Room temperature mechanical loss of high stress silicon nitride film measured by cantilever ring-down method on double-side coated cantilever

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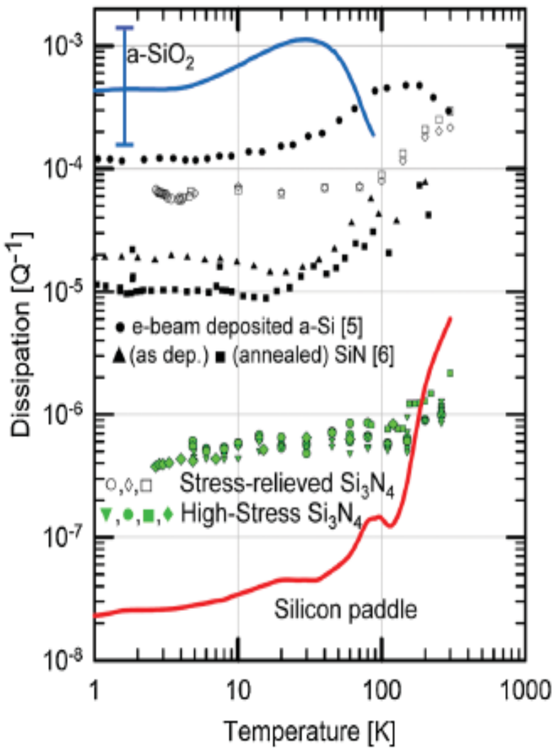
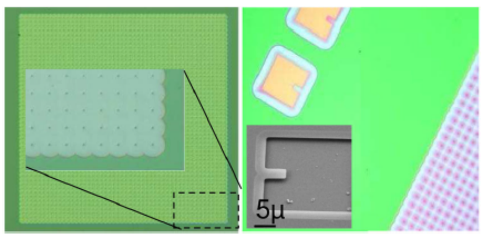
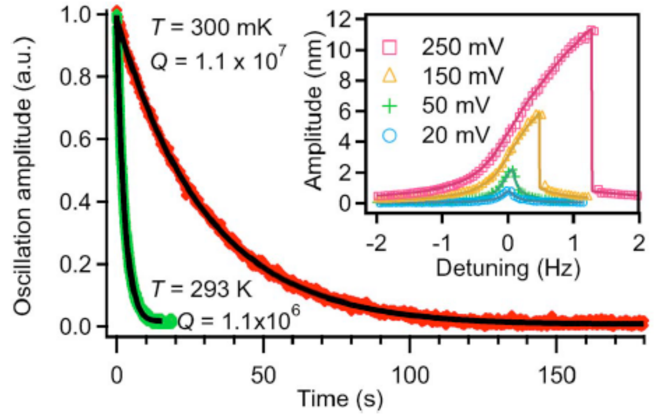
R.O.C.

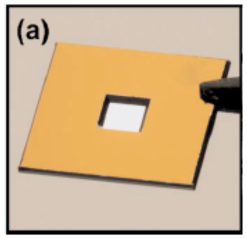
Why silicon nitride





Ref. 1: D. R. Southworth , et al.PhysRevLett. **102**.225503(2009)





