Studies of materials to reduce coating thermal noise

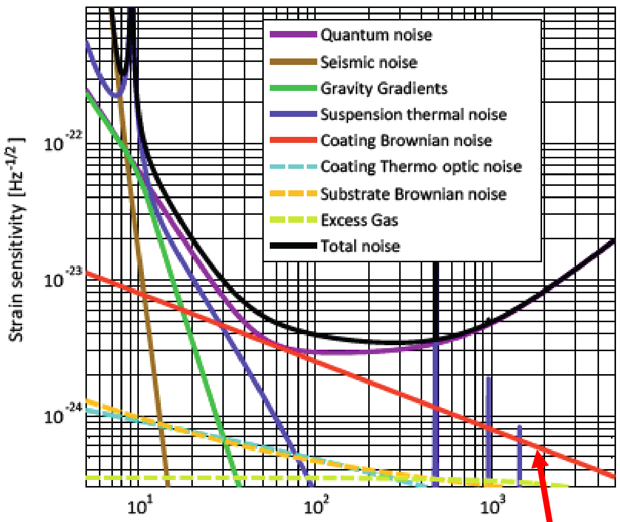
I.W. Martin[1], S. Reid[2], M. Abernathy[1], R. Bassiri[1,4], K. Borisenko[3], K. Craig[1], A. Cumming[1], K. Evans[1], K. Haughian[1], M. M. Fejer[4], A. Gretarsson[5], G. M. Harry[6], G. Hofmann[7], J. Hough[1], J. Komma[7], A. Lin[4], I. MacLaren[1], S. Penn[8], R. Nawrodt[7], R. Route[4], S. Rowan[1], J. Scott[1], C. Schwarz[7], E. Wisniewski Barker[1], L. Wittrock[9]

[1] SUPA, University of Glasgow
[2]SUPA, University of the West of Scotland
[3]Oxford University
[4]Stanford University
[5]Embry-Riddle Aeronautical University
[6]American University
[7]University of Jena
[8]Hobart and William Smith College
[9]Leibniz University Hannoever

GWADW, Hawaii, May 2012

Reducing coating thermal noise

- Development of coatings with reduced thermal noise for:
  - Enhancements to Advanced LIGO (LIGO3)
    - May operate at cryogenic temperature (120 K?) or room temperature (or both – cryo-xylophone)
    - May operate around 1550 nm
  - 3rd generation detectors e.g. ET (LF)
    - Cryogenics (10 or 20 K)
    - Change of wavelength to 1550 nm



GWINC aLIGO noise budget

Coating thermal noise

$$S_x(f,T) \approx \frac{2k_B T}{\pi^2 f}\frac{d}{w^2 Y}\phi\left(\frac{Y'}{Y}+\frac{Y}{Y'}\right)$$

Temperature; Coating thickness; Laser beam radius; Coating mechanical loss

Paths to improved coating TN performance

- Better amorphous coatings - we know they work! Just starting to understand what causes their dissipation
  - (alternate materials - amorphous silicon for 1550nm?)

- Crystalline coatings:
  - Intrinsic Brownian loss of AlGAs shown to be low (G. Cole talk)
    - Low Brownian noise after being transferred to new substrate?
    - Can they be used successfully on silicon at low temperature?
  - GaP/AlGaP alternative - lattice matched to silicon - what is loss?

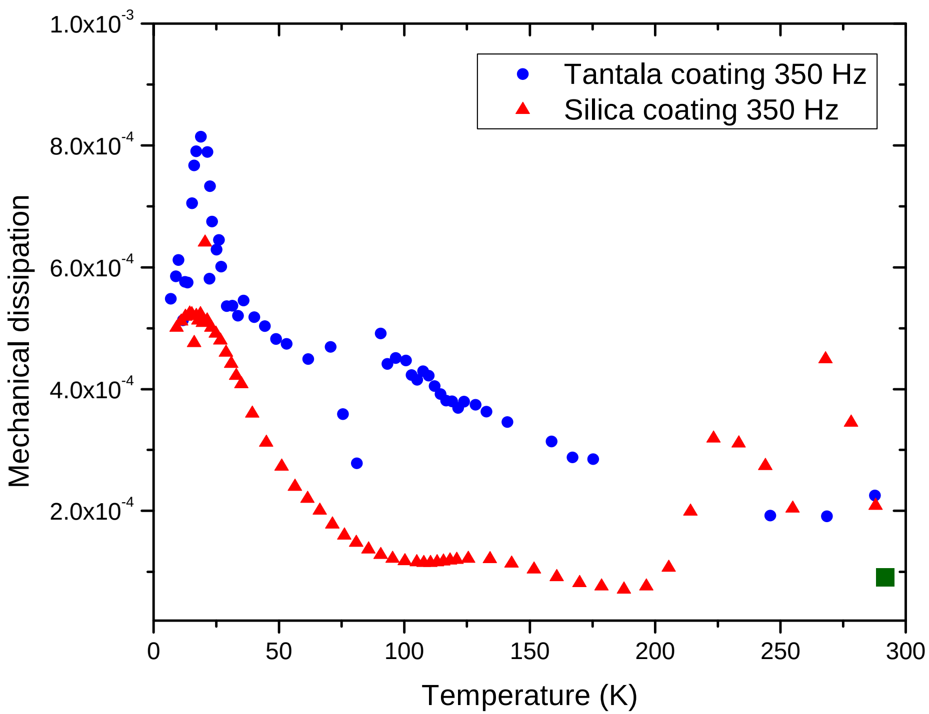
- Remove coatings entirely?
  - lots of increased (lossy?) surface area - what really is the thermal noise? (S. Kroker talk)

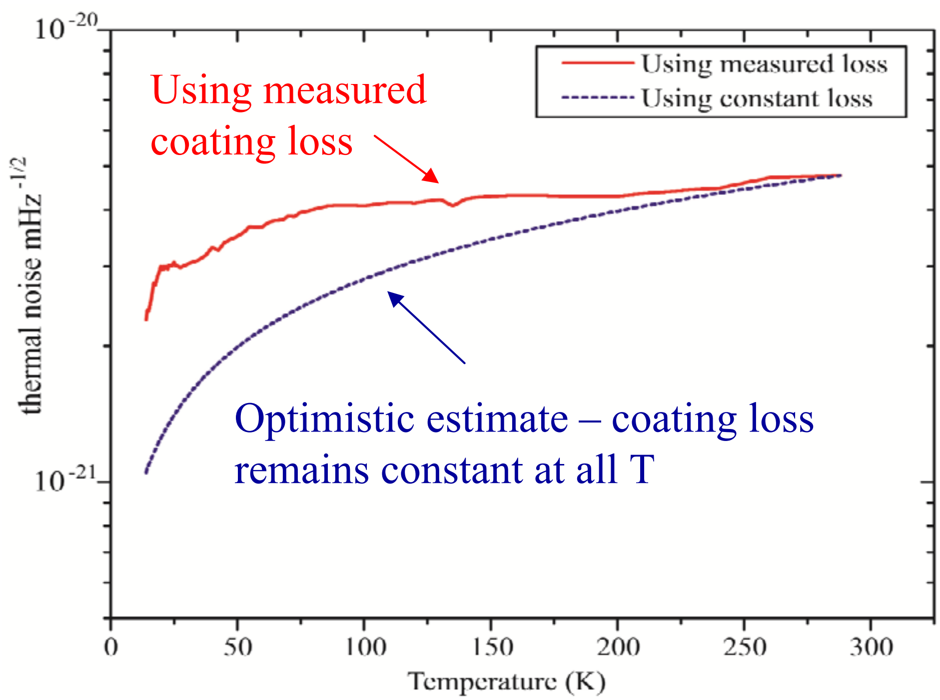
- Way ahead not yet clear – studies ongoing in each of these areas

- Plus - need to know relevant materials properties to correctly evaluate coating thermal noise

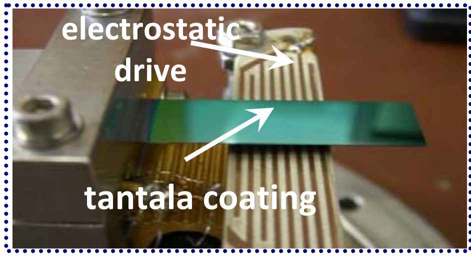
Current coatings – silica/tantala

- Cryogenic loss peaks in tantala and silica films suggest only a factor of 1.9 reduction in coating thermal noise from cooling to 20 K
- Analysis of peaks and studies of atomic structure can provide information about loss mechanisms
- Evidence that low-temperature loss can be altered by heat-treatment and doping – evidence of correlations between loss, structure and doping level (R. Bassiri talk)

