Silicon and Sapphire
- mechanical, thermal and optical properties -

Ronny Nawrodt

on behalf of the ELiTES and ET R&D material groups

3rd ELiTES Annual Meeting

Tokyo 10/02/2015

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University of Hamburg

H. Lück, C. Krüger, R. Schnabel

And many more…

Overview

- Introduction
- Mechanical properties
- Thermal properties
- Optical properties
- Open questions
- Summary

focus

INTRODUCTION

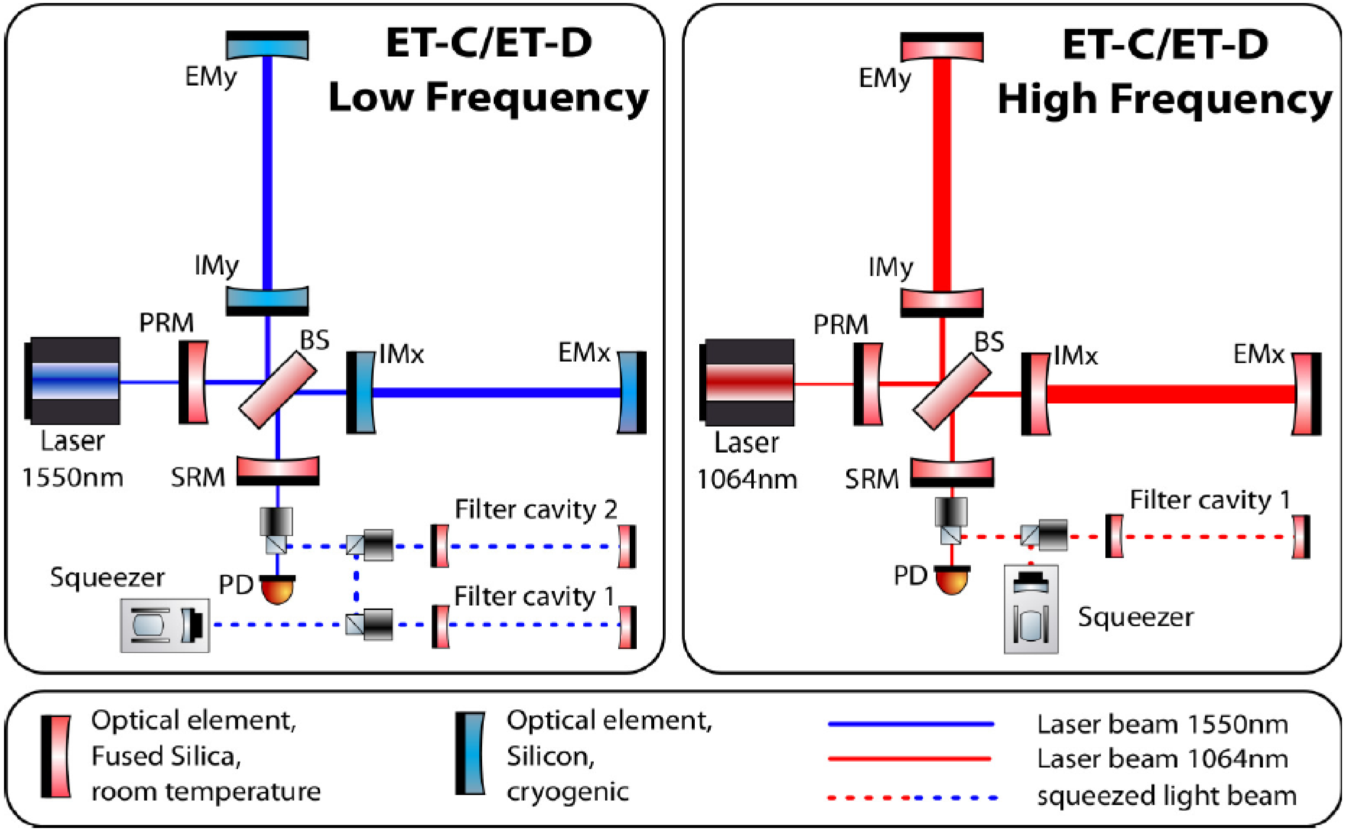
Introduction

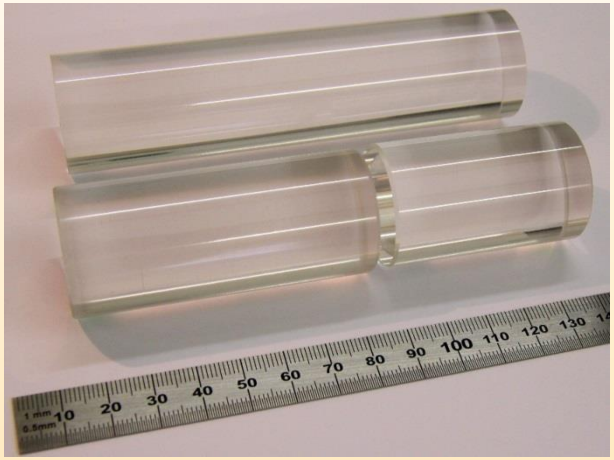
- novel materials needed beyond 2^{nd} generation of GW detectors
- besides national project coordinated EU efforts lead to pan-european efforts:
  - ELiTES (scientist exchange with Japan)
  - ET R&D (technologies for ET)

Introduction

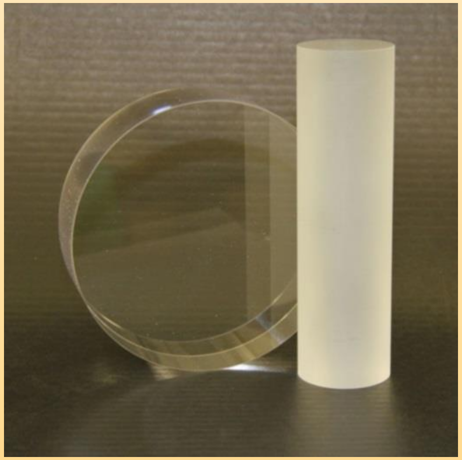
- design of the Einstein Telescope in Xylophone configuration

