Optical measurements at cryogenic temperatures

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GWADW Elba

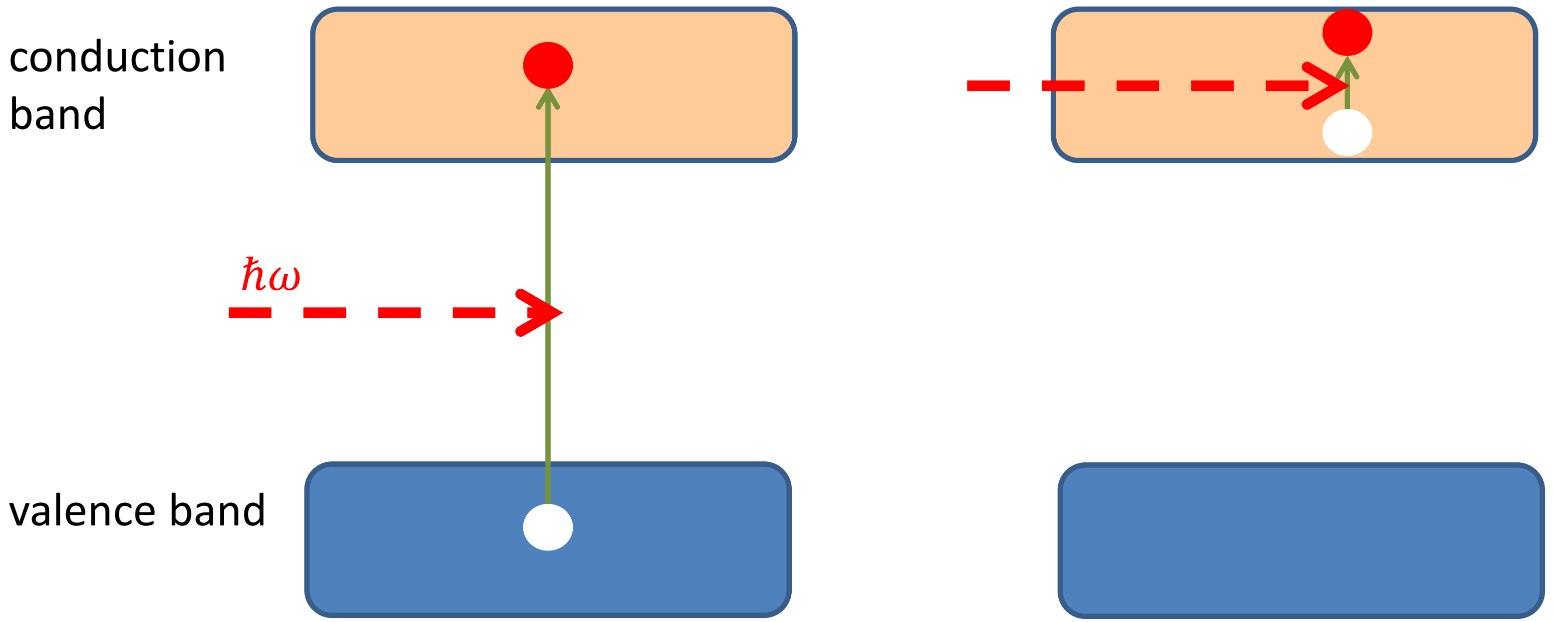
Outline

- absorption processes in semiconductors
  → direct/indirect semiconductors
  → phonon assisted absorption
  → electronic absorption measurement

- absorption measurement techniques
  → deflection
  → calorimetric

- temperature dependent absorption measurements of silicon
  → influence of doping

Absorption processes in semiconductors

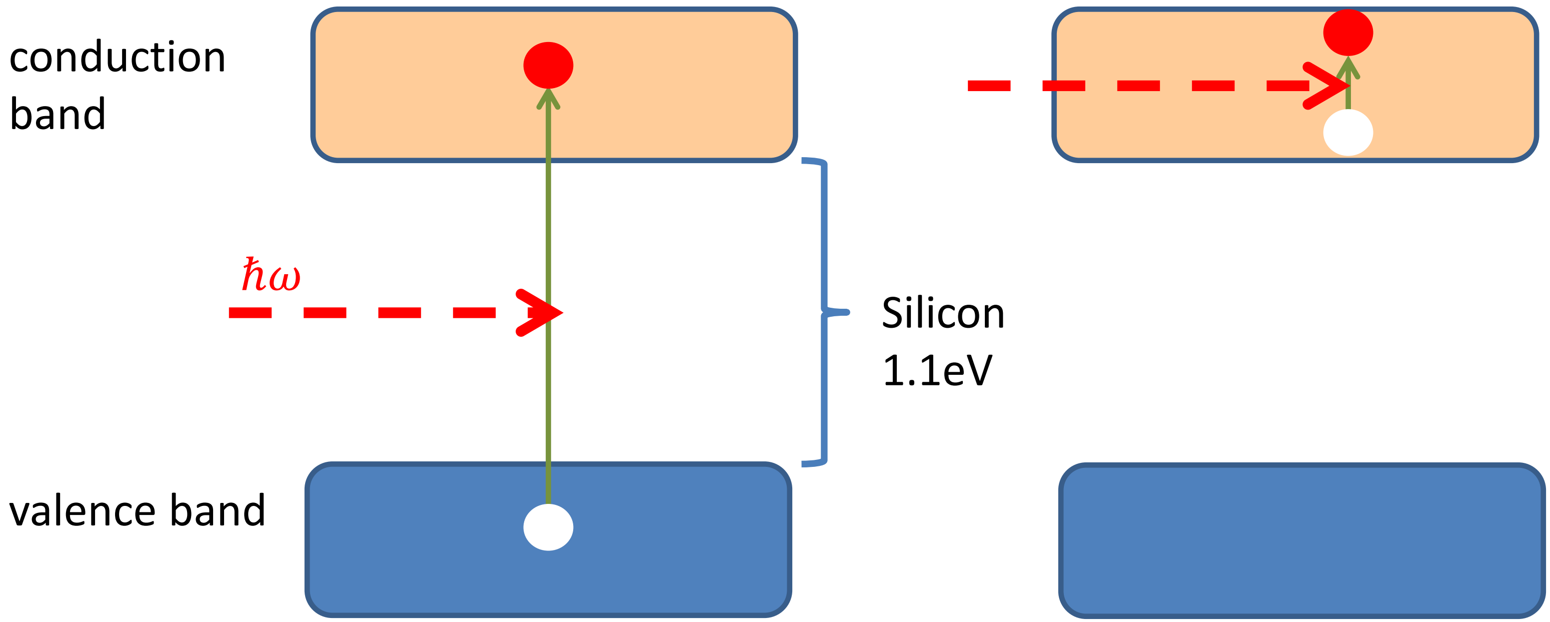


band band absorption/
inter band absorption

intra band absorption/
free carrier absorption

$$\alpha_{fc} \sim N$$
$$\alpha_{fc} \sim \lambda^2$$

Absorption processes in semiconductors



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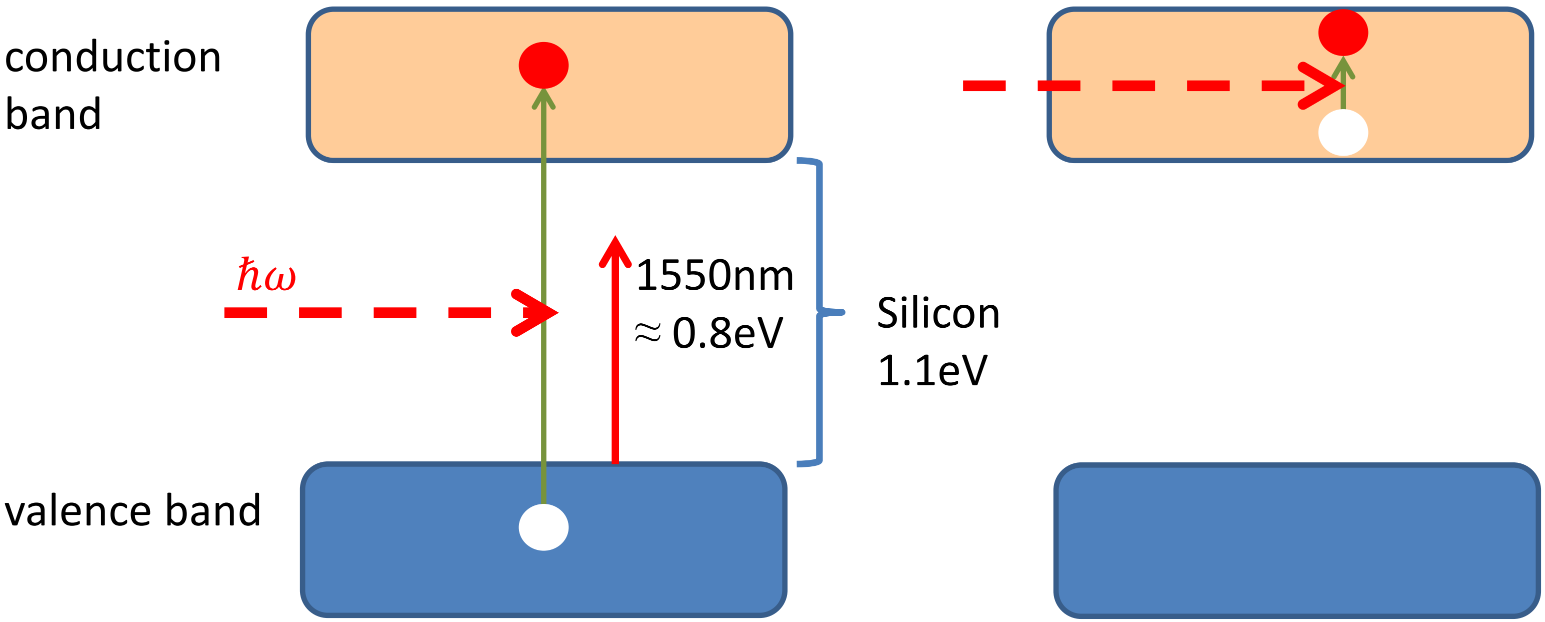

