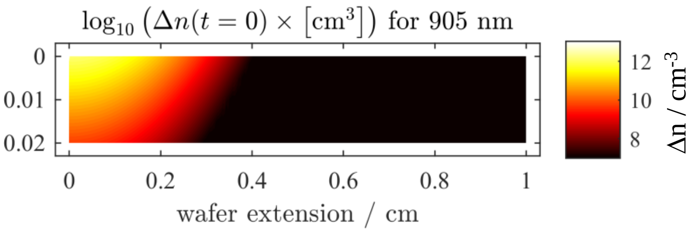
- Two excitation wavelengths
  - 635 nm / 905 nm



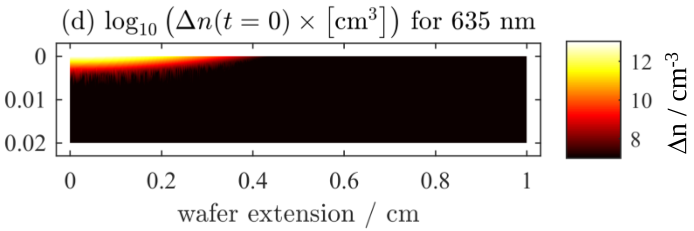
Heinz et al., APL **110** (2017) 042105

3. Recombination at Surfaces

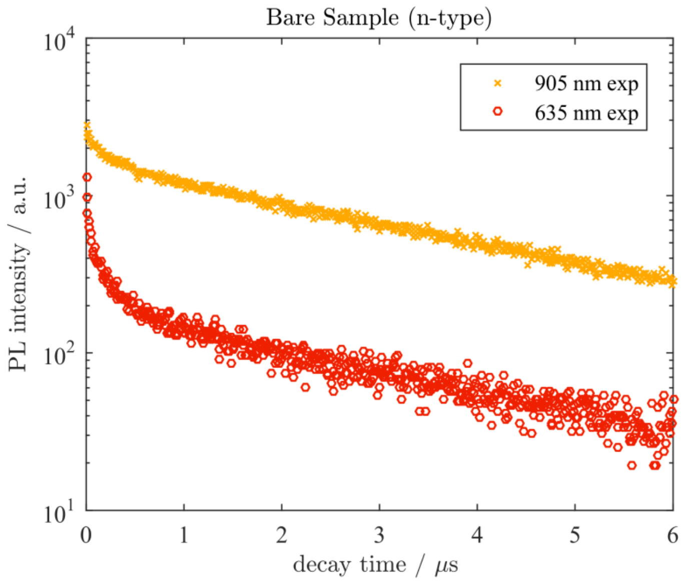
Influence on PL Decay



$\log_{10}\left(\Delta n(t=0) \times [\mathrm{cm}^3]\right)$ for 905 nm



(d) $\log_{10}\left(\Delta n(t=0) \times [\mathrm{cm}^3]\right)$ for 635 nm



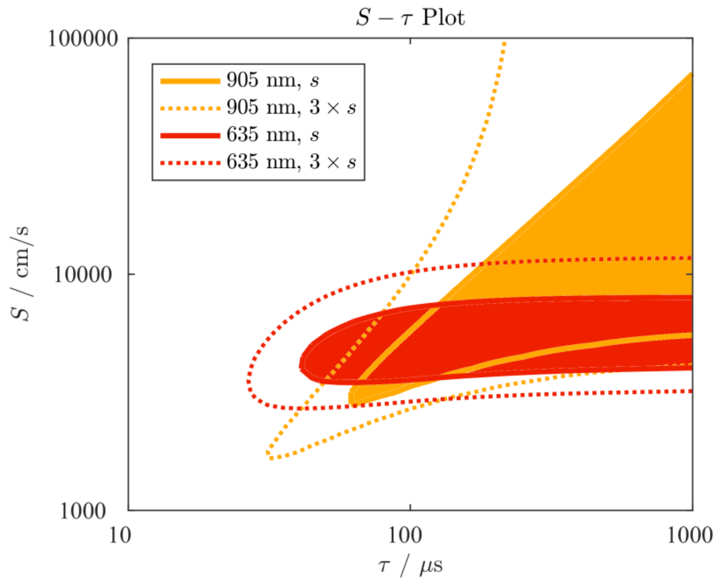
Bare Sample (n-type)

