Optics for future GW detectors

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- GWADW 2013 -

20.05.2013

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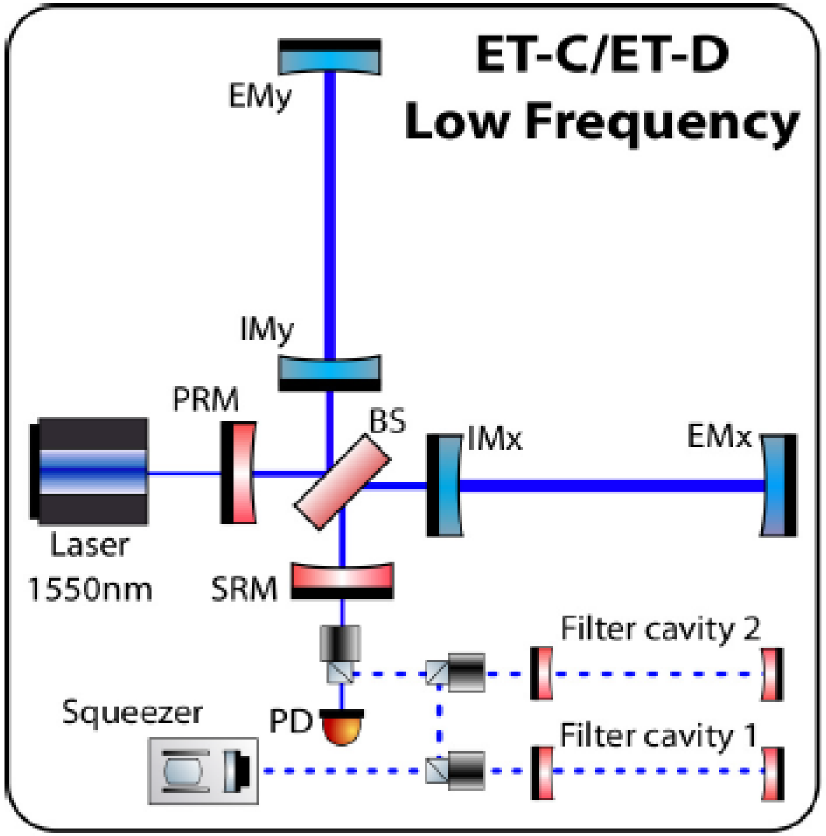
Overview

- Materials
- Crystal Growth
- Homogeneity
- Surface Quality
- Stress
- Birefringence

