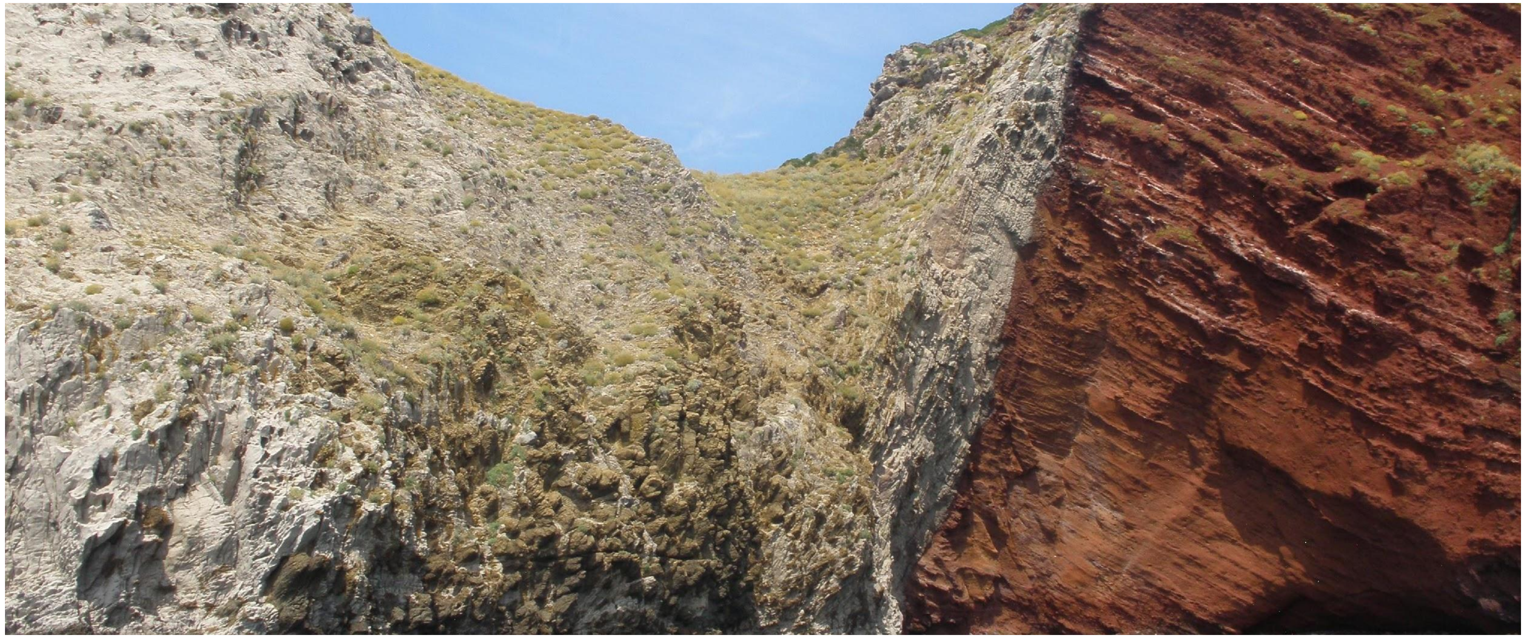

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Coating Thermal Noise workshop summary

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 activitiy on IBS SiNx coatings
    - R&D activity on IBS TiO2:GeO2 coating
    - Status of multimaterial/ternary coatings

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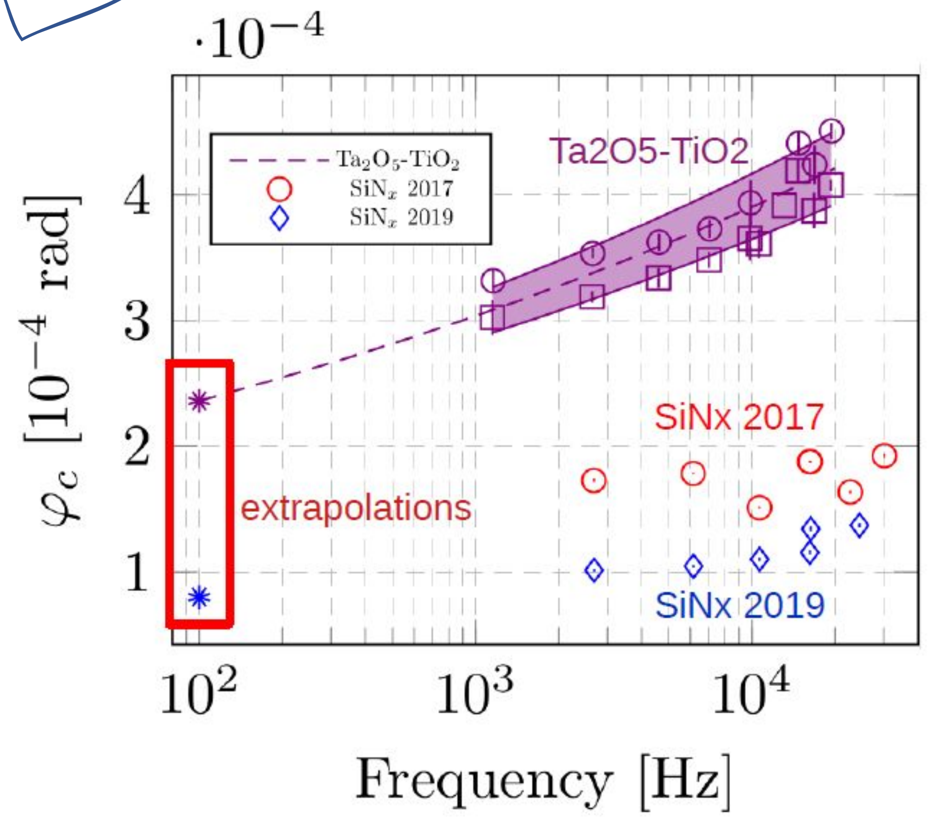
R&D on IBS SiNx coatings (M. Granata and M. Magnozzi)