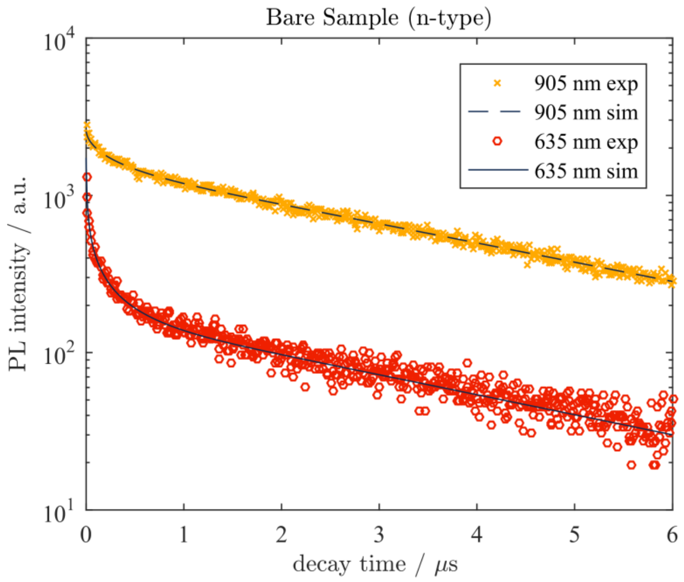
Heinz et al., APL **110** (2017) 042105

3. Recombination at Surfaces

Separation of Bulk and Surface Recombination

- Simulate PL intensity & calculate reduced Chi-squared for $S-\tau$ pairs



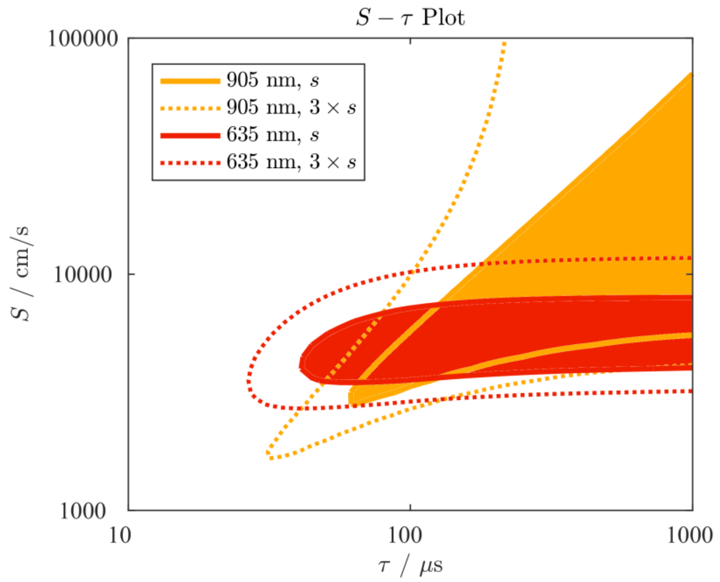


Heinz et al., APL **110** (2017) 042105

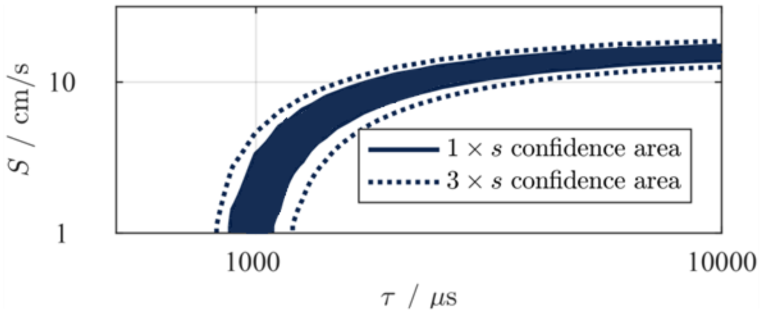
3. Recombination at Surfaces

Separation of Bulk and Surface Recombination

- Simulate PL intensity & calculate reduced Chi-squared for $S - \tau$ pairs
- $\chi^2_{\mathrm{red}}(c, S, \tau_{\mathrm{b}}) = \frac{1}{N_{\mathrm{dof}}} \sum_{i=1}^{N} \frac{\left[I_{\exp}(t_i) - c \times I_{\mathrm{sim}}(t_i, S, \tau_{\mathrm{b}})\right]^2}{\sigma_i^2}$



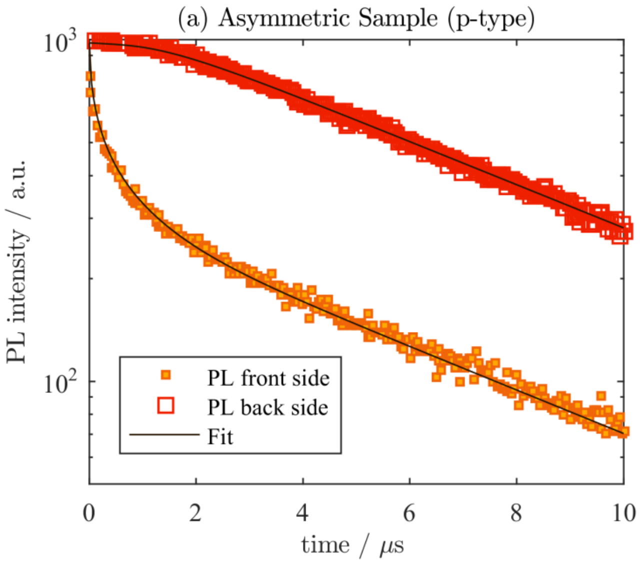
- Passivated sample (AL_2O_3)
- Surface and bulk recombination indistinguishable

