Low temperature dissipation in coating materials

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Overview

- Introduction and experimental details
- Measurements of the low temperature dissipation peak in Ta_2O_5 coatings
  - Possible dissipation mechanism in ion beam sputtered Ta_20_5
  - Effect of TiO_2 doping on the loss in Ta_2O_5 coatings
  - Effect of annealing on the loss in Ta_2O_5 coatings
- Comparison of dissipation in Ta_2O_5 and SiO_2 films as a function of temperature
- Magnetron sputtered SiO_2 results from Jena University (slides courtesy of Ronny Nawrodt)
- Preliminary results of Hafnia.

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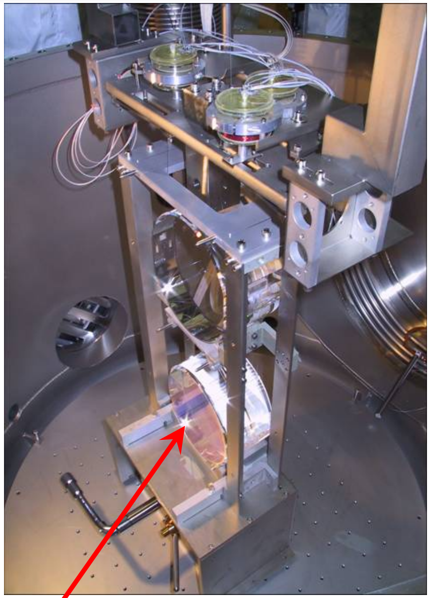
Introduction

- 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



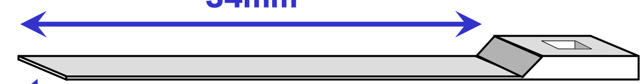
GEO600 mirror suspension, with HR coating on front face.

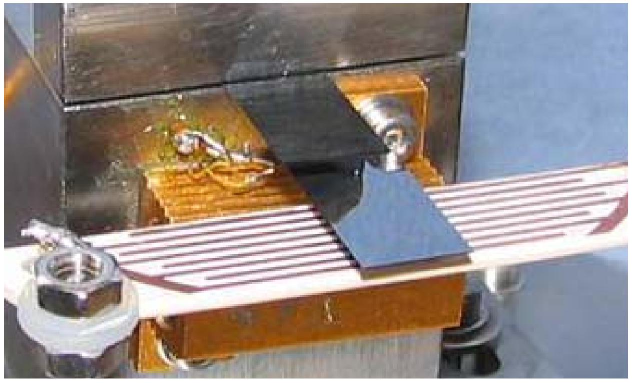
- Mechanism responsible for the observed mechanical loss in Ta_2O_5 as yet not clearly identified

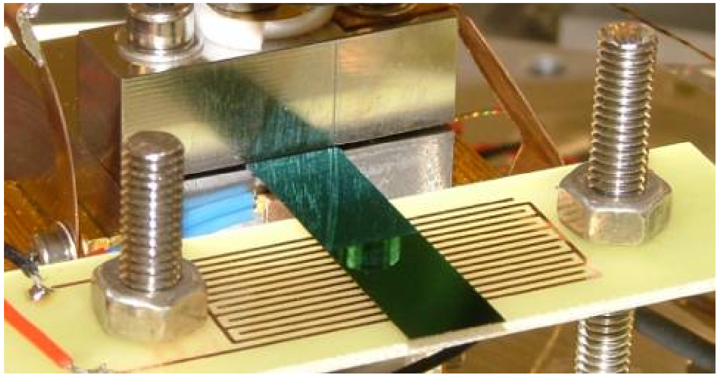
- Studying dissipation as a function of temperature of interest to:
  - Determine dissipation mechanisms in the coatings, possibly allowing dissipation to be reduced
  - Evaluate coating for possible use in proposed cryogenic gravitational wave detectors

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

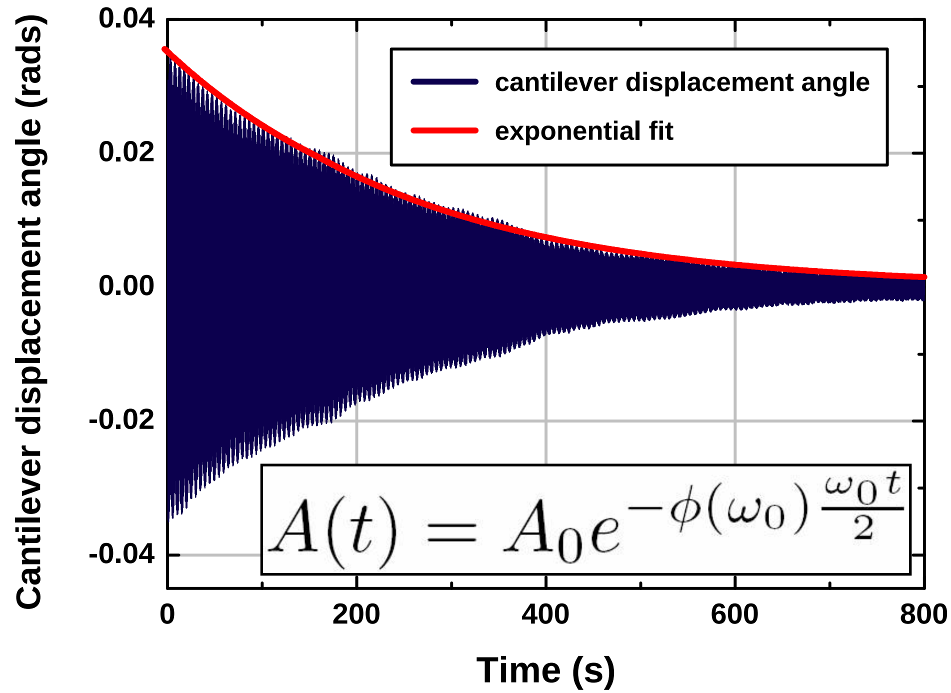

Titania doped tantala coated silicon cantilever in clamp

- Samples etched from silicon wafers, 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 and (d) hafnia

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 of ring-down

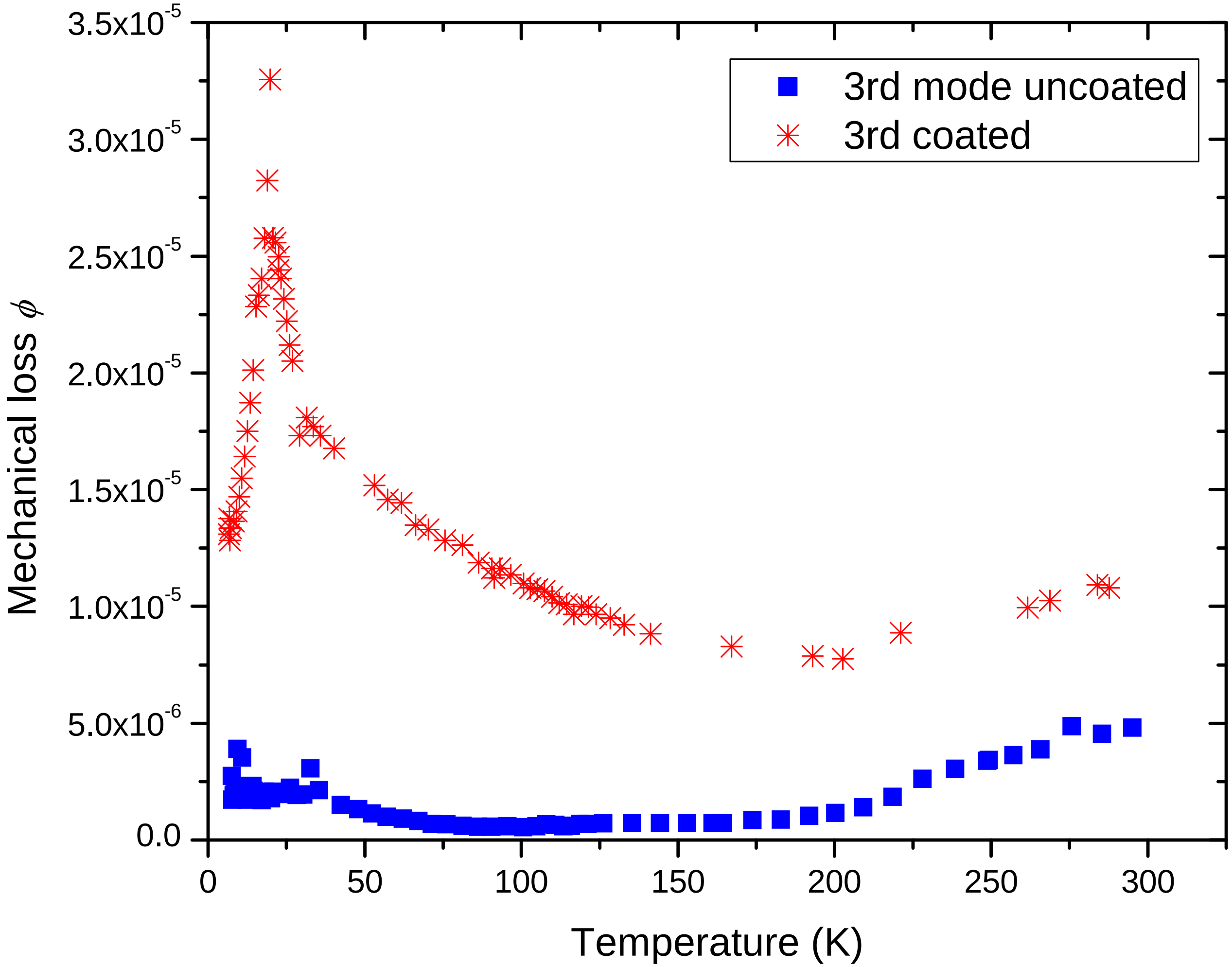
$$\phi_{\text{coating}} = \frac{E_{\text{coated-sample}}}{E_{\text{coating}}}(\phi_{\text{coated sample}} - \phi_{\text{uncoated sample}})$$