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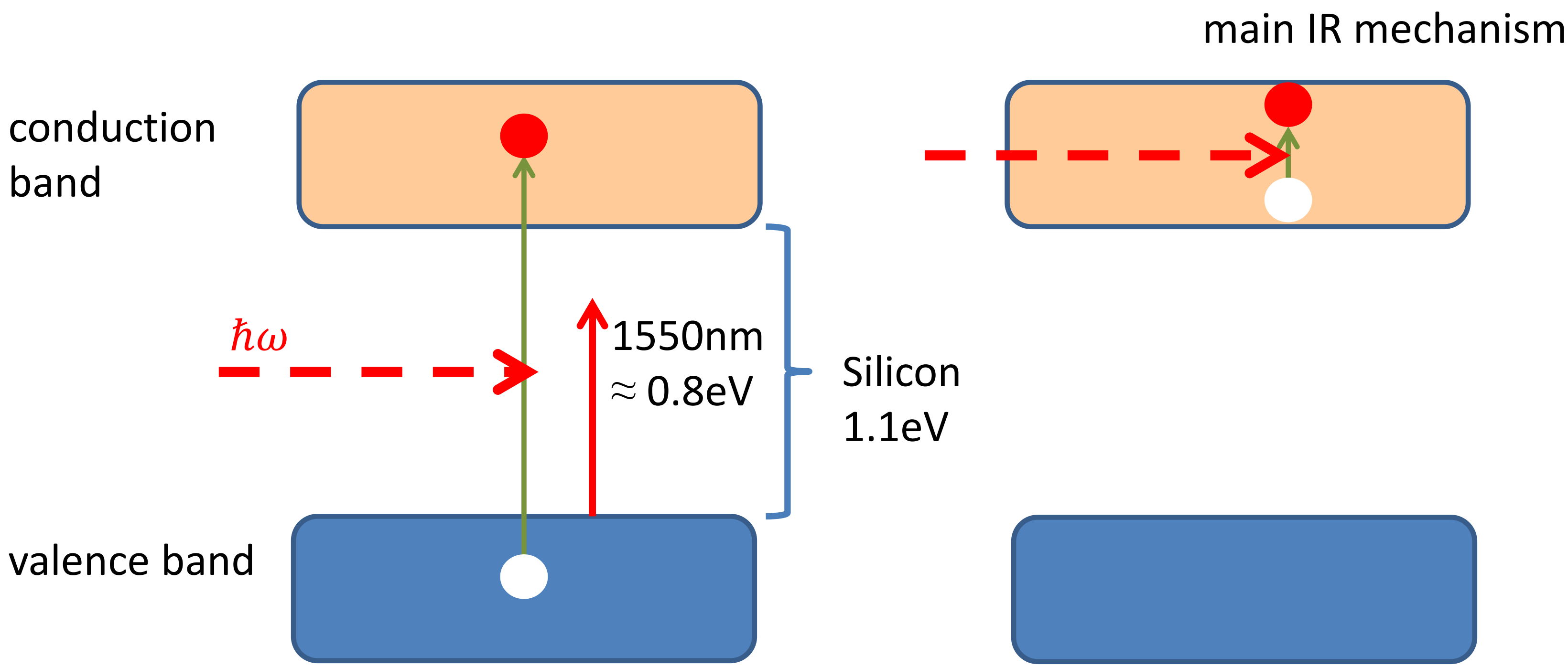
→ high transmission for 1550 nm
→ low absorption

Absorption processes in semiconductors



band band absorption/
inter band absorption

intra band absorption/
free carrier absorption

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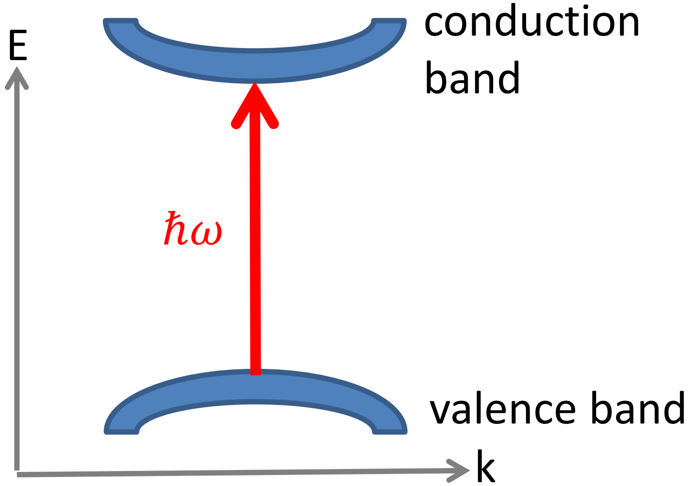
Direct and indirect semiconductors

Direct semiconductor

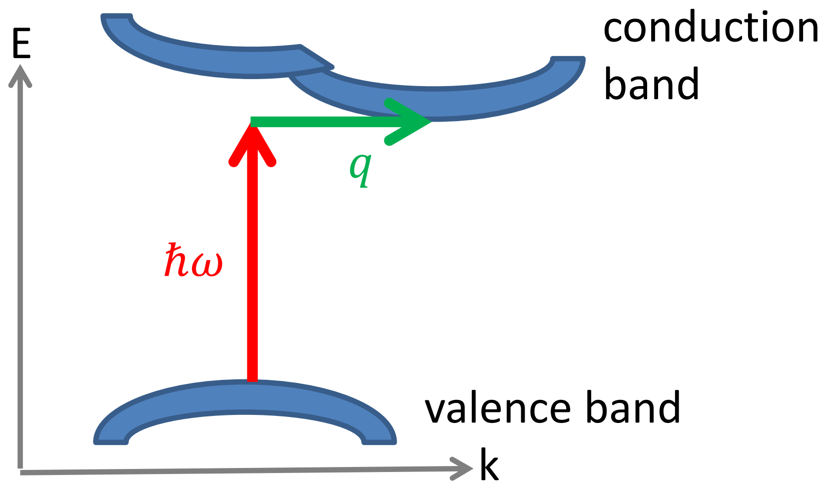
- typical: GaAs
- energy of a photon $\hbar\omega$
- momentum of a photon ≈ 0



$$\alpha_{direct\ HL} \sim (\hbar\omega - Eg)^{1/2}$$

Indirect semiconductor

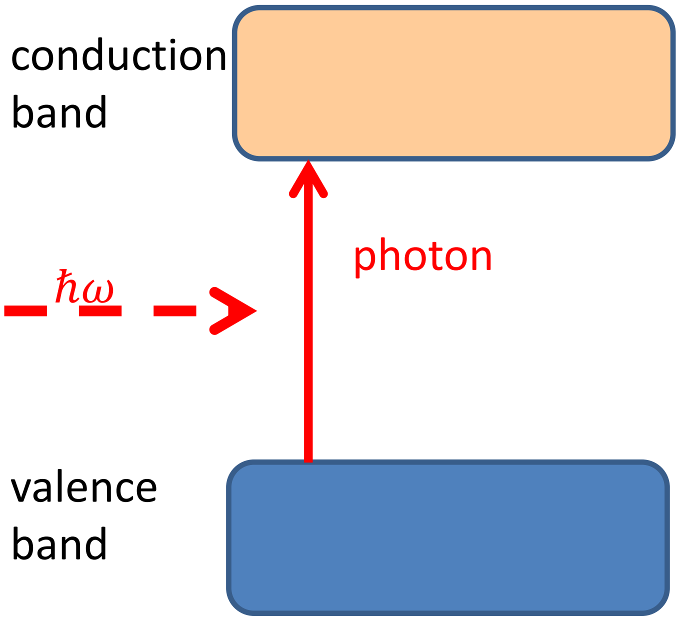
- typical: Si, Ge
- energy of a photon $\hbar\omega$ + momentum of a phonon q

