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A Mirror Coating Solution for the Cryogenic Einstein Telescope

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Planned, cryogenic gravitational-wave detectors will require improved coatings with a strain thermal noise reduced by a factor of 25 compared to Advanced LIGO. In this article, we present investigations of HfO$_2$ doped with SiO$_2$ as a new coating material for future detectors. Our measurements show an extinction coefficient of $k = 6 \times 10^{-6}$ and a mechanical loss of $\phi = 3.8 \times 10^{-4}$ at 10 K, which is a factor of 2 below that of SiO$_2$, the currently used low refractive-index coating material. These properties make HfO$_2$ doped with SiO$_2$ ideally suited as a low-index partner material for use with a-Si in the lower part of a multimaterial coating. Based on these results we present a multimaterial coating design which, for the first time, can simultaneously meet the strict requirements on optical absorption and thermal noise of the cryogenic Einstein Telescope.

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Introduction — During the first two observing periods of advanced interferometric gravitational-wave detectors, 10 gravitational-wave signals from binary black hole mergers and one from a binary neutron star inspiral have been measured [1–6]. To improve upon the sensitivities of advanced interferometric gravitational-wave detectors, 10 gravitational-wave signals from binary black hole mergers and one from a binary neutron star inspiral have been measured [1–6].

To improve upon the sensitivities of the current generation of detectors, Advanced LIGO [7–8] and Advanced Virgo [9], it is essential to reduce coating thermal noise (CTN). The CTN amplitude is proportional to the square root of the mirror temperature [10]. Therefore, gravitational-wave detectors such as KAGRA [11, 12] and the low frequency detector of the planned Einstein Telescope (ET-LF) [13] will operate at low temperatures. At frequencies around 10 Hz, ET-LF will be 100 times more sensitive than Advanced LIGO and Virgo at the same frequency. This improved sensitivity will increase the observable volume of space by a factor of 100$^3$ and open up the 1–10 Hz frequency band. This may allow multiple detections of known young pulsars [14], first detections of a Galactic Type Ia supernova [15], and many distant and possibly new types of sources. The expansion of the frequency range will also allow inspirals to be observed for a longer time before the final merger events.

The interferometer mirror coatings are made of alternating layers of materials with low and high refractive index $n$. In the simplest case, the layers are a quarter of a wavelength (QWL) in optical thickness ($n \times t$) with the geometric thickness $t$). To avoid thermal deformation of the mirrors, and to maintain the desired cryogenic temperature, heating must be minimised. Therefore in addition to low CTN, low optical absorption at the ppm ($10^{-6}$) level is required.

SiO$_2$ and Ta$_2$O$_5$ (or Ta$_2$O$_5$ doped with TiO$_2$ [16]), deposited using ion-beam sputtering (IBS), are widely used coating materials with very low absorption and scattering [17]. A complication of cooling is that CTN is proportional to the square root of the mechanical loss, which is temperature dependent. Both SiO$_2$ and Ta$_2$O$_5$ (doped or un-doped) show mechanical loss peaks at low temperatures [18–20].

Another complication is that fused silica, the currently-used mirror substrate material, is not suitable for low temperature operation due to a large peak in mechanical loss at around 40 K [23, 25]. For ET-LF, the use of crystalline silicon (c-Si) is planned [13] – the material is also used for the mechanical spacer (at 124 K) in stable reference cavities for optical frequency standards [26]. c-Si is not transparent at 1064 nm. Therefore a change to a longer laser wavelength is required [27], with 1550 nm planned for ET-LF.

Amorphous silicon (a-Si) is a very interesting coating material, due to low mechanical loss at low temperatures [28, 29]. Currently, the best estimated absorption for a highly-reflective multilayer a-Si/SiO$_2$ coating is 7.6 ppm at 1550 nm and room temperature ($k_{\text{aSi}} = 1.22 \times 10^{-5}$ [30]. There is also potential for further reduction at a higher wavelength and a lower temperature [31, 32]. To obtain the minimum optical absorption in a-Si, heat-treatment at 400°C is required. Thus a low-index partner material also must have good optical properties and mechanical loss at this heat-treatment temperature.

