Inhibition of Cryogenic Mechanical Loss in Thin Films by Thickness Reduction

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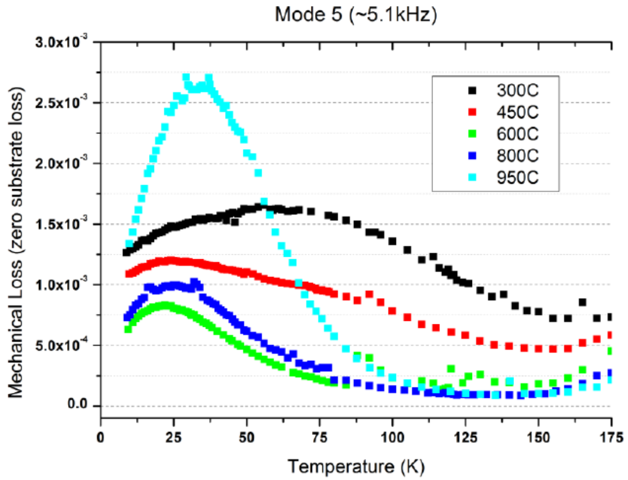
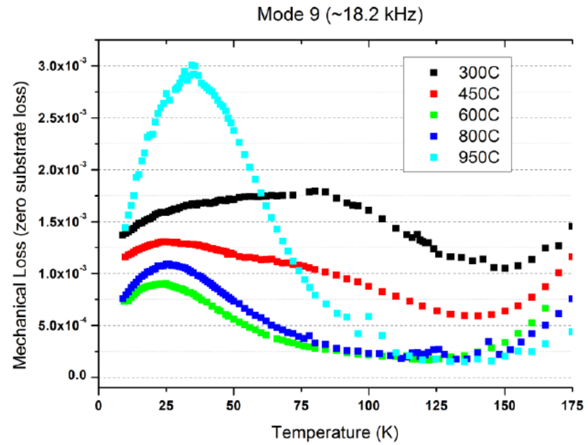
LIGO-G1800300-v2

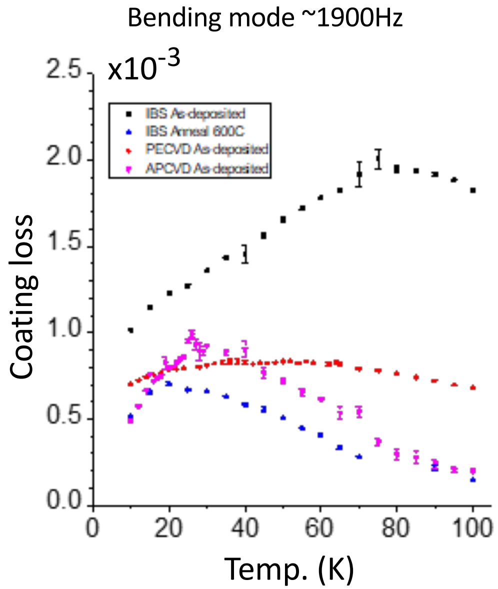
Cryogenic loss peak of SiO_2 thin films (review)

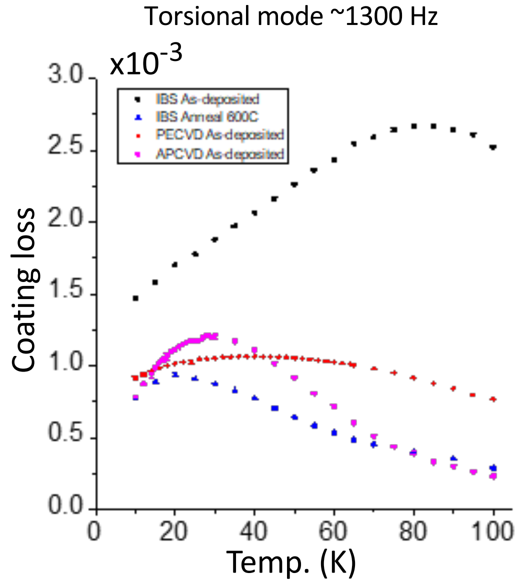
IBS [R. Robie et al., LIGO-G1601854 (2016)]





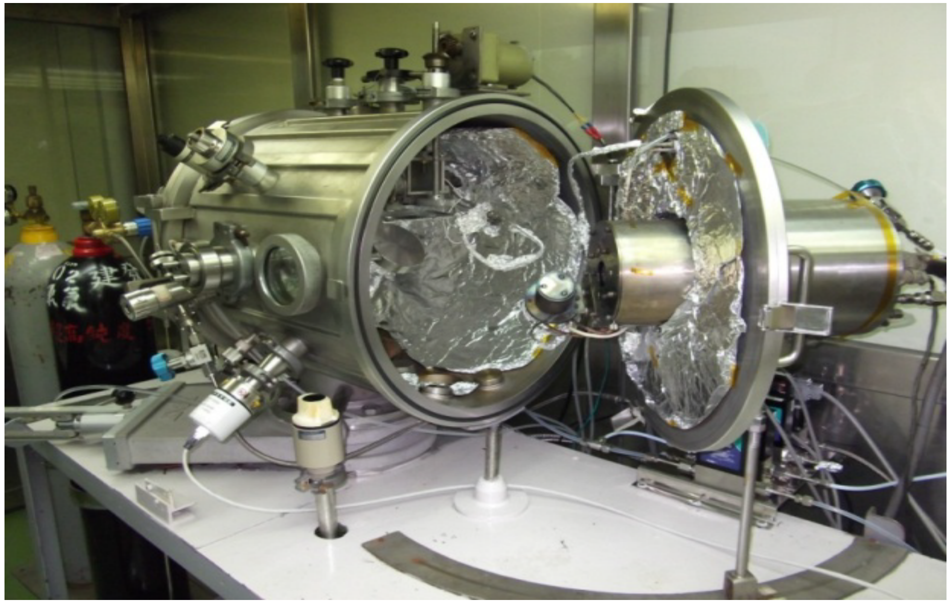
IBS, PECVD and APCVD [L.C. Kuo et al., LIGO-G1700300 (2017)]