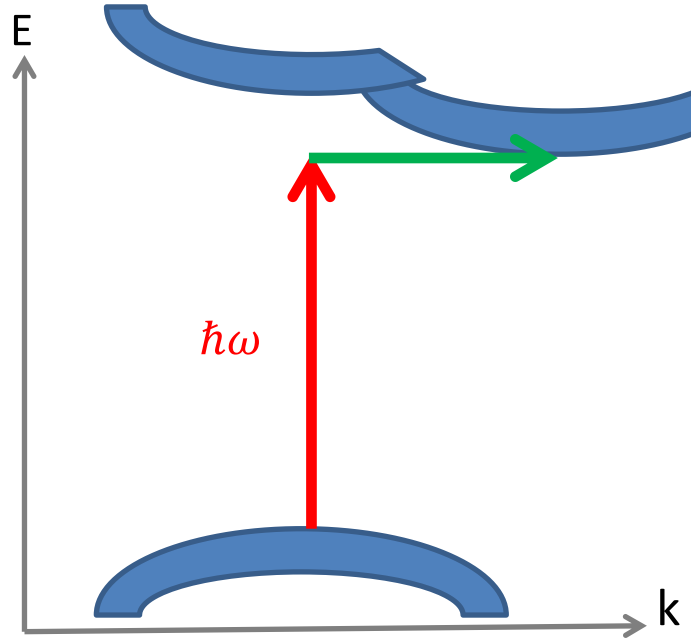


$$\alpha_{indirect\ HL} \sim (\hbar\omega - Eg \pm \hbar\Omega)^2$$

Phonon assisted band-band absorption

- band band absorption





Phonon assisted band-band absorption

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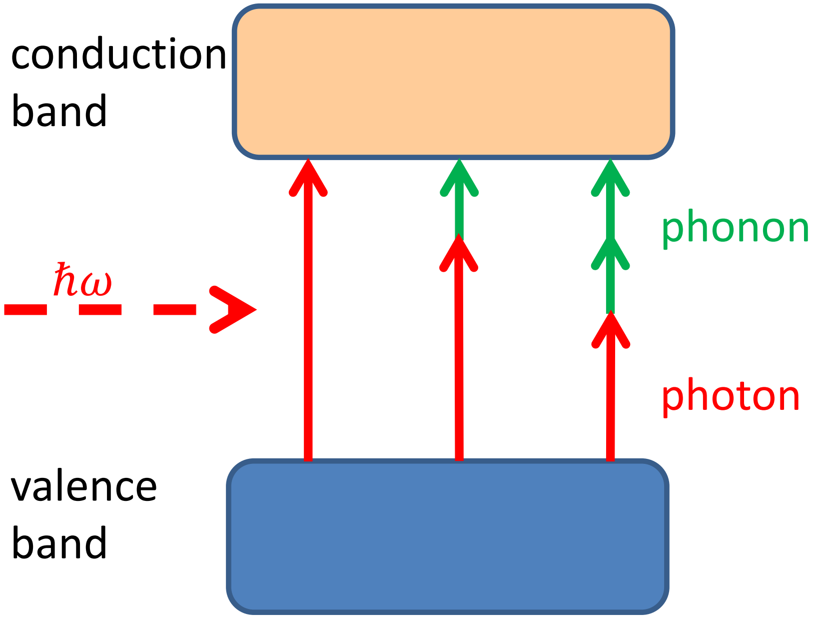
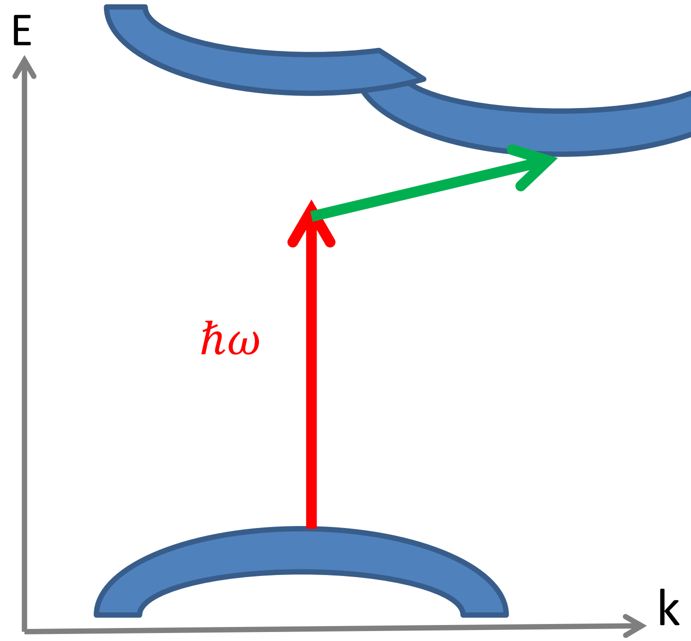
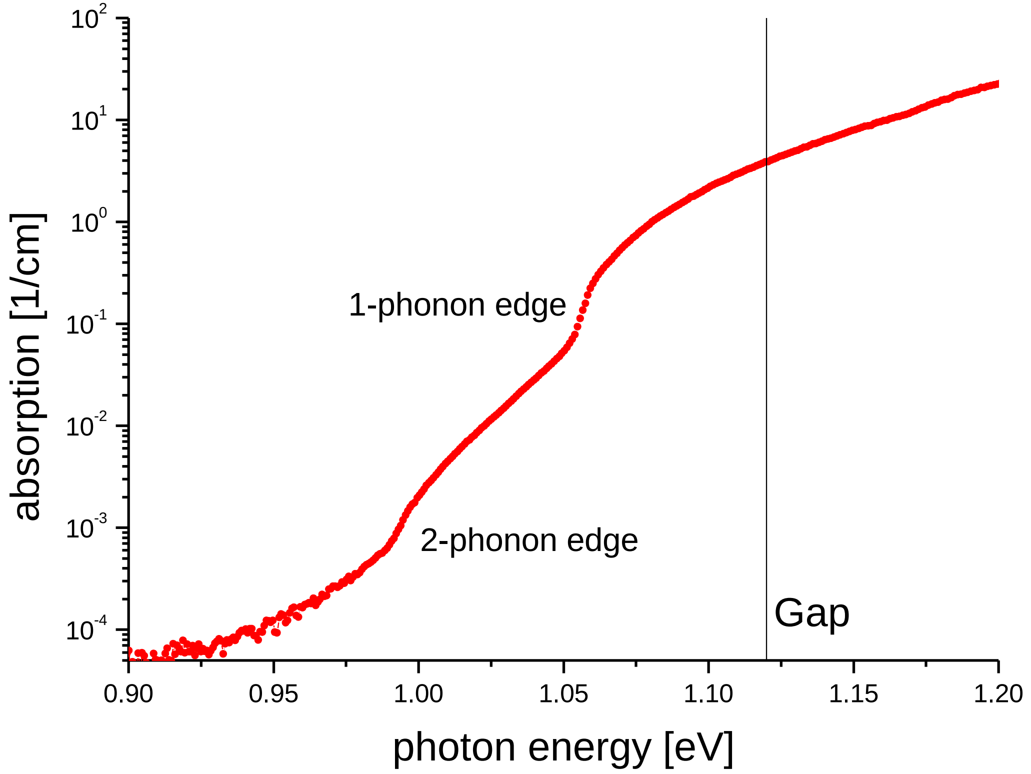


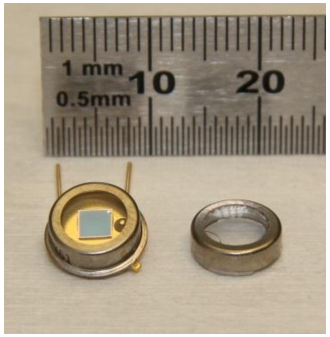


→ absorption below the gap energy is possible

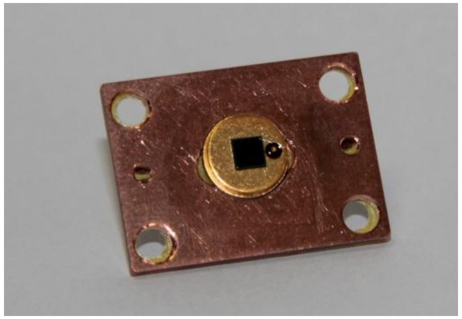
Electronic absorption

due to phonons absorption below the energy gap is possible



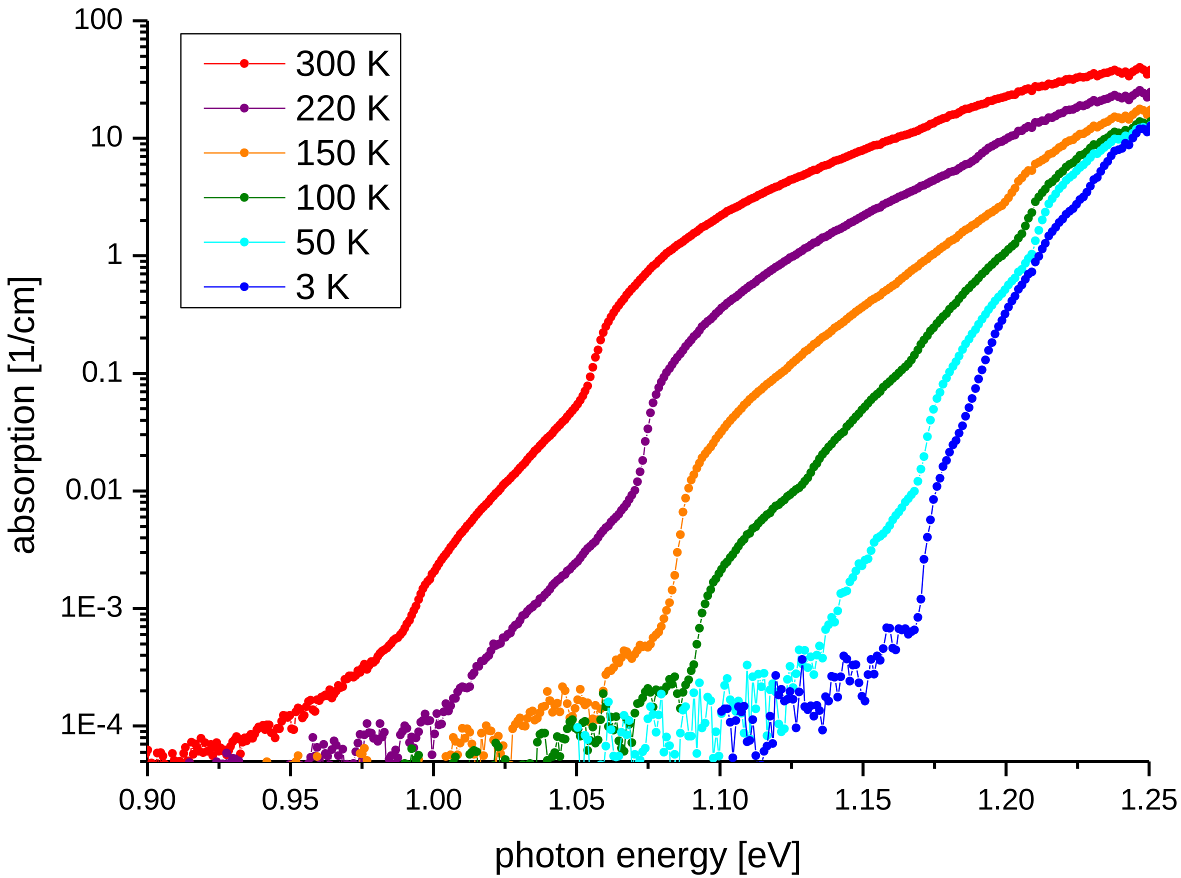


silicon photodiode



photodiode inside
a sample holder

Temperature dependent absorption



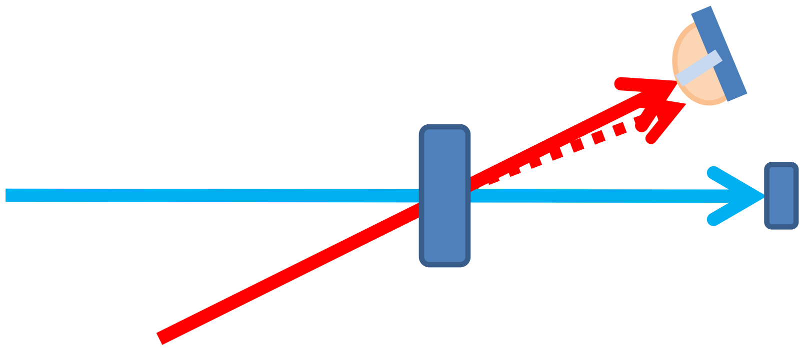
- for lower temperatures phonons freeze out → absorption below the gap is getting smaller

