Optical properties of silicon at low temperatures

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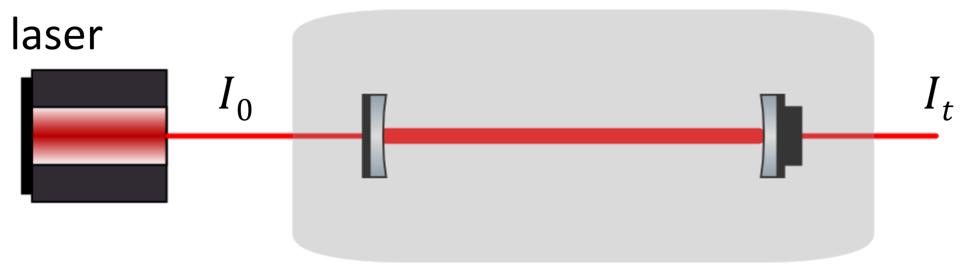
Outline

- motivation
- temperature dependence of the refractive index of silicon
  - measurement principle and experimental setup
  - acquired data
  - results
- outlook : absorption measurements

Motivation

- silicon is one material of interest for optical components for future detectors
- n, dn/dT for low temperatures are unknown, but needed for noise calculations
  - for example in the ET design study there are only extrapolated values for temperatures below 30 K
- for the design of the cryogenic parts of future detectors the optical absorption is needed (thermal equilibrium)

Fabry Perot Cavity (FPC)



- for a FPC the reflected light is:

$$\mathrm{I_r} = \frac{I_0}{1 + \pi^2 / 4F^2 \sin^2\theta}, \quad \theta = \frac{2\pi n l}{\lambda}$$

l…cavity length, F … finesse of the FPC, λ …wavelength

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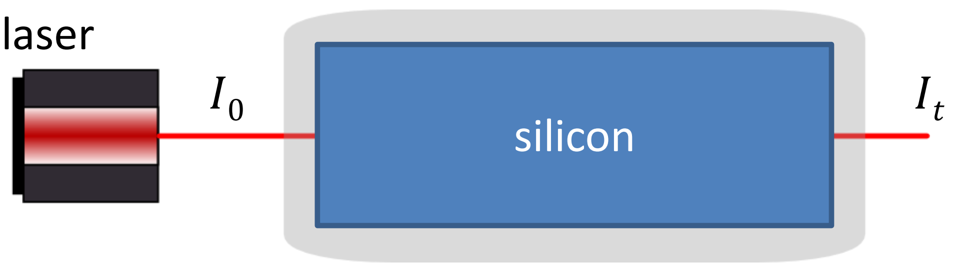

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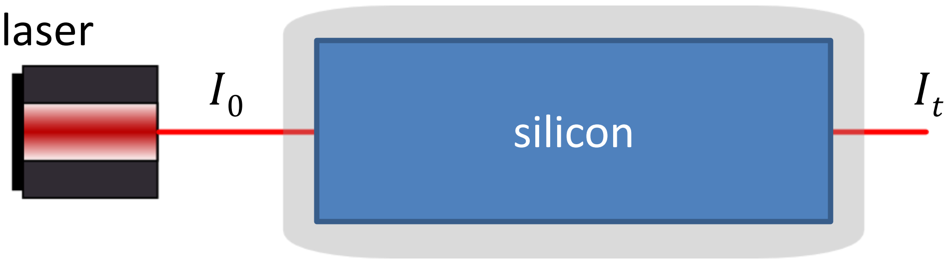