Detector layout

- Critical components: low temperatur IF $\rightarrow$ ITM

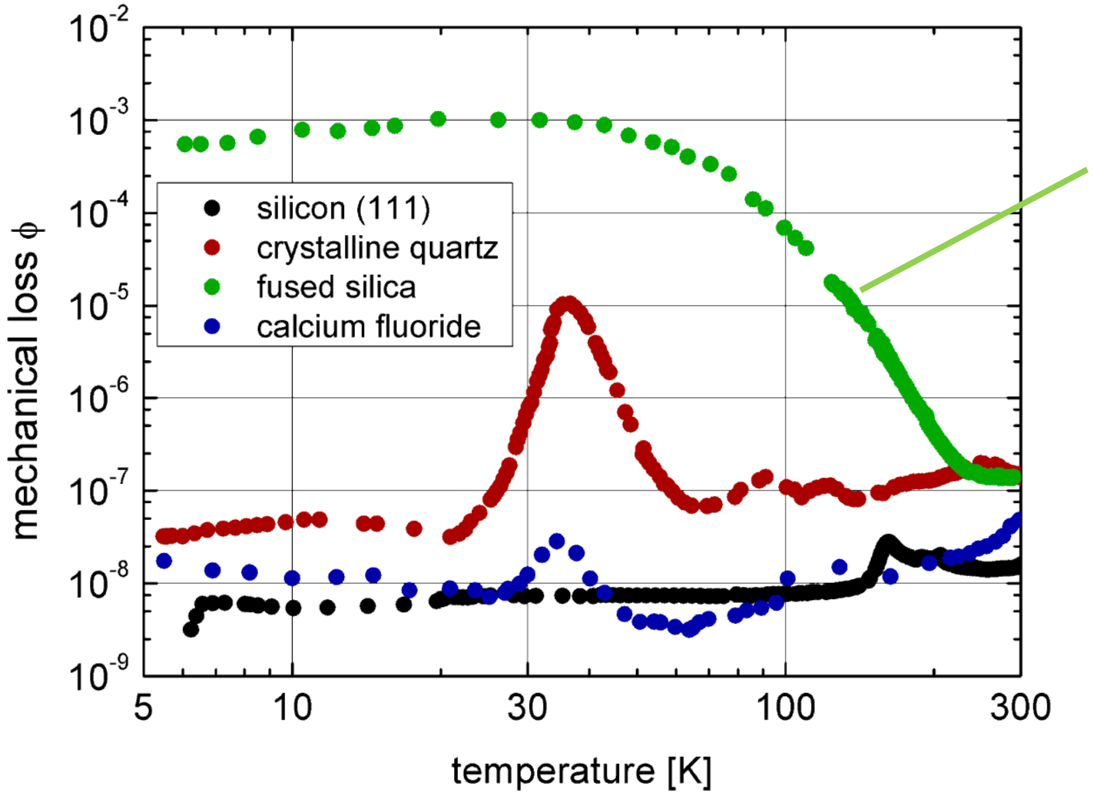


ET-HF properties clear and promising -> upscaling of existing fused silica work

Materials - Overview

Brownian thermal noise (mirror, suspension) ~ T×φ

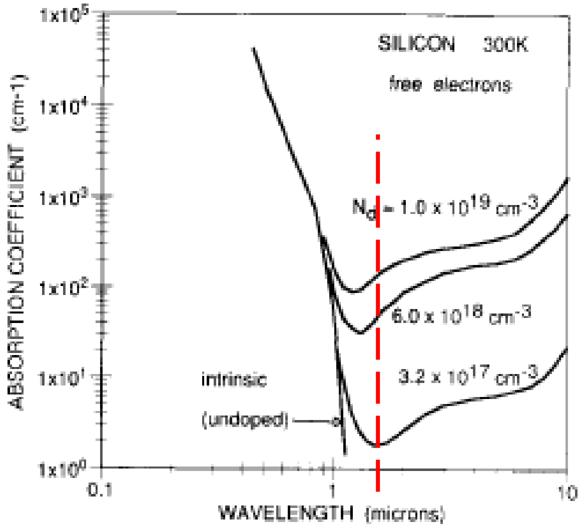
T ↓ φ ↓



large loss peak at low temperatures due to amorphous state

Materials - Choice

- currently 2 materials under consideration
  - silicon (main candidate)
  - sapphire (backup for ET– due to possible size limitations with sapphire)
- wavelength for silicon operation: 1550 nm



[Soref, Proc. IEEE 81 (1993)]

Alternatives?

- lower λ: fundamental gap absorption
- larger λ: increasing free carrier absorption

Materials – known and unknown parameters

- mechanical properties
  - mechanical loss
  - Young‘s modulus
  - strength (CZ better than FZ, oxygen getters dislocations)

    ⟶ design of suspensions [Poster by G. Hammond et al.]

- thermal properties
  - thermal conductivity
  - coefficient of thermal expansion

Materials – known and unknown parameters

- optical properties
  - dn/dT
  - absorption

    free carriers are playing cruical role [Talks by J. Komma, M. Granata]

$$\alpha_{fc} = \frac{Ne^2}{\epsilon_0 c n m^* \tau} \frac{1}{\omega^2}$$

N … free carrier density

τ … free carrier lifetime

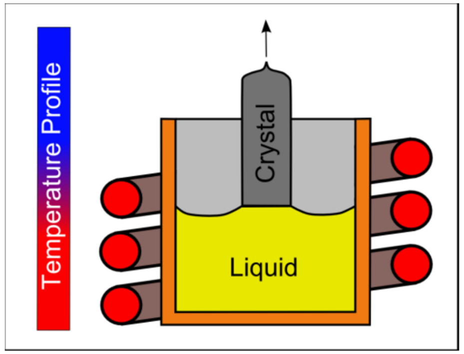
dependent on temperature and impurity concentration

  - new noise forms due to free carriers

    coupling between free carrier density and refractive index

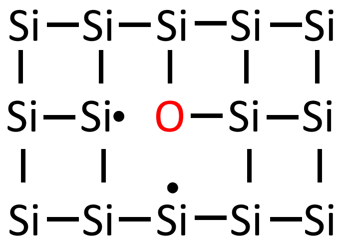
[collaboration is forming: welcome to join]

Crystal growth - size



Czochralski method

- large crystals (size limit: homogeneity of the temperature of the melt)
- industry changes wafer chucks to 450 mm technique $\rightarrow$ crystals available
- main impurities:
  oxygen (from silica cruicible, small corridor of possible concentrations around 10^{18} cm^{-3})
  carbon (from graphite heating)

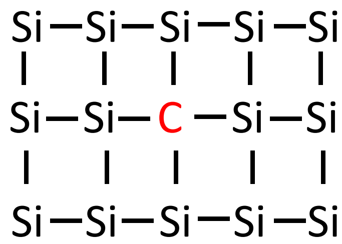


electrical/optical active

[Talk by G. Hofmann]

big variety of defects including oxygen

e.g. Si-O-vacancy defects



electrical/optical inactive

Crystal growth - size

float zone refining

- high purity crystals due to zone refining
- (some) impurities dissolve better in melt than in solid
  $\rightarrow$ cleaning process
- size limits:
  surface tension has to hold liquid region
  small slide @ high temperatures $\leftrightarrow$ high thermal conductivity