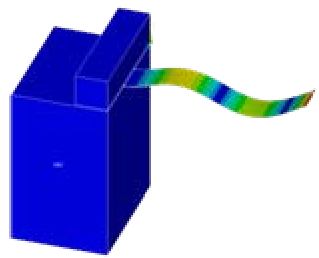


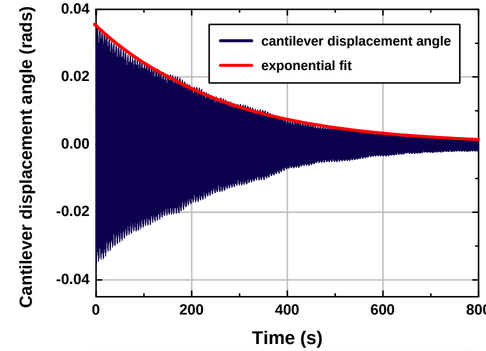


Cryogenic coating loss measurements



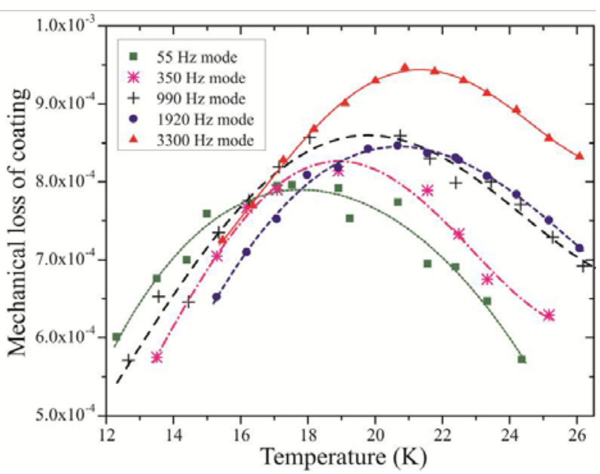
$$\phi(f_0) = \frac{\Delta f}{f_0} = \frac{E_{\text{lost per cycle}}}{2\pi E_{\text{stored}}}$$





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

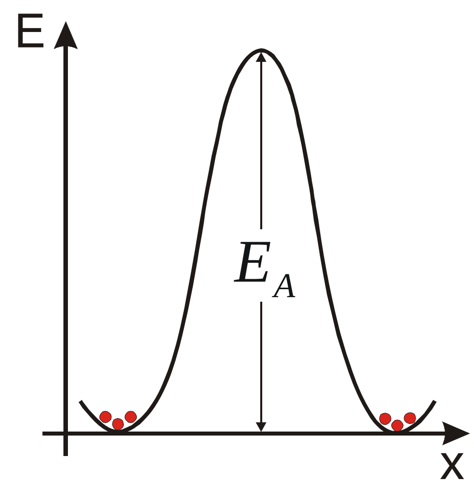
- Loss measured from ringdown experiments using coated cantilever samples
- Analysis of cryogenic loss peaks can reveal characteristics of microscopic energy loss mechanisms



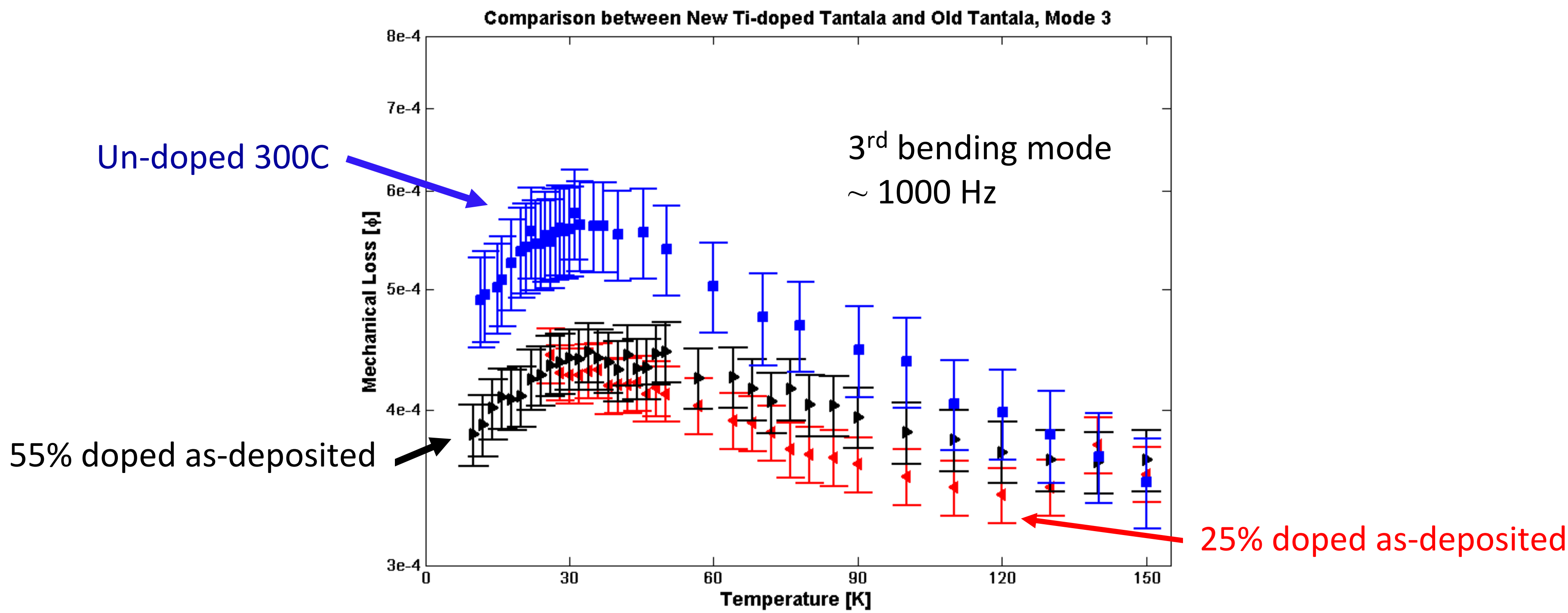
$$\tau = \tau_0 e^{\frac{E_a}{K_B T}}$$

τ_0 = relaxation constant

E_a = activation energy



Loss reduction in current coatings highly TiO_2-doped tantala

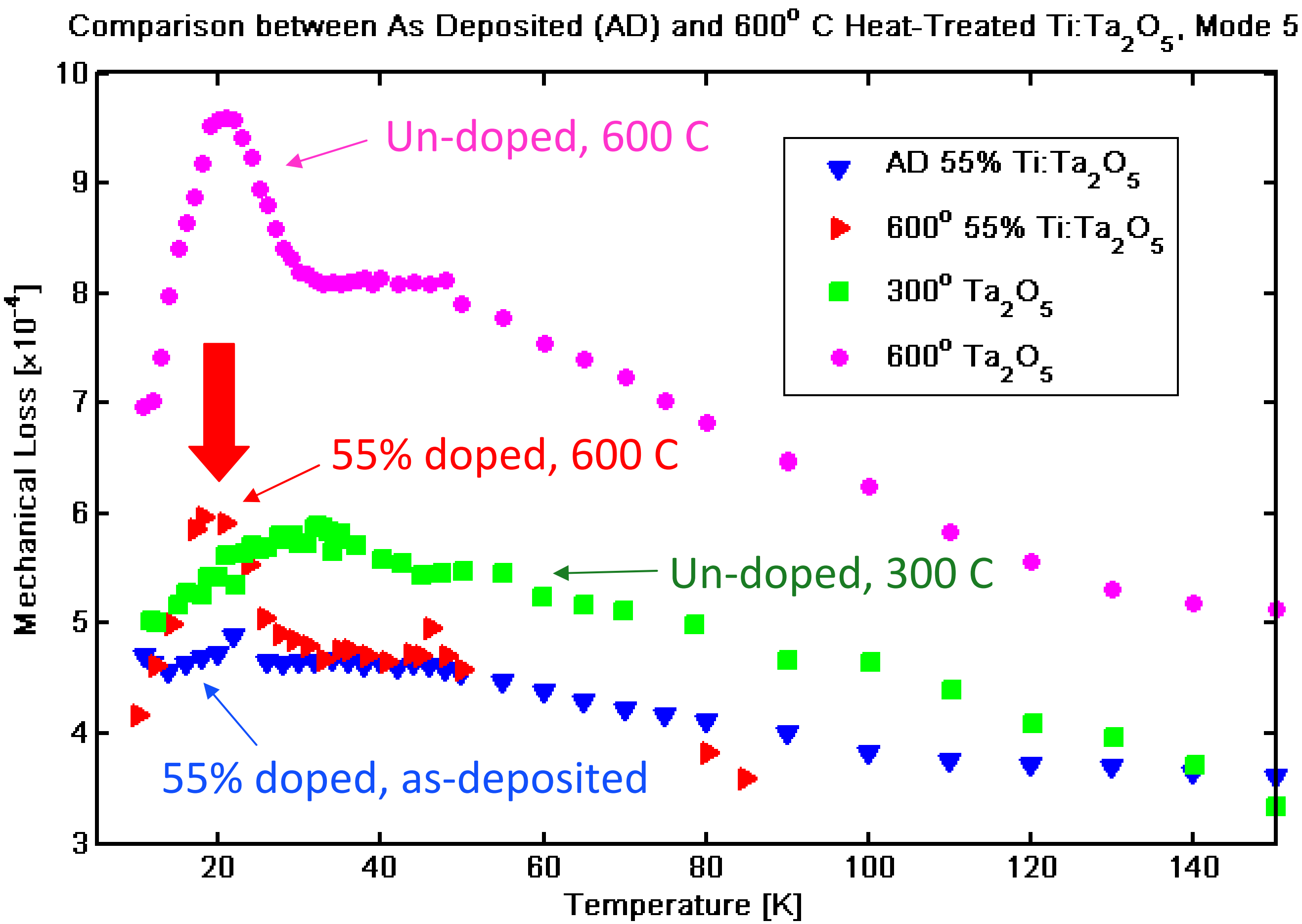


Loss of (a) 55% TiO_2-doped Ta_2O_5 (b) 25% TiO2-doped Ta2O5 and (c) undoped Ta_2O_5 heat-treated at 300 C

