LIGO-G1500330

Status of Nano-layered Coating Developments

Riccardo DeSalvo & the INFN AdCOAT Team

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Outlook

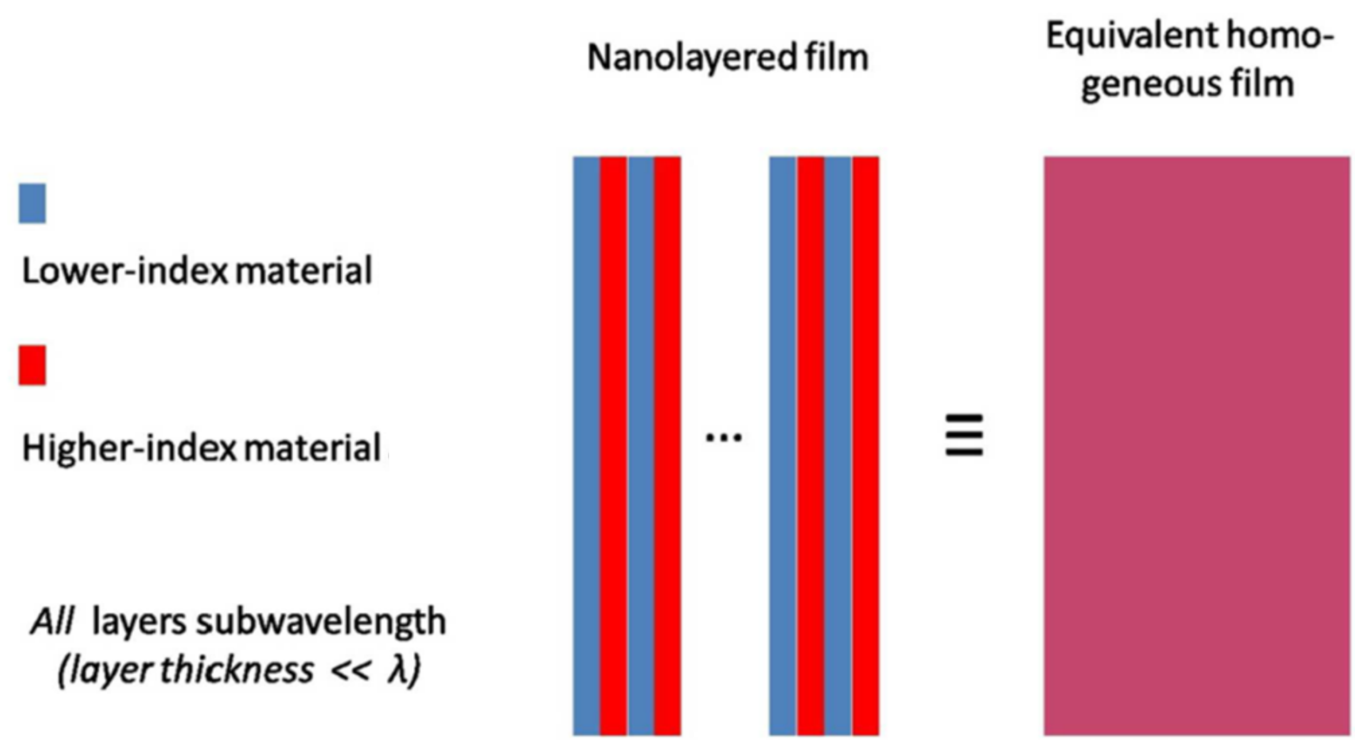
Nano-layers: What / How / Why

Development: Survey / Results / What's Next

Conclusions & Acknowledgements

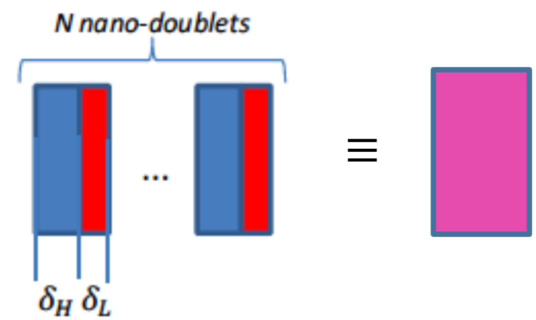
Sub-Wavelength Nano-layers

Stratified composites, whose properties depend in a *very simple way* on the constituents' properties and the thick-ness ratio



Nano-layer Prototypes

Consist of nominally identical **cascaded nano-doublets**, and are thus specified by (N, δ_H, δ_L).



Equivalent TiO_2/SiO_2 subwavelength doublet based, QWL thick composites with n_{eff}=2.09

Can adjust refraction index by changing the nano-layer thickness ratio

Can adjust the super-layer optical thickness by adjusting the number of layers

Example of segmentation of a ¼ wavelength (qwl.) super-layer

N	$\delta_{TiO_2}[nm]$	$\delta_{SiO_2}[nm]$
1	78.0559	49.2168
2	39.0279	24.6084
3	26.0186	16.4056
4	19.514	12.3042
5	15.6112	9.84337
6	13.0093	8.20281
7	11.1508	7.03098
8	9.75699	6.1521
9	8.67288	5.46854
10	7.80559	4.92168
11	7.09599	4.47426
12	6.50466	4.1014
13	6.0043	3.78591
14	5.57542	3.51549
15	5.20373	3.28112
16	4.87849	3.07605
17	4.59152	2.89511
18	4.33644	2.73427
19	4.1082	2.59036
20	3.90279	2.46084
21	3.71695	2.34366
22	3.548	2.23713
23	3.39373	2.13986
24	3.25233	2.0507
25	3.12224	1.96867

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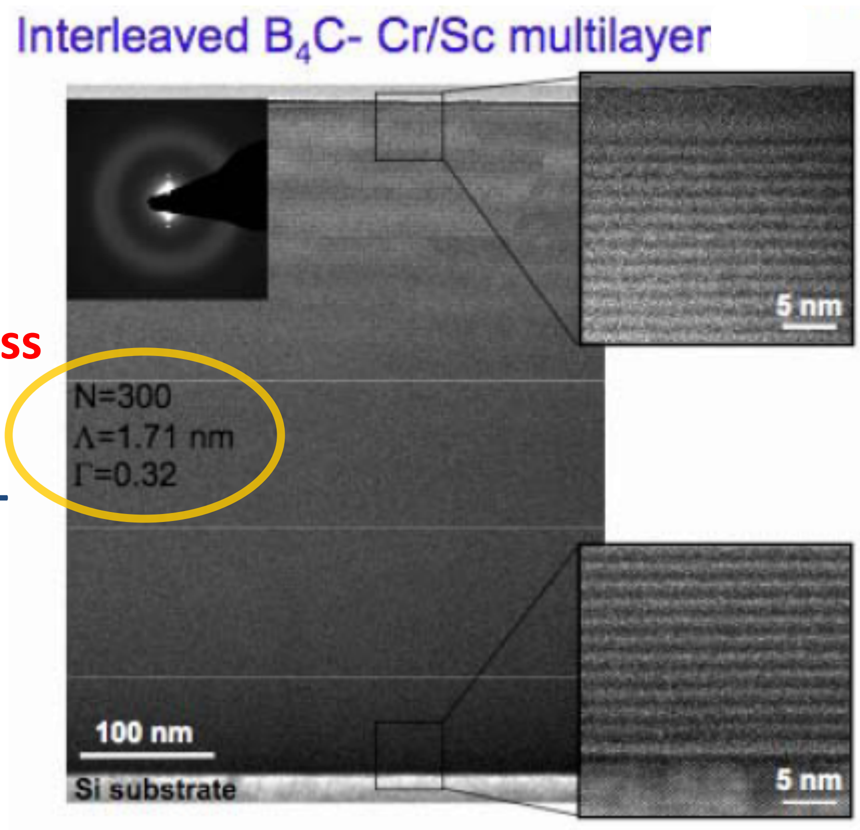
Predecessors

X-Ray Nano-layered Coatings

X-ray interference mirrors consisting of hundreds/thousands of nm scale layers, With sub - nm precision [see, e.g., Proc . 10th PXRMS Conf. (2008)] , using

- Interleaved nm-scale "buffering" layers prevent to crystallization & maintain flatness [E. Gullikson, Proc. 8th PXRMS (2006)]
- Ion assisted (modulated) magnetron sputtering [N. Ghafoor et al., Thin Sol. Films 516 (2008) 982]

Control of stress, crystallite size, and roughness [D.L. Windt, Proc. SPIE (2007) vol 6688]

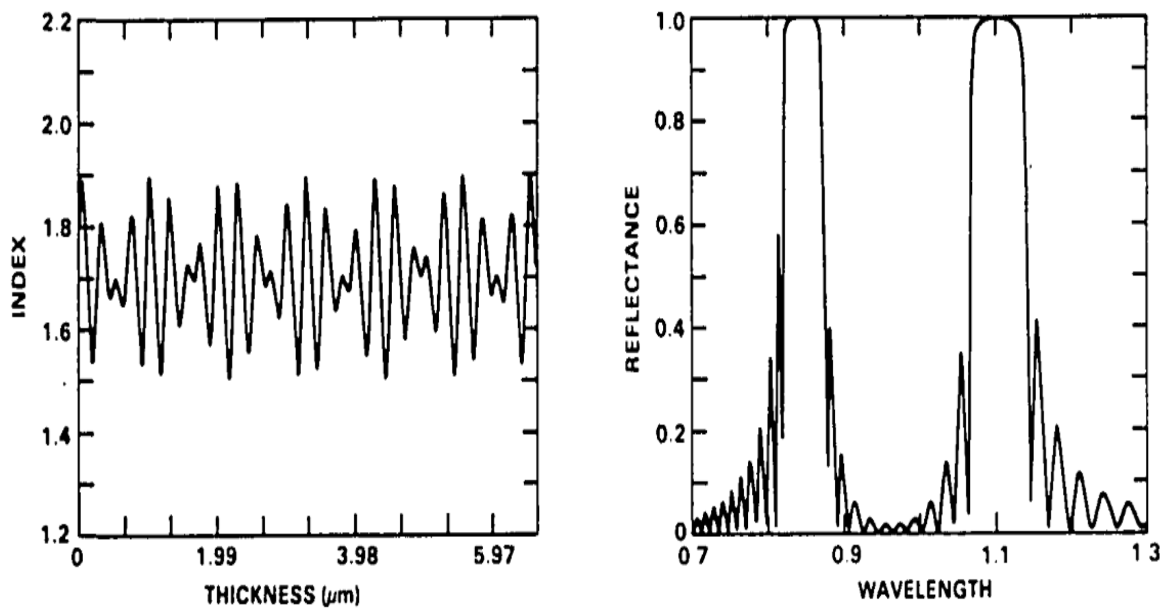


See also [R. DeSalvo, LIGO-G080106] for discussion.

Rugate Optical Filters

Rugates have been around since long. They use a *continuously varying* index distributions, to synthesize, e.g., a *dichroic response* [see, e.g.., W. H. Southwell, Appl. Opt. 24 (1985) 457-460]

Rugate dichroic mirror coating



***Mimic a continuous,* periodically-changing refraction index function by a staircase *of stacked, optically-thin homogeneous layers*…**

Requirements / Technological Challenges

relatively large thickness errors
in the *individual* low/high index nanolayer *thicknesses*
are *Irrelevant*.

IF *each layer is sub-wavelength* and
total thickness ratio has the design value

Are there any other technological issues ?

Try and see …

Outlook

Nano-layers:
- What
- How
- Why ⇦

Experiments:
- Survey
- Results
- What's Next

Conclusions & Acknowledgements

Doping Hinders Crystallization

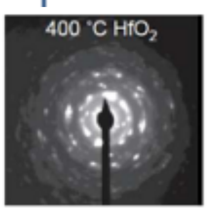
- **Silica doping contrasts crystallization** [S. Pond, Appl. Optics, 28 (1989) 2800]

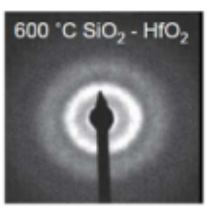
30% SiO_2 doped HfO_2 (0.5 μm thick on Silicon cantilever)

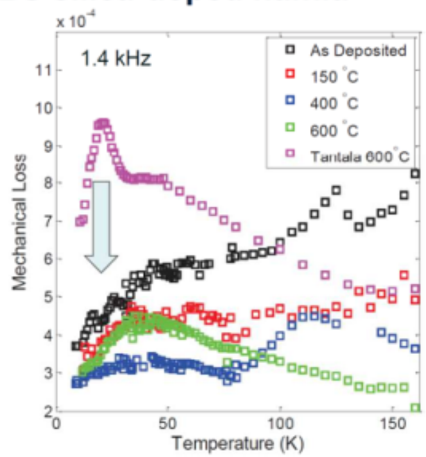
University of Glasgow

Loss measurements of IBS silica-doped hafnia

- Heat treatment reduces loss with 400 °C giving lowest loss
- Heat treated silica-doped hafnia coatings have a loss roughly a factor of 3-4 lower than 600 °C tantala at 20K







[P. Murray, LIGO G-1400275]

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Investigation of Ion-Beam-Sputtered Silica-Titania Mixtures for Use in Gravitational Wave Interferometer Optics

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Abstract: Ion-beam-sputtered mixtures of silica and titania are investigated as potential coating materials for use in gravitational wave interferometer optics. Such coatings must have both low optical and mechanical loss to maximize detection sensitivity.
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OCIS codes: (230.4170) Multilayers; (160.4670) Optical Materials; (240.0310) Thin Films.

