LSC LIGO Scientific Collaboration

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Nano-coatings
the reasons and the R&D status

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Gravitational Wave Advanced Detector Workshop, Waikoloa Marriott Resort, Hawaii, May 14 2012

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Universita degli Studi del Sannio

The Waves Group

INFN Istituto Nazionale di Fisica Nucleare

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Outline

- Reasons to study nanometer coatings
- Status of R&D

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First interest for nanocoatings

- RDS participated to the PXRMS conference Big Sky – Montana
- X-ray mirror coating community
- LIGO-G080106-00-R

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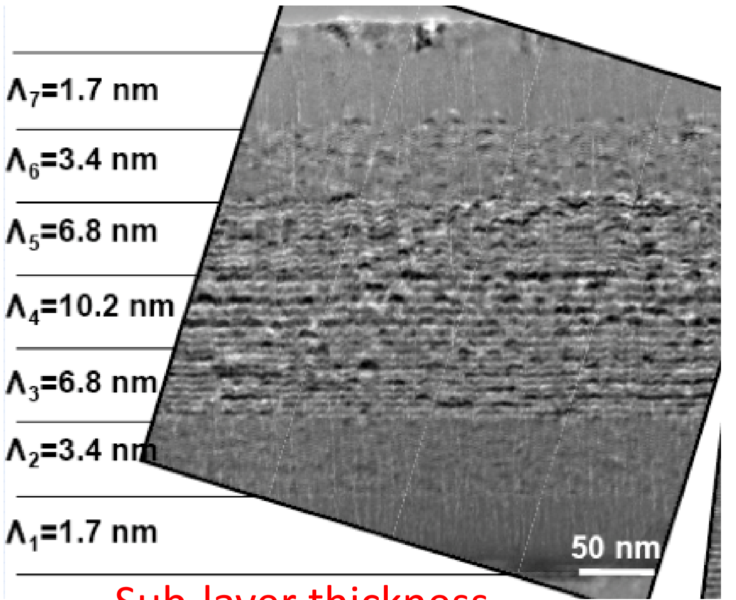
Lessons from x-ray community

- Extremely thin layers are always glassy
- More stable !
- Different atomic radius and oxydation pattern assure glassy structure around the interface between different materials

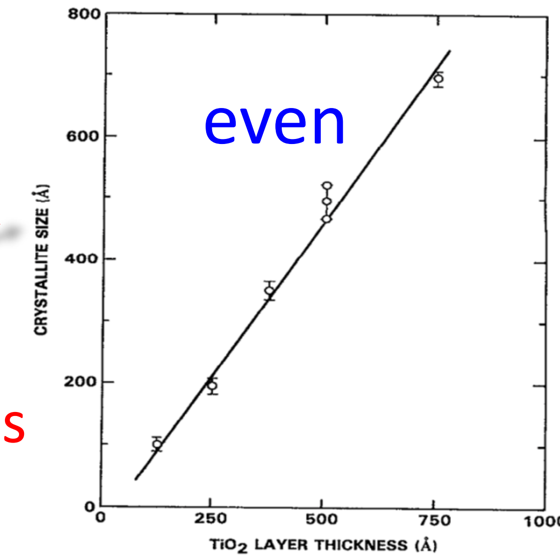


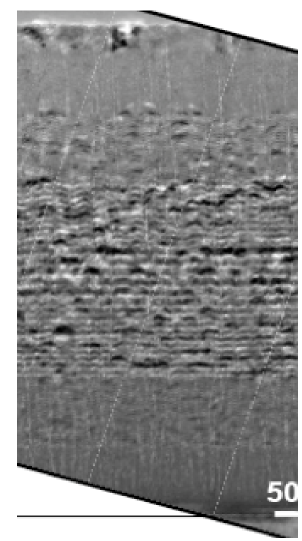
Sub-layer thickness

- Natural doping due to inter-diffusion may also play a relevant role

Lessons from x-ray community, II

- Good glass formers remain glassy for large thicknesses even
- Poor glass formers
  - first produce crystallites inside the glass
    - Invisible to x-rays
  - Then crystallites grow into columnar-growth poli-crystalline films
- Crystallites are bad for scattering
- Probably bad for mech. losses also
- (Dopants induce better glass formers)





N.S. Gluck et al., J. Appl. Phys., 69 (1991) 3037
Ghafor et al. Thin Solid Films, 516 (2008) 982

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Lessons from x-ray community, III

- Not surprising Chao first managed to reduce scattering in gyrolaser dielectric mirrors by inventing the SiO_2 doped TiO_2
- But the important message is that thinner coatings are more stable !
- They will probably have even less scattering (crystallite free)
- Will they also have less mechanical losses?

Shiuh Chao, et al., "Low loss dielectric mirror with ion beam sputtered TiO2-SiO2 mixed films" Applied Optics. Vol.40, No.13, 2177-2182, May 1, 2001.

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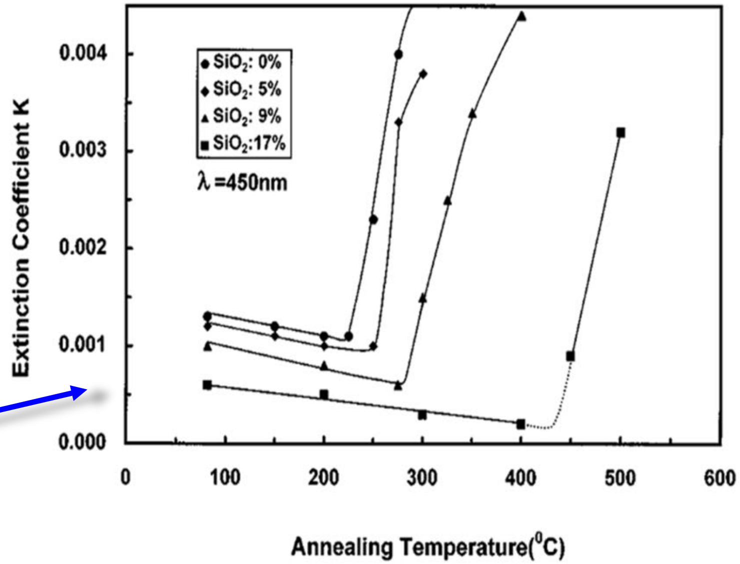
Layer thickness vs. Annealing

- Higher T annealing reduces losses
- In co-sputtering large percentages of dopant (SiO_2 in TiO_2) are needed
- Thinner layers require less (%) SiO_2 for the same annealing stability



W.H. Wang and S. Chao, Optics Lett., 23 (1998) 1417;
S. Chao, W.H. Wang, M.-Y. Hsu and L.-C. Wang, J. Opt. Soc. Am. A16 (1999) 1477;
S. Chao, W.H. Wang and C.C. Lee, Appl. Opt., 40 (2001) 2177

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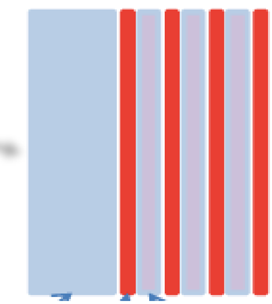
Why using layered SiO_2::TiO_2

Titania | Silica | TiO2 Doped Tantala

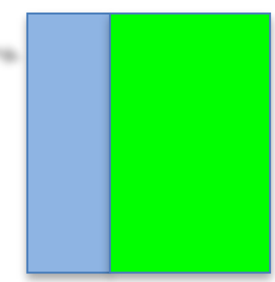
- Comparing:

  stratified 66%TiO_2 36%SiO_2



  with same refraction index as

  TiO_2 doped Ta_2O_5



- 1) If mech. losses in TiO2::Ta_2O_5 are the same as in glassy TiO_2 (worst case)

  Mech. dissipation reduction ~ 36%

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How much gain from layered TiO_2:: SiO_2

If we trust Effective Medium Theory,

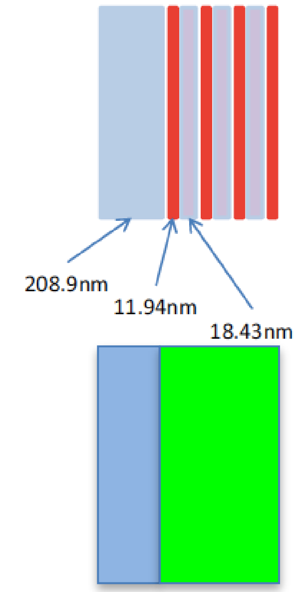
- Measured loss angles from TNI:

plain Ta_2O_5 : $4.72 \pm 0.14 \ 10^{-4}$

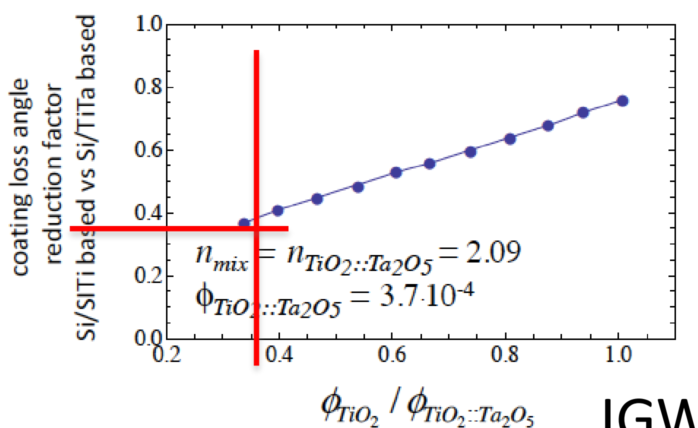
TiO_2 doped Ta_2O_5 : $3.66 \pm 0.29 \ 10^{-4}$

