ET-LF Wavelength Workshop - Core Optics

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Core Optics - wavelength considerations

- Need to meet thermal noise targets and optical absorption targets by development of suitable mirror substrates and mirror coatings `

- The wavelength choice limits material choice due to optical absorption
    - e.g. Si substrates not transmissive at 1064 nm
    - e.g. aSi coating absorption lower at longer wavelength

- Impact on suspension design - heat extraction

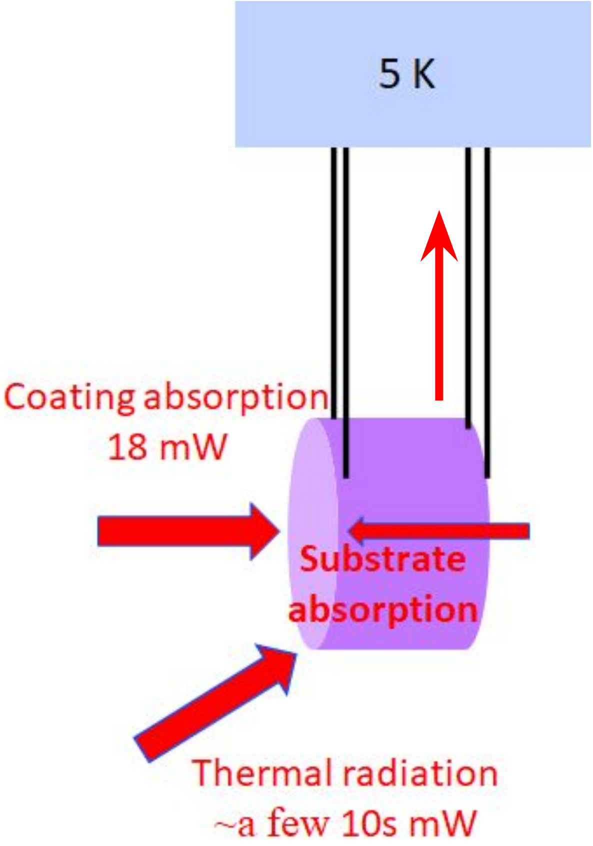
- Practical considerations, dimensions
    - e.g. float zone silicon has very attractive absorption, but not available in required size for test masses

Absorption in ET-LF

- Assume
  - 18 kW cavity power, and 32 W transmitted through ITM
  - 1ppm coating absorption - gives 18 mW absorbed power

- Assume similar substrate absorption contribution - we would need (210 kg and 45 cm diameter)
  <= 10 ppm/cm absorption in Si substrate
  <= 17 ppm/cm absorption in sapphire substrate

- This gives a total heat load of 36 mW (plus any other radiative heating) to be extracted along the suspension fibres

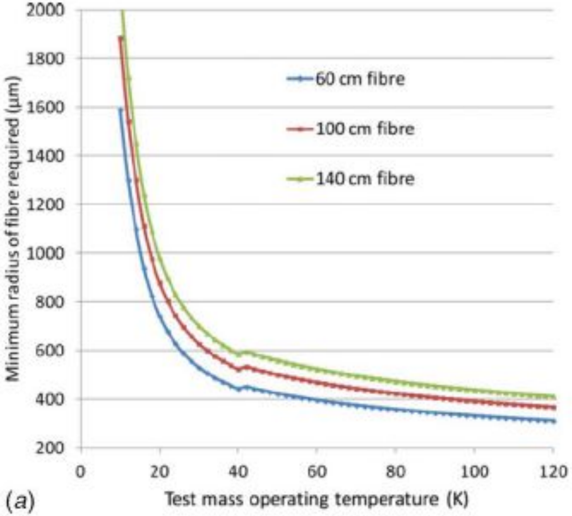


Impact on Suspensions

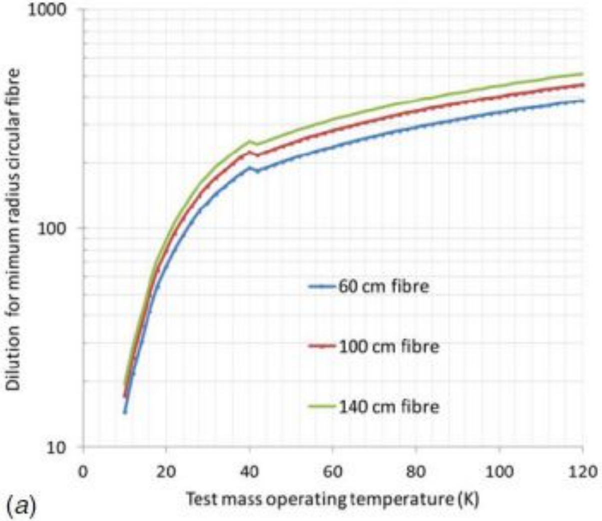
- Heat extraction at 10 K has significant implications for suspension thermal noise
  - Fibre dimensions need optimised for strength, heat extraction and TN

