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Transmission electron microscopy of mirror coatings for advanced and future gravitational wave detectors ID:LIGO-G0900581

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Introduction

LIGO has achieved displacement sensitivities of ≈ 10^{-19} m/√(Hz) with planned upgrades to an advanced detector system aiming for a factor of 10 to 15 times improvement in sensitivity [1,2].

Noise from various sources is a major challenge when attempting to reach such sensitivities. In the most sensitive frequency range (from a few 10's Hz to several 100 Hz) thermal noise is an important noise source.

The mirrors used in ground-based interferometric gravitational wave detectors are formed from test masses of ultra pure fused silica SiO_2 with multi-layer amorphous mirror coatings required for high reflectivity. The coatings currently used in GEO600 and LIGO are made up of multiple λ/4 thickness layers of Ta_2O_5 and SiO_2. Thermal noise from the mechanical dissipation of the mirror coatings is expected to be the dominant noise source in advanced detectors in this frequency range. Currently the microscopic properties which cause mechanical loss in these coatings are not well understood.

Coating mechanical loss studies suggest the dominant source of loss is from the amorphous ion-beam-sputtered Ta_2O_5 component of the coatings with low-temperature loss peaks observed (See figure 1), possibly analogous to the well known peak observed in SiO_2 at 30 to 50K [3, 4]. Heat-treatment of the Ta_2O_5 is observed to change the behaviour of the low temperature loss peak, [see poster by I.Martin et al].