→ poster

Absorption measurement setups

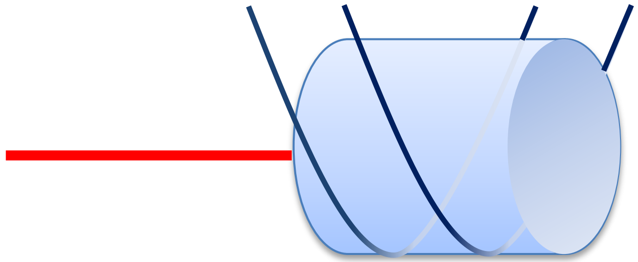
Deflection/Mirage effect

- state of the art technology
- sensitivity < ppm/cm possible
- in-depth resolution
- bulk and coating can be measured
- calibration or modeling needed



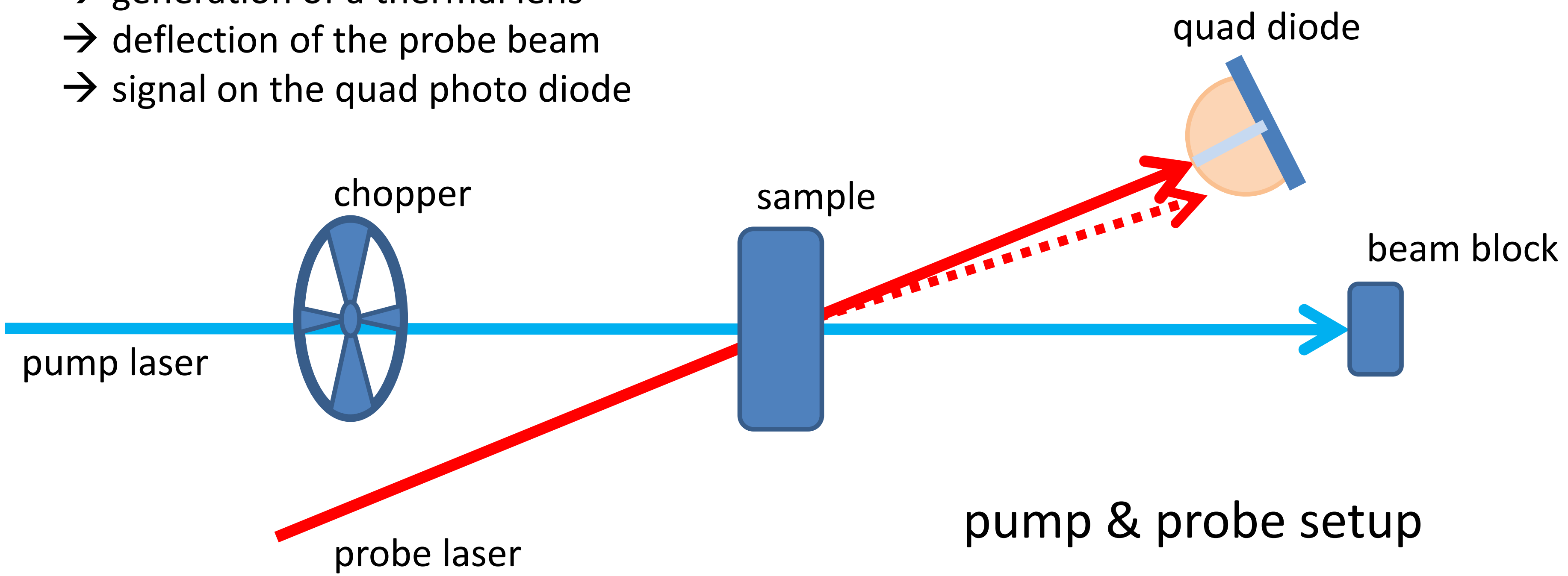
Calorimetric

- heating the sample with a laser
  → measure the temperature rise
  → calculate the absorption
- no need for a focused laser beam
- high sensitivity at low temperatures



Mirage / deflection measurement

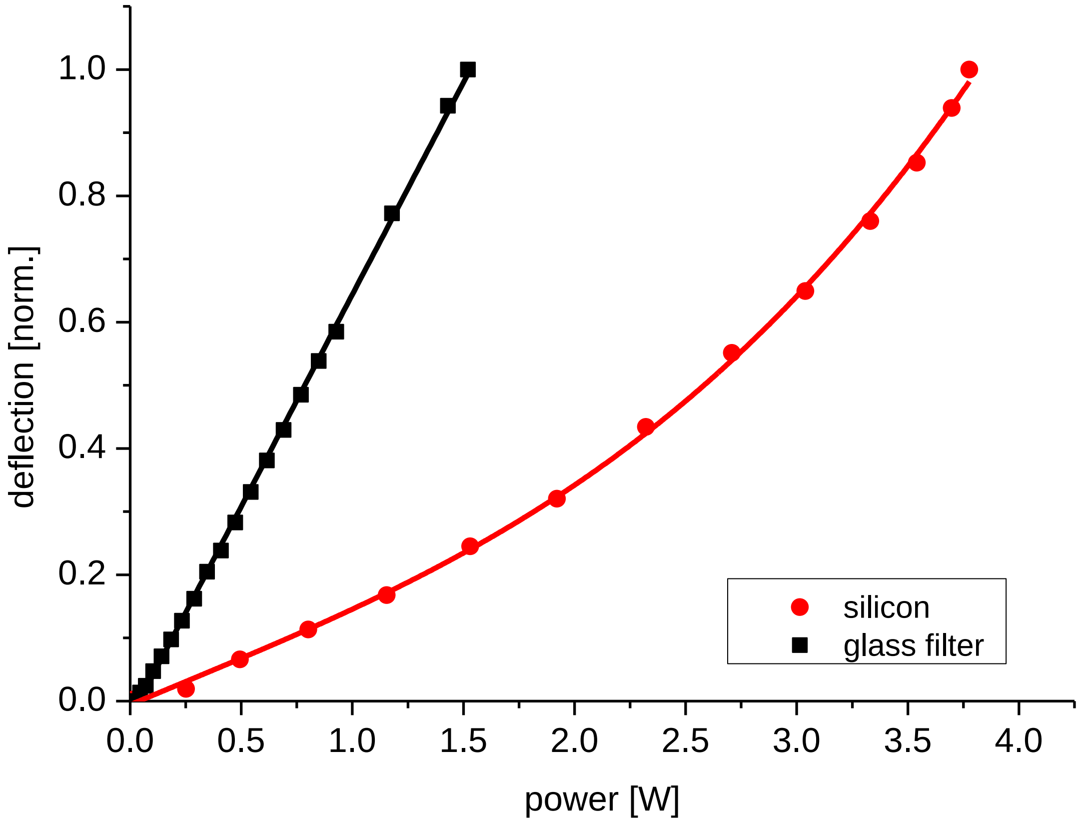
heating the sample with the pump laser beam
→ generation of a thermal lens
→ deflection of the probe beam
→ signal on the quad photo diode



pump & probe setup

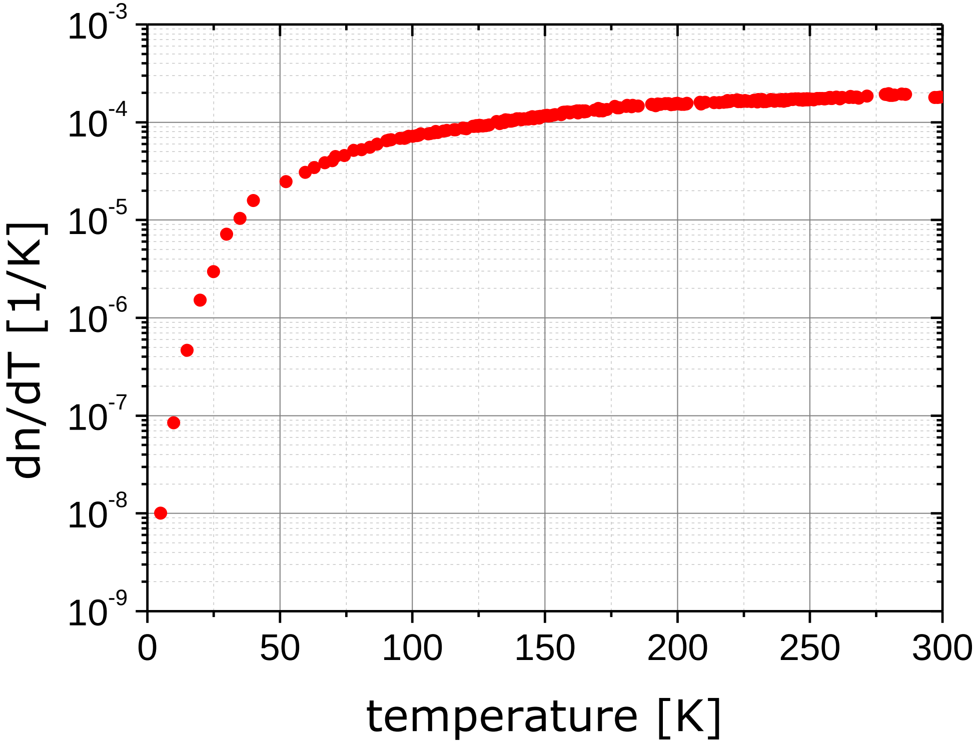
Deflection measurement (pump & probe)

- calibration necessary
- for high laser power and small laser beam size
  → non linear effect (two photon absorption)
  → quadratic rise of the absorption with the laser power



Deflection measurement (pump & probe)

