Developments in test mass and suspension materials for future detectors

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Introduction

- To achieve the desired sensitivities of future long-baseline gravitational wave detectors will require a reduction in thermal noise associated with test masses and their suspensions

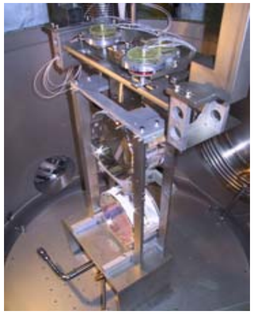
- Extend research in the development of low dissipation quasi-monolithic suspensions, acquired through designing suspensions for GEO 600 and Advanced LIGO, to:

  - develop ultra-low thermal noise suspensions for ‘GEO-HF’ capable of sustaining high optical powers (room temperature)

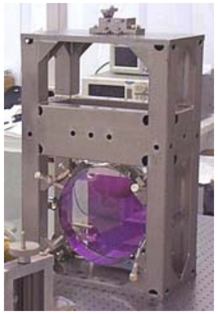
  - develop ultra-low thermal noise suspensions for EGO and equivalent 3rd generation detections (cryogenic temperatures)

Suspension technology status

current detectors eg:

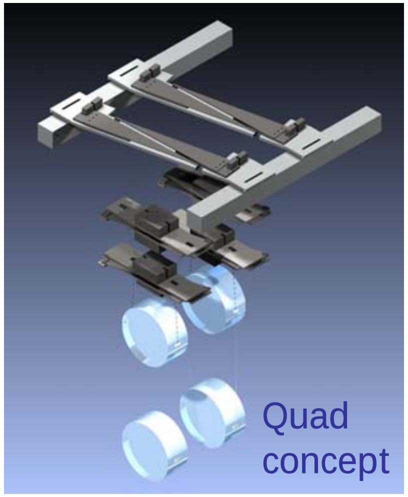


GEO 600
Silica suspension.
Arm length: 600 m.



Initial LIGO
Wire loop.
Arm length: 4 km.

advanced detectors



e.g. Advanced LIGO
Quadruple stage.
Sapphire/silica.
Ribbons/fibres.
Arm length: 4 km.

being designed

operational

current research

future detectors

e.g. GEO-HF, EGO, others?

Silicon suspension technology.

- **Studies of:**
  - **fabrication of, and dissipation in silicon suspension elements**
  - **intrinsic dissipation in bulk silicon**
  - **fabrication and dissipation of monolithic silicon pendulums**

See talk by Jim Hough

Challenges for future detectors – why silicon ? #1

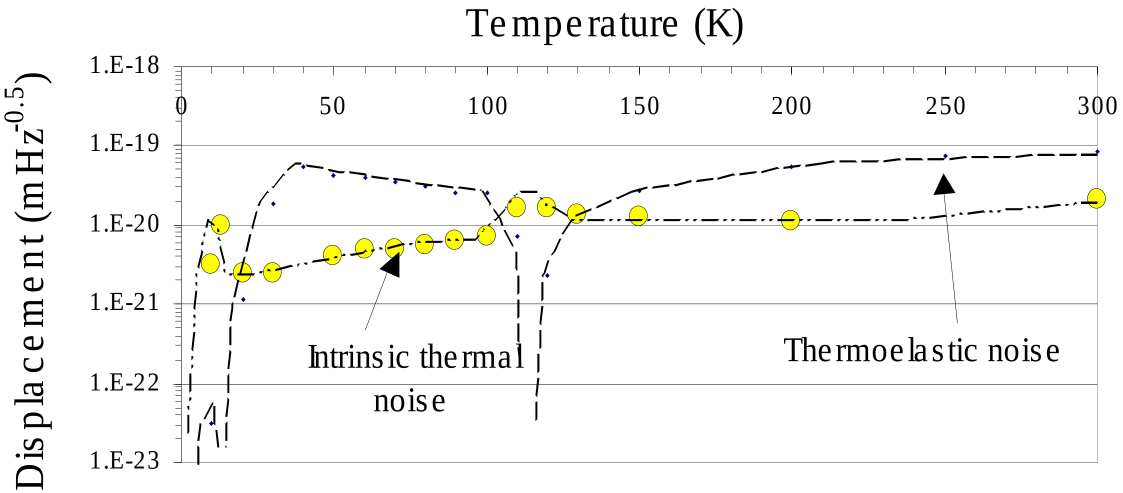
- To improve shot noise limited sensitivity, future detectors may require higher levels of laser power than currently used
  - Require mirror substrates capable of sustaining high thermal loads whilst maintaining optical figure
  - Thermally induced deformation of mirror surface is proportional to α/k_{th} [Winkler *et al.*, 1991].

