Low temperature dissipation in tantala and silica films

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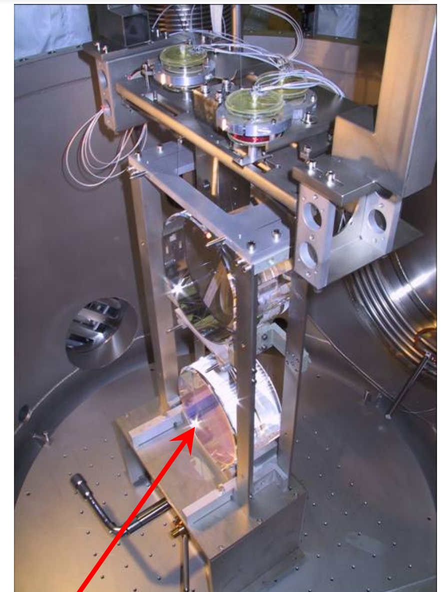
Introduction

- Mechanical dissipation from dielectric mirror coatings is predicted to be a significant source of thermal noise for advanced detectors.

- Experiments suggest
  - Ta_2O_5 is the dominant source of dissipation in current SiO_2/Ta_2O_5 coatings
  - Doping the Ta_2O_5 with TiO_2 can reduce the mechanical dissipation



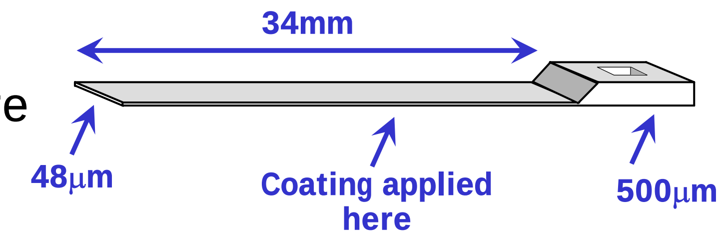
GEO600 mirror suspension, with HR coating on front face.

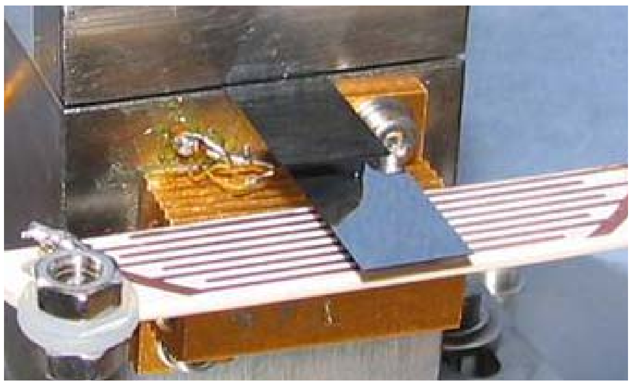
- Mechanism responsible for the observed mechanical loss in Ta_2O_5 as yet not clearly identified

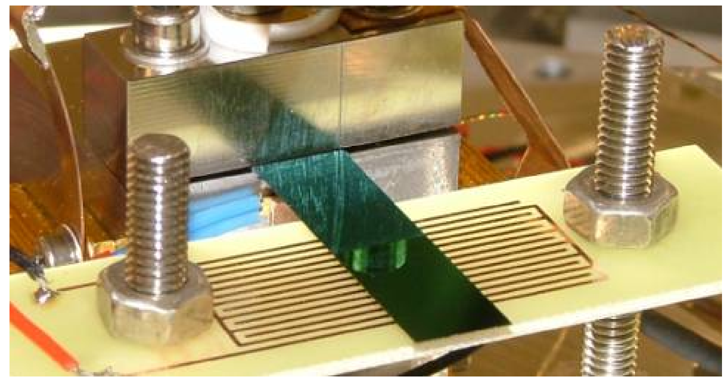
- Studying dissipation as a function of temperature of interest to:
  - Determine dissipation mechanisms in the coatings, possibly allowing dissipation to be reduced
  - Evaluate coating for possible use in proposed cryogenic gravitational wave detectors

Single layer coating samples for low temperature studies

- Thin silicon substrates used for coating
  - Loss of silicon decreases at low temperature
  - Coating will dominate the loss




Uncoated silicon cantilever in clamp


Titania doped tantala coated silicon cantilever in clamp

- Samples etched from silicon wafers by colleagues at Stanford, with thicker clamping block to isolate cantilever from clamp

- 0.5 μm thick films deposited by ion beam sputtering, including (a) Ta_2O_5 doped with (14.5 ± 1)% TiO_2 (b) un-doped Ta_2O_5 (c) SiO_2

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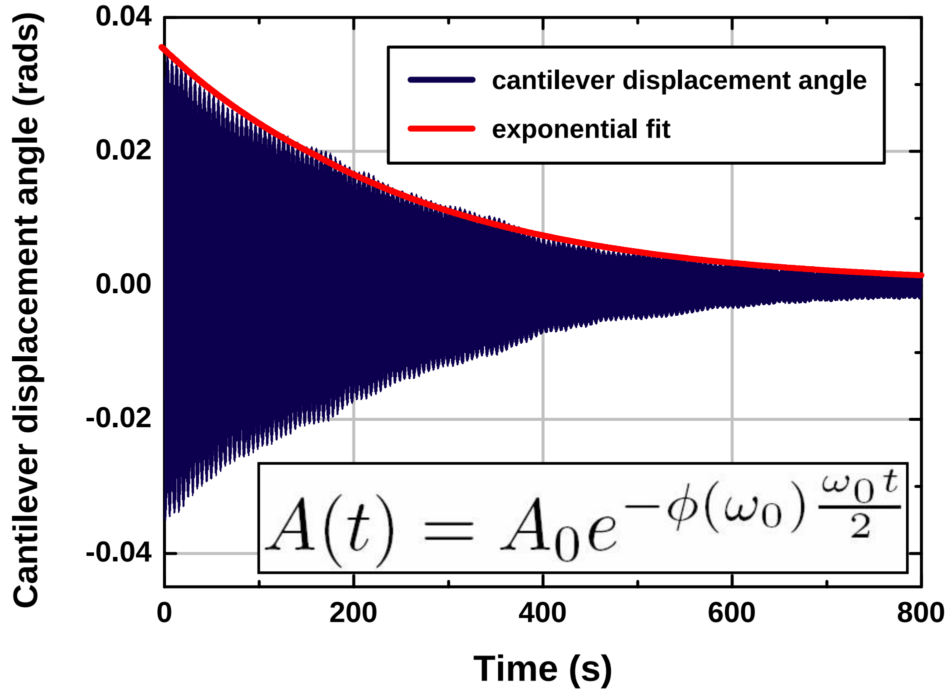
Measuring coating loss