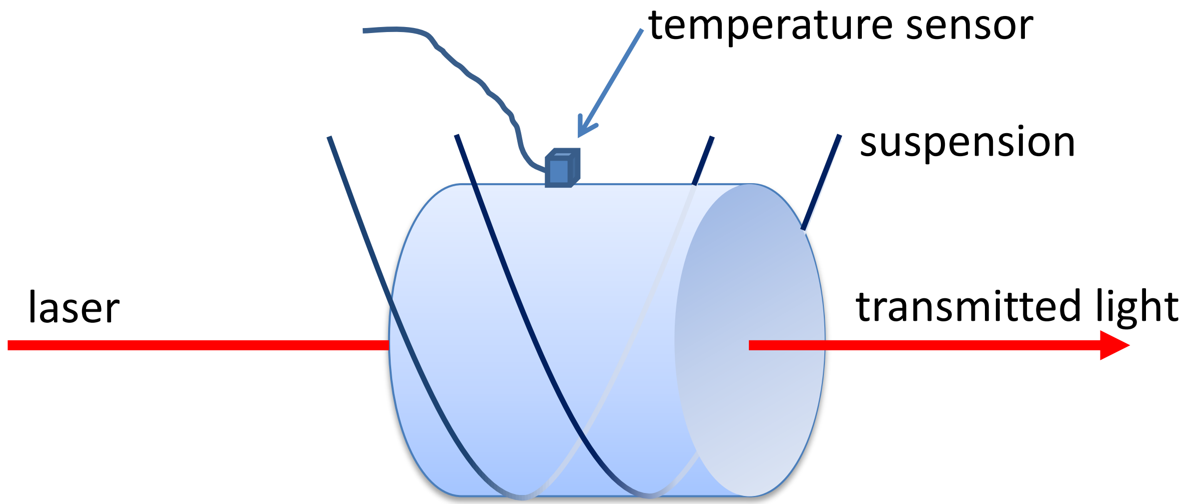
- → sensitivity loss down to lower temperatures
  → but measurement still possible → next talk



J. Komma, C. Schwarz, G. Hofmann, D. Heinert, and R. Nawrodt,Appl. Phys. Lett. 101, 041905 (2012).

Calorimetric absorption measurement

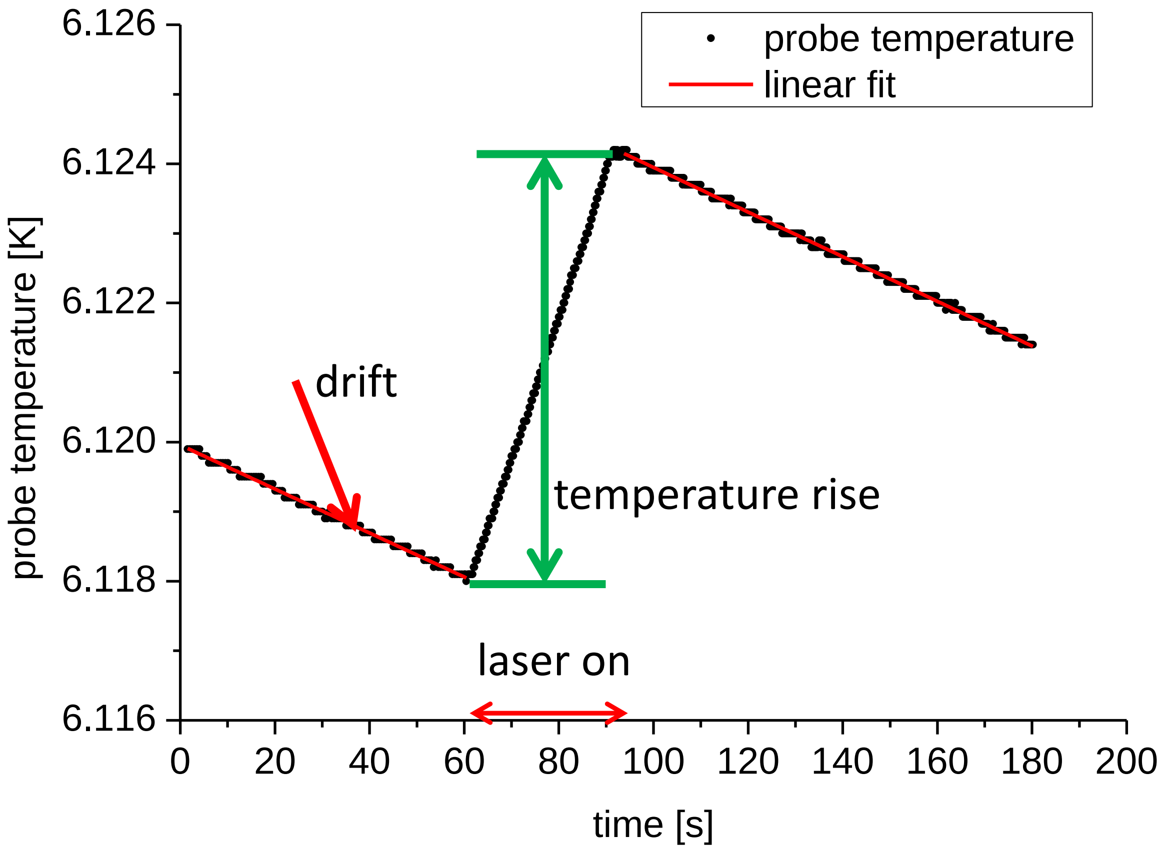
- Calorimetric measurement → measure the temperature rise ΔT due to the absorbed laser power P_{abs} in a time Δt :
- $\Delta T = \frac{\Delta t \, P_{abs}}{m \, C}$



calorimetric setup

Calorimetric measurement

- Measurement data evaluation
- ΔT = temperature rise + temperature drift



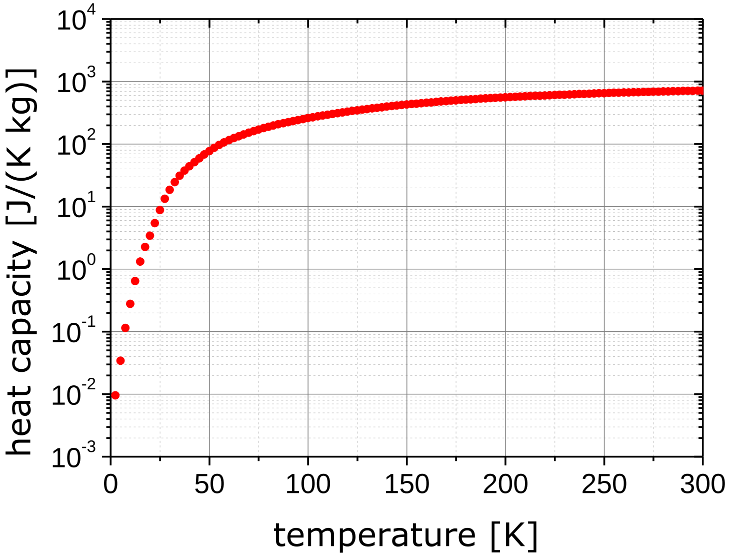
typical heating curve, 3.5 kg silicon@20K

Calorimetric measurement

- for example 1 kg silicon, 1 W laser power, 60 s heating time, 10 cm sample length, 10 ppm/cm:

temperature [K]	ΔT [K]
300	8.5 µK
30	320 µK
10	22 mK
5	164 mK

$$\Delta T = \frac{\Delta t\, P_{abs}}{m\, C}$$



temperature dependent heat capacity of silicon[1]

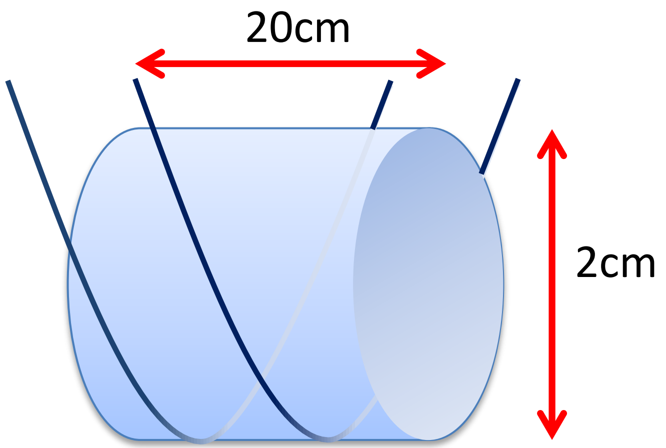
[1]R. Hull, Properties of Crystalline Silicon, The Institution of Engineering and Technology, (1999).

Sensitivity at low temperatures

- Sensitivity under optimal circumstances:
  sample geometry
  → a long rod with a small diameter
  → 20 cm length still fits in our cryostat
- temperature sensor with a resolution about 10 µK
- 5 W laser power

→ 3.5 ppb/cm @ 10K
(0.5 mK temperature rise)

→ scattering light,.. ?



Free carriers absorption dependence

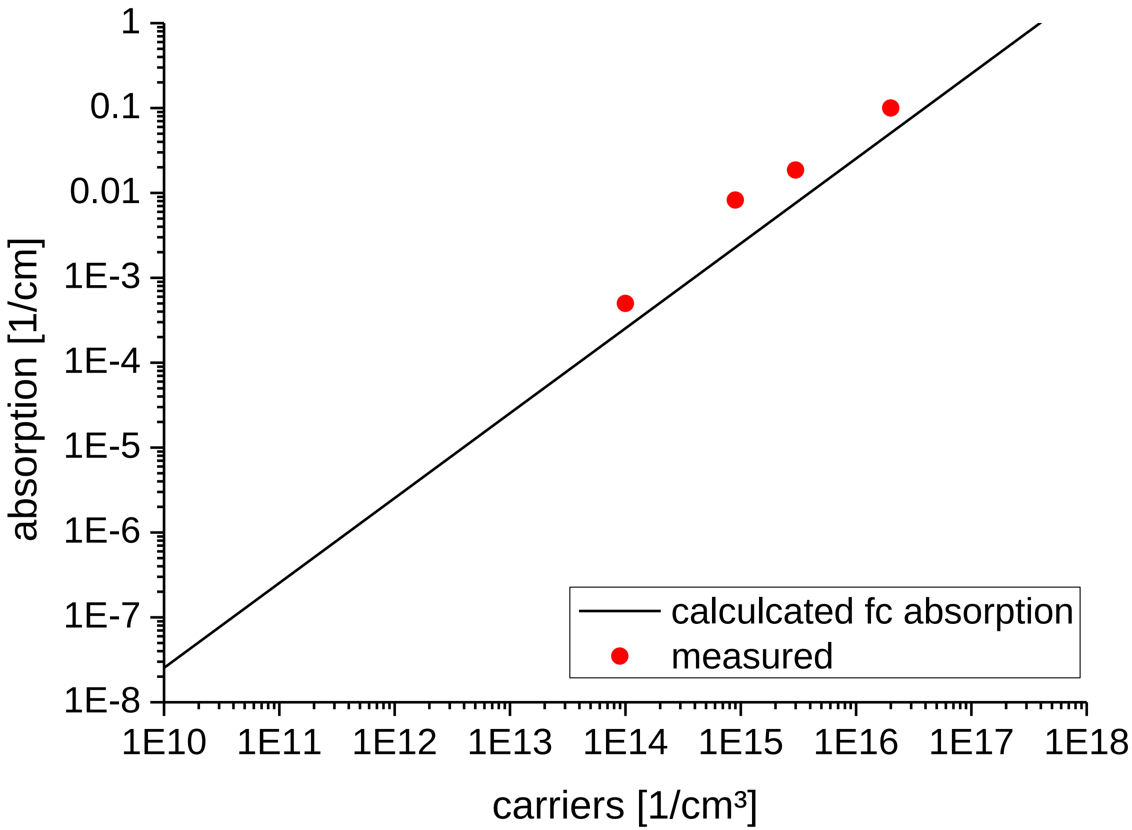
- $$\alpha_{fc} = \frac{N\, e^2}{m^* \varepsilon_0\, n\, c\, \tau} \frac{1}{\omega^2}$$

  number of carriers (N); scattering rate (τ); frequency (ω)

