Amorphous Coatings for Future Detectors

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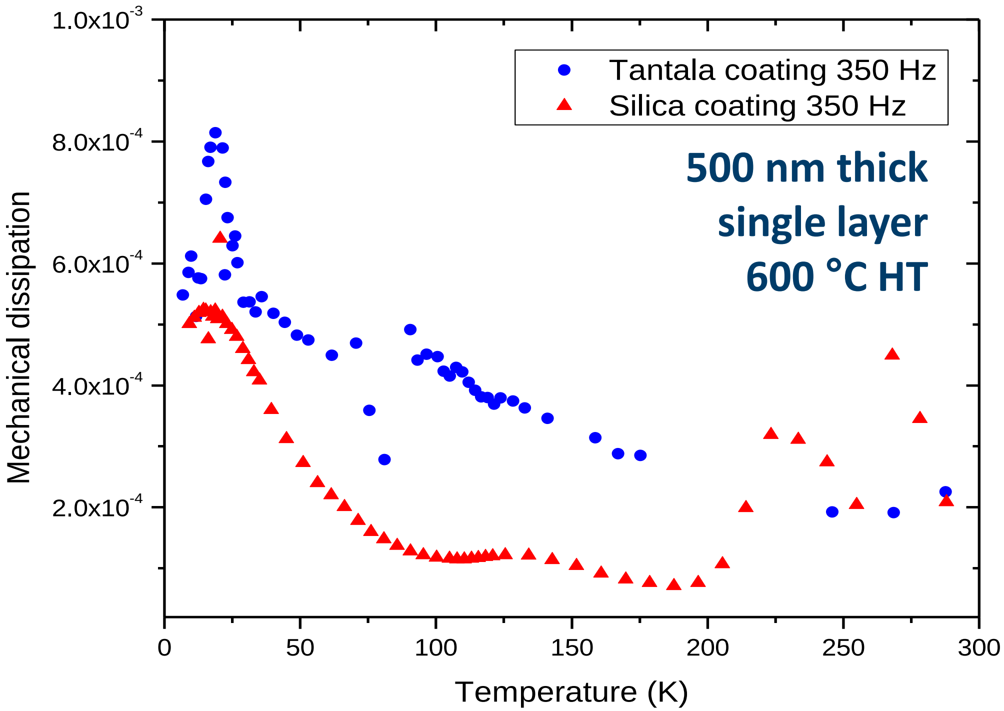
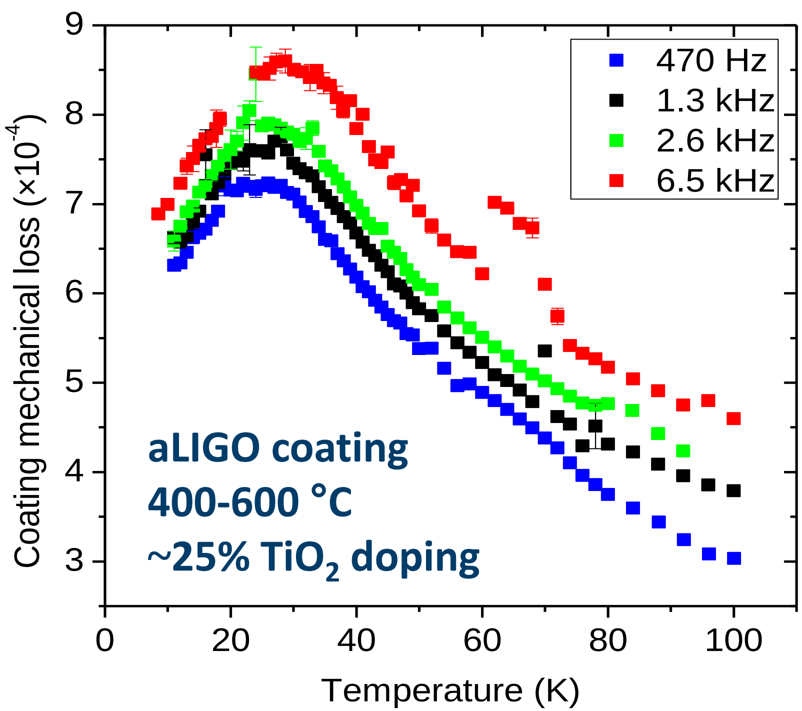
Current Coatings

- **Cryogenic loss peaks in tantala / silica films suggest a reduction in coating thermal noise by ~2× by cooling to 20 K**
- Observed on both single layers[1,2] and aLIGO coating[3]





- **Peaks at higher temperature (~30 K) in multilayer coatings (aLIGO)**
- **No strong peak in SiO_2/Ta2O_5 on sapphire measured at ICRR[4]**

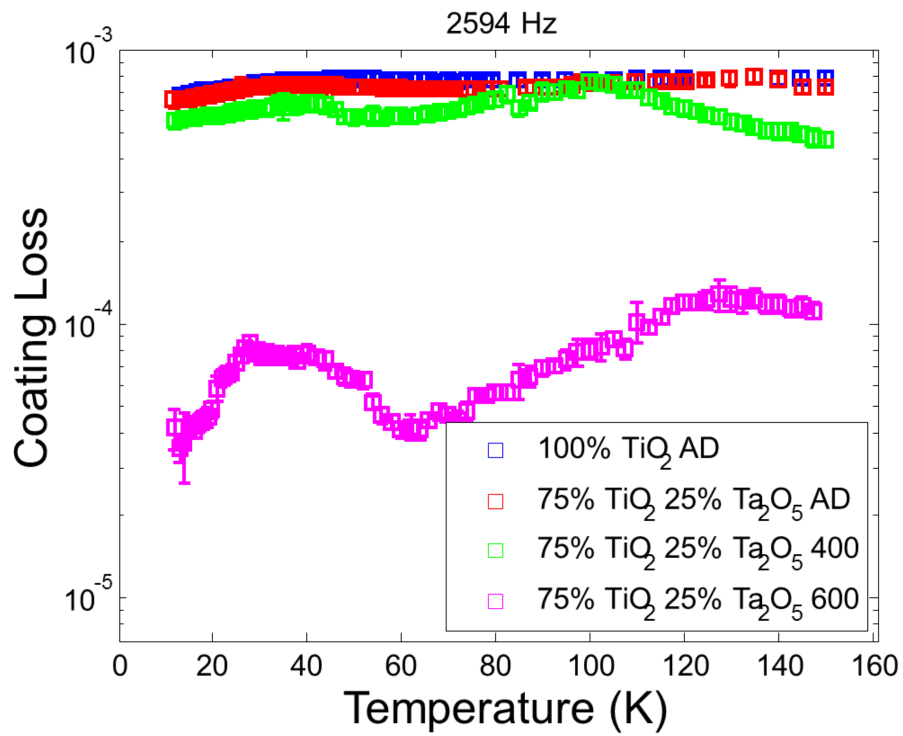
[1]Martin et al., CQG (2014), [2]Martin et al., CQG (2010), [3]Granta et al., Opt. Lett. 38 (2013), [4]E. Hirose et al., PRD (2014)

Some open questions…

- **Why is the loss of silica so much lower, at room temperature, than other oxide materials?**

- **What is the origin of the cryogenic loss peaks in tantala?**
- Starting to get some evidence to disentangle doping and heat-treatment and correlate with structural data

- **600 °C heat treated**
  75% TiO_2/Ta_2O_5 coating
- large reduction in loss
- plus evidence of crystallisation
- However, interesting to obtain such a low loss from this material system
- Studying onset of low loss (500 °C HT)

