DFG SFB TR7

Silicon and Sapphire as test masses for cryogenic detectors

D. Heinert
Friedrich-Schiller-Universiät Jena

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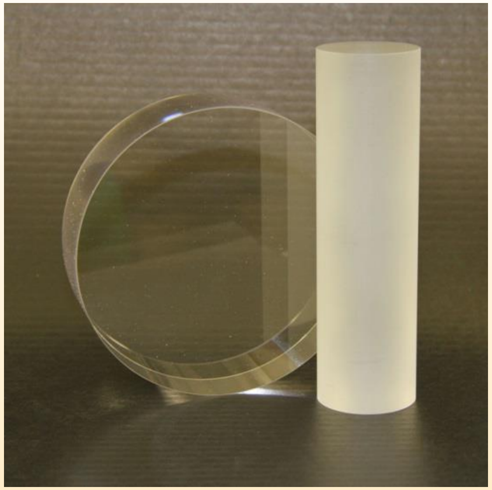
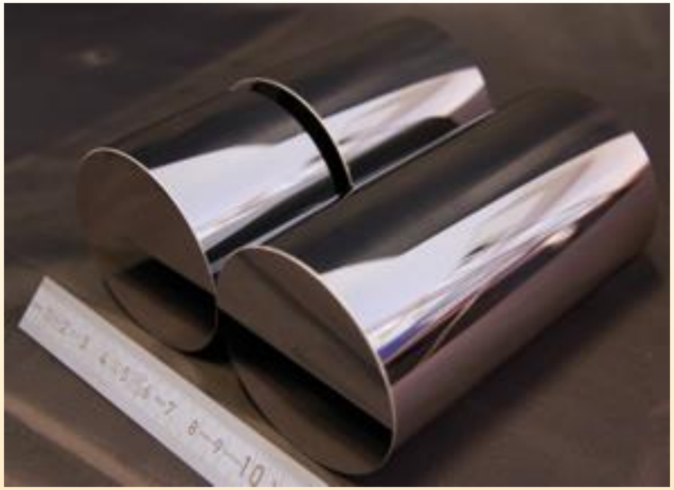
Outline

- Part 1: Mechanical loss measurements on silicon and sapphire
- Part 2: A new kind of thermal noise in semiconductors





G. Hofmann, C. Schwarz, J. Komma, D. Heinert, R. Nawrodt (FSU Jena)

K. Yamamoto, D. Chen, A. Khalaidovski (ICRR)

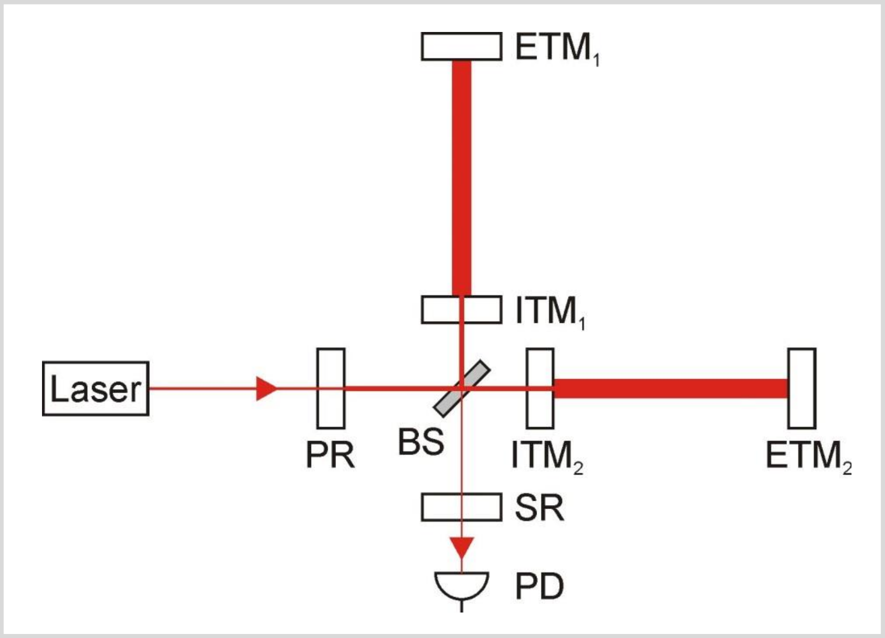
P. Murray, K. Haughian, I. Martin, R. Douglas, M. van Veggel, K. Craig, S. Rowan, J. Hough, G. Hammond (IGR)

A. Bertolini, E. Hennes (Nikhef)

SILICON AND SAPPHIRE

Why sapphire and silicon?

- Cryogenic detectors to decrease thermal noise
- Low loss at low T
  → crystalline materials
- Large dimensions available to further decrease noise

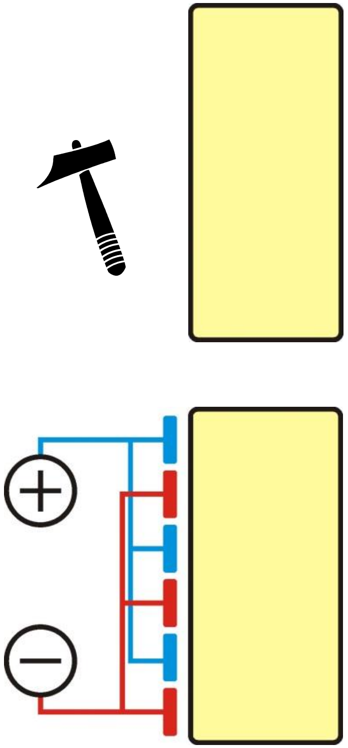


- Low absorption and high thermal conductivity to provide an operation at cryogenic temperatures