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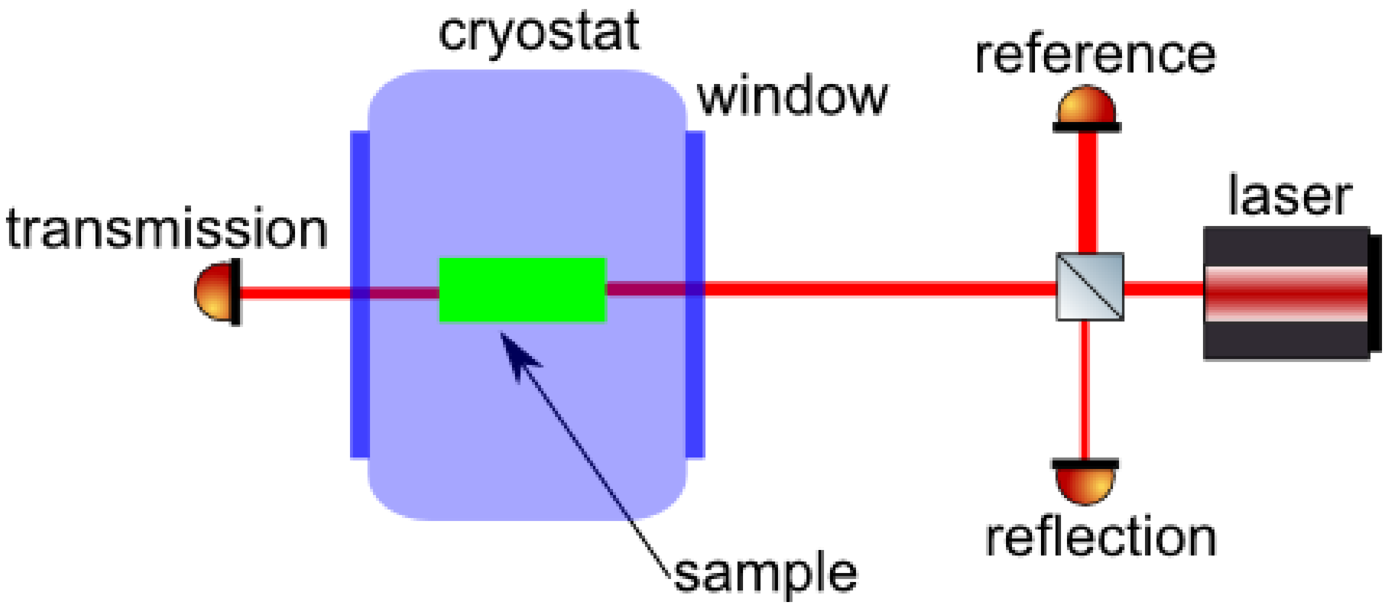
optical path length

geometric path length

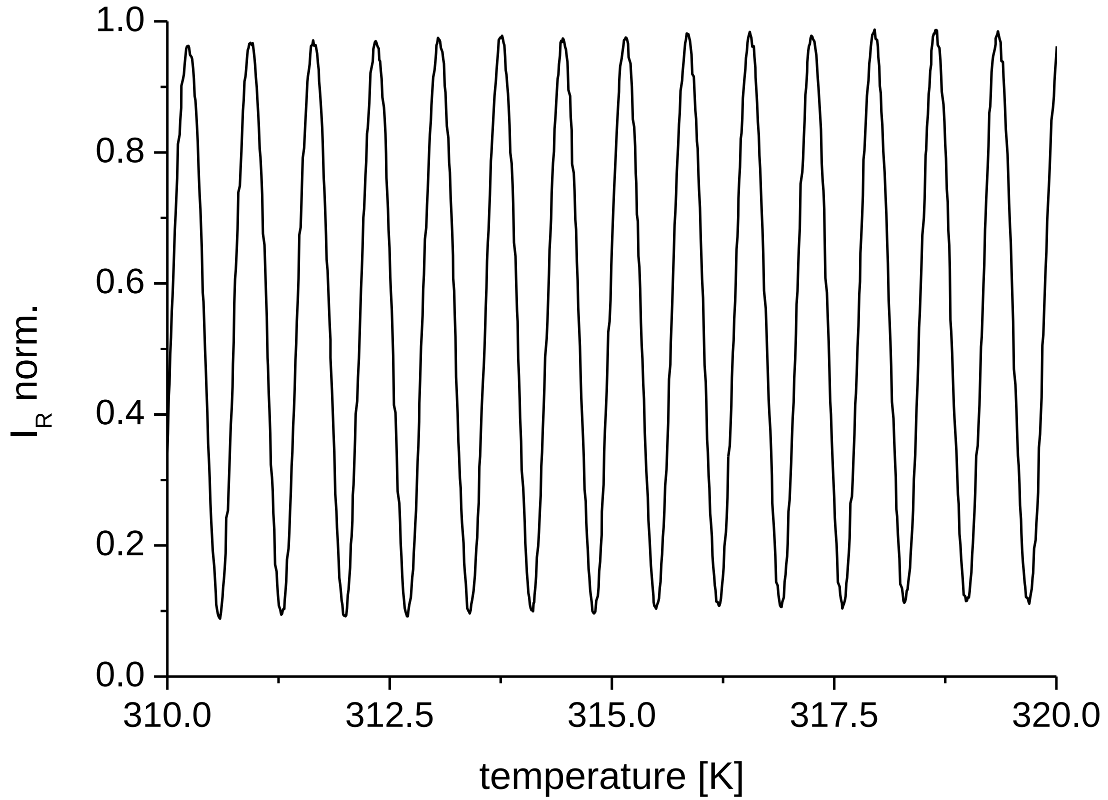
l…cavity length, F … finesse of the FPC, λ …wavelength

