EINSTEIN TELESCOPE

The interplay between optical properties and structure of coatings for GWD

Spectroscopic Ellipsometry of coatings

ADCOAT: first results

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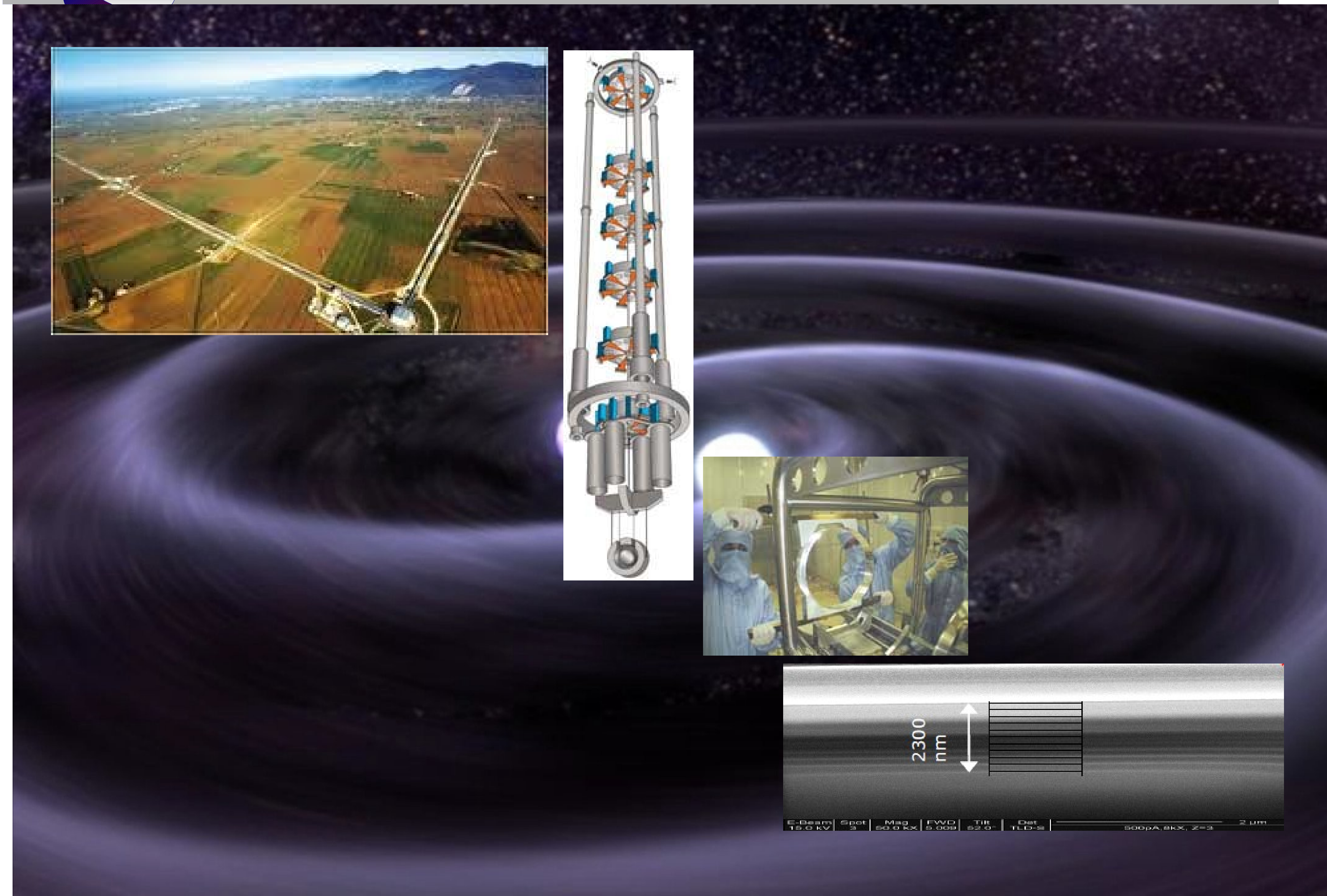
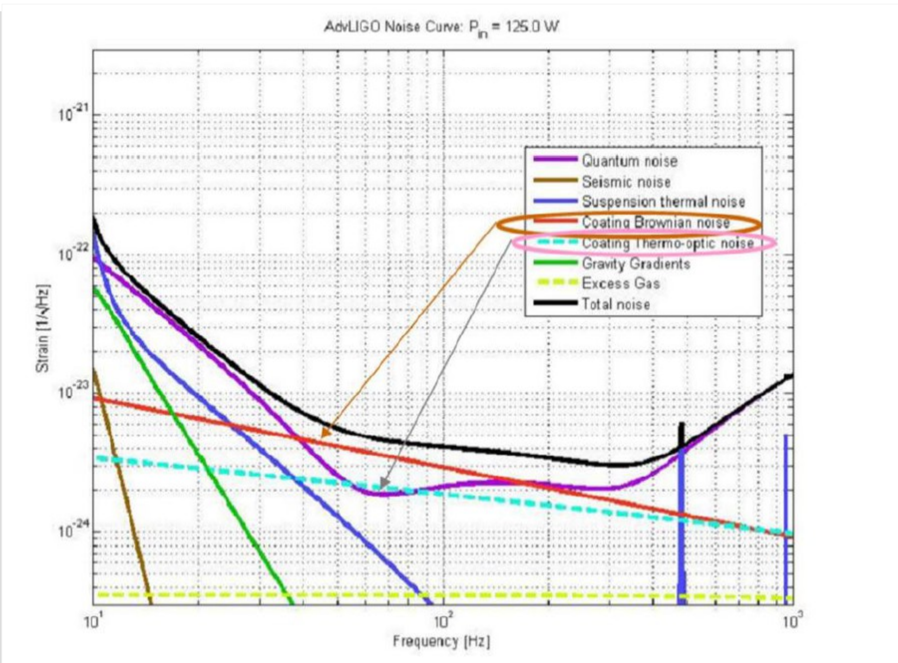
A long travel … from cosmology … to nanophysics



