Carrier dynamics in doped Germanium measured at the free electron laser FELBE

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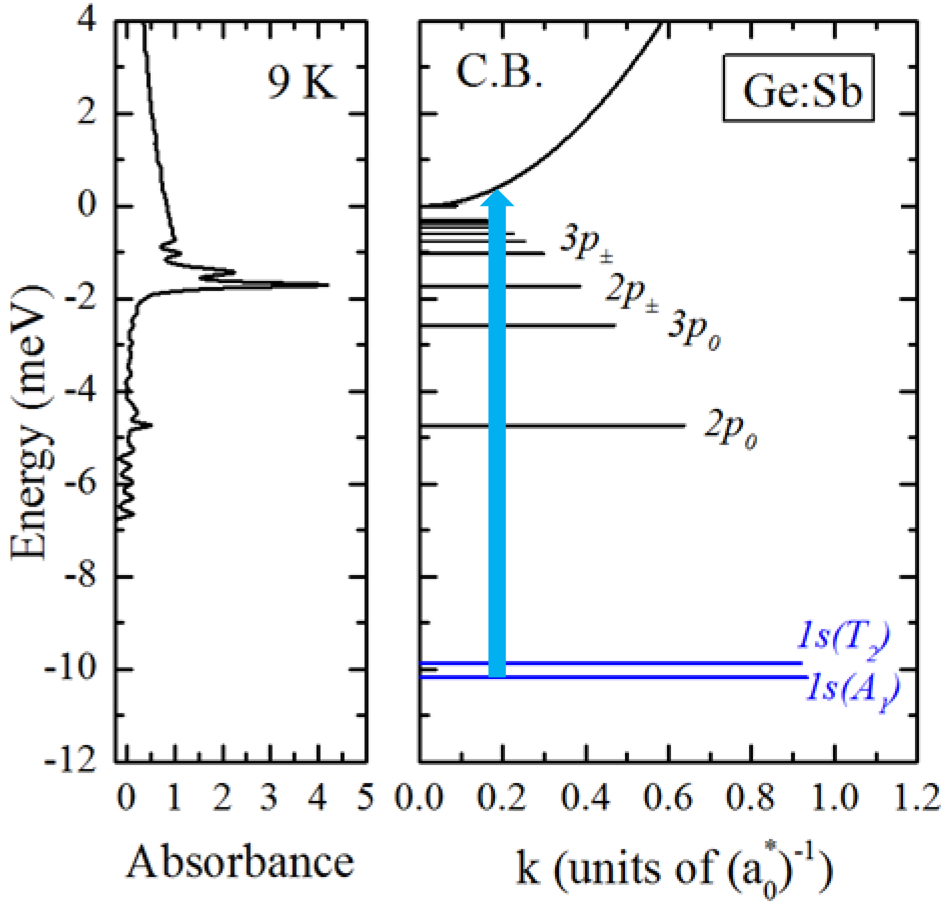
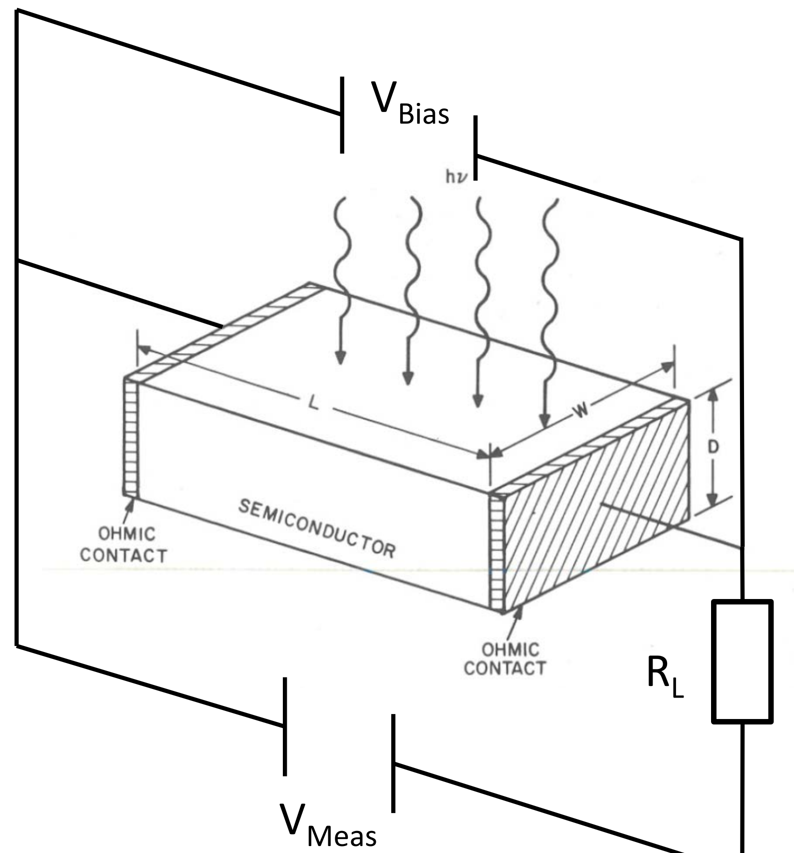
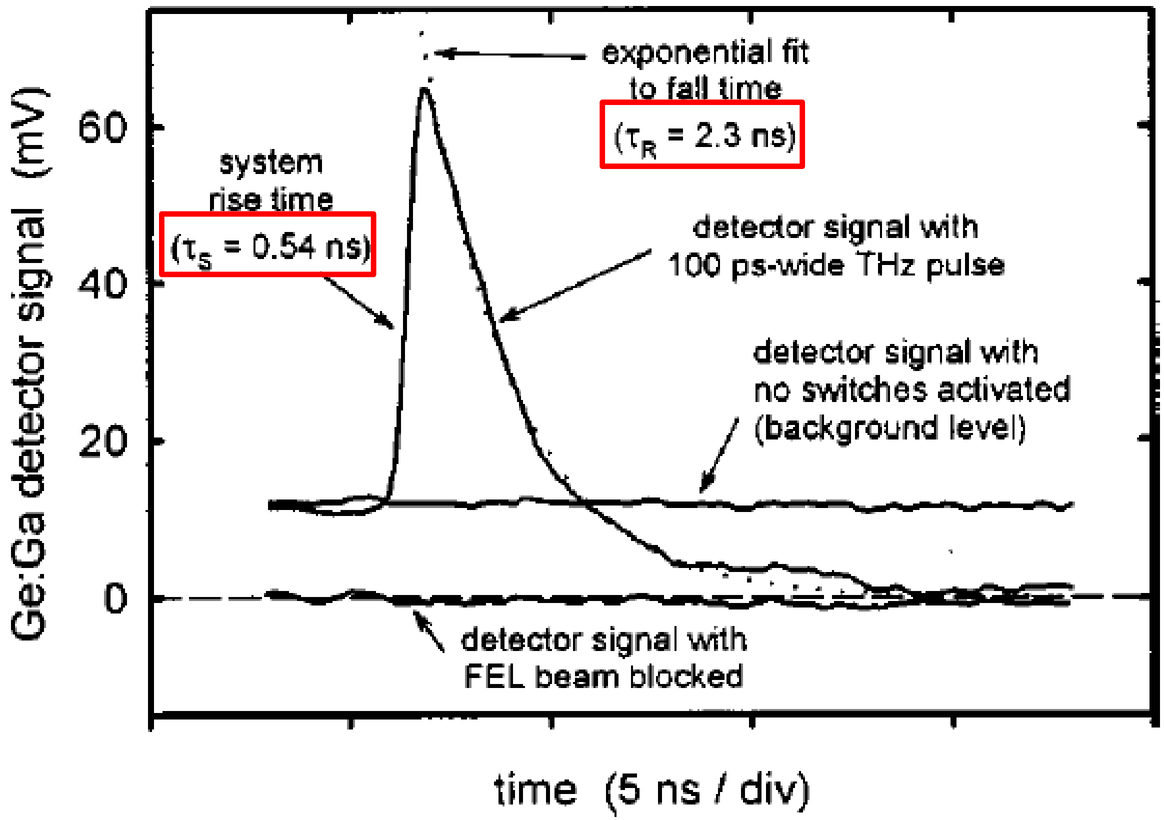
[4]Helmholz-Zentrum Dresden-Rossendorff, Bautzner Landstr. 400, 01328 Dresde , Germany
[5]Leibniz-Institute for Crystal Growth, Max-Born-Str. 2, 12489 Berlin Germany

