

Cryogenic loss angle of IBS SiNx thin films

M. Granata, A. Lemaître, L. O. Mereni, B. Sassolas,
L. Silenzi, F. Travasso



High-reflection (HR) coatings

- Mirror coatings of ALL current detectors (LIGO, Virgo, KAGRA) by LMA

Pinard et al, [doi.org/doi.org/10.1364/AO.56.000C11](https://doi.org/10.1364/AO.56.000C11)

Degallaix et al, [doi.org/doi.org/10.1364/JOSAA.36.000C85](https://doi.org/10.1364/JOSAA.36.000C85)

Granata et al, doi.org/10.1088/1361-6382/ab77e9

- Thickness-optimized Bragg reflectors

Villar et al, doi.org/10.1103/PhysRevD.81.122001

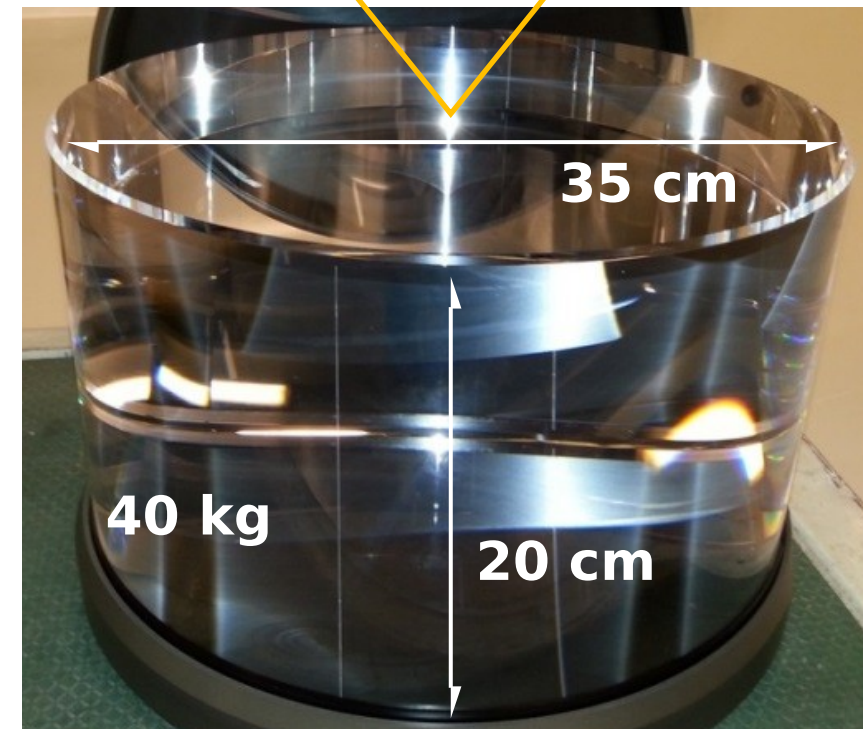
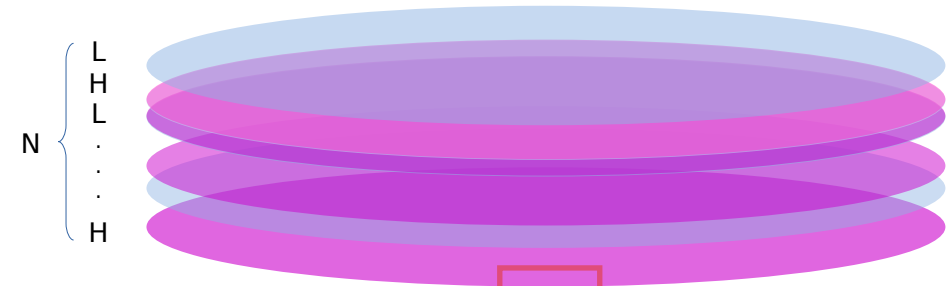
- Stack of thin films of metal oxides

- high index, n_H : Ta_2O_5 (- TiO_2)

- low index, n_L : SiO_2

Granata et al, doi.org/10.1088/1361-6382/ab77e9

	T	N	t_H (nm)	t_L (nm)	r	t_c (nm)
ITM	1.4%	18	727	2080	0.32	2807
ETM	4 ppm	38	2109	3766	0.56	5875



Key parameters

temperature

coating thickness

coating loss angle

For a Fabry-Perot cavity mirror:

$$S_{\text{CTN}} \propto T \frac{d\phi}{w^2}$$

Harry et al, doi.org/10.1088/0264-9381/19/5/305

laser beam
radius

Objectives

higher index contrast

$$c = (n_H - n_L)/(n_H + n_L)$$

thinner coating

lower loss

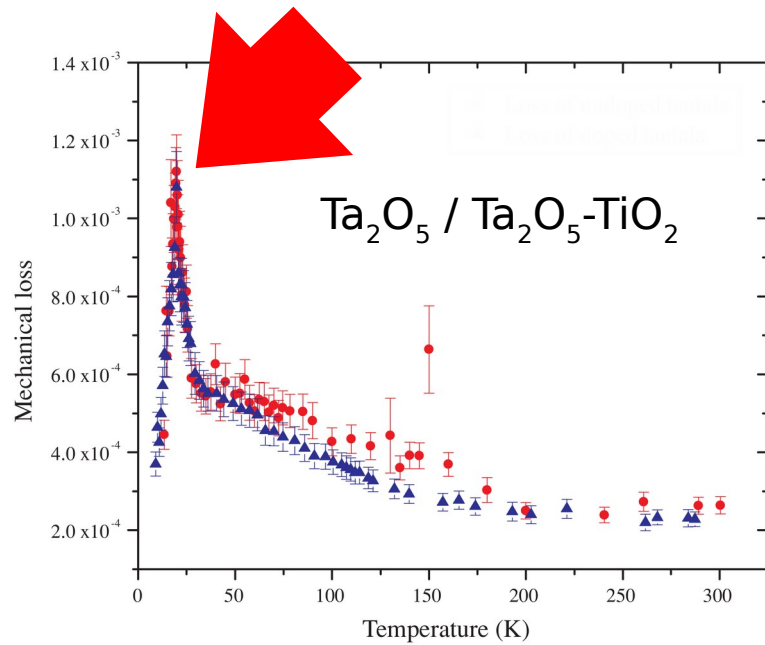
$$S_{\text{CTN}} \propto T \frac{d\phi}{w^2}$$



without increasing current optical losses

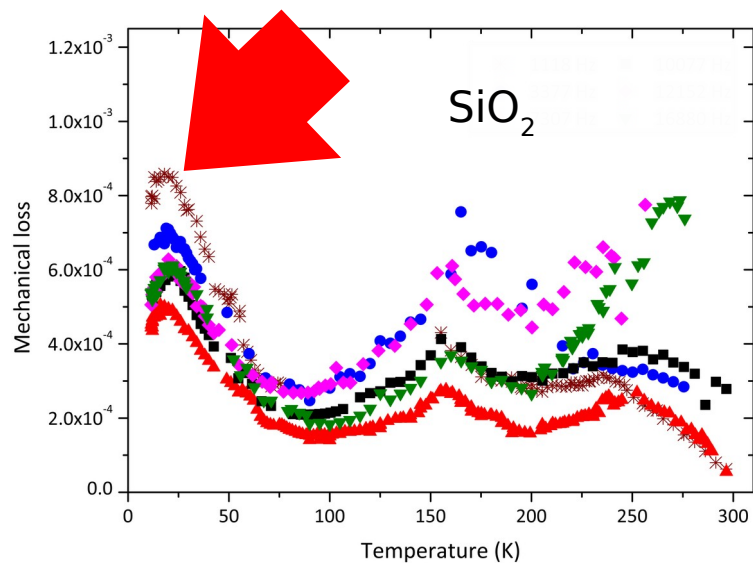


Issue



Martin et al, doi.org/10.1088/0264-9381/26/15/155012

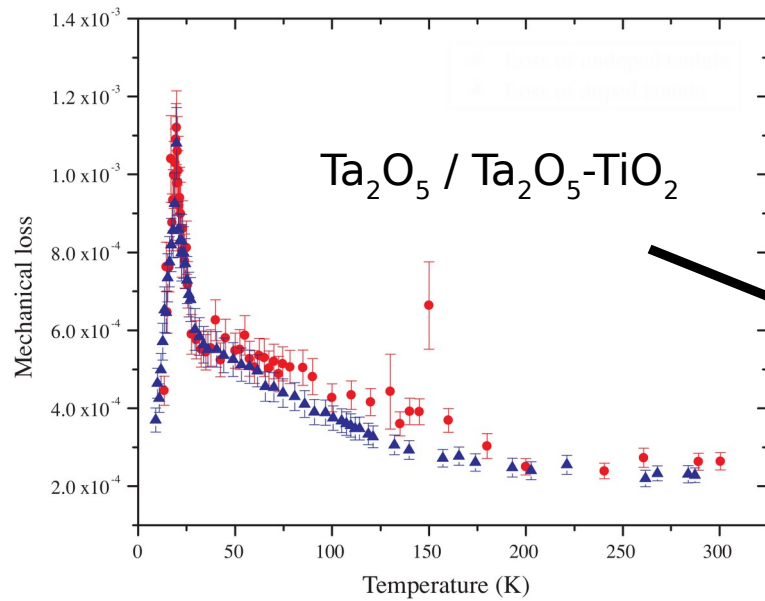
IBS oxide layers of present detectors have a dissipation peak at low temperature



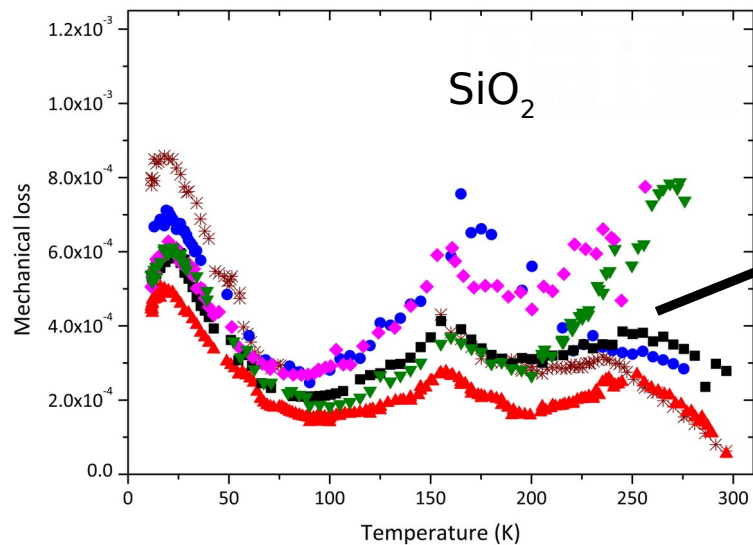
Martin et al, doi.org/10.1088/0264-9381/31/3/035019

