Optical Coatings R&D Status

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- On Behalf of the Coating Working Group -

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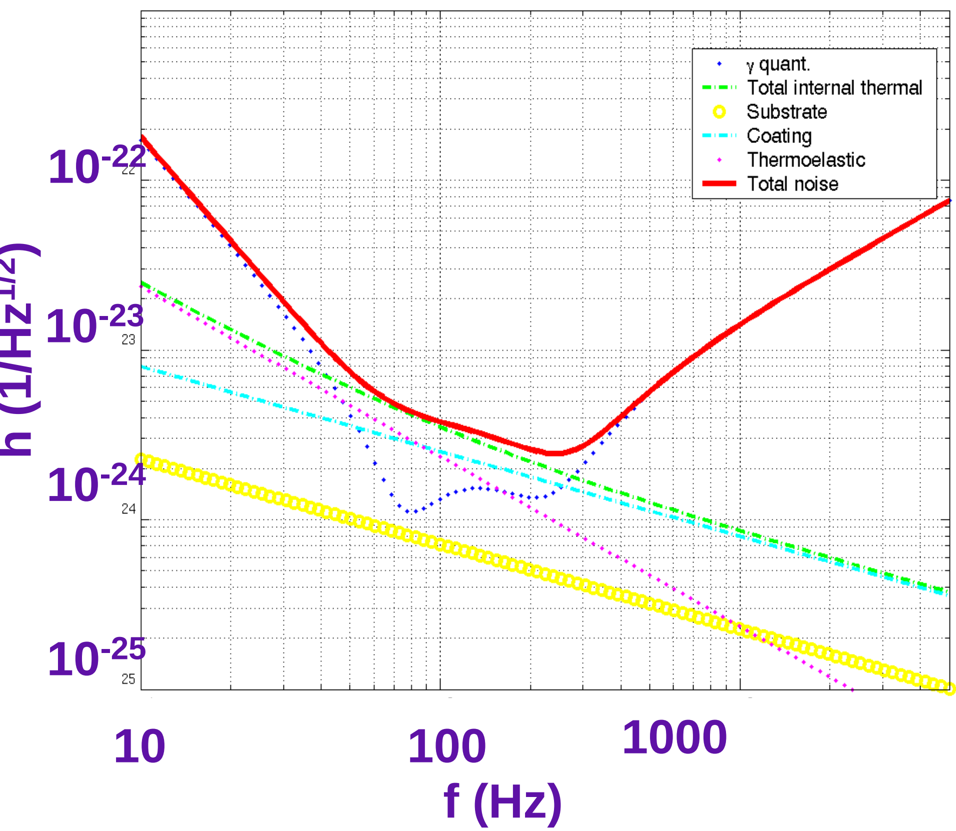
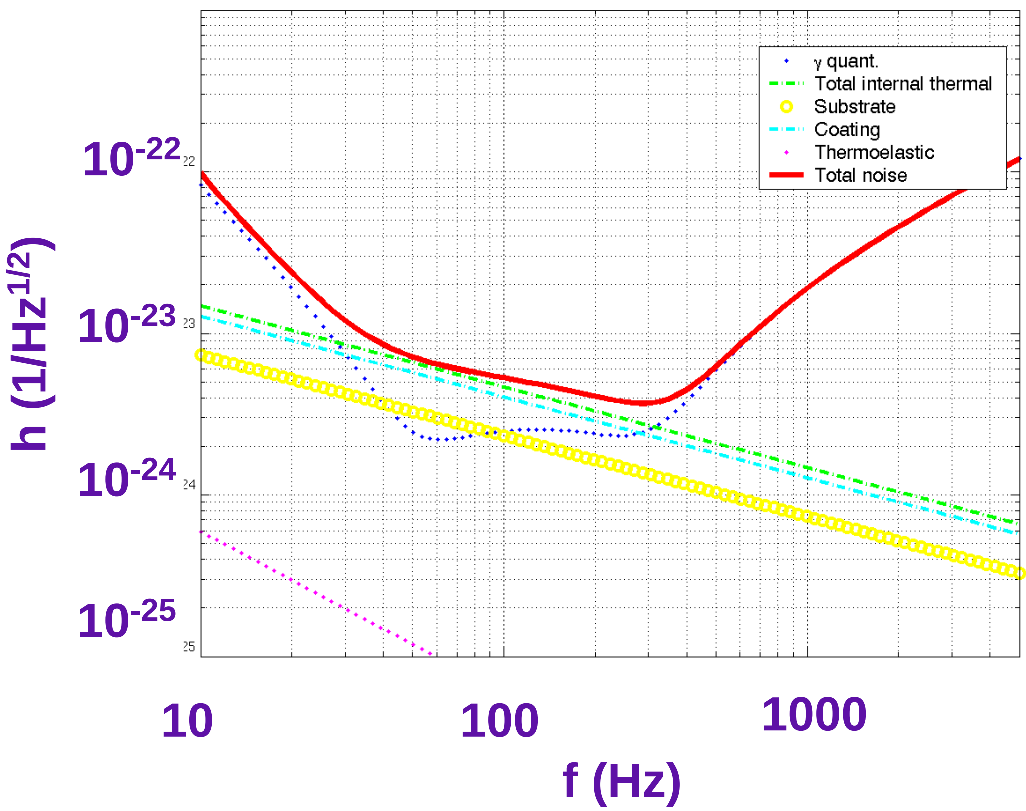
LIGO-G040330-00-R