    α = substrate expansion coefficient

    k_{th} = substrate thermal conductivity
  - Would like a substrate material for which this figure of merit is minimised
- In addition, further reductions in test mass and suspension thermal noise are required
- Possible material meeting these requirements is silicon
- GEO considered silicon mirrors Circa early 90's - at that time purchased substrates polished by Zeiss – but laser/diffractive technology not mature at that time
- Over past few years re-visiting this incorporating recent developments

Challenges for future detectors – why silicon ? #2

- Two relevant types of mechanical dissipation:
  - **“Intrinsic” dissipation (eg: due to point defects or line dislocations)**
  - **Thermoelastic dissipation, associated with temperature fluctuations throughout the mass (depends on fundamental material properties)**
- Silicon can have low intrinsic dissipation but thermal noise at low frequencies dominated by thermoelastic noise
- Both thermoelastic and intrinsic thermal noise may be reduced by cooling:



Calculated intrinsic thermal and thermoelastic noise @ 10 Hz in a single silicon test mass, sensed with a laser beam of radius ~ 6 cm

- Thermoelastic noise is proportional to α and should vanish at T ~120 K and ~18 K where α tends to zero
- Intrinsic thermal noise exhibits two peaks at similar temperatures
- Silicon may allow significant thermal noise improvements at low temperatures but material properties need further study

In more detail

- From Braginsky et al:

$$x^2(\omega) = \frac{8}{\sqrt{2\pi}}\,\alpha^2(1+\sigma)^2\,\frac{k_b T^2}{\rho\, C}\,\frac{a^2}{r_0^3}\,\frac{1}{\omega^2}$$

(1) Need values for α(T), C(T), K$_{th}$(T)

(2) Formula is valid for $\omega \gg a^2/r_0^2 \sim 1/\tau$

α = coefficient of thermal expansion
σ = Poisson's ratio
ρ = density
C = specific heat capacity
$a^2 = K_{th}/\rho C$: K_{th} = thermal conductivity

r_0 = beam radius at which intensity drops to 1/e
ω = angular frequency

$$x^2(\omega) = \text{Constant}\;\frac{\alpha^2\; T^2}{C}\,\frac{1}{r_0}\,\frac{a^2}{r_0^2}\,\frac{1}{\omega^2}$$

$$= \text{Constant}\;\frac{\alpha^2\; T^2}{C}\,\frac{1}{r_0}\,\frac{1}{\omega\,\tau}\,\frac{1}{\omega}$$

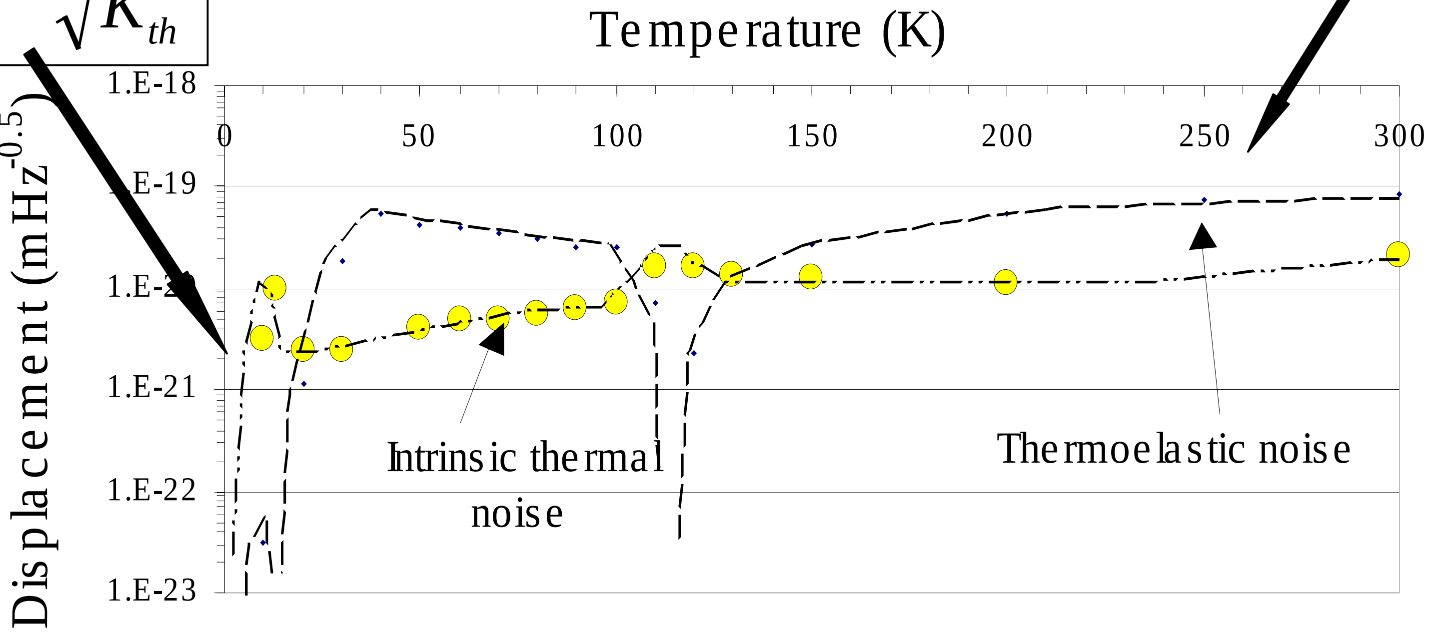
Following classical thermo-elastic damping - more generally replace $\frac{1}{\omega\,\tau}$ by $\frac{\omega\,\tau}{1+\omega^2\tau^2}$