are consistent with a loss angle for

glassy TiO_2 : $1.2 - 1.4 \ 10^{-4}$



➡ Mech. dissipation reduction ~ 65%



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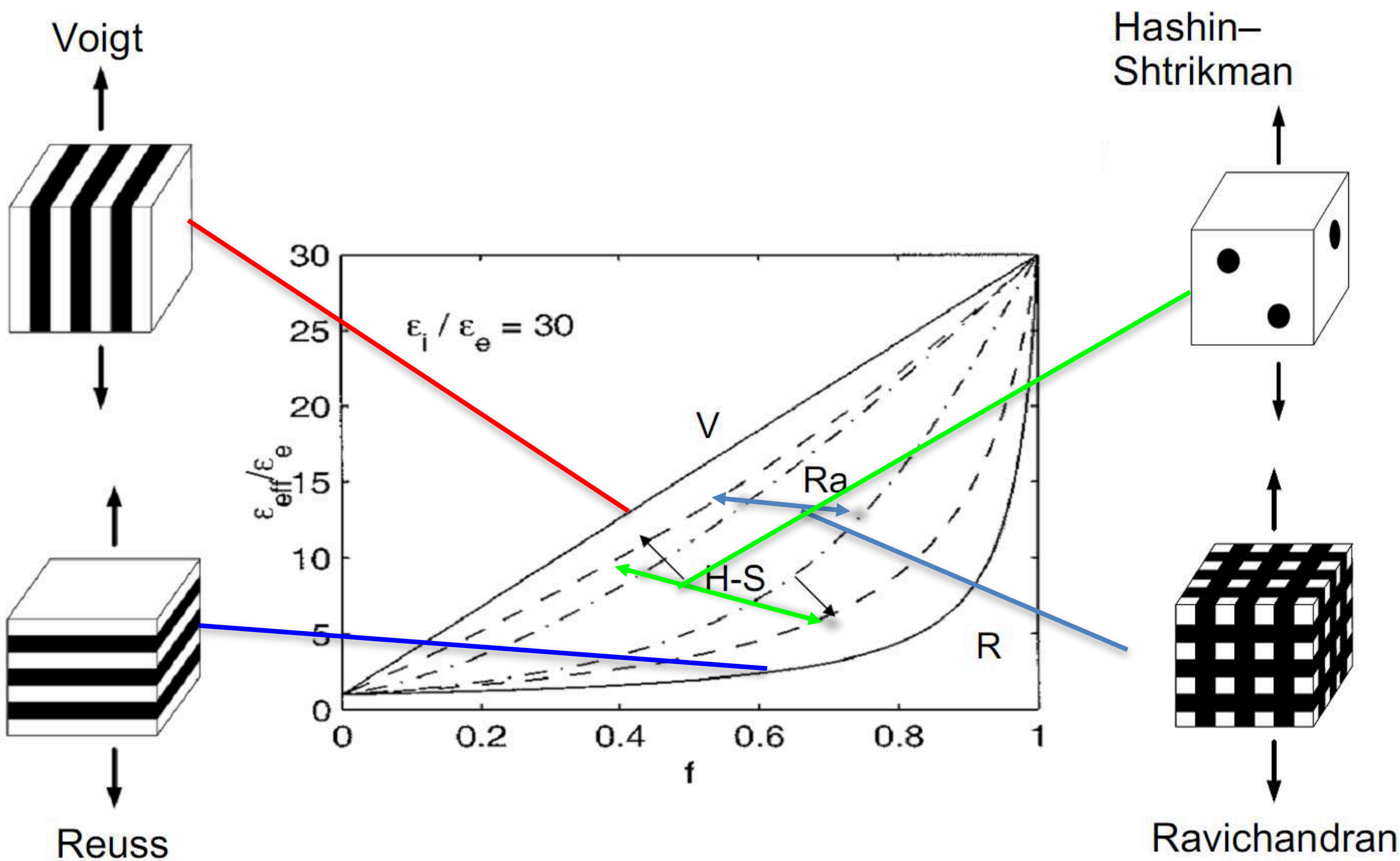
Dielectric Mixtures

Structure makes differences in refraction index



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Titania Doped Tantala

- Years after Chao introduced SiO_2-TiO_2 coatings
- LMA discovered that TiO_2-Ta_2O_5 coatings have
  - less mechanical noise,
  - better thermal noise performance

- Is it because TiO_2-Ta_2O_5 is a more stable glass?
- Or because of atomic level stress due to doping?
- Or both?

Why stress may be important?

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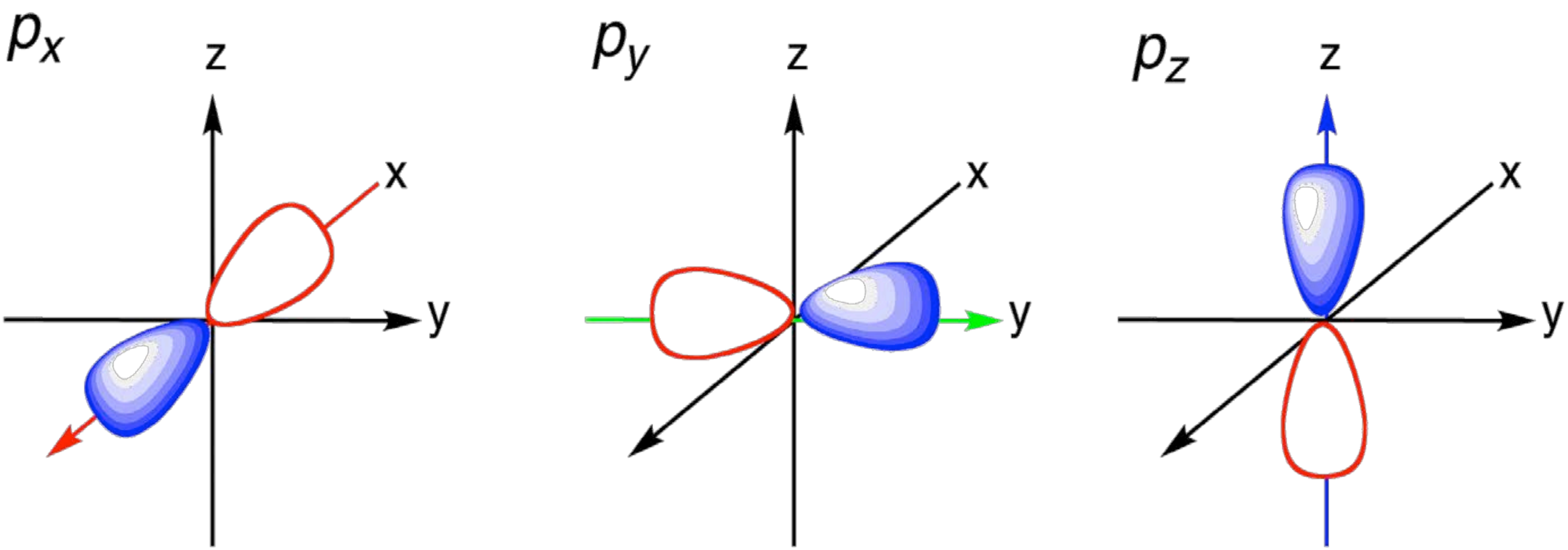
Example: hydrogen dissipation in metals

- A metal has P orbitals …



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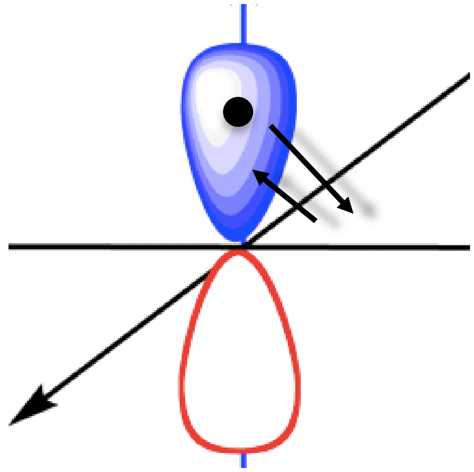
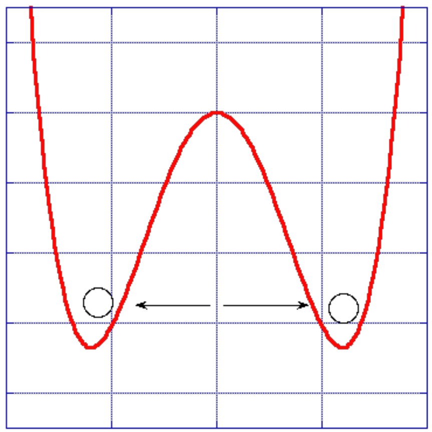
Example: hydrogen dissipation in metals

- Hydrogen resides in electron cloud
- = > Double well potential !
- Flip-flops between wells
- Indifferent equilibrium





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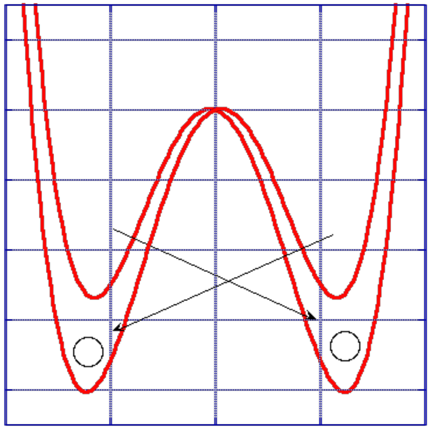
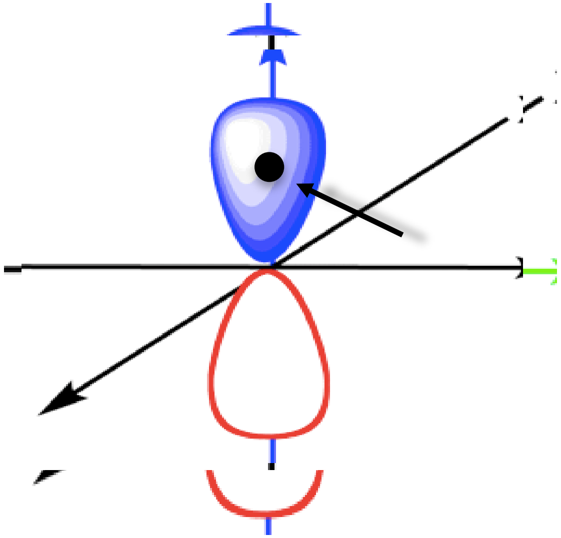
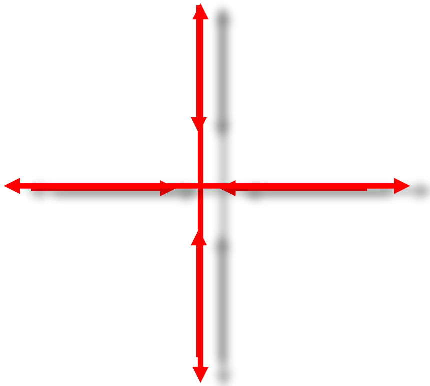
…In the presence of an acoustic wave

- horizontal compression:
  - Proton jumps down
- Vertical compression
  - Proton jumps up







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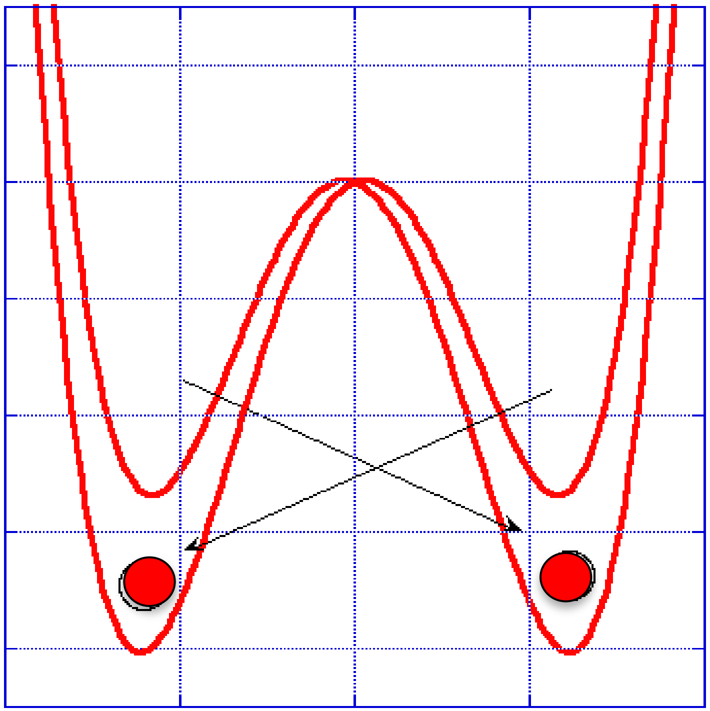
Losses in a glass

- Double well potential

- Oscillating stress
- Well to well jumping

- Each jump gives loss

- How to stop it?



