Point defects in IBS coating for very low loss mirrors

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Abstract

High reflective coatings are used in many physics experiments. Despite the high quality of the optical coating, the performances of the mirrors is altered by the scattered light induced by micrometers size defects in the coating layers. The topic of this paper is the study of the point-like scatterers present in the coating of the mirrors such as the ones used in gravitational wave detectors. To our knowledge, it is a first insight into the formation of these defects depending on the deposition parameters tested. The point-like scatterers density increases with the layer thickness and is reduced when samples are annealed.

Keywords : Thin films, Scattering light, Point defects, Gravitational wave detectors

1 Introduction

The year 2015 was marked by the first direct detection of a Gravitational Wave (GW), a confirmation of Albert Einstein’s theory of general relativity proposed a century ago [1]. This discovery offers us a new way to observe and understand the Universe around us. The detection was achieved by the two laser interferometers LIGO which was later joined by VIRGO for subsequent detection [2]. The detector Virgo located near Pisa in Italy uses a Michelson interferometer with Fabry-Perot cavities in the arms to search for gravitational waves. The Laboratoire des matériaux avancées (LMA) in Lyon (France) performed coating development deposition and metrology on the main mirrors of all the existing detectors.

At the heart of gravitational waves detectors, we found some of the most reflecting mirrors in the world. The detector core mirrors are substrates of fused silica (Heraeus Suprasil 3001 and 312) with a diameter of 350 mm for a thickness of 200 mm, weighting 40 kg. These mirrors have very low wave front distortion (2 nm peak-to-valley on the central 150 mm diameter) as well as a roughness inferior to 1 Å RMS [3]. The mirror high reflective coatings present one of the lowest absorption in the world (below 0.3 ppm for a 3 ppm transmission stack) [4].

However, the mirrors exhibit point defects in the thin layers that scatter the light inducing a loss of the laser power of the order of a few tens of parts per million (ppm). Light loss has two consequences: a loss of optical power in the interferometer arm amplified by the arm cavity gain and the addition of a phase noise when the scattered light is recombined to the main beam after reflection on the walls of the vacuum tubes that are mechanically excited by the micro seism [5]. Both of these phenomena limit the sensitivity of the detector impacting the ability to detect astrophysical events [6]. The scattered light is one of the main sources of noise under study for the Advanced Virgo upgrade scheduled for 2020 [7]. The improvement of these detectors requires
an understanding of the origin and nature of the defects in order to reduce their densities. This research effort is essential to improve the optical performances of the mirrors in view of the next generation of coating. This paper describes the first results of the analysis of the relation between the deposition parameters and the point-like scatterers density for tantala and silica thin films.

2 Experience

The mirrors in the interferometers are Bragg mirrors composed of stacks of thin layers, alternating thin films made of Ta$_2$O$_5$ and SiO$_2$. Deposition is performed at the Laboratoire des Matériaux Avancés (LMA) in Lyon using Ion Beam Sputtering (IBS) process [4].

Each mirror was characterized after coating in term of defect density and scattering level. These measurements provided information for the full stack independently of the layer material. In order to better understand the process generating the defects, we studied tantala and silica monolayers separately. Moreover several parameters were tested in order to determine their impact on the point-like scatterers density.

The IBS deposition is done in a vacuum chamber, with a 12 cm Veeco ion source providing a 200 mA Argon positive ion beam at 1 keV [8]. We deposited layers with different thicknesses on micropolished fused silica substrates of 1” diameter from Coastline Optics. These substrates are of very good quality and have a very low defect density of the order of 0.04 defects/mm$^2$ and a RMS roughness amount 1 Å RMS.

After the depositions, the samples were studied with an instrument called MICROMAP, an optical profilometer that has been customized for the detection of defects in dark field. The MICROMAP scans surfaces and when it detects a contrast difference in the field, the image is stored. A post treatment measures the defect size. The instrument is able to measure their size within 1 and 15 microns, giving a cartography of the sample with the number, size and localisation of the point-like-scatterers on the sample. It scans an area of 18 mm diameter centred on the 1” sample.

The scattering light is measured by a C.A.S.I. Scatterometer (Complete Angle Scan Instrument) [9]. This instrument composed by a laser and a detector allows to measure the scattered light at different scattering angles. A sample is illuminated at variable incidences and the detector scans the plane to measure the Bidirectional Reflectance Distribution Function (BRDF). The integrated value considers a pure isotropic emission, then this integrated value is given in parts per millions (ppm). Measurements are made with a source laser at 1064 nm, the same wavelength used by LIGO and VIRGO interferometers.

2.1 Influence of the thickness of the layer on the number of defects

Different samples were produced with different thicknesses (see Table 1). The layers were deposited under the same conditions.

Figure 1 shows the number of defects according to the layer thickness before (top) and after annealing (bottom) for SiO$_2$ (right) and Ta$_2$O$_5$ (left) respectively. We observe very precisely, for the two materials, that the number of point-like scatterers increases with the layer thickness.