10-20 K, 18 kW, 1550 nm   300 K, 3 MW, 1064 nm

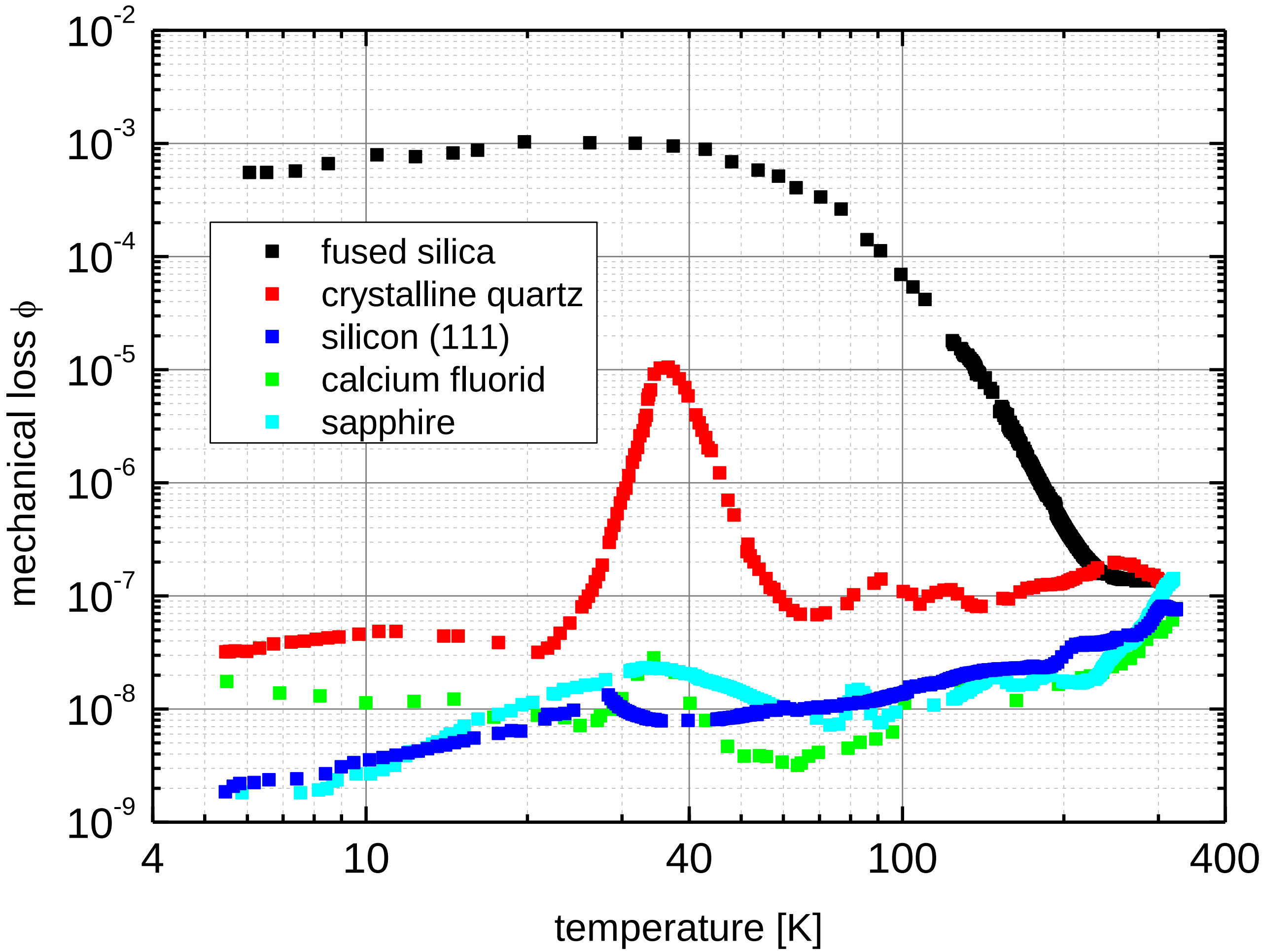




MECHANICAL PROPERTIES

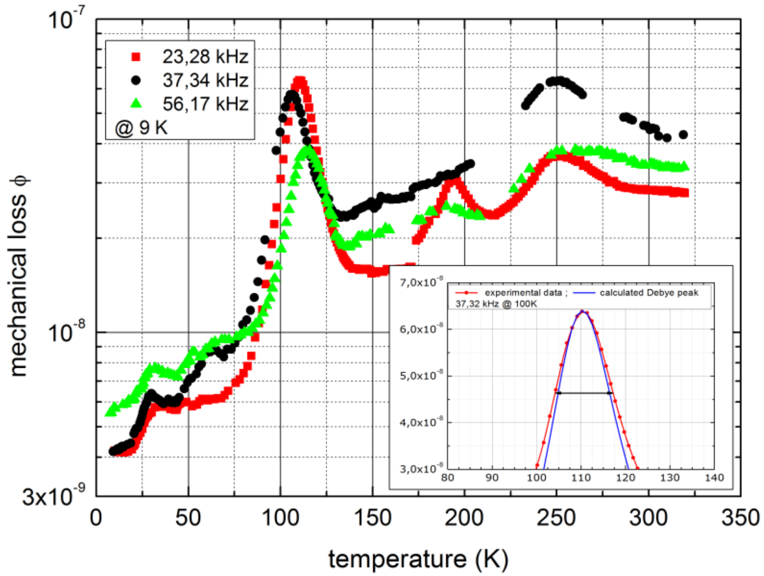


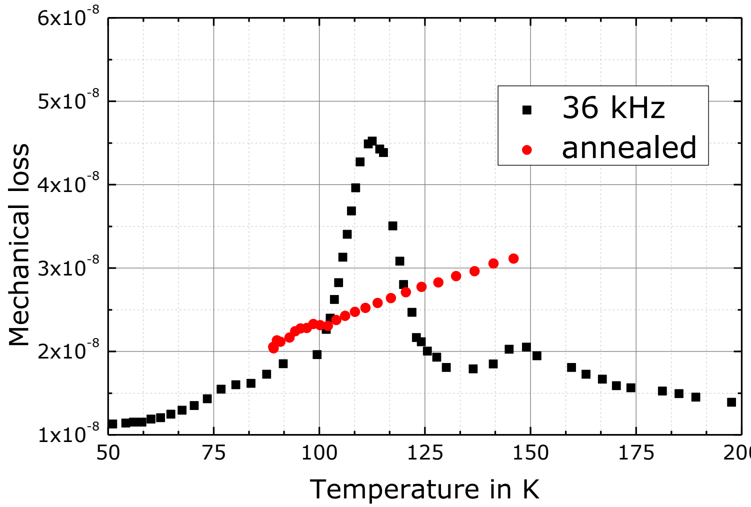
Mechanical loss of bulk materials

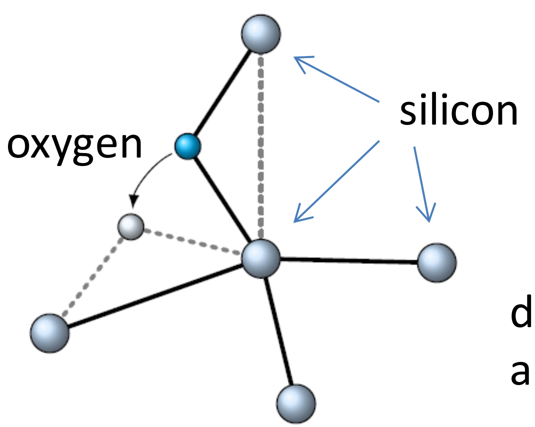


complex dynamics in solids lead to different mechanical losses

Oxygen defect in silicon





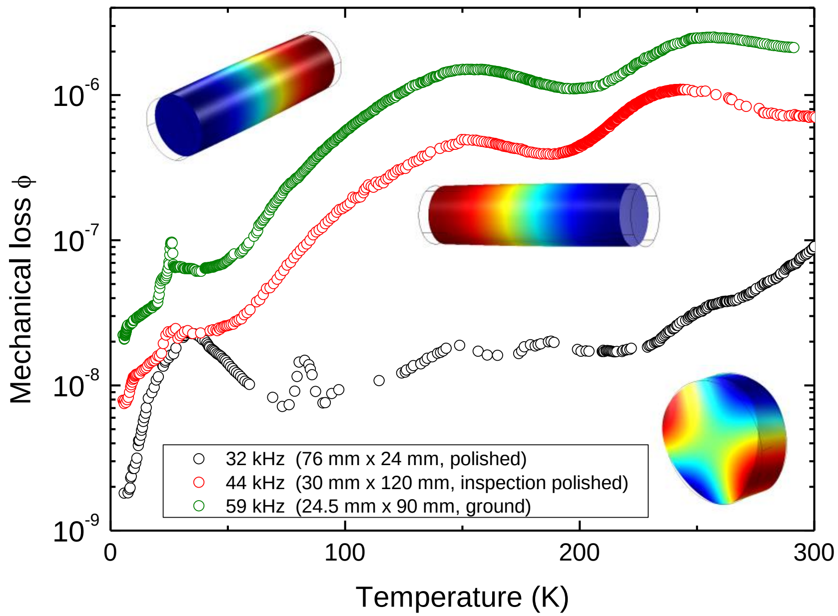


diffusion not
able to describe loss

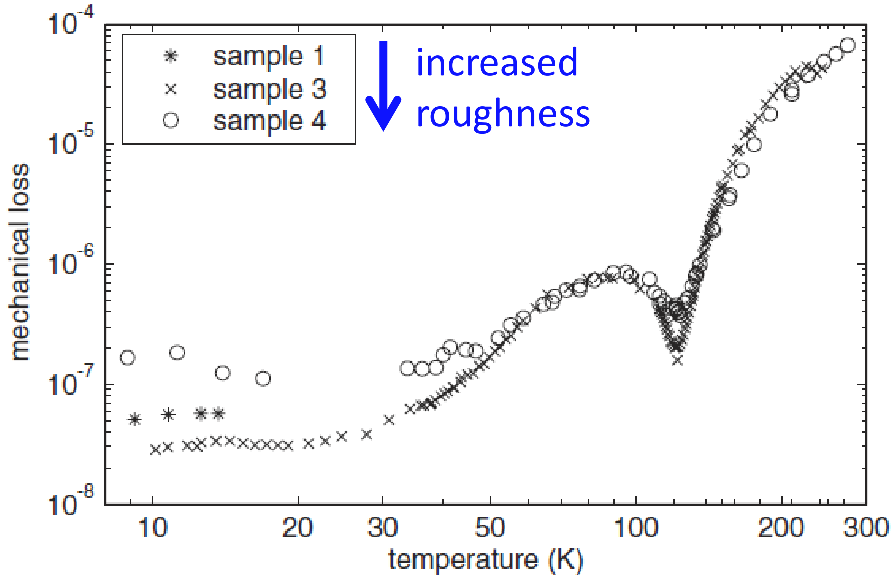
- detailed annealing reduced loss peak
- IR absorption peak for interstitial oxygen is also reduced

Surface effects on the mechanical loss

- surfaces introduce additional losses → detailed study



sapphire



silicon

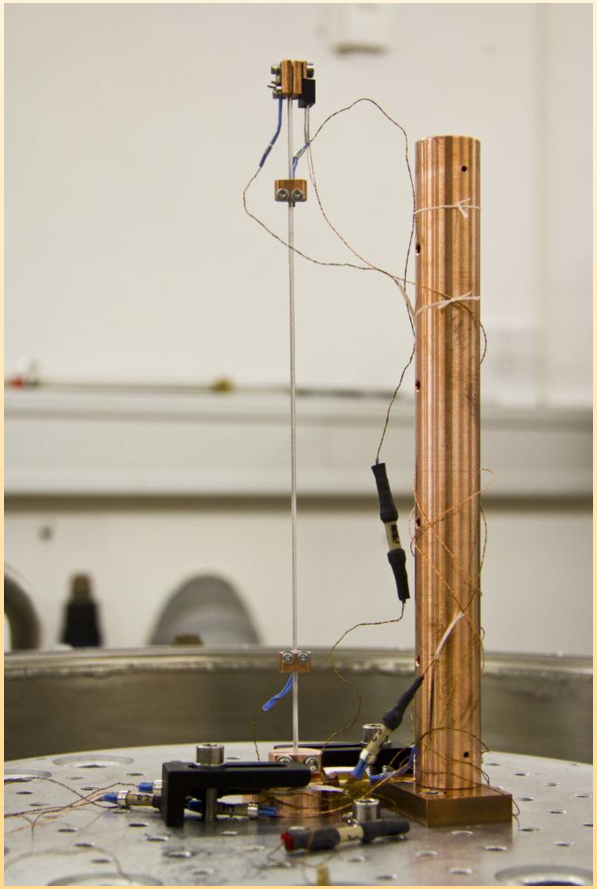
Mechanical properties

- Young's modulus influences deformation energy and this thermal noise