Granata et al, doi.org/10.1515/amm-2015-0060

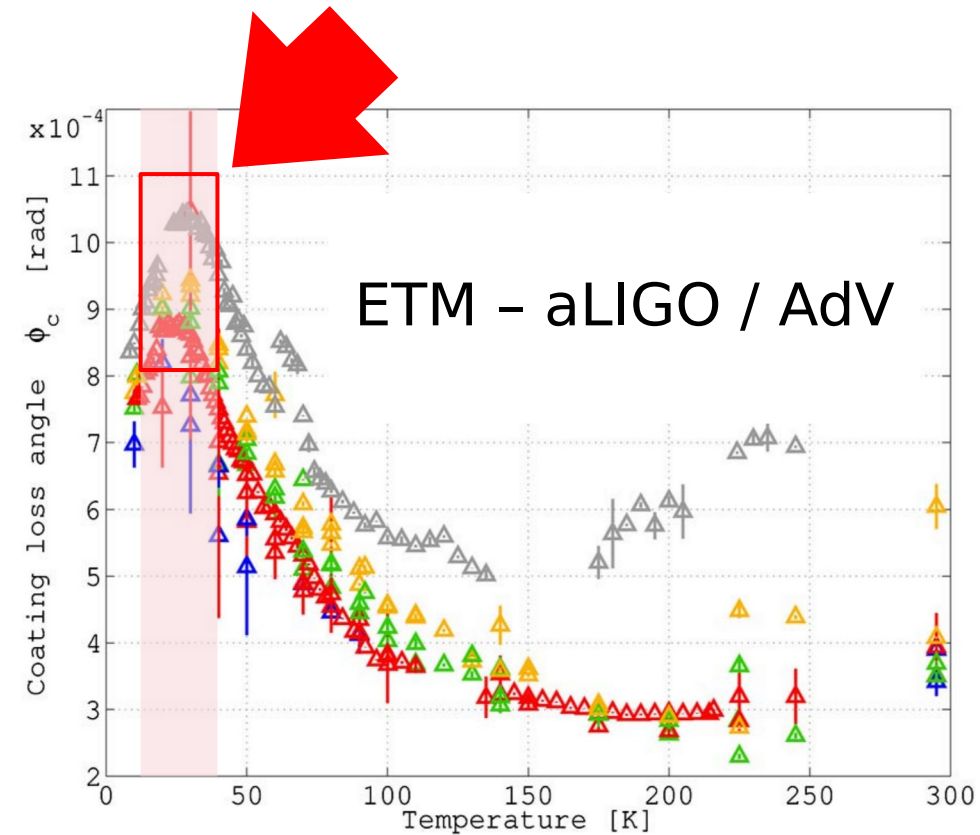
Issue



Martin et al, doi.org/10.1088/0264-9381/26/15/155012



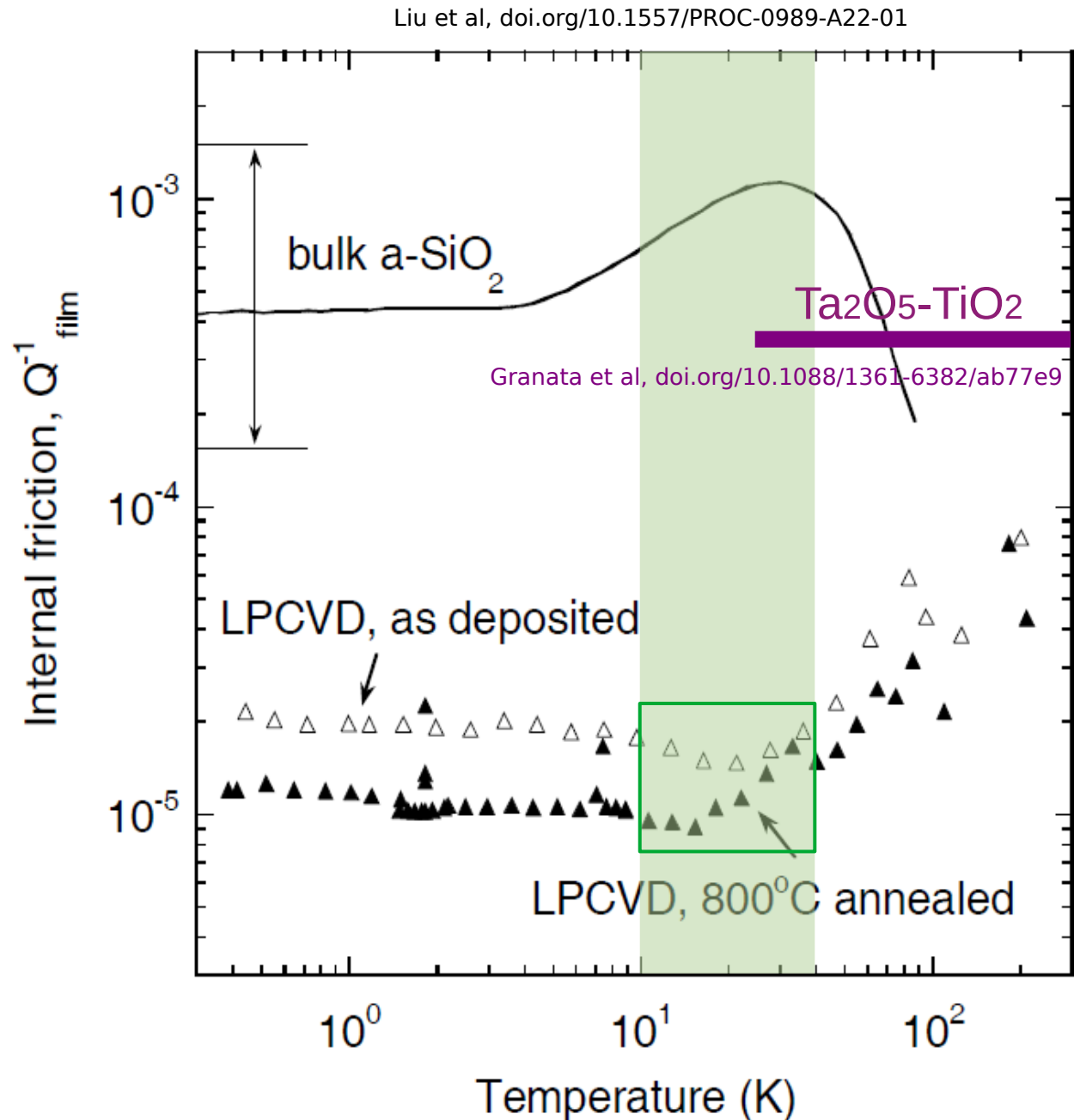
Martin et al, doi.org/10.1088/0264-9381/31/3/035019
Granata et al, doi.org/10.1515/amm-2015-0060



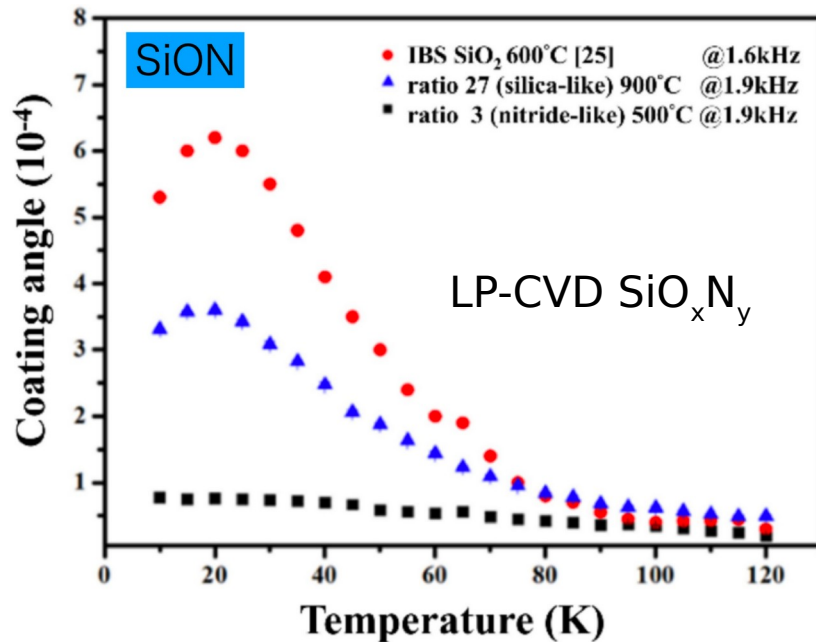
Granata et al, doi.org/10.1364/OL.38.005268

SiNx

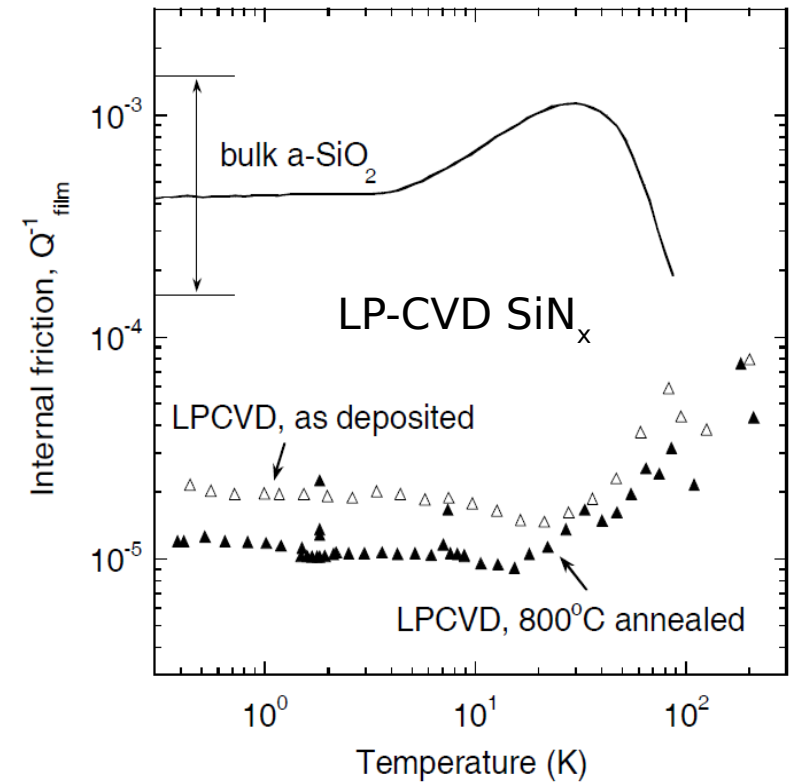
- Low loss angle
 - at room temperature
 - at low temperature
 - High index contrast
 - $n_{\text{SiNx}} \sim 2.1$ at 1064 nm
 - vs $n_{\text{SiO}_2} \sim 1.5$
 - vs $n_{\text{a-Si}} \sim 3.5$
- candidate for present and future detectors
- Advanced Virgo+
 - Advanced LIGO#
 - KAGRA
 - Einstein Telescope LF
 - Einstein Telescope HF



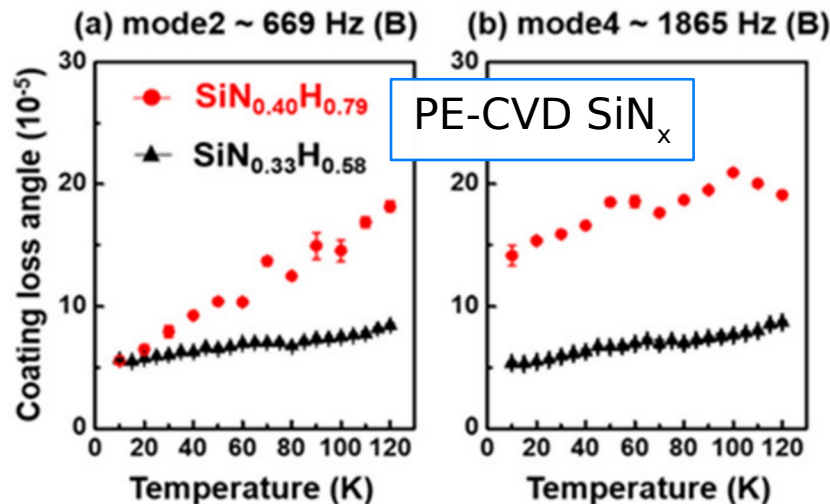
Low-T loss angle



Inoue et al, G2600545



Liu et al, doi.org/10.1557/PROC-0989-A22-01

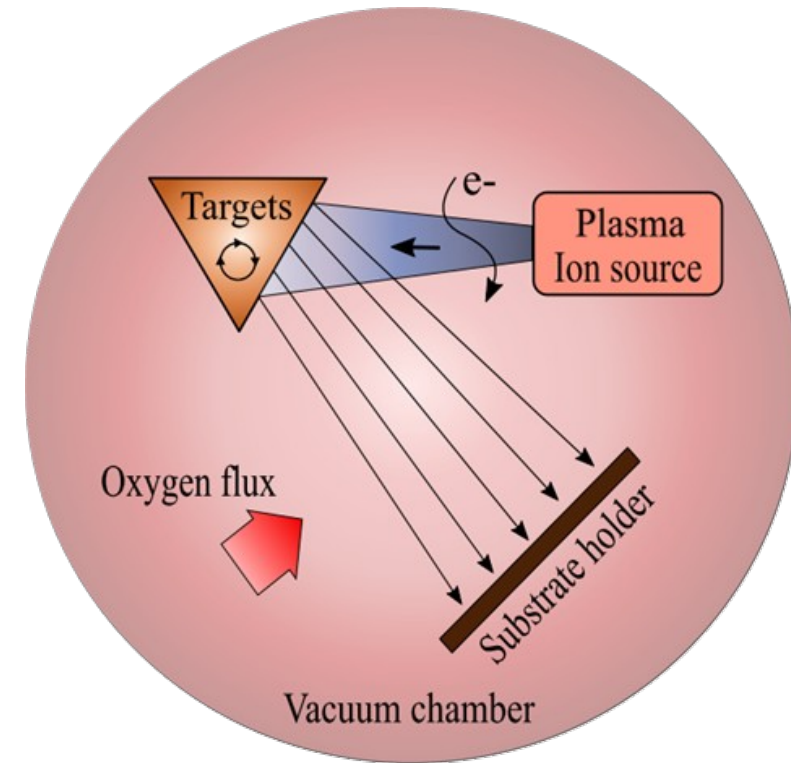


Tsai et al, doi.org/10.1088/1361-6382/ac79f6

IBS SiN_x ?