The coating affair: issues



- **Very ultra low optical absorptions**
  ~ ppm
- **Ultra High Uniformity**
  "bulk"& surface
- **Very ultra low mechanical Losses**
  main source of thermal noise
  @ 100-300 Hz

$\lambda/4$ Ta_2O_5/SiO_2 multilayers

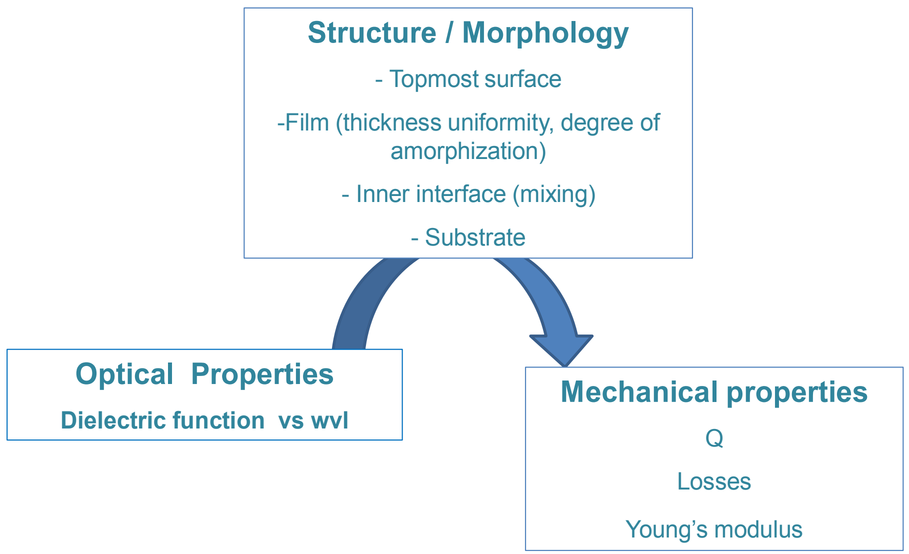
Ta_2O_5:Ti still the best option for the high index material in $\lambda/4$ multilayers

Mechanical Losses: Main trends (@LMA)

- no significant dependence on thickness of Ta_2O_5:Ti sub-unit
- significant increase with the number of interfaces in multilayers
- Losses on multilayers larger than the sum of monolayer losses
- Losses for ALD films comparable to IBS films

"nano-bugs" at interfaces & film

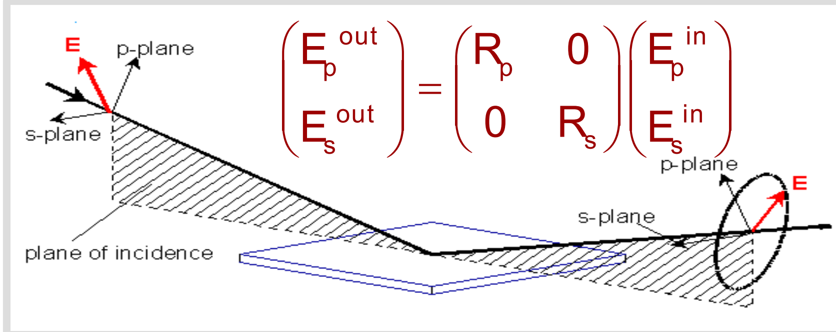
Spectroscopic Ellipsometry of GWD coatings



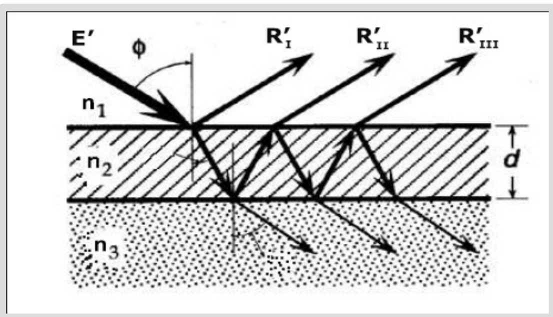
Ta_2O_5/SiO_2

1 unit

Spectroscopic Ellipsometry
(isotropic systems: Fresnel theory)



$$\begin{pmatrix} E_p^{out} \\ E_s^{out} \end{pmatrix} = \begin{pmatrix} R_p & 0 \\ 0 & R_s \end{pmatrix} \begin{pmatrix} E_p^{in} \\ E_s^{in} \end{pmatrix}$$



$$\rho = t\,g\Psi e^{i\Delta} = \frac{R_p}{R_s} = \frac{r_{0,1}^p + r_{1,2}^p e^{-2i\beta}}{1 + r_{0,1}^p r_{1,2}^p e^{-2i\beta}} \cdot \frac{1 + r_{0,1}^s r_{1,2}^s e^{-2i\beta}}{r_{0,1}^s + r_{1,2}^s e^{-2i\beta}}$$

$$\beta = 2\pi \frac{d}{\lambda} \sqrt{\tilde{N}_1^2 - \tilde{N}_0^2 \sin^2 \Phi}$$

