Nanometer - Layered SiO_2::TiO_2 Mixtures For High Reflectance /Low Noise Coatings Status Update

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Outline

Rationale

Prototypes

Measurements

Future Work

Good Coating Materials

Low mechanical loss-angle per unit thickness *(b)*

Depends ***both*** on complex Young modulus $Y = Y(1 - i\phi)$, ***and*** refractive index n_H;

High dielectric contrast (n_H/n_L)

helps ***reducing the number of layers*** (coating thickness) needed for a prescribed coating transmittance;

Low dielectric losses ($Im[n_H]$)

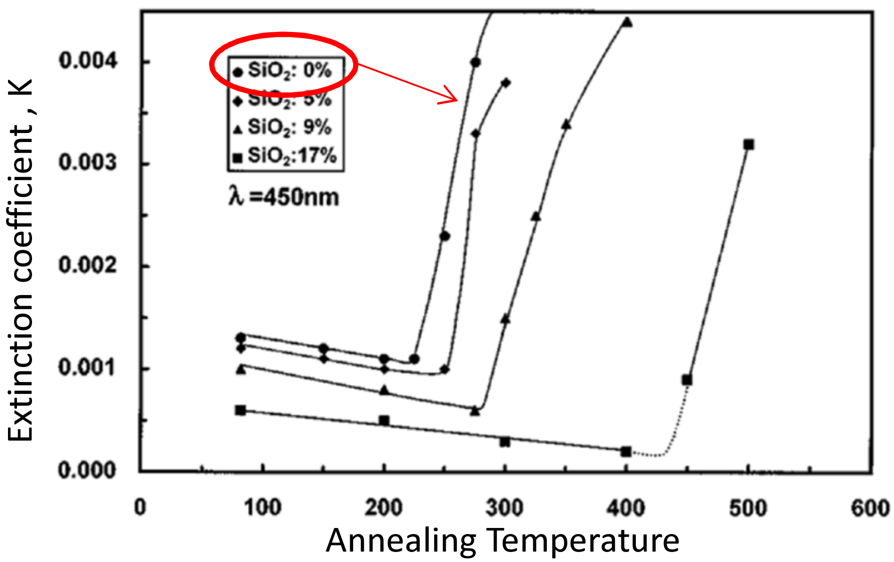
increases power-handling capability.

Coating Materials

Several candidate materials scrutinized so far, e.g, [R. Flaminio et al., CQG 27 (2010) 084030]

	SiO_2	Al_2O_3	$Ti{:}Ta_2O_5$	TiO_2	Nb_2O_5	ZrO_2
Mechanical losses	0.5×10^{-4}	2.4×10^{-4}	2×10^{-4}	6.3×10^{-3} ?	4.6×10^{-4}	2.3×10^{-4}
Density ($kg\ m^{-3}$)	2200	3700	6425	4230	4590	6000
Thermal conductivity ($W\ m^{-1}\ K^{-1}$)	0.5	3.3	0.6	0.45	1	1.09
Specific heat ($J\ K^{-1}\ kg^{-1}$)	746	310	269	130	590	26
Expansion coefficient (K^{-1})	0.5×10^{-6}	8.4×10^{-6}	3.6×10^{-6}	0.5×10^{-6}	5.8×10^{-6}	10^{-5}
Thermo-optic coefficient (K^{-1})	8×10^{-6}	1.3×10^{-6}	14×10^{-6}	-1.8×10^{-4}	1.43×10^{-5}	10^{-4}
Young modulus (GPa)	60	210	140	290 ?	80	200
Poisson coefficient	0.17	0.22	0.28	0.28	0.2	0.27
Refraction index	1.45	1.63	2.07	2.3	2.21	2.1

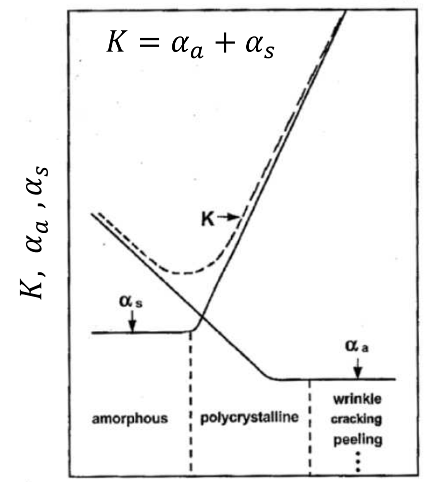
Annealing Titania



W.H. Wang and S. Chao, Opt. Lett. 23 (1998) 1417.
S. Chao et al., JOSA A16 (1999) 1477
S. Chao, W.H. Wang, C.C. Lee, Appl. Opt 40(2001) 2177.

- *Thick* TiO_2 *crystallizes* upon annealing above ~ 200ºC, signaled by blow-up of optical extinction coefficient;
- *Mechanical losses* blow up in parallel;
- *Can be mitigated doping* SiO_2 *w.* SiO_2 (cosputtered);
- Related to *growth of crystallites* formed during deposition…

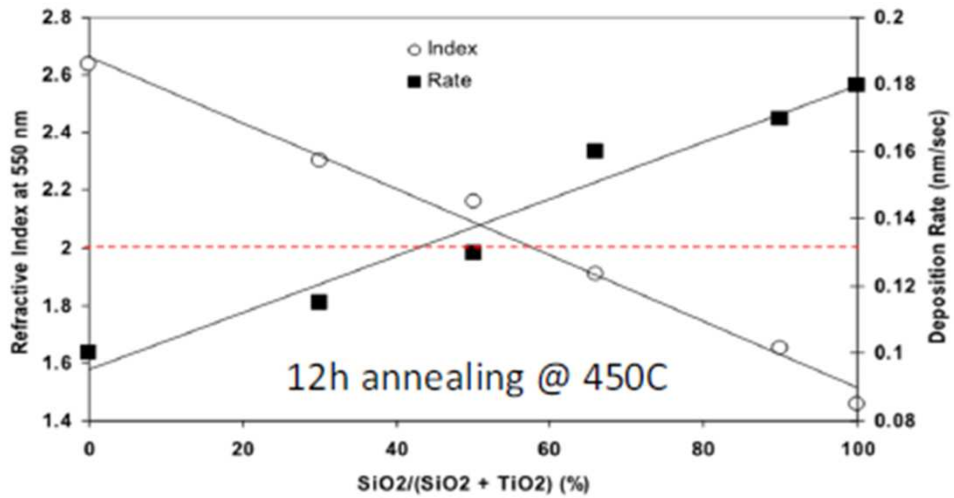
Extinction coefficient , K
Absorption coefficient , α_a
Scattering coefficient , α_s



Annealing Temp.