- First cryogenic measurements of tantala films with no heat-treatment
- A broad loss peak at ~ 35 K is present in both un-annealed 25% and 55% TiO_2-doped Ta_2O_5 . Similar to the 35 K loss peak observed in un-doped tantala heat-treated at 300°C, but with slightly lower loss.
- Suggests 30-35 K loss peak intrinsic to IBS tantala coatings, not produced by heat-treatment

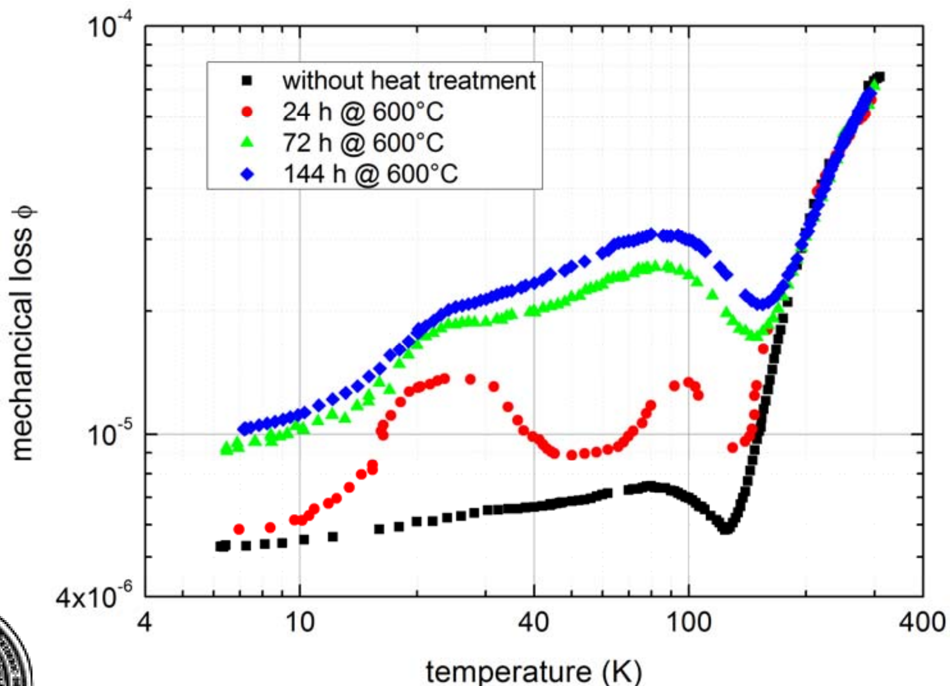
Heat-treatment of highly-doped tantala

- Studies of effect of heat-treatment on the 25% and 55% TiO_2-doped samples in progress
- High TiO_2 doping may suppress low temperature loss peak in coatings heat-treated at 600°C



Annealing time of e-beam tantala

- annealing of tantala (Ta_2O_5) layers – collaboration with University of Jena
  - previous investigations have shown heat treatment at 600 and 800°C triggering low-temperature loss peaks (800°C crystallises the coating)
  - now: investigation of time dependence of heat-treatment



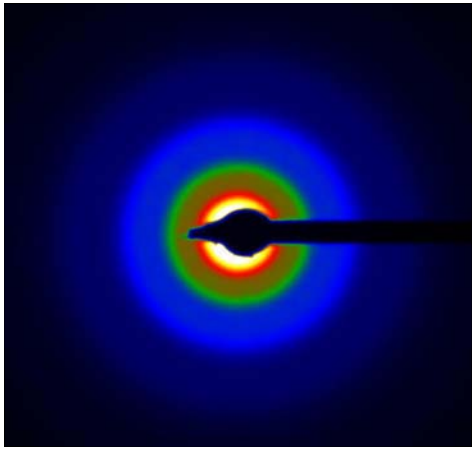
Mechanical loss of a coated silicon cantilever

time dependent process observed
possible explanation:

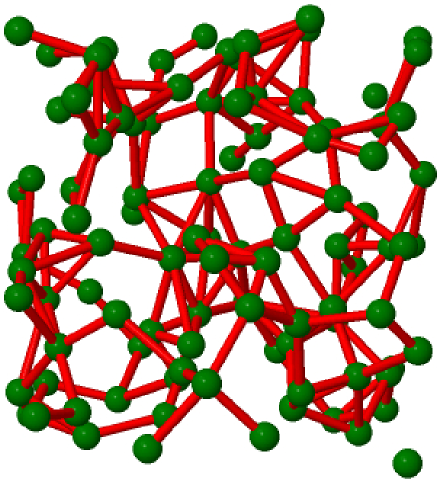
- formations and growth of micro and nano crystallites within the coating

Alternative coating materials amorphous silicon

- Particularly high refractive index (n=3.5), of interest for 1550nm operation
- Literature shows e-beam / magnetron amorphous Si has relatively low loss[1], ~ 1E-4 at room temperature and as low as 1E-6 at cryogenic temperatures
  - Hydrogenation of amorphous Si can reduce the loss by up to a factor of 10 –passivation of dangling Si bonds
- Studying ion-beam sputtered amorphous silicon
- Measurements of optical absorption at Stanford
  - Further studies of effect of heat-treatment, hydrogenation, deposition parameters on loss and optical absorption planned
- Structural studies (TEM electron diffraction) show a-Si heat-treated at 450°C remains amorphous



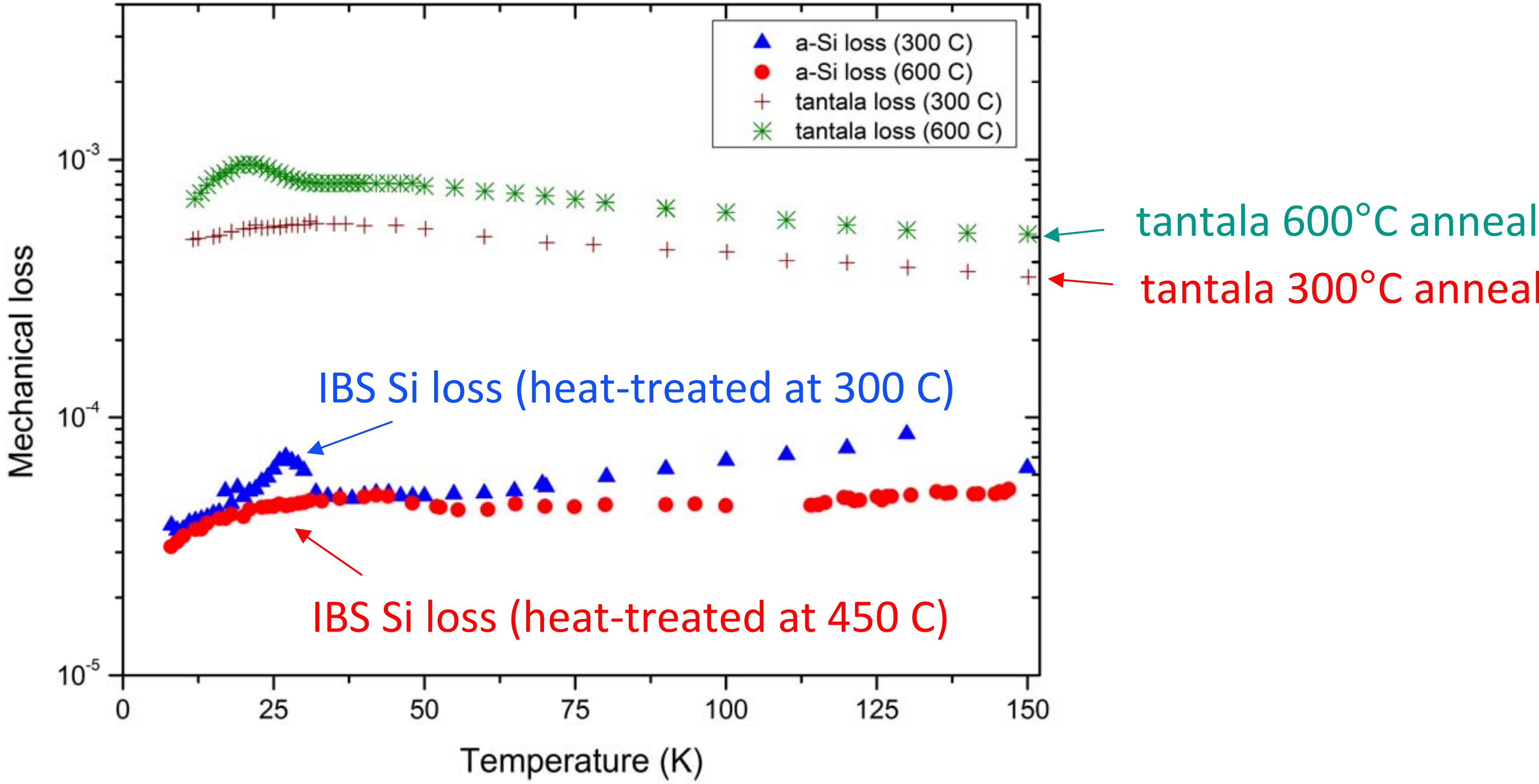
Electron diffraction pattern of a-Si



Atomic model of IBS a-Si film

[1] Liu and Pohl, Phys. Rev. B, 58 (1998)

IBS amorphous silicon coatings



- So far, only coated cantilevers studied
- A conservative upper limit to Si loss can be estimated, by assuming all of the loss originates in the coating. However, actual coating loss is highly likely to be lower than this as the cantilever substrate will be contributing to the measured loss
- Loss peak observed at 25 K in a-Si heat-treated at 300°C, but not at 450°C.