$$\rho = \rho(\tilde{N}_0, \tilde{N}_1, \tilde{N}_2, d, \lambda, \phi)$$

Comparison data/simulations: needs a model of the optical system

If ambient and substrate properties are known with precision

One needs

(n,k) and d of the film

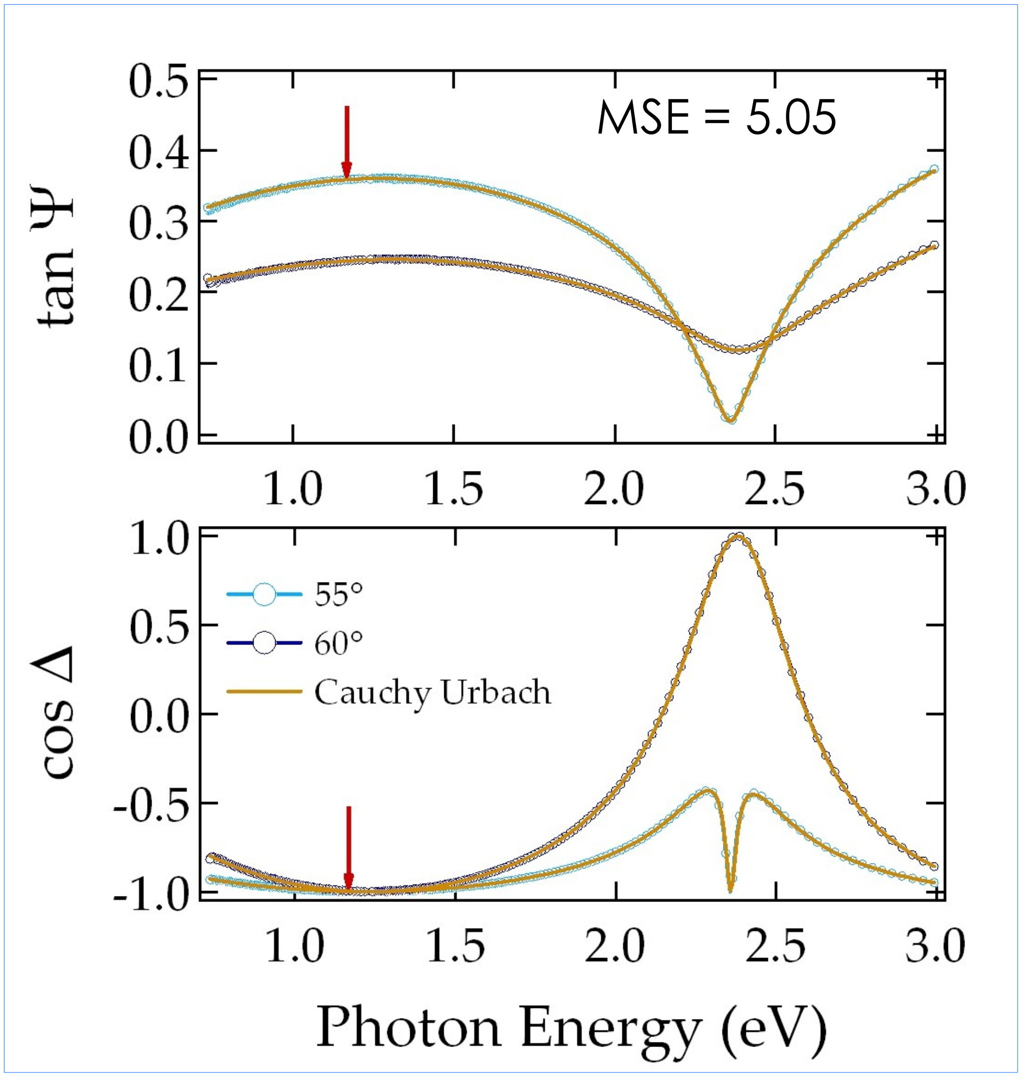
$$MSE = \frac{1}{2N-M} \sum_{i=1}^{N} \left[\left(\frac{\Psi_i^{mod} - \Psi_i^{exp}}{\sigma_{\Psi,i}^{exp}} \right)^2 + \left(\frac{\Delta_i^{mod} - \Delta_i^{exp}}{\sigma_{\Delta,i}^{exp}} \right)^2 \right] = \frac{1}{2N-M} \chi^2$$

Ta_2O_5 (LMA)

nominal thickness: 131 nm

Transparency region: thickness and n

No surface, no interface…



Ta_2O_5
Suprasil 311

Cauchy – Urbach model

$$n = A + \frac{B}{\lambda^2} + \frac{C}{\lambda^4}$$

$$k = D \cdot e^{F(h\nu - G)}$$

thickness ~ **134 nm**

n@1064nm = **2.057**

k@1064nm < 10^{-3}

R. Flaminio et al.
Class.Quantum Grav. **27** (2010) 084030

n@1064nm ~ 2.06

Monolayer absorption ~ 1.2 ppm (i.e. k ≈ 2 10^{-7})

Extending the wavelength range over the gap
0.75-5 eV (245-1700 nm)