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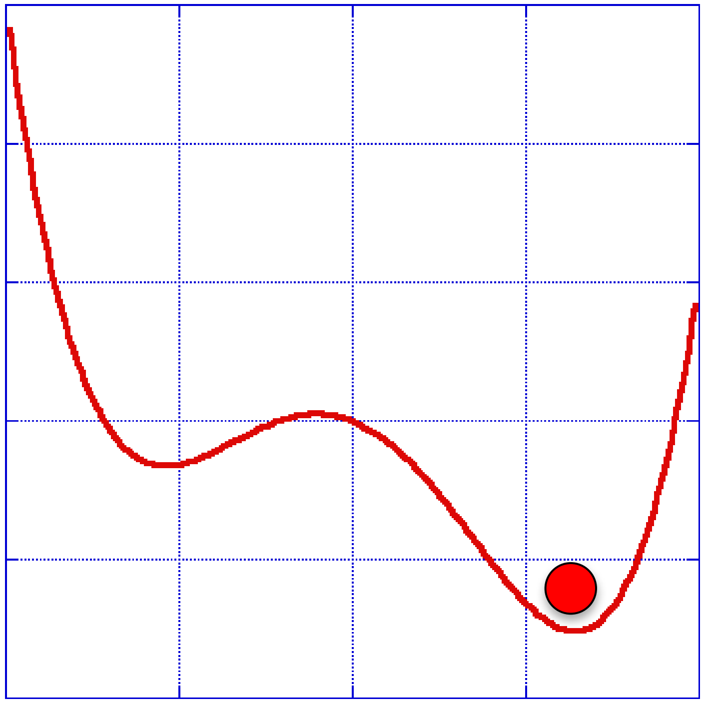
Stress the glass !

- Static stress
- Asymmetric double well
- State lives always in the lower hole



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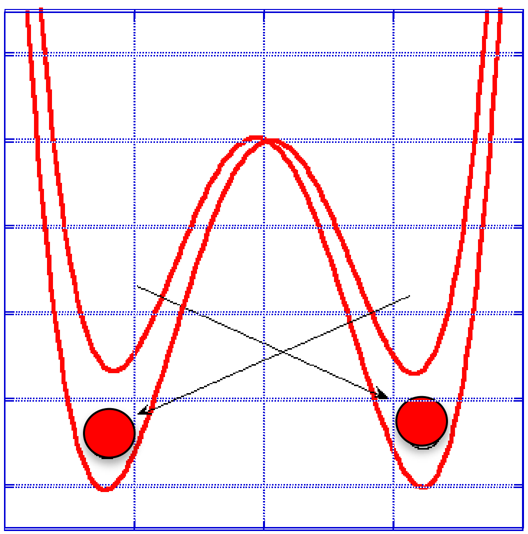
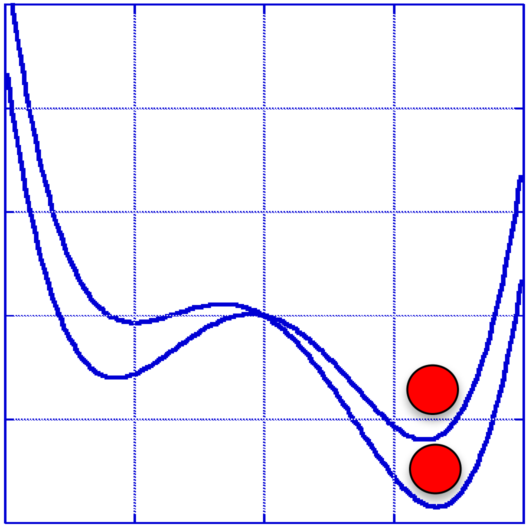
Acoustic oscillations in double well potential

- No stress
- Well to-well jumping
- Dissipation



Stress

- No jumping
- No dissipation



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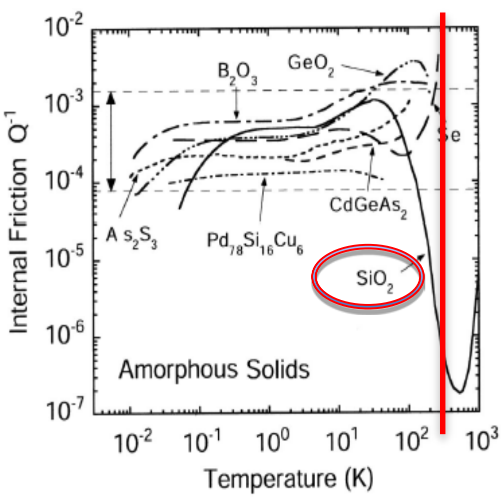
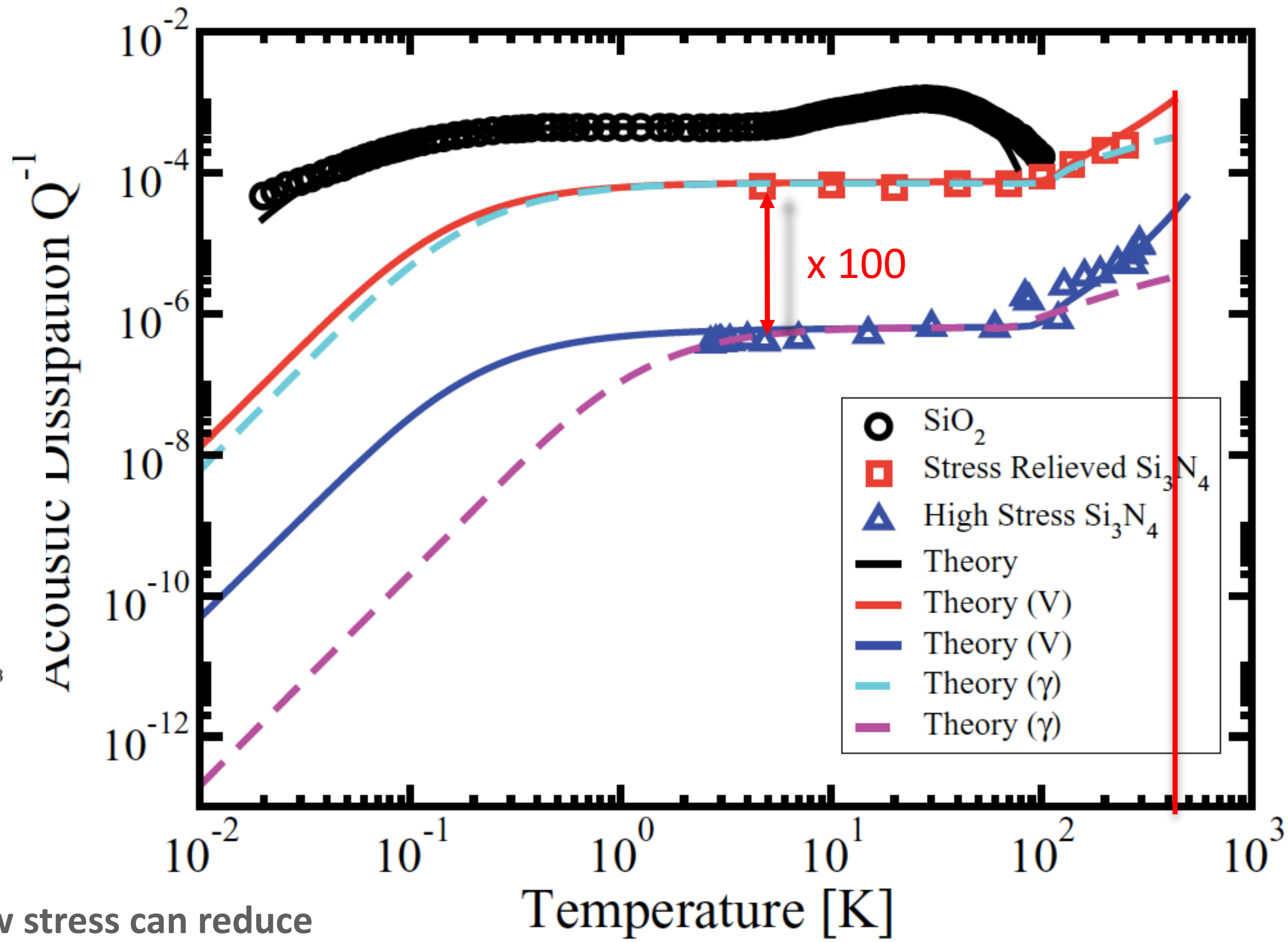
Effects of Stress in Si_3N_4

- High stress
- Low loss





J.S. Wu and C.C. Yu, "How stress can reduce dissipation in glasses," Phys. Rev. B84 (2011) 174109.