$(\lambda/4, \lambda/4)^{15}$	$10^4 \times$ (residual loss angle)	n_H
Ta_2O_5 / SiO_2	4.4 ± 0.2	2.02
TiO_2:: Ta_2O_5 / SiO_2 (15::85)	2.4 ± 0.2	2.07
SiO_2:: Ta_2O_5 / SiO_2 (35::65)	2.5 ± 0.4	1.83
→ TiO_2:: Si_2O_2 / SiO_2 (35::65)	1.7 ± 0.4	1.77

Thin(ner) Layers ..

… crystallize at *high(er)* annealing temperatures

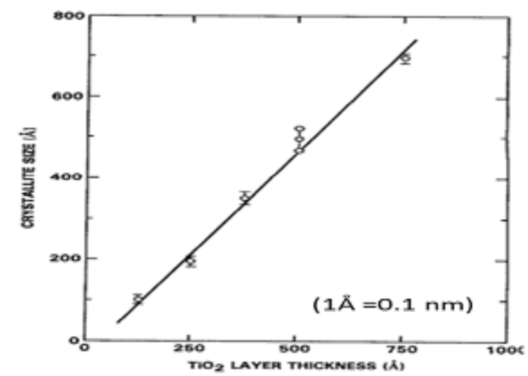
Seminal work on ***thin – layer Titania*** films by Sankur & Gunning [J. Appl. Phys. 66 (1989) 4747]

"Thinner layers (< 250 Å) required higher temperatures [to crystallize]. 65 Å layer films exhibit diffraction only after annealing at 600°C."

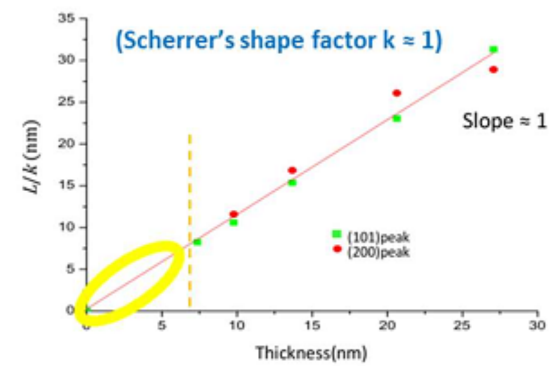
"Grain size, as deduced from diffraction line broadening, was comparable to the layer thickness"

"Thicker layers remain in the Anatase phase and never transform into Rutile, even for prolonged (72 h) annealing at the highest temperature s (1100°C). Thinner layers (65 Å) convert into Rutile starting at 900°C"

"Below a certain critical thickness crystallization in pure TiO_2 films is inhibited"



[Gluck et al., J. Appl. Phys. 69 (1991) 3037]



[S. Chao et al., LIGO-G1300921]

Fraction of silica can be reduced, thus increasing n_{high}/n_{low} contrast =>

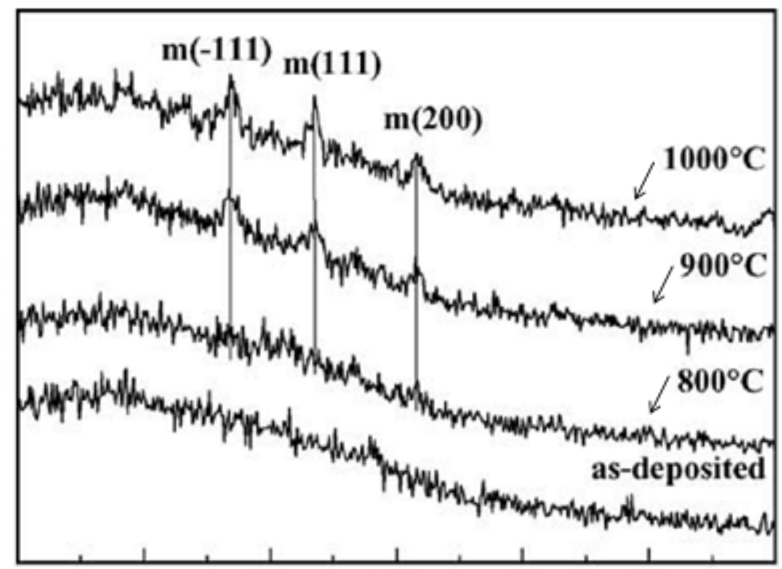
=> For same reflectivity reduce number of layers / thermal noise

Hafnia-Alumina Nano-layers

Nanometer-layered **Hafnia (12nm)/Alumina (3nm) composites** ***do not*** **crystallize upon annealing, up to temperatures of 800 ºC**

[M. Liu et al., Appl. Surf. Sci. 252 (2006) 6206].

- "XRD analysis shows that the films remain amorphous up to an annealing temperature of 800 ºC"
- "FTIR indicates that no interface layer forms during annealing up to 800 ºC"

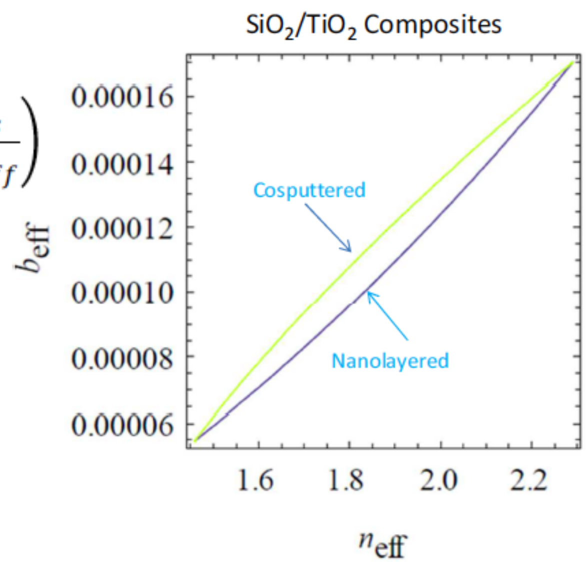


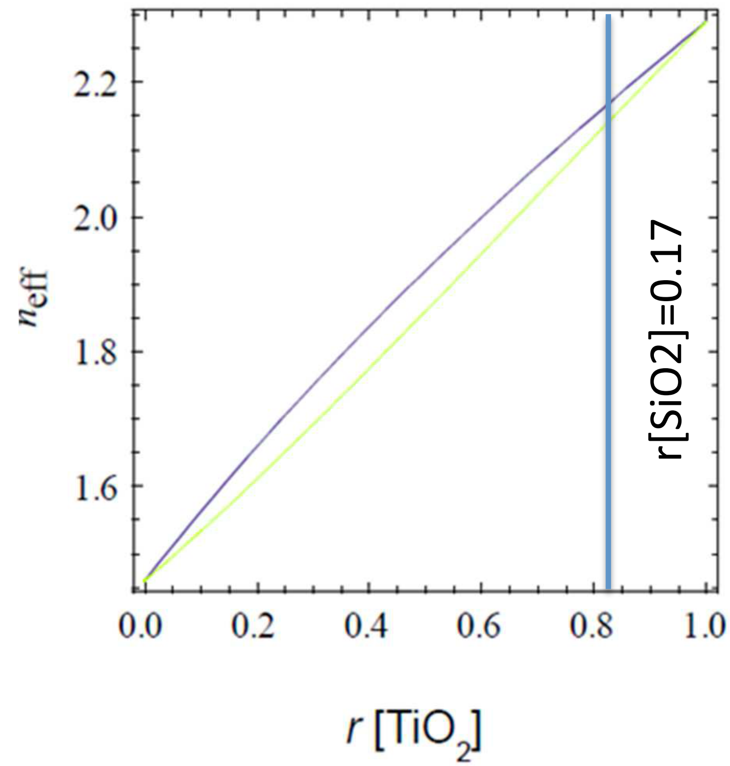
Our own results shown later

Nano-layered vs. Doped

- **Nano-layered can be better in terms of noise compared to doped with the same optical density**

$$b_{eff} = \frac{\phi_{eff}}{n_{eff}}\left(\frac{Y_{eff}}{Y_s} + \frac{Y_s}{Y_{eff}}\right)$$

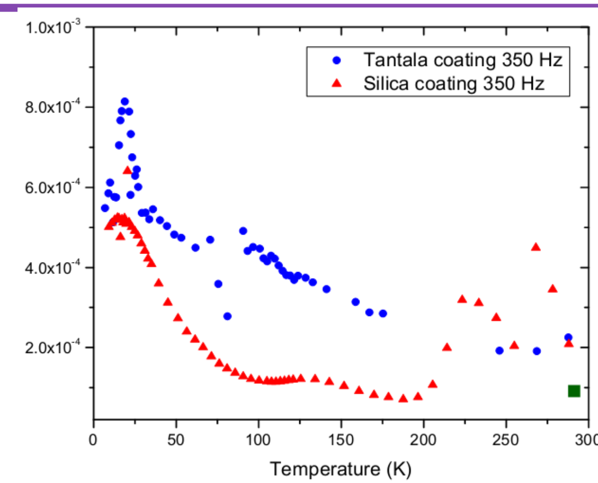




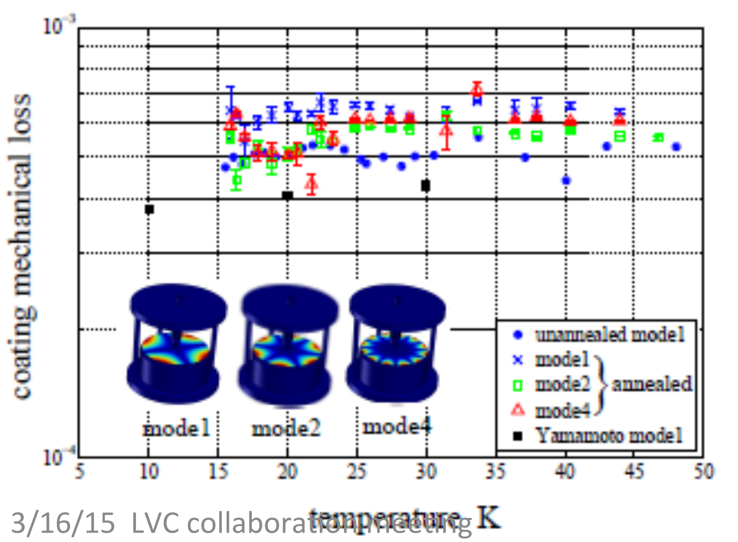
- **Nano-layered are much easier modeling compared to doped**
  [Pinto et al., LIGO-G100372]

The Cryo-Peak Puzzle

Mechanical loss measurements on *single-layer Titania-doped-Tantala and Silica films* show a mechanical loss peak at ~ 30K [Martin et al., CQG **25** (2008) 055005]



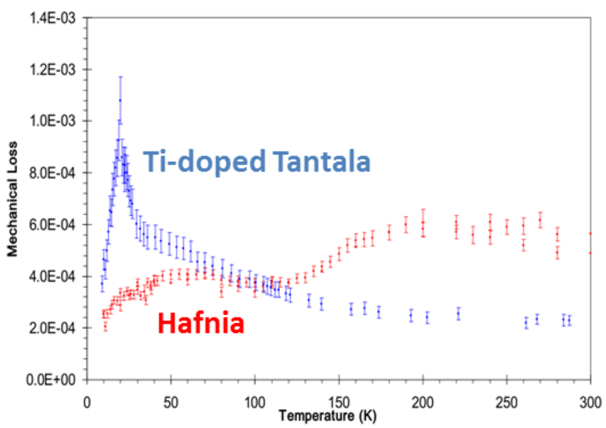
Mechanical loss measurements on ***multilayer*** *Titania-doped-Tantala coatings on Silicon* (annealed at 400 C~ 600 C) also show a cryo-peak at ~ 30K [Granata et al., Opt. Lett. 38, 5268 (2013)].



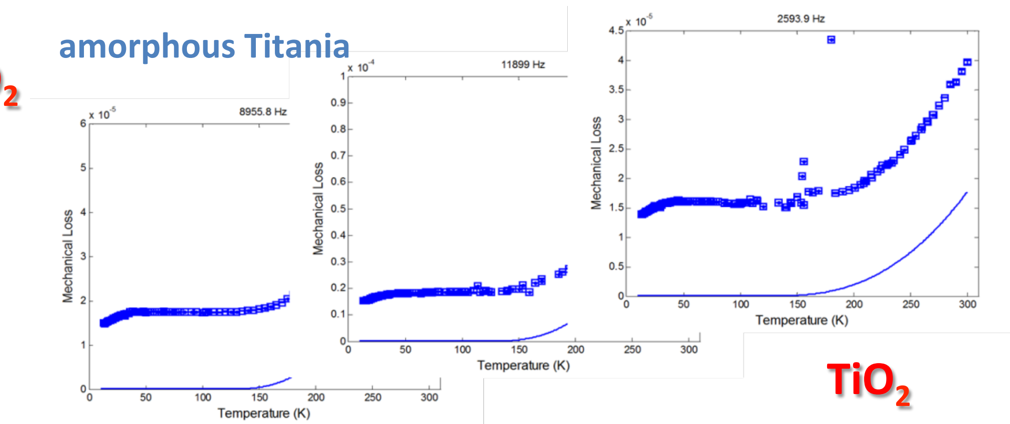
Mechanical loss measurements on *multi-layer Tantala/Silica coatings on Sapphire do not show such peak*, yielding almost temperature & annealing schedule independent losses

[Yamamoto et al., PRD-74 022002 (2006); Hirose et al., LIGO-P1400107] .

