Materials issues for cryogenic interferometric detectors

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- Gravitational Exchange Meeting -

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Overview

- Introduction
- Thermal noise issues
  - Thermal noise in GW detectors
  - Important material properties for thermal noise estimates
- Optical properties of silicon as a candidate material for the Einstein Telescope
- Conclusions and Summary

Introduction

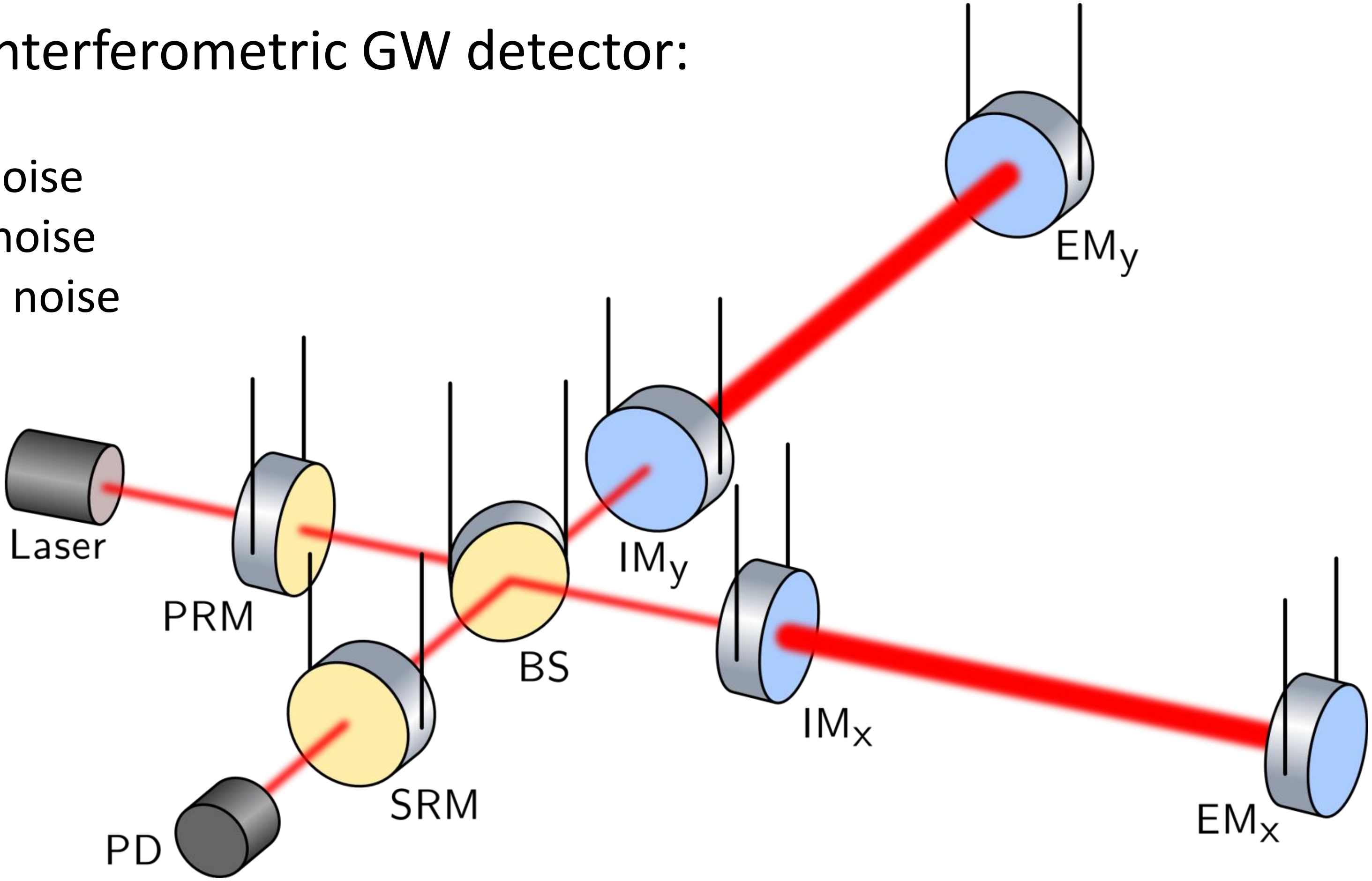
- GW detectors are amongst the most sensitive instruments ever built.
- most limitations: intrinsic noise sources
- technical noise minimized as good as possible

- noise limitations due to:
  - seismic noise
  - thermal noise
  - quantum noise

Noise in interferometric GWDs

simplified interferometric GW detector:

seismic noise
thermal noise
quantum noise



Introduction

- limits of GW detectors
- use of cryogenic temperatures to overcome thermal noise issues

- no feeling for temperature regime → investigations of materials needed as new physics has to be explored

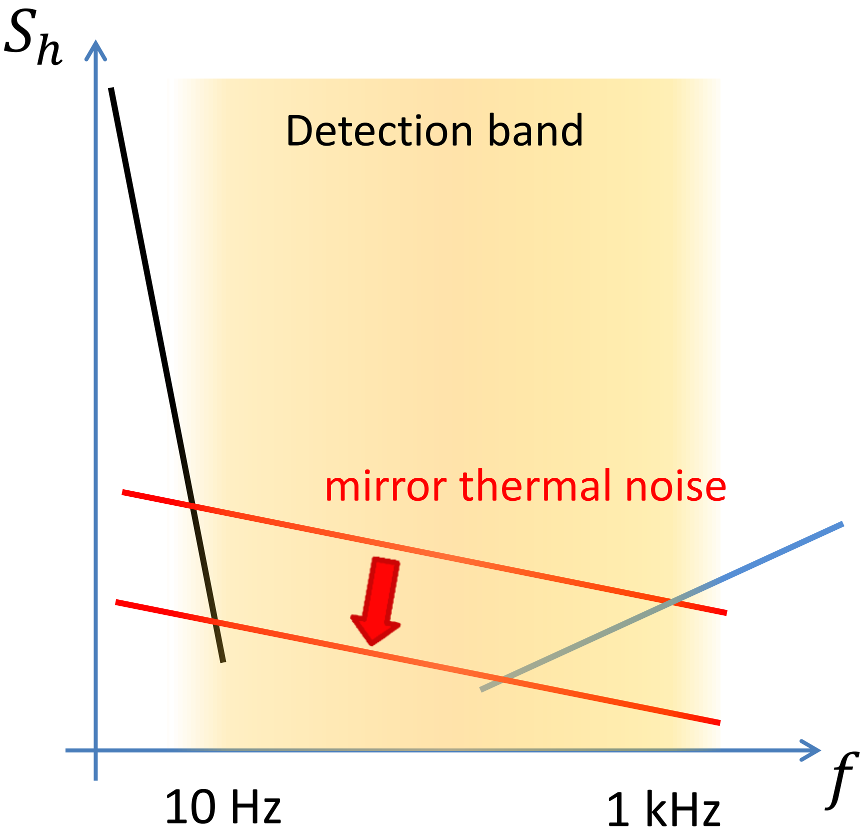
- main issues:
  - thermal noise
  - optical properties (mainly absorption)

Thermal noise in GW detectors

- thermal noise of optical components is a limiting factor at the most sensitive part (together with quantum noise)

- thermal noise of the suspension elements limits the low temperature performance of the detector together with quantum noise

-> 2 aims: reduction + understanding
the sources of noise



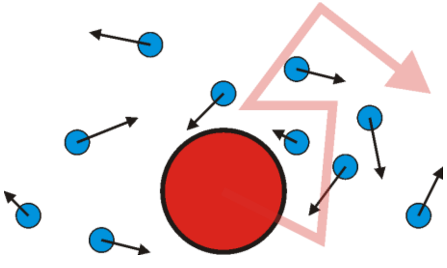
Thermal noise issues

- What is thermal noise for us?
  - „Thermal noise“ throughout this talk does not mean the whole thermal noise of the optics but the part that is seen by the laser beam.

- types of thermal noise
  - triggered by thermal energy $k_B T$
  - triggered by temperature fluctuations δT that couple via temperature dependence of material properties

Thermal noise issues

- Thermal energy triggered noise – Brownian thermal noise



VIDEO
(not included in online version)

- size too large-

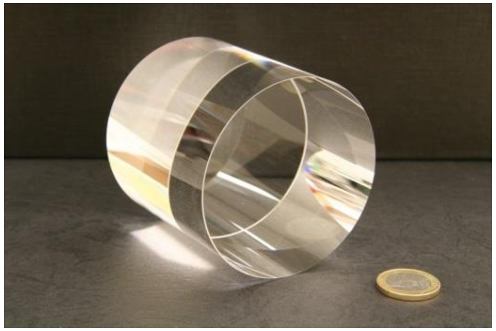
Thermal noise issues

- Thermal energy triggered noise – Brownian thermal noise

- example: thermal noise of a mirror substrate

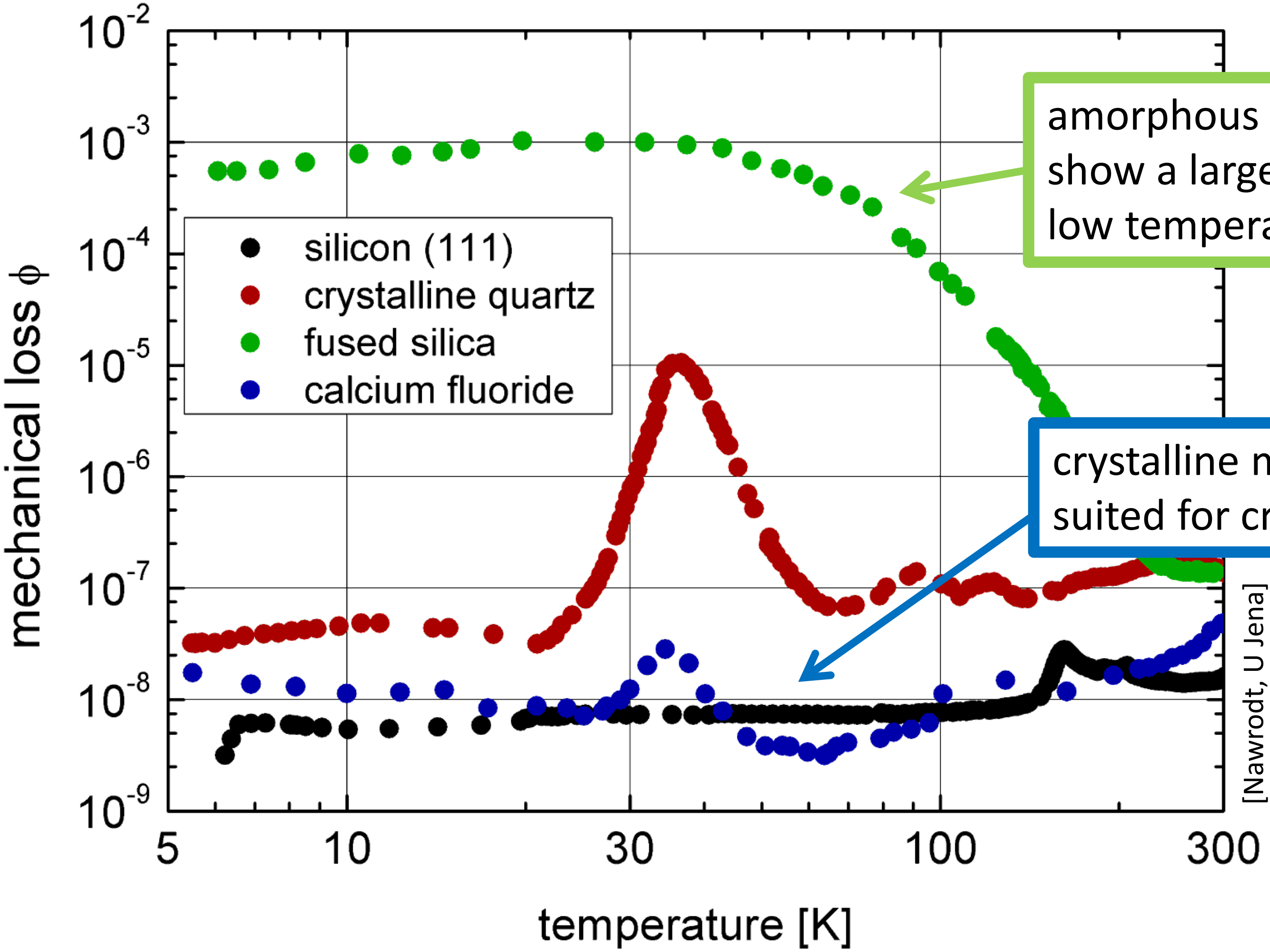
$$S_X^2(f,T) = \frac{2k_B T}{\pi^{3/2} f} \times \frac{1-\sigma^2}{wY} \times \phi_{substrate}(f,T)$$