- 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 to high

SINGLE LAYER



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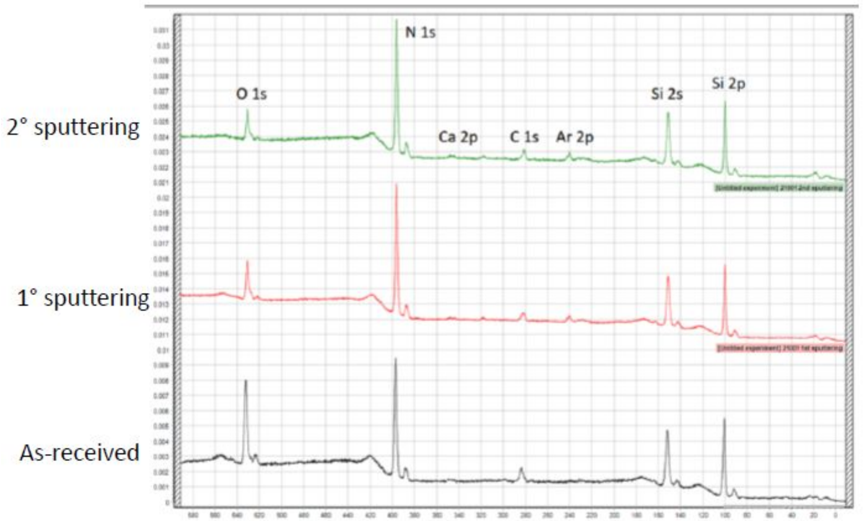
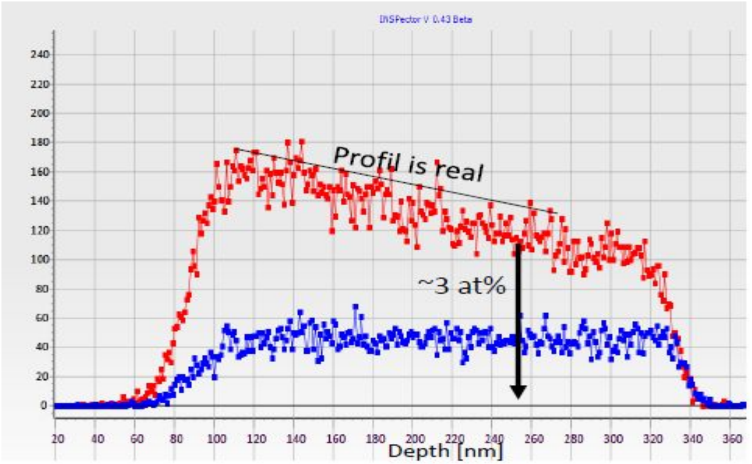
R&D on IBS SiNx coatings (M. Granata and M. Magnozzi)

- ➢ 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

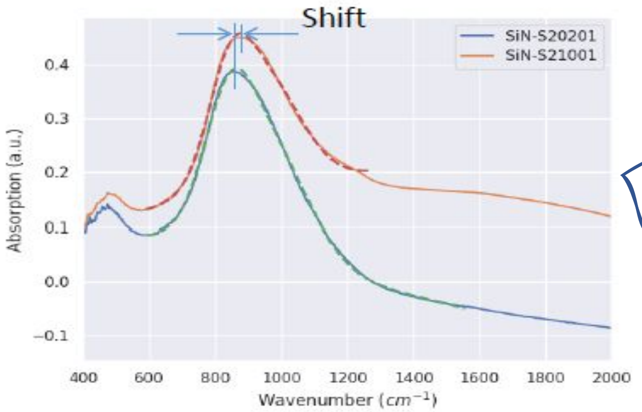
XPS data before and after sputtering (**Roma1**)



H content and vertical gradient measured with ERDA (**SAFIR/Navier**)



Presence of Oxygen evaluated by FTIR (**Padova**)



CONTAMINATION ISSUE

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R&D on IBS SiNx coatings (M. Granata and M. Magnozzi)

- refractive index increased n(@1064 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~~	✓completed
~~HR samples~~	✓completed
annealing tests	~1 week
• coater B	
single-layer tests	still ~2 weeks (list has been extended)
HR samples	~2 weeks
annealing tests	~1 week

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

NB: works in Grand Coater starting ~July

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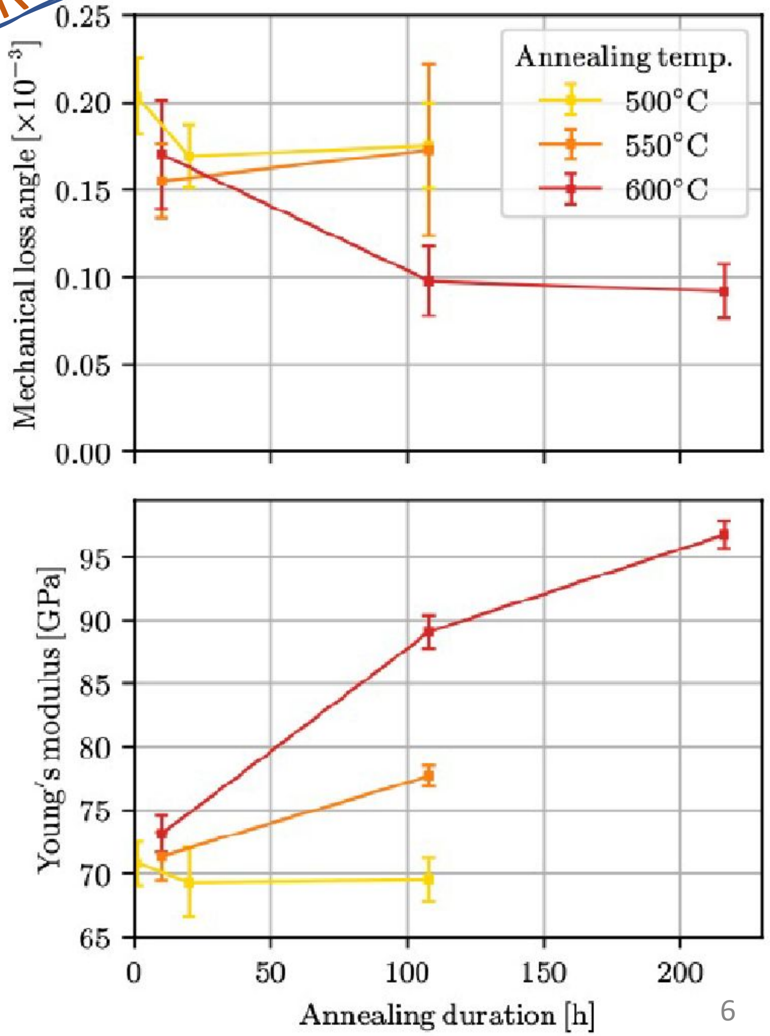
R&D on IBS TiO2:GeO2 coatings (G. Vajente and S. Khadka)

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

SINGLE LAYER



Parameter	Value
Cation concentration, Ti/(Ti+Ge)	44%
Refractive index at 1064 nm	1.88
Density	3700 kg/m^3
Young's modulus	90.3 ± 1.3 GPa
Poisson ratio	0.24 ± 0.05
Loss angle	$(0.96 \pm 0.18) \times 10^{-4}$
Optical absorption for a QWL	2.3 ± 0.1 ppm

TABLE I. Measured parameters for the best TiO_2:GeO_2 mixture, after annealing at 600°C for 108 hours.

