Institute of Physics Publishing
Journal of Physics: Conference Series **32** (2006) 413–417
doi:10.1088/1742-6596/32/1/063
Sixth Edoardo Amaldi Conference on Gravitational Waves

Investigation on mechanical losses in TiO_2/SiO_2 dielectric coatings

P. Amico†[1], L. Bosi†, F. Cottone†, A. Dari$^+$, L. Gammaitoni†, F. Marchesoni$^+$, M. Punturo‡, F. Travasso†, H. Vocca†

† Department of Physics and INFN Perugia, Via A. Pascoli 1, I-06100 Perugia, Italy
‡ INFN Perugia, Via A. Pascoli 1, I-06100 Perugia, Italy
$^+$ Department of Physics University of Camerino and INFN Perugia, Via A. Pascoli 1, I-06100 Perugia, Italy

Abstract. Interferometric gravitational wave detectors use test masses made by large mirrors whose coating is usually made by multiple layers of dielectric materials, most commonly alternating layers of SiO_2 (silica) and Ta_2O_5 (tantala). It is foreseeable that in future interferometric gravitational wave detector projects (LCGT, EGO, VIRGO,), the mirrors will be cooled down to cryogenic temperature in order to reduce the noise generated by the thermally activated motion of the masses. However, low temperature mechanical losses in the Ta_2O_5/SiO_2 coatings might limit the design sensitivity for such cryogenic detectors by setting a lower limit for the expected thermal noise. Here we present some measurements of mechanical losses in the TiO_2/SiO_2 coatings at room and low temperature (80K-300K).

1. Introduction

The goal sensitivity of the gravitational wave detectors (VIRGO [1], LIGO [2], GEO [3], TAMA [4]) in the observation band between few tens and few hundreds Hz is limited by the mirror thermal noise. The present generation of test masses for the VIRGO interferometer are made using fused silica substrates with coatings. The mirrors are supported using two loops of steel wires. In a possible advanced VIRGO design, they will be most probably made by using a so-called monolithic fused silica suspension [5]. The coatings are formed by ion-sputtering alternating layers of silicon dioxide (SiO_2) and tantalum pentoxide (Ta_2O_5) at $\lambda/4$ ($\lambda = 1064nm$). Due to the general attitude toward cooling down future generation of interformetric detectors questions arise about the behavior at low temperature of mirror mechanical losses, as related to expected thermal noise limit to the detector sensitivity [6, 7, 8]. Little experimental information is available [9] about the coating loss at low temperature.

2. Experimental apparatus

In order to measure the behavior of coatings losses at various temperatures (from room temperature down to cryogenic temperature) we realized in our laboratory a new facility aimed at taking measurements in mirror samples. The cryogenic part consists of a commercial cryostat supplied by Janis Research. Here the sample can be cooled down to liquid helium temperature. The cryostat was modified in order to locate the sample mounting surface in vacuum as opposed

[1] Email: paolo.amico@pg.infn.it

to the standard setup which locates the sample in flowing helium vapor. This was necessary in order to reduce the dynamical losses of the samples due to external sources such as residual gas damping. The dewar body consists of welded stainless steel liquid helium and liquid nitrogen reservoirs, surronded by an insulating space. To pump out the vacuum jacket, a turbomolecular pumping station has been introduced, which permits to reduce the pressure until 1×10^{-5}mbar. In this work only liquid nitrogen has been used to cool down the cryostat and then the lowest attained temperature is about 80 K.

As a measuring sample we used square fused silica membranes ($1'' \times 1''$; the thickness is $50\mu m$). The membranes are coated with a coating formed by alternating layers of silicon dioxide (SiO_2) and Titanium dioxide (TiO_2) at $\lambda/4$ ($\lambda = 1064nm$). Titanium dioxide could be an interesting material for the mirror coating in interferometric gravitational waves detectors, because it is possible to obtain high reflectance at $1\mu m$ wavelength. The coating thickness is $5\mu m$, about 10% of the sample thickness. In such a way the effect of mechanical losses in the coating material is much emphasized compared to the expected effect in standard VIRGO mirrors. The coatings have been applied by e-beam evaporation by SILO (Società Italiana Lavorazione Ottiche). A corner of the membrane has been clamped vertically by two copper pieces and then left to hang freely (figure 1). The temperature of the sample is monitored by using a thermometer located in the sample clamping system. The motion of the membrane is detected by shadow meter technique: a telescope expands an external laser beam that enters the cryostat through the cold windows, in order to make the laser waist larger than the membrane thickness. The shadow made by the membrane is recorded by a photodiode connected to pick-up electronics and sent to a digital analyzer. The membrane can be put into motion by means of an electrostatic actuator placed few millimeters apart from the membrane surface. Voltages of typically few hundred volts are used. During the experiment, the membrane has been excited at its resonant frequencies and the loss angle has been calculated by measuring the ringdown decay time of the output signal amplitude, after the excitation has been switched off. The measurements have been made at a pressure $\leq 10^{-5}$mbar. Loss angle measurements at variable temperature have been made on membranes with and without coating in the 300K - 70K range. The results quoted in the present paper are the best values obtained from several thermal cycles; their repeatability during several runs is within 20%.

