Optical & Mechanical Characterisation of Ion-Plated Silica and Tantala

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Introduction

Coating thermal noise which arises from thermal vibrations in highly-reflective mirror coatings will soon become a limiting factor on the performance of current and future gravitational wave detectors. The magnitude of coating thermal noise stems from the coatings internal friction or mechanical loss. Materials with a lower mechanical loss exhibit lower levels of off-resonance thermal noise and are thus more favoured. Future detectors such as the proposed Einstein Telescope (ET) and Advanced LIGO Voyager upgrade plan to operate at cryogenic temperatures and switch from the current operating wavelength 1064nm, to 1550nm or 2µm. Therefore any proposed coating material must have optimally low mechanical and optical loss properties under these proposed conditions. As current Advanced LIGO (aLIGO) test mass mirrors require <0.5ppm and 3rd generation detectors hoping to further improve upon this other deposition techniques are of interest. Ion plating is one such a deposition method (250°C deposition temperature), which shows very promising optical absorption compared to Ion-Beam Sputtered coatings (≈100°C deposition temperature) on silicon substrates.

Mechanical Loss

The mechanical loss of a resonator can be determined from the exponential amplitude decay of excited resonant modes where all sources of external damping are suitably minimised. The associated mechanical loss due to the addition of a deposited coating can be calculated from the ratio of the energy stored in the substrate and the coating respectively, and multiplied by the difference in their loss (ϕ) in the uncoated and coated states

$$\phi_{coating} = \frac{E_s}{E_c}(\phi_{coated} - \phi_{uncoated}) \qquad (1)$$

Where the energy stored in the substrate and coating are determined by the Young's' modulus and thickness of the respective materials.

Optical absorption Using Photothermal Common Path Interferometry (PCI)

