Temperature dependence of the mechanical dissipation in single layer tantalum pentoxide coatings on thin single-crystal silicon substrates.

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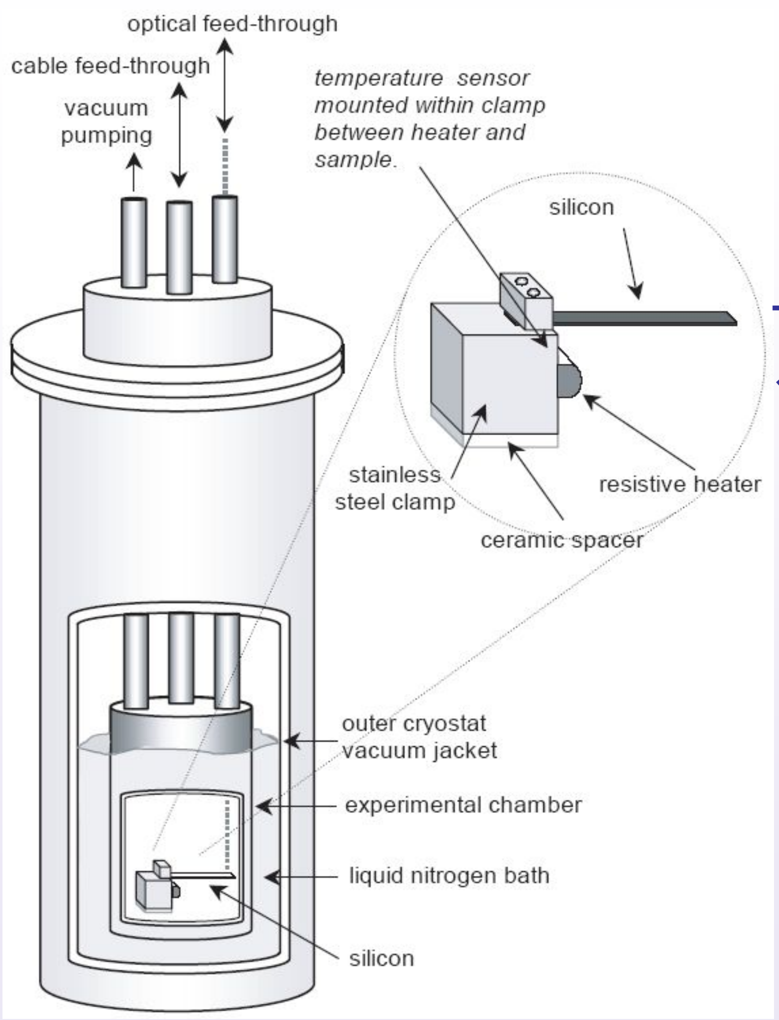
Scientific motivation

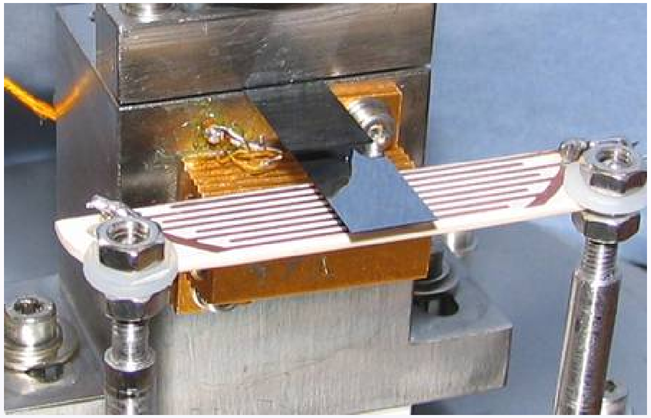
- Silicon is of interest as a mirror substrate material for future detectors – its mechanical loss is predicted to decrease at low temperatures
- Mechanical dissipation from dielectric mirror coatings is predicted to be a significant source of thermal noise for advanced detectors. (Coatings must also be of low optical loss.)
- Experiments suggest
  - Ta_2O_5 is the dominant source of dissipation in current ion-beam-sputtered SiO_2/Ta_2O_5 coatings
  - Doping the Ta_2O_5 with TiO_2 can reduce the mechanical dissipation
- Mechanism responsible for the observed mechanical loss in Ta_2O_5 as yet not clearly identified