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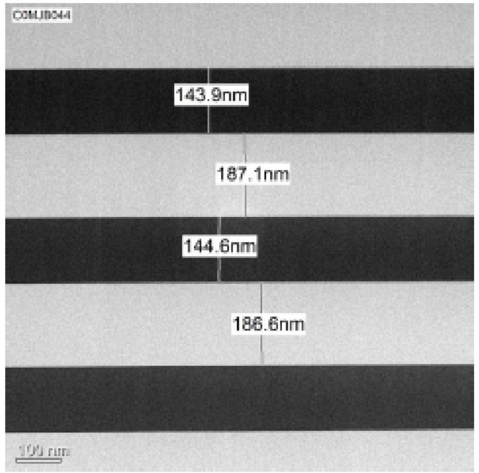
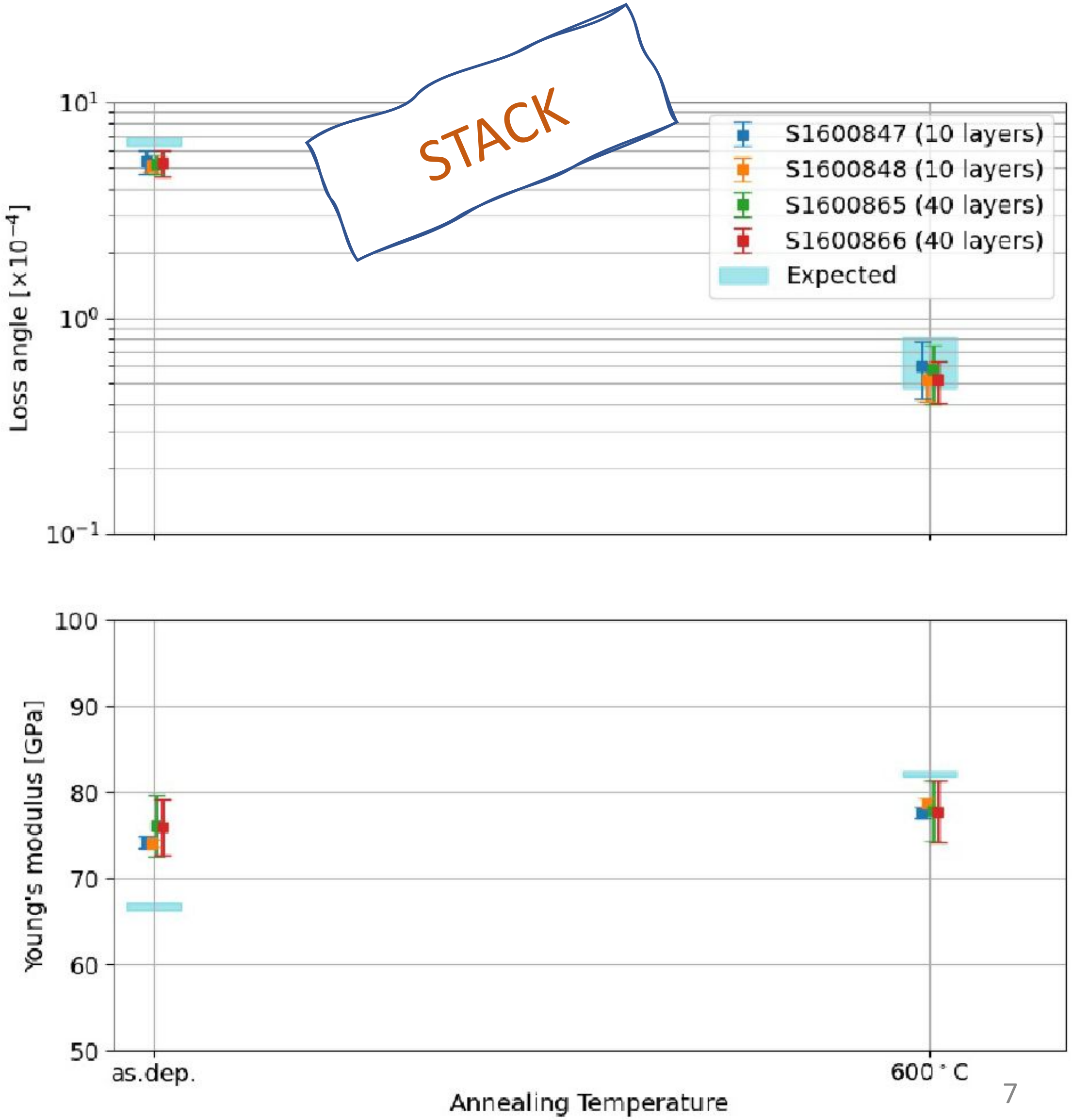
R&D on IBS TiO2:GeO2 coatings (G. Vajente and S. Khadka)

- 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 to high, but still room for improvements

TEM image of SiO_2 / $Ti:GeO_2$ stack

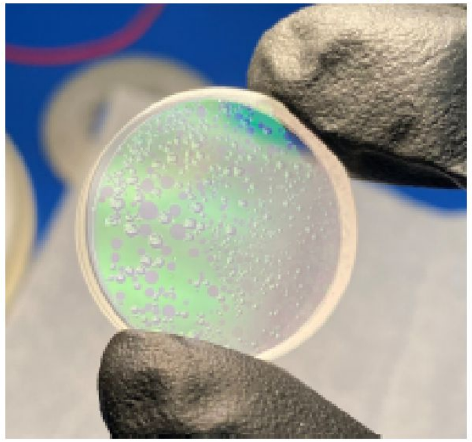




R&D on IBS TiO2:GeO2 coatings (G. Vajente and S. Khadka)

- 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

Normal stress SiO2 layers



Low-stress SiO2 layers

DELAMINATION ISSUE

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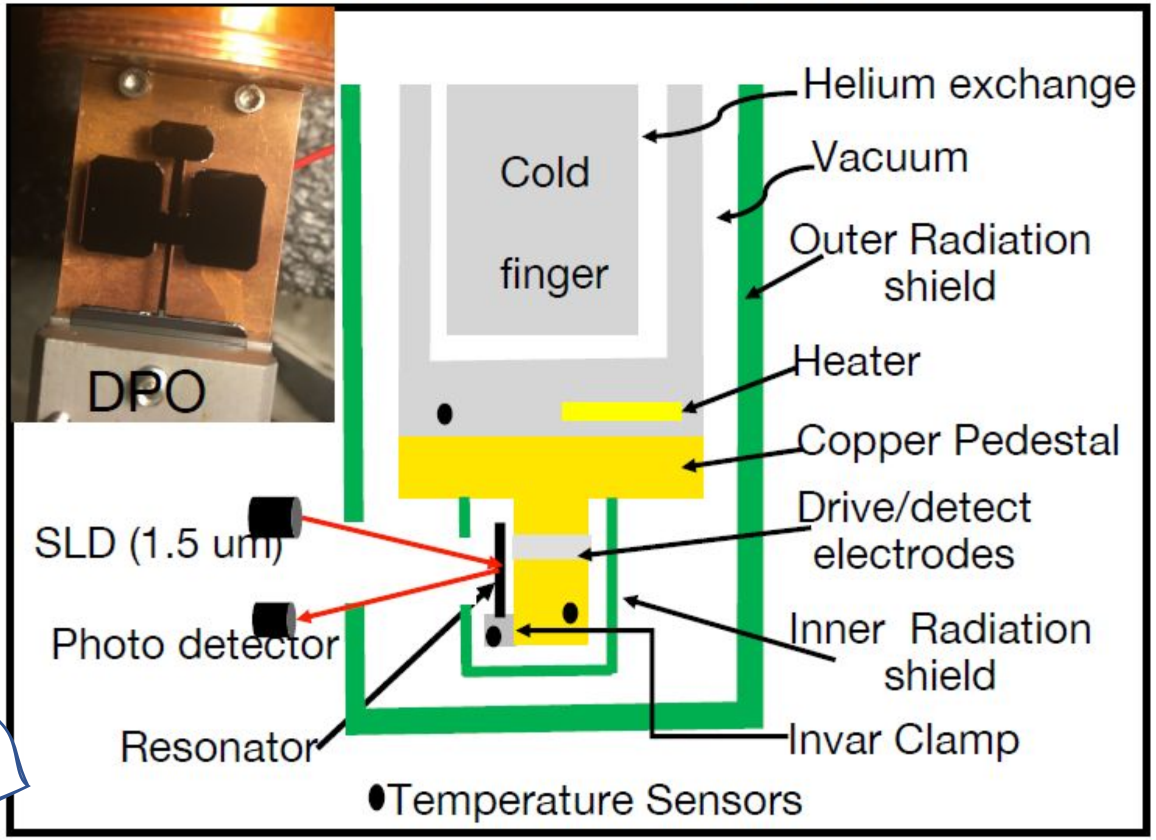
R&D on IBS $TiO_2:GeO_2$ coatings (G. Vajente and S. Khadka)