IBS

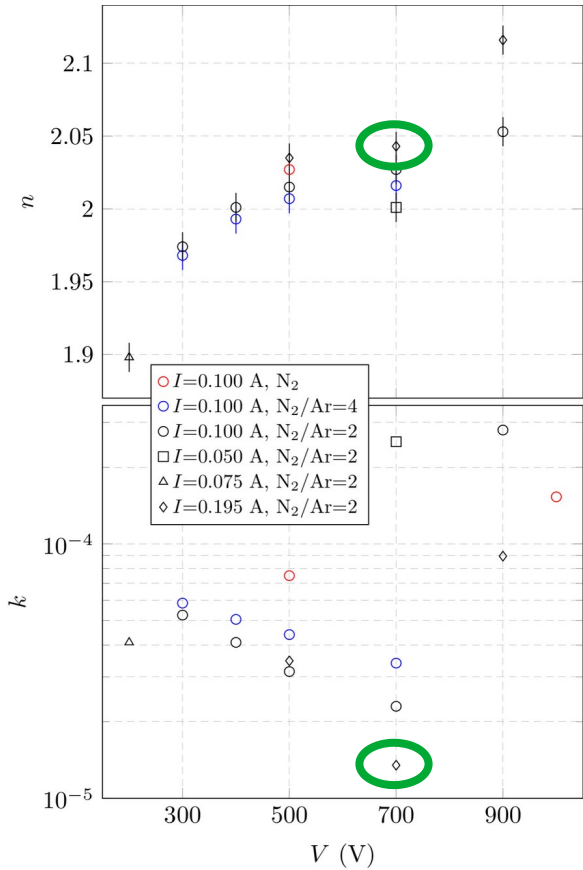
- Very low optical loss ✓
 - On any substrate ✓
 - size (up to $\varnothing = 1$ m)
 - material
 - Synthesis conditions:
 - ions' energy and current
 - growth rate
 - (reactive) working pressure
 - bombardment
 - substrate temperature
 - post-deposition *annealing*
 - soaking temperature and duration
 - heating and cooling ramps
 - atmosphere
- very large parameters' space



Our thin films

Sample	V (V)	I (mA)	Ar (sccm)	N ₂ (sccm)	n	k × 10 ⁵
20043	1000	100	0	10	(*)	15.3
21012	400	100	5	10	2.00 ± 0.01	4.1
21013	500	100	5	10	2.02 ± 0.01	3.2
21014	300	100	5	10	1.97 ± 0.01	5.3
21016	200	75	5	10	1.90 ± 0.01	4.1
21017	400	100	3	12	1.99 ± 0.01	5.1
21018	500	100	3	12	2.01 ± 0.01	4.4
21019	300	100	3	12	1.97 ± 0.01	5.9
21020	700	100	3	12	2.02 ± 0.01	3.4
21021	700	100	5	10	2.03 ± 0.01	2.3
21022	900	100	5	10	2.05 ± 0.01	28.0
21023	700	50	5	10	2.00 ± 0.01	25.2
21025	700	195	5	10	2.04 ± 0.01	1.4
22013	900	195	5	10	2.12 ± 0.01	9.0
22014	500	195	5	10	2.04 ± 0.01	3.5
22015	500	100	0	10	2.03 ± 0.01	7.5

(*) Not defined.



Amato et al, doi.org/10.1103/PhysRevD.111.042003

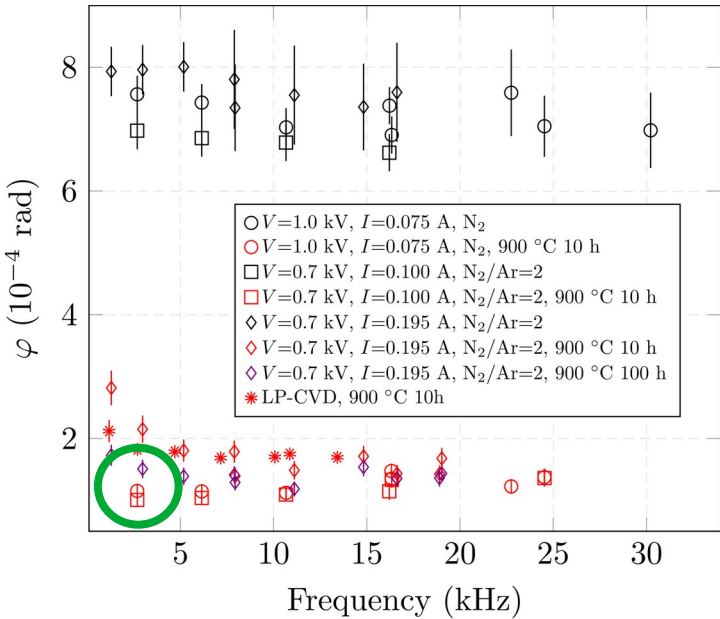
- $k \sim 1\text{e-}5$ as deposited, $\sim 6\text{e-}6$ annealed
- $\phi \sim 1\text{e-}4$ at 300 K
- $Y = 256$ GPa
- $\nu = 0.25$
- $\rho = 3.0$ g/cm³

NB: Si-rich

Sample	V (V)	H	N	Si	O	Ar	Mo	Ta	N/Si
22022	500		51.6	45.7	2.5	0.18	0.013	0.001	1.13
22020	700	0.4(*)	50.4	46.4	3.0	0.17	0.014	0.004	1.08
22023	900		48.4	48.5	2.9	0.16	0.036	0.017	1.00

(*) As measured on sample 23017, deposited under identical conditions.