[Liu, Thorne 2000]



- lower temperature T
- increase beam diameter w
- decrease mechanical loss ϕ

Thermal noise issues



[Nawrodt, U Jena]

amorphous materials show a large loss peak at low temperatures

crystalline materials well suited for cryogenic use

Thermal noise issues

- Temperature fluctuation triggered thermal noise

- mechanism:
  - at given temperature T fluctuation always δT
  - material properties influence read out of laser beam (e.g. coefficient of thermal expansion determines position of surface, refractive index determines phase of transmitted light)

  - Fluctuations of temperature couple directly into the phase read out

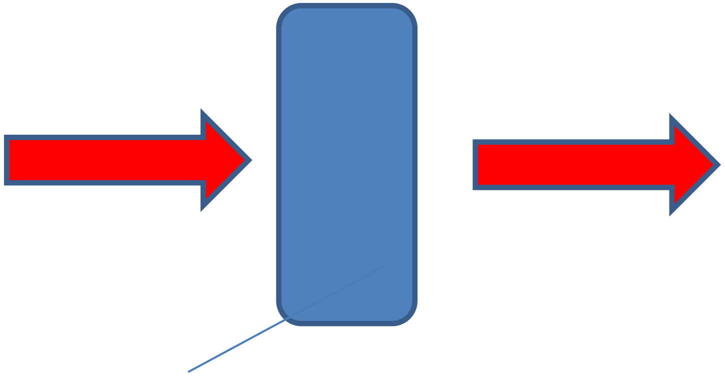
    = noise

Thermal noise issues

- Temperature fluctuation triggered thermal noise

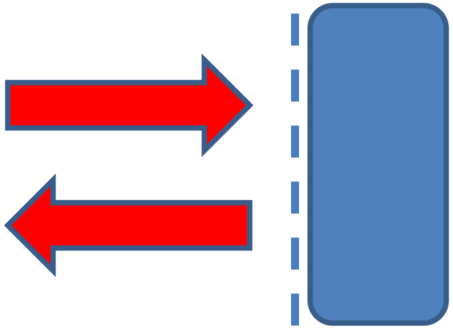
- example:

transmissive optics
(e.g. ITM)



refractive index is temperature dependent (dn/dT)

reflective optics



CTE determines front face

Thermal noise issues

- in both case – cryogenic operation
  - reduction of thermal energy
  - reduction of „coupling coefficients“ by means of 3rd law of thermodynamics

„All temperature dependent parameters become constant towards T = 0 K.“

- However: high laser power desired for reduction of quantum noise → optimization process needed

Thermal noise issues

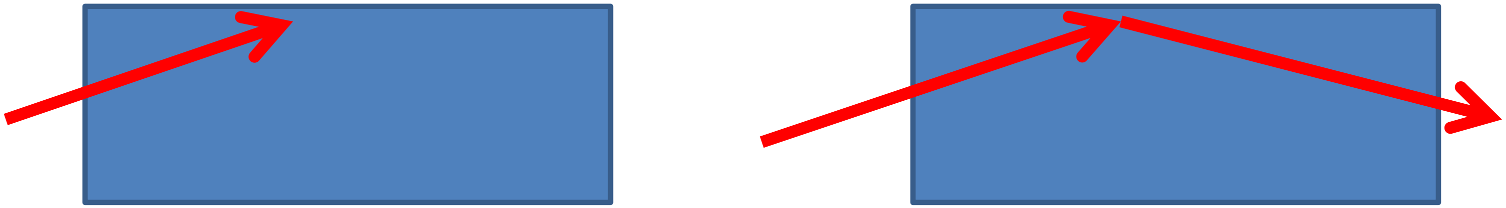
- unknown parameters?
  - thermal parameters
  - mechanical parameters
  - optical parameters

- measurement of these parameters needed
  - thermal conductivity (collaboration with KAGRA people)
  - Q-factor measurements for mechanical loss spectrocopy
  - dn/dT measurement
  - …

Thermal conductivity of Sapphire fibers

- Heat extraction is cruicial for cryogenic operation.
- KAGRA uses sapphire fibers to remove heat from the mirrors.

- example: check of influence of surface quality

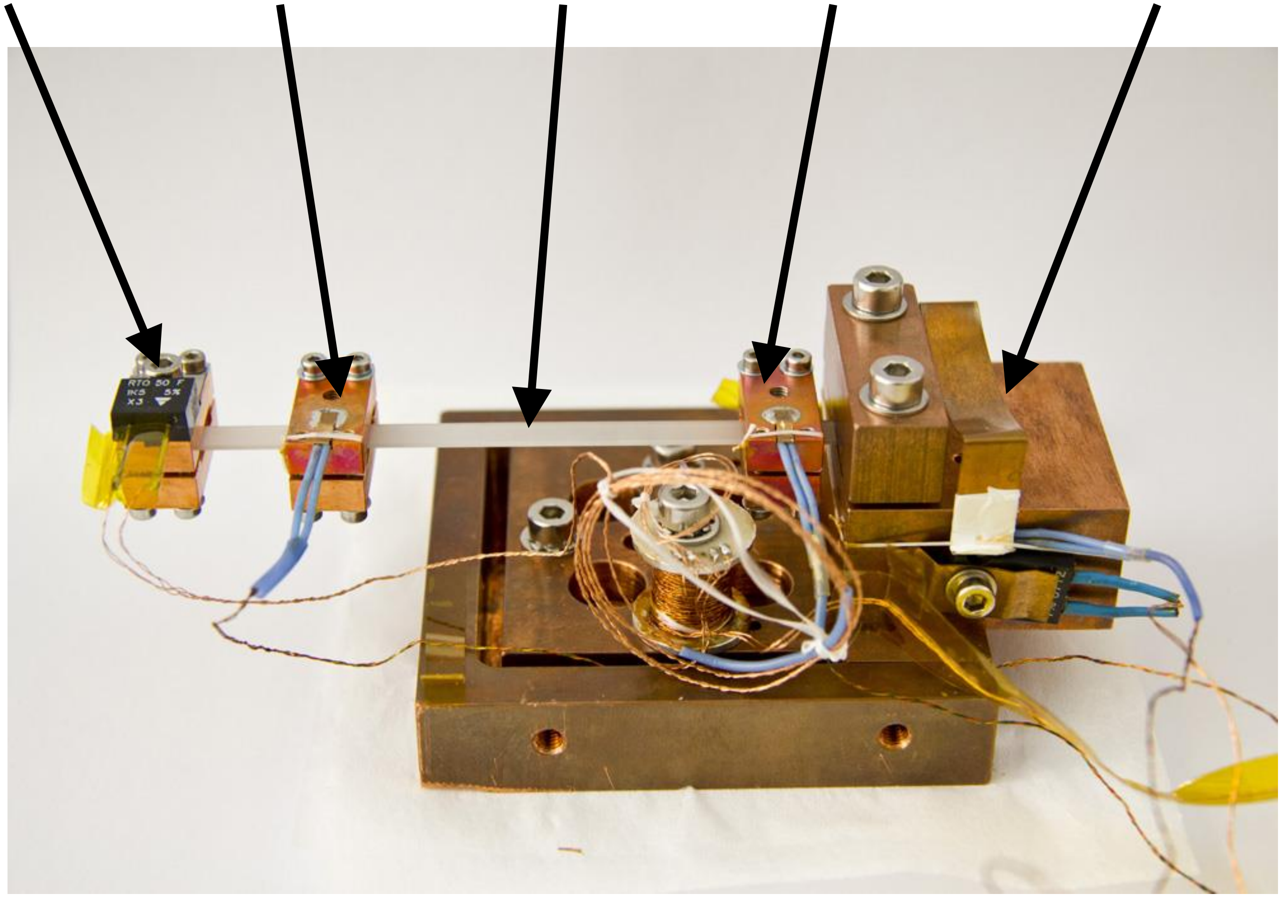


rough surface:
phonon gets scattered at surface

polished surface:
phonon gets reflected at surface

- investigation in collaboration with Nikhef (surface quality) and ICRR (test of nailhead fibres)

Thermal conductivity of Sapphire fibers



Sample Heater

Temperature Sensor 1

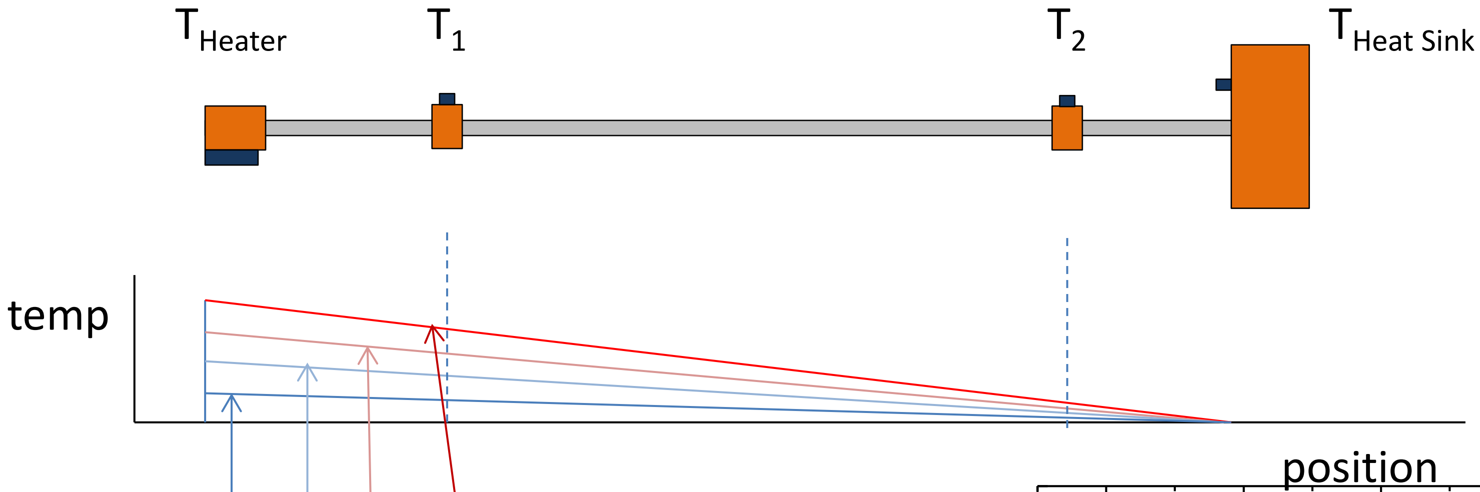
Sample

Temperature Sensor 2

Temperature Controlled Heat Sink

[credits to G. Hofmann, C. Schwarz]