ratio of energy stored in cantilever to energy stored in coating

difference in loss between coated and un-coated cantilevers

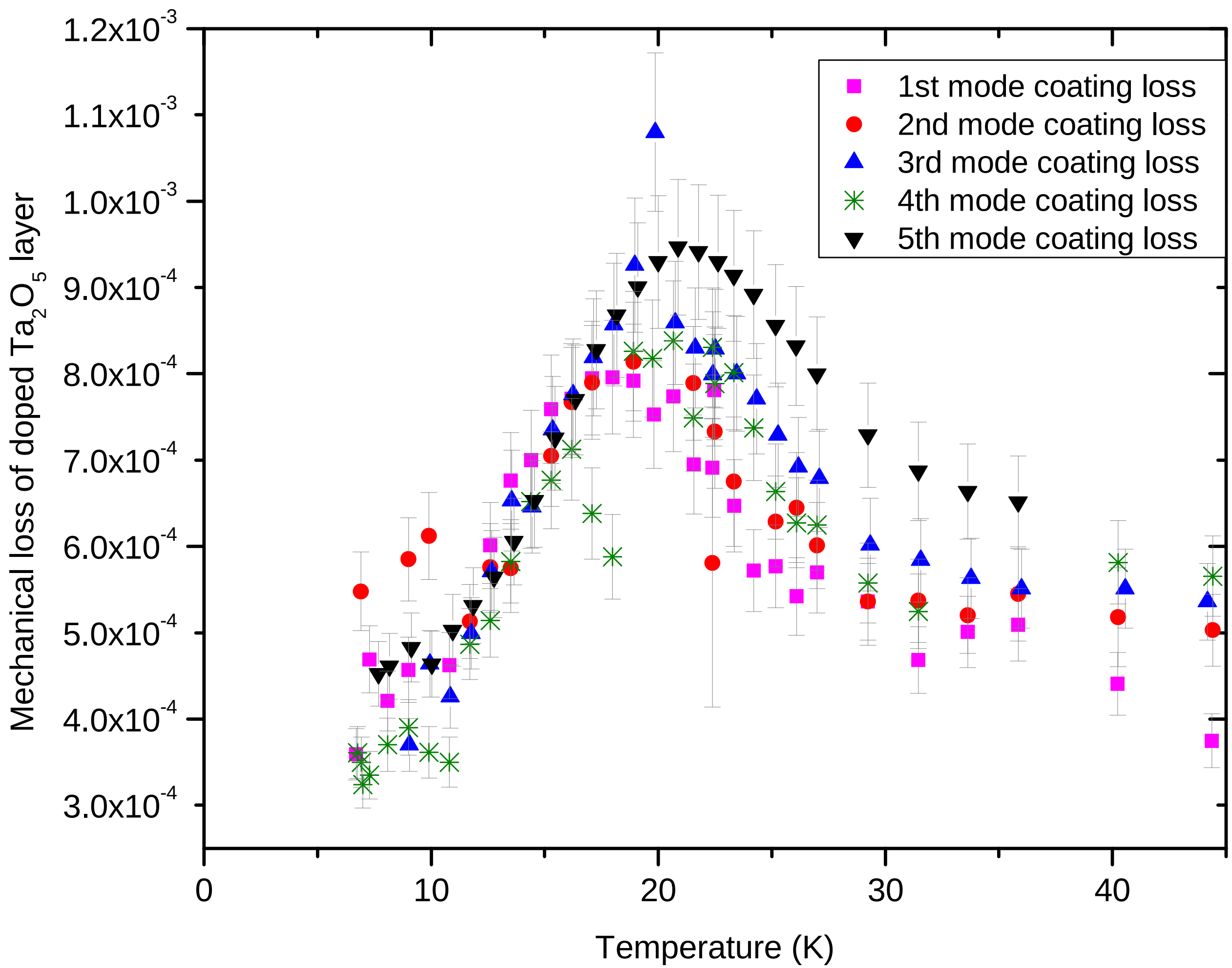
Mechanical loss measurements

- 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, and an identical un-coated cantilever (in collaboration with Jena University)



Low temperature coating loss peak

- A dissipation peak at ~18-20 K observed in both TiO_2-doped Ta_2O_5 (see figure) and pure Ta_2O_5



Interpretation and analysis

- Most internal friction mechanisms may be thought of as relaxation processes associated with transitions between equilibrium states, and typically:

$$\phi(\omega) = \Delta \frac{\omega\tau}{1+(\omega\tau)^2}$$

where τ is the relaxation time
Δ is a constant related to height of peak

- Thermally activated processes follow Arrhenius equation:

$$\tau^{-1} = \tau_0^{-1} e^{-\frac{E_a}{K_B T}}$$

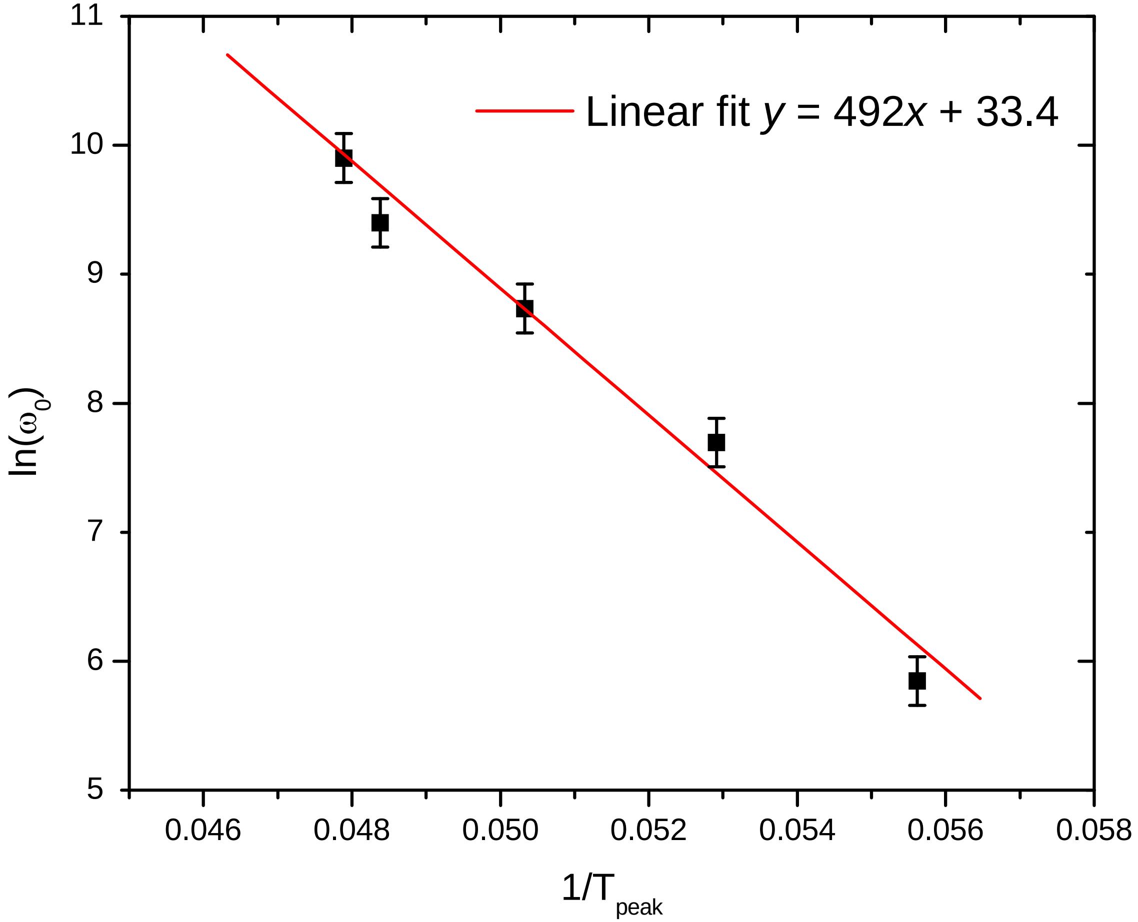
where τ_0^{-1} is the rate factor and E_a is the activation energy for the process