Fiber Cross Section

$$S = \frac{PL}{4\kappa\Delta T}$$



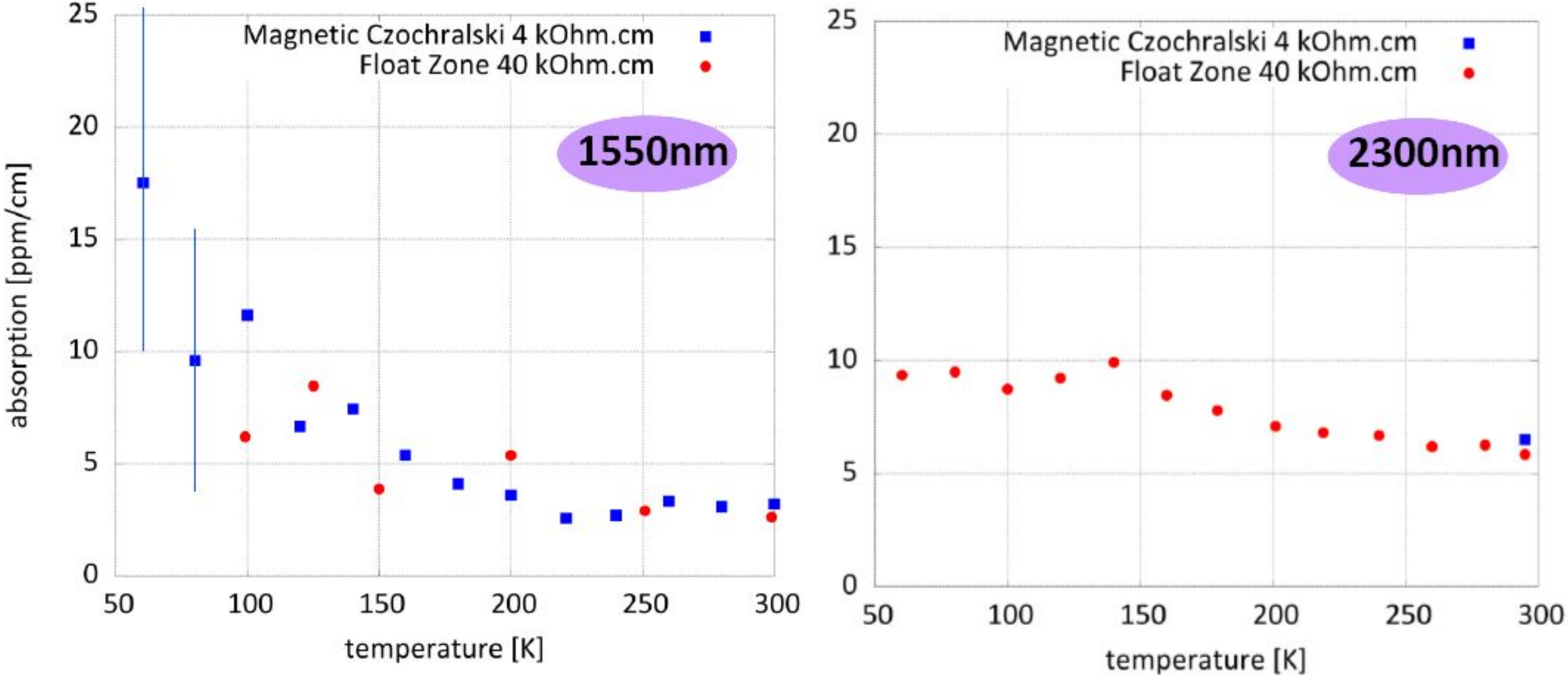
Minimum fibre radius required to extract 18 mW heat, vs mirror temperature



Dissipation dilution factor for minimum fibre diameter, vs mirror temperature

Cumming et al, CQG 31 (2014) 025017

Silicon substrate absorption



- Absorption of float-zone and magnetic Czochralski Si slightly higher at longer wavelength (probably not significant)