Figures of merit in different regimes

- From Braginsky et al:

$$x(\omega) \propto \frac{\alpha T}{\sqrt{K_{th}}}$$

$$x(\omega) \propto \frac{\alpha T \sqrt{K_{th}}}{C} \frac{1}{\omega}$$



Calculated intrinsic thermal and thermoelastic noise @ 10 Hz in a single silicon test mass, sensed with a laser beam of radius ~ 6 cm

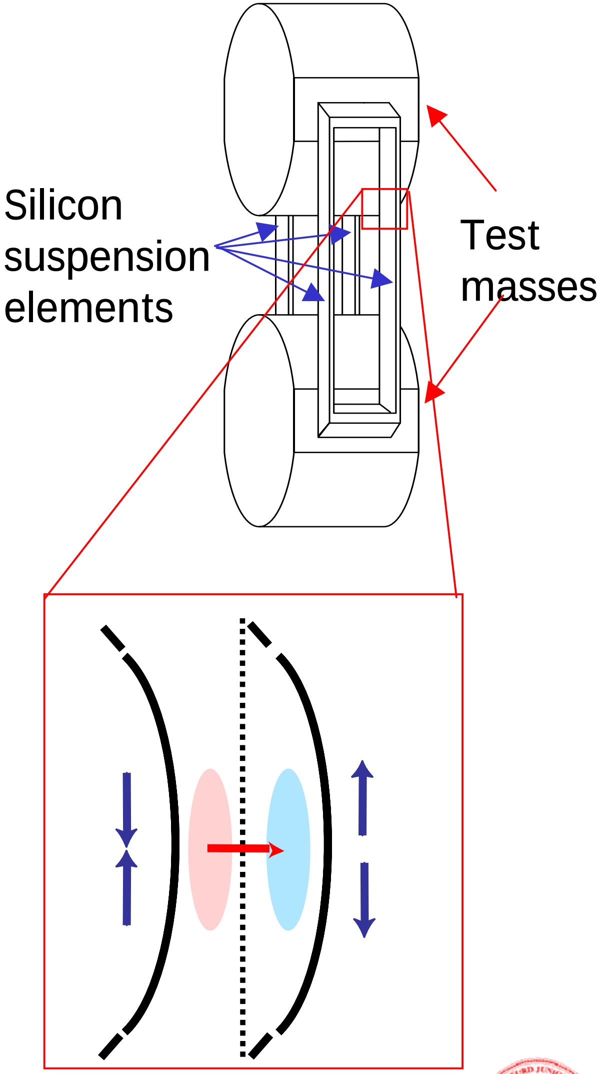
- From Touloukian, K_{th} of silicon can vary significantly, especially at low temperatures, depending on doping

Dissipation in silicon suspension elements

- Thermoelastic dissipation, $\phi_{th}(\omega)$, is associated with the flexing of thin suspension elements [see,eg: Nowick and Berry]

$$\phi_{th}(\omega)=\frac{E\alpha^2T}{\rho C}\frac{\omega\tau}{1+\omega^2\tau^2}\qquad \tau=\frac{1}{2\rho f_{char}}\qquad f_{char}=\frac{\pi K_{th}}{2\rho C t^2}$$

- These provide a convenient means to study:
  - (a) thermoelastic dissipation and its dependence on material properties and temperature
  - (b) other sources of dissipation associated with suspension elements – eg surface effects