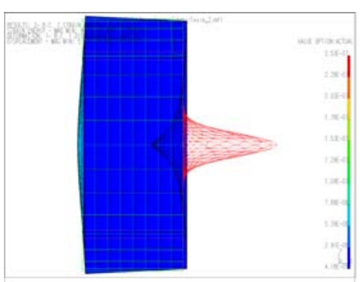
Reminder of Coating Thermal Noise

Sapphire Mirrors
165 Mpc BNS Range



Silica Mirrors
140 Mpc BNS Range





$$S_x(f) = 2\, k_B T / (\pi^2 f^2)\, W_{diss}/F_0^{\,2}$$

State of Mechanical Loss Studies c. Jan 2004

Coating Mechanical Loss

Layers	Materials	Loss Angle
30	[a] $\lambda/4\ SiO_2$ - $\lambda/4\ Ta_2O_5$	$2.7\ 10^{-4}$
60	[a] $\lambda/8\ SiO_2$ - $\lambda/8\ Ta_2O_5$	$2.7\ 10^{-4}$
2	[a] $\lambda/4\ SiO_2$ – $\lambda/4\ Ta_2O_5$	$2.7\ 10^{-4}$
30	[a] $\lambda/8\ SiO_2$ – $3\lambda/8\ Ta_2O_5$	$3.8\ 10^{-4}$
30	[a] $3\lambda/8\ SiO_2$ – $\lambda/8\ Ta_2O_5$	$1.7\ 10^{-4}$
30	[b] $\lambda/4\ SiO_2$ – $\lambda/4\ Ta_2O_5$	$3.1\ 10^{-4}$
30	[c] $\lambda/4\ SiO_2$ – $\lambda/4\ Ta_2O_5$	$4.1\ 10^{-4}$
30	[d] $\lambda/4\ SiO_2$ – $\lambda/4\ Ta_2O_5$	$5.3\ 10^{-4}$
30	[b] $\lambda/4\ SiO_2$ – $\lambda/4\ Nb_2O_5$	$2.8\ 10^{-4}$
43	[e] $\lambda/4\ Al_2O_3$ – $\lambda/4\ Ta_2O_5$	$2.9\ 10^{-4}$

[a] LMA/Virgo, Lyon, France
[b] MLD Technologies, Mountain View, CA
[c] CSIRO Telecommunications and Industrial Physics, Sydney, Australia
[d] Research-Electro Optics, Boulder, CO
[e] General Optics (now WavePrecision, Inc) Moorpark, CA

- *Loss is caused by internal friction in materials, not by interface effects*
- *Differing layer thickness allow individual material loss angles to be determined*