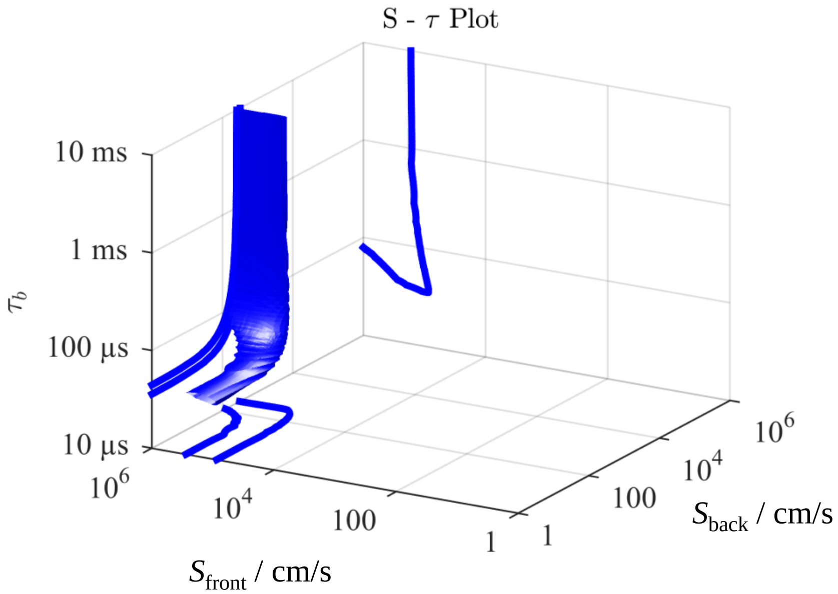


Heinz et al., APL **110** (2017) 042105

3. Recombination at Surfaces
Asymmetric Sample

- One side passivated sampe
- Measure PL decay from both sides
- Simulation and χ^2_{red}-analysis: three parameters S_{front}, S_{back}, τ



