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PIANO NAZIONALE DI RIPRESA E RESILIENZA

INFN
Istituto Nazionale di Fisica Nucleare

Coating Thermal Noise

Diana Lumaca

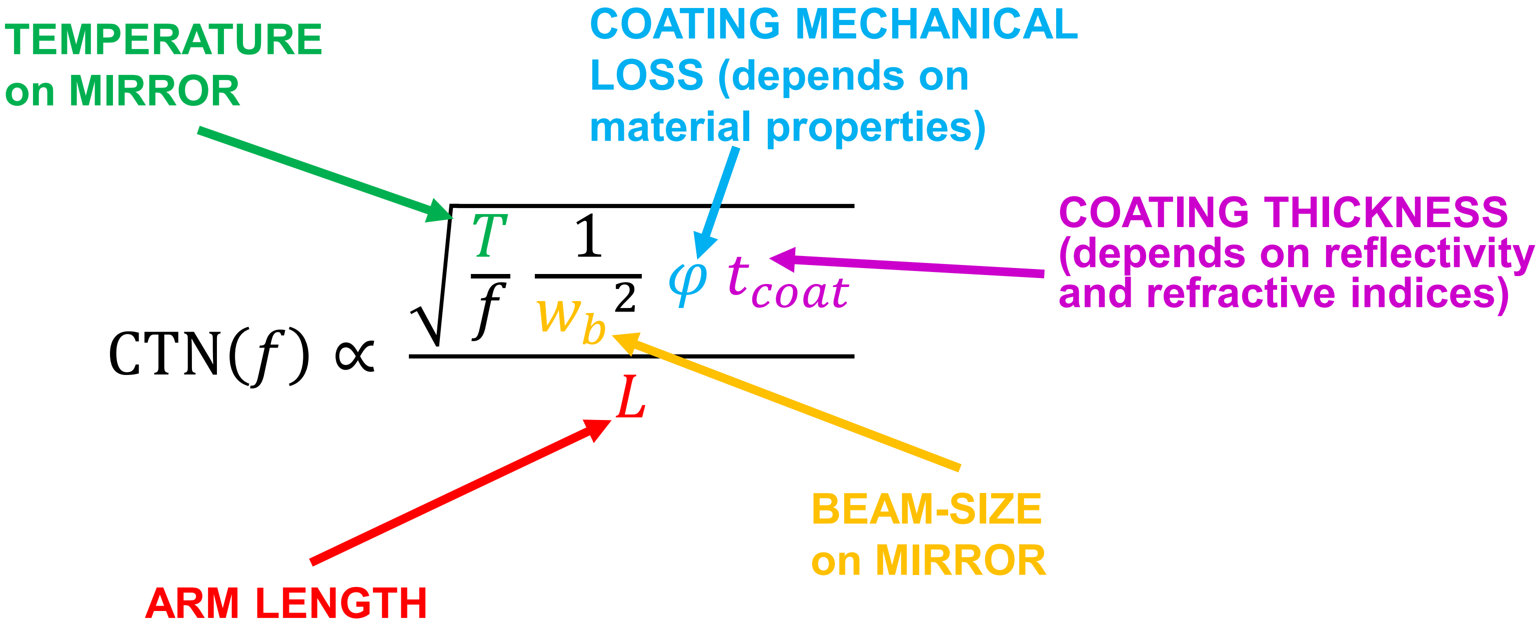
INFN – Sezione di Roma
Tor Vergata

Outline

- Coating thermal noise and sensitivity curve in future upgrade
- Mirror: state of the art
- Optical properties and characterization
- Mechanical properties and characterization
- Insight on metrology issues
- Research on new amorphous materials
- Origin of absorption and multi-technique investigation
- Crystalline coatings

Coating Thermal Noise

- Coating thermal noise (CTN) limits the detection in the middle frequency bandwidth
- The key parameters are:



TEMPERATURE on MIRROR

COATING MECHANICAL LOSS (depends on material properties)

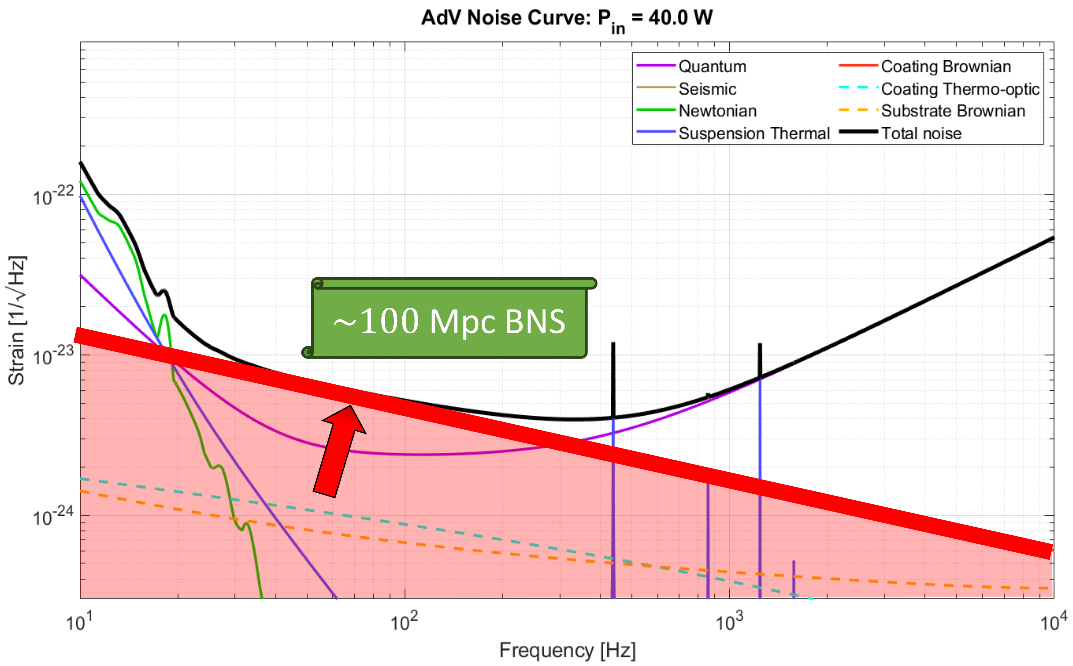
$$\mathrm{CTN}(f) \propto \frac{\sqrt{\frac{T}{f}\,\frac{1}{{w_b}^2}\,\varphi\, t_{coat}}}{L}$$

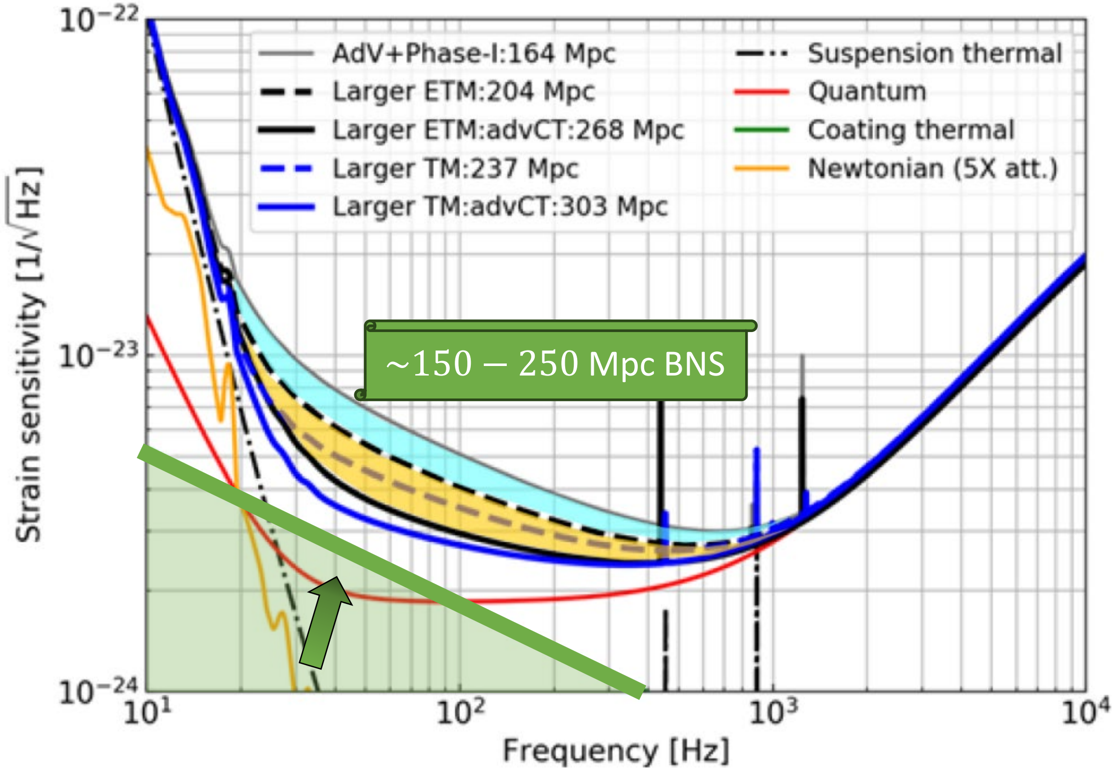
COATING THICKNESS (depends on reflectivity and refractive indices)

BEAM-SIZE on MIRROR

ARM LENGTH

Coating Thermal Noise in Advanced Virgo plus (AdV+)

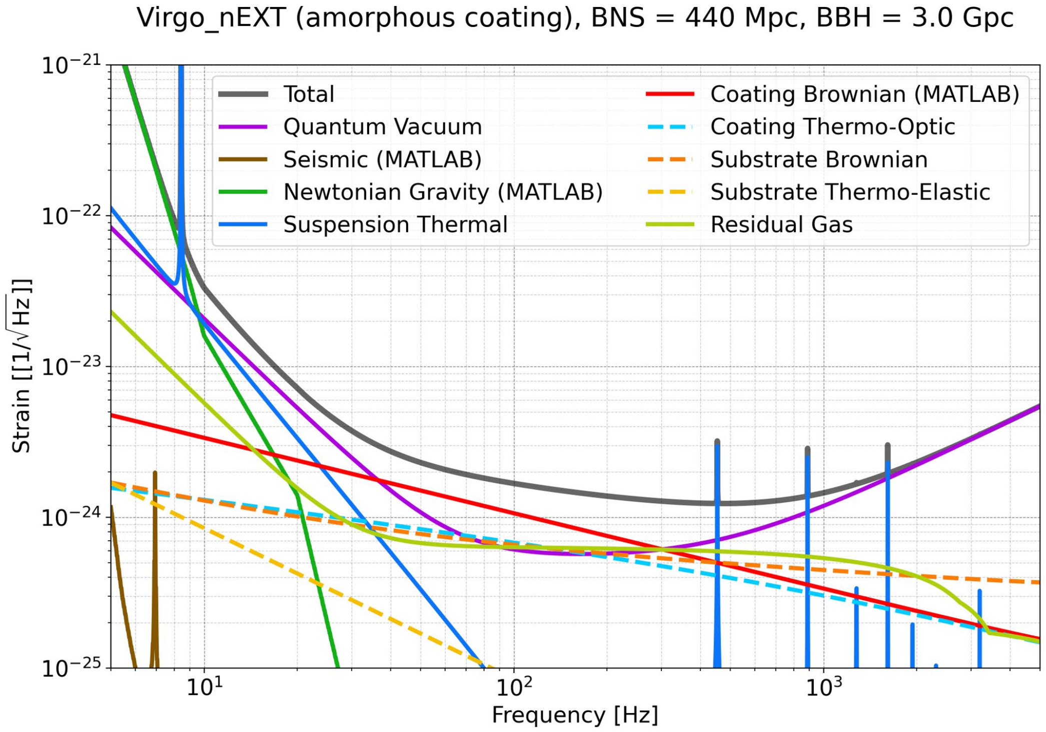


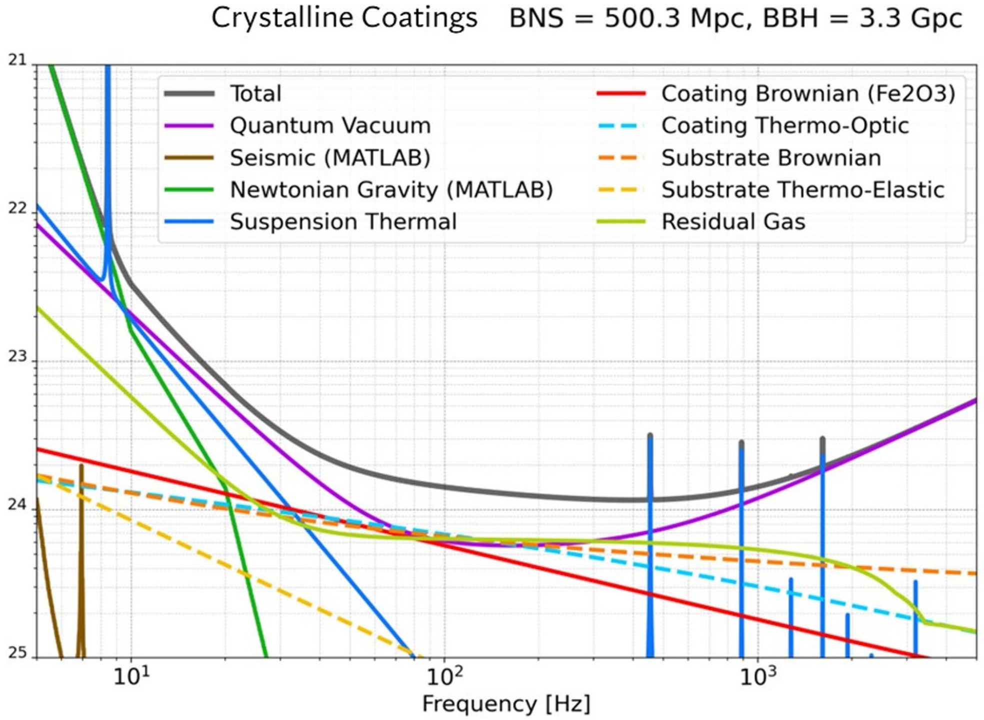


Post O4 / O5 preparation upgrades:

- Reduction of coating loss angle (foreseen a factor 3)
- Beam size increase on ETM (from 58 mm to 96 mm / ETM mass from 42 kg to 105 kg)

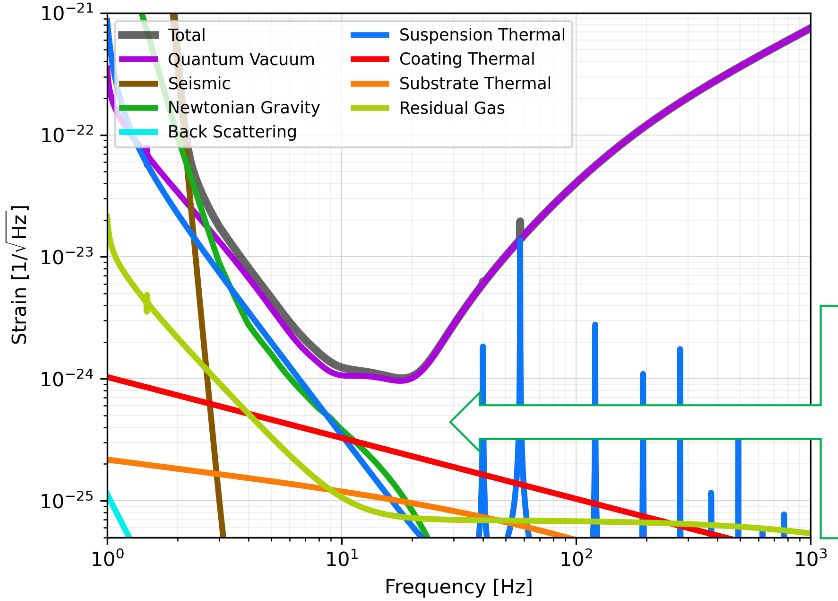
Coating Thermal Noise in Virgo_nEXT (PO5)


Virgo_nEXT (amorphous coating), BNS = 440 Mpc, BBH = 3.0 Gpc


Crystalline Coatings BNS = 500.3 Mpc, BBH = 3.3 Gpc

Coating Thermal Noise in Einstein Telescope

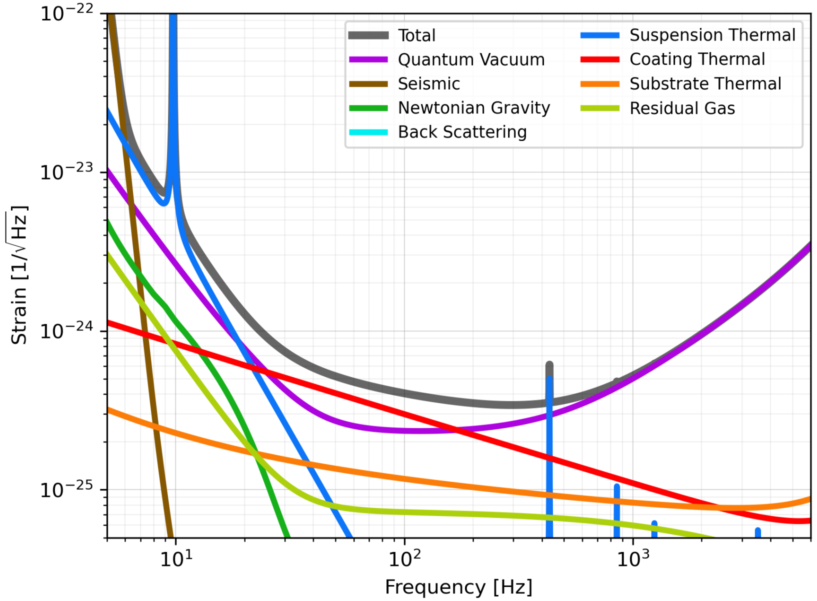
Sensitivity curve LF-ET



Cooling at **low temperature** (10K 20K or 120 K?) means **reduce thermal noise at its origin.**

Different laser wavelength, different **materials** (**substrates and coatings**), take **absorption** under control to ensure cryogenics operation

Sensitivity curve HF-ET



Same wavelength, substrate material and temperature as LIGO and Virgo detectors. New coating materials to **tolerate high laser power**

Substrate material: Silica as a key material

Fused silica is a type of glass containing primarily silica in **amorphous** (non-crystalline, short-range order) form. The main distinguishing characteristic is its **purity** but other spectacular properties are accomplished:

- **Optical**

  optical transmission is enormous
  "A 10 m thick quartz glass disk does not affect sight at all. The view is not different than looking through a normal window glass."

- **Mechanical**

  very low losses at room temperature, **bulk loss angle** is $f \approx 10^{-9}$ (steel has $f \approx 10^{-4}$)

- **Thermal**

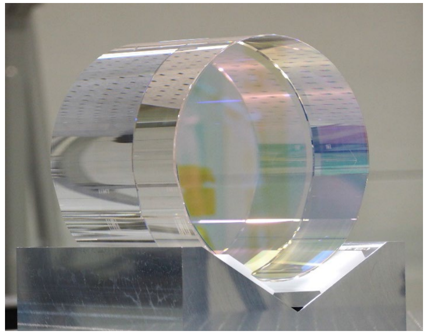
  low thermal expansion coefficient of approximately $0{,}5 \cdot 10^{-6}$ K^{-1}, compared to stainless steel, is 30 times lower during heating.

enormous thermal shock resistance.
The quartz glass **withstands high temperature** and **exposure to cold water** without any damage.

Substrate material: ET core optics

ET-HF:

➢ **Silica SiO_2**
✓ low thermoelastic effect
✓ low optical absorption
✓ low mechanical losses.
✓ properties are well-known

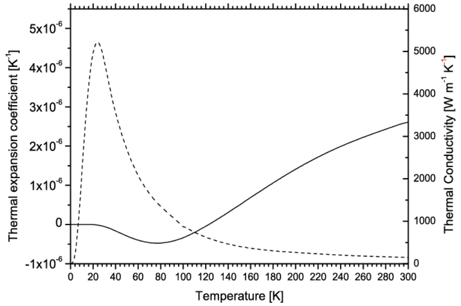


ET-LF:

➢ **Sapphire** (LF-ET)
✓ High Young's modulus
✓ Transparent for 1064 nm, low mechanical loss at low temperature
→ **birefringence**, **absorption** and **scattering** in dependence of manufacturers (axis orientation)

ET-LF:

➢ **Silicon** (LF-ET)
✓ low mechanical loss at cryogenic temperatures, thermal expansion coefficient at 123 K and 18 K (suppression of thermoelastic of substrate and thermal expansion effects)
→ **change of the wavelength** 1550 nm or 2000 nm (suitable also with aSi as coating material)
→ large size and low optical absorption



Mirror Coatings basics

Enabling technology for GW detectors:

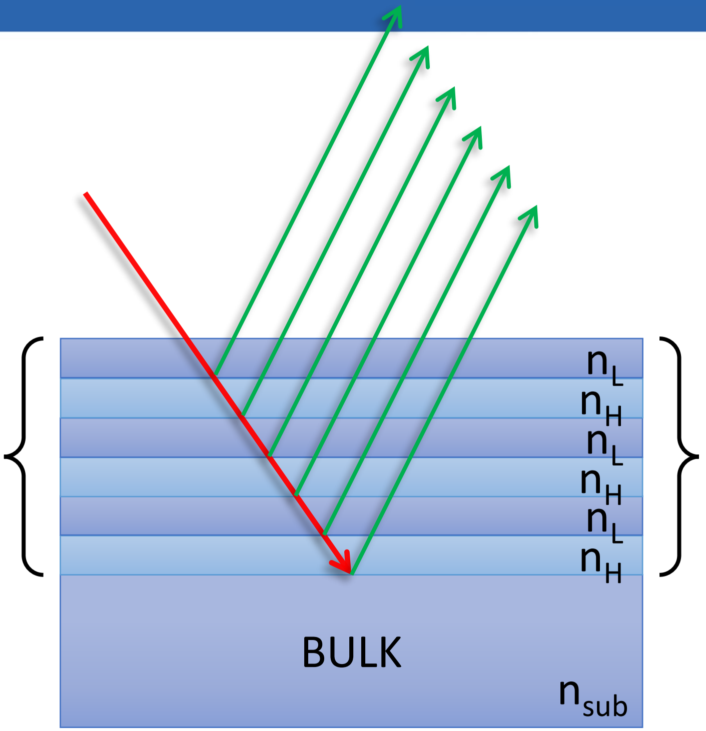
- ➢ dielectric mirrors = bulk + reflective multilayer coatings

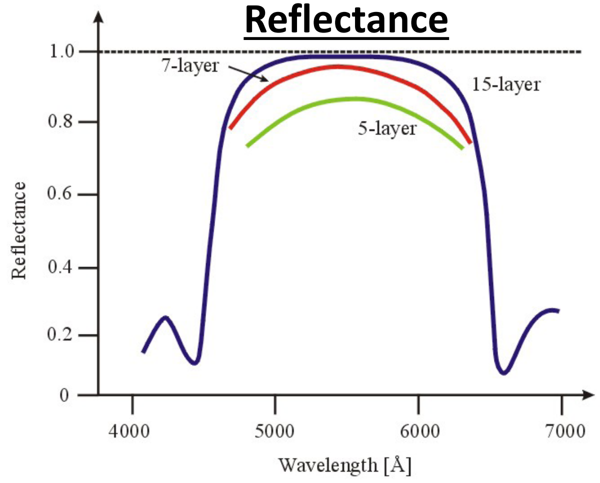
Bragg reflectors

- It is a structure formed by ***multiple layers*** of alternating materials with periodic variation of refractive index
- In GW mirrors is a substrate + a stack of alternate layers of ***high- and low- refractive index materials*** (n_H and n_L)
- ***Accurate choice of thickness*** $\cong {}^{\lambda}/_{4}$
  - ➢ Constructive interference
  - ➢ High-quality reflector

$$R = |r^2| = \frac{1 - n_{sub}\left(\frac{n_L}{n_H}\right)^{2N}}{1 + n_{sub}\left(\frac{n_L}{n_H}\right)^{2N}}$$

N doublets



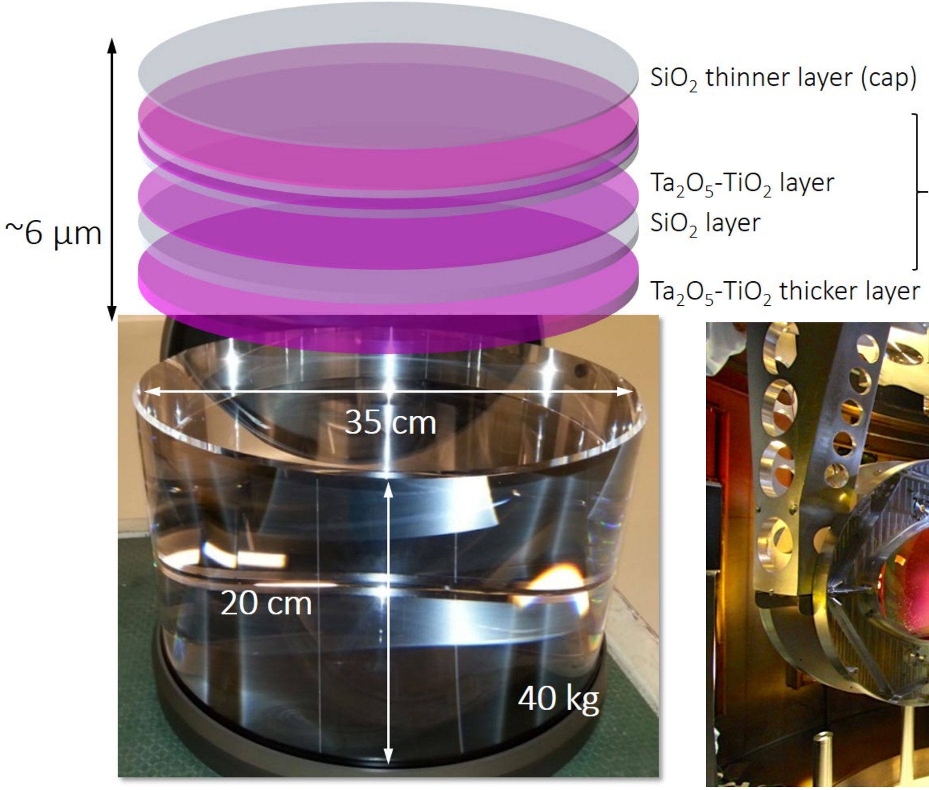


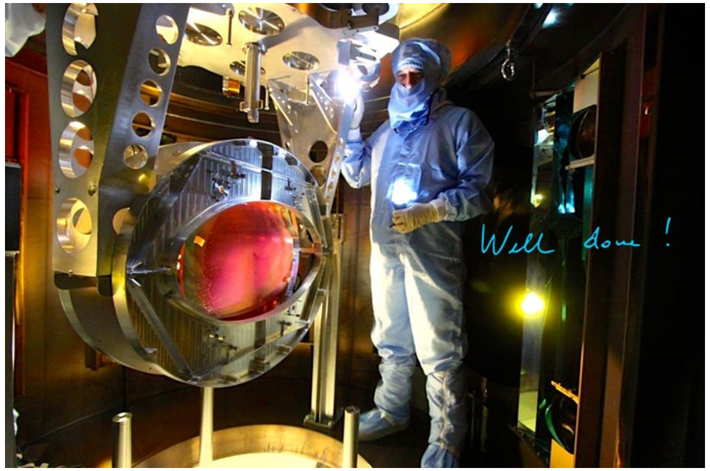
State of the Art (Virgo/LIGO)