Experimental setup

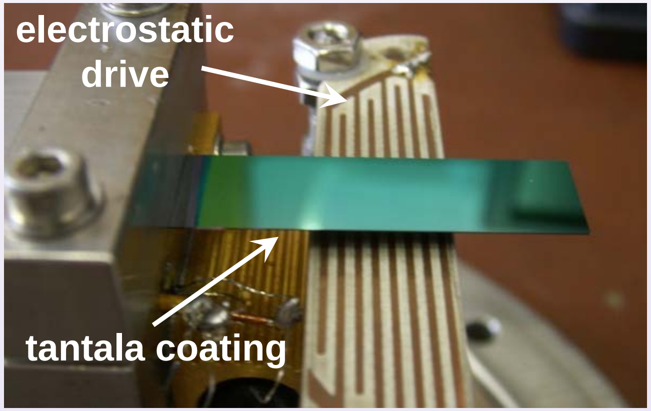
schematic of cryostat



samples



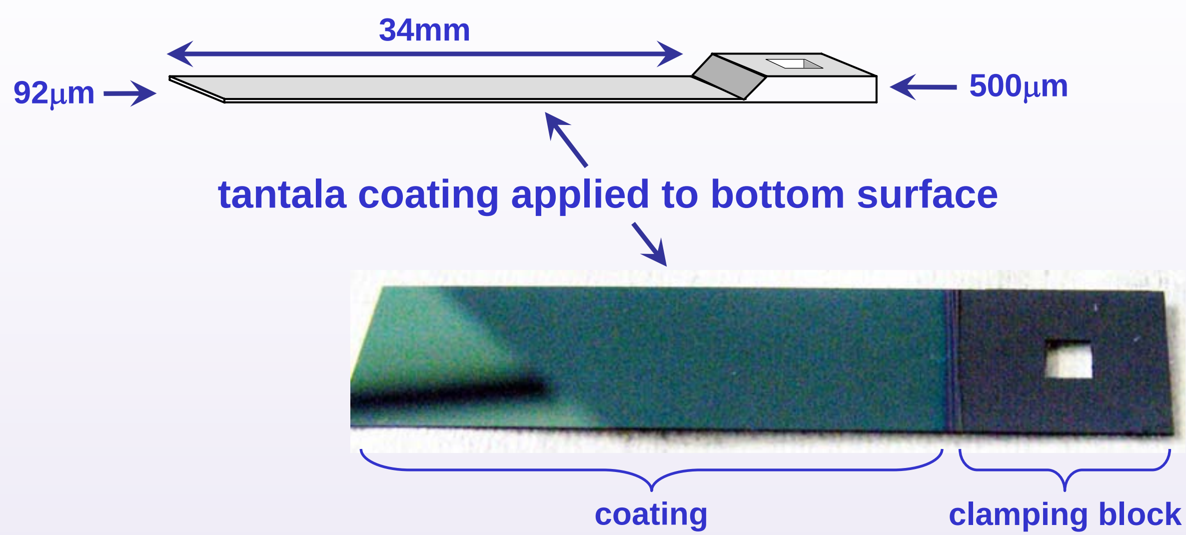
uncoated cantilever in situ



coated cantilever in situ

Silicon cantilever with coating

- The silicon samples have been fabricated by wet etching from silicon wafers at Stanford (Stefan Zappe)
- The coatings were deposited by LMA.

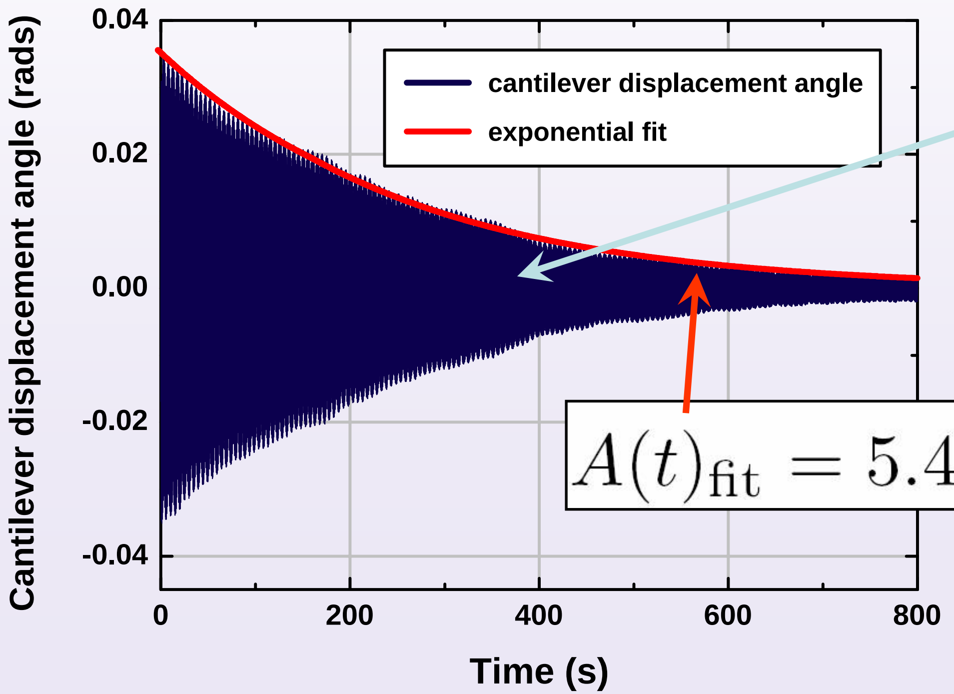


- **Silicon substrate properties:**
  - ~ **92 μm thick**, P-type Boron doped, resistivity = **10-20 Ω-cm**
- **Tantala coating properties:**
  - **0.5 μm** single layer **tantala**, doped with ≈**14.5 ± 1 % titania** (Formula 5)

Experimental procedure

- 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.

Amplitude ring-down of uncoated silicon cantilever for the third bending mode at f~1.9 kHz at 120K