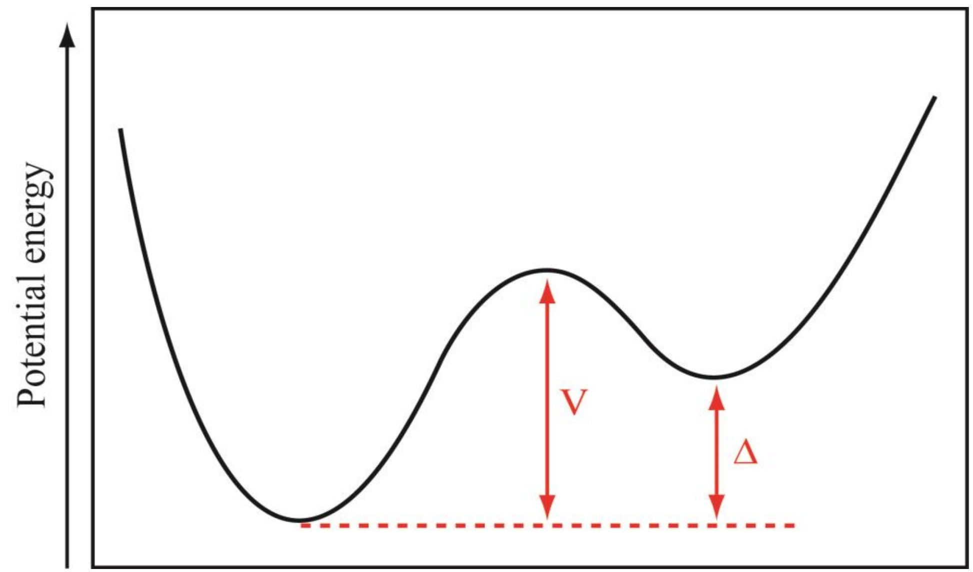


Some open questions…

- **Various high-index materials are showing some promise: SiO_2:HfO_2, aSi, work on silicon nitride and nano-layering by Chao, Pinto et al.**
- **To maximise improvement in TN from any of these materials, require more work on low-index layers**
- Understand cryogenic loss of IBS silica
- Possible alternative materials?
- **Little improvements (discussed at Stanford workshop)**
- Rather than looking for a magic bullet, can we find lots of incremental improvements which add up to a significant TN reduction?
  - i.e. UK Cycling "Marginal Gains"
- e.g. multi-material coatings to exploit low loss of aSi
- Other optimisations?

Loss mechanisms in amorphous coatings

- **Amorphous structure results in distribution of potential barrier heights g(V)**
- Activation energy calculated from Arrhenius law corresponds to the average barrier height in this distribution
- The barrier height distribution function g(V) can be calculated from temperature dependent loss data



$$\phi = \frac{\pi \gamma^2 f_0}{C_{ii}} k_B T g(V)$$

γ represents the coupling between strain and the dissipation mechanism

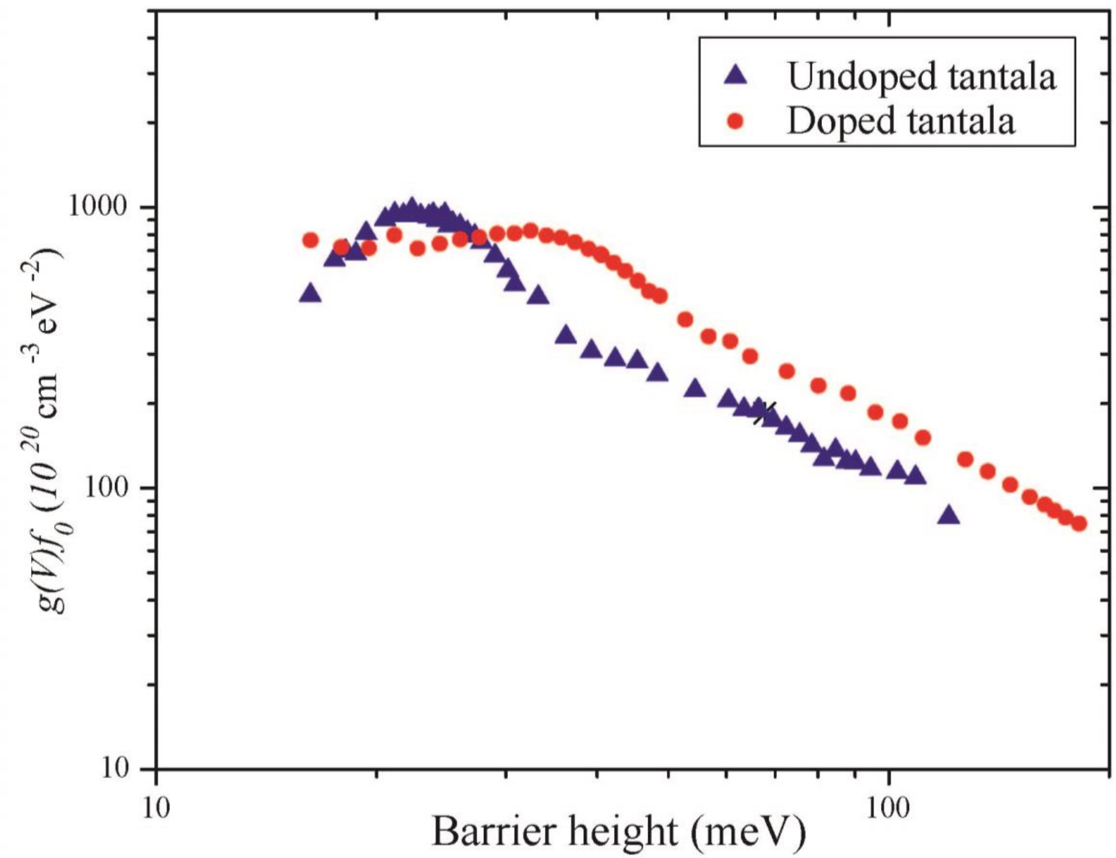
C_{ii} is the elastic constant of the material

- Activation energy and time constant of process responsible for loss

[1]Philosophical Magazine B 43 (1981) 735 [2]Z. Phys. B: Condens. Matter 101 (1996) 235

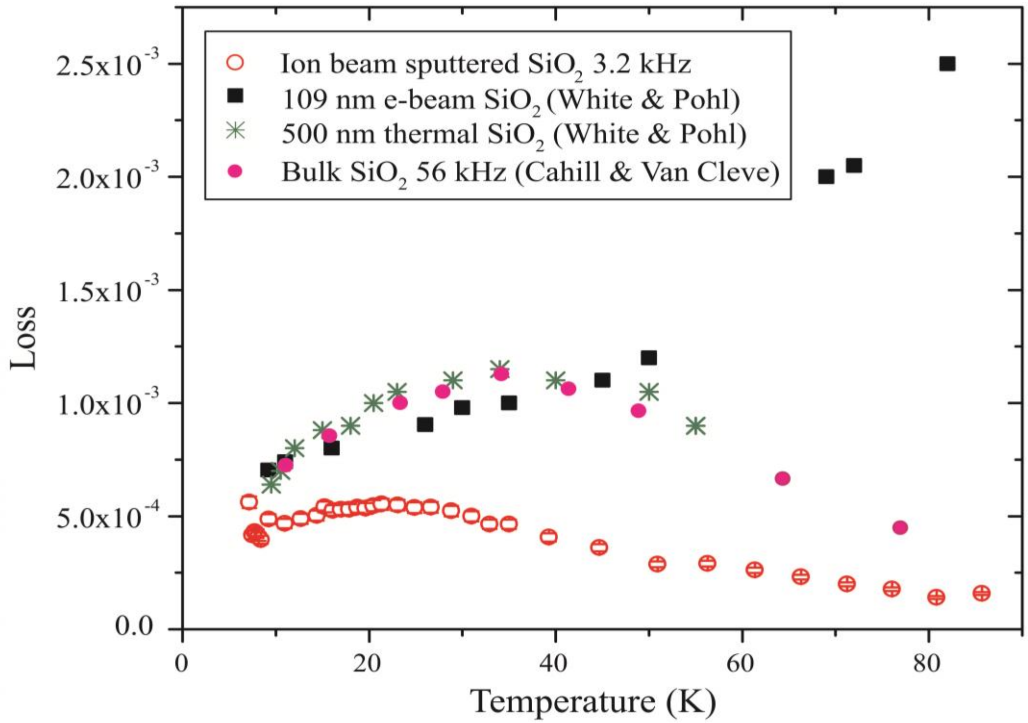
Loss mechanisms in amorphous coatings

- **Barrier height distribution function can be calculated from cryogenic loss**
- **TiO_2 doping shifts distribution to a higher energy, increases width of distribution**
- Thus reducing loss
- **Other methods of altering distribution**
- Perhaps heat treatment?
- **Structural work**
- Understand amorphous structure and loss mechanisms