- At the dissipation peak, $\omega\tau = 1$ and $\omega = \tau_0^{-1} e^{-\frac{E_a}{K_B T_{peak}}}$

hence

$$\ln\omega = \ln\tau_0^{-1} - \frac{E_a}{K_B T_{peak}}$$

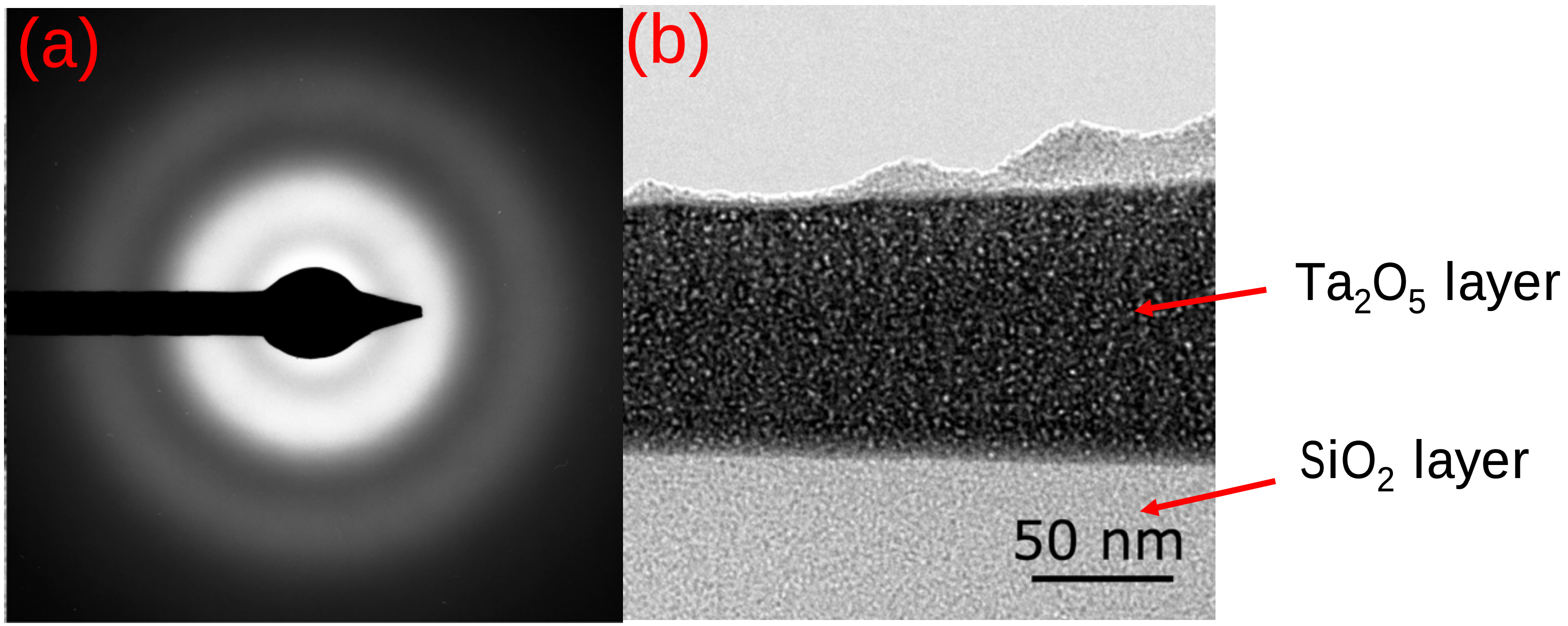
Fitting to Arrhenius equation



- This gives an activation energy associated with the dissipation peak in doped tantala of (42 ± 2) meV, and a rate factor of 3.3×10^{14} Hz.

Coating Structure

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



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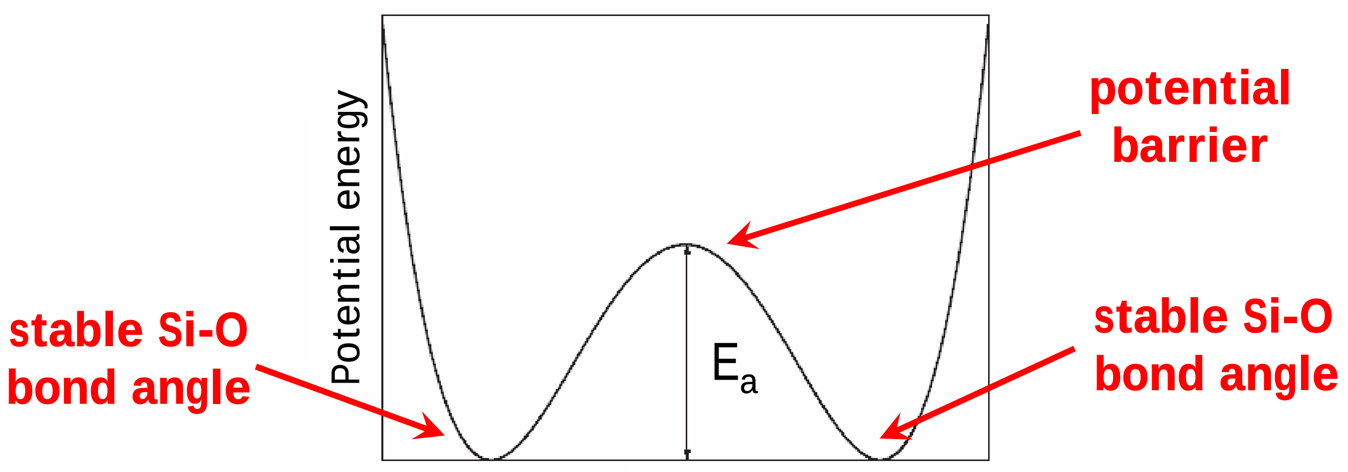
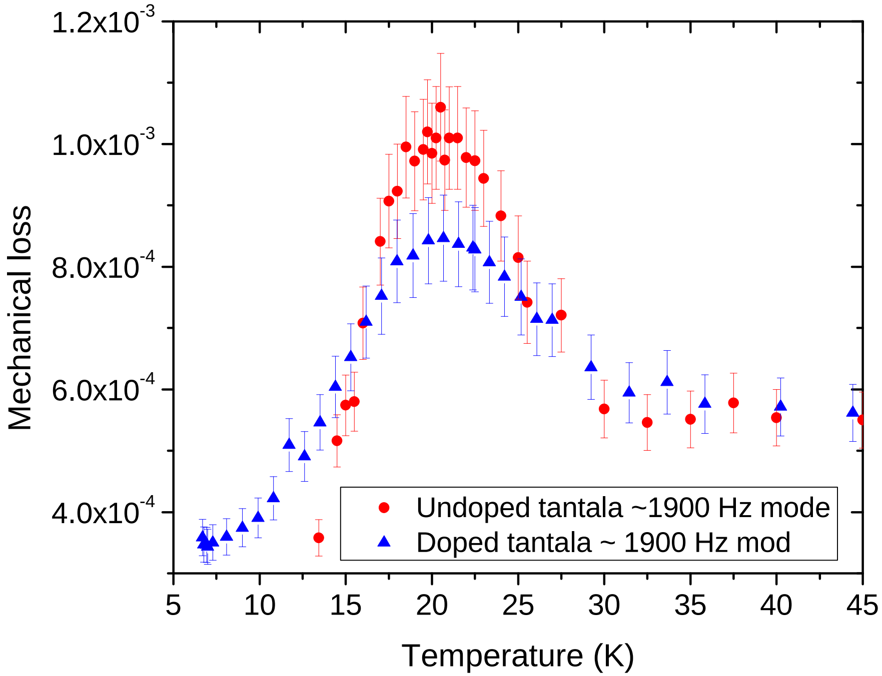
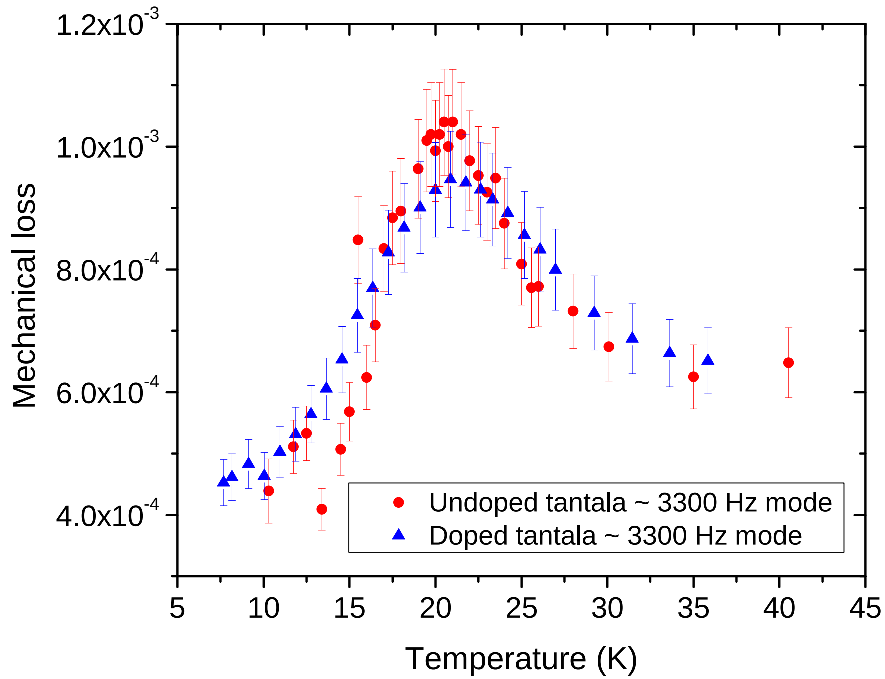
Interpretation – double well potential