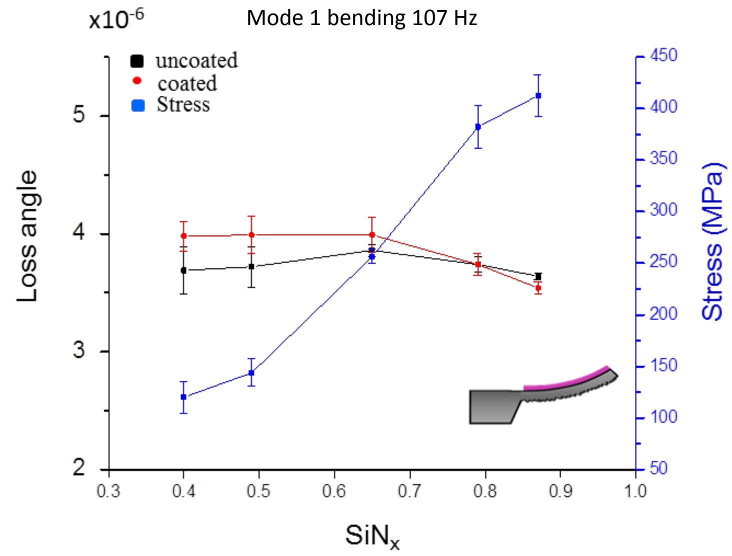
1 mm x1 mm x 50 nm
Norcada x-ray membrane.

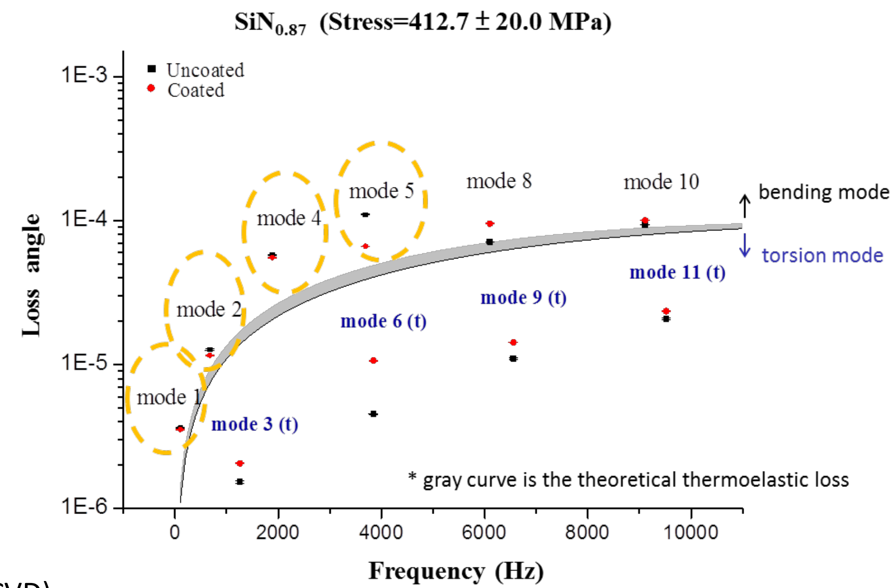
Ref. 2: B. M. Zwickl, et al. Appl. D Phys. Lett. **92**, 103125 (2008)

Stressed SiN film has low loss, particularly at cryogenic temperature.

Our objective is to study this property in the frequency range of laser interference gravitational wave detector and explore the possibility of using CVD method for mirror deposition.

What we had previously





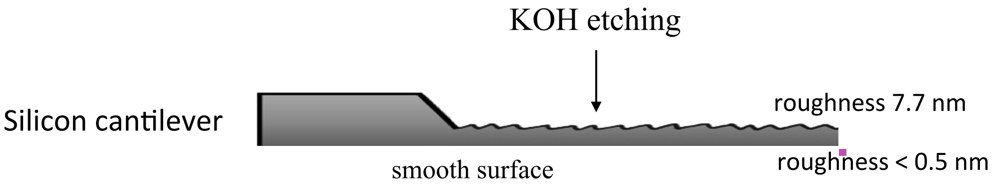
Coating method: Plasma Enhanced Chemical Vapor Deposition (PECVD)