Loss of silica coatings

- **Loss of silica very dependent on deposition method**
- Thermally grown SiO_2 on Si is very similar to bulk SiO_2
- Whereas IBS SiO_2 performs worse than bulk (3.2 kHz plotted here)

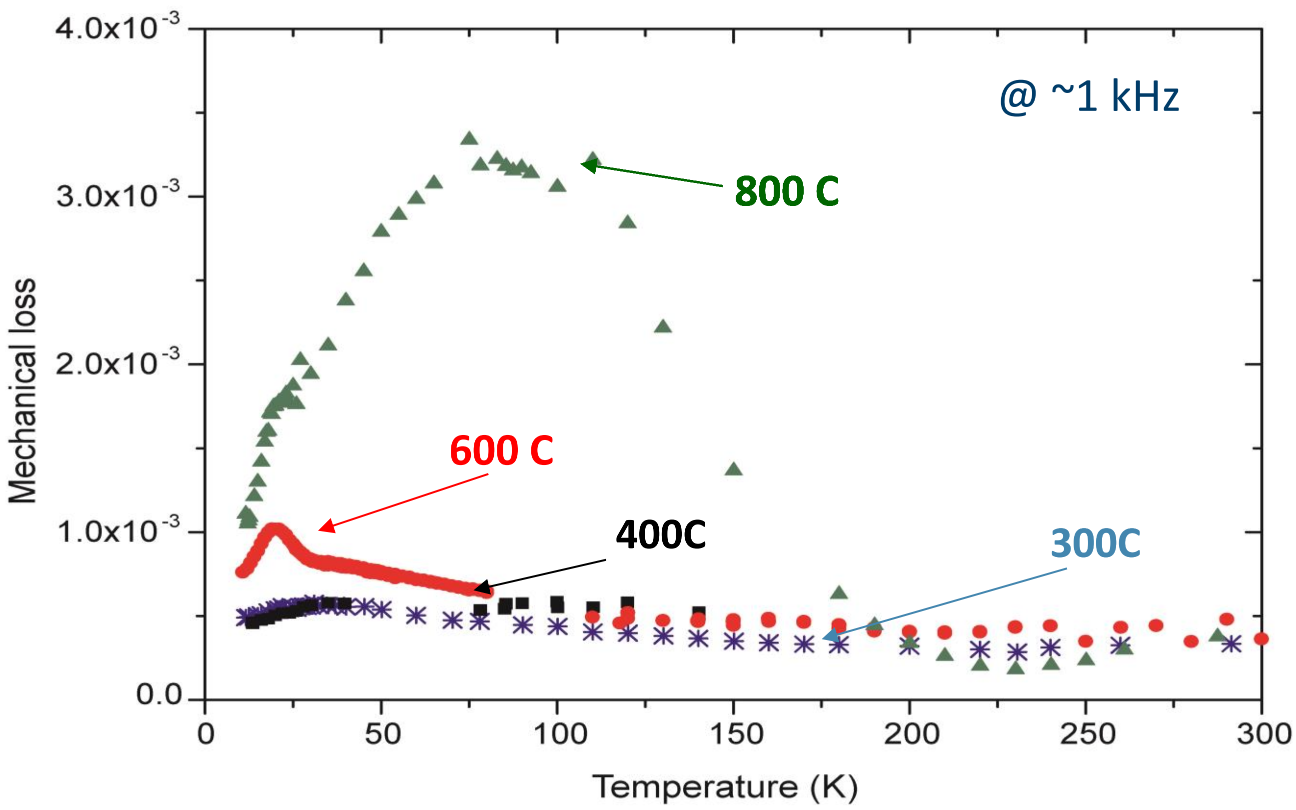


- **Structural differences/ deposition method are clearly really important**
- Could stress be a factor too?

[1]White and Pohl, Phys. Rev. Lett. 75 (1995) 4437, [2]Cahill and Van Cleve Rev. Sci. Inst. 60 (1989) 2706.

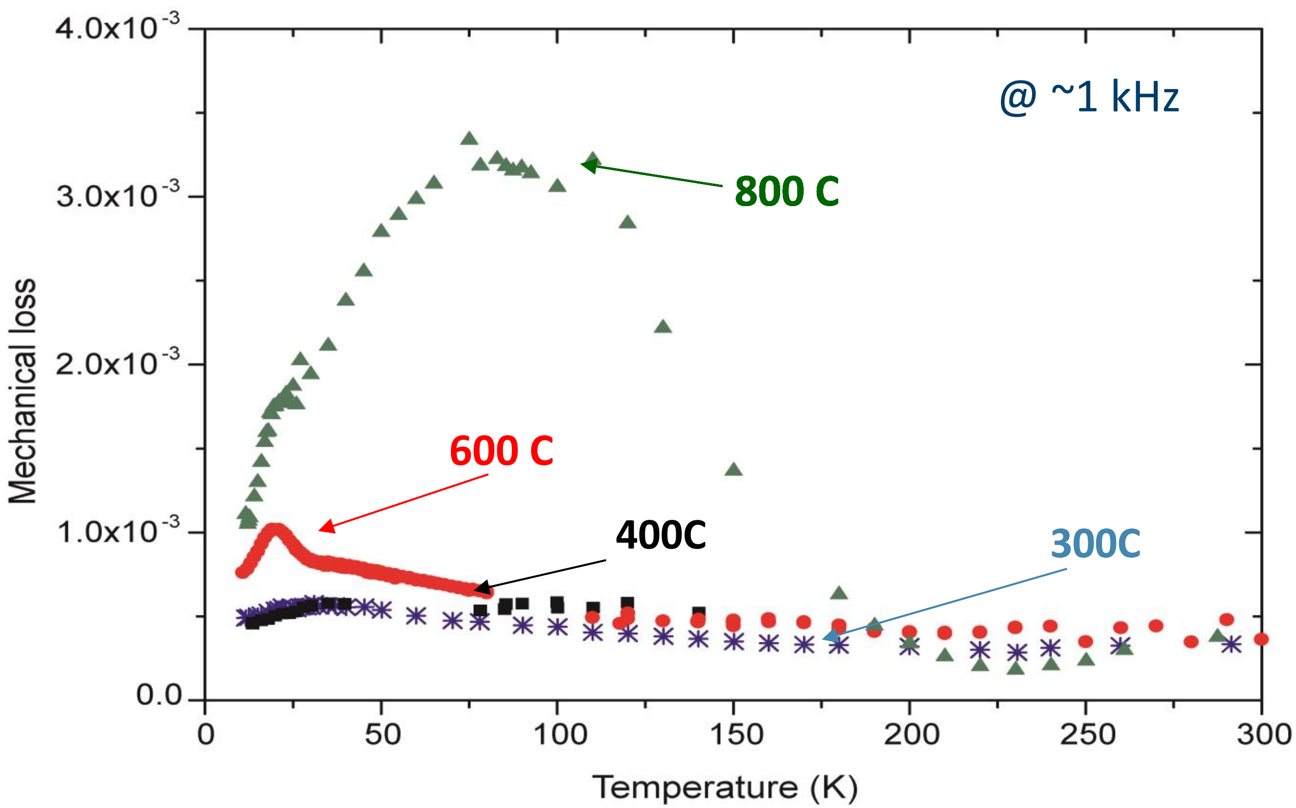
Cryogenic loss of tantala coatings

- **Effect of heat-treatment on mechanical loss and atomic structure of tantala films**
- Investigated un-doped tantala and different percentage dopings with titania
- **Found that heat treatment can significantly alter the temperature dependence of mechanical loss**
- True of both un-doped tantala films and TiO2-doped tantala films
- **The emergence of mechanical loss peaks after heat treatment of particular interest**



