Mechanical loss of crystalline and amorphous coatings

I. Martin[1,] K. Craig[1], P. Murray[1], R. Robie[1], S. Reid[2], A. Cumming[1], R. Bassiri[3], M. M. Fejer[3], J. Harris[3], M. Hart[1], G. Harry[4], K. Haughian[1], D. Heinert[6], J. Hough[1], A. Lin[3], I. MacLaren[1], R.Nawrodt[6], S. Penn[5], R. Route[3], S. Rowan[1]

[1] SUPA, University of Glasgow
[2]SUPA, University of the West of Scotland
[3]Stanford University
[4]American University
[5]Hobart and William Smith College
[6]University of Jena

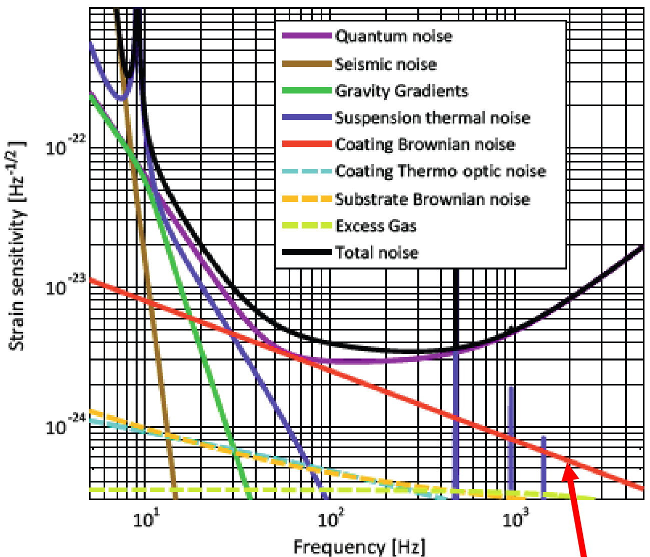
GWADW, Takayama, May 2014

Outline

- Introduction
- Measurements of crystalline coatings
  - AlGaAs on silica and silicon
  - AlGaP
- Measurements of amorphous coatings
  - TiO_2 / Ta_2O_5 coatings
  - SiO_2 doped-HfO_2

Coating thermal noise

- Reductions in coating thermal noise required for planned future detectors e.g.
  - Enhancements to Advanced LIGO
    - May operate at cryogenic temperature 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

Temperature

Coating thickness

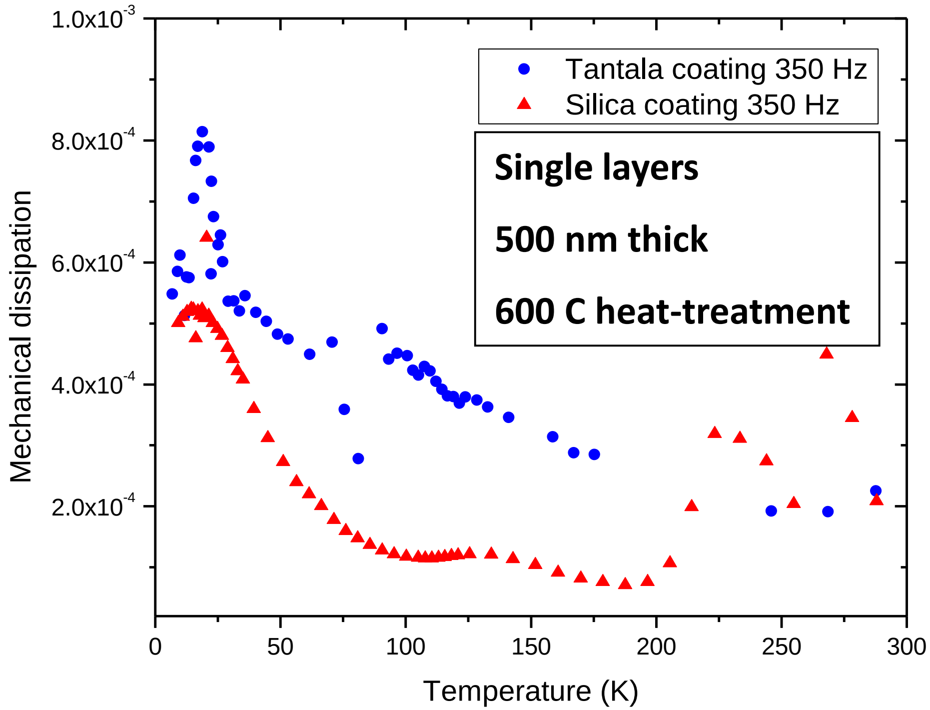
$$S_x(f,T) \approx \frac{2k_B T}{\pi^2 f} \frac{d}{w^2\, Y} \phi \left(\frac{Y'}{Y} + \frac{Y}{Y'} \right)$$

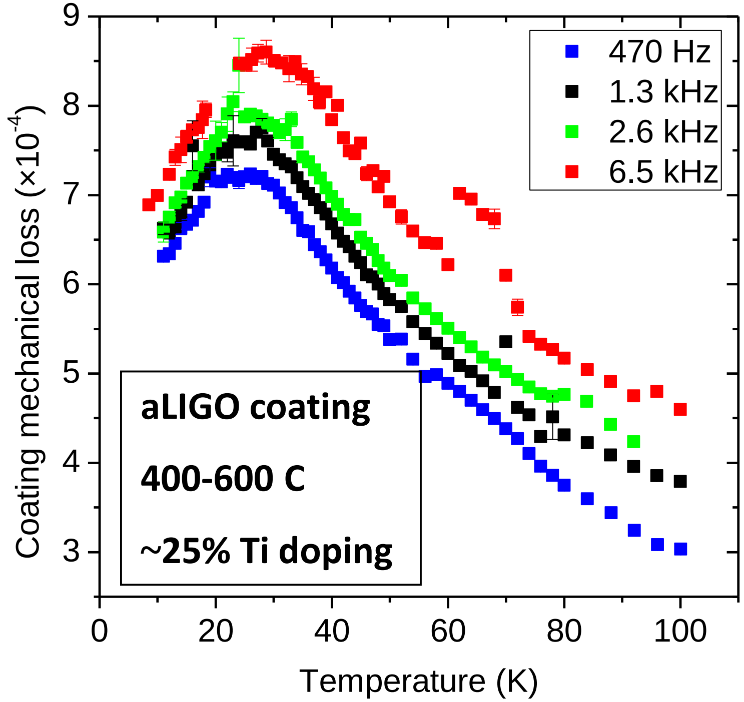
Laser beam radius

Coating mechanical loss

Current coatings – silica/tantala

- Cryogenic loss peaks in tantala / silica films (single layers[1,2] and aLIGO coating[3]) suggest reduction in coating thermal noise by ~2x by cooling to 20K
  - ET-LF requires loss reduction by ~4x (20 K operation) or ~1.6x (10 K operation)
  - Peaks at higher temperature (~30 K) in multilayer coatings (aLIGO & SiO_2/Ta_2O_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, in preparation