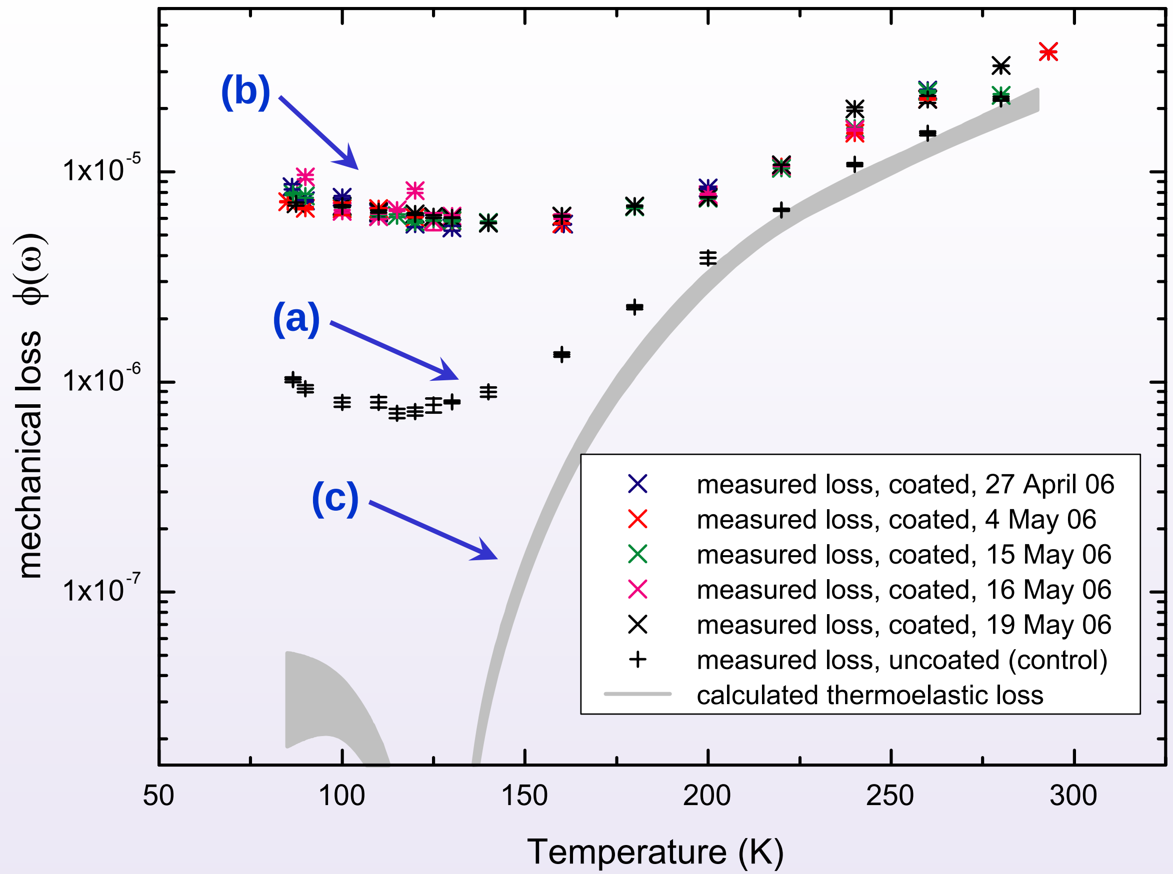
$$A(t) = A_0 e^{-\phi(\omega_0)\frac{\omega_0 t}{2}}$$

$$A(t)_{\mathrm{fit}} = 5.46 \times 10^{-2} e^{-3.99\times10^{-3} t}$$

$$\phi(\omega_0) = 6.5 \times 10^{-7}$$

Coated silicon cantilever

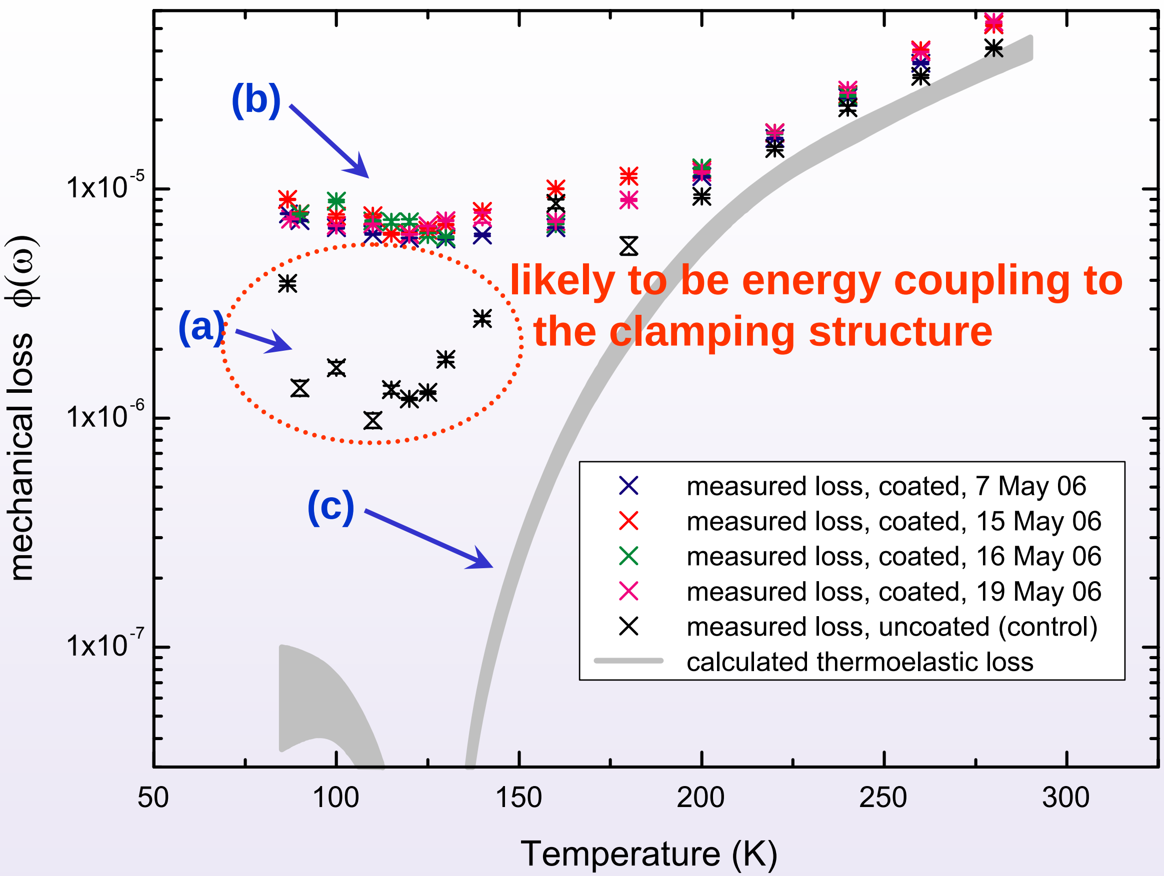
- Results – third bending mode at ~1.9kHz



Temperature dependence of (a) measured uncoated loss, (b) measured coated loss and (c) calculated thermoelastic loss for the third bending mode at ~1.9kHz.