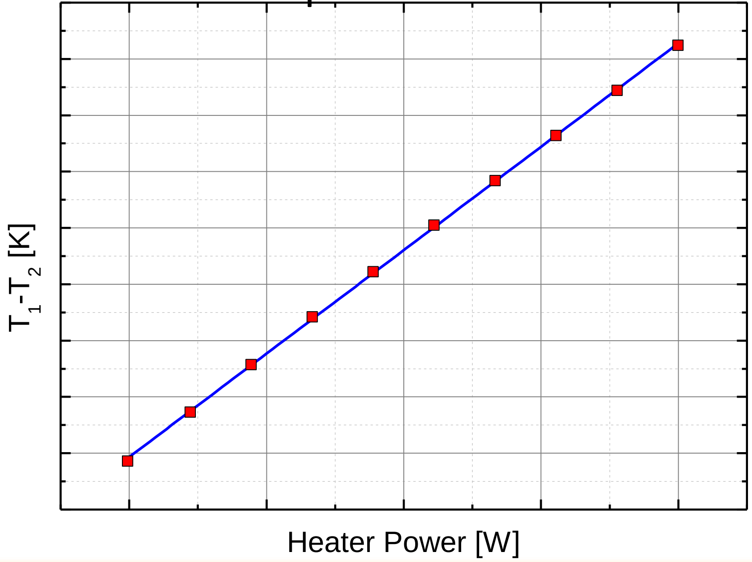
Thermal conductivity of Sapphire fibers



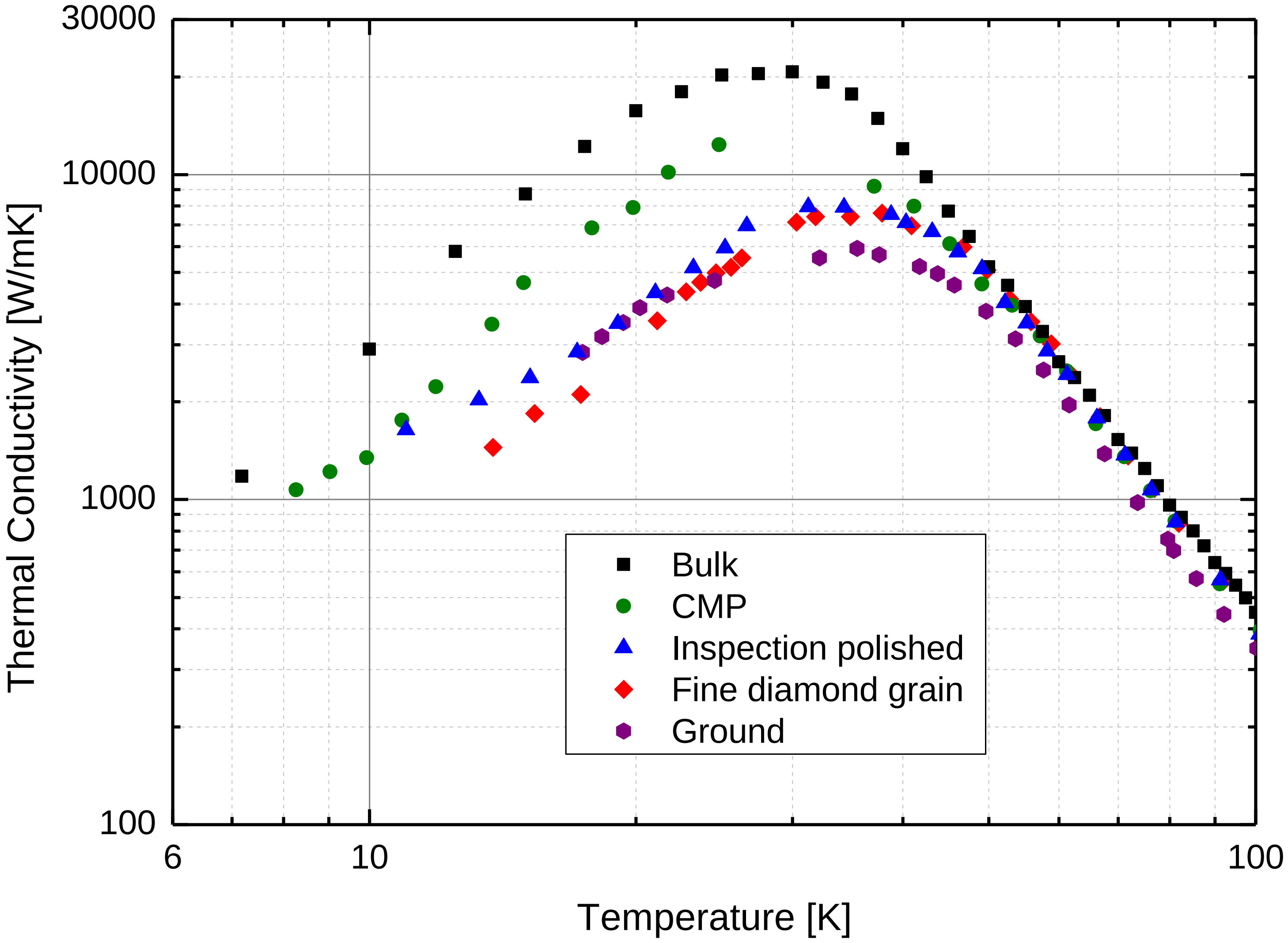
$P_1 < P_2 < P_3 < P_4$

$\Delta T = T_1 - T_2$

$\Delta T_1 < \Delta T_2 < \Delta T_3 < \Delta T_4$

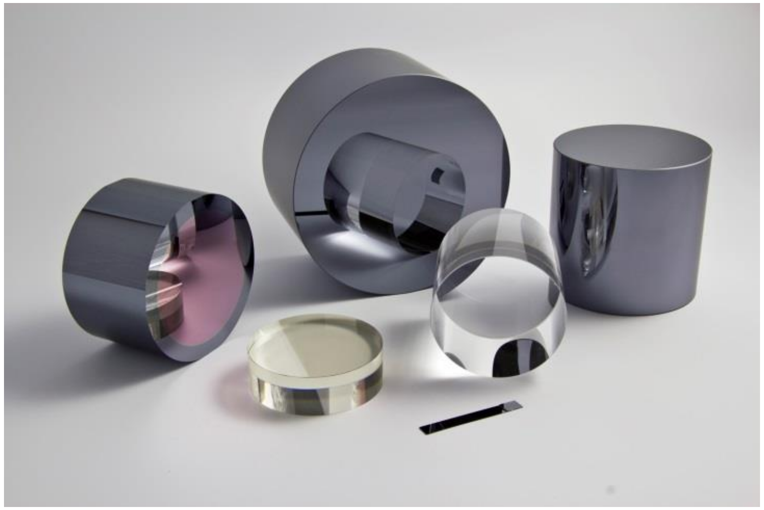


Thermal conductivity of Sapphire elements

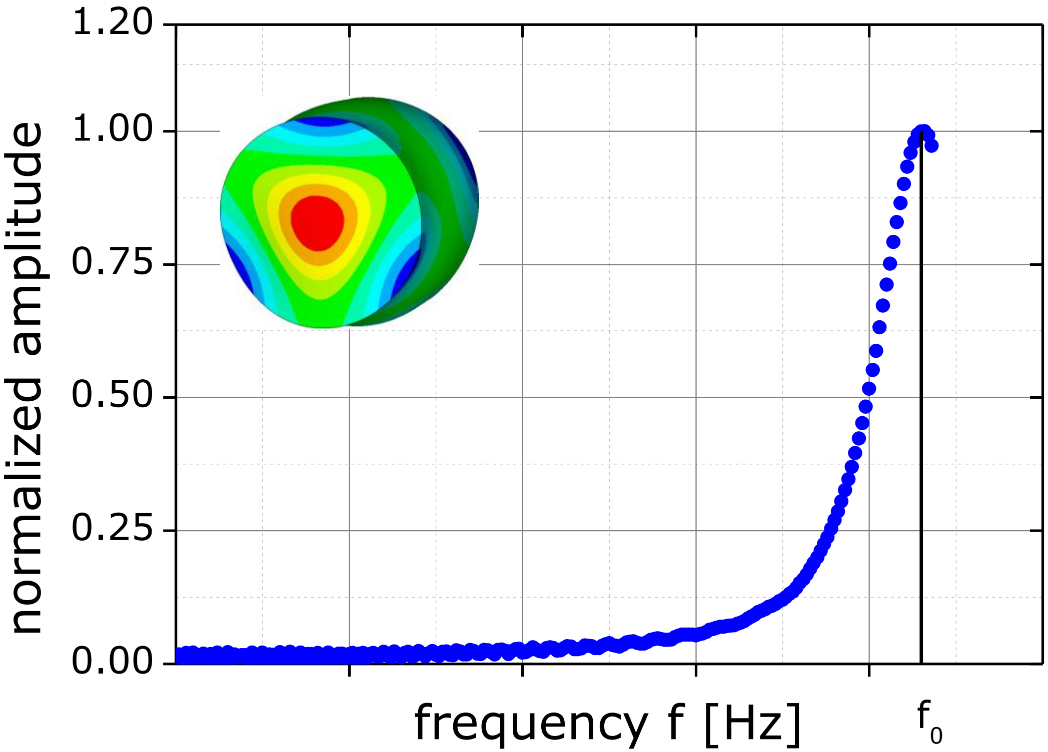


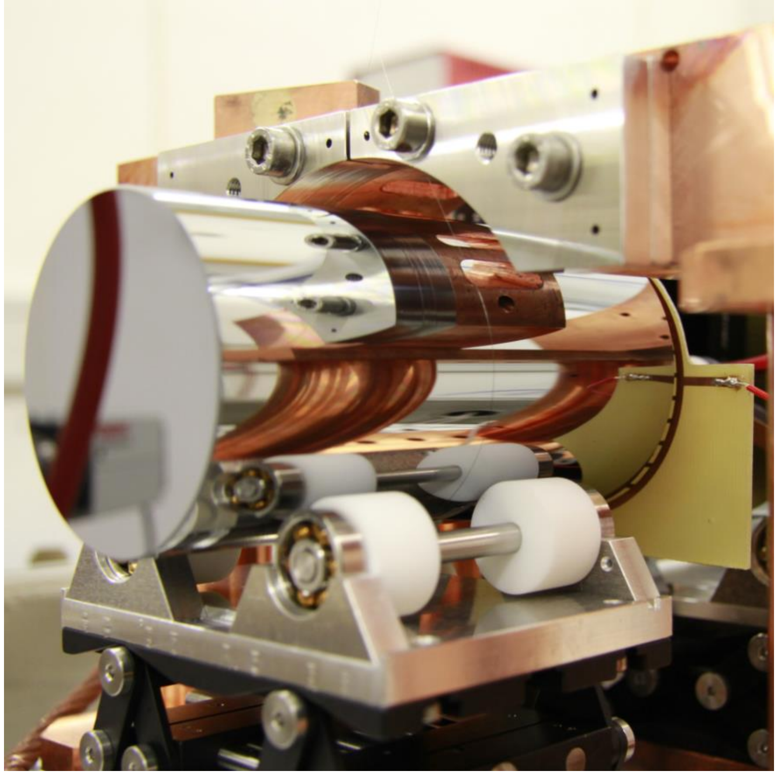
Mechanical loss spectroscopy

- mechanical loss is important parameter for thermal noise estimates, also gives insight into the solid state physics of the sample
- cryogenic mechanical spectroscopy is used to study this parameter