VIRGO
LMA LABORATOIRE MATÉRIAUX AVANCÉS

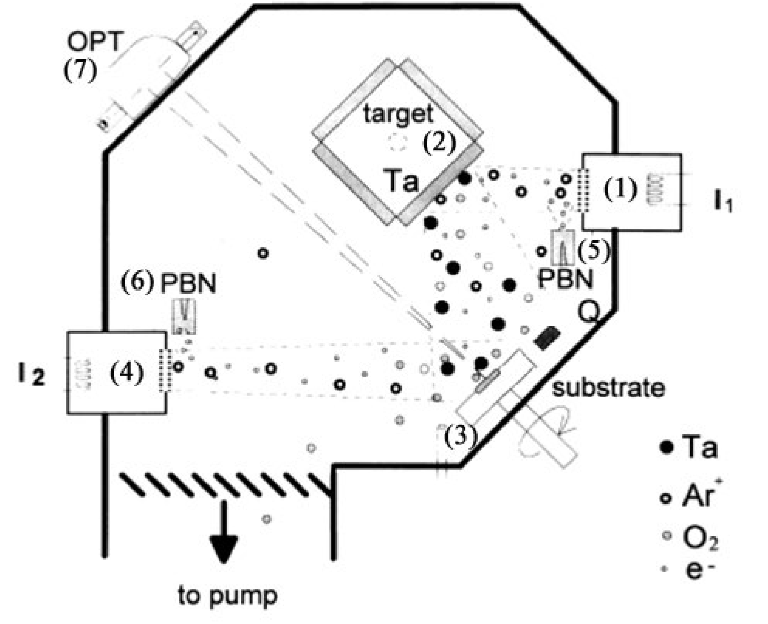
Silica SiO2 n=1.45

Tantala TiO2:Ta2O5 n=2.09





Ion Beam Sputtering (IBS) deposition at Laboratoire de Materiaux Avances, in Lyon.



Mirror Coatings basics

Required properties:

- **Low scattering** (from e.g. defects or micro-roughness or micro-crystals)
  - To avoid *diffused light* in the ITF
  - Only purely amorphous or single-crystalline materials suitable
- **Low optical absorption**: below 1 ppm (10^{-6})
  - To avoid *thermal effects* in room temperature detectors
  - To avoid *heating* in cryogenic detectors

Livia's talk

OPTICAL PROPERTIES

Lorenzo's talk

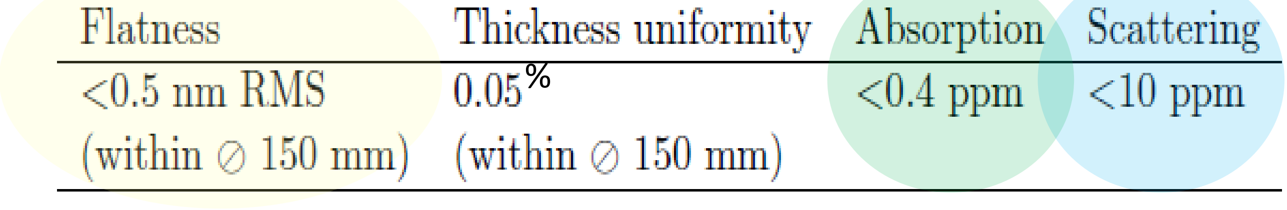
- **Low coating thermal noise** (CTN):
  - Linked to *mechanical dissipation*
  - Material research

MECHANICAL PROPERTIES

Optical properties and losses

The ***outstanding optical properties*** of the present mirrors are linked ***to optical losses*** in the cavities:

- the optical losses in the cavities increase the signal to noise ratio of the shot noise ***degrading thus the detector sensitivity at high frequencies.***
- low losses in the two arm cavities will reduce ***the risk of having bad contrast defects*** coming from the asymmetry of the two arms.
- the diffused light due to the surface figure error of the mirrors can couple back in the ITF, ***adding noise***.



Flatness	Thickness uniformity	Absorption	Scattering
<0.5 nm RMS (within ⊘ 150 mm)	0.05% (within ⊘ 150 mm)	<0.4 ppm	<10 ppm

The **round-trip losses** in the arm cavities (fraction of light lost after a round-trip in the cavity**) should be very small** in order to reach a good detector sensitivity.

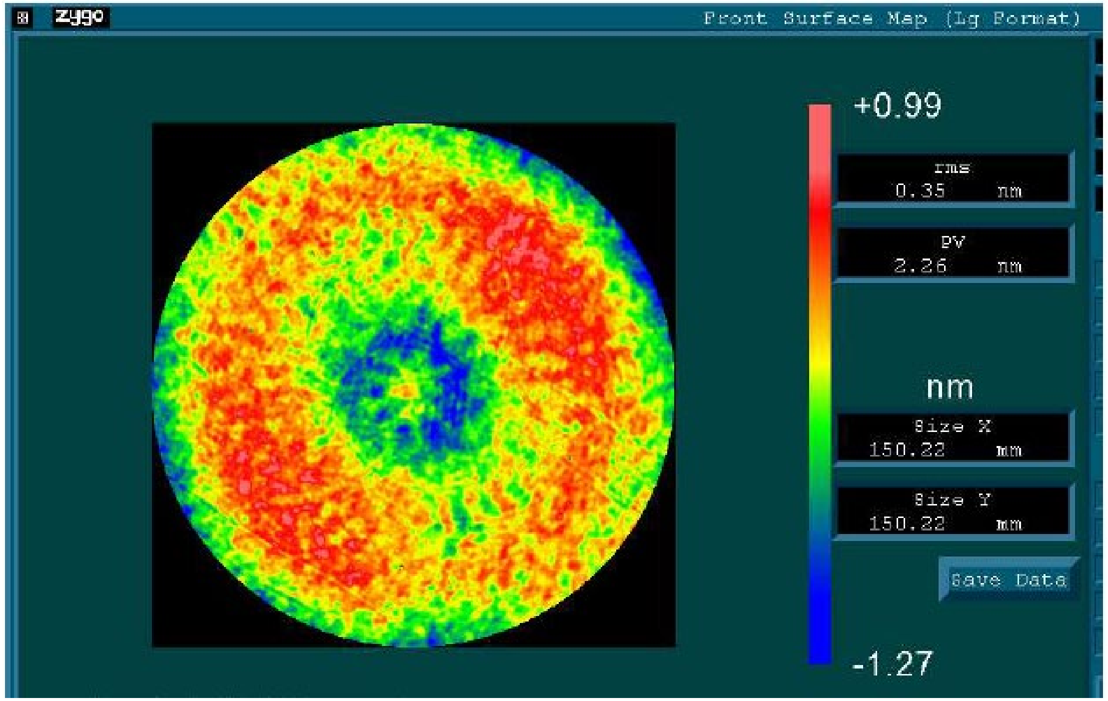
The losses in a cavity are due to:

- ***diffraction*** at low spatial frequency (depending on flatness)
- ***scattering*** at high spatial frequencies (depending on micro-roughness)
- ***absorption*** in the coating/substrate
- ***punctual defects*** on the mirror surface, scratches, digs and points defects.

State of the Art (Virgo/LIGO) – optical properties

FLATNESS: Surface Roughness 0.35 nm RMS ⌀ 150 mm

Wavefront Surface 1 (HR), incidence 0° (∅150 mm)



rms 0.35 nm
PV 2.26 nm
Size X 150.22 mm
Size Y 150.22 mm

For checking the **level of diffraction at low spatial frequency**

The **surface roughness** is measured to check the flatness of the mirror (low spatial frequency)

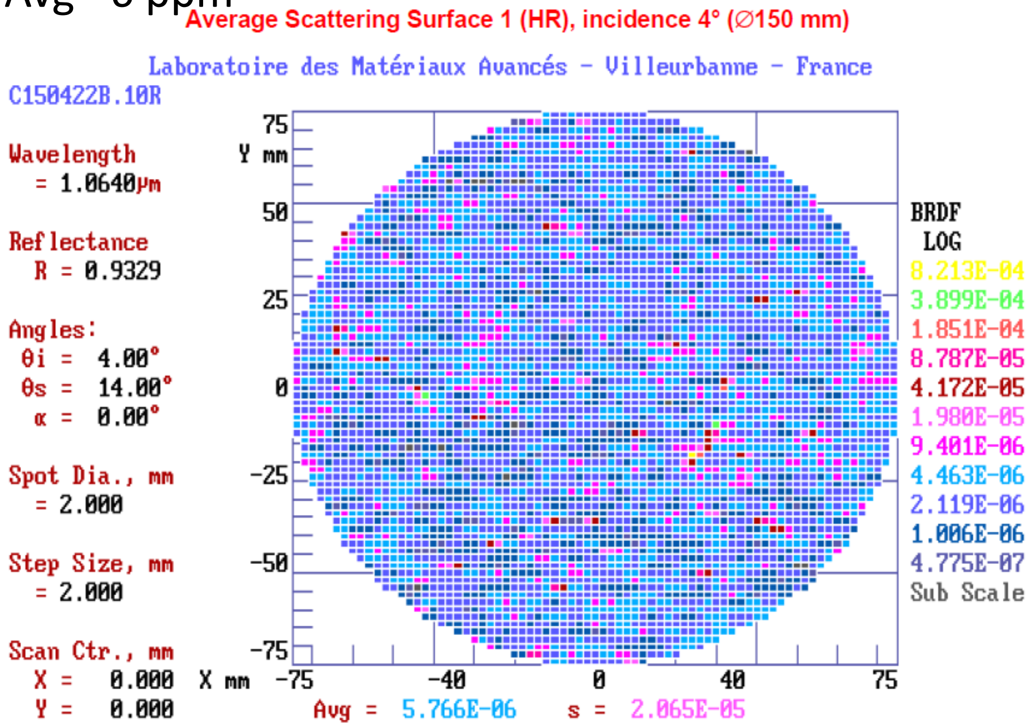
The flatness of a mirror surface can be seen as **deviations from an ideal surface**, either plane or spherical depending on the optics

The low surface figure of a substrate is **measured** typically **with a phase-shifting interferometer**

The parameter commonly used to express the flatness of a surface is the root mean square (RMS) fluctuation in height of the surface.