Orientation	⟨100⟩	⟨110⟩	⟨111⟩
Normal energy	0.77	0.52	0.3
Shear energy	0.23	0.40	0.45
S_z without defects	1	0.91	0.88
S_z with defects	3.05	4.48	4.92

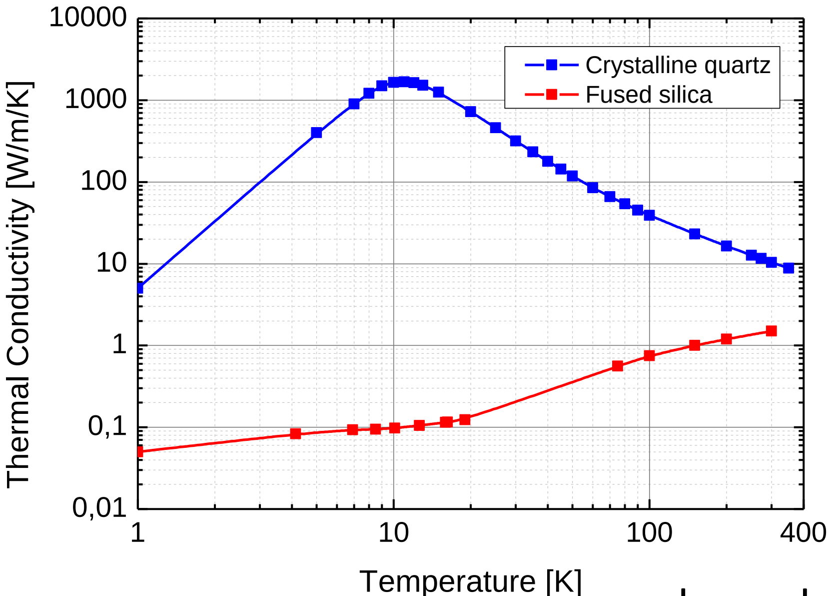
- Breaking strength tests of Si-Si, Si-Sapphire, Sapphire-Sapphire samples

THERMAL PROPERTIES



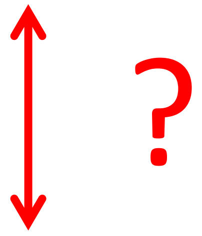
Thermal properties

- absorption of samples → residual heat needs to be extracted through suspension
- conductivity dependent on surface quality (phonon scattering)



large dynamics

high thermal conductivity



good thermal noise performance

Measurement techniques

- static method

like measuring a resistor

feeding heat in, measurement of temperature difference

limits: calibration uncertainty of sensors at high conductivities

- dynamic method

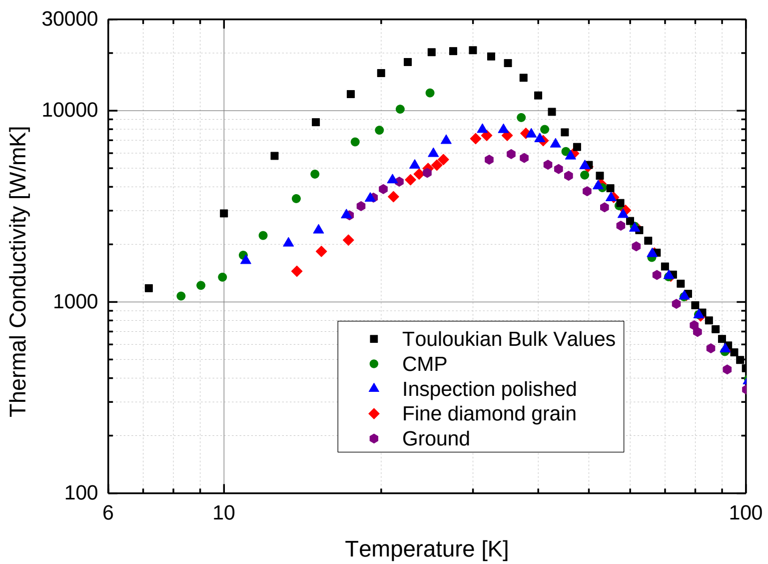
pulse propagation contains all information needed

