Coating Thermal Noise workshop summary
Conveners: E. Cesarini, S. Reid, G. Cagnoli
Summary of Monday’s session

● Discussion devoted to next future choice of coating recipe for A+/AdV+

● R&D activity on IBS SiNx coatings

● R&D activity on IBS TiO2:GeO2 coating

● Status of multimaterial/ternary coatings
R&D on IBS SiNx coatings (M. Granata and M. Magnozzi)

- Low mechanical loss and high refractive index
- IBS SiNx single layer loss angle a factor three better than TiO2:Ta2O5
- SiNx still amorphous after annealing in air at 1000 °C for 10 h
- extinction coefficient still too high
R&D on IBS SiNx coatings (M. Granata and M. Magnozzi)

- substantial oxygen contamination observed in single-layer samples, likely from residual water pressure
- change of the protocol and oxygen contamination considerably reduced,
- current absorption still to high likely dominated by stoichiometry

Presence of Oxygen evaluated by FTIR (Padova)
R&D on IBS SiNx coatings (M. Granata and M. Magnozzi)

- refractive index increased \( n(\lambda=1064\text{ nm})=2.05 \)
- index gradient is now negligible (Dn<1%)
- extinction decreased by 48%, still far from target:<1e-6

### Results & Roadmap

**Roadmap**

- **Short-term objective:** definitive assessment for A+ / AdV+ since April 19th:
  - Coater A
    - Single-layer tests
    - HR samples
    - Annealing tests
    - ✔ completed
    - ✔ completed
    - ~1 week
  - Coater B
    - Single-layer tests
    - HR samples
    - Annealing tests
    - still ~2 weeks (list has been extended)
    - ~2 weeks
    - ~1 week

- **Mitigation of bubble-like defects (if any):** ~4 weeks

**NB:** Works in Grand Coater starting ~July
R&D on IBS TiO2:GeO2 coatings (G. Vajente and S. Khadka)

- Single layer results
- Very promising candidate for A+ coatings
- Annealing at 600°C for 100+ hours gives the best loss angle without crystallization

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cation concentration, Ti/(Ti+Ge)</td>
<td>44%</td>
</tr>
<tr>
<td>Refractive index at 1064 nm</td>
<td>1.88</td>
</tr>
<tr>
<td>Density</td>
<td>3700 kg/m³</td>
</tr>
<tr>
<td>Young’s modulus</td>
<td>90.3 ± 1.3 GPa</td>
</tr>
<tr>
<td>Poisson ratio</td>
<td>0.24 ± 0.05</td>
</tr>
<tr>
<td>Loss angle</td>
<td>(0.96 ± 0.18) × 10⁻⁴</td>
</tr>
<tr>
<td>Optical absorption for a QWL</td>
<td>2.3 ± 0.1 ppm</td>
</tr>
</tbody>
</table>

TABLE I. Measured parameters for the best TiO₂:GeO₂ mixture, after annealing at 600°C for 108 hours.
R&D on IBS TiO2:GeO2 coatings (G. Vajente and S. Khadka)

- Multi-layer stacks of 10 and 40 layers total measured
- No evidence of excess loss in the stack
- Optical absorption of a 40 layer stack 3.4 ppm, still too high, but still room for improvements
R&D on IBS TiO2:GeO2 coatings (G. Vajente and S. Khadka)

- Main issue delamination/bubbles when annealing at 500°C and below
- It seems dependent on the stresses in the deposited film because bubbles reduce with deposition of lower stress silica
- The phenomenon is well known in IBS technique. Seen in ZrO2/SiO2, Nb2O5/SiO2, Ta2O5/SiO2
- According to LMA experience it is linked to Argon clustering
- Carmen suggested also a possible link with Oxygen flux used during growth
Temperature dependent loss measurements of GeO\textsubscript{2} and Ti-GeO\textsubscript{2} using DPOs.