$\phi_{Ta2O5} = 4.6\ 10^{-4}$

$\phi_{SiO2} = 0.2\ 10^{-4}$

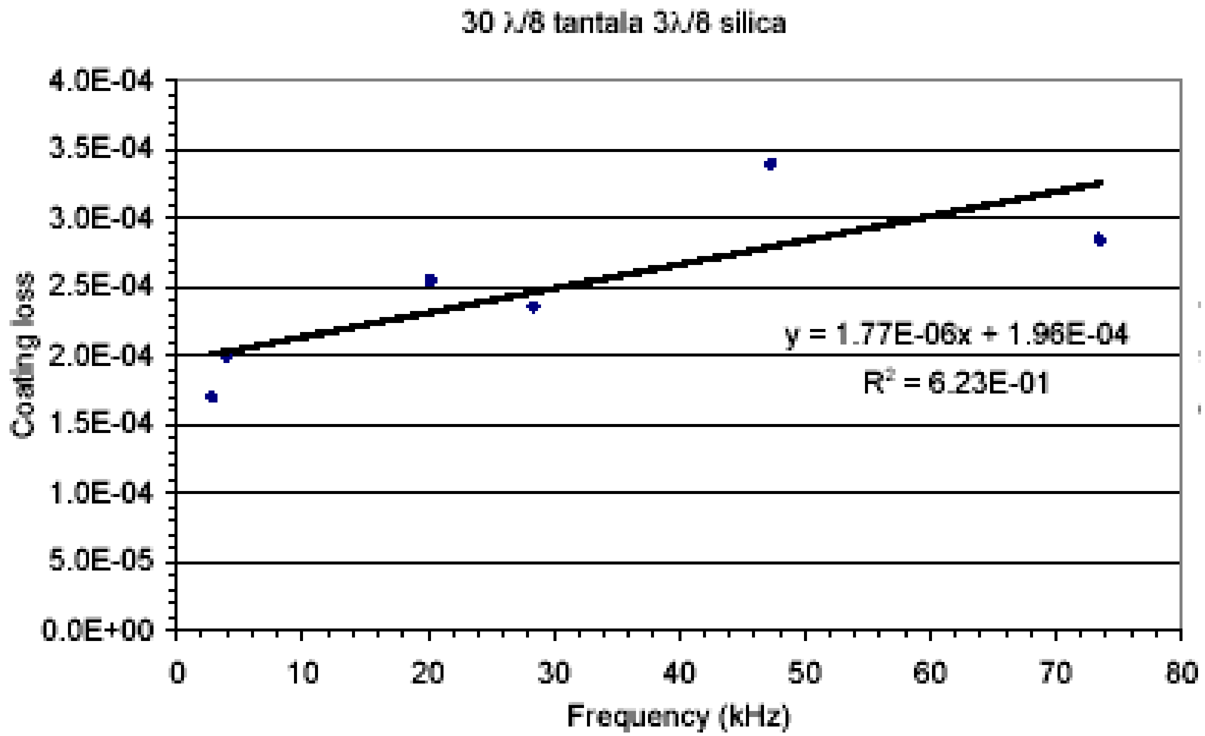
$\phi_{Al2O3} = 0.1\ 10^{-4}$

$\phi_{Nb2O5} = 6.6\ 10^{-4}$

Goal : $\phi_{coat} = 5\ 10^{-5}$

Frequency Dependence of Coating Loss

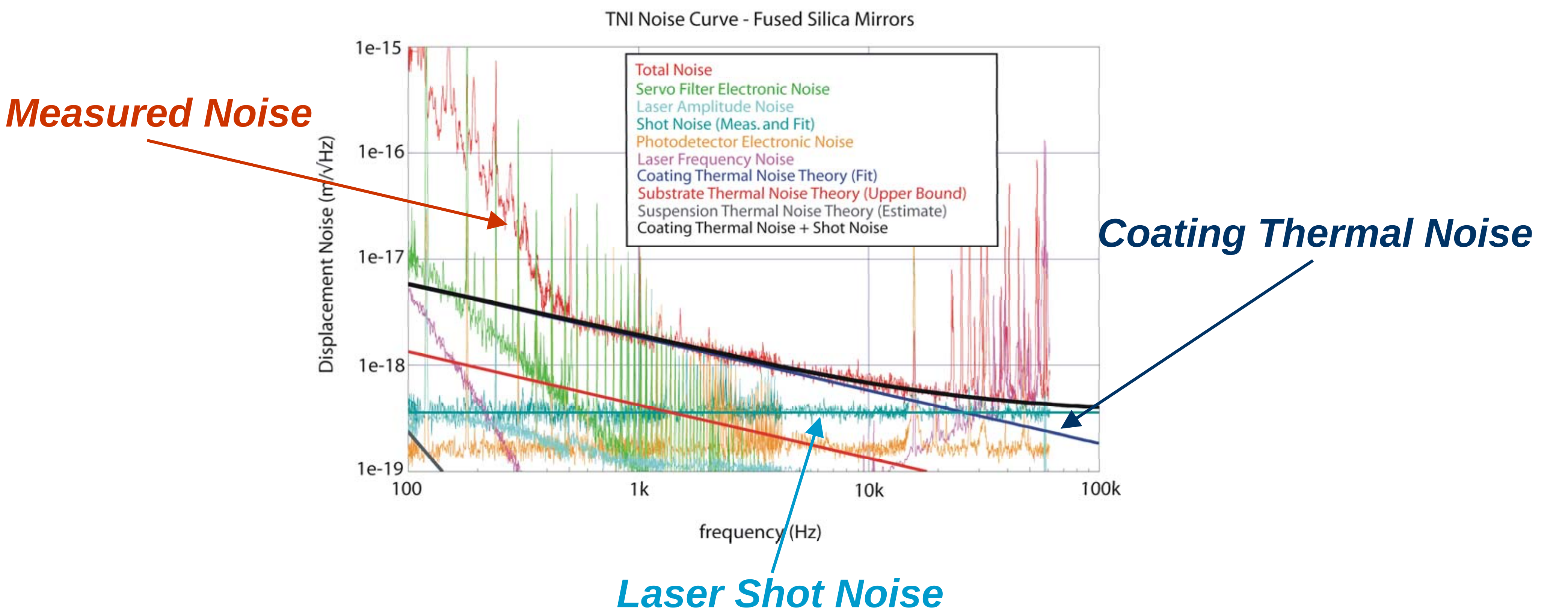
- *Evidence of frequency dependence of coating mechanical loss*
- *Coating loss lower at lower frequencies, so in LIGO's favor*
- *Primarily in SiO_2*
- *Frequency dependence known in bulk silica*
- *Results rely on small number of thin sample modes*



$$\phi_{Ta2O5} = (4.2 +/- 0.4)\ 10^{-4} + f\ (0.4 +/- 0.9)\ 10^{-9}$$
$$\phi_{SiO2} = (0.4 +/- 0.3)\ 10^{-4} + f\ (2.7 +/- 0.9)\ 10^{-9}$$

TNI Result

- *1 cm long arm cavitites, 0.15 mm laser spot size*
- *Consistent with ~ 4 10^{-4} coating loss angle*



Research Status

- ***Working with 2 vendors***
  - ***LMA/Virgo in Lyon, France***
  - ***CSIRO in Sydney Australia***

- ***LMA Progress***
  - ***Unsuccessful attempt to coat with HfO_2 as high index material***
  - ***Single layer coatings of both SiO_2 and Ta_2O_5***
  - ***Four coatings (Formulas 1-4) runs with TiO_2 dopant in Ta_2O_5***
    - ***Each run had higher TiO_2 concentration***
    - ***Final run in large coater***
    - ***Formulas 1,3,4 also on sapphire substrates***

- ***CSIRO Progress***
  - ***Two coating runs with SiO2/Ta2O5***
    - ***Secondary ion gun grid adjusted between runs***
  - ***Study of stoichiometry, optical loss, and Young's modulus of Ta_2O_5***