measuring the speed of a thermal pulse

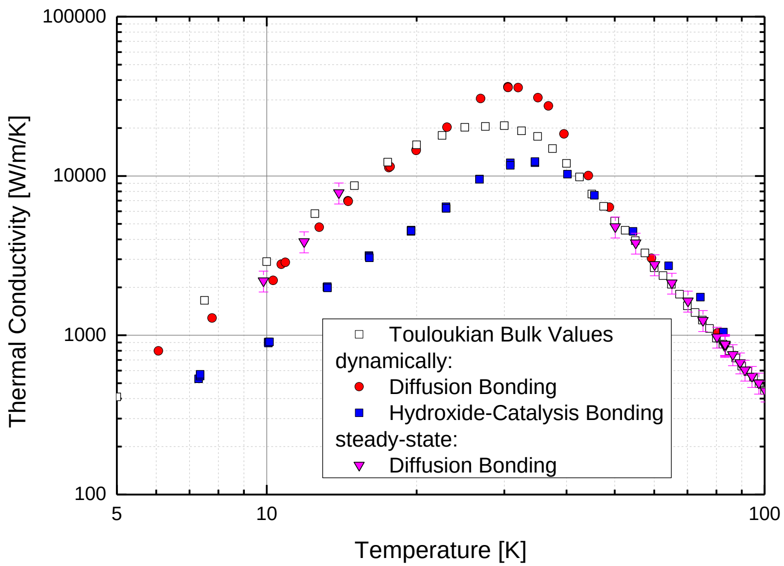
limits: time (!), system acts like a low pass with very low cut-off frequency (< 1 Hz)

Study of highly conductive elements

- suspension elements, bonds, etc. needed

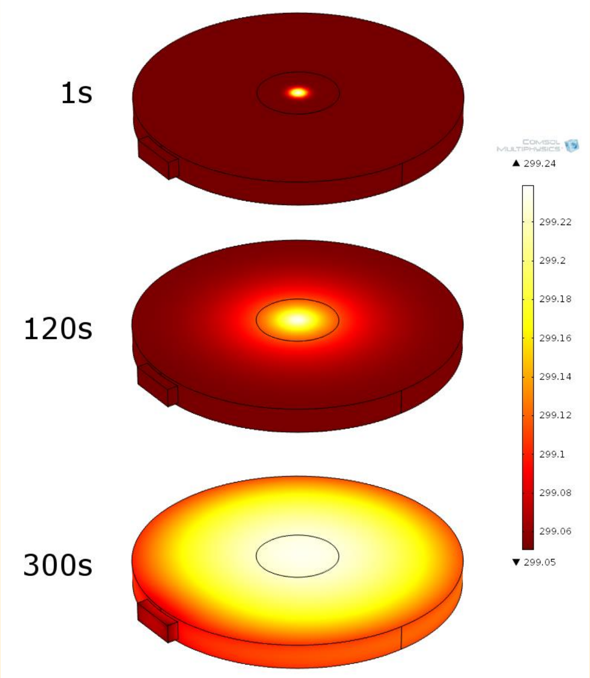


dependence of TC of surface quality



proof of principle for bonded samples

→ detailed study needed!