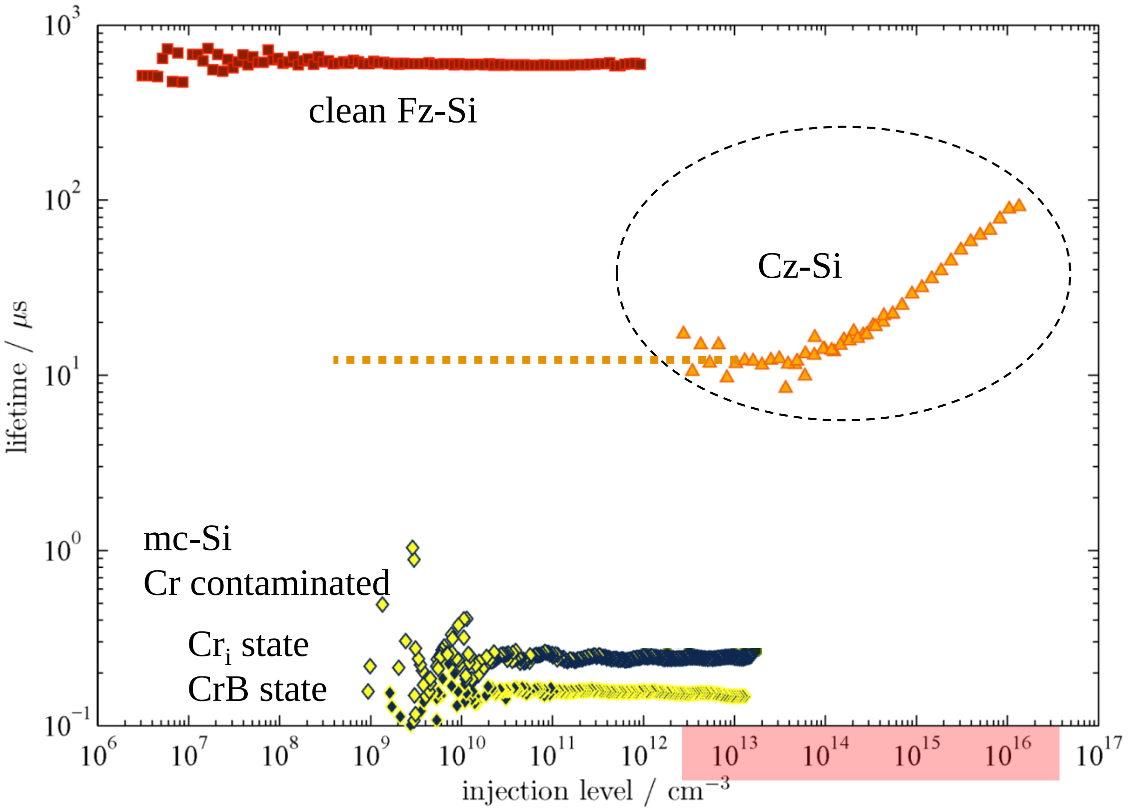


Heinz et al., APL **110** (2017) 042105

4. Analysis of Trap Levels

Low Injection Lifetime on Cz-Si

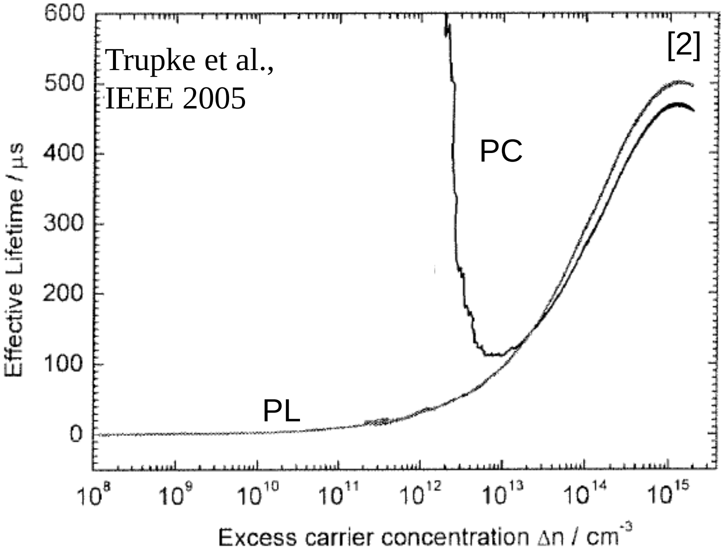
- Closer look to Cz Silicon
  - Low injection?

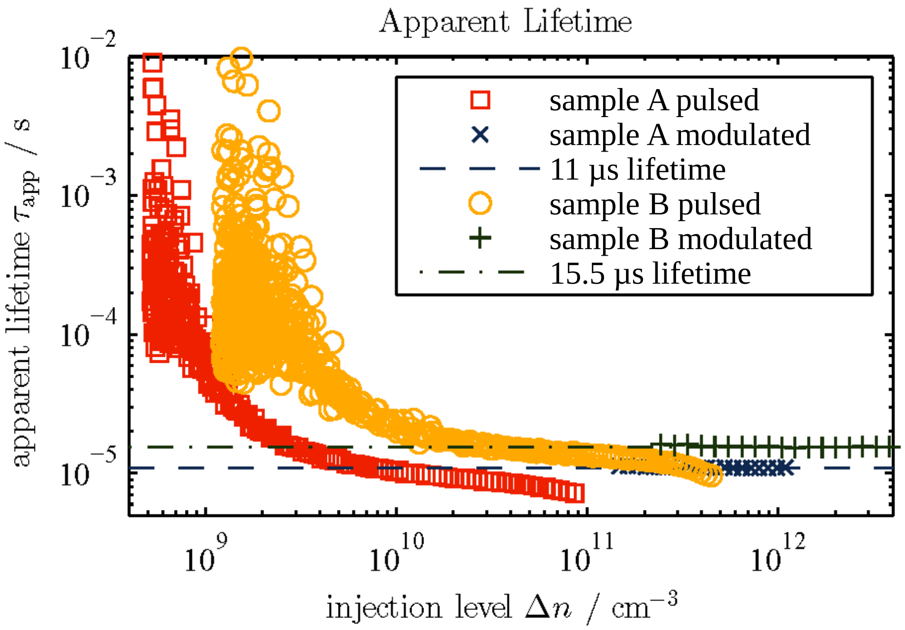


4. Analysis of Trap Levels

Low Injection Lifetime on Cz-Si

- Unexpected measured lifetime after single excitation pulses
- Resemblance to the trapping effect