Homogeneity

- crystal growth from the melt

  → diffusion or mechanical stirring

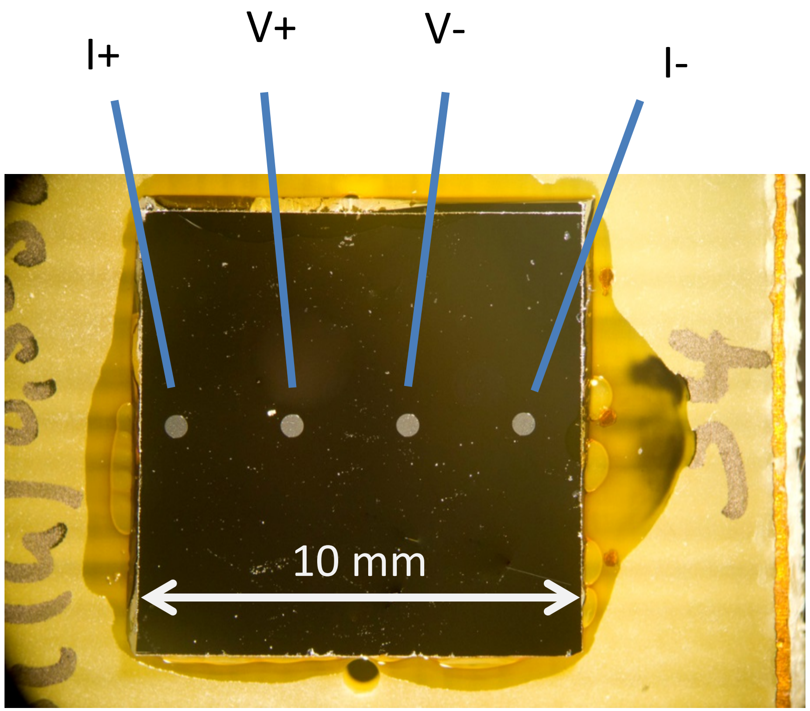
  → inhomogeneous distribution of defects, doping, etc. expected

  status 1970s: 30-50% lateral fluctuation on wafer

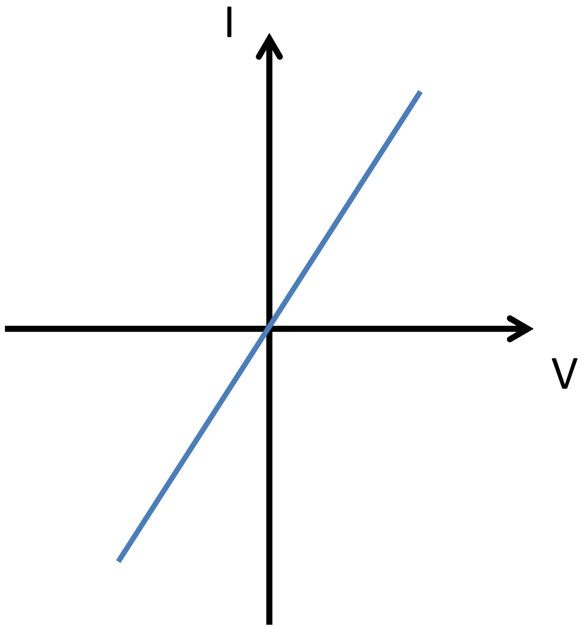
- distribution of:
  - oxygen, carbon, etc. (most likely defects in CZ/FZ silicon)
  - doping (electrical properties → link to absorption and refractive index)
  - mechanical stress
  - birefringence?

Homogeneity

- critical parameters (refractive index, absorption) dependent on local free carrier density → doping distribution needed at a local region on the crystal / wafer