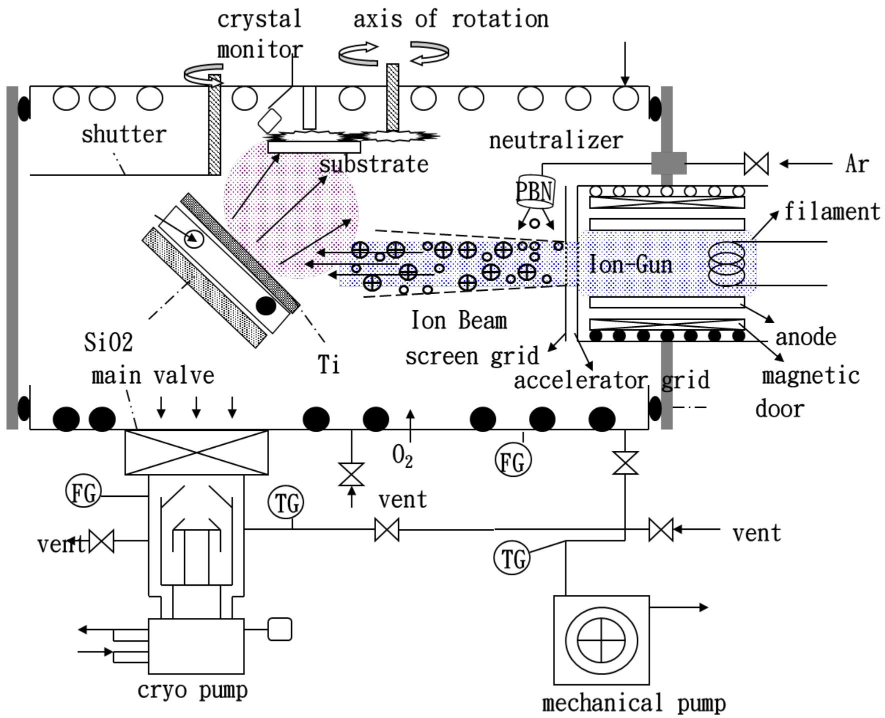




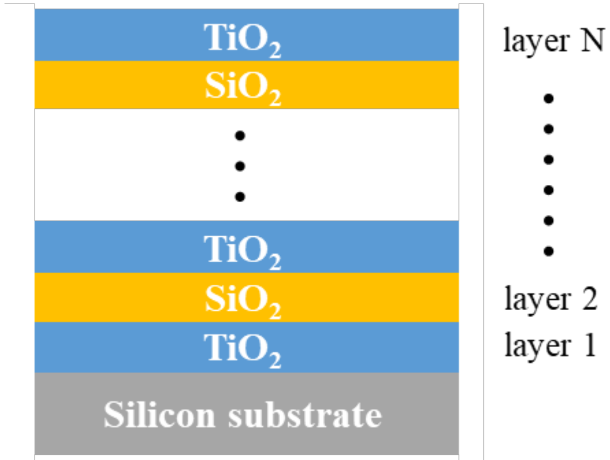
Method	IBS		PECVD	APCVD
Deposition temperature	80°C	80°C	300°C	980°C
Annealing temperature	none	600°C	none	none
Peak temperature	83K	22K	40K	32K
Peak height (1900Hz)	1.94×10^{-3}	7.01×10^{-4}	8.31×10^{-4}	9.16×10^{-4}