Paths to improved coating TN performance

- Improved amorphous coatings:
  - Beginning to understand causes of dissipation
  - Further improvements to current coatings?
  - Alternative materials?

- Crystalline coatings:
  - Intrinsic loss of AlGAs shown to be very low (G. Cole)
    - Measurements of 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, also very low loss - possible alternative?

- Different solutions may be required for different operating temperatures / wavelengths / mirror substrates – studies ongoing

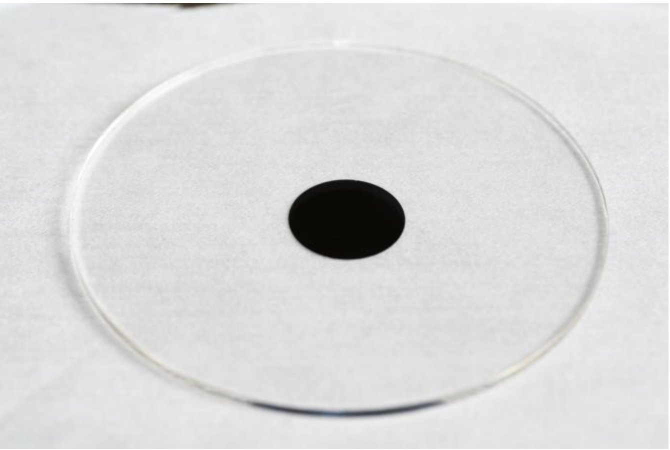
AlGaAs loss measurements

- AlGaAs micro-resonators - very low mechanical loss (2.5E-5 at room temperature, 4.5×10^{-6} at 10 K[1])

- Grown on GaAs, transferred to required mirror substrate
  - Optical cavity measurement – loss of ~4E-5 at room temperature[2]
  - Small laser beam will not probe loss of entire bonded coating with equal sensitivity
  - More measurements at frequencies closer to GWD band

- AlGaAs samples
  - 81 alternating layers of GaAs and $Al_{0.92}Ga_{0.08}As$
  - Thickness 6.83 μm, HR at 1064 nm
  - Diameter 16.4 mm

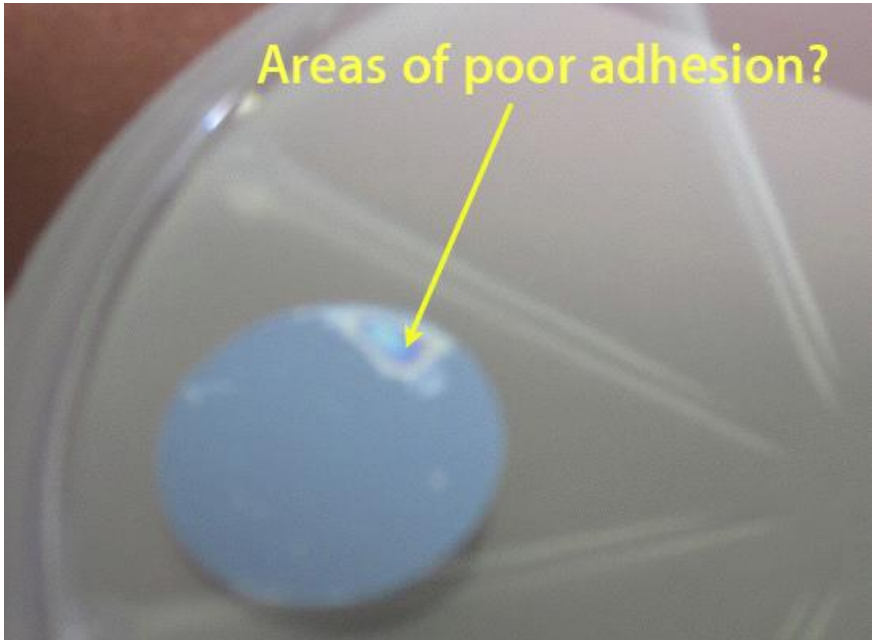
- Bonded to disk substrates by G. Cole
  - SiO_2 substrate – 1.8mm thick x 3” diameter
  - Si substrate – 465 μm thick x 1.54” diameter



[1]G. Cole, Applied Physics Letters 92 (2008) 261108, [2]G. Cole, Nature Photonics 7 (2013) 644

Adhesion of AlGaAs to silica

- Previous measurements by Steve Penn and Gregg Harry suggested coating loss of 2.1E-4
- A second sample had visible features between coating and substrate – areas of poor adhesion? Areas changed over time.
- Our sample – appears much better, although some possible defects still visible



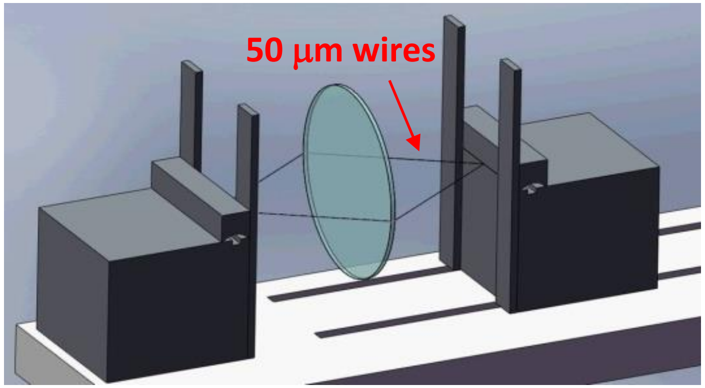
LHS: Samples measured S. Penn and G. Harry