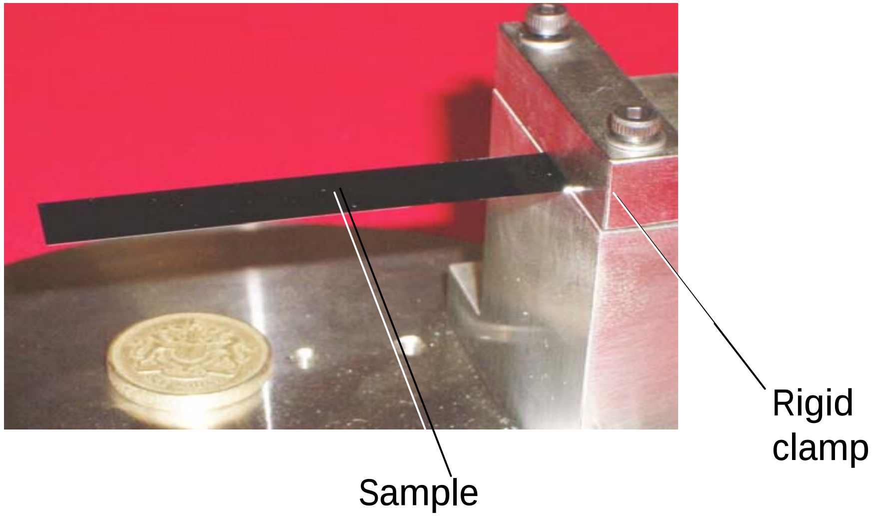


Heat flow in a flexing ribbon

Silicon suspension elements

- Initial samples have been fabricated by:
  - machining from bulk pieces of silicon by a commercial vendor

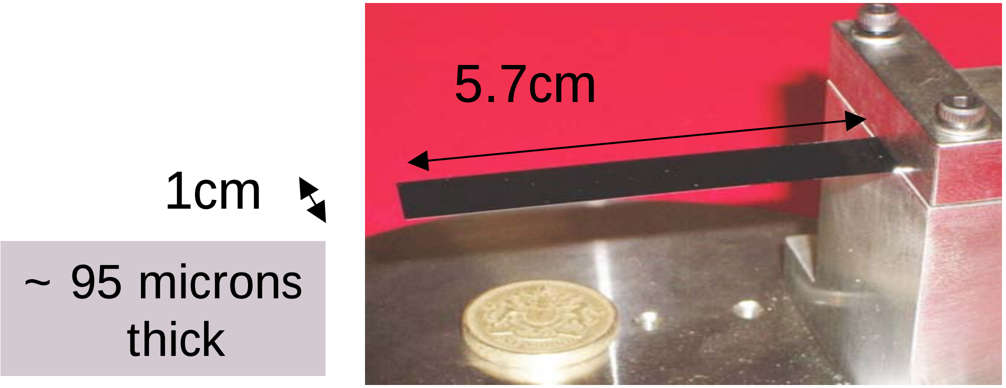
  - etching from silicon wafers by collaborators at Stanford University



Experimental measurements

- Set of samples fabricated with varying properties and dimensions:
  - 1×10^{-3} Ohm-cm to >100 Ohm-cm
  - ~40 microns thick to ~100’s microns thick

- Measurements in progress on first etched sample:



P-type doping (Boron),
Resistivity = 10-20 Ohm-cm

  - Resonant modes of samples excited using an electrostatic drive
  - Sample displacement monitored using shadow sensor
  - Measure rate of decay of the mode amplitudes, from which mechanical dissipation, $\phi(\omega_0)$ can be determined. For any mode of amplitude A, and frequency ω_0,

$$A = A_0 e^{-\phi(\omega_0)\frac{\omega_0 t}{2}}$$

Experimental measurements

- Measured dissipation is the sum of dissipation arising from a number of sources:

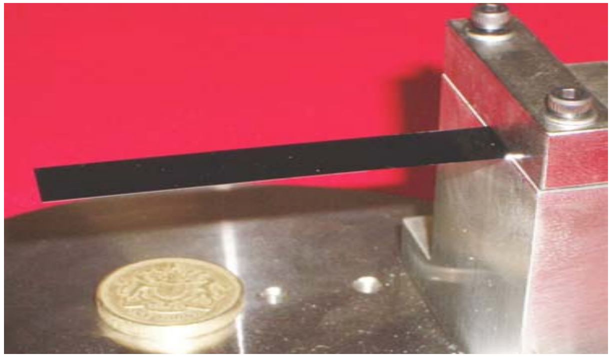
$$\phi_{meas}(\omega)=\phi_{thermoelastic}(\omega)+\phi_{bulk}(\omega)+\phi_{surface}(\omega)+\phi_{gas}(\omega)+\phi_{clamp}(\omega)+\phi_{other}(\omega)$$

calculate from silicon material properties

measurements of samples of varying surface to volume ratios should allow estimates