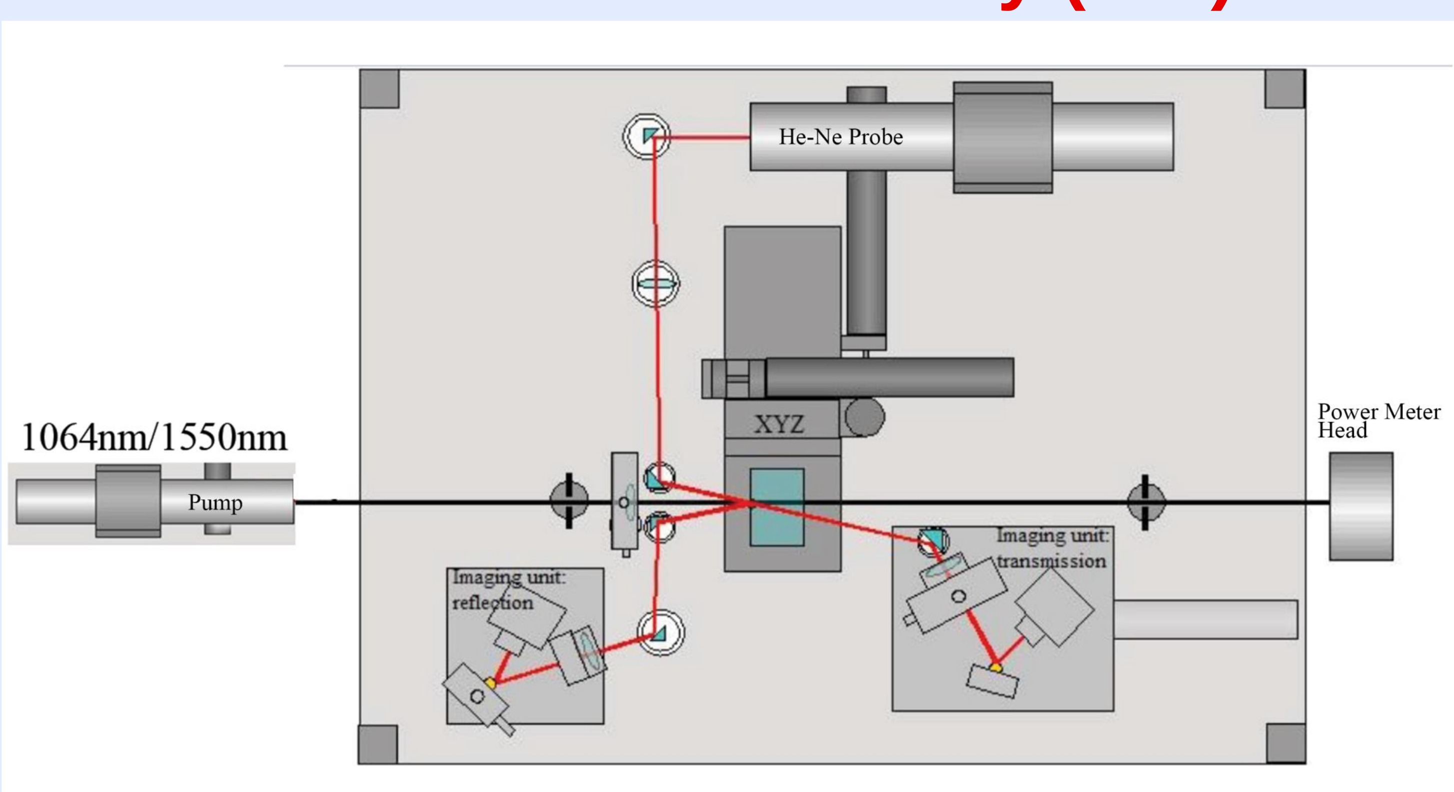

Figure 2. Top view of the PCI-03 instrument with both transmission and reflection photodetectors. Probe beam shown red. [1]

PCI uses two beams of high and low intensity (pump and probe respectively) to induce a thermal lensing effect in the measured sample. Due to the change in refractive index with temperature (dn/dT) a change in optical length is induced in the sample, in this case ion-plated Ta_2O_5 on a C7980 substrate. As the diameter of the probe beam is much larger than that of the pump beam , at the crossing point only the overlapping portion of the probe beam is affected by the induced optical length change, shifting this portion of the beams phase relative to the unaffected potions of the beam. The phase shifted and unaltered beam sections interfere, producing an interference pattern which is directly proportional to the absorption of the sample. To investigate how the ion-plated coatings would behave under current and future aLIGO conditions two different wavelength pump sources were used (1064nm & 1550nm).

Effect of heat-treatment conditions on absorption

As has been shown previously[2] heat treatment on silica and silicon coatings results in a decrease in both mechanical and optical losses for these materials as the atoms inside the material gain enough thermal energy to move to a lower potential state. 500nm thick ion plated Ta_2O_5 coatings were deposited on Corning 7979 and 7980 fused silica substrates. To investigate any possible stoichiometry changes during heat-treatment, 30 minute annealing steps in both air and vacuum conditions were carried out.

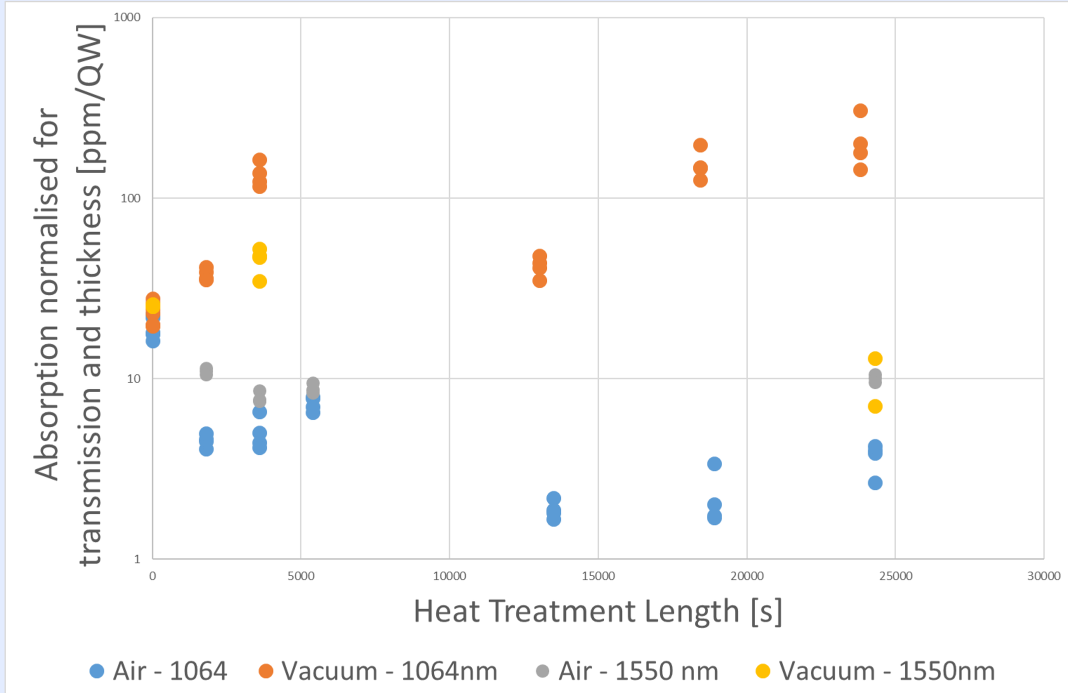

Figure 3: Shows the effects of 30 minute increment heat-treatments at 400 °C ion ion-plated Ta2O5 under atmospheric and vacuum conditions measured at 1064nm and 1550nm