- Bending modes of cantilever excited electrostatically, loss $\phi(\omega)$ obtained from exponential amplitude ringdown
- Loss of coating material calculated from losses of coated and un-coated cantilevers
- Loss of coating material is given by:



Typical amplitude ringdown

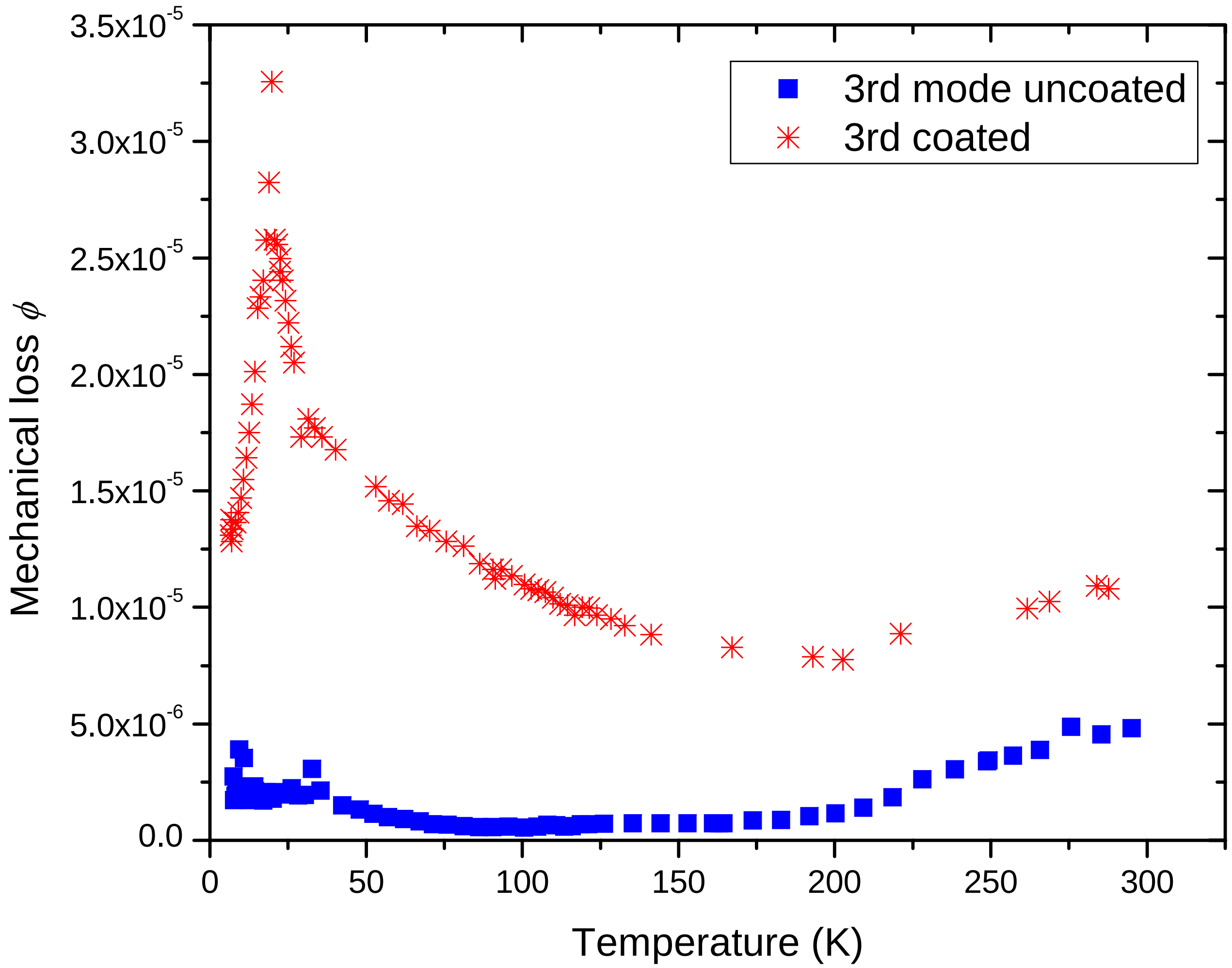
$$\phi_{coating} = \frac{Y_{cantilever}}{3Y_{coating}} \frac{t_{cantilever}}{t_{coating}} \left(\phi_{coated-sample} - \phi_{un-coated-sample}\right)$$