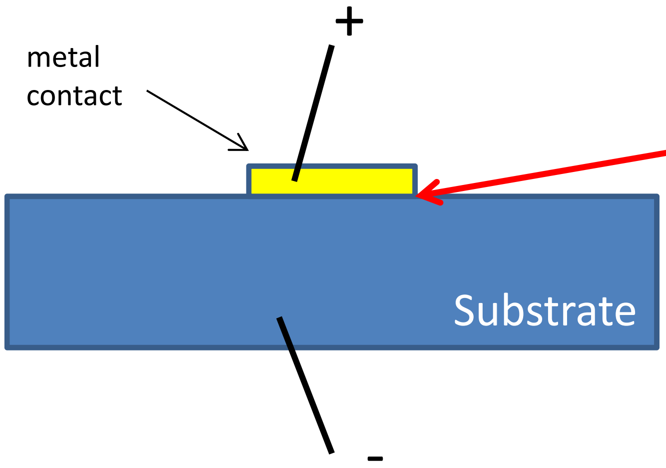


with correct metal pads:
ohmic behaviour of material
→ conductivity



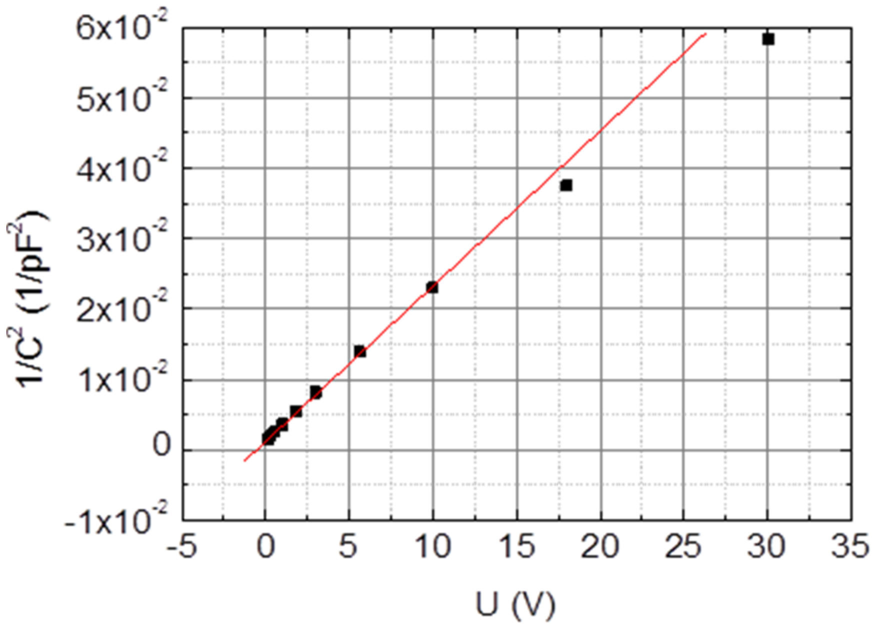
Homogeneity

- CV measurement



Capacity of space-charge region (per unit area):

$$C = \sqrt{\frac{eN\epsilon}{2(U_{BI} - U - {}^{1}/_{\beta})}} = \frac{\epsilon}{w}$$



formation of a Schottky-barrier
reverse bias: barrier capacity is voltage dependent -> CV-spectroscopy

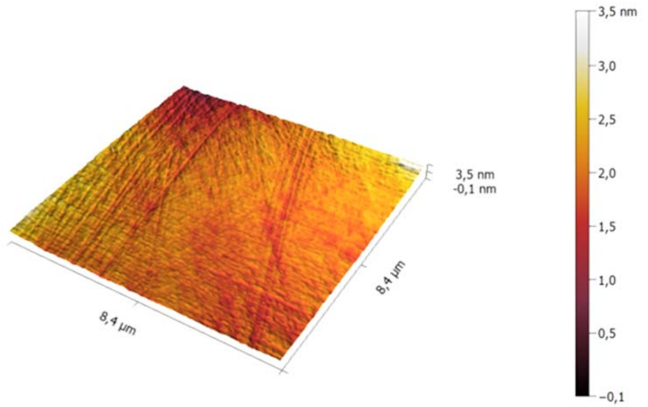
Surface quality

- roughness

  optical scattering

  $\sim n^2$ $\qquad$ $\sim {}^{1}/_{\lambda^4}$

  Fresnel $\qquad$ Rayleigh



- exact shape at cryogenics (ROC, astigmatism, etc.)

[Talk by J. Degallaix]

Interfaces

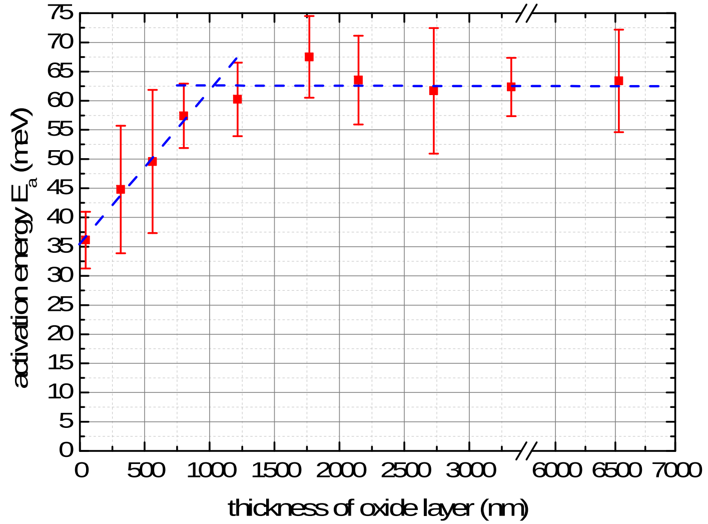
- absorption effects at interfaces / surfaces

  [Poster A. Khaleidovski et al.]