Introduction





Introduction



F. A. Hegmann et al., “Time-resolved photoresponse of a gallium-doped germanium photoconductor using a variable pulse-width terahertz source,” *Appl. Phys. Lett.*, vol. 76, no. 3, p. 262, 2000.1

FELs in Europe

Dedicated MIR/THz Pump-Probe setups available at:

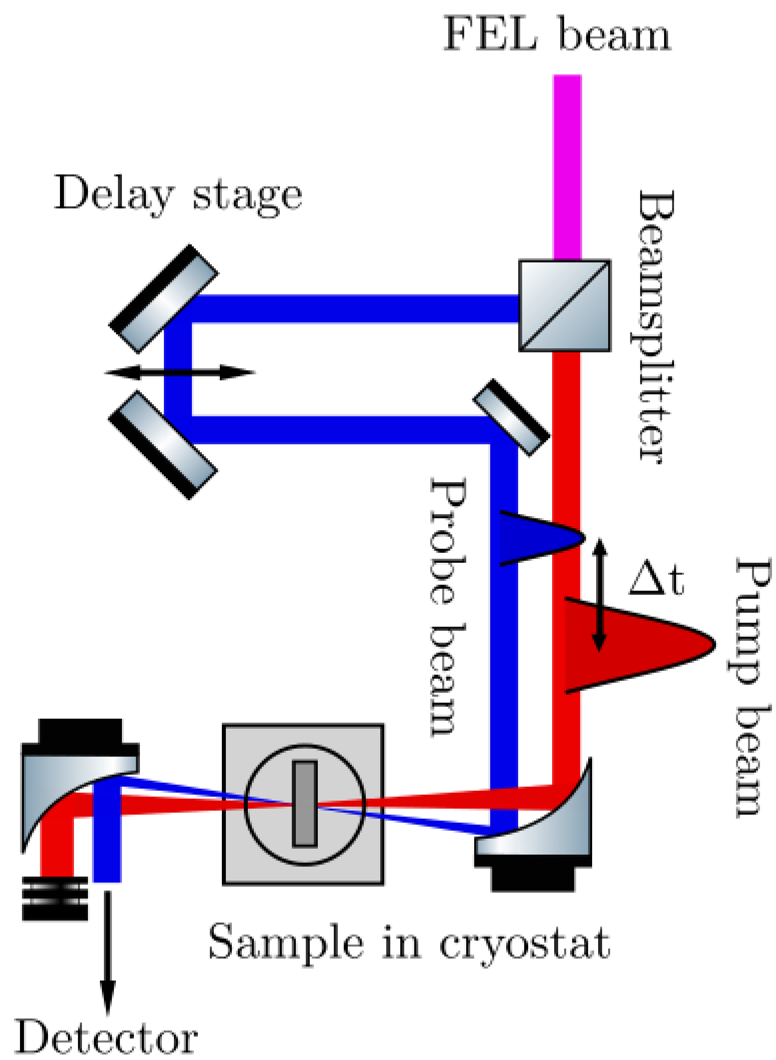
FELBE[1](S. Winnerl)
FELIX[2] (A.F.G. van der Meer)

In the frame of German-Russian project „InTerFEL“ now also at NovoFEL

[1] S. Winnerl *et al.*, *Phys. Rev. Lett.* **107,** 237401 (2011).
[2] P. T. Greenland, P. T. *et al.*, *Nature* **465,** 1057–61 (2010).

Setup (FELBE - U100)

- Undulator period 100 mm
- # periods 38
- K 0,3 – 2,7
- Max. power > 100 W
- **Wavelength 18 – 250 µm**
- **Max. pulse energy > 0,01 – 2 µJ**
- **Pulse duration 1 – 25 ps**
- **Repetition rate 13 MHz**



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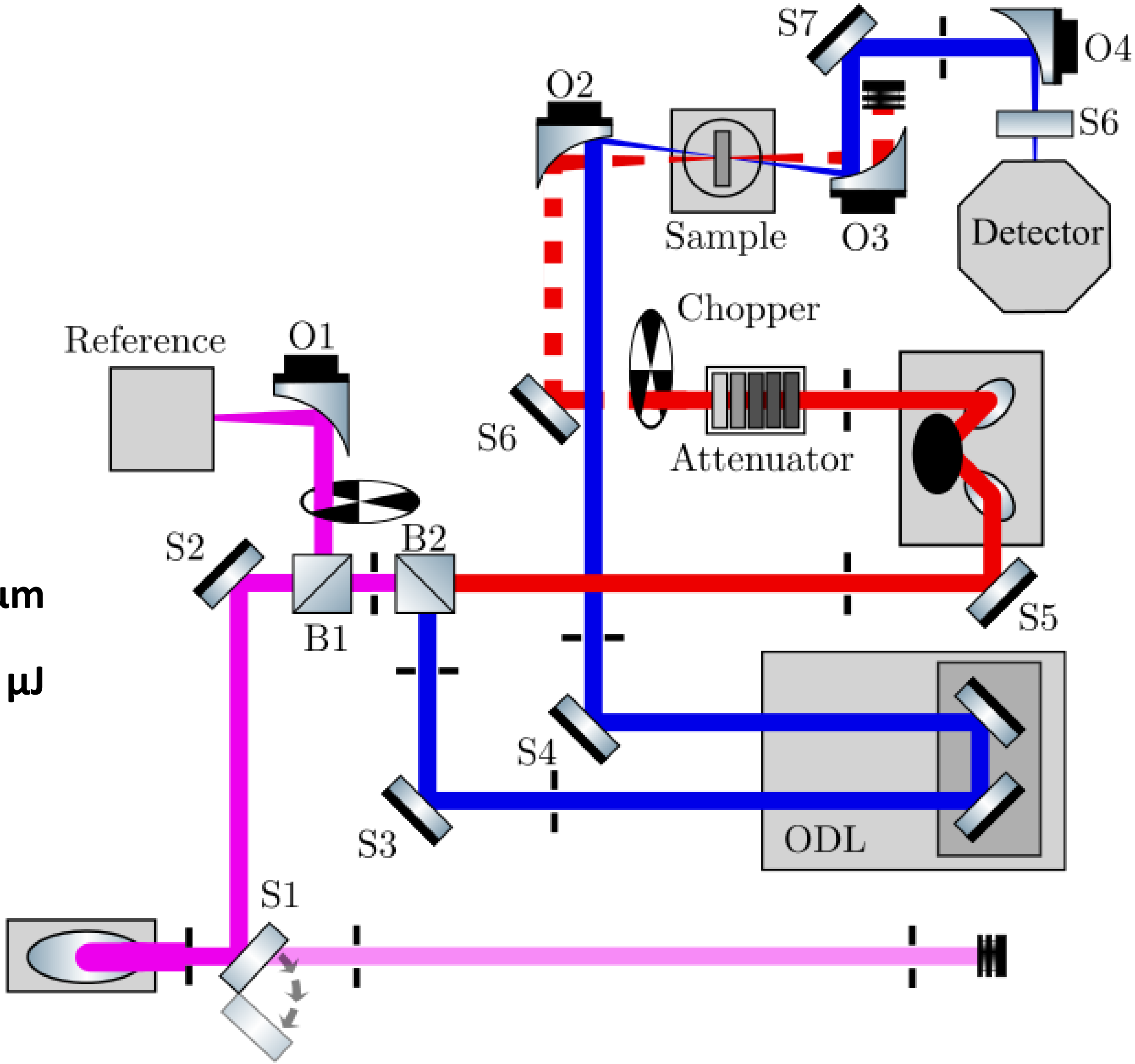
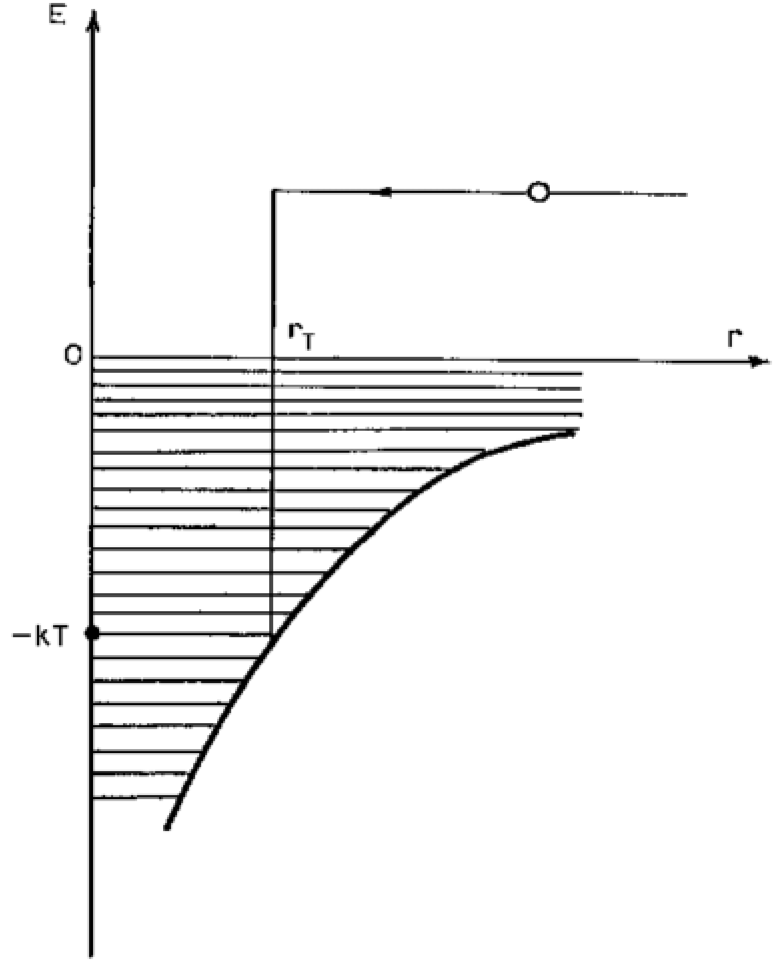