Cosputtered Silica-Titania

R.P. Netterfield and M. Gross, "*Investigation of Ion Beam Sputtered Silica Titania Mixtures for Use in GW Interferometer Optics*," Optical Interference Coatings (OIC) Conference, Tucson AZ, USA, 2007, paper Thd2.



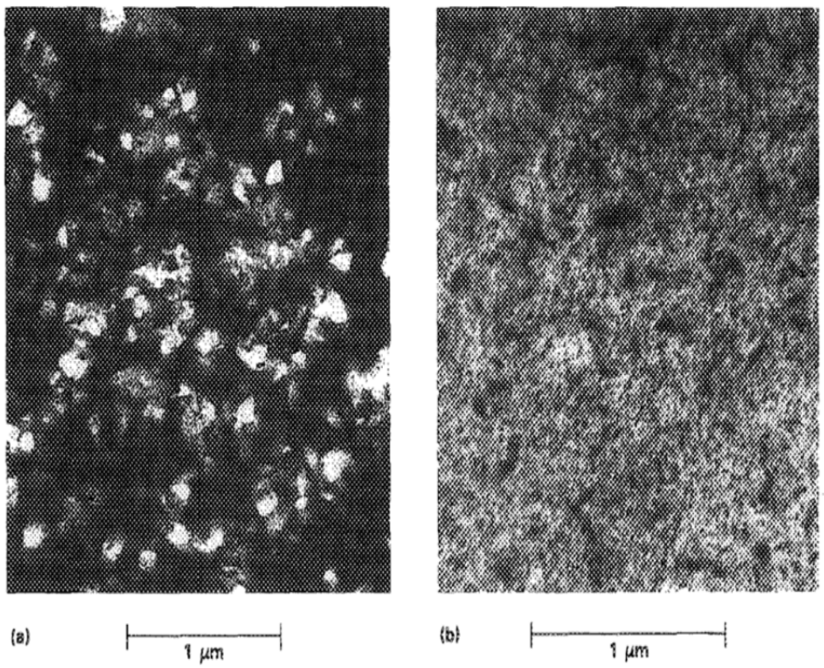
Claims: Annealing at 500C did ***not*** produce crystallization

15 QWL doublets SiO_2 / TiO_2::SiO_2 with 35% Titania coating prototype:
- Absorption loss *better* than TiO_2::Ta_2O_5
- Optical index slightly *lower* than TiO_2::Ta_2O_5
- Mechanical losses slightly *higher* than than TiO_2::Ta_2O_5

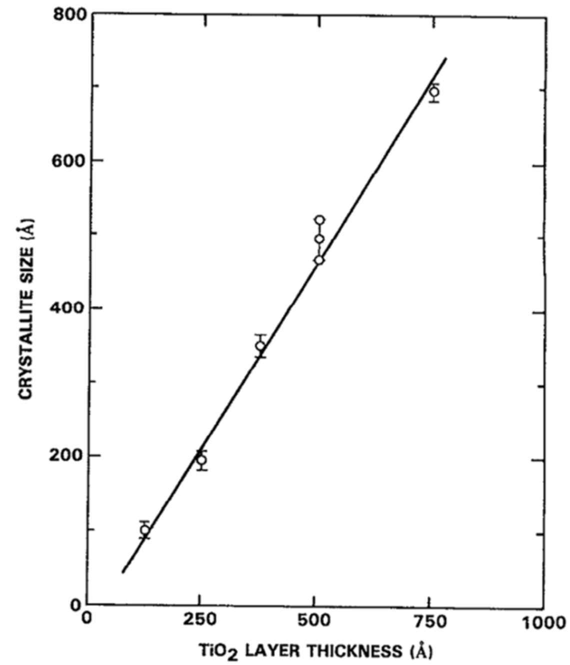
No better than LMA no. 5 in terms of noise...

Annealing Titania

The *maximum annealing temperature* above which TiO_2 crystallizes *increases* by *increasing SiO_2 content* (co-sputtered SiO_2::TiO_2 mixtures) and/or *decreasing TiO_2 thickness* (layered SiO2::TiO2 mixtures).