$$E_g = (3.6 \pm 0.1) \text{ eV}$$

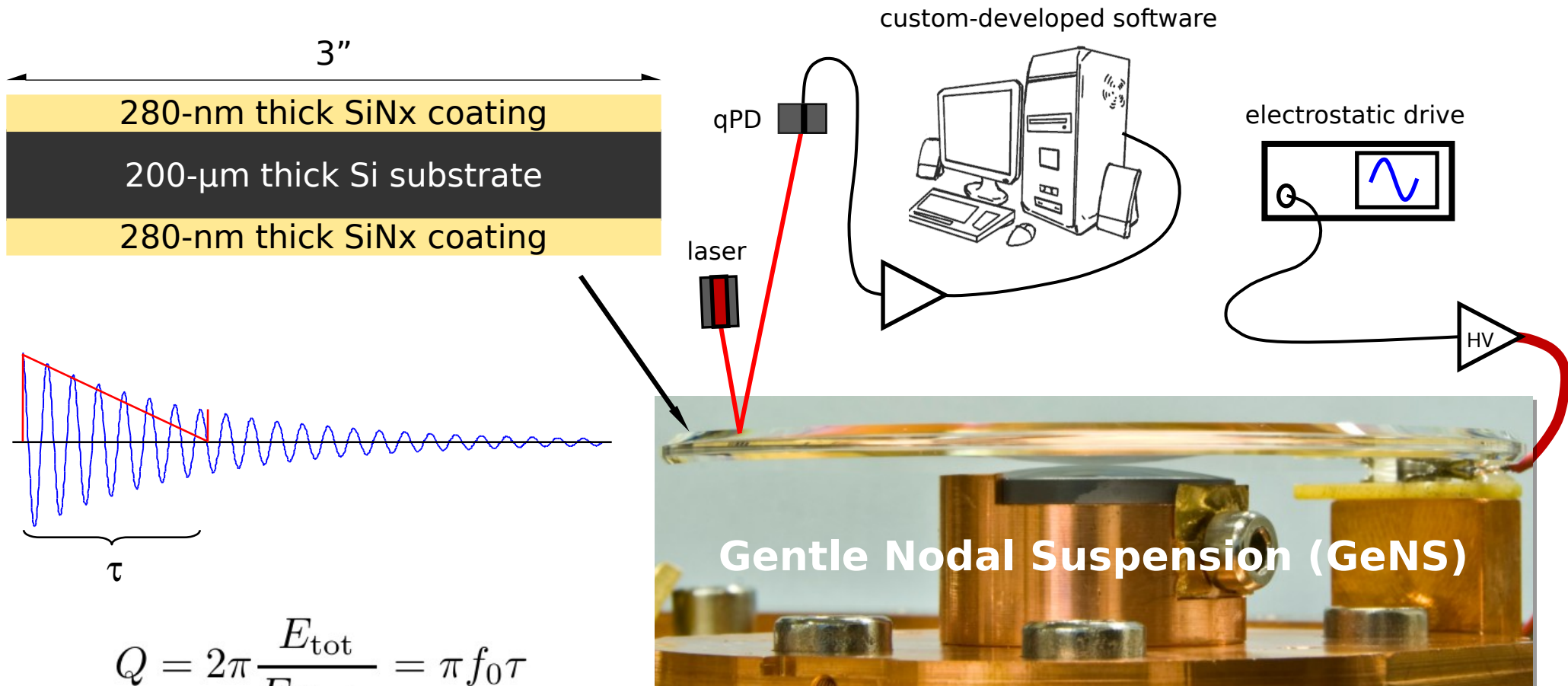


Our experiment

- A cryogenic GeNS system
- 2 nominally-identical thin samples

Granata et al, doi.org/10.1515/amm-2015-0060

Silenzi et al, doi.org/10.1088/1361-6382/ad8543



Granata et al, doi.org/10.1103/PhysRevApplied.17.034058

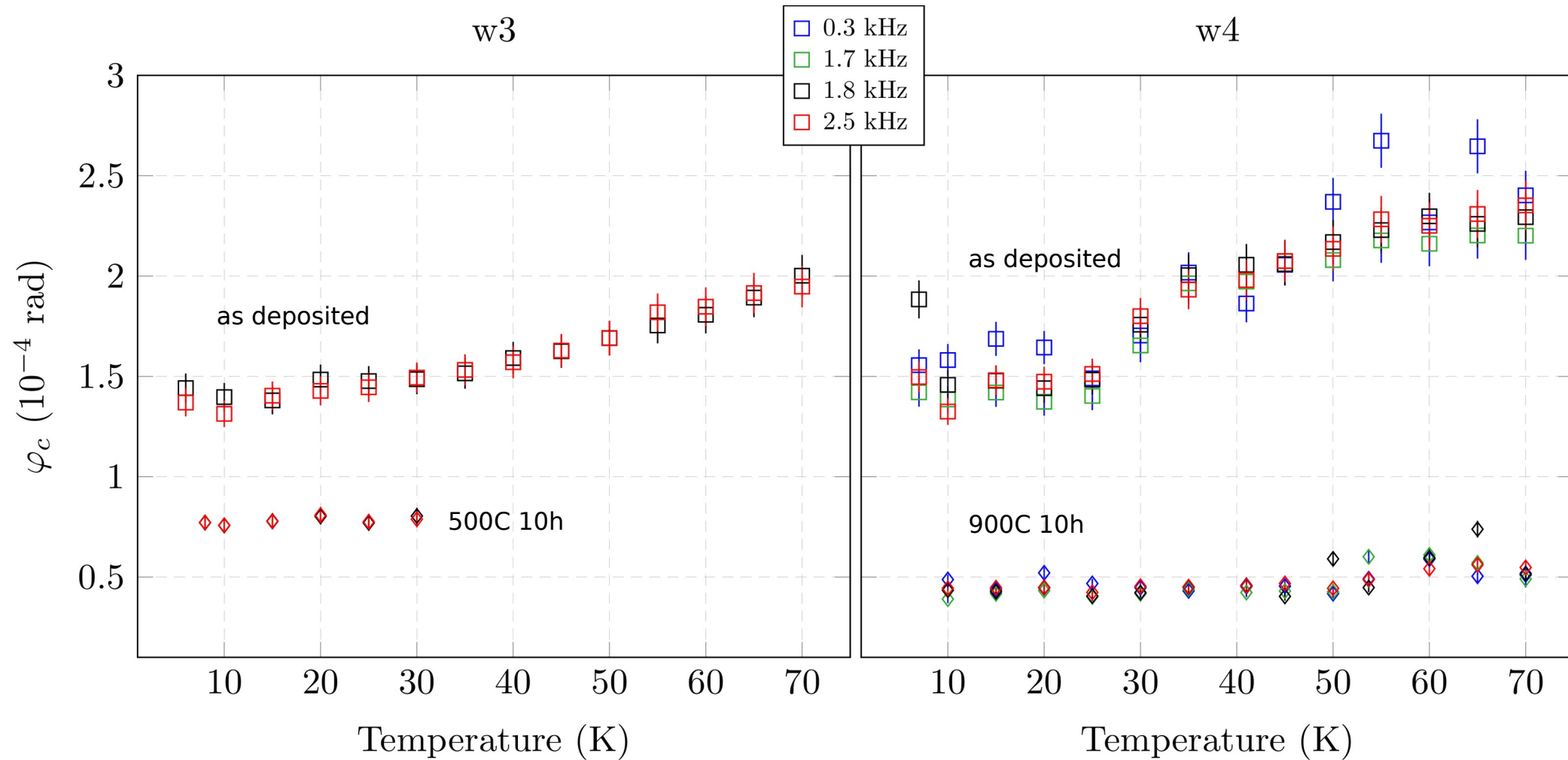
Amato et al, doi.org/10.1103/PhysRevD.106.082007

Granata et al, doi.org/10.1088/1361-6382/ab77e9

Granata et al, doi.org/10.1103/PhysRevD.93.012007

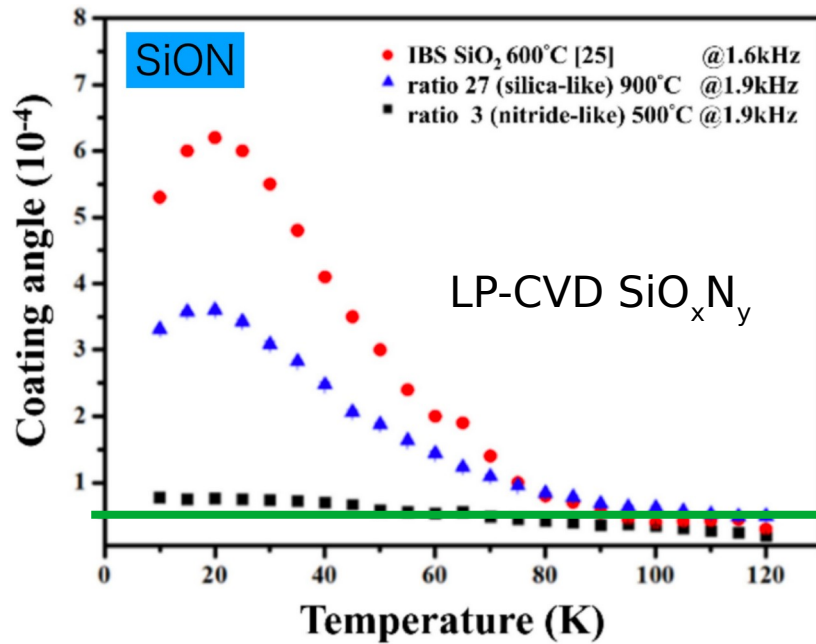
Cesarini et al, doi.org/10.1063/1.3124800

Coating loss angle

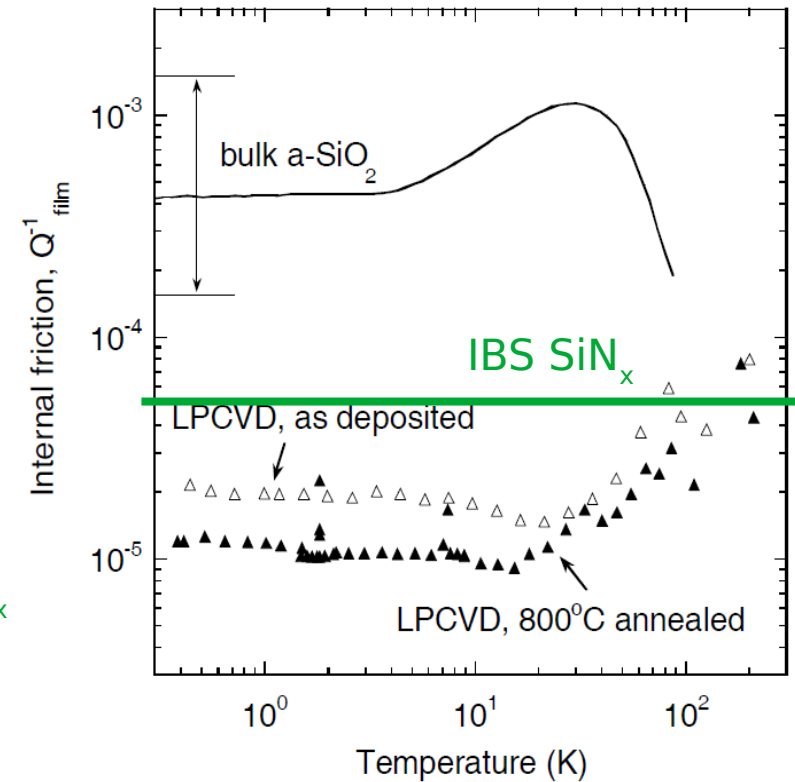


P2600356 / VIR-0535B-26 - submitted for publication

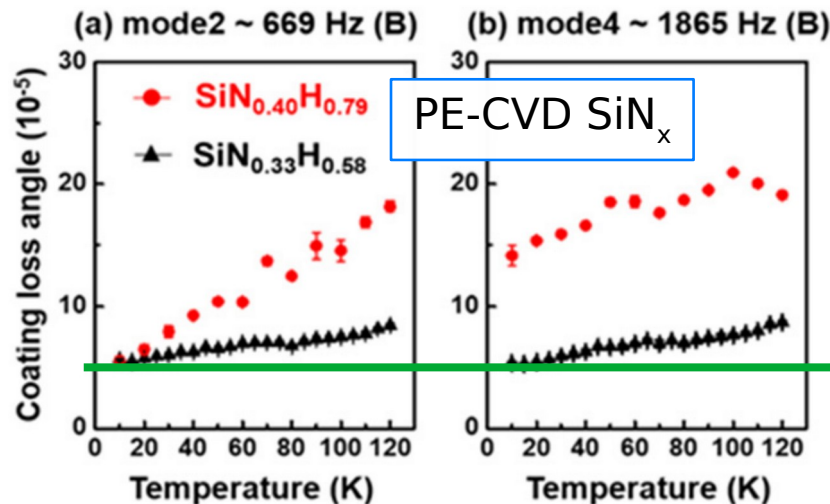
Comparison



Inoue et al, G2600545

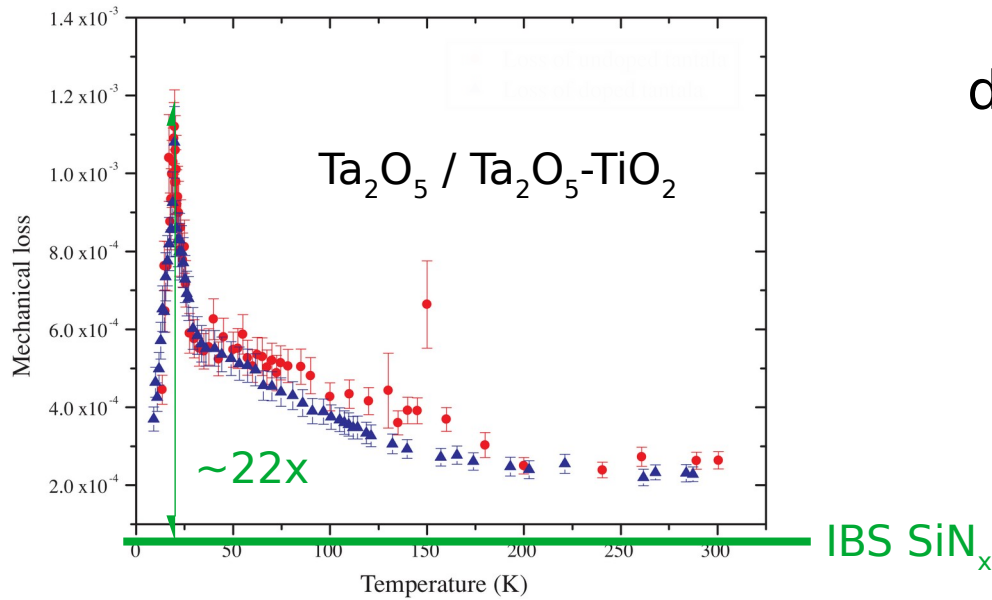


Liu et al, doi.org/10.1557/PROC-0989-A22-01

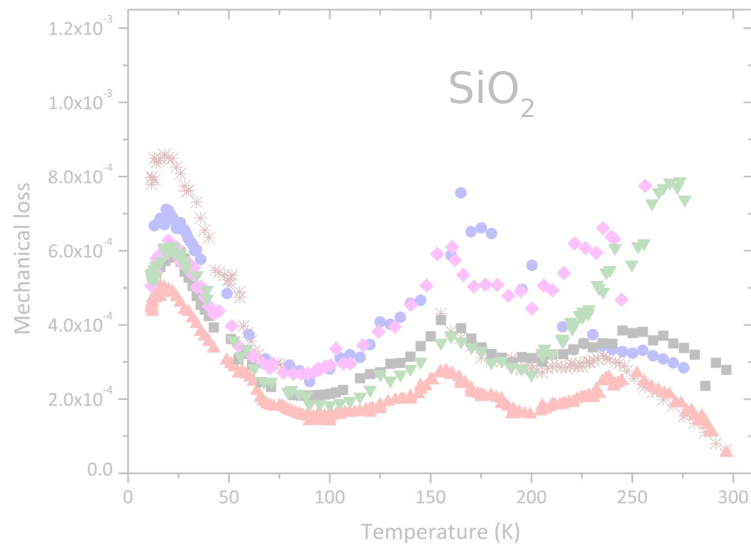


Tsai et al, doi.org/10.1088/1361-6382/ac79f6

KAGRA

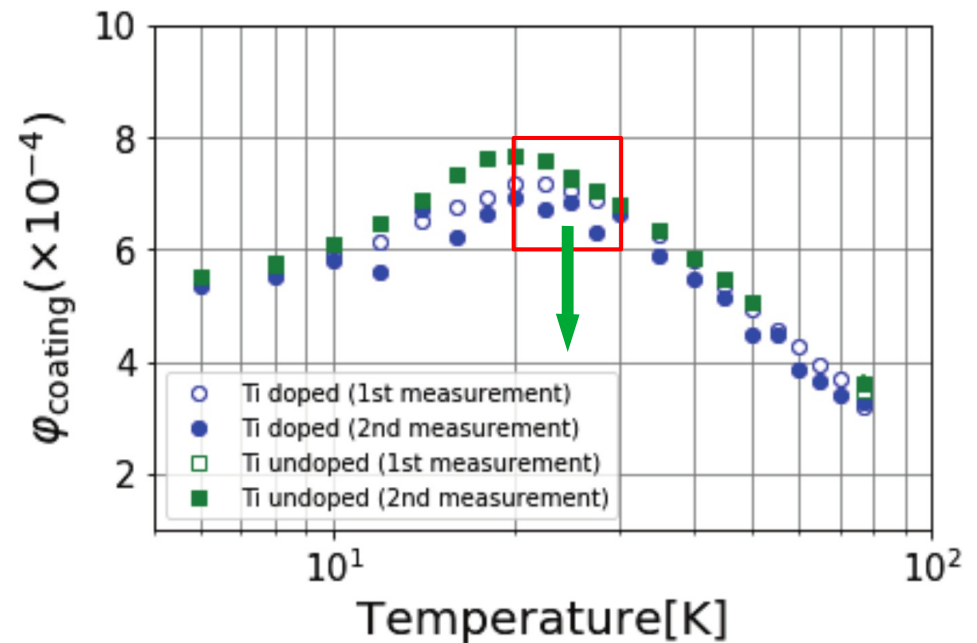


Martin et al, doi.org/10.1088/0264-9381/26/15/155012



Martin et al, doi.org/10.1088/0264-9381/31/3/035019
Granata et al, doi.org/10.1515/amm-2015-0060

dilution/decrease of the HR low-T peak
→ CTN reduction up to a factor
 ≥ 2
(depends on T and low-index layer)