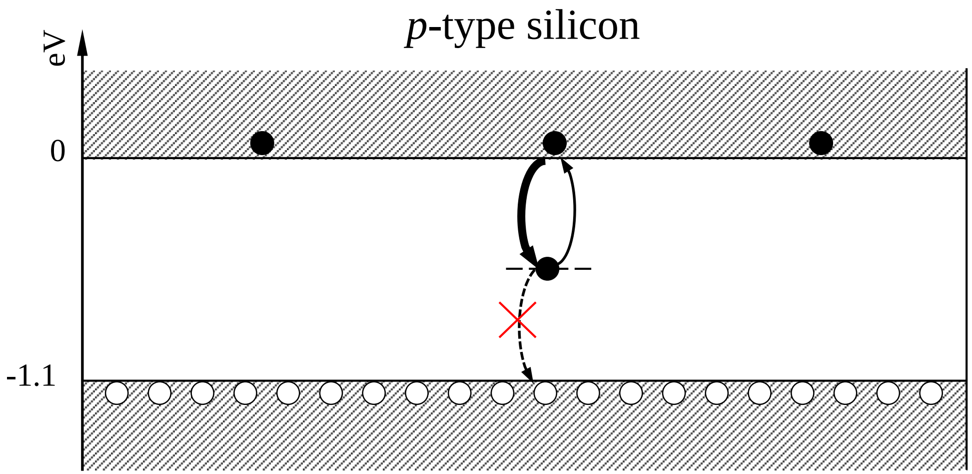


Heinz et al., Solmat 158 (2016) 107–114

4. Analysis of Trap Levels

Low Injection Lifetime on Cz-Si

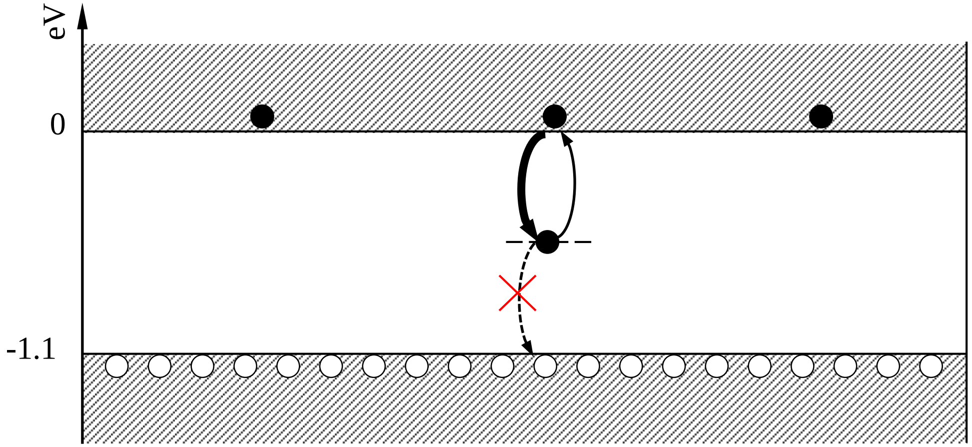
- A possible concept of traps (p-type)
  - Deep energy levels in bandgap
  - Re-emission of electron into conduction band more probable than capture of hole
  - Not (necessarily) recombination active



4. Analysis of Trap Levels

Influence of Traps on PC and PL

- Photoconductance
  - „photodoping“
  - $\sigma_{\text{measured}} = \sigma_{\text{excess}} + \sigma_{\text{trap}}$
  - If $\sigma_{\text{trap}} > \sigma_{\text{excess}}$
    apparent high charge carrier densities/lifetimes



- Photoluminescence
  - $I_{\text{pl}} \sim n_{\text{e}}\left(n_{\text{h}} + N + n_{\text{trap}}\right)$
  - Steady state: no influence, as long as $N \gg n_{\text{trap}}$
  - Transient case?

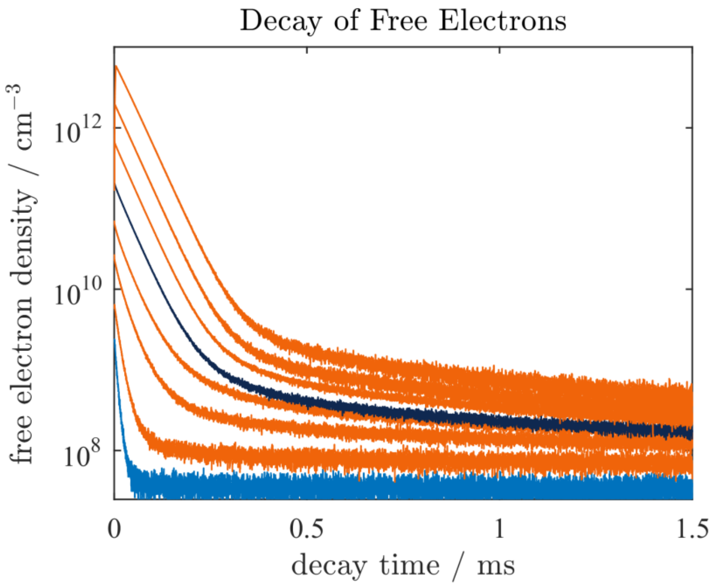
$I_{\text{pl}} \sim n_{\text{e}} \times N$ (low injection)