H. Sankur and G. Gunning,
J. Appl. Phys. 66 (1989) 4747.



N.S. Gluck et al., J. Appl. Phys. 69 (1991) 3037

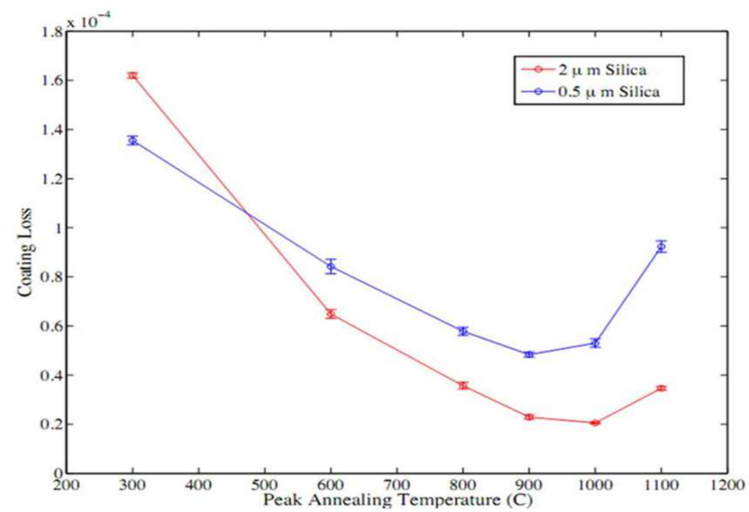
Annealing Silica

Loss angle of *un-annealed* Silica *decreases* with *decreasing* thickness

Loss angle of *annealed* Silica *increases* with *decreasing* thickness

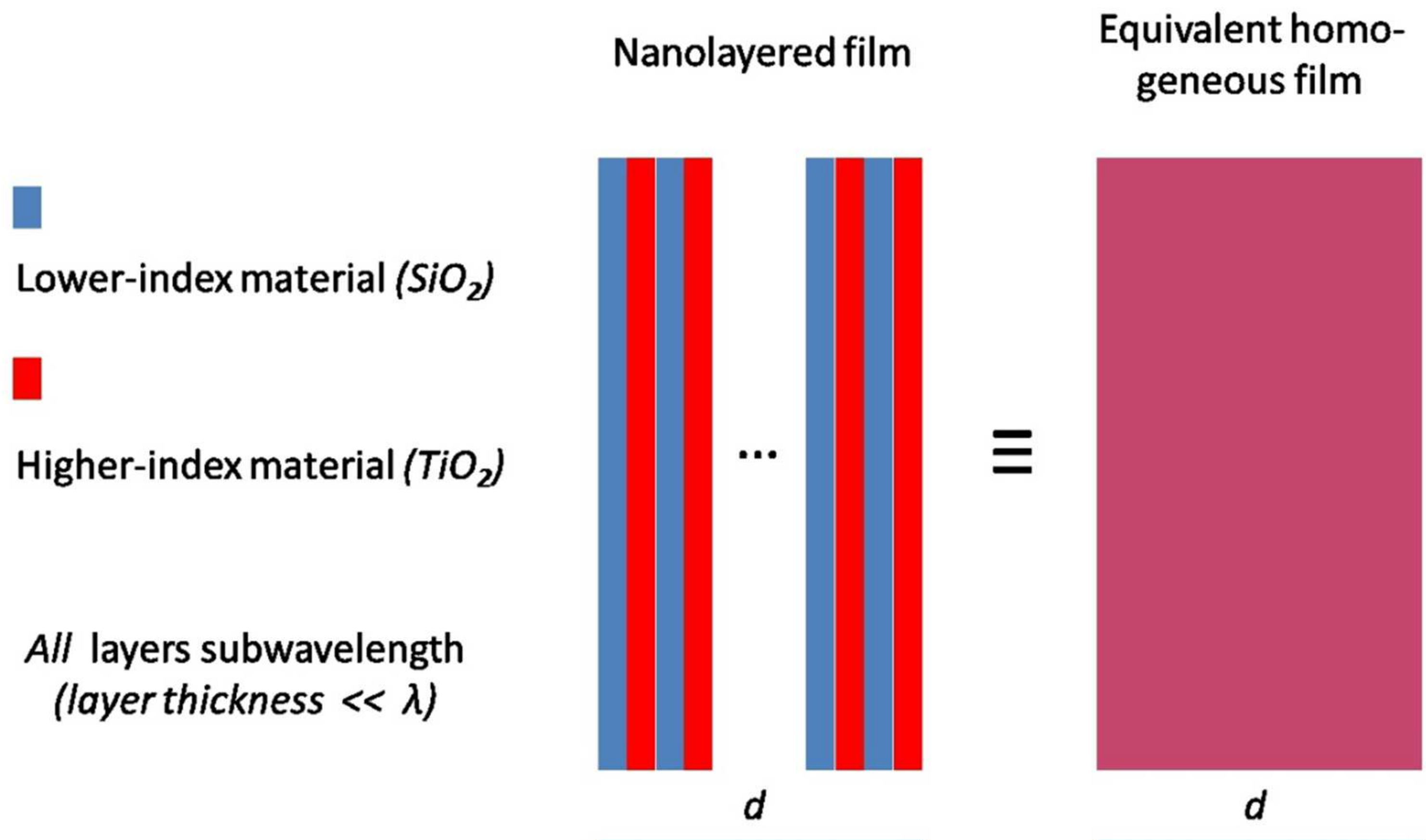
Slope of loss angle vs annealing T *decreases* with *decreasing* thickness

Lower annealing T needed for Silica-Titania nanometer layered materials ?

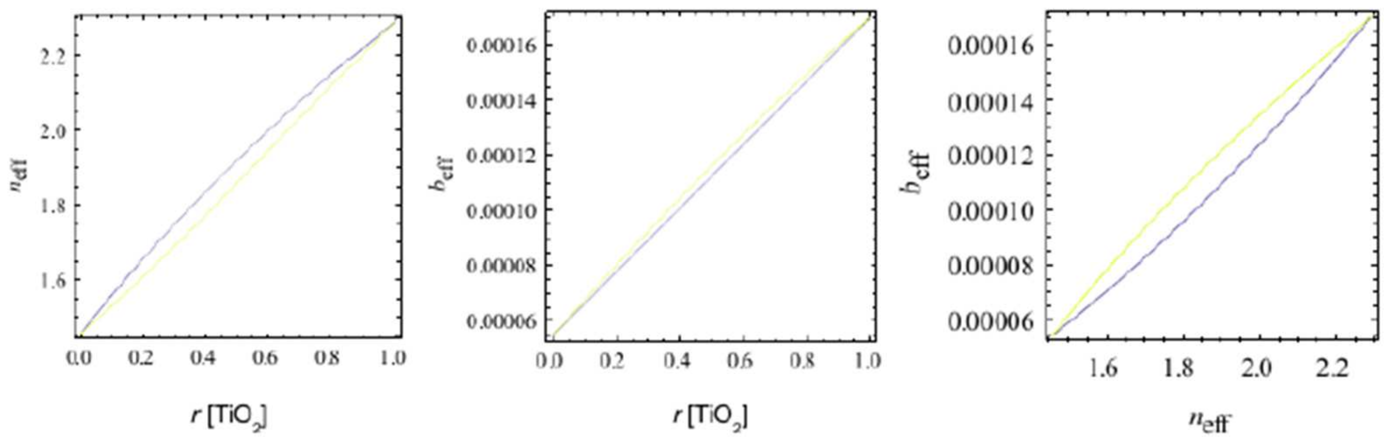


[S. Penn et al., LIGO-G1000932]

nm-Layered SiO_2 TiO_2 Films



Cosputtered vs nm-Layered



Layered SiO2::TiO2 mixture "bertter" than isotropic mixture at all stoichiometries

Modeling

nanometer → subwavelengh thick

$$n_f = \left[r_H n_H^2 + (1 - r_H) n_L^2 \right]^{1/2}$$

$$Y_f^{\perp} = \left[r_H / Y_H + (1 - r_H) / Y_L \right]^{-1} \quad , \quad r_H = \frac{z_H}{z_L + z_H}$$