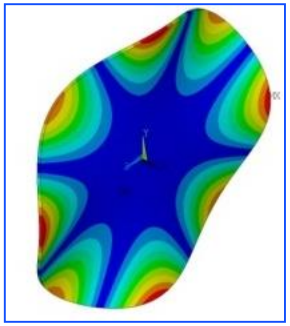
RHS: Our sample, zoomed in to show some features

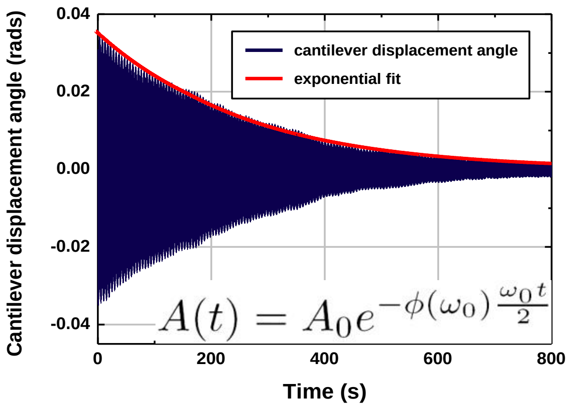
AlGaAs loss measurements

- Disks suspended in a nodal support

- Vibrational modes excited electrostatically, loss from amplitude ring-down





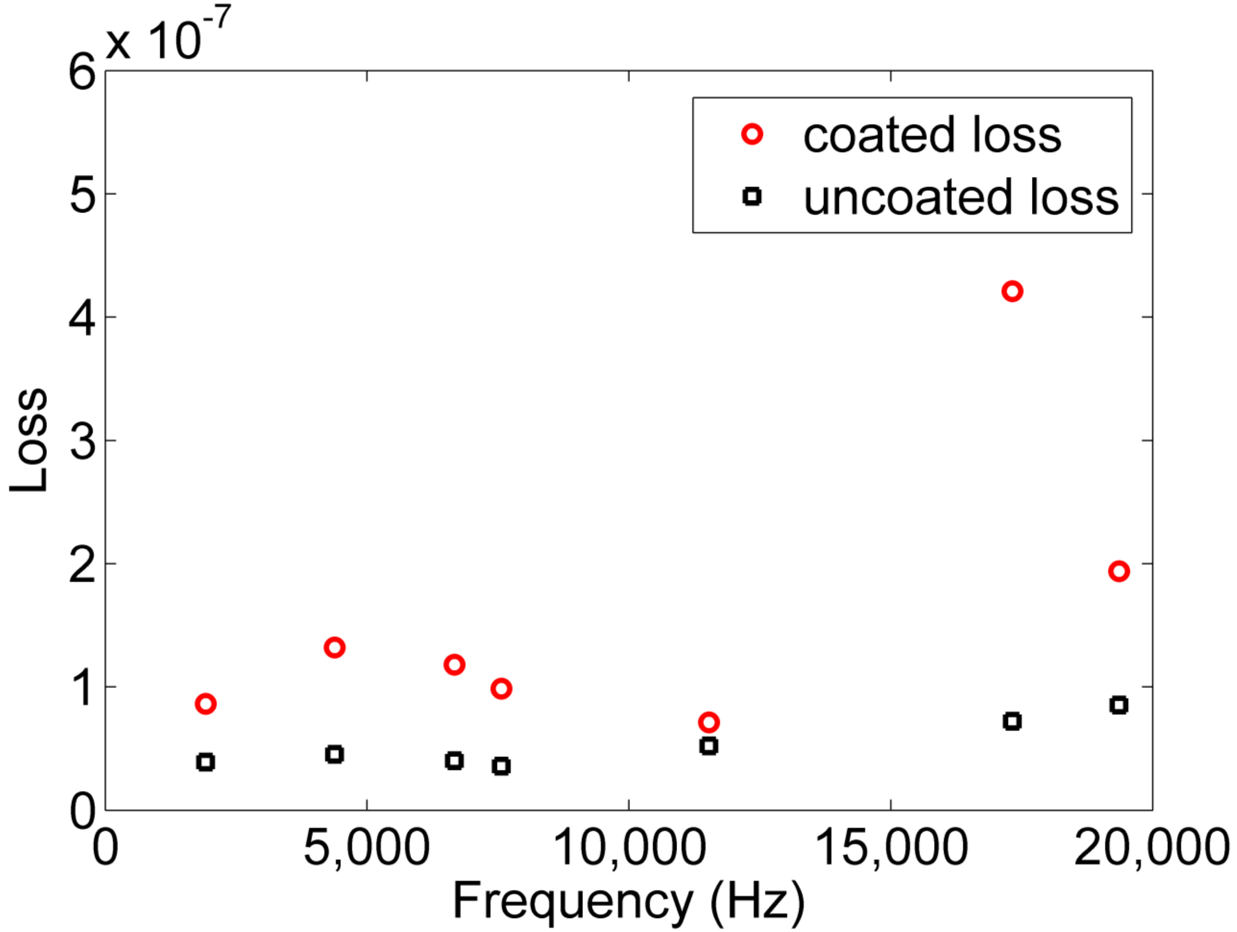


$$\phi_{\text{coating}} = \frac{E_{\text{substrate}}}{E_{\text{coating}}}(\phi_{\text{coated}} - \phi_{\text{un-coated}})$$