Setup for dn/dT measurement



- with the continuous helium flow cryostat it is possible to measure from <4 K up to 325 K
- sample thickness: 0.3 … 14 mm

Data at room temperature



typical data from the measurement at RT

Extracting of dn/dT from exp data

- remember: $\mathrm{I_r} = \frac{I_0}{1+\pi^2/\,4F^2\sin^2\theta}, \qquad \theta = \frac{2\pi n l}{\lambda}$

- for the analysis θ is the term of interest.

- $\frac{\partial \theta}{\partial T} = \frac{2\pi}{\lambda}\left(l\,\frac{\partial n}{\partial T} + n\,\frac{\partial l}{\partial T}\right) = \frac{2\pi l}{\lambda}\left(\frac{\partial n}{\partial T} + n(T)\alpha(T)\right)$

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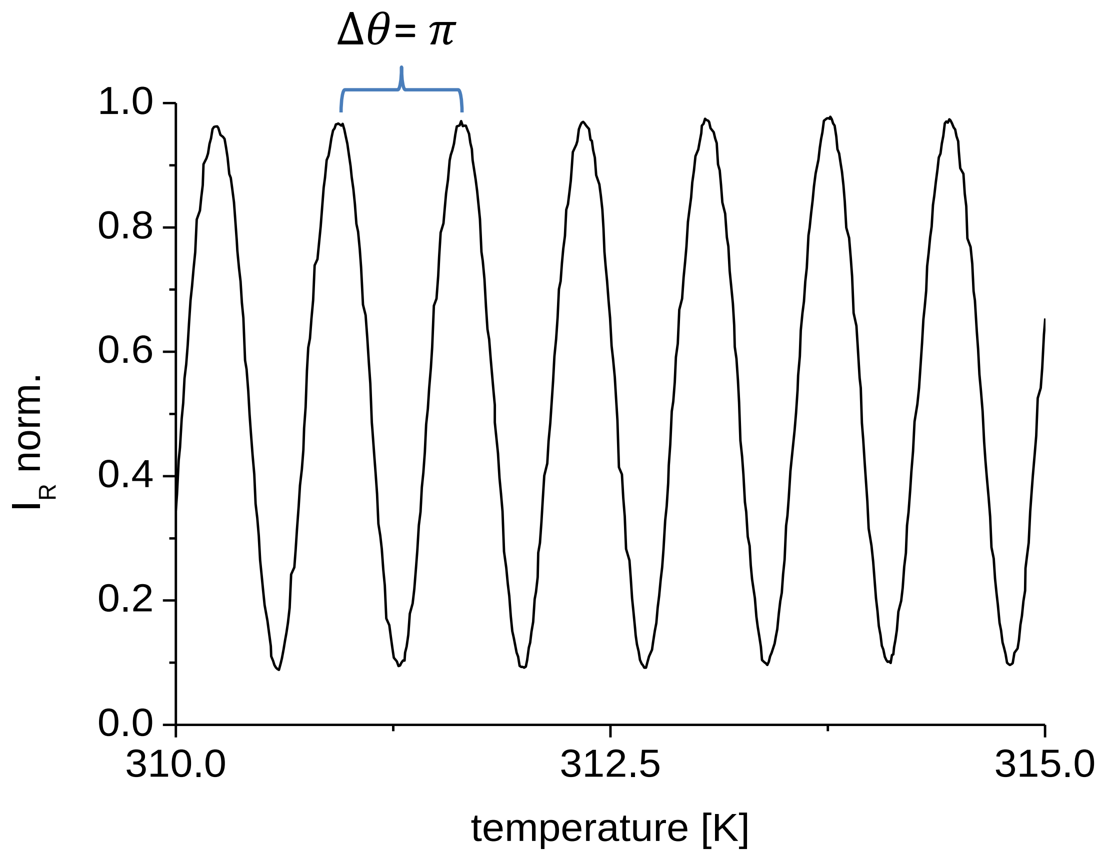
Extracting of dn/dT from exp data

