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Phys. Rev. D **92**, 062001 — Published 10 September 2015

DOI: 10.1103/PhysRevD.92.062001

Ion-beam sputtered amorphous silicon films for cryogenic precision measurement systems

Peter G. Murray,* Iain W. Martin,* Kieran Craig, James Hough, Raymond Robie, and Sheila Rowan
SUPA, School of Physics and Astronomy, University of Glasgow, Glasgow, G12 8QQ, Scotland.

Matt R. Abernathy
SUPA, School of Physics and Astronomy, University of Glasgow, Glasgow, G12 8QQ, Scotland. and LIGO Laboratory, California Institute of Technology, MS 100-36, Pasadena, CA 91125, USA.

Teal Pershing
SUPA, School of Physics and Astronomy, University of Glasgow, Glasgow, G12 8QQ, Scotland. and University of California Davis, Davis, CA 95616, USA.

Steven Penn
Hobart & William Smith Colleges, Geneva, NY 14456, USA.

Thermal noise resulting from the mechanical loss of multi-layer dielectric coatings is expected to impose a limit to the sensitivities of precision measurement systems used in fundamental and applied science. In the case of gravitational wave astronomy, future interferometric gravitational wave detectors are likely to operate at cryogenic temperatures to reduce such thermal noise and ameliorate thermal loading effects, with the desirable thermo-mechanical properties of silicon making it an attractive mirror substrate choice for this purpose. For use in such a configuration of precision instrument, appropriate coatings of low thermal noise are essential. Amorphous silicon (*a*-Si) deposited by e-beam and other techniques has been shown to have low mechanical loss. However, to date, the levels of mechanical and optical loss for *a*-Si when deposited by ion-beam-sputtering (the technique required to produce amorphous mirrors of the specification for gravitational wave detector mirrors) are unknown. In this paper results from measurements of the mechanical loss of a series of IBS *a*-Si films are presented which show that reductions are possible in coating thermal noise of a factor of 1.5 at 120 K and 2.1 at 20 K over the current best IBS coatings (alternating stacks of silica and titania-doped tantala), with further reductions feasible under appropriate heat treatments.

PACS numbers: 42.79.Wc, 77.84.Bw, 81.15.Cd, 81.40.Gh
Keywords: amorphous silicon, thin films, ion-beam sputtering, cryogenic mechanical loss, thermal noise

I. INTRODUCTION

Several long baseline interferometric gravitational wave detectors in the world-wide network have been upgraded, or are in operation, and are used in the search for gravitational radiation emitted from a range of astrophysical bodies [1–5]. These detectors are designed in such a way that a passing gravitational wave will induce displacements of highly reflective mirrors, suspended as pendulums at the end of each of the interferometer arms. One significant limit to the sensitivity of such detectors will result from thermal noise associated with these highly reflective mirror coatings applied to the fused silica test masses. These are required to reflect the high power 1064 nm laser light used to illuminate the instruments [2, 6–9]. Precision interferometry is also commonly used in fundamental and applied science to measure optical path changes in high-finesse cavities for the high-precision frequency-stabilisation of lasers [10–12], in high-resolution optical spectroscopy [13], optical frequency standards [14] and fundamental quantum measurements [15]. Consequently, coating thermal noise is also expected to limit the performance of such applications.

In order to reduce thermal noise in the case of gravitational wave astronomy, there are plans for future detectors to operate at cryogenic temperatures, including schemes to upgrade existing detectors using cryogenic cooling to either 20 K or 120 K [16, 17], by the current construction of cryogenic detectors such as KAGRA, designed to operate at 20 K [18, 19] or the proposed Einstein Telescope (ET) low frequency detector at 10 K [20–23]. However, cryogenic operation will require a change of baseline test-mass material, because the mechanical loss, and therefore the thermal noise, of bulk fused silica increases rapidly at low temperatures to a broad peak at approximately 40 K [24–27]. Crystalline silicon is under consideration as an alternative test-mass material due to its low mechanical loss and thermoelastic noise at cryogenic temperatures [28–30] and its favourable thermal properties [31]. Silicon is not transparent at 1064 nm and thus the use of silicon optics would require a change in the interferometer laser wavelength, with wavelengths around 1550 nm currently being considered.

* iain.martin@glasgow.ac.uk, peter.murray@glasgow.ac.uk

The power spectral density of coating thermal noise can be approximated as [8]:

$$S_x(f) = \frac{2k_BT}{\sqrt{\pi^3}f}\frac{1-\sigma^2}{w_0Y}\Big\{\phi_{\text{substrate}} + \frac{1}{\sqrt{\pi}}\frac{d}{w_0}\frac{1}{YY'(1-\sigma'^2)(1-\sigma^2)} \times[Y'^2(1+\sigma)^2(1-2\sigma)^2\phi_{\|} + YY'\sigma'(1+\sigma)(1+\sigma')(1-2\sigma)(\phi_{\|}-\phi_{\perp}) + Y^2(1+\sigma')^2(1-2\sigma')\phi_{\perp}]\Big\}, \quad (1)$$

where f is frequency in Hz, T is temperature in Kelvin, Y and σ are the Young's modulus and Poisson's ratio of the substrate, Y' and σ' are the Young's modulus and Poisson's ratio of the coating. $\phi_{\|}$ and $\phi_{\perp}$ are the mechanical loss values for the coating for strains parallel and perpendicular to the coating surface, d is the coating thickness and w_0 is the laser beam radius.

In addition to low thermal noise, coatings for use in gravitational wave detectors are required to have very low levels of optical absorption and optical scatter loss [32]. The mirror coatings used in such detectors are typically deposited by ion-beam sputtering [33], since this technique usually provides the best optical properties (i.e. low scattering and low absorption). Current mirror coatings are made from alternating layer stacks of silica and titania-doped tantala [34]. However, some of the benefit provided by reducing the temperature at which a gravitational wave detector operates is reduced by the presence of low temperature loss peaks in the mechanical loss of both silica and titania-doped tantala films [35–37].