Ion Beam Sputter Apparatus at NTHU





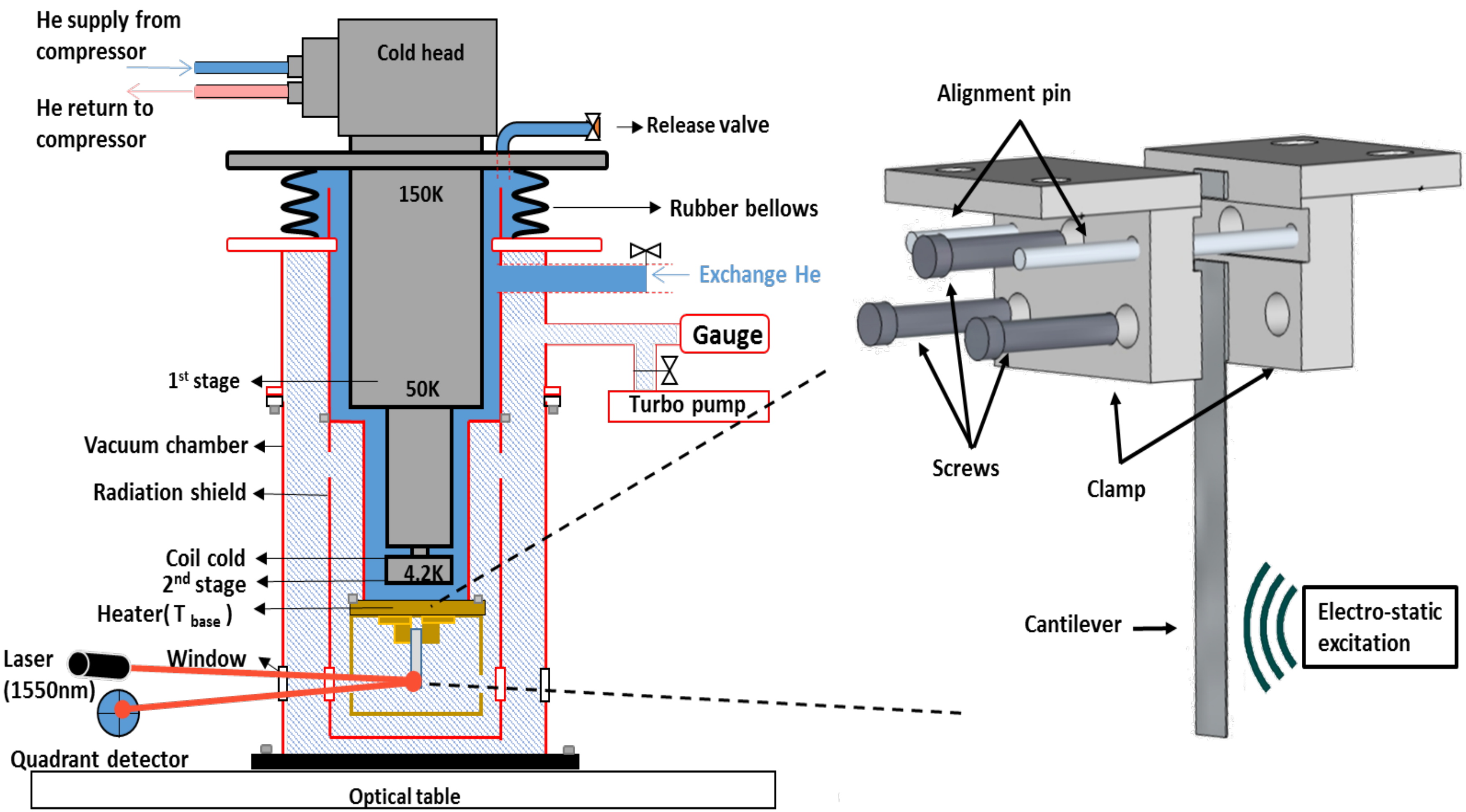
Nano-meter scale ultra-thin layers deposition at NTHU



Schematics of the nano-meter scale thin film stack

[S. Chao et al., LIGO-G1300921 (2013)]

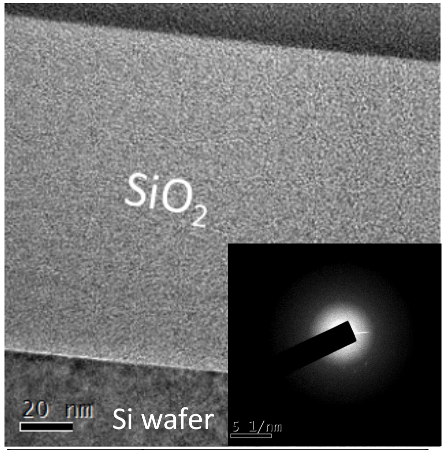
Cryogenic loss measurement setup at NTHU (cantilever ring-down)



[S. Chao et al., LIGO-G1700301 (2017)]

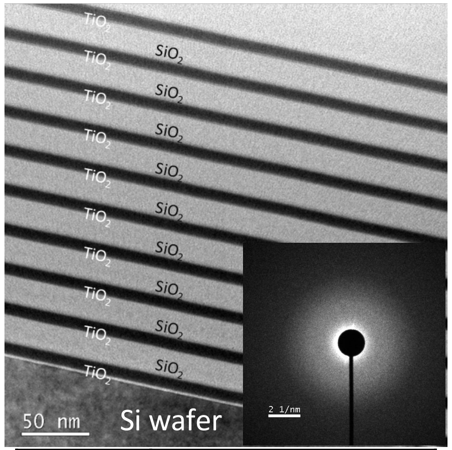
Ultra-thin TiO_2/SiO_2 alternate-stacking samples (deposited by ion-beam sputter)

Single SiO_2*



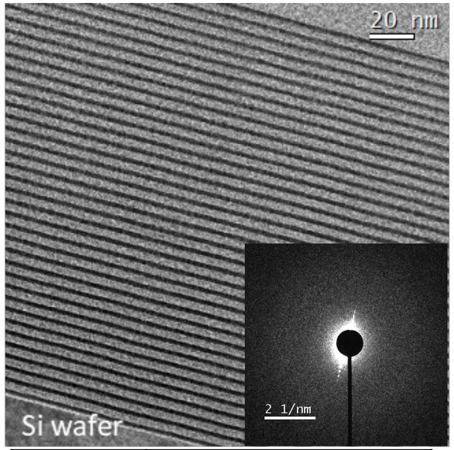
	thickness (nm)
SiO_2	130.5 ± 0.1
TiO_2	0
$r = 0$	

