Aspects of silicon for use in the suspensions of gravitational wave detectors

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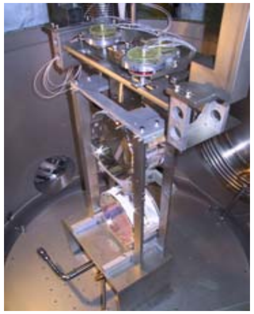
Introduction

- 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

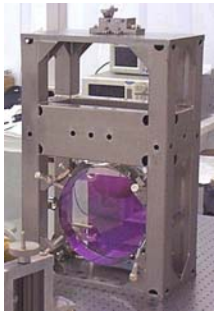
- Working on extending technology in the development of low dissipation quasi-monolithic suspensions, acquired through designing suspensions for GEO 600 and Advanced LIGO, to:
  - develop ultra-low thermal noise suspensions for EGO and equivalent 3rd generation detections (cryogenic temperatures)

Suspension technology status

current detectors eg:



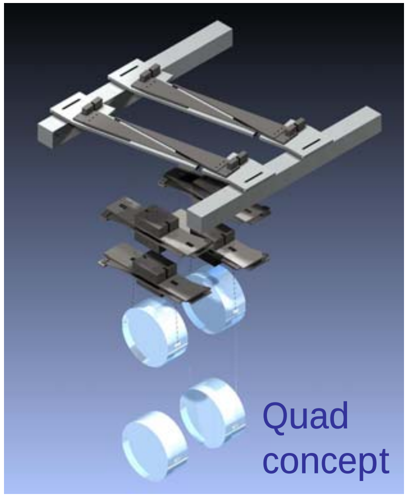
GEO 600
Silica suspension.
Arm length: 600 m.



Initial LIGO
Wire loop.
Arm length: 4 km.

operational

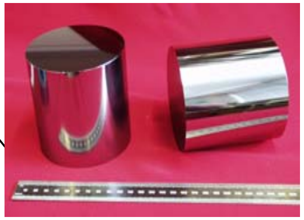
advanced detectors

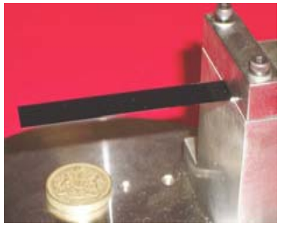


e.g. Advanced LIGO
Quadruple stage.
silica.
Ribbons/fibres.
Arm length: 4 km.

being designed

future detectors





e.g. GEO-HF, EGO

Silicon suspension technology.

current research

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

Challenges for future detectors – why silicon?

- 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].

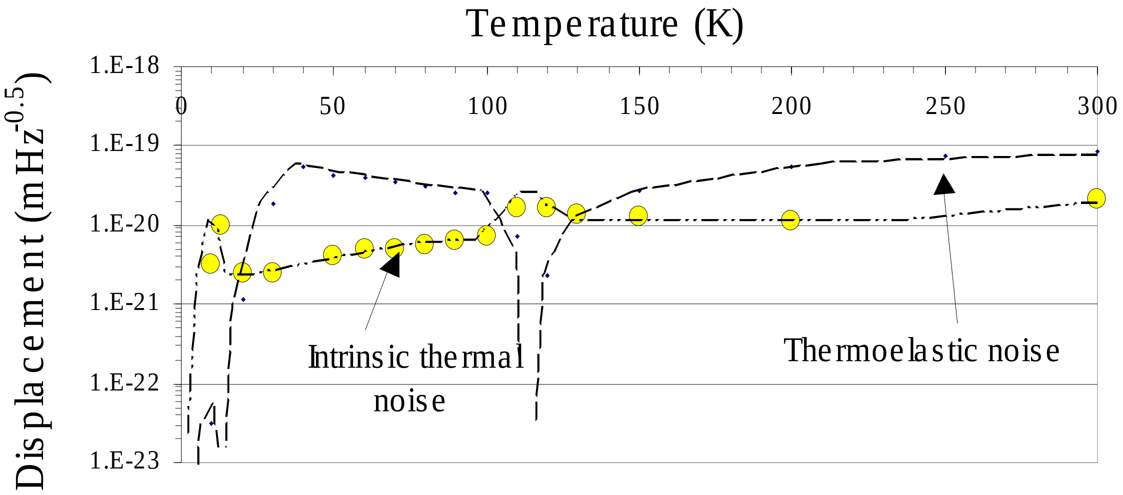
  α = substrate expansion coefficient

  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 – see talks by Roman and Peter

Mechanical dissipation of silicon

- 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:

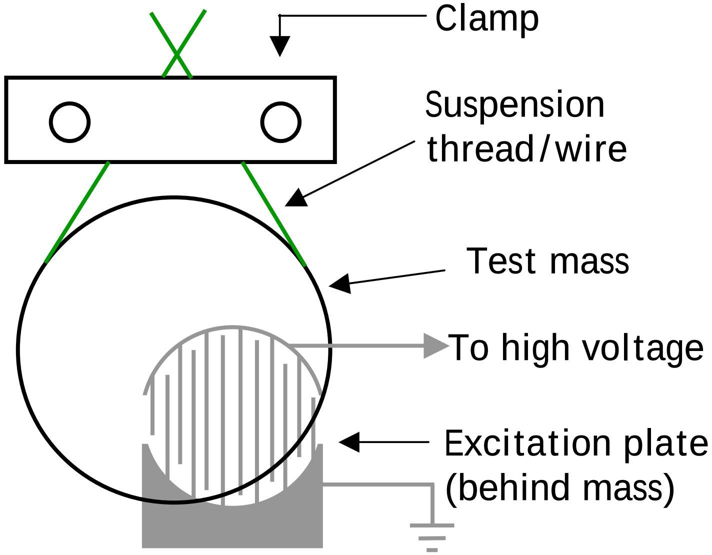


Calculated intrinsic thermal and thermoelastic noise @ 10 Hz in a single silicon test mass, sensed with a laser beam of radius ~ 6 cm

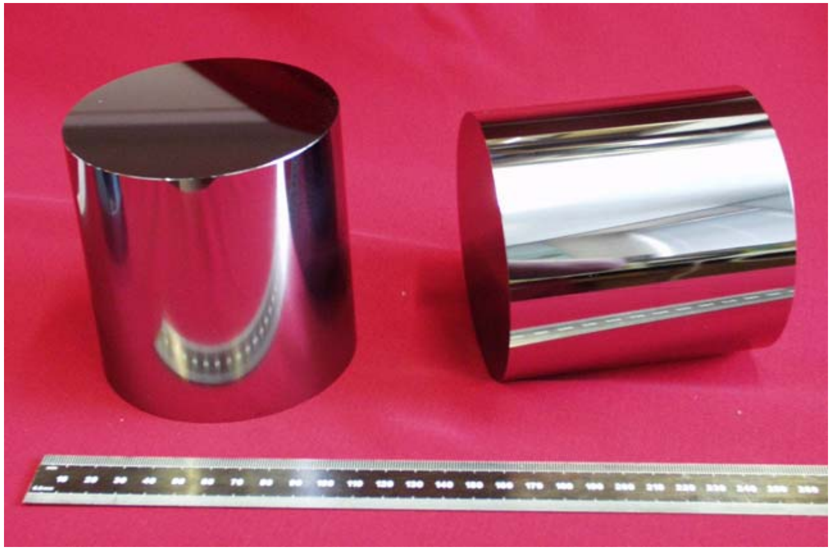
- Thermoelastic noise is proportional to α and should vanish at T ~120 K and ~18 K where α tends to zero
- Intrinsic thermal noise exhibits two peaks at similar temperatures
- Silicon may allow significant thermal noise improvements at low temperatures but material properties need further study

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.

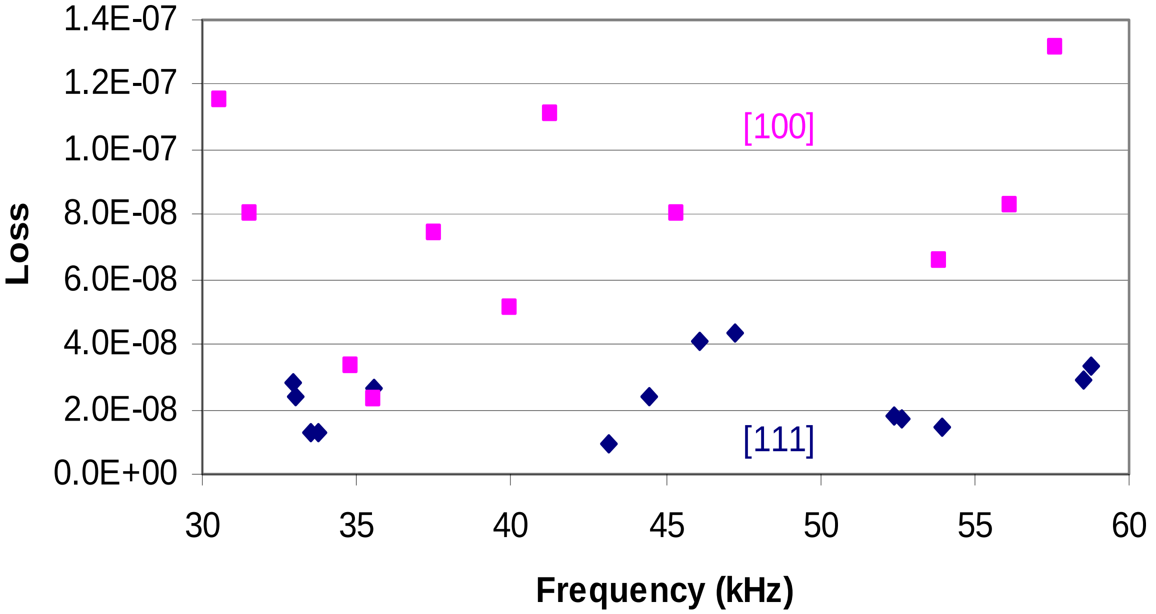


Silicon samples cut along different crystal axes, [111] *and* [100]. *The* [111] *sample was boron-doped.*

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

Results for silicon at room temperature

Measured loss factors for two samples of bulk silicon



The doped [111] sample typically showed lower dissipation, though whether this was due to the crystalline orientation of the sample, the dopant, or some other reason, is as yet unknown.