interference maximum $\leftrightarrow \Delta\theta = \pi$

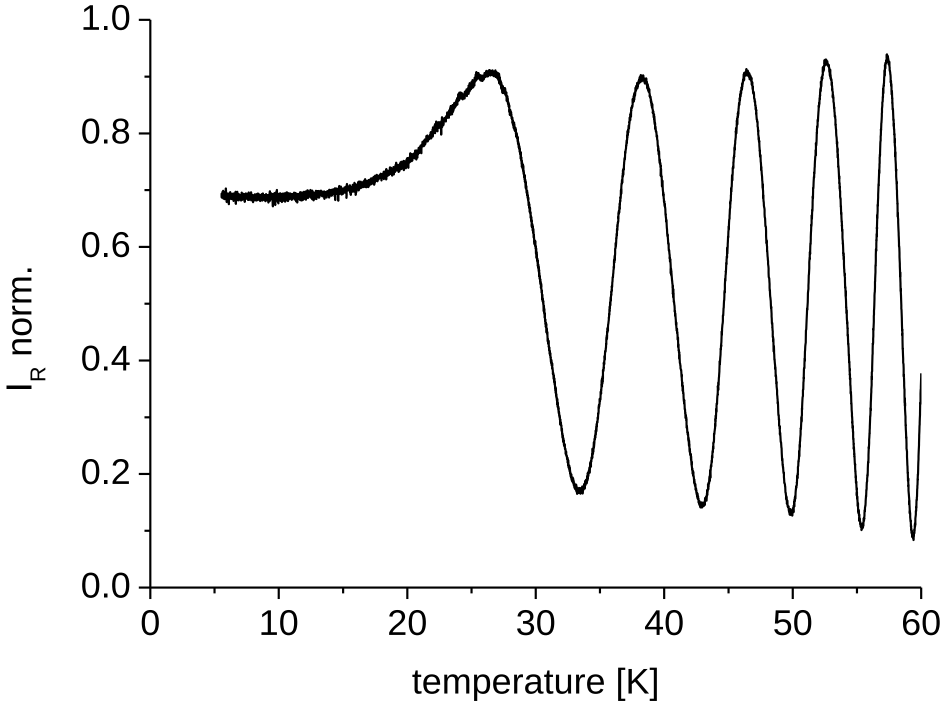
$$\rightarrow \frac{dn}{dT} = \frac{\lambda}{2l\,\Delta T} - \mathrm{n(T)}\alpha(\mathrm{T})$$