State of the Art (Virgo/LIGO) – optical properties

SCATTERING: Scattering Surface 4° AOI ⌀ 150 mm
Avg= 6 ppm


Average Scattering Surface 1 (HR), incidence 4° (∅150 mm)

Laboratoire des Matériaux Avancés - Villeurbanne - France

C150422B.10R

Wavelength
= 1.0640µm

Reflectance
R = 0.9329

Angles:
θi = 4.00°
θs = 14.00°
α = 0.00°

Spot Dia., mm
= 2.000

Step Size, mm
= 2.000

Scan Ctr., mm
X = 0.000
Y = 0.000

Avg = 5.766E-06 s = 2.065E-05

Roughness at high spatial frequency is measured with a scatterometer

For checking the **level of diffraction at high spatial frequency**

The *bidirectional reflectance distribution function* (BRDF) is measured **at 4° of incidence**

*The function takes an incoming light direction, **w**$_i$, and outgoing direction, **w**$_r$, and returns the **ratio of reflected radiance** exiting along w$_r$ **to the irradiance incident** on the surface from direction:*

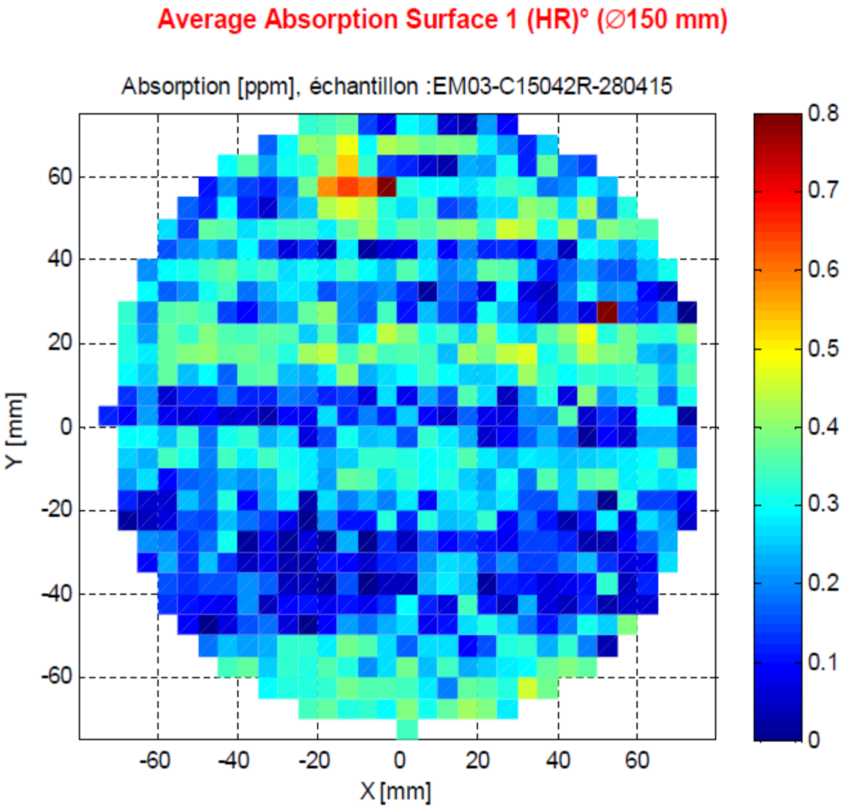
$$f_r(\omega_i,\omega_r)=\frac{dL_r(\omega_r)}{dE_i(\omega_i)}=\frac{dL_r(\omega_r)}{L_i\,(\omega_i)\cos\vartheta_i\,d\omega_i}$$

L = radiant flux emitted, reflected, transmitted or received by a given surface, per unit solid angle per unit projected area [W/sr·m^2]

E= radiant flux received by a surface per unit area [W/m^2]
q = angle between wi and normal surface

State of the Art (Virgo/LIGO) – optical properties

Optical Absorption 0.24 ppm ⌀150 mm

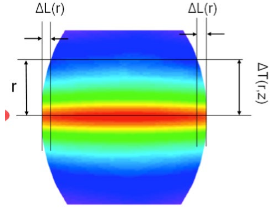


Absorption of optical power in the coating and substrate of the optics is a **dynamical thermal effect.** It needs to be under 1 ppm to avoid **thermal effects**

Lorenzo's talk

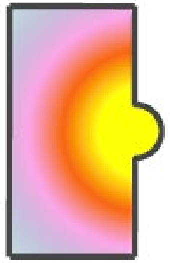
- Thermal lensing

$$\Delta OPL_T = \frac{dn}{dT}\int_S \Delta T ds$$



OPL distortions due to **dependence of refractive index from temperature variation**

- Thermo-elastic effect

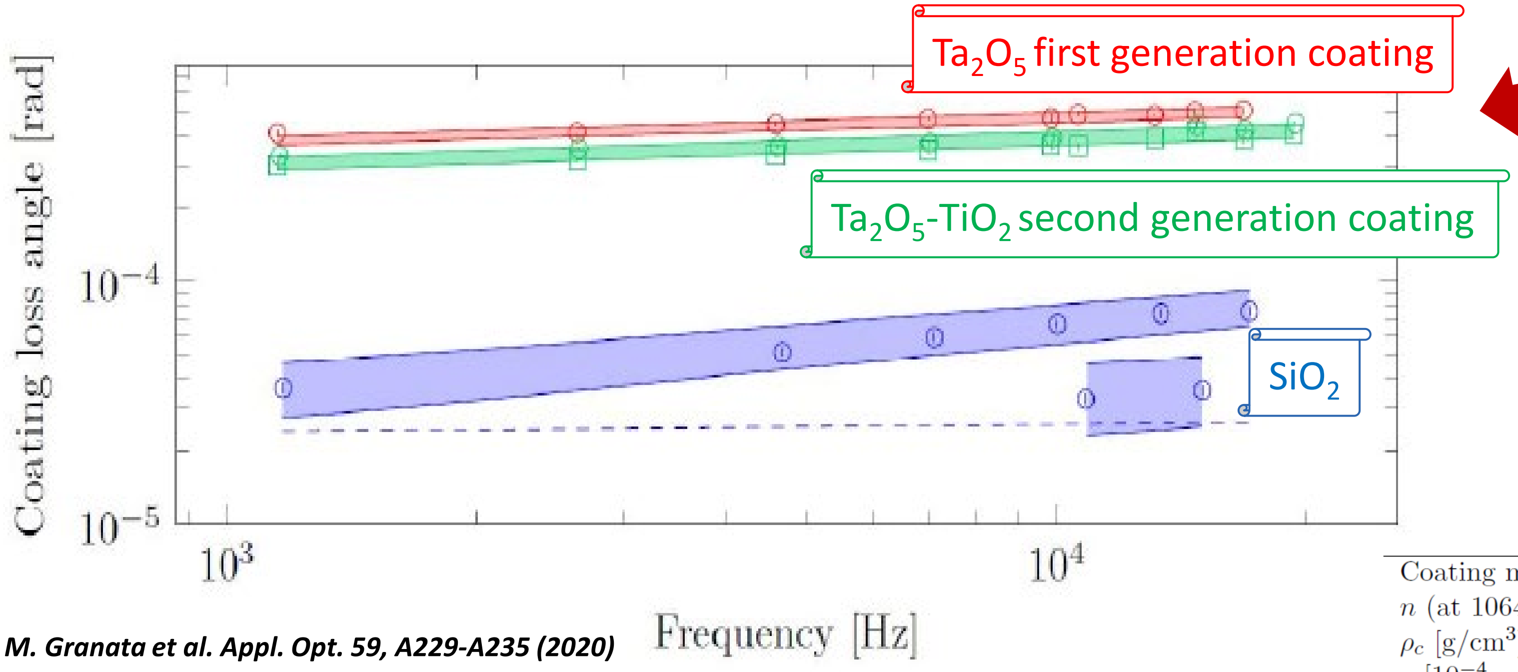


$$\Delta u \approx \alpha \int_S \Delta T ds$$

Change of RoC of mirrors due to the absorption of laser power

- a system for the compensation of thermal effects is provided

State of the Art (Virgo/LIGO) – mechanical properties

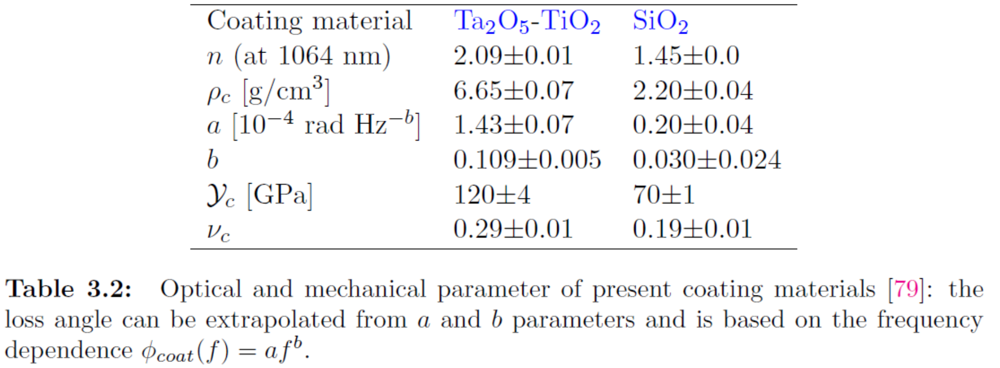


Lossy material

Loss angle dependent from frequency in a simple form in amorphous material: $\varphi = a \cdot f^b$

M. Granata et al. Appl. Opt. 59, A229-A235 (2020)

Elastic parameters



Coating material	Ta_2O_5-TiO_2	SiO_2
n (at 1064 nm)	2.09±0.01	1.45±0.0
ρ_c [g/cm^3]	6.65±0.07	2.20±0.04
a [10^{-4} rad Hz^{-b}]	1.43±0.07	0.20±0.04
b	0.109±0.005	0.030±0.024
$\mathcal{Y}_c$ [GPa]	120±4	70±1
ν_c	0.29±0.01	0.19±0.01

Table 3.2: Optical and mechanical parameter of present coating materials [79]: the loss angle can be extrapolated from a and b parameters and is based on the frequency dependence $\phi_{coat}(f) = af^b$.

How can we measure loss angle of a coating?

Metrology of mechanical properties a long way…

Loss Angle

Alex's talk

Essential quantities to characterize the dissipative behaviour of materials:

Quality factor $\boldsymbol{Q} \equiv 2\pi \frac{E_{tot}}{E_{diss}}$

- Systems with high dissipations have low Q and larger off-resonance contribution, and viceversa

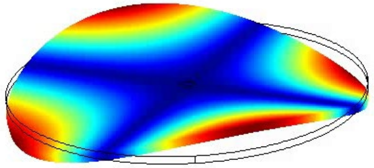
A system is dissipative whenever its *response to a step input* is characterized by a finite *relaxation time* $\tau \rightarrow$ **phase lag between input and response** $\rightarrow$ ***Loss angle*** $\boldsymbol{\varphi(\omega)} = \frac{1}{2\pi}\frac{E_{diss}}{E_{tot}}$

- At resonance $\varphi(\omega_0) = \frac{1}{Q}$
- Additive quantity

Any physical system can be composed by many different parts (i), whose stored energies (s) can be dissipated by many different mechanisms (m)

- ***Dilution factor*** $\boldsymbol{D_{i,s}(\omega)} = \frac{E_{i,s}}{E_{tot}}$
- $\varphi_{tot} = \sum_i \frac{E_{diss,i}}{2\pi E_{tot}} = \sum_i \sum_s D_{i,s}(\omega) \sum_m \varphi_{m,i}^{s}$

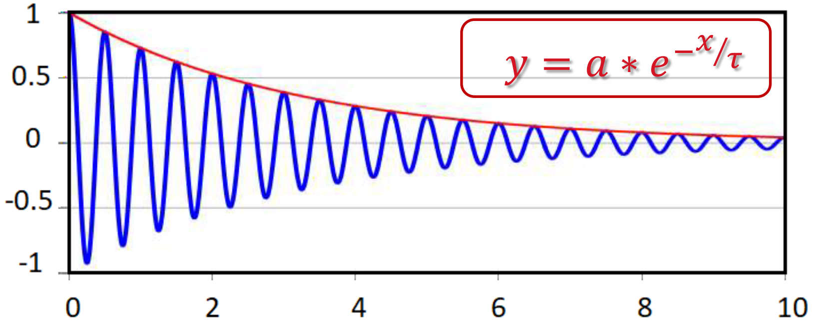
Metrology of loss angle



- Resonant **ring-down method** and **Ge**ntle **N**odal **S**uspension

  Vibrating body (disc-shaped sample, properly suspended) **damping characteristic time** of free oscillation; the loss angle can be measured looking at the **free decay** of a resonance, and working out the damping rate

$$\boxed{\varphi = \frac{1}{\pi f \tau}} \quad \rightarrow \quad \varphi_{TOT} = \frac{E_{sub}}{E_{TOT}}\varphi_{sub} + \frac{E_{coat}}{E_{TOT}}\varphi_{coat}$$



- Coating loss angle detection:

$$\varphi_{coat} = \frac{E_{TOT}}{E_{coat}}\left(\varphi_{TOT} - \frac{E_{sub}}{E_{TOT}}\varphi_{SUB}\right) \cong \frac{E_{sub}}{E_{coat}}\left(\varphi_{sub+coat} - \varphi_{sub}\right)$$