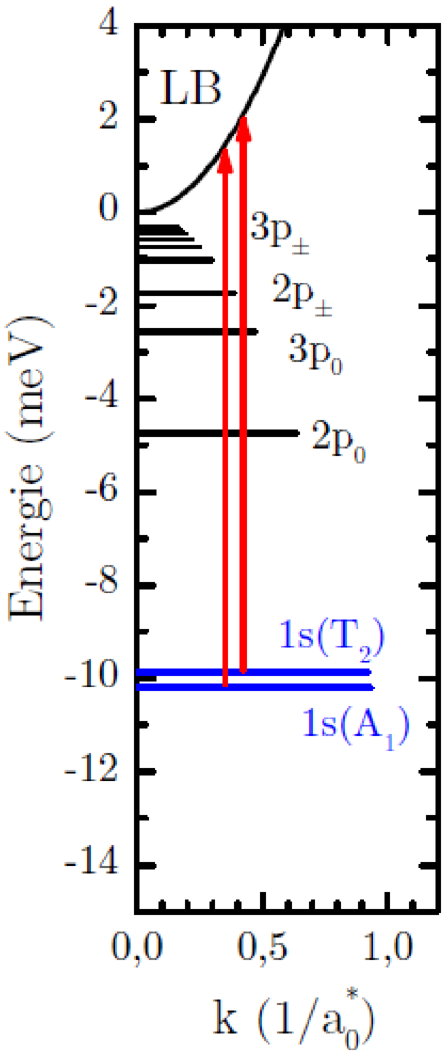
Cascade capture model

- Collision theory (Thomson), basend on probability for capture in high-excited state
- Energy relaxation in a cascade of small steps by emssion of accustical phonons
- Pracitcally bound if binding energy > kT
- Refinements by Abakumov, Perel', Yassievich, with prediction of two capture regimes



M. Lax, *Phys. Rev.* **119,** 1502–1523 (1960).
V. N. Abakumov et al., *Zh. Eksp. Theor. Fiz* **45,** 354–360 (1977).

Samples and investigated transitions

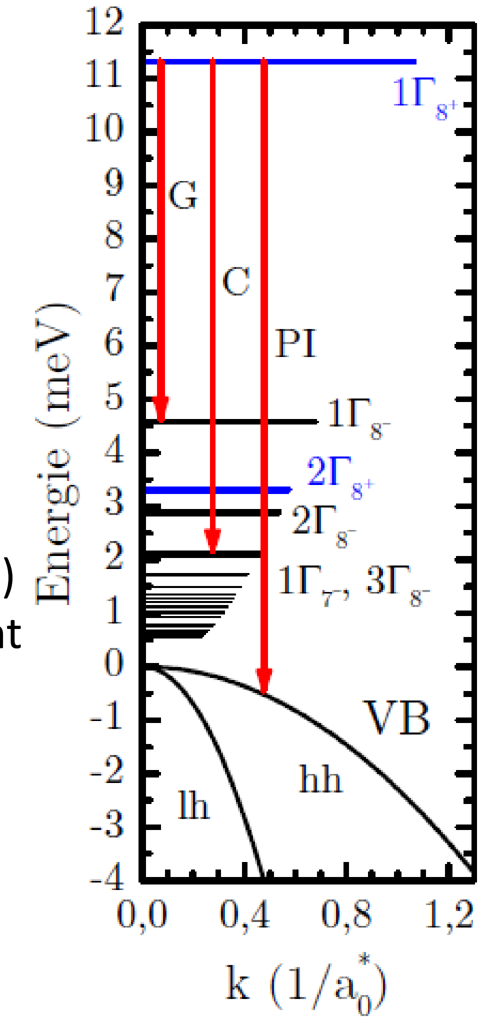


Sample - n:Ge:Sb

- Czochralski grown (IKZ)
- 1×10^{15} cm^{-3}
- $0.5 \times 10 \times 10$ mm^3

Experiment

- Flux dependent recombination (105 µm)
- Temperature dependent recombination



Sample – p-Ge:Ga

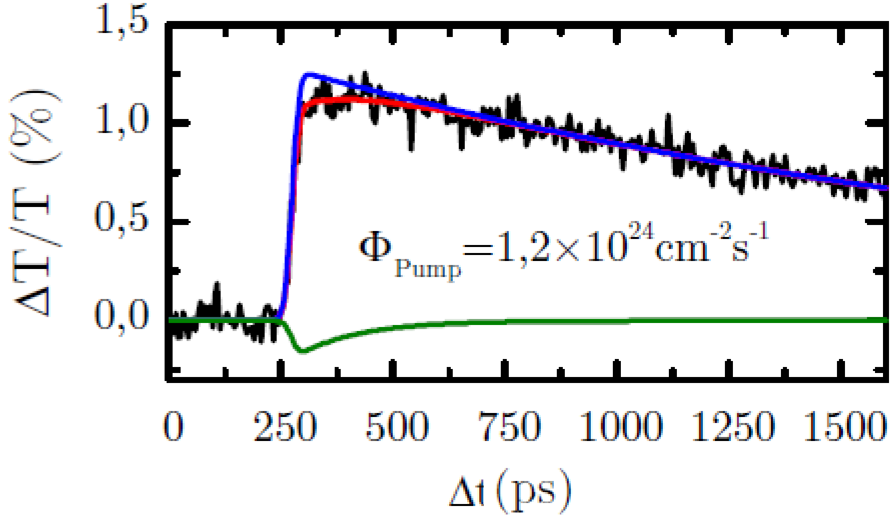
- Czochralski grown (IKZ)
- 2×10^{15} cm^{-3}
- $0.5 \times 10 \times 10$ mm^3