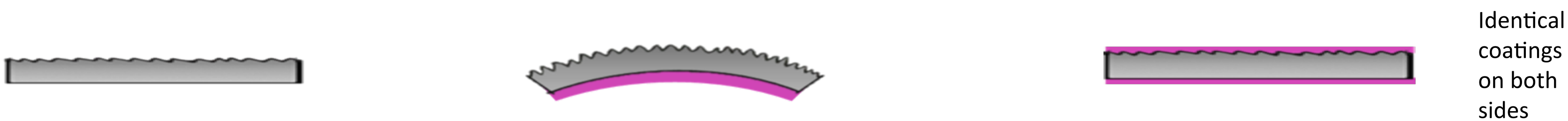
- The SiNx films were coated on silicon cantilever. Stress of the SiNx increased with x.
- The coated cantilevers were warped due to the tensile stress of the film.
- Loss angle of the high stress coated cantilever was lower than that of the uncoated, i.e. inversion, for most of the bending modes, but none of the torsion modes showed inversion.
- The measured resonant frequency of the coated cantilever differed from that of the uncoated by less than 0.1%, far less than the estimated frequency variation required for dissipation dilution, i.e. coefficient of dissipation dilution* approximately equaled to 1. (* : Phys. Rev. B 84, 174109, 2011)
- Since the torsion modes of the silicon cantilever are not susceptible to thermoelastics loss, therefore, we speculated that the inversion of the bending modes could be caused by reduction of the thermoelastics loss of the silicon cantilever under stress.

How to obtain the loss angle of the inverted bending modes for the high stress SiN_x film on Si cantilever?

double-side coating

Double-side coating

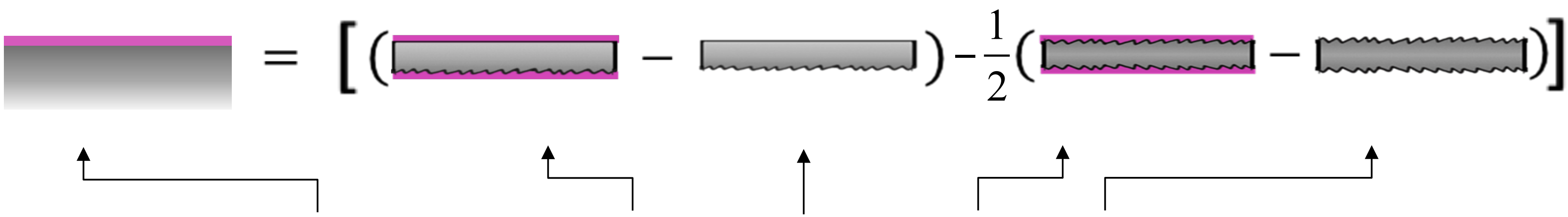




uncoated
radius of curvature = 1247.0 m

coated on smooth surface
radius of curvature = 54.8 m

double-side coated
radius of curvature = 1079.0 m



$$\phi_{film}^{smooth} = \frac{Y_s t_s}{3Y_f t_f}\left[(\phi_{rm} - \phi_{unrm}) - \frac{1}{2}(\phi_{rr} - \phi_{unrr}) \right]$$

[see appendix for derivation]

- ϕ_{film}^{smooth} is the loss angle of a film coated on the smooth surface of a substrate that has infinite stiffness or infinite thickness such that there is no warping**. Referred to as the "flat" film**.
- The stress of the "flat" film should be larger than that of the warped film.
- Four types of samples were prepared and the loss angles ($\phi_{rm}, \phi_{unrm}, \phi_{rr}, \phi_{unrr}$) were measured and ϕ_{film}^{smooth} was then deduced.