- Energy ratio calculated using FE modelling

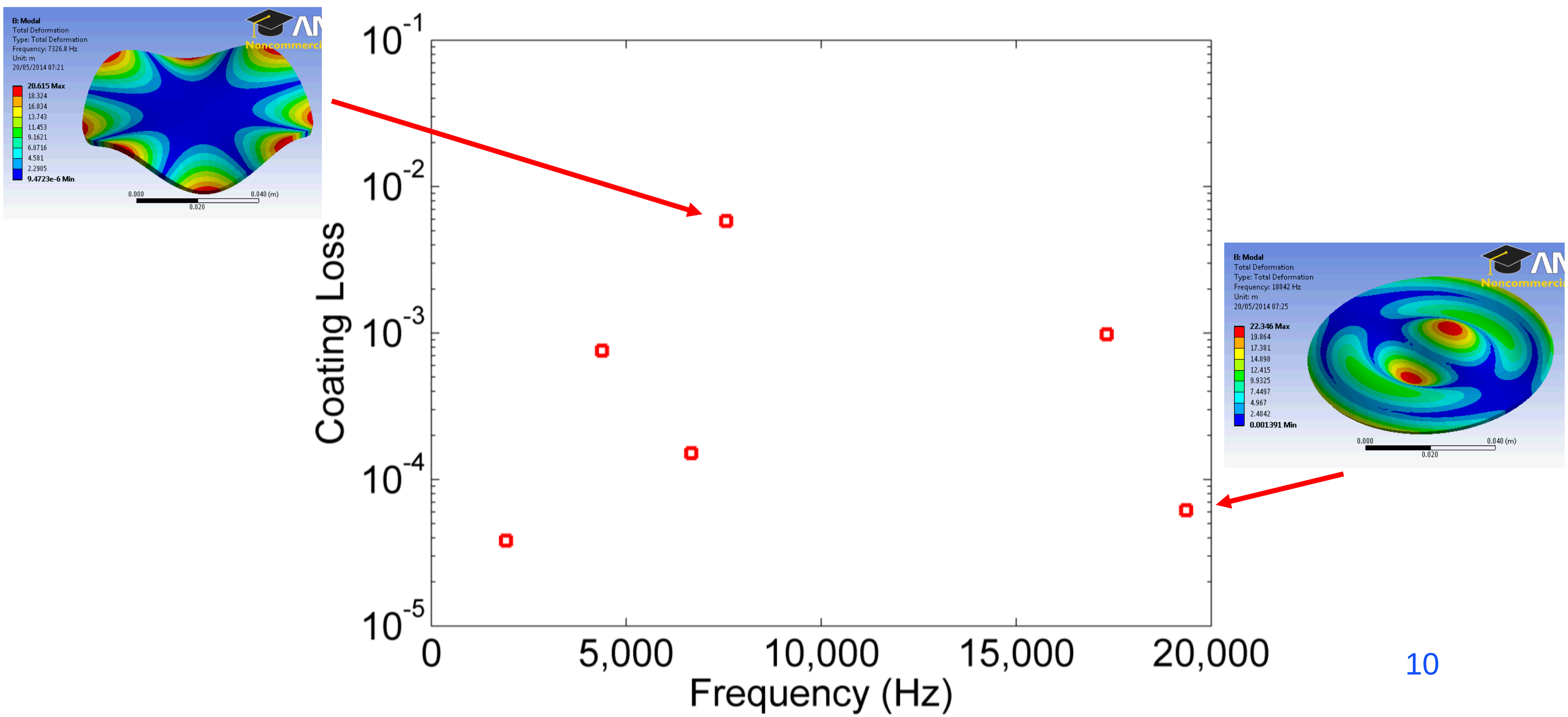
AlGaAs on SiO_2

- Room temperature loss measurements of silica disk before and after application of AlGaAs coating



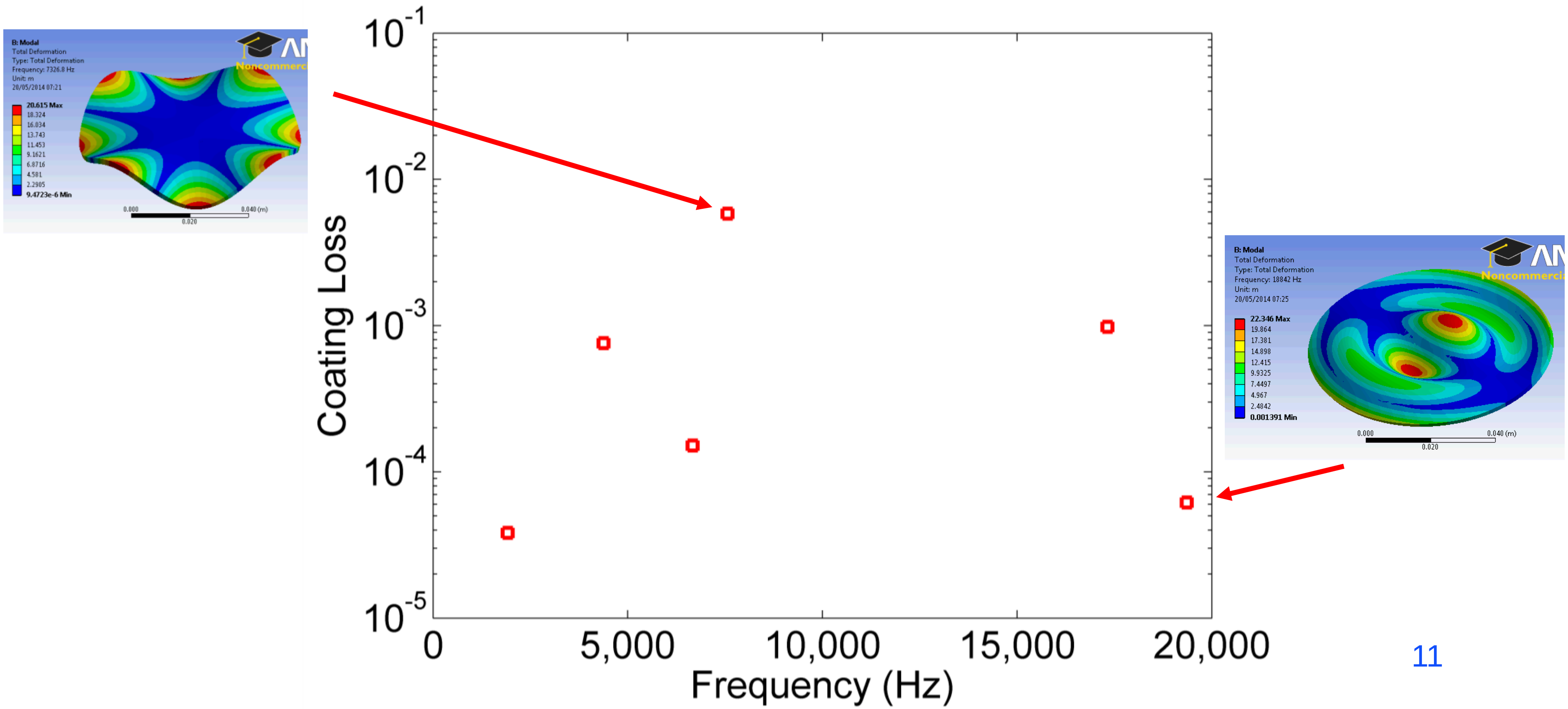
AlGaAs on SiO_2 – preliminary results

- Calculated coating loss varies significantly for different vibrational modes
- Two modes give losses 3.8E-5 and 6.1E-5 – comparable with (2.5-4)E-5 (Cole 2013)