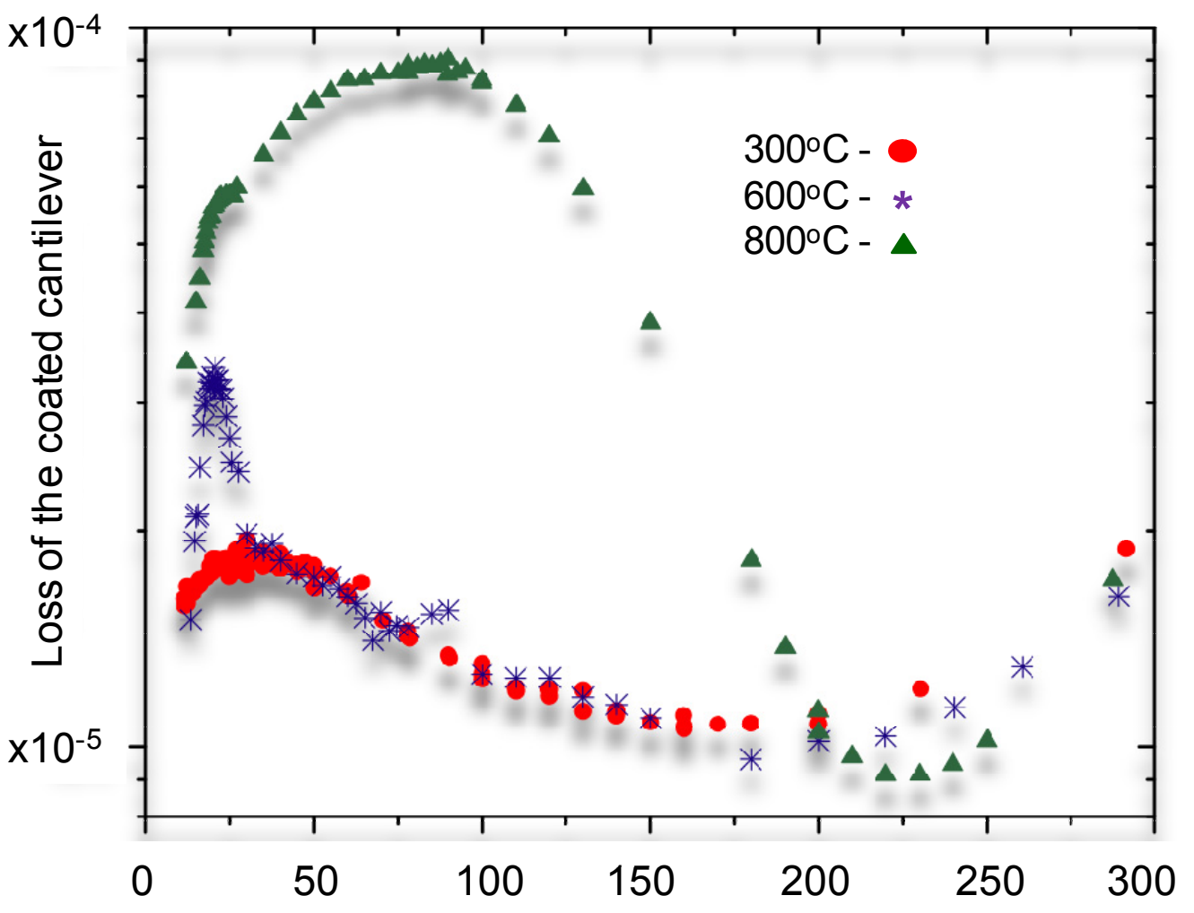

Figure 1. *Measured mechanical loss of coatings heat treated at 300, 600 and 800°C [5]*

Here we use transmission electron microscopy and associated analysis techniques to study for the first time the local structures and bonding in ion-beam-sputtered Ta_2O_5 which has been heat treated to a variety of temperatures, as a preliminary step towards identifying a quantitative relation between atomic structure and macroscopic coating mechanical loss.

Transmission electron microscopy

The transmission electron microscope (TEM) gives the ability to probe and characterise the atomic structure of the amorphous mirror coatings through imaging, diffraction and spectroscopy.

Initial results from the TEM measurement have shown a possible link between crystallisation and mechanical dissipation.