- passivation layers

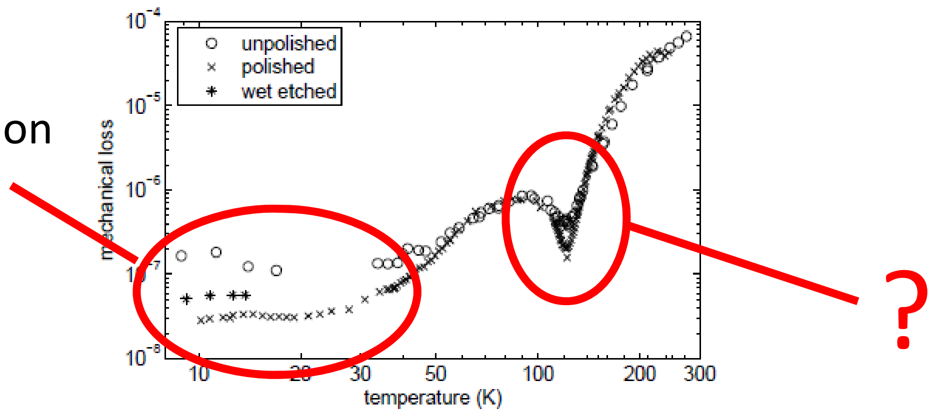
- surface loss

Dependence of the activation energy of a thermal oxide layer on silicon



[Poster G. Hofmann et al.]

Dependence of mechanical loss on surface quality



[R. Nawrodt et al., CQG 30 (2013)]

Thermal stress

- crystalline materials: large CTE

  temperature shock → buildup of large stress → breaking along symmetry axes

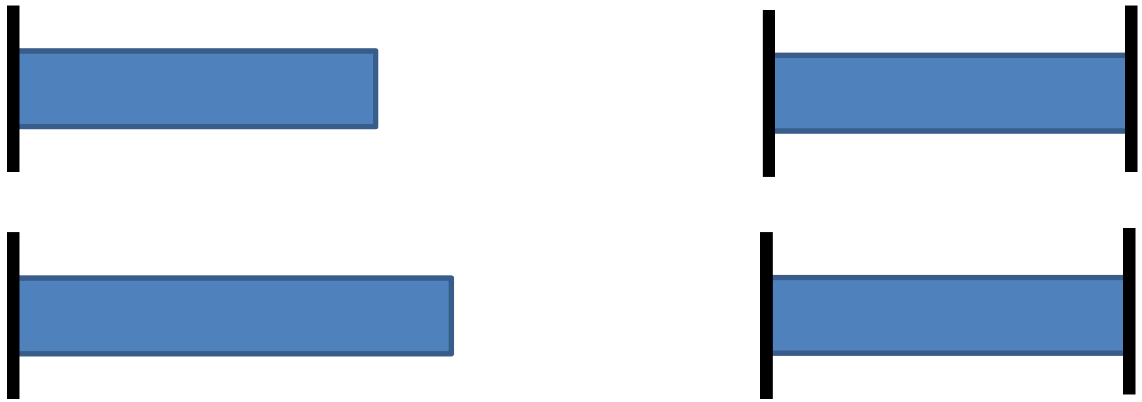
- interface: different CTEs

broken CaF_2 crystal due to thermal shock (ΔT ~ 10 K), CaF_2 (111)

[credits to D. Heinert]

Stress at interfaces - basics

- Temperature change in a clamped - free and clamped - clamped sample



$\sigma_{th} = 0, \varepsilon_{th} = \alpha\, \Delta T$

$\varepsilon_{tot} = \varepsilon + \varepsilon_{th} = 0, \sigma_{th} = C\varepsilon = -C\, \alpha\, \Delta T$

$$\sigma_{ik} = -K\alpha\Delta T\delta_{ik} + K\varepsilon_{ll}\delta_{ik} + 2\mu\left(\varepsilon_{ik} - \frac{1}{3}\delta_{ik}\varepsilon_{ll}\right)$$