Using a-Si (instead of Ta$_2$O$_5$) in a highly-reflective coating with SiO$_2$ would significantly decrease CTN at
low temperatures. However, this decrease is limited by
the mechanical loss of the SiO$_2$ layers. To meet the ET-
LF requirements it is therefore essential to find an alter-
native low-index material for combination with a-Si.

This letter presents IBS HfO$_2$ doped with SiO$_2$
(SiO$_2$:HfO$_2$) as a low-index material for ET-LF coat-
ings. HfO$_2$ films have been observed to be partially$^{129}$
poly-crystalline, with the degree of crystallinity increas-
ing$^{33}$ upon heat-treatment. This poly-crystalline structure$^{33}$
causes a problematically high level of optical scatter-
ing$^{33}$. However, HfO$_2$ shows lower mechanical loss$^{33}$
than SiO$_2$. Doping HfO$_2$ with SiO$_2$ has been shown$^{34}$
to stabilise the coating against crystallization following$^{35}$
heat-treatment at temperatures up to 550°C$^{34}$.$^{35}$.$^{36}$

We show that SiO$_2$:HfO$_2$ used with a-Si can meet the$^{37}$
optical absorption requirements ($<5$ ppm) and the CTN$^{38}$
requirements of ET-LF at an operating temperature of$^{38}$
10 K$^{15}$ when used together with SiO$_2$ and Ta$_2$O$_5$ in a$^{39}$
multimaterial design.

Deposition and heat treatment – Coating mechanical loss was measured with a ring-down technique as described in$^{15}$ using cantilevers coated with a HfO$_2$ layer doped with 27% SiO$_2$ (measured by X-ray photoelectron spectroscopy). The coatings were deposited by CSIRO using IBS. Ellipsometry was used to estimate the thickness of the as-deposited coating to be$^{40}$ (483 ± 3) nm. The cantilevers were made of c-Si, which has low mechanical loss below 150 K$^{37}$.$^{38}$, to maximize sensitivity to the coating loss. Prior to coating$^{40}$, deposition an oxide layer (SiO$_2$) was grown on the cantilevers by thermal oxidation, to ensure good adhesion of the coating. The oxide layer was approximately 20 nm thick, which was also measured via ellipsometry.$^{40}$

Optical coatings are commonly heat-treated to reduce the stress and optical absorption$^{49}$. Coating mechanical loss is also often strongly dependent on heat treatment$^{49}$. Therefore, the coated cantilevers were heat treated for 24 hours at temperatures of 150, 300, 400 and 600°C by CSIRO to cover the typical temperature range used by commercial vendors. There is some evidence in$^{50}$
the literature of the growth of a few nm of oxide due to heat treatment for HfO$_2$ films on c-Si$^{40}$: although it should be noted that this is predicted to occur at higher temperatures than used here. Our ellipsometry measurements showed no significant variation in thickness of the SiO$_2$:doped HfO$_2$ coating due heat treatment. For the oxide layer, there was no evidence of a significant increase in thickness after heat-treatment at 400°C – the temperature used for the mechanical-loss results presented here. For heat treatment at 600°C, a maximum possible increase in oxide thickness of 6 nm was estimated. It should be noted that variations of up to 3 nm were observed for samples with identical heat treatment.

Transmission electron microscope measurements of coatings deposited on SiO$_2$ substrates indicated that all of the heat-treated coatings remained amorphous (see Fig. 1). This keeps optical scattering low and makes SiO$_2$:HfO$_2$ potentially useful as a coating material for gravitational wave detectors.

Mechanical loss and Young’s Modulus – The Young’s modulus, Y, of the coating is required for calculation of the coating mechanical loss$^{49}$. For SiO$_2$:HfO$_2$, Y = 180 GPa was calculated using the moduli of both SiO$_2$ and HfO$_2$ (see Tab. 1).