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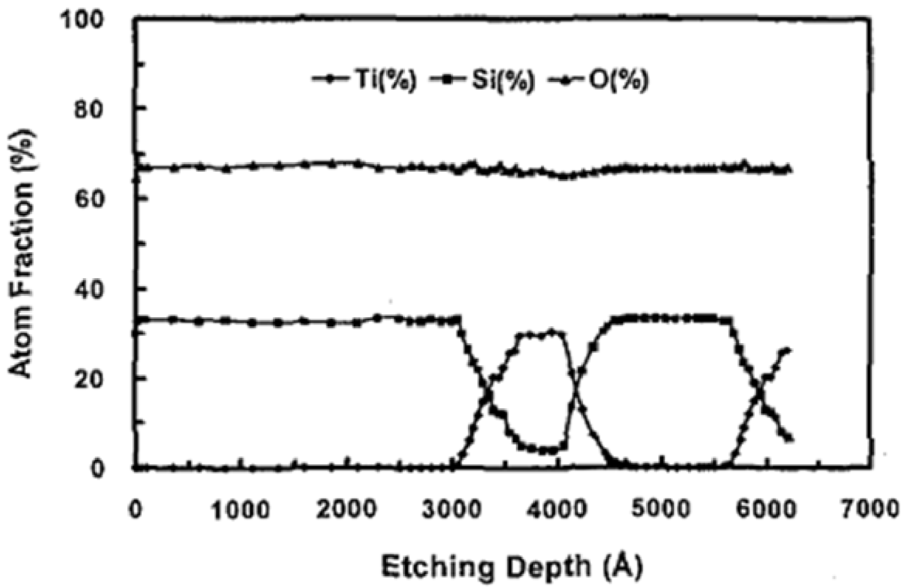
How to add Stress to the coating

- Adding TiO_2 in Ta_2O_5 introduce random stress
  - Stress from different oxidation pattern (random distribution)
    - Observed Lower losses
- Alternating thin layers TiO_2 to SiO_2 introduce *ordered* stress
  - Stress from different atomic spacing (ordered)

How to add Stress to the coating

- How thick an optimal layer?
  - 1 interlayer diffusion length thick ?
    - Uniformly graded concentration => uniform stress ?
      - Will it lead to Lower mechanical losses?



S.Chao, et al., Appl. Optics, 40 (2001) 2177.

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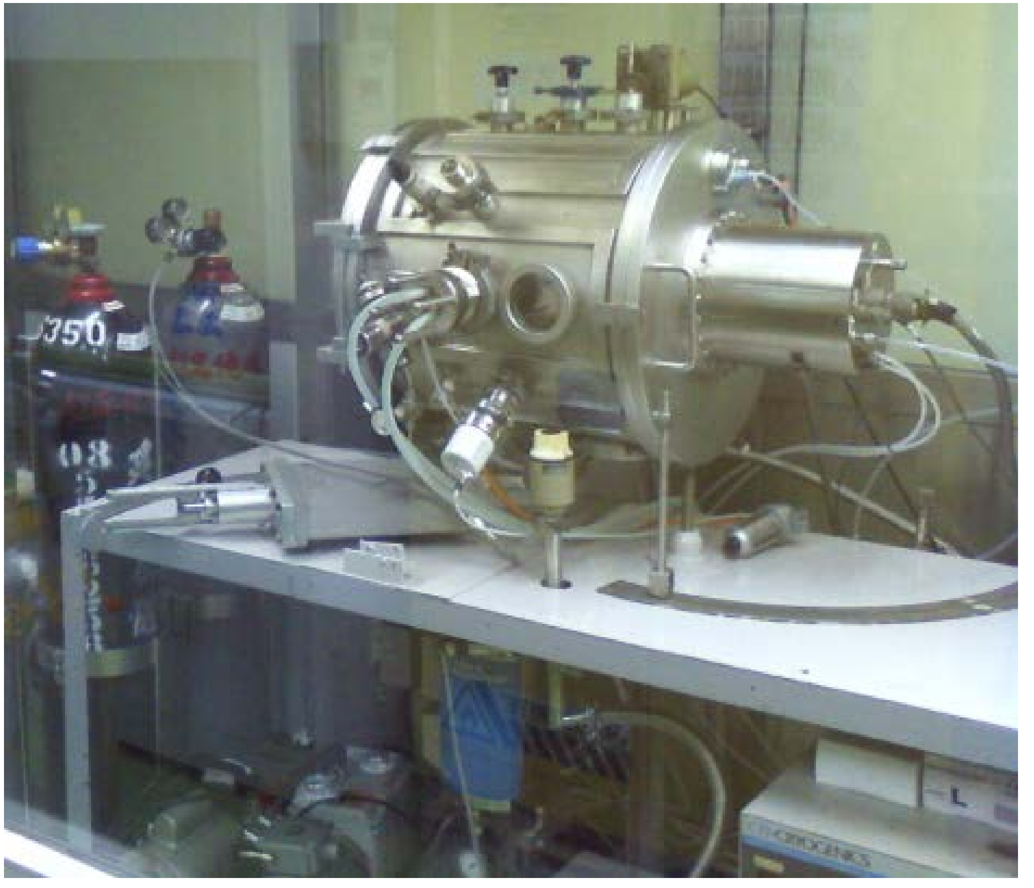
- So far for the reasons to try nm layered coatings

- Now let's look at the experimental activity on nm coatings at Chao's Lab in the National Tsing Hua University in Taiwan

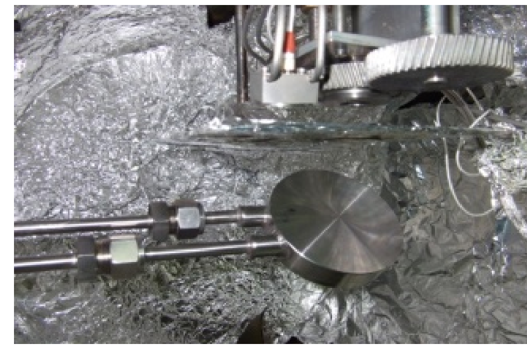
Refurbished ion-beam-sputterer

- Fast cycling Coater for SiO_2, TiO_2, Ta_2O_5
- For multi-layers and mixtures



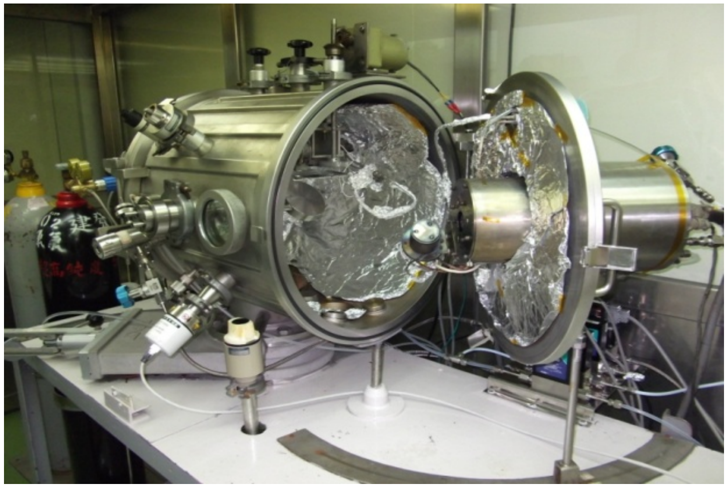
Refurbished ion-beam-sputterer

Exchangeable twin target holder



Sputter target and rotator

Kaufman ion gun and neutralizer



Kaufman-type ion beam sputter system in a class 100 clean compartment within a class 10,000 clean room

Previously used to develop low-loss mirror coatings for ring-laser gyroscope

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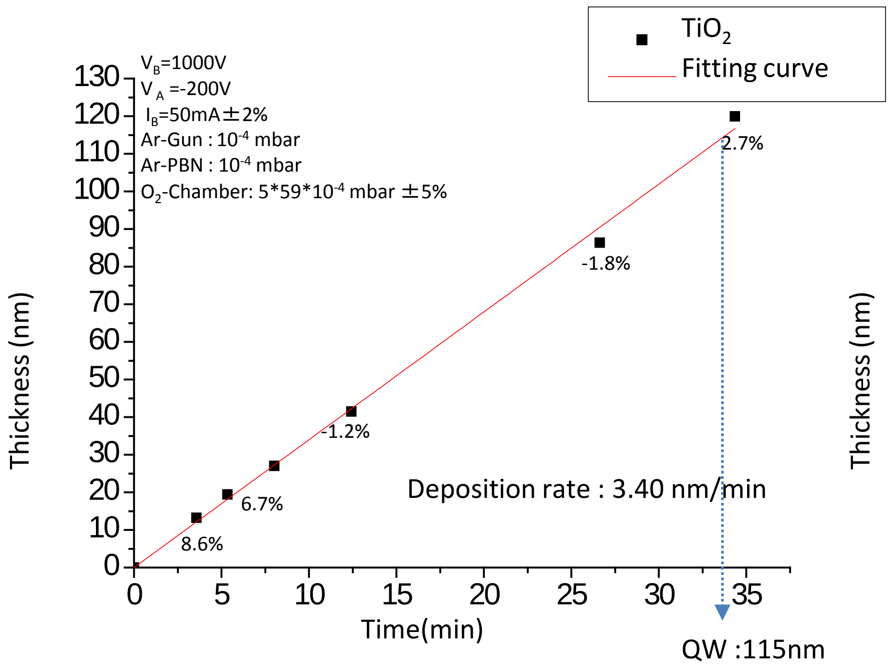
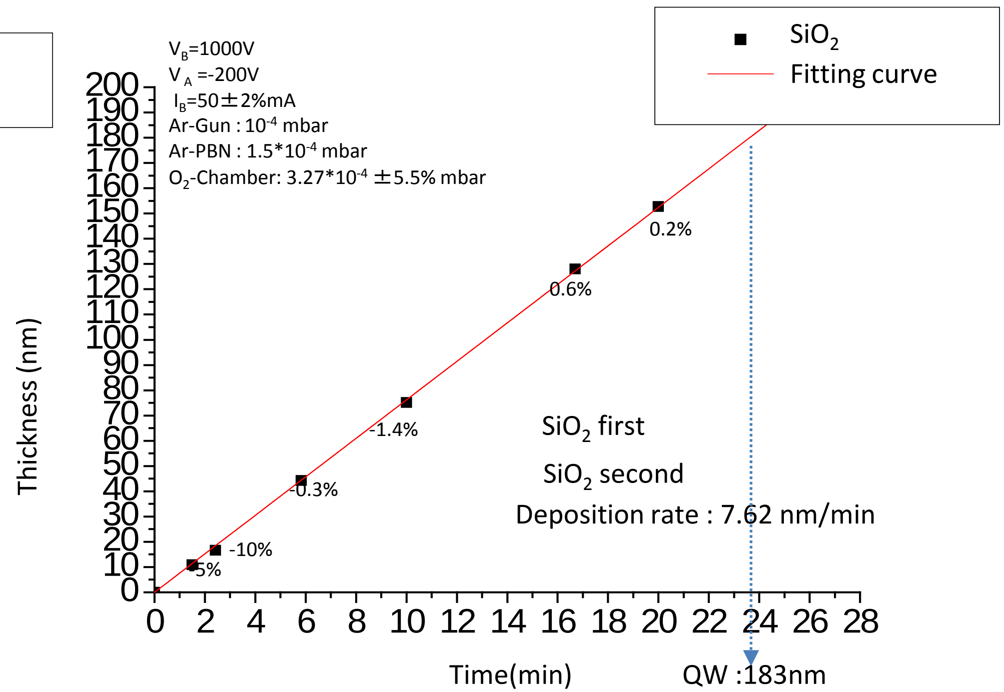
Nano-layer coating preparations