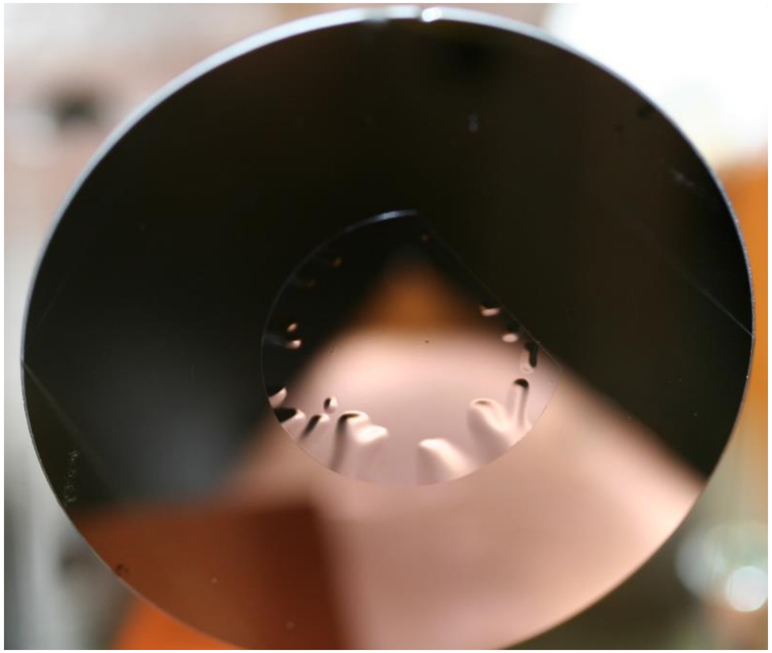
AlGaAs on SiO_2 – preliminary results

- Why is there so much variation in coating loss?
  - Possible energy loss to suspension wires – re-suspend and repeat
  - Relative energy stored in coating varies significantly with mode shape. Sensitivity to coating loss varies with mode.
  - Coating thermoelastic effects? Further modelling required.



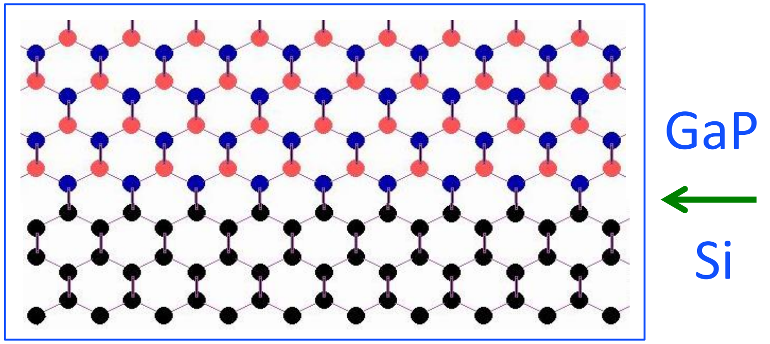
AlGaAs on Si – cryogenic loss

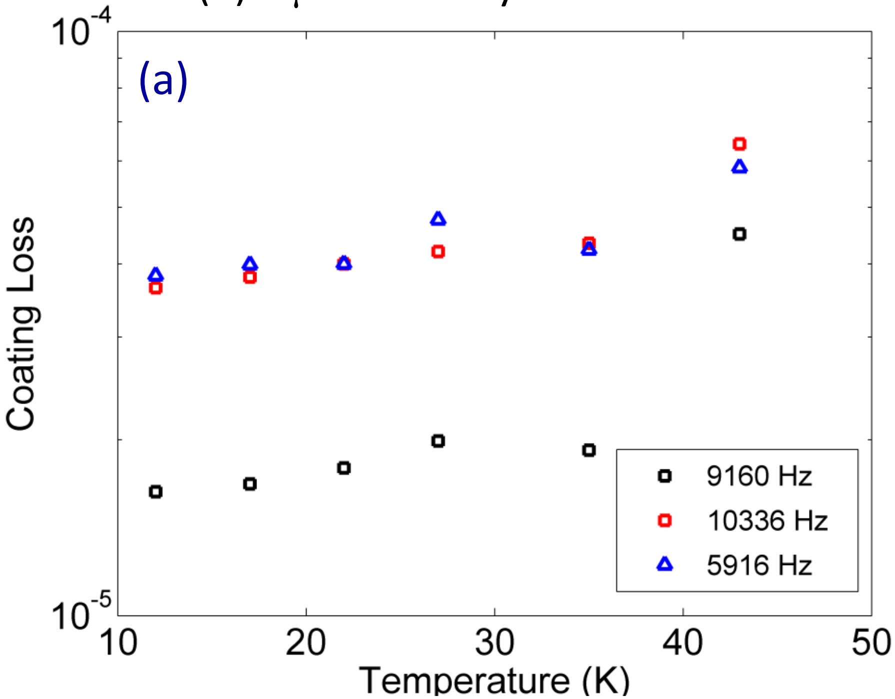
- Delamination observed around edges after 2 cooling cycles to ~14 K (period of ~48 hrs)
  - Garret Cole carried out cooling tests on smaller sample, which survived. Methods of strengthening the bond under investigation

