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Silicon-based optical mirror coatings for ultra-high precision metrology and sensing

(originally: Silicon-based optical coatings with a 12 times thermal noise reduction)

dcc: P1800004

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Why is aSi interesting?

- Known for low cryogenic mechanical loss
  - Measurements of IBS aSi suggest a factor of 40 or more lower loss than tantala at 20 K

    P. G. Murray, I. W. Martin, M. R. Abernathy, K. Craig, J. Hough, T. Pershing, S. Penn, R. Robie, S. Rowan, Phys. Rev. D **92**, 062001 (2015)
  - Even lower loss demonstrated (e.g. elevated temperature deposition work)

    X. Liu, D. R. Queen, T. H. Metcalf, J. E. Karel, F. Hellman Phys. Rev. Lett. **113** 025503 (2014)
  - High index (n ~ 3.5 – 4) – thinner films and fewer bilayers: direct thermal noise reduction
  - BUT: optical absorption typically significantly higher than required

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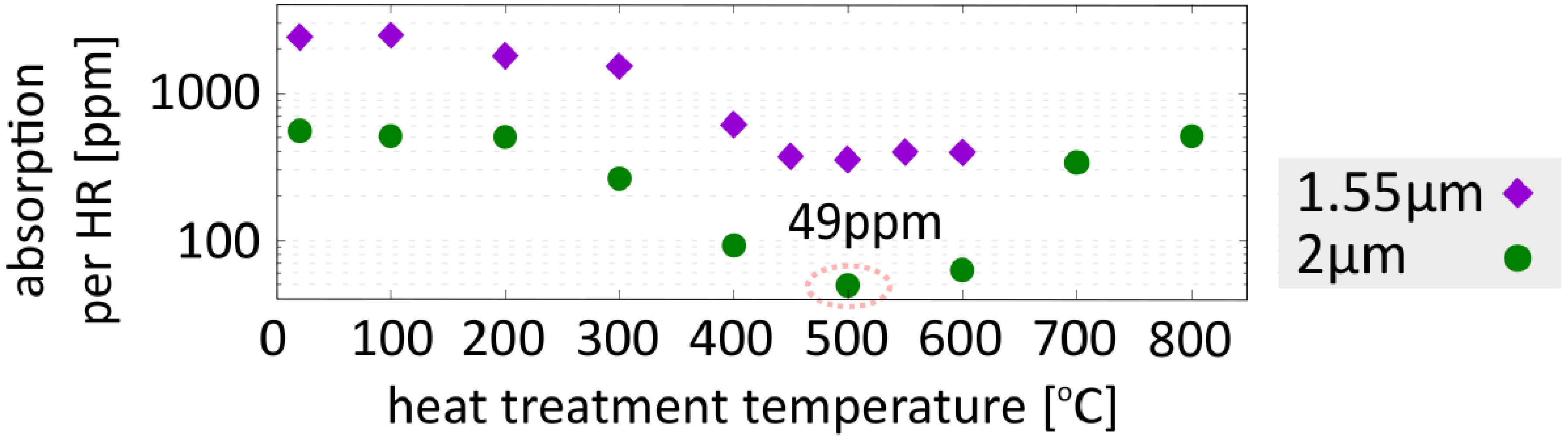
Paper summary

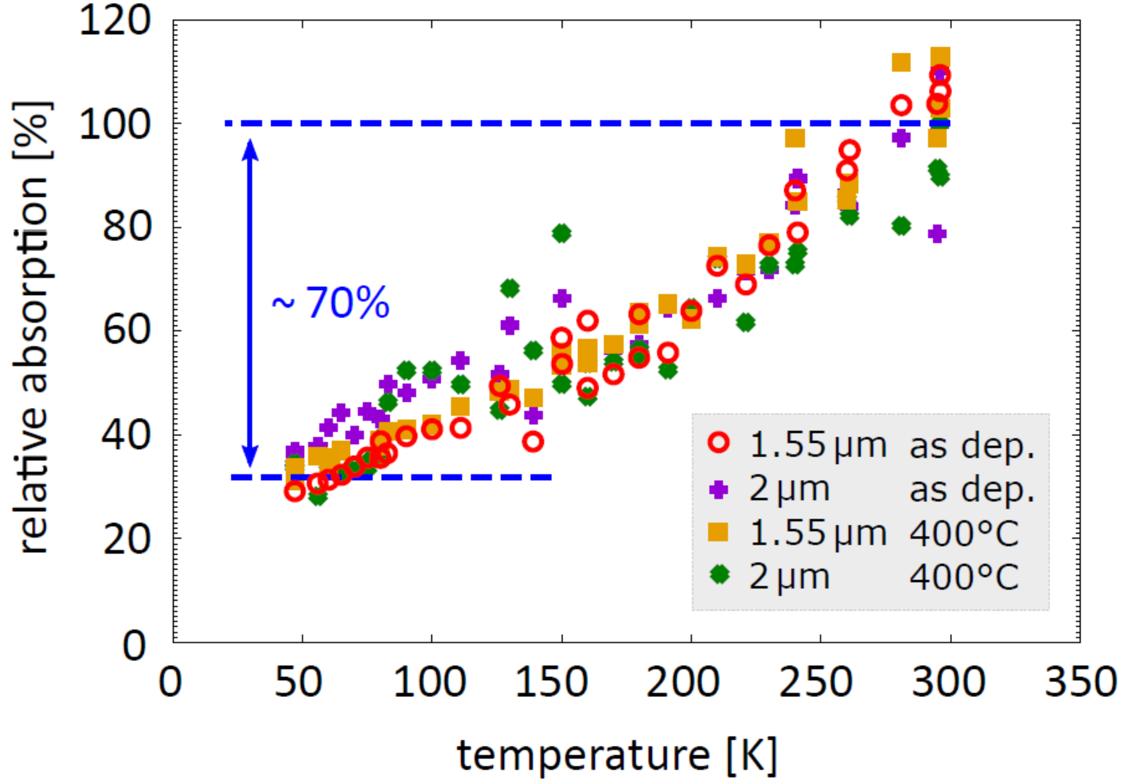
- Here we investigate
  - Deposition method – ion-plating (dep. temp. ~250°C)
    http://www.tafelmaier.de/index.php?page=beschichtung&lng=en
  - Absorption
    - Effect of post-deposition heat-treatment on absorption
    - Absorption at 1.55 and at 2 μm
    - Effect of cooling
  - Mechanical loss
  - Thermal noise performance