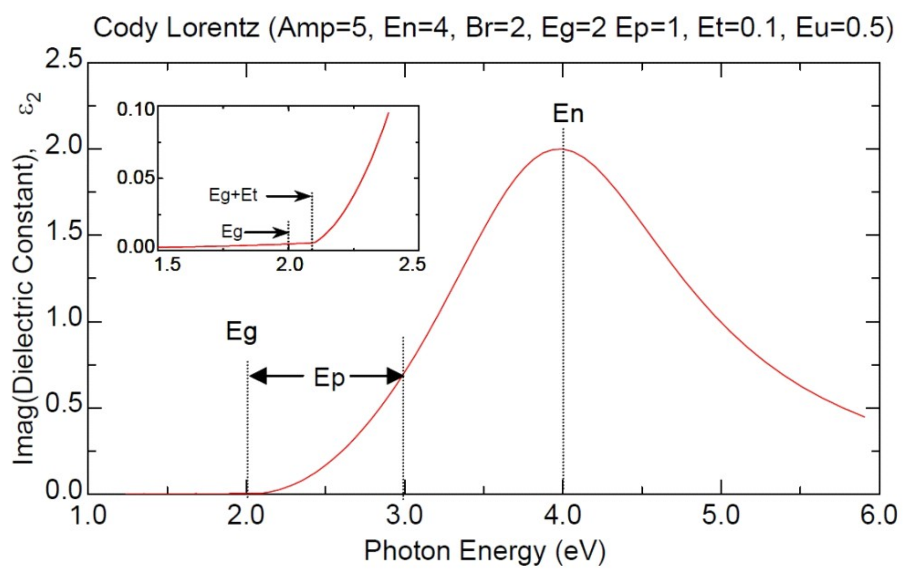
Including defects

Amorphous oxides: Cody-Lorentz model + Urbach tail

[A. S. Ferlauto et al., Journal of Applied Physics 92 (2002)]

$$\varepsilon_2(E) = \begin{cases} \left(\frac{E_1}{E}\right) e^{\left[\frac{(E-E_g-E_t)}{E_u}\right]} & 0 < E \le (E_g + E_t) \\ \frac{(E-E_g)^2}{(E-E_g)^2 + E_p^2} \frac{A E_0 \Gamma E}{[(E^2 - E_0^2)^2 + \Gamma^2 E^2]} & E > (E_g + E_t) \end{cases}$$

$$\varepsilon_1(E) = \varepsilon_1(\infty) + \frac{2}{\pi} P \int_{E_g}^{\infty} \frac{\xi \varepsilon_2(\xi)}{\xi^2 - E^2} d\xi$$

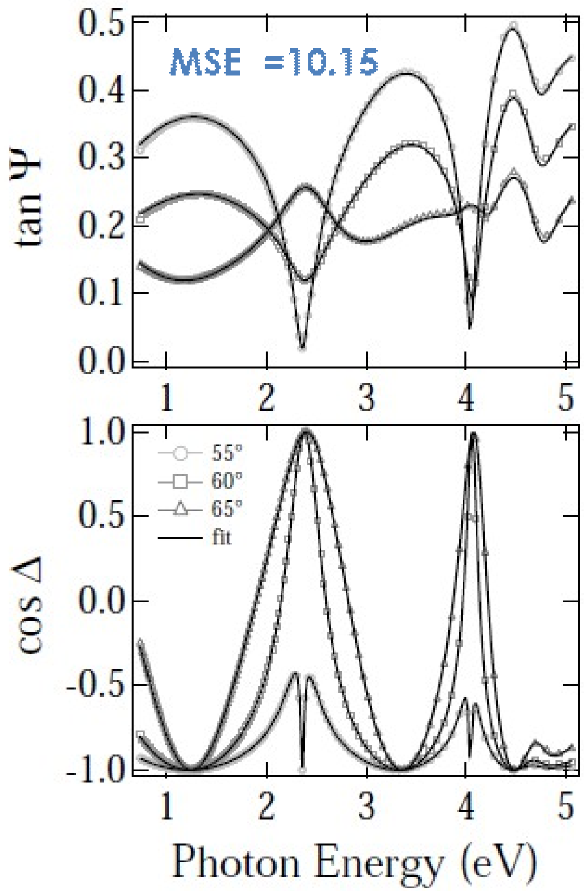


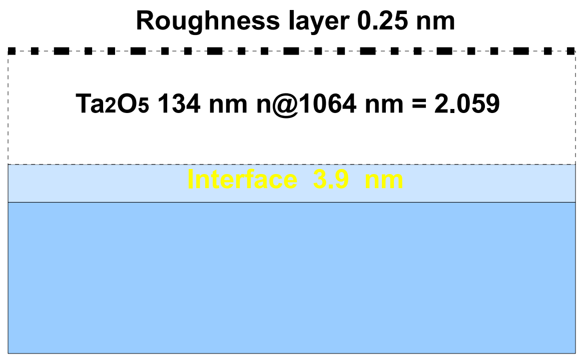
Ta2O5/SiO2 (LMA)

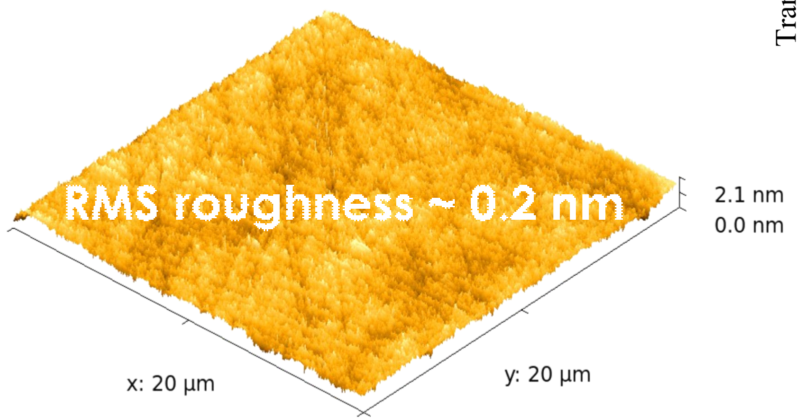
Prato et al., Thin Solid Films 519 (2011) 2877