- Lowest loss obtained so far = (9.6 +/- 0.3) x 10^{-9}
- Comparable with the lowest loss factors measured at room temperature
- Plan to extend these measurements to cryogenic temperatures

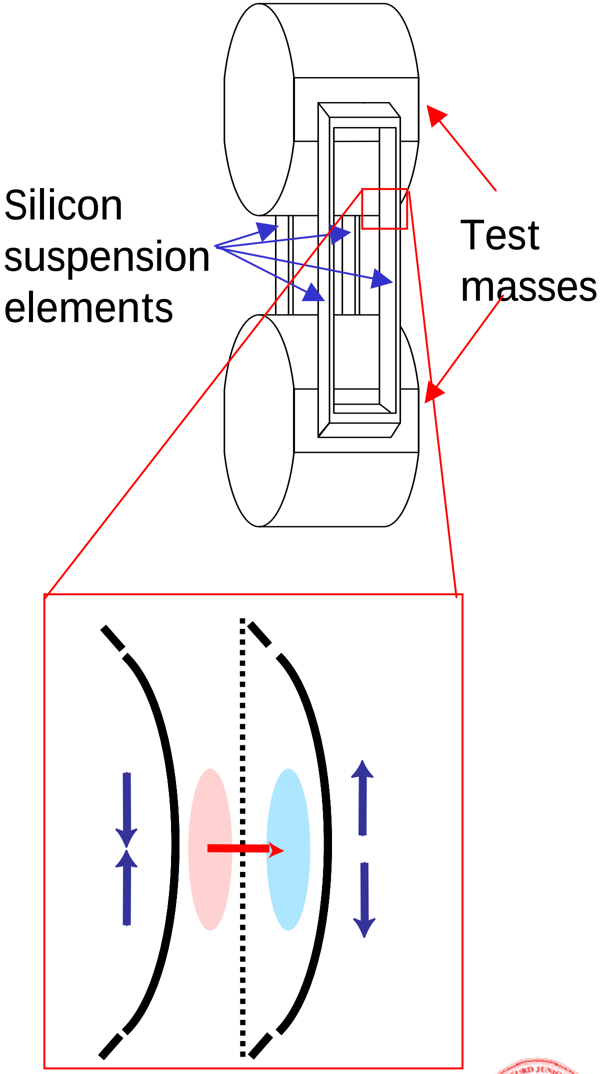
- Recall, varying dopant concentrations can vary the thermal conductivity of silicon.
- This can impact both levels of thermoelastic dissipation and mirror figure distortion under thermal loads – requires further study.