Ratio of energy stored in cantilever to energy stored in coating

Difference in loss between coated and un-coated cantilevers

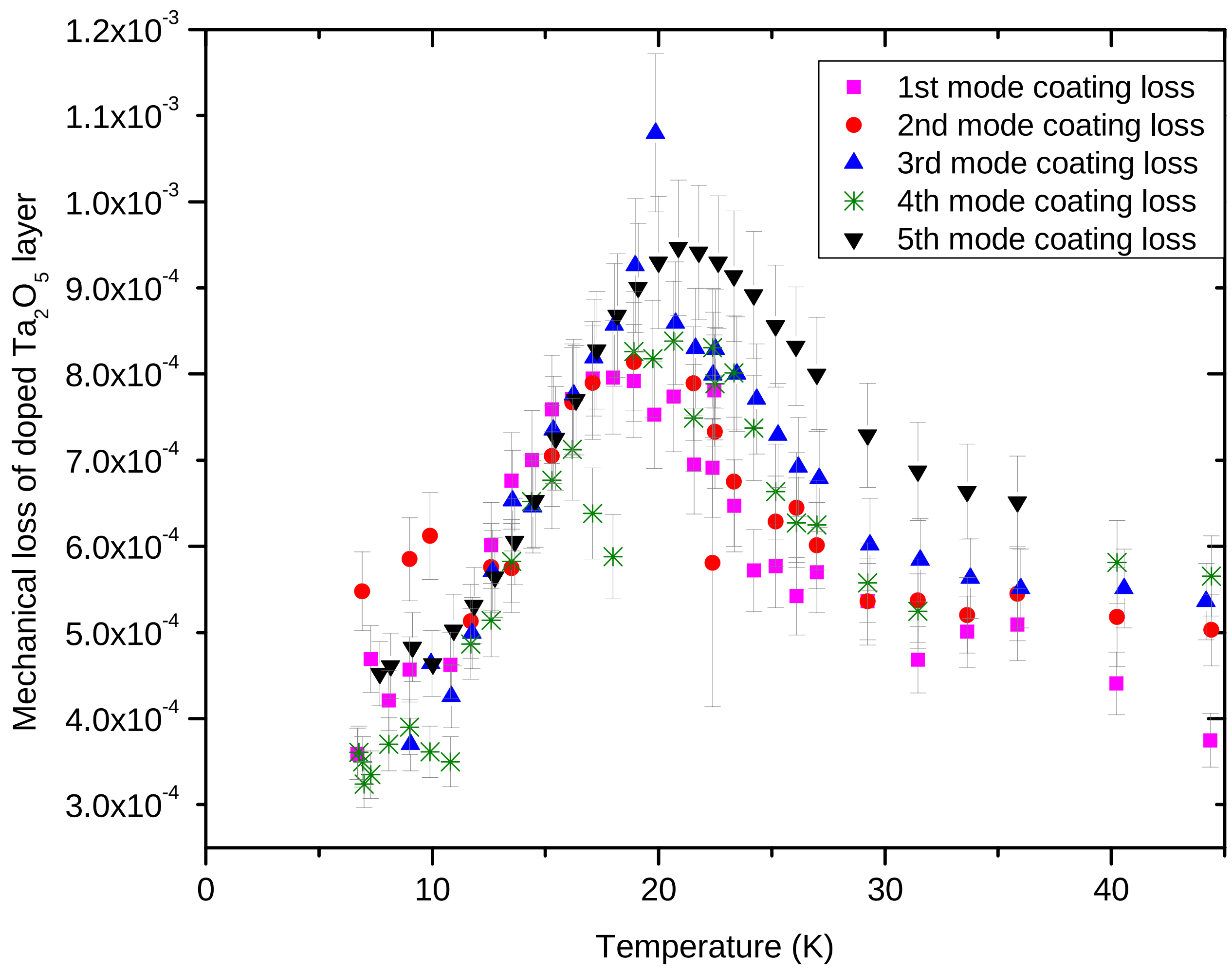
Mechanical loss measurements

- Comparison of the mechanical loss of the third bending mode (~1000 Hz) for a cantilever coated with Ta_2O_5 with 14.5 % TiO_2 (LMA), and an identical un-coated cantilever