3. Results and discussion

Here we present some preliminary results on measurements realized during cooling down and warming up of the sample. For each measurement the measuring time is small enough that we can consider the temperature stable within 0.1K during the data taking operation. The resonant frequency of each resonant mode changes with temperature, as expected due to mechanical properties of the sample. Figure 3 shows the behaviour of a resonant frequency vs temperature. In the same graph. the expected value from a finite element model (FEM) is plotted. Table 1 compares both measured and calculated resonant frequencies of the coated membrane.

Table 1. Resonance frequencies of the clamped membrane with multilayer coating

Experimental (Hz)	FEM (Hz)
66	76
378	443
460	541
1189	1253
2134	2291

Figure 4 reports behavior of the measured loss angle of the resonant mode at $\simeq 1.2kHz$ vs temperature in both coated - uncoated membrane. The 1525 Hz uncoated mode is the same mode as the 1186 Hz coated mode, with the difference in frequency due to the coating induced stress. In the same plot is reported also the resonant mode at $\simeq 1.7kHz$ vs temperature of uncoated membrane. Figure 5 shows the measured loss angle of all investigated resonant modes at several temperatures for the coated (a) and uncoated (b) membrane. Assuming all other losses to be negligible, the total loss angle ϕ in a coated sample could be expressed in the following form [10]:

$$\phi_{total}(\nu_0) \simeq \phi_{bulk}(\nu_0) + \frac{E_{coating}}{E_{bulk}} \phi_{coating}(\nu_0) \quad , \tag{1}$$

where ν_0 is the resonant frequency, ϕ_{bulk} is the loss angle of the bulk (fused silica), $\phi_{coating}$ is the loss angle of the multilayer coating TiO_2/SiO_2 and $\frac{E_{coating}}{E_{bulk}}$ is the ratio of the energy stored in the coating to the energy stored in the substrate. From the FEM it has been possible to extract the information that $\phi_{coating} \simeq 10^{-3}$. Figure 2 shows the stress distribution on the coated membrane at 1.2KHz. Since the FEM seems to predict more accurately the mechanical behaviour of the membrane at high frequency, the resonance mode at 1189 Hz has been used for the calculation. From figure 4 it appears that the loss angle of the uncoated membrane is slightly larger than the expected value of pure SiO_2 (less than 10^{-6}). The excess losses (at high frequency) in the uncoated membrane are probably due to a number of causes. Among these the presence of surface defects might be one of the most relevant. In addition to the losses from the Si-O-Si bond in bulk silica, a separate loss mechanism exists in the surface of the glass. The losses here can be expressed as [11]:

$$\phi = \phi_{bulk} + \mu \alpha_s \frac{S}{V} \quad , \tag{2}$$

where S is the surface area of the sample, V is the sample volume μ is a factor of order unity that depends on the mode shape, and α_s is a surface loss parameter. In the case of our uncoated sample the $\frac{S}{V}$ ratio is equal to 4×10^4 so an α_s value of $2.25 \times 10^{-10} m$ could be calculated from the loss angle value measured at room temperature. This result could be compatible with the abrasively polished surfaces of our membrane [11]. Moreover the increase of the uncoated membrane loss at low temperature could be explained by the mechanical dissipation in pure fused silica arising from an asymmetric double-well potential of the bond angle, which at audio frequencies has a peak in the cryogenic range 20-60K [11].

In the same graph it is possible to appreciate the coating effect on the total loss angle. In this case the effect of the temperature dependence is much less evident.

Figure 5 shows that in both coated 5(a) - uncoated 5(b) membrane (in the 100-3000Hz range) the thermoelastic damping contribution does not affect the loss angle behavior in a significant way because the loss angle seems to be constant above 500Hz. The sharp rise of the loss angle for low frequencies in the uncoated samples is probably due to recoil losses and/or clamping losses that are more efficient at low frequencies while are quite negligible in the high frequency limit.

4. Conclusions

We measured the mechanical losses in thin fused silica coated membranes in a wide range of temperature and frequencies. For these samples the mechanical losses in the coating dominate over other losses in the sample and seem to be almost temperature independent for the range of temperature under consideration. Moreover the losses in the multilayer TiO_2/SiO_2 coating seem to be comparable with the loss angle of Ta_2O_5/SiO_2 coating measured in [9]. The deposition

Figure 1. Cryogenic clamping system

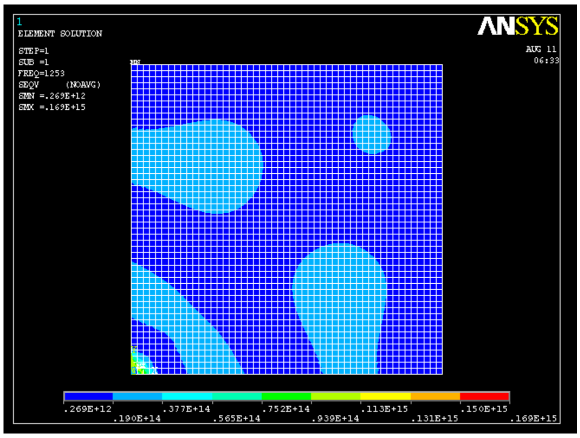


Figure 2. Stress distribution on the coated membrane ($\nu = 1200Hz$)