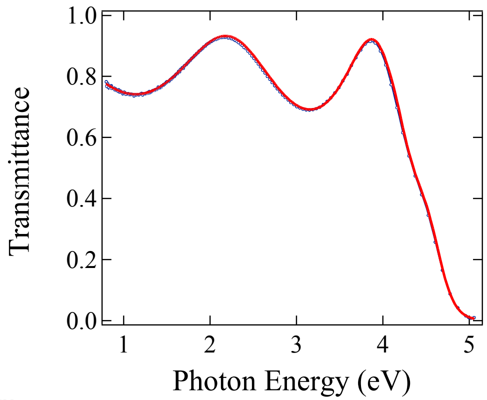
Including non-uniformity

The "simplest model" : Roughness layer + transition layer







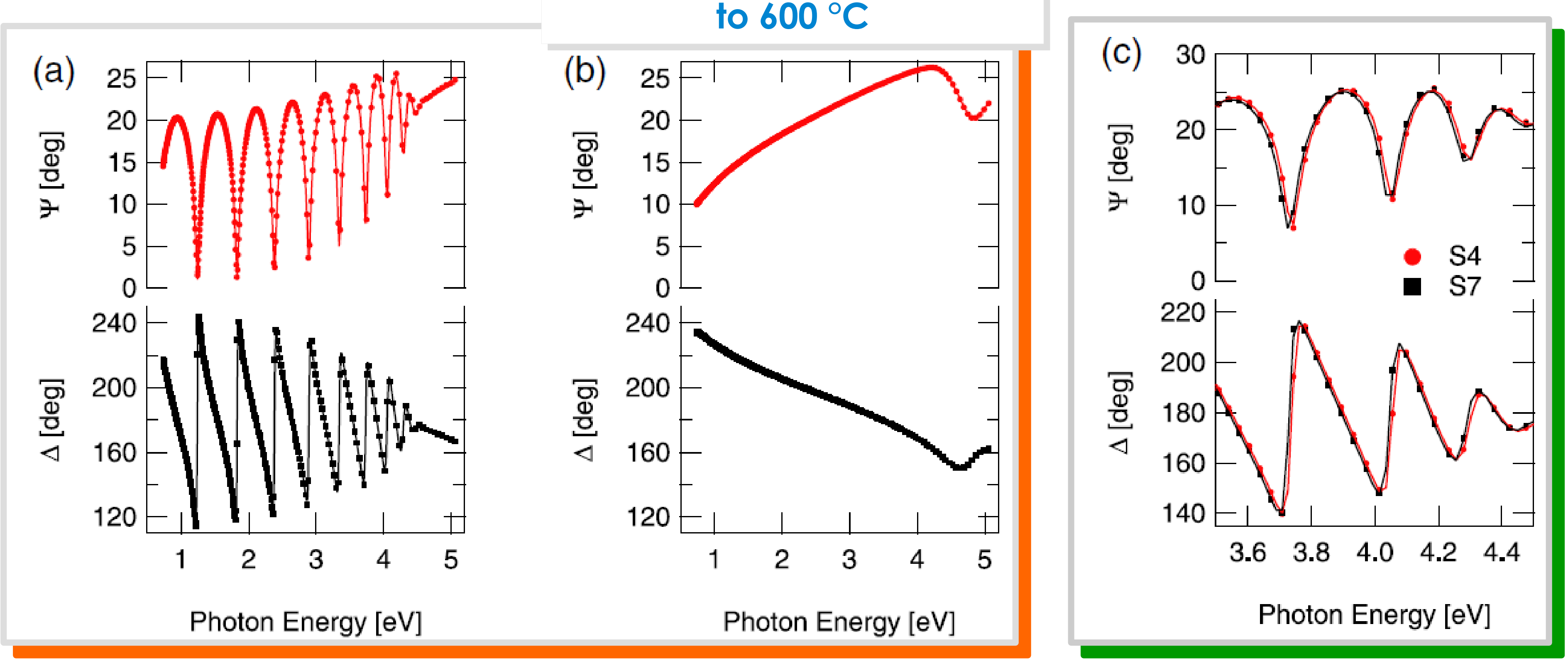


...Non-ideal interface....

Spectroscopic Ellipsometry + PCI@1064nm (Ta_2O_5/SiO_2- CSIRO)

Anghinolfi et al., JPhysD 46 (2013) 455301

Two sets of samples annealing temperature up to 600 °C



	Id	T_{ann} (°C)	CL (E_g)	TL (E_g)	TP (CL,TL,Psemi)	Thickness (nm)	Abs.@1064 nm(ppm)
40 nm	S1	n/a	4.15	4.13	4.20 ± 0.1	38.2	0.9
	S2	450	4.18	4.17	4.24 ± 0.1	38.9	3.2
	S3	550	4.16	4.16	4.24 ± 0.1	39.1	2.9
500 nm	S4	300	4.13	4.13	4.19 ± 0.1	514.6	1.1
	S5	400	4.13	4.13	4.19 ± 0.1	515.6	1.4
	S6	500	4.13	4.13	4.19 ± 0.1	517.6	2.1
	S7	600	4.15	4.13	4.19 ± 0.1	519.9	1.9

Ta2O5/Void Graded EMA (Maxwell-Garnett)