- Low temperature dissipation peak in fused silica has similar activation energy (44 meV)
  - Oxygen atoms can undergo thermally activated transitions between two possible energy states in a double well potential
  - Width of the dissipation peak thought to be related to the distribution of Si-O bond angles in the sample
  - The dissipation mechanism in doped Ta_2O_5 may be similar, but requires further study



Effect of doping Ta_2O_5 with 14.5 % TiO_2

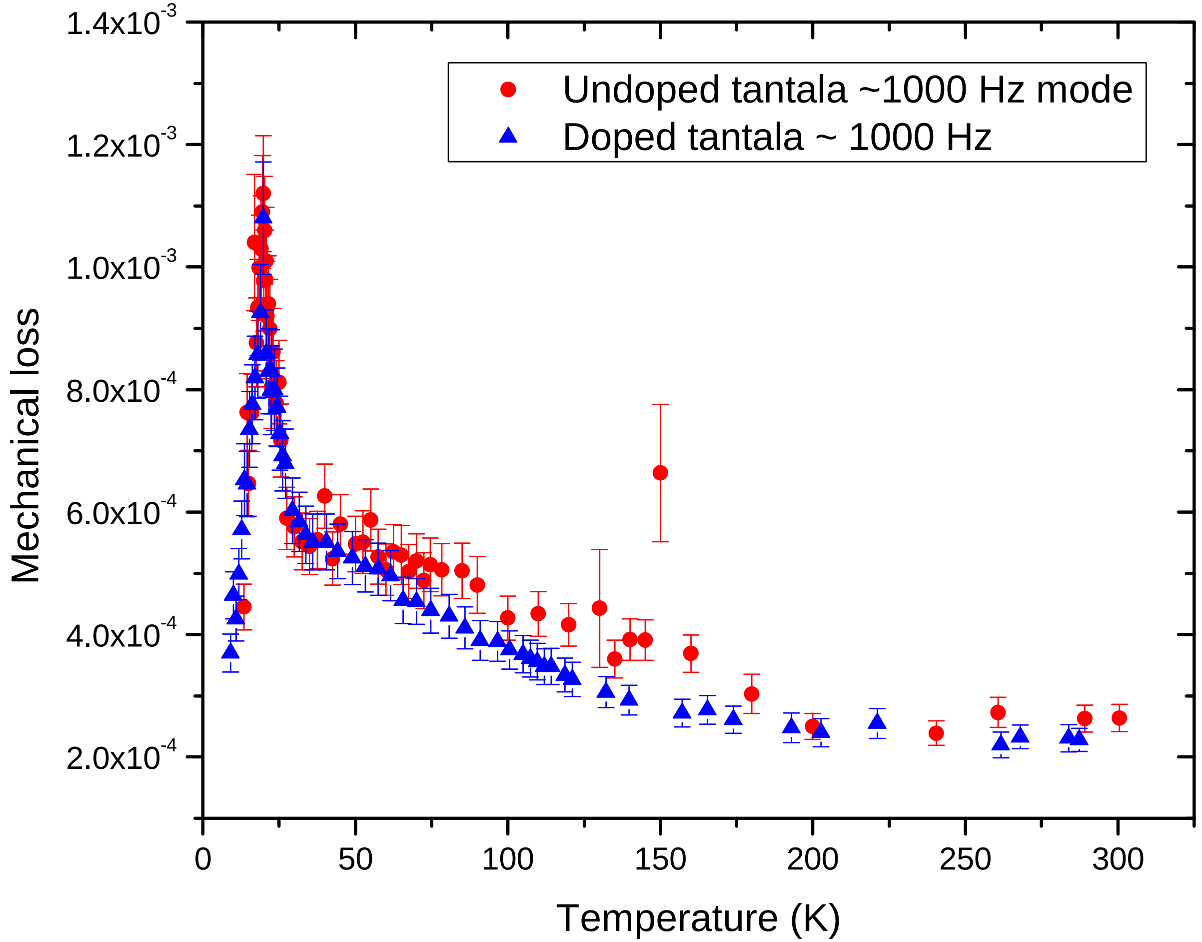




Comparison of dissipation peak in doped and un-doped Ta_2O_5 for 4^{th} (left) and 5^{th} bending modes (right).