19-layer



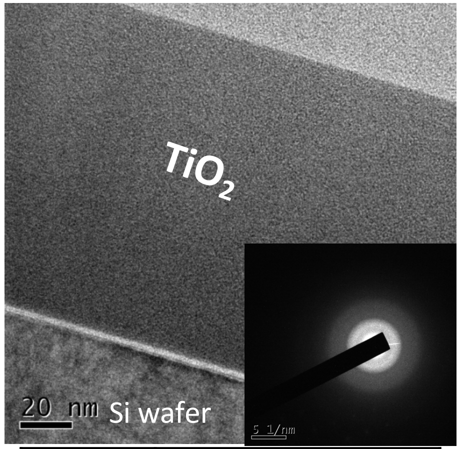
	thickness (nm)
SiO_2	19.3 ± 0.1 (x9)
TiO_2	8.3 ± 0.2 (x10)
$r = 0.32$	

75-layer



	thickness (nm)
SiO_2	3.6 ± 0.1 (x37)
TiO_2	1.8 ± 0.1 (x38)
$r = 0.33$	

Single TiO_2 *

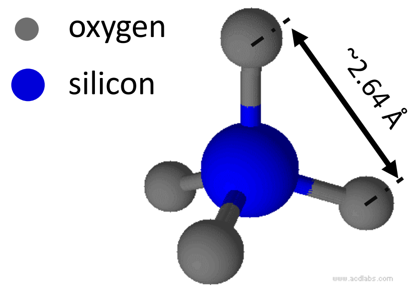


	thickness (nm)
SiO_2	0
TiO_2	131.1 ± 0.1
$r = 1$	

$$\phi_c = r \cdot \frac{Y_{TiO_2}\phi_{TiO_2}}{Y_c} + (1-r) \cdot \frac{Y_{SiO_2}\phi_{SiO_2}}{Y_c}$$

$$Y_c = \frac{Y_{TiO_2}T_{TiO_2} + Y_{SiO_2}T_{SiO_2}}{T_{TiO_2} + T_{SiO_2}} = r \cdot Y_{TiO_2} + (1-r)Y_{SiO_2}$$

r : thickness ratio $T_{TiO_2}/(T_{SiO_2}+T_{TiO_2})$
Y : Young's modulus
ϕ : mechanical loss angle
T : total thickness

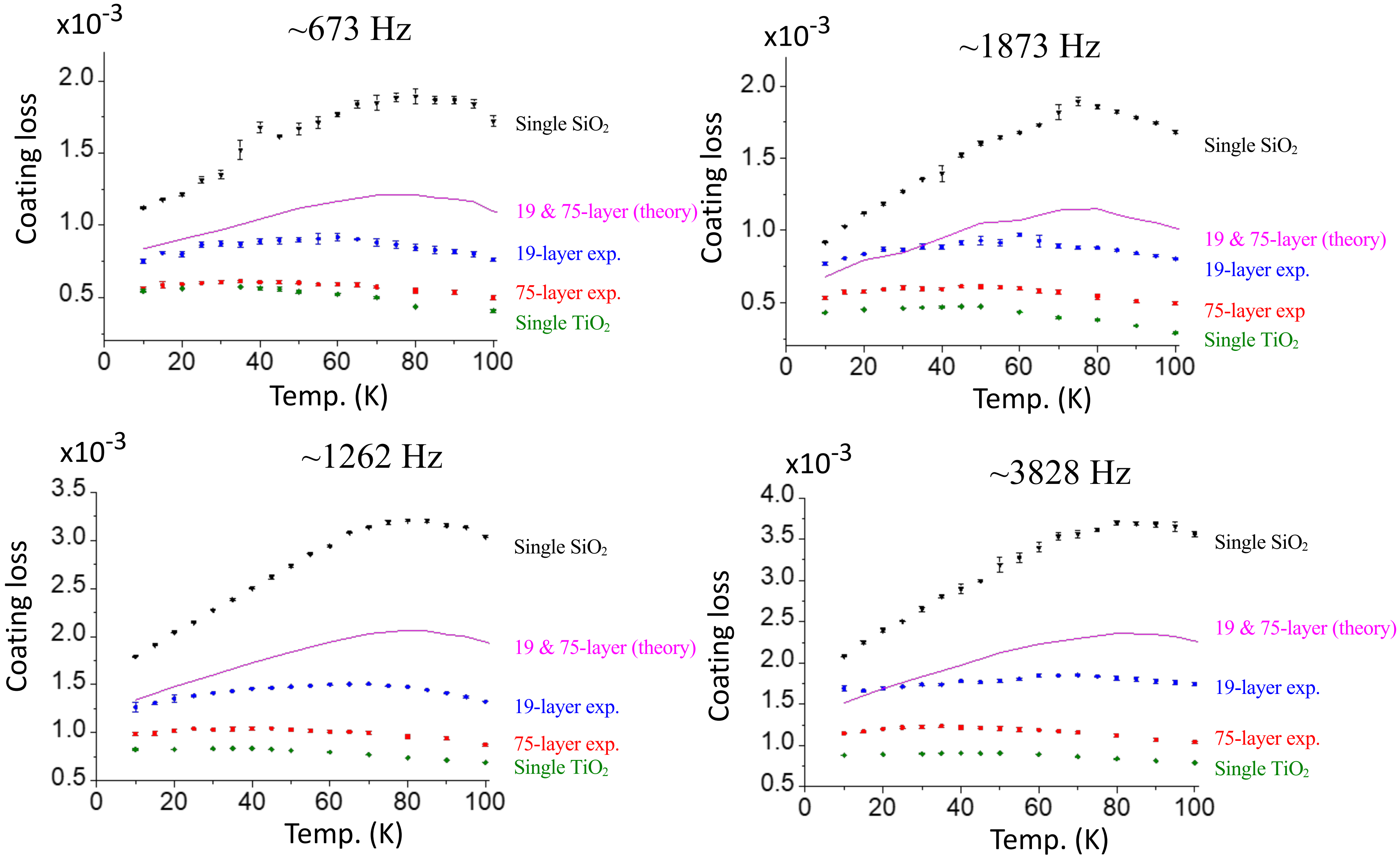


Theoretical coating loss depends only on thickness ratio but not on the individual layer thicknesses