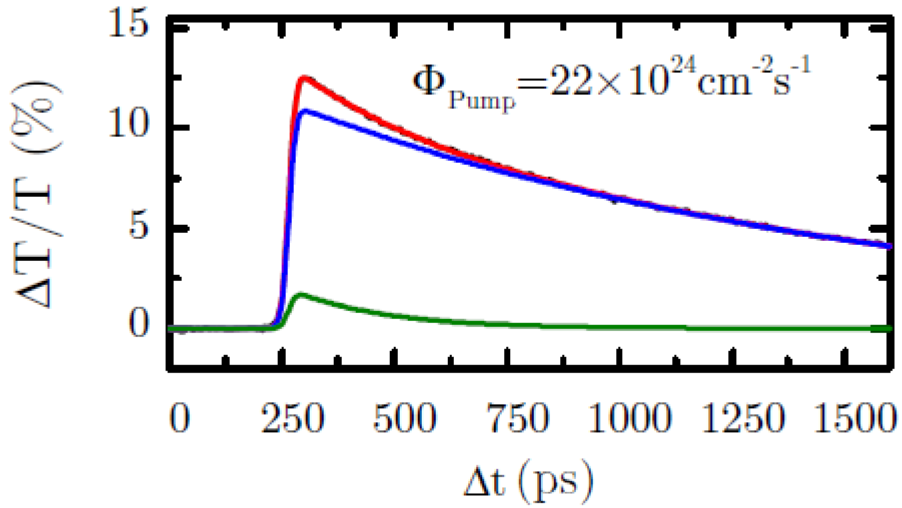
Experiment

- Flux dependent recombination (105 µm)
- Lifetime of two excited states

n-Ge

Czochralski, 1×10^{15} cm^{-3}, Sb donors, $0.5 \times 10 \times 10$ mm^3



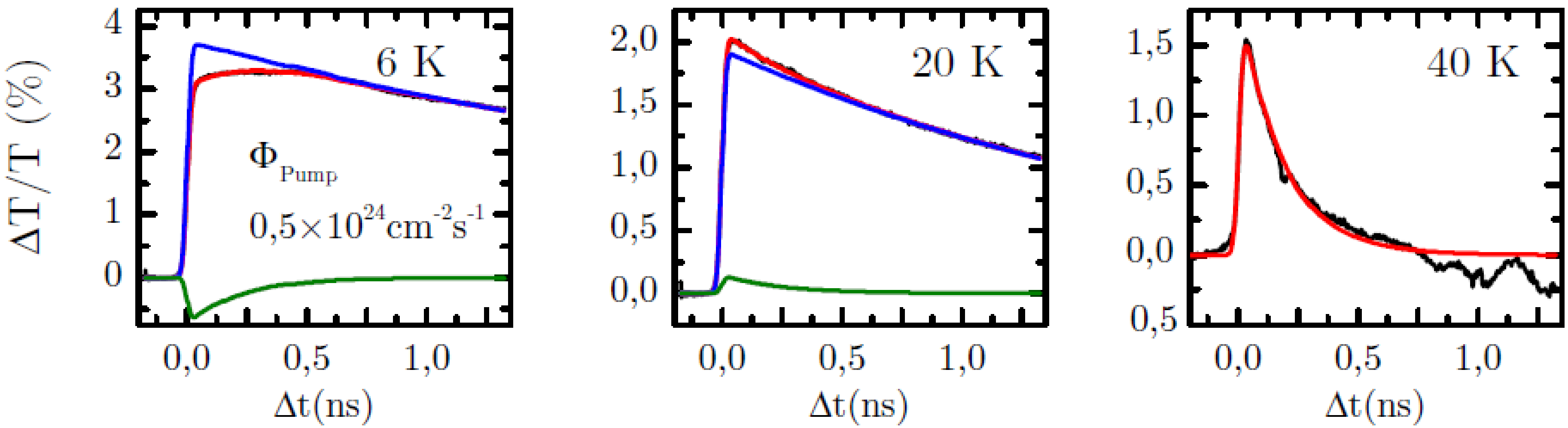


- two exponential components describe data
  - 1 (blue) – recombination (few ns)
  - 2 (green) – intraband relaxation (~200 ps)

N. Dessmann *et al.*, *Phys. Rev. B* **89,** 35205 (2014).

n-Ge

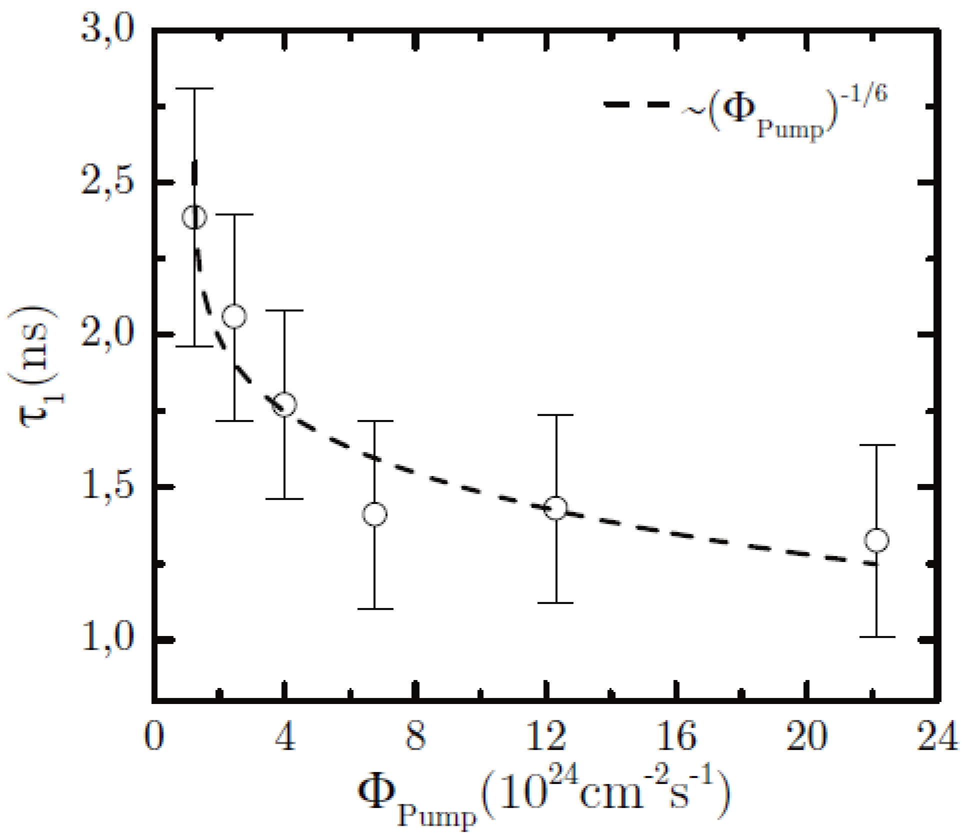
Czochralski, 1×10^{15} cm^{-3}, Sb donors, 0.5 × 10 × 10 mm^3



- Increasing Temperature leads to thermal ionization of impurity centers
- contribution of components is changed
- Intraband relaxation dominates at T > 40 K

n-Ge

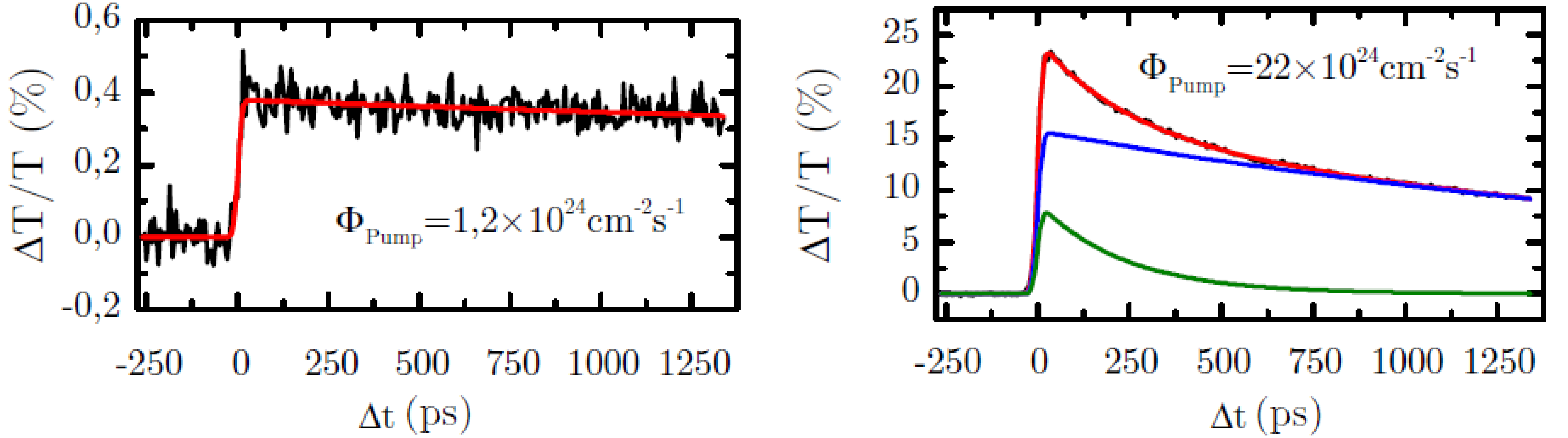
Czochralski, 1×10^{15} cm^{-3}, Sb donors, $0.5 \times 10 \times 10$ mm^3