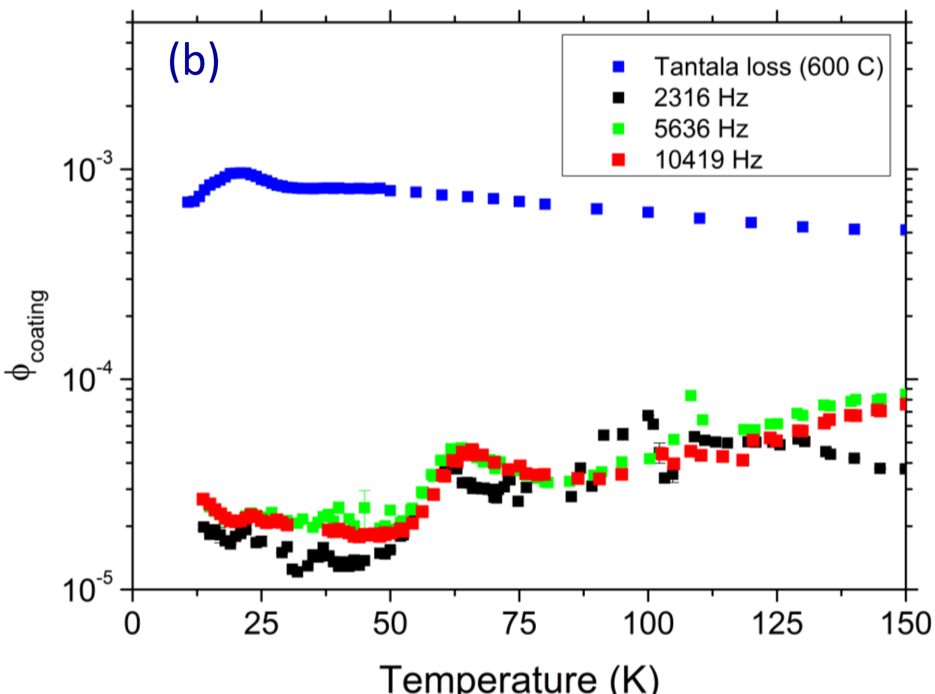


GaP/AlGaP coatings

- Alternative crystalline coating system - GaP/AlGaP
- Lattice matched to Si – grown epitaxially on Si substrates (A. Lin et al, Stanford)
- Measurements of
  - (a) 10 GaP/AlGaP bi-layer stack on Si disk[1]
  - (b) 1 μm thick layer of GaP on Si cantilever







[1]A. Cumming et al, submitted

Crystalline coatings

- AlGaAS
  - On silica, 290 K – lowest coating loss 3.6E-5
  - On silicon – coating detaching after two temperature cycles
- AlGaP
  - First coating, loss <~4E-5 below 40 K
  - Consistent with upper limit for single layer GaP

Cryogenic loss of tantala / titania coatings

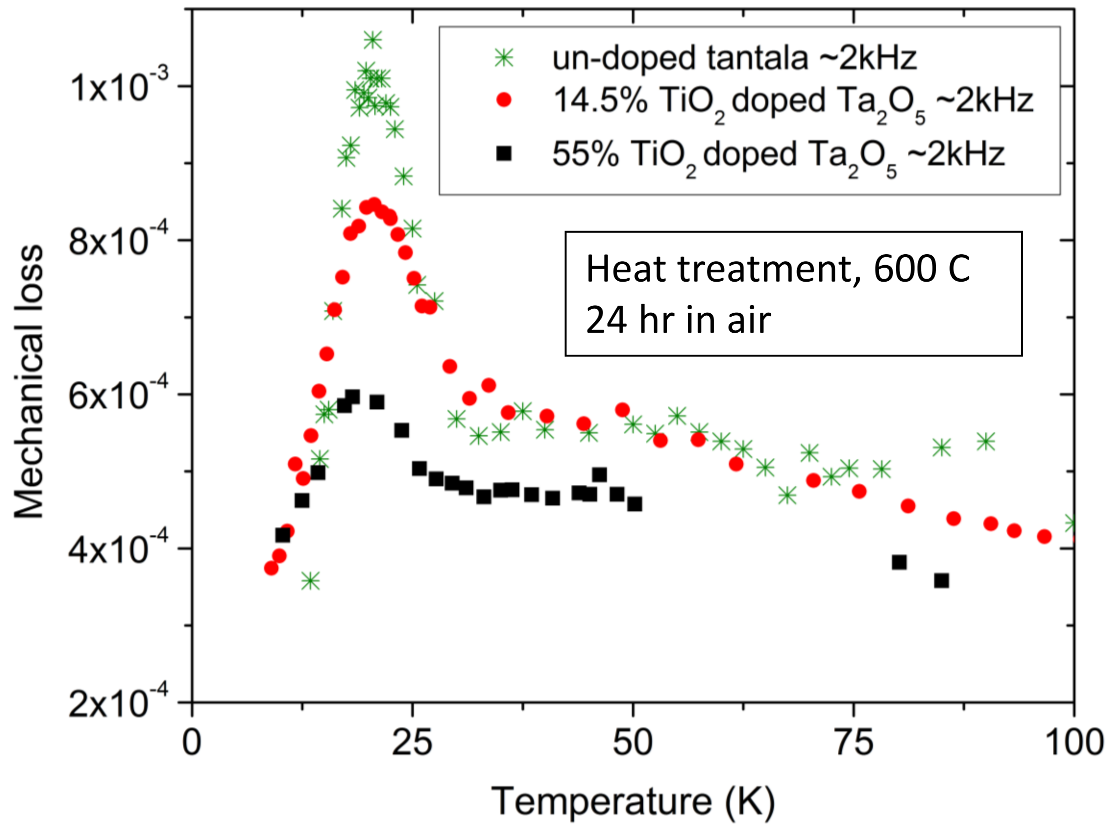
- Increased TiO_2 doping reduces the cryogenic loss, particularly with heat-treatment
  - Insight into loss mechanisms, parallel structural measurements (R. Bassiri talk)

- New studies of:

- pure TiO_2
  - Interest for nano-layer coatings (Shiuh Chao, Innocenzo Pinto)
  - Y_{TiO2} = 141 GPa (Shiuh Chao, IBS TiO_2)