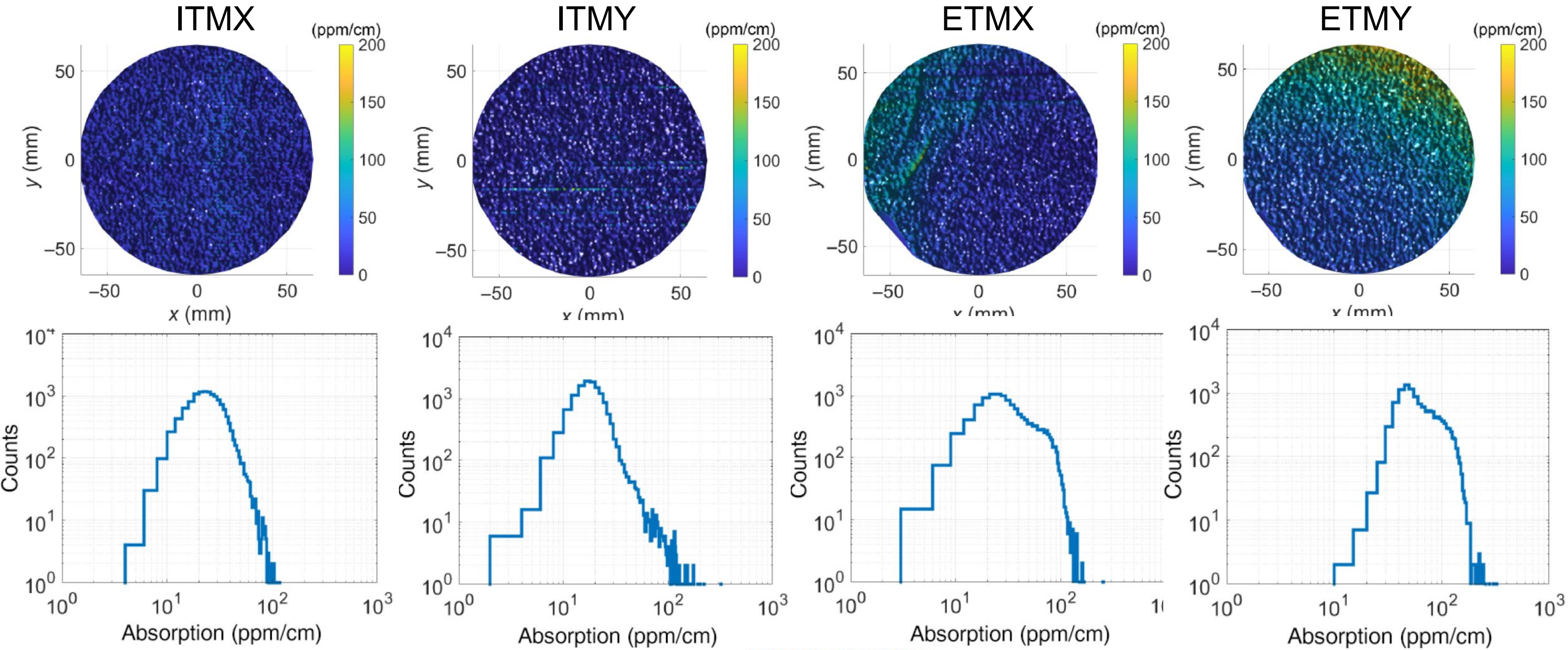
A. Markosyan, A. Bell LIGO-G1700480

Sapphire substrate absorption

1064 nm

ITMs grown by Shinkosha

ETMs grown by GT Crystals Systems



S1, S2, and S3 are the names of planes parallel to the mirror surface. S1 and S2 are about 10 mm below the surface, while S3 is located between them.