$\approx 1\times10^{-4}$ 1/K $\approx 1\times10^{-6}$ 1/K

$(l = 14\ mm, T = 300\ K)$

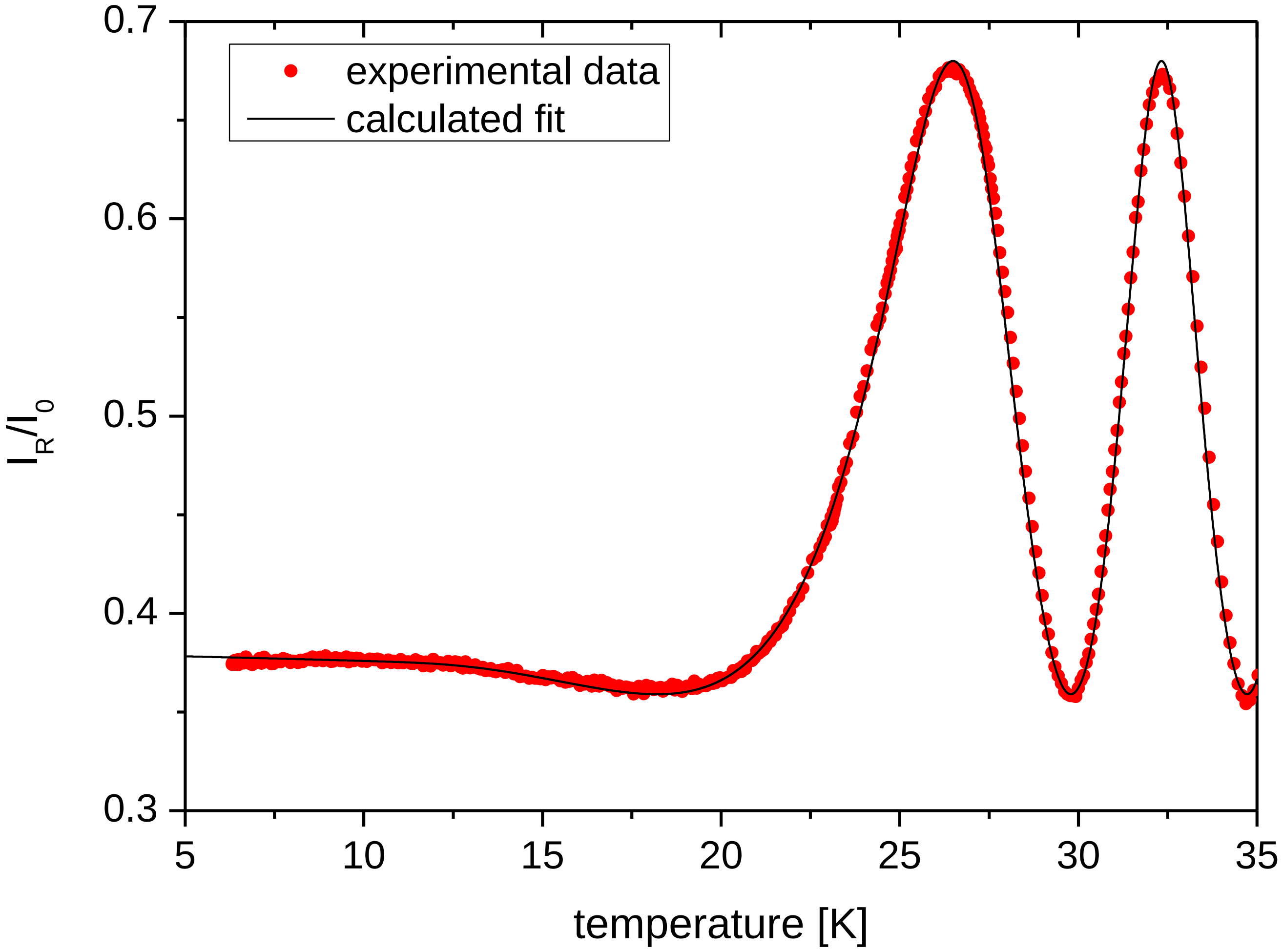


Data at low temperatures