Mori et al, doi.org/10.1103/PhysRevD.109.102008

ET-LF

IBS SiN_x features

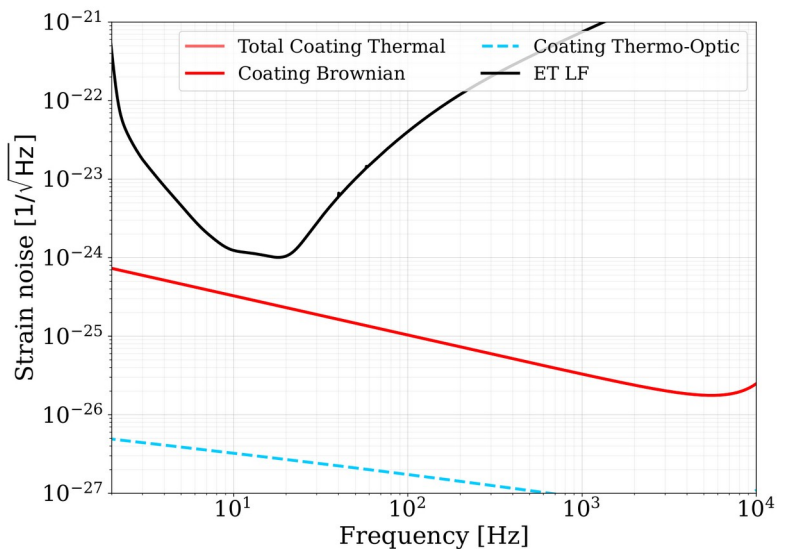
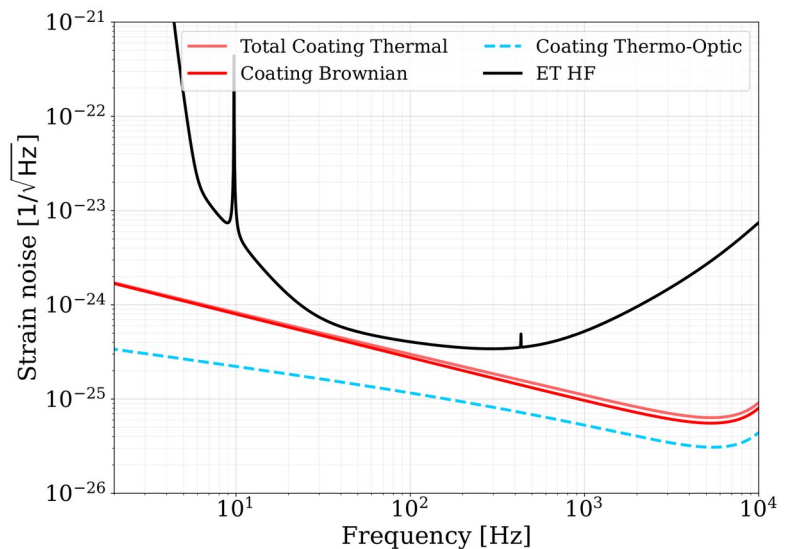
✓ 8x lower loss angle
than current reference choice



Table 6: Parameters of coatings of ET LF detector.

Parameter	Units	LF Detector
Ta ₂ O ₅		
Layer material		Ta ₂ O ₅
Young's modulus	Pa	1.4×10^{11}
Poisson's ratio	1	0.28
Specific heat	J/(kg.K)	2.1×10^6
Thermal expansion coefficient	1/K	3.6×10^{-6}
Thermorefractive coefficient, dn/dT	1/K	1.4×10^{-5}
Thermal conductivity	W/(m.K)	33.00
Refractive index	1	2.05
Loss angle	1	5.0×10^{-4}
SiO ₂		
Layer material		SiO ₂
Young's modulus	Pa	7.2×10^{10}
Poisson's ratio	1	0.17
Specific heat	J/(kg.K)	1.6×10^6
Thermal expansion coefficient	1/K	5.1×10^{-7}
Thermorefractive coefficient, dn/dT	1/K	8.0×10^{-6}
Thermal conductivity	W/(m.K)	1.38
Refractive index	1	1.44
Loss angle	1	8.5×10^{-4}
SiO ₂ : HfO ₂		
Layer material		SiO ₂ : HfO ₂
Young's modulus	Pa	1.8×10^{11}
Poisson's ratio	1	0.20
Specific heat	J/(kg.K)	1.6×10^6
Thermal expansion coefficient	1/K	5.1×10^{-7}
Thermorefractive coefficient, dn/dT	1/K	8.0×10^{-6}
Thermal conductivity	W/(m.K)	1.38
Refractive index	1	1.91
Loss angle	1	3.8×10^{-4}
a-Si		
Layer material		a-Si
Young's modulus	Pa	1.5×10^{11}
Poisson's ratio	1	0.20
Specific heat	J/(kg.K)	2.1×10^6
Thermal expansion coefficient	1/K	3.6×10^{-6}
Thermorefractive coefficient, dn/dT	1/K	1.4×10^{-5}
Thermal conductivity	W/(m.K)	33.00
Refractive index	1	3.48
Loss angle	1	1.7×10^{-5}

ET-0007C-23 - Conceptual design and noise budget of Einstein Telescope



BONUS – ET-HF

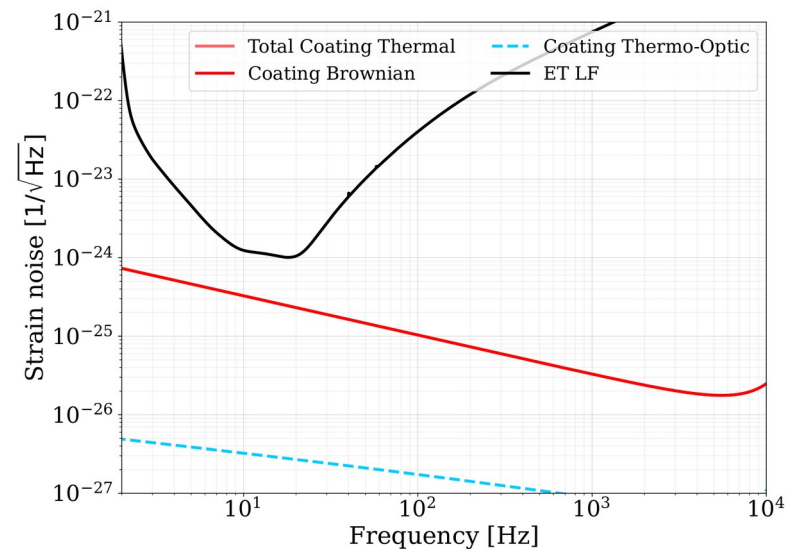
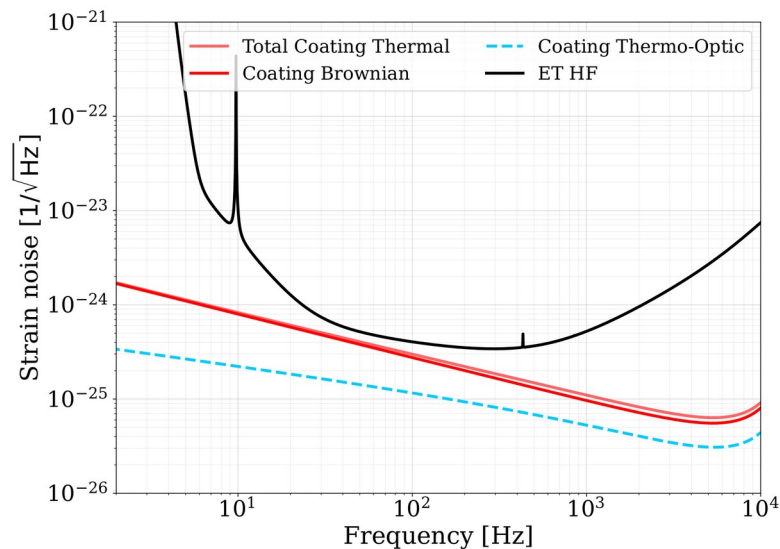
✓ IBS SiN_x compliant w/ specifications



Table 4: Parameters of coatings of ET HF detector.

Parameter	Units	HF Detector
ITM coating bi-layers		8
ETM coating bi-layers		17
High-n layers material		TBD
Each layer thickness	Wavelength	0.25
Young's modulus	Pa	1.2×10^{11}
Poisson's ratio	1	0.29
Volumetric heat capacity	$\text{J}/(\text{m}^3 \cdot \text{K})$	2.1×10^6
Thermal conductivity	$\text{W}/(\text{m} \cdot \text{K})$	33.0
Thermal expansion coefficient	$1/\text{K}$	3.6×10^{-6}
Refractive index		2.09
Thermorefractive coefficient	$1/\text{K}$	1.4×10^{-5}
Loss angle	1	$9.0 \times 10^{-5} \times f^{0.10}$
Low-n layers material		TBD
Layer optical thickness	Wavelength	0.25
Young's modulus	Pa	7.0×10^{10}
Poisson's ratio	1	0.19
Volumetric heat capacity	$\text{J}/(\text{m}^3 \cdot \text{K})$	1.6×10^6
Thermal conductivity	$\text{W}/(\text{m} \cdot \text{K})$	1.4
Thermal expansion coefficient	$1/\text{K}$	5.1×10^{-7}
Refractive index	1	1.45
Thermorefractive coefficient	$1/\text{K}$	8.0×10^{-6}
Loss angle	1	$1.2 \times 10^{-5} \times f^{0.00}$

ET-0007C-23 - Conceptual design and noise budget of Einstein Telescope



Perspectives

- ✗ Optical absorption still too high
k $\sim 1\text{e-}5$ as deposited, $\sim 6\text{e-}6$ annealed