Dissipation in silicon suspension elements

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

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

- 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



Silicon suspension elements

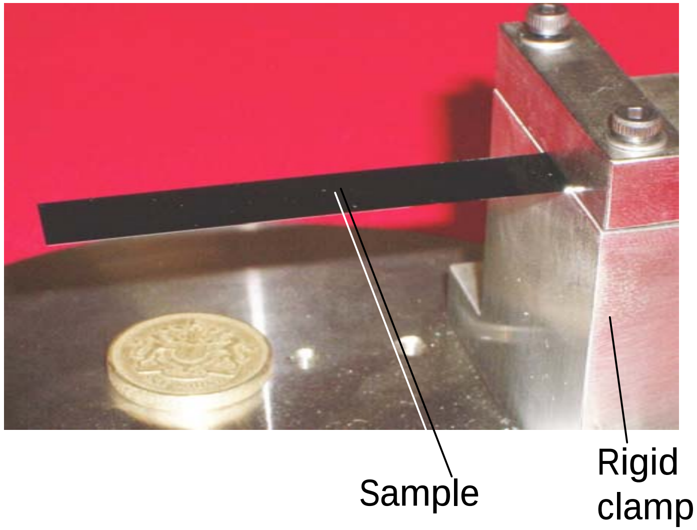
Test masses

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

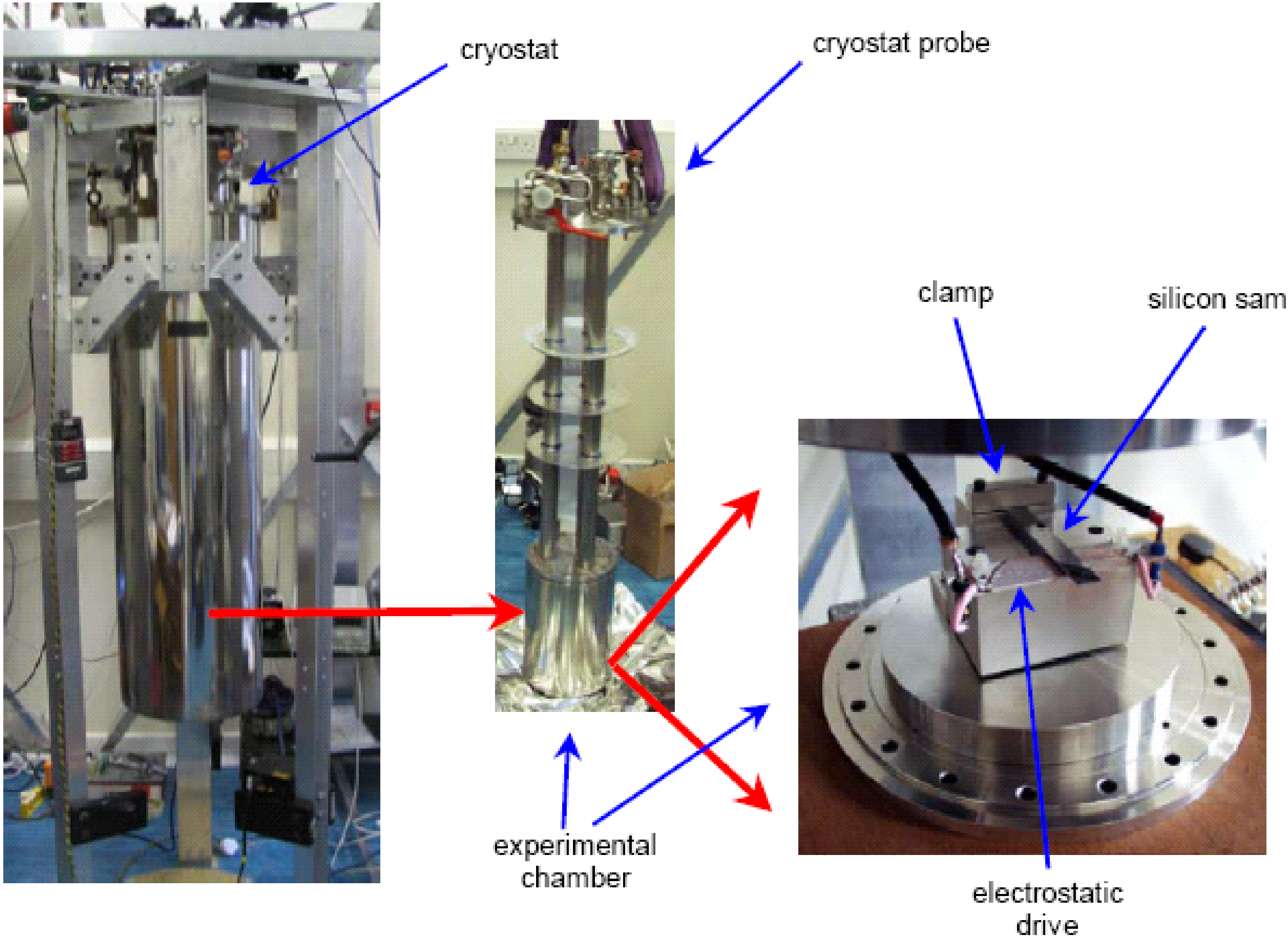
  - etching from silicon wafers by collaborators at Stanford University



Set of samples fabricated with varying properties and dimensions:

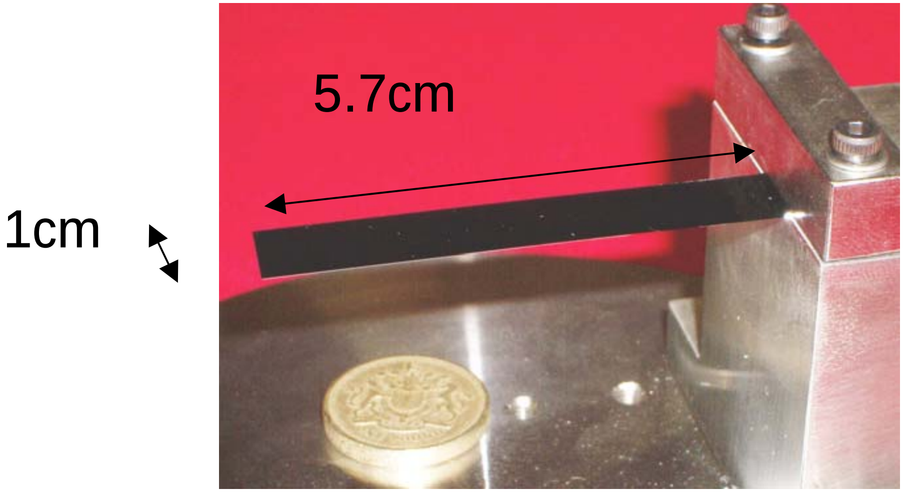
- 1×10^{-3} Ohm-cm to >100 Ohm-cm
- ~40 microns to ~100’s μm thick