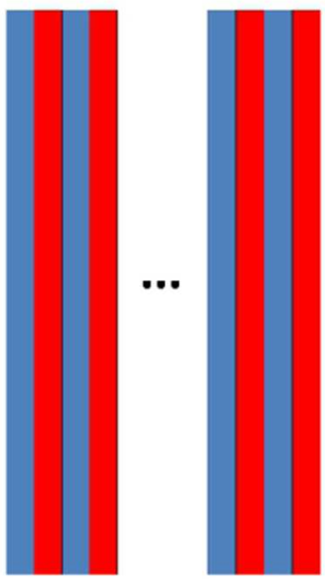
$$Y_f^{||} = r_H Y_H + (1 - r_H) Y_L$$

$z_{L,H}$ = physical thickness of L/H index material

$$\phi_f = \frac{\left(\frac{Y_s}{Y_H} + \frac{Y_H}{Y_s} \right) r_H \phi_H + \left(\frac{Y_s}{Y_L} + \frac{Y_L}{Y_s} \right) (1 - r_H) \phi_L}{Y_s \left[r_H / Y_H + (1 - r_H) / Y_L \right] + Y_s^{-1} \left[r_H / Y_H + (1 - r_H) / Y_L \right]^{-1}}$$

Isorefractive nm-Layered Films

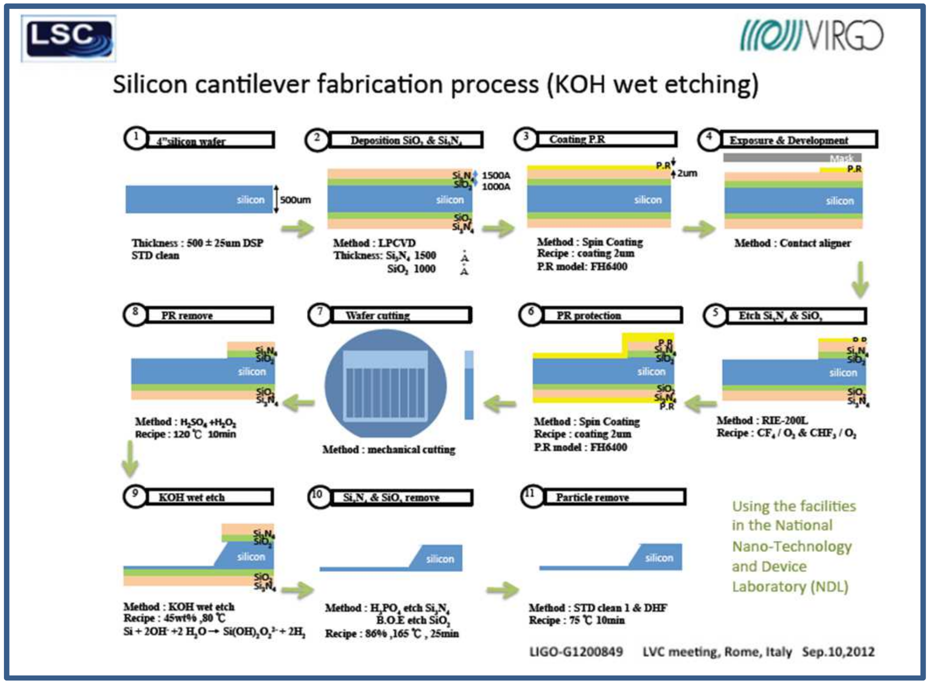
Number of nanolayers

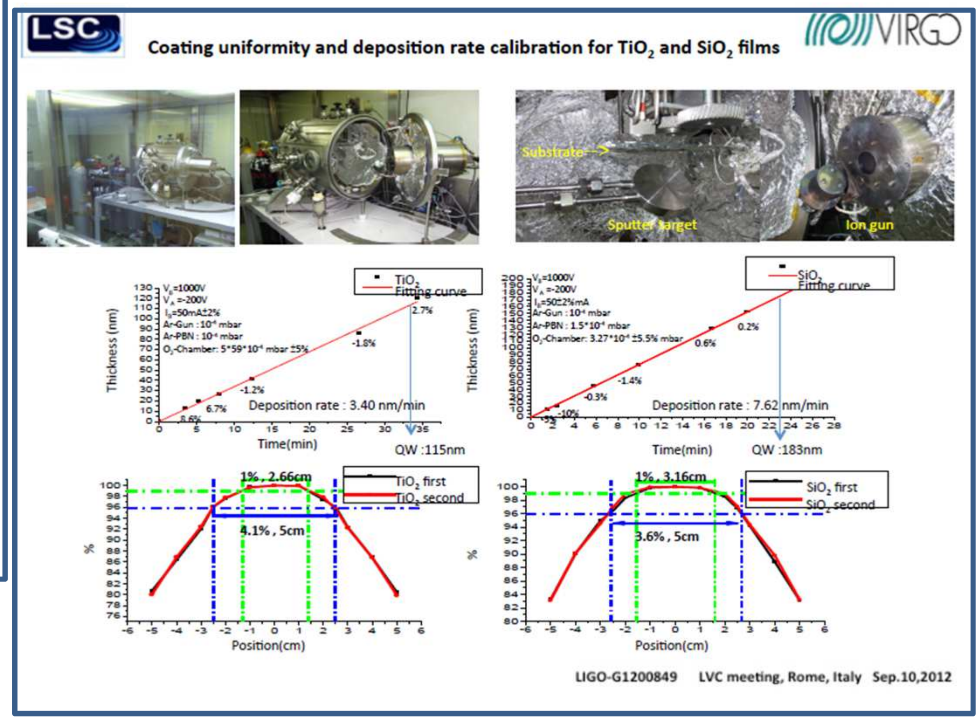


N TiO2	Thickness TiO2 [nm]	N SiO2	Thickness SiO2[nm]
2	42.56	1	42.15
3	28.37	2	21.07
4	21.28	3	14.05
5	17.02	4	10.54
6	14.19	5	8.43
7	12.16	6	7.02
8	10.64	7	6.02
9	9.46	8	5.27
10	8.51	9	4.68

All designs have the same refractive index (2.09), the same physical thickness (127.27 nm) and he same optical thickness (QWL at 1064nm)