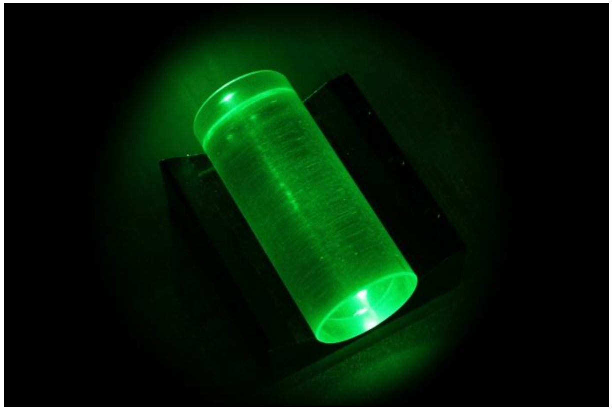


OPTICAL PROPERTIES

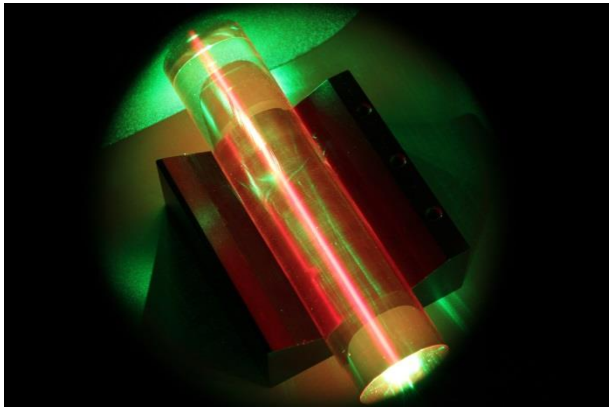
Defects in Sapphire

- often: residual amounts of chromium

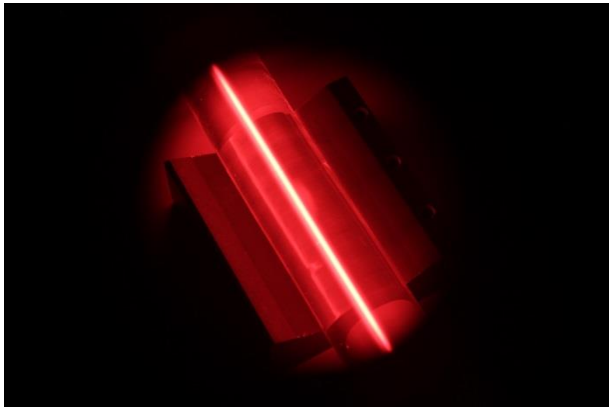
  → ruby laser transition @ 694 nm



excitation at 532 nm



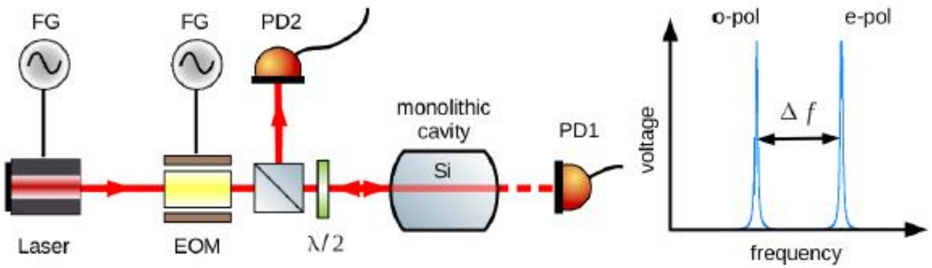
high concentration of chromium

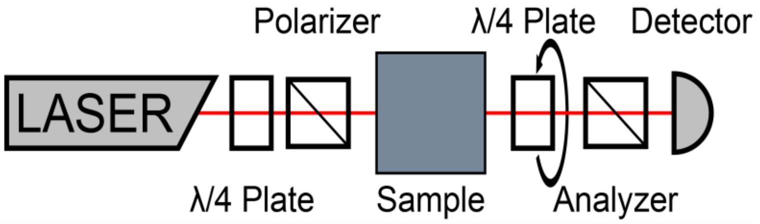


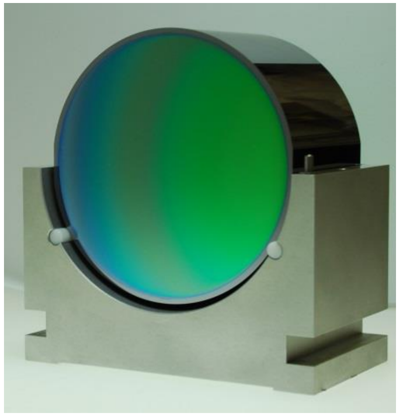
low concentration of chromium

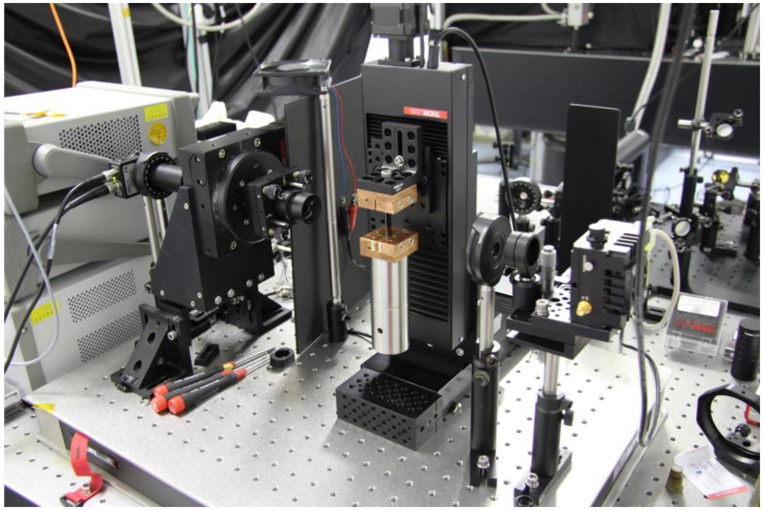
(additional 694 nm narrow band filter)

Birefringence

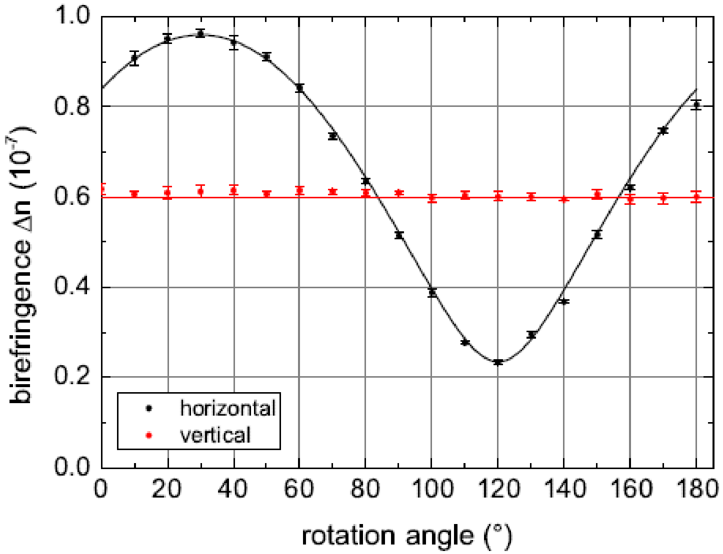






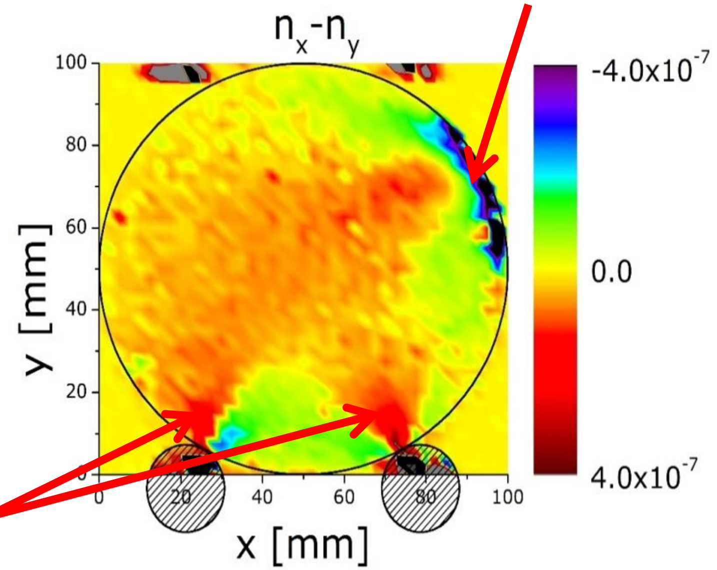


Birefringence



imaging of birefringence allows imaging of stresses

internal stress (defect)

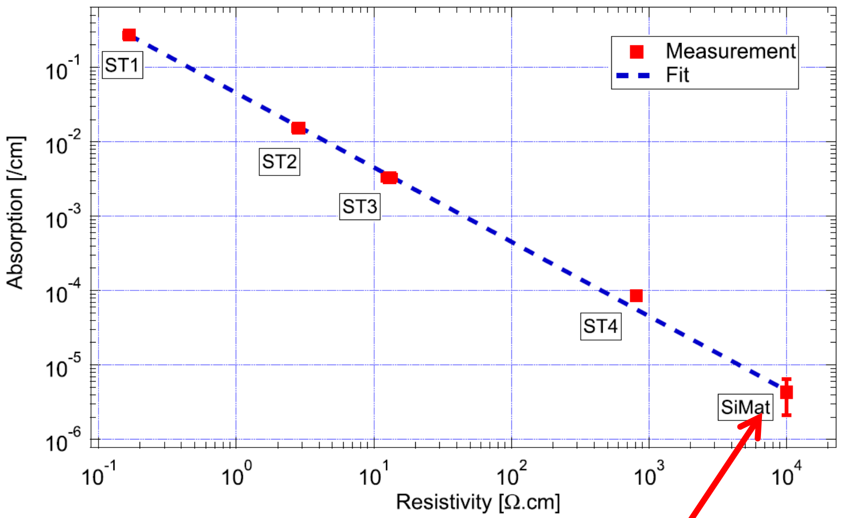


different loads and load pattern can be fully described

external stress (here: gravity)