Thin Solid Films 517 (2009) 6058–6068

Contents lists available at ScienceDirect

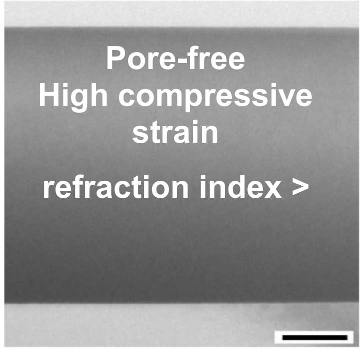
Thin Solid Films

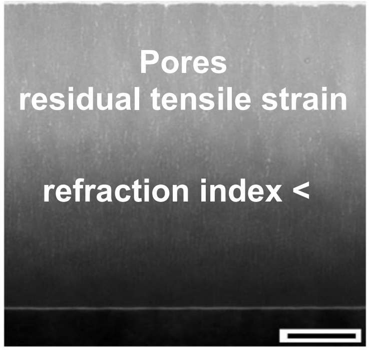
journal homepage: www.elsevier.com/locate/tsf

The correlation between mechanical stress, thermal shift and refractive index in HfO_2, Nb_2O_5, Ta_2O_5 and SiO_2 layers and its relation to the layer porosity

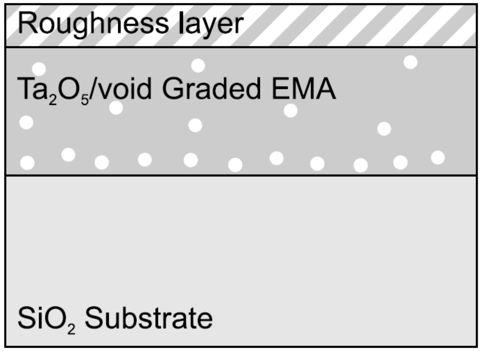
O. Stenzel [a,*], S. Wilbrandt [a], N. Kaiser [a], M. Vinnichenko [b], F. Munnik [b], A. Kolitsch [b], A. Chuvilin [c], U. Kaiser [c], J. Ebert [d], S. Jakobs [e], A. Kaless [e], S. Wüthrich [f], O. Treichel [g], B. Wunderlich [h], M. Bitzer [h], M. Grössl [i]

“pores are helpful to obtain a reasonable balance between optical and mechanical layer properties”





Cfr. O. Stenzel JPhysD2009



Nano-voids size<<λ (not at scale)

No intermixing

Three models for absorption edge of amorphous semiconductors

Anghinolfi et al., JPhysD 2013

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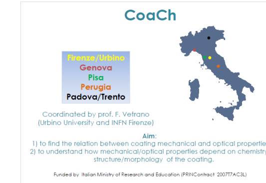
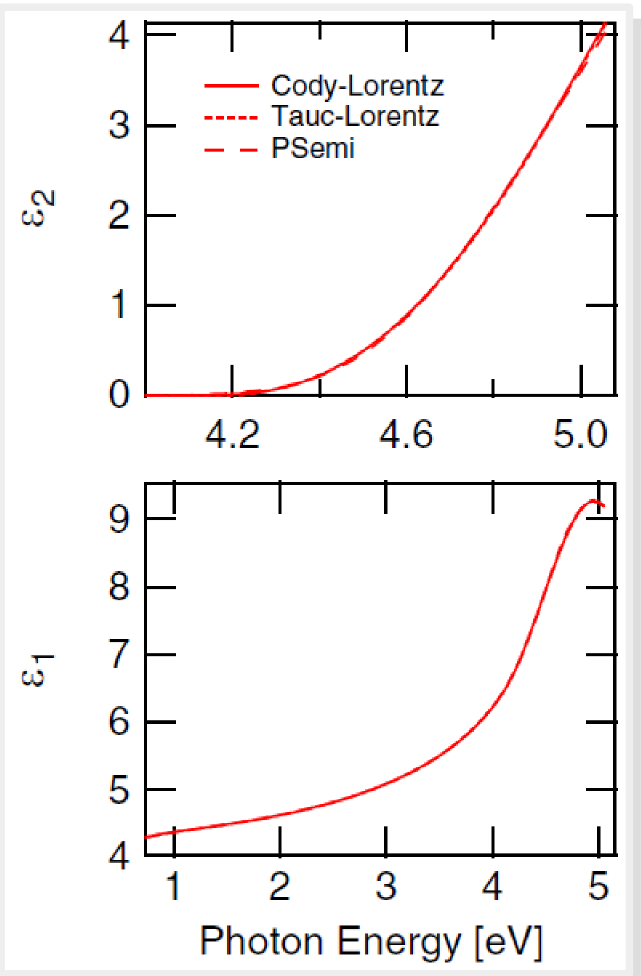
Ta2O5/SiO2- CSIRO



- Best fit independent from the model
- 6-7% of porosity
- empty, spherical nano-pores
- quasi-uniform distribution across the film.