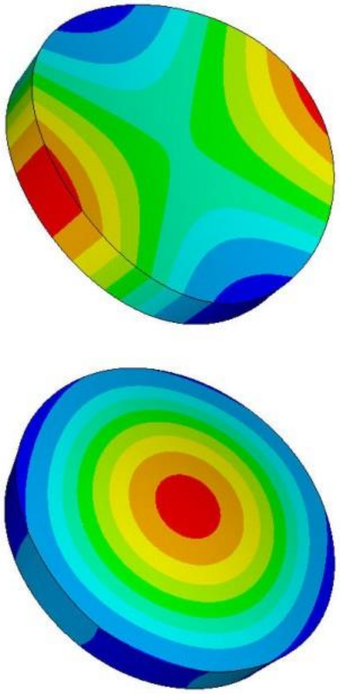
Experimental setup

- Mechanical loss measurements

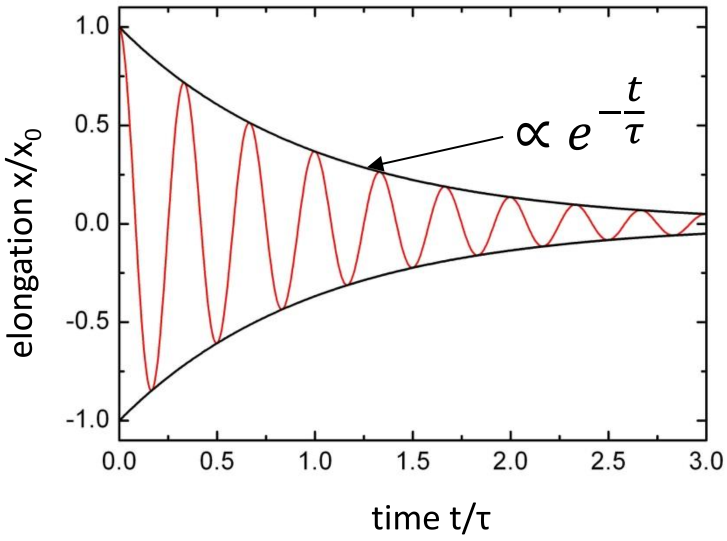
Resonant excitation



Formation of mechanical eigenmodes



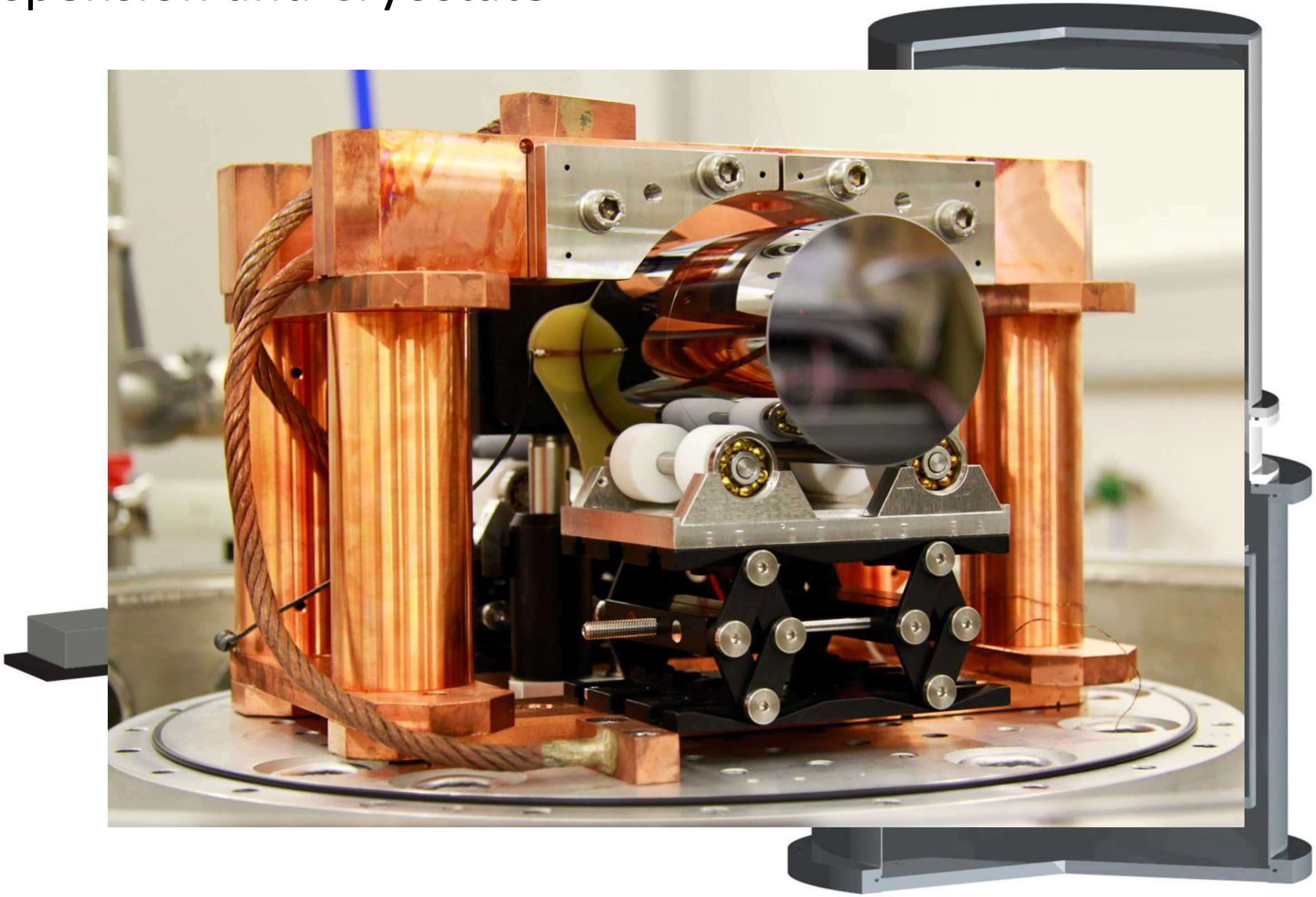
Recording of ring down



$$\phi = \frac{1}{\pi f \tau}$$

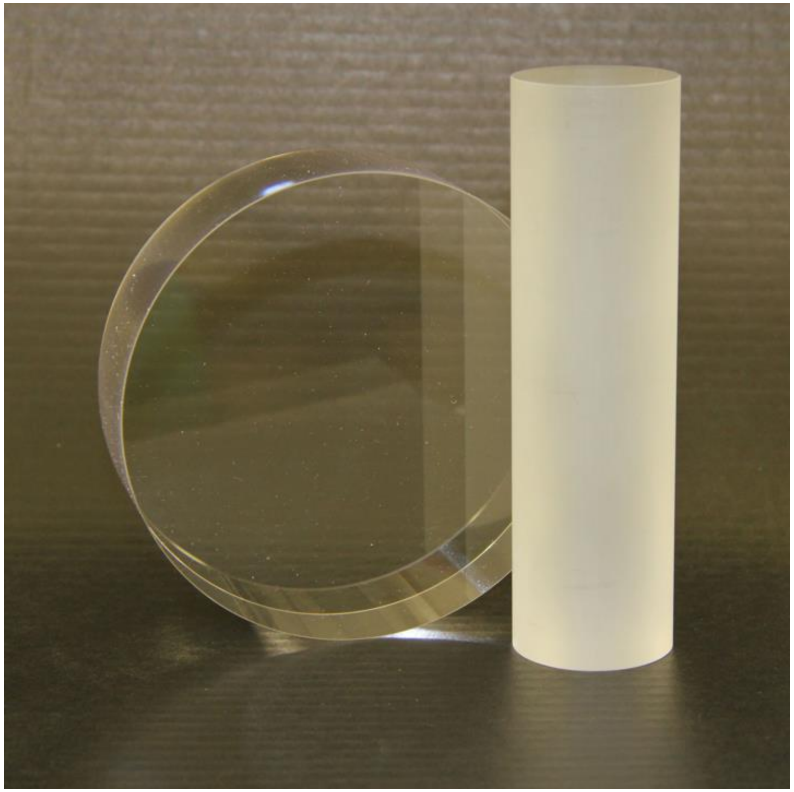
Experimental setup II

- Suspension and Cryostate

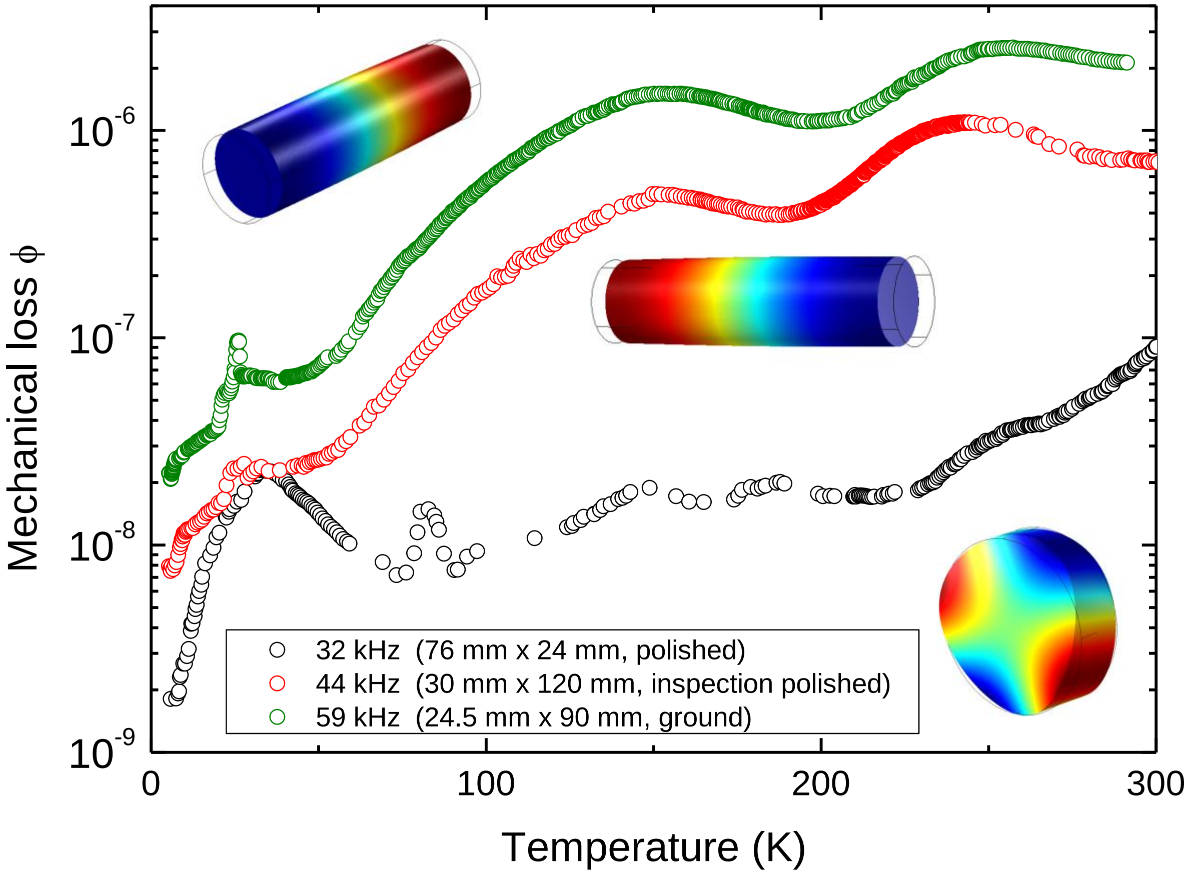


Sapphire results I

- Cylindrical samples with different surface roughness
  - Sample 1:
    Ø 7.6 cm x 2.4 cm,
    polished
  - Sample 2:
    Ø 3.0 cm x 12.0 cm,