Another promising alternative technique to optimised amorphous ion-beam sputtered coatings, for use in an interferometric detector operating at 1550 nm, is through the use of single-crystalline coating materials, grown using molecular beam epitaxy (MBE). Cole et al. reported mechanical losses of 2×10^{-5} for a multi-layer gallium arsenide/aluminium gallium arsenide coating (GaAs/AlGaAs): a factor of 10 lower than an equivalent silica/tantala coating [38] and recent measurements of a gallium phosphide/aluminium gallium phosphide (GaP/AlGaP) multi-layer coating reported similar mechanical losses of $1.4 - 3.7 \times 10^{-5}$ at 12 K, [39]. However, such MBE coatings are not yet fully demonstrated over the large area required to produce optics for use in a future gravitational wave detector.

Amorphous silicon (*a*-Si) is an interesting candidate as a high-index coating material for low thermal noise, because *a*-Si films, when heat-treated after being deposited by electron beam (e-beam) evaporation, magnetron sputtering and self-ion implantation have all been found to have very low mechanical losses, with losses as low as $2 - 6 \times 10^{-5}$ observed at cryogenic temperatures (10-100 K) [40, 41]: over an order of magnitude lower than the lowest mechanical loss measured on ion-beam sputtered tantala films [36]. These losses were measured on the ∼5.5 kHz anti-symmetric mode of a double paddle silicon oscillator. Recent work by Liu et al. [42] reported that further improvements to the loss of e-beam films can be made at low temperatures by depositing the coatings with an elevated substrate temperature. Furthermore, *a*-Si films grown using hot-wire chemical vapour deposition (HWCVD) to produce hydrogenated *a*-Si-H were observed to have losses as low as $\sim 4 \times 10^{-7}$ at 10 K [40, 41, 43, 44]. This is over three orders of magnitude lower than observed on tantala films at a similar temperature. In addition, the high refractive index of *a*-Si (3.5 at 1550 nm [45]) would allow for a significant reduction in the thickness of a highly-reflective mirror stack, providing an additional reduction in coating thermal noise.

A highly-reflective (HR) multi-layer is usually composed of a stack of alternating layers of high and low refractive index materials. The optical thickness of each layer, $\delta = nt$ where n is the refractive index and t is the physical thickness of the layer, is equal to $\lambda/4$ for the wavelength at which reflectivity is required. The total reflectivity of an HR coating stack depends on the number of bi-layers and the difference in refractive index between the two materials. Thus, for example a silica/tantala coating stack ($n_{\text{silica}} \simeq 1.45$, $n_{\text{tantala}} \simeq 2.1$ at 1064 nm) [46] requires eighteen such bi-layers plus a half wavelength silica protection layer, and a quarter wavelength tantala transitional layer between the substrate and the bi-layers for a reflectivity of over 99.99995%. A coating of the same reflectivity composed of *a*-Si/silica would require fewer bi-layers. This reduces the required number of bi-layers to seven and thus the total thickness of the coating by over 60%, providing a direct reduction in coating thermal noise.

While the optical absorption of amorphous silicon (deposited by ion-plating) is typically significantly higher than required for use in gravitational wave detectors [47], recent work has suggested the use of *a*-Si as a replacement for the lower layers of tantala in a coating stack, where the light power is so low that the absorption requirements are significantly relaxed [48, 49].

Here we present, for the first time, measurements of the mechanical loss of a series of *a*-Si films deposited by ion-beam sputtering, and estimate the coating thermal noise in an *a*-Si/SiO_2 multi-layer mirror coating.

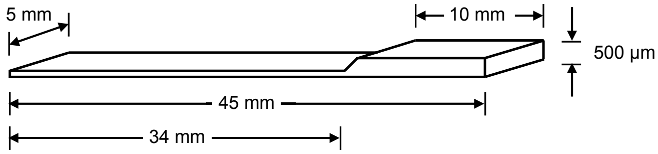

FIG. 1. A schematic diagram of a silicon cantilever. The cantilever length is parallel to the [110] crystal axis. The coatings are ion-beam sputtered onto the underside of the flexure.

II. SAMPLE PREPARATION

The *a*-Si coatings were deposited onto silicon cantilever substrates, designed with one thick end which is used for mounting the samples with minimal frictional energy loss in a clamping structure [50, 51]. In addition to being an interesting substrate material for cryogenic gravitational wave detectors, the low mechanical loss and high thermal conductivity make silicon a good substrate for use in the studies of thin film dissipation at low temperature [52]. The mechanical loss of a thin film can be calculated from the change in the mechanical dissipation of a silicon cantilever after the addition of a film to its surface.

The *a*-Si coatings were deposited by Advanced Thin Films using ion-beam sputtering, with a crystalline silicon target [53]. Post-deposition heat-treatment is often used to improve the optical properties of coatings. To investigate the effect of heat-treatment on the mechanical loss of the films, two coated cantilevers were heat-treated at 300 °C, two at 450 °C, while four cantilevers underwent no post-deposition heat-treatment (referred to as the 'as-deposited' samples). The heat-treatment temperatures were chosen by the coating vendor, with 450 °C being the highest temperature to which they recommended treating the *a*-Si films, where the optical absorption was observed to be at a minimum [54]. Prior to coating, thermal oxide layers of approximately 25 nm thickness on each face were grown on the cantilevers to ensure proper adhesion of the coating [55].