The mechanical losses of several bending modes in the frequency range 0.5 kHz to 9.5 kHz were measured between 10 K and 200 K. After a complete measurement cycle, the cantilever was re-clamped and the measurements repeated. This ensures that unintentional variations in the clamping procedure did not affect the results. The mechanical loss of the coatings was calculated by comparing the mechanical loss of the coated c-Si cantilevers with nominally identical oxidized, uncoated samples using$^{49}$. Underestimating the oxide thickness of the heat-treated, coated samples would result in a small overesti-
TABLE I. Material properties used for CTN calculations. The
heat treatment temperature for the losses (ϕ) was 450°C for SiO2 and
400°C for all other materials, with loss values at 600°C in brackets.

<table>
<thead>
<tr>
<th>Material</th>
<th>ϕ (10^-4)</th>
<th>n</th>
<th>k (10^-5)</th>
<th>Y (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO2</td>
<td>8.5 (5)</td>
<td>1.44</td>
<td>0.008*</td>
<td>72</td>
</tr>
<tr>
<td>HfO2</td>
<td>2.20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SiO2:HfO2</td>
<td>3.8 ± 0.3</td>
<td>1.91</td>
<td>0.40 ± 0.09</td>
<td>180</td>
</tr>
<tr>
<td>Ta2O5</td>
<td>5 (7)</td>
<td>2.05</td>
<td>0.008*</td>
<td>140</td>
</tr>
<tr>
<td>a-Si</td>
<td>≤0.17**</td>
<td>3.48</td>
<td>1.22 ± 0.21</td>
<td>38</td>
</tr>
</tbody>
</table>

*Effective k value chosen for αHR ≤ 0.5 ppm. This assumes the effective k value for the stack at 1550 nm is identical to 1064 nm [48], so that the absorption just scales with layer thickness.

**Only measured at room Temperature.

Optical Absorption — Fused silica discs were coated with SiO2:HfO2 in the same coating run as the cantilevers used for mechanical loss studies. The absorption of the coatings was measured at 1550 nm using photothermal common-path interferometry [51] — a technique based on measuring a thermal effect due to optical absorption. The absorption of the as-deposited coating was found to be (25 ± 5) ppm for a 500 nm thick layer. The error originates from variations in absorption across the sample and from reproducibility after realignment. This absorption corresponds to an extinction coefficient of k = (6.4 ± 1.3) × 10^-6. The absorption coefficient of a coating layer, α, is related to the extinction coefficient, k, by α = 4πk/λ. The total absorption of an HR coating, αHR, also includes the effect of interference in the layers. After heat treatment at 400°C, which is the optimum temperature for mechanical loss, the absorption reduces to (16 ± 3) ppm (k = (4.0 ± 0.9) × 10^-6).

Discussion — Figure 3 shows the total strain noise of the Advanced LIGO detectors (gray, dashed curve) at their design sensitivity. The black, solid curve represents the total strain noise of the ET-LF design [13]. This strain noise can be converted into displacement noise by multiplying by the detector arm-length (4 km for aLIGO, 10 km for ET-LF), allowing comparison between detectors to be unbiased by differing arm-lengths. The coating displacement thermal noise of the whole detector, CTND, includes contributions from the two input test-masses (ITMs) and the two end test-masses (ETMs) forming the interferometer arm cavities:

\[
CTN_D = (2 \times CTN_{ETM}^2 + 2 \times CTN_{ITM}^2)^{\frac{1}{2}}.
\]  

The CTND requirement for ET-LF is \(3.6 \times 10^{-21} \text{ m/} \sqrt{\text{Hz}}\) at a reference frequency of 10 Hz (shown in terms of strain noise by the red, solid line) — this is about a factor of 25 below the CTND of Advanced LIGO (blue, dashed line) [52].