$$K = \frac{Y}{3(1-2\sigma)}$$

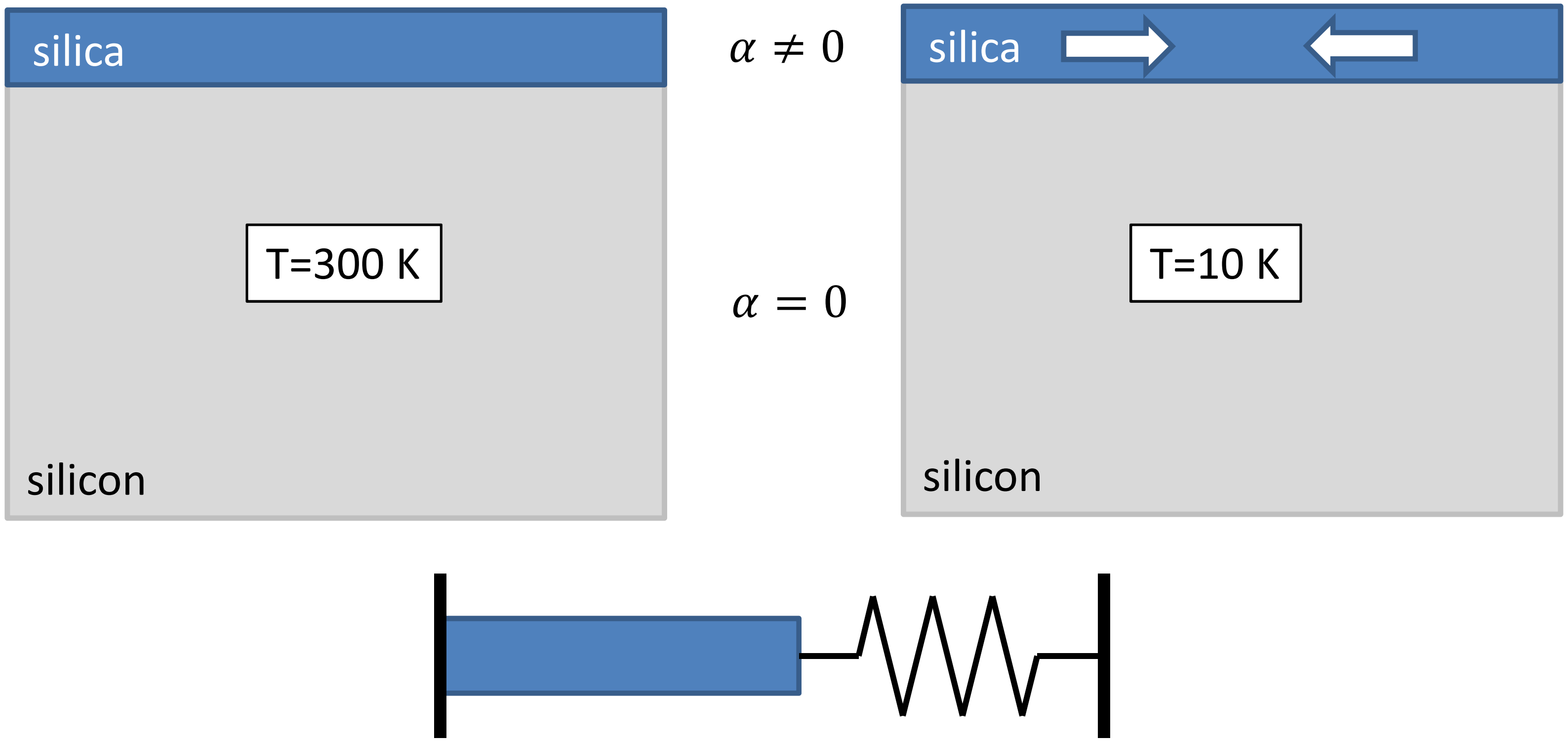
$$\mu = \frac{Y}{2(1+\sigma)}$$

[Landau + Lifshitz, Elasticity]

[credits to D. Heinert]

Stress at interfaces - modelling

- Silica layer (as example substitute for the HR stack) on top of an ET-LF silicon substrate

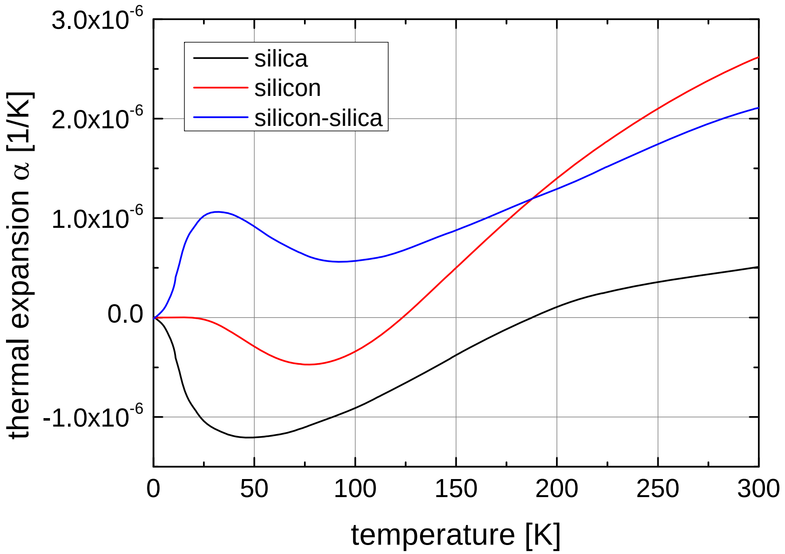


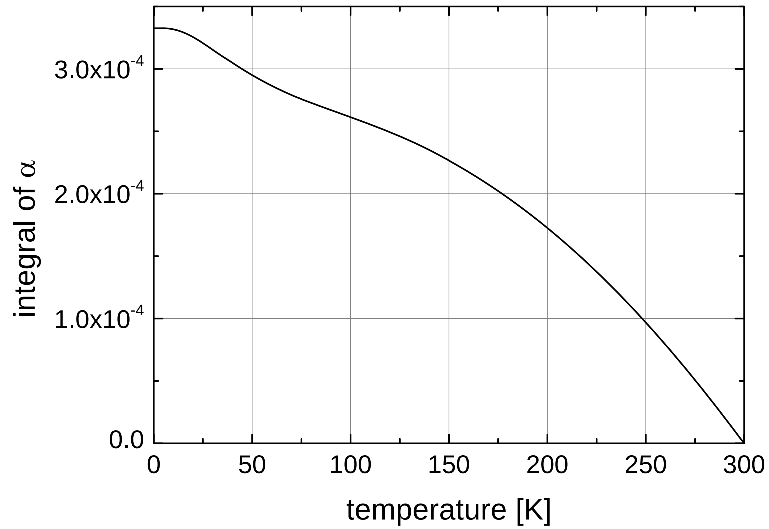
[credits to D. Heinert]