- For all IBS films studied in this work, cryogenic loss is found to be higher than RT loss.
- Unlike the RT loss, cryogenic loss of thin film GeO\textsubscript{2} is lower than that of bulk GeO\textsubscript{2} (from literature).
- RT loss is seen to increase with Ti concentration
- Temperature dependent measurements are needed to study the energy landscape
Multimaterial option (I. Martin, V. Pierro and I. Pinto)

Multimaterial coatings

- Use of more than two materials in coating stack
- Allows trade-off between thermal noise and absorption
- Possible motivations:
  - Reduce coating thermal noise
  - Reduce coating absorption
  - **Reduce coating thickness** - directly reducing thermal noise, possible mitigation of possible defects during deposition, stress / annealing effects

![Thick coating with low index contrast](image1.png)  ![MM design to achieve same reflectivity with fewer layers](image2.png)
Multimaterial option (I. Martin, V. Pierro and I. Pinto)

**Multimaterial coatings**

- Experimental demonstration of $\text{Ta}_2\text{O}_5/\text{SiO}_2/\text{a-Si/SiO}_2$ design
- Multimaterial loss and absorption behave as expected with annealing

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**Graphs:**

- Mechanical loss versus heat treatment temperature [°C]
- Absorption versus heat treatment temperature [°C]

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Tait et al., PRL 125 011102 (2020)
Multimaterial option (I. Martin, V. Pierro and I. Pinto)

aSi @ 20 K
cSi substrate

Pareto manifold

From LIGO-G2101040

See also Pierro et al., https://arxiv.org/abs/2012.02146 DCC: P2000519
Steinlechner and Martin, Phys. Rev. D 103 (2021)
Multimaterial option (I. Martin, V. Pierro and I. Pinto)

Room temperature – possible application to candidate coatings for A+, V+, ET-HF, CE to reduce optical absorption / reduce coating thickness

- viable solution for HR stack:
  - Ta2O5/SiO2 + TiO2:GeO2/SiO2
  - TiO2:Ta2O5/SiO2 + SiNx/SiO2
Discussion questions - Monday

Recipe choice - planned for July 2021:

➢ Boundary condition: two Coating Pathfinders are not possible.
➢ Is there a clear winner between SiNx and TiO2:GeO2?
➢ Do we need MM coating for both?
   ○ Complexity risk ↑ Coating performance risk ↓ ??
   ○ Any issue with annealing strategy (GeO2/Ta2O5 similar, however SiNx annealed ~900C first, then overcoat TaO2?)

How can (should) progress be supported during Pathfinder

➢ Bubbles, defects and annealing remain a challenge.
   ○ Reducing adsorbed/implanted Ar during coating e.g. ‘low-stress silica’ from CSU?
   ○ Removing trapped Ar through annealing / minimising Ar aggregation through ramp time/steps
     ■ In 1 atm of O2, that O2 can diffuse ~3 um in 10 hours at 500 C (Fejer calculation from Williams 1965 Journal of the American Ceramic Society).
➢ Composition optimisation for TiO2:GeO2 - important?
Summary of Wednesday’s session

● Continued discussion devoted to next future choice of coating recipe for A+/AdV+

● Talk: Metrology open issues in GeNS measurements [Francesco Piergiovanni].

● Poster talks:
  ○ Properties of amorphous SiC films [Diana Lumaca]
  ○ Optical and mechanical characterization of ion-beam-sputtered MgF2 and AlF3 thin films [Matteo Bischi]
  ○ Performance of Optimized Ternary Coatings at Ambient and Cryo Temperatures [Innocenzo Pinto]
  ○ Substrate Transferred Crystalline AlGaAs Coatings Status [Gregg Harry]
  ○ Ultralow Absorption Conductive Al:ZnO Films for Charge Dissipation in LIGO Vacuum Mirrors [Aykutlu Dana].
Discussion summary

CSU 54-layer TiO2:GeO2

CEC/Strath/Glas 52-layer TiO2:GeO2

600°C anneals

- Both TiO2:GeO2 and SiNx look promising from TN perspective.
- Absorption too high for both
  - TiO2:GeO2 ~2ppm (optimistic to reduce to 1ppm)
  - SiNx requires multimaterial (Ta2O5) design
- Biggest challenge is bubble/delamination/defects upon annealing.
- Need to identify the cause and the fixes
  - Trapped argon
    - Long anneal at lower temp in Argon-free atmosphere? Diffusion.
    - Changes to dep parameters e.g. CSU low-stress.
  - Stress
    - Is this coating vs substrate stress?
    - Is this total elastic energy from multilayers?