[L.D. Landau et al., Theory of Elasticity 3rd edn (Oxford: Pergamon) (1986)]
[S.D. Penn al., *Mechanical loss in tantala/silica dielectric mirror coatings,* Class. Quant. Grav. 20 2917-2928 (2003)]

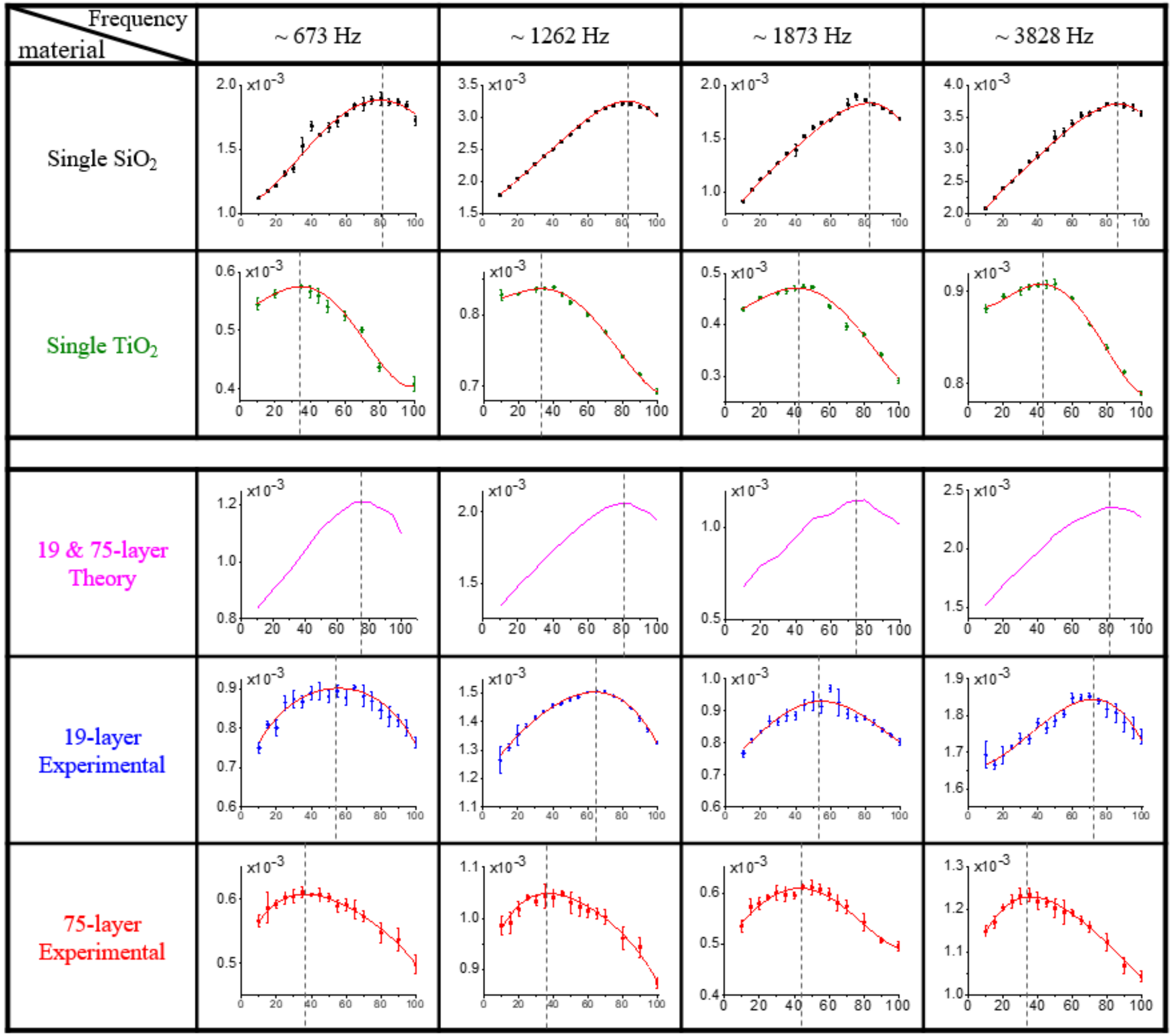
*Archive TEM pictures for single SiO_2 film and single TiO_2 film deposited under the exact same conditions.