Perspectives

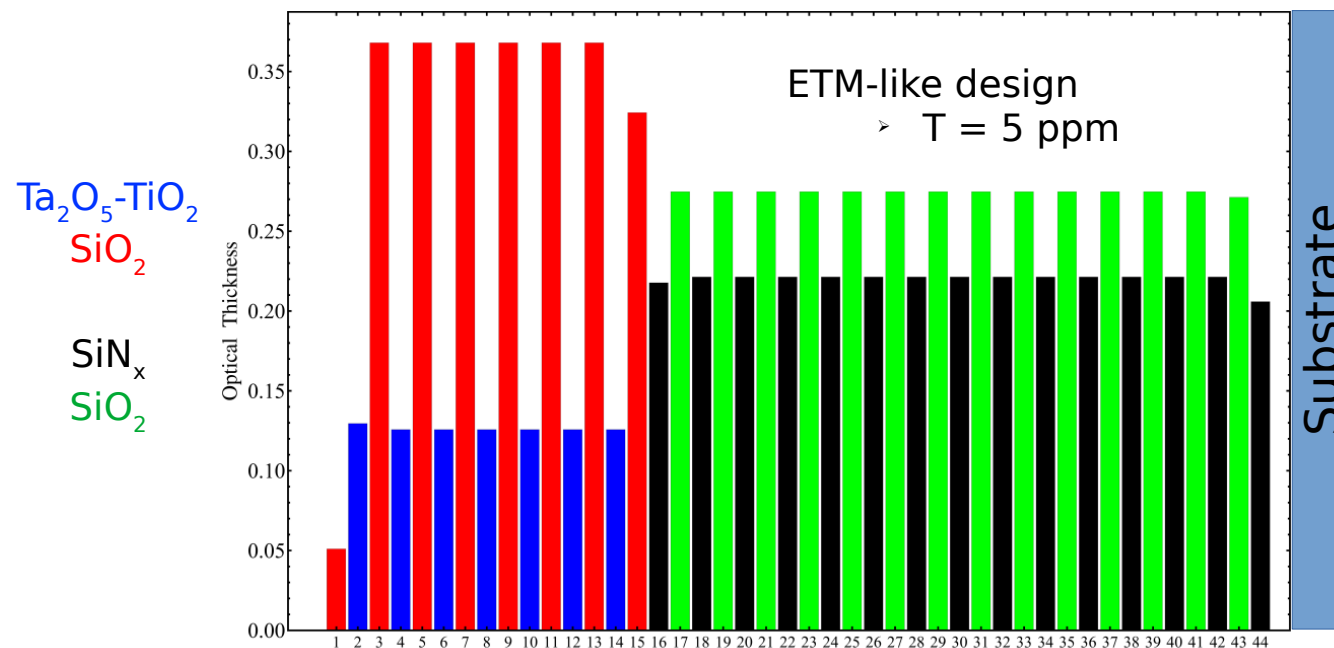
✗ Optical absorption still too high

✓ Multi-material design demonstrated



Sample	CTN ($10^{-18} \text{ m Hz}^{-1/2}$)	a_{CTN} (ppm)	a_{PTD} (ppm)
10036	$(10.3 \pm 0.2) \times \left(\frac{100 \text{ Hz}}{f}\right)^{0.50 \pm 0.03}$	1.3 ± 0.5	1.9 ± 0.2
ETM	$(13.7 \pm 0.3) \times \left(\frac{100 \text{ Hz}}{f}\right)^{0.45 \pm 0.02}$	0.5 ± 0.2	0.27 ± 0.07

Amato et al, doi.org/10.1103/PhysRevD.111.042003



✗ Optical absorption still too high

✓ Multi-material design demonstrated

New optimization campaign ongoing

✓ upgraded r&d coater

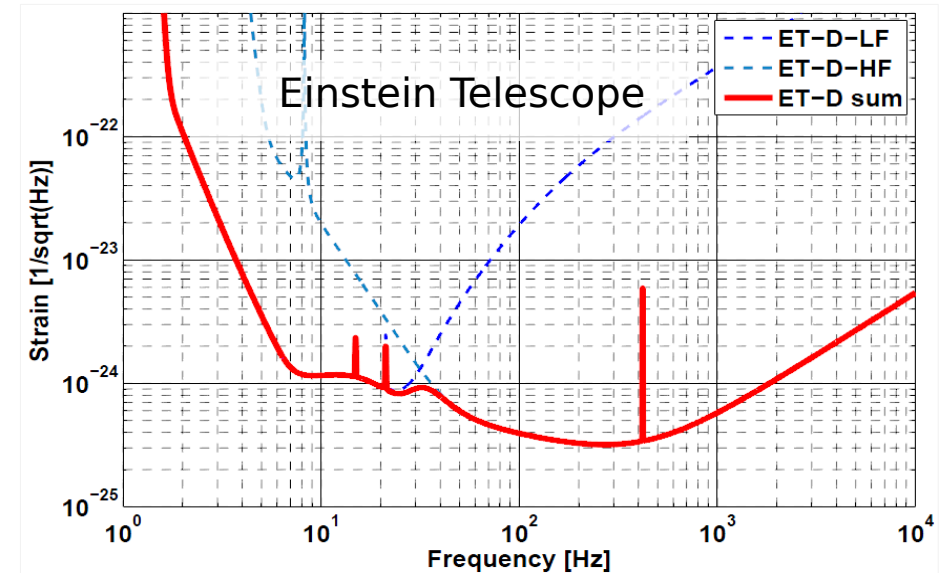
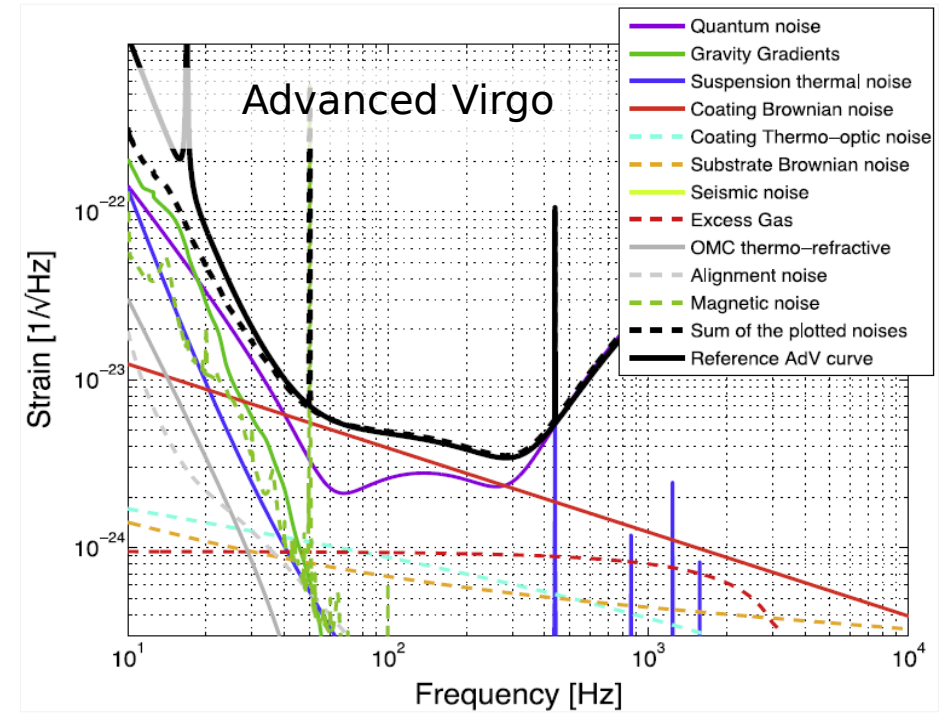
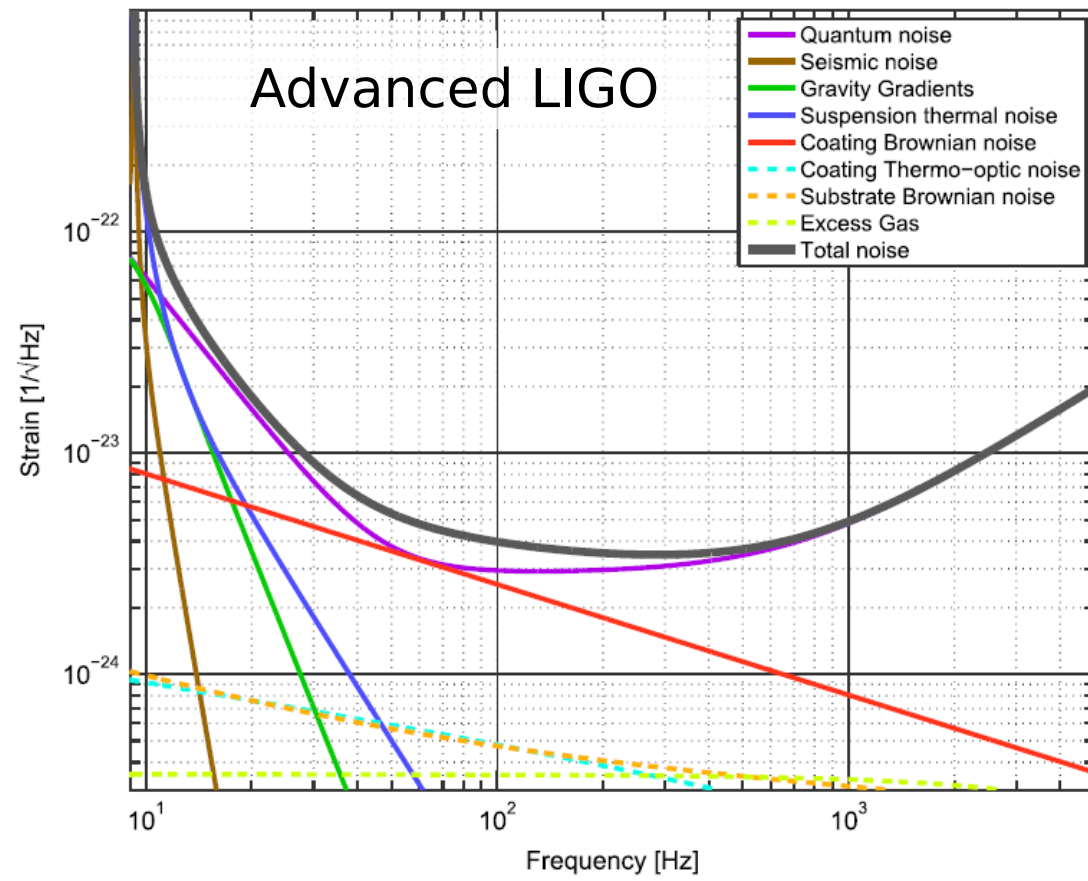
Sample	N/Si (wt%)	n	k	k	k
				500 °C	900 °C
26018	0.76 ± 0.04	2.05	4.7×10^{-4}	3.1×10^{-4}	3.1×10^{-4}
26019	0.72 ± 0.04	2.07	7.0×10^{-4}		
26020	0.38 ± 0.02	2.70	$\sim 10^{-2}$		
26021	0.73 ± 0.04	2.02	6.0×10^{-5}	9.2×10^{-6}	4.1×10^{-6}
26022	0.74 ± 0.04	2.01	6.8×10^{-5}	9.6×10^{-6}	3.4×10^{-6}
26023	0.42 ± 0.02	2.60	5.0×10^{-3}		

Table 1: Refractive index n and extinction coefficient k at 1064 nm.