Stress at interfaces – CTE‘s

- $\alpha_{rel} = \alpha_{Si} - \alpha_{SiO_2}$

$$\int_{300K}^{T} \alpha(T)dT$$



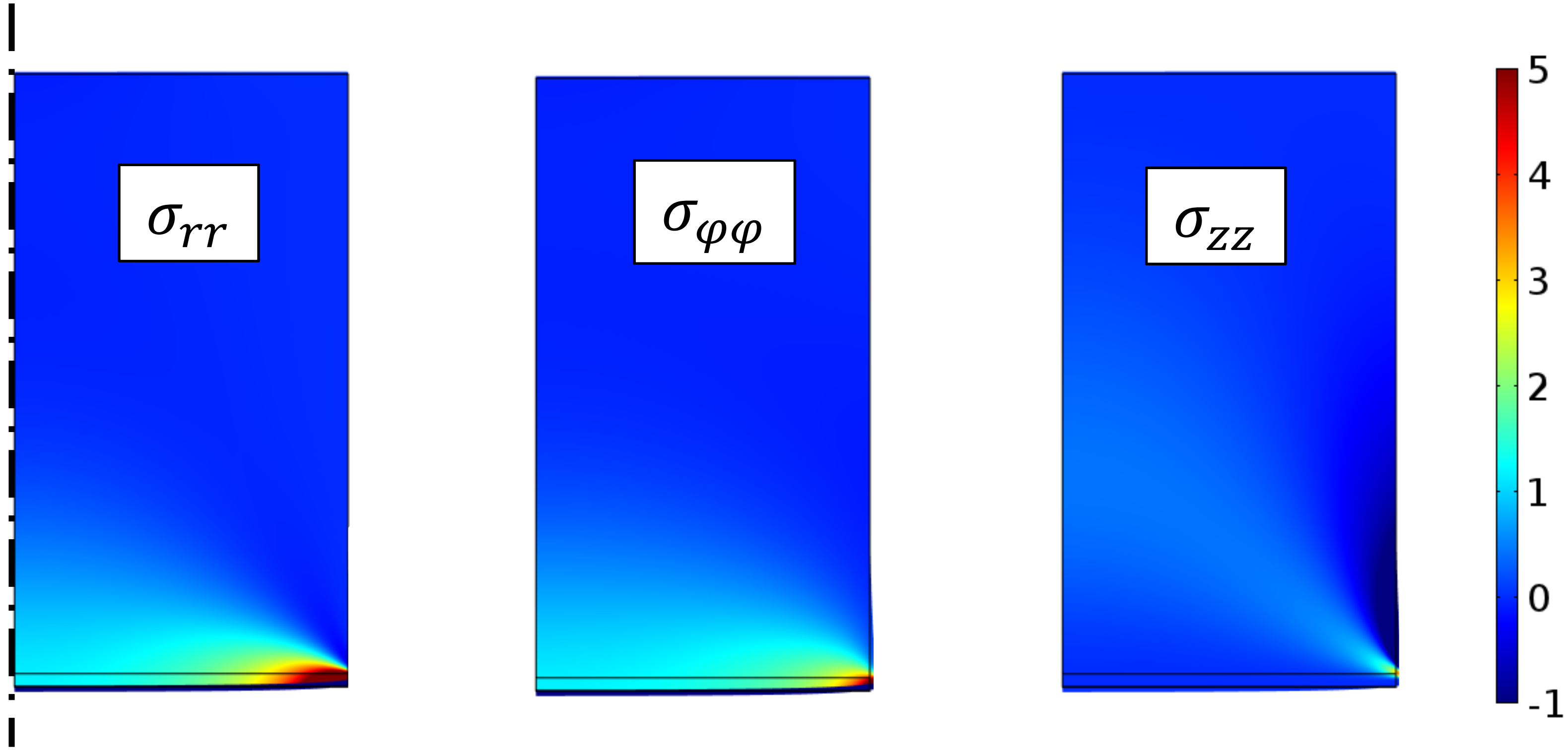


[G. K. White and M.L. Minges, Int. J. Thermophys. 18 (1997), 1269-1327]

[G. K. White, J. Phys. D: Appl. Phys. 6 (1973), 2070-8]

[credits to D. Heinert]