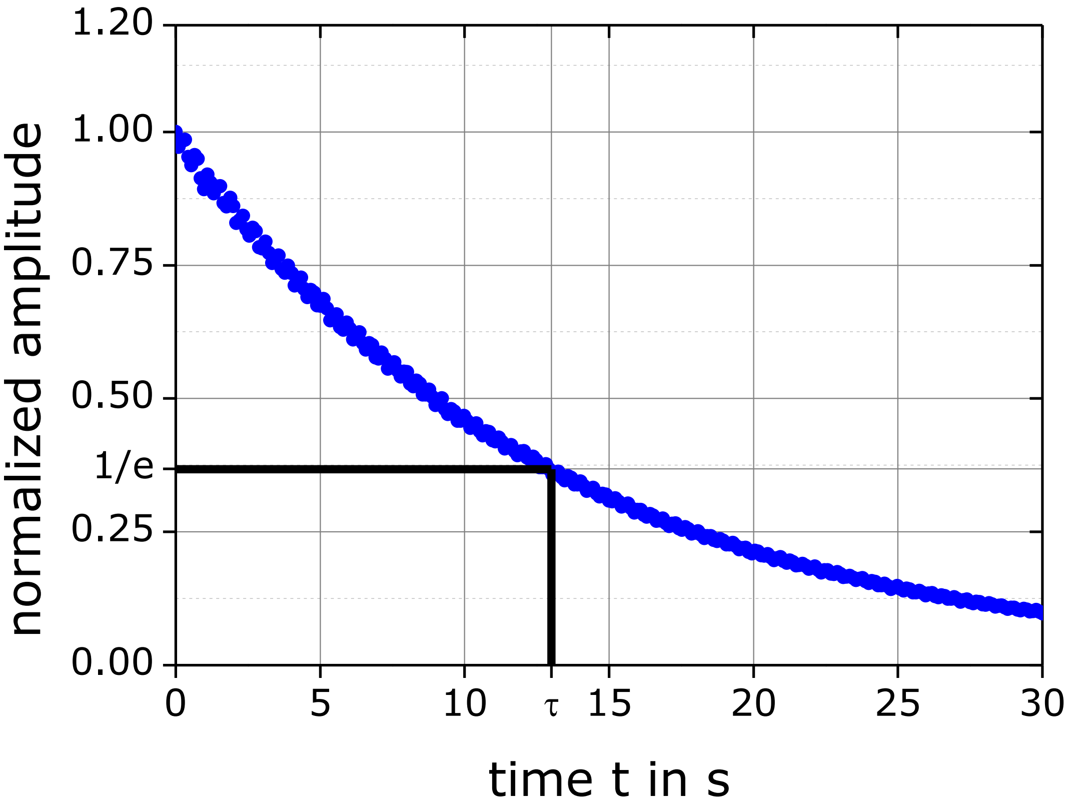


Mechanical loss spectroscopy





Mechanical loss spectroscopy



Freely decaying ring down of the oscillation at f_0:

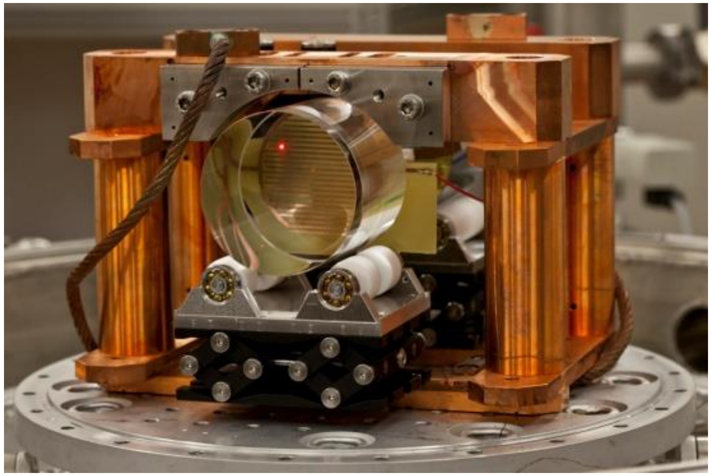
$$x(t) = x_0 \exp\frac{-t}{\tau}\cos\omega_0 t$$

Ratio of dissipated to stored energy per cycle yields the mechanical loss:

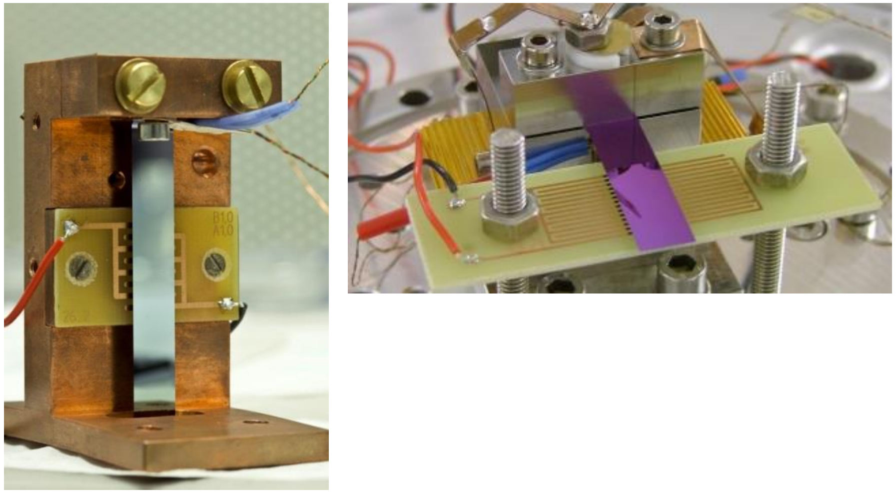
$$\phi = \frac{\Delta E}{2\pi E} = \frac{1}{\pi f \tau}$$

Mechanical loss spectrocopy

- Aim: measuring *intrinsic* loss → avoid external dissipation → sophisticated setups are needed



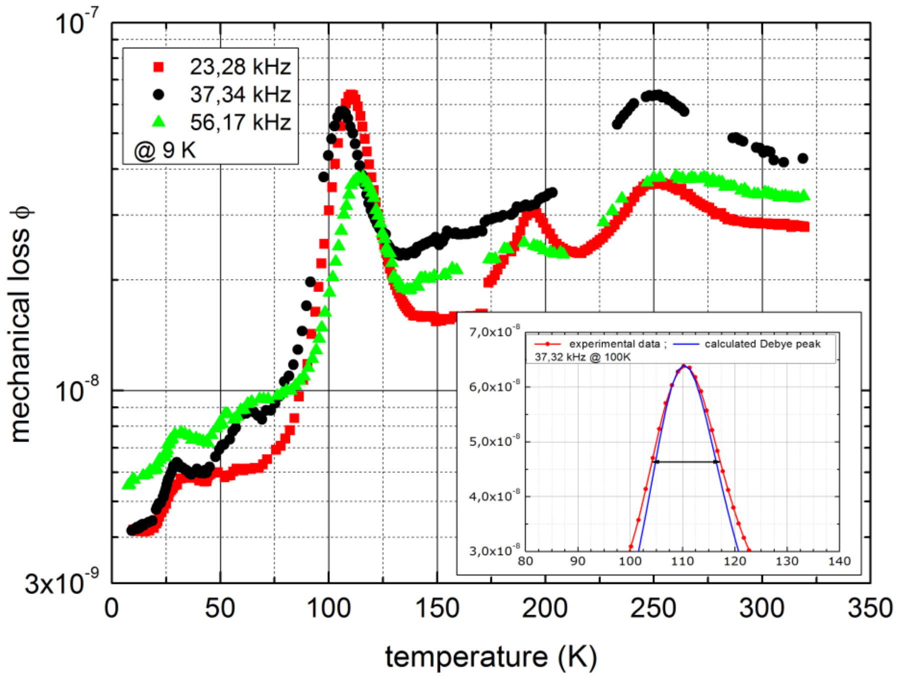
thin wire suspension
for bulk materials

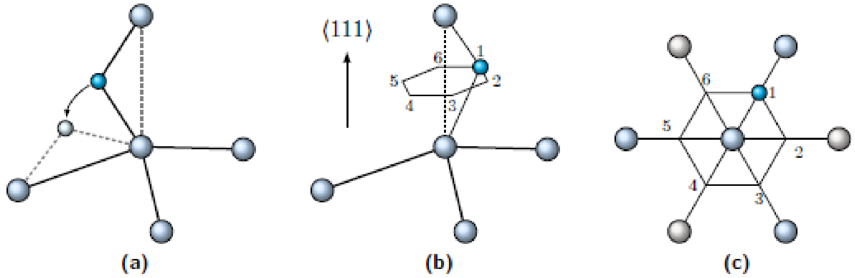


thin silicon blades
used for coating and surface
investigations

Mechanical loss spectroscopy

- f_0 and T are changed to obtain a mechanical loss spectrum



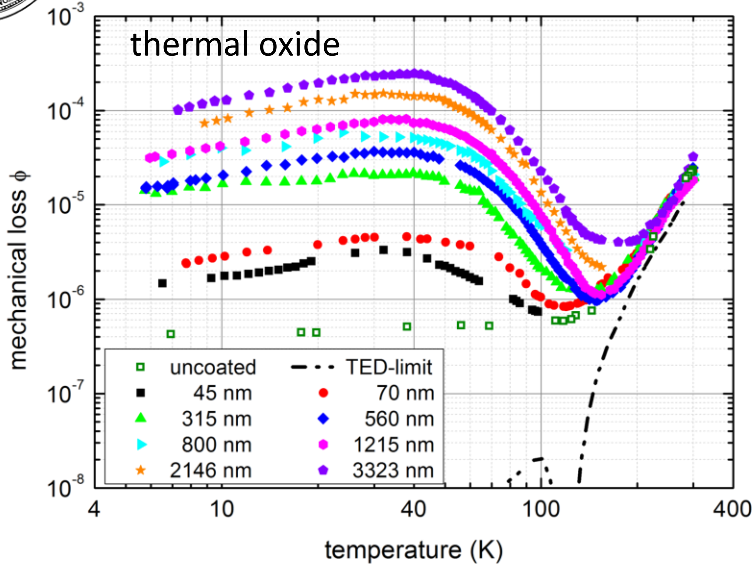


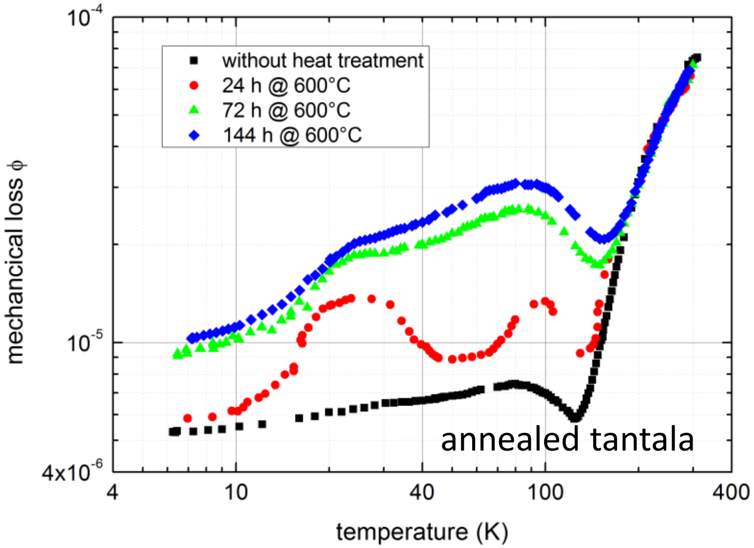
oxygen changes positions within the Si
→ relaxation → damping at 125 K