Cryogenic mechanical loss results



Zoom-in plots are on next page

Cryogenic mechanical loss results (zoom-in)



Important features beyond predictions from the existing theory as films become thinner:

1. Peak height decreased.
2. Peak position shifted to lower temperature.

LIGO-G1800300-v2 LVC meeting at Sonoma State University, CA, USA Mar. 20th, 2018

Peak position shifts

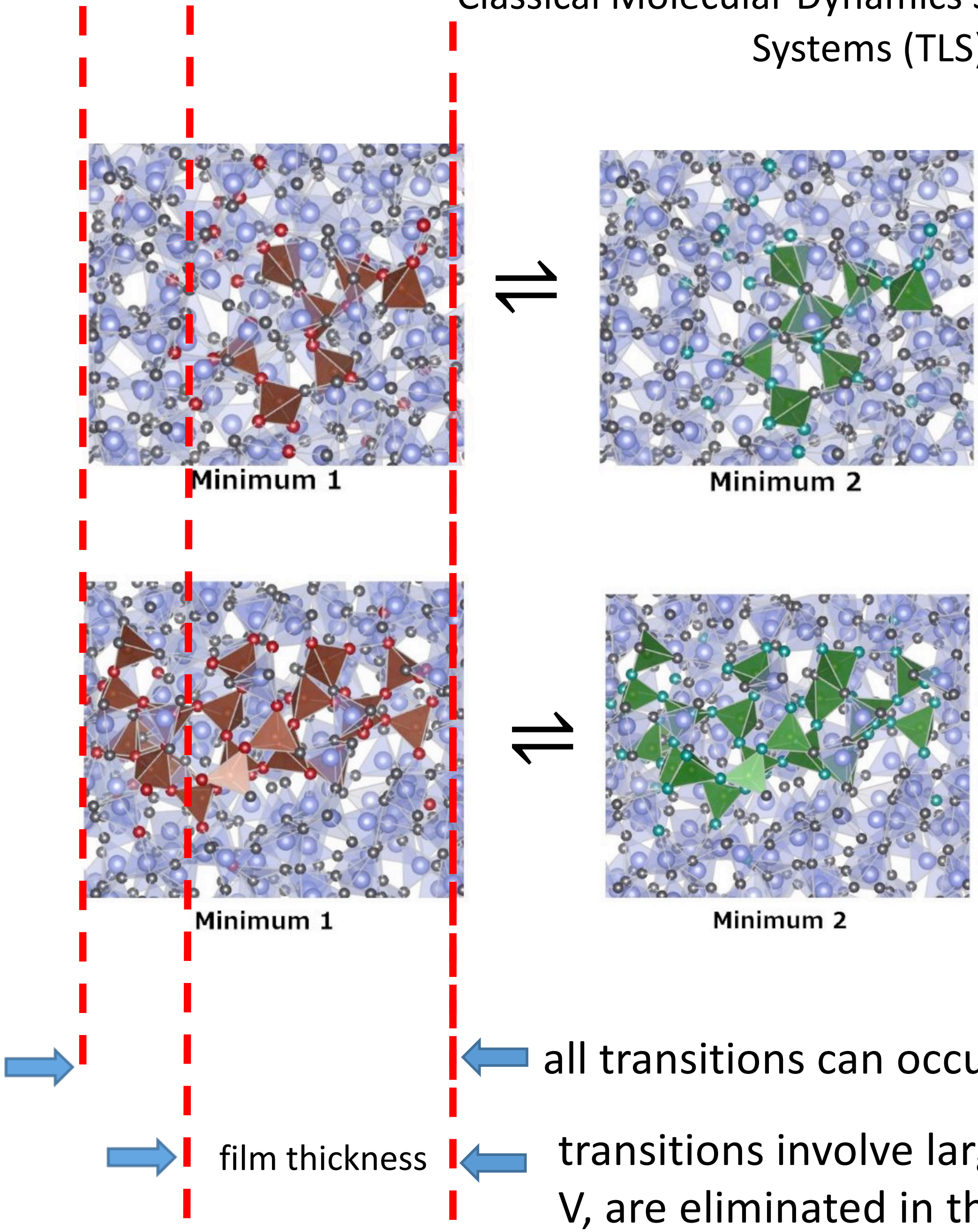
unit: K

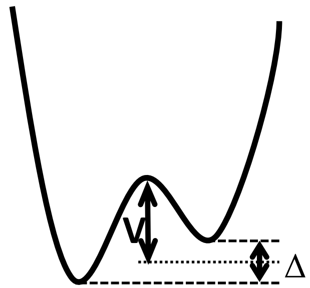
Frequency / material	~ 673 Hz		~ 1262 Hz		~ 1873 Hz		~ 3828 Hz	
	T_{peak}	Peak shift	T_{peak}	Peak shift	T_{peak}	Peak shift	T_{peak}	Peak shift
SiO_2	79.4	--	83.0	--	82.2	--	86.4	--
TiO_2	34.6	--	32.7	--	40.8	--	41.8	--
theory	75.2	0	80.4	0	74.0	0	81.5	0
19-layer	55.6	-19.6	64.2	-16.2	54.8	-19.2	71.8	-9.7
75-layer	36.3	-38.9	36.8	-43.6	43.2	-30.8	36.0	-45.5

- Error for peak position determination mainly came from clamping, it was estimated to be < ±3K for these samples from several re−clamping trials.
- The error was much smaller than the observed peak shifts.
- The error was yet too large for determination of the activation energies of the transition from the ln(ω) vs. 1/T plot.

The mechanism (I)

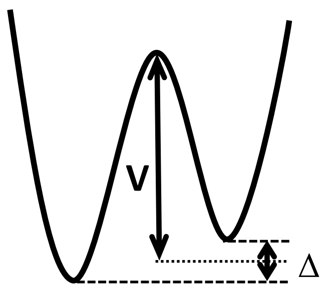
Classical Molecular Dynamics Simulation of the Two-level Systems (TLS) (Ref. 1,2)





Peak at 20K
48 atoms

Transition of larger group corresponds to larger barrier height and occur at higher temp.



Peak at 120K
79 atoms

Ref.1 [H.P. Cheng et al., LIGO-G1601068 (2016)]
Ref. 2 [C.R. Billman et al., Phys. Rev. B 95, 014109 (2017)]

all transitions can occur in thick film

transitions involve larger groups, i.e. larger V, are eliminated in the thinner film.