Coated silicon cantilever

- Results – fifth bending mode at ~3.8kHz



Temperature dependence of (a) measured uncoated loss, (b) measured coated loss and (c) calculated thermoelastic loss for the fifth bending mode at ~3.8kHz.

Coated silicon cantilever – energy distribution

- Interpretation: calculating the energy stored in the coating layer

The energy stored in the surface layer as it stretches may be described as:

$$E_{\text{surface}} = \frac{Y_{\text{surface}} hb}{2L} \Delta L^2$$

where the increase in length, ΔL may be written as:

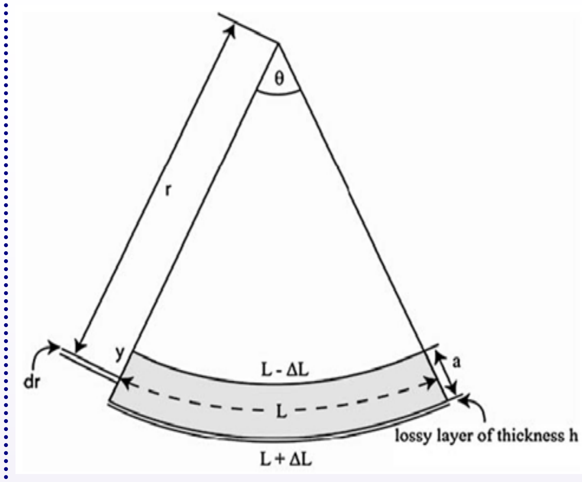
$$\Delta L = \frac{a}{2}\theta$$

The energy stored in the half of the beam under compression may be written as:

$$dE = \frac{Y_{\text{bulk}} b \Delta L^2}{2L} dr$$

where $\Delta L=(r-R)\theta$ and integrating over half the beam thickness gives:

$$\frac{E_{\text{beam}}}{2} = \int_r^{r+\frac{a}{2}} \frac{Y_{\text{bulk}} b\theta^2}{2L}(r-R)^2 dr = \frac{1}{48}\frac{Y_{\text{bulk}} b\theta^2 a^3}{L}$$



deflected beam with a lossy surface layer (Heptonstall et al PLA 2006)

a = thickness of substrate

h = thickness of coating

b = width, L = initial length

$L+\Delta L$ = increased (stretched) length

E_{surface} = energy stored in the surface

E_{beam} = energy stored in the beam

Y_{surface} = Young's Modulus of the surface

Y_{beam} = Young's Modulus of the beam

Coated silicon cantilever – energy distribution

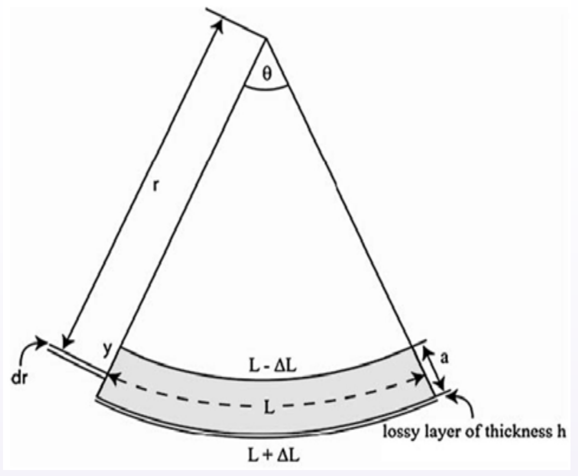
- Interpretation: calculating the energy stored in the coating layer *ctd*

We can approximate the energy stored in the compressed half of the beam to be equal to the energy stored in the stretched half. Scaling by a factor of two therefore gives the ratio of energies stored in the surface layer (coating) and the bulk to be:

$$\frac{E_{\text{surface}}}{E_{\text{beam}}} = 3\frac{Y_{\text{surface}}}{Y_{\text{beam}}}\frac{h}{a}$$

The mechanical loss of the coating layer can now be calculated from the measured loss of the coated sample by scaling by this energy ratio, such that:

$$\phi_{\text{coating}} = \frac{E_{\text{coated-sample}}}{E_{\text{coating}}}(\phi_{\text{coated sample}} - \phi_{\text{uncoated sample}})$$



deflected beam with a lossy surface layer (Heptonstall et al PLA 2006)

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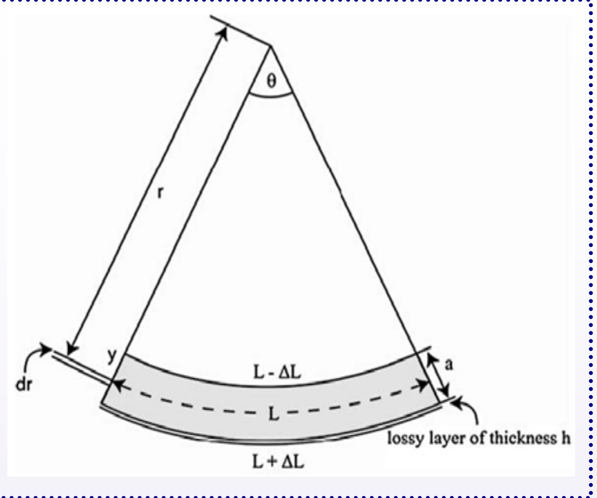
$L+\Delta L$ = increased (stretched) length
E_{surface} = energy stored in the surface
E_{beam} = energy stored in the beam
Y_{surface} = Young's Modulus of the surface
Y_{beam} = Young's Modulus of the beam