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

Effect of doping Ta_2O_5 with 14.5 % TiO_2



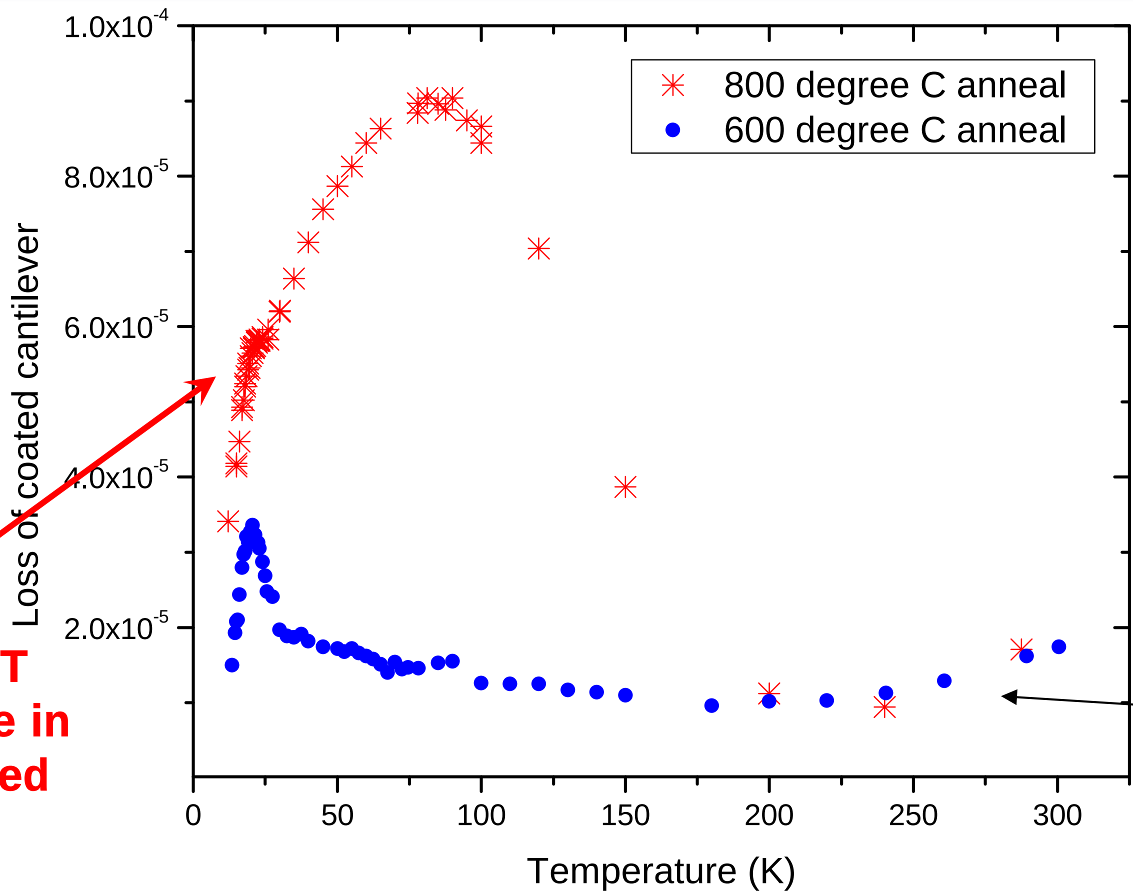
Comparison of the dissipation of TiO_2-doped and un-doped Ta_2O_5

- Doping reduces loss of Ta_2O_5 throughout temperature range

Effect of annealing

- Heat treatment can reduce the dissipation in SiO_2 possibly by changing distribution of bond angles
    - If dissipation mechanism in Ta_2O_5 is indeed similar to SiO_2 it may be possible to modify characteristics of the dissipation peak by heat treatment
    - Ta_2O_5 known to crystallise above ~ 650 °C
- Experiment currently underway to measure un-doped Ta_2O_5 coatings annealed at 300, 400, 600 and 800 °C
- Initial results for 800 °C anneal

Effect of annealing temperature



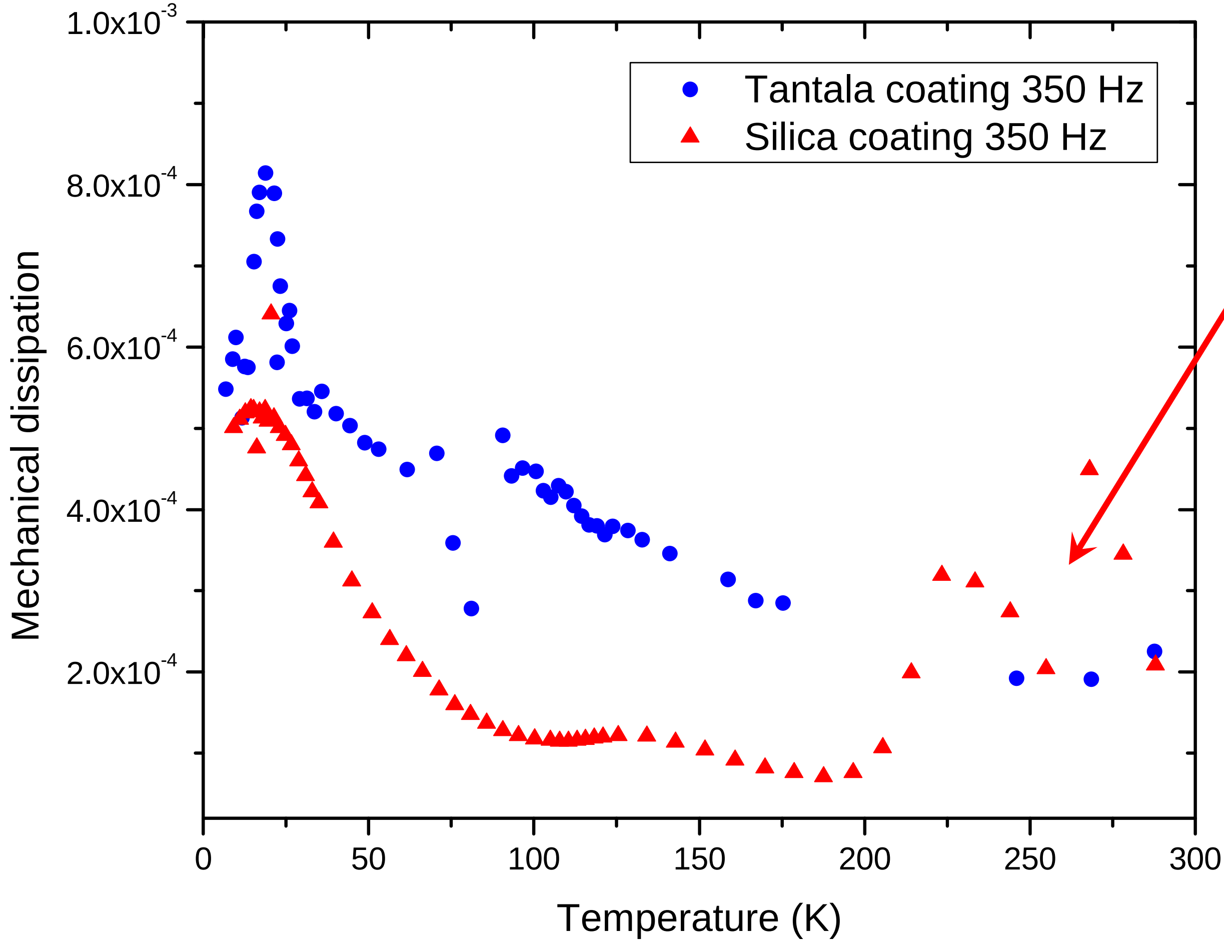
effect of low T peak still visible in sample annealed to 800 °C

Losses similar close to room temperature

Loss at 1900 Hz of Ta_2O_5 annealed at 800 °C and 600 °C

- Large peak at ~ 80 to 90 K in coating annealed at 800 °C, perhaps due to onset of polycrystalline structure?

Comparison of SiO_2 and Ta_2O_5



scatter at higher temperatures possibly due to loss into clamp.

Recent data suggests SiO_2 loss of ~4×10^{-5} at room temperature.