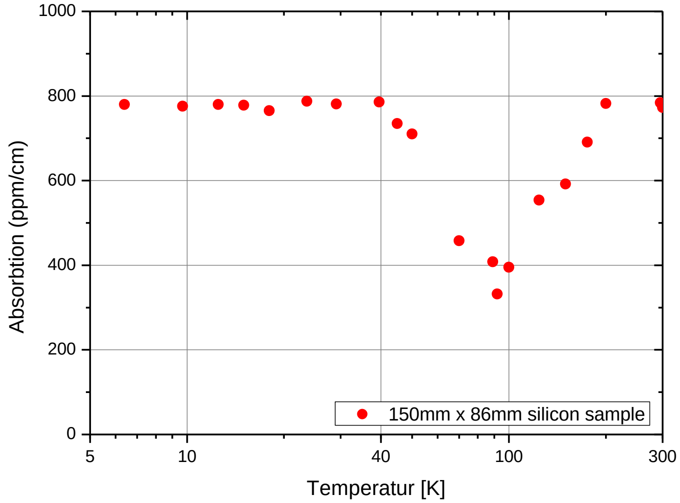
Optical absorption of silicon

- room temperature



4 ppm/cm demonstrated

- cryogenic temperature

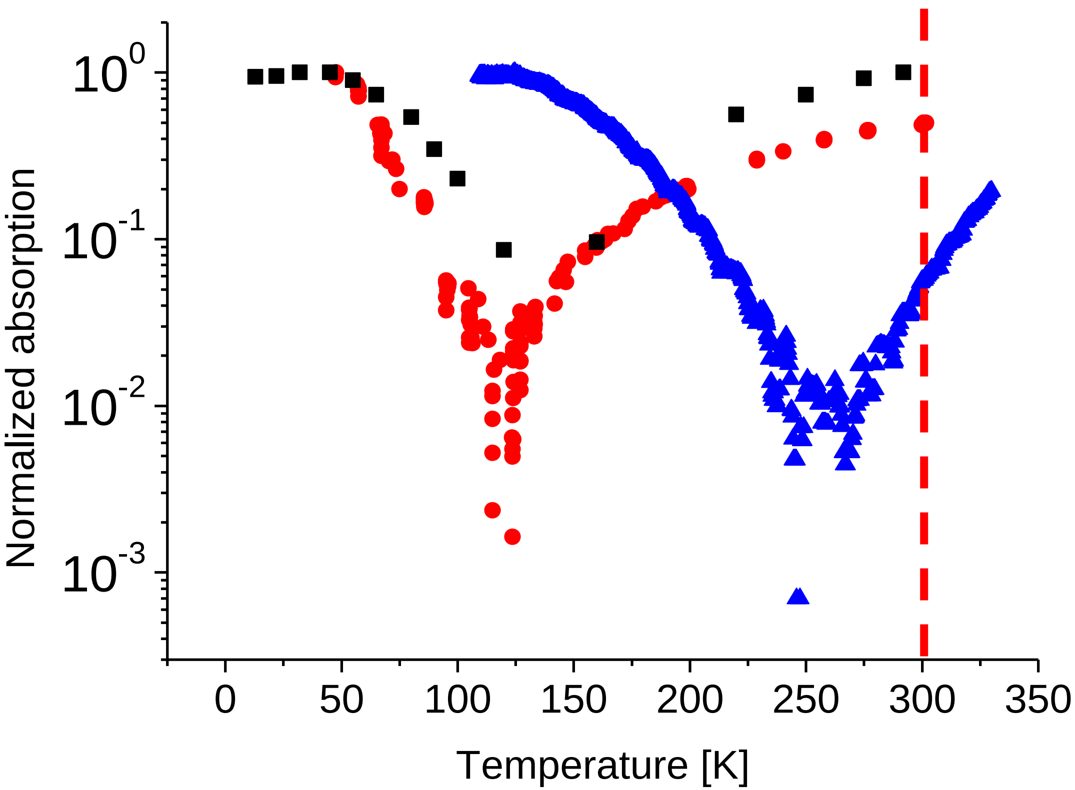


level at low temperatures ~ level at room temperature for this given sample

[J. Degallaix et al., Optics Letters **38** (2013) 2047-2049]

Optical absorption of silicon

- systematic studies in different labs with different techniques and dopants

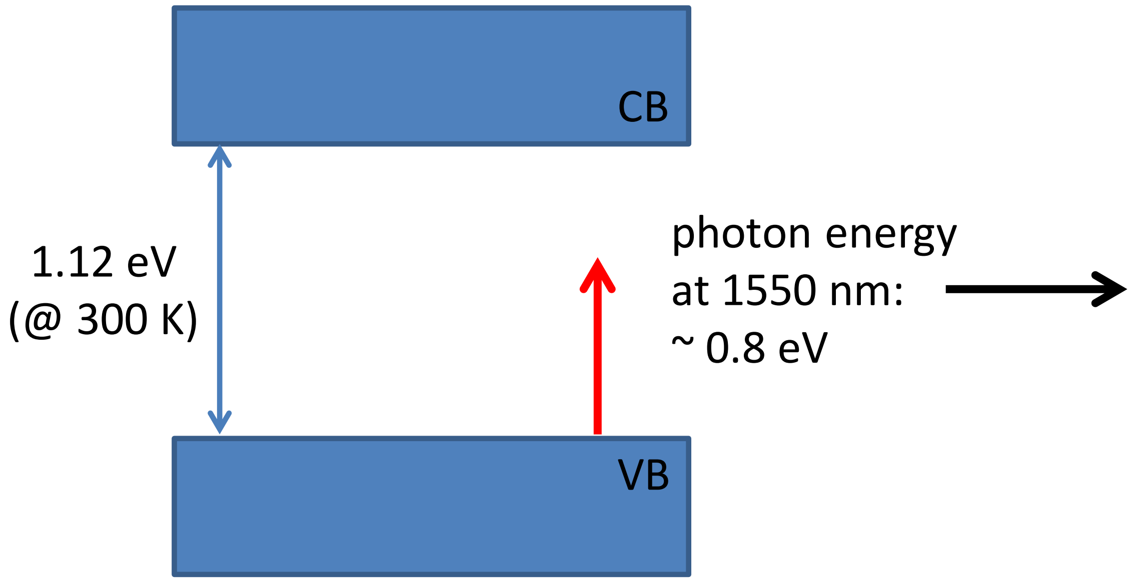


phosphorus	FSU	~ 44 meV
boron	LMA	~ 44 meV
gallium	IGR	~ 72 meV

- different „dip temperatures“
- different depth of the dip
- different ratio between 300 K and low temperatures