    inspection polished
  - Sample 3:
    Ø 2.45 cm x 9.0 cm,
    ground



Sapphire results II



- surface roughness affects measured loss

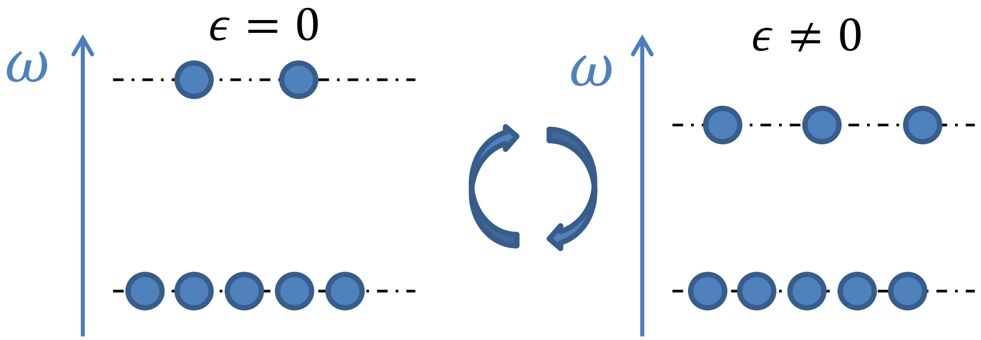
Akhieser loss

- Elastic strain deforms phonon dispersion

$$d\omega = \omega_0 \gamma \, d\epsilon$$

γ- Grüneisen parameter

- Redistribution of phonon population



Phonon collision rate from

$$\kappa = \frac{1}{3} C_p \rho c \tau$$

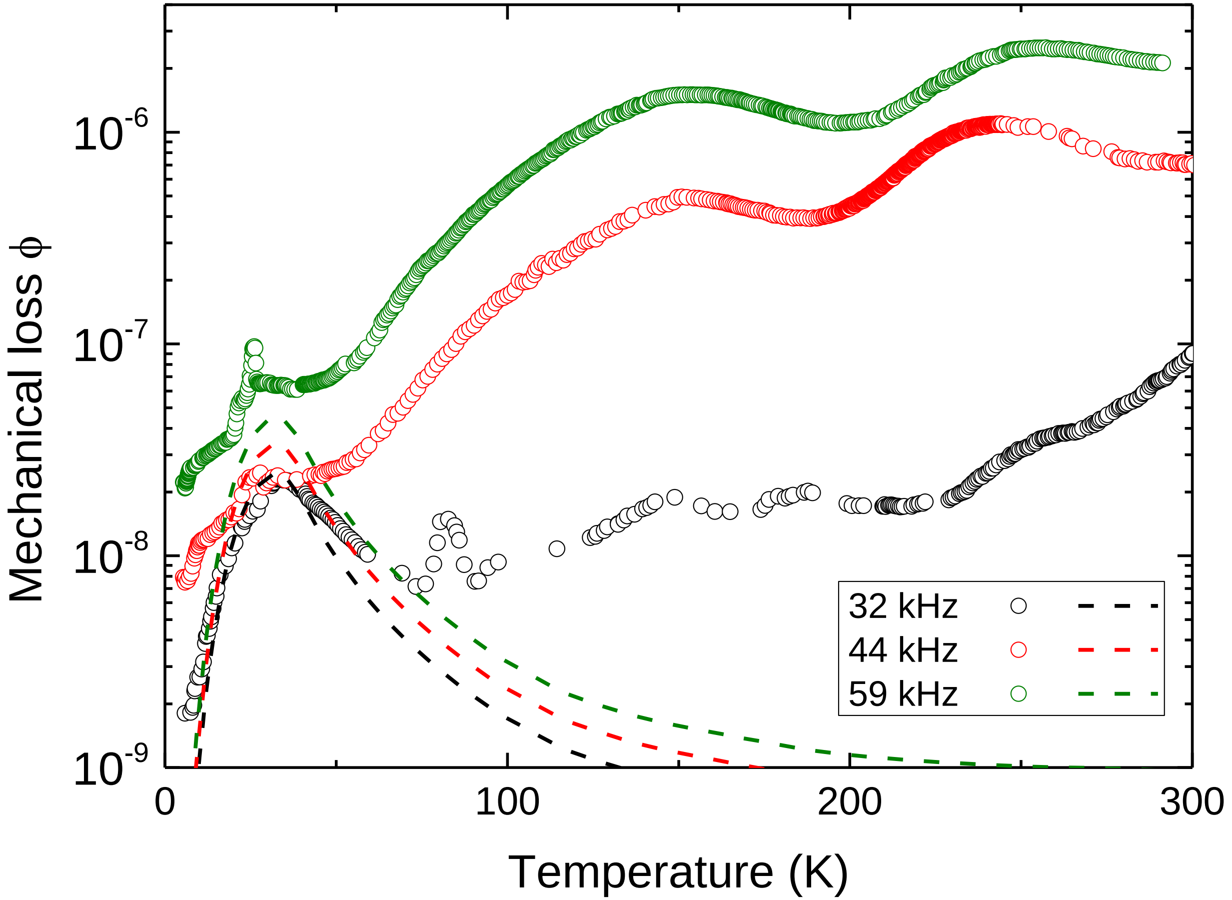
c – speed of sound

- Mechanical loss

$$\phi = \frac{C_p T \gamma^2}{c^2} \frac{\omega\tau}{1 + (\omega\tau)^2}$$

[Akhieser 1939, J. Phys. (USSR) 1]