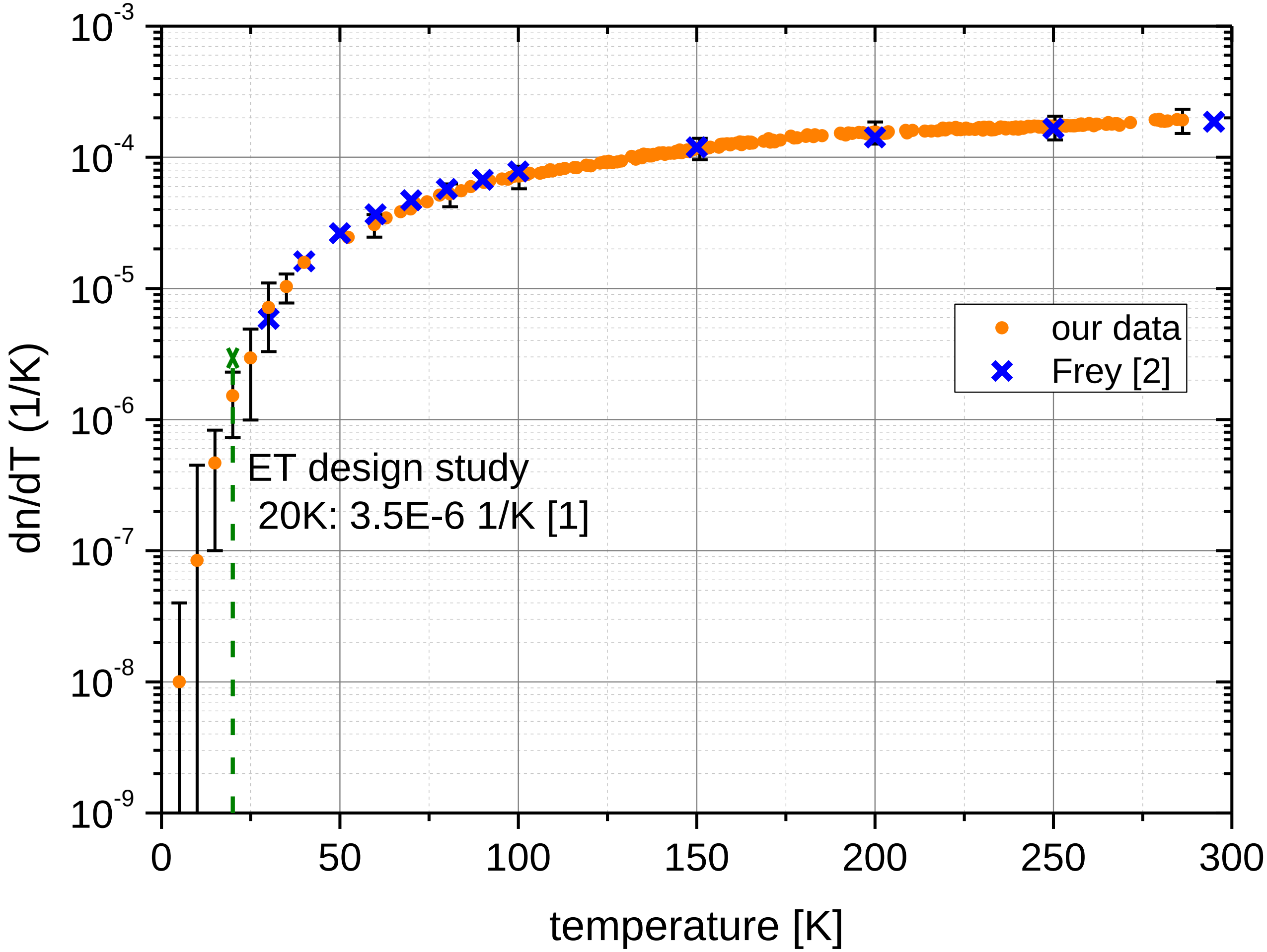


- problem: only a small change of n at low temperatures → only a few fringes
- dn/dT → 0 for T → 0 (3rd law of thermodynamics)