Stress at interfaces - FEA

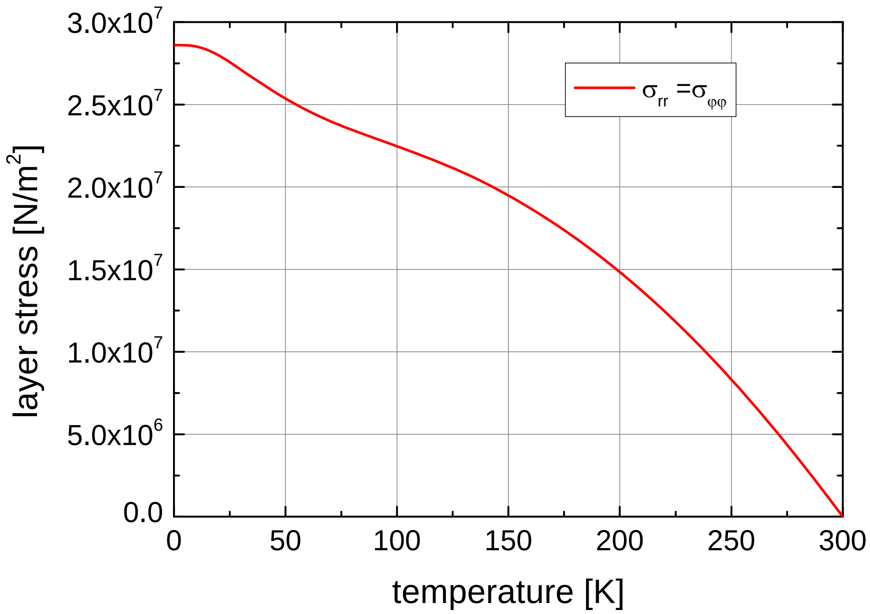


in the layer: $\sigma_{\varphi\varphi} = \sigma_{rr} =$ const.

symmetry: $\sigma_{r\varphi} = \sigma_{\varphi z} = 0$

[credits to D. Heinert]

Stress at interfaces – layer stress



$$\sigma_{xx} = \sigma_{rr}\cos^2\varphi - \left(\sigma_{r\varphi} + \sigma_{\varphi r}\right)\cos\varphi\sin\varphi + \sigma_{\varphi\varphi}\sin^2\varphi,$$

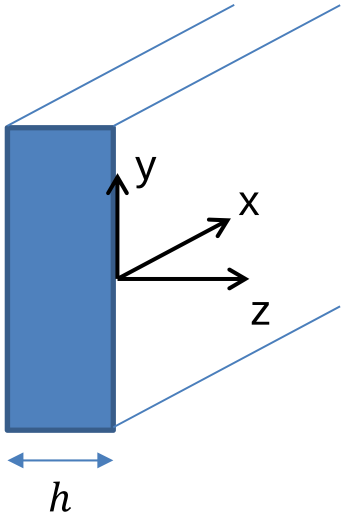
$$\sigma_{yy} = \sigma_{\varphi\varphi}\cos^2\varphi + \left(\sigma_{r\varphi} + \sigma_{\varphi r}\right)\cos\varphi\sin\varphi + \sigma_{rr}\sin^2\varphi$$

[credits to D. Heinert]

Stress induced birefringence

$$n_1 - n_2 = \frac{1}{2} n_0^3 (q_{11} - q_{12})(\sigma_{xx} - \sigma_{yy})$$

q - stress-optical coefficients



Resulting phase change:

$$\delta = \frac{2\pi}{\lambda} h\,(n_1 - n_2) = \frac{2\pi}{\lambda} Ch(\sigma_{xx} - \sigma_{yy})$$

With C as the ‚effective' stress optical coefficient

$$C = \frac{1}{2} n_0^3 (q_{11} - q_{12})$$

For fused silica @ 300 K and 1550 nm

$$C \simeq 30 \times 10^{-13}\ {}^{1}/_{\mathrm{Pa}}$$

[A. J. Barlow, D. N. Payne, IEEE J. Quantum Electron. QE-19 (1983), 834-9]

At low T (fused silica): $\sigma \simeq 3 \times 10^7\ \mathrm{Pa} \Rightarrow n_1 - n_2 \simeq C\sigma \simeq 10^{-4}$

Stress induced birefringence – next tasks

- investigation of stress + birefringence within ET R&D project
  (Aspera) between different groups in Europe
- symmetry of stress $\rightarrow$ symmetry of birefringence
  (both in coatings and bulk)
- coupling into the interferometer (which stress is dangerous?)

Summary and Conclusions

- many properties are promising for Si use in cryo IF (both 125 K and < 20 K)
- dynamics of free carriers (at low temperatures) needs to be investigated in more detail $\rightarrow$ effects on noise and absorption
- investigation of homogeneity of parameters
- if only CZ silicon large enough: check if compensated material can fulfill requirements $\rightarrow$ mechanical loss, thermal properties, optical properties, free carrier density at low temperatures