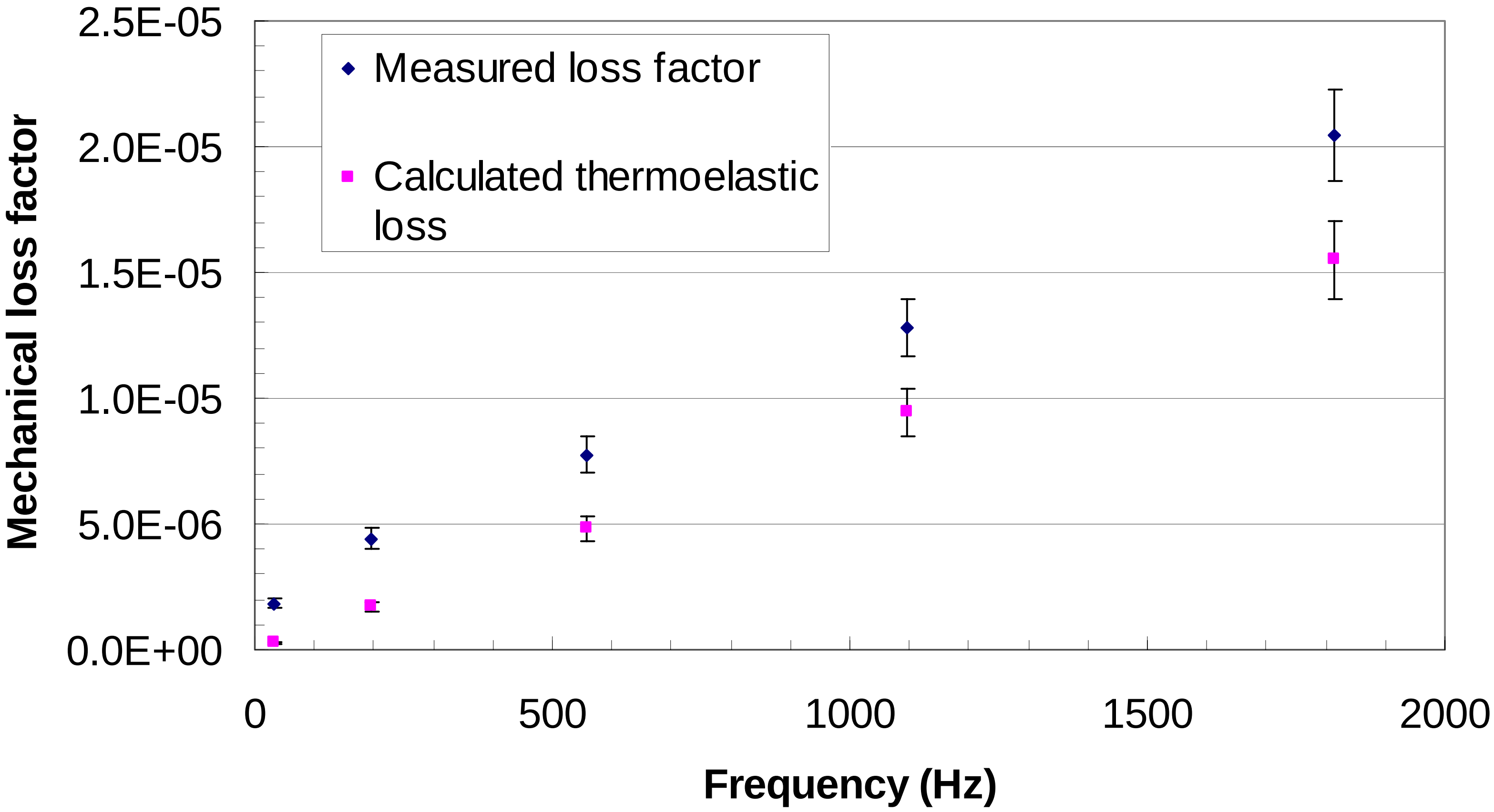
measurements in vacuum - $<10^{-5}$ Torr