Cryo – Friendly Oxides…



HfO$_2$



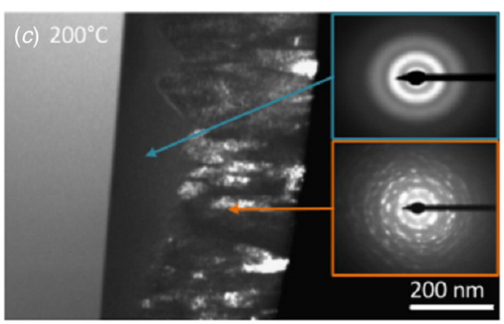
TiO$_2$

[Chalkley et al., LIGO-G080314]

[IMartin & Murray, GWADW 2014, preliminary]

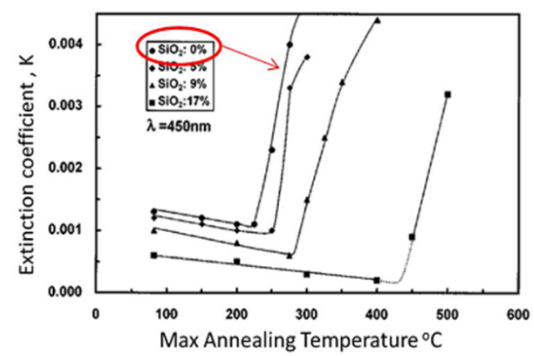
… *crystallize upon annealing* *(needed for optical properties)*

[Abernathy et al., CQG 28(2011) 195017]



HfO$_2$

Chao and Wang, Appl. Opt 23 (1998) 1417



TiO$_2$

Outlook

Nanolayers:
- What
- How
- Why

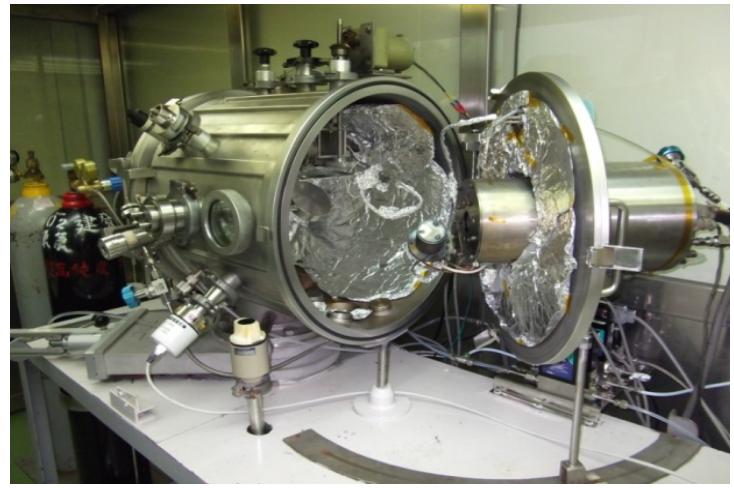
Development:
- Survey of Technical means ⇦
- Results
- What's Next

Conclusions & Acknowledgements

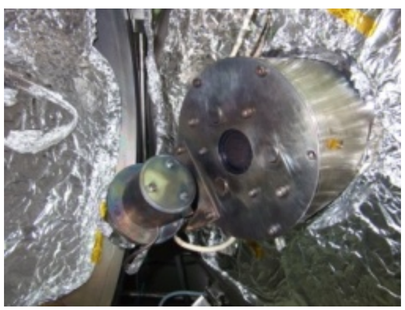
NTHU Deposition Facility

Kaufman-type ion beam sputterer in Class 100 clean compartment within Class 10000 clean room.

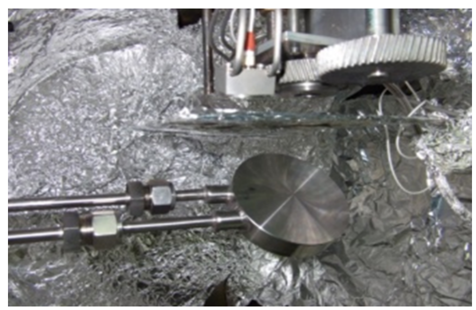
[S. Chao et al, LIGO-G1101083, G1200489, G1300921]



Kaufman gun & neutralizer



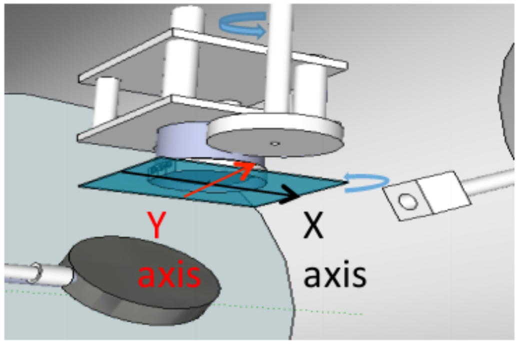
Sputter target and rotator

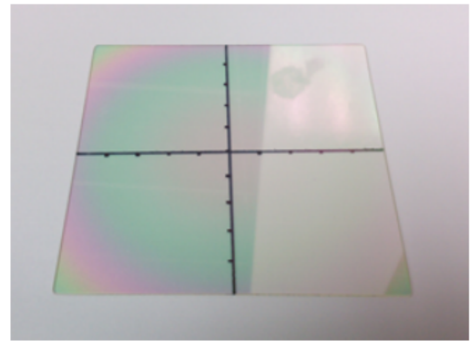


Twin exch. target holder

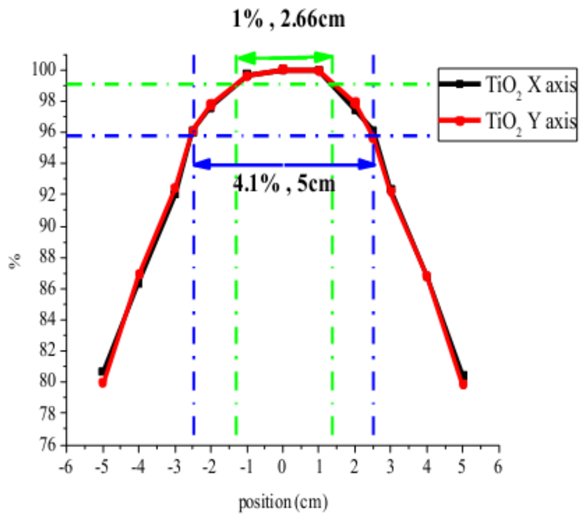
- **Several witness samples are deposited together with a few cantilevers in each run for structural/optical characterization.**

Deposition Uniformity

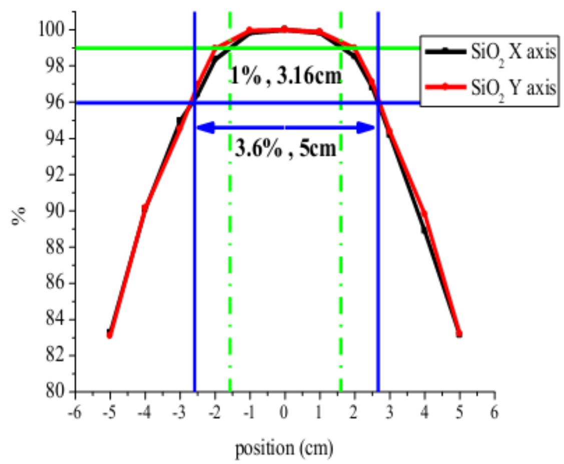




TiO$_2$



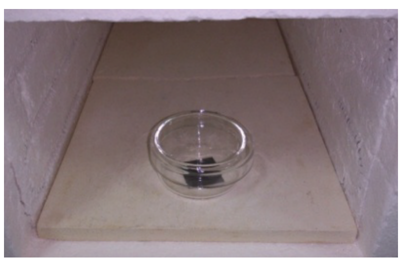
SiO$_2$

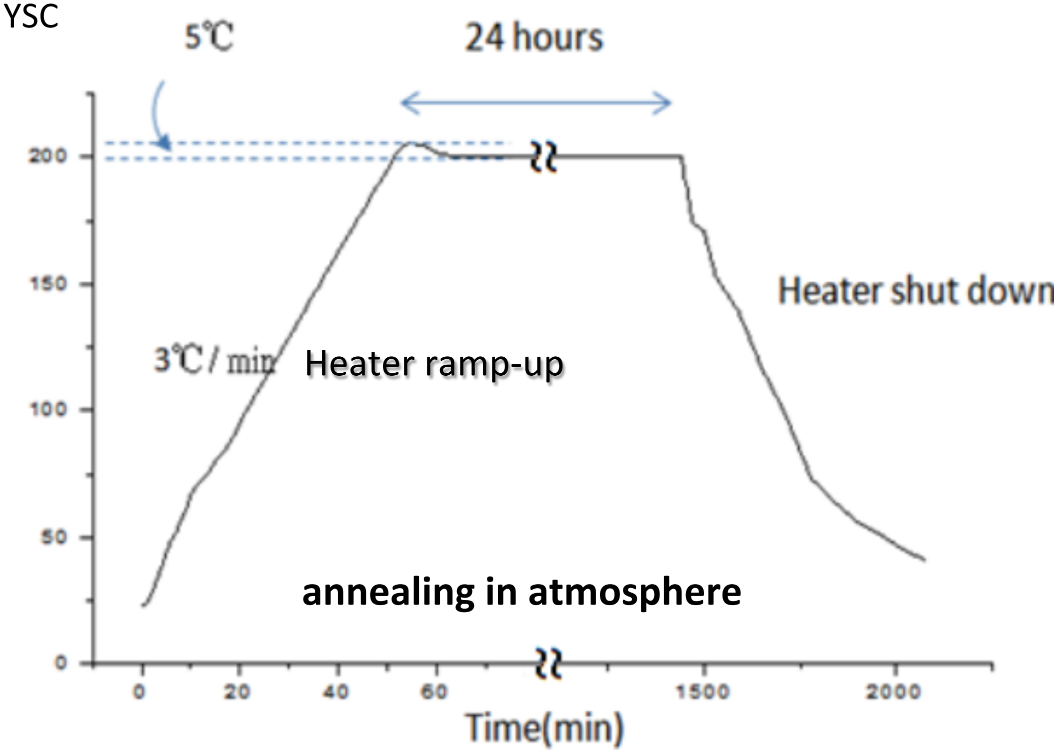


[S. Chao et al., LIGO-G1300921]

NTHU Annealing Facility

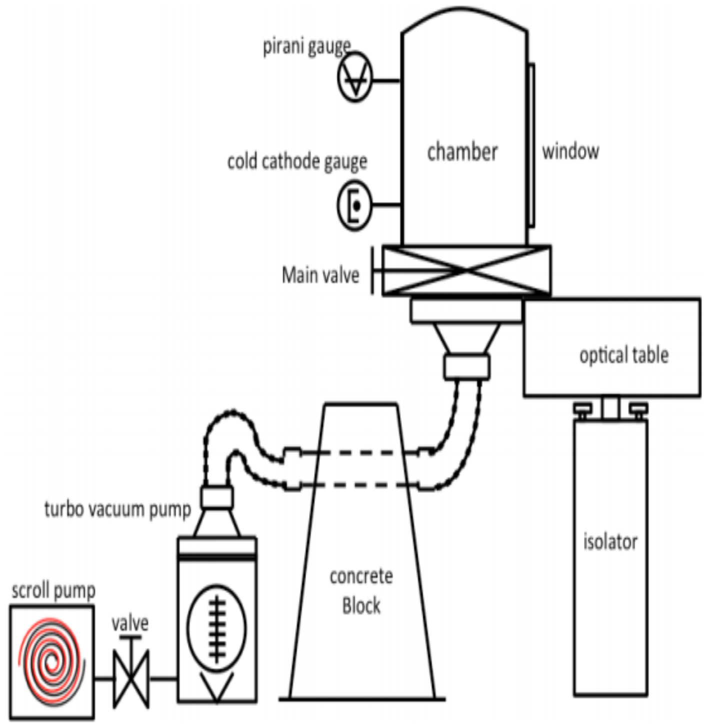
Model : YF-4
Company : YSC

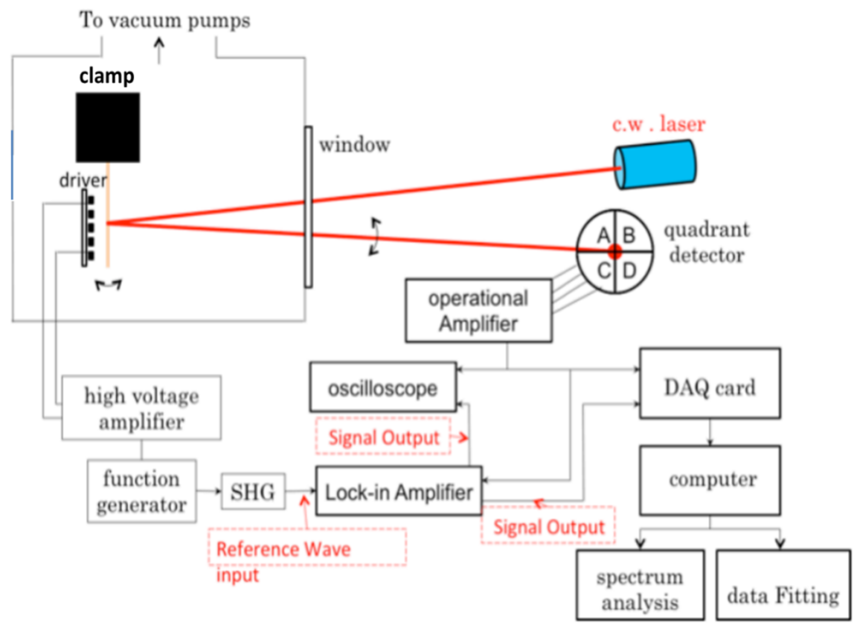




[S. Chao et al., LIGO-G1300921]