As expected: free carrier absorption rises linear with the amount of free carriers

→ pure silicon samples for low absorption needed (@RT)

→ alternative: compensation

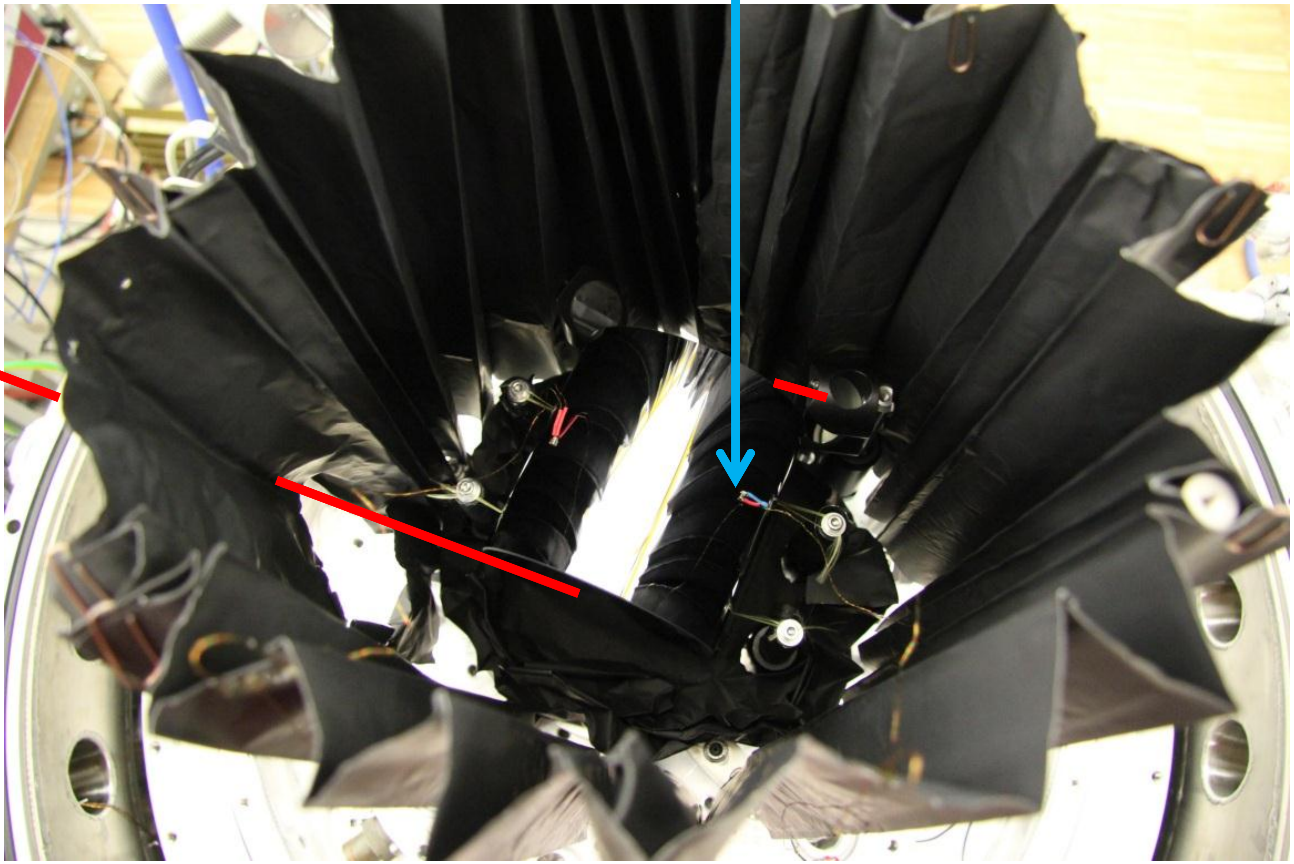


Measurement setup

- Black foil against scattering light

temperature sensor

laser



setup inside the cryostat

Highly doped sample

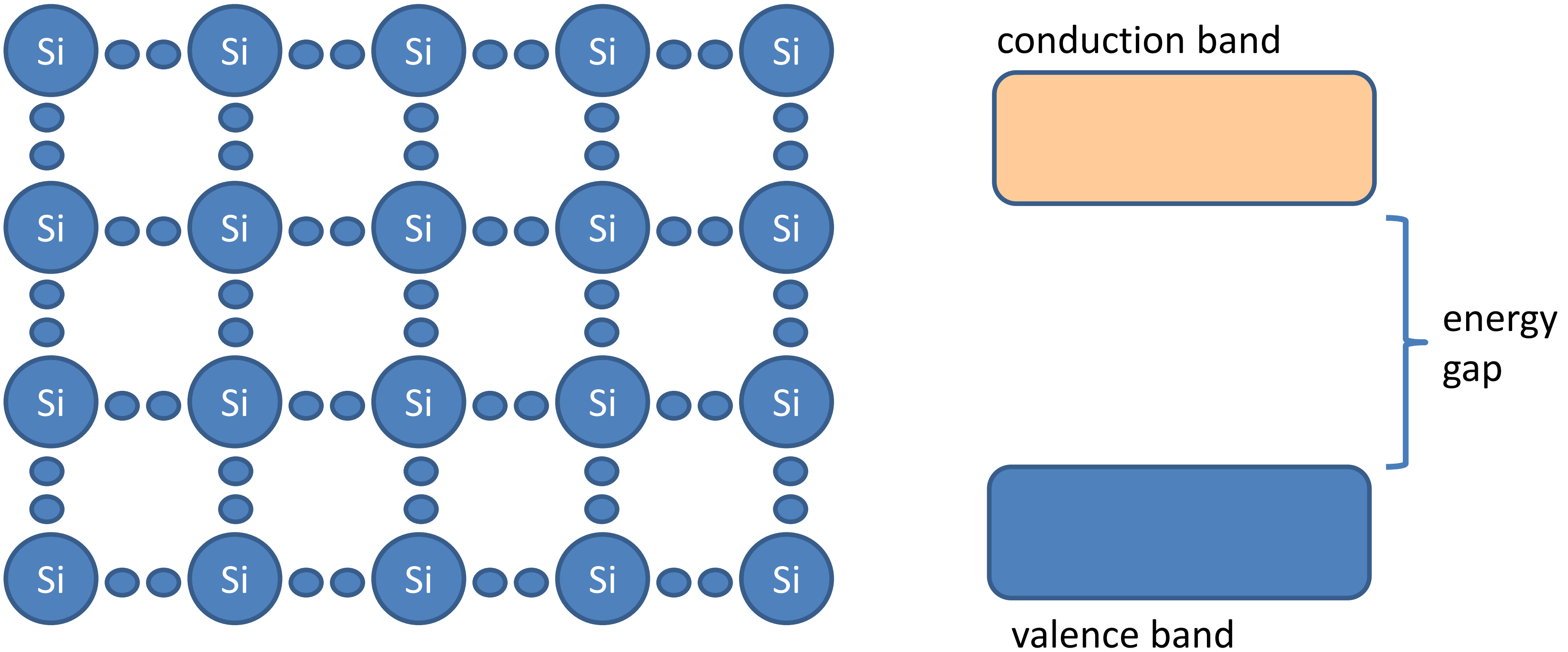
- → check if the calorimetric measurement agrees with transmission measurements
- sample with 200-300 mΩcm resistivity
  → absorption 0.1 1/cm

temperature [K]	measured ΔT [K]	absorption [1/cm]
300	0.020	0.1
100	0.050	0.1
6	3.96	0.1