III. EXPERIMENTAL PROCEDURE

When a coating is thin in comparison with the substrate flexure, the temperature dependence of the mechanical loss of a thin film, $\phi(\omega_0)_{\text{coating}}$, can be measured by comparing the mechanical loss of the bending resonant modes of a substrate at a range of temperatures before and after deposition of the film [56]:

$$\phi(\omega_0)_{\text{coating}} = \frac{Y_{\text{s}} t_{\text{s}}}{3 Y_{\text{c}} t_{\text{c}}} (\phi(\omega_0)_{\text{coated}} - \phi(\omega_0)_{\text{substrate}}), \quad (2)$$

where ω_0 is the angular frequency of the bending mode, $\phi(\omega_0)_{\text{coated}}$ is the loss factor of the coated cantilever, $\phi(\omega_0)_{\text{substrate}}$ is the loss factor of the un-coated reference cantilever, t_{s} and Y_{s} are the thickness and Young's modulus (166 GPa [57]) of the substrate respectively and t_{c} and Y_{c} are the thickness and Young's modulus of the coating respectively. The Young's modulus of an as-deposited (AD) *a*-Si film was measured by nano-indentation to be 147 ± 4.7 GPa [58], using the apparatus and techniques described by Abernathy et al. [59].

The cantilevers were held in a stainless steel clamp fastened securely to the liquid helium cooled baseplate of the vacuum chamber of a temperature controlled cryostat[60]. The bending modes of the sample can be excited in turn using an electrostatic actuator aligned a few millimetres below the cantilever. This dissipation $\phi(\omega_0)$ can then be found by making a fit of the free exponential decay of the resonant motion [56]

$$A(t) = A_0 e^{-\phi(\omega_0)\omega_0 t/2}. \quad (3)$$

The motion was sensed by illuminating the oscillating section of the cantilever with a laser beam which was then reflected onto a split photodiode sensor outside the cryostat. Several measurements cycles were carried out on each sample, during which the cantilever temperature was increased systematically from approximately 10 K to 300 K using a Lakeshore Model 336 Cryogenic Temperature Controller, maintained typically to within 0.1 K of the set-point. The temperature of the cantilever was recorded using a Lakeshore DT-670-SD silicon-diode sensor mounted inside a small hole on the clamp just below the fixed end of the cantilever. The samples were removed and re-clamped between temperature cycles. This experimental techniques is discussed in greater detail in Martin et al. [36].

IV. RESULTS AND ANALYSIS

Figure 2 shows the results obtained for silicon cantilevers coated with 500 nm of amorphous silicon for the resonant modes at approximately 0.51 kHz, 1.43 kHz, 2.81 kHz and 4.64 kHz, measured as-deposited and after 300 °C and 450 °C heat-treatments. The difference in loss above 200 K between the un-coated cantilever and the predicted level of thermoelastic loss is due to the presence of the additional thermal oxide layer for better adhesion of the coating.

Figure 3 summarises the mechanical loss of the *a*-Si films as a function of temperature. It is clear that the losses of these films all are significantly lower than a 600 °C heat-treated, undoped Ta_2O_5 coating below 150 K [36]. The loss of the as-deposited *a*-Si film is $\sim 3 \times 10^{-5}$ at 10 K, over an order of magnitude lower than the tantala coating at the same temperature. The as-deposited *a*-Si film shows consistently a broad peak in mechanical loss centered around ∼50 K. There is evidence that heat-treatment at 300 °C and at 450 °C suppresses this peak and reduces the magnitude of the loss at cryogenic temperature by over a factor of two. At temperatures below 100 K no significant difference in the loss was observed

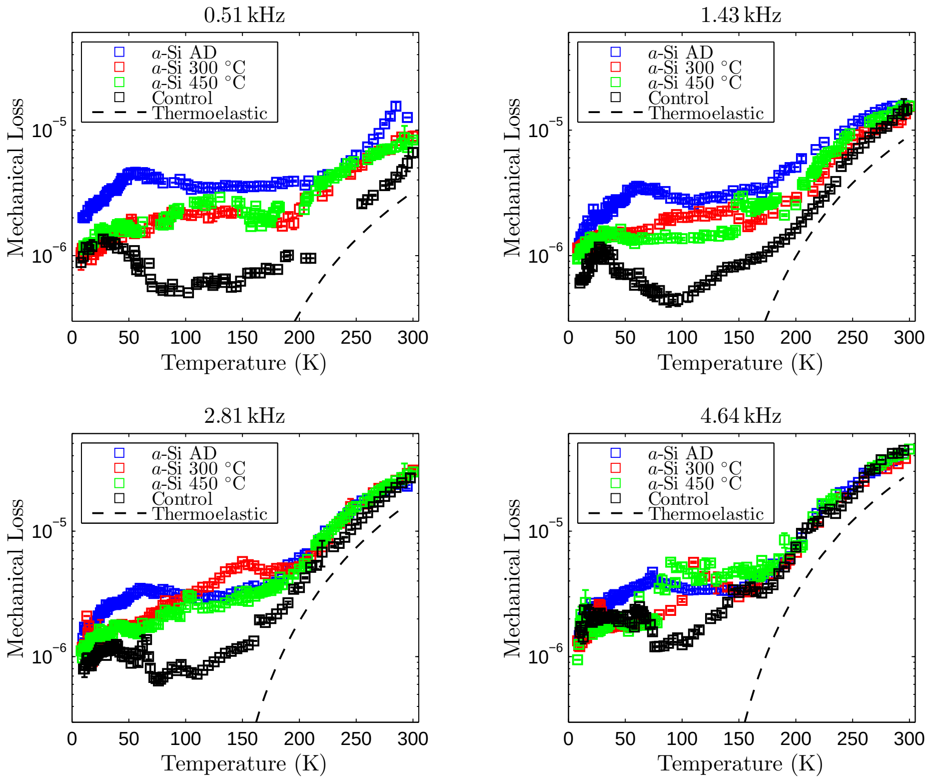

FIG. 2. Measured mechanical loss of the 0.51 kHz, 1.43 kHz, 2.81 kHz and 4.64 kHz bending modes as a function of temperature of a 34 mm long by 5 mm wide by 65.5 μm thick silicon cantilever coated with a 500 nm thick as-deposited *a*-Si film (blue) and after 300 °C (red) and 450 °C (green) heat treatments. Also measured mechanical losses of a nominally identical silicon cantilever used as a control (black), plotted together with the calculated thermoelastic loss of the substrate at each of the frequencies (dashed).

between the coatings heat-treated at 300 and 450 °C. There is some evidence that the higher heat-treatment may slightly reduce the loss at higher temperatures.