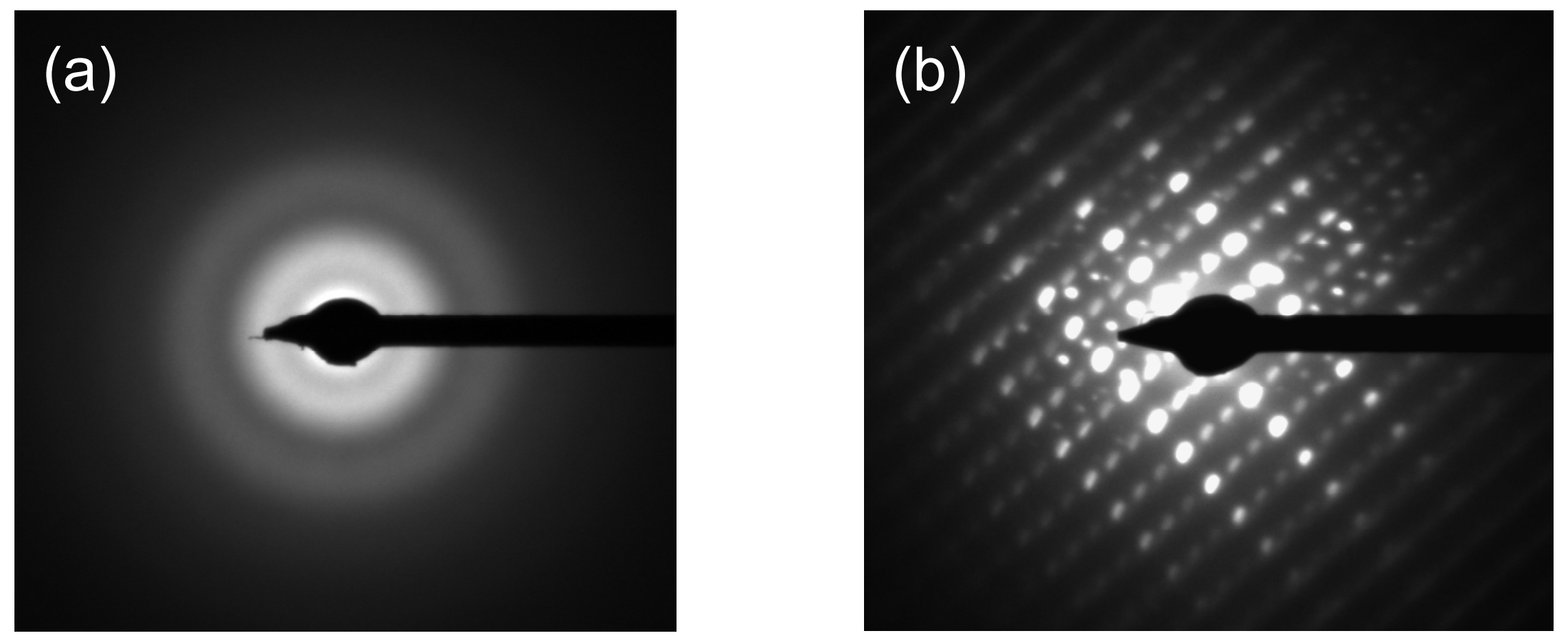

Figure 2. *(a) Amorphous and (b) crystalline diffraction patterns recorded from 300°C and 800°C heat treated coatings, respectively.*

Mechanical loss studies showed that a Ta_2O_5, coating heat treated at 800°C had a large loss peak at 80 - 90K. A sample with the same coating heat treated at 600°C did not show this peak. (see figure 1).

The diffraction pattern from the tantala coating heat treated at 800°C has shows sharp spots indicating that it has crystallised on heat-treatment (figure. 2 (b)), in contrast to the amorphous structure of coatings heat treated at lower temperatures (figure 2 (a)). The loss peak at 80-90K for the 800°C heat treated sample thus appears to be associated with the onset loss of crystallisation. Of further interest is the material structure for the coatings heat treated at lower temperatures.

Reduced density functions

Amorphous materials have no long range order. However, they do have short range order and this can be studied by using diffraction patterns to get the reduced density function (RDF) [6]. The RDF is a statistical representation of where atoms sit with regards to a central atom [6] . The peak intensity, G(r), describes the probability of finding a particular atom at a certain distance.