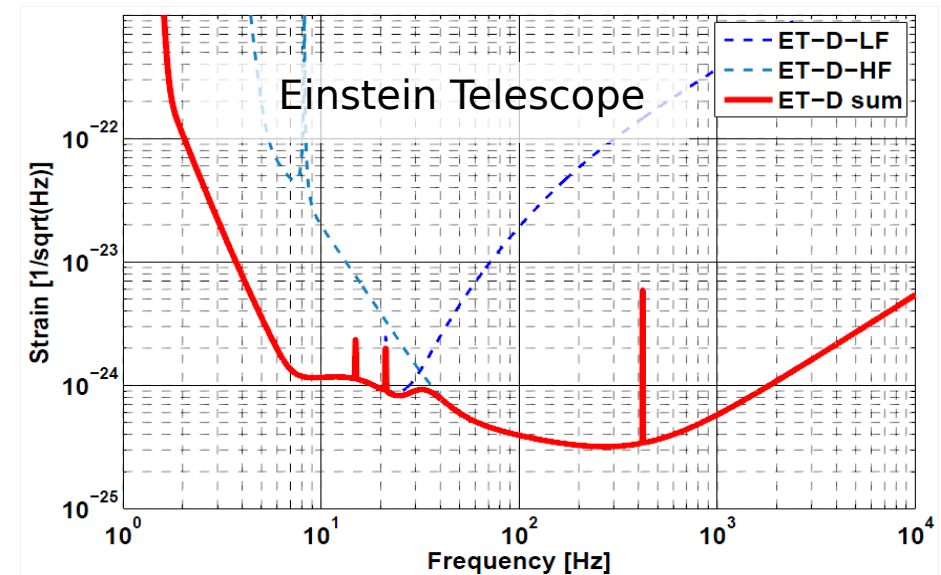
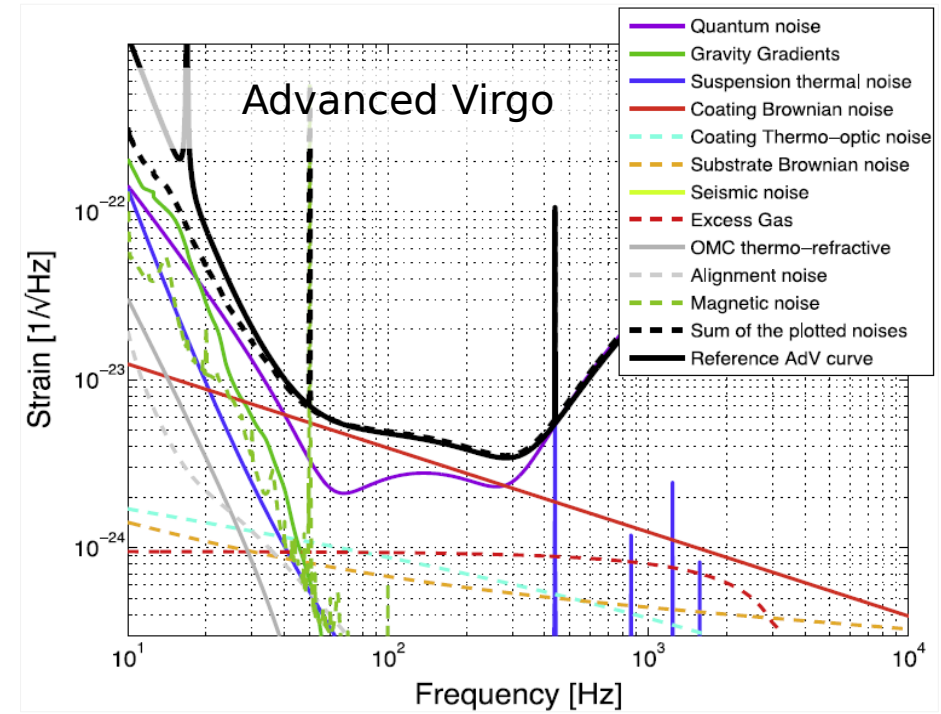
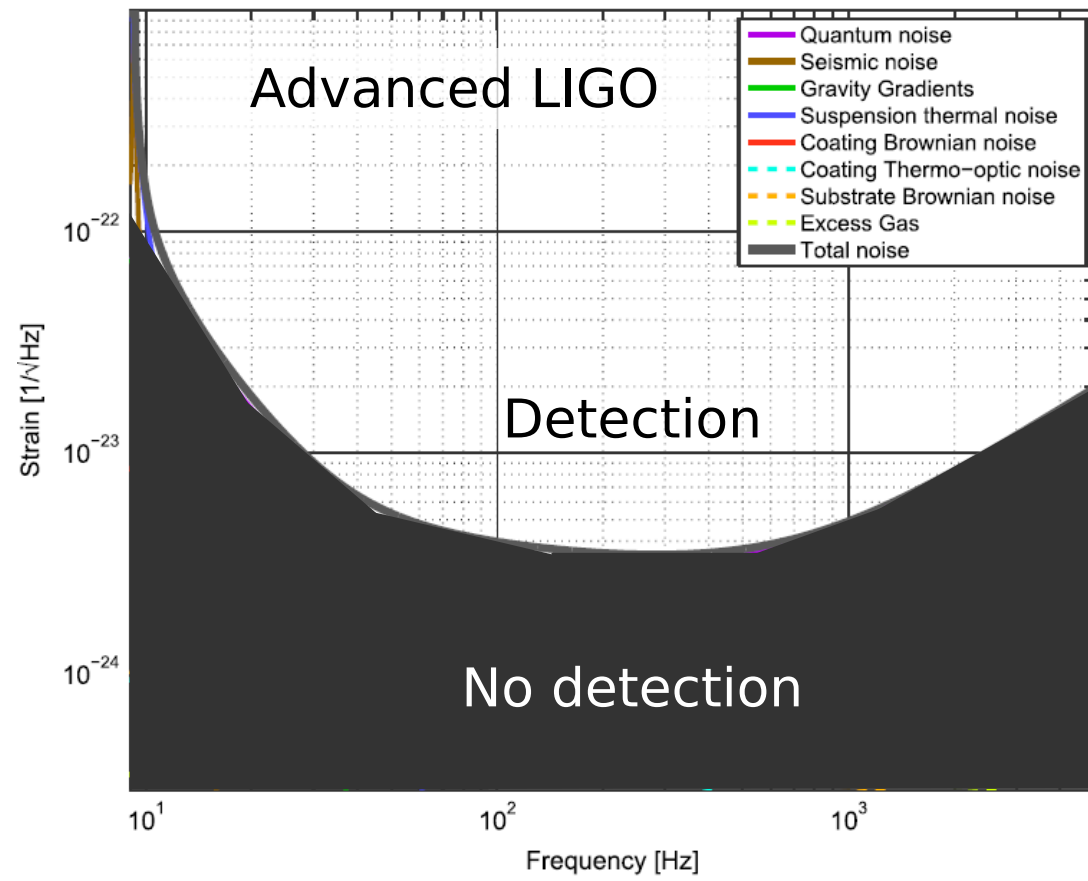




Sensitivity



Sensitivity



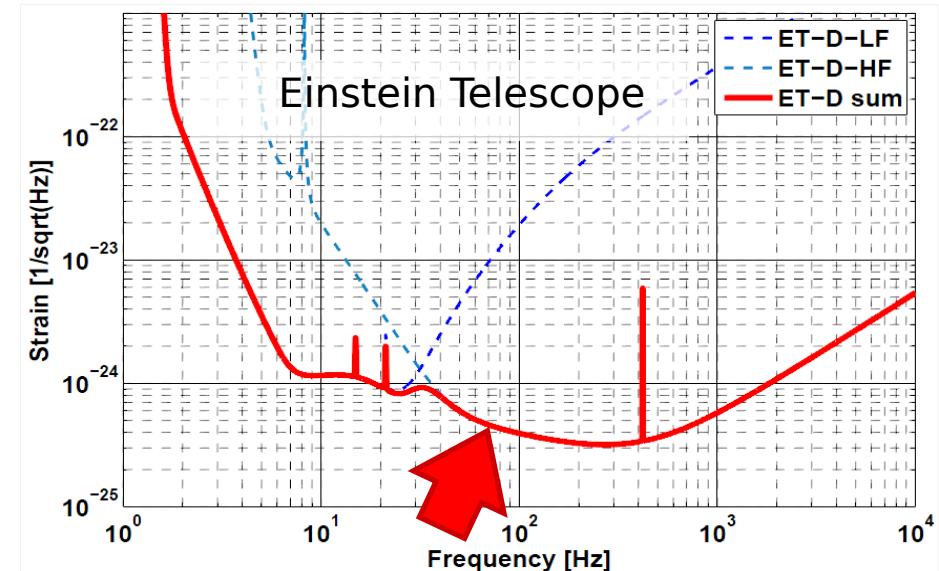
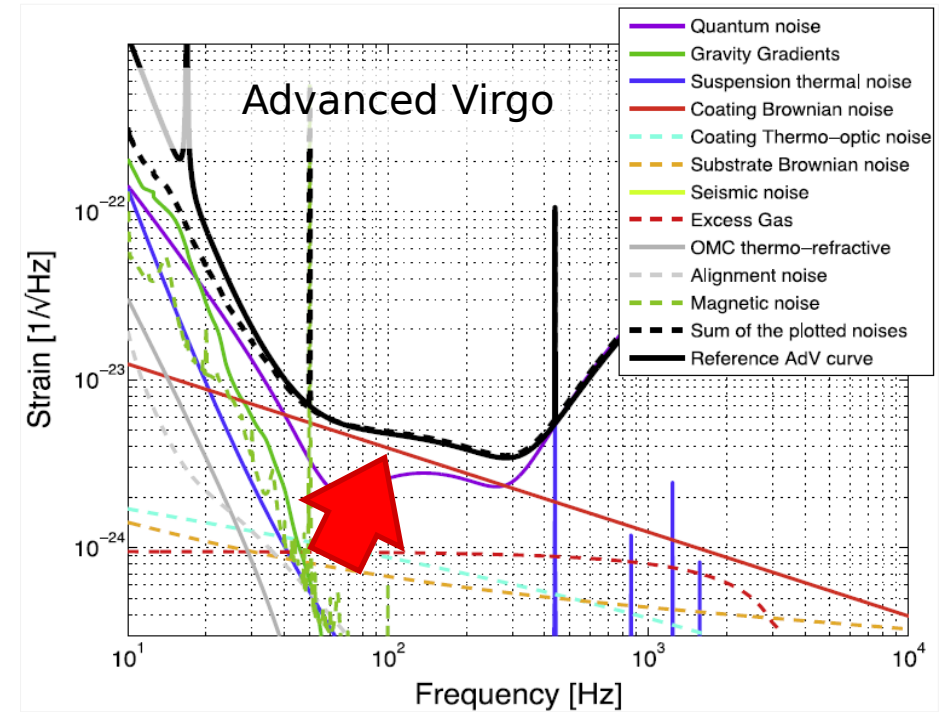
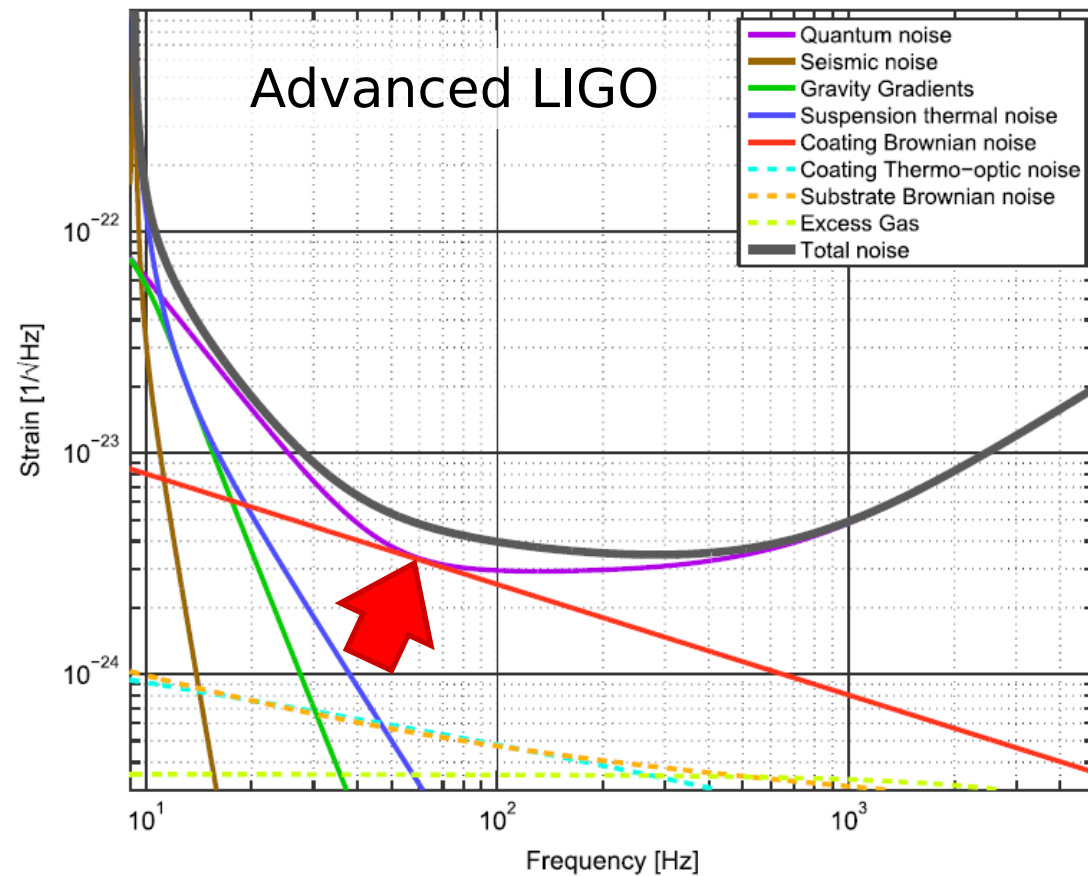
Coating thermal noise (CTN)