Extracting of dn/dT from exp data

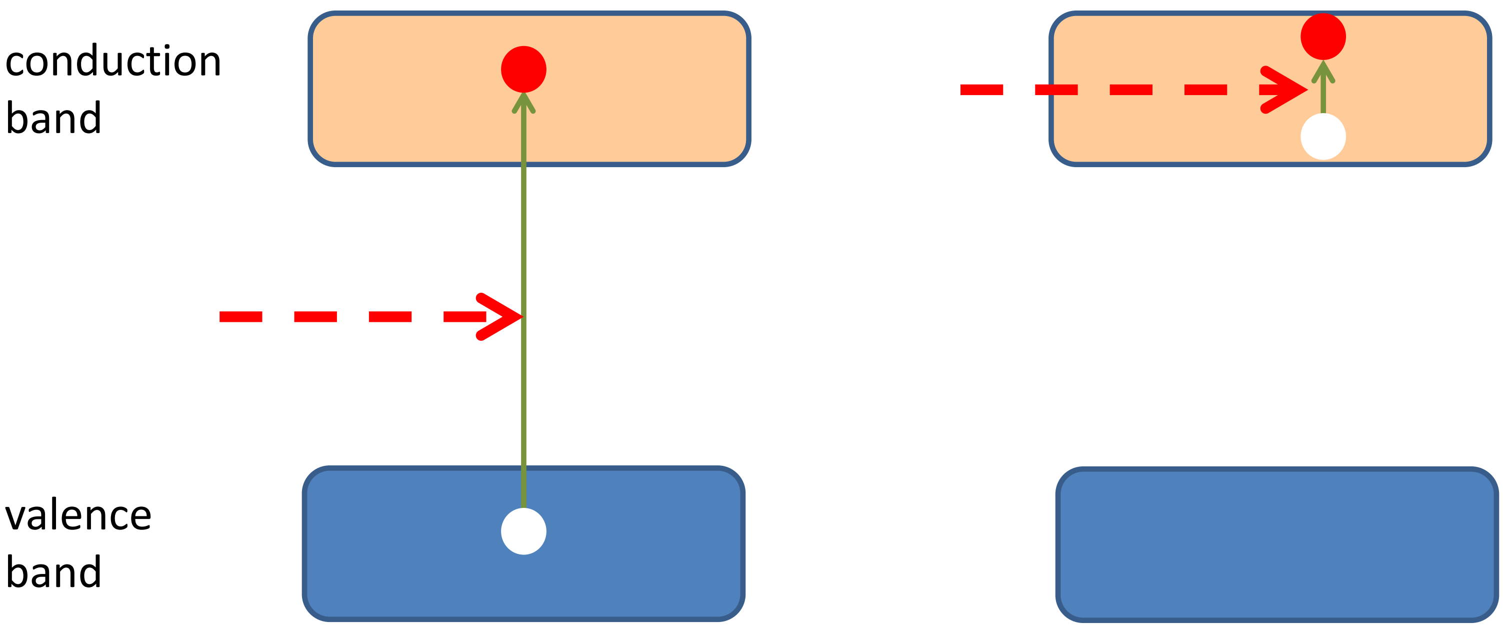


Results for dn/dT



[1] The Einstein gravitational wave Telescope conceptual design study
M. Abernathy et al.
[2] **Temperature-dependent refractive index of silicon and germanium**
Bradley J. Frey et al.