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

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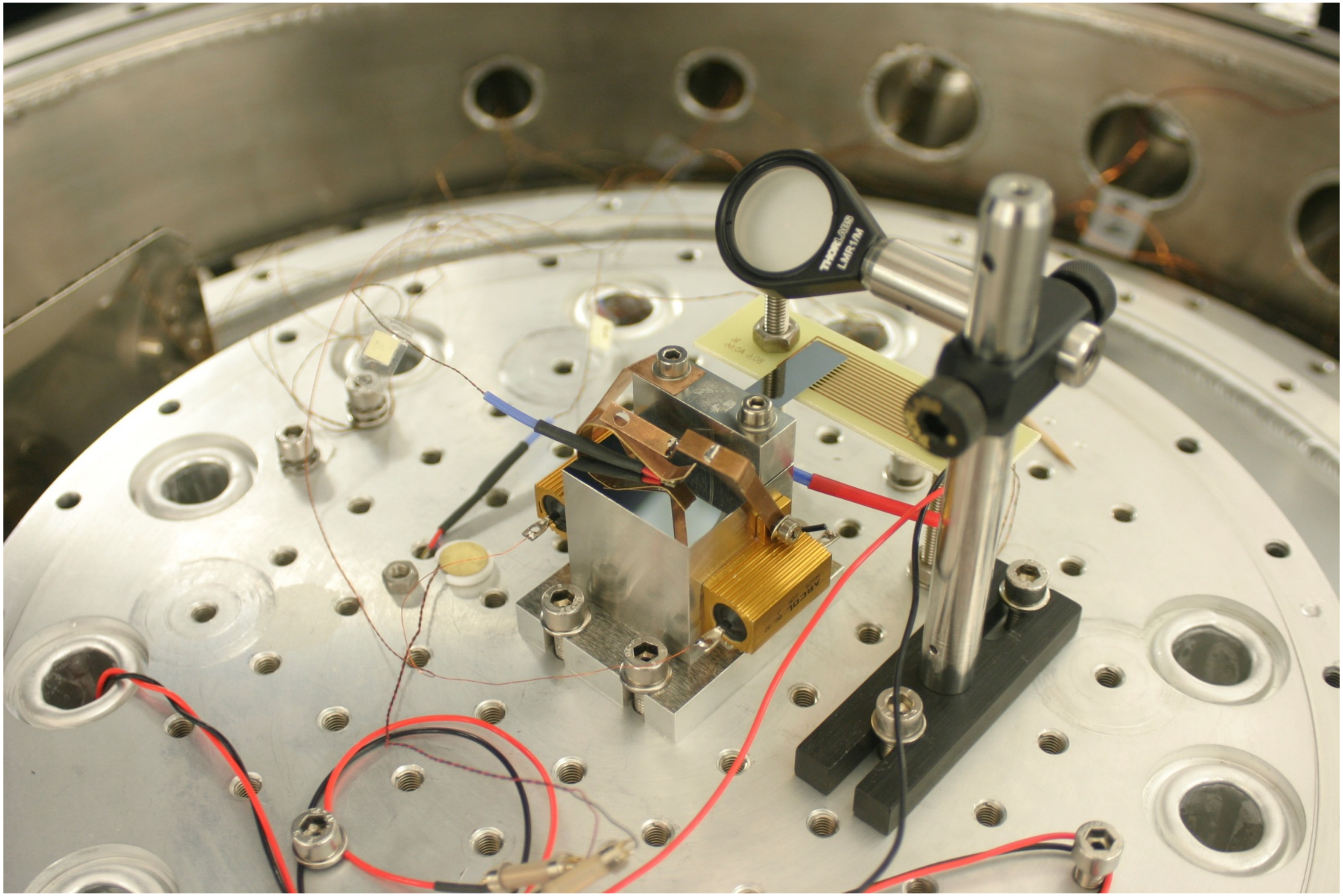
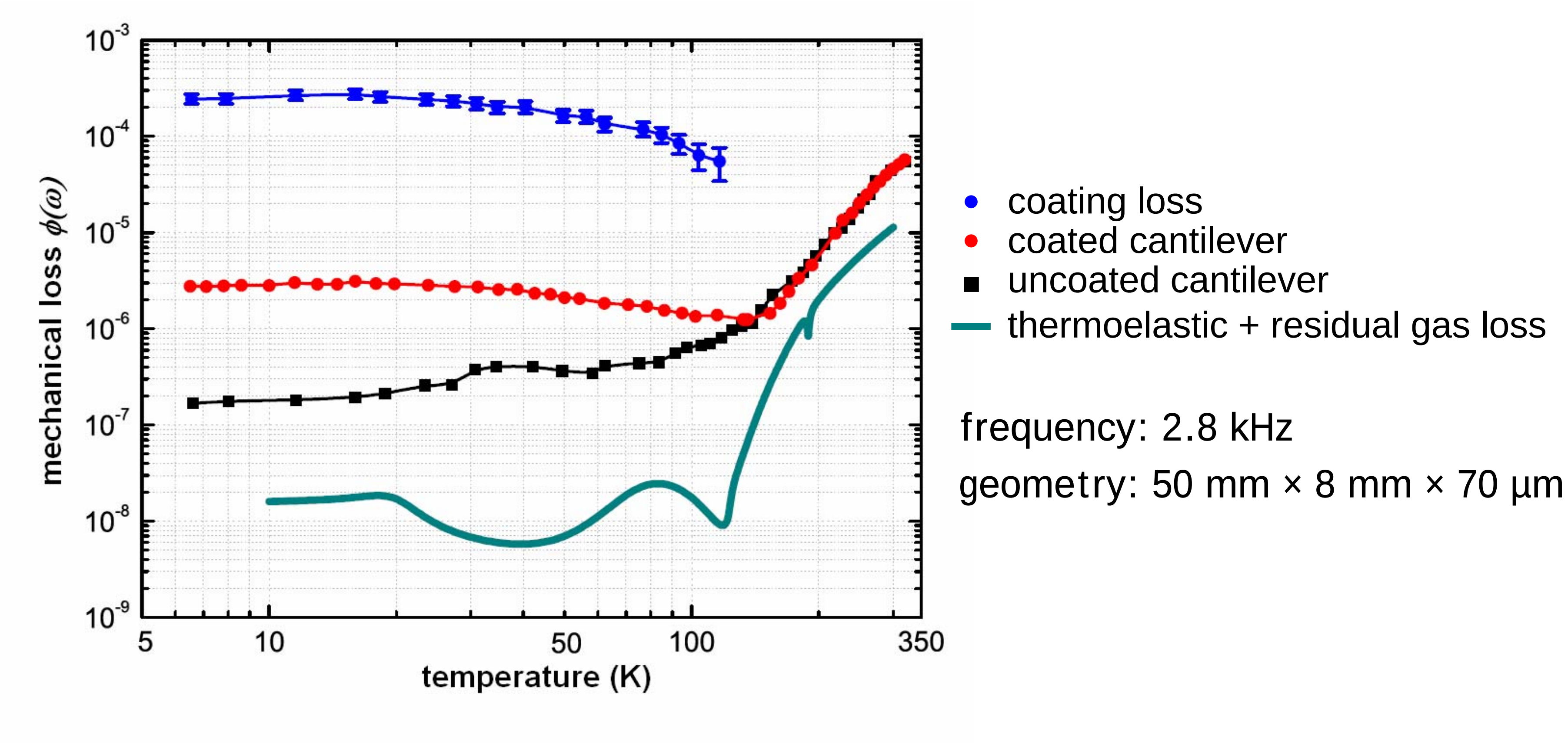
Conclusions – Ta_2O_5

- Dissipation peak observed at ~ 20 K in both pure Ta_2O_5 and in Ta_2O_5 doped with 14.5 % TiO_2
- Activation energy of dissipation process calculated to be 42 ± 2 meV (for doped coating). Possible dissipation mechanism is thermally activated transitions of the oxygen atoms, similar to that in fused silica
- Some evidence that TiO_2 doping reduces the height of the dissipation peak in Ta_2O_5, 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.
- A full understanding of the dissipation mechanism may allow
  - Mechanical loss at room temperature to be further reduced
  - Reduction of loss at particular temperatures of interest for future cryogenic detectors
- Ta_2O_5 has higher loss than SiO_2 between 10 and 300 K