- Calibrating deposition rate for TiO_2 and SiO_2





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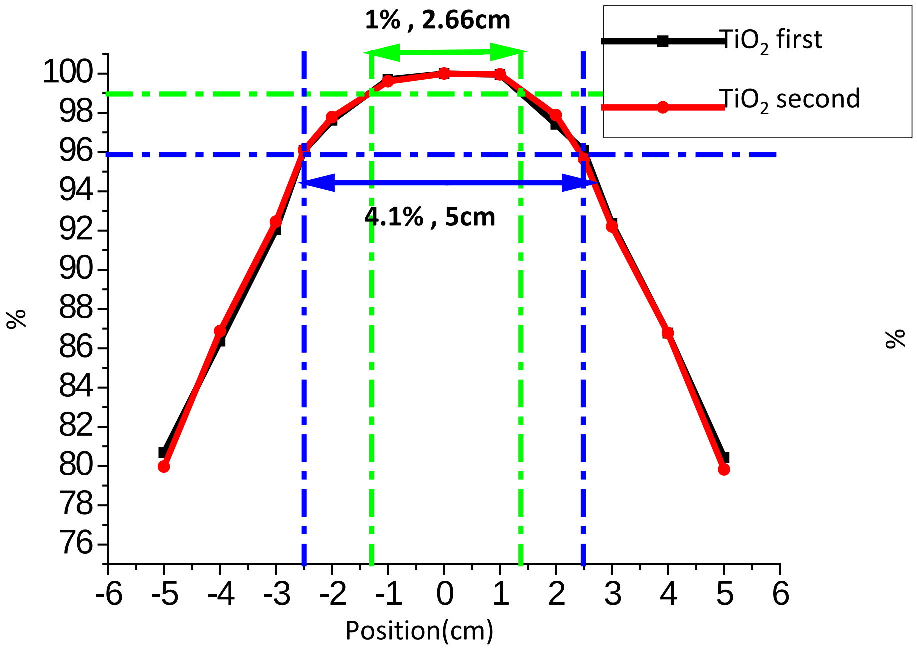
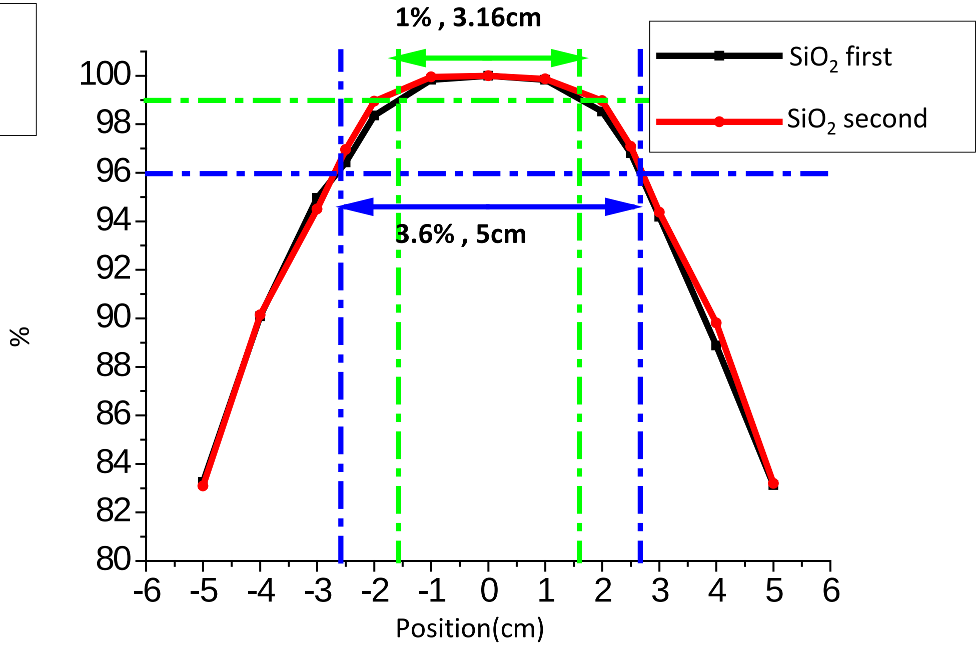
Nano-layer coating preparations

- Uniformity distribution for TiO_2 and SiO_2





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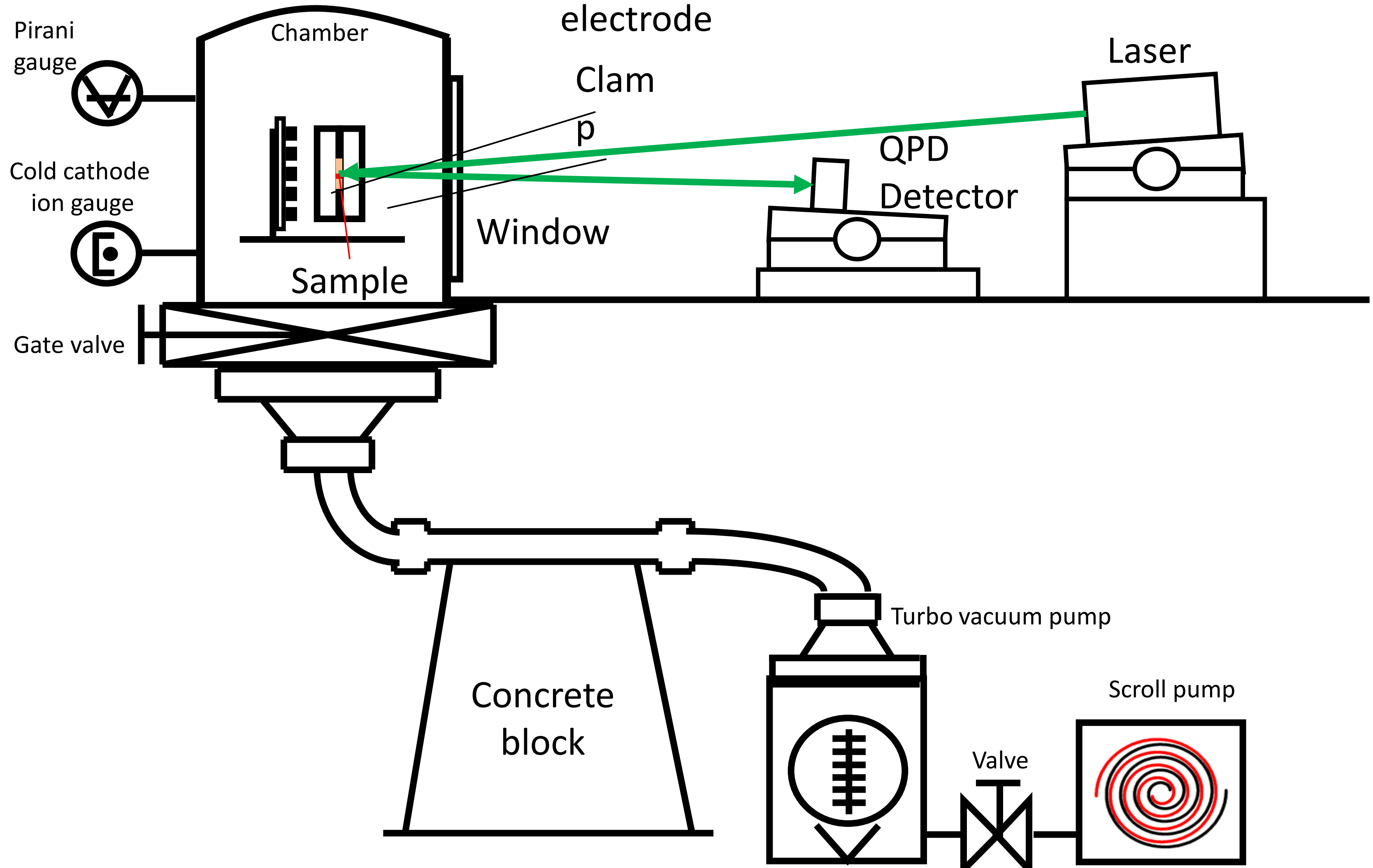
Q Measurement setup



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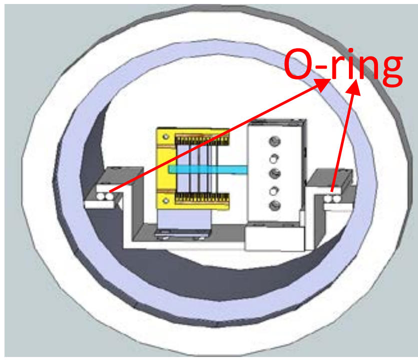
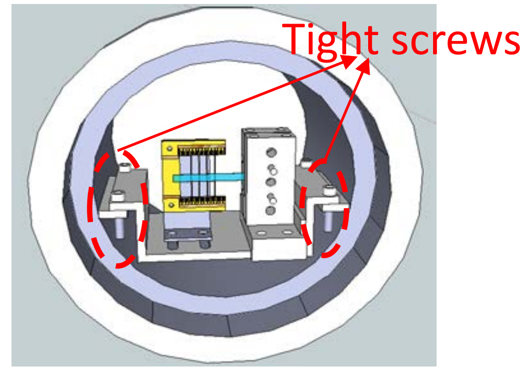
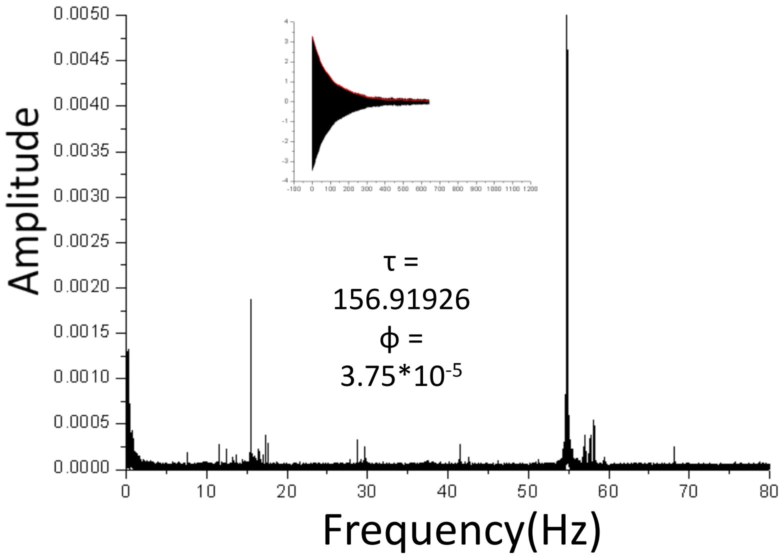
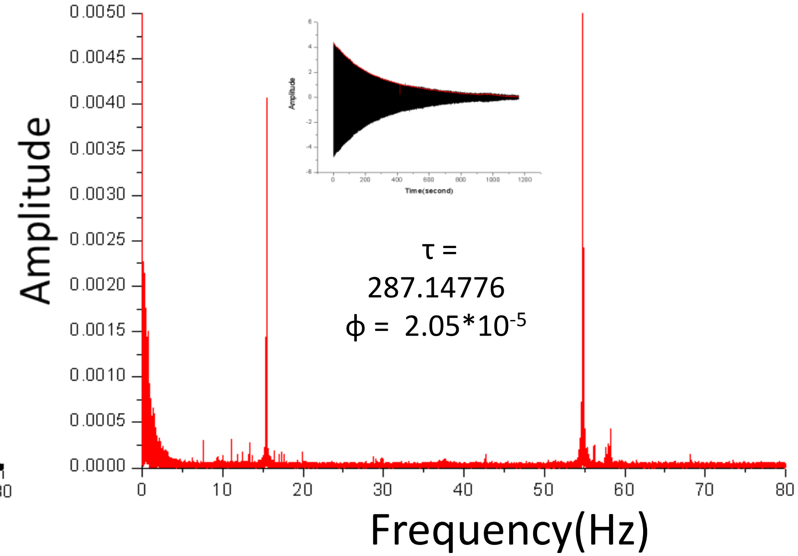
Loss hunting