LIGO Scientific Collaboration

国立清華大學
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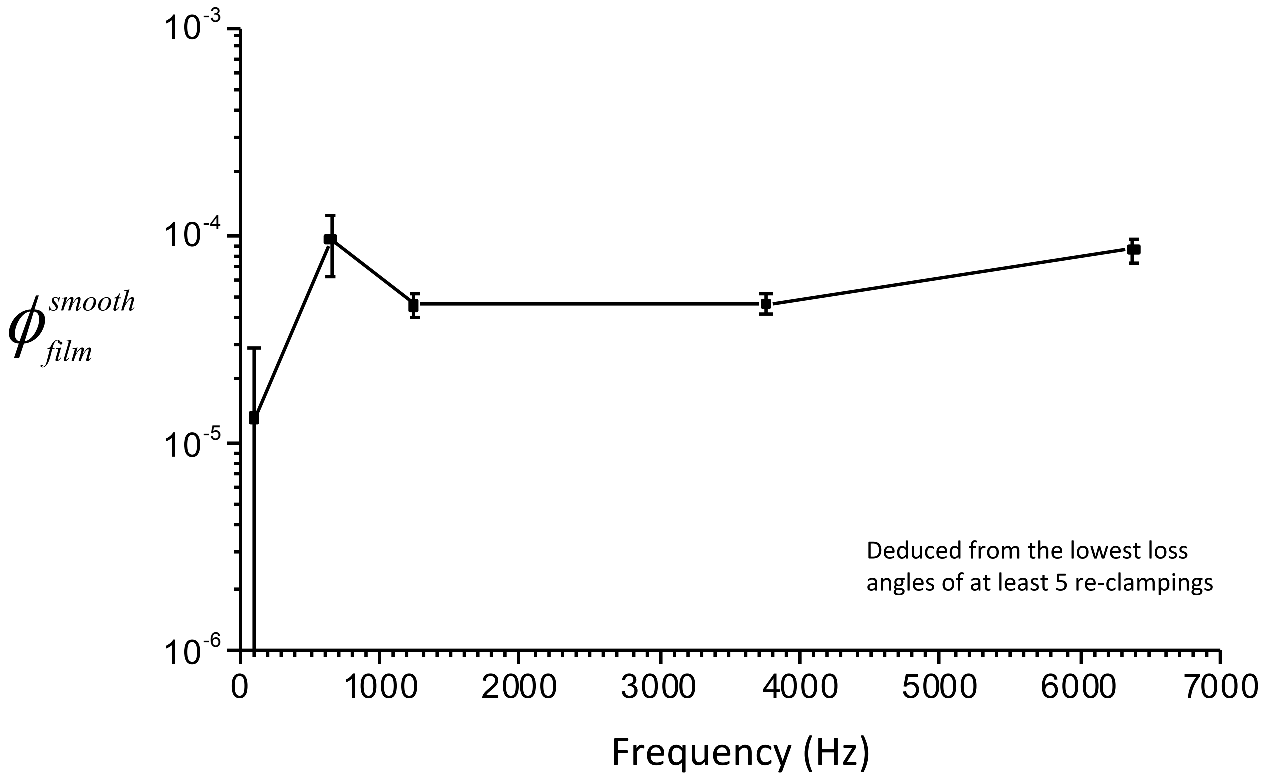
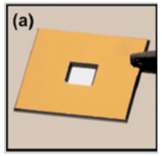
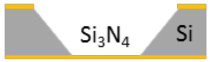
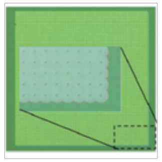
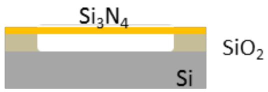
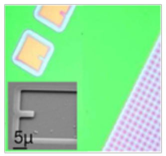
Loss angle of the "flat" $SiN_{0.87}$ film



- The un-annealed PECVD $SiN_{0.87}$ film has room temperature loss angle in the range of 10^{-5} for frequency ~100 Hz to 6500 Hz. It is lower than that of the 600°C annealed 14.5% TiO_2-doped tantala.
- Notice that the "flat" film should be the state of the stressed film on the mirror because the thickness of the mirror substrate can be considered to be infinite.