Magnetron Sputtered Silica (400 nm) - Jena

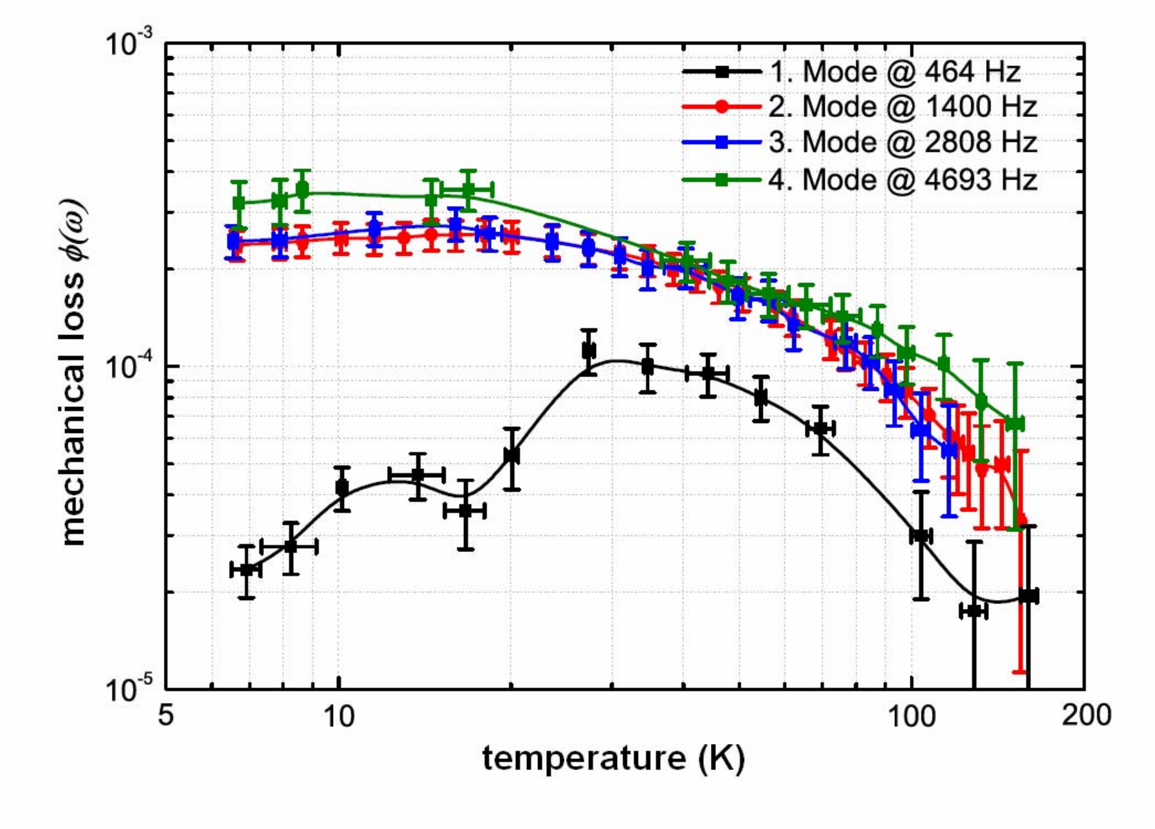


Magnetron Sputtered Silica (400 nm) - Jena



- Comparable level of observed loss associated with the magnetron sputtered silica coating at ~100 K to ion-beam sputtered silica.
- However, below 100 K no dissipation peak observed in magnetron sputtered silica

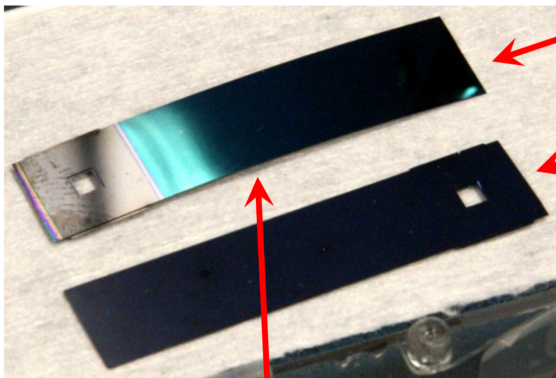
Magnetron Sputtered Silica (400 nm) - Jena



- 464 Hz mode – resonance with clamping structure
- Loss increases for all modes at low temperatures

Preliminary studies on HfO_2

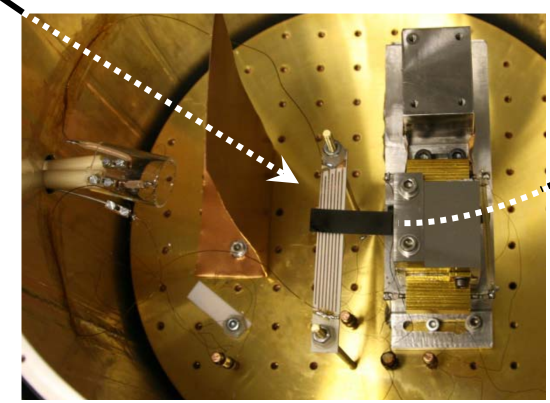
- New cryogenic setup in Glasgow:

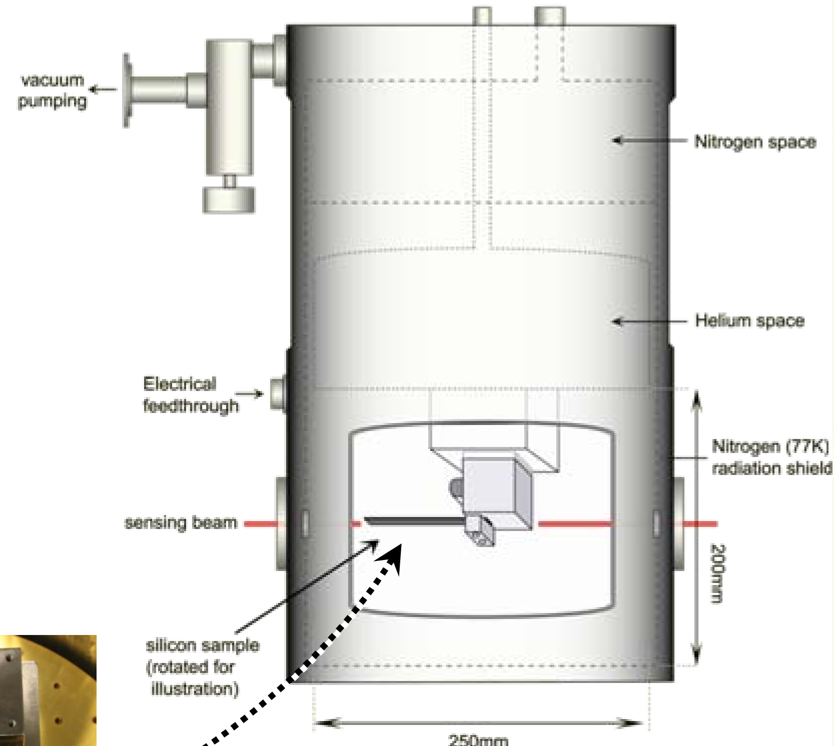


500nm HfO_2 coating on a silicon cantilever

uncoated silicon cantilever

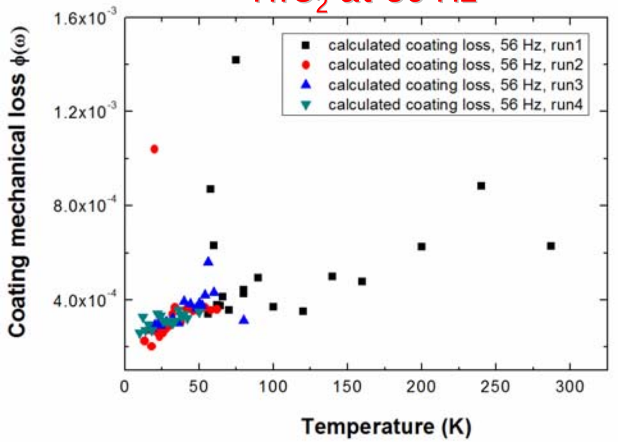
thermal stresses in coating clearly observed in the bending of the silicon substrate