- Weak dependence of recombination time supports refined cascade capture model

p-Ge

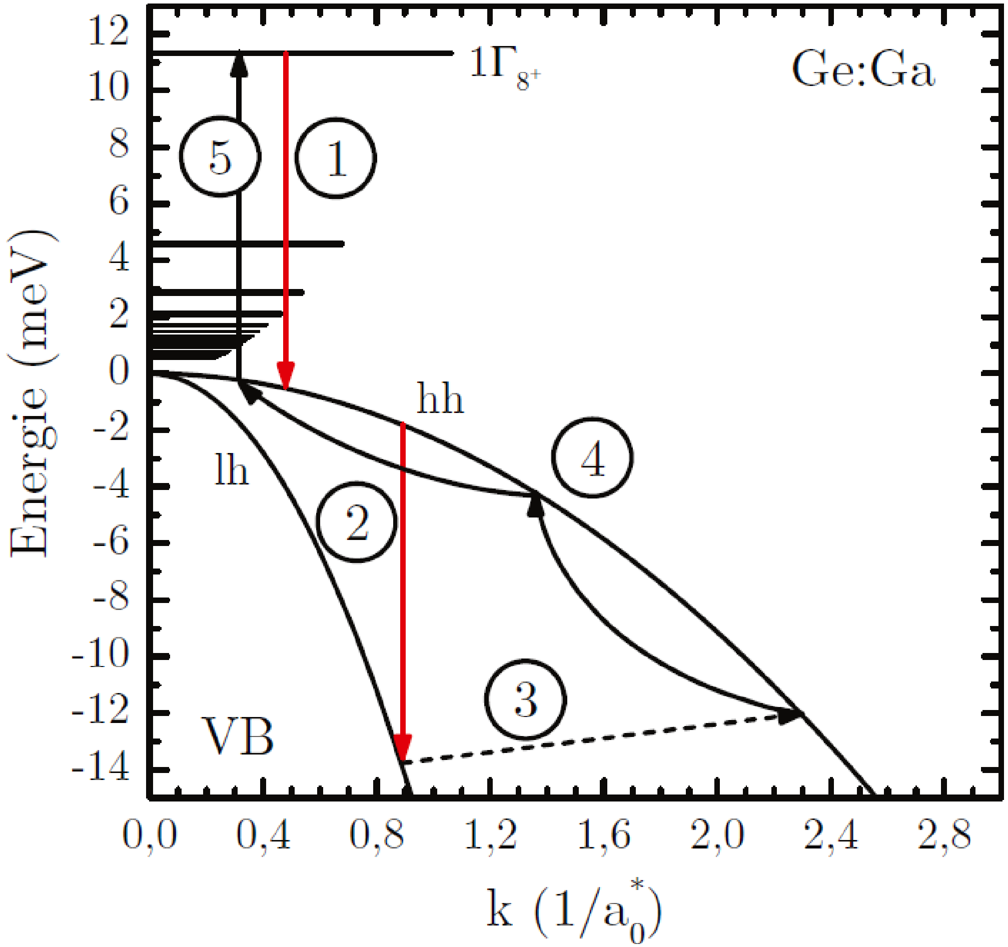
Czochralski, 2×10^{15} cm^{-3}, Ga donors, 0.5 × 10 × 10 mm^3



- two exponential components to describe data
  - 1 (blue) – recombination (few ns)
  - 2 (green) – intraband relaxation (~200 ps)
- more pronounced than in n-Ge due to valence band structure

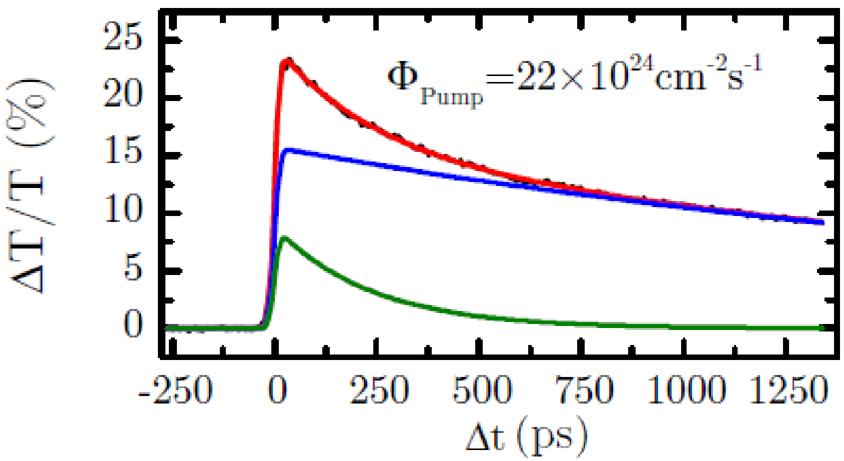
p-Ge

Czochralski, 2×10^{15} cm^{-3}, Ga donors, $0.5 \times 10 \times 10$ mm^3



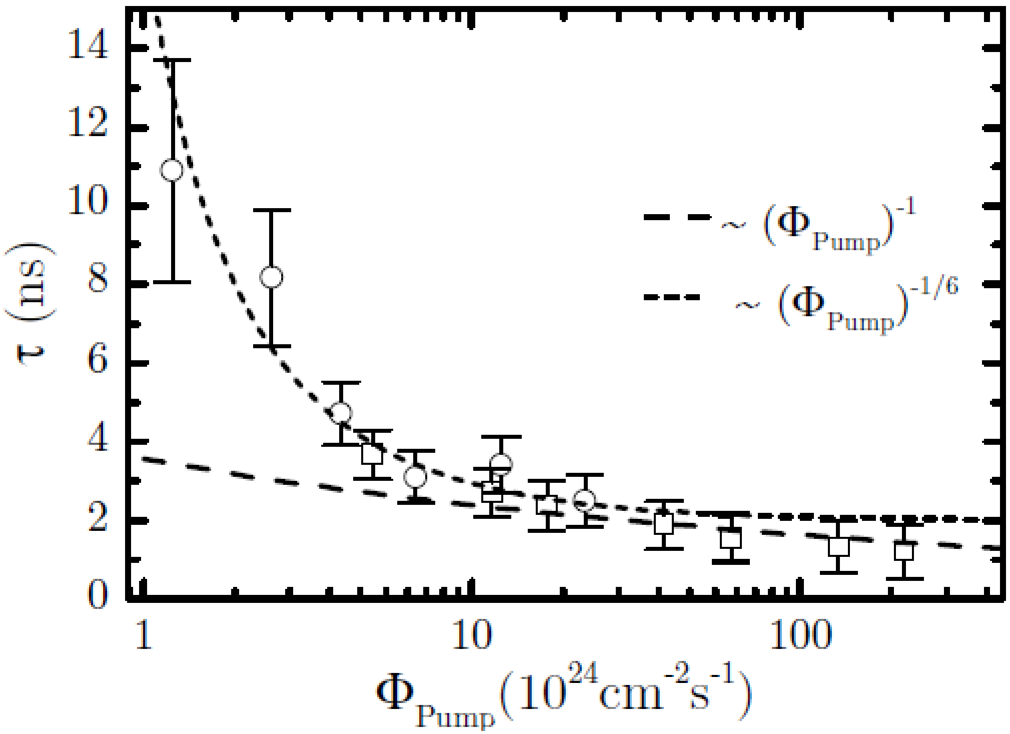
5-step process to describe signal

1. Photoionization
2. Intersubband absorption
3. Light to heavy hole scattering (few ps)
4. Intraband relaxation (200 ps)
5. Recombination (few ns)



p-Ge

Czochralski, 2×10^{15} cm^{-3}, Ga donors, $0.5 \times 10 \times 10$ mm^3



- Stronger dependence of recombination time on photon flux
- possible coverage of two predicted regimes

p-Ge

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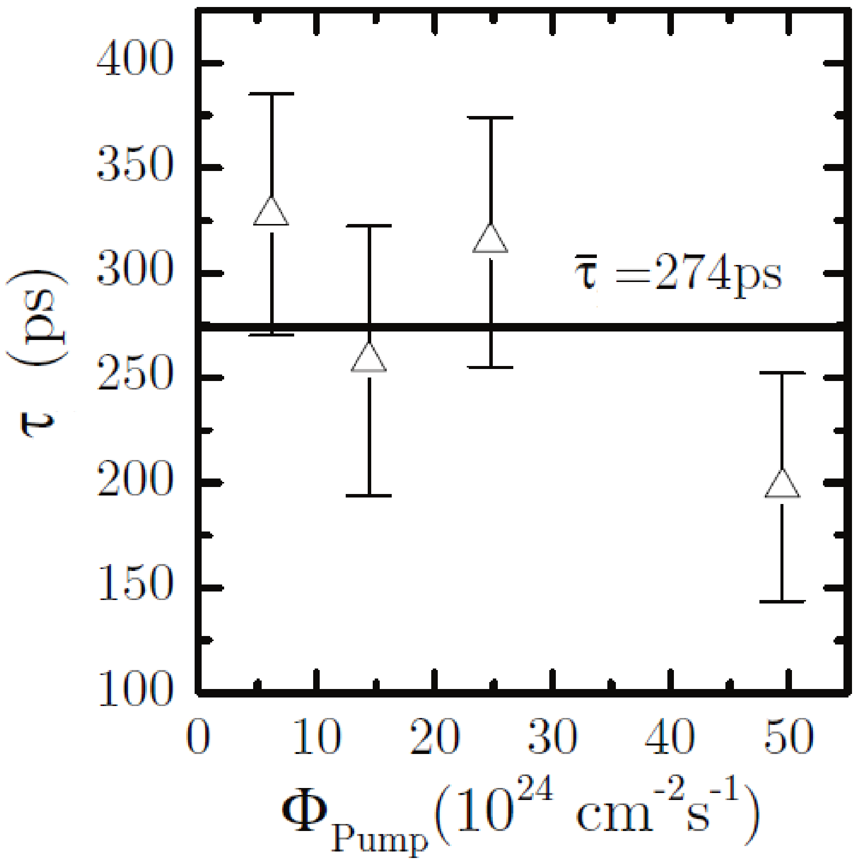