Analysis shows that heat treatment 400°C in atmospheric and vacuum conditions yields different resulting absorption values at 1064nm. After 6hrs 45 minutes under atmospheric heat treatment a ~5 times reduction in the measured absorption is observed, with the same heat treatment parameters under vacuum conditions increasing the absorption by approximately a factor of 8. It is thought that these coatings are deposited in an oxygen deficient state, which is then rectified with HT under atmospheric conditions. HT under vacuum conditions however appears to draw more oxygen out of the coatings during the heating process resulting in a higher measured absorption. This effect does not seem to be as prominent at a measuring wavelength of 1550nm, where there is an initial increase in measured absorption, due to vacuum HT but after 6hrs 45 minutes the effect subsides producing absorption values which on average differ by <1%.

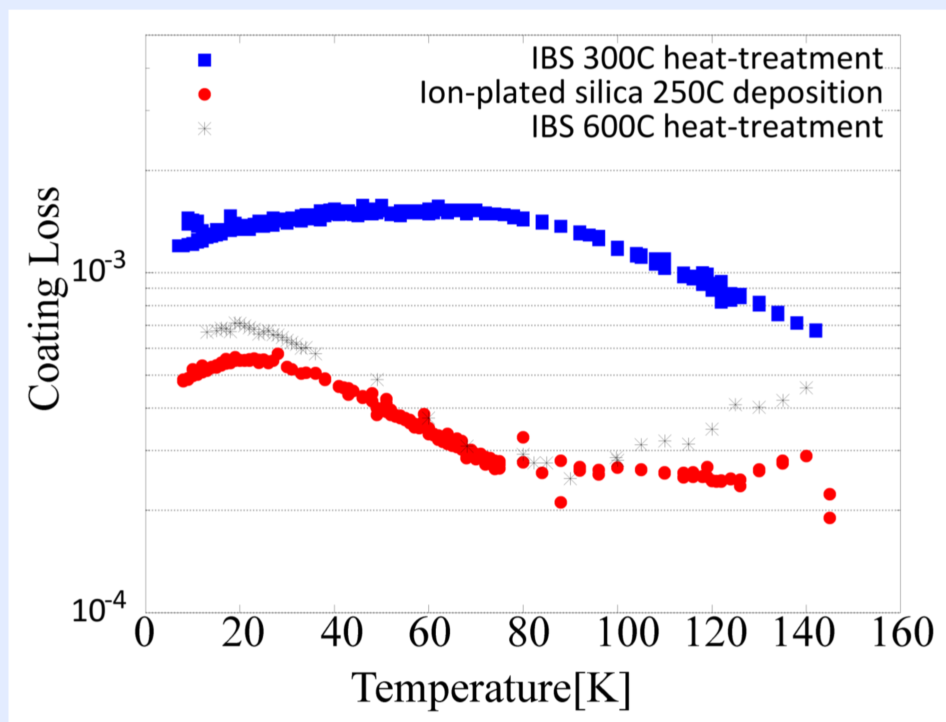

Figure 4. Cryogenic mechanical loss measurements of the 2.6kHz resonance on ion plated silica (as deposited) compared with ion beam sputtered silica on silicon cantilevers.

Cryogenic mechanical loss measurements between 10K-150K were also performed for ion-plated silica (deposition temperature 250°C) and ion beam sputtered silica at 300°C and 600°C post deposition heat treatments. It is clearly shown that the ion plated silica in the as-deposited state exhibits a lower coating mechanical loss than the IBS counter parts, even after HT at 600°C. It is possible that these low loss properties may be related to the elevated temperature deposition of the ion-plated coatings, which is not present in IBS (deposited at 90°C. However care is needed in comparing different deposition techniques, and the difference in loss may be due to other differences between the deposition techniques. Further study of the effect of heat-treatment on the loss and absorption is planned. A further factor 4 reduction in absorption would make ion-plated coatings a possible contender for future gravitational wave detector upgrades. This may be obtainable be heat-treatment at higher temperatures.

[1] Photothermal Testing System. (2013) [ebook] Stanford University. Available at: http://www.stan-pts.com

[2] Jessica Steinlechner, Iain W Martin, et. al.
Optical Absorption of Ion-Beam Sputtered amorphous silicon Coatings
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