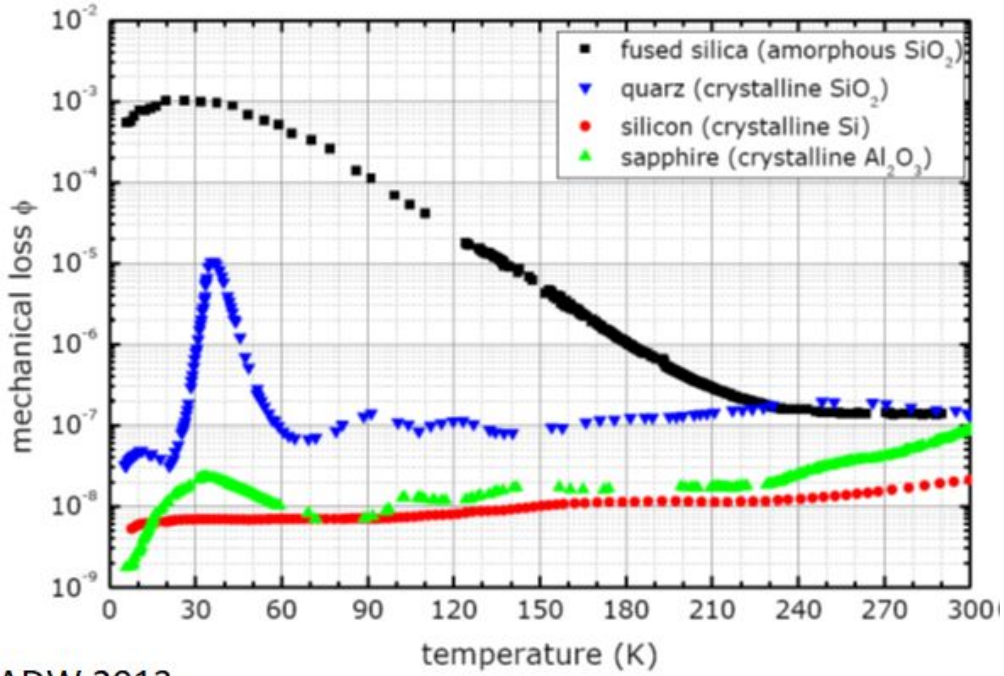
Test mass	S1 (ppm/cm)	S2 (ppm/cm)	S3 (ppm/cm)
ITMX	27.1 (11.0)	31.5 (10.5)	24.8 (10.5)
ITMY	21.2 (12.3)	22.8 (18.2)	33.4 (23.4)
ETMX	41.2 (23.1)	64.3 (23.3)	59.9 (19.8)
ETMY	72.1 (31.1)	87.3 (38.2)	93.4 (36.5)

Size = 22 cm x 15 cm

Phys. Rev. Applied **14**,014021 (2020)

Substrate thermal noise

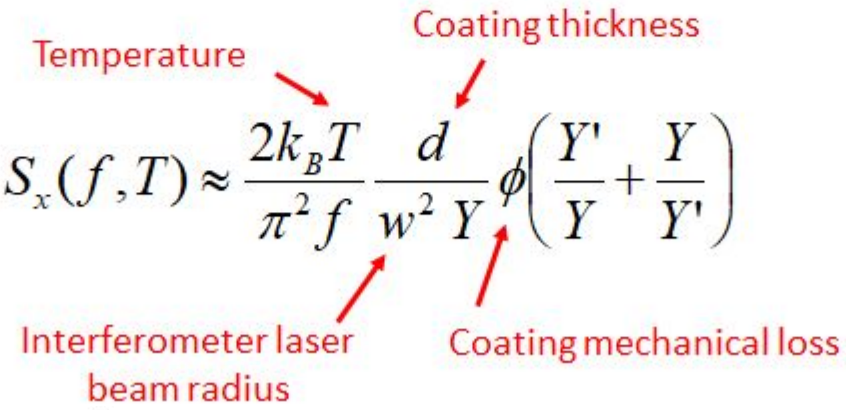
- Sapphire and silicon can both have very low cryogenic mechanical loss - Brownian thermal noise will be dominated by mirror coatings



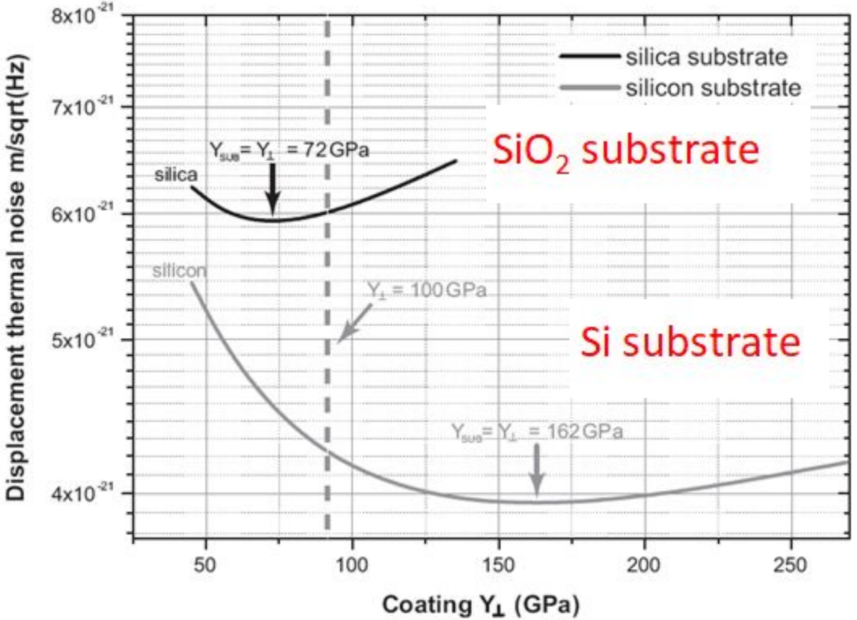
G Hofmann, GWADW 2013

Coating thermal noise

- Better coatings required due to relatively high loss of silica/tantala coatings at low temperatures
- Important properties for TN
  - Mechanical loss
  - Thickness (set by refractive index of materials)
  - Young's modulus (ideally should match substrate modulus)