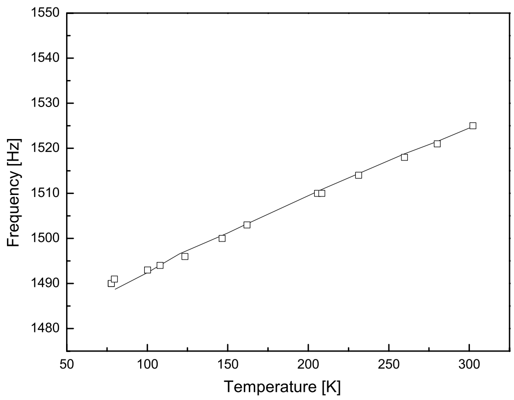


Figure 3. Resonance frequency of the uncoated membrane vs temperature: (□) experimental; (solid line) FEM

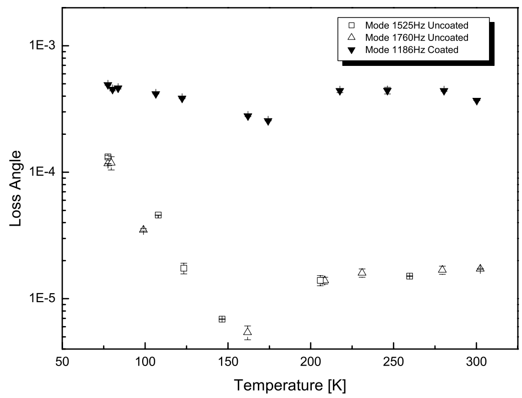
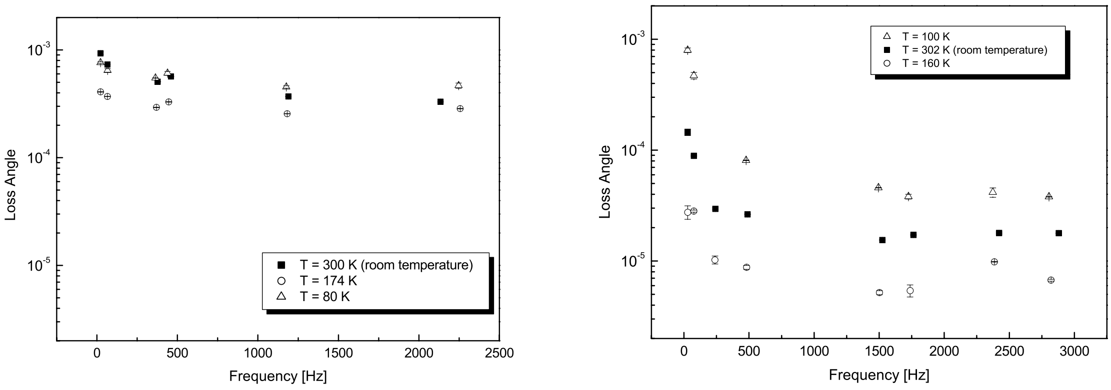


Figure 4. Loss angle vs temperature of uncoated (□, △) and coated (▼) membrane

technique of the coated samples investigated in this paper is not viable for the coating of mirrors in actual detectors at room temperature in which ion sputtering technique produces better optical properties. The measurements presented here represent just a preliminary result of the ongoing effort to better characterize the coating effect on the expected thermal noise limit of the VIRGO advanced configuration. More results will be presented in a future report, including measurements in the temperature range 5k-20k.



(a) coated membrane; coating formed by alternating layers of silicon dioxide (SiO_2) and Titanium dioxide (TiO_2) at lambda/4 (lambda=1064nm)

(b) not coated membrane (pure SiO_2)

Figure 5. Loss angle of several resonant modes vs temperature

Acknowledgments
This research has been supported by the Istituto Nazionale di Fisica Nucleare (INFN) under the Virgo Project.

References
[1] VIRGO collaboration 1997 *VIRGO Final Design Report*
[2] Abramovici A *et al* 1992 *Science* **256** 325
[3] Danzmann K *et al* 1994 Proposal for a 600m laser-interferometric gravitational wave antenna Max-Planck-Institut fur Quantenoptik Report 190 Garching, GermanyA.
[4] Ando M *et al* 2001 *Phys. Rev. Lett.* **86** 3950
[5] P.Amico *et al* 2002 *Review of Scientific Instruments* **73** 3318
[6] Levin Y. 1998, *Phys. Rev. D* **57** 659
[7] Yamamoto K. *et al* 2002, *Class. Quantum Grav.* **19** 1689
[8] Penn S.D. *et al* 2003 *Class. Quantum Grav.* **20** 2917-2928
[9] Yamamoto K *et al* 2004 *Class. Quantum Grav.* **21** 1075-1081
[10] Harry G M *et al* 2002 *Class. Quantum Grav.* **19** 897-918
[11] Penn S.D. *et al* 2005 *arXiv:gr-qc/0507097 v1 23 Jul 2005*