increasing *T*ann-

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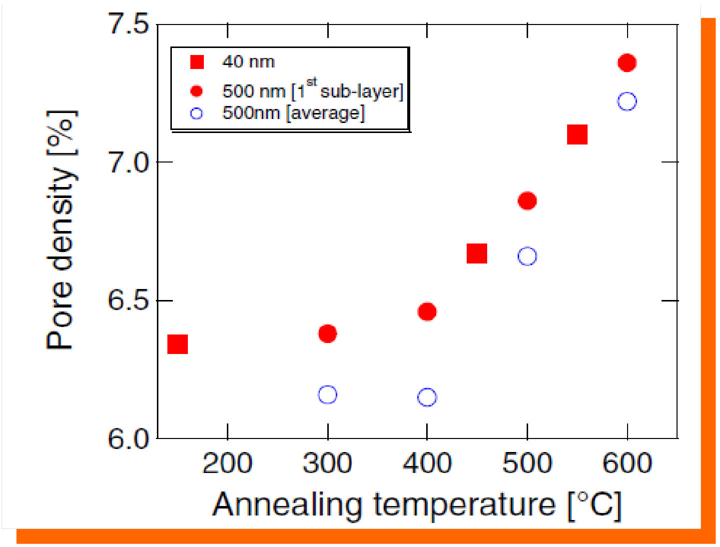
- slight increase (1-2%) of thickness

Tiny blue-shift of Eg

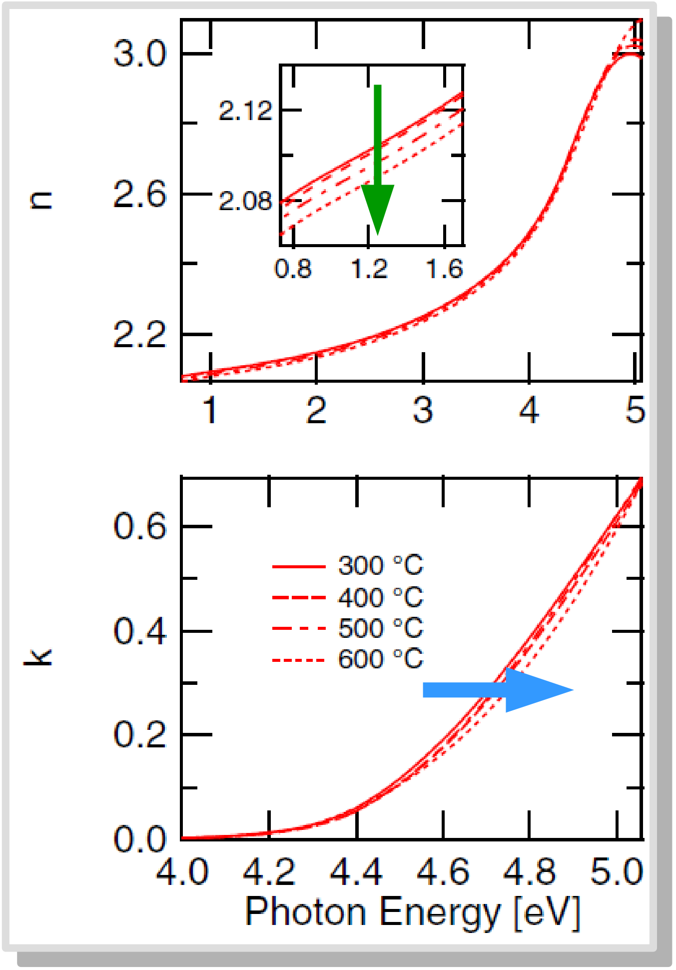
increase of NIR absorption losses (PCI at 1064 nm).

Ta2O5/SiO2- CSIRO: increasing Tann

increase of the average pore density



small reduction of n

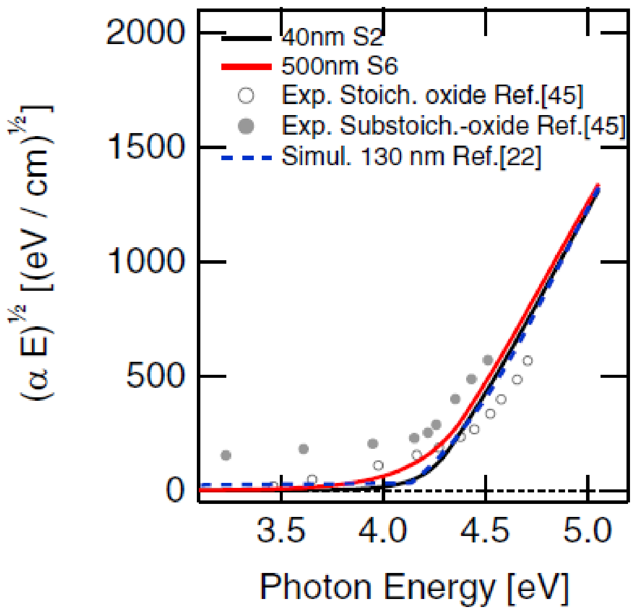


slight blue-shift of Eg (+ evident on the 40 nm thick coating)

Improved stoichiometry

Onset of (nano)-crystallization (to be checked e.g. With Raman)

Ta2O5/SiO2- CSIRO: increasing Tann



Optical properties vs. Tann testify micro-structural modifications → (nano-pores model)

pores may play a crucial role in the release of compressive strain induced by the *densification @ deposition*

pores (especially open ones) tend to reduce the effective refractive index of the coating. The relatively modest effects on n are consistent with a main population of closed pores

the increase in d_{Ta2O5} and in the average pore density with increasing *T*ann, coupled to the reduction of *n* can be associated with the expansion of nano-cavities

future

- extending the range in the UV → 190 nm
- scatterometry (in-plane)
- couple SE with high ex-situ sensititivity structural probes (Raman, XRD) and with TEM
- study SiO2/Ta2O5/SiO2 system vs annealing
- real time SE to monitor slow annealing

Moving ahead (glassy-oxide paradigm)

- **"Debugging" Ta_2O_5:Ti**
  - better control of annealing process (T, t)
  - unambiguous "decoding" of trends
  - How and why "dopants" work?