$$I_{\text{pl}} \pm \delta I_{\text{pl}} \begin{cases} \boxed{\sim (n_{\text{e}} \pm \delta n_{\text{e}}) \times N} \\ \sim n_{\text{e}} \times (N \pm \delta N) \end{cases}$$

4. Analysis of Trap Levels

Capture of Charge Carriers into Traps

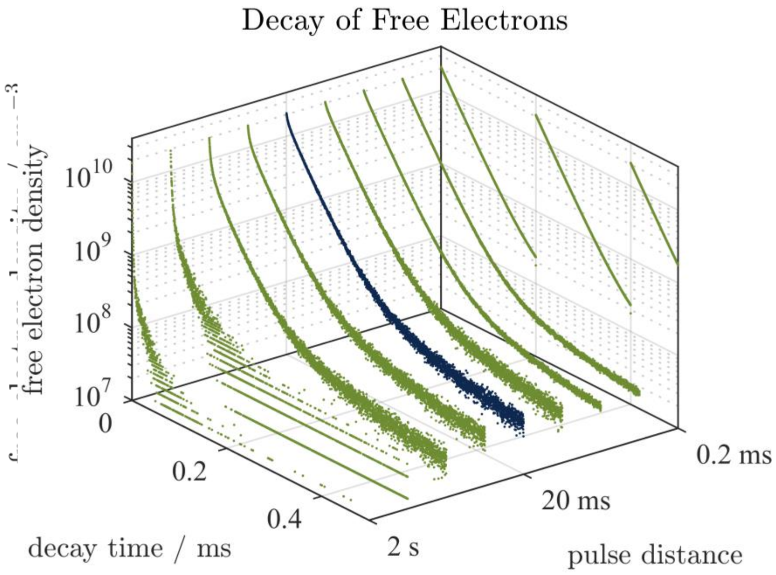
- Observation on p-type Cz-Si
  - Initial exponential decay
  - Tail
  - Low injection: fast initial decay

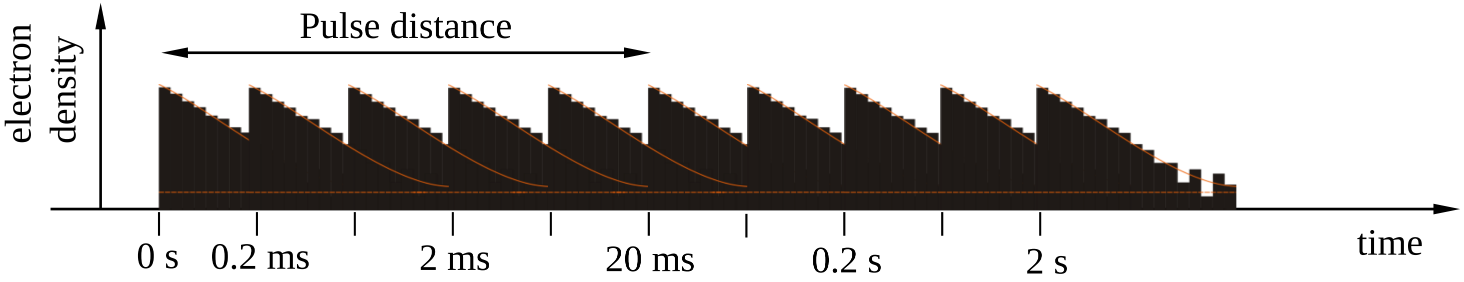


Heinz et al., pss(a) 1700292 (2017)

4. Analysis of Trap Levels
Capture of Charge Carriers into Traps

- Fast initial decay
  - Exclude injection density or surface effect
- Vary excitation pulse distance





Heinz et al., pss(a) 1700292 (2017)

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Capture of Charge Carriers into Traps