- Support losses









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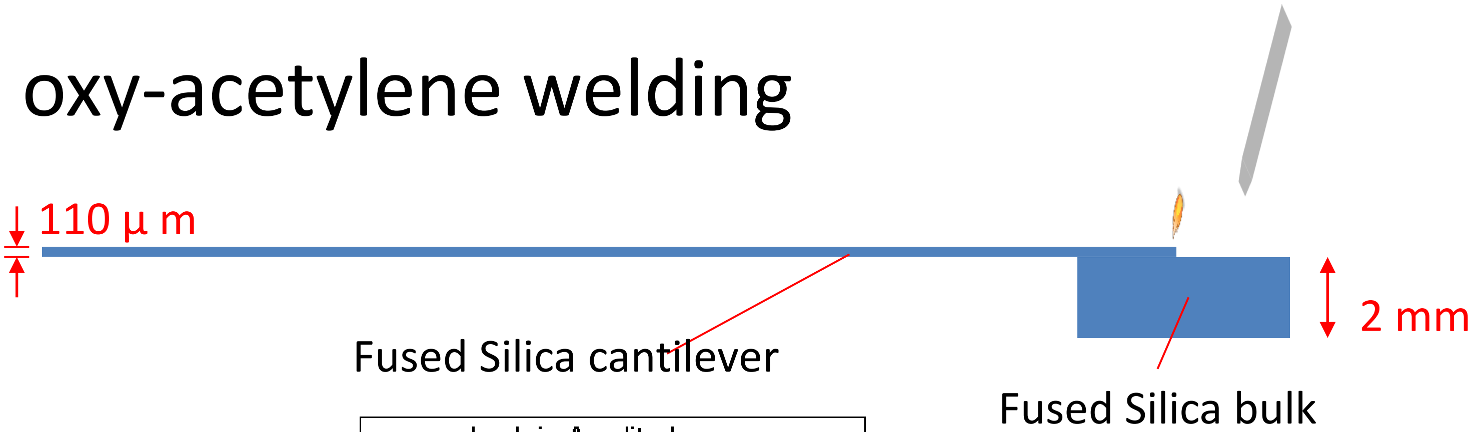
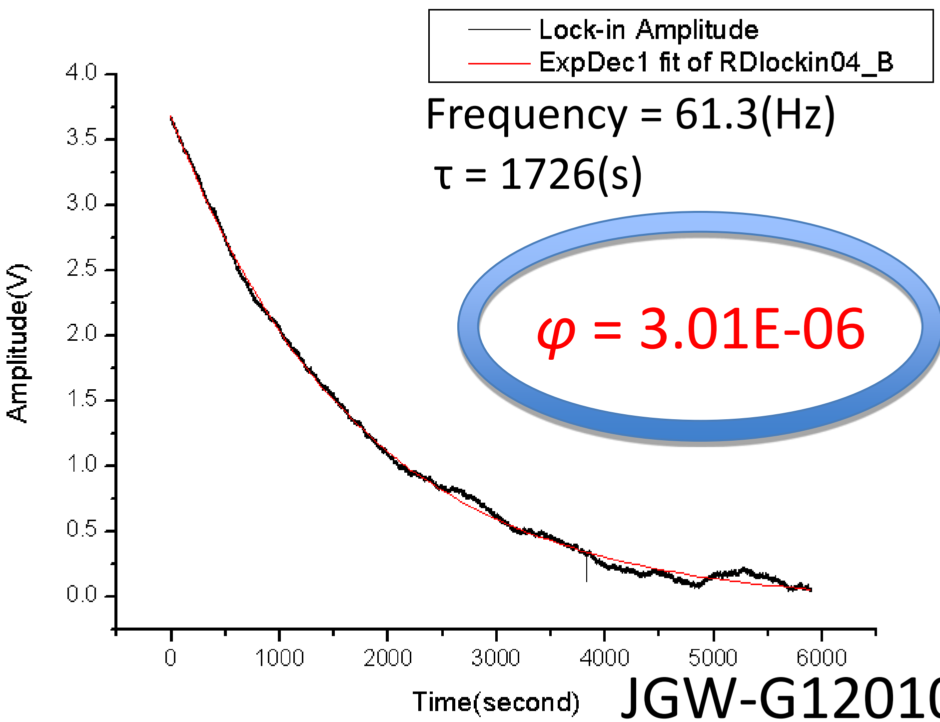
Neutralizing clamp losses

- oxy-acetylene welding

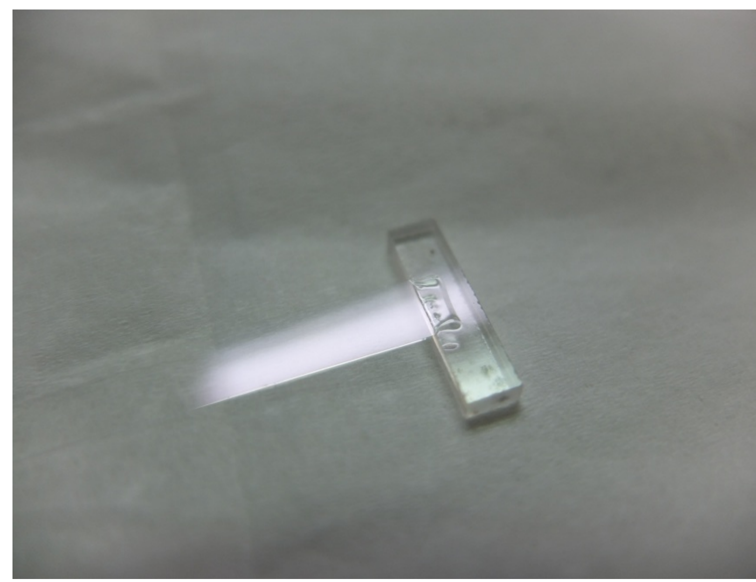




Frequency = 61.3(Hz)

τ = 1726(s)

φ = 3.01E-06



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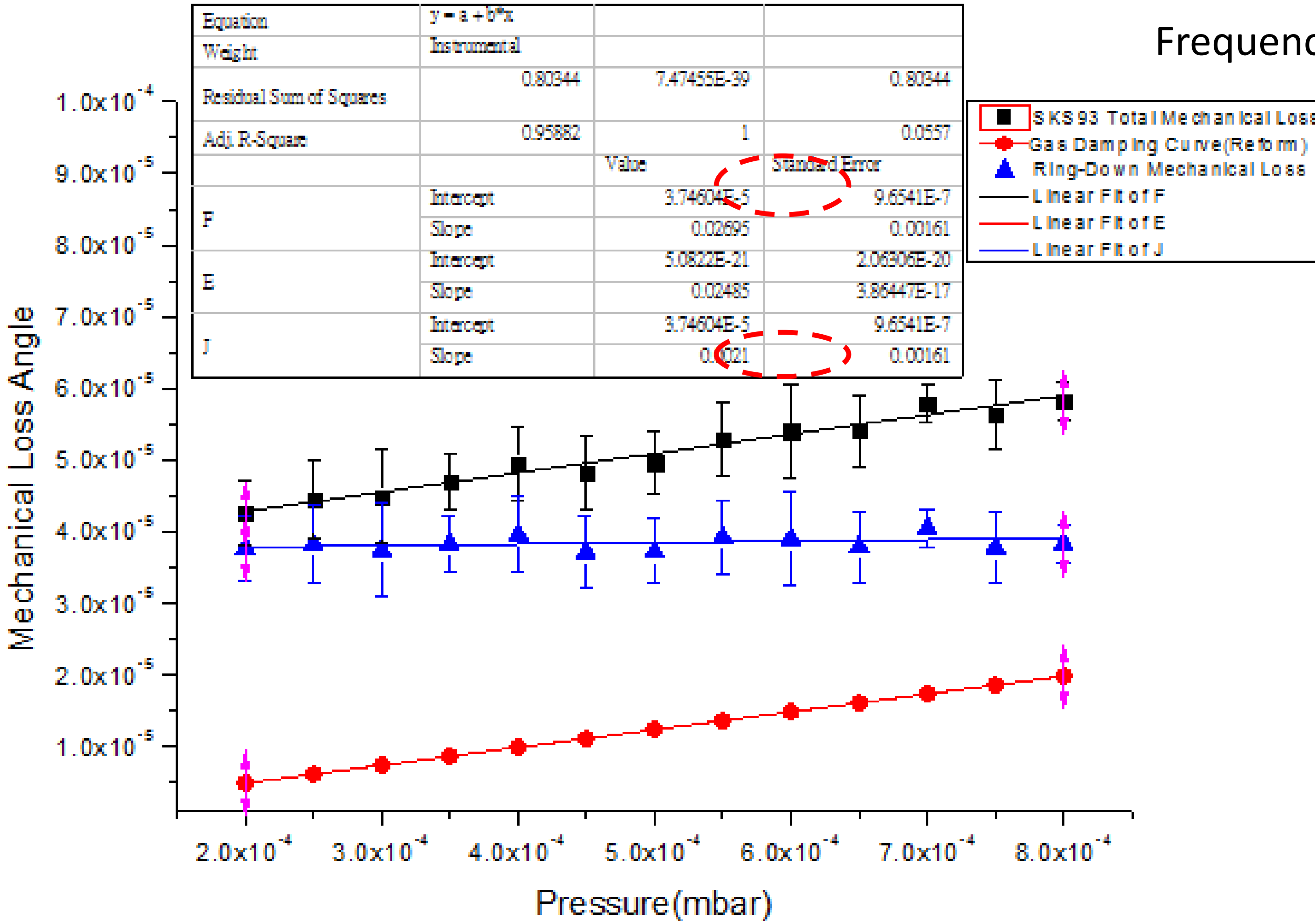
Neutralizing Residual gas effects