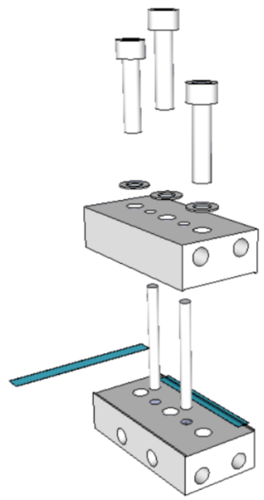
NTHU quality factor control Cantilever Setup

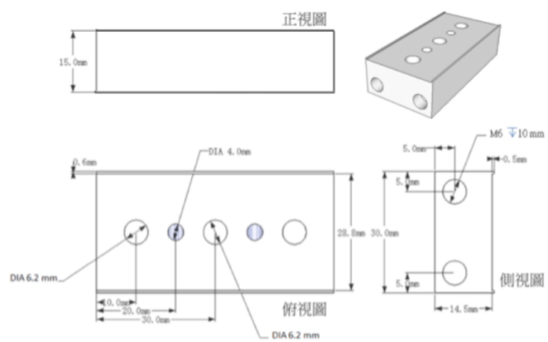


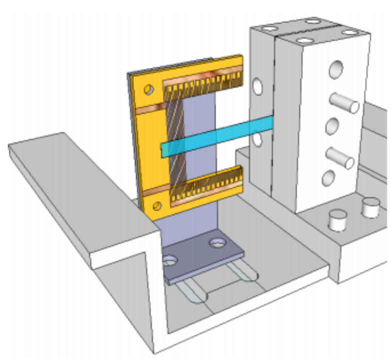


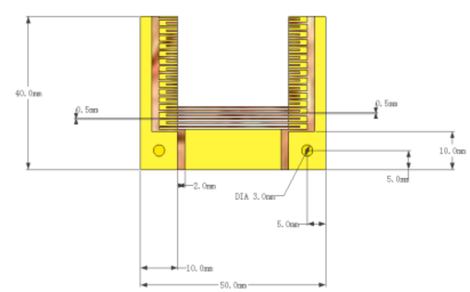
[S. Chao, LIGO-G1200489]

Clamp/Exciter Design









國 立 清 華 大 學

碩 士 論 文

題目 ： 應用於雷射干涉重力波偵測器開發工作之單晶矽懸臂樑之機械震動性質研究

Study of mechanical vibration and loss of silicon cantilever for development of the high-reflection mirror in the laser interference gravitational wave detector

系所：光電工程研究所

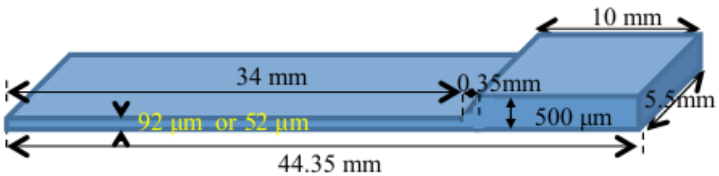
學號姓名：9966701 王薇雅（Wei-Ya Wang）

指導教授：趙煦 教授 （Prof. Shiuh Chao）

中華民國一百零二年八月

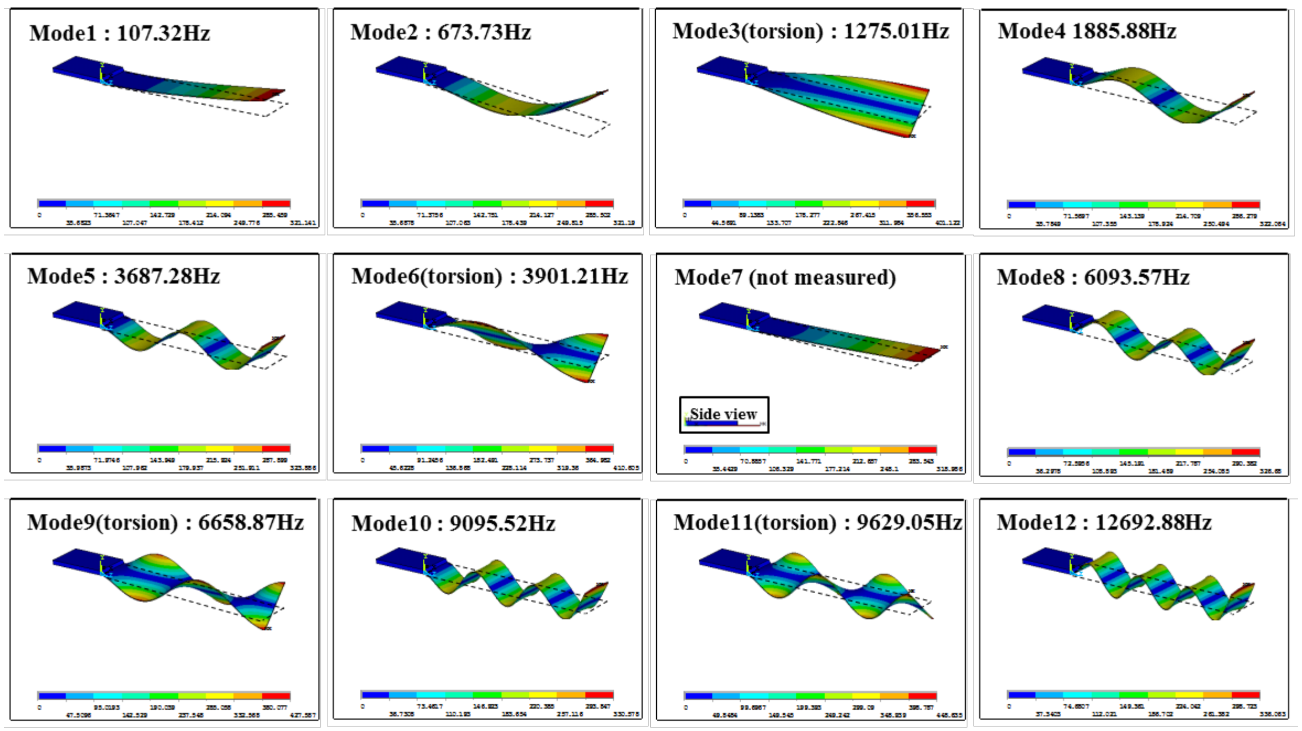
[J. Wang, MA Thesis, NTHU, 2012]

Cantilever Design



Cantilever fabricated from (100, undoped) 4” silicon wafer by KOH wet etching.

[S. Chao, LIGO-G1200849]

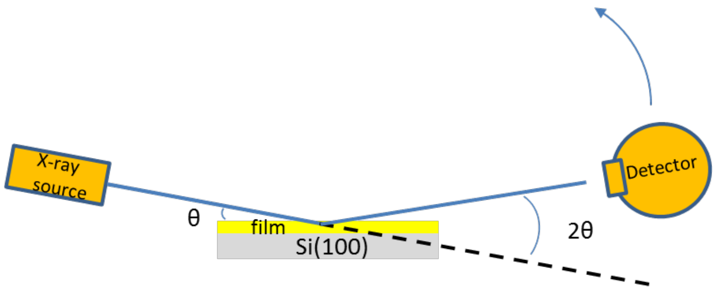


[J. Wang, MA Thesis, NTHU, 2012]

NTHU XRD Facility

Model : X'Pert Pro (MRD)
Company : PANalytical
X-ray source ： Cu (Kα ； λ= 0.154 nm)
Generator voltage : 45kV
Tube current : 40mA
Detector ： Proportional Counter
Beam size ： 12 mm × 0.4 mm
Sample size ： 10mm X 10mm

Incidence angle(θ) : 0.5 °
Scan range (2θ): 20 ° ~65 °
Scan step size : 0.02 °
Time per step : 0.5s



The INFN AdCOAT Project (2014-15)

Mission:

“Investigating, characterizing and comparing the properties (morphological, structural, optical and viscoelastic) of Silica::Titania and Silica::Hafnia mixtures, both nm-layered and co-sputtered, at ambient and cryogenic temperatures.”

Working Groups:
USannio **(PI, nanolayer modeling and design);**
Genoa **(structural/optical characterization);**
Perugia **(dissipation modeling in glasses; viscoelastic parameter measurements);**
Rome **(cryogenic GeNS based loss angle measurement setup).**

Outlook

Nano-layers:
- What
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- Why

Experiments:
- Survey
- Old and new Results
- What's Next

Conclusions & Acknowledgements

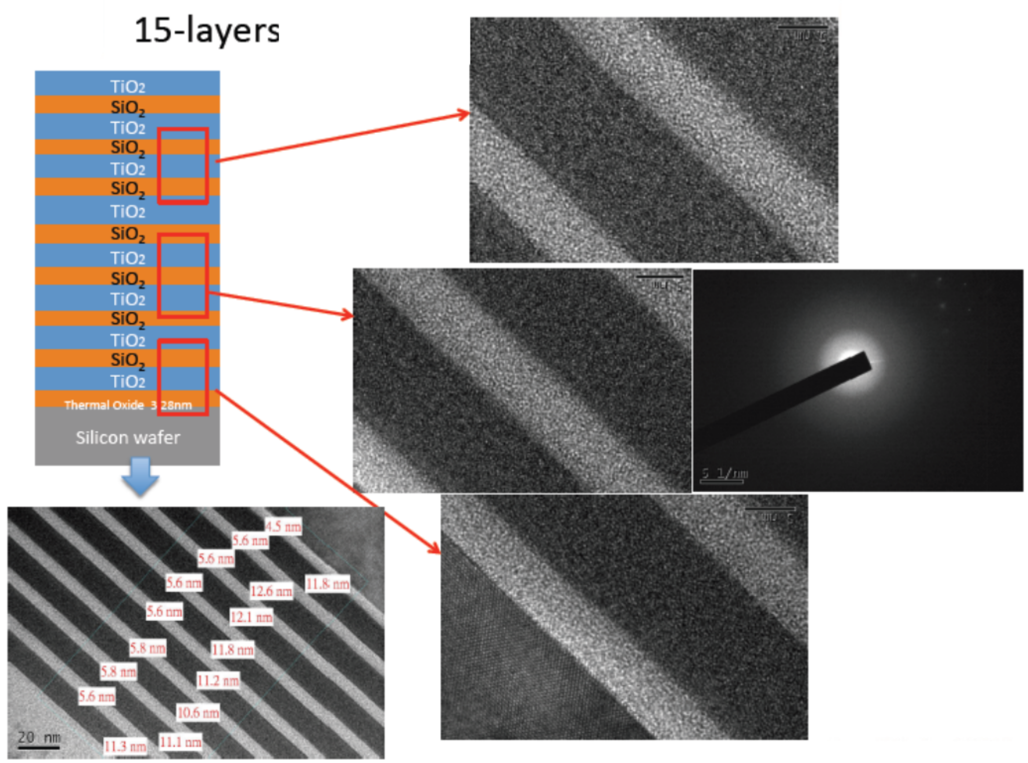
1^{st} Generation Prototypes

	Total thickness (nm)	Averaged thickness of TiO_2 and SiO_2 layer(nm)	
		TiO_2	SiO_2
single TiO2	121.9	121.9	0
3 layer	119.8	40.9	40.7
5 layer	119.2	26.2	20.3
7 layer	120.0	20.6	12.5
11 layer	119.3	13.7	7.4
15 layer	112.4	9.8	4.8
19 layer	112.6	7.4	4.3

[S. Chao et al., LIGO-G1300921]

All prototypes QWL thick @ 1064nm, all with *n = 2.065*

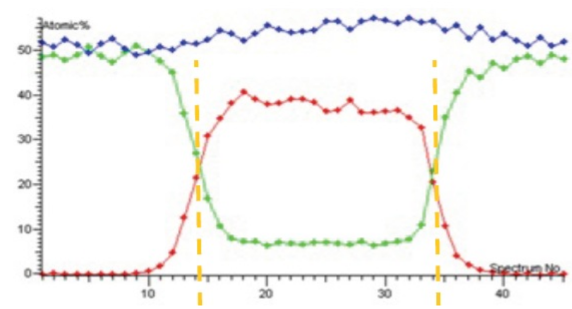
Morphology (As Deposited)



[S. Chao et al., LIGO-G1200489]

Morphology of witness samples investigated using TEM and electron diffraction.