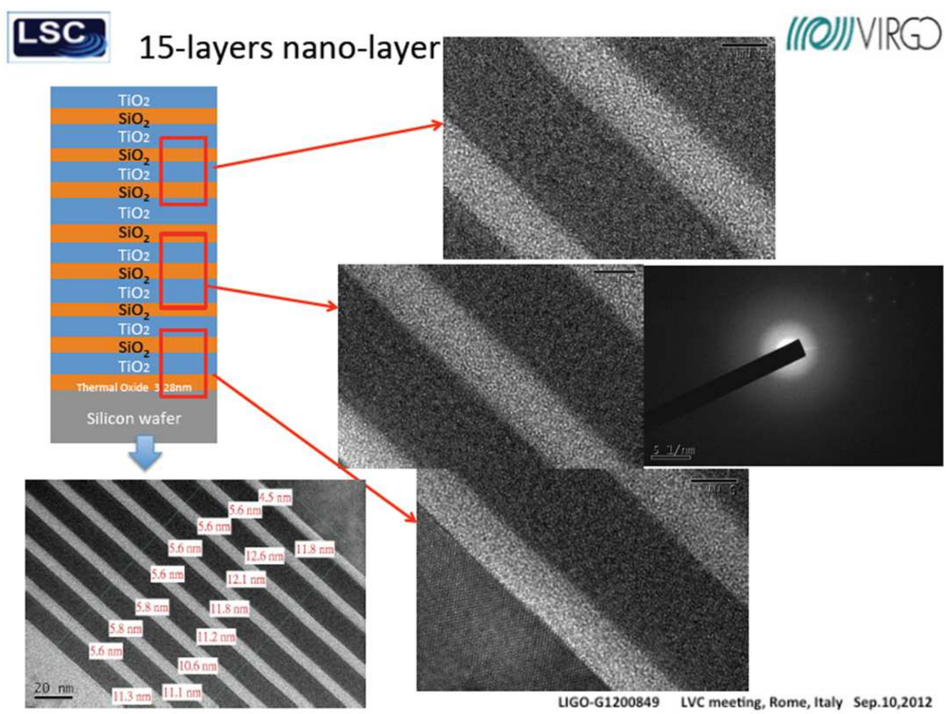
Prototype Fabrication at NTHU





Full details in S. Chao et al., LIGO-G1200849

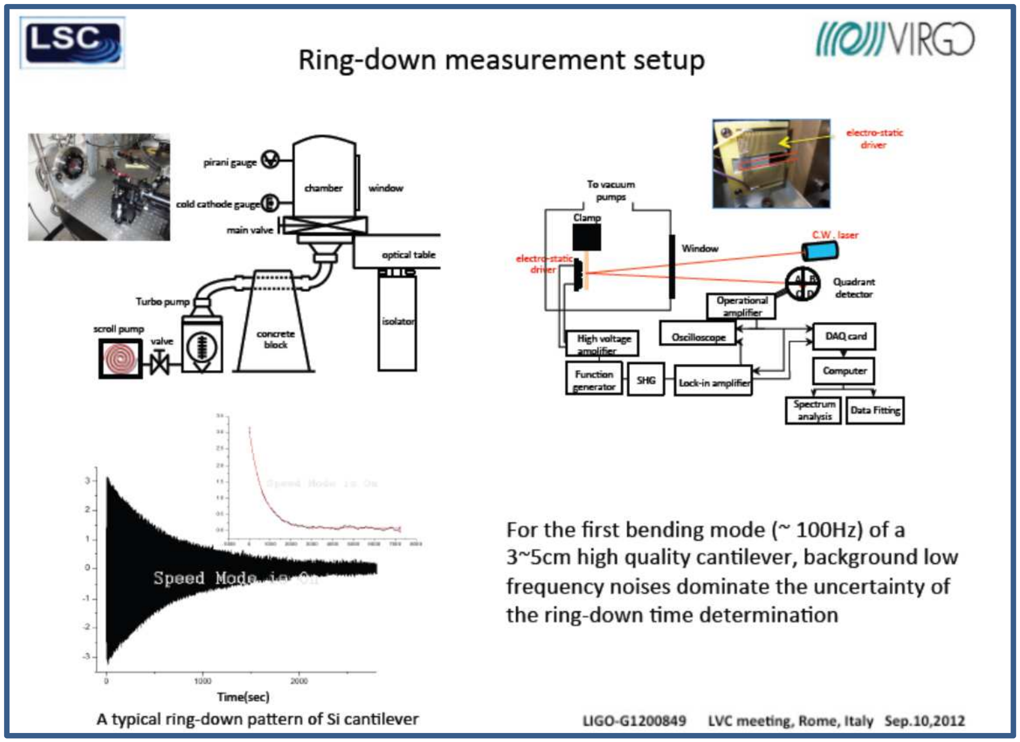
Prototype Characterization at NTHU



Deposition rate: TiO_2 3.40 nm/min SiO_2 7.79 nm/min						
layer	Designed thickness	Deposition time	Measured thickness (TEM)	Thickness error	Measured thickness (Ellipsometry)	Thickness error
15	10.64nm	3'8"	11.30 nm	6.2%	Not available	
14	6.02nm	46"	5.60 nm	7.0%		
13	10.64nm	3'8"	11.10 nm	4.3%		
12	6.02nm	46"	5.80 nm	3.8%		
11	10.64nm	3'8"	10.60 nm	0.4%		
10	6.02nm	46"	5.80 nm	3.7%		
9	10.64nm	3'8"	11.20nm	5.3%		
8	6.02nm	46"	5.60nm	7.0%		
7	10.64nm	3'8"	11.80nm	11%		
6	6.02nm	46"	5.60 nm	7.0%		
5	10.64nm	3'8"	12.10 nm	13.7%		
4	6.02nm	46"	5.60nm	7.0%		
3	10.64nm	3'8"	12.60 nm	18.4%		
2	6.02nm	46"	5.60 nm	7.0%		
1	10.64nm	3'8"	11.80 nm	10.9%		
Tio_2 average thickness for layer1 : 12.06 nm Standard deviation : 0.14 nm SiO_2 average thickness for layer 2 : 5.24 nm Standard deviation : 0.20 nm						