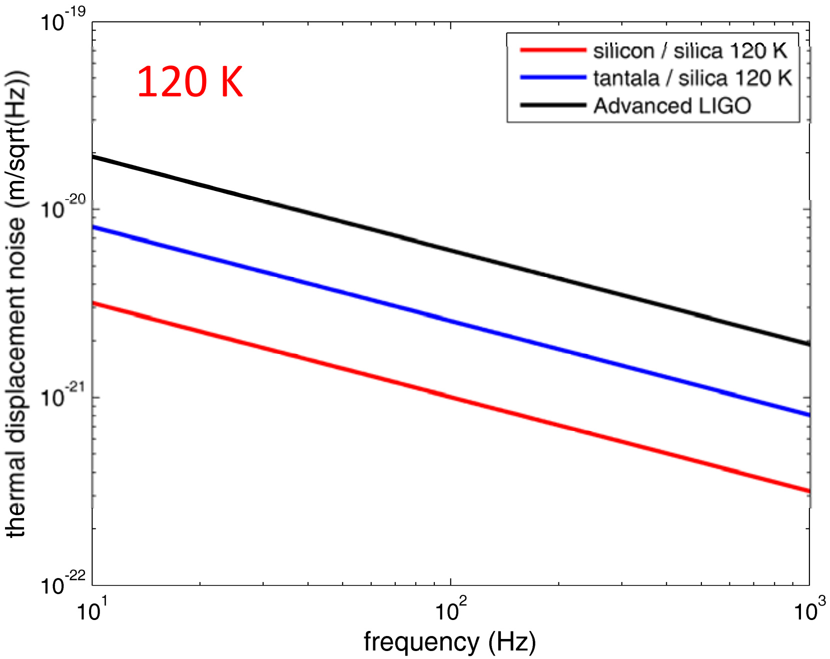
Comparison of coating Brownian noise

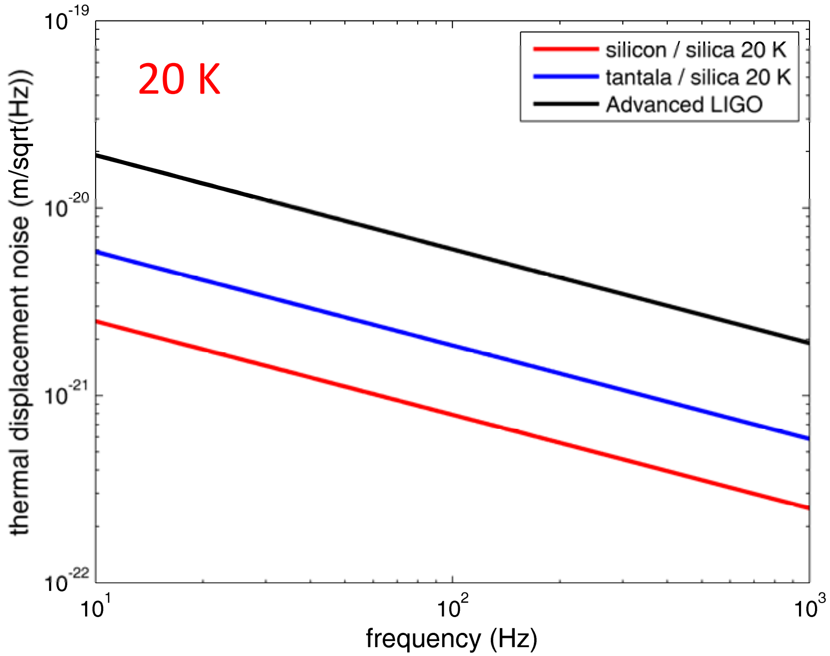
- SiO_2/Si requires 6 doublets for equivalent reflectivity as 15 doublets of SiO_2/Ta_2O_5)
- Loss of Si is significantly lower than Ta_2O_5 at cryogenic temperatures. Limited by loss of silica layers at low temperature
- If lower optical absorption can be achieved, a-Si is a promising coating material

Thermal noise reduction in comparison to Advanced LIGO

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

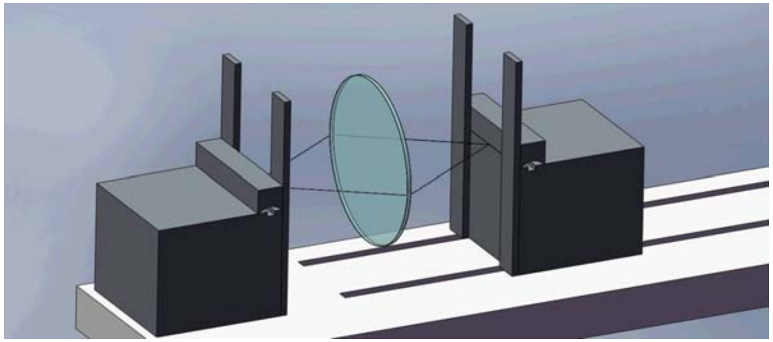
Assuming beam radius 9.95 cm (Strawman Red)

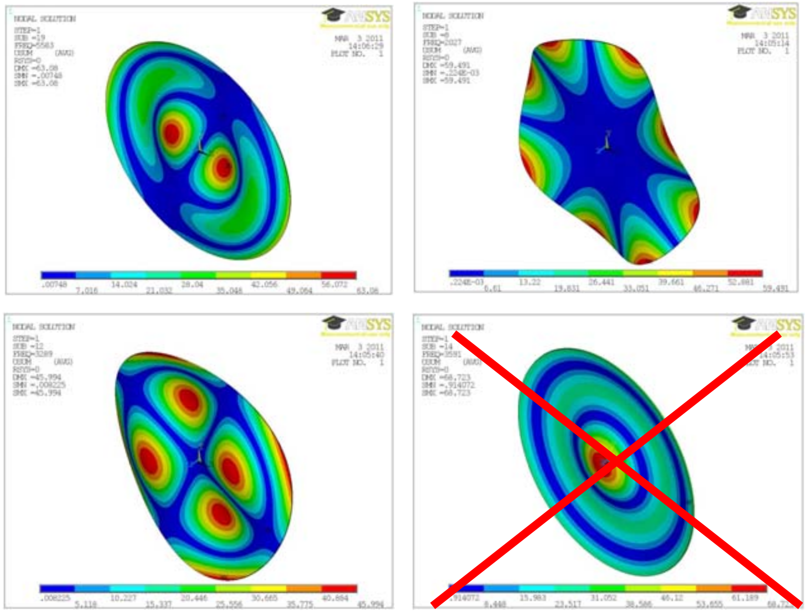




Alternative coating materials
GaP/AlGaP single crystalline coatings

- Single-crystal coatings can have low mechanical loss
  - e.g. loss of AlGaAs coatings has been measured to be at least 4.5E-6 at 4 K (G. Cole)
- GaP/AlGaP – lattice matched to silicon, can grow coatings directly on silicon substrates (see A. Lin talk)
- Coatings on silicon and GaP disks. Loss of various modes measured using a nodal support technique
  - Accuracy of measurements at room temperature limited by thermoelastic loss in disk substrates
  - Preliminary results at room temperature suggest the loss of GaP/AlGaP coatings has to be less than a few $\times 10^{-4}$ (no difference in loss between coated and un-coated samples)