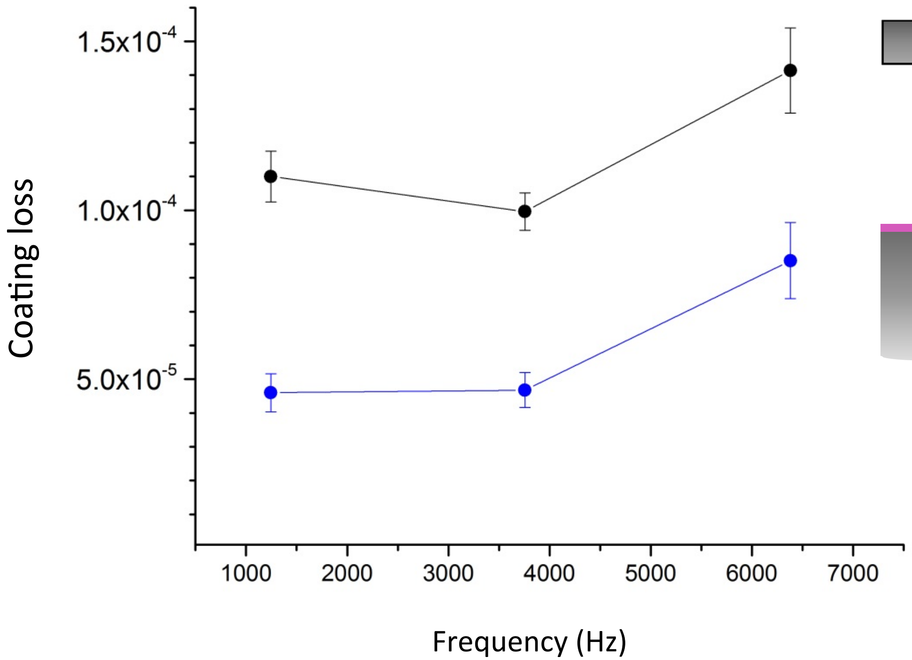
How much is the stress in the flat film

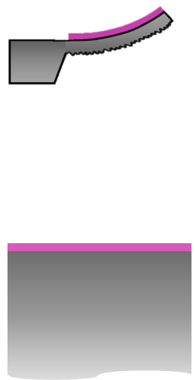
Geometry & cross-section schema	Stress (MPa)	Loss angle at RT (1/Q)
Si_3N_4 membrane (1 mm x 1 mm x 50 nm) [1]  	800	9.09×10^{-7}
Si_3N_4 membrane (255 um x 255 um x 30 nm) [2]  	1200±50	$\sim 2 \times 10^{-6}$
Si_3N_4 stress –relieved cantilever [2]  	Stress relieved NA	$\sim 2 \times 10^{-4}$
SiNx doubly- clamped beam [3] (15 um x 200 nm x 120nm)  	1200±50	1×10^{-4}
SiNx singly- clamped cantilever [3] 	Stress relieved NA	2.5×10^{-4}

These references showed that "flat" film (stress un-relieved) has stress in the vicinity of ~1000 MPa).

[1]B. M. Zwickl, et al. Appl. Phys. Lett. 92, 2008.[2]D. R. Southworth, et al. PRL 102, 2009.[3]S. S. Verbridge, et al. J. Appl. Phy. 99, 2006.