Low temperature coating loss peak

- A dissipation peak at ~18-20 K observed in TiO_2-doped Ta_2O_5

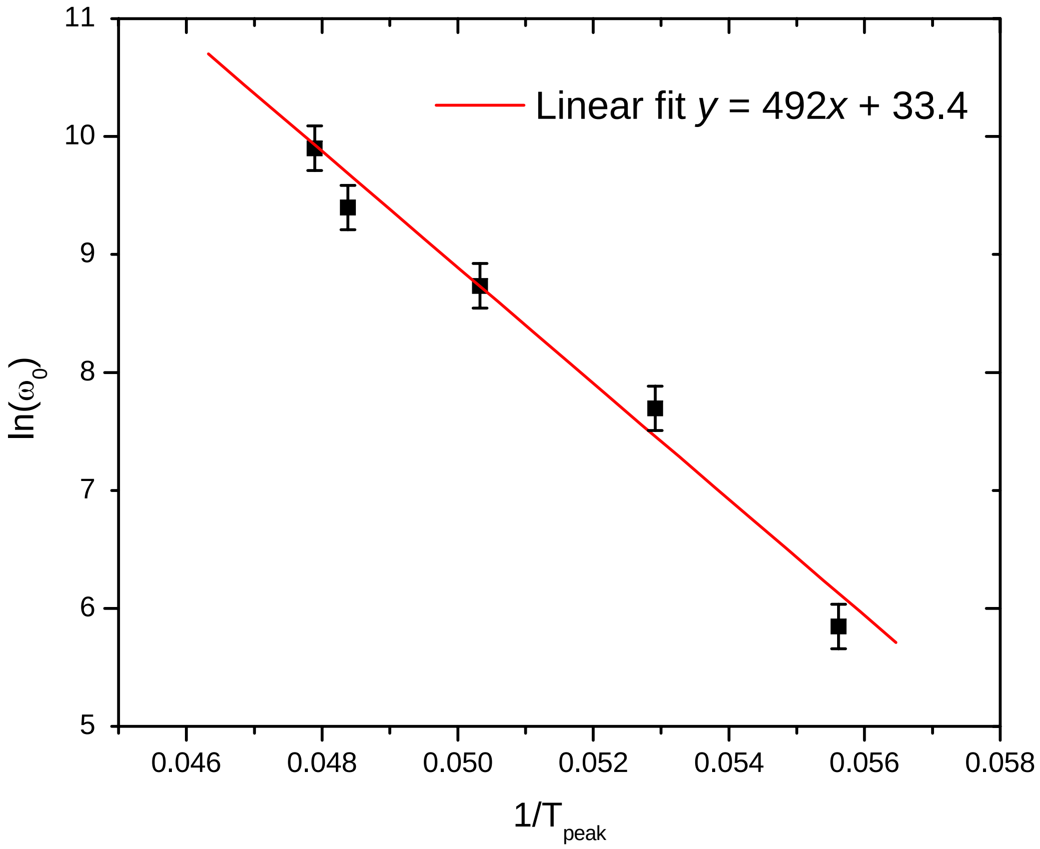


Relation of mode frequency to temperature of loss peak

- Can calculate an activation energy associated with the dissipation peak of (42 ± 2) meV

- The low temperature dissipation peak in fused silica has a similar activation energy (44 meV)

- Oxygen atoms can undergo thermally activated transitions between two states in a double well potential, corresponding to stable bond angles

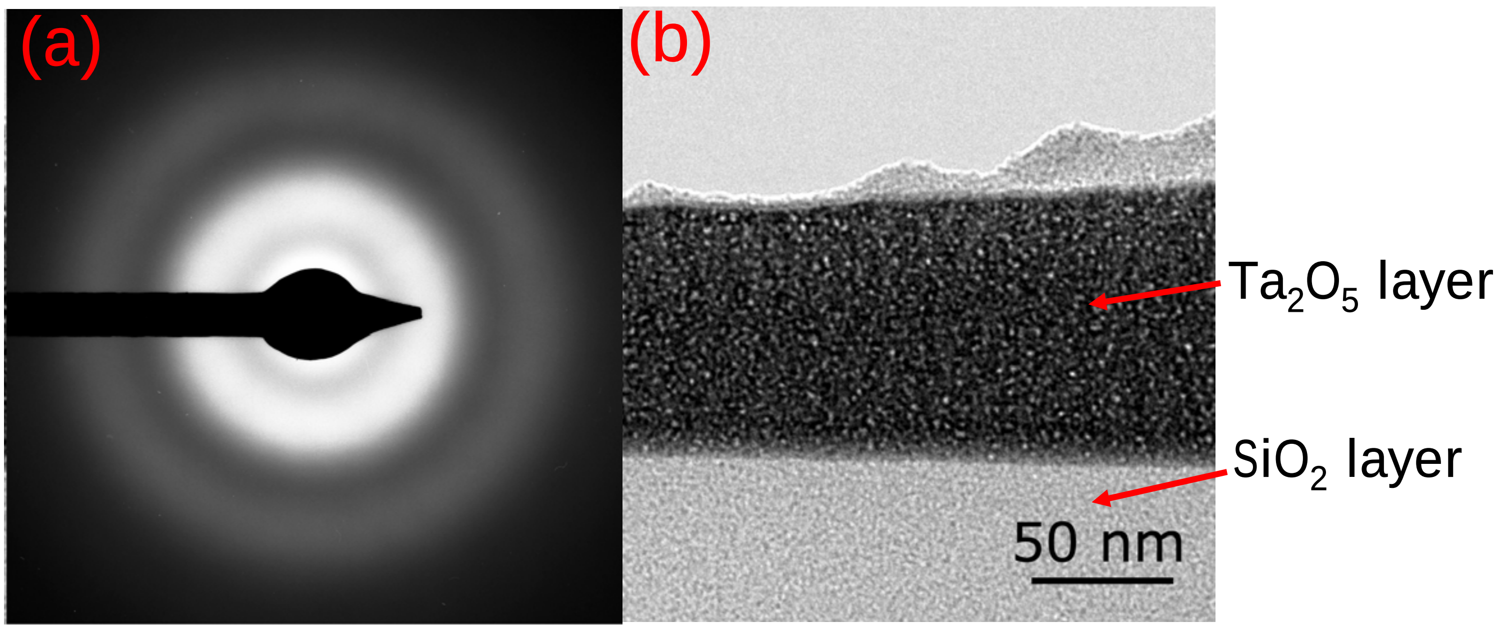


- Width of the dissipation peak thought to be related to the distribution of Si-O bond angles in the sample