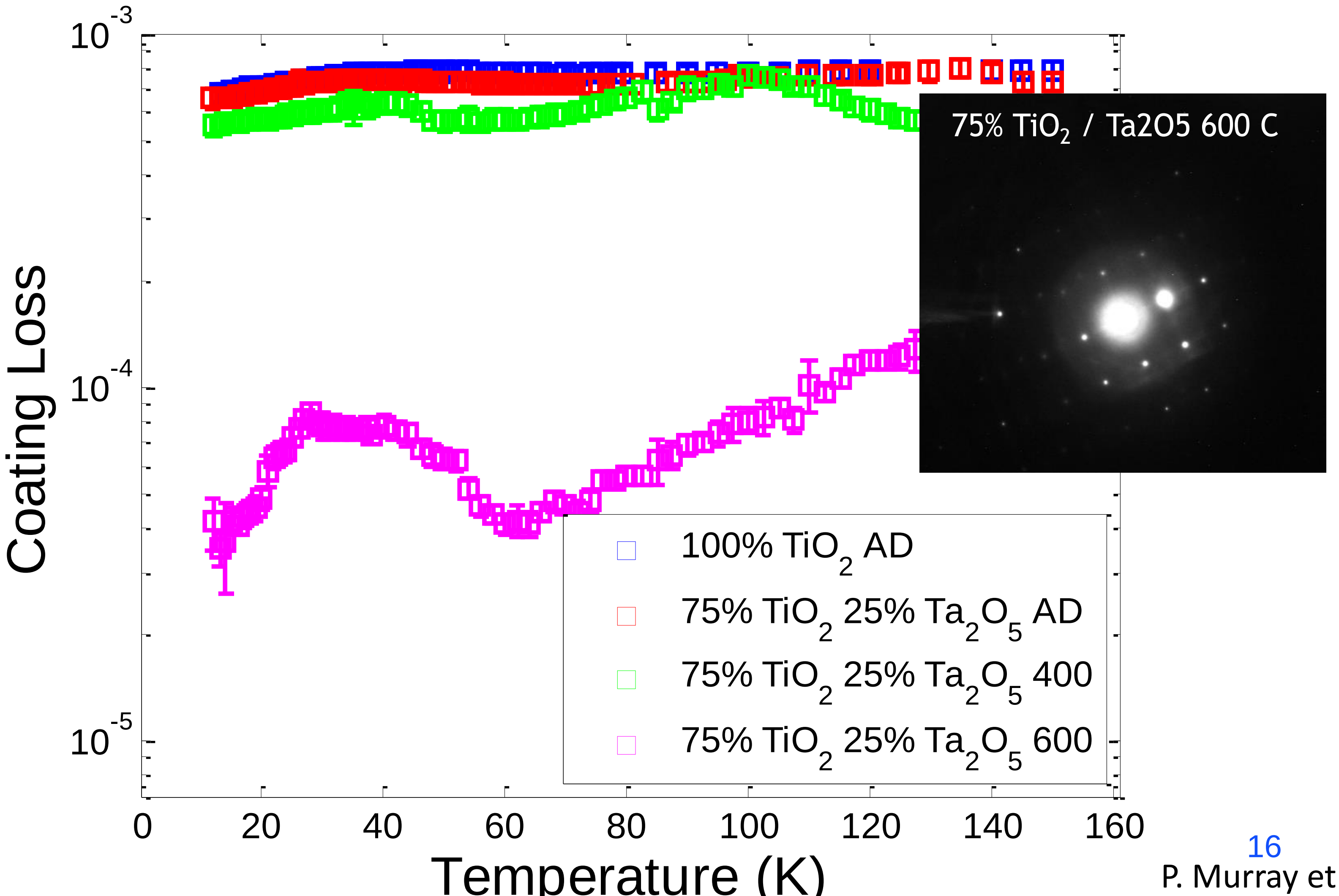
- 75% TiO_2 / 25% Ta_2O_5
  - Further improvement in loss?

- 0.5 μm thick films, ~60 μm thick Si cantilever substrates



TiO_2/Ta_2O_5 coating loss results

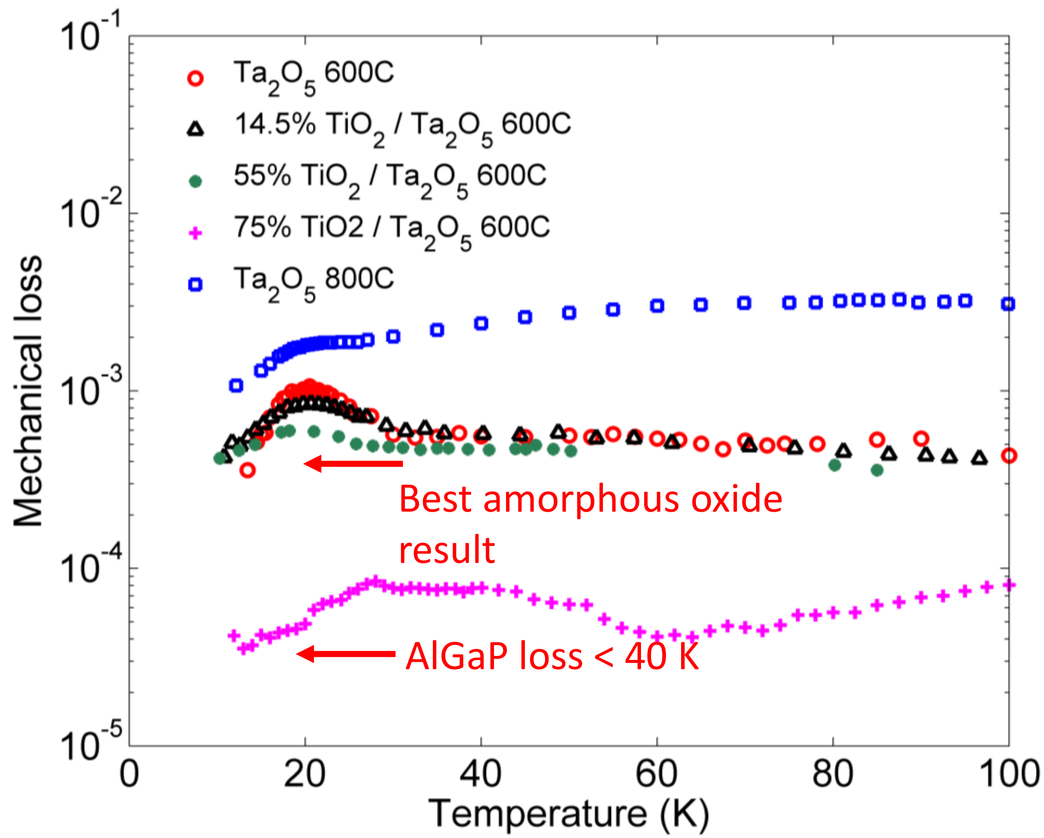
- Cryogenic loss of as-deposited TiO_2 and 75% TiO_2 / 25 % after various heat treatments