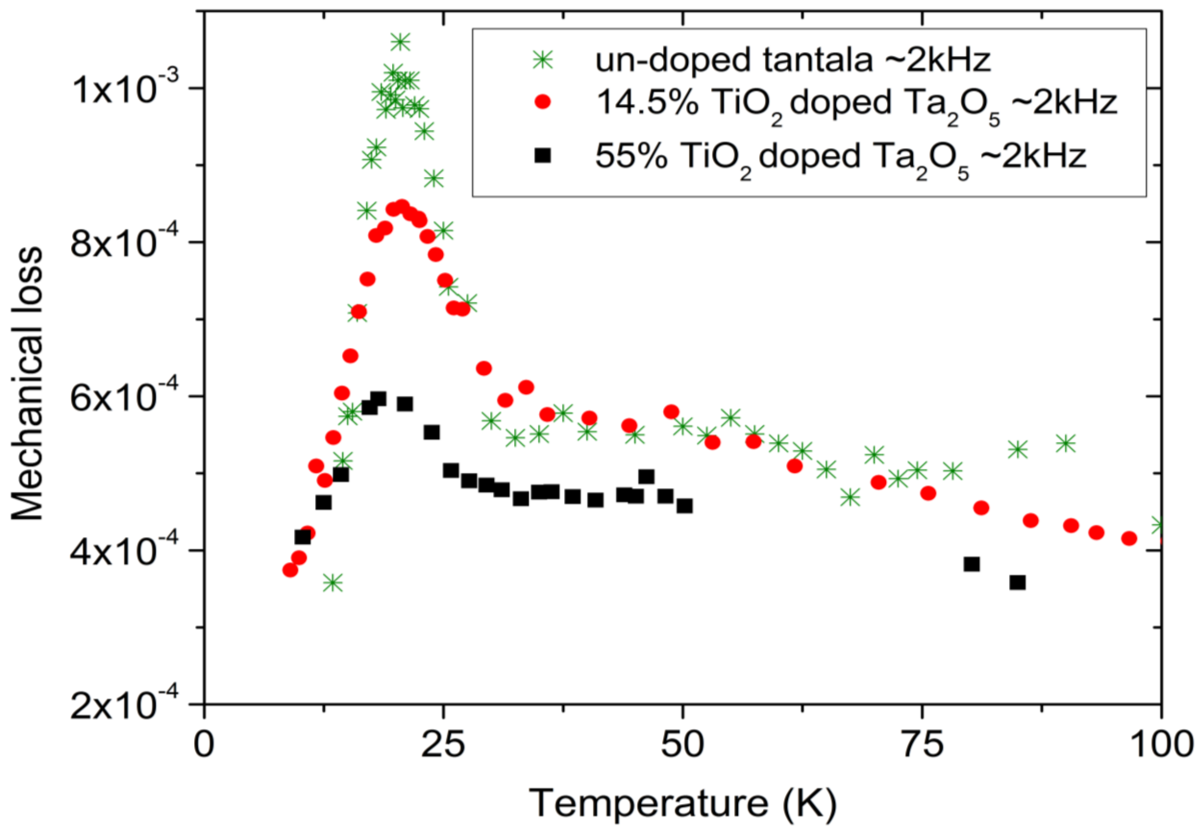
Cryogenic loss of tantala coatings

- **Higher heat-treatments result in low-temperature loss peaks**
- **Three mechanical loss peaks identified in tantala films:**
- Low, broad peak ~35 K after both 300 °C and 400 °C Heat Treatment
  - Also present in as-deposited tantala
- Sharper peak at ~20 K following 600 °C HT
- Large, broad peak ~90 K following 800 °C HT
  - Thought to be associated with the crystallisation of the coating at this heat treatment temperature



Cryogenic loss of tantala/titania coatings

- **Studied the effect of heat treatment on the cryogenic mechanical loss of Ta_2O_5 films doped with various concentrations of TiO_2**
- **Results indicate, for 600 °C HT, increasing the concentration of titania doping tends to suppress cryogenic loss**



Tantala/titania coatings

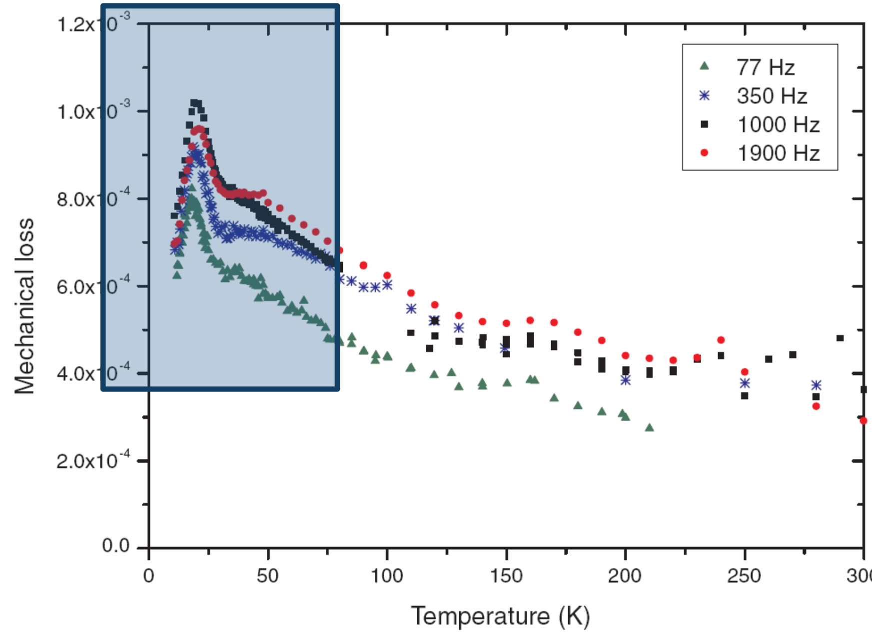
- **TiO_2-Ta_2O_5 – optimisation of heat-treatment**
- Doping may allow losses similar to room-temperature to be achieved

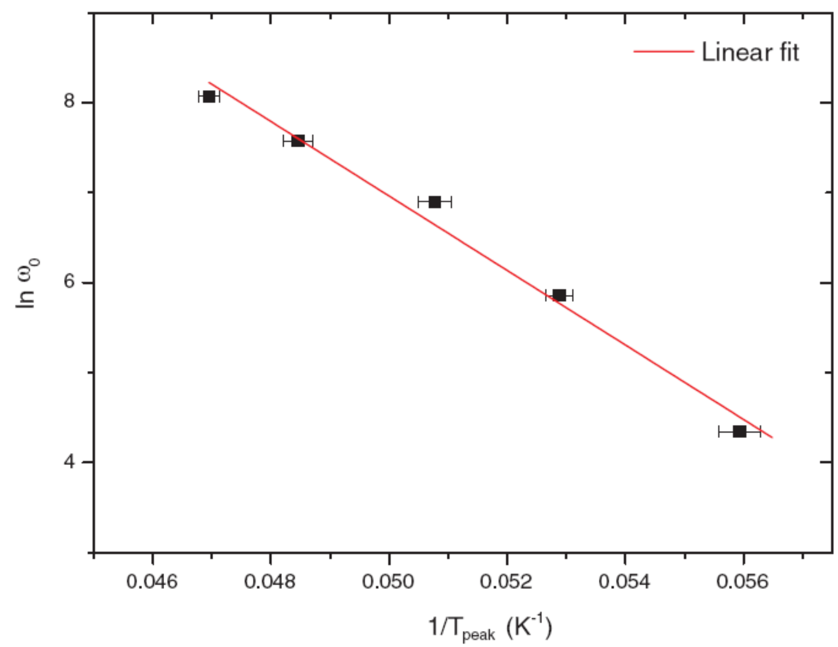
- **Effect on optical absorption?**

- **Multilayer coating loss?**
- Loss peak in silica layers
- Similar reduction in loss of silica required