Frequency = 54 Hz



Equation	y = a + b*x		
Weight	Instrumental		
Residual Sum of Squares	0.80344	7.47455E-39	0.80344
Adj. R-Square	0.95882	1	0.0557
		Value	Standard Error
F	Intercept	3.74604E-5	9.6541E-7
	Slope	0.02695	0.00161
E	Intercept	5.08822E-21	2.06306E-20
	Slope	0.02485	3.86447E-17
J	Intercept	3.74604E-5	9.6541E-7
	Slope	0.0021	0.00161

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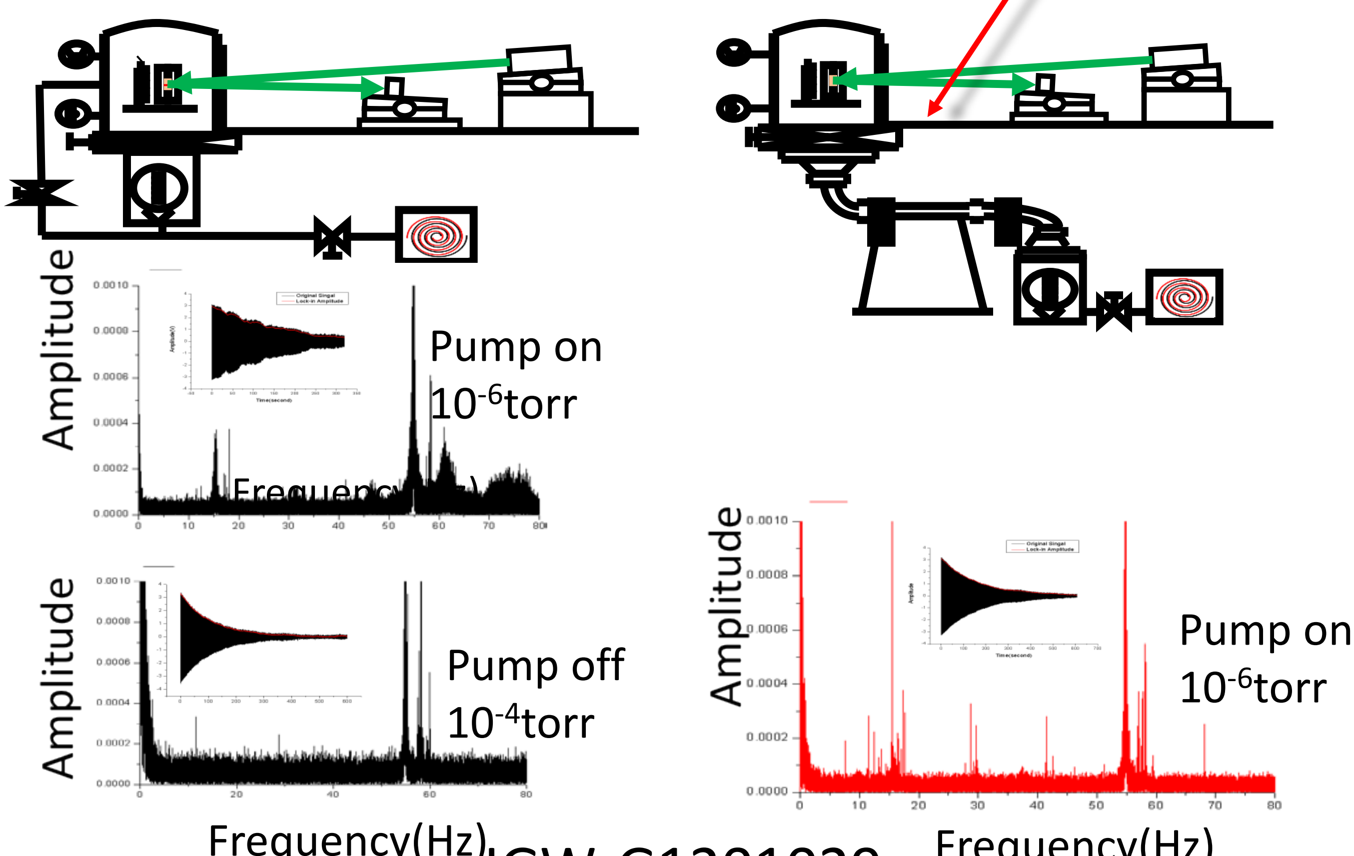
Neutralizing pump vibrations

- Added flexible tube sank in lead pellets
  - Allow continuous pumping



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Preparing Silicon cantilevers

- For cryogenic measurements

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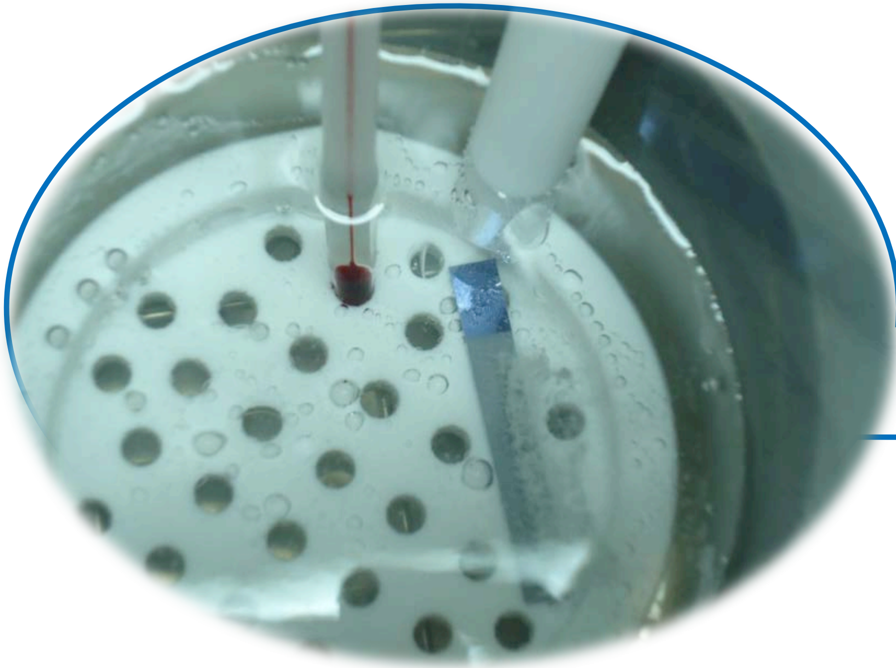
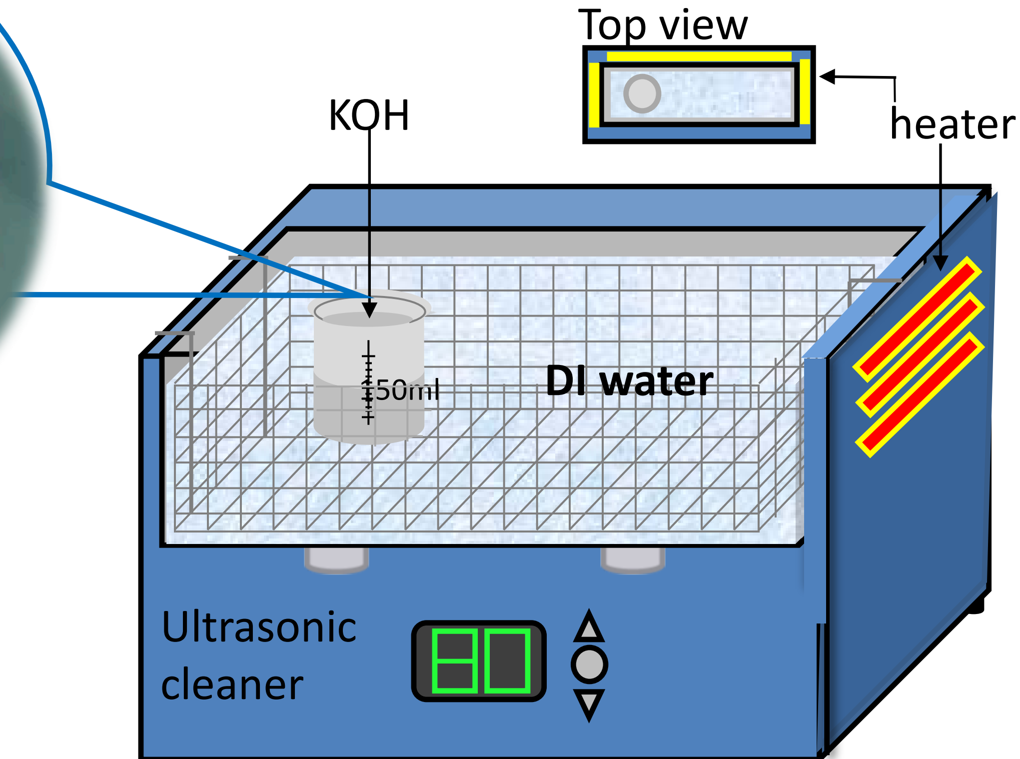
KOH wet etching





$$Si_{(s)} + 2(OH)^{-} + 2H_2O$$
$$\rightarrow$$
$$Si(OH)_2O_2^{2-} + 2H_{2(g)}$$