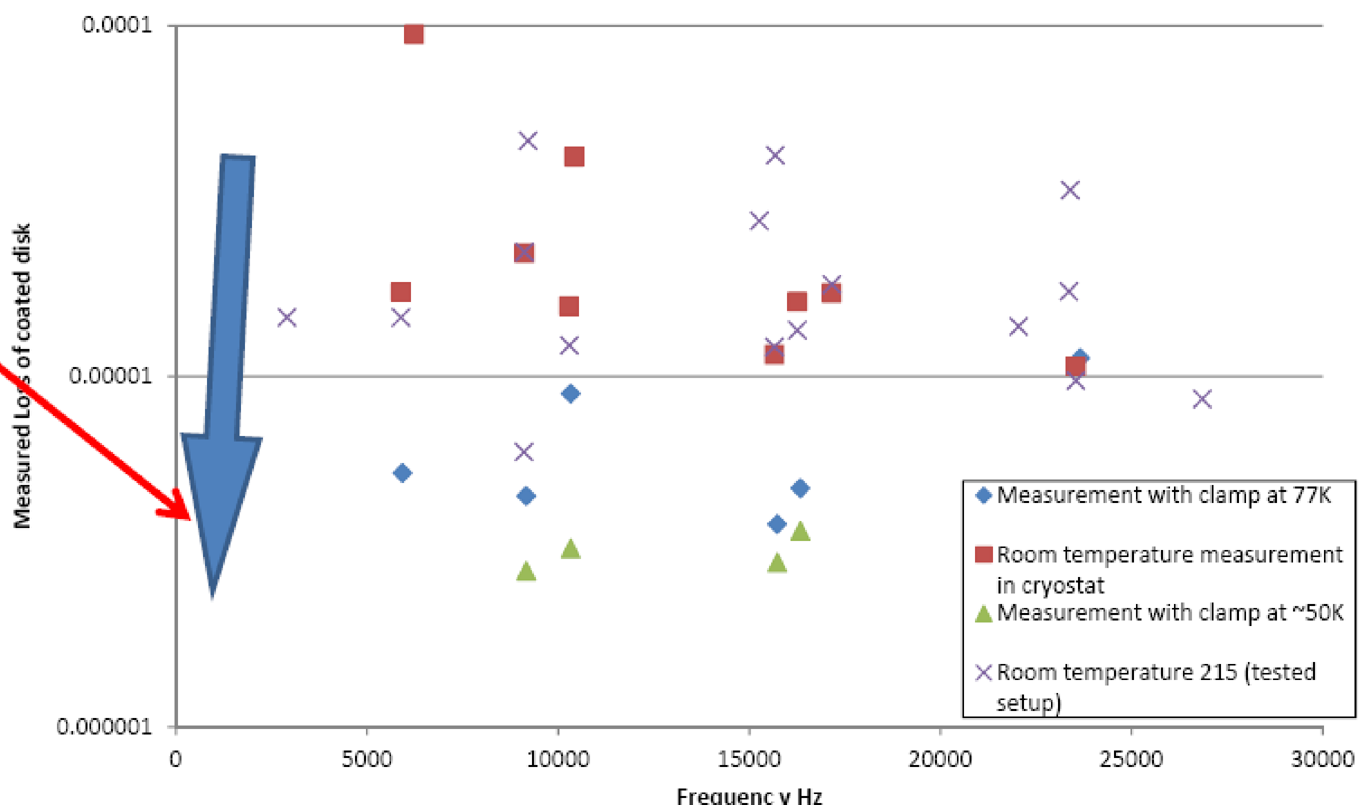




Preliminary AlGaP cryogenic loss measurements

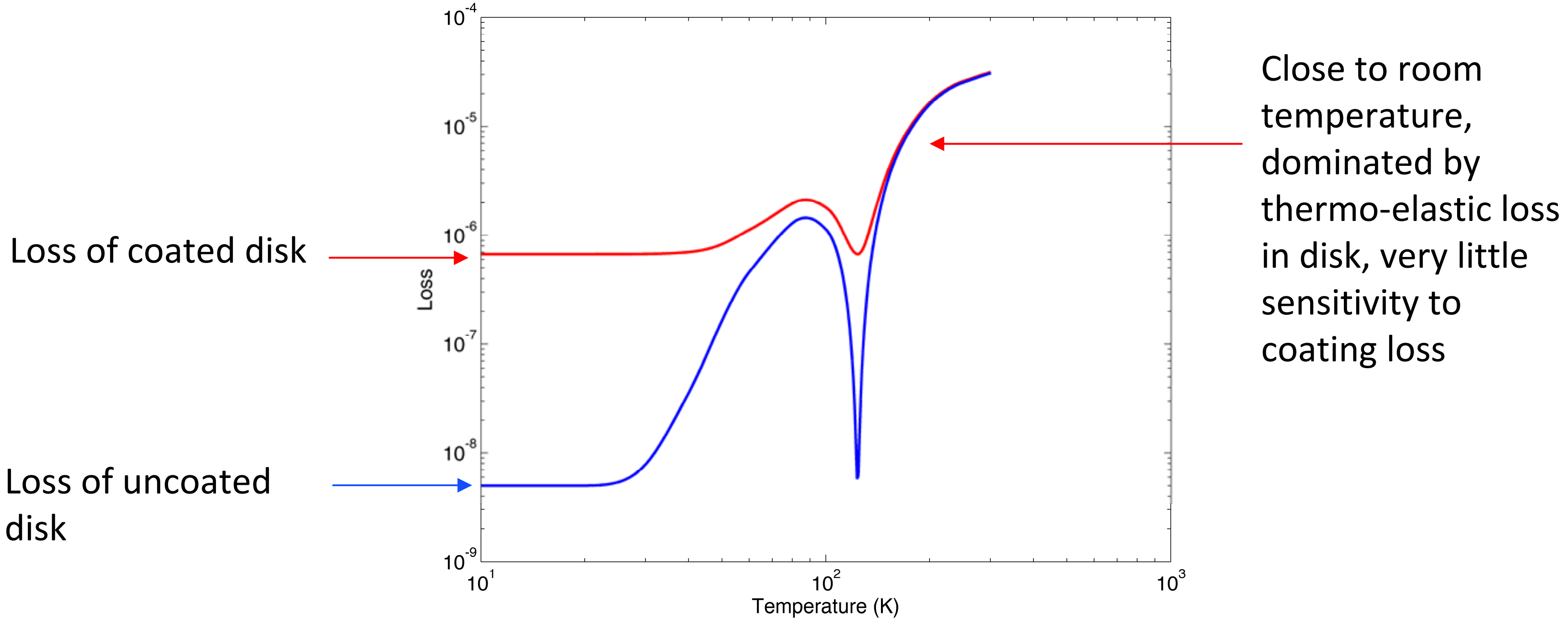
- Very first cryogenic run (no temperature calibration yet)
- Measurements at room temperature, with clamp at 77 K and with clamp at 50 K.
- General trend – reduced loss at low temperature

Measured loss is decreasing with temperature, but likely still dominated by thermoelastic loss in the substrate



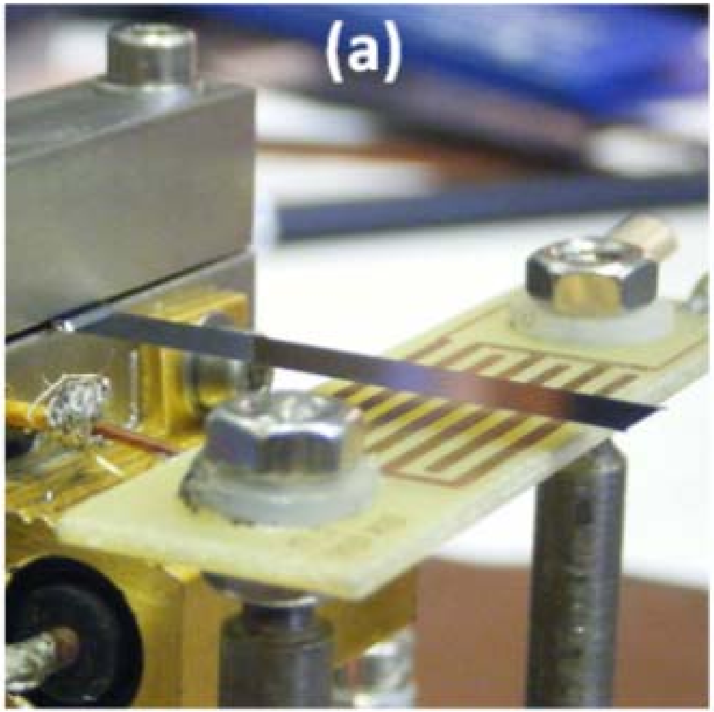
AlGaP loss measurements

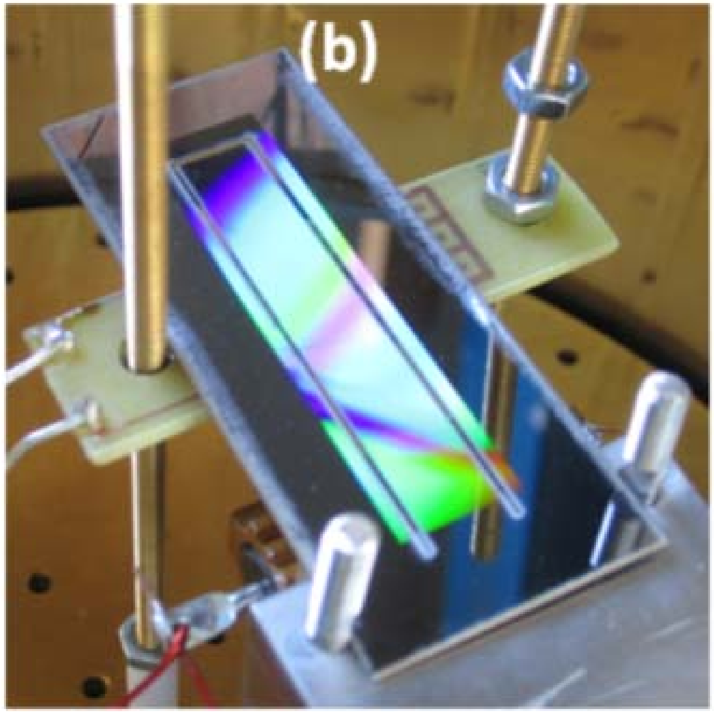
- Expect to be most sensitive to the coating loss below ~ 30K (likely to be limited by thermoelastic loss of disk at higher temperatures)
- Initial results of loss of disk reducing with temperature consistent with thermo-elastic limited loss
- Work on-going to calibrate temperature of disk, using exchange gas for thermal contact



Removal of coating entirely nanostructured silicon

- The mechanical loss associated with nanostructured silicon was investigated in order to evaluate the effect on Brownian thermal noise
- Nanostructured silicon is required for the fabrication of proposed diffractive optics and monolithic waveguide coatings.