A. Investigations of Coating Mechanical Loss at Room Temperature

At temperatures above 150 K, the difference in the loss measured between the coated and uncoated samples becomes increasingly small due to the presence of the thermal oxide layer and also the rapid increase of the thermoelastic loss of the silicon cantilever. As a result, it is not possible to measure the coating loss with adequate sensitivity in this temperature range. Thus the results are focussed below 150 K, which is the temperature range of interest for cryogenic gravitational wave detectors.

However, amorphous silicon may also be of interest as a high index coating material in the upgrades to room temperature detectors. Thus coating loss measurements were carried out at room temperature using fused silica disk substrates, which have sufficiently low bulk and thermoelastic loss at room temperature to provide the required sensitivity to the coating loss [61]. Details of the silica substrates, and the method used to suspend them for loss measurements, are given in [61]. The samples are brought to resonance using an electrostatic drive, and the ringdown is measured using ellipsometry. The data is filtered by a lock-in amplifier ($f_{\text{beat}} \approx 0.3$ Hz) and fit to a damped sinusoid with minor frequency variations used to account for fluctuating sample temperature during long ringdowns. From the ringdown time constant, τ, the sample loss is given by $\phi_{\text{sample}} = \frac{2}{\omega_0 \tau}$. Modes are measured up to 30 kHz. The sample loss is composed of its constituent losses

$$\phi_{\text{sample}} = \frac{E_{\text{substrate}}}{E_{\text{total}}}\phi_{\text{substrate}} + \frac{E_{\text{coating}}}{E_{\text{total}}}\phi_{\text{coating}} \qquad (4)$$

where the energy ratios are calculated using the finite element software, COMSOL Multiphysics [62], and $\frac{E_{\text{substrate}}}{E_{\text{total}}} \approx 1$. Assuming structural (frequency-independent) loss factors, the data can be fit to extract ϕ_{coating} and $\phi_{\text{substrate}}$. Using the best fit value for $\phi_{\text{substrate}}$, one can display the frequency dependence of ϕ_{coating}.

The as-deposited coating was dominated by excess low frequency losses, visible in figure 4, due most likely to residual stress. The 450 °C annealed sample had a coating loss of $\phi_{\text{coating}} = 9.0 \pm 0.1 \times 10^{-5}$, which is approximately a factor of three lower than tantala [63] and a

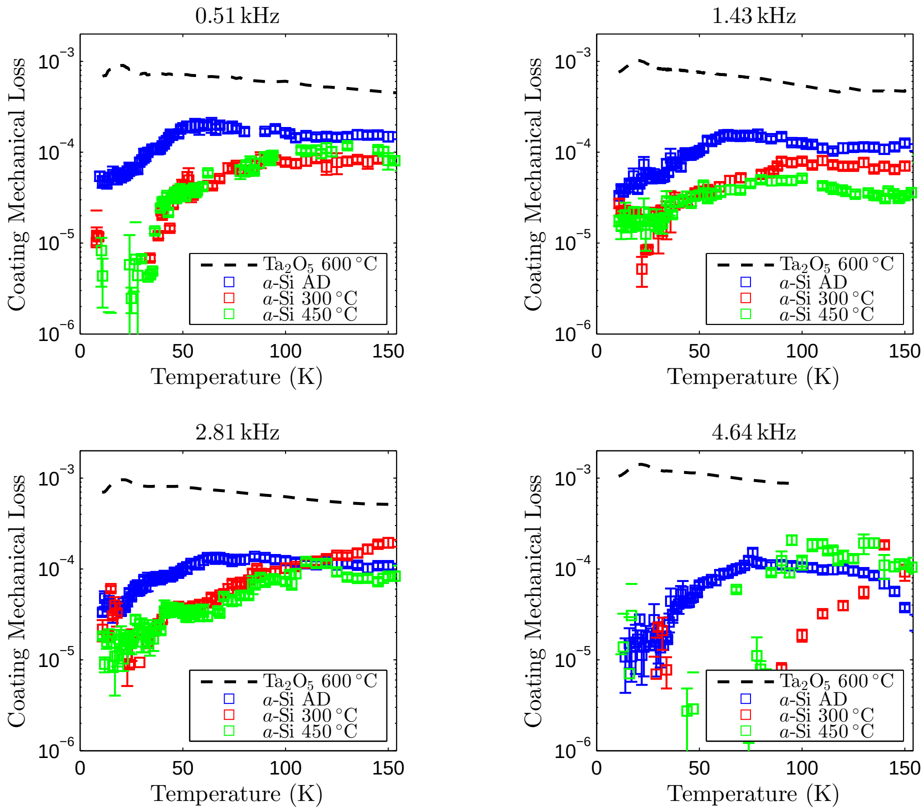

FIG. 3. Coating Mechanical loss of the 0.51 kHz, 1.43 kHz, 2.81 kHz and 4.64 kHz bending modes as a function of temperature of 500 nm thick films; as-deposited *a*-Si (blue), 300 °C heat-treated *a*-Si (red) and 450 °C heat-treated *a*-Si (green). The dashed line shows the coating loss of an undoped tantala film heat-treated to 600 °C at each of the resonant frequencies for comparison [36].