Full details in S. Chao et al., LIGO-G1200849

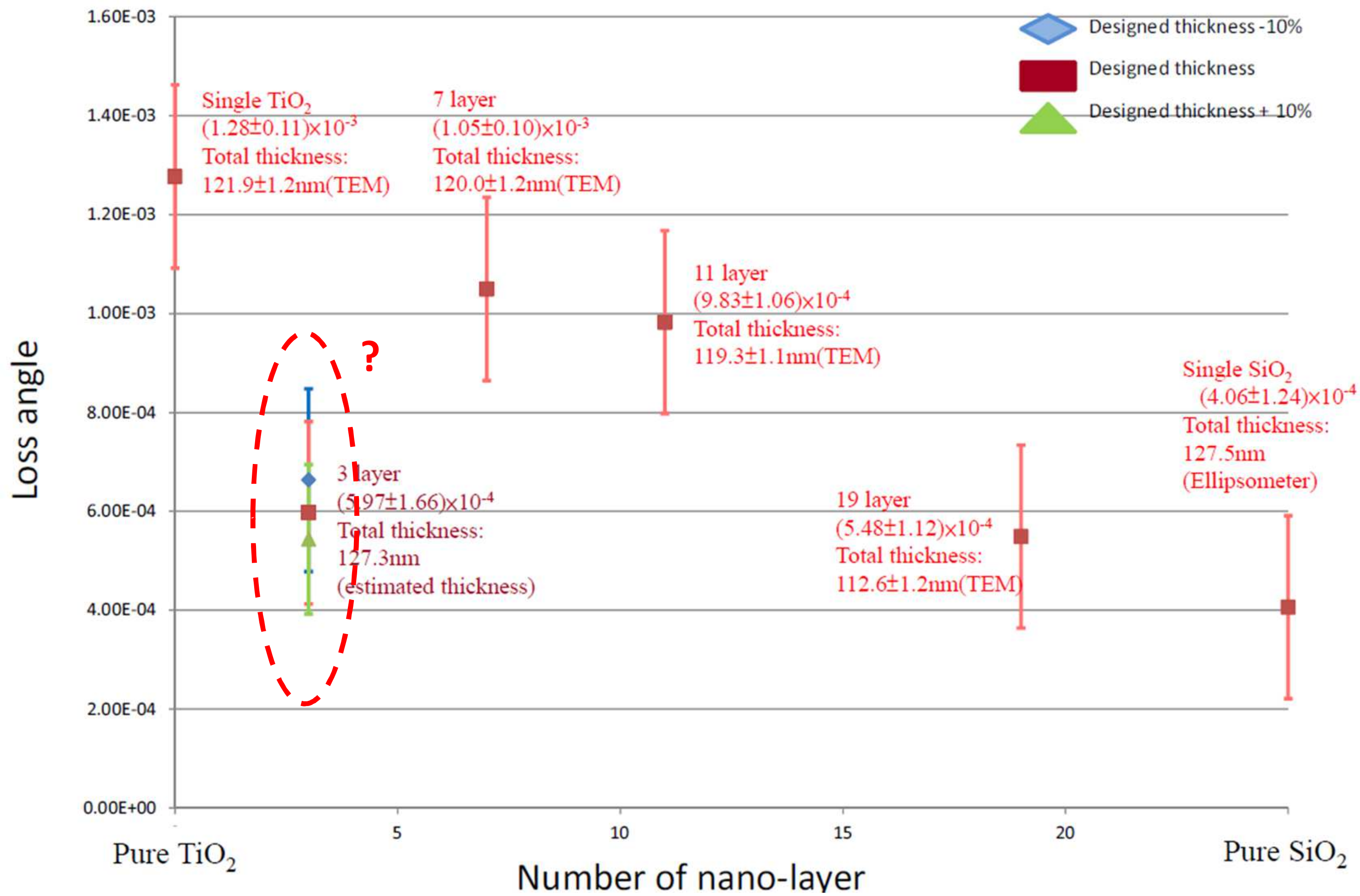
Prototype Loss Angle Measurement at NTHU



- Errors from background noise and re-clamping fully analyzed and well understood;
- Background noise statistics estimated;
- Negligible effect of re-clamping scratches were found;
- 29 ring-down measurements (from 5 re-clampings) for each prototype taken.

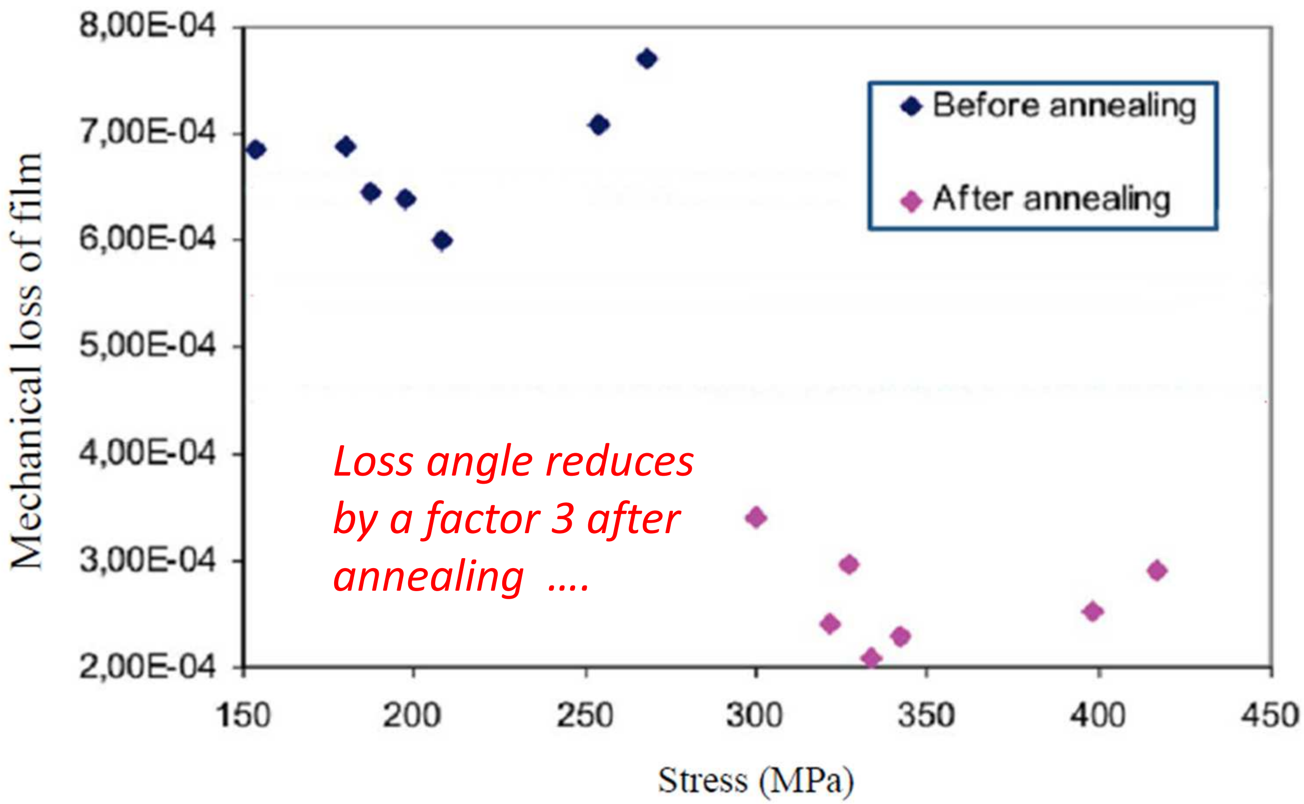
Full details in S. Chao et al., LIGO-G1200849