Sapphire results III



- Akhieser damping seems to limit all samples at $T < 50$ K

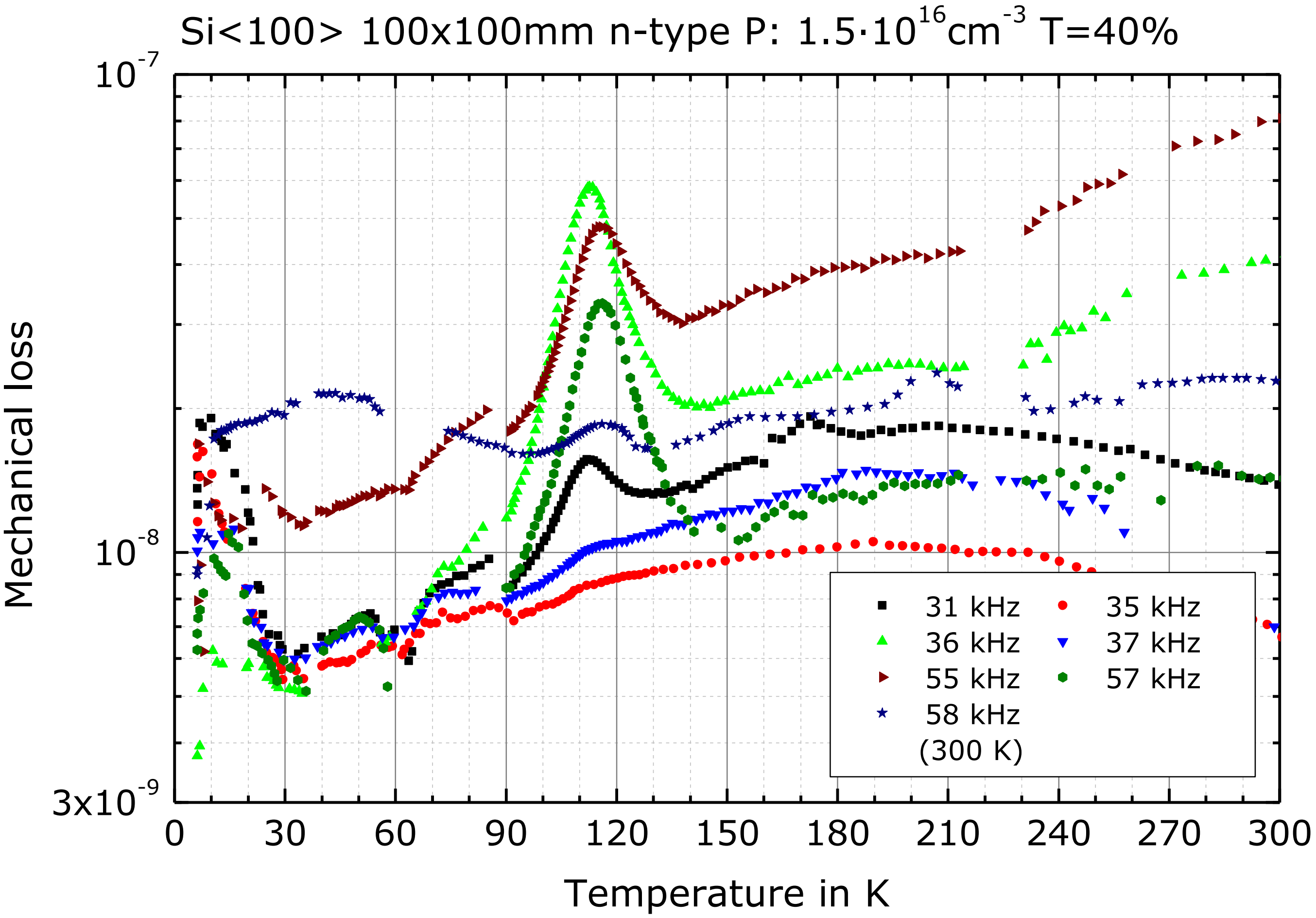
Silicon results

- Investigations ongoing with respect to
  - Doping
  - Surface termination
  - Crystalline orientation

- Samples under investigation
(Ø 10.0 cm x 10.0 cm, (100)-orientation)
  - Phosphorus-doped samples
    - Sample 1: 294 – 328 mΩcm ($n_d = 2 \times 10^{16}\ \mathrm{cm}^{-3}$)
    - Sample 2: 600 – 665 mΩcm ($n_d = 9 \times 10^{15}\ \mathrm{cm}^{-3}$)
    - Sample 3: 20 – 25 Ωcm ($n_d = 2 \times 10^{14}\ \mathrm{cm}^{-3}$)
  - Boron-doped samples
    - Sample 4: 2 – 4 Ωcm ($n_d = 5 \times 10^{15}\ \mathrm{cm}^{-3}$)