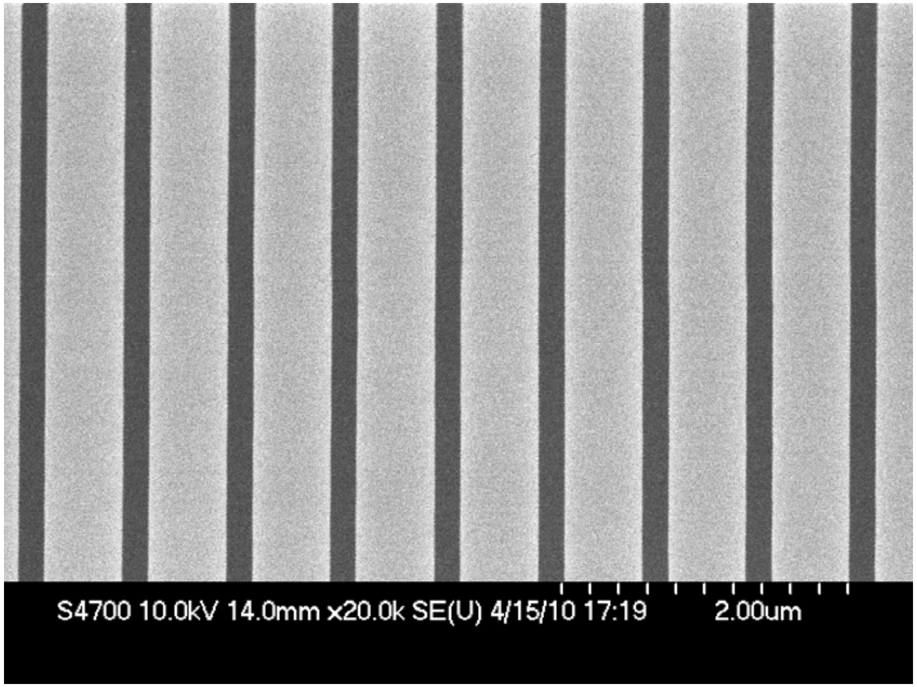


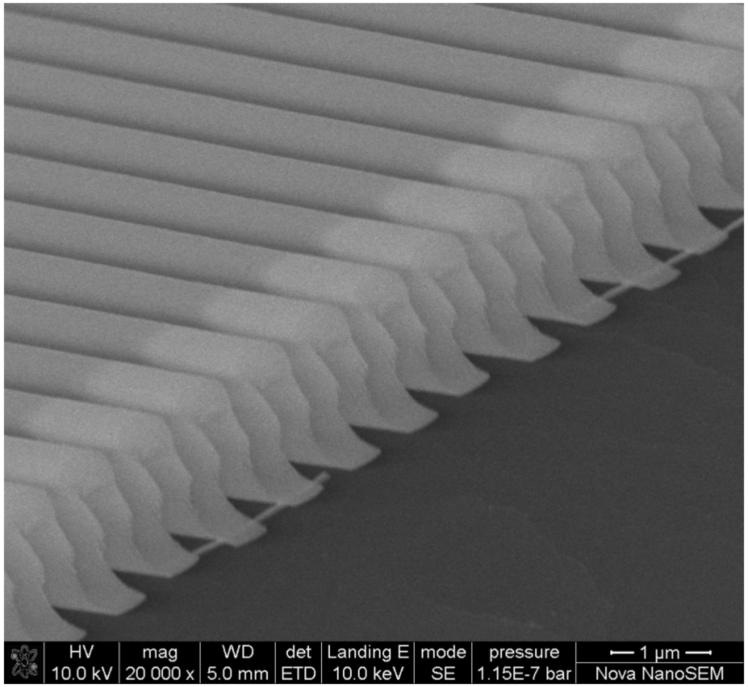


Pictures of (a) silicon cantilever fabricated by KNT (Glasgow) and (b) silicon cantilever fabricated in Jena (with additional clamping frame).

Grating structure

SEM images of Glasgow grating, fabricated by KNT



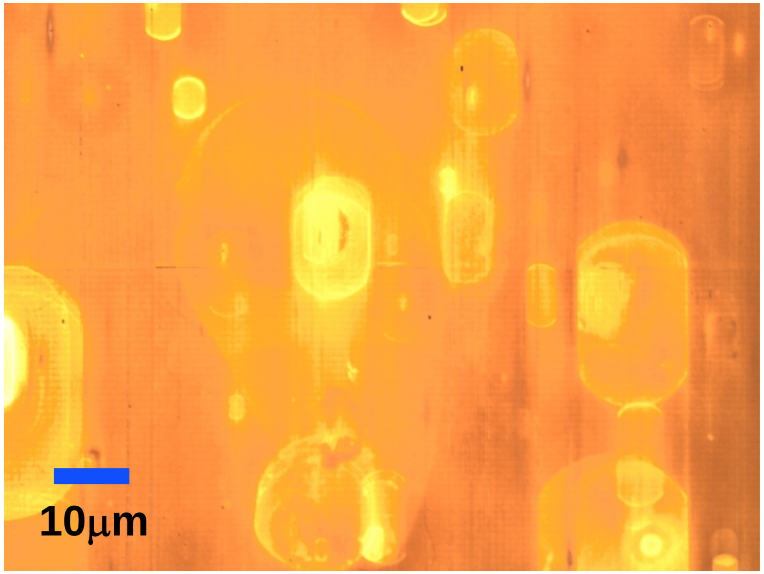


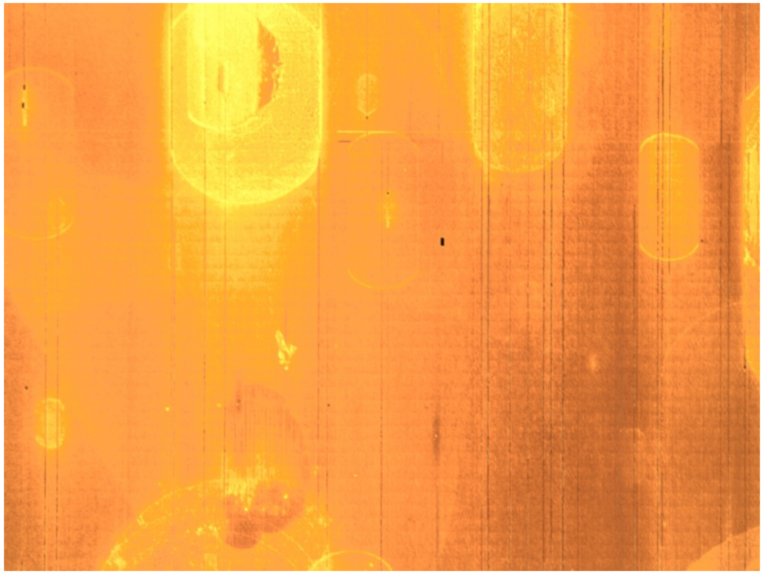
Vertical and tilted SEM view of grating structure

700nm period, 1um depth, ~ 455nm wide channels with ~ 235nm between (unetched)

Grating surface contamination

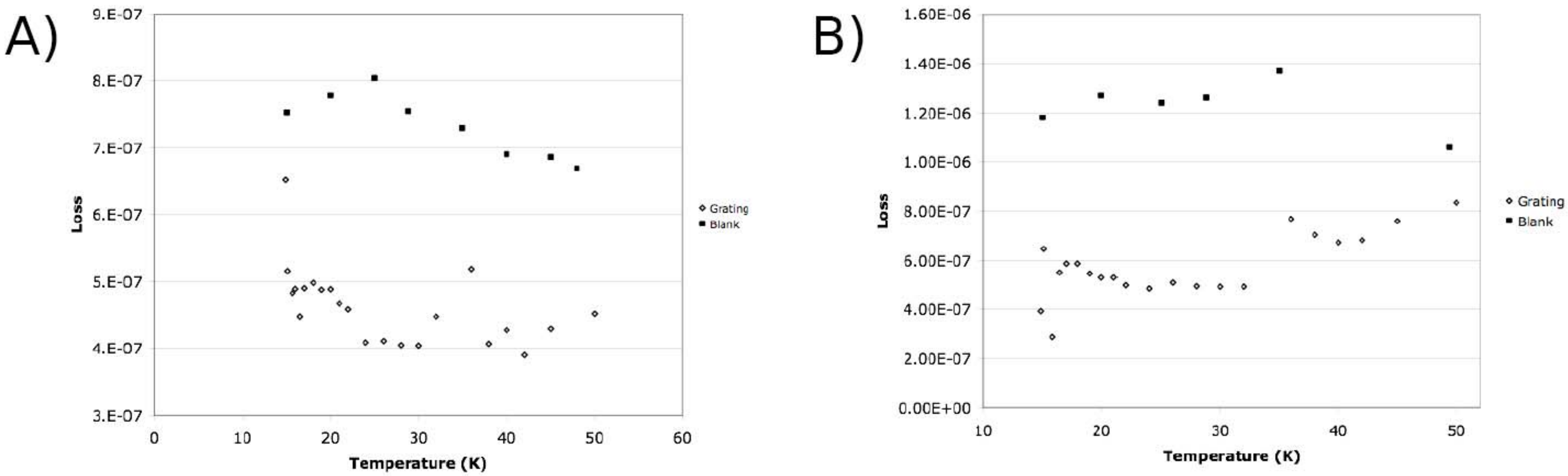
Optical images of Glasgow grating





Optical images of gratings fabricated in Glasgow show surfaces staining, believed to result from over etching in hydrofluoric acid, leaving fluorine based contaminates that could not be removed with standard cleaning techniques.