Temperature dependent loss measurements of GeO_2 and Ti-GeO_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_2 is lower than that of bulk GeO_2 (from literature).
- ➢ RT loss is seen to increase with Ti concentration
- ➢ Temperature dependent measurements are needed to study the energy landscape

Schematic of flow cryostat



MEASUREMENTS AT LOW T

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Multimaterial option (I.Martin, V. Pierro and I. Pinto)

IDEA

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

MM design to achieve same reflectivity with fewer layers

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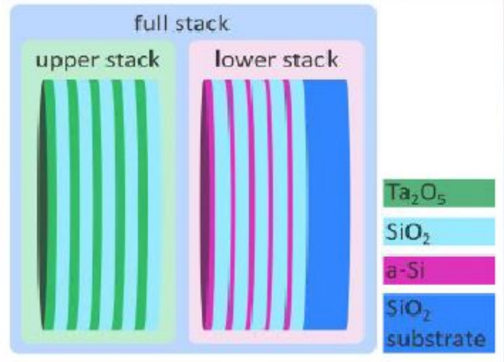
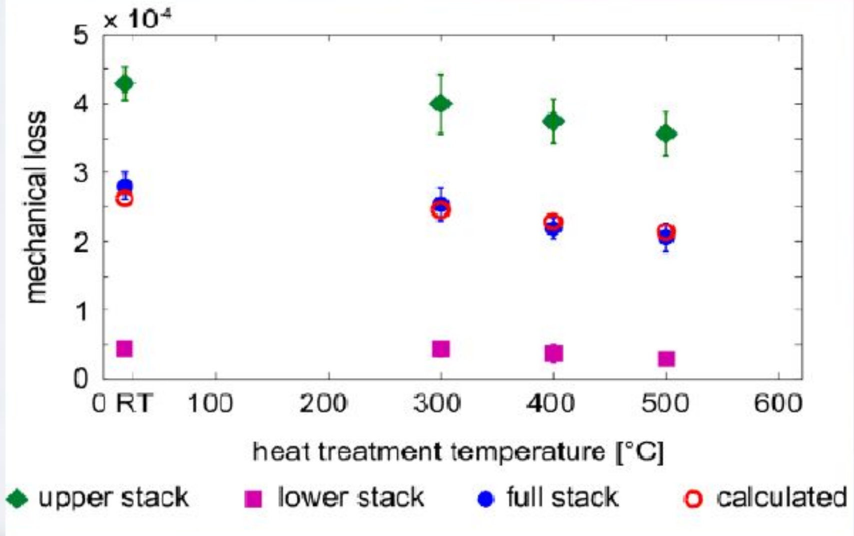
Multimaterial option (I.Martin, V. Pierro and I. Pinto)

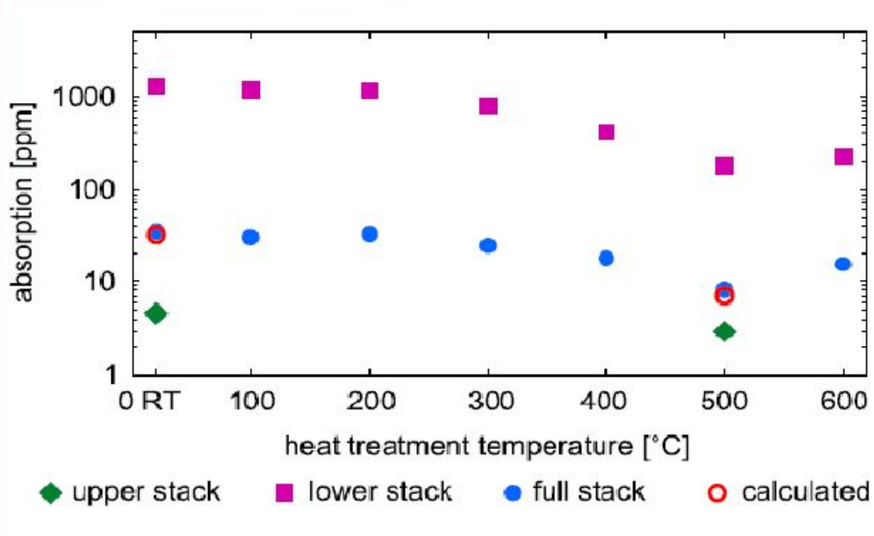
EXPERIMENTAL DEMONSRATION

Multimaterial coatings

- Experimental demonstration of Ta_2O_5/SiO_2/a-Si/SiO_2 design
- Multimaterial loss and absorption behave as expected with annealing







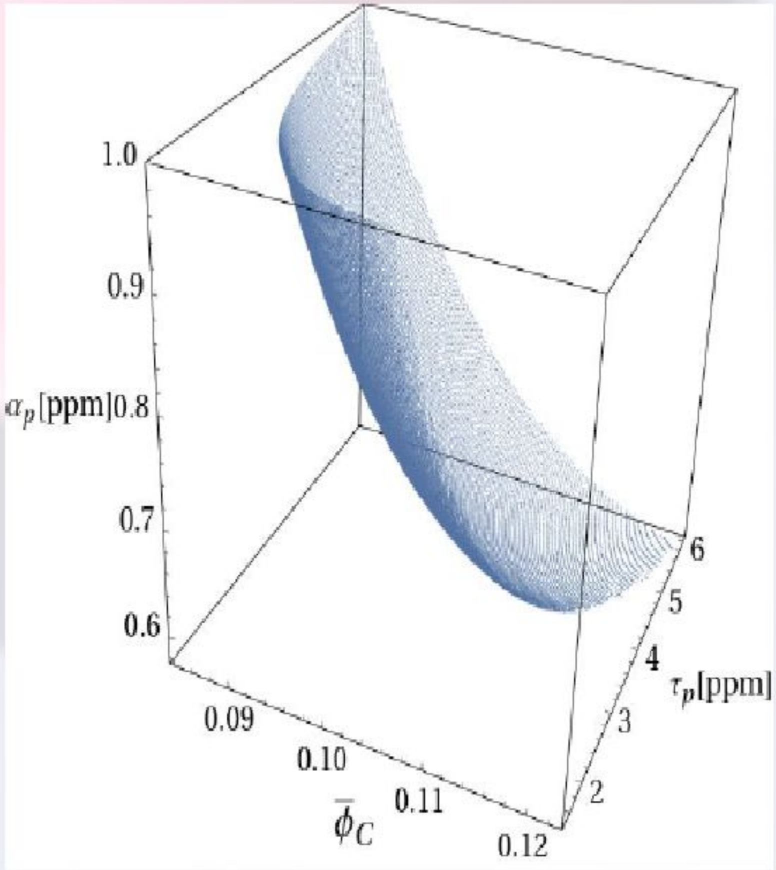
Tait et al., PRL 125 011102 (2020)