Measured Nano Films Loss Angle



TiO_2::Ta_2O_5 (before/after anneal)

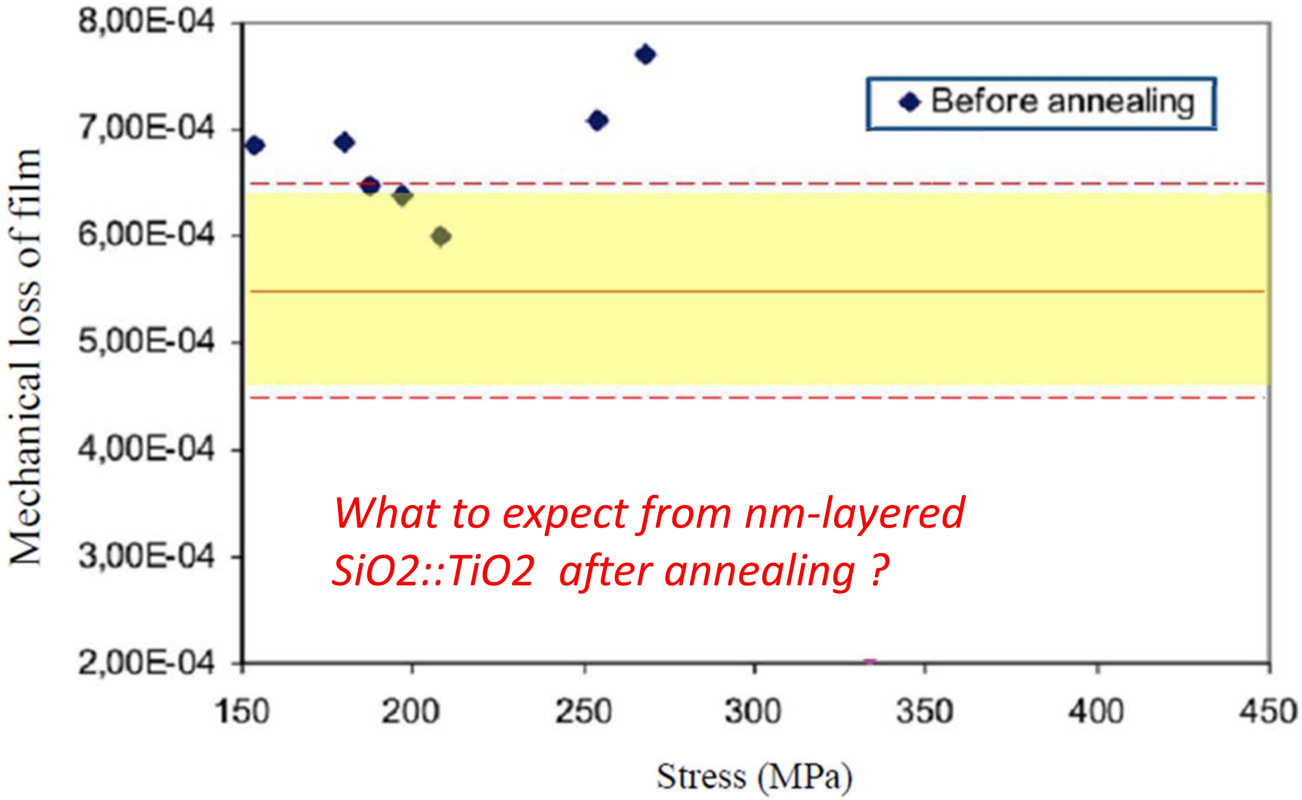
TiO_2::Ta_2O_5 film prototypes (LMA "formula 5") and related stresses



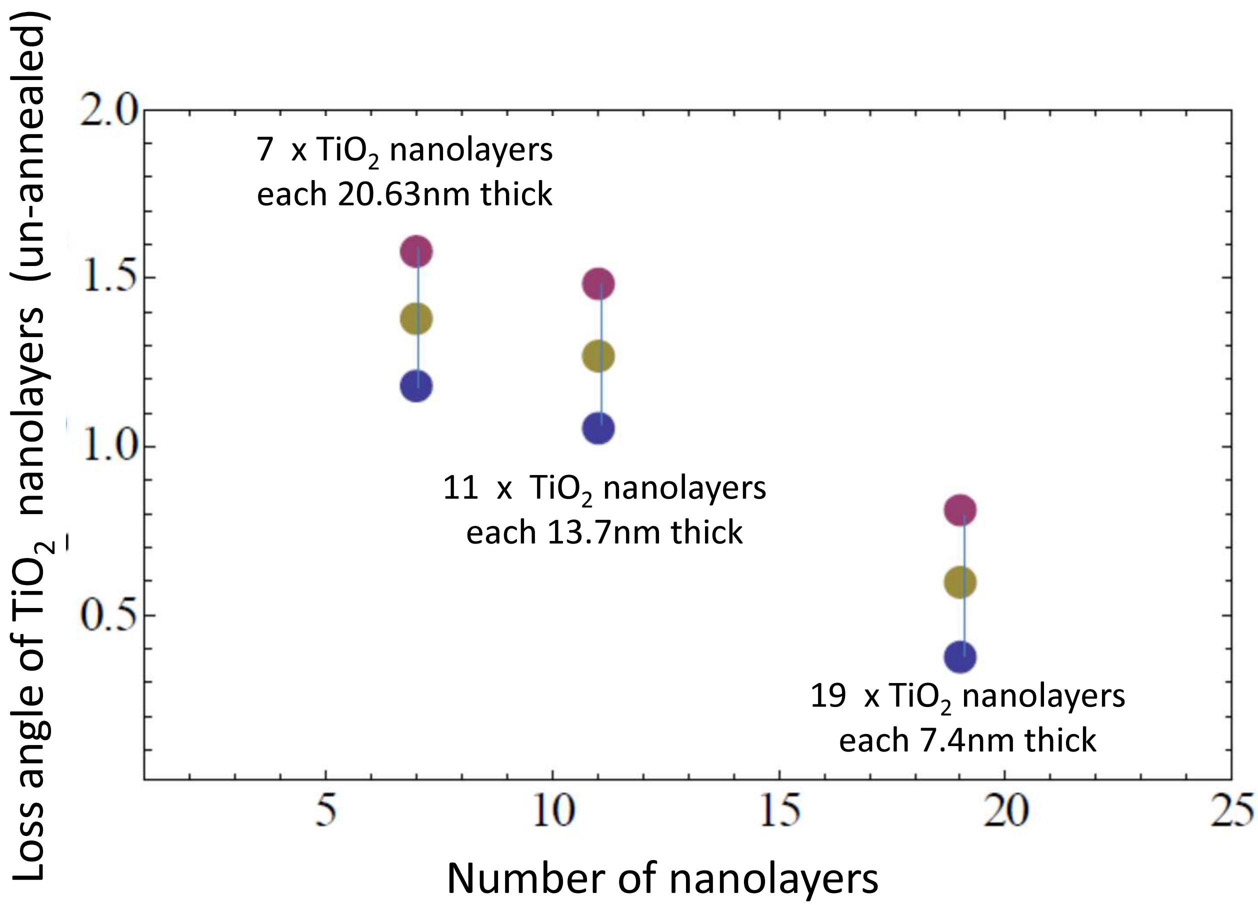
TiO_2::SiO_2 vs TiO_2::Ta_2O_5 (un-annealed)