Loss peak at 120 K

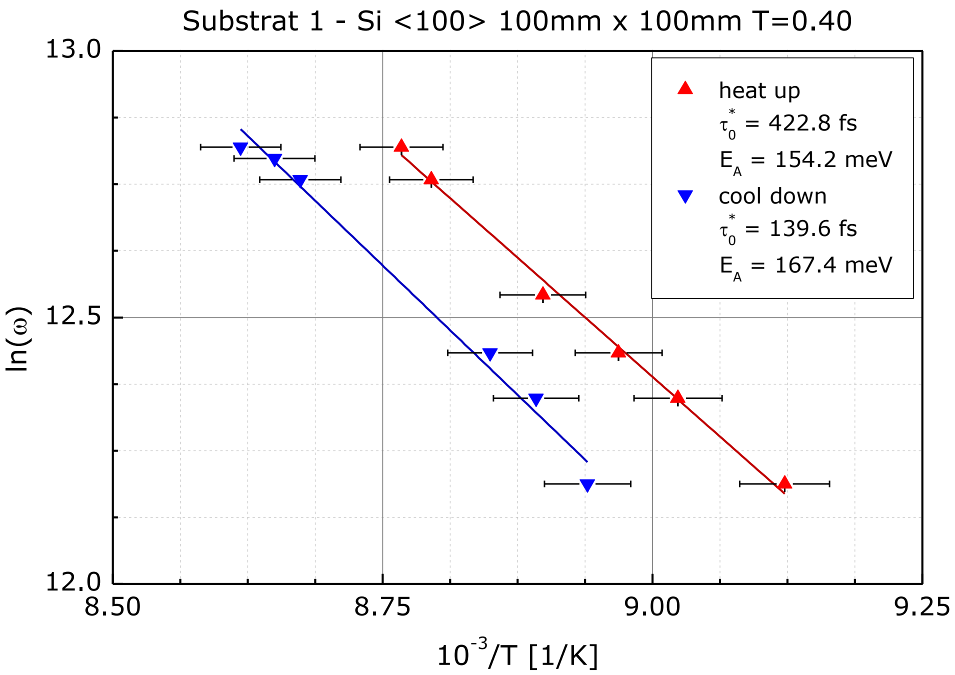
- Exemplary results for Sample 1



Loss peak characterization

- Arrhenius plot
  - Thermally activated process
  - Activation energy

$$E_a = (160 \pm 10)\ \mathrm{meV}$$

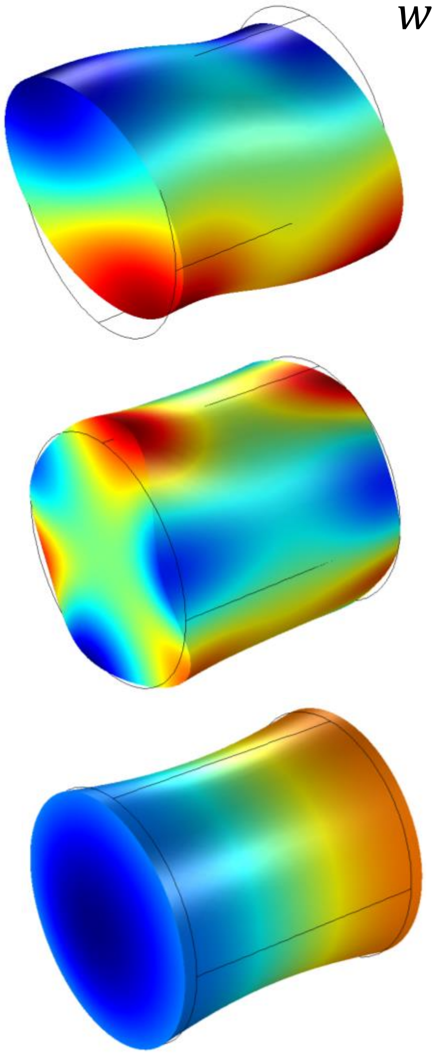


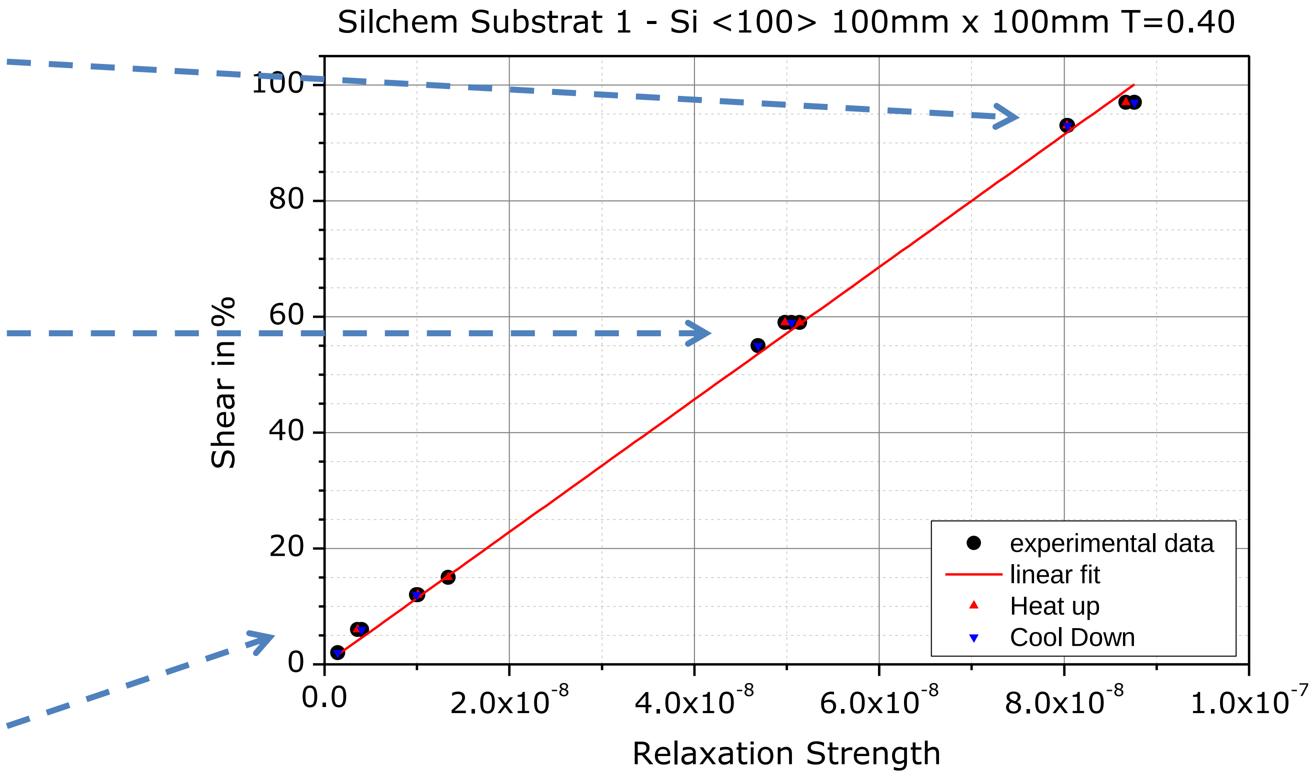
- Mechanical energy distribution

$$w = \frac{1}{2}\left(\sigma_{xx}u_{xx} + \sigma_{yy}u_{yy} + \sigma_{zz}u_{zz}\right) + \sigma_{xy}u_{xy} + \sigma_{xz}u_{xz} + \sigma_{yz}u_{yz}$$

Mode dependency of loss peak

$$w = \frac{1}{2}\left(\sigma_{xx}u_{xx} + \sigma_{yy}u_{yy} + \sigma_{zz}u_{zz}\right) + \sigma_{xy}u_{xy} + \sigma_{xz}u_{xz} + \sigma_{yz}u_{yz}$$

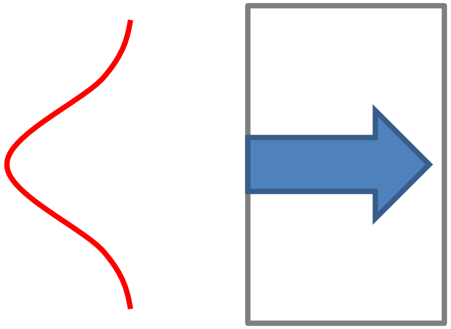




- Strong correlation between shear part of mechanical energy and peak height

Implications for a GW detector

- Orientation of the test mass might become crucial as it modifies the amount of shear energy
- Numerical estimate of Brownian substrate noise