Loss angles of the torsion modes

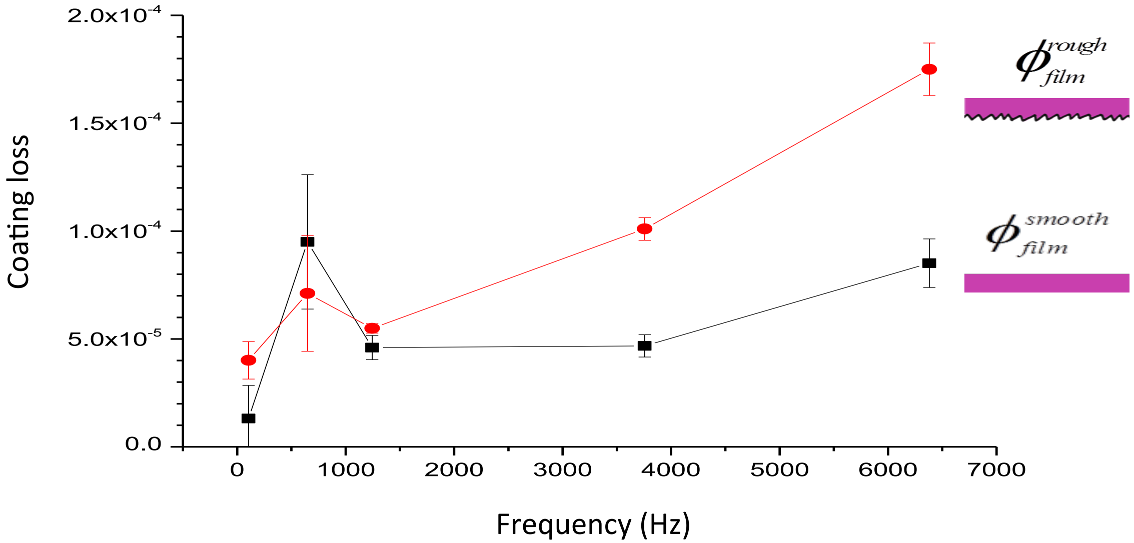




- We have not measured the stress of the "flat" film yet (a film on substrate of very large thickness).
- But, assuming that the stress of the flat film is in the same order of magnitude as the references in the previous slide, i.e. in the vicinity of 1000 MPa, then this result, i.e. the loss angle of the torsion modes for the warped film are larger than that of the flat film, provides direct evidence that the stress indeed reduces the mechanical loss of the SiNx film within the frequency range of laser interference gravitational wave detector.

A secondary gain

Loss angle of the rough interface



The rough interface

$$\phi_{rough\ interface} = \frac{Y_f t_f}{3Y_\delta t_\delta}(\phi_{film}^{rough} - \phi_{film}^{smooth})$$

Frequency (Hz)	$\phi_{rough\,interface}$		
104.2	2.2E-04	±	1.5E-04
647.6	NA		
1245.2 (t)	7.8E-05	±	5.1E-05
3755.9 (t)	4.7E-04	±	6.2E-05
6380.3 (t)	8.0E-04	±	1.4E-04

Young's modulus of silicon = 169 GPa
Young's modulus of $SiN_{0.87}$ Y_f = 138GPa
Young's modulus of the rough interface Y_δ
= average of silicon and $SiN_{0.87}$ = 153.5 GPa
Thickness of the rough interface t_δ
= roughness 7.7 nm
Thickness of the smooth film t_f = 218 nm

Conclusion

- We have developed a method to deduce the loss angle of the high stress PECVD SiN_x film by using the double-side coatings.

- High stress un-annealed PECVD $SiN_{0.87}$ film has room temperature loss angle in the range of 10^{-5} for frequency range from 100 Hz to 6500 Hz . It is lower than that of the 600°C annealed 14.5% TiO_2-doped tantala.

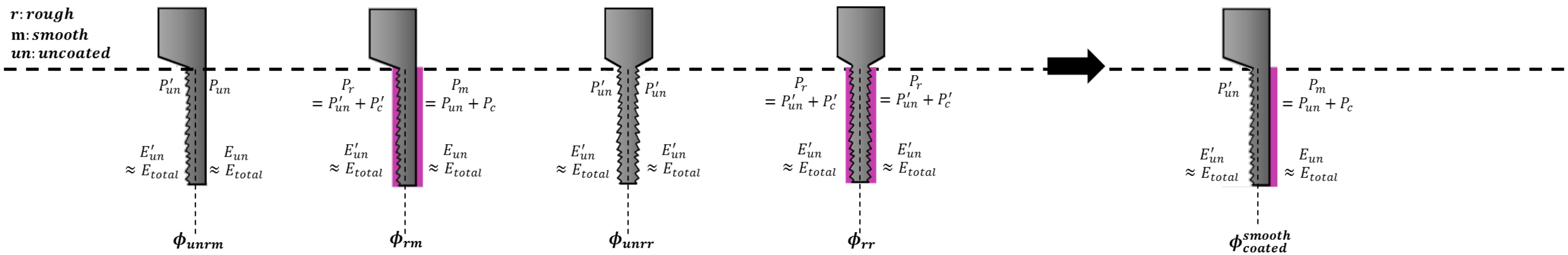
- Loss angle of the torsion modes for the warped film and the flat film provided direct evidence that the stress in the SiN_x film indeed reduces the mechanical loss.