The mechanism (II)

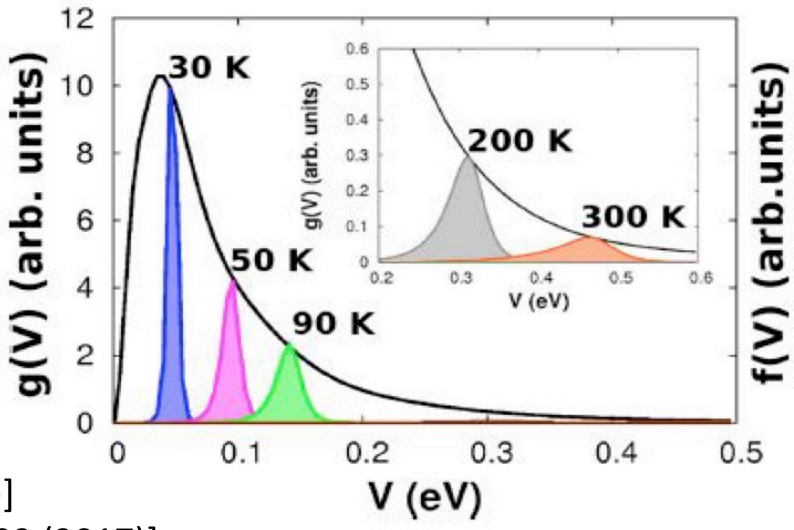
Loss for a TLS :

$$q^{-1} = \left(\frac{1}{(3kT)Y}\right)\left(\frac{\omega\tau}{1+\omega^2\tau^2}\right)\gamma^2\left(\frac{\Delta}{E}\right)^2 \mathrm{sech}^2\left(\frac{E}{2kT}\right)N(\Delta,V)$$

N (Δ,V)=g(V)f (Δ)
Number density function

Loss from all TLS :

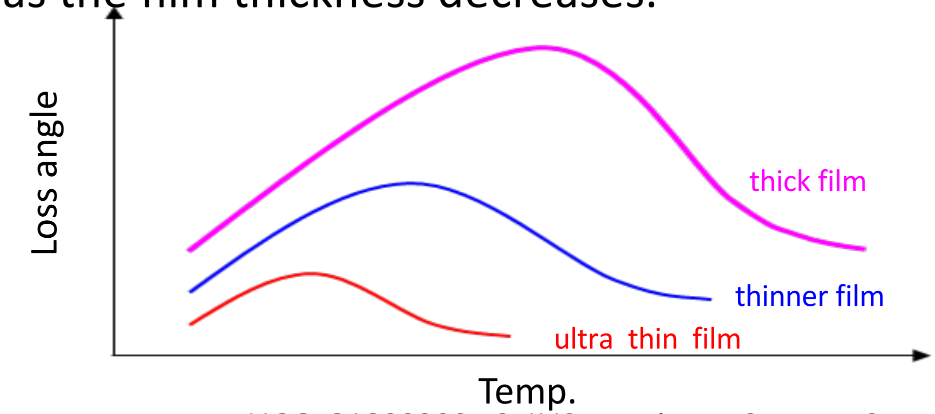
$$Q^{-1} = \iint q^{-1}\, d\Delta dV$$



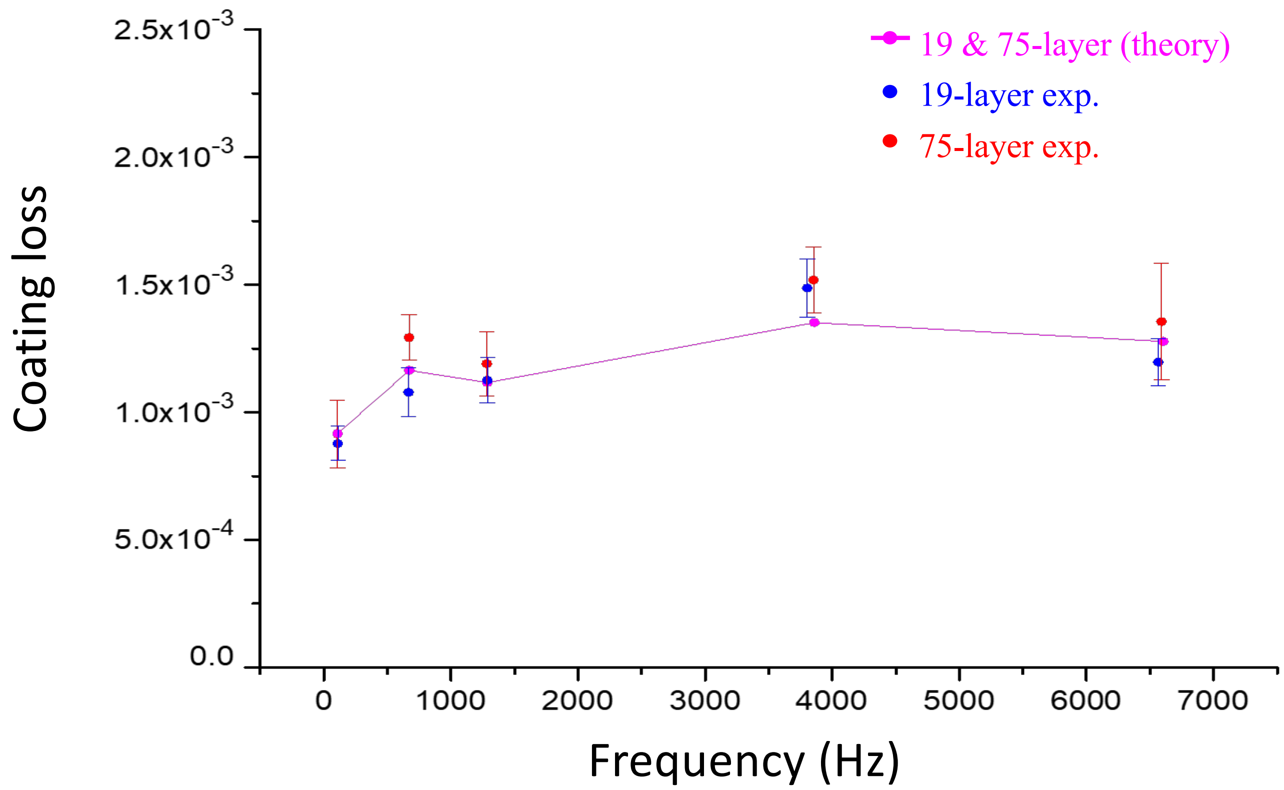
[1. H.P. Cheng et al., LIGO-G1601068 (2016)]
[2. C.R. Billman et al., Phys. Rev. B 95, 014109 (2017)]