Experimental setup



Experimental measurements

- Measurements in progress on first etched samples:



~ 95 microns thick

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:

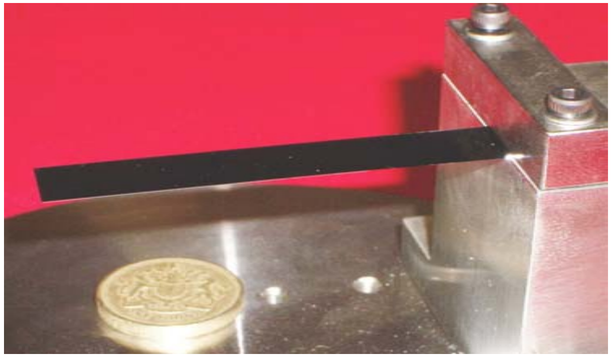
$$\phi_{meas}(\omega)=\phi_{thermoelastic}(\omega)+\phi_{bulk}(\omega)+\phi_{surface}(\omega)+\phi_{gas}(\omega)+\phi_{clamp}(\omega)+\phi_{other}(\omega)$$

calculate from silicon material properties

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

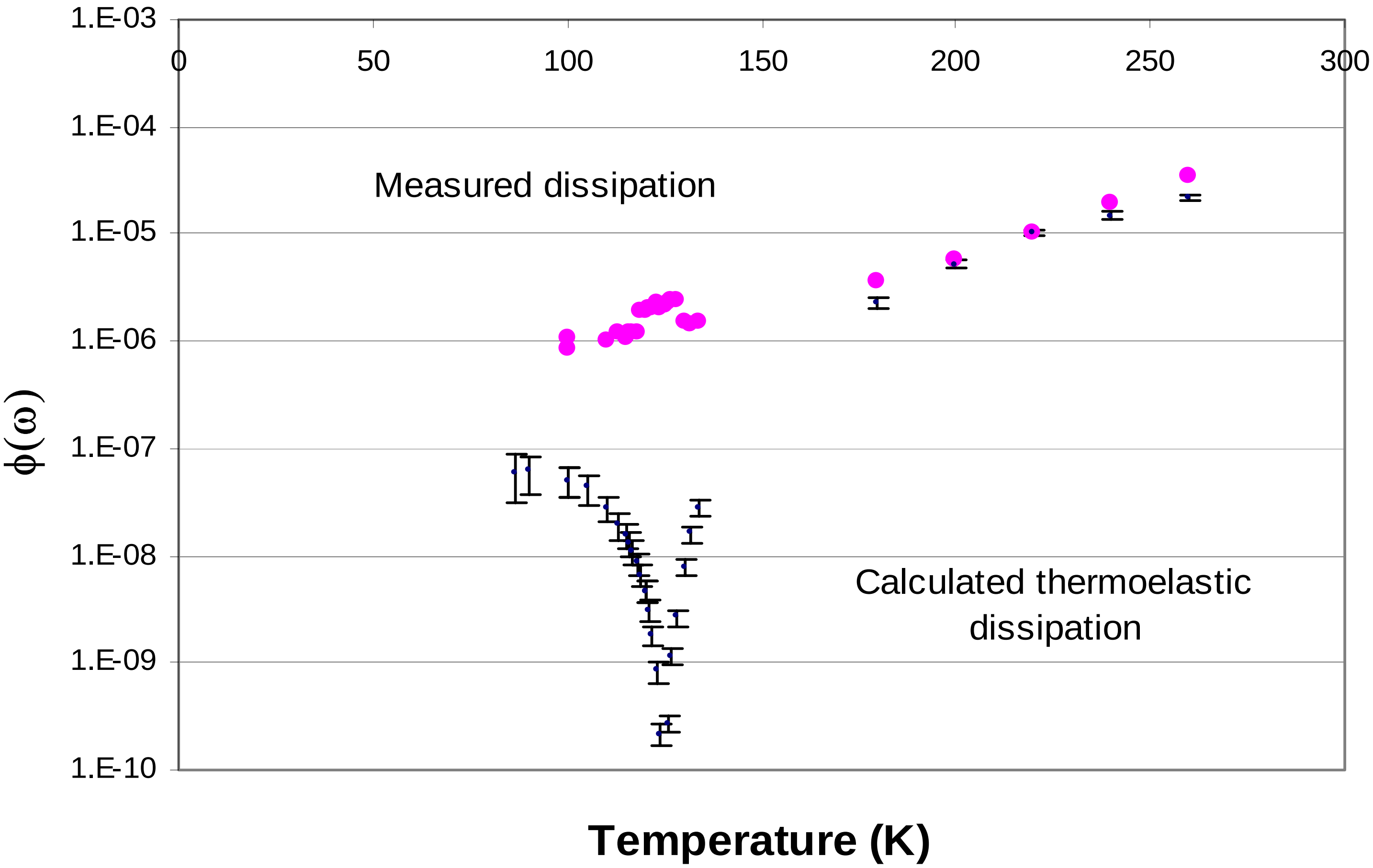
measurements in vacuum - $<10^{-5}$ Torr