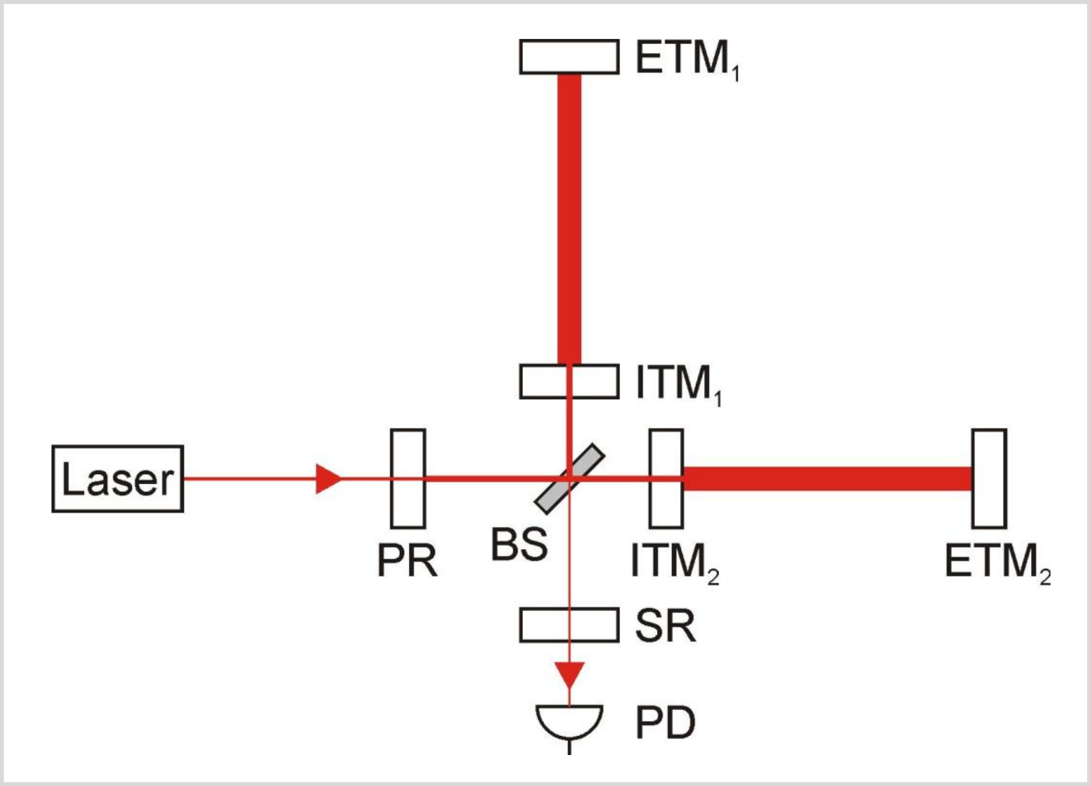
Orientation	$\langle 100 \rangle$	$\langle 110 \rangle$	$\langle 111 \rangle$
Normal energy	0.77	0.52	0.3
Shear energy	0.23	0.40	0.45
S_z without defects	1	0.91	0.88
S_z with defects	3.05	4.48	4.92

D. Heinert, A. Bell, G. Cagnoli, J. Degallaix, G. Gemme, S. Hild, J. Hough, H. Lück, I. W. Martin, R. Nawrodt, S. Rowan, S. P. Vyatchanin

A NEW KIND OF THERMAL NOISE: CARRIER DENSITY NOISE

Noise in transmissive elements

- Conventional GWD scheme



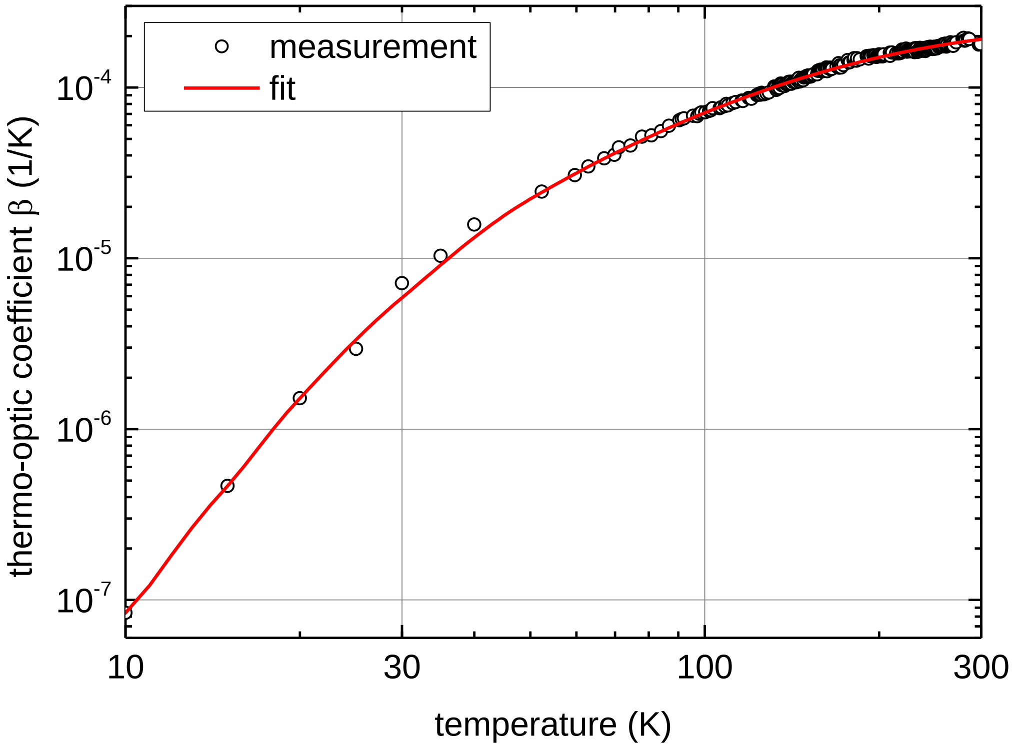
- ET-LF proposal: Si test masses (Ø 50 cm x 46 cm)

Thermorefractive noise

- Temperature dependence of refractive index

$$\beta = \frac{dn}{dT}$$

- TR noise in transmitted devices (e.g. ITM)



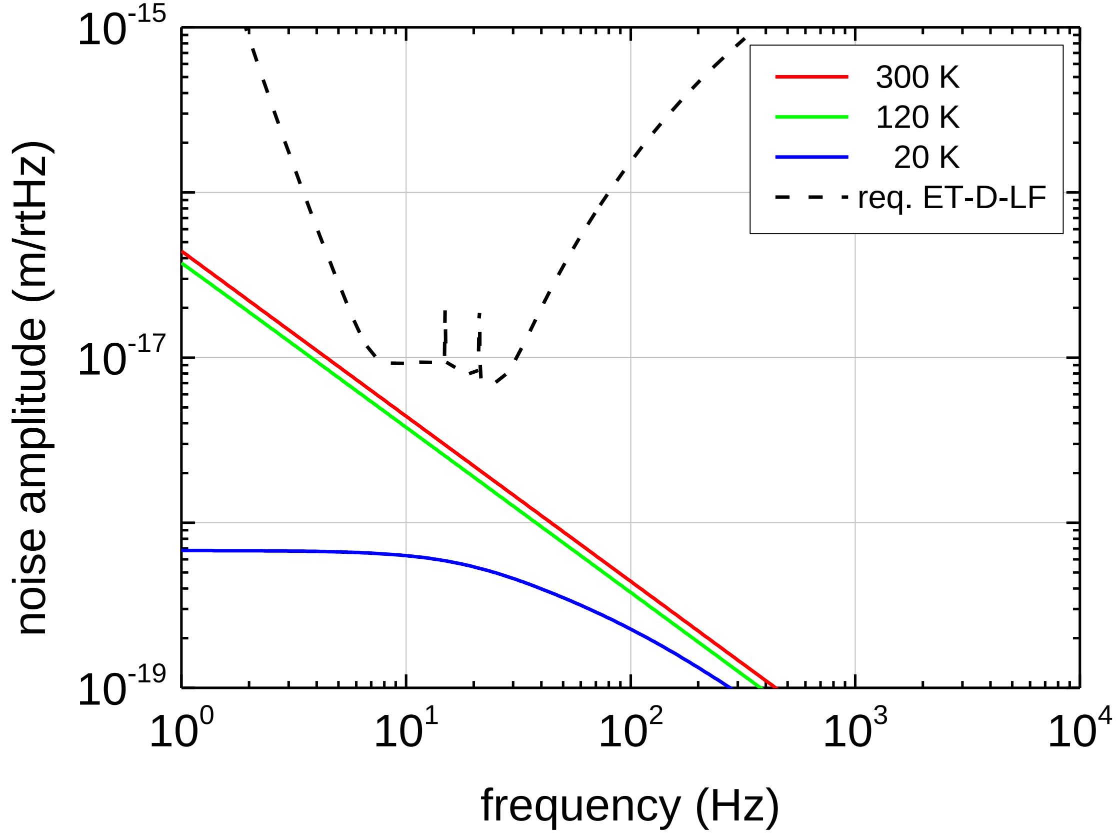
Extended values of β for silicon at low temperatures at 1550 nm