2.2 Influence of the annealing on the number of defects point

The impact of the post deposition annealing on the number of defects has been also studied. All samples were annealed in an oven for thermal annealing at 500°C after deposition during approximatively 10 hours. This treatment allows to reduce the mechanical stress in the deposition-related layer and brings other benefits such as densification of the layer, homogeneity, stoichiometric adjustment and optical absorption decrease. Annealing is observed to reduce the density of point defects by 40% for silica layers and by 50% for tantala. Nevertheless, the curves retain the trend observed before annealing.

2.3 Scattering light from defects points

To quantify the impact of the defects on the scattered light, we measured the 8 samples with the CASI after annealing. Measurement were made on a diameter of 16 mm. The results are summarized in Tab.1. The thickest
Figure 1: Number of point-like scatterers in SiO$_2$ layers (right) and Ta$_2$O$_5$ (left) as a function of the layer thickness. Results are shown for materials as coated (in blue) and after annealing (in green). The measurements were repeated and the error bars shows the region containing 99.95% of the results. Measurements before annealing were not repeated.

SiO$_2$ sample has a scattering of 11.5 ppm whereas the thinnest one 5.1 ppm. Similarly, for Ta$_2$O$_5$ samples, the thinnest sample scatters 5.8 ppm while the thickest, 11.6 ppm.

It is worth mentioning that the uncoated substrates used in this study has an optical scattering level below 3 ppm. So the thin layer coating and particularly the addition of defects contribute to the scattered light.

While there is a factor 10 on the number of defects between the thickest sample of silica and tantala, the difference on scattered light is only about a factor 2. Moreover, the comparison of the defect density with the scattering value, would tend to show that the defect present in the layers of Ta$_2$O$_5$ scatter less light than the defects present in the SiO$_2$.

Figure 2 shows the scattering light of the two materials as a function of the layer thickness. Ta$_2$O$_5$ coating seems to have a stable scattering for the first three thinnest layers that increases for the thickest one.

Table 1: Scattering light and defect density measurement for each material according to their layer thickness. One Coastline substrate without coating has been measured to compare the scattering value with the different samples.

| Material | Layer Thickness No | (nm) | Defect density (def/mm$^2$) | Scattering (ppm) |
|----------|--------------------|------|-----------------------------|-----------------|
| Substrate | 0                  | 0.04 | 3                           |                 |
| SiO$_2$  | L1 523             | 0.14 | 5.1 ± 1.2                   |                 |
|          | L2 1005            | 0.32 | 4.5 ± 0.6                   |                 |
|          | L3 1550            | 0.52 | 9.4 ± 0.5                   |                 |
|          | L4 2053            | 0.61 | 11.5 ± 1.6                  |                 |
| Ta$_2$O$_5$ | H1 543            | 0.12 | 5.8 ± 0.8                   |                 |
|          | H2 1083            | 0.25 | 5.3 ± 0.2                   |                 |
|          | H3 1626            | 1.52 | 5.2 ± 0.5                   |                 |
|          | H4 2167            | 5.16 | 11.6 ± 0.1                  |                 |
3 Discussion

These experimental results show that there are several factors involved in the generation of defects in the layers. The defect density increases with the deposited thickness regardless of the material.

The defect density generated in the SiO$_2$ samples is much lower than the one of Ta$_2$O$_5$. However, the behavior is different for the 2 materials. For the SiO$_2$, the defect density is linearly dependent on the thickness, while for Ta$_2$O$_5$ it follows a power law. The hypothesis that the difference between the two materials is due to particles detaching from the walls of the frame gradually during successive depositions is excluded since the SiO$_2$ deposition series was made after the deposition series of Ta$_2$O$_5$ without cleaning the chamber.

However, the defect density as a function of the thickness of SiO$_2$ varies linearly with the thickness. Furthermore, deposition layers were made in the following order for SiO$_2$: L2, L4, L3, L1 and for Ta$_2$O$_5$: H2, H4, H1, H3. Hence the defect level in the Ta$_2$O$_5$ layers is not due to a cleanliness issue.

It has been shown that the heating during the deposition and the post-deposition annealing make it possible to reduce significantly (∼ 40-50%) the density of defects for the SiO$_2$ and the Ta$_2$O$_5$. This behavior could be the consequence of processes thermally activated during the deposition. The steady state temperature in the frame is reached for silica but not for the tantala. Deposition temperature are the same for all layers but the deposition of silica layers is quite long compared to tantala. So the silica substrate temperature is in a steady state contrary to the tantala where the temperature is involving during deposition. To confirm this hypothesis, it is planned to make several depositions with different thicknesses during which the structure would be preheated to reach thermal equilibrium so that the depositions are all made at the same temperature.

From figures 1 and 2, we can notice that the level of scattering is not directly proportional to the density of point defects. While the number of defects in tantala is 7 times more important than in silica, the scattering values would suggest that there is a kind or a size of defect which scatters more in silica.

For the three thinnest layer of Ta$_2$O$_5$, scattered light seems to be constant but regarding to the SiO$_2$ layers, it was only the two first. This visible effect on both materials can be explain by the background noise of the measurement. To verify this, a layer with a thickness lower than 500 nm will be deposited.

Improving the deposition process and thermal annealing is essential if we want to reduce the amount of defects. According to our study, the use of some materials are more prouve to have defects, but this does not
necessarily imply an increase in the optical scattering as we saw with the Ta$_2$O$_5$.

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