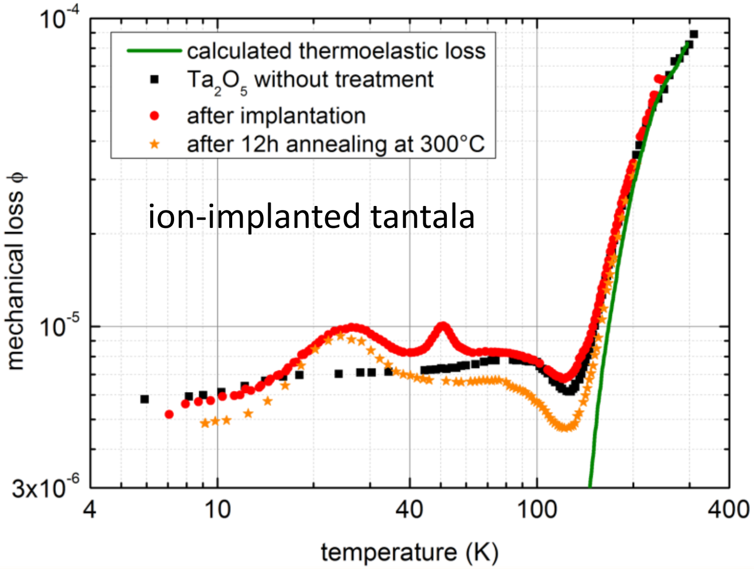
[Schwarz et al. SSP 184 (2012)]

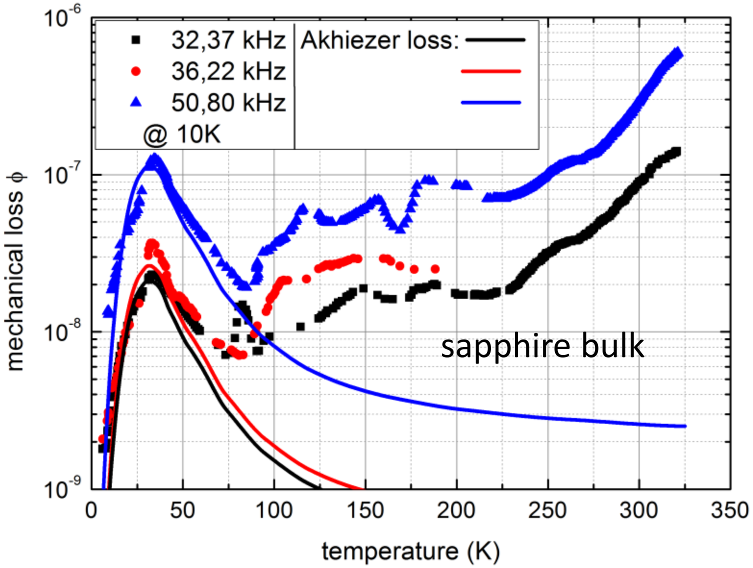
- collaboration with IGR at Glasgow
- aim: understanding the origin of the loss to avoid it

Mechanical loss spectroscopy









Mechanical loss spectroscopy

- Questions that can be answered with this technique:
  - optimum operational temperature
  - active or inactive impurities
  - methods to lower the mechanical loss

  - evaluation of the Brownian thermal noise without need to directly measure it

Silicon as a baseline material for ET-LF

- low mechanical loss
- high thermal conductivity
- good mechanical stability

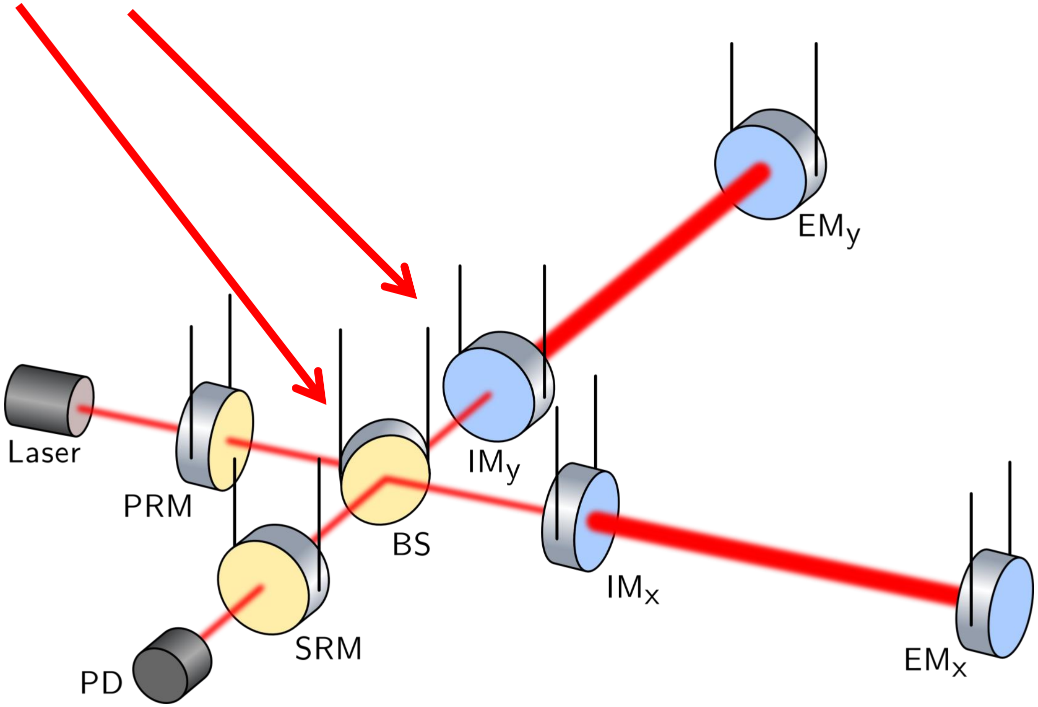
- many existing techniques (growing, polishing, cutting) due to semiconductor industry

- available in large size and high quality (up to 450 mm diameter)

- however: not transparent at 1064 nm → change to 1550 nm needed → optical parameters need to be investigated

Thermo-refractive noise in GW detectors

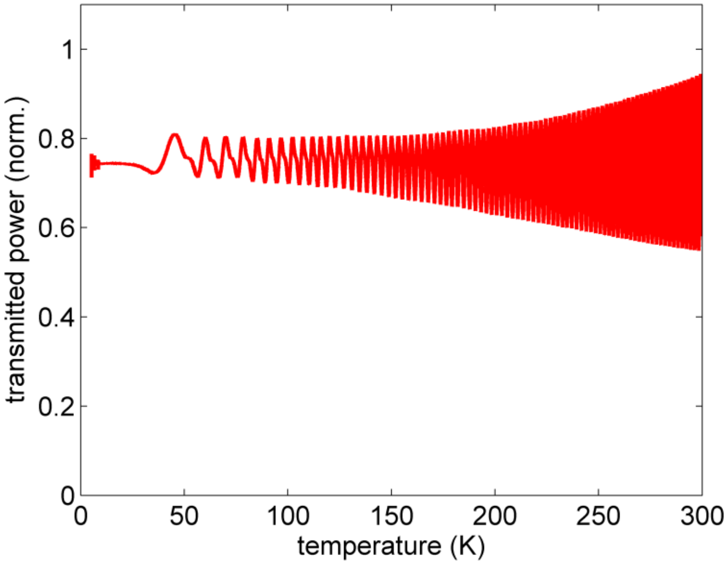
- Temperature fluctuations cause the refractive index to fluctuate as well → how much, expecially at low temperatures?
- possible optics: BS, ITM



Thermo-refractive coefficient of silicon

- Thermo-refractiv coefficient dn/dT needed at cryogenic temperatures and at 1550 nm