Coated silicon cantilever – energy distribution

- Interpretation: calculating the energy stored in the coating layer *ctd*
  - We have also evaluated the energy ratios by Finite Element analysis and they agree within a few %.
  - The energy ratio used:

$$E_{surface}/E_{beam} = \mathbf{0.014}$$



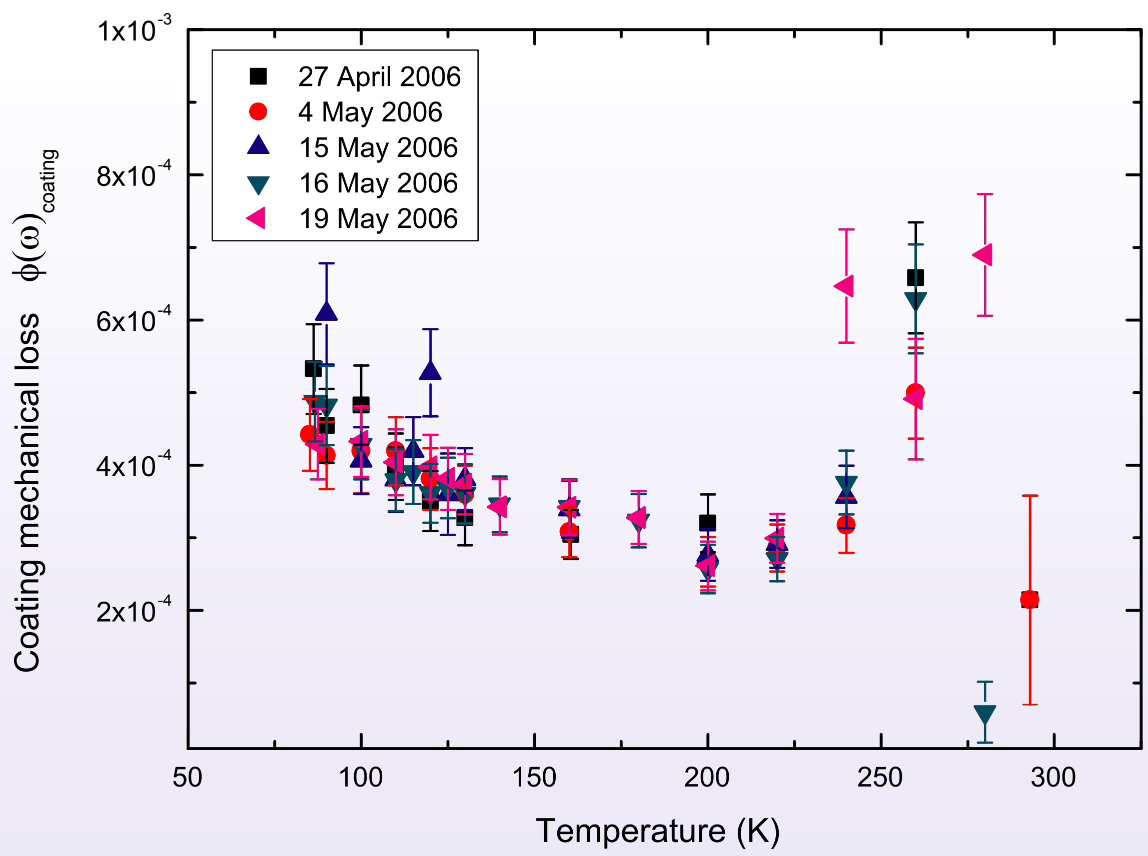
deflected beam with a lossy surface layer (Heptonstall et al PLA 2006)

Young's modulus of silicon substrate: **162.4 GPa**
Reid et al, PLA 2005

Young's modulus of tantala coating: **140.0 GPa**
K. Srinivasan et al, LIGO-T970176-00-D 2001,
"Coating Strain Induced Distortion in LIGO Optics"
http://www.ligo.caltech.edu/docs/T/T970176-00.pdf

Coating loss - results

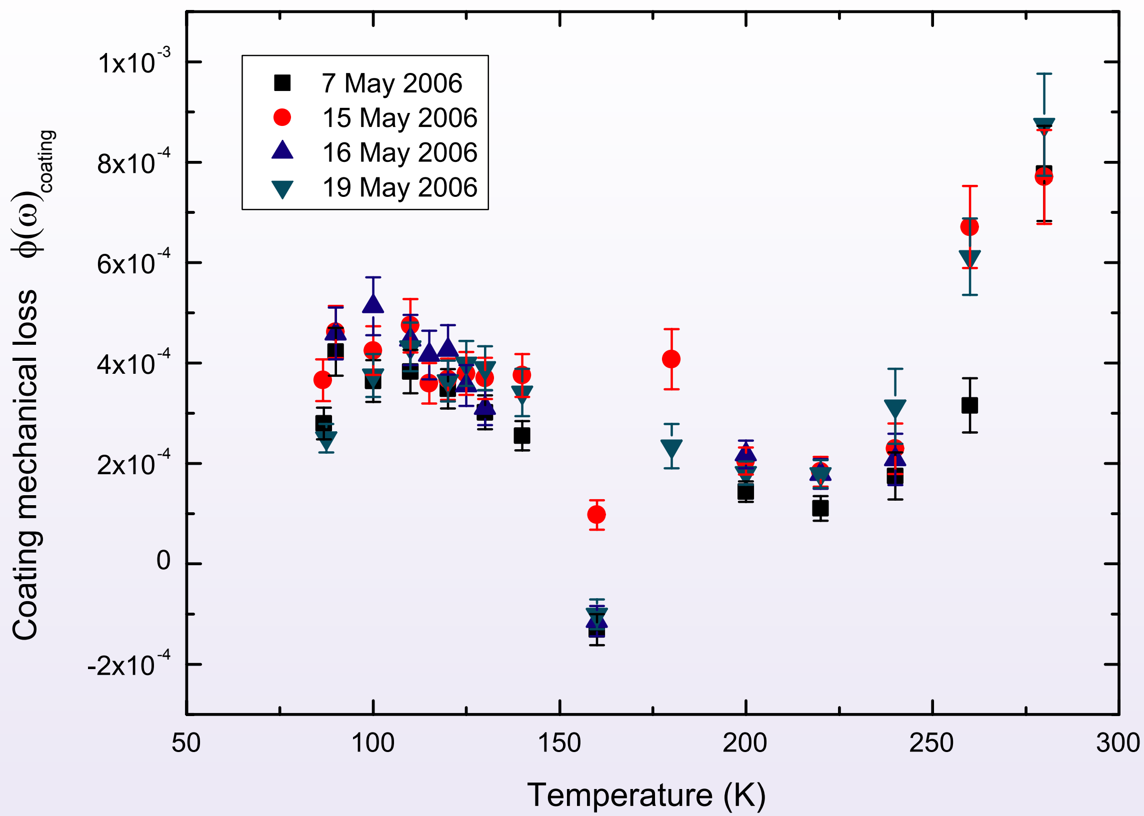
- Results – third bending mode – coating loss