Absorption versus heat-treatment at 1.55 and 2 μm



- Measured on: single layer, 1 μm thick at 1.55 μm and 2 μm
- Scale to estimate the absorption in an HR aSi/SiO2 stack (7 bilayers, assuming negligible absorption in the SiO_2 layers)
- 85%/89% absorption reduction at 1.55/2 μm following optimum heat-treatment
- Minimum absorption is x7.2 lower at 2 μm than at 1.55 μm

Absorption versus temperature at 1.55 and 2 μm



- Cooling to 47K: approximately 70% reduction in absorption for heat-treated and as-deposited coatings, at both wavelengths
- 2 μm measurements corrected for substrate absorption using uncoated measurements

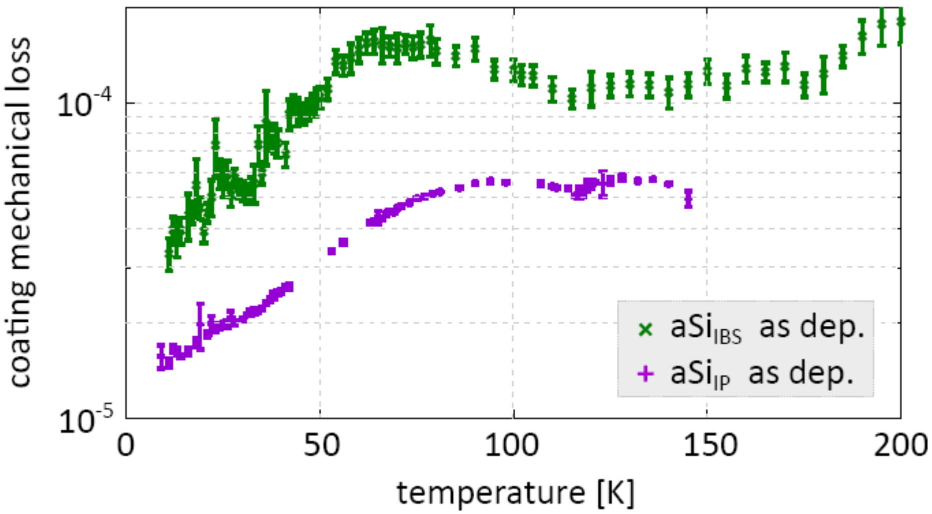
Absorption summary

- Absorption
  - Heat-treatment: x 2.3 reduction
  - Moving from 1.55 to 2 μm: x7.2 reduction
  - Cooling (to 47 K, here): x 3.3 reduction

  - Total reduction compared to as-deposited, room temperature at 1550nm: x55

Mechanical loss

- aSi loss
  - 290K, as deposited: 1×10^{-4}
  - 290K, heat treated: 2×10^{-5}
  - 20K, as deposited: 2×10^{-5}
  - 20K, heat treated: ???



- Silica loss (7.8E-4 @ 20K, dominates thermal noise of aSi/SiO_2 HR coating
- Use silicon nitride as low-index (n=2.17) partner layer for aSi
  - Low cryogenic loss in literature (plus work of Shiuh Chao et al)
  - We measured absorption at 2 μm, finding a k = 4.3E-6, used to predict absorption of HR coatings.