Titania Dopant in Tantala

Work done in collaboration with LMA/Virgo in Lyon, France as part of advanced LIGO coating research

$\lambda/4$ SiO_2 – $\lambda/4$ Ta_2O_5 Coatings with TiO_2 dopant

Dopant Conc.	Loss Angle: Thin	Loss Angle: Thick
None	$2.7 \pm 0.1 \times 10^{-4}$	$(2.5 \pm 0.4) \times 10^{-4} + f\,(14 \pm 9) \times 10^{-10}$
Low	$1.8 \pm 0.1 \times 10^{-4}$	$(1.8 \pm 0.9) \times 10^{-4} + f\,(24 \pm 19) \times 10^{-10}$
Medium	$1.6 \pm 0.1 \times 10^{-4}$	$(1.3 \pm 0.3) \times 10^{-4} + f\,(18 \pm 7) \times 10^{-10}$
High	*$2.1 \pm 0.1 \times 10^{-4}$	$(1.4 \pm 0.4) \times 10^{-4} + f\,(2 \pm 8) \times 10^{-10}$

**preliminary*

Increasing dopant concentration reduces mechanical loss

- *How far can this effect be pushed?*
- *Is there a better dopant?*
- *Will this compromise optical performance?*

Secondary Ion-beam Bombardment And Mechanical Loss

Work done in collaboration with CSIRO in Sydney, Australia as part of advanced LIGO coating research

$\lambda/4$ SiO_2 – $\lambda/4$ Ta_2O_5 Coatings

Mode	Thin Sample ϕ_{coat} Grid 1	Thin Sample ϕ_{coat} Grid 2
7	$4.1\ 10^{-4}$	$3.2\ 10^{-4}$
8	$4.2\ 10^{-4}$	$3.1\ 10^{-4}$
9	$5.0\ 10^{-4}$	$4.0\ 10^{-4}$
10	$4.1\ 10^{-4}$	$3.5\ 10^{-4}$
12	$4.4\ 10^{-4}$	$2.3\ 10^{-4}$

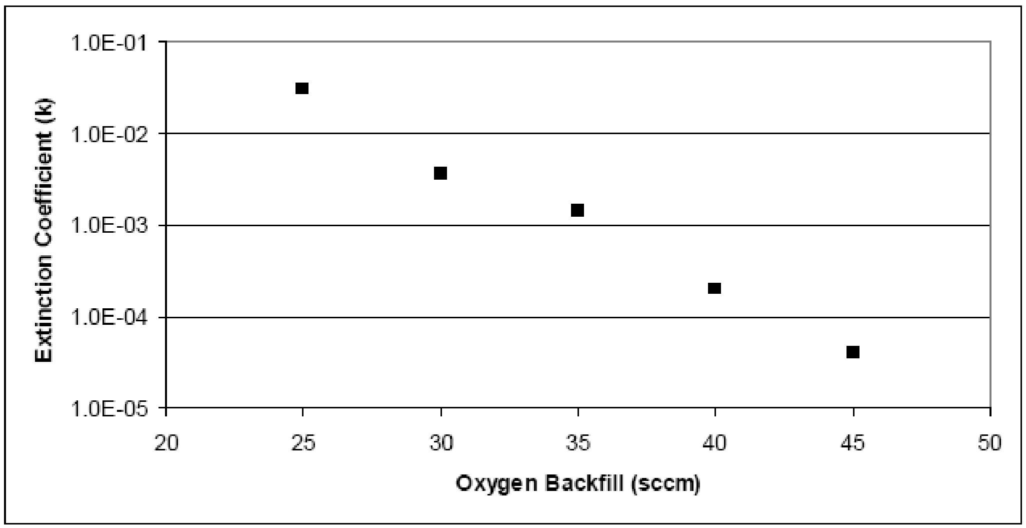
Thick Sample $\phi = (4.1 +/- 0.6)\ 10^{-4} + f(1 +/- 13) 10^{-10}$