Temperature dependence of the measured loss in a single layer doped tantala coating applied to a 92μm silicon substrate at ~1.9kHz

Coating loss - results

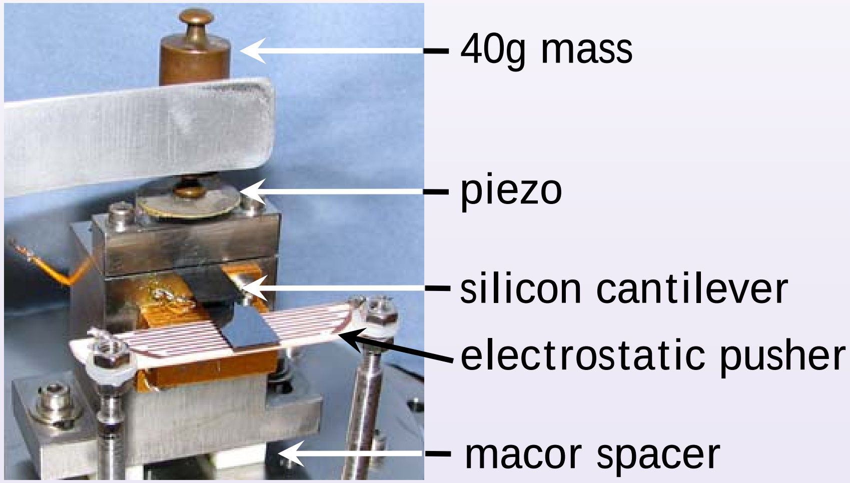
- Results – fifth bending mode – coating loss



Temperature dependence of the measured loss in a single layer doped tantala coating applied to a 92μm silicon substrate at ~3.8kHz

Investigation to study energy coupling to the clamping structure.

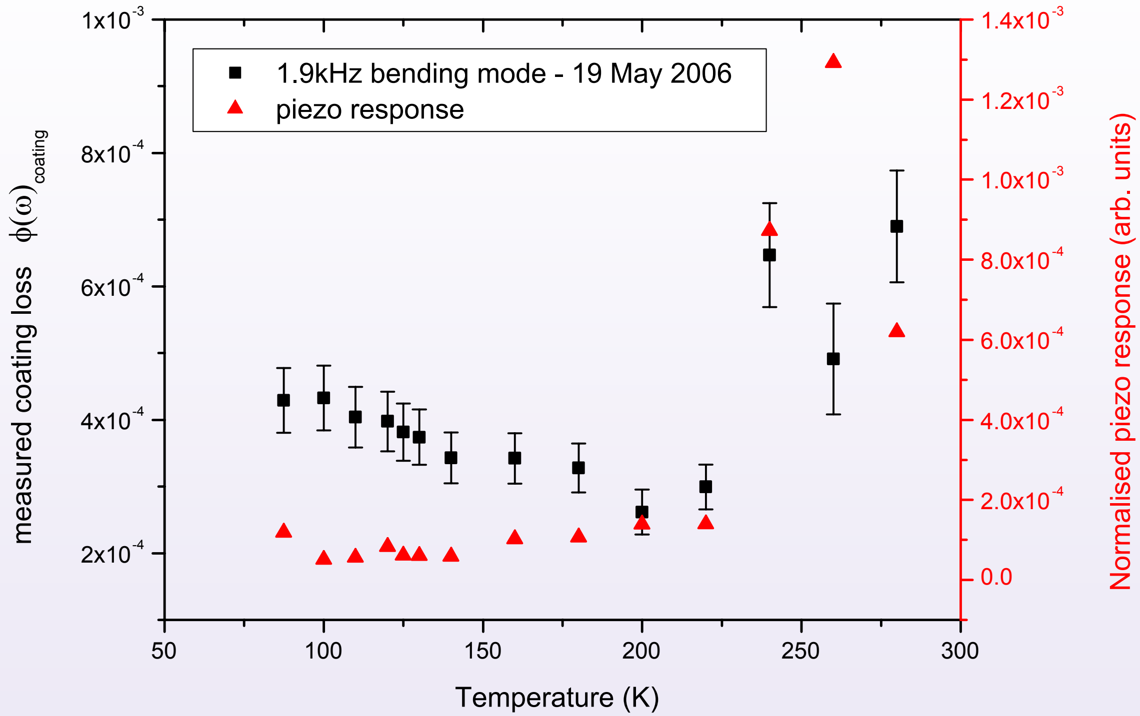
- Both sets of results show similar features, with the loss of the tantala coating typically decreasing with temperature from 290→200K then increasing from 200→80K.
- Need to investigate whether energy coupling to clamping structure is responsible for any of these features.
- This can be carried out using a piezo-sensor mounted to the clamping structure.