P. Murray et al

75% TiO_2/Ta_2O_5 coating

- 75% TiO_2 (600C) coating has anomalously low loss
- Crystallized pure Ta_2O_5 displayed large 90 K loss peak
- 75% coating - crystallized more fully?
- Absorption / scatter measurements of interest



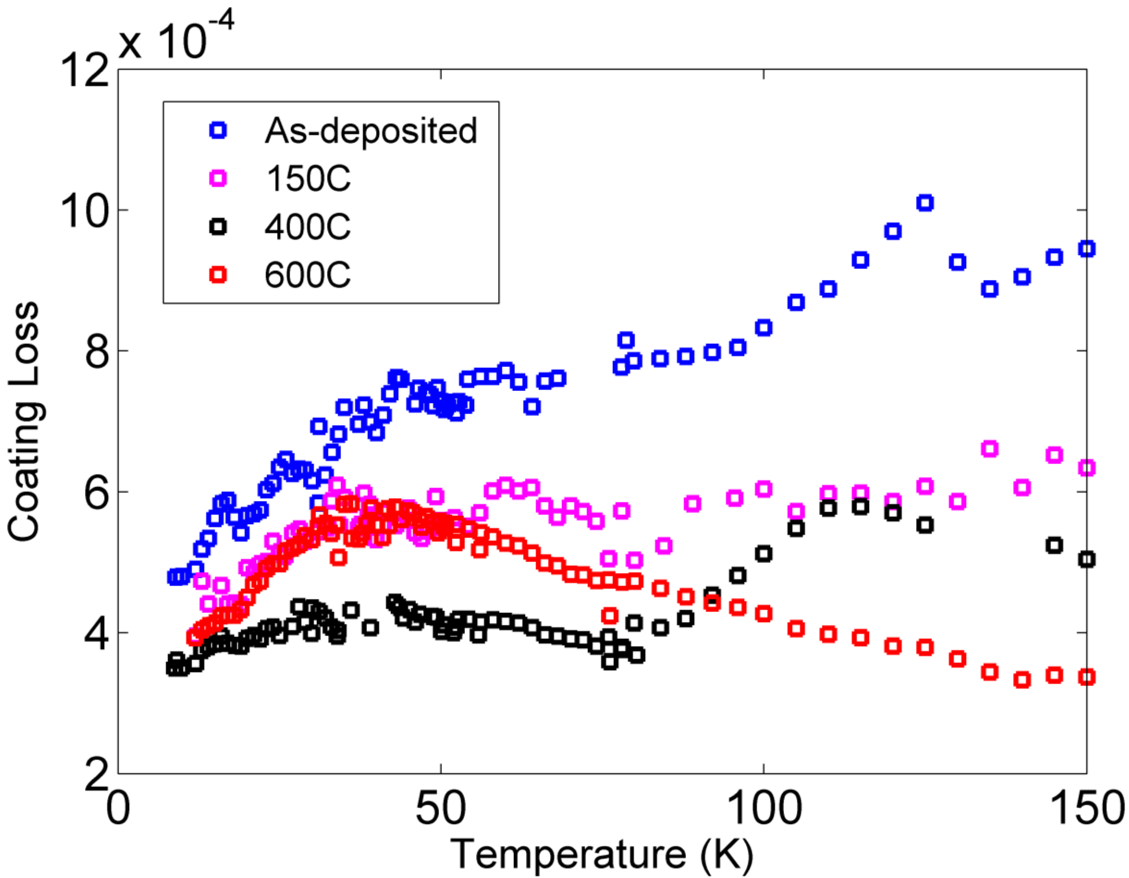
G. Cole AlGaAs free-standing loss

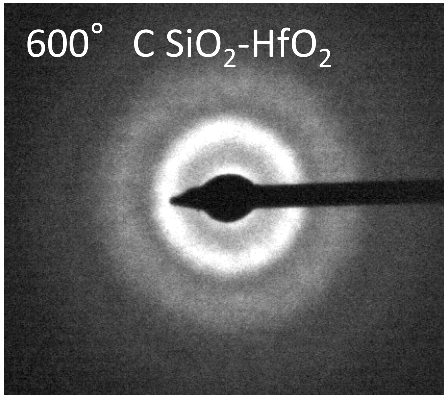
TiO_2/Ta_2O_5 coatings

- Titania doping can suppress cryogenic loss peak in tantala
- 75% TiO_2/Ta_2O_5
  - 400C heat treatment reduces cryogenic loss
  - crystallises at 600C, anomalously low cryogenic loss

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





K. Craig et al, in preparation

Alternative amorphous materials

- Silica-doped hafnia (400C) close to meeting ET-LF (10K) loss requirements

- As Innocenzo suggested, SiO_2-doped TiO_2 may be of interest (good room temperature loss, prevent crystallization)

Summary

- Crystalline coatings
  - AlGaAs on SiO_2 - loss 3.6×10^{-5} @ 290 K
  - AlGaAs on Si – partially detached during cryogenic cycling
    - work required to produce stronger bond
  - Prototype GaP/AlGaP MBE coating on Si is $<4\times 10^{-5}$ below 40 K

- Amorphous coatings
  - Anomalously low loss for crystallized 75%TiO_2/Ta_2O_5 (600C)
  - SiO_2-doped HfO_2 (400C) best amorphous oxide so far, no low T peak
  - SiO_2 doping in TiO_2 of interest

AlGaAs on SiO_2

- Coating thermoelastic loss (Fejer et al, 2004)
  - Maximum TE loss is shown in the plot
  - Calculate fraction of energy γ associated with volume change for each mode

$$\phi_{\text{coating}} = \phi_{\text{intrinsic}} + \gamma\phi_{\text{coating TE}}$$

- $\phi_{coating\ TE}$ using AlGaAs properties from Cole 2013
- Coating TE loss likely has significant contribution to coating loss
- Further FE modelling required