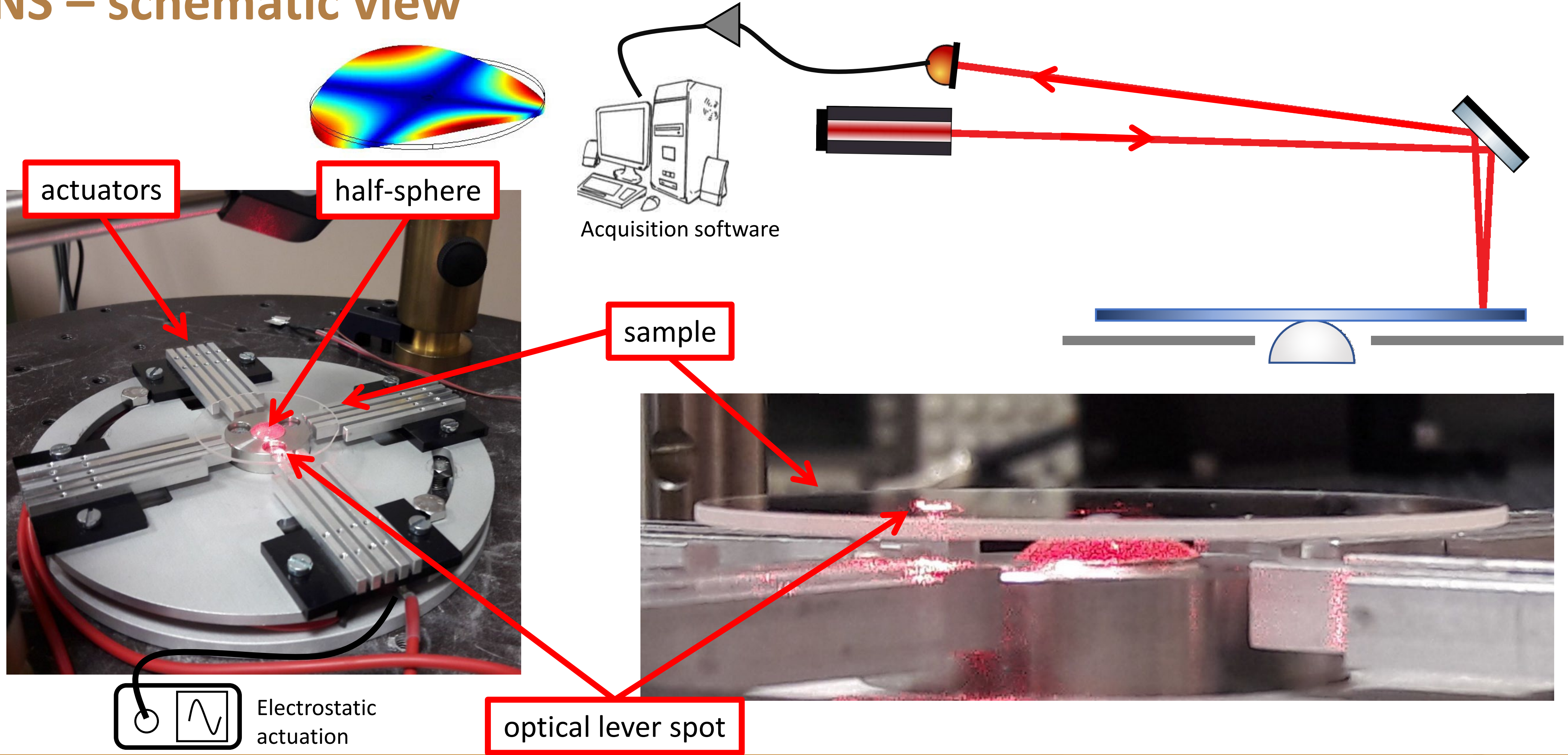
  - ✓ Substrate mechanical characterization **before coating deposition**;
  - ✓ ***Substrate losses supposed independent of the coating deposition process***;
  - ✓ Coated sample mechanical characterization **after coating deposition**;
  - ✓ Dilution factor directly evaluable by mode frequency shift measurement before and after coating deposition:

$$\mathrm{D} \cong 1 - \left(\frac{f_0}{f}\right)^2 \frac{m_0}{m} \cong \frac{3\mathcal{Y}_{coat} t_{coat}}{\mathcal{Y}_{sub} t_{sub}}$$

- **Stability** of the **substrate's losses** and **resonant frequencies** is mandatory
- **Spurious frequency shifts** need to be avoided or controlled and subtracted

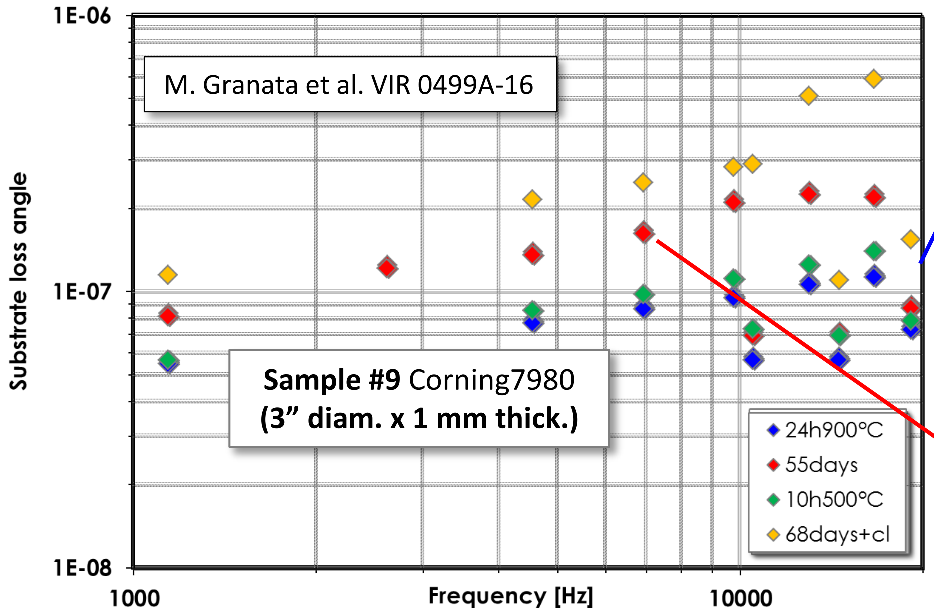
GeNS – schematic view

E. Cesarini et al. Review of Scientific Instruments 80, 053904 (2009)



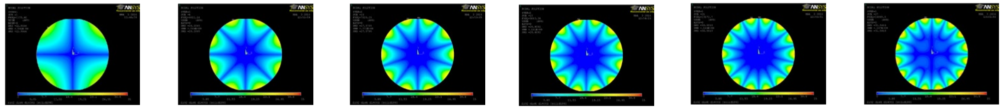
Metrology issues – substrate stability

To enhance substrate mechanical quality and its stability a **specific thermal treatment** is used (annealing)

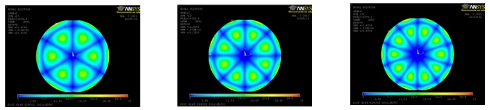


G. Cagnoli et al. Physics Letters A, Volume 382, Issue 33, 2018,

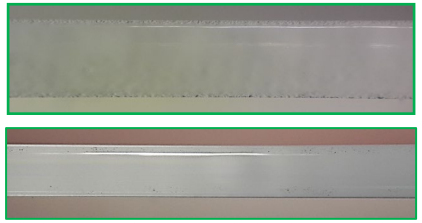
- Shape dependence → **family modes**
  - Butterfly modes, azimuthal nodal lines

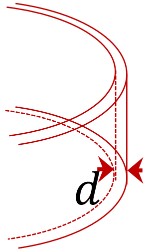


  - Mixed modes, azimuthal and radial nodal lines



- Time dependence → **ageing**





D. Lumaca et al. Journal of Alloys and Compounds, Volume 930, Issue 5, 2023

- Surface losses $\varphi_{TOT} = D_{disc}\varphi_{disc} + D_{barr}\,\varphi_{barr} = Af^{B} + d\varepsilon\varphi_{barr}$

Metrology issues – frequency shift monitoring

To have a good estimation of the coating loss angle ϕ_{coat}, we need a full characterization of the substrate before any treatment and a **monitoring of resonance frequencies**. The dilution factor **D**, in fact, is **frequency dependent** and we are assuming that **any possible frequency and mass variations are attributable only to coating deposition**.

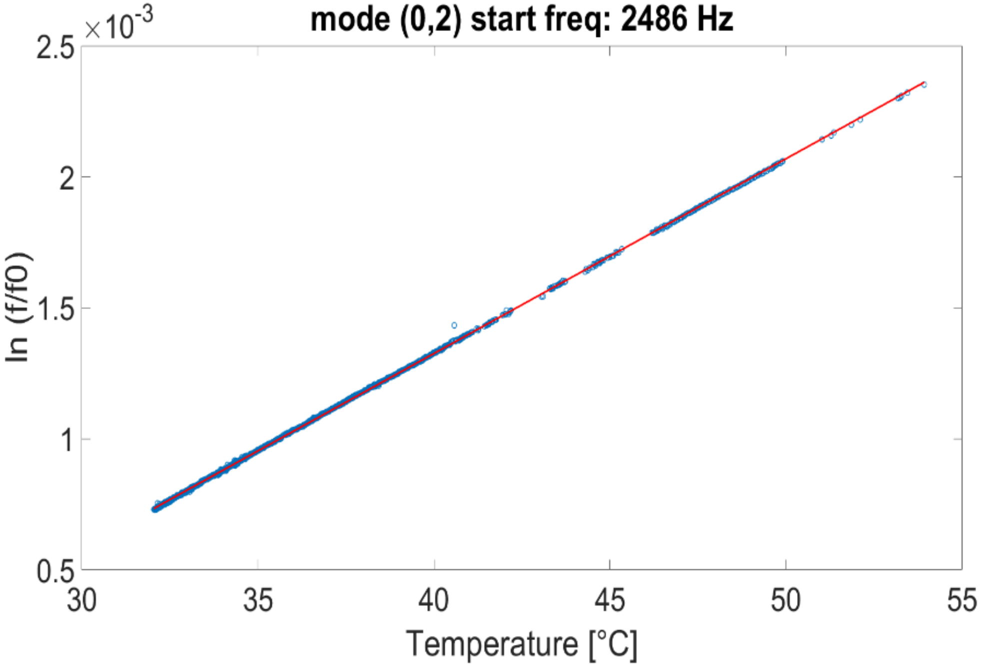
$$\varphi_{coat} = \frac{1}{\mathrm{D}}\left[\varphi_{sub+coat} - (1 - D)\varphi_{sub}\right]$$

$$D = 1 - \left(\frac{f_{sub}}{f_{sub+coat}}\right)^2 \left(\frac{m_{sub}}{m_{sub+coat}}\right)$$

TEMPERATURE

Different temperature condition can determine systematics on dilution factor measurement by frequency shifts

- Temperature witness sample
- Temperature correction to measured frequencies



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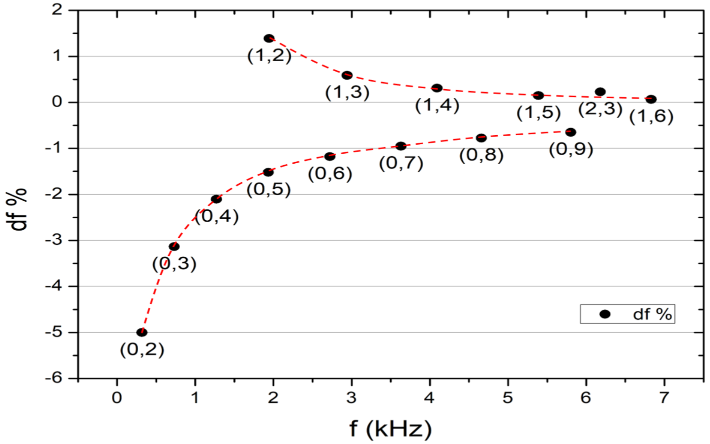
$$D = 1 - \left(\frac{f_{sub}}{f_{sub+coat}}\right)^2 \left(\frac{m_{sub}}{m_{sub+coat}}\right)$$

SUBSTRATE ANNEALING

A substrate thermal treatment produces frequency shift. Typical temperature of 900 °C does not make the substrate stable: frequencies are changed by further annealings.

- Frequency shifts are **not related to geometrical deformation** but to a **variation of elastic properties** (Poisson coefficient)
- Annealing at 1000 °C is a better choice (small frequency shift, sample stability)

Frequency shift after 900°C 20 h annealing



Metrology issues – coating losses modelling

- Separating the **contributions** of different elastic strains, different loss mechanisms
- Focusing on structurally **isotropic coatings**. When they grow amorphous, this does not usually induce a significant structural anisotropy.
- Assuming the **elastic response** fully captured by just two elastic constants and the film loss given by the two related contributions associated with either **bulk or shear strains**

$$\phi_c = D_{\mathrm{bulk}} A_1 f^{\alpha_1} + D_{\mathrm{shear}} A_2 f^{\alpha_2} \, ,$$

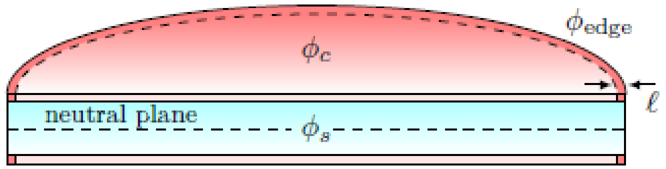
- Bulk strain is related to **volume change**
- Shear strain is related to **parallel deformation**

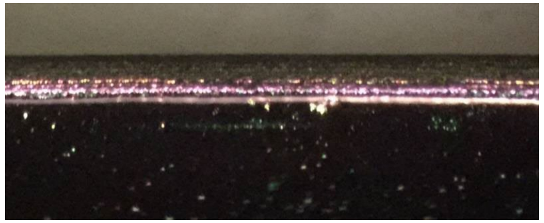
BUT, an **excess edge losses may arise** from a variety of reasons such as, coating **thickness non-uniformity** at the edge, coating **spill-off** during the deposition, **tapering/shading** due to the sample holder during deposition, or coating deposition on an unpolished surface and an associated **lack of adhesion** near the edge.