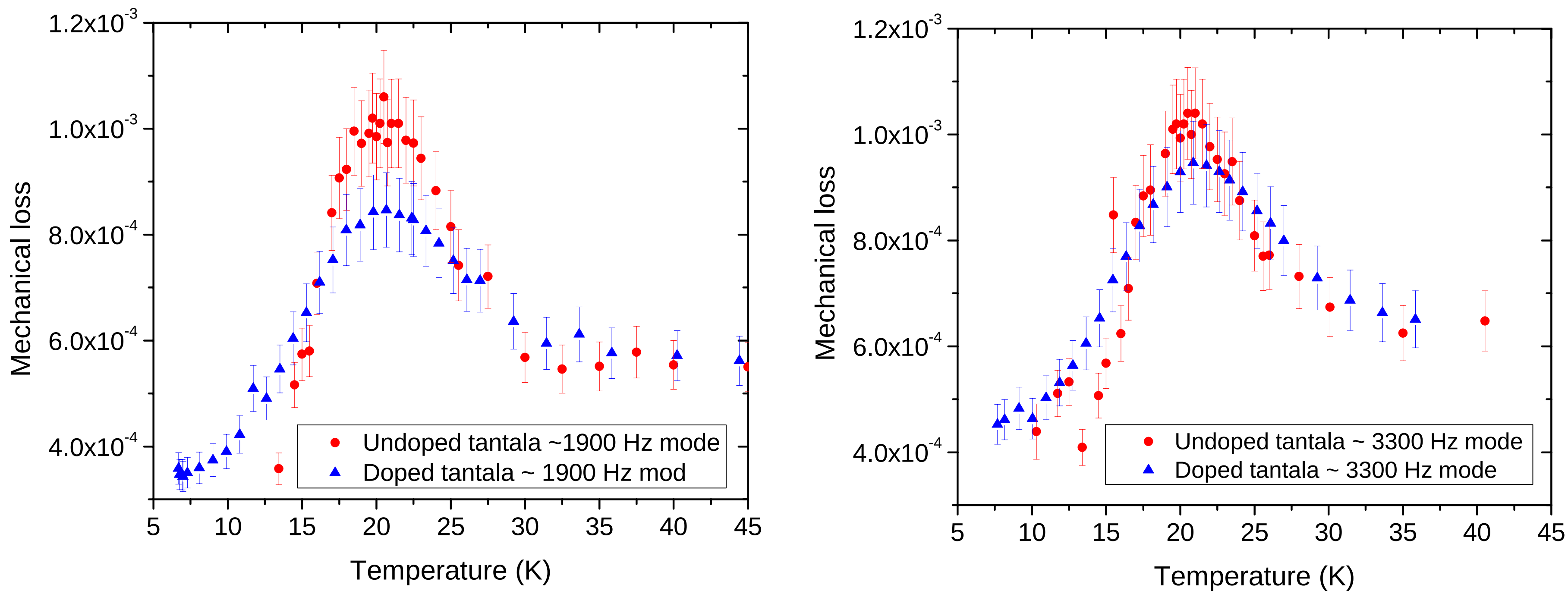
- Results suggest a similar dissipation mechansims may be responsible for low temperature loss peak in Ta_2O_5

TEM studies of coating structure

- Convergent beam electron diffraction measurements (a) of a doped ion-beam sputtered Ta_2O_5 layer (see TEM image, (b)) showing only diffuse rings of intensity, confirming that the layer is amorphous.



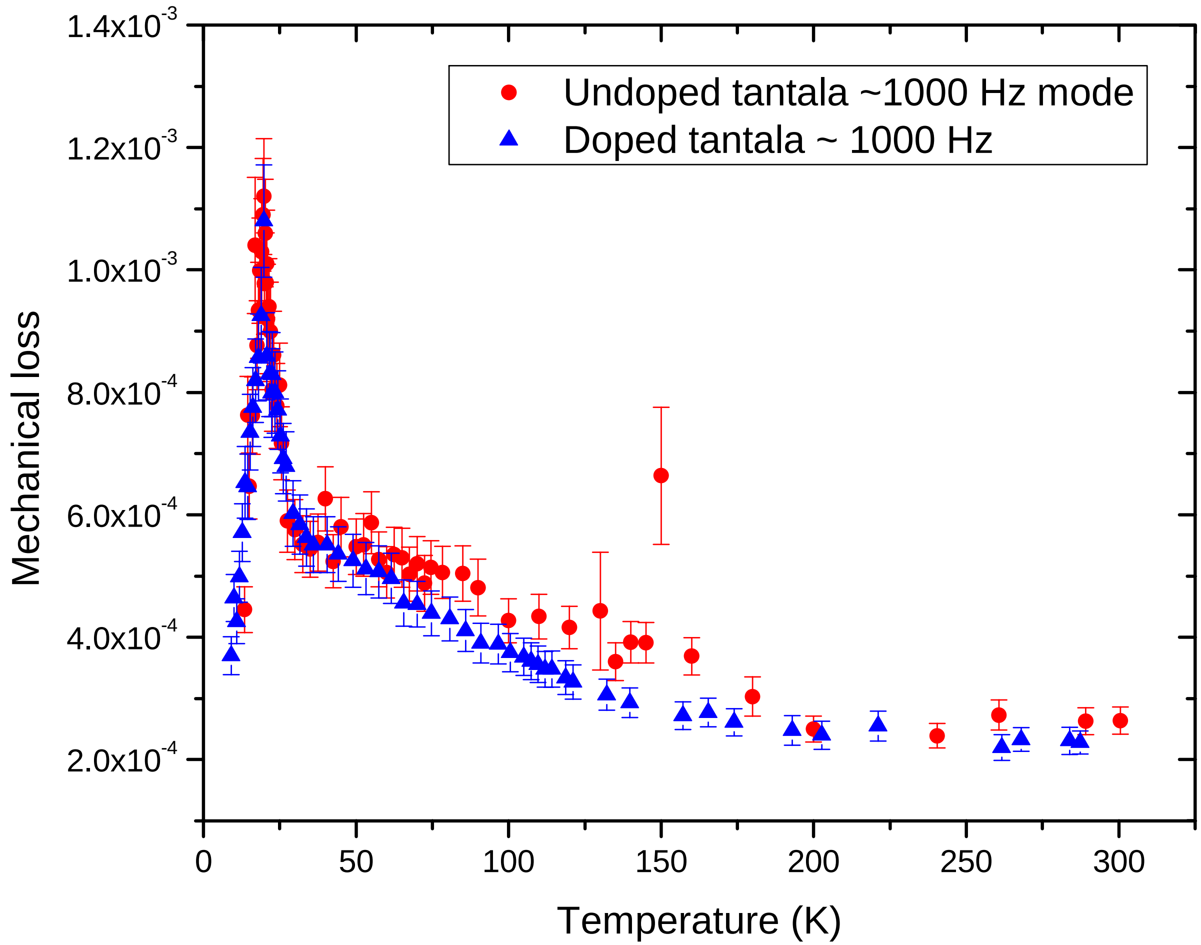
Effect of doping Ta_2O_5 with 14.5 % TiO_2