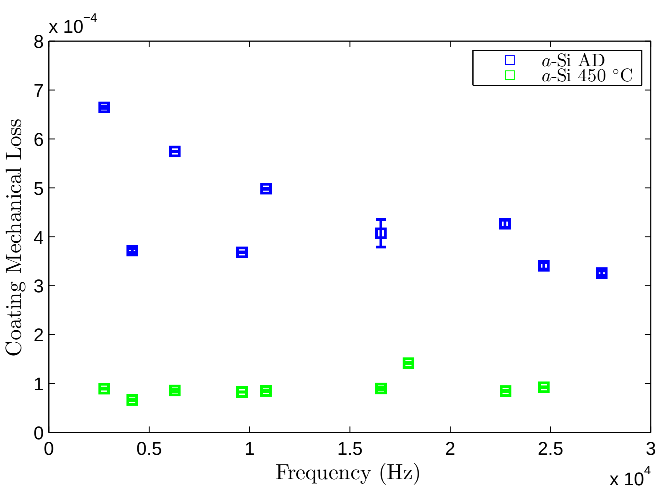

FIG. 4. Room temperature coating mechanical loss of a 500 nm thick *a*-Si film on a 3 inch diameter by 0.1 inch thick fused silica disk; as-deposited (blue) and after a 450 °C heat-treatment (green).

factor of five lower than both magnetron and e-beam sputtered *a*-Si films, as shown in Table I. The 450 °C annealed data shows the coating mechanical loss is reduced after the heat treatment and with no notable frequency dependence. A discrepancy in fitting the drumhead modes was observed, suggesting a difference in the bulk and shear losses, which is under investigation.

B. Comparison with other deposited amorphous silicon films

Liu et al. [40, 41, 43, 44] conducted investigations on the $\sim$ 5.5 kHz anti-symmetric mode of a double paddle silicon oscillator created using several different deposition techniques. As summarised in table I, the losses of both magnetron sputtered and e-beam *a*-Si films are higher at 10 K and 100 K, but similar improvement in the losses were observed after heat treatment. The losses of the ion-beam sputtered coatings here are comparable to $^{28}Si^{+}$ implanted amorphous silicon films. They also have a level of loss similar to a series of low-pressure hot-wire chemical vapor deposited (HWCVD) and plasma-enhanced chemical-vapour deposition (PECVD) amorphous silicon films grown in H_2 diluted silane (*a*-Si H_2:SiH_4) at differing deposition and flow rates in order to vary the hydrogen content. HWCVD hydrogenated amorphous silicon

TABLE I. Loss of a-Si films at 10 K, 100 K and 300 K deposited using a variety of different techniques.

Film Deposition	Loss of a-Si Film ($\times 10^{-4}$) 10 K	100 K	300 K
Magnetron sputtered AD [41]	0.9	2.5	5
Magnetron sputtered 350 °C [41]	0.2	1.5	6
e-beam AD [41]	1.5	3	3.3
e-beam 350 °C [41]	0.6	2	5.3
e-beam (T_{sub} 350 − 400 °C) [42]	0.01 − 0.05	-	-
$^{28}Si^{+}$ implantation AD [41]	0.5	1	0.9
$^{28}Si^{+}$ implantation 300 °C [41]	0.2	0.8	-
HWCVD a-Si H [44]	0.005 − 0.9	0.035 − 5	-
HWCVD a-Si H_2:SiH_4 [44]	0.25 − 0.4	0.8 − 1.5	-
PECVD [44]	0.035 − 0.4	0.045 − 8	-

(a-Si H) films grown at differing deposition rates to vary the hydrogen content show a large range in the loss, with a-Si H films produced with one atomic percentage of hydrogen (1 at.% H) observed to have levels of loss more than two orders of magnitude smaller than coatings produced by all other deposition techniques.

C. Calculation of an upper limit of the loss for the 4.64 kHz resonant mode

It is clear from figure 2 that there is a loss peak below 50 K in the levels of loss of the uncoated cantilever. This is believed to be due to the thermal oxide layer present on the cantilevers. This peak is seen on the 4.64 kHz mode to be similar to the levels of loss measured on the coated samples. This increase makes it hard to distinguish the loss of the films from the substrate loss, yielding, on occasion, an un-physical negative coating loss. It is, however, possible to calculate an upper limit for the loss of the a-Si films at this frequency using the predicted level of thermoelastic loss for such a cantilever, as shown in figure 5. This upper limit of the loss for the different heat treatments is still over an order of magnitude better at low temperatures than that of a 600 °C heat treated tantala film.

V. ARRHENIUS ANALYSIS OF LOSS PEAKS IN AS-DEPOSITED FILM

On the as-deposited a-Si film a dissipation peak was observed between 60 and 90 K. Furthermore, the peak temperatures were found to vary with frequency. This behaviour is characteristic of a thermally activated dissipation process, similar to those previously seen in tantala [36] and titania-doped tantala films [63]. Such processes can be characterized by a rate constant, τ_0, and an activation energy, E_a, which are related by the Arrhenius

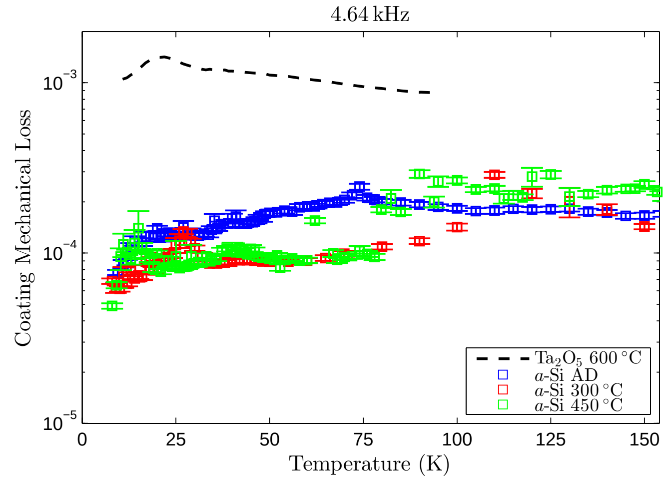

FIG. 5. Upper limit of the coating mechanical loss calculated using thermoelastic loss of the 4.64 kHz resonant mode as a function of temperature of a 500 nm thick films; as-deposited a-Si (blue), 300 °C heat-treated a-Si (red) and 450 °C heat-treated a-Si (green).