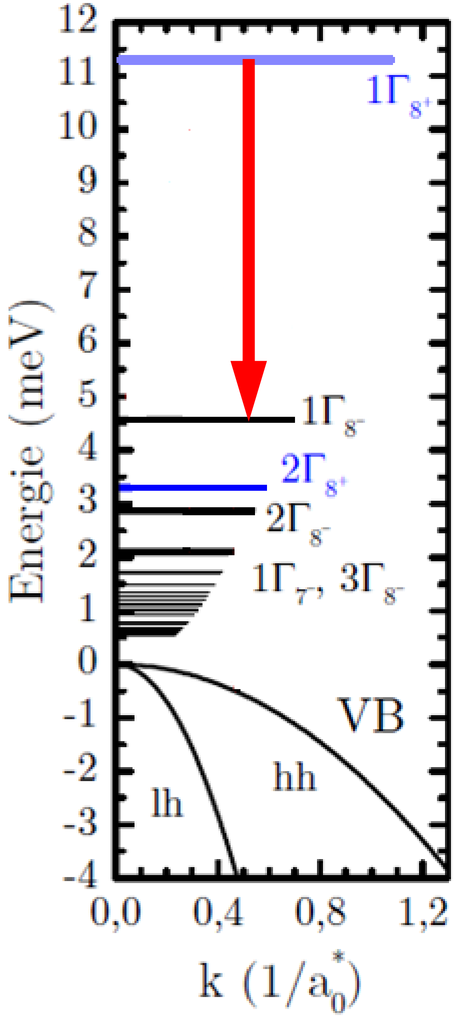

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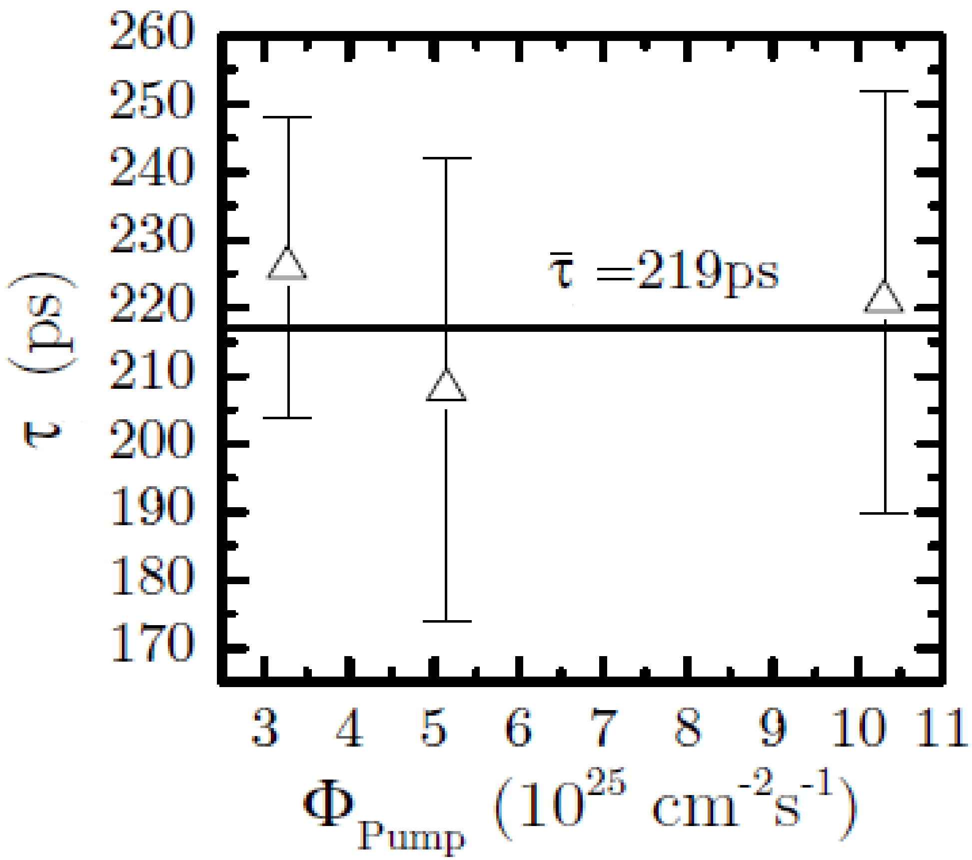

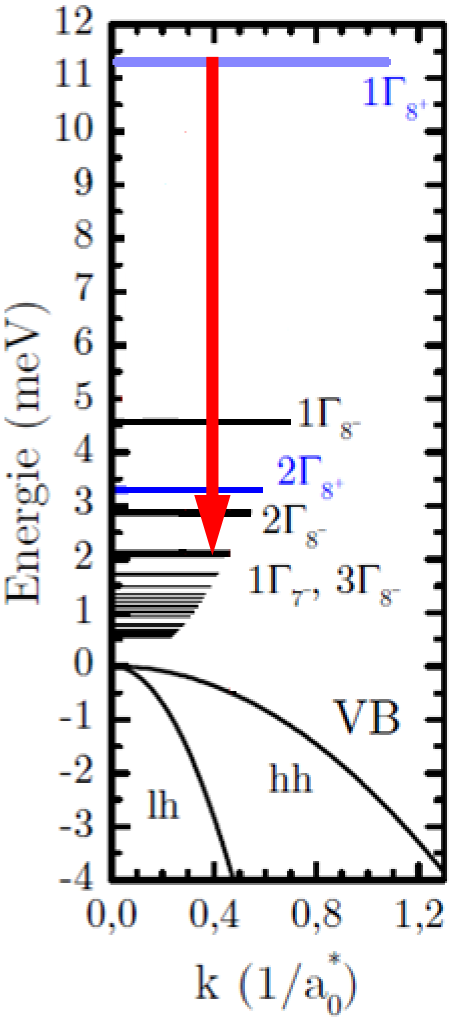

Summary

- First direct investigation of recombination times and lifetimes of excited states in p-/n-Ge in the time-domain
- Recombination times in the ns-range, as expected from previous, direct detector mode measurements
- Weak dependence of the recombination time on the Photon flux (pump) in accordance with the theory
- Explanation of biexponential decay of pump-probe-signal with intraband processes
- Lifetimes of two excited states in p-Ge:Ga shown to be ~200 ps

FELBE (U100)