Investigation of transmission through a parallel sample during cooling

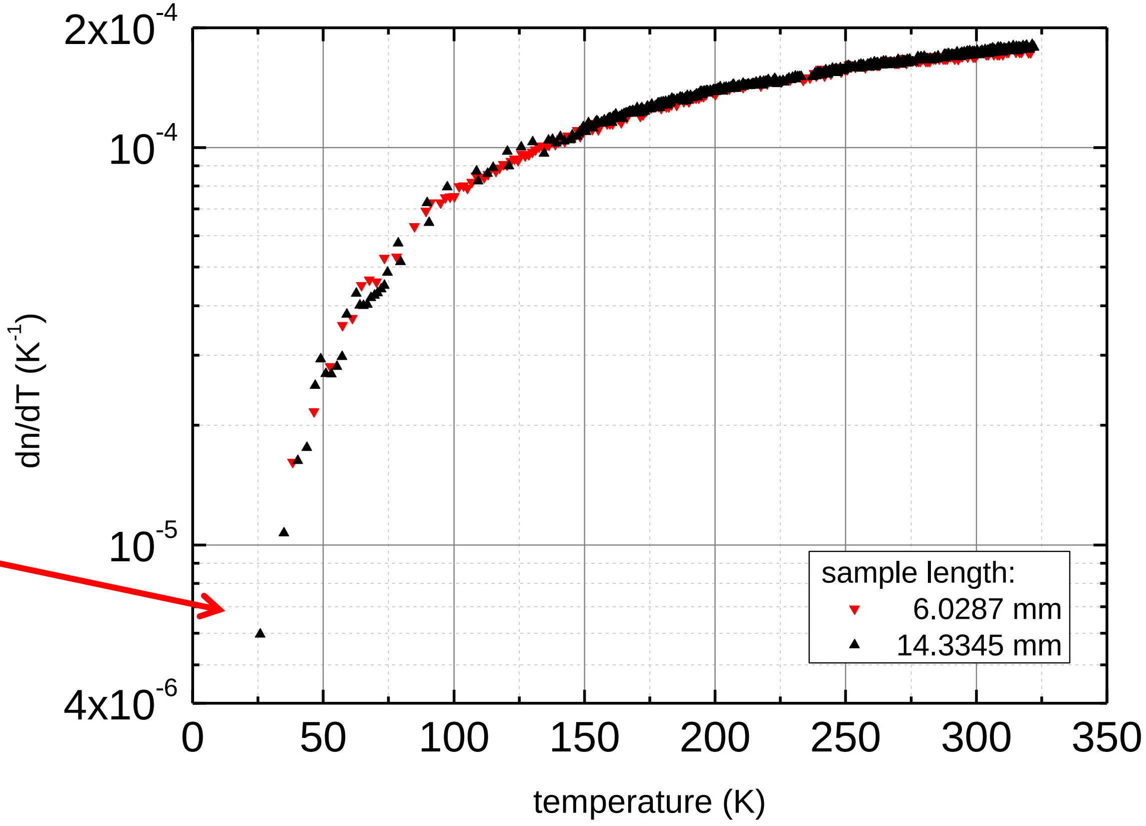


fringes contain both CTE and dn/dT

Thermo-refractive coefficient of silicon

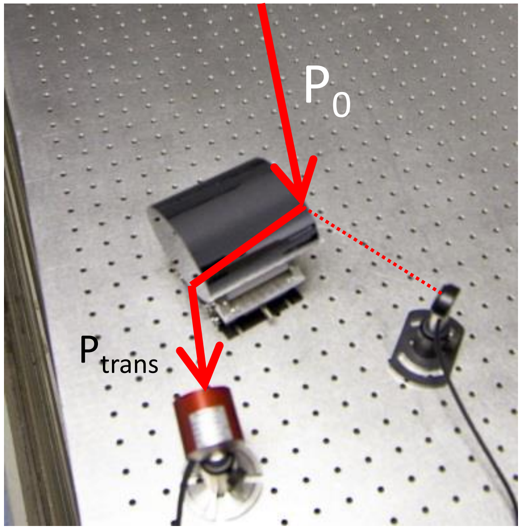
- Extraction of dn/dT reveales ist temperature dependence

very small at
low temperatures



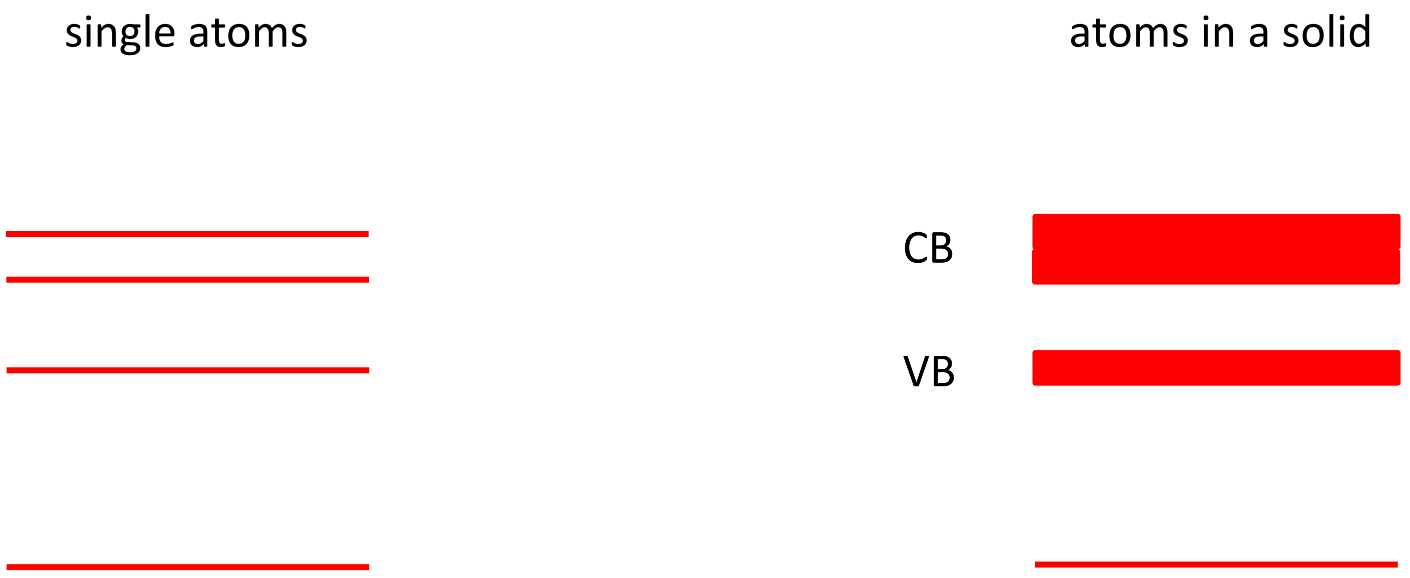
Optical absorption of silicon

- Cryogenic operation needed for crystalline materials
  - high thermal condcutivity of suspension elements needed (seen before)
  - low optical absorption needed in transmissive components



Optical absorption of silicon

- band structure of semiconductors

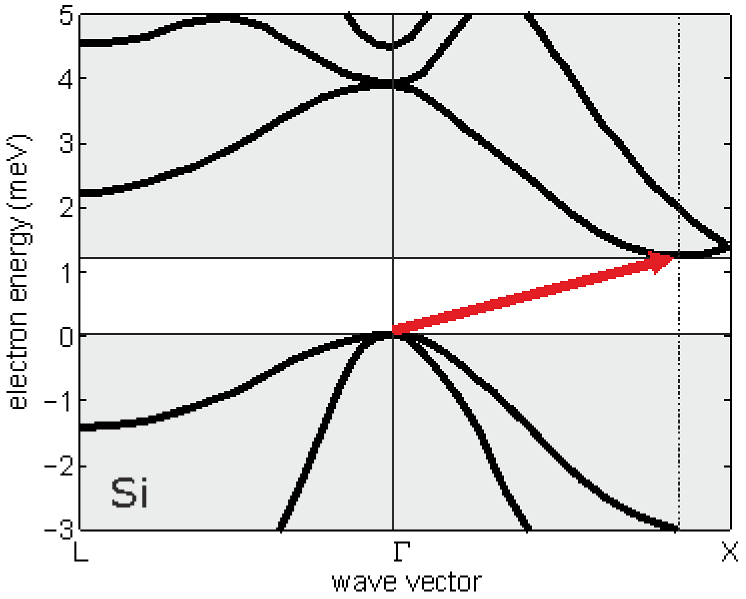


discrete energy levels with
forbitten gaps in between

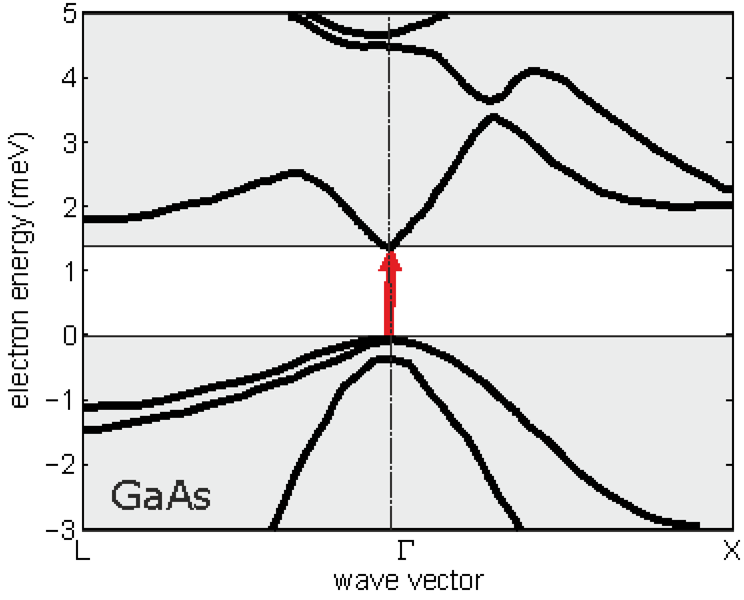
energy levels split (Pauli principle),
formation of bands

Optical absorption of silicon

- band structure of semiconductors – direct and indirect transitions



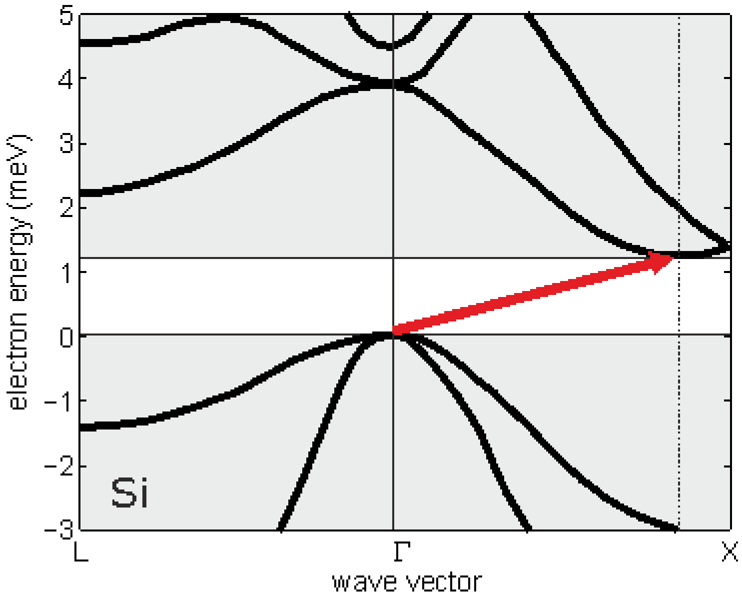
Electronical band structure of silicon. The maximum of the valence band occurs at the Γ point, whereas the minium of the conduction band is located at 0.8 X.
Indirect transitions from the valence band to the conduction band are only possible if Δk ≠ 0 and if the energy of the photon is larger than 1.12 eV (gap energy).



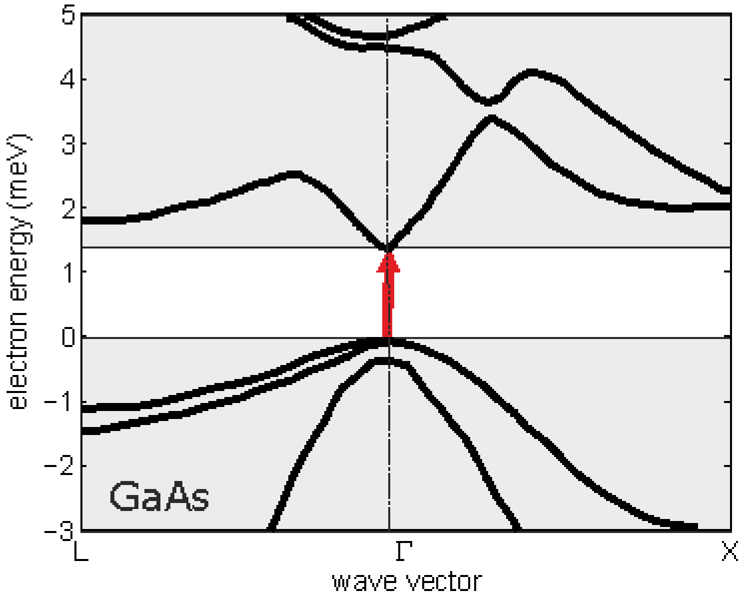
Electronical band structure of gallium arseide. The maximum of the valence band occurs at the Γ point as well as the minimum of the conduction band.
Direct transitions from the valence band to the conduction band demand Dk = 0 and are possible as soon as the photon energy is larger than 1.42 eV (gap energy).