Multimaterial option (I.Martin, V. Pierro and I. Pinto)

OPTIMIZATION CODE

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)

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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:

- Ta_2O_5/SiO_2 + $TiO_2:GeO_2/SiO_2$
- $TiO_2:Ta_2O_5/SiO_2$ + SiN_x/SiO_2

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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 TiO_2:GeO_2?
- ➢ Do we need MM coating for both?
  - ○ Complexity risk ↑ Coating performance risk ↓ ??
  - ○ Any issue with annealing strategy (GeO_2/Ta_2O_5 similar, however SiNx annealed ~900C first, then overcoat TaO_2?)

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 O_2, that O_2 can diffuse ~3 um in 10 hours at 500 C (Fejer calculation from Williams 1965 Journal of the American Ceramic Society).
- ➢ Composition optimisation for TiO_2:GeO_2 - important?

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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].

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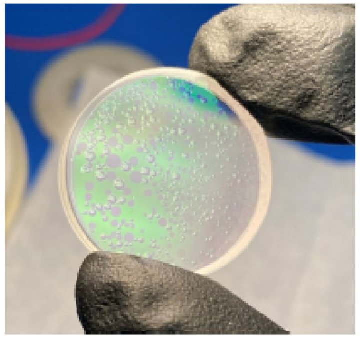
Discussion summary

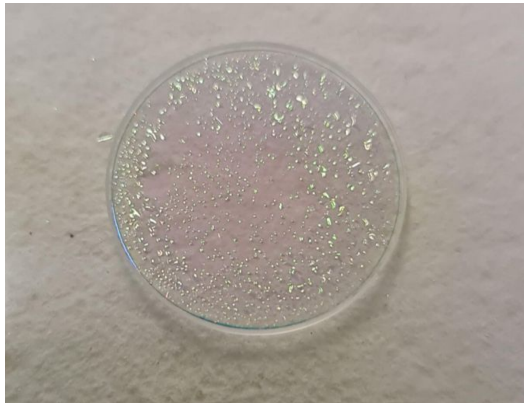
CSU 54-layer $TiO_2:GeO_2$

Normal stress SiO_2 layers



Low-stress SiO_2 layers

CEC/Strath/Glas 52-layer $TiO_2:GeO_2$



600C anneals

- Both $TiO_2:GeO_2$ and SiNx look promising from TN perspective.
- Absorption too high for both
  - $TiO_2:GeO_2$ ~2ppm (optimistic to reduce to 1ppm)
  - SiNx requires multimaterial (Ta_2O_5) 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?

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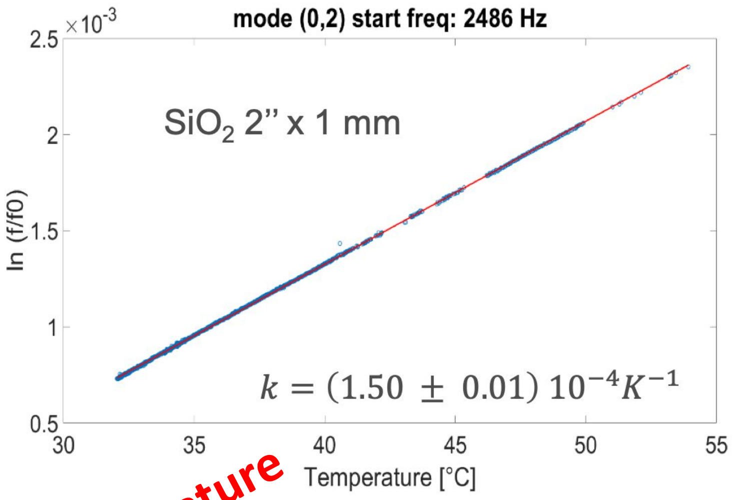
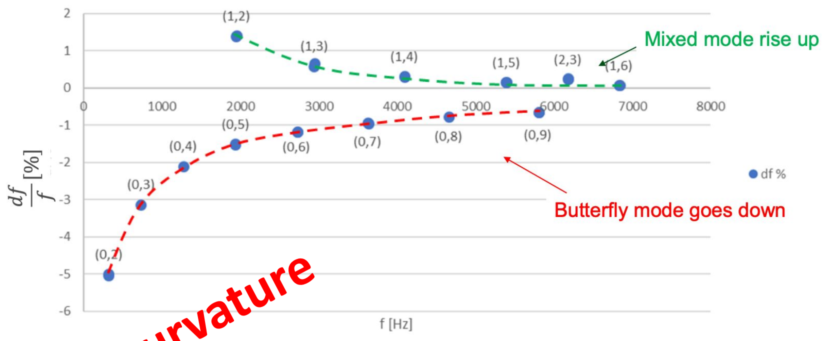
Need to plan systematic investigations to test hypotheses for bubble origin and mitigation

If this is achieved, the path to A+/AdV+ coating solution may be almost complete

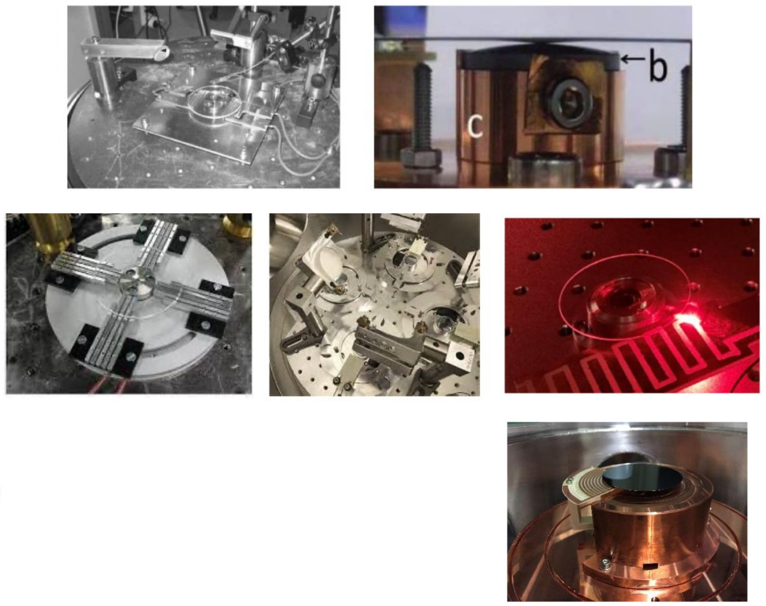
Metrological open issues in GeNS measurements (Francesco Piergiovanni)