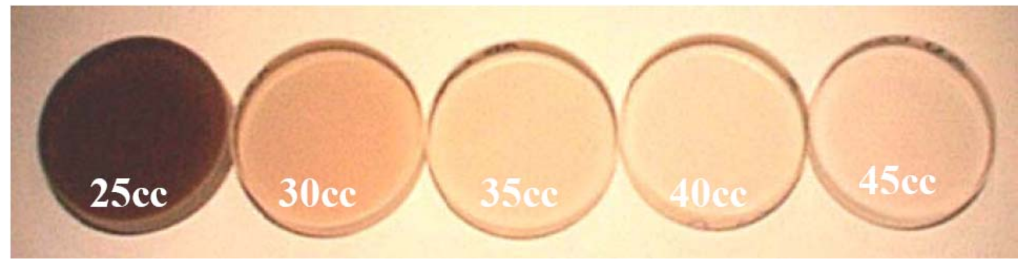
Grid was adjusted from 1 to 2 to increase uniformity

- *How far can this effect be pushed?*
- *Will this compromise optical performance?*

Stoichiometry Effects on Optical Loss and Young's Modulus

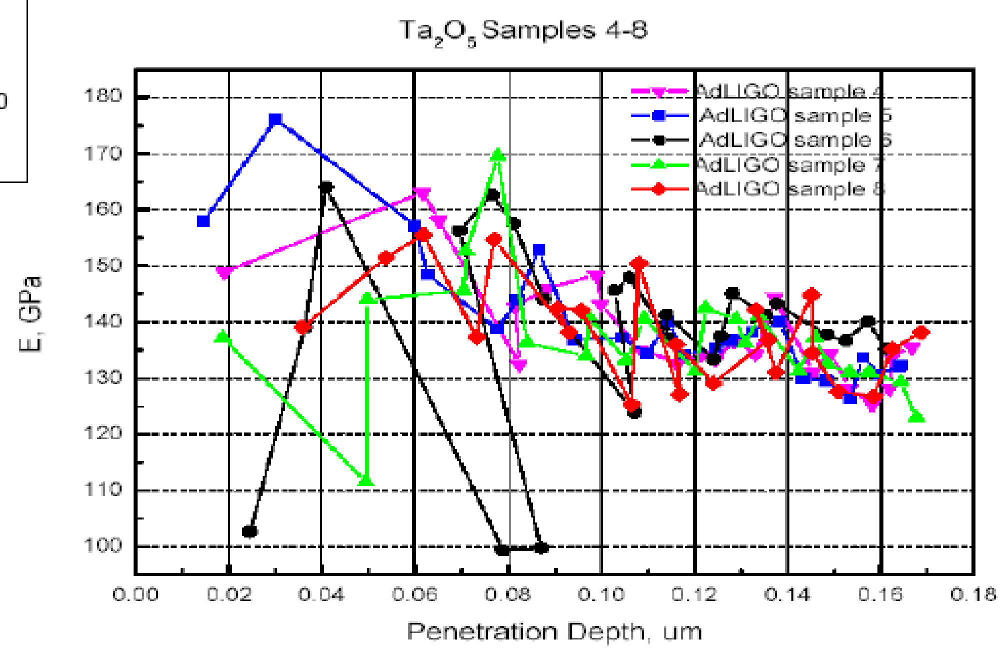
Modeled optical loss of unannealed Ta_2O_5 at 1.064 μm vs oxygen flow rate





Visible appearance of samples

Young's modulus vs probe penetration depth for samples with different stoichiometery



Future Plans

- ***More study of coatings on sapphire substrates***
  - ***Start using alumina as low index material***
  - ***Measure Young's modulus of alumina***
- ***With LMA/Virgo***
  - ***Experiment with new dopants for Ta_2O_5***
  - ***Examine Si/O/N alloy***
  - ***Possibly explore other high index materials, HfO_2 again?***
- ***With CSIRO***
  - ***Measure mechanical loss of Ta_2O_5 on varying stoichiometry samples***
  - ***Explore effects of changes in annealing cycle on mechanical loss in Ta_2O_5/SiO_2***