- **Searching for "the best" glassy oxide mixture**
  "failed" sofar

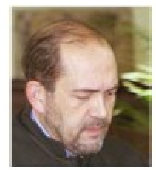
- **Optimizing the design**
  - e.g. fine tuning of thickness of bilayer units [Villar et al., PRD 81 (2010) 122001]

- **Testing new materials and multilayers**
  - e.g for low T operation (silica doped Hafnia)
  - **nanolayered composites** (Titania::Silica and Hafnia::Silica)

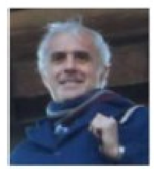
- **modelling (Effective Medium Theory)**
  - mechanical losses [Villar et al., LIGO- G1100 976]
  - optical properties [Anghinolfi et al. JphysD, 2013]

- **Testing**
  - extensive trial-and-error

ADCOAT People

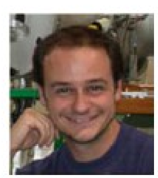


Innocenzo M. Pinto (PI, AdCOAT Coordinator) Vincenzo Galdi, Vincenzo Pierro, Maria Principe, Dario Castellano, Silvio Savoia



Maurizio Canepa (PI), Corrado Boragno, Francesco Buatier de Mongeot, Mauro Giovannini, Lorenzo Mattera, Gianluca Gemme, Martina Neri

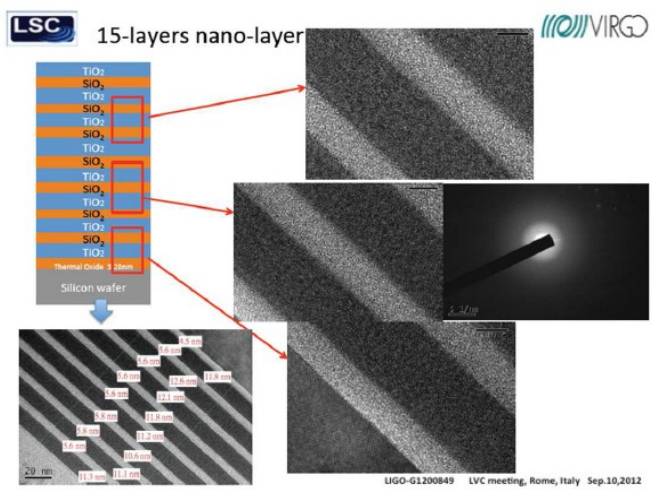
Helios Vocca (PI), Marzia Colombini , Luca Gammaitoni, Fabio Marchesoni, Maurizio Mattarelli, Igor Neri



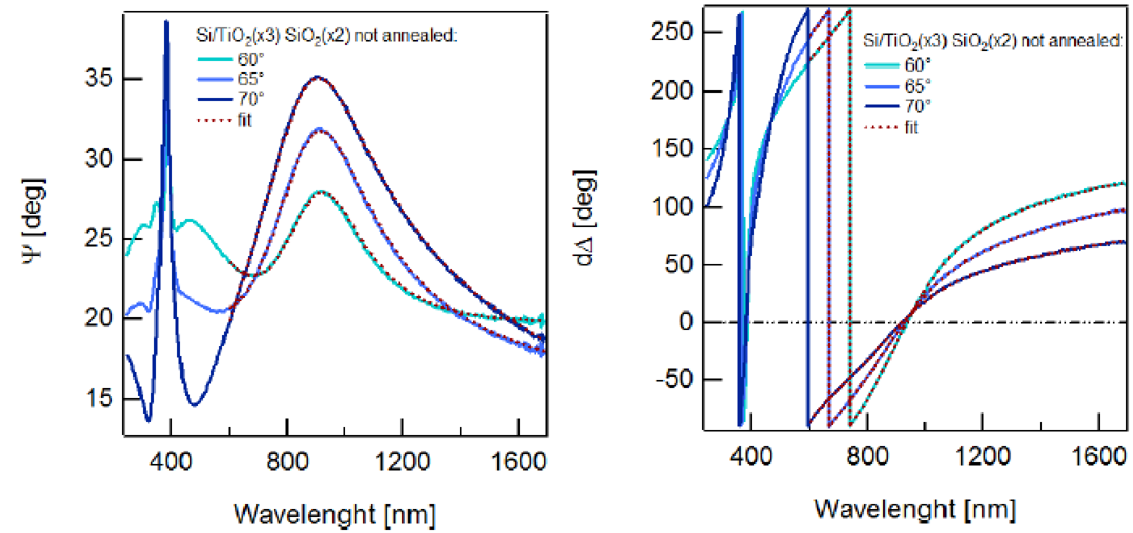
Alessio Rocchi (PI), Elisabetta Cesarini, Eugenio Coccia, Viviana Fafone, Yuri Minenkov

Courtesy I. Pinto

ADCOAT Nanolayer composites Prototypes



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



Titania-Silica (5 units) on Si
First stage of analysis
Cauchy layers + roughness layer
Transparency range
600-1700 nm

As deposited

$d_{(TiO_2)}$ = 27.30 (±0.05) vs. 27.1 nominal
$n_{@1064nm(TiO_2)}$ = 2.32
$d_{(SiO_2)}$ = 20.15 (±0.05) vs. 19.9 nominal
$n_{@1064nm(SiO_2)}$ = 1.48

Work in progress … 19 units
M. Magnozzi, M. Neri, I. Solano, S. Uttiya