The Einstein Telescope design study suggests an operation temperature of 10 K, with the optical absorption of the coating required to be ≤ 5 ppm [13]. The design transmission of the ETMs is T = 6 ppm and of the ITMs T = 7000 ppm [13]. For the coating materials used in current gravitational-wave detectors, SiO2 and Ta2O5, CTND would be \(6.45 \times 10^{-21} \text{ m/} \sqrt{\text{Hz}}\) at 10 Hz and 10 K (see Tab. I(a), calculated using (11)). Table II also shows CTN for the ETMs and ITMs separately. For the ITMs, CTN is lower as fewer layers are required to provide the lower design reflectivity.

Coating (b) in Tab. II demonstrates the potential of using SiO2:HfO2 as a low-index material alongside a-Si. Based on the results presented here, this combination of materials results in a CTND = \(2.4 \times 10^{-21} \text{ m/} \sqrt{\text{Hz}}\) at 10 K. This surpasses the requirement for ET-LF. However, the absorption of this coating, of \(11.9 \pm 2.3\) ppm at 1550 nm, exceeds the required value by more than a factor of two.
TABLE II. CTN of different coatings on cSi substrates at a reference frequency of 10 Hz, a temperature of 10 K and a beam radius of 9 cm. The material parameters used are shown in Tab. I.

<table>
<thead>
<tr>
<th>Case</th>
<th>bilayers</th>
<th>Transmission</th>
<th>Heat</th>
<th>CTN (ETM)</th>
<th>CTND</th>
<th>αHR</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>18 (7) × SiO2/Ta2O5</td>
<td>4 (8500)</td>
<td>600</td>
<td>4.0 (2.4)</td>
<td>6.6</td>
<td>0.6</td>
</tr>
<tr>
<td>(b)</td>
<td>10 (4) × SiO2:HfO2/a-Si</td>
<td>2 (9000)</td>
<td>400</td>
<td>1.4 (0.9)</td>
<td>2.4</td>
<td>11.9</td>
</tr>
<tr>
<td>(c)</td>
<td>2 × SiO2/Ta2O5 + 10 (4) × SiO2:HfO2/a-Si</td>
<td>4.4 (6000)</td>
<td>400</td>
<td>1.9 (1.6)</td>
<td>3.5</td>
<td>3.4</td>
</tr>
</tbody>
</table>

ET-LF requirement [13] 5

Note that this coating design is a suggestion for how to use SiO2:HfO2 calculated based on measurements results of single layers of the different materials. An actual highly-reflective multilayer coating is yet to be produced and verified.

**Conclusion** – We have shown 30% SiO2:HfO2 to be an excellent low-index material for use in highly-reflective mirror coatings together with a-Si. Unlike pure HfO2, SiO2:HfO2 is stable against crystallization for heat treatment up to 600°C, which prevents excess scattering – essential for materials to be suitable for gravitational-wave detectors. The mechanical loss of SiO2:HfO2 at a temperature of 10 K is significantly lower than observed for pure SiO2. After heat treatment at 400°C, which is the optimum temperature to minimize the optical absorption of a-Si, the mechanical loss of SiO2:HfO2 is more than a factor of 2 below that of SiO2.

A multi-material coating made of a-Si and SiO2:HfO2, with two bilayers of SiO2 and Ta2O5 on top, has been demonstrated to fully meet the requirements of ET-LF on CTND [55] and on optical absorption for the first time.

There are many other challenges to be overcome to realize the cryogenic Einstein Telescope, but this coating design is an important step towards the detector being able to meet its goal of a factor of 100 improvement in sensitivity over aLIGO at frequencies around 10 Hz.

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[26] "CSIRO."


[31] R. R. Robie, Characterization of the mechanical properties of thin-film mirror coating materials for use in fi-


At a slightly more conservative (and perhaps more likely) operating temperature of 20 K, CTN_D would only be a factor of 1.5 above the ET-LF design.