Based on Ref. 1 and 2, high barrier height TLS corresponds to transition for longer-range group of atoms, and transitions of TLS with high barrier height occur at higher temperature, statistically.

→ Therefore, we speculate that the transitions for groups of atoms larger than the film thickness are eliminated by the finite film thickness, the overall loss angle decreases and the peak shifts to lower temperature as the film thickness decreases.



Room temperature mechanical loss



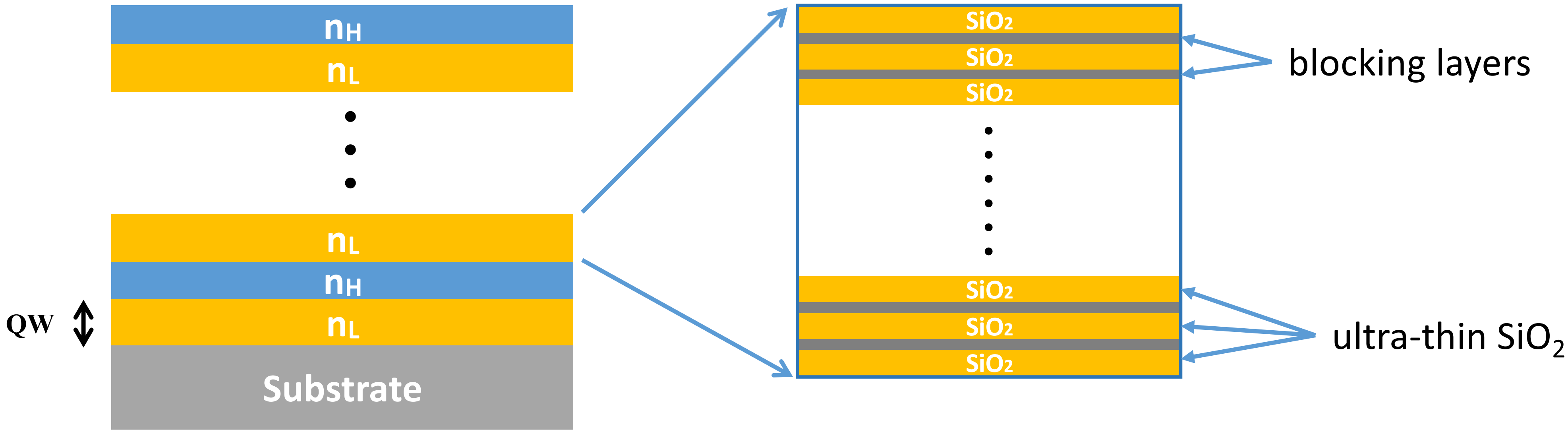
Room temperature mechanical loss did not show the inhibition effect.

The TLS density function at room temperature is too small to have profound effect on the mechanical loss as shown on graph in previous slide. The room temperature mechanical loss observation consistent with our hypothesis.

Proposal for a new HR coatings

Conventional QW stack HR with L=SiO_2

Composite L-layer with blocking layers



Blocking layer must be :

(1) Optically compatible with SiO_2 , i.e. optical thickness of the composite stack to be QW, the effective refractive index remains low and low optical extinction coefficient.

(2) “Mechanically opaque” to transitions of the TLSs. Titania definitely is a good candidate.

- Same phenomenon might also occur in Ta_2O_5 and Ti:Ta_2O_5 H-layer. The cryogenic loss of the H-layer could also be inhibited using the blocking layers.

Conclusion

- Through the amorphous multi-layer stacks of TiO_2/SiO_2, we demonstrated that the cryogenic mechanical loss can be inhibited beyond the prediction of the existing equation by reducing the film thickness.
- The cryogenic mechanical loss, mainly the loss of the SiO_2 film, decreased and the loss peak shifted to lower temperature as the thickness decreased.
- We attributed the effect to the elimination of the long-range TLS transitions, i.e. transitions of groups of atoms larger than the film thickness, by the reduced film thickness.
- We propose a new HR coatings that has blocking layers in between the ultra thin SiO_2 layers to replace the QW SiO_2 in the conventional coatings.
- Same effect could occur in the H-layer as well.