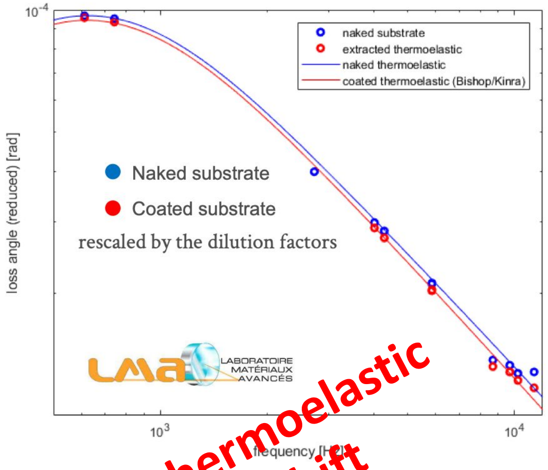


temperature

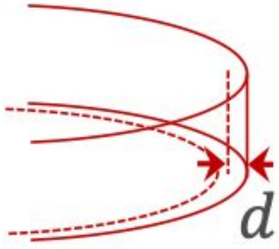


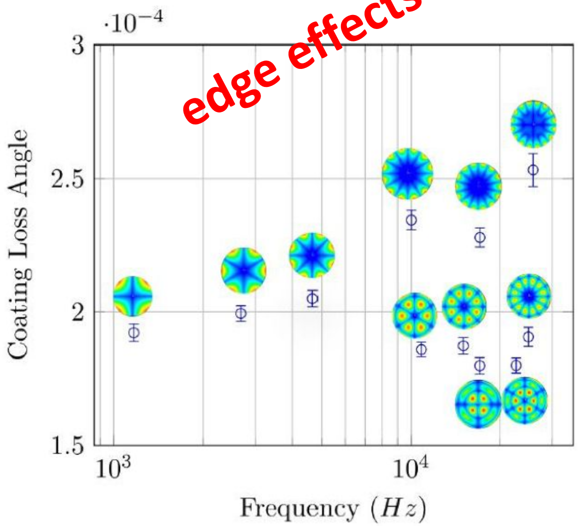
curvature





thermoelastic shift





edge effects

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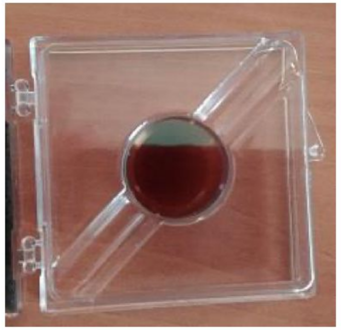
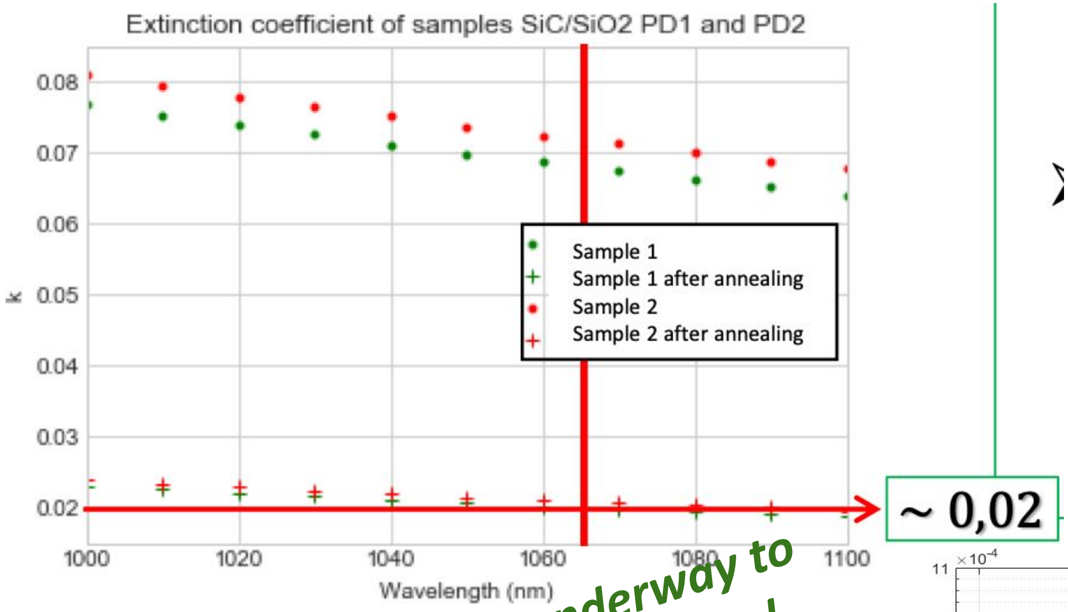
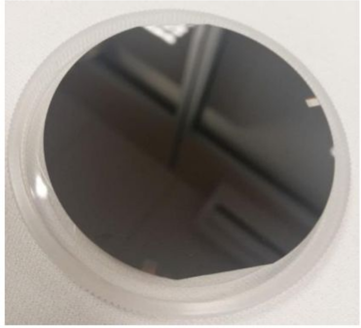
Properties of SiC films (Diana Lumaca)



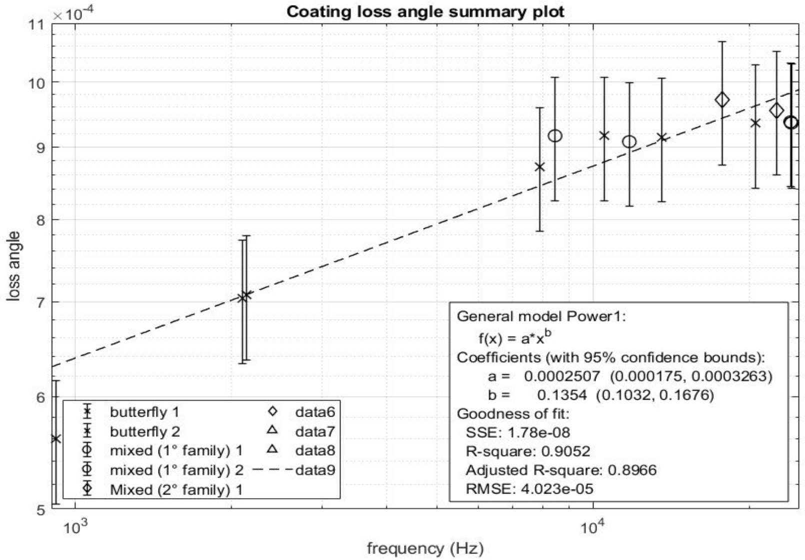
high coordination number - expected to have lower TLS density