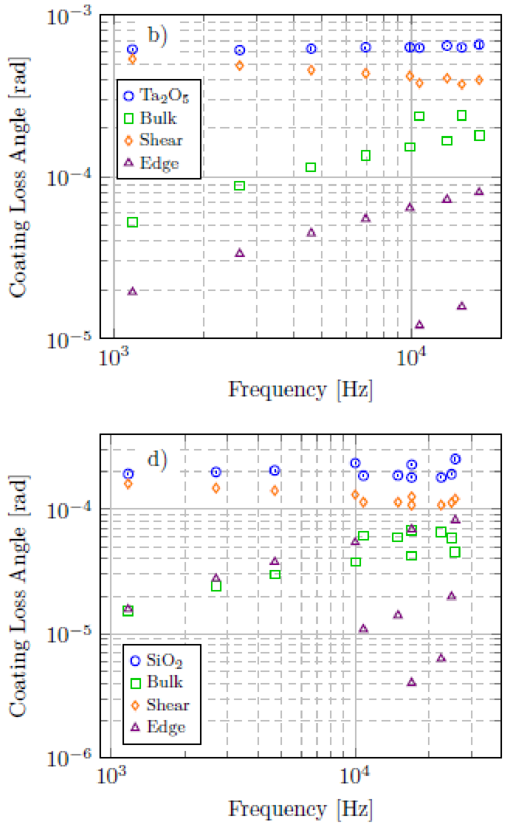
$$\phi_c = \left(D_{\mathrm{bulk}} - \frac{\ell}{R}\varepsilon^{\mathrm{edge}}_{\mathrm{bulk}} \right) \phi_{\mathrm{bulk}} + \left(D_{\mathrm{shear}} - \frac{\ell}{R}\varepsilon^{\mathrm{edge}}_{\mathrm{shear}} \right) \phi_{\mathrm{shear}}$$

$$D^{\mathrm{edge}}_{\mathrm{bulk}} = \frac{\ell}{R}\varepsilon_{\mathrm{bulk}}$$

$$D^{\mathrm{edge}}_{\mathrm{shear}} = \frac{\ell}{R}\varepsilon_{\mathrm{shear}}$$



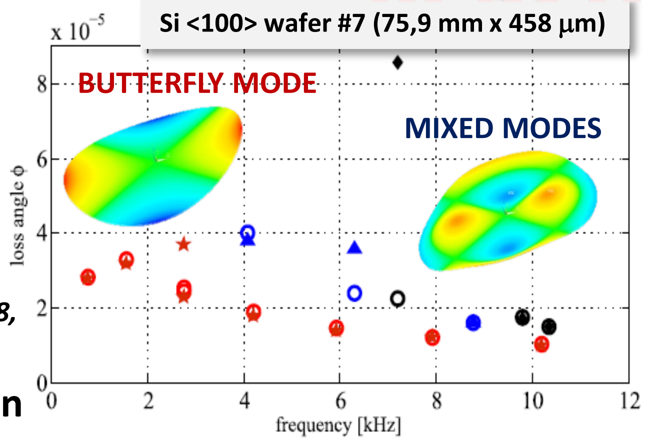




A. Amato et al. Phys. Rev. D **106**, 082007, **2022**

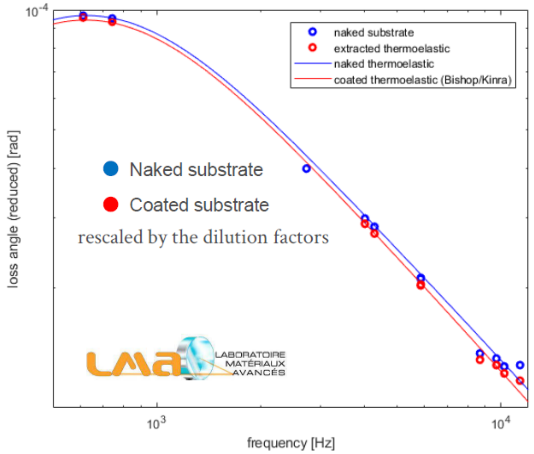
Metrology at low T

- Future GW detectors are proposed to be operated at **cryogenic temperatures**
- The knowledge of **mechanical properties** at **low temperatures** is strongly required to predict their thermal noise limited sensitivity
- Cryogenic loss angle measurements are necessary to understand the **loss mechanism** in the more general physics of amorphous materials

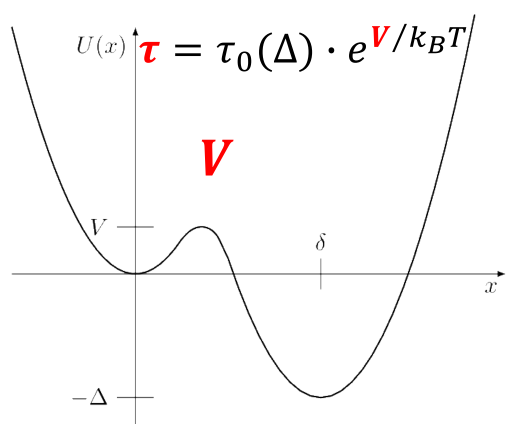


G. Cagnoli et al. Physics Letters A, Volume 382, Issue 33, 2018,

- **Crystalline substrates** need to e used to characterized at all T, due to a **high dissipation peak of amorphous SiO2 at low T**.
- But **crystalline materials** such as silicon and sapphire are dominated by **thermoelastic dissipation** especially at room temperature. This dissipation mechanism can be completely modelled in disk shaped samples
- The **thermoelastic dissipation of the substrate is changed by the presence of the coating**. We have **models** for computing coated samples thermoelastic losses, but **thermo-mechanical parameters are generally poorly known**
- Innovative strategies need to be identified: i.e. **use different geometry** to excite longitudinal modes that do not suffer of thermoelastic.



Material Research – Amorphous Material – TLS



$$\tau = \tau_0(\Delta) \cdot e^{V/k_BT}$$

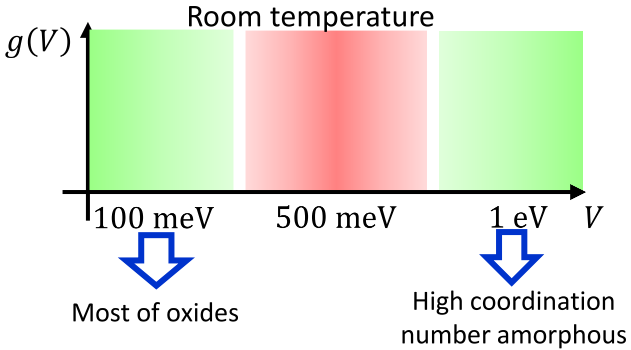
V

K. S. Gilroy and W. A. Phillips, Philos. Mag. B, vol. 38, p. 735, 1981).

- The anelastic behaviour of amorphous materials is explained by the presence of a number of **metastable states**. Any two of these states that are **separated by an energy barrier** is called a Two-Level System (TLS).
- The lifetime t and the loss angle φ, at acoustic frequency w, resulting from a density N of such double wells of barrier height V and asymmetry D is given by:

$$\phi = N\frac{\gamma^2}{Yk_BT}\frac{\omega\tau}{1+\omega^2\tau^2}sech^2\left(\frac{\Delta}{k_BT}\right)$$

- The **number density of TLS** can vary a lot from material to material or even within the same material depending on the production technique or treatments used.

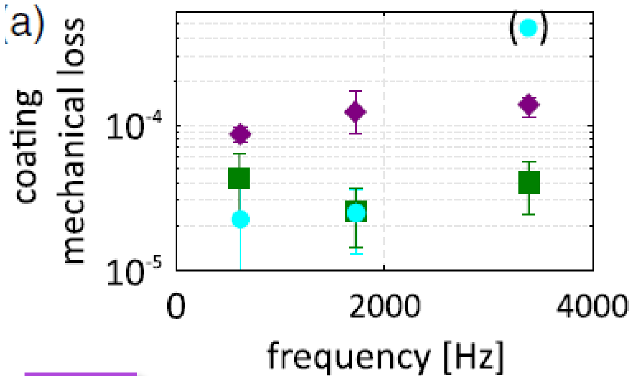


The ones that are **active** are only those that have a **relaxation time comparable to the period of the strain wave propagating in the material**.

In the case of GW detection, the frequency band of interest gives a period ~10^{-3} s. Considering that the temperature dependence of the relaxation time follows an Arrhenius' law and that the fundamental time constant is t_0 ~10^{-13} s then the TLS that contribute to the mechanical losses at room temperature are those that have a barrier height of **0.5 eV**.

Material research – High Coordination Number materials

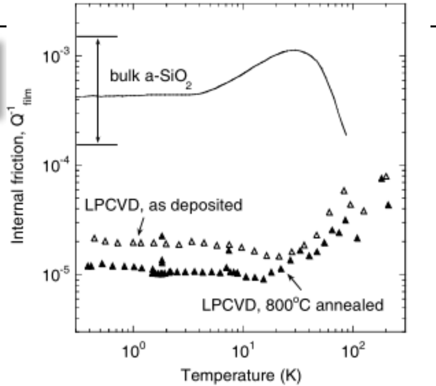
In order to reduce the loss angle of amorphous materials a **reduction of the total number density of TLS** can be pursued

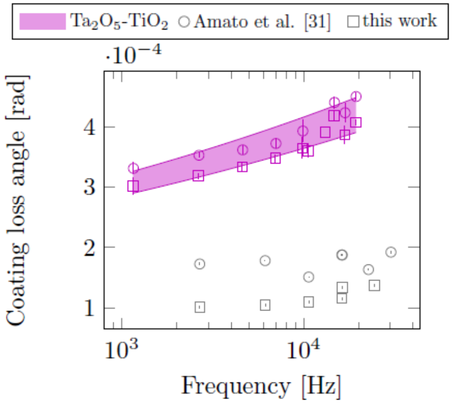


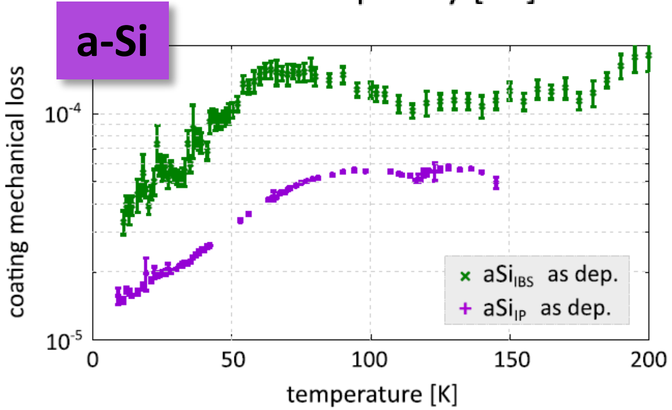
Depositing amorphous films whose **coordination number** of their constitutive atoms are superior to 3, the **structure** is more **rigid** and **TLS are unlikely**.
The structural units of these **high number coordination materials** are often linked via their edges or their faces making structural reorganization more difficult.

Frozen structure materials = Low TLS density
- **Nitrides** (**SiN**, GaN)
- **Carbides** (SiC)
- **Amorphous semiconductor** (**aSi**, GaAs, GaP, InP, CdTe, AlSb,…)

SiN





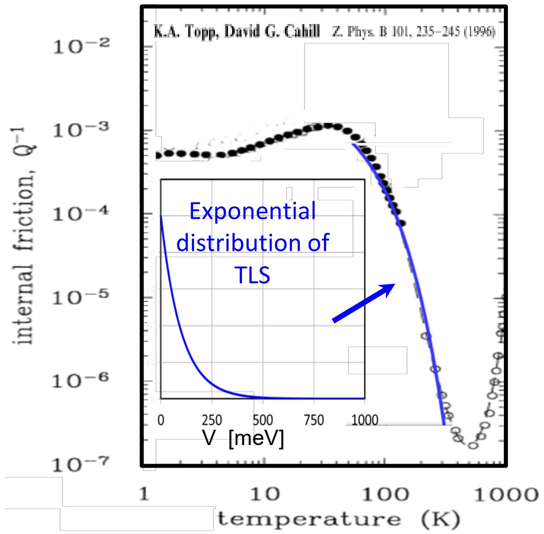


Material research – deposition and post deposition

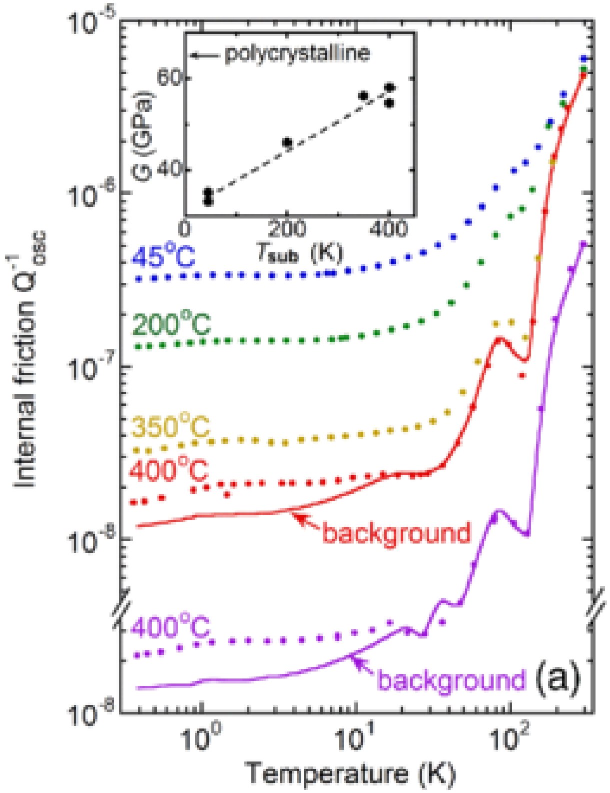
In order to reduce the loss angle of amorphous materials another basic ideas is to provide **a wise/optimal TLS distribution**

Floppy structure materials = Wise TLS distribution
- **Post Deposition Annealing (SiO2)**
- **High Temperature Deposition (a-Si)**

F. Travasso et al. Europhys. Lett., vol. 80, 2007.



The **annealing** is believed to **change the distribution of the TLS**, reducing those with higher barrier and **increasing the small** ones. Deposited SiO2 shows a *significant reduction of losses* from an increase of annealing temperature and duration.