Un-annealed TiO_2::Ta_2O_5 film prototypes (LMA “formula 5”) and related stresses

… uncertainty strip of 19-nanolayers isorefractive TiO2::SiO2 film prototype



TiO_2 Loss Angle vs Thickness



Cryogenic Peak Free Mixtures ?

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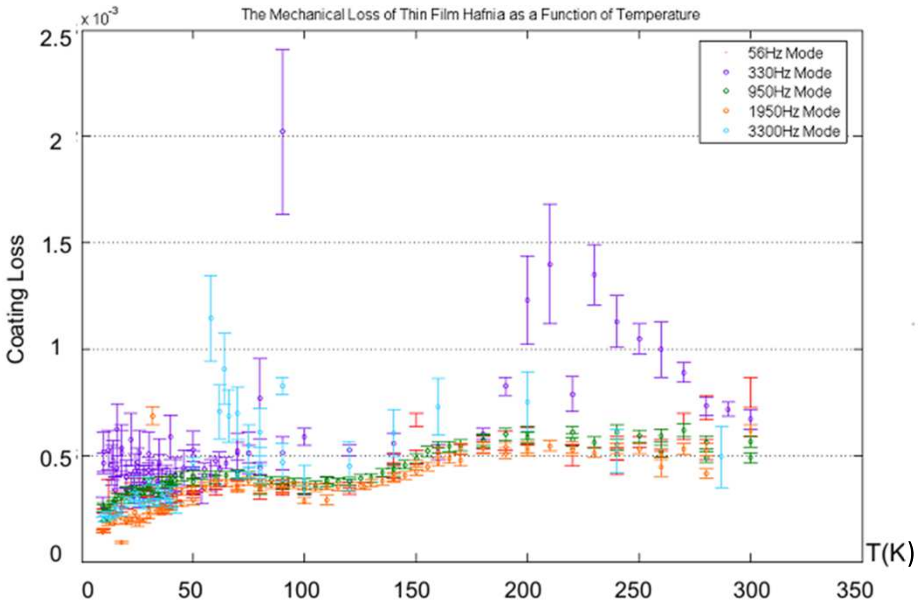
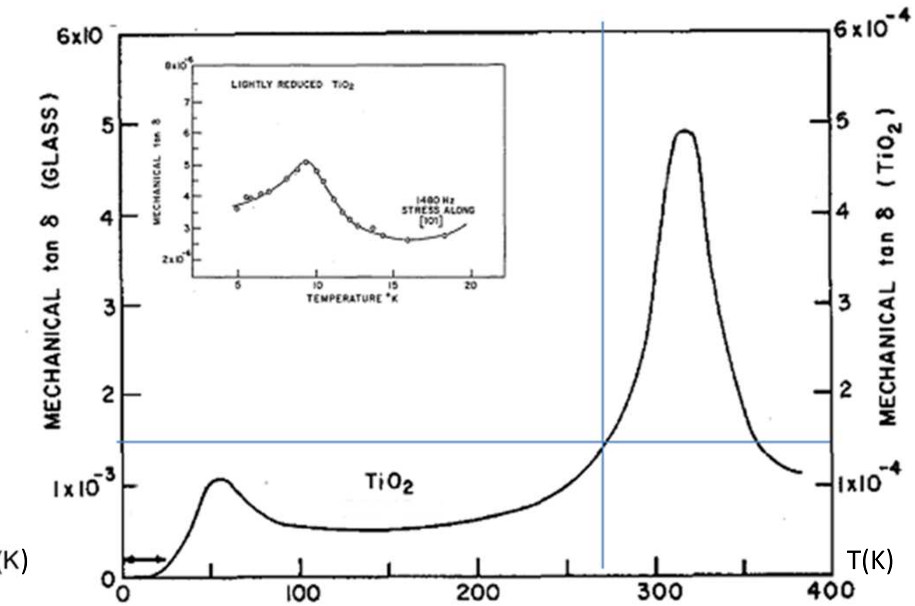
Fiducially, both TiO2 and HfO2 (while amorphous) are cryogenic - peak free



[Chalkley et al., LIGO-GG080314]



[Scott and MacCrone, rev. Sci. Instr. 39 (1968) 821]

Nanometer layered HfO_2::TiO_2 mixtures may have any refraction index between 1.9 (pure Hafnia) and 2.3 (pure Titania). The dielectric contrast between (ideal) HfO_2 buffered TiO_2 and TiO_2 buffered HfO_2 can be ~ 1.2 (vs ~ 1.4 for Tantala/Silica)

Future Work

Encouraging results from NTHU measurement of loss angle in nm-layered Silica-Titania films;

Amorphous un-annealed Titania loss angle found to be of the order of 10^{-4} , thickness dependent;

Amorphous un-annealed Titania Young modulus found to be roughly 165 Gpa;

Annealing is bein planned. Preliminary Results may be hopefully available for the next LVC