Need to plan systematic investigations to test hypotheses for bubble origin and mitigation
If this is achieved, the path to A+/AdV+ coating solution may be almost complete
Metrological open issues in GeNS measurements (Francesco Piergiovanni)

Temperature, curvature, edge effects, thermoelastic shift.
Properties of SiC films (Diana Lumaca)

- High coordination number - expected to have lower TLS density

- Extinction coefficient of samples SiC/SiO2 PD1 and PD2

- MD simulations underway to help investigate higher-than-expected mechanical losses

- Further studies underway to identify source of optical absorption

- Coating loss angle summary plot

- Rate $10^4$ K/ns

- Rate $10^5$ K/ns

- CF: 50-80%

- CF < 5%
Optical and mechanical characterization of ion-beam-sputtered MgF2 and AlF3 thin films
(Matteo Bischi)

Absorption higher than tolerable.

Mechanical loss $2 \times 10^{-4}$

Index both lower than SiO2
Performance of Optimized Ternary Coatings at Ambient and Cryo Temperatures (Innocenzo Pinto)

Noise PSD reduction factor w.r.t. reference (aLIGO-like) design

<table>
<thead>
<tr>
<th>Optimized</th>
<th>20K (on cSi)</th>
<th>120K (on cSi)</th>
<th>290K (on Silica)</th>
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</thead>
<tbody>
<tr>
<td>aSi</td>
<td>Ti::Ta2O5</td>
<td>SiO2</td>
<td>(H’HL)²(H’L)⁵</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.084</td>
</tr>
<tr>
<td>SiNₓ</td>
<td>Ti::Ta2O5</td>
<td>SiO2</td>
<td>(H’HL)²(H’L)⁹</td>
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<tr>
<td></td>
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<td>0.14</td>
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Noise PSD reduction factor w.r.t. sequence-optimized QWL ternary-design [Pierro and Pinto, LIGO-P200051]

<table>
<thead>
<tr>
<th>H'</th>
<th>20K (on cSi)</th>
<th>120K (on cSi)</th>
<th>290K (on Silica)</th>
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<tbody>
<tr>
<td>aSi</td>
<td>(HL)⁴(H’L)⁶</td>
<td>(HL)⁴(H’L)⁶</td>
<td>(HL)⁴(H’L)⁴H’</td>
</tr>
<tr>
<td></td>
<td>0.78</td>
<td>0.77</td>
<td></td>
</tr>
<tr>
<td>SiNₓ</td>
<td>(HL)⁶(H’L)⁶</td>
<td>(HL)⁶(H’L)⁶</td>
<td>(HL)⁶(H’L)⁵H’</td>
</tr>
<tr>
<td></td>
<td>0.82</td>
<td>0.85</td>
<td>0.87</td>
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Substrate Transferred Crystalline AlGaAs Coatings Status (Gregg Harry)

\[ \varphi_{11} = \varphi_{12} \leq 8 \times 10^{-5} \]
\[ \varphi_{44} < 1 \times 10^{-7} \]

- Phase 1: 10 and 20 cm diameter
- Phase 2: 30 cm diameter/20 cm thick
  - By 2025, US$20 M

GWADW Online 2021
Ultralow Absorption Conductive Coatings for Charge Dissipation in LIGO mirrors (Aykutlu Dana)

- Sub-ppm absorption demonstrated with ALD AZO films on HR mirrors
  - 15nm thick, 580 GΩm/sq and 0.3 ppm absorption at 1064 nm
  - Total absorption including HR mirror is 0.95 ppm
- Sub-ppm absorption demonstrated with Magnetron AZO films on HR mirrors
  - 12nm thick, 6.3 TΩm/sq and 0.2 ppm absorption at 1064 nm
  - Total absorption including HR mirror is 0.8 ppm
- 12nm thick, 300 TΩm/sq and <0.05 ppm absorption at 1064 nm
  - Total absorption including HR mirror is 0.55 ppm
Highlights from discussion

Recipe choice ~ July 2021:
➢ SiNx or TiO2:GeO2.
➢ MM design can be used for reaching A+/AdV+ goal

Challenges
➢ Bubbles, defects and annealing remain a challenge.
  ○ Reducing stress.
  ○ Reducing adsorbed/implanted Ar during coating e.g. ‘low-stress silica’ from CSU?
  ○ Removing trapped Ar through annealing / minimising Ar aggregation through ramp time/steps
    ■ In 1 atm of O2, that O2 can diffuse ~3 um in 10 hours at 500 C (Fejer calculation from Williams 1965 Journal of the American Ceramic Society).