- A secondary gain of this research is that the loss angle of the rough interface can be obtained by our method. We showed that for a interface with 7.7 nm roughness between the silicon and the $SiN_{0.87}$, the loss angle was in the range from $8x10^{-5}$ to $8x10^{-4}$

Appendix

Derivation of the loss angle for the "flat" film

P : power loss
E : stored energy
ω : angular frequency**
ϕ : loss angle=P/ωE



$$\phi_{unrm} = \frac{1}{\omega}\frac{P'_{un} + P_{un}}{E'_{un} + E_{un}} = \frac{1}{\omega}\frac{P'_{un} + P_{un}}{2E_{total}}$$

$$\phi_{rm} = \frac{1}{\omega}\frac{P_r + P_m}{E'_{un} + E'_{un}} = \frac{P_r}{2\omega E_{total}} + \frac{P_m}{2\omega E_{total}} = \frac{1}{2}\phi_{rr} + \frac{P_m}{2\omega E_{total}}$$

$$\Rightarrow \phi_{rm} - \frac{1}{2}\phi_{rr} = \frac{P_m}{2\omega E_{total}}$$

$$\phi_{unrr} = \frac{1}{\omega}\frac{P'_{un} + P'_{un}}{E'_{un} + E'_{un}} = \frac{1}{\omega}\frac{2P'_{un}}{2E_{total}} = \frac{1}{\omega}\frac{P'_{un}}{E_{total}}$$

$$\phi_{rr} = \frac{1}{\omega}\frac{P_r + P_r}{E'_{un} + E_{un}} = \frac{1}{\omega}\frac{2P_r}{2E_{total}} = \frac{1}{\omega}\frac{P_r}{E_{total}}$$

$$\Rightarrow \phi^{rough}_{film} = \frac{Y_s t_s}{3Y_f t_f}(\phi_{coated} - \phi_{uncoated}) = \frac{Y_s t_s}{3Y_f t_f}(\phi_{rr} - \phi_{unrr})$$

$$\phi^{smooth}_{coated} = \frac{1}{\omega}\frac{P'_{un} + P_m}{E'_{un} + E_{un}} = \frac{1}{\omega}\frac{P'_{un}}{2E_{total}} + \frac{1}{\omega}\frac{P_m}{2E_{total}} = \frac{1}{2}\phi_{unrr} + \left(\phi_{rm} - \frac{1}{2}\phi_{rr}\right)$$

$$\Rightarrow \phi^{smooth}_{film} = \frac{Y_s t_s}{3Y_f t_f}(\phi^{smooth}_{coated} - \phi_{unrm}) = \frac{Y_s t_s}{3Y_f t_f}\left[(\phi_{rm} - \phi_{unrm}) - \frac{1}{2}(\phi_{rr} - \phi_{unrr})\right]$$

ϕ^{smooth}_{film} is the loss angle of a film coated on the smooth surface of a substrate that has infinite stiffness or infinite thickness such that there is no warping. **Referred to as the "flat" film**.

** Experimentally, we found that the resonant frequency of the double-side coated samples varied less than 0.1% of the uncoated sample. All samples were considered to have the same frequency.