Initial results – low T

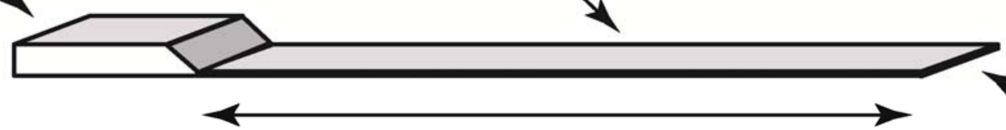


Low temperature loss measurements for A) mode 4 and B) mode 5 for both the grating and blank etched samples

Loss of cantilevers with gratings have lower loss than control sample

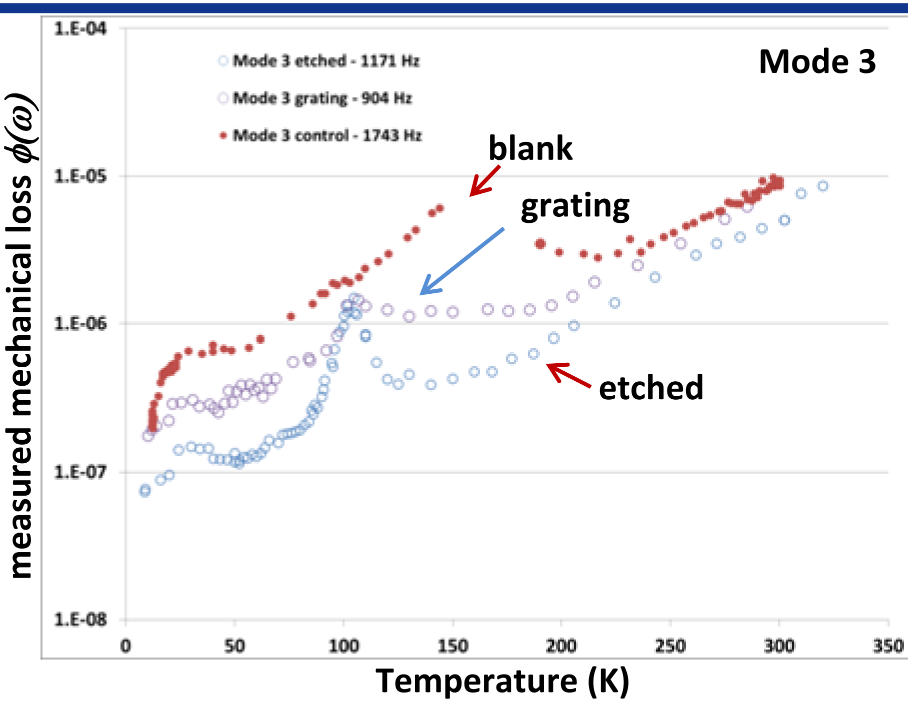
Loss does not scale with increased surface area – therefore likely that we are seeing the reduction in loss associated with surface removal

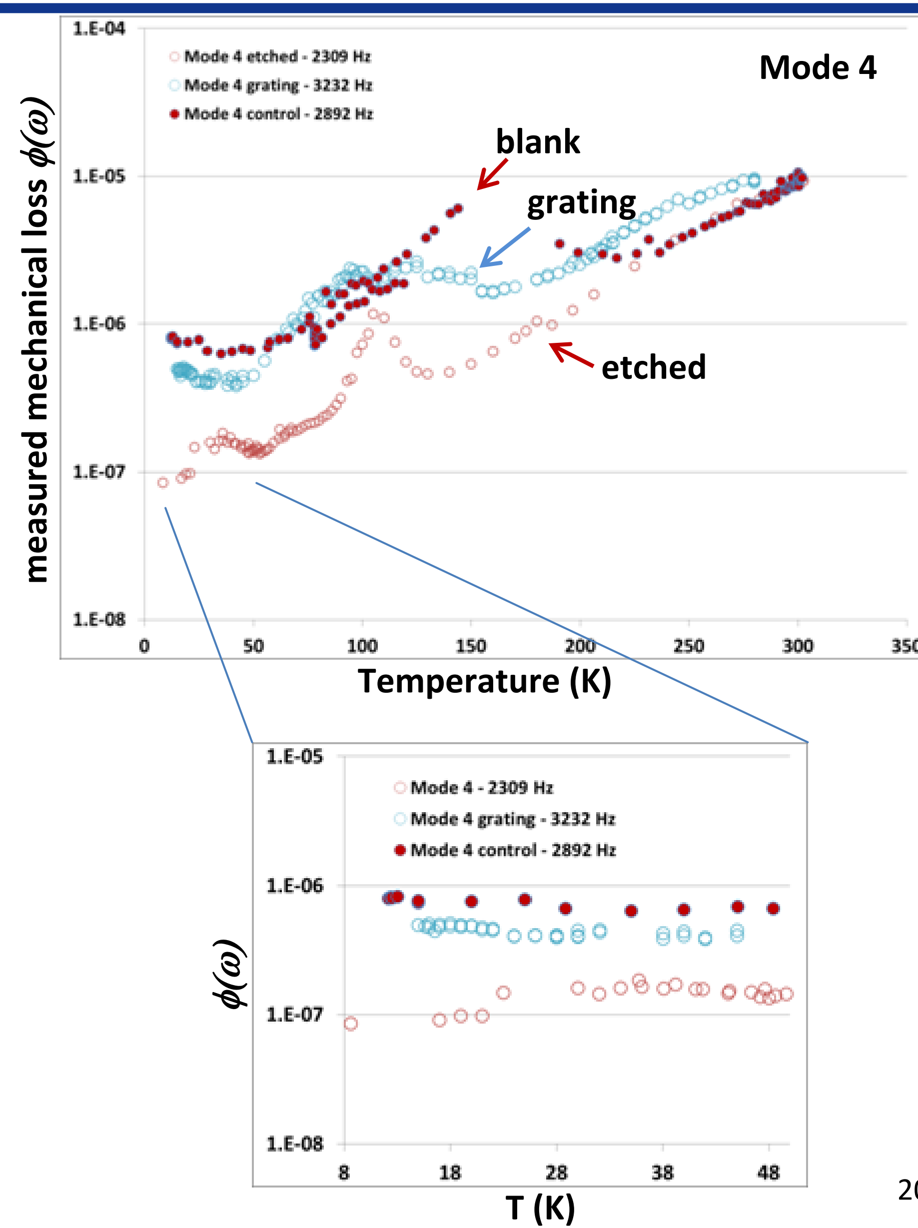
Investigation of surface removal



- Gratings were etched onto the bottom surface of cantilevers (as above)
- This surface is mechanically polished
- In order to evaluate the effect of partial removal of this surface, we asked KNT to fabricate cantilevers with 1μm homogenously etched

Nanostructured silicon





Comparison of mechanical losses between (a) blank cantilever, (b) cantilever with etching grating, and (c) homogenously etched silicon cantilever.

Conclusions – nanostructured Si

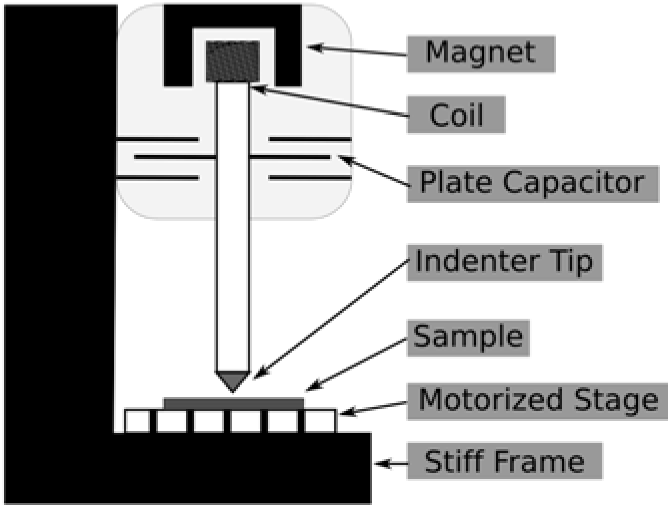
- Currently have measurements for:
  - 1 x blank cantilever (ϕ ~ **7-8×10^{-7}** between 10-50 K)
  - 2 x grating cantilever (ϕ ~ **4-5×10^{-7}** between 10-50 K)
  - 2 x etched cantilevers (ϕ ~ **1-2×10^{-7}** between 10-50 K)
- Experimental evidence suggests that change in mechanical loss measured here is not related to the addition of grating but from the surface removal.
- Mechanical loss appears to reduce by a factor ~2 after fabrication of grating compared to blank cantilever
- Suggests that thermal noise associated with monolithic nanostructured silicon is at least a factor of 10 lower than standard HR coatings (assuming 1μm depth nanostructures, and scaling with simple ϕ.d relationship, excluding interaction of light in nanostructured layers)