Optical absorption of silicon

- band – band – absorption

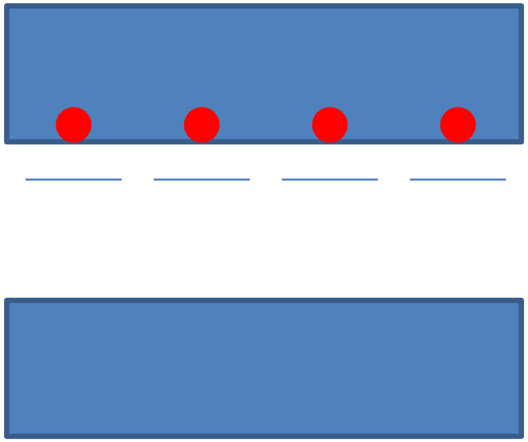


extremly low band-band-absorption expected by multi-phonon processes

- other process needed

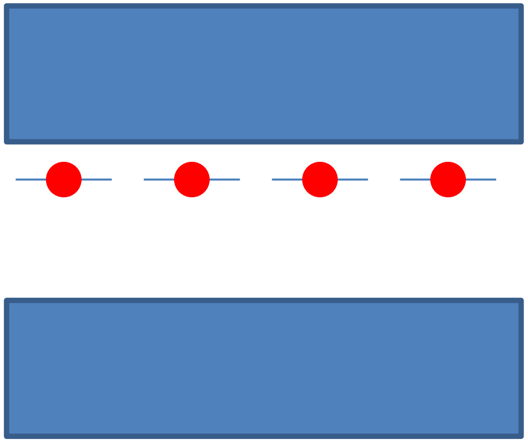
Optical absorption of silicon

- room temperature



- all dopants (shallow impurities) ionized

- cryogenic temperatures

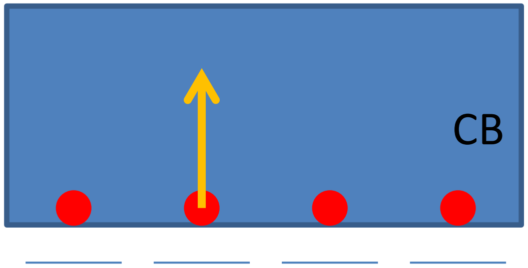


- all dopants (shallow impurities) in their ground state

Optical absorption of silicon

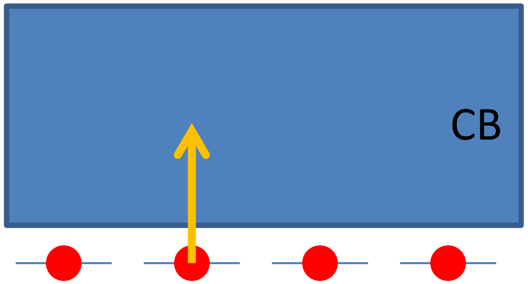
- room temperature

absorption of 1550 nm light by free carriers



- cryogenic temperatures

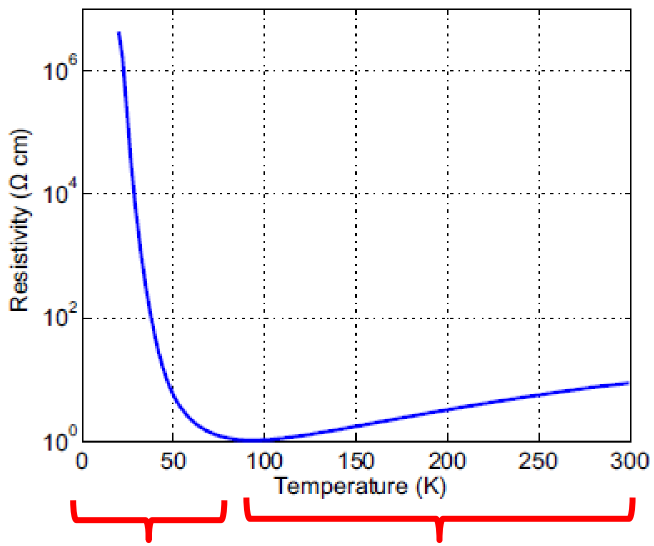
absorption of 1550 nm light by neutral dopants



so far: simplified model, more detailed model includes real band structure and phonon-assistance for transitions (silicon -> indirect semiconductor)

Optical absorption of silicon

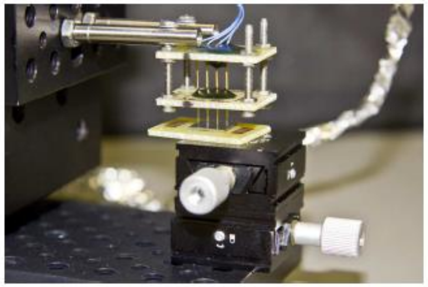
- free carrier absorption (high temperature limit)

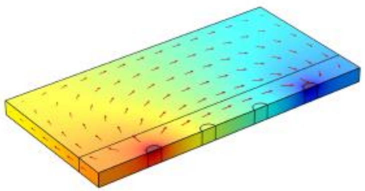


freeze-out to neutral dopans

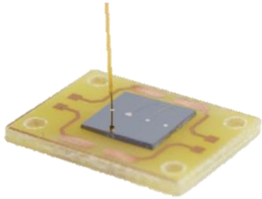
roughly constant density of carriers

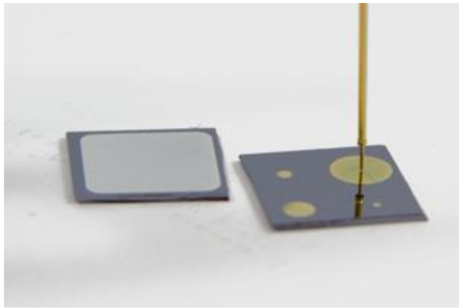
[J. Degallaix et al., Class. Quantum Grav. **31** (2014) 185010]



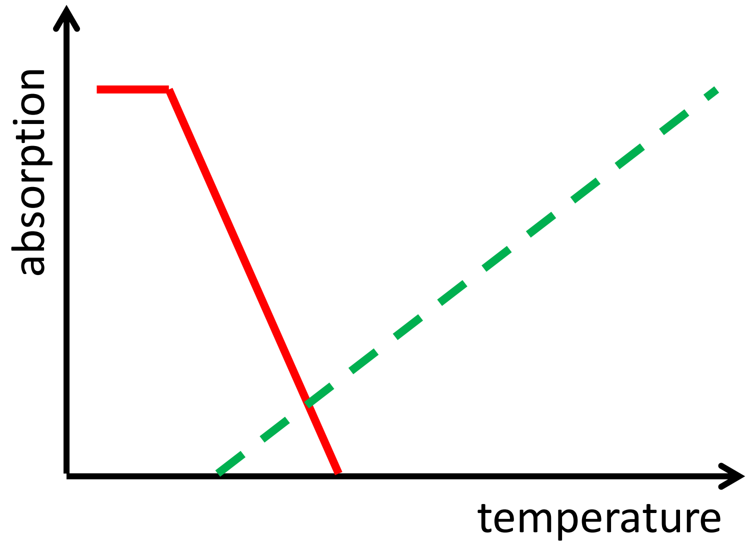


temperature dependence on carrier density studied by: Hall measurements, CV-measurements, 4-probe resistivity measurements





Optical absorption in silicon



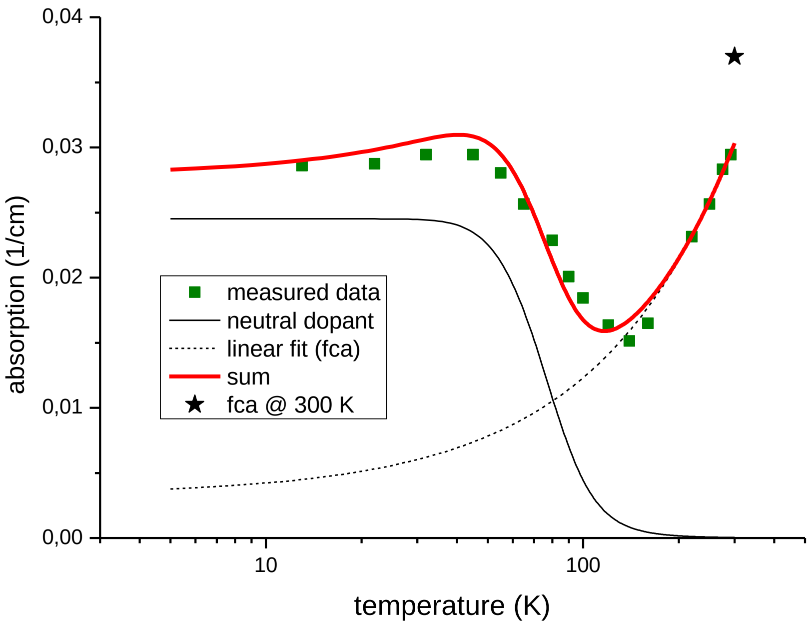
absorption at neutral dopants (absorption dependent on dopant-> reason for different observed levels to low temperatures)