Comparison of dissipation peak in doped and un-doped Ta_2O_5 for 4th (left) and 5th bending modes (right).

- Doping appears to reduce the height of the peak and slightly increase the width of the peak

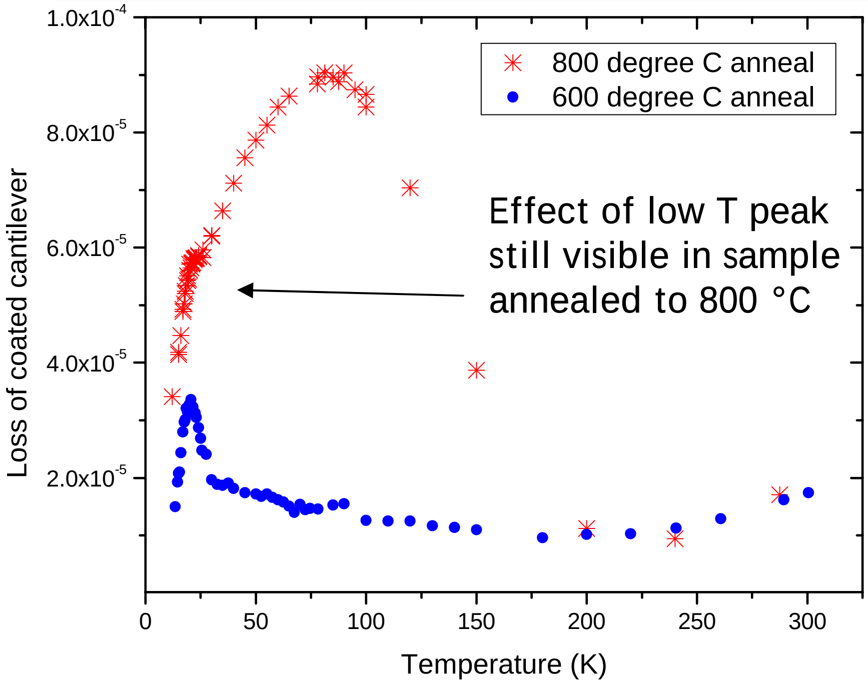
Effect of doping Ta_2O_5 with 14.5 % TiO_2