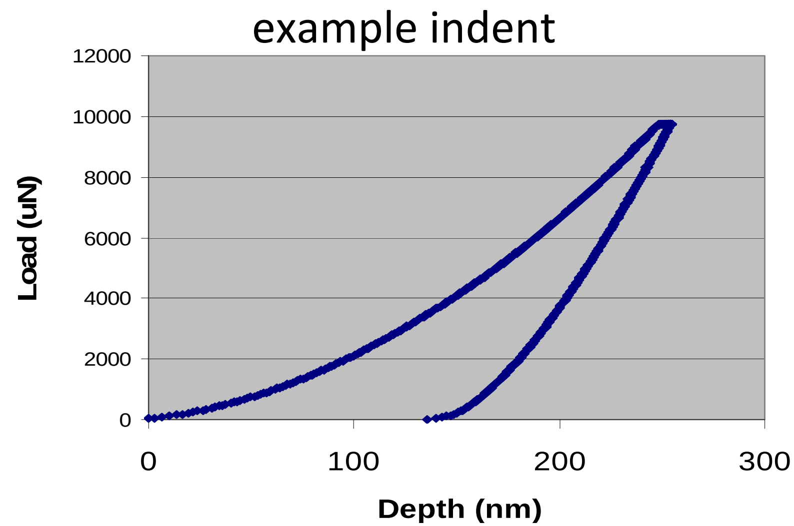
<u>Future studies</u>

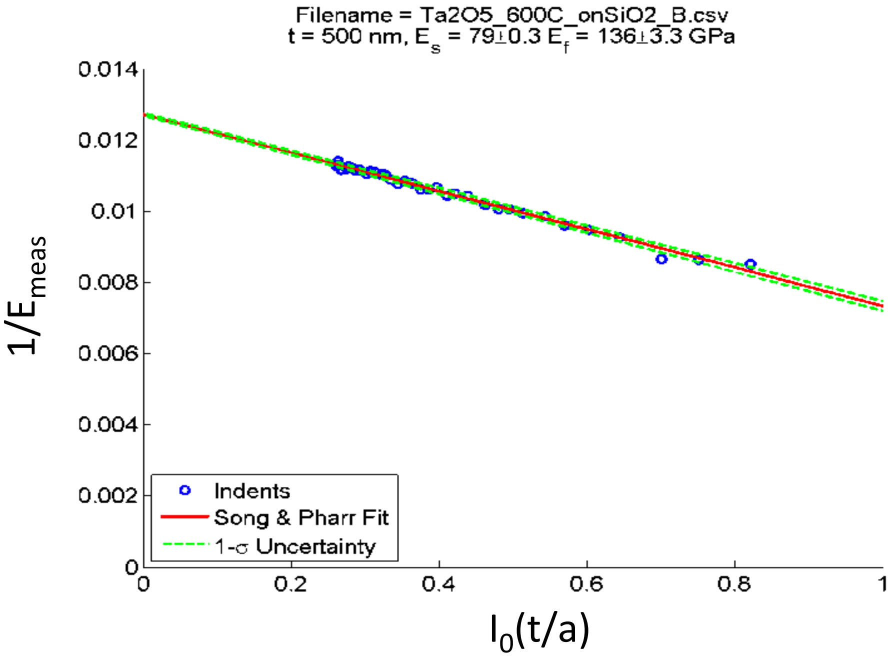
•Is the dissipation peak at 100 K related to surface effects (*e.g.* fluorination) or other (*e.g.* bulk)?
- If related to fluorination of surface, then can we removed?

•Previous studies of surface loss show that surface roughness is important in the measured loss (Nawrodt, Jena) - does the surface roughness change with SF6 etching?

Coating property characterisation
Young’s modulus - nano-indentation

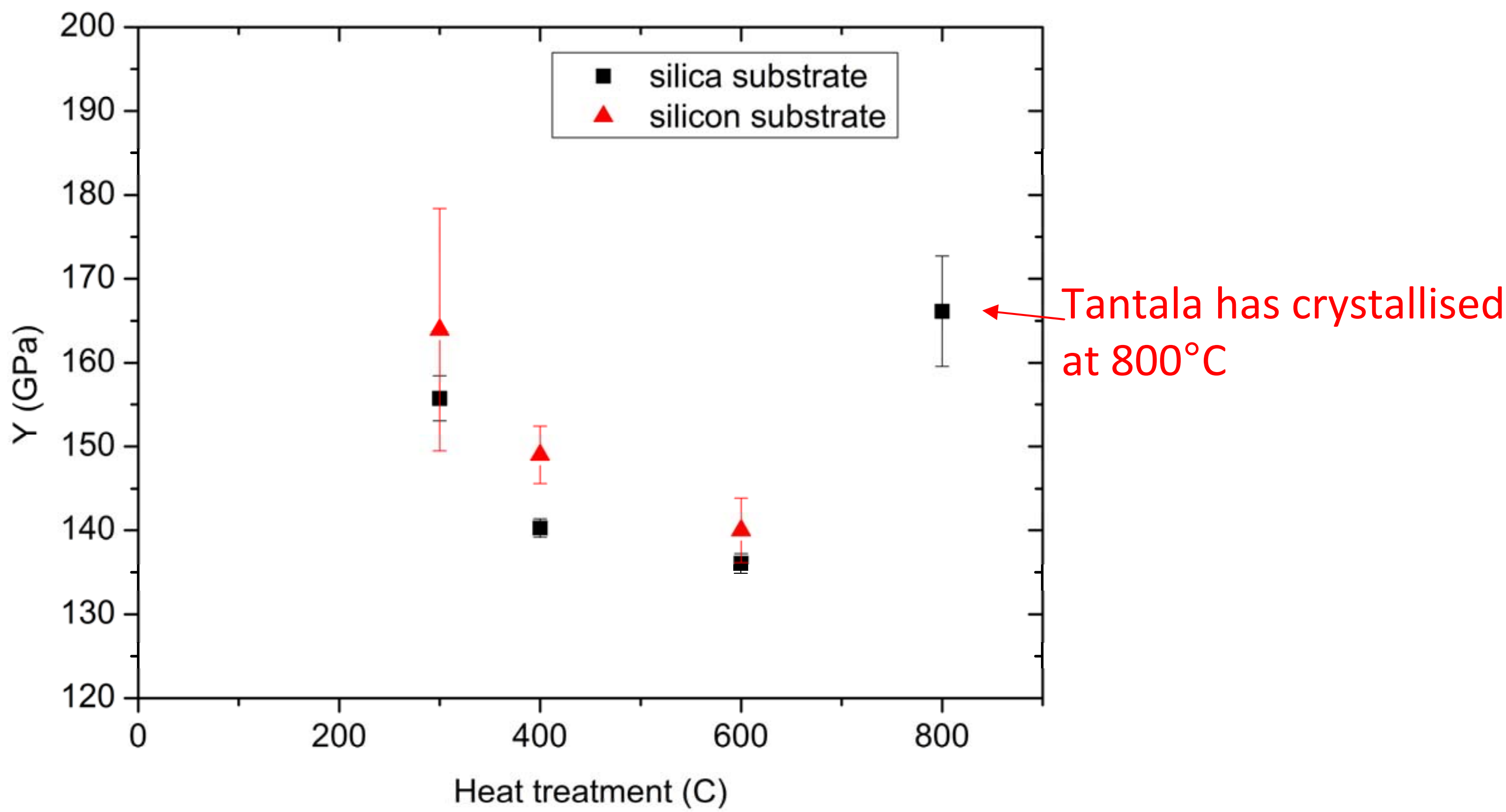






- Each indent produces a modulus containing information on coating and substrate
- Indent at many different depths and extrapolate to zero depth to get coating modulus

Young's modulus of un-doped tantala



- General trend of Y decreasing with increased heat-treatment temperature up to 600°C
- Slightly higher Y values measured on Si - perhaps due to effects of substrate stiffness.
- For 600 C heat-treatment, Y ~ 136 – 140 GPa – consistent with several literature values
- Ongoing measurements of doped tantala and other coatings

Summary

- Better amorphous coatings
  - Evidence that high titania doping may suppress low temperature loss peak – titania may stabilise structure against changes induced by heat-treatment
  - Heat-treatment duration is important for emergence of low-temperature loss peaks – optimisation of loss and optical absorption?
  - At cryogenic temperature, Si/SiO_2 coatings likely to give at least a factor of 3 reduction in thermal noise compared to Ta_2O_5/SiO_2
  - Optical absorption of a-Si needs further study / development
- Single crystalline coatings
  - Initial results suggest the loss of GaP/AlGaP MBE coatings grown on silicon is < a few $\times 10^{-4}$. Low-temperature measurements will begin soon
- Remove coatings entirely

- Coating materials properties characterisation
  - Young's modulus of Ta_2O_5 reduces with increasing heat-treatment up to 600°C
  - Y $\sim$136 – 140 GPa for Ta_2O_5 heat-treated at 600°C