It is believed that the **increased mobility** obtained through the **high temperature** makes the amorphous materials **exploring the configurational space at an extremely fast rate** so that statistically it reaches a **minimum energy state** that has a low density of TLS.

X.Liu PRL 113, 025503 (2014)

Origin of Absorption

- **Level of absorption and its origin**

Material Choice

- ○ **Energy bandgap** need to be **high enough to be transparent** at the used wavelength
- ○ **Refractive index** need to be **high enough to guarantee a high optical contrast** and small thickness of layers

Optical Absorption origin

- ○ There is not yet a well-established model
- ○ **Target** values for each material are given by the **crystalline form**
- ○ Amorphous structure produces **localized states in the band gap**
- ○ The bandgap needs to be clean of electronic states

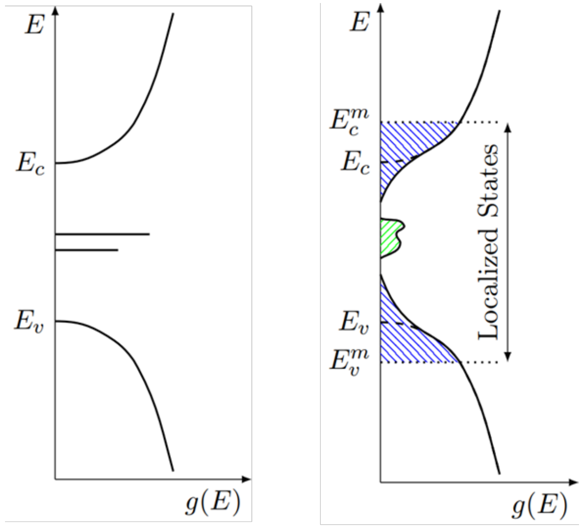
Possibles causes of absorption

- ○ Wrong **stoichiometry**
- ○ Presence of **contaminants**
- ○ Presence of **structural defects**

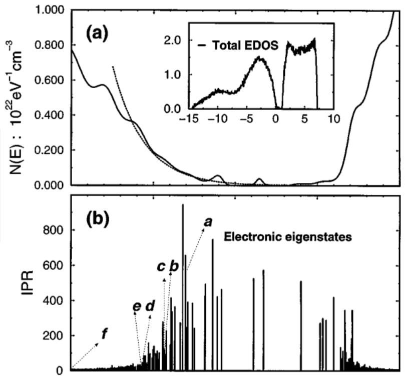
Possibles solutions

- ○ Improve the **deposition technology**
- ○ Maximize the **coordination number**
  - Through HT deposition
  - Through annealing and controlled crystallization

Hanna's talk

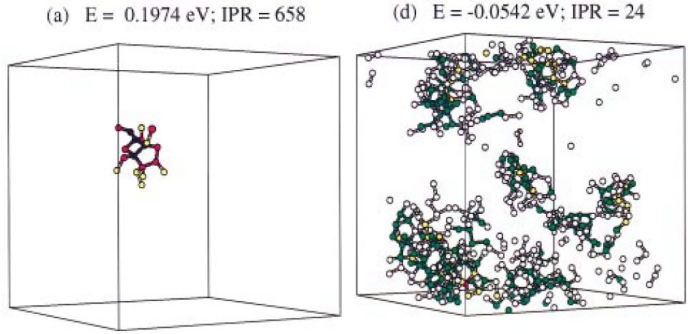


Crystals **Amorphous**



Atomistic Structure of Band-Tail States in Amorphous Silicon

Jianjun Dong and D. A. Drabold



Multi-technique investigation

- The absorption in thin films is determined by an **interplay of several factors** (stoichiometry; contaminants; films homogeneity; …)
- The **investigation** of the origin of absorption **involves (at least) three domains**

Optical properties

Quantity	Technique
n	Spectrophotom. Ellipsometry
k	Spectrophotom. Phototherm. defl. Ellipsometry
gradient	Spectrophotom. Ellipsometry

Chemical/compositional properties

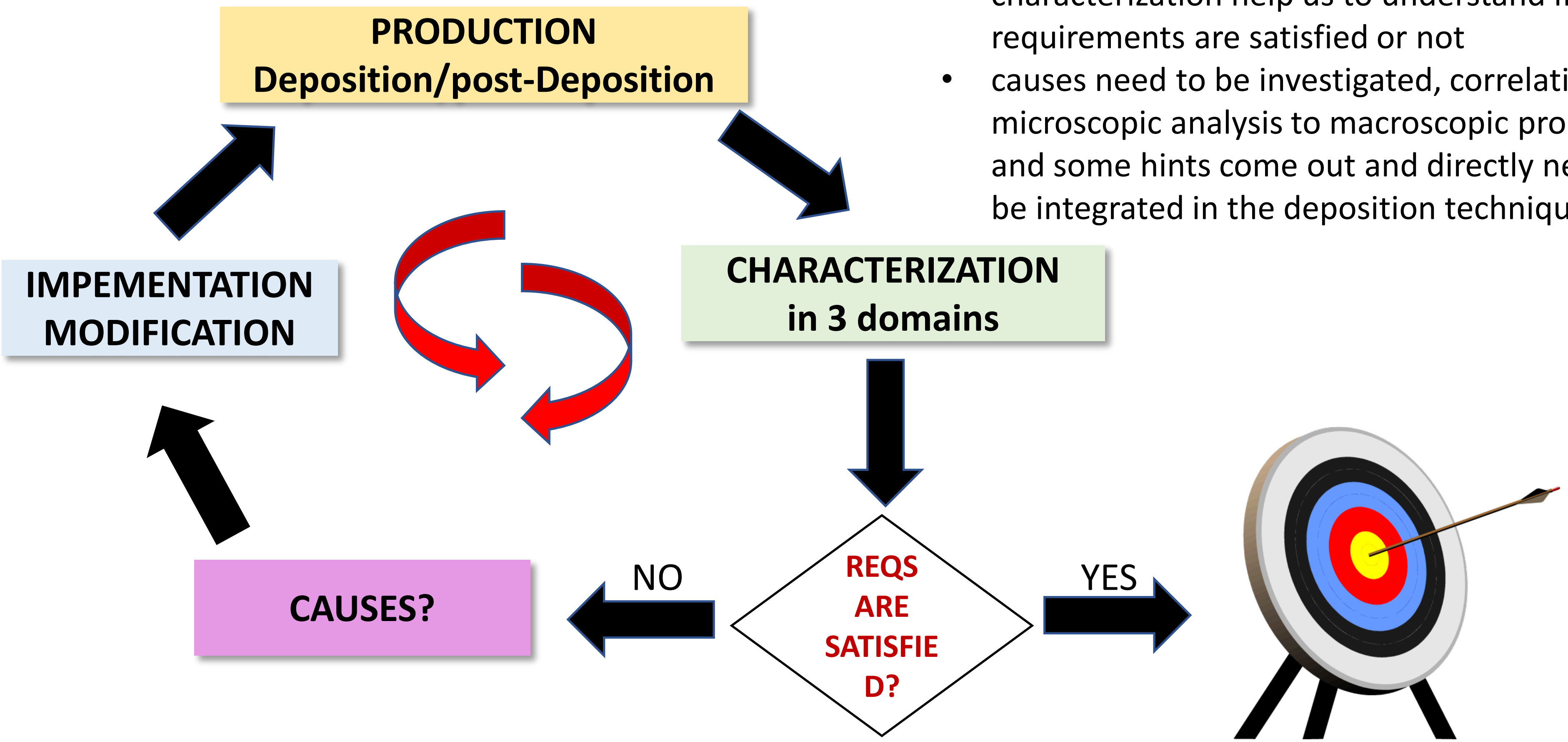
Quantity	Technique
Stoichiometry, H content, O content, Contaminants	EDX XPS '' Raman FTIR RBS SIMS ERDA RBS

Morphological/structural properties

Quantity	Technique
Thickness	Spectroph. Ellipsom.
Surface analysis	SEM AFM

Long list but not completed of set up with different characterization method that are commonly used.

Optimization Loop



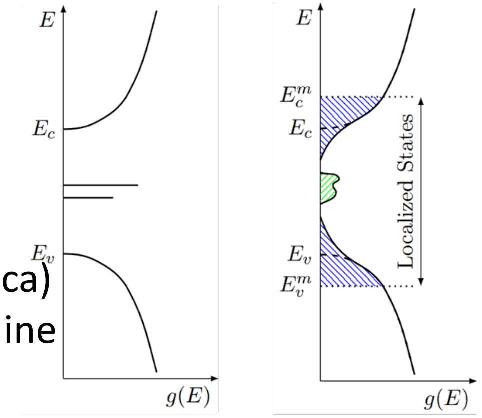
Loop for the optimization of deposition process:

- production
- characterization help us to understand if the requirements are satisfied or not
- causes need to be investigated, correlating microscopic analysis to macroscopic properties and some hints come out and directly need to be integrated in the deposition technique

Possible coating materials under investigation

- **Oxides**
- **HCNG** – Nitrides (SiN, GaN), Semiconductors (a-Si) –: high coordination number makes atom structure more rigid decreasing TLS density low loss dissipation
- **Multi-material Coating or ternary coatings**: multi-material coatings, in which the **top layers**, where the optical intensity is highest, consist of materials with **low optical absorption** but too large mechanical loss, while the **lower layers** consist of materials with **low mechanical loss** but too large optical absorption
  - ***Coating structure and design***
- **Crystalline Coating** – Semiconductor or Oxides –: **epitaxially grown** coatings consisting of alternating layers of **high and low index layers of crystalline materials** present an alternative method that avoids the mechanical loss issues associated with TLS in amorphous materials.

Crystalline coatings basics



Crystals

Amorphous

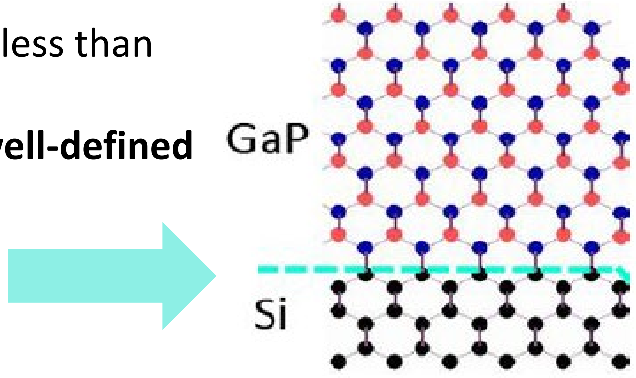
Many crystalline materials show very favorable properties:

- **Smaller or more narrow loss peak** at low temperature (i.e., crystalline quartz vs. amorphous silica)
- **Lower IR optical absorption**, maybe due to lack of electronic states in the band gap (i.e., crystalline silicon vs. amorphous silicon @2 um)

Single-crystalline multilayers:

Hanna's talk

- Deposited by **MBE** (Molecular Beam Epitaxy)
  - takes place in ultra-high vacuum (10^{-8}–10^{-12} Torr); deposition rate is typically less than 3,000 nm per hour, that allows the films to grow epitaxially
  - crystal growth in which new crystalline layers are formed with one or more **well-defined orientations** with respect to the **crystalline seed layer**
- requires **two lattice matched materials and lattice matched substrate**
  - Limited options for **high/low refractive index combinations**
  - Limited options for **substrate materials** to grow on



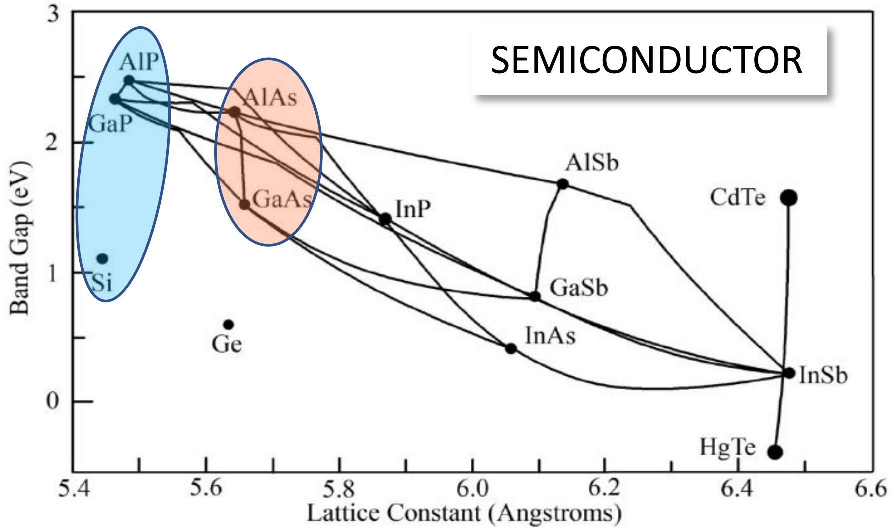
Size restricted due to maximum substrate size