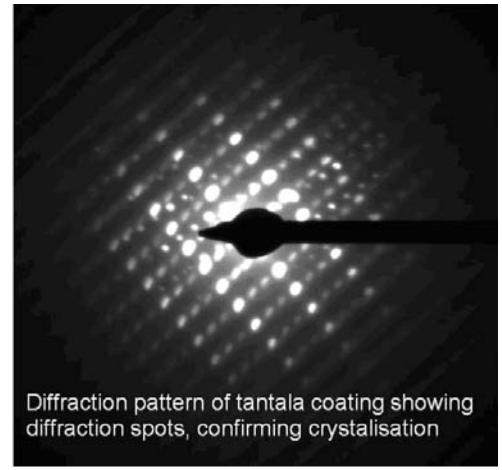


Comparison of the dissipation of TiO_2-doped and un-doped Ta_2O_5

- Doping reduces loss of Ta_2O_5 throughout temperature range

Effect of annealing

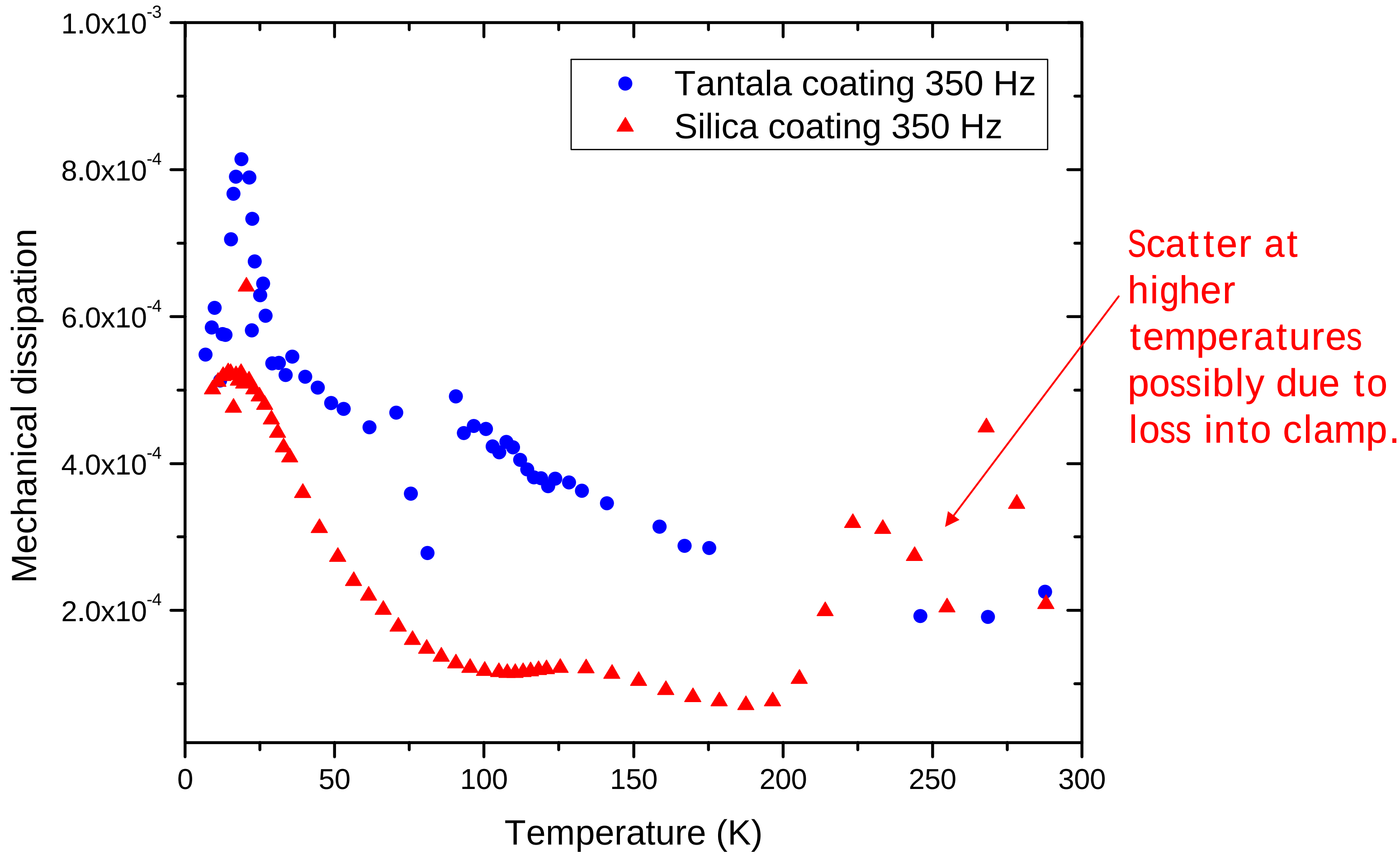




Left: Loss at 1900 Hz of Ta_2O_5 annealed at 800 °C and 600 °C. Right: Electron diffraction measurement of Ta_2O_5 annealed at 800 °C

- Heat treatment can reduce dissipation in SiO_2, possibly by changing bond angle distribution. May be possible to modify characteristics of the dissipation peak in Ta_2O_5 by annealing.
- Experiment underway to measure un-doped Ta_2O_5 annealed at 300, 400, 600 and 800 °C.
- Large peak at ~ 80 to 90 K in coating annealed at 800 °C, perhaps due to (expected) onset of polycrystalline structure, as shown in electron diffraction image above.

Comparison of SiO_2 and Ta_2O_5

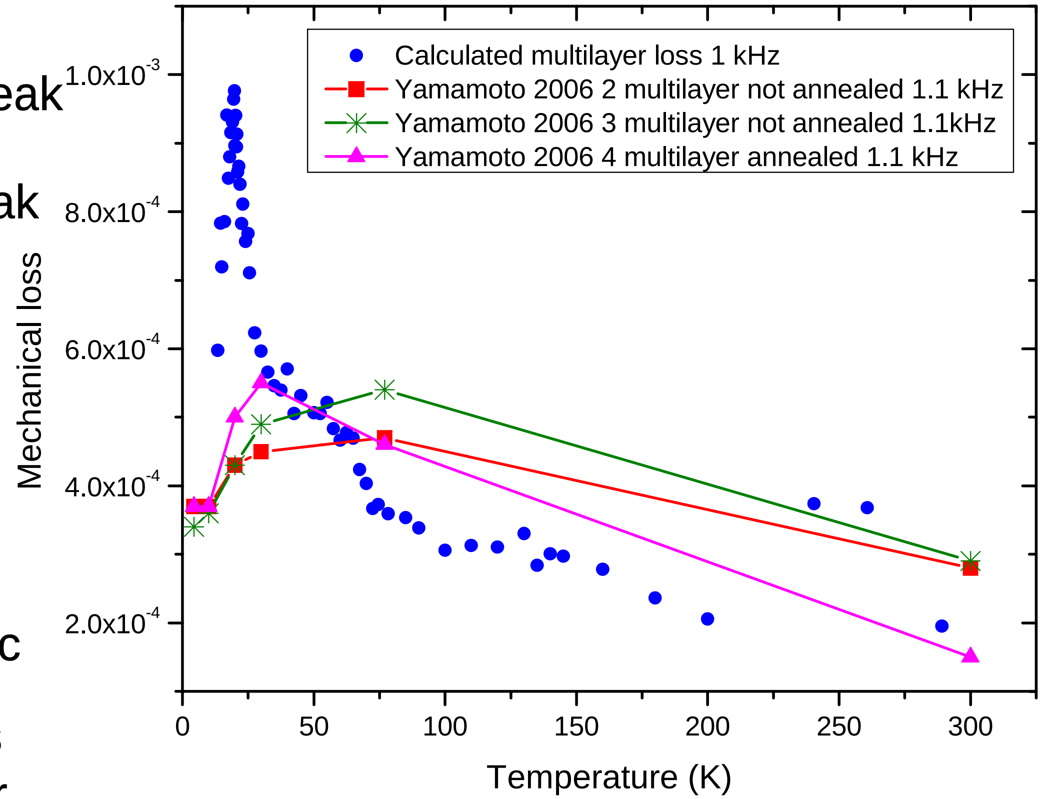


- Loss of ion beam sputtered SiO_2 is significantly lower than loss of Ta_2O_5 between 10 and 300 K.