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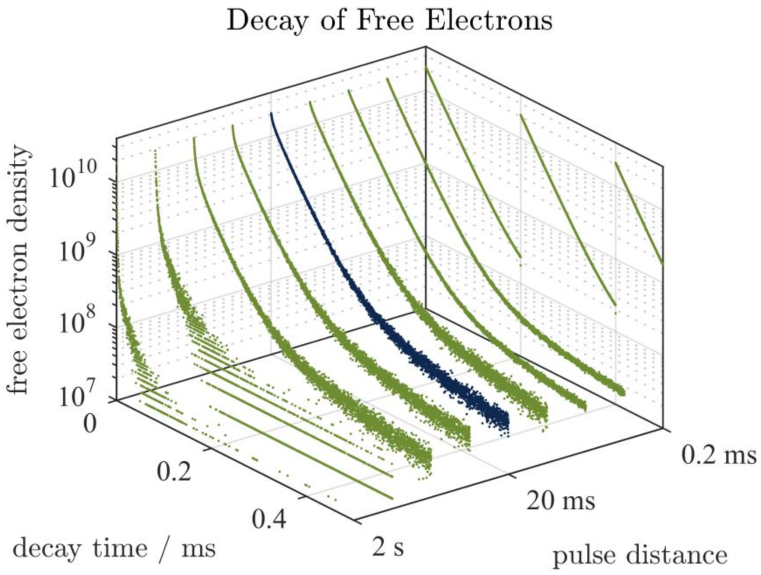
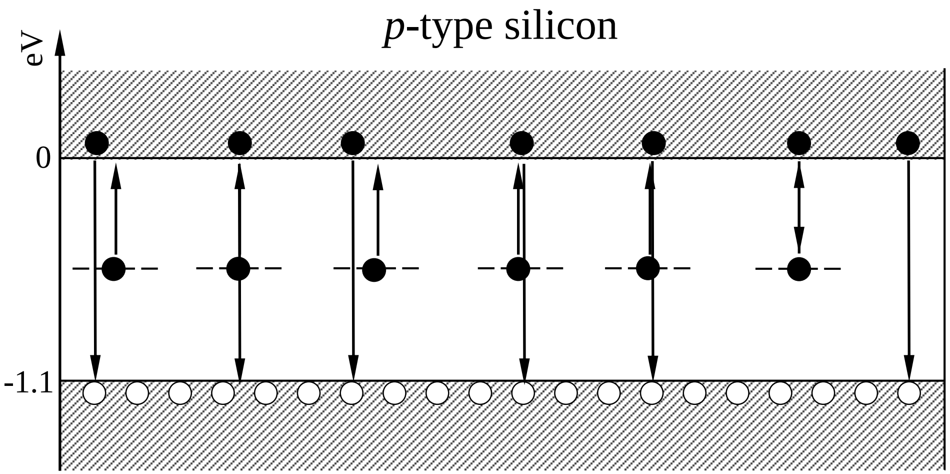


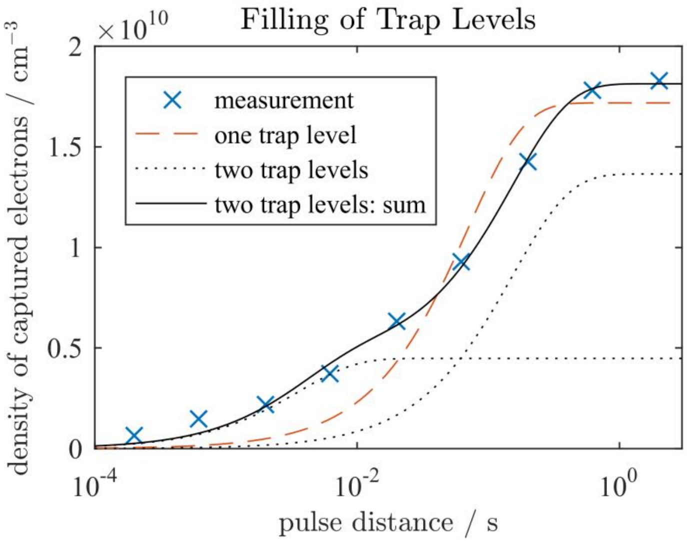


Heinz et al., pss(a) 1700292 (2017)

4. Analysis of Trap Levels

Emission of Charge Carriers from Traps

- Trap occupation at $t = 0$ depends on pulse distance
- Assumption:
  thermal depletion of trap levels
- Quantities obtained
  - Vacant trap level density
  - Depletion time constants