Optical absorption of silicon

- band structure of semiconductors – direct and indirect transitions

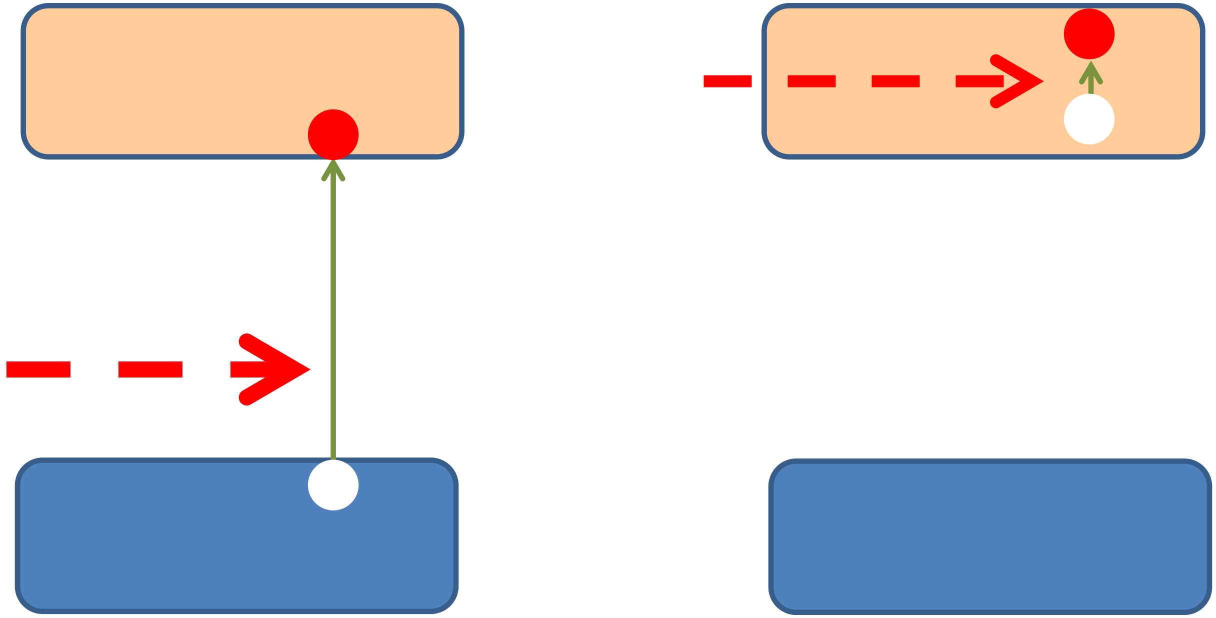


transition probablility low
(3 particles involved)



transition probablility high
(only 2 particles involved)

Optical absorption of silicon



conduction band

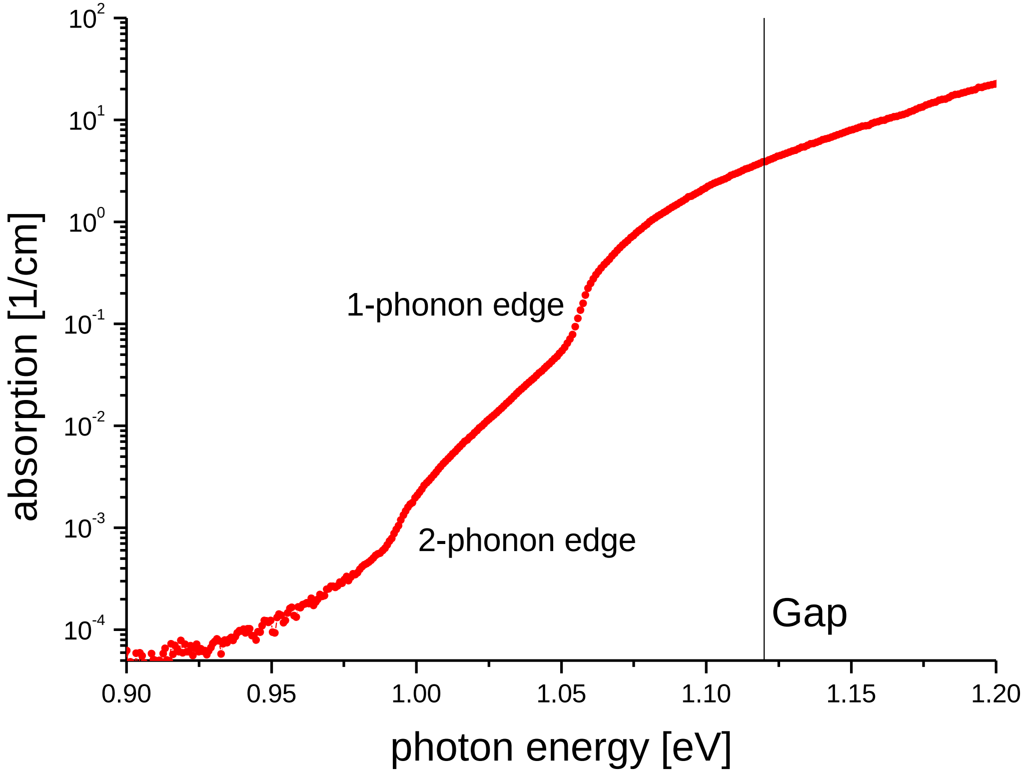
valence band

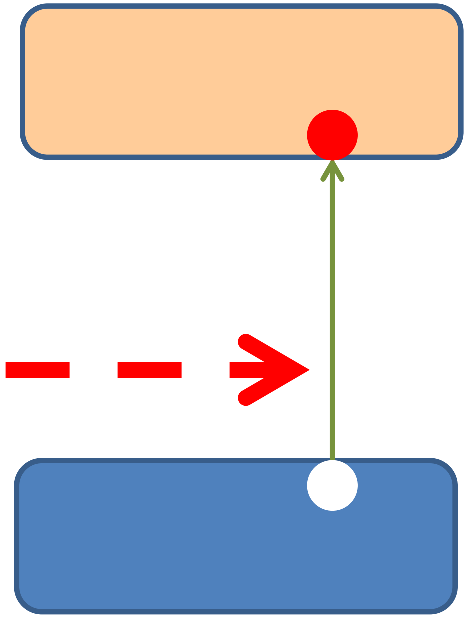
interband absorption (band-band abs.)

intraband absorption (free carrier abs.)

Optical absorption of silicon

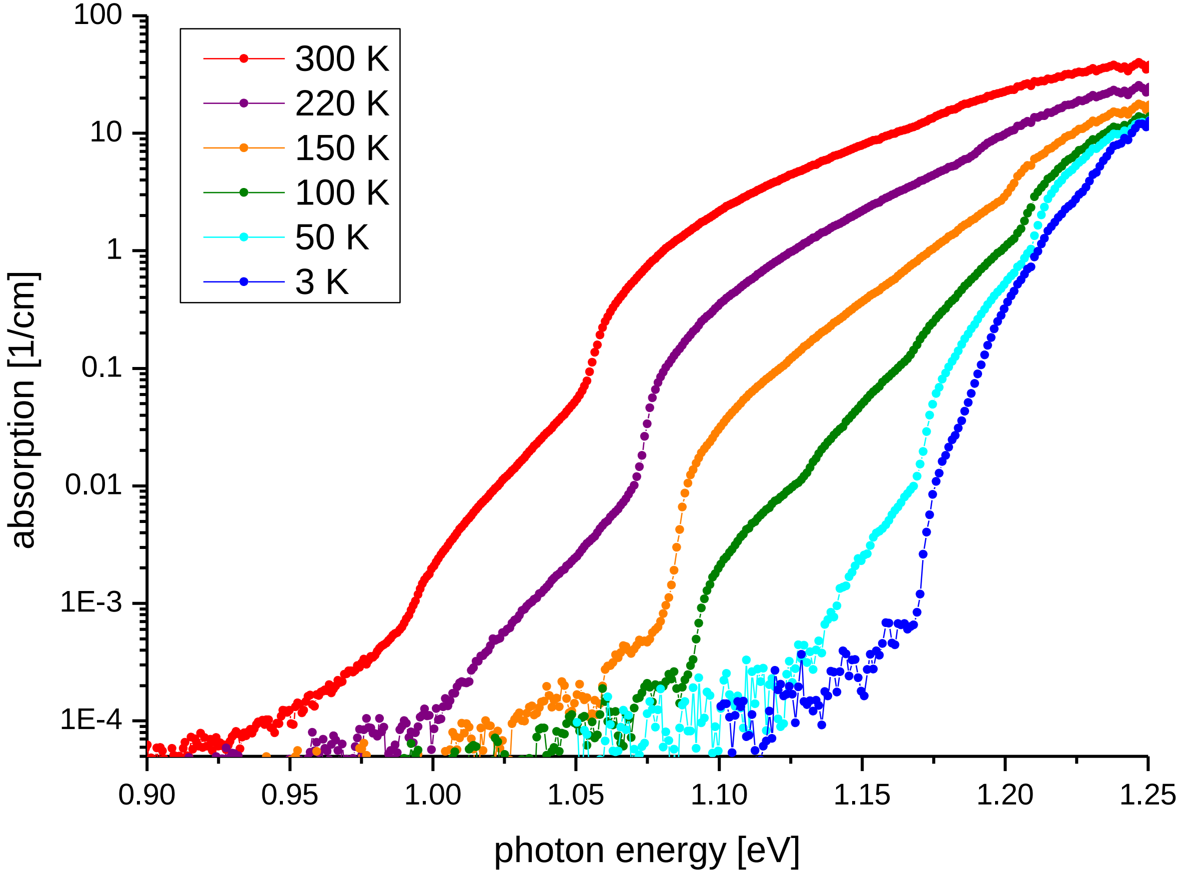
- Band-band-absorption

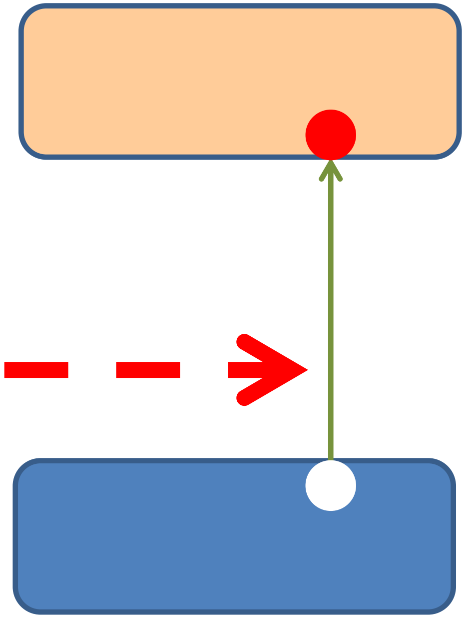




Optical absorption of silicon

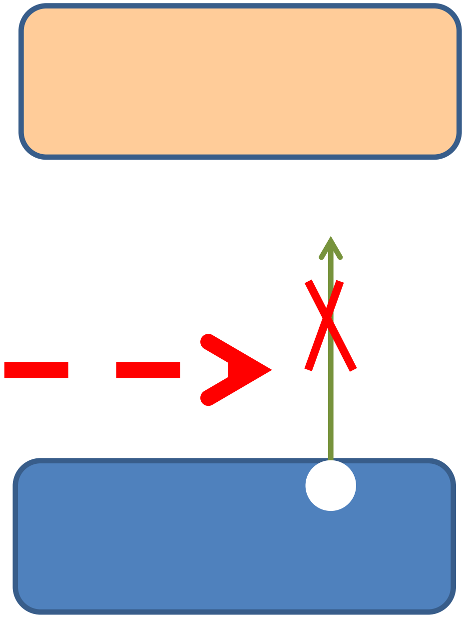
- Band-band-absorption





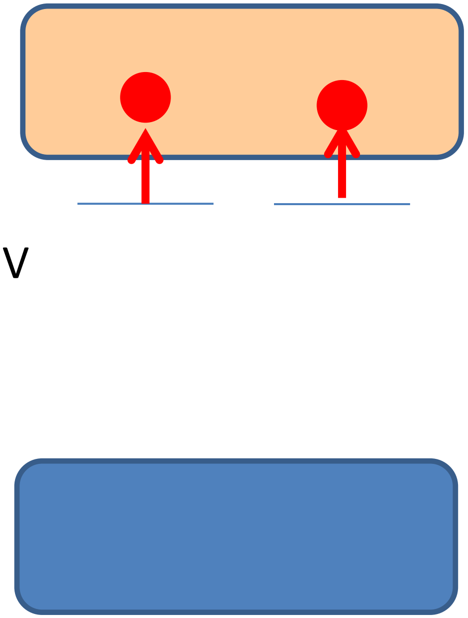
Optical absorption of silicon

- Band-band-absorption
  - Photon energy has to be near the gap energy
  - Phonon assisted absorption is temperature dependent.
  - use of light beyond the gap (e.g. 1550 nm)