rigid clamp holding thick end of sample

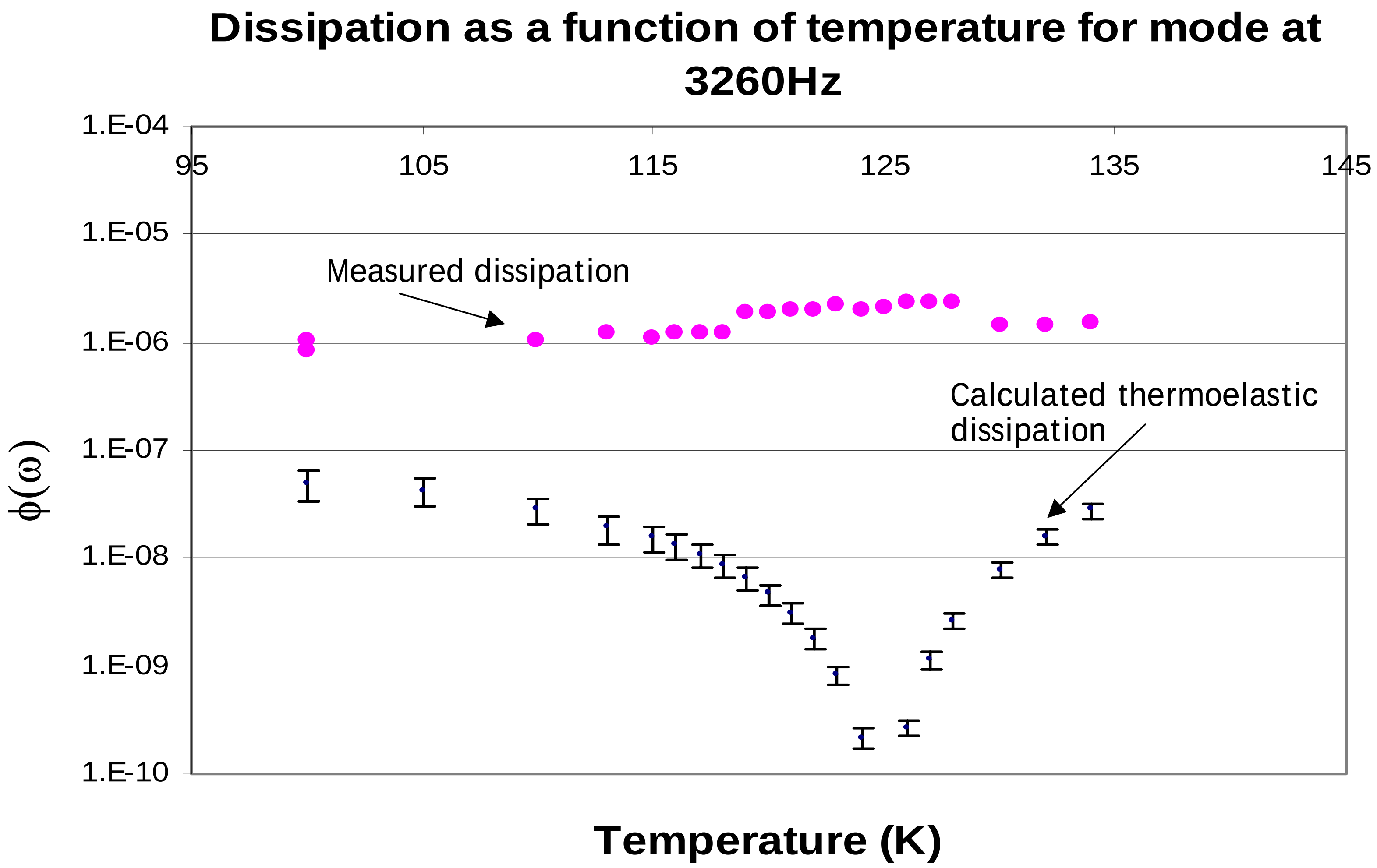


Results - Dissipation as a function of temperature for mode at f = 3260Hz

- Loss factors measured from 77K to 260K for first 5 resonant modes (240 to 3260Hz)
- Results for 3260Hz mode shown below:



Closer look at dissipation around 125K

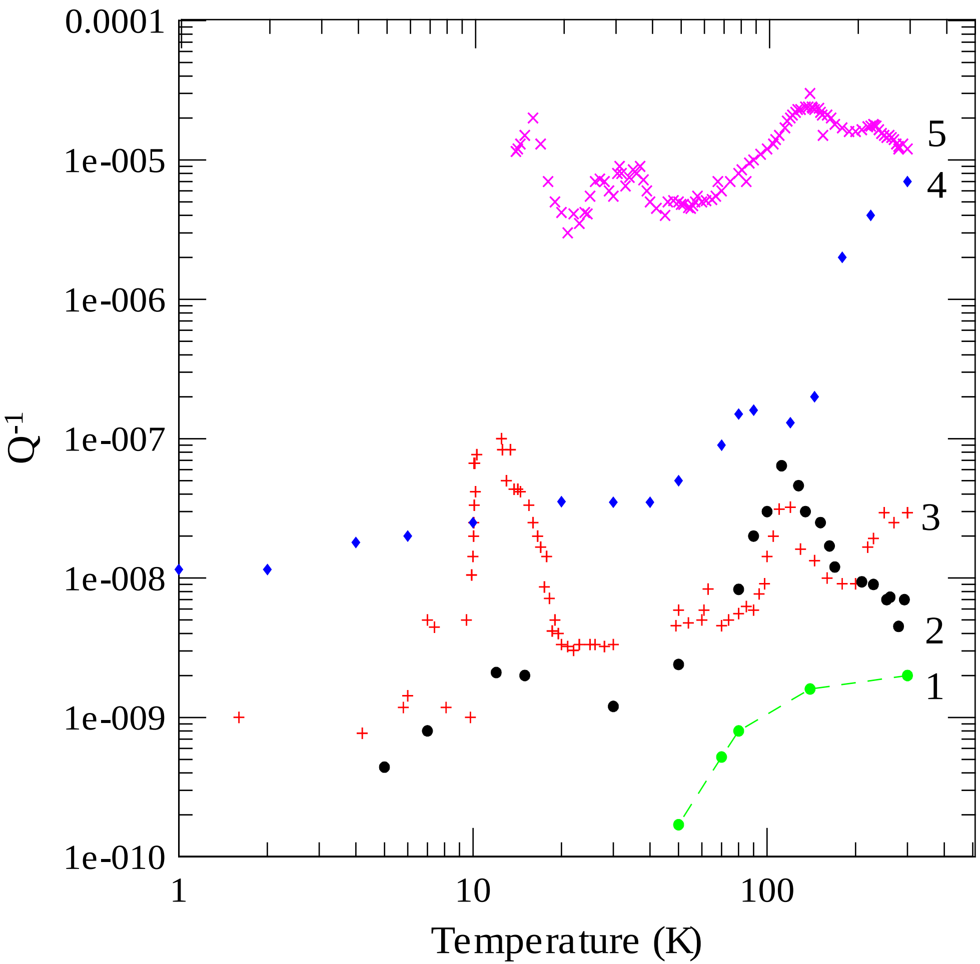


Results

- Similar behaviour for all modes studied
- Investigating magnitude of non-thermoelastic sources of loss for samples of our geometry – in particular:
  - Surface effects (sample is 95 microns thick)
  - Possible coupling to resonant modes of clamp

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

The measured dissipation Q^{-1} in silicon oscillators (kHz frequency band)



1 – Calculated from “phonon-phonon” mechanism (**f = 10 kHz**)

2 – MSU – 1980, unpublished (**t ~ 10 cm, f = 10 kHz**)

3 – *D.F. McGuigan et al*., J.Low Temp.Phys. 30 (1978), 621 (**t ~ 10 cm, f = 19.5 kHz**)

4 – *B.H.Houston et al*., Appl.Phys. Lett. 80 (2002), 1300 (**t ~ 100 μm, f = 5.5 kHz**)

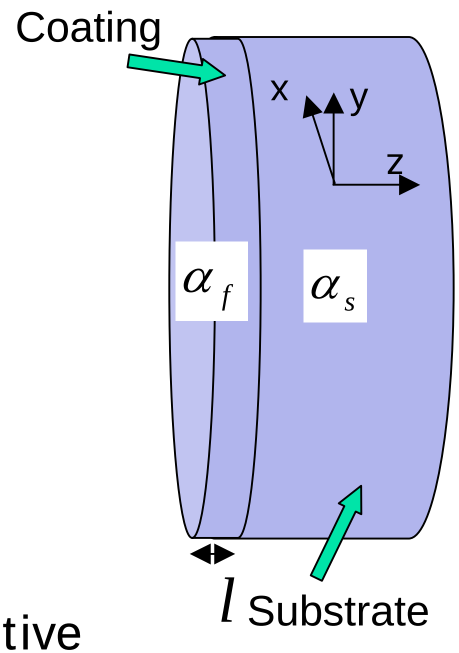
5 – *U.Gysin et al*., Phys.Rev. B69 (2004), 045403 (**t ~ 2 μm, f = 10.8 kHz**)