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

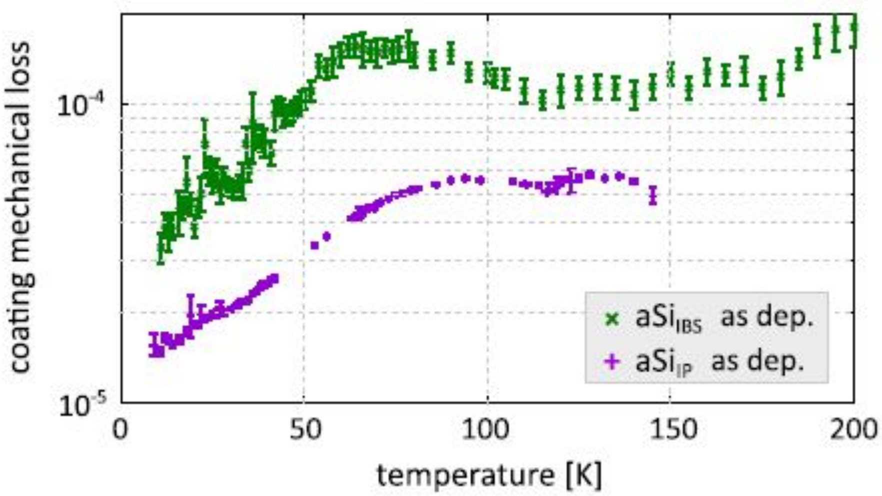


aSi coatings

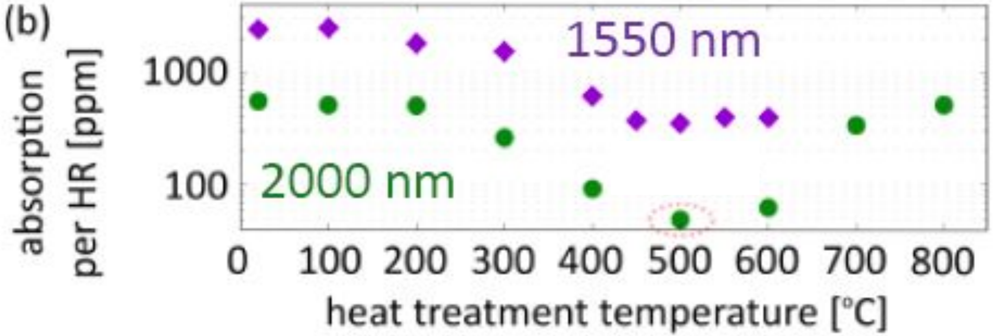
- Significant potential for meeting thermal noise requirements
  - loss more than 10x lower than Ta2O5 at 10/20 K.
  - High index, fewer and thinner layers