Substrate transfer (bonding) possible, if not directly grown on test mass

additional advantage: 'upside-down' bonding can bring 'good' layers to top (where intensity is high)

AlGaAs/GaAs

LSC groups looking into:
- ○ AlGaAs/GaAs on GaAs
- ○ GaP/AlGaP on Si



Advantages:
- ➢ Same/similar lattice constant
- ➢ Different band gap
- ➢ Dopants help matching the lattice constant, but reduce the bandgap/refractive index contrast

GaAs/AlGaAs coating grown on **GaAs wafers** bonded to fused silica or silicon

✓ Refractive index: ≈ 3.5 for GaAs and ≈ 3.0 for AlGaAs @1064nm

Requires more, but thinner layers than SiO_2/Ta_2O_5

✓ Promising results for thermal noise

- ○ ~10 x below SiO_2/Ta_2O_5 in PSD
- ○ even better at 10K

✓ Low optical absorption

- ○ ~1ppm at 1064nm
- ○ Few ppm at 1550nm

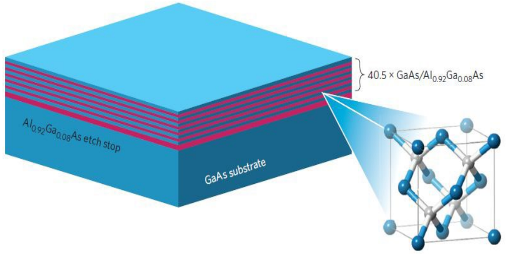
AlGaAs/GaAs

AlGaAs/GaAs on GaAs wafer at LSC

- **Well established** technology only for **small sizes**
- Size restrictions: GaAs wafers only available in sizes up to 200 mm
- At cryo T a **good bond quality is required** due to thermal expansion during cooling cycles (in the past, coating dissolved from substrate after several cooling cycles)

ONGOING ACTIVITIES

- **Birefringence** measurements
- Investigations of Pockels effect in AlGaAs (electro-optic noise, e.g., light-field induced birefringence)

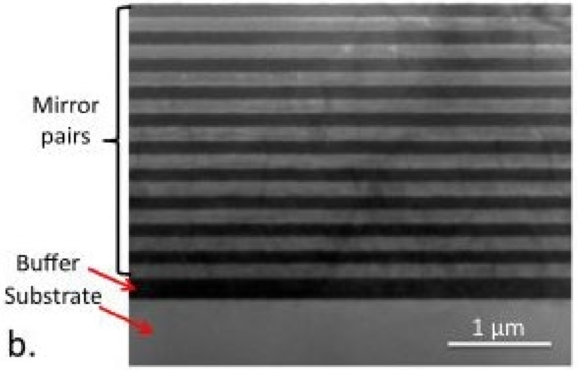


limitation for AlGaAs/GaAs **coating size**

- ○ Enough thermal-noise benefit to use slightly smaller coatings
- ○ Upscaling to ≈30cm mainly a cost question (Uniformity at 300 mm?)

GaAs size, large-scale bonding, bonding on silicon for cryogenics operation are the main issues

AlGaP/GaP

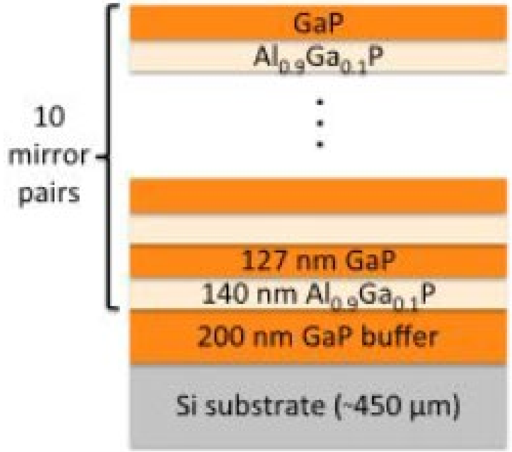


- ✓ AlGaP/GaP coatings **grown on Si wafers** - in principle possible **without bonding/substrate transfer**
  - ○ Considered for **cryogenics**
  - ○ MBE process slow due to ***health and safety issues*** etc.

- ✓ Refractive index: ≈ 3.05 for GaP and ≈ 2.77 for AlGaP at 1550nm

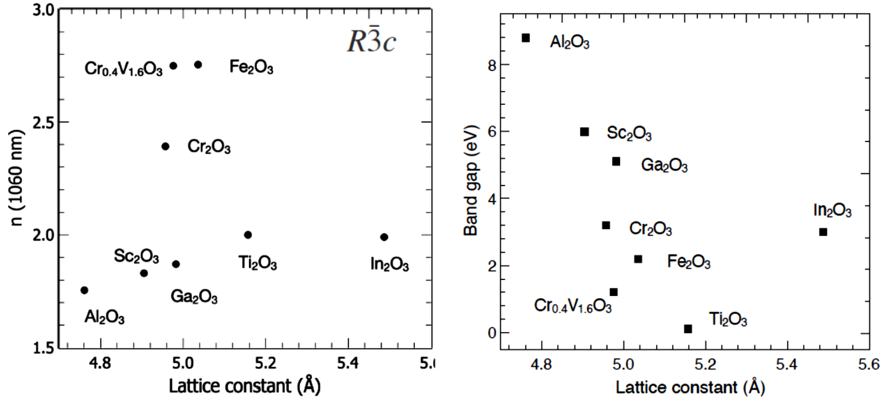
- ✓ **Promising results for mechanical loss** at low temperature
  - ○ **< 3 × 10–5** for a **GaP single layer** with 'bridge' layer to match silicon lattice at 20K,
  - ○ **1.4 × 10–5** for an AlGaP/GaP multilayer at 12 K (comparable to SiO2/Ta2O5 at room temperature)

- ✓ Optical **absorption** initially **rather high** (likely due to impurities)
  - ○ **≈ 2.3% at 1550nm**

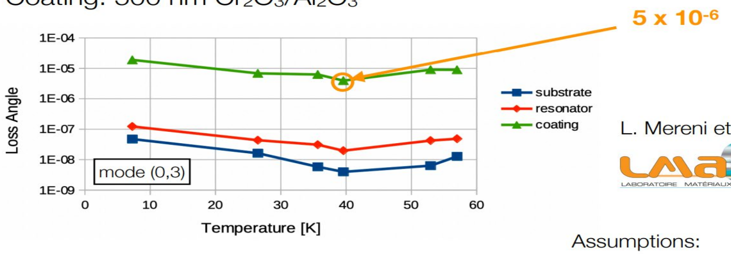


Crystalline Oxides

- Bandgap and refractive index



- Coating: 500 nm Cr_2O_3/Al_2O_3



L. Mereni et al.

- Dilution factor= 0.0034
  = 3 ($d_{coating}/d_{substrate}$)($Y_{coating}/Y_{substrate}$)

Assumptions:
$d_{coating}$ = 500 nm
$d_{substrate}$ = 0.3 mm
$Y_{coating}$ = 260 GPa
$Y_{substrate}$ = 385 GPa

➢ Can be **grow on sapphire,** that has no limitation in dimension of wafer and that has potentially high optical contrast to guarantee thinner multi-layer stack

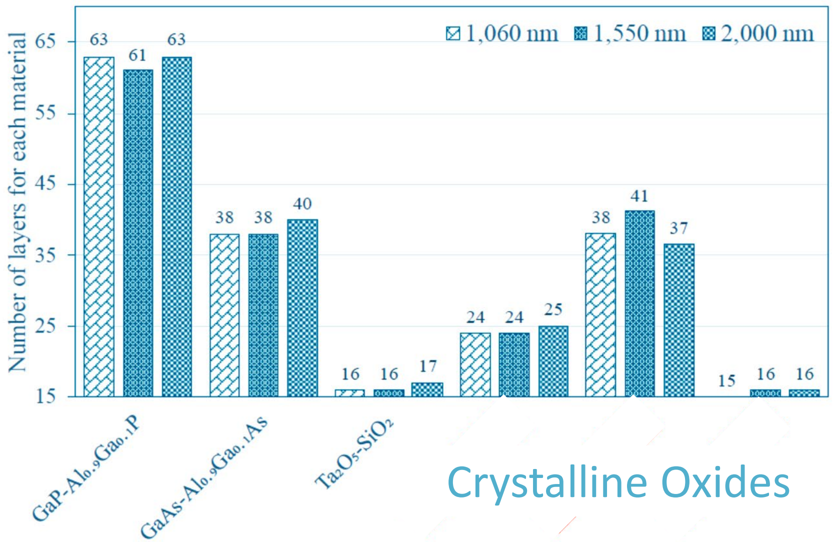
KU LEUVEN

Bilayer pairs

$$R_{2N} = \left[\frac{\left(n_s\left(\frac{n_H}{n_L}\right)^{2N} - n_0\right)}{\left(n_s\left(\frac{n_H}{n_L}\right)^{2N} + n_0\right)}\right]^2$$

- For R = 99,999% on Si

Gaurav Vats



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Thank you for your time and attention!

Development of materials for ultra-low loss optical coatings

GOAL:

increase the mechanical performances of today's reflective coatings, retaining their outstanding optical and morphological properties

Candidate materials

Trial and error approach VS systematic approach

- ➢ deeper understanding of the **underlying physical mechanisms driving the losses**

Amorphous materials

Overall disordered structure, locally arranged.

Dissipative mechanism

- *Two Level System (TLS)*: *metastable states* separated by an energy barrier

- ➢ Floppy (optimal distribution of TLS) materials
  - TiO2:GeO2, TiO2:SiO2
- ➢ Stiff (reduced number of TLS) materials
  - SiN, aSi

Crystalline coatings

Band gab free of localized states, dissipative mechanisms are limited

- ❖ transfer and maximum available size; development costs are currently a major limitation

- GaAs/AlGaAs, crystalline coatings

Development of materials for ultra-low loss optical coatings

GOAL:

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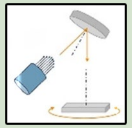


Different deposition methods and fine-tuning deposition parameters

- Ion Beam Sputtering (IBS)
- Magnetron Sputtering (MS)
- Chemical Vapor Deposition (CVD)
- Molecular-beam epitaxy (MBE)

Post-deposition treatments

Annealing

- improve the **atomic organization** of the coating in the medium-range order and reduce its mechanical loss angle
- modify the **chemical composition** (desorption of contaminants)
- **controlled crystallization**

Mixing

- **Enhances material properties** (like refractive index and mechanical losses)
- **Prevents crystallization**, allowing for higher annealing temperatures.
- **Reduces stress**

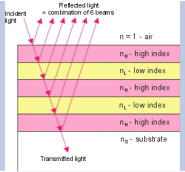
❖ Introduces an **additional variable** that must be precisely managed during fabrication

Development of materials for ultra-low loss optical coatings

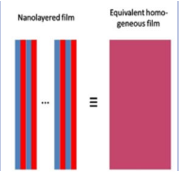
GOAL:

increase the mechanical performances of today's reflective coatings, retaining their outstanding optical and morphological properties

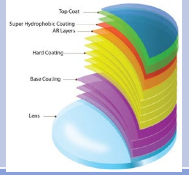
Coating structure and design



Bragg reflectors: thickness optimization, to maintain the desired reflectivity and reduce coating thermal noise (CTN)



Nano-layering: periodic stack of ultrathin (nanometer-scale) films that behaves like a homogeneous material with a tunable refractive index. It can be annealed at higher temperatures, thanks to geometrical suppression of crystallization



Multimaterial approach: Combination of different materials with low optical absorption near the surface and minimized mechanical losses deeper within

Development of materials for ultra-low loss optical coatings

GOAL:

increase the mechanical performances of today's reflective coatings, retaining their outstanding optical and morphological properties

Candidate materials → ***Coating deposition techniques and treatments*** → ***Coating structure and design***

Investigation techniques:

- *Optical properties*: measurement of optical absorption and/or extinction coefficient and refractive index (spectroscopic ellipsometry)
- *Mechanical dissipation properties*: measurement of loss angle and substrate preparation procedure (thermal annealing and polishing of barrel), density and elastic constants (Brillouin spectroscopy); numerical simulations (molecular dynamics, FEA)
- *Microscopic structure*: chemical composition and stoichiometry (XPS), crystallization (XRD, Raman spectroscopy); local molecular structures (Raman sp.); topology and surface composition (AFM and SEM)
- *Thermal and opto-thermal properties*: optical path as a function of temperature (thermo-refractive measurement); measurement of the coefficient of linear thermal expansion (Curvature measurement)

➢ ***Comprehensive picture of the relevant physics of a given material***