Interface profiles characterized
via energy-dispersive X-ray dif-fraction (EDXRD)

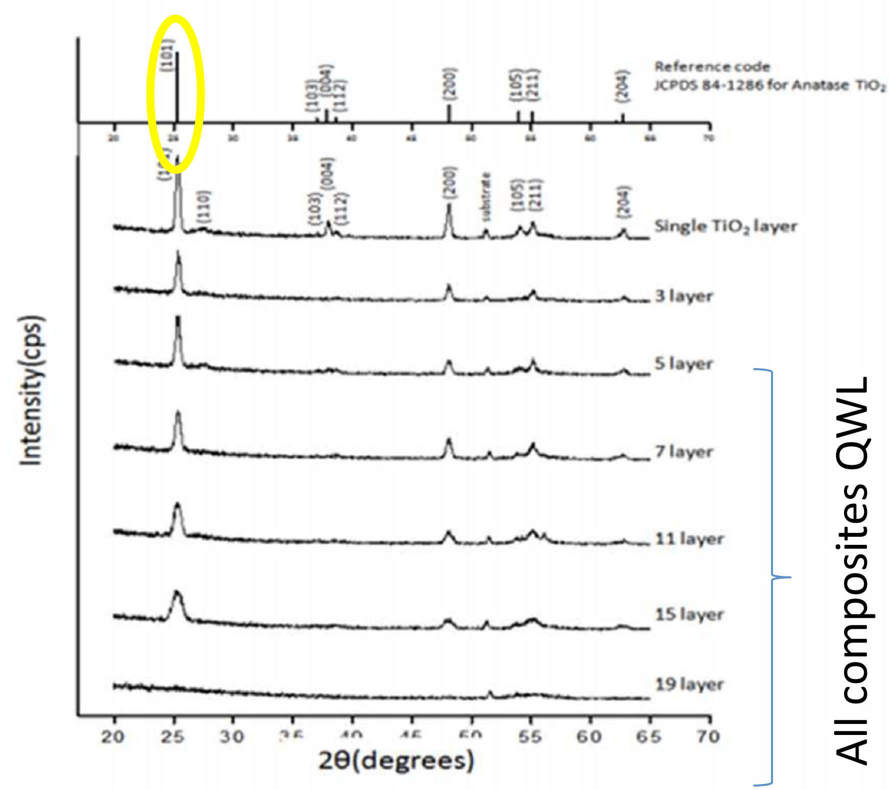


XRD Spectra after Annealing

Threshold anneal temperature
For crystallization
increases with :
the number of layers
decreasing the Titania layer thickness.

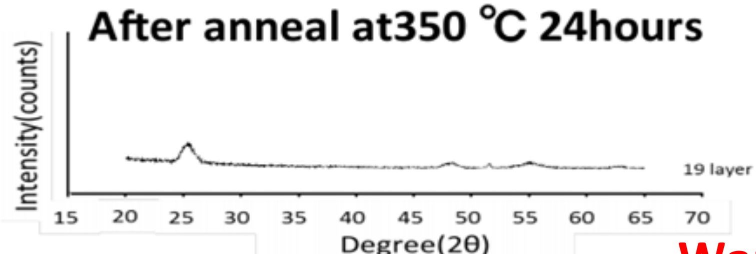
At 300C the Anatase peak gets smaller and broader as the nanolayer thickness decreases (and the nanolayer number Increases), signaling progressive crystallization frustation,
until it disappears for N=19.

After anneal at 300℃ 24hours



All composites QWL
with $n = 2.065$

After anneal at350 ℃ 24hours



[Chao et al., LIGO-P1400122; Optics Express Nov. 2014]

Warning:
Appearance of crystallites is not a step function

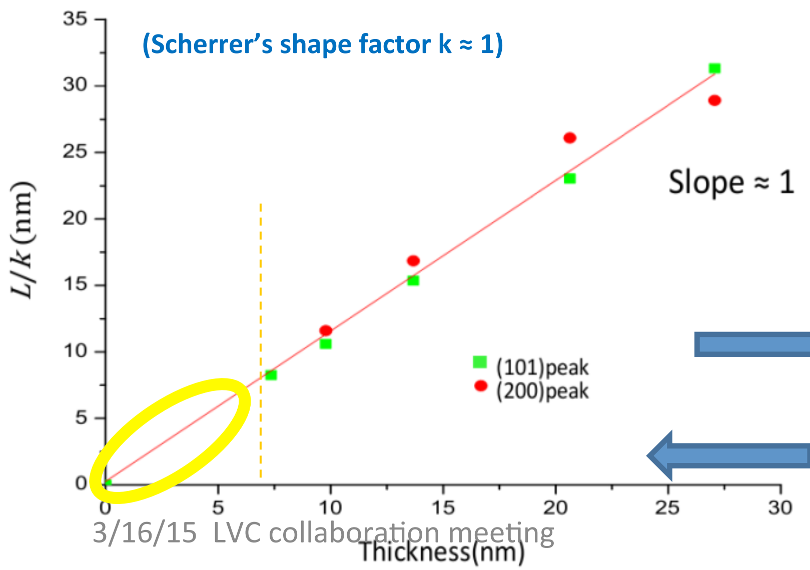
Crystallization

Anneal Condition / Crystallization / Sample	Before annealing	225 ℃ 24hr	250 ℃ 24hr	300 ℃ 24hr	350 ℃ 24hr
Single TiO_2	No	No (explained)	Yes FWHM=0.37 °	Yes FWHM=0.37 °	- -
3 layer	No	Yes FWHM=0.37 °	Yes FWHM=0.40 °	Yes FWHM=0.35 °	- -
5 layer	No	No	Yes FWHM=0.50 °	Yes FWHM=0.44 °	- -
7 layer	No	No	Yes FWHM=0.53 °	Yes FWHM=0.50 °	- -
11 layer	No	No	Yes FWHM=0.81 °	Yes FWHM=0.65 °	- -
15 layer	No	No	No	Yes FWHM=0.93 °	- -
19 layer	No	No	No	No	Yes FWHM=1.32 °

Crystallite Size vs Nano-thickness

Crystallite sizes L/k of the nano-layers after anneal at 300C 24hr

	Thickness of TiO2 (nm)	Anatase TiO2 Peak (101)				Anatase TiO2 Peak (200)			
		2θ	β_{exp} (degree)	$\beta_s \cos\theta$ (degree)	L/k (nm)	2θ	β_{exp} (degree)	$\beta_s \cos\theta$ (degree)	L/k (nm)
Single TiO2	121.9	25.344	0.356	0.160	55.162	48.088	0.392	0.180	49.087
3-layer	40.9	25.371	0.390	0.223	39.569	48.108	0.424	0.233	37.942
5-layer	26.2	25.351	0.428	0.282	31.330	48.096	0.476	0.305	28.916
7-layer	20.6	25.355	0.504	0.383	23.034	48.099	0.502	0.338	26.097
11-layer	13.7	25.330	0.668	0.574	15.366	48.094	0.666	0.524	16.854
15-layer	9.8	25.315	0.910	0.833	10.597	48.048	0.899	0.761	11.602
19-layer	7.4	25.416	1.140	1.068	8.258	--	--	--	--



Crystallite size decreases almost linearly with thickness down to thickness ≈ 7nm

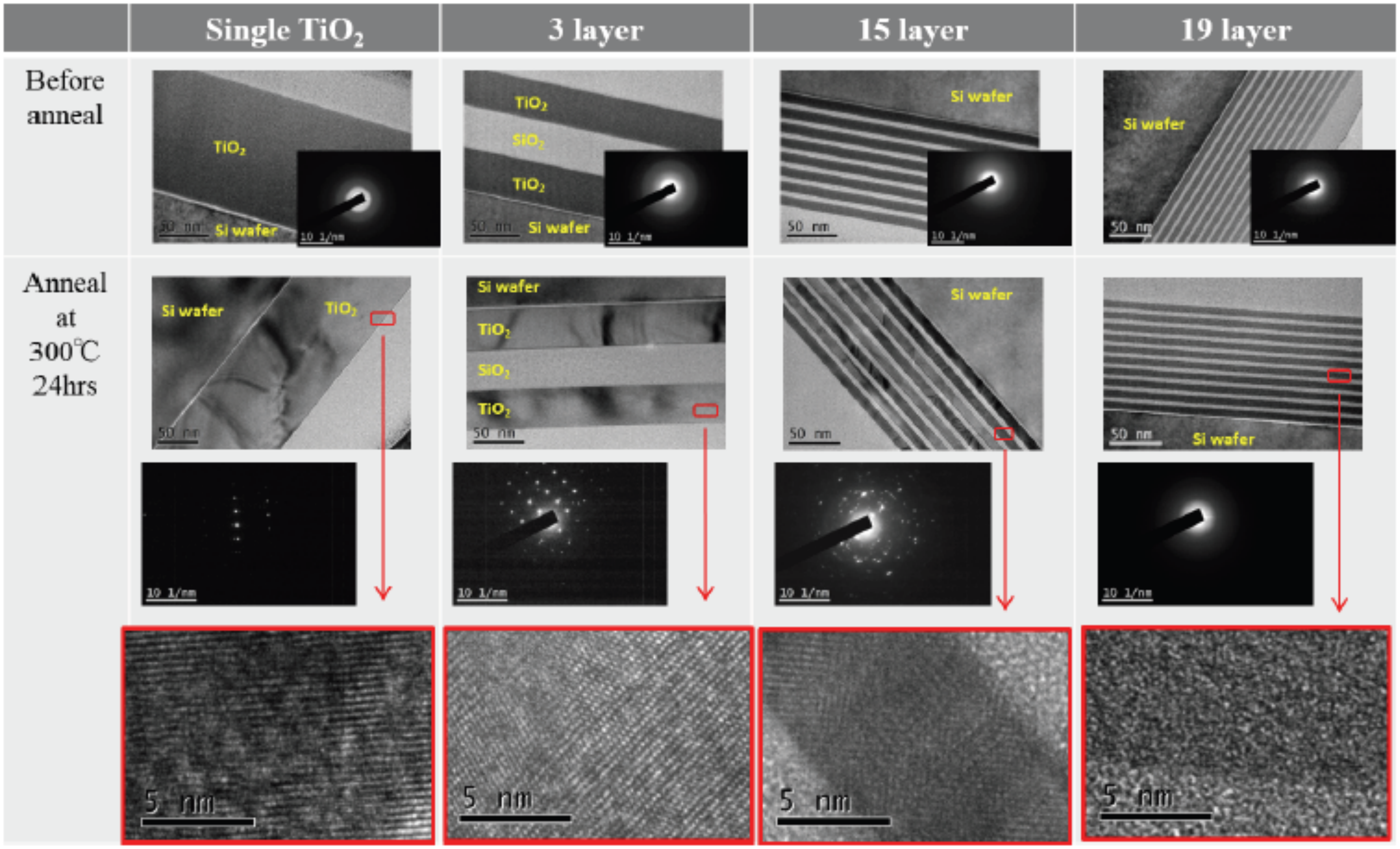
[S. Chao et al., LIGO-G1300921]

Sankur-Gunning results confirmed

Next to be tried

layers ~1 nm, no interdiffusion in X-ray mirrors

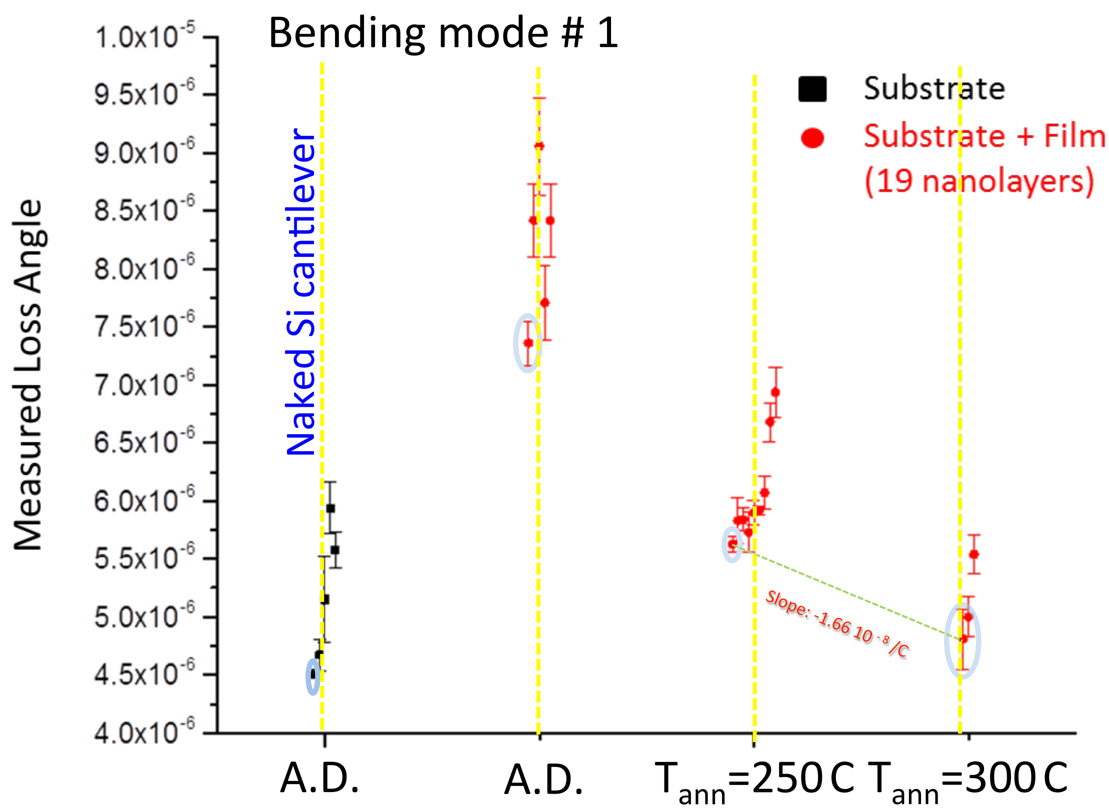
TEM Before/After Annealing



[S. Chao et al., LIGO-G1300921]

TEM shows that no significant across-interface diffusion occurs during annealing

Loss Angle Before/After Annealing



Different bars correspond to different re-clampings.