- Absorption is significantly higher than aLIGO / Advanced Virgo coatings

- Absorption can be 7-10x lower at 2 um compared to 1.55 um



Mechanical loss of IBS and ion-plating aSi

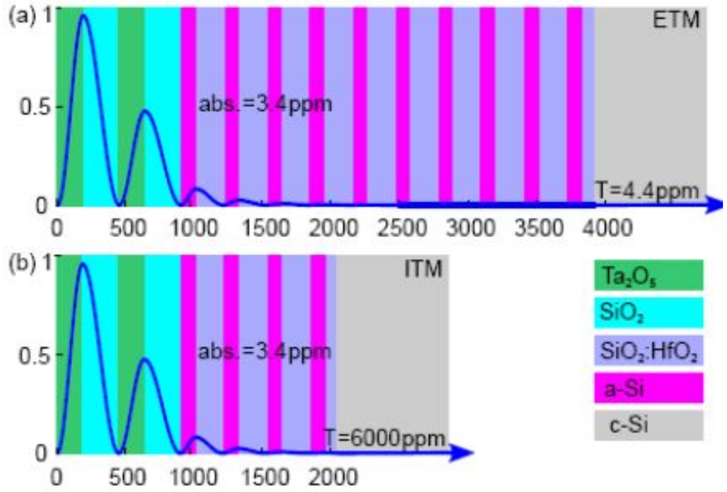


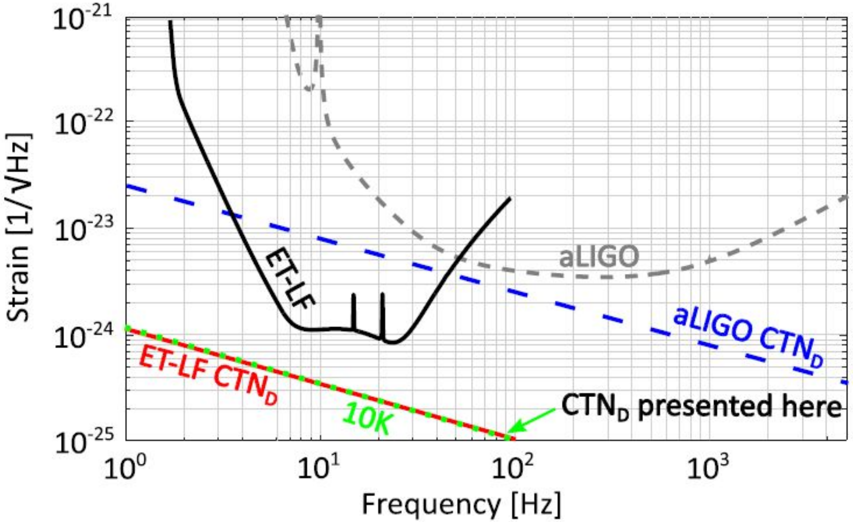
Absorption of HR aSi/SiO2 stack (ion plating aSi, room temperature, scaled from single layer measurements)

Multimaterial coating designs to reduce absorption

- Currently, multimaterial designs and 2 um look like a promising way to get close to 1ppm absorption with aSi-based coatings

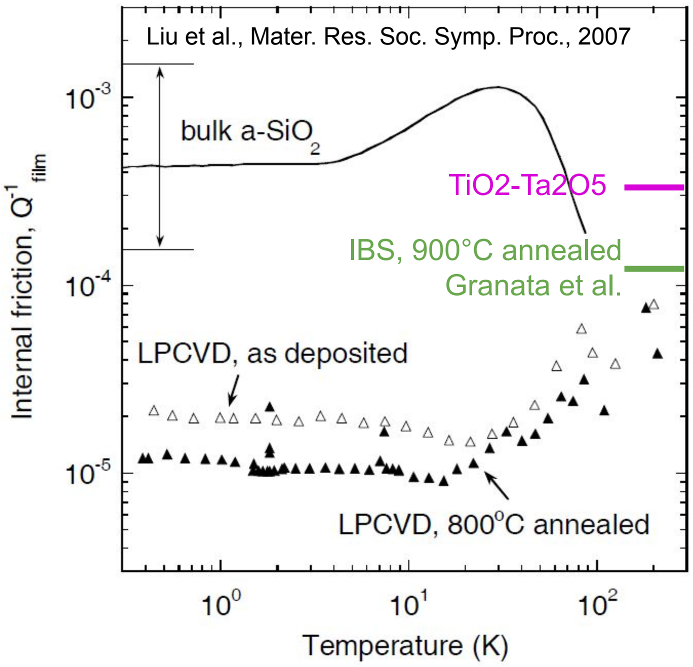
- Example: multimaterial design meeting (theoretically, based on single layer measurements) ET-LF CTN target at 10 K for 3.4ppm absorption (ETM) at 2um





Coating design and projected thermal noise - Craig et al, PRL 122 (2019)

SiNx coating



Chao & al., LIGO-G1700304, 2017

🟥 $SiN_{0.40}$ (n = 2.30@1064, n=2.28@1550)

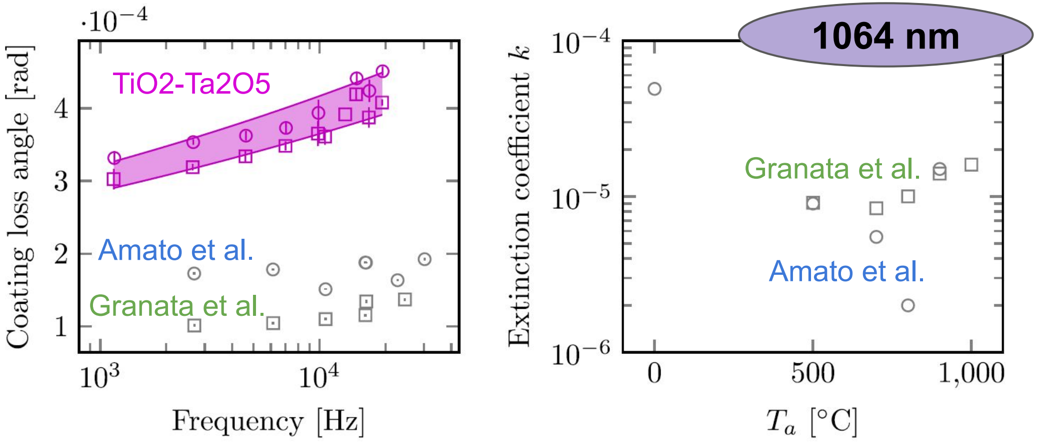
🟩 $SiN_{0.65}$ (n = 1.93@1064, n=1.92@1550)