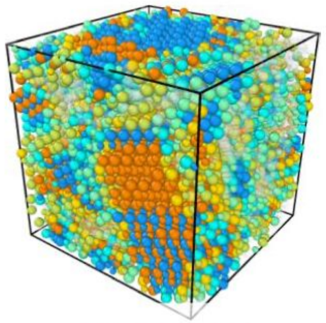


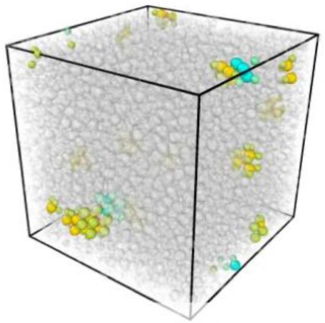


MD simulations underway to help investigate higher-than-expected mechanical losses

further studies underway to identify source of optical absorption







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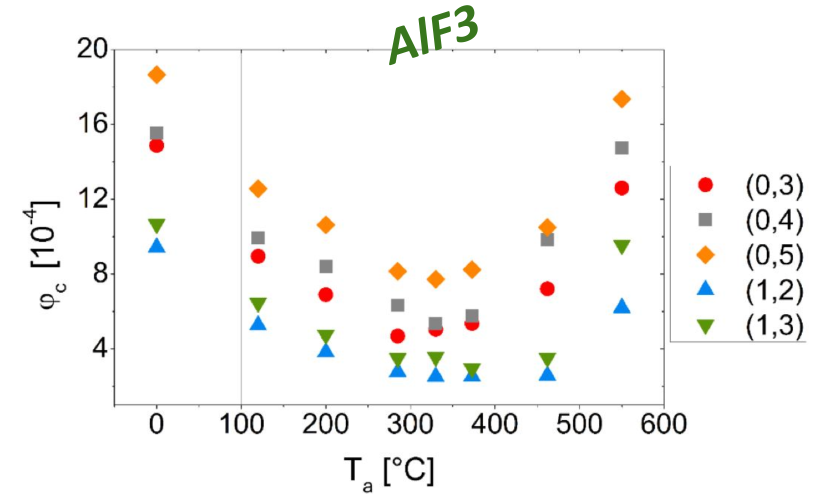
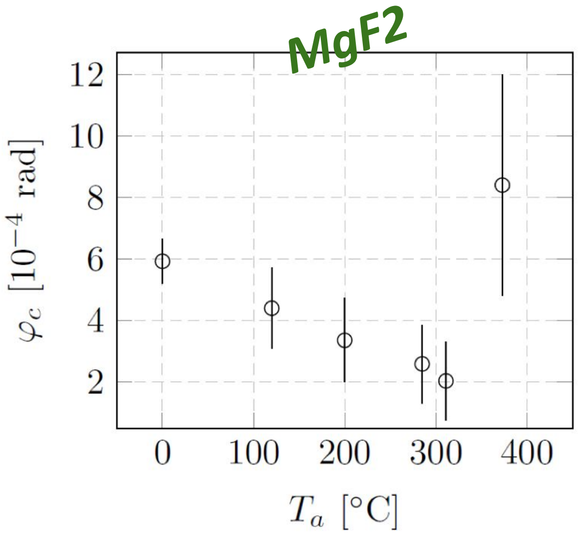
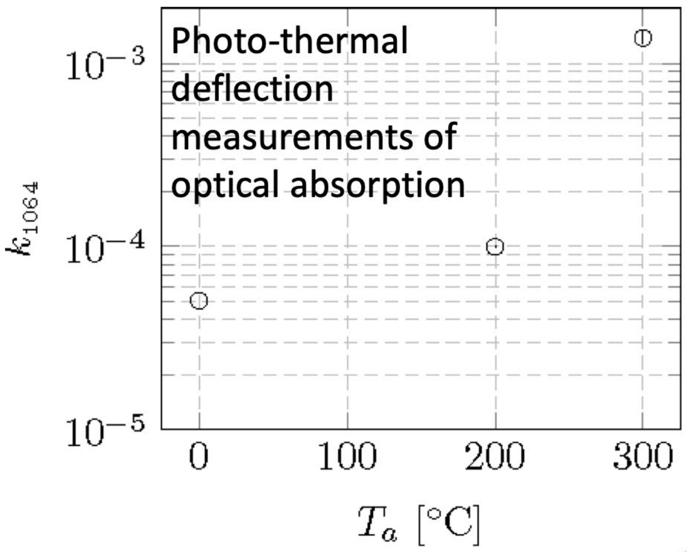
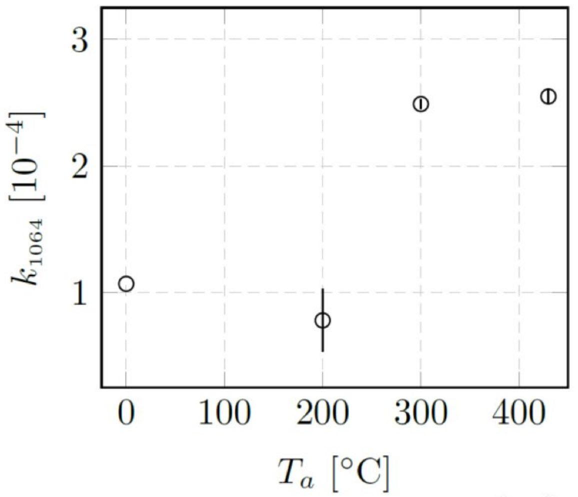
Optical and mechanical characterization of ion-beam-sputtered MgF2 and AlF3 thin films

(Matteo Bischi)







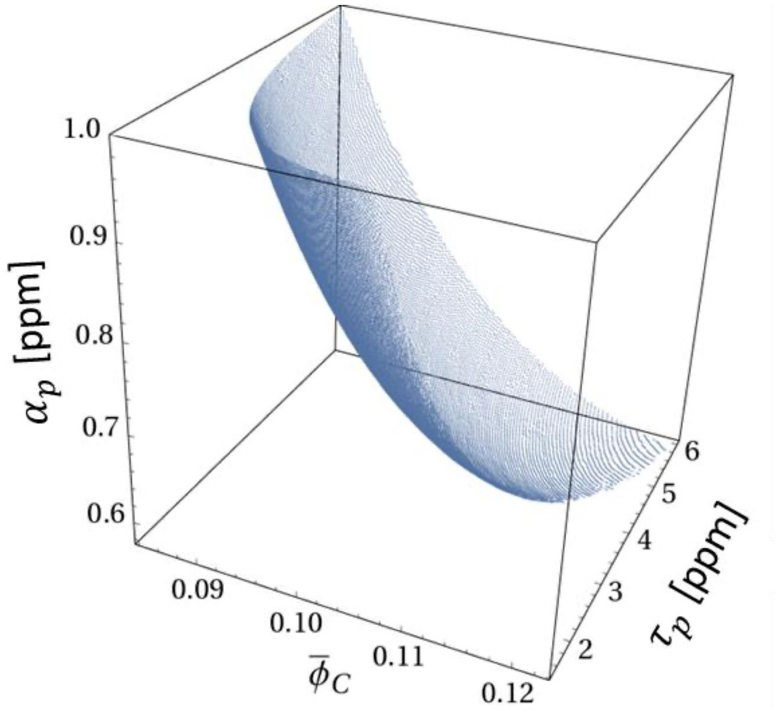


Absorption higher than tolerable.