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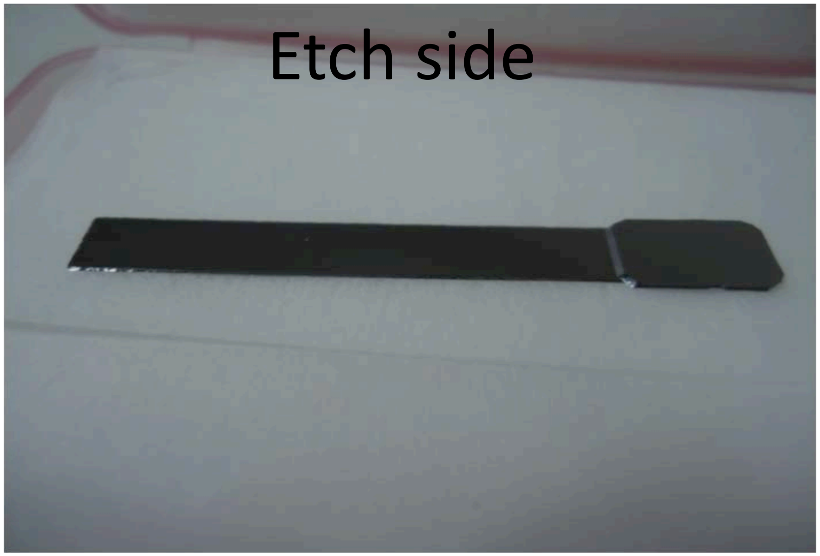
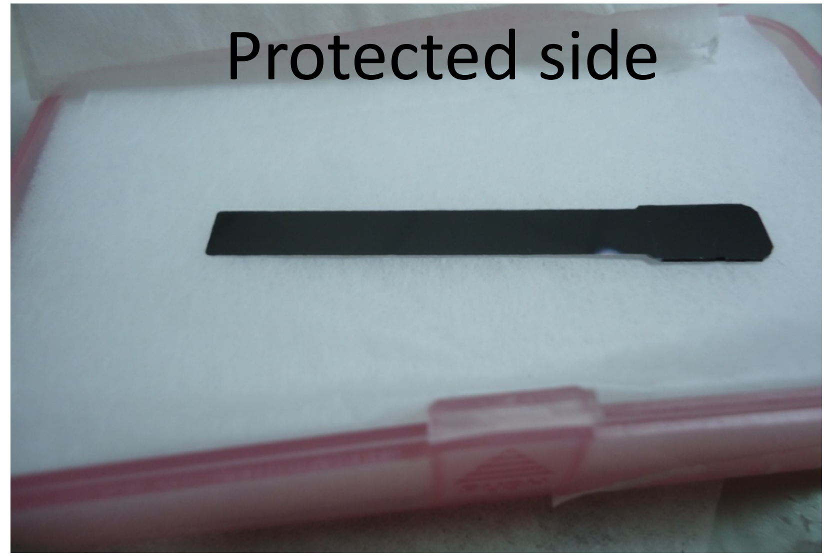
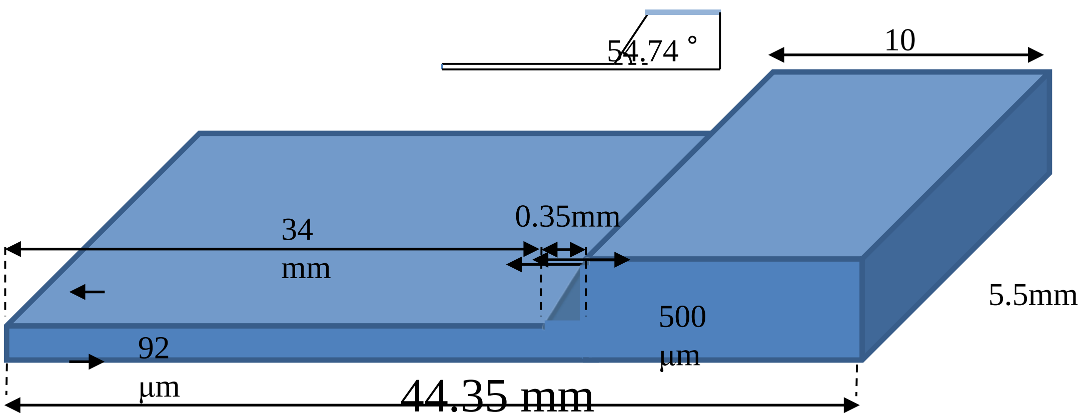
Silicon cantilevers







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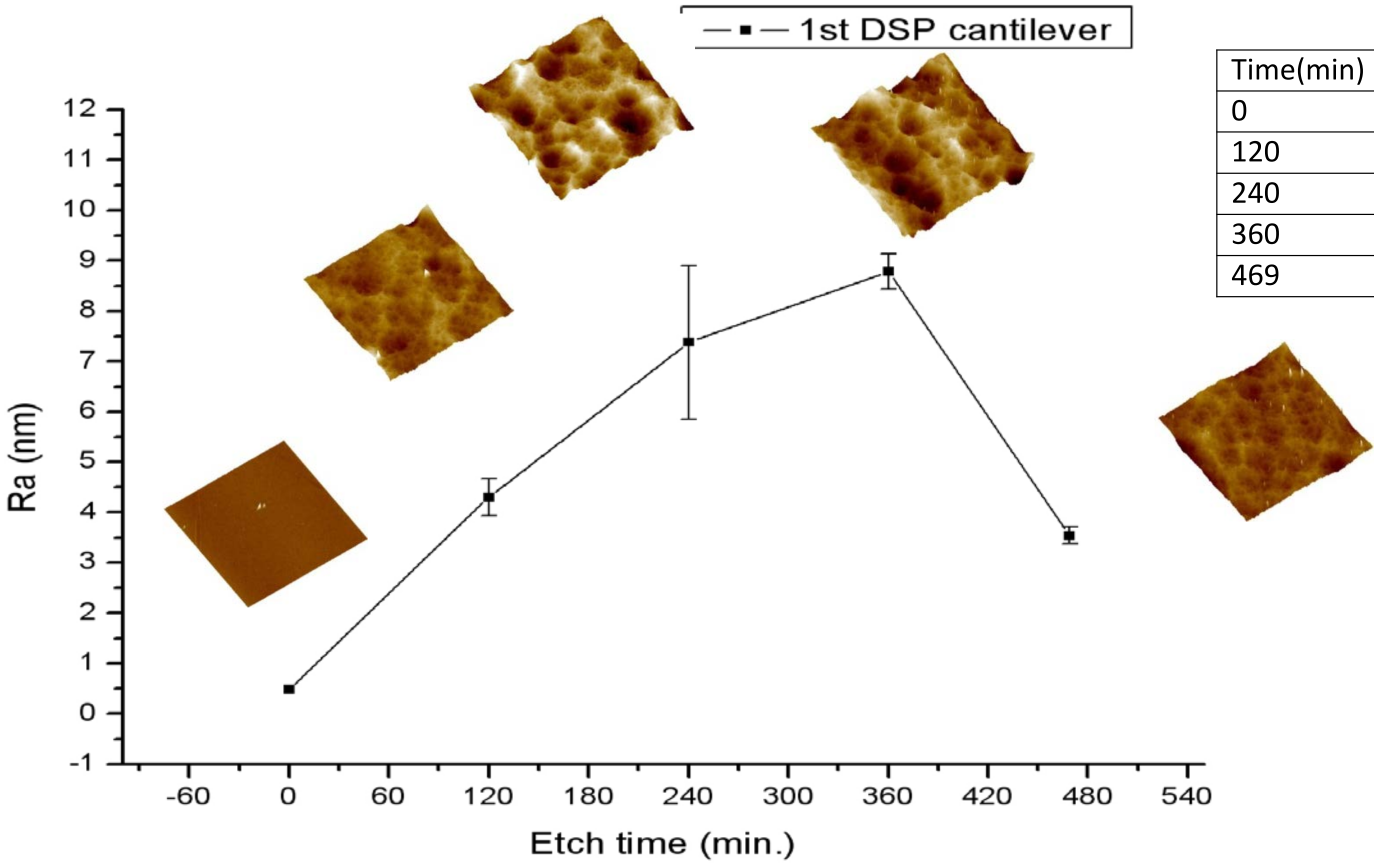
Roughness of cantilever



Time(min)	Ra(nm)	error
0	0.48	-
120	4.296	0.36882
240	7.376	1.51907
360	8.782	0.34932
469	3.539	0.16881

Incidentally . . .

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Silicon cliff

- We live here !
- That's Scary ! ! !
- Is this the reason why cryogenic mirrors do not improve?

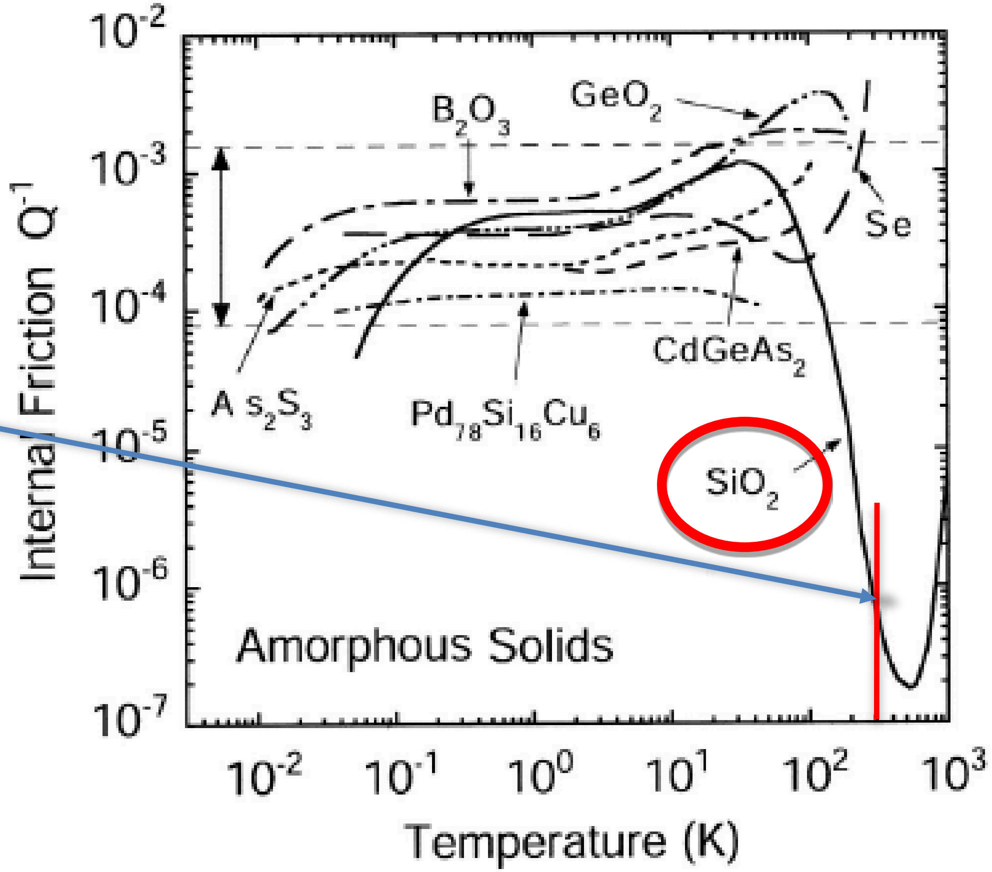

FIG. 2. Internal friction of several amorphous solids (Topp and Cahill, 1996). Between 0.1 and 10 K, the internal friction is nearly independent of temperature and measuring frequency. Within this temperature range, the magnitude of the internal friction for all glasses falls within about a factor of 20 as shown here by the dashed straight lines and the double arrow, called the glassy range, except for some a-Si films that are mentioned later. For a discussion of the dropoff below ~0.1 K, see the text.

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Better cryo coatings?

- What can we do to get better cryo coatings ? ?
- Is getting away from silica a simple answer???
- Should we switch to Al_2O_3 instead ? ? ?
- More work to do

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