Optical absorption of silicon

- Free carrier absorption
  - origin of carriers

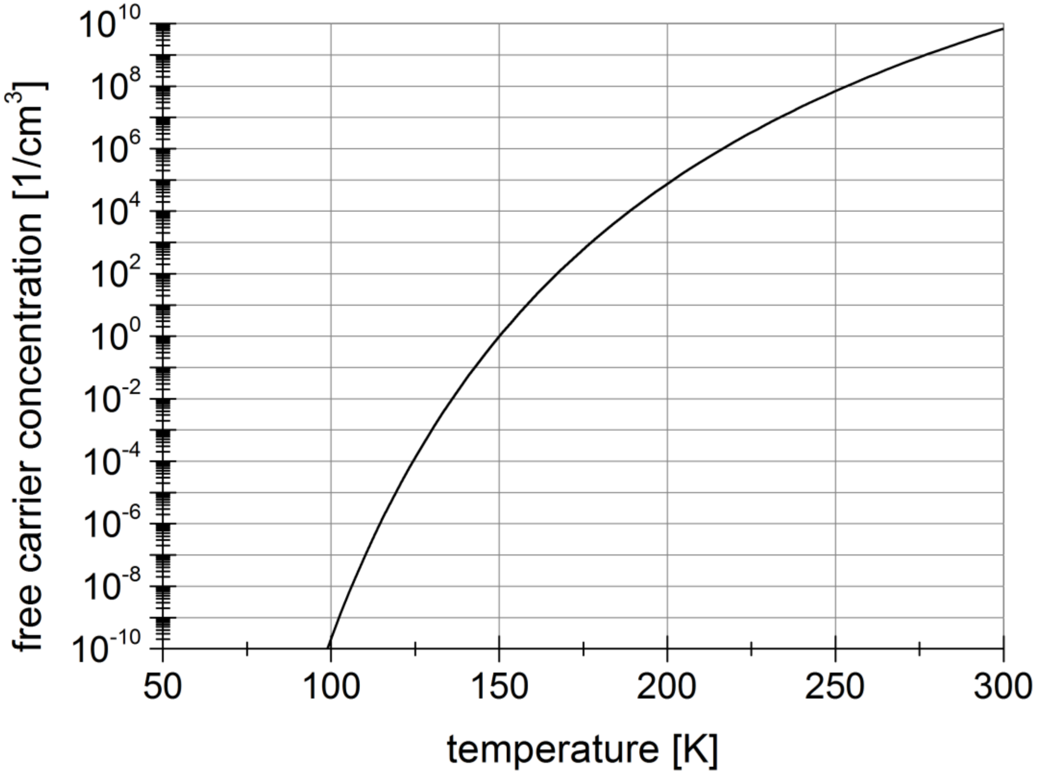


typ. 45 meV

Free carriers are released from doping states. Necessary energy is taken from thermal bath.

Optical absorption of silicon

- Free carrier concentration as function of temperature

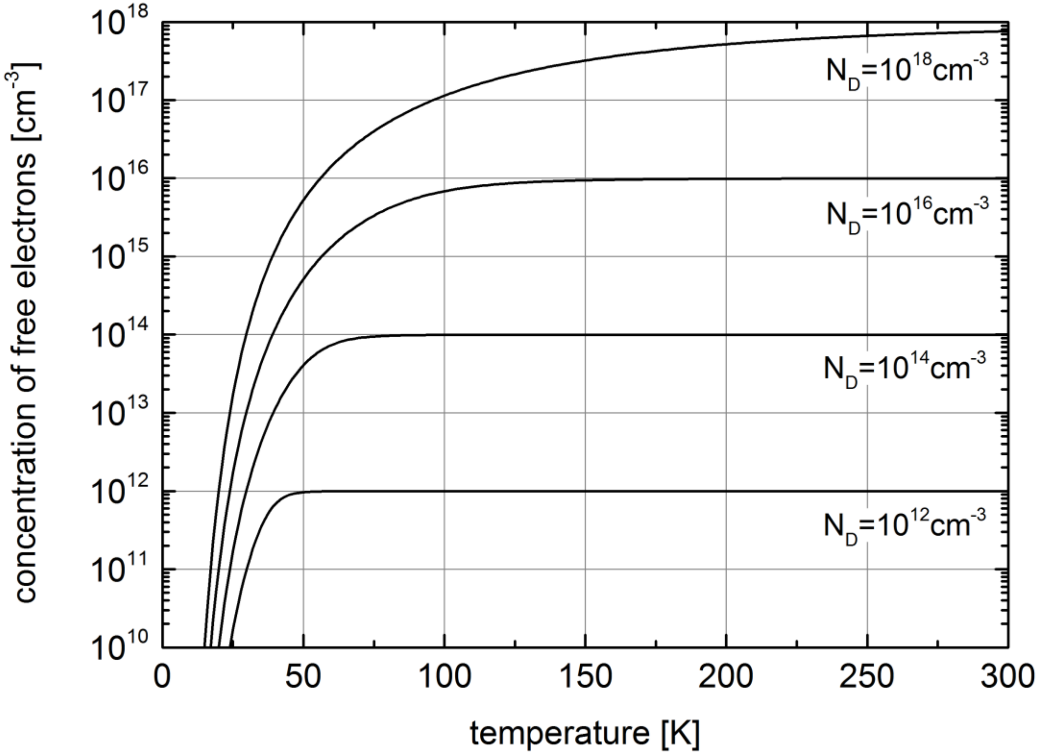


undoped silicon

- Free carrier concentration drops very rapidly (1/cm^3 at 150 K)

Optical absorption of silicon

- Free carrier concentration as function of temperature

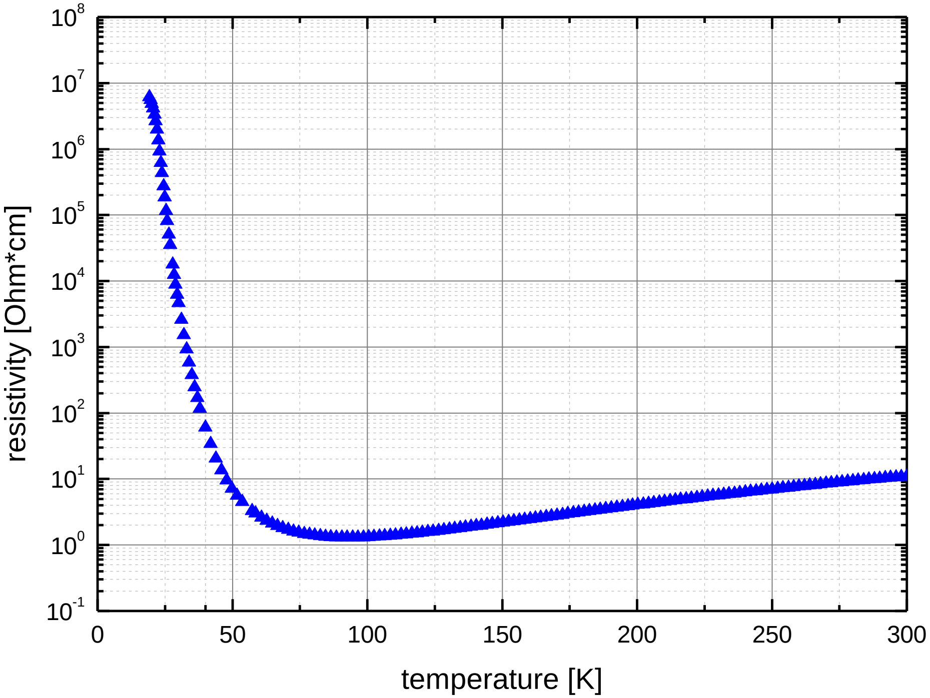


doped silicon
N_D – doping concentration

- Very low temperatures needed (below 50 K) to get rid of FCA!

Optical absorption of silicon

- freeze-out of carriers can be observed electronically by means of resistivity measurements



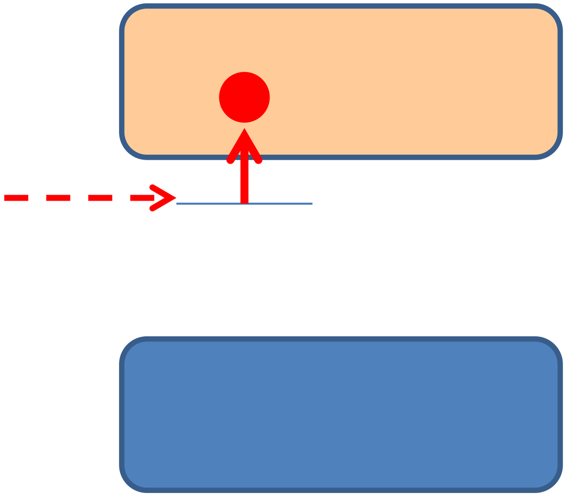
Free carriers are bound to their ground state at low temperatures.

Optical absorption of silicon

- However:

  Optical absorption is observed to be nearly temperature independent but scales with concentration of doping.

- Further studies needed…



- Possible mechanism due to the optical absorption from the ground state of the dopand into the conduction band.

Optical absorption of silicon

- additional noise sources can arise from free carriers

- free carrier density influences the refractive index
  - fluctuating carrier density (thermal, via absorption, etc.) causes fluctuations of refractive index
  - refractive index change causes „carrier noise“

- further investigations are ongoing

Summary and Conclusions

- Material investigations are important for future cryogenic GW detectors due to the unknown parameters.

- Silicon and sapphire are promising candidate materials for cryogenic applications and provide suitable properties.

- Silicon as a test mass material brings free carriers into the „thermal noise game“ -> new noise sources ?