→ no temperature dependence between 6 and 300 K

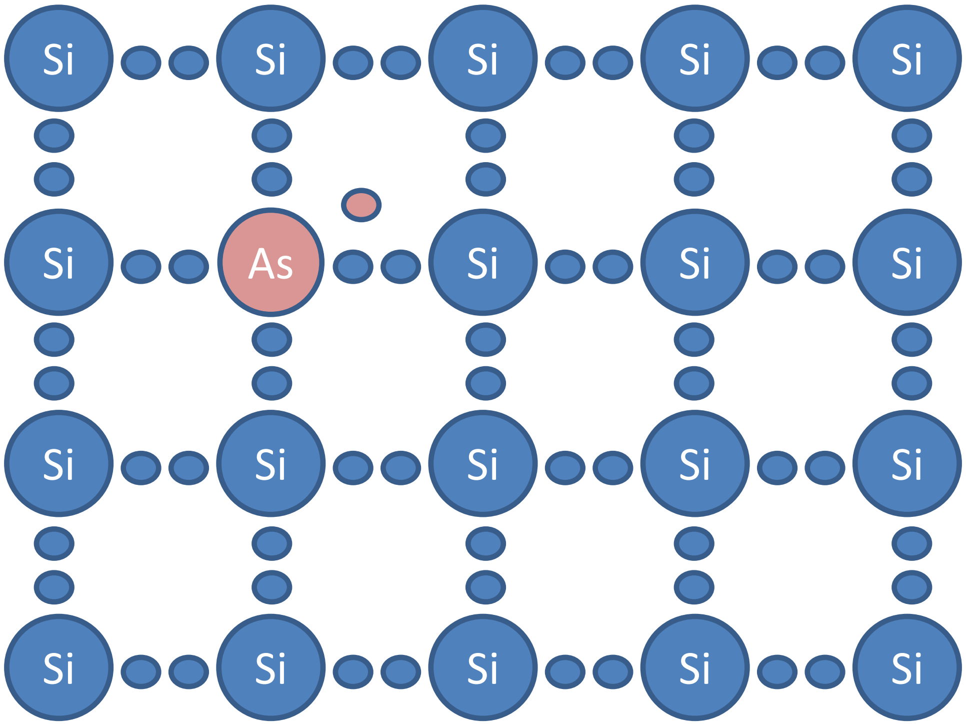
Influence of doping

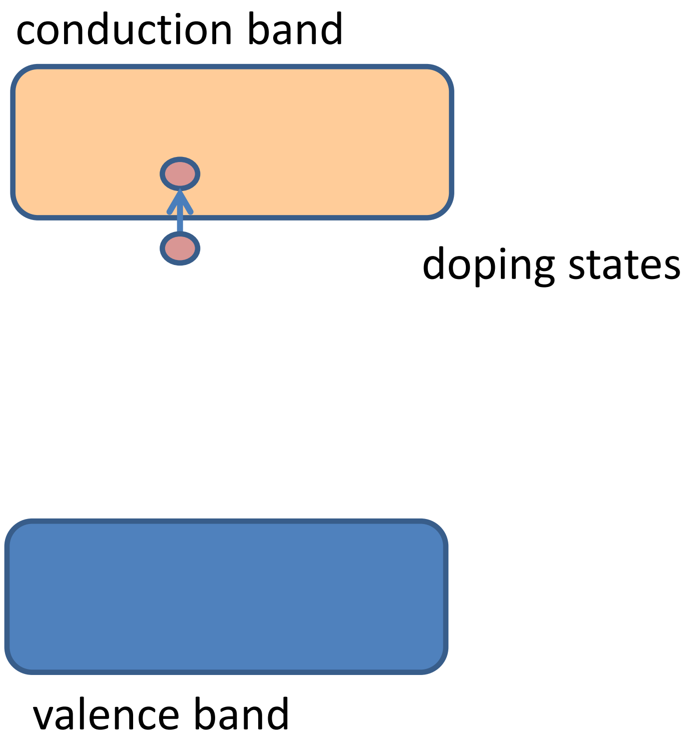
- undoped silicon crystal



Influence of doping

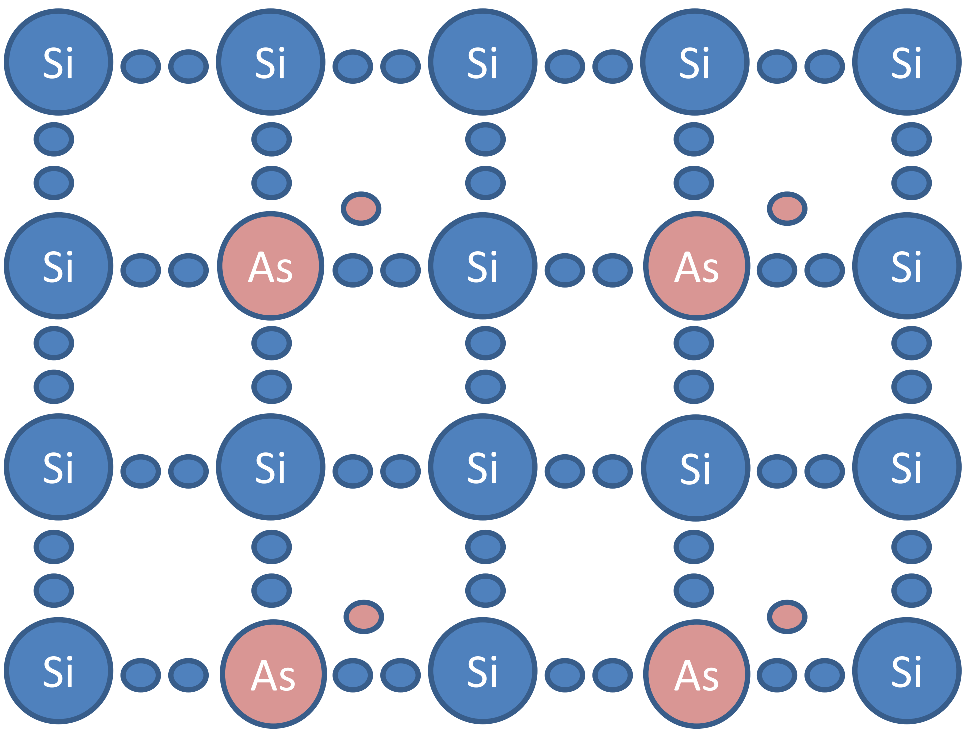
- n-doped silicon crystal
- thermal activated carriers

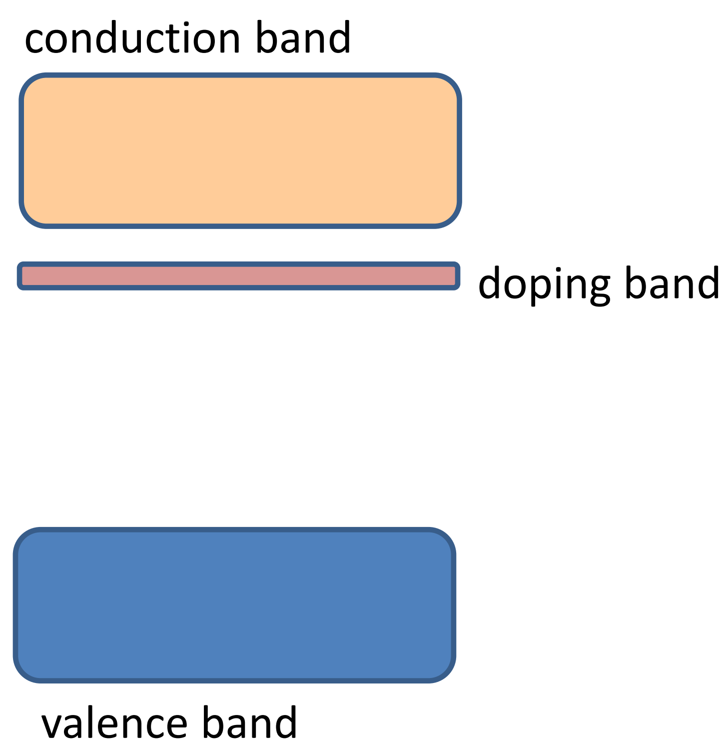




Influence of doping

- highly doped silicon crystal → degenerate semiconductor
- overlap of the impurity wave functions
- always free carriers inside the conduction band → metal like behavior