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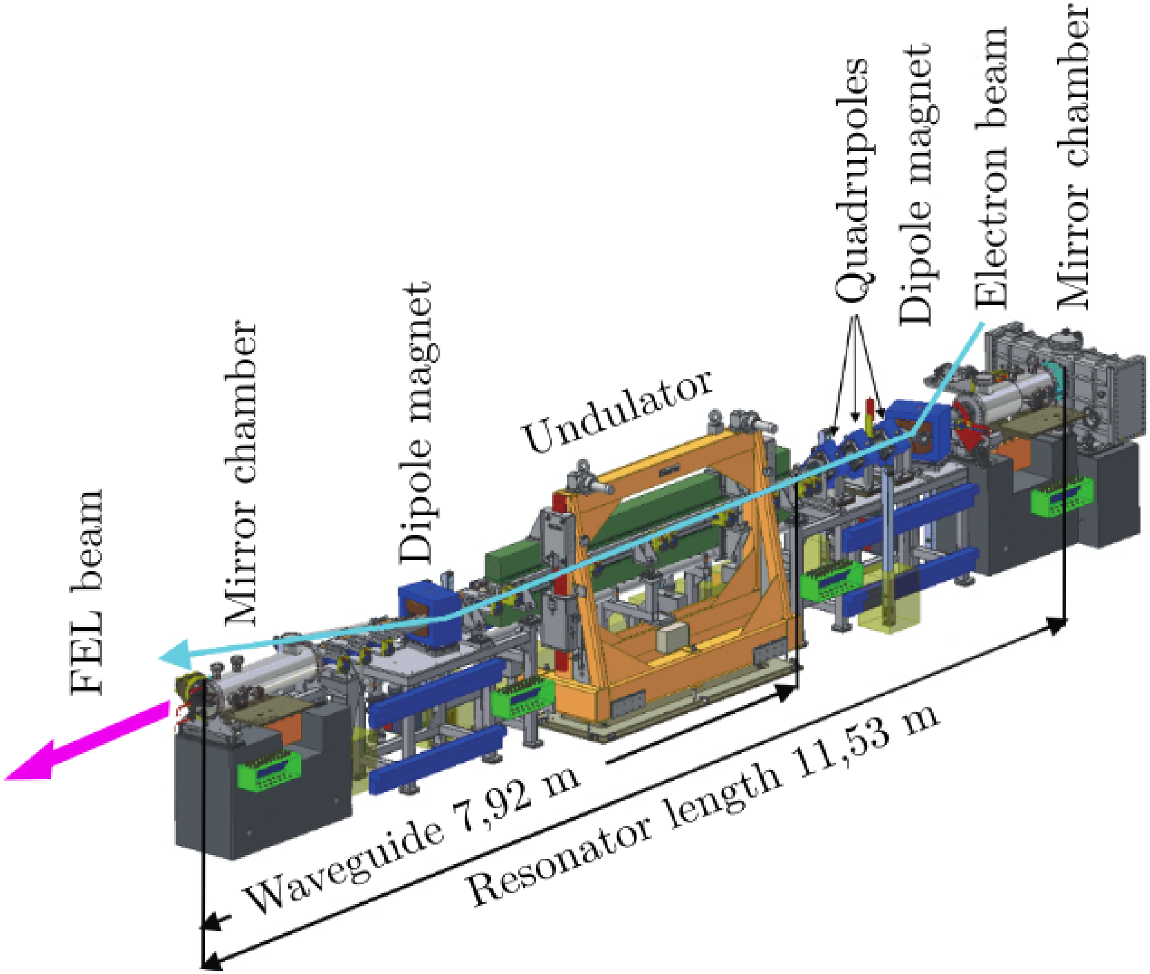
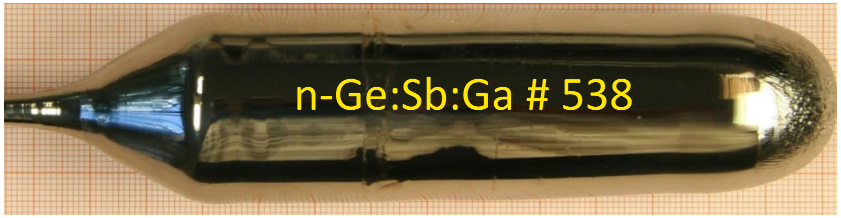
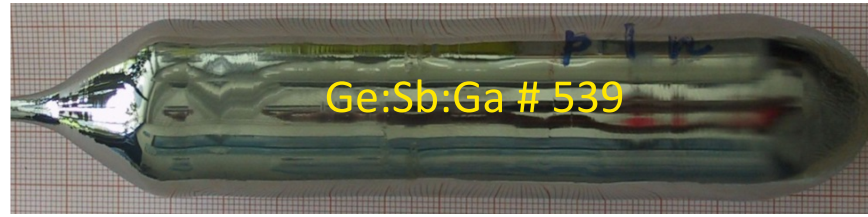
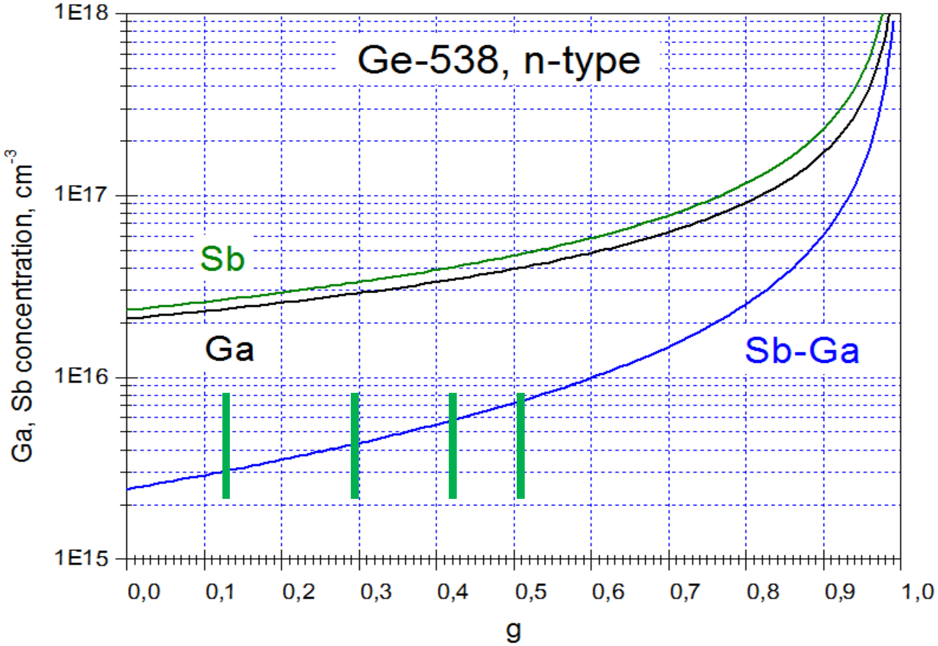
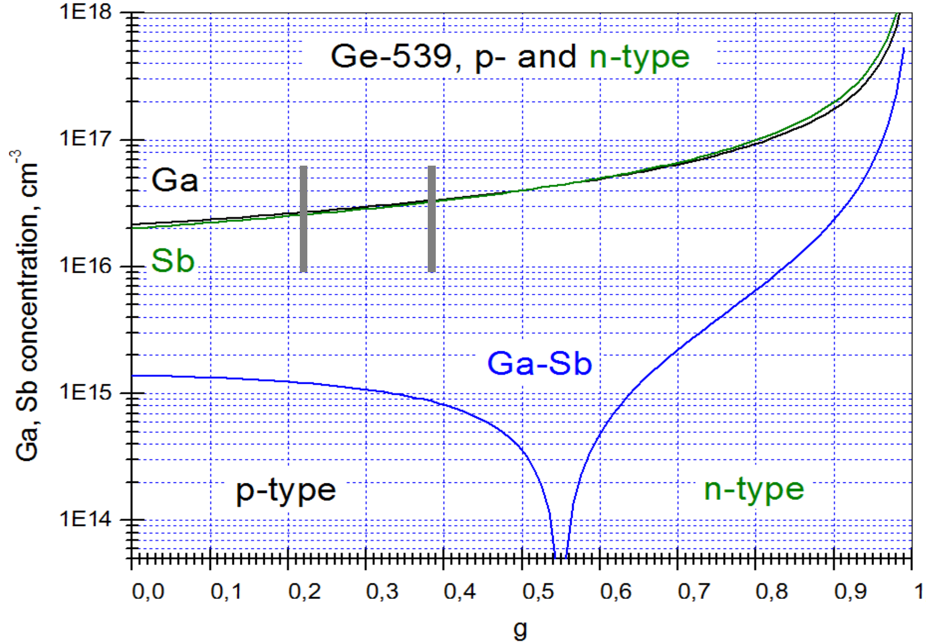


Results (Compensated Germanium)