rigid clamp holding thick end of sample



Results

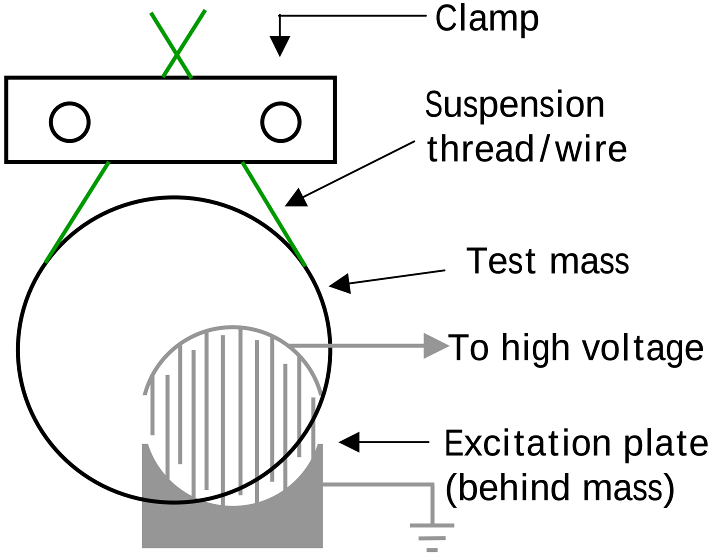
- Measured loss factor for first 5 resonant modes:



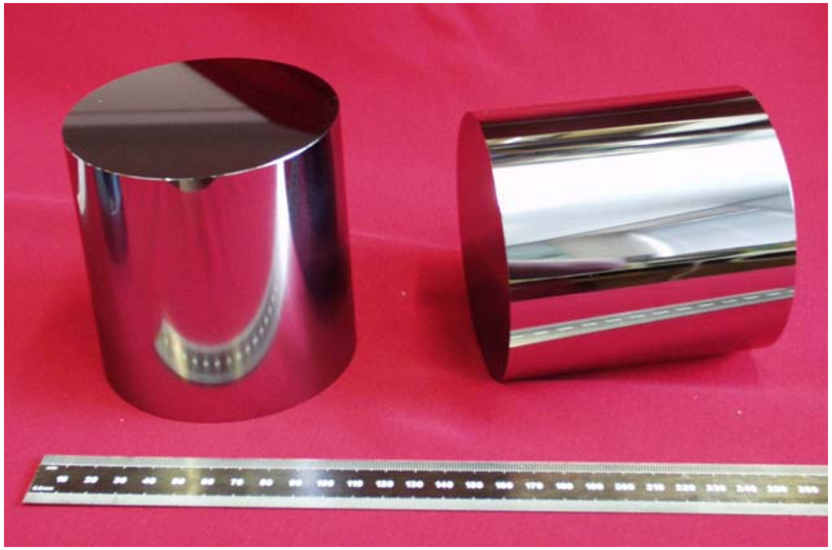
- Consistent with mostly thermo-elastic loss – ‘excess’ loss tbd
- Work ongoing – cryostat commissioned and cooled to 78K

Studies of silicon as a test mass substrate

- Preliminary room T measurements made of mechanical dissipation of bulk silicon samples suspended on silk thread or wire loops
    - Internal resonant modes of the samples excited; decay of mode amplitude measured



Schematic diagram of front view of suspended test mass.