Setup for monitoring energy residing in the clamping structure

Results – energy residing in clamping structure

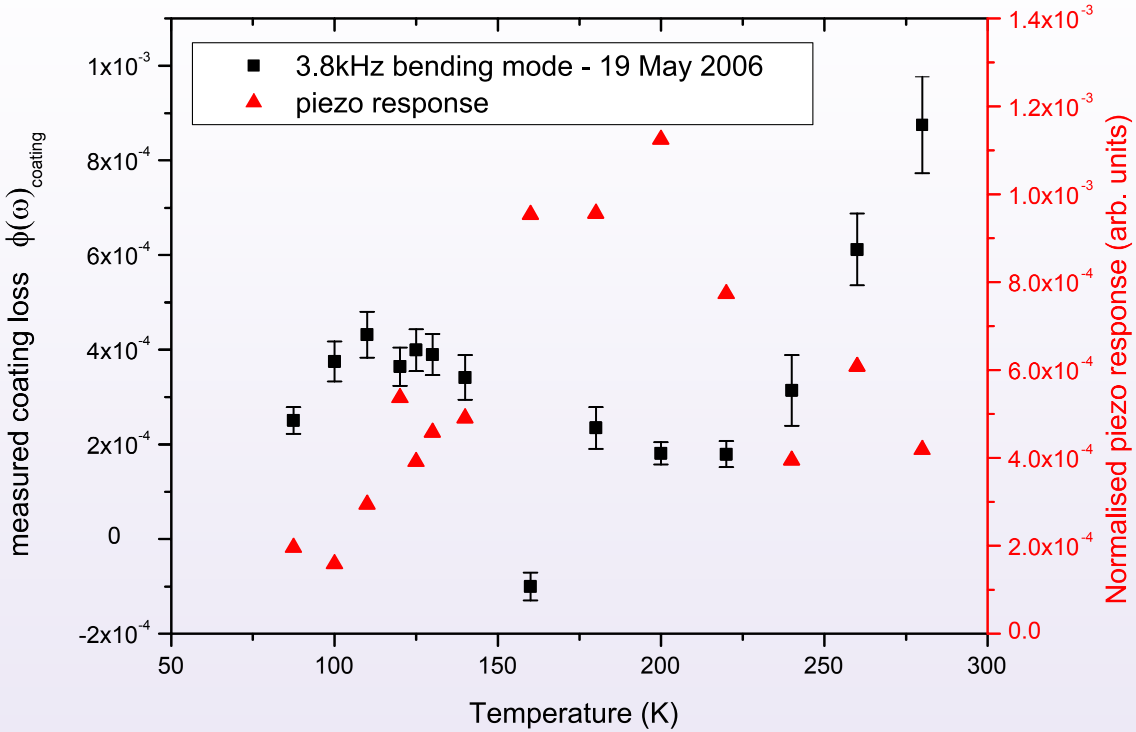
- Investigation to study energy coupling to clamping structure (third mode)



Plot of the measured loss of the third bending mode at f~1.9kHz compared with the normalised magnitude of the signal from the piezo-sensor

Results – energy residing in clamping structure

- Investigation to study energy coupling to clamping structure (fifth mode)



Plot of the measured loss of the fifth bending mode at f~3.8kHz compared with the normalised magnitude of the signal from the piezo-sensor

Conclusions

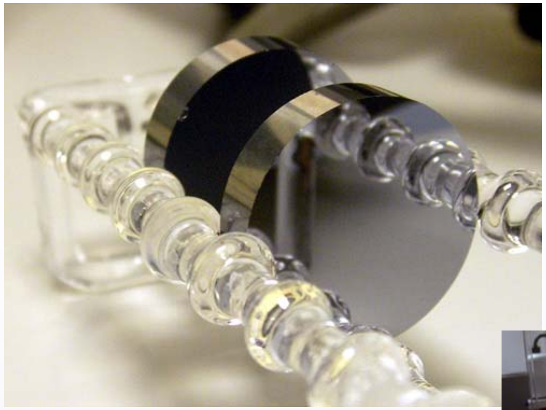
- Evidence for coupling of energy to clamp affecting loss at room temperature for 3rd bending mode.
- Story not so clear for other mode studied – measurements continuing
- However results at lower temperature consistent with

  (a) loss ~2 x 10^{-4} at ~200 K

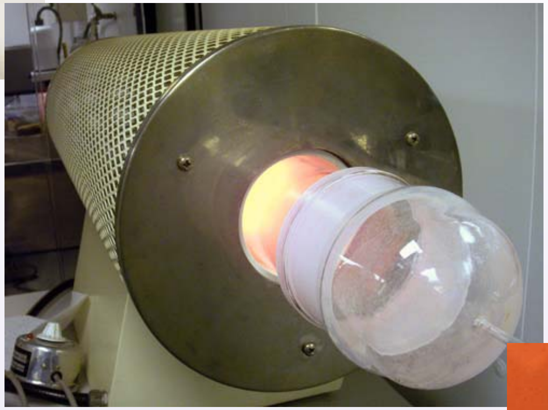
  (b) loss increasing as temperature decreases