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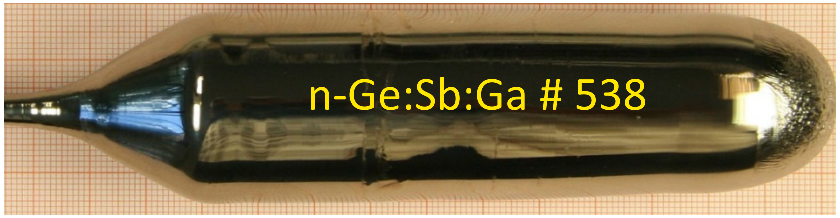
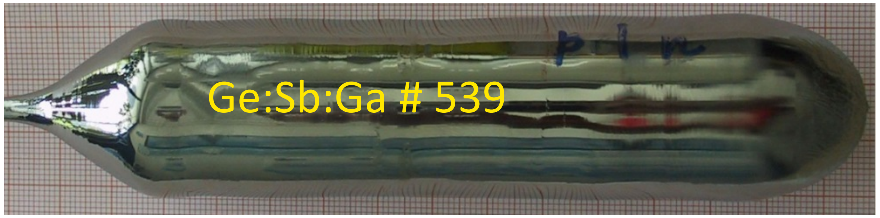
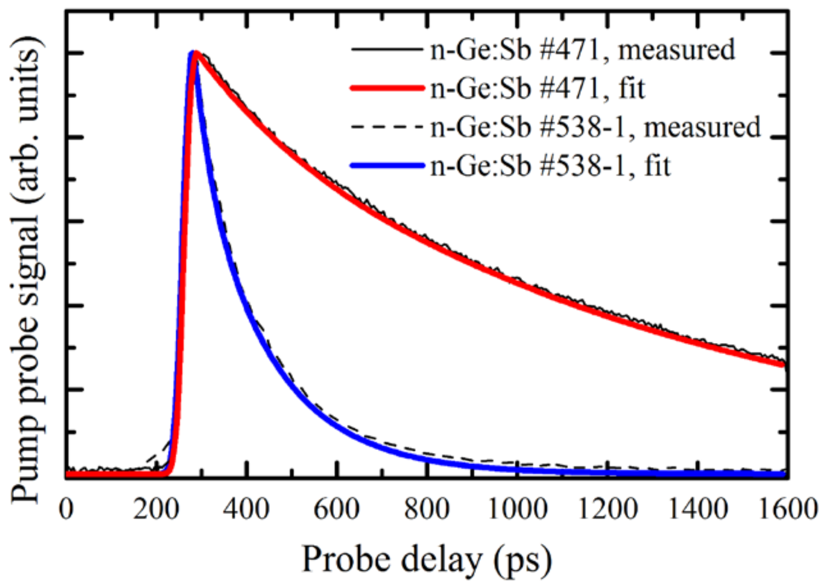


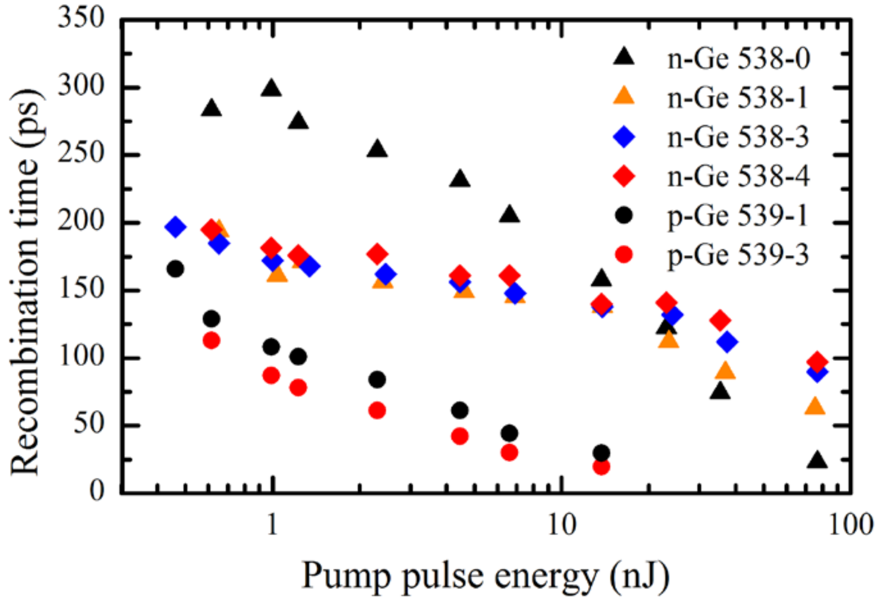


DOPING CONCENTRATIONS OF INVESTIGATED GERMANIUM SAMPLES

Sample	N_{Ga} (cm^{-3})	N_{Sb} (cm^{-3})	N_{net} (cm^{-3})	Comp (%)
Ge-539-1	2.72×10^{16}	2.6×10^{16}	(p) 1.2×10^{15}	95.6
Ge-539-3	3.4×10^{16}	3.31×10^{16}	(p) 9×10^{14}	97.3
Ge-538-0	2.3×10^{16}	2.6×10^{16}	(n) 3×10^{15}	88.5
Ge-538-1	2.9×10^{16}	3.3×10^{16}	(n) 4×10^{15}	87.9
Ge-538-3	3.45×10^{16}	4.0×10^{16}	(n) 5.5×10^{16}	86.2
Ge-538-4	4×10^{16}	4.7×10^{16}	(n) 7×10^{15}	85.1

Results (compensated Ge)





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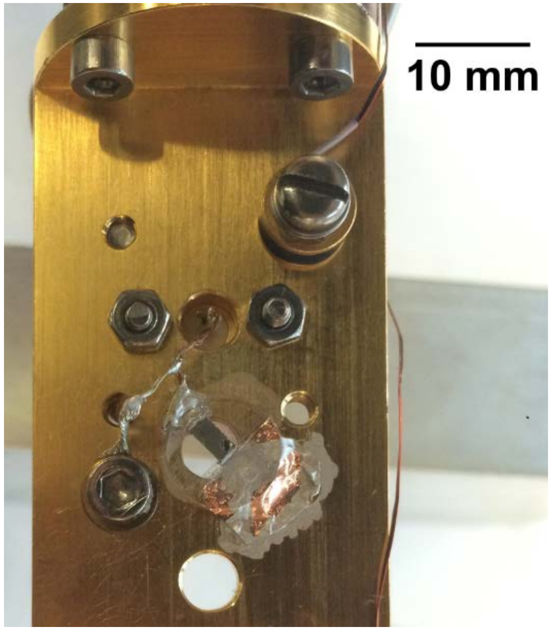

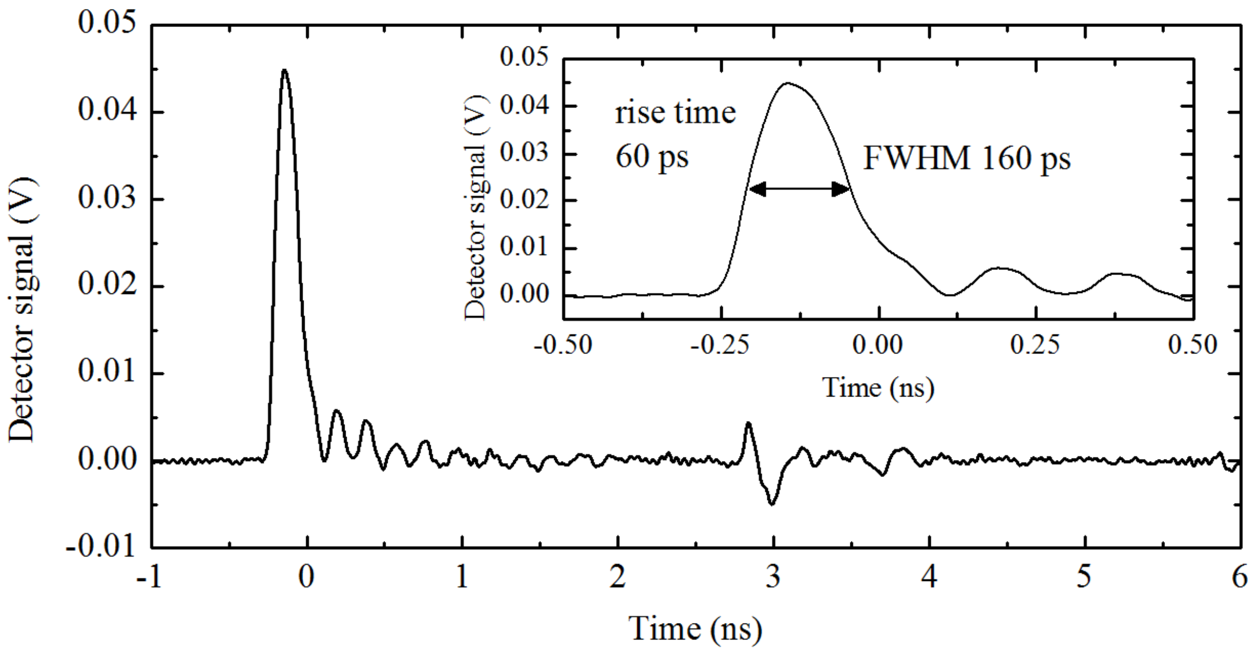

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