Loss mechanisms in amorphous coatings

- **Ta_2O_5 coating heat treated at 600 °C**
- **The temperature at which the dissipation peak ~20 K occurred was found to vary with frequency**
  - Typical characteristic of this thermally activated dissipation process
- **The activation energy and rate constant are calculated from a linear fit to an Arrhenius plot**
  - $E_a = 35.6 \pm 2.5$ meV
  - $\tau_0 = (9.9 \pm 0.5) \times 10^{-13}$ s

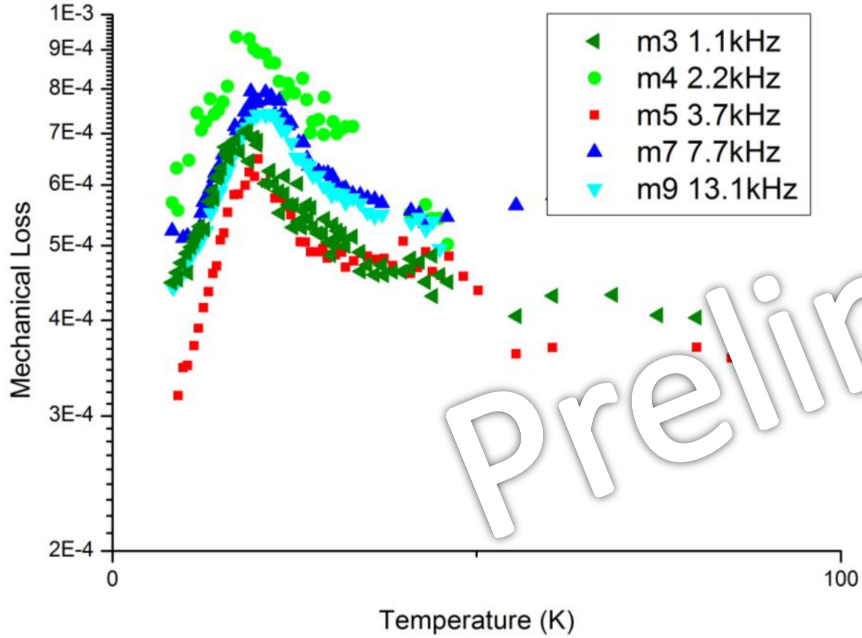


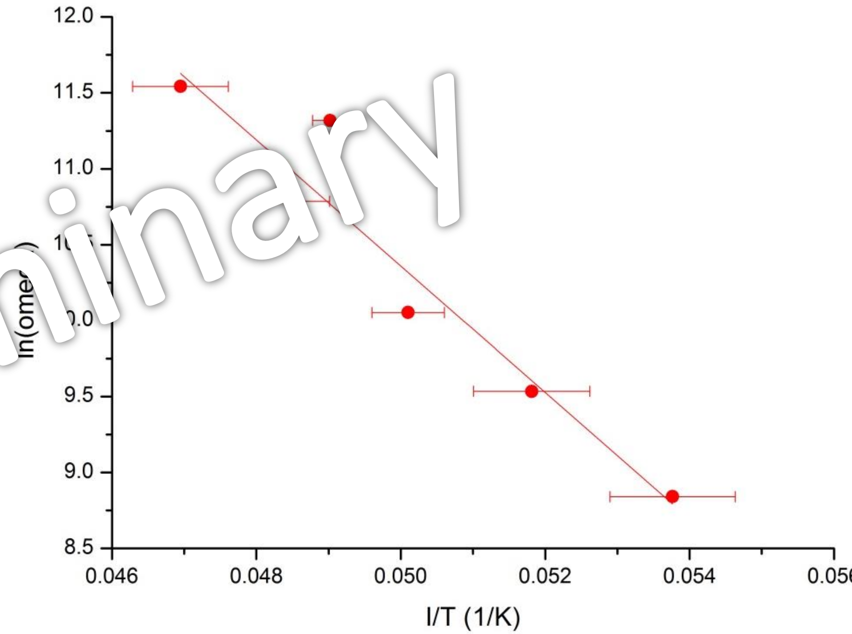


Martin et al., CQG (2010)

Loss mechanisms in amorphous coatings

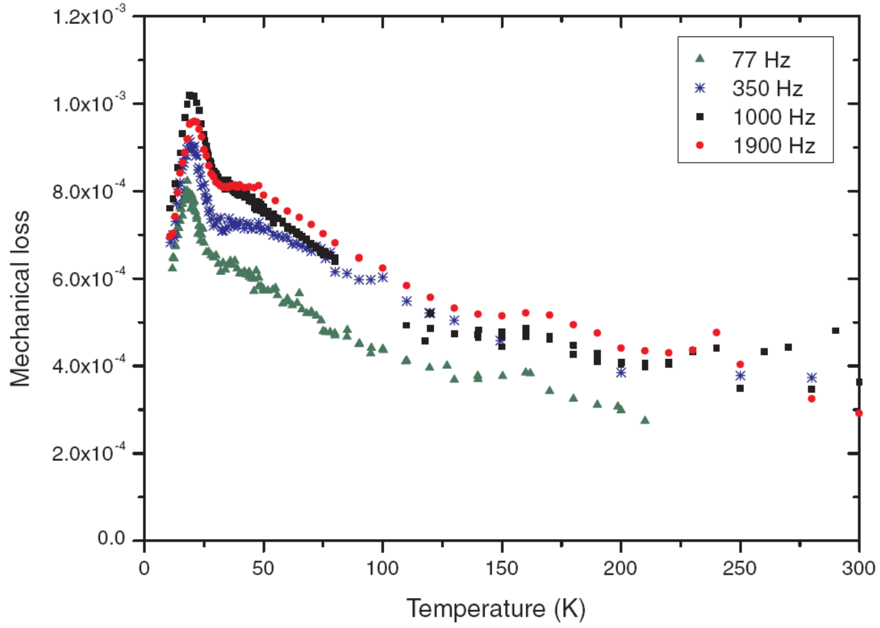
- **Recently measured a 55%-TiO_2 doped Ta_2O_5 coating with a 600 °C HT**





- **Again the dissipation peak was observed to vary with frequency**
- **The activation energy and rate constant for this coating**
- $E_a = 35 \pm 5$ meV
- $\tau_0 = (3 \pm 2) \times 10^{-14}$ s
- **Suggests doping doesn't strongly influence the 20 K loss peak**