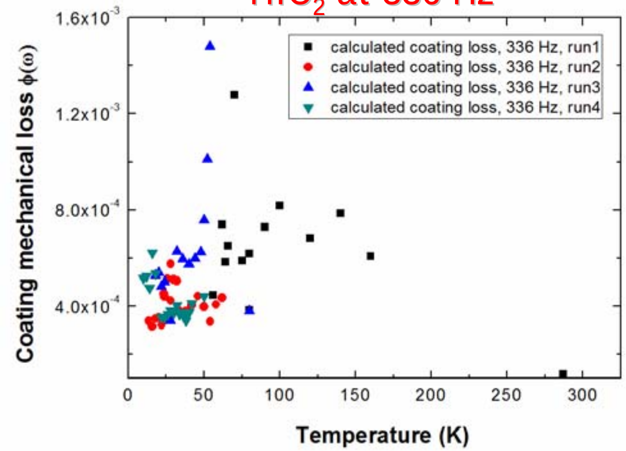


Preliminary studies on HfO_2 and compared to Ta_2O_5

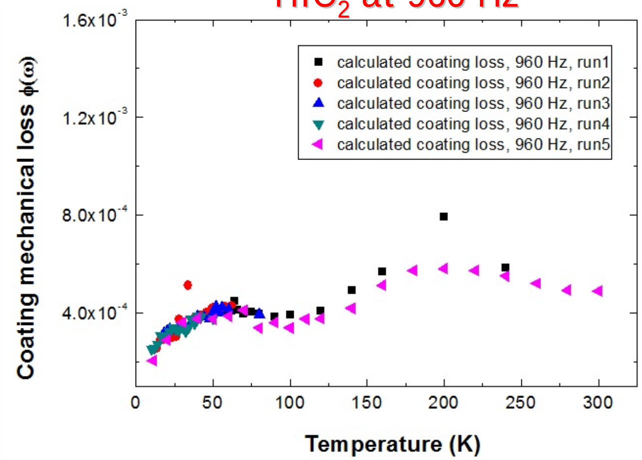
HfO_2 at 56 Hz



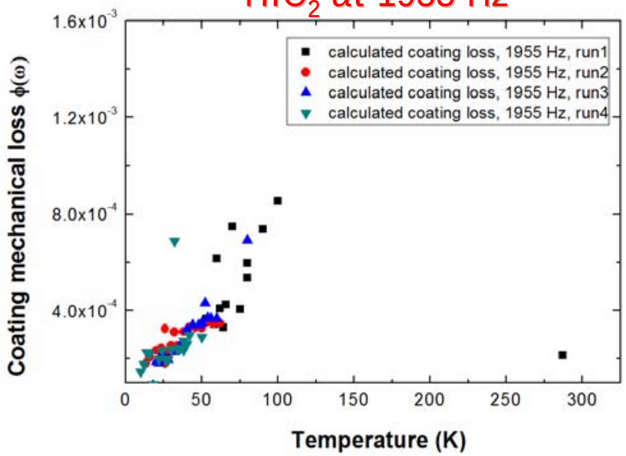
HfO_2 at 336 Hz



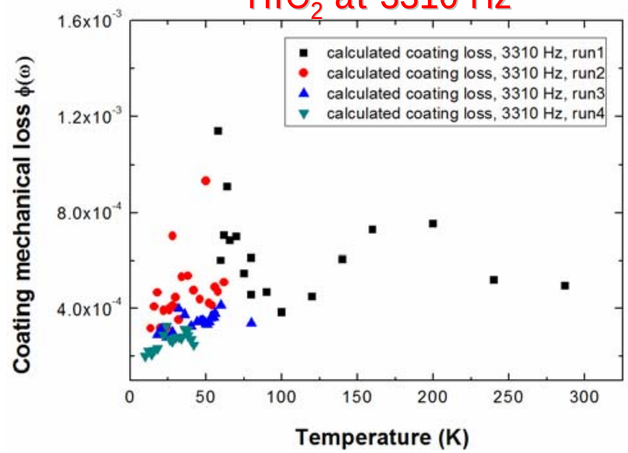
HfO_2 at 960 Hz



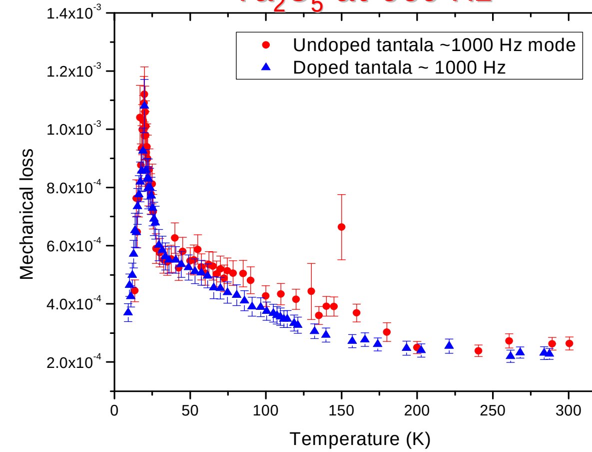
HfO_2 at 1955 Hz



HfO_2 at 3310 Hz

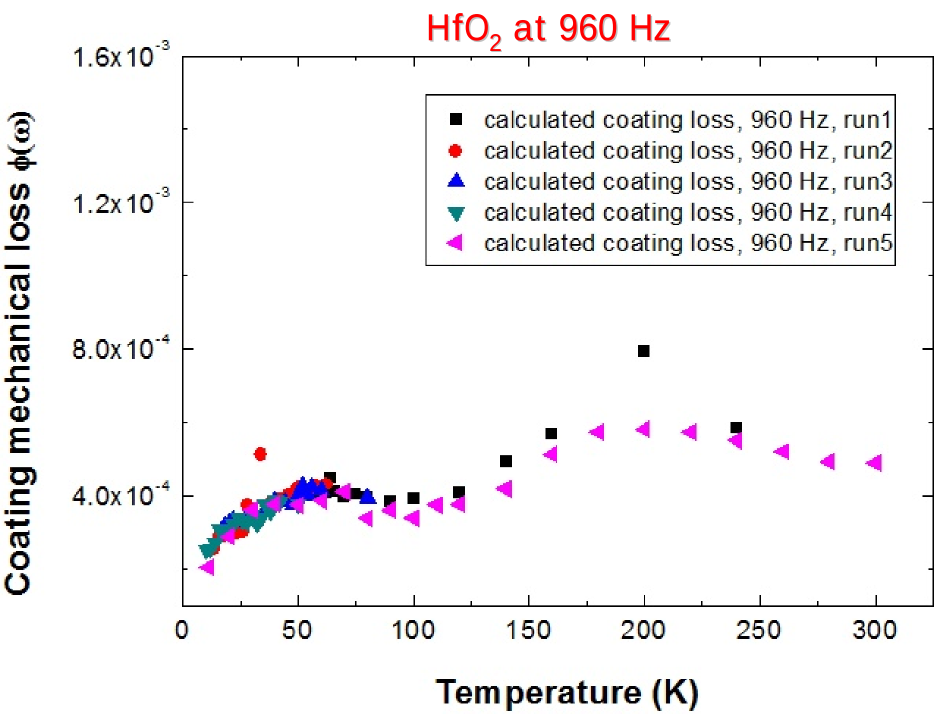


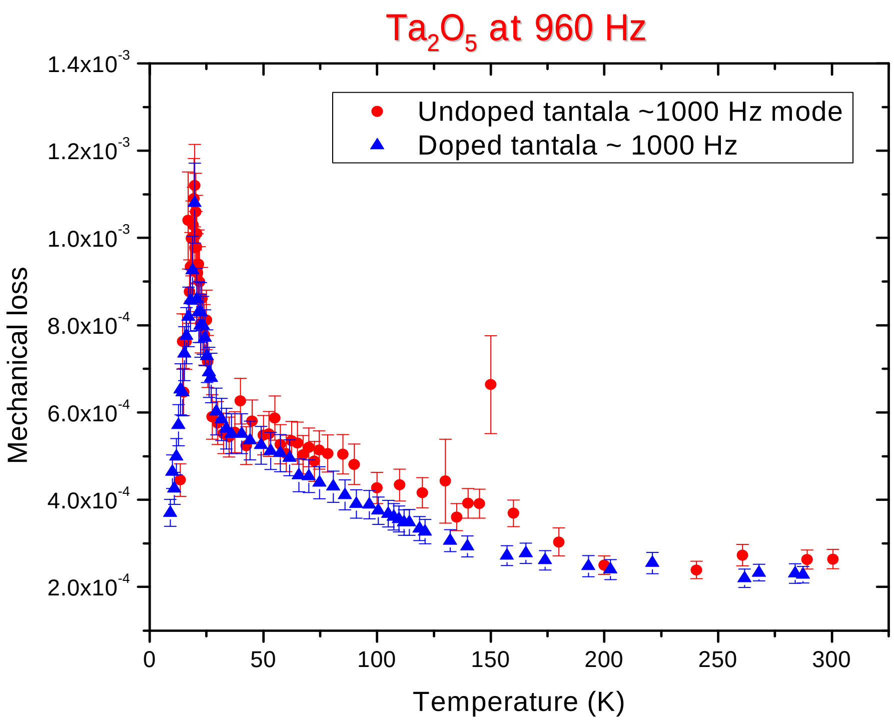
Ta_2O_5 at 960 Hz



- Observed scatter in initial mechanical losses suggest energy coupling to clamp resonances for several of the resonant modes studied.

Preliminary HfO_2 compared to Ta_2O_5





- At 100 K, the level of mechanical loss associated with both doped tantala and hafnia appear at a level $\phi(\omega)_{coating}$ ~ 4×10^{-4}.
- Below 100 K, the loss of tantala is observed to rise to a dissipation peak, whereas the loss of hafnia appears to decrease to below 3×10^{-4} at ~15 K.

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Preliminary HfO_2 compared to Ta_2O_5

- Preliminary results of the mechanical loss of Hafnia does not show a large dissipation peak at low T.
- Note: the higher Young's modulus of Hafnia should lead to lower thermal noise for the same ϕ.d (loss-thickness product) – in the case of silicon optics (not true for other materials *e.g.* fused silica).
- Initial room temperature studies on a multi-layer silica-hafnia coating on a fused silica substrate were found to be $\phi_{hafnia}=(5.7\pm0.3)\times10^{-4}$.

- However material properties for thin-film Hafnia are not well studied and any changes over bulk properties will change the results presented here.

- The optical properties also require further investigation, where initial recent absorption studies of a multilayer silica-hafnia coating by Markosyan et al. (Stanford University) lie in the range 60-80ppm, which is considerably higher than required.