Lowest-average bar yields most trustable value.

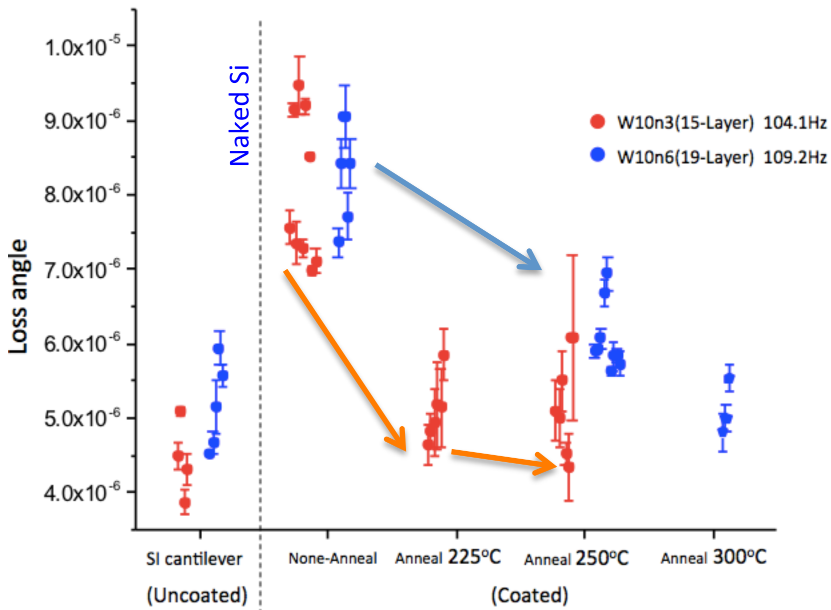
Multiple measurements taken for each re-clamping, yielding error bars.

	Loss Angle	
T_{ann}	μ	σ/μ
A.D.	7.36 10^{-6}	0.082
250	5.64 10^{-6}	0.074
300	4.81 10^{-6}	0.074
substrate + film (19 layers)		

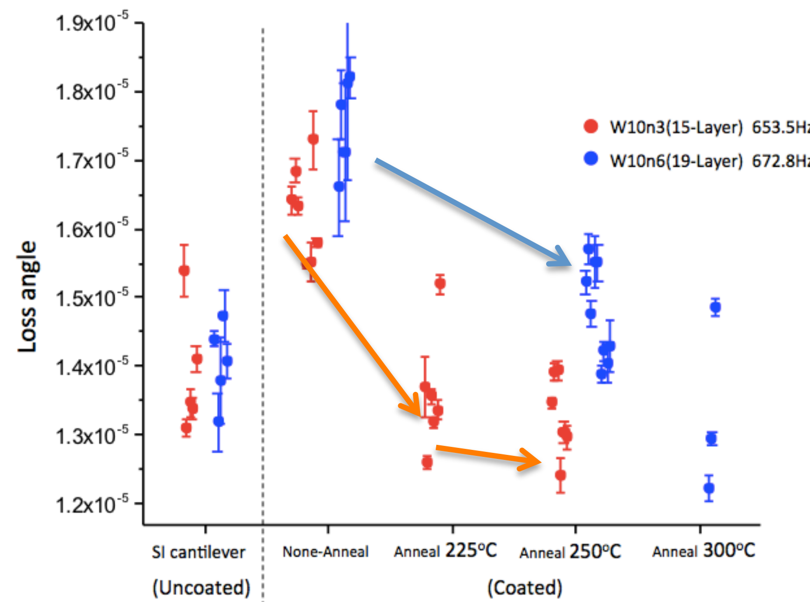
[preliminary results , S. Chao et al., LIGO-G1401055]

Puzzles?

1st bending mode ~107 Hz



2nd bending mode ~660 Hz



Is there an optimal Ti thickness (or distributed stress) to reduce mechanical losses?

Is there a physical saturation effector simply because coating losses are already almost indistinguishable from Si substrate's

Need improved measuring system, make one free of re-clamping noise.

[preliminary results , S. Chao , NTHU]

Nanolayer Loss Angle

Young modulus of substrate (169 GPa, Silicon 100)

thickness of substrate (92$\pm$1 μ)

$$\phi_{nl} = \frac{Y_s h_s}{3Y_{nlc} h_{nlc}} (\phi_{coated} - \phi_{naked})$$

measured loss angle of naked cantilever (substrate)

Young modulus (Voigt) of nanolayered composite

measured loss angle of coated cantilever

$$Y_{nl} = z_1 Y_1 + (1 - z_1) Y_2$$

Volume (thickness) fractions of composite ingredients (0.654 for TiO_2, for the 19-layers prototypes)

Young moduli of composite ingredients (165Gpa for TiO_2, 72 Gpa for SiO_2)

thickness of nanolayered composite (112.5 nm, for the 19-layer prototypes)

[Pierro et al., LIGO-T060173]

TiO_2 Loss Angle in Nanolayer

… Use fiducial value of Silica loss angle ($5\ 10^{-5}$) to retrieve loss angle of *a*-Titania *in the nm-layered composite* ….

$$\phi_{nlc} = \frac{\left(\frac{Y_s}{Y_1} + \frac{Y_1}{Y_s}\right) z_1 \phi_1 + \left(\frac{Y_s}{Y_2} + \frac{Y_2}{Y_s}\right)(1 - z_1)\phi_2}{Y_s\left[\frac{z_1}{Y_1} + \frac{1 - z_1}{Y_2}\right] + Y_s^{-1}\left[\frac{z_1}{Y_1} + \frac{1 - z_1}{Y_2}\right]^{-1}}$$

Yields loss angle values $\sim 10^{-4}$ for *a*-TiO_2 , consistent with **[Scott and MacCrone, Rev. Sci. Instr. 39 (1968) 821].**

TiO_2 Loss Angle in Nanolayer

…yielding for our 19-layers nm-layered composite the following estimates for the loss angle as a function of the annealing temperature (with typical 10% uncertainties)

$\phi = 1.04\ 10^{-3}$ (as deposited)
$\phi = 0.43\ 10^{-3}$ (after annealing 24h @ 250°C)
$\phi = 0.13\ 10^{-3}$ (after annealing 24h @ 300°C)

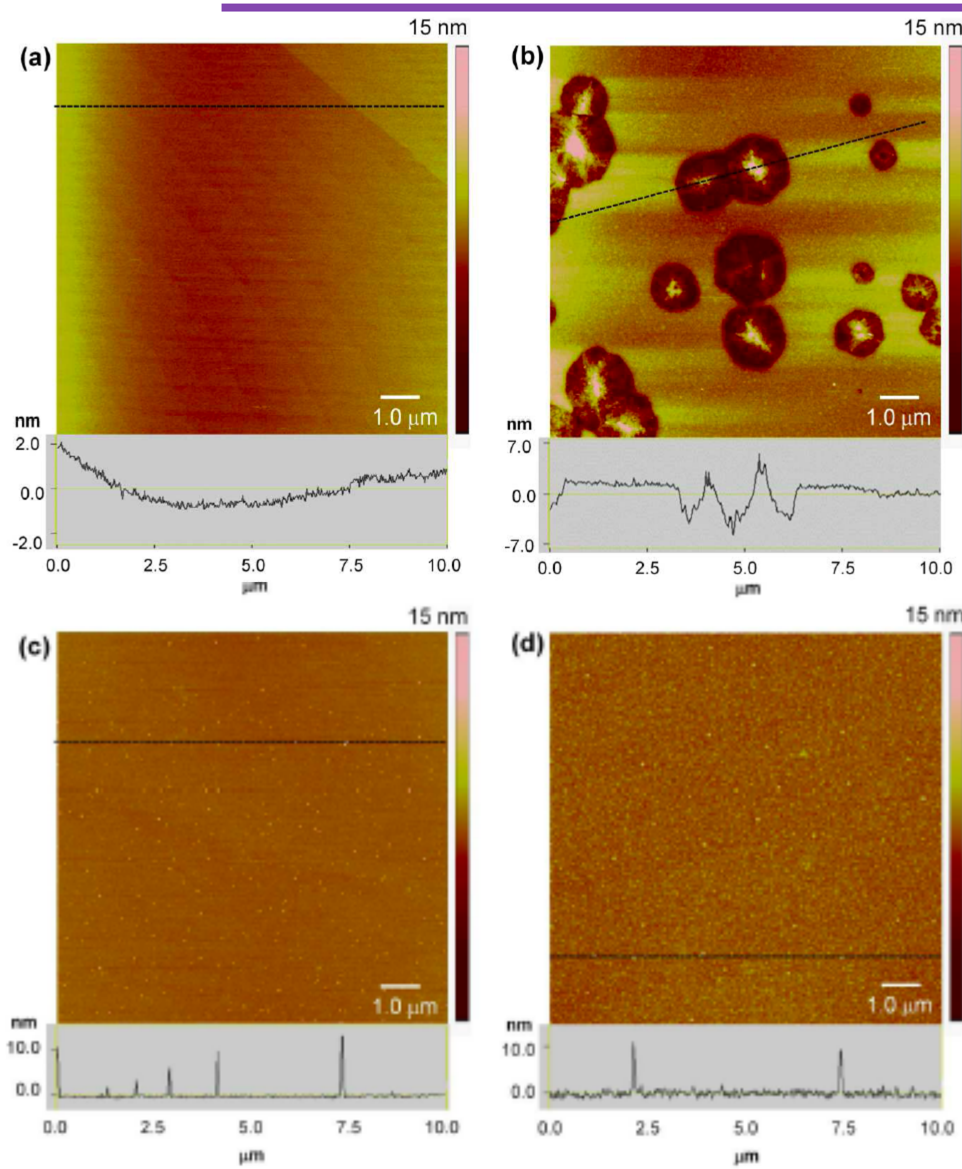
Preliminary

…comparable to or better than Ti-doped Tantala !

Note: the effective refractive index of our nm-layered composite is (Drude formula):

$$n_{nl} = [z_1 {n_1}^2 + (1 - z_1){n_2}^2] \approx 2.063\ \ (@1064nm)$$

AFM Characterization (AdCOAT)



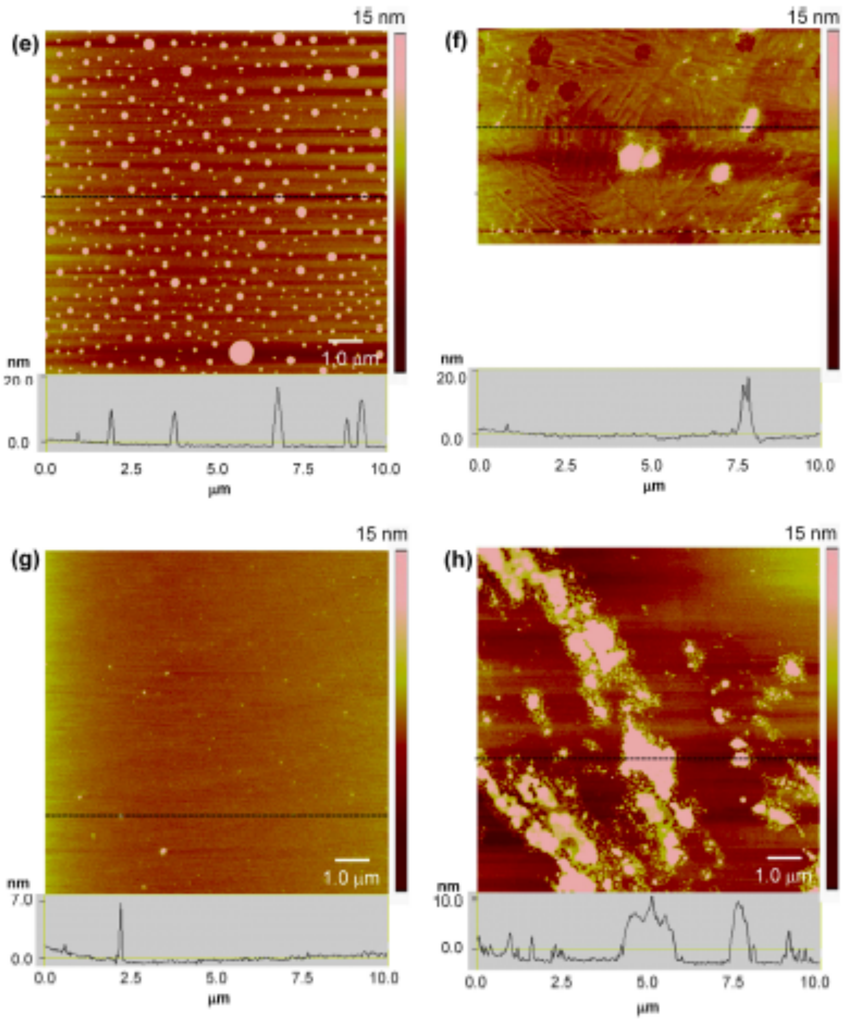
AFM (Dimension 3000)

AFM images of single Ti layer qwl. on silicon
(a) as-deposited
(b) as-annealed at 250°C,

AFM images of single silica layer qwl. on silicon
(c) as-deposited
(d) as-annealed at 300°C.