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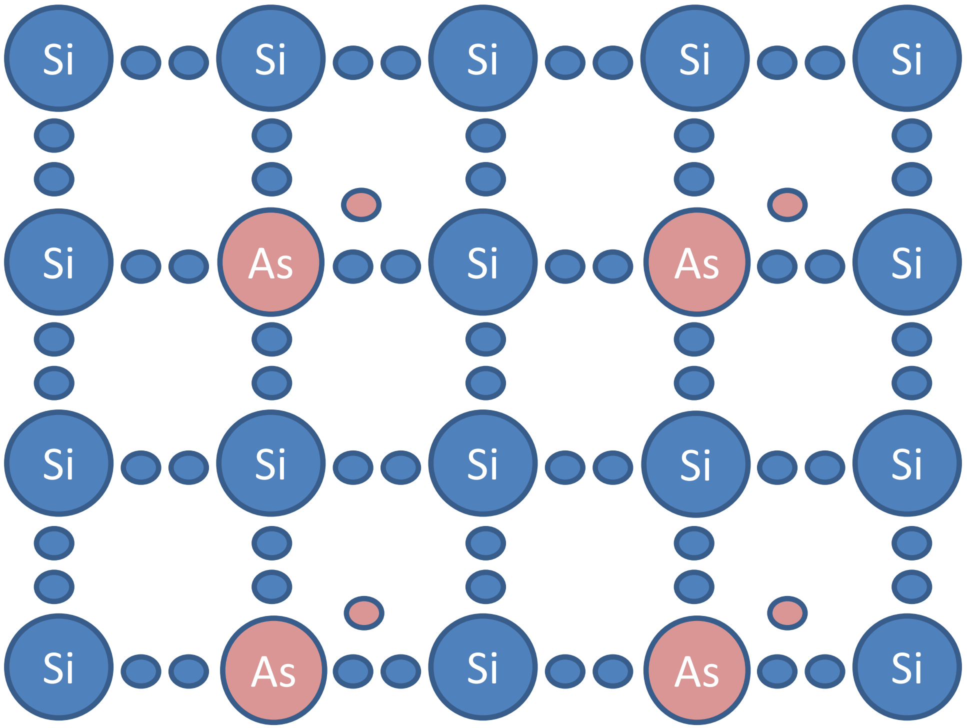
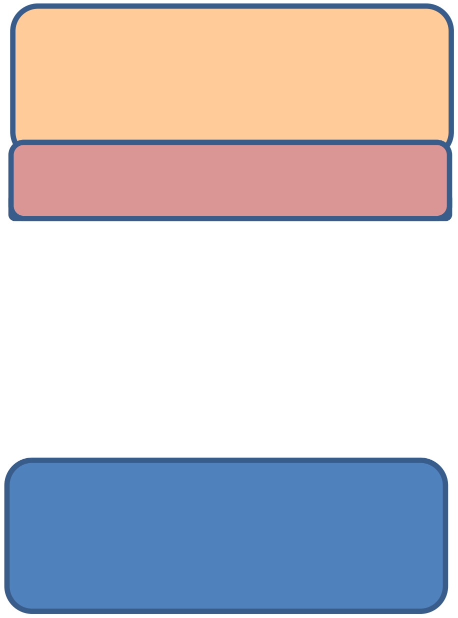
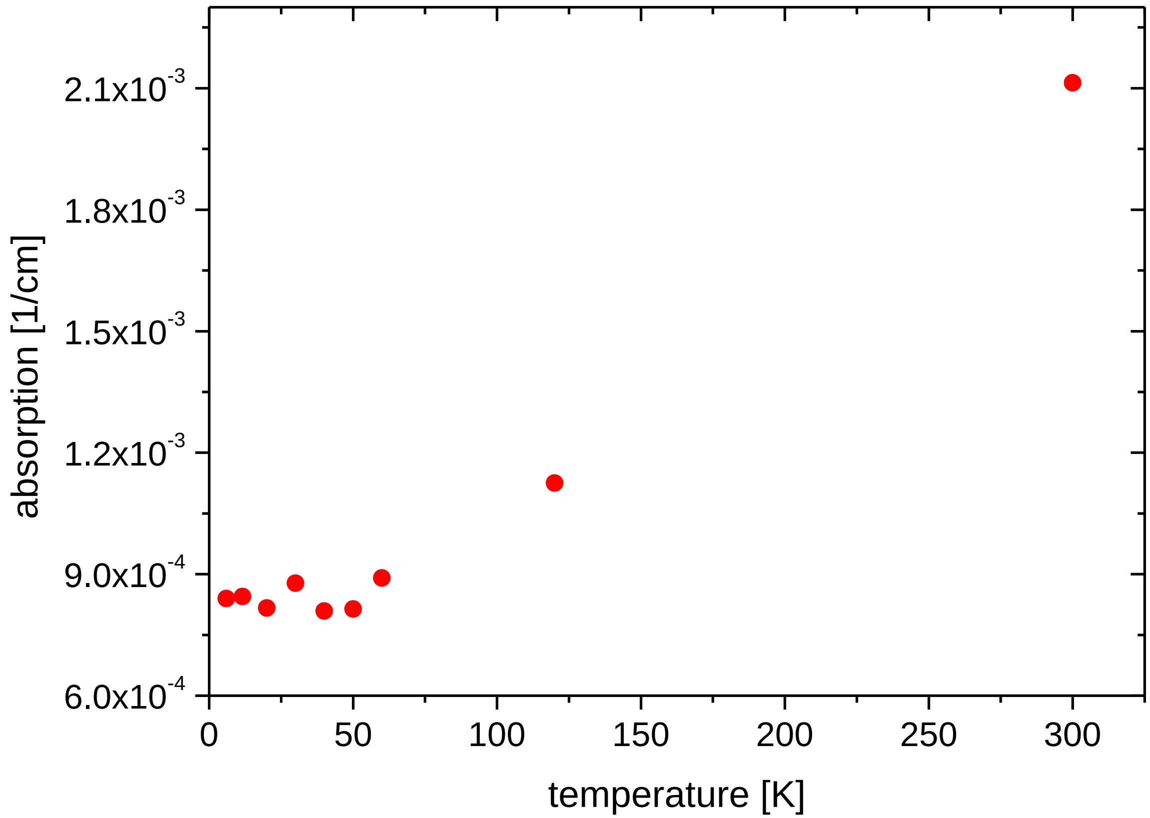


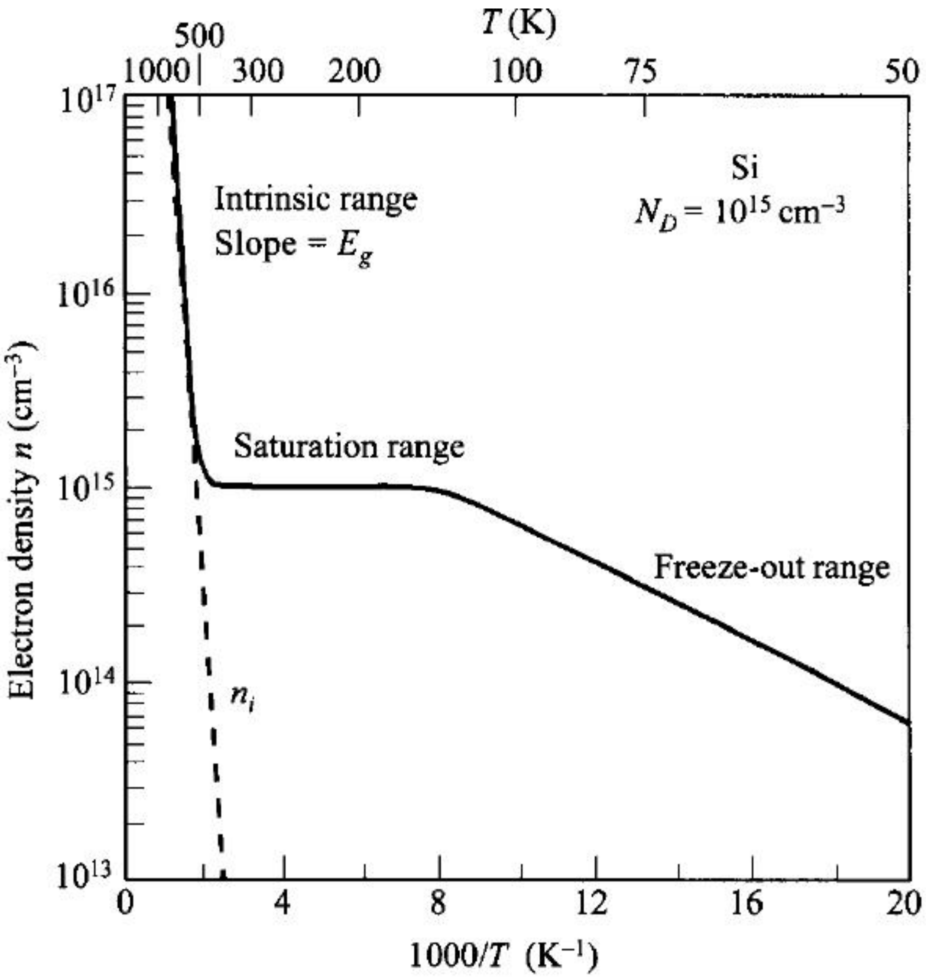


temperature dependence

- dia. 150x86 mm, 100 Ωcm
- → absorption $2{\cdot}1\times10^{-3}$ 1/cm @RT, $8.4{\cdot}10^{-4}$ 1/cm @6 K



What do we learn at solid state physics lectures

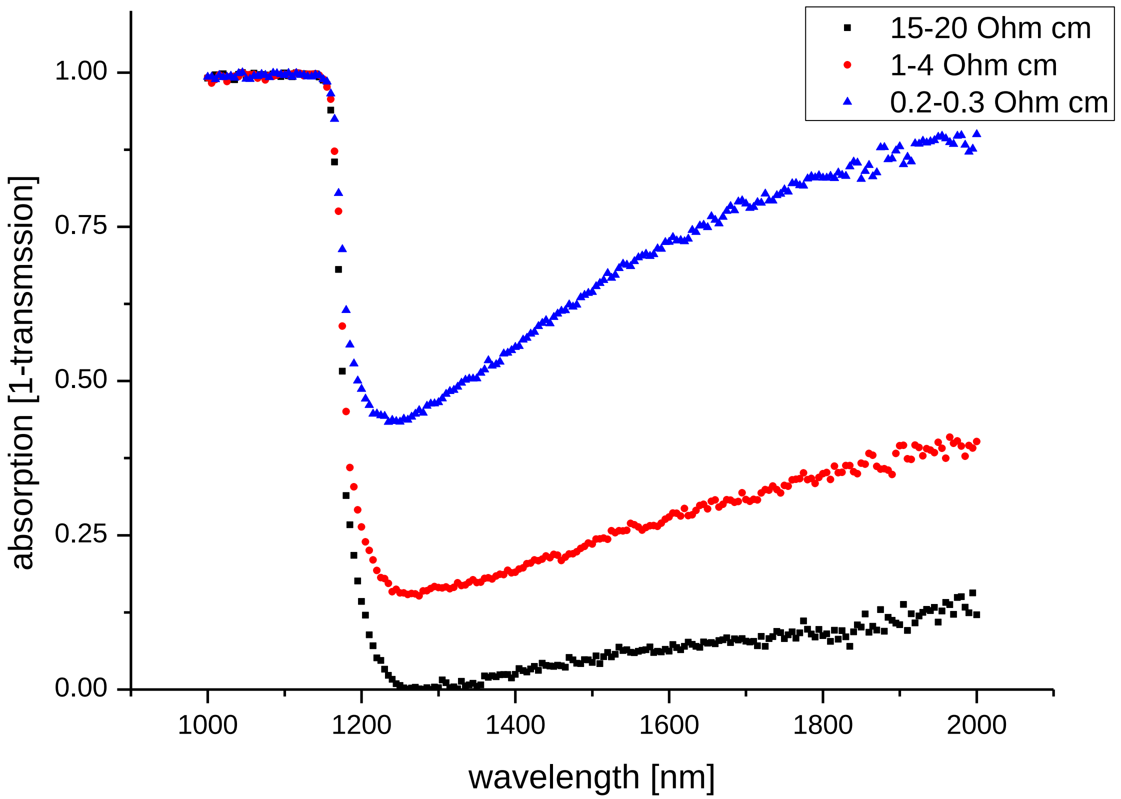


Sze - Physics of Semiconductor Devices

expect: orders of magnitude lower absorption for low temperatures

Doping and wavelength dependence @RT

resistivity [Ω cm]	absorption [1/cm] @1550nm
15-20 Ωcm	$8 \cdot 10^{-3}$
1-4 Ωcm	$2 \cdot 10^{-2}$
0.2-0.3 Ωcm	$1 \cdot 10^{-1}$



for greater wavelength absorption rises

→ 1550 nm laser or smaller wavelength

Summary

- different absorption processes:
  → band band
  → free carrier absorption → absorption 1550nm

- highly doped silicon samples show temperature independent absorption (metal like behavior)
- intra band absorption is linear to the amount of free carriers

- absorption rises for greater wavelength (above the gap)

- → next step: temperature dependent electronic characterization (can we freeze out carriers ?)