- Sensitivity limit of present and future detectors

Aasi et al, doi.org/10.1088/0264-9381/32/7/074001

Acernese et al, doi.org/10.1088/0264-9381/32/2/024001

ET Coll, ET-0007B-20, <https://apps.et-gw.eu/tds/ql/?c=15418>



Currently

IOP Publishing

Class. Quantum Grav. **37** (2020) 095004 (20pp) <https://doi.org/10.1088/1361-6382/ab77e9>

Amorphous optical coatings of present gravitational-wave interferometers*

M Granata^{1,5} , A Amato¹ , L Balzarini^{1,6}, M Canepa^{2,3}, J Degallaix¹, D Forest¹, V Dolique^{1,7}, L Mereni¹, C Michel¹, L Pinard¹, B Sassolas¹, J Teillon¹ and G Cagnoli⁴

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Research Article

Vol. 59, No. 5 / 10 February 2020 / *Applied Optics* **A229**

applied optics

Progress in the measurement and reduction of thermal noise in optical coatings for gravitational-wave detectors

M. GRANATA,^{1,*} A. AMATO,¹ G. CAGNOLI,² M. COULON,¹ J. DEGALLAIX,¹ D. FOREST,¹ L. MERENI,¹ C. MICHEL,¹ L. PINARD,¹ B. SASSOLAS,¹ AND J. TEILLON¹

REVIEW

ADVANCED PHOTONICS RESEARCH

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Mirror Coating Research and Developments for Current and Future Gravitational-Wave Detectors

Alex Amato, Michele Magnozzi, and Janis Wöhler*

SiNx coatings in the LVK

- 2010-17: LP-CVD membranes

LUH / IGR

Steinlchner, Ph.D. Thesis, doi.org/10.15488/8175

Steinlchner et al, doi.org/10.1103/PhysRevD.96.022007

Fletcher et al, doi.org/10.3389/fmats.2018.00001

norcada.com

- 2013-present – CVD SiNxHy / SiOxNy

NTHU / NCU

PE-CVD SiNxHy: G1300171, G1501068, G1601298, G1601702, G1700304, G1701790, G1900305, G1902341, G2101774

Kuo et al, doi.org/10.1590/1980-5373-MR-2017-0869

Pan et al, doi.org/10.1103/PhysRevD.97.022004

Pan et al, doi.org/10.1103/PhysRevD.98.102001

Tsai et al, doi.org/10.1088/1361-6382/ac79f6

PE-CVD SiOxNy: G2200700

Chao et al, doi.org/10.1103/PhysRevLett.130.081403

LP-CVD SiNx: G2101792, G2301831, G2600545

LP-CVD SiOxNy: G2400933, G2401675, G2600545

- 2016-present – IBS SiNx

LMA-IP2I

Amato, Ph.D. Thesis, hal.science/tel-02475821

G1701420, G1701598, VIR-0916A-20, G2100484, VIR-0272B-21, VIR-0375A-21, G2101086, G2101459

Amato et al, doi.org/10.1088/1742-6596/957/1/012006

Granata et al, doi.org/10.1364/AO.377293

Amato et al, doi.org/10.1103/PhysRevD.111.042003

Diksha et al, doi.org/10.3390/coatings15121465



SiNx coatings in the LVK

- 2023-present – CVD / IBS, SiNx / SiOxNy
IGR/US/UWS/EPOC
IBS Si(O)Nx: G2301781, G2401701, G2500625, G2600685,
Wallace et al, doi.org/10.1088/1361-6382/ad35a1
PE-CVD SiNx/SiOxNy: P2600206
Saunders et al, doi.org/10.1364/AO.578011
UniPD [coming soon]
- Since last year – MS SiNx
UniPD
ET-0439A-25
IGR/US/UWS/EPOC
PA-MS: Lindsay et al, doi.org/10.1364/AO.578043

SiNx as low index layer

PHYSICAL REVIEW LETTERS **120**, 263602 (2018)

Silicon-Based Optical Mirror Coatings for Ultrahigh Precision Metrology and Sensing

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coatings

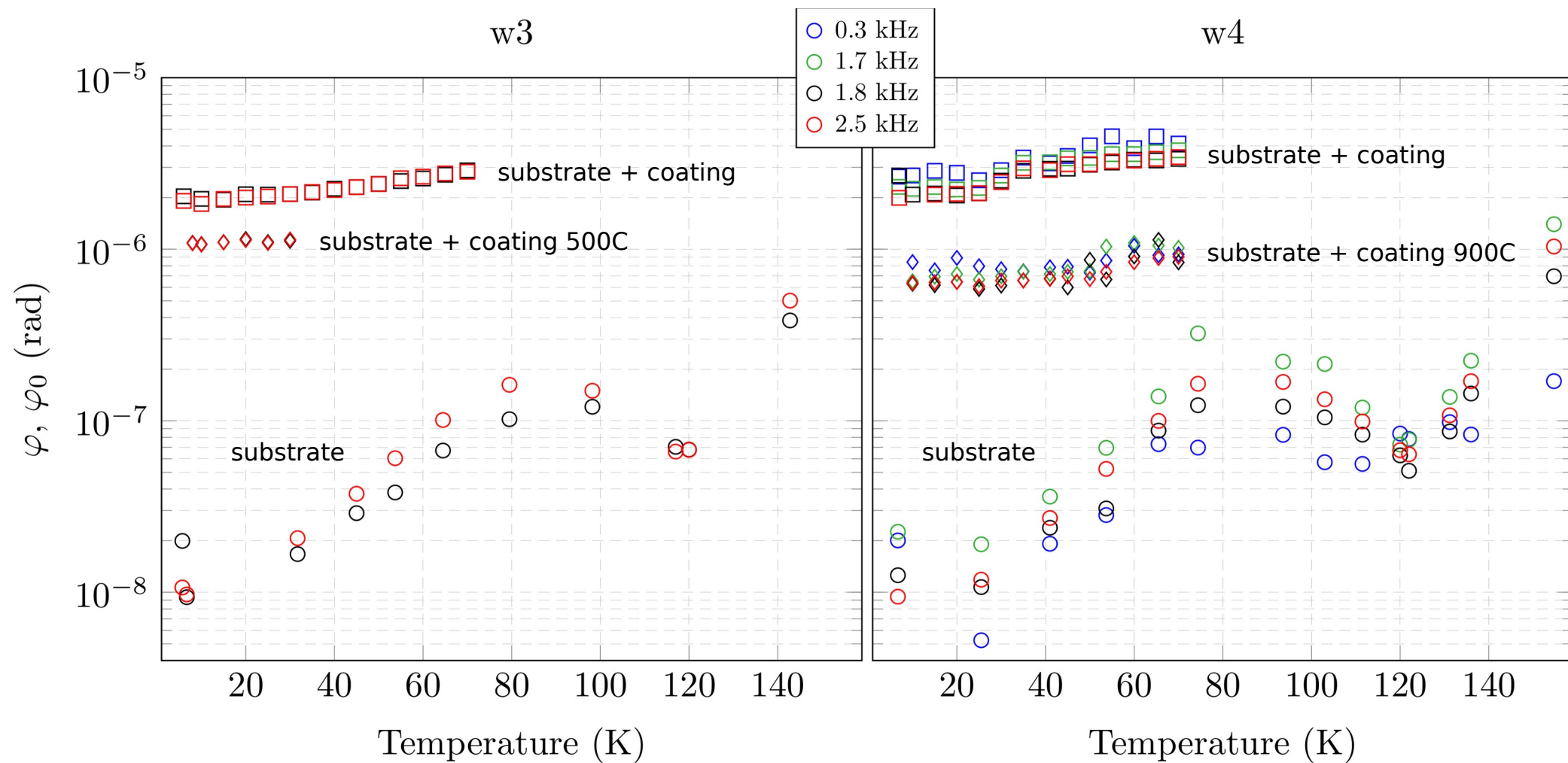


Article

Optical Properties at 1550 nm of Ion-Beam Sputtered Silicon Nitride Thin Films

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Massimo Granata ⁵ and Jessica Steinlechner ^{1,2,6,*}

Raw data



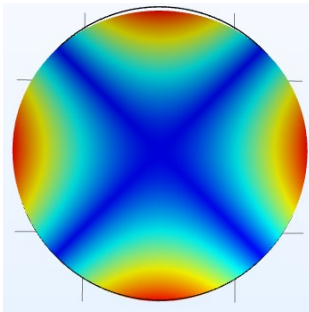
$$\Delta\varphi/\varphi \sim 10\text{-}20\% \Rightarrow \varphi \sim 10^{-9} - 10^{-7}$$

$$\Delta\varphi/\varphi \leq 5\% \Rightarrow \varphi \gtrsim 10^{-6}$$

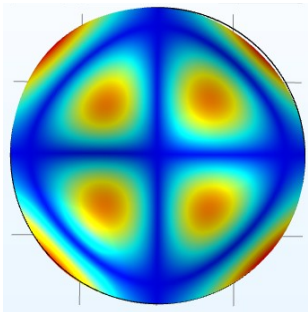
Results

Sample	$\varnothing$ (mm)	t_0 (μm)	t (nm)	m_0 (g)	m (g)	m_c (g)
w_3	76.18 ± 0.01	196 ± 5	277 ± 3 / 279 ± 3	2.0690 ± 0.0002	2.0774 ± 0.0003	0.0084 ± 0.0004
w_4	76.19 ± 0.04	195 ± 5	279 ± 3 / 280 ± 3	2.0674 ± 0.0003	2.0755 ± 0.0003	0.0081 ± 0.0004

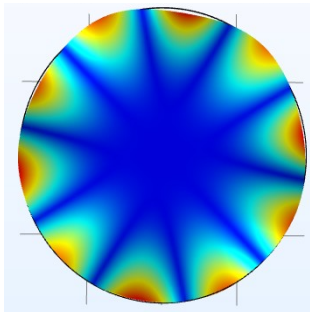
Sample	f (Hz)	f_{sim} (Hz)	$(r, a)_k$	D
w_3	1797.85 ± 0.07	1790.63	$(0,5)_{11}$	1.66
	2533.5 ± 0.1	2527.84	$(0,6)_{16}$	1.39
w_4	264.88 ± 0.01	262.62	$(0,2)_1$	1.69
	1740.46 ± 0.07	1725.71	$(1,2)_{10}$	1.61
	1788.69 ± 0.07	1781.29	$(0,5)_{11}$	1.42
	2523.3 ± 0.1	2514.65	$(0,6)_{16}$	1.41



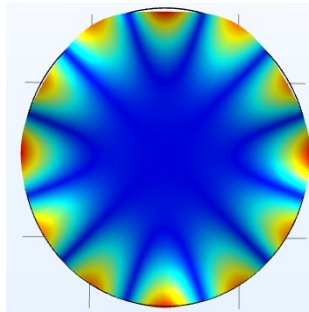
(0,2)



(1,2)



(0,5)



(0,6)