(M. Canepa, INFN Ge)

AFM Characterization (AdCOAT)



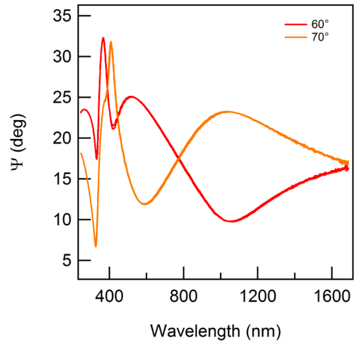
AFM (Dimension 3000)

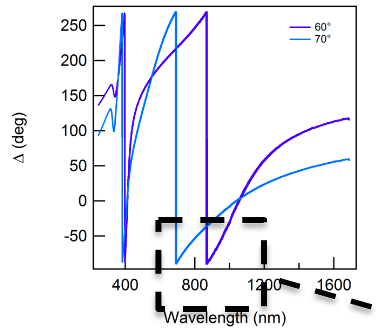
AFM images of 1 QWL (5 layers) Ti/Si on silicon
(e) as-deposited
(f) as-annealed at 300°C,

AFM images of 1 QWL (19 layers) Ti/Si on silicon
(g) as-deposited
(h) as-annealed at 300°C.

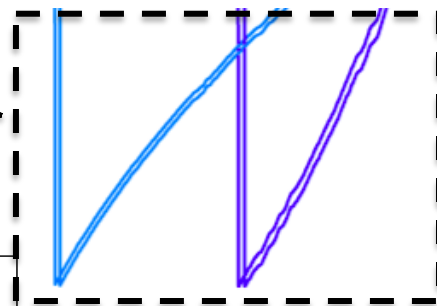
(M. Canepa, INFN Ge)

Ellipsometry-Optical Characterization (AdCOAT)

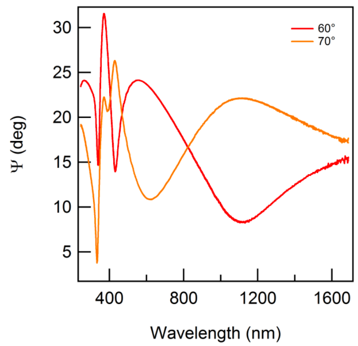


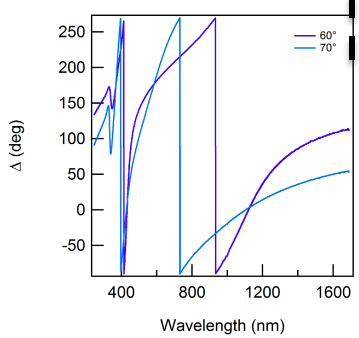


Single Titania layer on silicon
Un-annealed

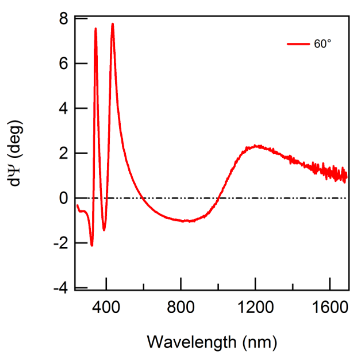


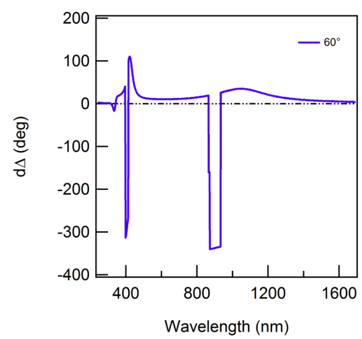
Very Good Uniformity





Crystallized (250° C)

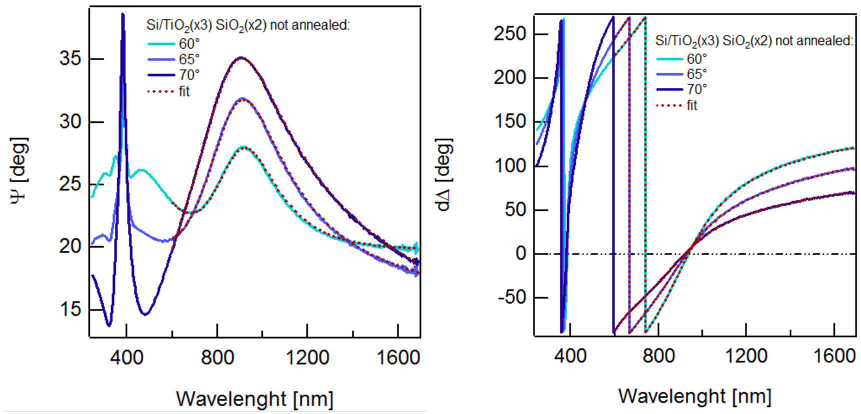




Difference not-annealed/annealed

Ellipsometric spectroscopy
(Woollam 2000, VASE)
(M. Canepa, INFN Ge)

Optical Characterization (AdCOAT)



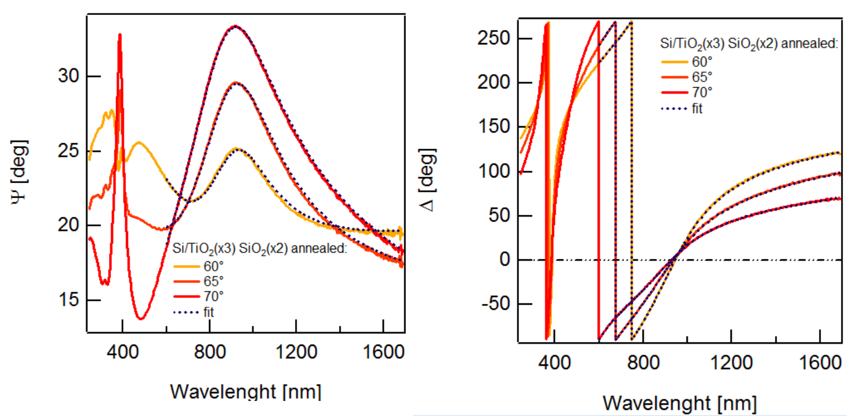
d_{cauchy_Tio2}=27.30± 0.02 nm A_{n_Tio2}=2.275 B_{n_Tio2}=0.05

d_{cauchy_Sio2}=20.15 ± 0.02 nm A_{n_Sio2}=1.478 B_{n_Sio2}=0.0048

$d_{roughness}$=1.20 ± 0.04 nm d_{Sio2_jaw}=1.64 ± 0.07 nm

MSE= 8.575

n_{TiO2}[λ=1064 nm]= 2.319 n_{SiO2}[λ=1064 nm]= 1.482



d_{cauchy_Tio2}=26.98± 0.02 nm A_{n_Tio2}=2.31 B_{n_Tio2}=0.05

d_{cauchy_Sio2}=19.01 ± 0.02 nm A_{n_Sio2}=1.453 B_{n_Sio2}=0.0048

$d_{roughness}$=02.65± 0.04 nm d_{Sio2_jaw}=3.16.± 0.07 nm

MSE= 9.78

n_{TiO2}[λ=1064 nm]= 2.354 n_{SiO2}[λ=1064 nm]= 1.457

5 layer Titania/Silica nominal thickness 27.1 nm (Titania x3) ; 19.9 nm (Silica x2)

Un-annealed

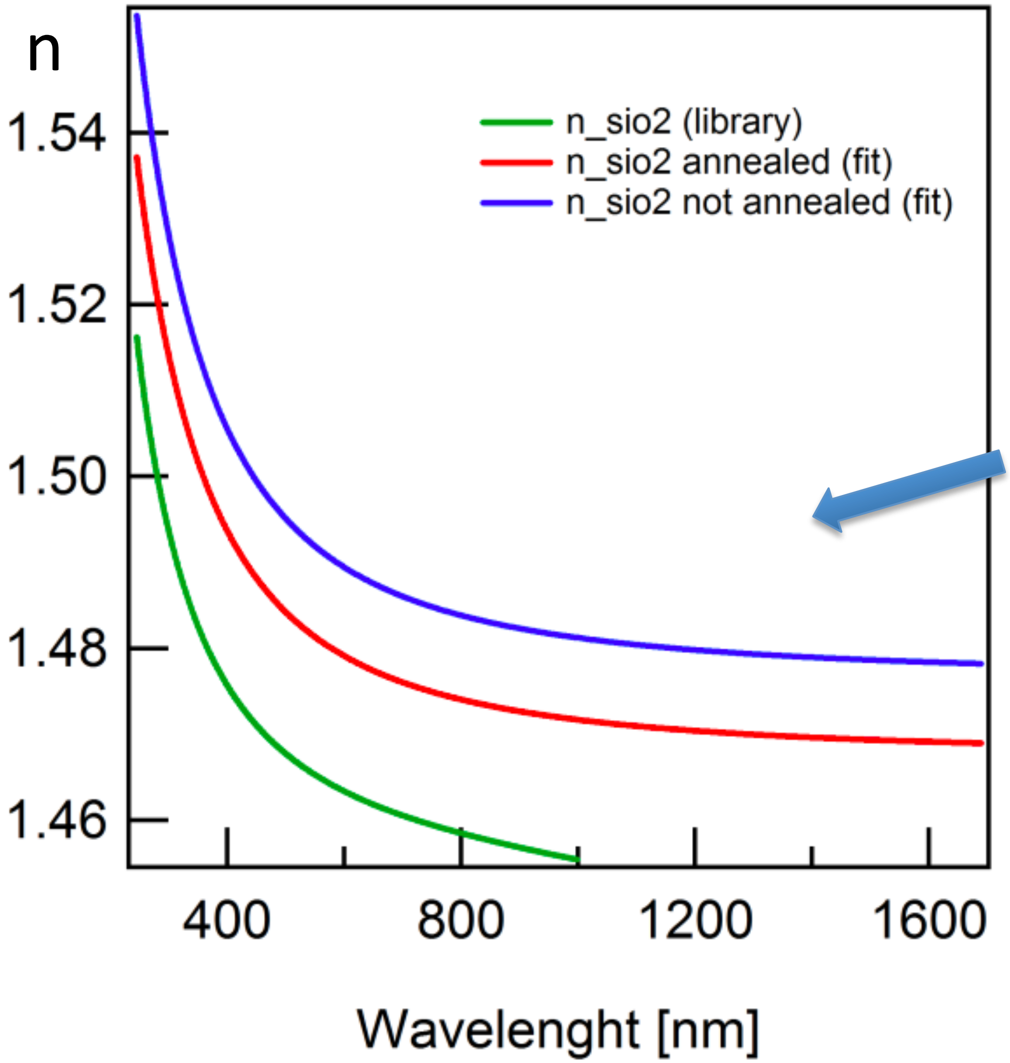
Annealed (300° C)

Very good fit using EMT (BruggeMann and/or Drude formulas)

Optical losses are below measurement sensitivity (1ppm)

Ellipsometric spectroscopy (Woollam 2000, VASE) *(M. Canepa, INFN Ge)*

Optical Characterization (AdCOAT)



REFRACTION INDEX
SINGLE SILICA LAYER
ON SILICON

Visibly annealing relaxes deposited silica towards the molten silica glass state

Ellipsometric spectroscopy
(Woollam 2000, VASE)
(M. Canepa, INFN Ge)

Characterization tools

We have good eyes to see !

Outlook

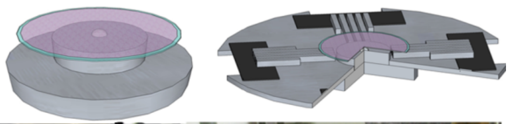
Nanolayers:
- What
- How
- Why

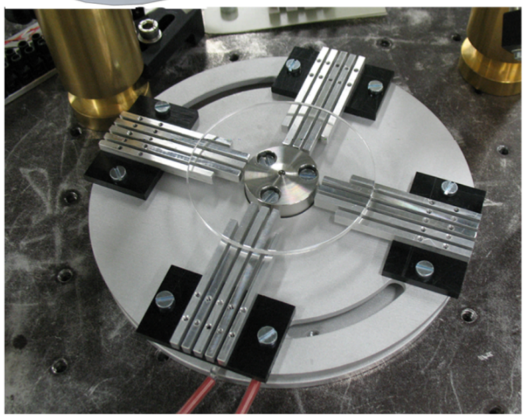
Development:
- Survey
- Results
- What's Next

Conclusions & Acknowledgements

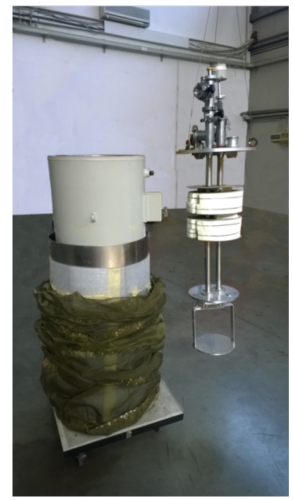
GeNS Setup, T_{amb} & Cryo (AdCOAT)

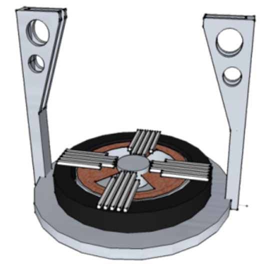
GeNS (Gentle Nodal Suspension)





AdCOAT INFN Rome WG - is building a GeNS based setups for mechanical Q measurement at ambient and (soon) cryogenic temperatures.





mechanical drawings by Matteo Lorenzini

1” Silicon disks being sent to Chao for coating Tamb measurements to start soon (June 2015).