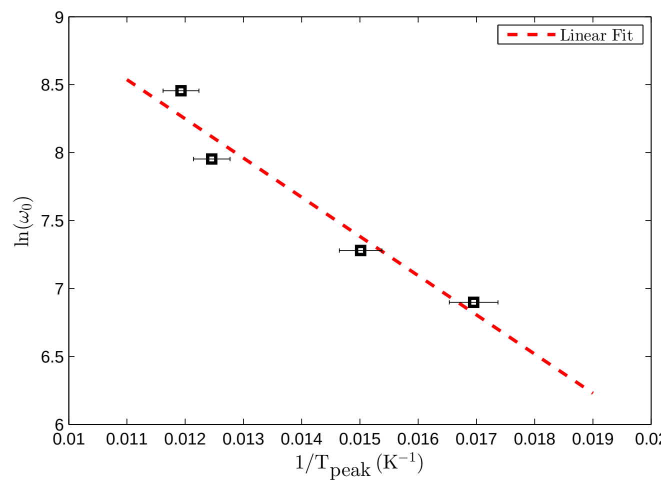

FIG. 6. Arrhenius plot of the loss peaks at 60 - 90 K observed in the as-deposited a-Si film.

equation [64]:

$$\tau = \tau_0 \exp\left(\frac{E_a}{k_B T}\right) \tag{5}$$

where τ is the relaxation time associated with the dissipative system returning to its equilibrium after being perturbed. The temperature of the dissipation peak T_{peak}, at resonant angular frequency ω_0, is related to the activation energy and rate constant as follows [64]:

$$\omega_0 \, \tau_0 \exp\left(\frac{E_a}{k_B T_{peak}}\right) = 1. \tag{6}$$

Therefore, plotting log ω_0 against $1/T_{peak}$ should give a straight line fit, from which the activation energy and rate constant for the dissipation process can be calculated. Figure 6 shows this analysis for the peak, observed between 60 and 90 K, on the as-deposited a-Si film. The activation energy and rate constant calculated from this linear fit, were found to be (24.9 ± 4.2) meV and $(8.2 \pm 0.5) \times 10^{-6}$ s respectively. There is further evidence of a dissipation peak around 100 K at 5.5 kHz on magnetron sputtered and e-beam films [40, 41].

VI. PREDICTION AND MEASUREMENT OF THE LOSS OF AN A-SI/SIO$_2$ BI-LAYER

In a first step towards estimating the thermal noise in an a-Si/SiO$_2$ coating, measurements of both a single layer of SiO$_2$ and a quarter-wavelength a-Si/SiO$_2$ bi-layer were carried out. The measured losses are shown in figure 7. Using a Young's Modulus of 72 GPa for silica, the loss of the silica film for the four resonant modes can then be calculated, as shown in figure 8.

The loss of such a a-Si/SiO$_2$ bi-layer film can be calculated from the single-layer data measured on a silicon substrate presented in figure 7. Assuming that the loss of these films is independent of thickness, and that no additional loss is associated with the interfaces in a multi-layer film, the total loss of a quarter wavelength bi-layer can be estimated as:

$$\phi_{\mathrm{coating}} = \frac{Y_{\mathrm{SiO_2}} t_{\mathrm{SiO_2}} \phi_{\mathrm{SiO_2}} + Y_{a-\mathrm{Si}} t_{a-\mathrm{Si}} \phi_{a-\mathrm{Si}}}{Y_{\mathrm{coating}} t_{\mathrm{coating}}}. \tag{7}$$

It can be shown from composite materials theory that the effective Young's modulus in an isotropic multi-layer coating consisting of two materials, in this case a-Si and SiO$_2$, is stated by [65]:

$$Y_{\mathrm{coating}} = \frac{Y_{a-\mathrm{Si}} t_{a-\mathrm{Si}} + Y_{\mathrm{SiO_2}} t_{\mathrm{SiO_2}}}{t_{a-\mathrm{Si}} + t_{\mathrm{SiO_2}}}, \tag{8}$$

giving, in this case, an effective Young's Modulus of the bi-layer coating of 94.2 GPa. Using the data for the losses of the a-Si and SiO$_2$ films in figure 8 it is possible to predict the loss of an a-Si/SiO$_2$ bi-layer film, as shown by the dashed region, where the largest uncertainty comes from the effective Young's Modulus.

Advanced Thin Films produced a silicon cantilever coated with a bi-layer film comprising of a 112 nm thick a-Si and a 267 nm thick SiO$_2$ layer. The measured mechanical losses of this coated cantilever are shown in figure 7. The loss of this bi-layer coating was then calculated using the effective Young's Modulus and plotted together, and in reasonable agreement, with the predicted levels of loss in figure 8.

VII. ESTIMATION OF THE THERMAL NOISE OF A MULTI-LAYER A-SI/SIO$_2$ FILM

The measured mechanical loss of the a-Si/SiO$_2$ bi-layer film can used to estimate the thermal noise performance of an a-Si/SiO$_2$ mirror coating at low temperature. For a standard $\lambda/4$ HR coating, the required layer thicknesses for operation at 1550 nm can be found using $\delta = nt$, as detailed earlier, to be 112 nm and 267 nm for amorphous silicon and silica respectively. The reflectivity of such a coating is given by:

$$R_{2N} = \left(\frac{n_{\mathrm{S}} f - n_0}{n_{\mathrm{S}} f + n_0} \right)^2, \tag{9}$$

where n_{S} is the refractive index of the substrate and $f = (n_{a\text{-}\mathrm{Si}}/n_{\mathrm{SiO_2}})^{2N}$, n_0 here is 1 for the case of incident light in a vacuum and N is the number of coating layer pairs. Therefore the number of bi-layers required to give an equivalent reflectivity to an Advanced LIGO End Test Mass (ETM) coating (99.99995%) on a silicon substrate can be found to be seven. At 295 K the average loss of the a-Si layers was taken from figure 4 and from Martin et al. for the SiO$_2$ layers [37]. The linear spectral density of the Brownian thermal noise arising from a multi-layer a-Si/SiO$_2$ film is shown for 295 K and also at 120 K and 20 K, as an indication of temperatures at which a future cryogenic detector may operate, in figure 9 [16, 17, 66]. For comparison, the Brownian noise of an Advanced LIGO ETM on a silicon substrate, with the thicknesses adjusted to operate at 1550 nm, is plotted for 295 K, 120 K and 20 K.

