Mechanical loss of crystalline and amorphous coatings

I. Martin¹, K. Craig¹, P. Murray¹, R. Robie¹, S. Reid², A. Cumming¹, R. Bassiri³, M. M. Fejer³, J. Harris³, M. Hart¹, G. Harry⁴, K. Haughian¹, D. Heinert⁶, J. Hough¹, A. Lin³, I. MacLaren¹, R. Nawrodt⁶, S. Penn⁵, R. Route³, S. Rowan¹

¹SUPA, University of Glasgow
²SUPA, University of the West of Scotland
³Stanford University
⁴American University
⁵Hobart and William Smith College
⁶University 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$_2$O$_5$ 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

\[
S_x(f, T) \approx \frac{2k_BT}{\pi^2f} \frac{d}{w^2} Y \phi\left(\frac{Y'}{Y} + \frac{Y}{Y'}\right)
\]
Current coatings – silica/tantala

- Cryogenic loss peaks in tantala / silica films (single layers\textsuperscript{1,2} and aLIGO coating\textsuperscript{3}) suggest reduction in coating thermal noise by \(\sim 2x\) by cooling to 20K
  - ET-LF requires loss reduction by \(\sim 4x\) (20 K operation) or \(\sim 1.6x\) (10 K operation)
  - Peaks at higher temperature (\(\sim 30 K\)) in multilayer coatings (aLIGO & \(\text{SiO}_2/\text{Ta}_2\text{O}_5\) on sapphire measured at ICRR\textsuperscript{4}).

1\textsuperscript{Martin et al, CQG (2014)}, 2\textsuperscript{Martin et al, CQG (2010)}, 3\textsuperscript{Granta et al, Opt. Lett. 38 (2013)}, 4\textsuperscript{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 K¹)

- Grown on GaAs, transferred to required mirror substrate
  - Optical cavity measurement – loss of ~4E-5 at room temperature²
  - 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 Al₀.₉₂Ga₀.₀₈As
  - Thickness 6.83 μm, HR at 1064 nm
  - Diameter 16.4 mm

- **Bonded to disk substrates by G. Cole**
  - SiO₂ substrate – 1.8mm thick x 3” diameter
  - Si substrate – 465 μm thick x 1.54” diameter

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.
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

![Graph showing loss vs. frequency]
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)
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.
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
  - (b) 1 μm thick layer of GaP on Si cantilever

\[ \text{Coating Loss} \]

\[ \text{Temperature (K)} \]

\[ 1 \text{A. Cumming et al, submitted} \]
Crystalline coatings

- **AlGaAS**
  - On silica, 290 K – lowest coating loss $3.6 \times 10^{-5}$
  - On silicon – coating detaching after two temperature cycles

- **AlGaP**
  - First coating, loss $<4 \times 10^{-5}$ 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)
    - $Y_{\text{TiO}_2} = 141$ GPa (Shiuh Chao, IBS TiO$_2$)
  - 75% TiO$_2$ / 25% Ta$_2$O$_5$
    - Further improvement in loss?
  - 0.5 μm thick films, ~60 μm thick Si cantilever substrates

![Graph showing mechanical loss vs. temperature with data points for different dopings.](image-url)
TiO₂/Ta₂O₅ coating loss results

- Cryogenic loss of as-deposited TiO₂ and 75% TiO₂ / 25% after various heat treatments

![Graph showing coating loss results](attachment:image.png)

- 100% TiO₂ AD
- 75% TiO₂ 25% Ta₂O₅ AD
- 75% TiO₂ 25% Ta₂O₅ 400
- 75% TiO₂ 25% Ta₂O₅ 600
75% TiO$_2$/Ta$_2$O$_5$ coating

- 75% TiO$_2$ (600C) coating has anomalously low loss
- Crystallized pure Ta$_2$O$_5$ displayed large 90 K loss peak
- 75% coating - crystallized more fully?
- Absorption / scatter measurements of interest

![Graph showing mechanical loss vs temperature for different coatings and temperatures. The graph highlights the best amorphous oxide result, AlGaP loss < 40 K, and G. Cole AlGaAs free-standing loss.]}
Titania doping can suppress cryogenic loss peak in tantala

- 75% TiO$_2$/Ta$_2$O$_5$
  - 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

![Graph showing the coating loss vs temperature with different heat treatments.](image)

K. Craig et al, in preparation
Alternative amorphous materials

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

- As Innocenzo suggested, SiO₂-doped TiO₂ may be of interest (good room temperature loss, prevent crystallization)
Summary

- **Crystalline coatings**
  - AlGaAs on SiO$_2$ - loss $3.6 \times 10^{-5}$ @ 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$_2$O$_5$ (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 $\gamma$ associated with volume change for each mode

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

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