[Komma et al. 2012, APL 101]

Thermorefractive noise II

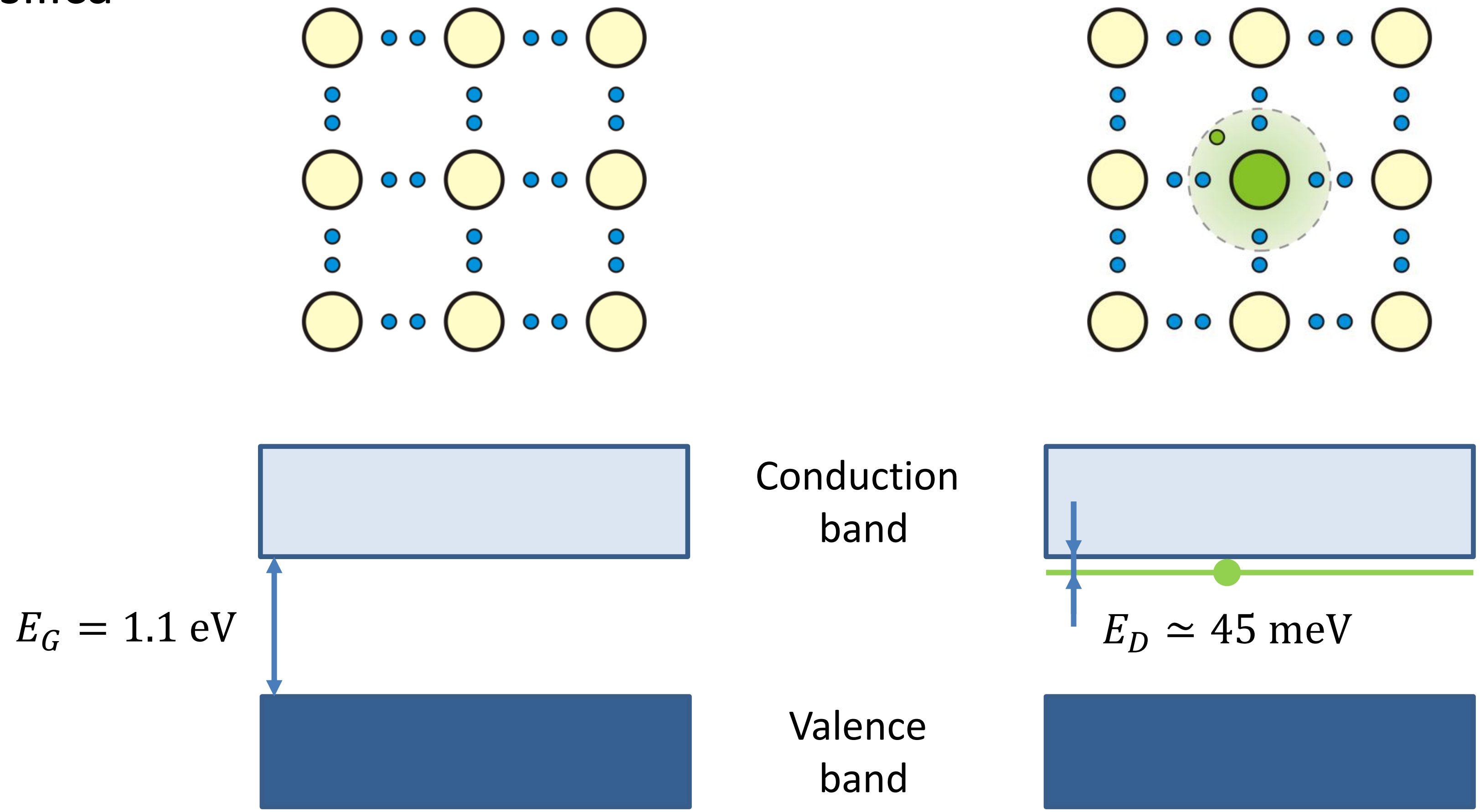
- Results of TR noise analysis in ET

[Heinert et al. 2011, PRD 84]



Silicon as a semiconductor

- Silicon shows different electronic properties compared to fused silica



Conduction band

Valence band

$E_G = 1.1\ \mathrm{eV}$

$E_D \simeq 45\ \mathrm{meV}$

Free carrier dispersion

- Density of free carriers (holes and electrons) affects refractive index of silicon

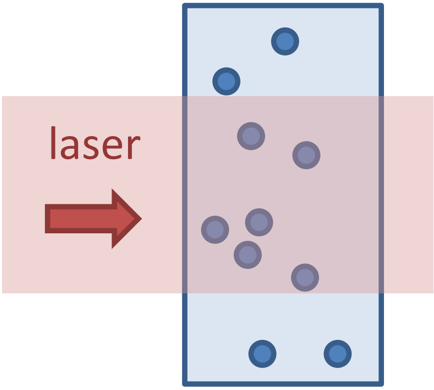
$$n = -8.8 \times 10^{-22} \left(\frac{n_e}{\mathrm{cm}^{-3}}\right) - 8.5 \times 10^{-18} \left(\frac{n_h}{\mathrm{cm}^{-3}}\right)^{0.8}$$

[Soref and Bennett 1987, IEEE J. Quant. Electron. QE-23]

- Density fluctuations of carriers induce noise

  → critical for transmissive silicon elements (ITM)

- Two types of carrier noise
  - Spatial motion characterized by diffusion
  - Excitation/recombination of carriers



Carrier density (CD) noise

- Modelling via Langevin approach

$$\frac{\partial n}{\partial t}(r,t) - D\Delta n(r,t) = F(r,t)$$

F- random force
D- diffusion coefficient for carriers

Uncorrelated fluctuational force $\langle F(r,t)F^*(r',t')\rangle = F_0\delta(t-t')$

- Particle density fluctuation of an electron gas

$$\langle n^2\rangle_V = \left(\frac{3}{\pi^4}\right)^{1/3}\frac{mk_BT}{\hbar^2}n^{1/3}\frac{1}{V}$$

→ determination of F_0

- Spectral density of CD noise

$$S_z(\omega) \simeq 4\sqrt[3]{\frac{3}{\pi^7}}\frac{H}{r_0^4}\frac{\gamma^2 mk_BT}{\hbar^2}\sqrt[3]{n}$$