■ $SiN_{0.87}$ (n = 1.78@1064, n=1.78@1550)

○ Granata et al. Class. Quantum Grav. 37, 095004 (2020)

○ Amato et al. J. Phys. Conf. Ser. 957, 012006 (2018).

□ Granata et al. Applied Optics 59, 5, pp. A229-A235 (2020)



- Could meet thermal noise requirements
  - Loss potentially lower than a-Si
- Refractive index related to stoichiometry
  - Could be used as high- or low-index layer
- Absorption is high but there is potential for improvement
  - HR SiN/SiO2 (Optimize as Vigo ETM): 44 ppm
- k of 4.3E-6 observed at 2um for LPCVD - further study of IBS coatings of interest

GaAs/AlGaAs crystalline coating

1064 nm

HR coating made of 35.5 doublets of epitaxial MBE GaAs/$Al_{0.92}Ga_{0.08}As$.
Originally grown on a 15-cm diameter GaAs wafer with negligible lattice mismatch with the low-index $Al_{0.92}Ga_{0.08}As$ layer.

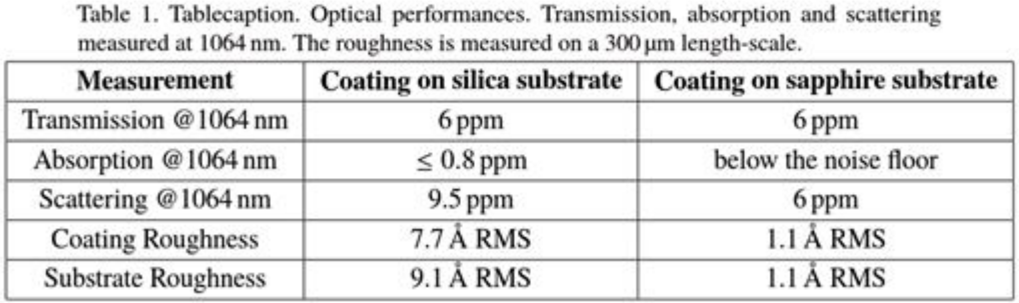


Table 1. Tablecaption. Optical performances. Transmission, absorption and scattering measured at 1064 nm. The roughness is measured on a 300 µm length-scale.

Measurement	Coating on silica substrate	Coating on sapphire substrate
Transmission @1064 nm	6 ppm	6 ppm
Absorption @1064 nm	≤ 0.8 ppm	below the noise floor
Scattering @1064 nm	9.5 ppm	6 ppm
Coating Roughness	7.7 Å RMS	1.1 Å RMS
Substrate Roughness	9.1 Å RMS	1.1 Å RMS

Marchiò et al. Optics Express 26, 5, 6114-6125 (2018)

- Excellent mechanical loss Cole et al. Proceedings Volume 8458, Optical Trapping and Optical Micromanipulation IX; 845807 (2012)
    - Potential for a loss angle below 5 × 10−6 at cryogenic temperatures
- Sub-ppm absorption at 1064 nm, 1550 nm, (2000 nm?)
    - AlGaAs can be used on sapphire or silicon
    - There is potential for 1064 nm application (in addition to 1550nm)
- Available for large mirrors?

Other coatings considerations

- AlGaAs coatings:
  - sub-ppm absorption at 1.55 um, excellent loss
  - growth and substrate transfer at ET-LF sizes is unproven and likely to require a significant financial investment (GaAs wafer diameter for growth). Other crystalline coatings e.g. AlGaP (Strathclyde/Glasgow) and other materials (Leuven / ET Pathfinder)

- Silicon nitride coatings have similar (maybe better) loss to aSi and comparable / better absorption, possibly with scope for improvement - of interest as low-index partner to aSi, or with other materials?

- Conclusion:
  - currently no coating fully meets all the ET-LF requirements (assuming <1ppm target).
  - aSi and SiNx show promise for thermal noise. Absorption higher than ideal, but can be lower at 2um than 1.55um
  - research is ongoing into these, and other, materials

Ice layer

- Ice forms on cryogenic mirrors due to cryo-pump effect.
- Growth rate 27 nm/day observed by KAGRA at 8E-5 mbar
- Mechanical loss of ice leads to increasing, oscillating thermal noise
- Absorption -> absorption bands at 1.5 and 2um (use a slightly different wavelength?)
- Possible solutions to the problem
  - Reduce vacuum pressure -> reduce growth rate
  - Annealing ice at 152 K can reduce mech. loss
  - Removal of ice by laser heating (CO2)?