Band-band and free carrier absorption

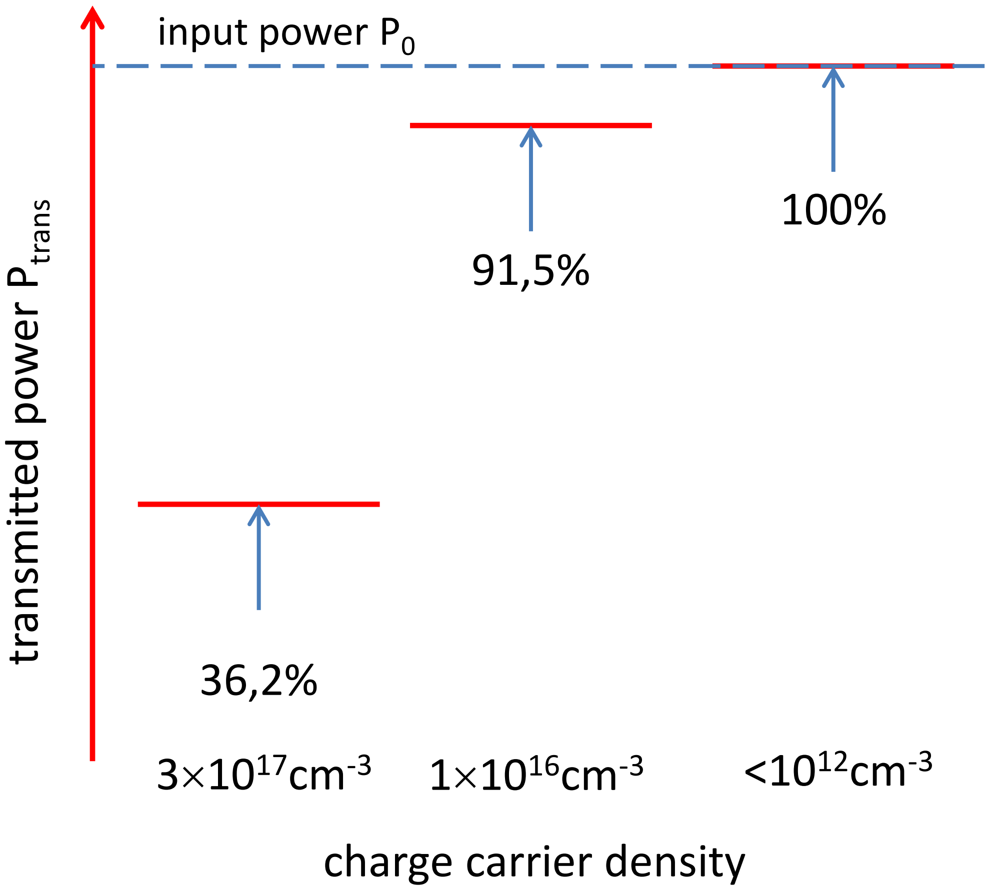


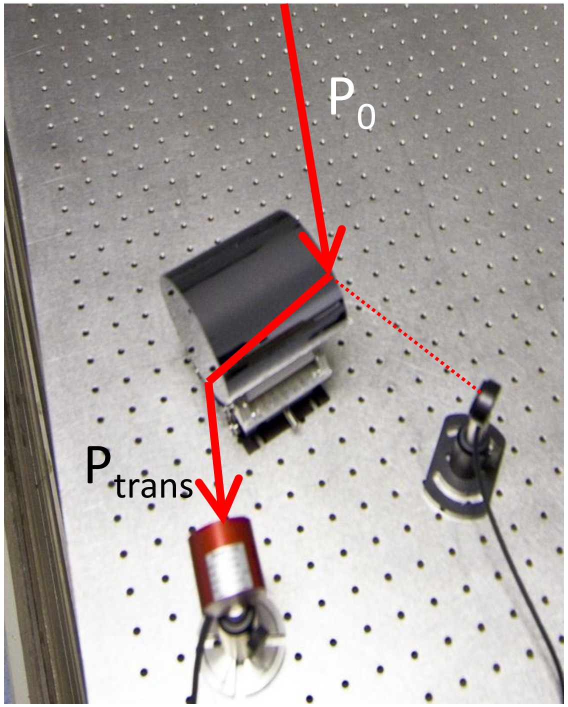
inter band absorption
(band-band abs.)

intra band absorption
(free carrier abs.)

Absorption measurement in brewster angle

- room temperature test for the absorption of different Si samples





Summary

- dn/dT was measured over a wide temperature range (5 … 300 K)

  $\frac{dn}{dT} = 1.5x10^{-6}$ 1/K @20K and $8x10^{-8}$ 1/K @10K

- experimental values are in agreement with values assumed for the ET design study

- free carrier absorption is the dominant process in silicon @ 1550 nm and 300 K → high purity samples needed

  (free carriers freeze out at cryogenics)

Acknowledgements: This work was supported by the German science foundation within the SFB TR7.