Mechanical loss 2->3 x 10^{-4}

Index both lower than SiO2

Performance of Optimized Ternary Coatings at Ambient and Cryo Temperatures (Innocenzo Pinto)



$\kappa_{aSi} = 10^{-4}$
$\kappa_{SiN_x} = 10^{-5}$

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

Optimized	20K (on cSi)	120K (on cSi)	290K (on Silica)
aSi|Ti::Ta2O5|SiO2	(H'HL)^5(H'L)^5 0.084	(H'HL)^4(H'L)^5 0.210	(H'HL)^4(H'L)^{4}H' 0.24
SiNx|Ti::Ta2O5|SiO2	(H'HL)^7(H'L)^9 0.14	(H'HL)^7(H'L)^9 0.33	(HLH')^7(LH')^8 0.42

Noise PSD reduction factor w.r.t. *sequence-optimized QWL* ternary-design [Pierro and Pinto, LIGO-P200051]

	20K (on cSi)	120K (on cSi)	290K (on Silica)
H'=aSi	0.70 (HL)^4(H'L)^6	0.78 (HL)^4(H'L)^6	0.77 (HL)^4(H'L)^{5}H'
H'=SiN$_X$	0.82 (HL)^6(H'L)^{10}	0.85 (HL)^6(H'L)^{10}	0.87 (HL)^6(H'L)^{9}H'

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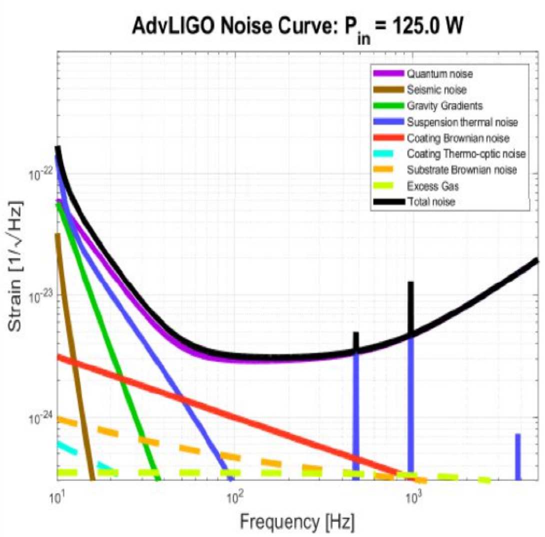
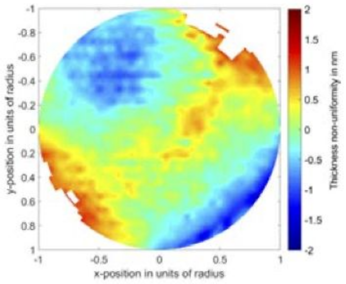
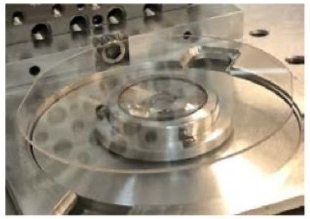
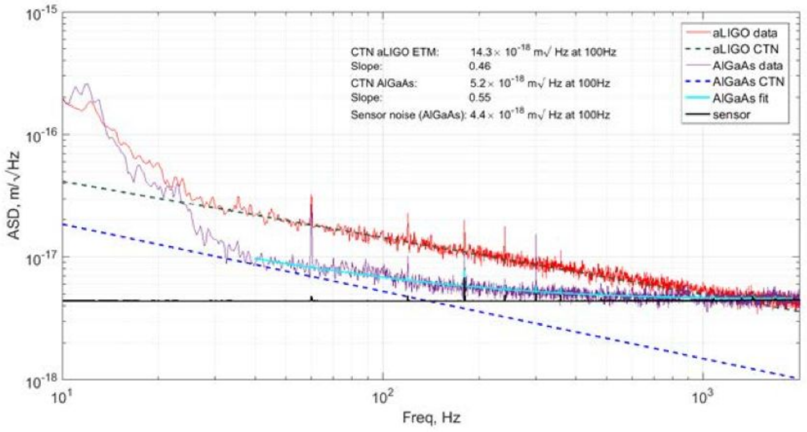
Substrate Transferred Crystalline AlGaAs Coatings Status (Gregg Harry)



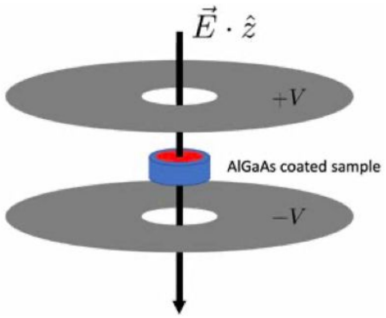






$$\varphi_{11} = \varphi_{12} \lesssim 8 \times 10^{-5}$$
$$\varphi_{44} < 1 \times 10^{-7}$$

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



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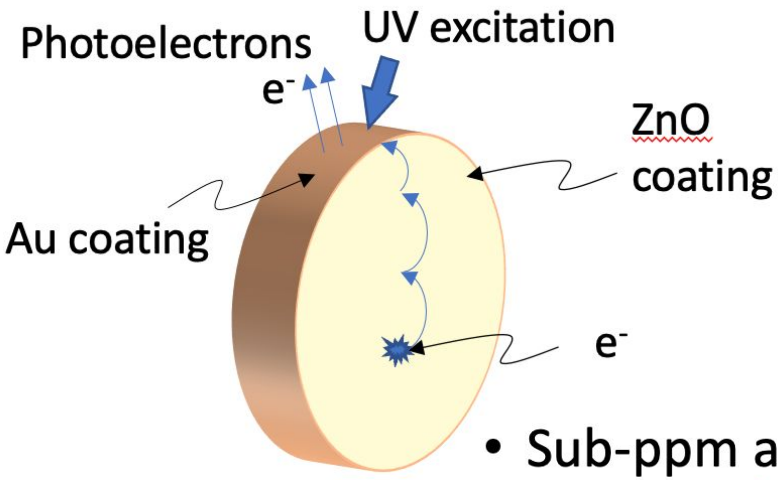
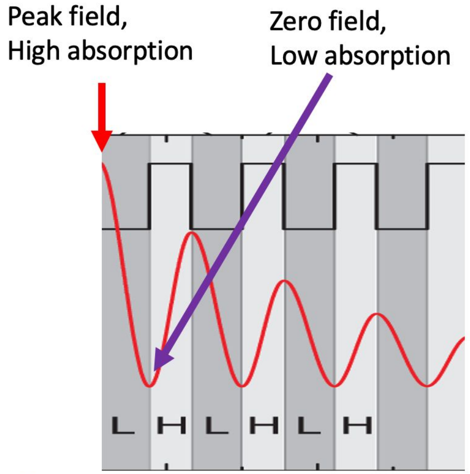
W.M. KECK FOUNDATION

NSF MAJOR RESEARCH INSTRUMENTATION

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 GOhm/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 TOhm/sq and 0.2 ppm absorption at 1064 nm
  - Total absorption including HR mirror is 0.8 ppm
  - 12nm thick, 300 TOhm/sq and <0.05 ppm absorption at 1064 nm
  - Total absorption including HR mirror is 0.55 ppm

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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).

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