Comparison to multilayer results of Yamamoto et al

- Loss of single SiO_2 and Ta_2O_5 layers used to calculate loss in a 31 layer multilayer coating, as measured by Yamamoto et al*

- Yamamoto's results:
  - Show no evidence of a large peak at 20 K
  - Are not inconsistent with a peak at slightly higher T, with T_{peak} possibly lowered by annealing
- Apparent discrepancy in results - could be explained by:
  - Differences in annealing temperature and / or coating layer thickness?
  - Different coating thermoelastic loss between coatings on sapphire and silicon substrates
  - Not enough data for multilayer coating

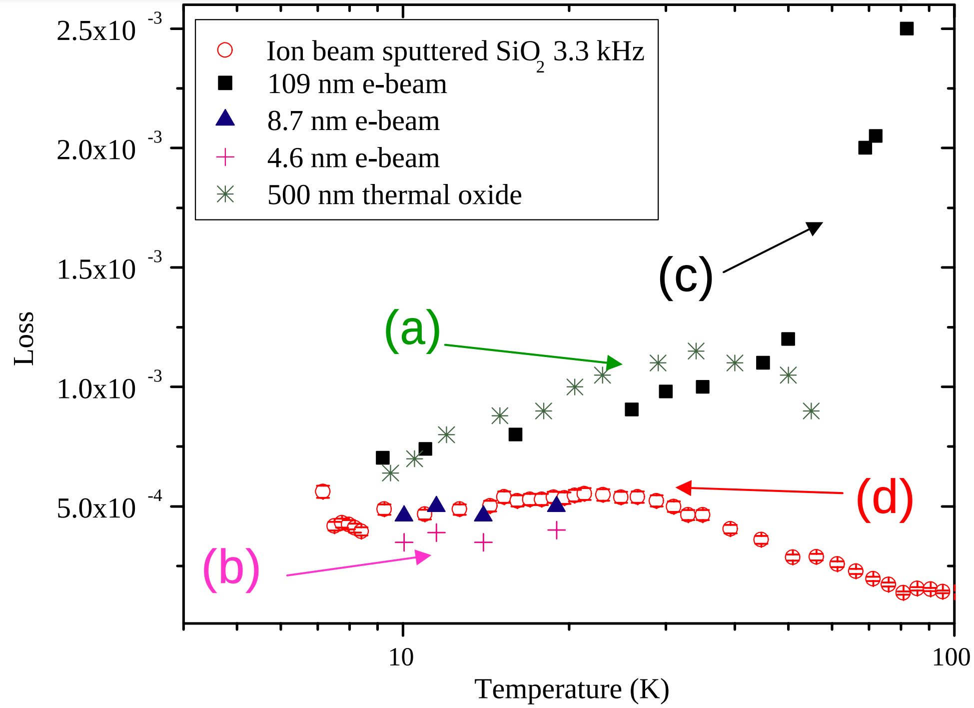


Calculated multilayer coating loss at 1 kHz compared to Yamamoto's measured multilayer loss at 1.1 kHz

*Yamamoto et al., Phys. Rev. D **74,** 022002 (2006)

Silica loss at low temperature – comparison of deposition methods

- Bulk silica & thermal oxide[1,2] (a) have dissipation peak at ~ 35 K
- e-beam SiO_2 (5.5 kHz)[1,2] (b),(c)
  - No dissipation peak at 30 – 40 K
  - Thin (few nm) films have lower loss than bulk SiO_2, loss is flat as T increased (b)
  - Thicker (tens to 100 nm) films have higher loss, rising rapidly above 10 K (c)



- Ion beam sputtered coating (d)
  - Broad loss peak between 20 and 30 K (d). Peak loss is lower (and at lower temperature) than in bulk / thermal SiO_2
  - Level of loss can be as low as for 4 to 8 nm of e-beam SiO_2, significantly lower loss and different temperature dependent behaviour to thick e-beam SiO_2
- Plan to continue these studies to gain better understanding of how the deposition technique/material microstructure is related to dissipation mechanism

[1]White and Pohl, Phys. Rev. Lett. 75 (1995) 4437 – 4439, [2]White and Pohl, Physica B 219&220 (1996) 267-269.

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Conclusions

- Dissipation peak observed at ~ 20 K in 500 nm films of Ta_2O_5, with activation energy 42 ± 2 meV. Possible dissipation mechanism is thermally activated transitions of the oxygen atoms.
- Some evidence that TiO_2 doping reduces the height of the dissipation peak in addition to reducing the loss at room temperature.
- Ta_2O_5 coatings annealed at 800 °C display a large dissipation peak at ~90 K.
- Ta_2O_5 has higher loss than SiO_2 between 10 and 300 K
- Ion beam sputtered silica has significantly lower loss than similar thicknesses of e-beam silica below 100 K – further studies of relation of deposition technique/material microstructure to dissipation mechanism planned
- A full understanding of the dissipation mechanisms in coatings may allow
  - Mechanical loss at room temperature to be further reduced
  - Reduction of loss at particular temperatures of interest for future cryogenic detectors

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Current and future work

- Measure effect of annealing temperature on loss in undoped Ta_2O_5 as a function of temperature
- Parallel TEM studies of the affect of annealing on the structure of Ta_2O_5
- Continued investigation of the effects of TiO_2 doping
- Collaboration with INFN lab at Legnaro to study the loss of silica films (ion beam sputtered and thermal oxide) at ultra-cryogenic temperatures – may yield more information on loss mechanisms
- Investigate mechanical loss of possible alternative high index materials – e.g. hafnia (see talk by Eleanor Chalkley)