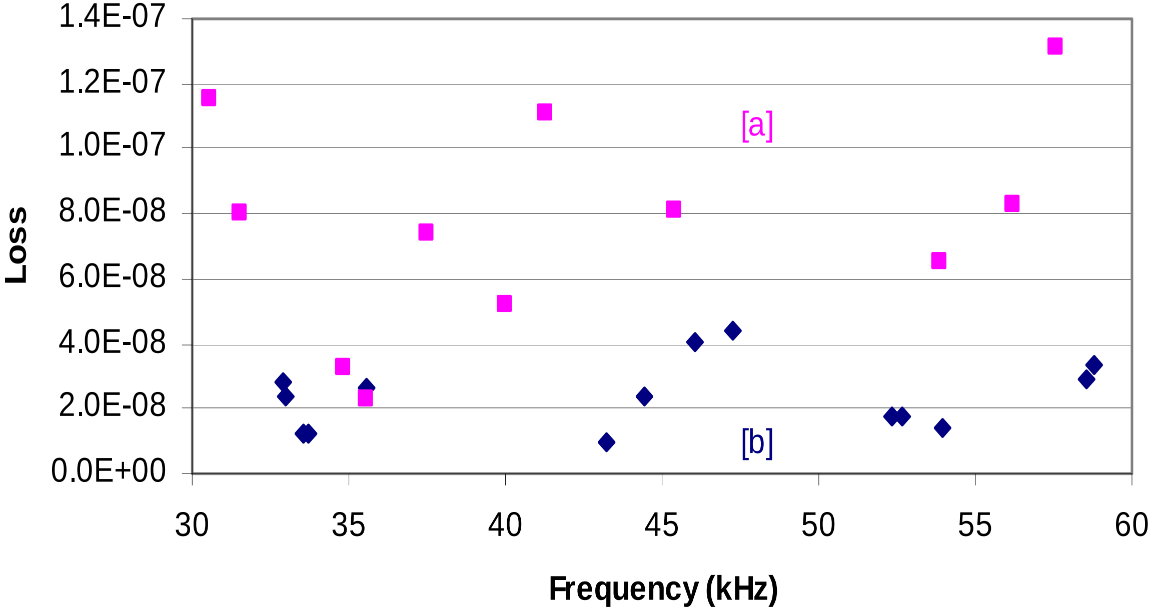


Silicon samples cut along different crystal axes, [111] *and* [100]. *The* [111] *sample was boron-doped.*

- Dissipation of two silicon samples of identical geometry, supplied by Stanford, was measured over a range of frequencies.

Results for silicon at room temperature

Measured loss factors for two samples of bulk silicon



Sample [b] typically showed lower dissipation

Sample [a]:
[100] cut, nominally undoped

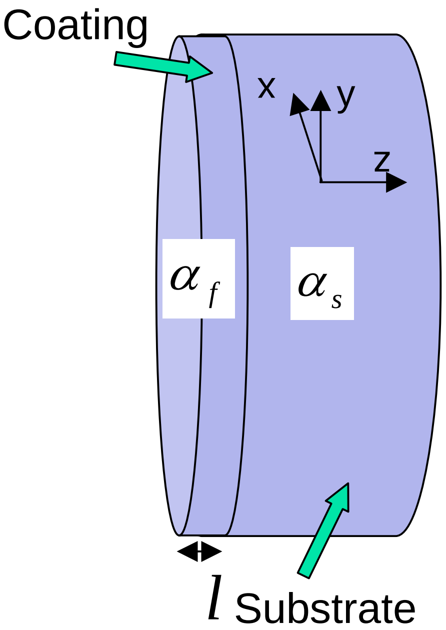
Sample [b]:
[111] cut, boron doped

Reason for difference seen in measured loss factors (eg crystalline orientation of the sample, the dopant, or some other reason) is as yet unknown – under investigation

- Lowest loss obtained so far = $(9.6 +/- 0.3) \times 10^{-9}$
- Comparable with the lowest loss factors measured at room temperature
  - Recall, varying dopant concentrations can vary the thermal conductivity of silicon.
  - This can impact both levels of thermoelastic dissipation and mirror figure distortion under thermal loads – requires further study.

Mechanical dissipation from coatings

- Research with LSC colleagues suggests that adding a typical ion-beam-sputtered (IBS) dielectric mirror coating to a fused silica test mass with a loss of 5 x 10^{-8} can increase the test mass thermal noise by 13 % or more.
- For future detectors it is vital to reduce, or mitigate the effects of, coating dissipation.



- Potential sources of loss (calculation and expt):
  - Dissipation intrinsic to the coating materials (defects, vacancies etc?)
  - Thermoelastic damping (see Fejer et al, gr-qc/0402034v1 Phys Rev D, resulting from the different thermal and elastic properties of the coating and the substrates
    - In both cases resulting thermal noise level depends on relative thermal and elastic properties of coating and substrate
    - It follows that the optimum coating for a fused silica or sapphire mass may not be the ideal choice for a silicon mass

Mechanical dissipation in coatings (cont^{d})

- Diffractive coatings:
  - If one wants to use silicon as a diffractive optic, either:

    (a) a diffraction grating can be etched on to the surface of the test mass onto which a coating is applied

    (Institute for Applied Optics, University of Jena);

    or

    (b) the test mass can be coated, and a diffraction grating etched into the coating surface

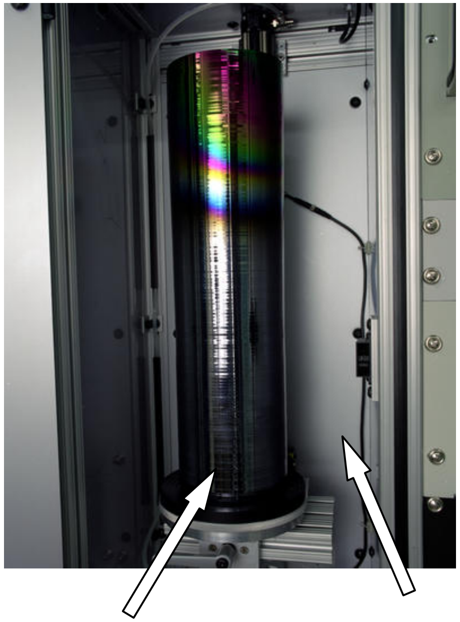
    (Lawrence Livermore National Laboratories).