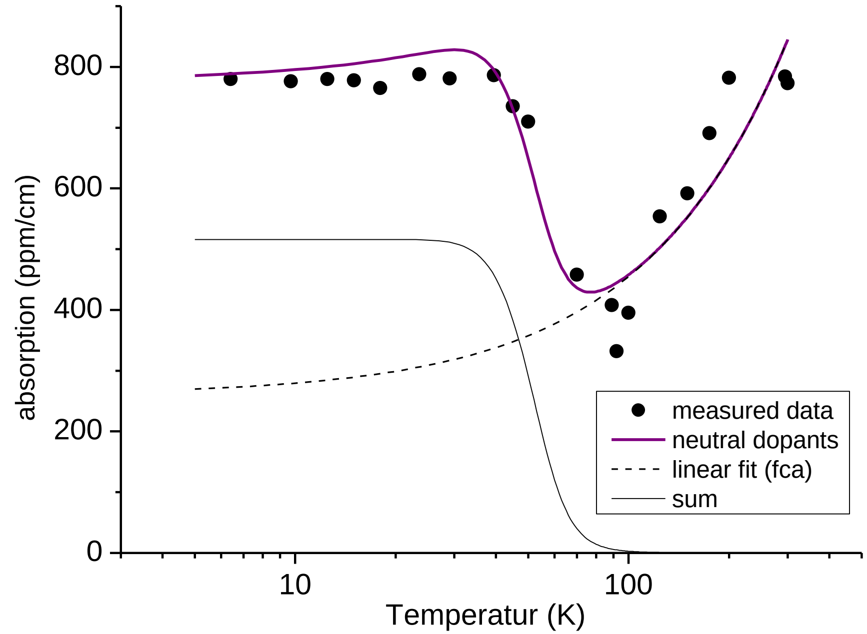
absorption involving free carriers

- free carrier density (nearly constant)
- mobility (highly temperature and impurity dependent parameter!)

Optical absorption of silicon

- interpretation of experimental data

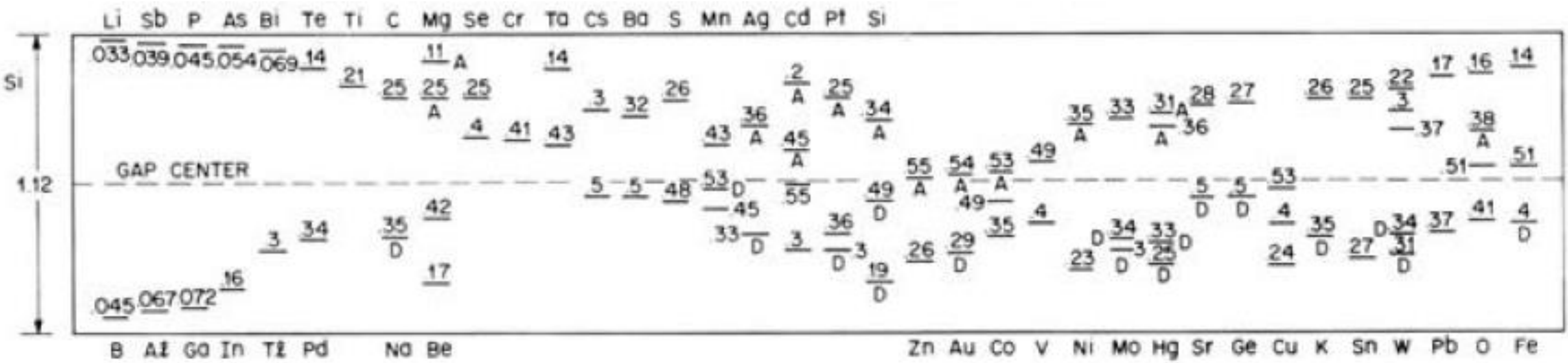




but so far: high temperature part fitted by (partially motivated) linear function

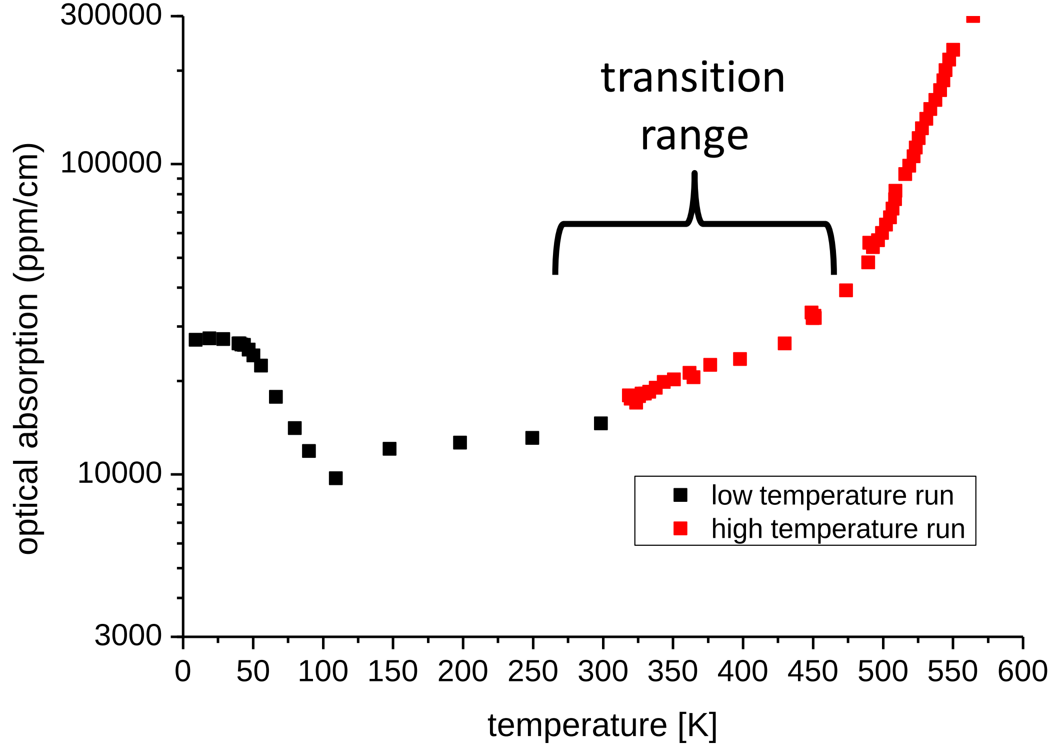
Optical absorption of silicon

- What about other impurities?



- shallow impurities under good control (otherwise no silicon electronics possible)
- deep impurities are neutral at room temperature $\rightarrow$ they already contributed to room temperature measurements (4ppm/cm!)

Measurements at high temperatures



transition range:

probably reason why fca does not 100% describe room temperature behaviour

for decades only empirical models available!

more studies needed to understand the processes…

Optical absorption of silicon

- What can we learn for ET?
  - 2 counteracting absorption processes
  - low temperature values in boron-doped material comparable to room temperature values
  - leading effect from shallow impurities (dopants)
  - at very high purity samples: contribution from other impurities expected
  - What is the minimum absorption we can hope for realistically?

$\rightarrow$ input for suspension team

OPEN QUESTIONS

Open questions

- impurities in materials and their electronical behaviour
- fabrication techniques for higher purity silicon
- size of materials
- polishing of material
- surface quality (surface analysis techniques)

- deliverable for ELiTES:

    document comparing sapphire and silicon mirrors

SUMMARY

Summary

- mechanical, thermal and optical properties of silicon and sapphire under study
- pan European activity with links to Japan
- choice of material (doping, orientation, etc.) depends on different aspects
- biggest open questions are technological issues

- ELiTES deliverable due until 27/02/2015