Slide courtesy of V. Mitrofanov, Moscow State University

Summarise

- Dissipation peaks observed by a number of workers
- Peaks occur at a variety of different temperatures in samples of different impurity levels and of different doping (~125K, 130K, 160K, 10-20K etc)
- Needs a systematic study to establish whether suitable samples exist for our purposes
- Carrying this out on a set of samples of different known dopings
- Nb: it is not clear whether there is a fundamental connection between the zeros in the expansion coefficient for silicon and observed dissipation peaks at the corresponding temperatures

Mechanical dissipation from coatings



- 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, Phys Rev D Braginsky and Vyatchanin, Phys Lett A) 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 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

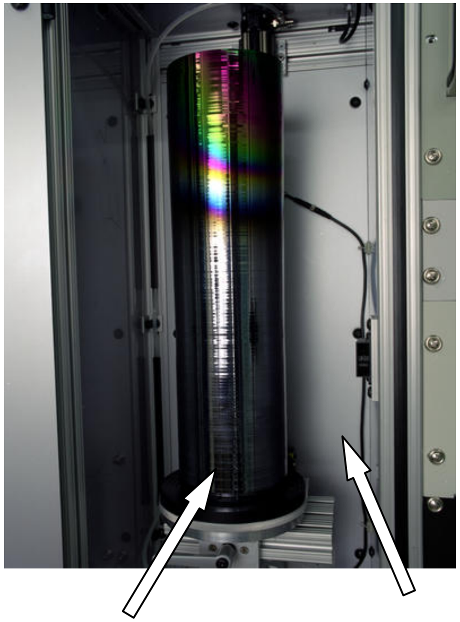
    - the test mass can be coated, and a diffraction grating etched into the coating surface

      (Lawrence Livermore National Laboratories).

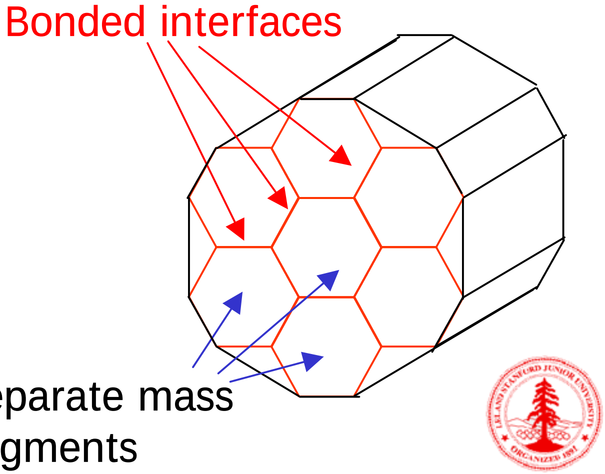
  - Through Roman Schnabel, we have now received (silica) substrates from Jena with diffraction gratings etched onto surface
  - Aim to collaborate with LLNL through Stanford Univ
  - We will investigate the mechanical dissipation associated with such gratings and coatings (room and cryo T's)

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.
- Preliminary work carried out on fabricating silicon-silicon bonds



Silicon ingot in growth furnace

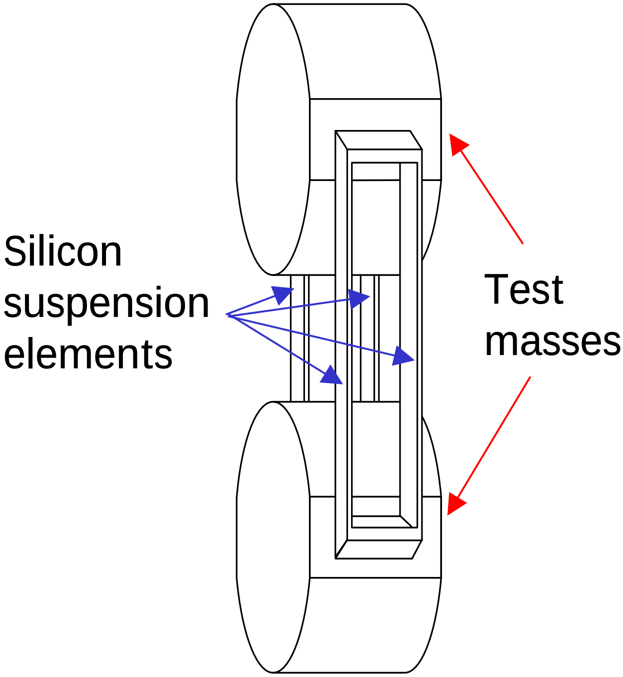


Further silicon-silicon bonding tests

- Collaborating with Astrium D in Friedrichshafen
  - Carrying out 16 day thermal cycling tests on silicate-bonded silicon samples
  - Samples will undergo 8 cycles from ambient to below 30K.
  - Should have these results by mid -February

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



- The overall goal of the programme is to develop low dissipation suspensions suitable possible 3rd generation detectors.
- Achieving sensitivities better than Adv LIGO needs more than improvements in thermal noise – silicon substrates may be of attractive for additional reasons