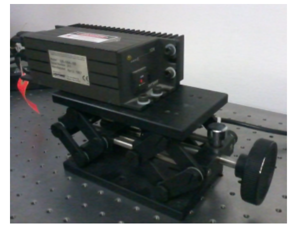
(courtesy A. Rocchi, INFN U-Rome-Tor Vergata)

Si_3N_4 Substrates (AdCOAT)

AdCOAT INFN U-Perugia Group is setting up a new MM interferometer for high Q (Norcada) Si_3N_4 membrane characterization (naked first, then nanolayer-coated).

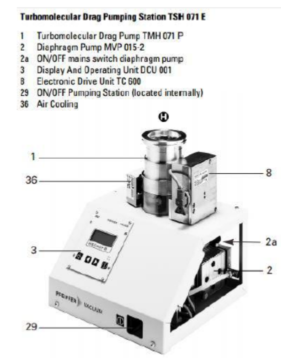
Designed for cryogenic operation.

Lightwave 126

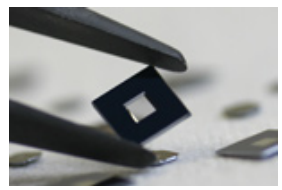


Thorlabs BS-011 & BB1-E03

Vacuum: Pfeiffer TSH 071E

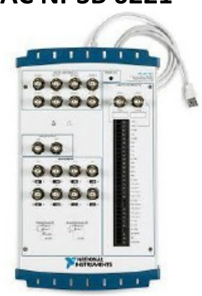


Norcada QX10500CS



NF 2011-FC

DAC NI-SB 6221



SR-844 Lock-In

Cryomech PT 405

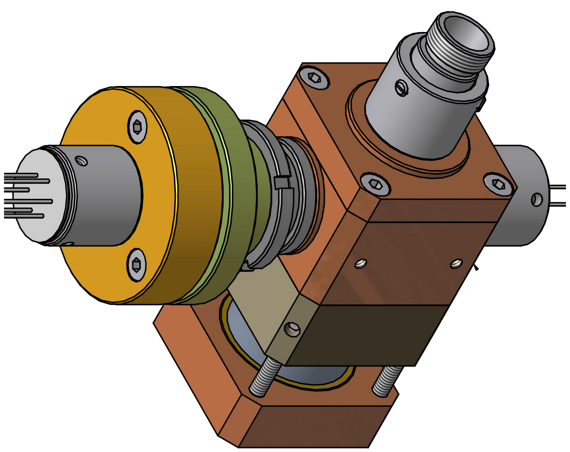
(courtesy H. Vocca, INFN, U-Perugia)

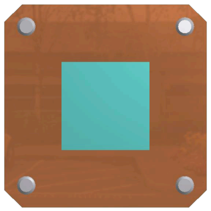
More on Si_3N_4 Substrates

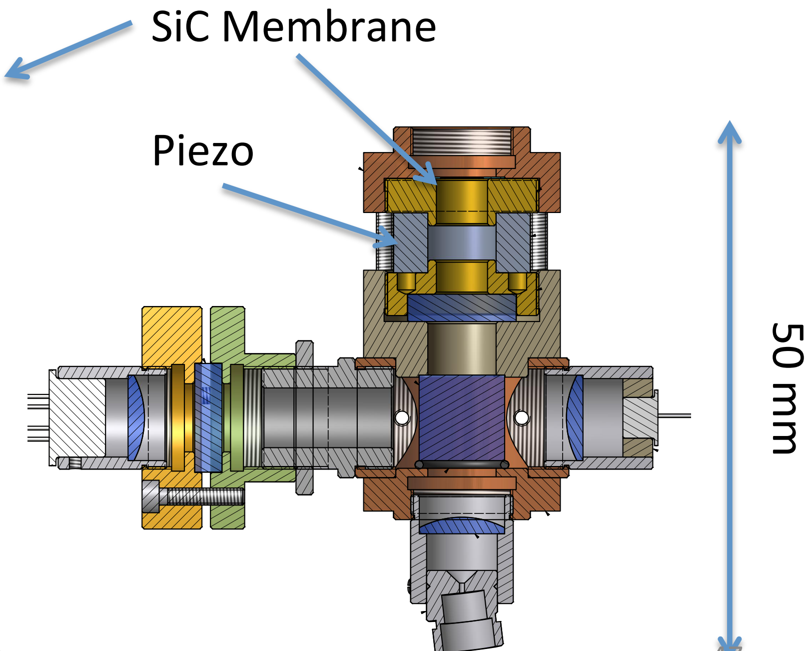
UniSannio / NTHU / CSULA

Designed for cryogenic operation in NTHU and Sannio cryostats.

- Michelson readout
- Piezo excitation/resonance track
- Fiber light feeding



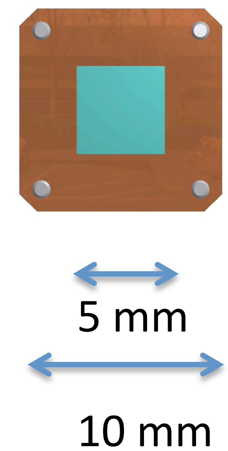




Si_3N_4 Substrates (AdCOAT)

Advantages / disadvantages of mechanical loss measurement on thin Silicon Nitride substrates

•Advantages:
- –Ultra-thin (~100nm), very low mechanical loss substrate
- –Coating losses by far dominating
- –Cheap modular substrate (e-microscope windows)



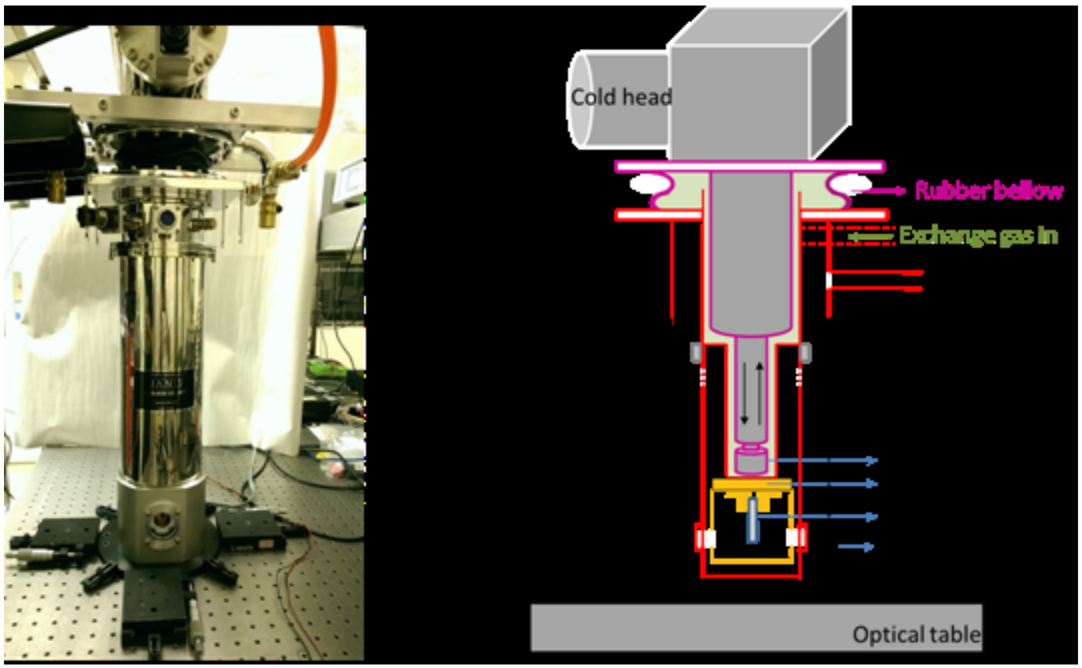
•Limitations:
- –High frequency operation
- –Membrane will bow under surface stress of deposited layer
  - + Directly measure surface tension variations during annealing
- –Probably limited to several nanolayers

•Possible problems:
- –Low reflectivity from membrane, low contrast

Zwickl, B. M., et al. "High quality mechanical and optical properties of commercial silicon nitride membranes." *Applied Physics Letters* 92.10 (2008): 103125-103125.

NTHU Cryo Upgrade (2014-15)

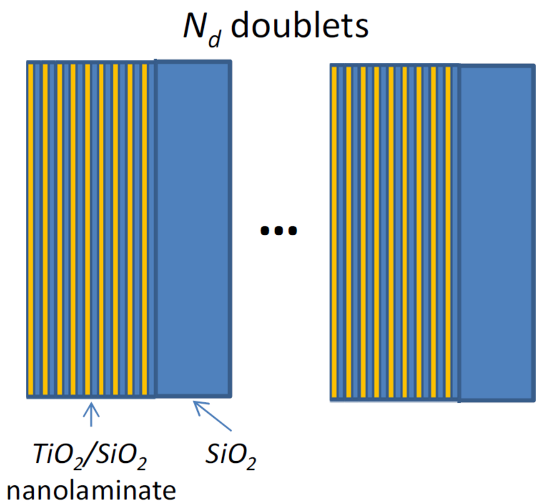
S. Chao at NTHU is upgrading his cantilever based Q measurement facility for cryogenic operation. New funding received from Taiwan National Research Council.



[S. Chao, LIGO-G1400806]

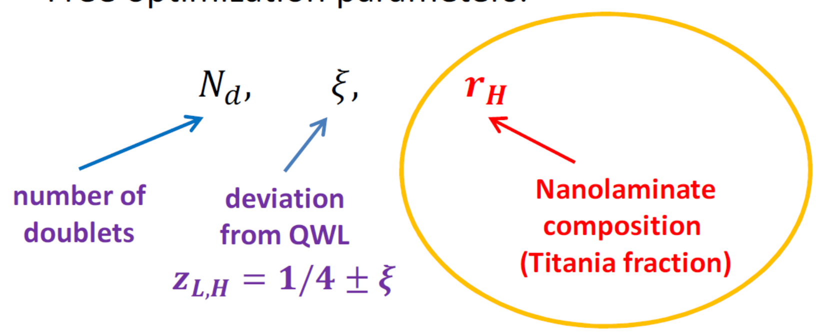
Design Optimization (AdCOAT)

Generalizing results in [Principe et al, ch 12 in Harry et al, "Thermal Noise in Precision Measurements," Cambridge Un. Press, 2012] to *nanolayer based coatings*



Constrained transmittance @ 1064nm (e.g., 278ppm, TNI)

Free optimization parameters:



... comparison (on paper) to optimized TNI mirrors based on plain and Ti-doped Tantala...

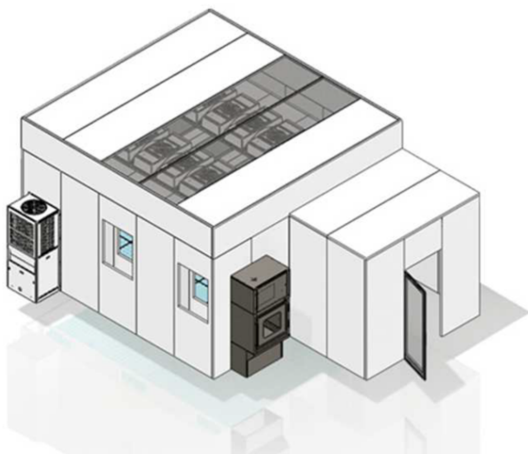
Little chance of being able to prototype such animal in Chao's Lab...`

(courtesy M. Principe, INFN, U-Sannio)

New Coating Facility (AdCOAT)

AdCOAT Usannio WG – new funding from Regione Campania for new "big" Laboratory Facilities

➡ Includes, among others,



MITEC 45 m^2 class 10000 reconfigurable clean room
9 m^2 class 100 room.

Optotech OAC-75F coater

New Coating Facility (AdCOAT)

Optotech OAC-75F coater

- 700 mm ϕ dome
- 75 mm ϕ useful coating area
- Cryo pumping 90 kl/s
- Op. temp 30 to 300^{o}K
- Multiple targets
- Ion gun 10 eV up to 300 eV
- Ar/O_2 atmosphere controls
- 6 MHz Quartz crystal (multiple) thickness control
- Shutters
- De-ionizing gun
- 2 replaceable wall liners
- Sander/cleaner

TBD

Make *thinner* layers (and hence more layers) to allow for *higher annealing temperatures*, and measure loss angle.

Practical thickness limit $\approx \mathbf{2}\,nm$, may allow $T_{ann} \approx \mathbf{400}\ C$;

Better (higher Q) substrates may be needed (Norcada's ?);

Complete optical characterization and investigate correlation with macroscopic strucural (TEM, AFM) features (Genoa)**.**

Need to characterize optical scattering losses of nanolaminates;

Collaboration w. other LVC/KAGRA Groups sought.

Investigate behaviour of nm-layered composites at cryogenic temperatures

Cryogenic ringdown measurement facilities are being implemented at NTHU, Rome (GeNS) and Perugia (Si_3N_4 membranes).

Upcoming upgrades

We are getting

Better eyes to see, and

Better hands to do !

Acknowledgements

This work has been sponsored in part by
EU through the EU-FP-7 ELiTES (IRSES) Project;
Italian National Institute for Nuclear Physics (INFN)
under the AdCOAT grant;
National Science Council of Taiwan under
NSC-1002221-E-007-099.