From figure 9 it can be seen that at 295 K there is a 30% improvement in the thermal noise switching from an Advanced LIGO ETM coating optimised for 1550 nm to a multi-layer a-Si/SiO$_2$ film. The linear spectral density of the coating thermal noise is proportional to the temperature of the coating, therefore cooling should provide a reduction in the thermal noise. However, it is also dependent on the mechanical loss of the constituent coating materials, and loss peaks have been observed at low temperatures in single layers of silica [37], titania-doped tantala [67] and in multi-layer doped Ta$_2$O$_5$/SiO$_2$ films [34]. Consequently, there is only a 40% improvement in the thermal noise of an Advanced LIGO ETM coating when cooled from 120 K to 20 K. Switching to a-Si as a high index material results in the required total thickness of coating to be much less, but, even using the levels from the as-deposited a-Si/SiO$_2$ film, the levels of Brownian thermal noise improve over an Advanced LIGO coating by almost 20% at 120 K, and, with no low temperature loss peaks evident on the bi-layer films, this is estimated to improve further the thermal noise such that it is 55% lower than the Advanced LIGO coating at 20 K.

Our measurements of the loss of single layer a-Si coatings suggest that this could be improved further by investigating the effect of heat treatment on the loss of a-Si/SiO$_2$ coatings. In order to estimate the linear spectral density of the Brownian thermal noise of a a-Si/SiO$_2$ coating after a 450 °C heat-treatment the level of loss at 20 K of the a-Si layers was taken from figure 4 and from Martin et al. for the SiO$_2$ layers [37] and the estimated level of noise plotted in figure 9. It is clear that the further significant improvement in noise performance is

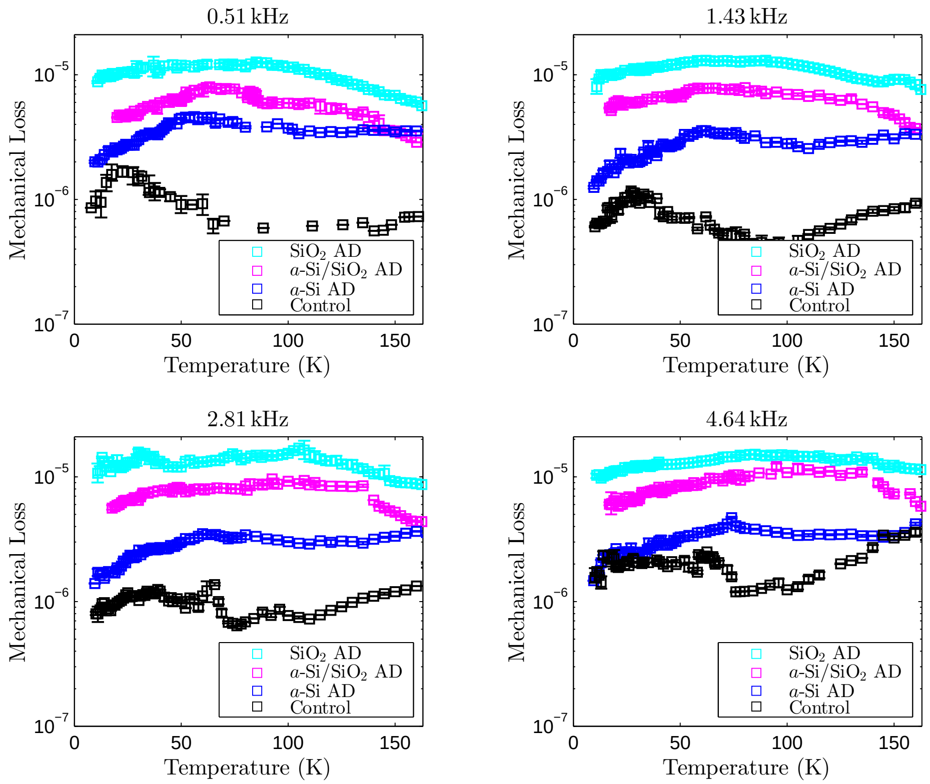

FIG. 7. Measured mechanical loss of the 0.51 kHz, 1.43 kHz, 2.81 kHz and 4.64 kHz bending modes as a function of temperature of a 34 mm long by 5 mm wide by 65.5 μm thick silicon cantilever coated with a 500 nm thick as-deposited *a*-Si film (blue), SiO_2 (cyan) and a 379 nm thick *a*-Si/SiO_2 bi-layer (magenta).

limited by the low index silica layers.

Using the coating loss of an ETM [68] (measured at 1.3 kHz) and the corresponding loss of the as-deposited a-Si/SiO_2 bi-layer from figure 8, it is possible to plot the Brownian thermal noise as a function of temperature at 100 Hz for an Advanced LIGO ETM and an*a*-Si/SiO_2 coating as shown in figure 10.