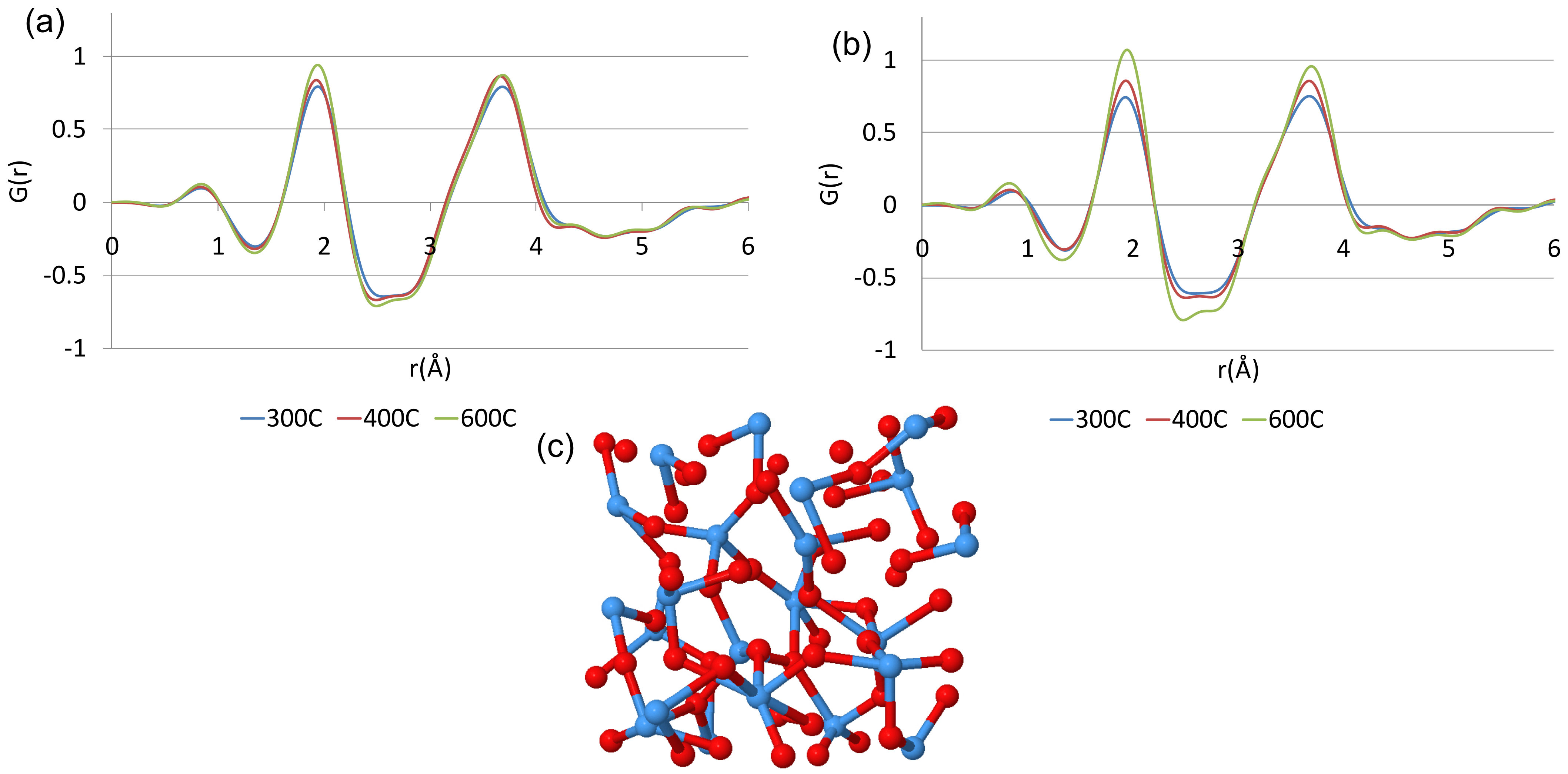

Figure 3. *(a) RDFs of coatings heat treated at 300, 400 and 600°C, (b) local structure variation showing a greater difference in RDFs at 300, 400 and 600 °C, (c) atomic model of amorphous Ta_2O_5 with oxygen in red and tantalum in blue.*

Figure 3(a) shows the average RDFs from tantala layers heat treated at 300°C, 400°C and 600°C respectively . These were obtained by averaging RDFs acquired at spatially different locations throughout the samples. There appears to be little significant difference in the structure of the average RDFs on heat-treatment suggesting that the average amorphous structure does not change. However preliminary investigation of local structural changes suggest a slight increase in the magnitude of the first peak of the RDFs as the heat-treatment temperature increases (see figure 3(b)). This corresponds to an increase in the local ordering of the material structure.

Along with information on the density and composition of the material, reverse Monte Carlo modelling can be used to produce an atomic-level model of the structure of the material from the RDF data [5]. Figure 3 (c) shows the atomic structure model generated for the Ta_2O_5 heat treated at 400 ° C. Preliminary results from this model show an average Ta to Ta bond length of 3.28Å and Ta to O bond length of 2.10Å. Future research will investigate possible variations in the structure of this model associated with the observed spatial variation in RDFs for increasing heat-treatment temperature to attempt to identify correlations between changes in mechanical loss behaviour with changes in atomic structure.

Spectroscopy

Electron energy loss spectroscopy (EELS) allows the identification and quantification of elements in the coating.

EEL spectra are used to quantify the ratio of tantalum to oxygen. Preliminary results suggest that as heat-treatment temperature increases from 300 to 600 °C the coatings become increasingly oxygen deficient. The 800 °C sample, that has crystallised, unusually shows a more oxygen rich environment than the 300 °C, this is possibly due to bubbles of oxygen forming in the coating as it crystallised.

Conclusions

The results from the RDFs of three heat treated tantala coatings show that although there is a negligible change in the average amorphous structure across the different temperatures, there may be some local changes in the sample showing an increase in Ta to O bonds. This will be investigated further using atomic modeling. EELS spectra show increasing oxygen deficiency as heat-treatment temperature increases prior to crystallisation. Future work combining all of the TEM techniques mentioned together with mechanical loss measurements will allow us to gain a better understanding of the mechanical loss behaviour in ion-beam sputtered coatings.

References

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