Loss mechanisms in amorphous coatings

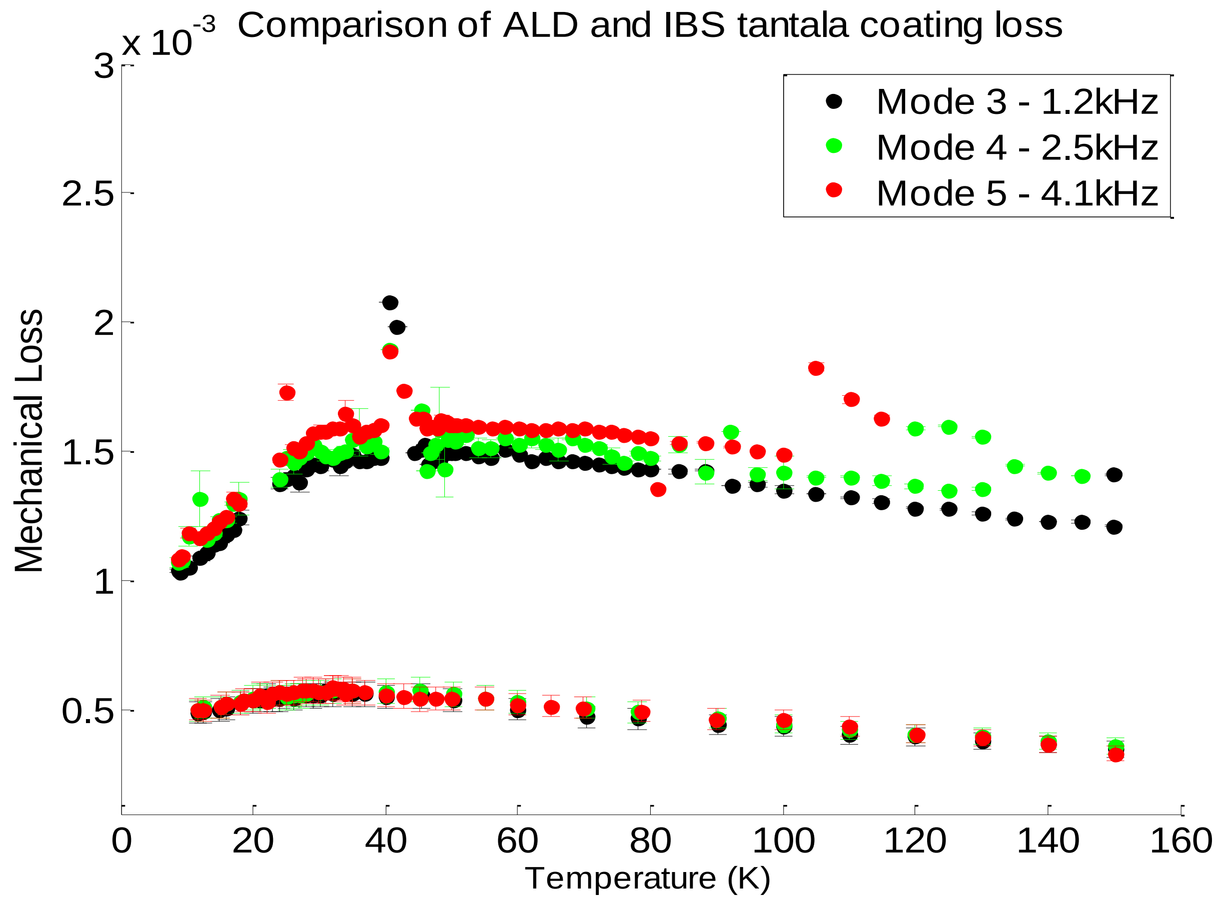


- **Looking back again at Ta_2O_5 coating heat treated at 600 °C**
- **The tail of the 20 K peak is not responsible for room temperature loss**
- **However, the tail of an underlying 35 K peak could be**
- **Perhaps the 20 K peak is largely a function of heat treatment**
- **The 35 K peak could actually be more strongly affected by doping**
- **This possibly accounts for:**
- The differences in room temperature loss with doping
- For the suppression of the cryogenic loss with doping

Martin et al., CQG (2010)

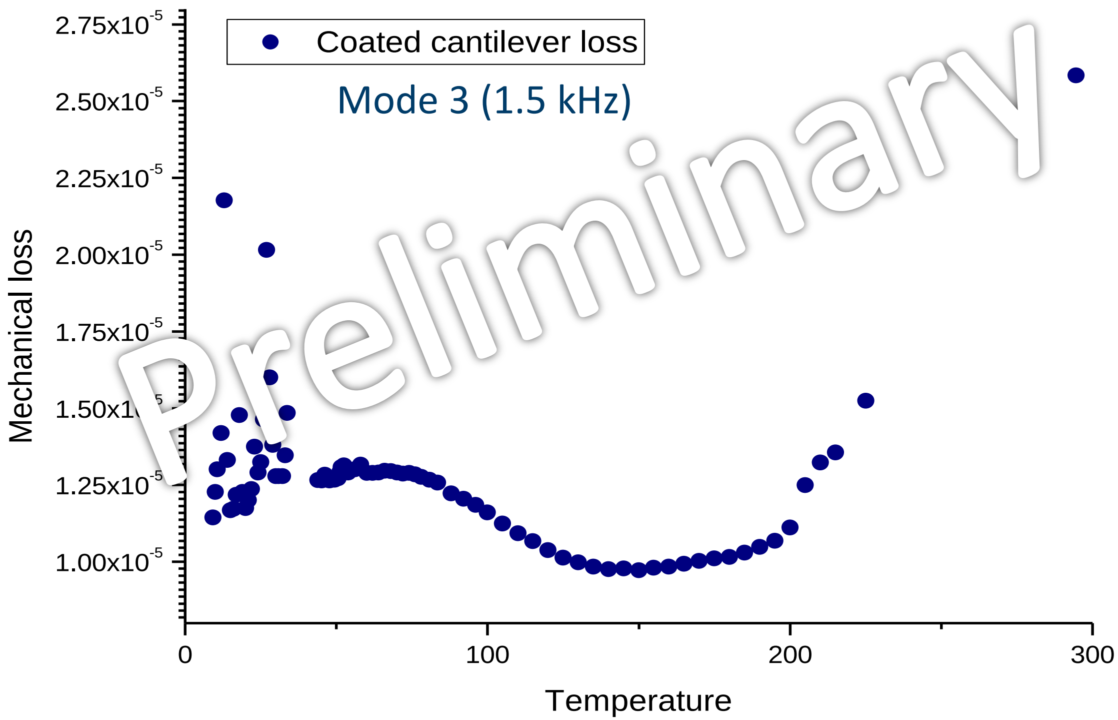
Atomic Layer Deposition (ALD) tantala

- **Of interest to compare different deposition methods**
- **ALD tantala dissipation measured on silicon cantilevers**
- **ALD compared to IBS tantala heat treated at 300°C**
- **Structural studies underway**
- **Note: ALD loss shown assumes no loss in the substrate under 150 K and is therefore only an upper limit**