  - Developing collaborations with (a) through colleagues in Hannover, and with (b) through Stanford, to investigate the mechanical dissipation associated with such coatings (room and cryo)

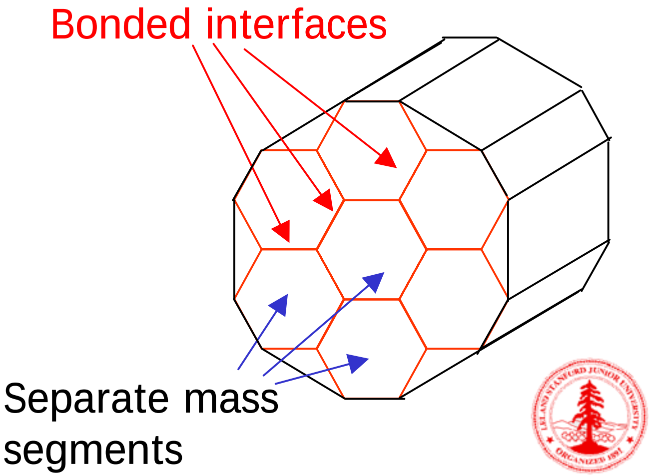
  - Experiments in progress (see talk in configurations session by Alexander Bunkowski) and planned in Glasgow investigating use of diffractive topologies

A problem of size

- For 3rd generation detectors, test masses of >50 kg are desirable, to minimise the effects of radiation pressure (see Warren's talk)
- Silicon ingots of 400 mm diameter and 450 kg mass have been manufactured, but are of an aspect ratio which is not optimal for use as a test mass.
- A solution to this could be to use composite test masses, where smaller pieces are joined together without introducing significant excess mechanical dissipation.
- A composite mass could look something like the schematic shown, the adjoining faces possibly joined by silicate bonding.
- New apparatus in Glasgow is currently being assembled to measure dissipation in larger masses (~40-50kg)

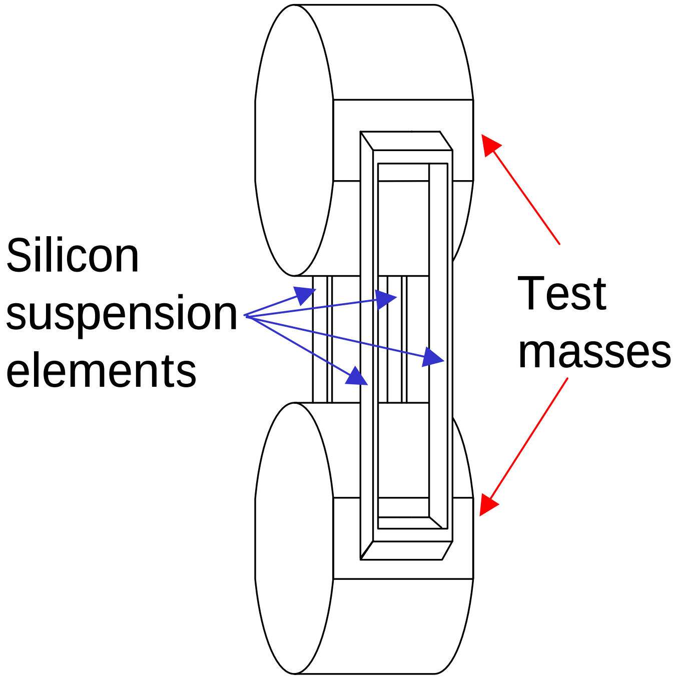


Silicon ingot in growth furnace



Research goals

- Aim to investigate:
  - thermoelastic dissipation as a function of T
  - effect of surface treatment/ fabrication technique on dissipation in thin samples
  - optimal geometry for suspension elements
  - internal dissipation of doped/un-doped bulk silicon as a function of temperature
  - effectiveness of techniques for reducing coating dissipation
  - dissipation due to aspects of test mass design related to use as diffractive optics
  - construction of composite test masses of low dissipation
- Perform a trade-off between the use of silicon and other materials



- The overall goal of the programme is to develop low dissipation suspensions suitable for GEO-HF and possible 3rd generation detectors.