  (c) possible dissipation peak ~100 K

Strength testing of Si-Si silicate bonds



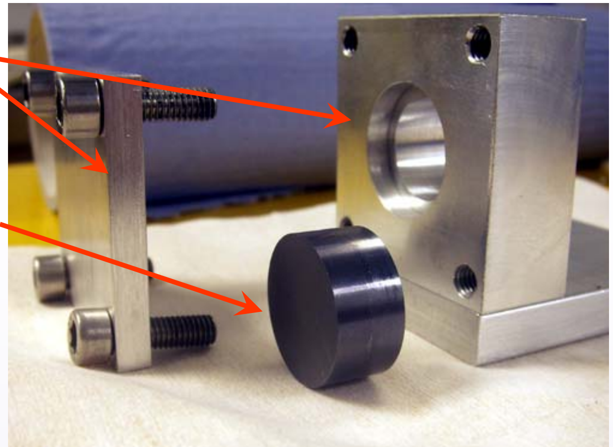
cleaned silicon samples



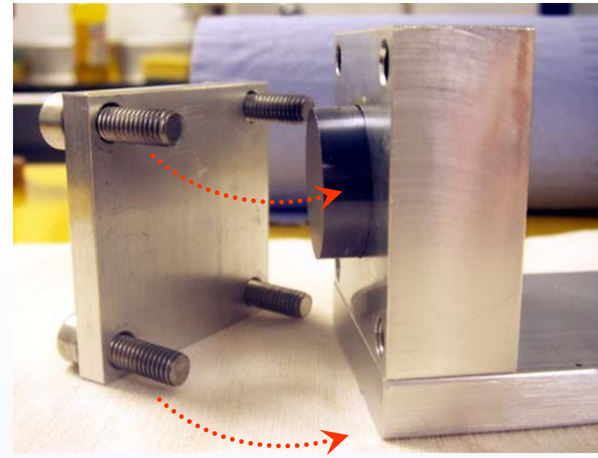
placed in furnace at 1000°C

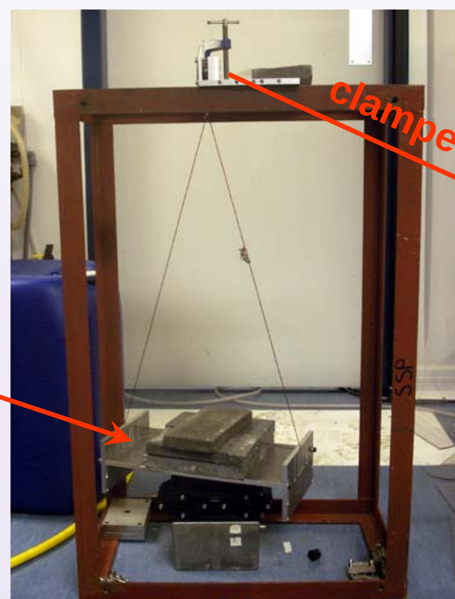
after ~1hr, 50 to 100nm oxide growth

Strength testing of Si-Si silicate bonds

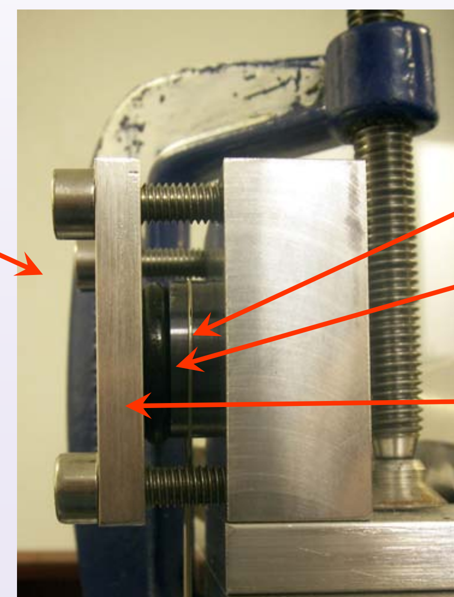


Si-Si bonded sample for testing


Si-Si sample placed in clamp



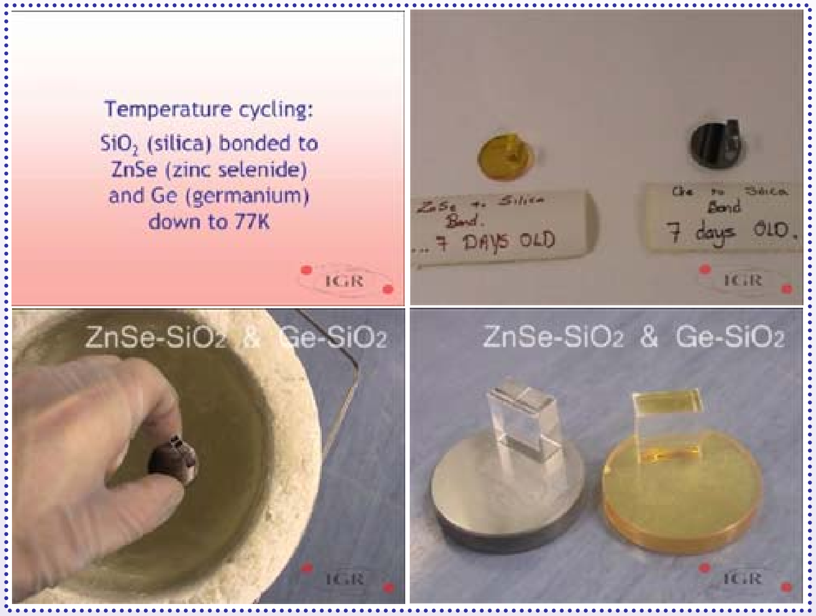
40Kg load suspended



Si-Si sample under load

Strength testing of Si-Si silicate bonds

- Initial strength tests on silicate bonded silicon samples has started.
- Further experiments will be carried out to find the ultimate breaking stress for Si-Si bonds.



Images from video of temperature cycling of SiO_2 bonded to ZnSe down to 77K