Zirconia/silica multilayer

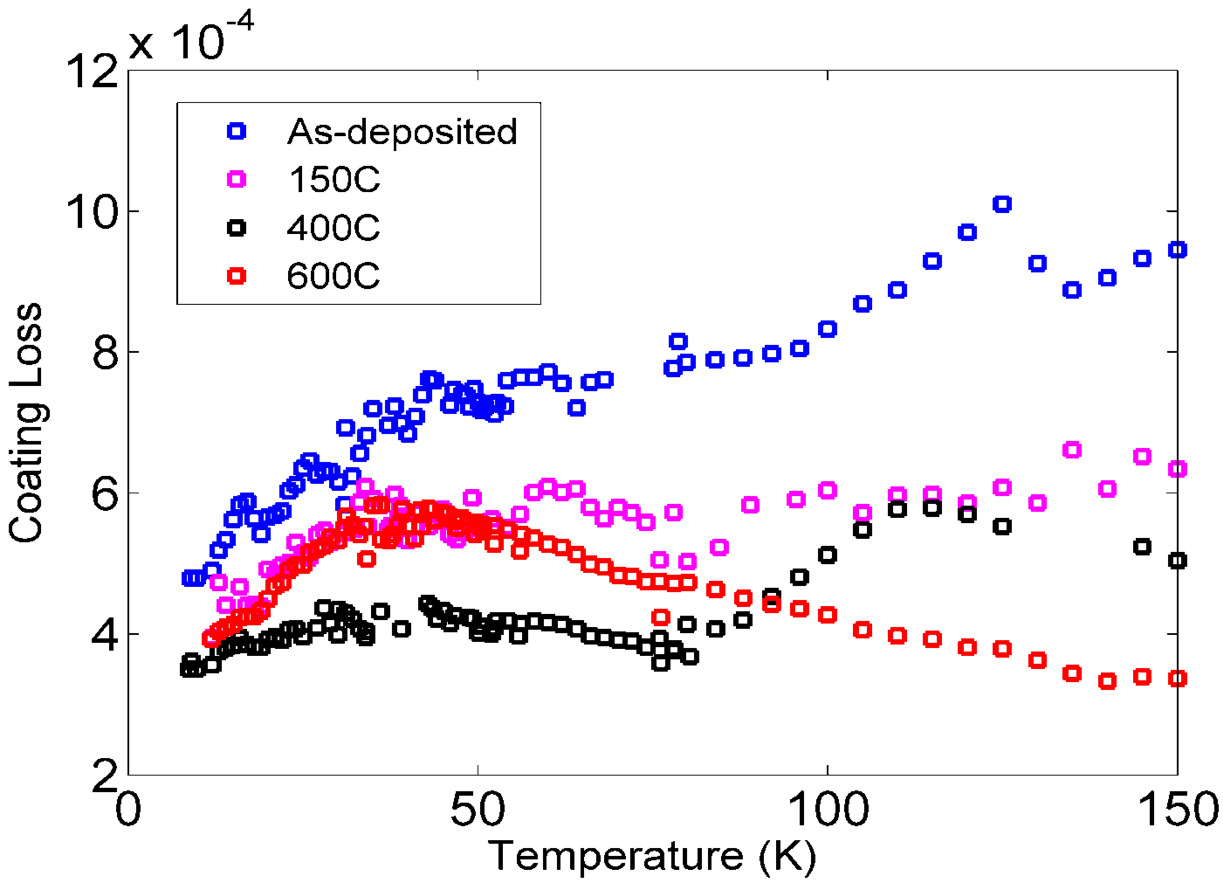
- **Investigating zirconia as a coating material**
- doped with silica to stabilize it and allow higher annealing temperature without crystallisation
- **Also as a dopant for other materials**
- E.g. in tantala testing modelling prediction that it should give structures with a similar flexibility to titania doping

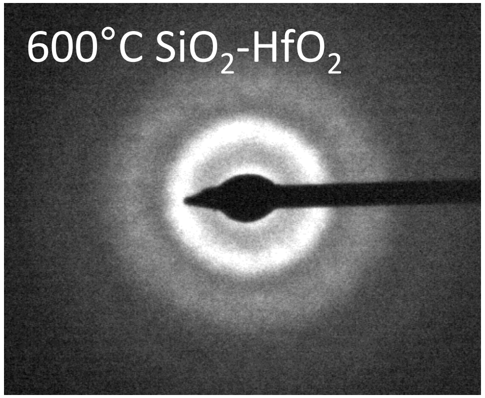


- **Multilayer coating:**
- zirconia/silica/zirconia/silica
- Quarter wavelength at 1064nm
- **Other modes need more data taken – too much scatter**
- **Coated cantilever loss (i.e. not pure coating loss) shown**

Alternative amorphous coatings

- **30% silica-doped hafnia (CSIRO, 500 nm, Si cantilevers)**
- Silica prevents crystallisation, heat-treatment up to 400 °C reduces loss
- Best amorphous oxide coating so far (almost) no low temperature loss peak
- Heat-treatment also reduces optical absorption

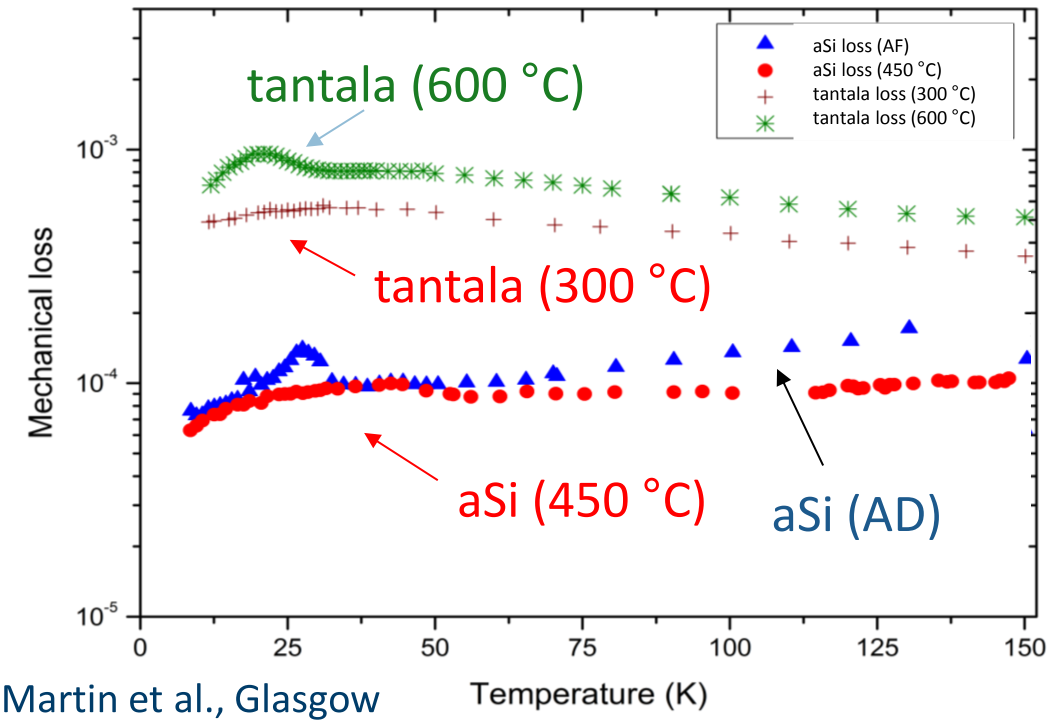




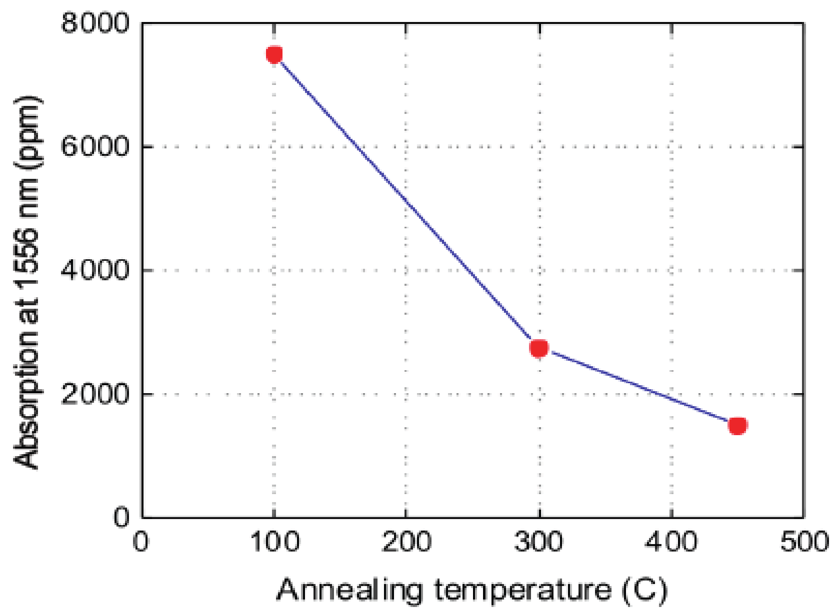
K. Craig et al., in preparation

aSi coatings

- **1550nm required**
- **Low mechanical loss**
- Mechanical loss of 0.5 µm IBS amorphous silicon is approximately a factor of ten lower than tantala below 100 K
- **So far, optical absorption significantly too high**
- still ~1000 ppm after HT



I. Martin et al., Glasgow



Optical absorption of α-Si coatings vs. annealing temperature (in air at room temperature)

Stanford - A. Markosyan, R. Bassiri et al.