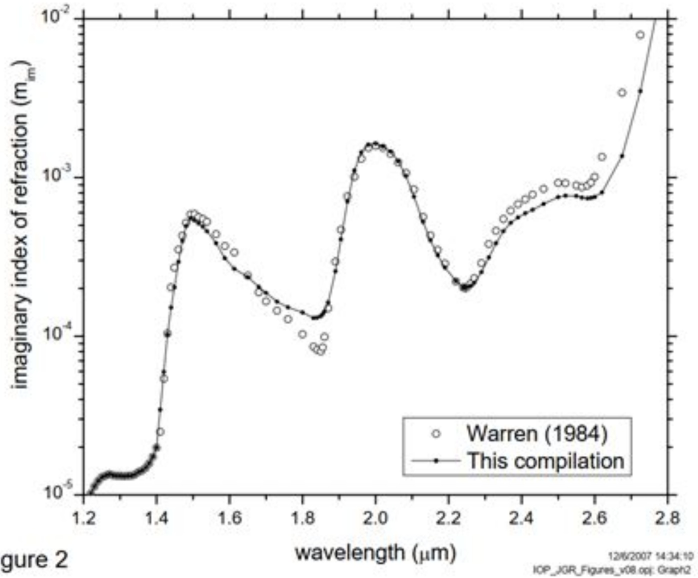


Figure 2

Warren SG. 2019 Optical properties of ice and snow. *Phil. Trans. R. Soc. A* **377**: 20180161

Summary of coating properties

Coating layer	**Loss Angle (10K)**	**k @1064nm**	**k @1550nm**	**k @2000nm**
Ta2O5	5E-4	< 2e-7 (IBS)	?	?
aSi	<=1.7E-5	?	6.25e-4*	8.6e-5
SiN	1E-5 (LPCVD)	1e-5 (IBS)	1.2e-5 (LPCVD)	4.3e-6 (LPCVD)

Coating stack	**Thermal noise (10K, 10 Hz) [x10^-22 m/sqrt(Hz)]**	**Stack thickness (um)**	**α [ppm]**
aSi/SiN**	1550nm: **4.1** 2000nm: **4.6**	1550nm: **3.2** 2000nm: **4.1**	1550nm: **10**** 2000nm: **1.7****
GaAs/AlGaAs	1064nm: **4.1** 1550nm: **4.9** 2000nm: **5.5**	1064nm: **6.7** 1550nm: **9.7** 2000nm: **12.5**	1064nm: **< 0.8** 1550nm: 2000nm:

* can be up to a factor of 5 lower for ECR-IBS (not measured at 2um due to unsuitable substrate material)

** assuming the best aSi (ECR-IBS) and that improvements in absorption with increasing wavelength and reduced temperature apply to this material

Some outstanding questions

- What is tolerable absorbed power from the test-masses? What are trade-offs between absorption / mirror temperature / suspension dimensions and thermal noise / coating thermal noise?

- How to obtain large enough Si substrates with low absorption? Magnetic Czochralski? Working with silicon manufacturers / researchers e.g. IKZ Berlin, isotopically pure Si, directional solidification? Composite masses?

- Can large sapphire mirrors with low absorption be realised?
  Work ongoing in Lyon (OSAG project): Production and characterization of large substrates.

- Can AlGaAs coatings be up-scaled to ET mirror diameters, at what cost and which time-scale?
  Development of other crystalline coatings - possibility of direct growth of silicon?

- Can absorption of aSi / SiN be further improved? Testing of possible multi-material designs?

- Nanolayer coatings show promise at preventing cryogenic loss peaks - may open up more possible coating materials / combinations

Comments from preparatory meeting:

- Need to share the table with material properties with the Payload WP.
  (Material database in the wiki.. Need to fill the table)

- If we are considering sapphire substrates, then 1064nm wavelength needs to be considered.
  (we should keep this in mind, however, 1064nm restricts low temp. coating options -> effort on developing 2 um is useful)

- Need to worry about stress in coatings? Is 2um worse than 1.5um? Needs to be considered?
  (Stack thickness higher at 2 um than 1.5 um. R&D is needed.)

- if BS is silica, then is there a grade that works for 1550/2um.

- BS absorption 100ppm/cm at 2um (for Voyager). Can we check if we expect any issues here with lower power?