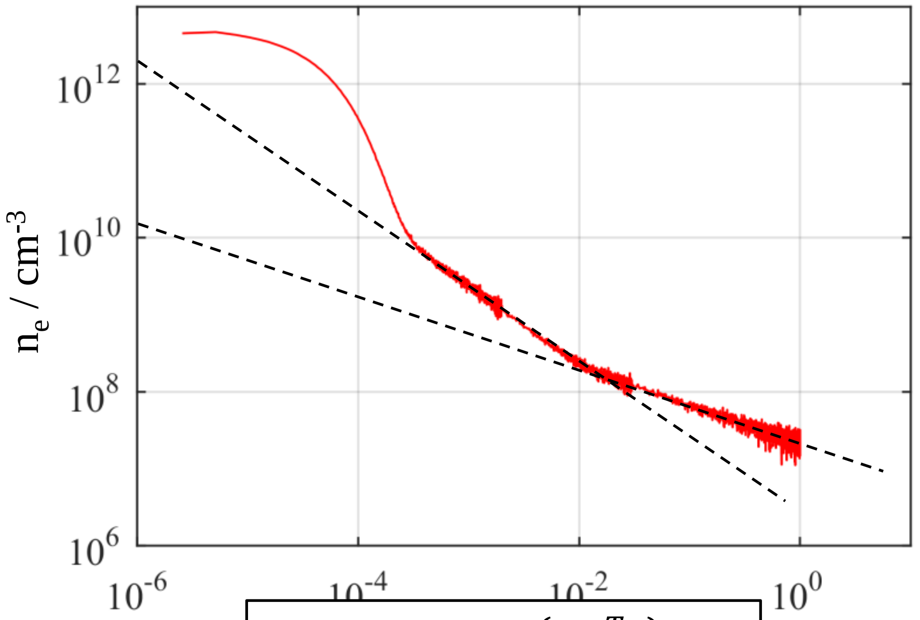


Heinz et al., pss(a) 1700292 (2017)

4. Analysis of Trap Levels

Emission of Charge Carriers from Traps

- Decay curve: three regimes
  - Band-Band recombination (exponential)
- Power law?
  - No.
- Multiple trapping mechanism
  - Proposed by Hornbeck[1]
  - Adaption of their work[2]
  - Assumption: traps independent
- New approach for investigating traps
  - Exclusive observation of fast PL decay



$$\frac{n_\mathrm{e}}{n_\mathrm{e,0}} = \frac{\exp\left(-\frac{T}{R+1}\right)}{\sqrt{1-\exp\left(-\frac{T}{R+1}\right)^2}}$$

$$T = \frac{\tau_\mathrm{t}}{\tau_r \tau_\mathrm{g}} t \qquad R = \frac{\tau_\mathrm{t}}{\tau_r}$$

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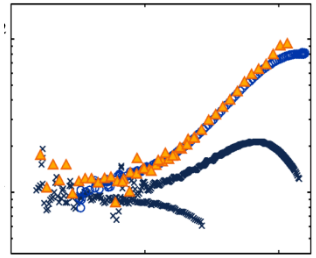
[1] Hornbeck & Haynes, Phys Rev B **97**(2) (1954)
[2] Heinz, Dissertation, Fraunhofer Verlag (2016)

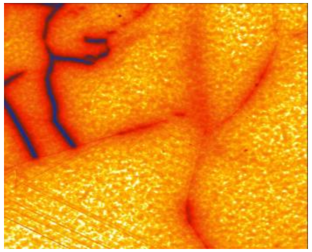
Summary

1. Transient PL spectroscopy
   - High time resolution and sensitivity
   - Evaluation and Interpretation

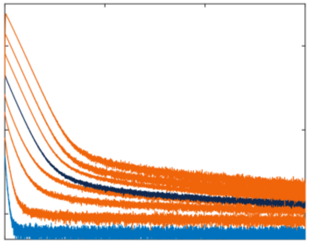


2. Quantitative Micro-Photoluminescence mapping

3. Separation of surface and bulk recombination



4. PL based analysis of trap levels
   - Charge carrier capture and emission in Cz-Si
   - Multiple trapping mechanism



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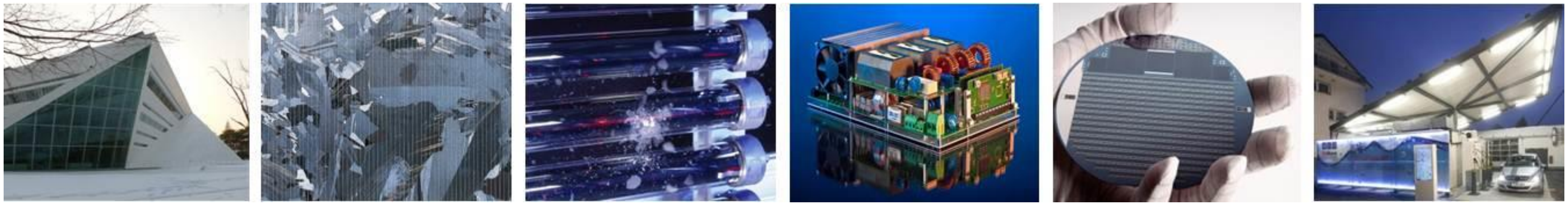
Thank you for your attention!



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