Thermal noise

A: 17 bilayers
SiO_2 (blue, 258 nm)
& $Ti{:}Ta_2O_5$ (green, 189 nm)
absorption 1.55 µm:
1.7 ppm; TN set to 100 %

B: 7 bilayers
SiO_2 (blue, 333 nm)
& aSi (pink, 143 nm)
absorption at 2 µm:
20 ppm; TN: 60 %

C: 18 bilayers
SiO_2 (blue, 258 nm)
& SiN (yellow, 179 nm)
absorption at 2 µm:
14 ppm; TN: 96 %

D: 11 bilayers
aSi (pink, 143 nm)
& SiN (yellow, 230 nm)
absorptionvat 2 µm:
27 ppm; TN: 8 %

TABLE I. Refractive index, n, and mechanical loss, ϕ, of the materials discussed.

Temper-ature	loss $\phi \times 10^{-4}$ SiO_2	$Ti{:}Ta_2O_5$	aSi			SiN
290 K	0.4 [15]	2.4 [15]	1.0 (IBS, ATF) [23]	0.2 (IP)	0.17(IBS, UWS)	0.8 [36]
120 K	1.7 [16]	3.3 [35]	0.8 (IBS, ATF) [23]			0.2 [36]
20 K	7.8 [16]	8.6 [35]	0.2 (IBS, ATF) [23]	< 0.2 (IP)		0.1 [36]
n	1.5	2.05	3.65			2.17 [37]

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

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absorptionvat 2 μm:
27 ppm; TN: 8 %

Coating	**ETM coating TN (120K/20K)**	**Absorption (120K/20K)**
17 bilayers SiO_2/ $Ti:Ta_2O_5$ (1.55μm)*	1/1	<1ppm/<1ppm
7 bilayers SiO_2/aSi (2μm)	0.54/0.60	67ppm/20ppm
18 bilayers SiO_2/SiN (2μm)	0.87/0.96	47ppm/14ppm
11 bilayers SiN/aSi (2μm)	0.19/0.08	90ppm/27ppm

- SiO_2/$Ti:Ta_2O_5$ at 120K has ~1.36× higher TN than at 20 K
- SiO_2/$Ti:Ta_2O_5$ at 120K has ~0.84× actual aLIGO ETM TN

UWS / Strathclyde aSi Coatings[1]

- IBS, mechanical loss of 0.17×10^{-4} at RT
- Absorption: ~20ppm for aSi/SiO_2 HR coating at 1550nm and RT

Coating	ETM coating TN (120K/20K)	Absorption (120K/20K)
17 bilayers SiO_2/ Ti:Ta_2O_5 (1.55μm)	1/1	<1ppm/<1ppm
7 bilayers SiO_2/aSi (1.55μm)	0.48/0.60	20ppm/20ppm
18 bilayers SiO_2/SiN (1.55μm)	0.77/0.96	36ppm/36ppm
11 bilayers SiN/aSi (1.55μm)	0.17/0.08	33ppm/33ppm

- Here, using room temperature 1550nm absorption
- Scope for significant further reduction in multi-layer absorption, based on results with other types of aSi
  - Absorption at 2μm?
  - Absorption and loss at low temperature?

[1] Birney, Reid, Vine, McFoy, Angelova, Gibson et al: see e.g. https://dcc.ligo.org/LIGO-G1700870

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What is possible using multi-material coatings?

120K

Coating	TN compared to SiO_2/Ti:Ta_2O_5 1.55µm(UWS)/2µm(IP)	Absorption 1.55µm(UWS)/2µm(IP)
11 bilayers SiN/aSi	0.17 / 0.19	33ppm / 90ppm
11 bilayers SiN/aSi + 1x SiO_2/ Ti:Ta_2O_5	0.25 / 0.28	16.5ppm / 45ppm
11 bilayers SiN/aSi + 2x SiO_2/ Ti:Ta_2O_5	0.33 / 0.38	8.3ppm / 22.5ppm
11 bilayers SiN/aSi + 3x SiO_2/ Ti:Ta_2O_5	0.41 / 0.46	4.1ppm / 11.3ppm
11 bilayers SiN/aSi + 4x SiO_2/ Ti:Ta_2O_5	0.47 / 0.53	2ppm / 5.7ppm
11 bilayers SiN/aSi + 5x SiO_2/ Ti:Ta_2O_5	0.53 / 0.61	1ppm / 2.8ppm

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Single layer versus multi-layer

- We compared the HR absorption predicted from single-layer measurements with absorption measured for an HR stack of RLVIP aSi/SiO_2
  - Single layer starts with a higher absorption after deposition than HR stack (possible reason: longer deposition time for HR stack = longer heating during deposition)
  - Measured HR stack reduces absorption by 57% (compared to 85% for the single layer)
  - HR stack reaches minimum absorption at 450°C (compared to 500°C for single layer)
  - Resulting absorption for HR stack about 20% higher than for an HR coating calculated from single layer measurements
- Could there be interface effects?
- Longer deposition time for HR stack: Changing absorption characteristics? Lower absorption as-deposited, less responsive to post-deposition heat-treatment?