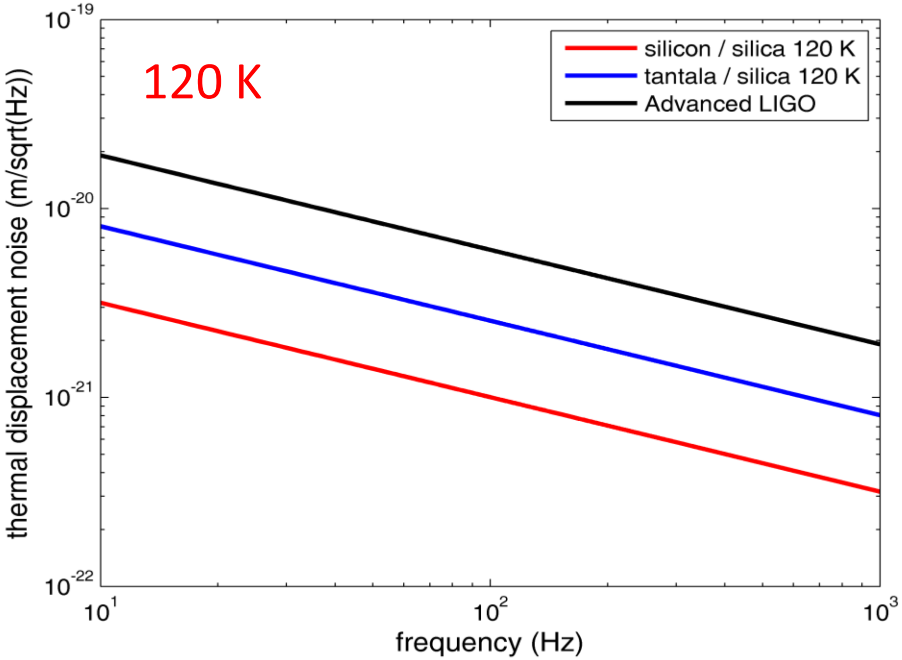
aSi coatings – Brownian thermal noise

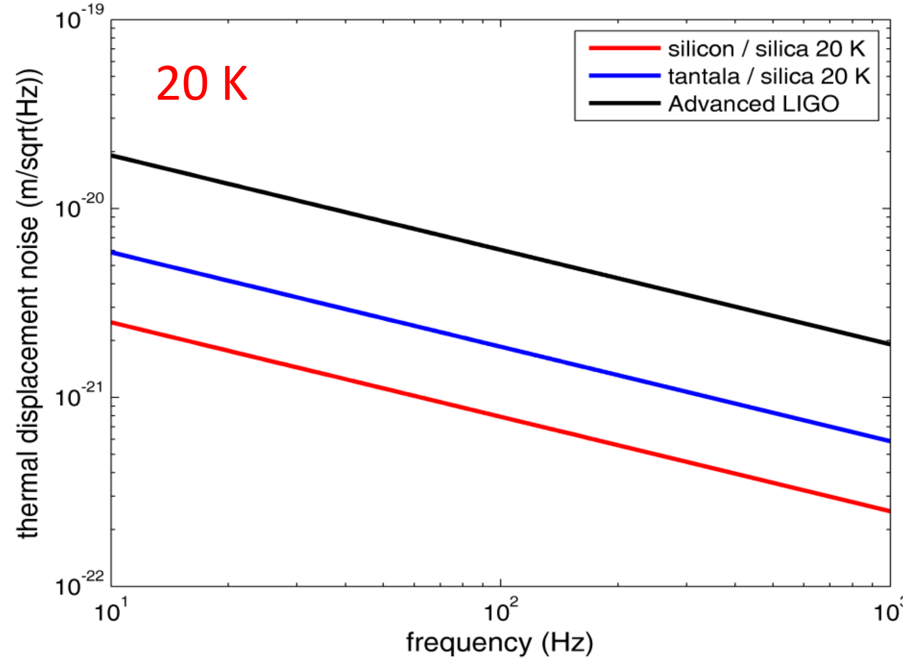
- **Si/SiO_2 requires only 6 doublets**
- For equivalent reflectivity as 15 doublets of Ta_2O_5/SiO_2
- **Saw loss of Si << Ta_2O_5 at cryogenic temperatures**
- Coating loss limited by cryogenic loss of silica layers

Thermal noise reduction in comparison to Advanced LIGO design*

	120 K	20 K
Ta_2O_5/SiO_2	2.3	3.2
Si/SiO_2	6.0	7.6

Assuming beam radius 9.95 cm (Strawman Red)

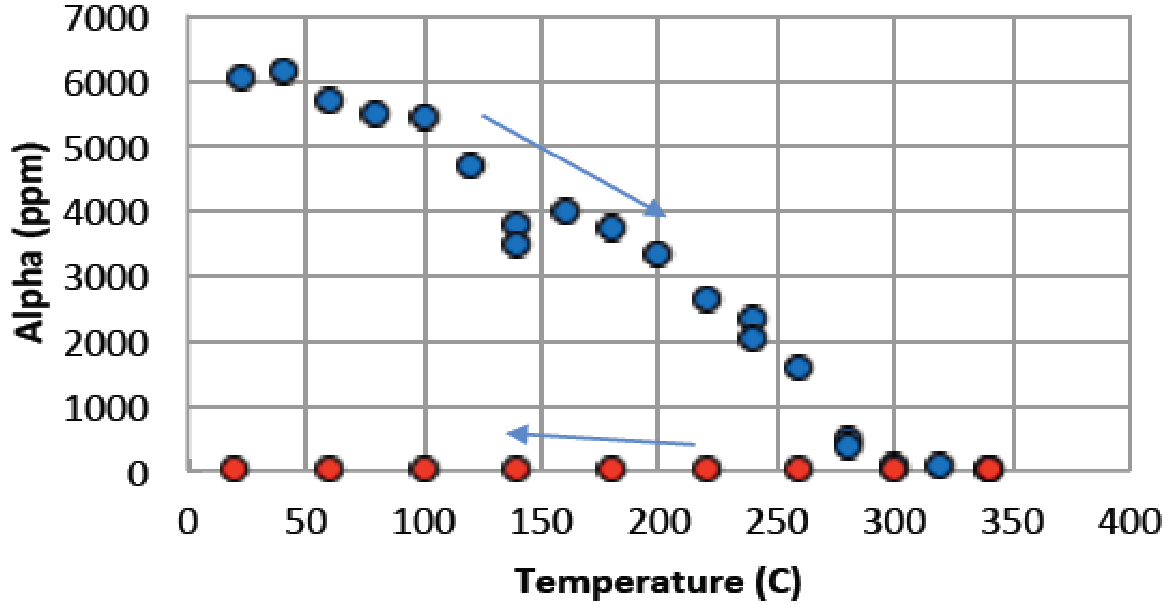




*λ=1064 nm, T=300 K, beam rad.= 6.2 cm

aSi coatings – what about absorption?

- **As seen with silica doped hafnia, heat-treatment can reduce absorption**
- **Hydrogenation?**
- Terminating dangling bonds can reduce mechanical loss
- Studies at Stanford and Glasgow
- **Interesting to note:**
  Large reductions in absorption can be achieved in some materials
- e.g. Ashot's talk at Stanford Coating Workshop on Al-ZnO
- absorption can be reduced from 6000ppm to 4.5ppm



Further work

- **A lot of progress towards improved high-index materials**
- **Need to consider low-index materials at low temperature**

- **Understanding loss, links between loss and structure, is important**
- see structural talks

- **Other methods of altering loss**
- Deposition parameters?
- Alternative materials?
- Alternative dopants – predicted by modelling/structural work?