Carrier density strain noise

- Parameter values: $\Delta n_{ref} = \gamma_e \Delta n_e + \gamma_h \Delta n_h$

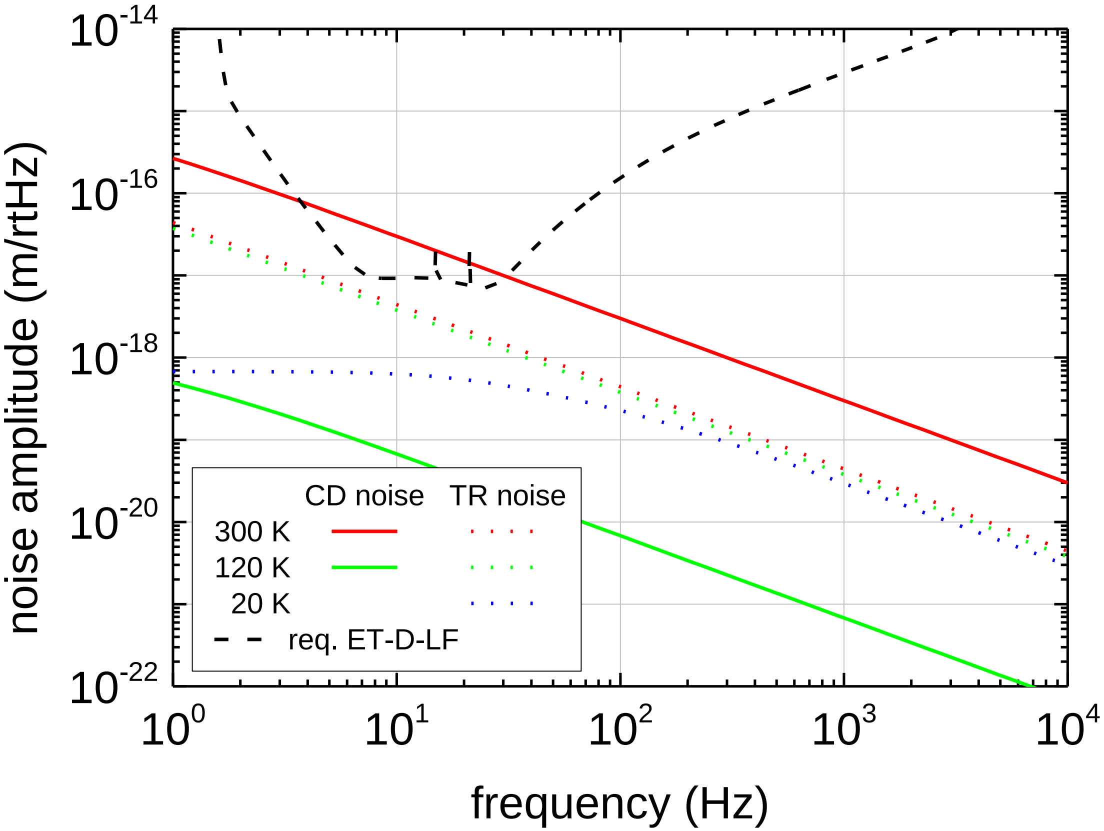
$$\gamma_e = -8.8 \times 10^{-22}\ \mathrm{cm}^3, \qquad \gamma_h = -10.2 \times 10^{-22}\ \mathrm{cm}^3, \qquad n \backsimeq 10^{10}\,\frac{1}{\mathrm{cm}^3}$$

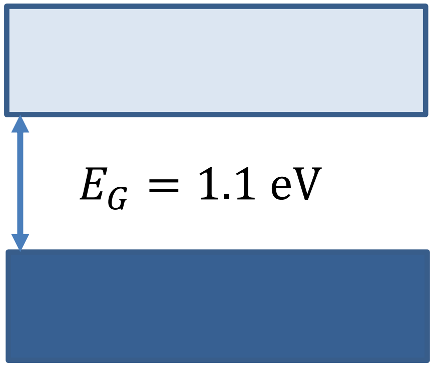
- Effect on detector strain sensitivity
  - Phase change in ITM $\Delta\varphi = \frac{4\pi}{\lambda}\Delta z$
  - Phase change due to GW $\Delta\varphi = \frac{4\pi}{\lambda} hL \frac{2}{\pi} F$
- Strain noise

$$S_z(\omega) = 2\left(\frac{2LF}{\pi}\right)^2 S_h(\omega)$$

Carrier density noise results

- CD noise due to intrinsic carriers in ET
  (Ø 50 cm x 46 cm, beam radius: 9 cm)

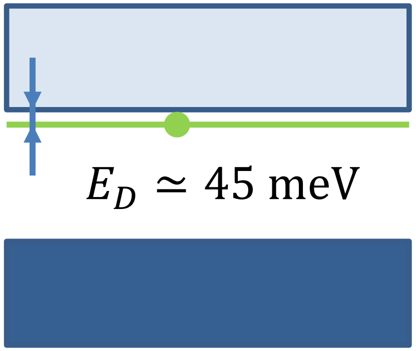




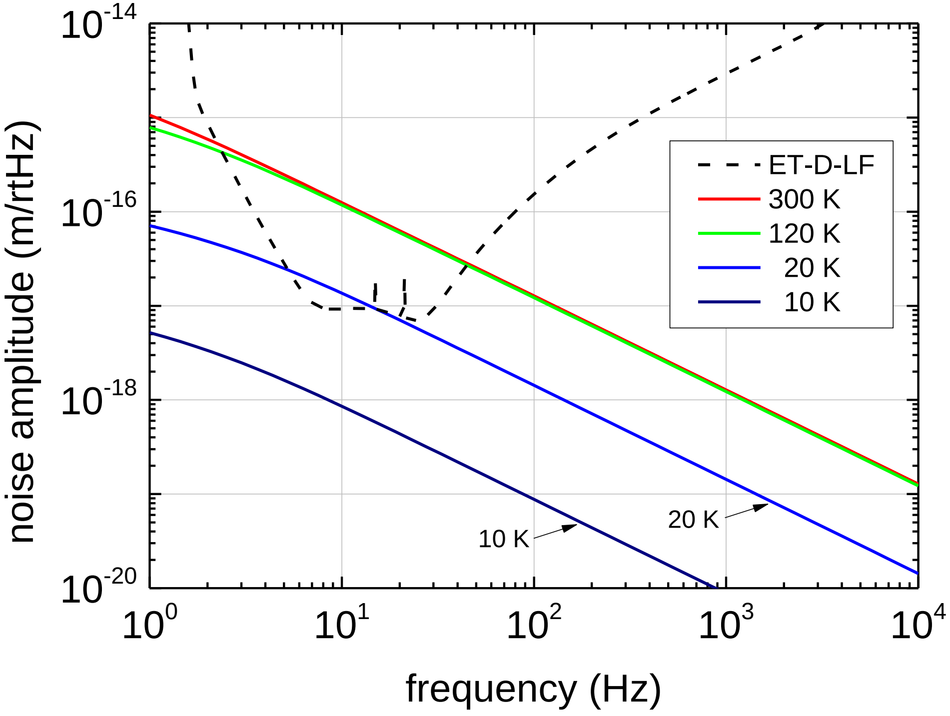
Carrier density noise results II

- CD noise due to dopants in ET (Ø 50 cm x 46 cm)

Model parameters	
dopand	phosphorus
Doping level	$10^{14}\ \mathrm{cm}^{-3}$
Beam radius	9 cm



$E_D \simeq 45\ \mathrm{meV}$



→ Dopants are likely to introduce a significant CD noise level

Conclusion

- Surface roughness affects sapphire loss mainly at T>50 K

- Loss peak at 120 K in silicon
  - does not depend on doping
  - might influence orientation of GW detector test mass

- Carrier density noise in Silicon
  - sets high limits on the purity of silicon
  - optimization of ET-LF design preferable