VIII. CONCLUSION

In the 10 to 150 K temperature range investigated here, the loss of ion-beam sputtered amorphous silicon is significantly lower than that of tantala. Losses of 3×10^{-5} have been measured at 10 K for an as-deposited *a*-Si film and there is evidence of a thermally activated dissipation process at 50 K. Heat-treatment at 450 °C is observed to reduce the loss by a factor of two, and remove the loss peak at 50 K. This makes *a*-Si a very exciting candidate coating material for use in a range of precision measurement systems. The loss of the 450 °C heat-treated coating was a factor of three lower than tantala at room temperature. It was observed that the as-deposited coating loss had a significant frequency dependence at room temperature, while after heat-treatment the loss was essentially constant with frequency. This is possible due to removal of residual stress by the heat treatment.

In the case of an interferometric gravitational wave detector, the levels of loss measured for an *a*-Si/SiO_2 bi-layer suggest that a significant improvement in the level of coating thermal noise over that of currently used coatings is possible even with an as-deposited *a*-Si/SiO_2 coating. At 295 K the level of Brownian thermal noise of a multi-layer *a*-Si/SiO_2 coating on a silicon substrate is reduced by 30% than that of an equivalent Advanced LIGO coatingvand at 20 K demonstrated to be more than two times lower. Our results suggest improvements can be made by heat treating *a*-Si/SiO_2 coatings. Any improvement in the loss will lead to improvements in the levels of thermal noise. Eventually, such levels of thermal noise will become limited by the low-temperature loss of the silica layers in the coating. To exploit fully the potential of amorphous silicon, reductions in the loss of the low-index layers are also required.

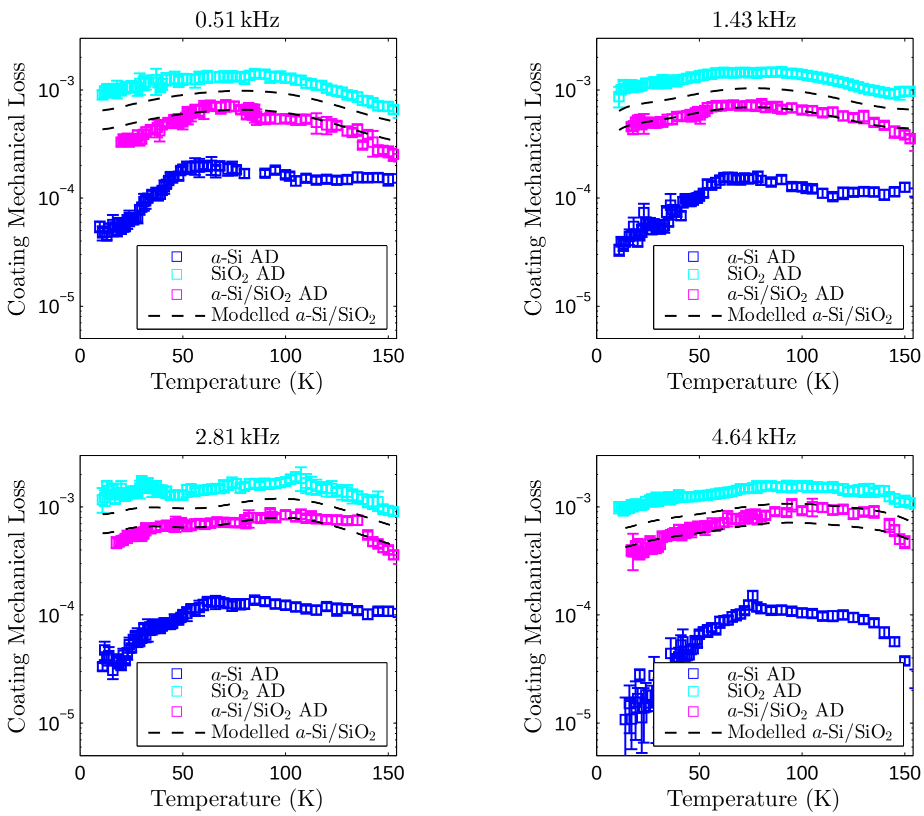

FIG. 8. Coating Mechanical loss of the 0.51 kHz, 1.43 kHz, 2.81 kHz and 4.64 kHz bending modes as a function of temperature of a 500 nm thick as-deposited *a*-Si film (blue) and SiO_2 (cyan). The dashed line represents the predicted level of loss of a 379 nm thick *a*-Si/SiO_2 bi-layer coating, compared with the measured coating loss of such a bi-layer (magenta).

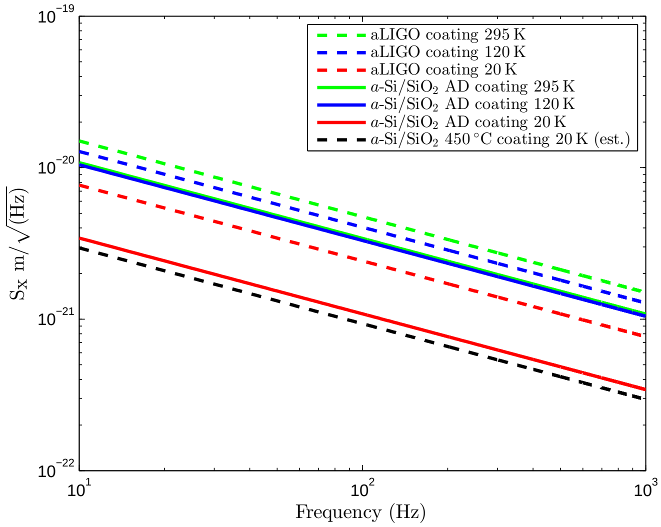

FIG. 9. Brownian thermal noise for an Advanced LIGO coating, optimised for 1550 nm, at 295 K (dashed green), 120 K (dashed blue) and at 20 K (dashed red) and for an as-deposited a-Si/SiO$_2$ coating at 295 K (green), 120 K (blue) and at 20 K (red). Note that the 295 K (green) and 120 K (blue) lines overlap. The dashed black line represents the estimated level of Brownian thermal noise at 20 K of an a-Si/SiO$_2$ coating after a 450 °C heat-treatment.

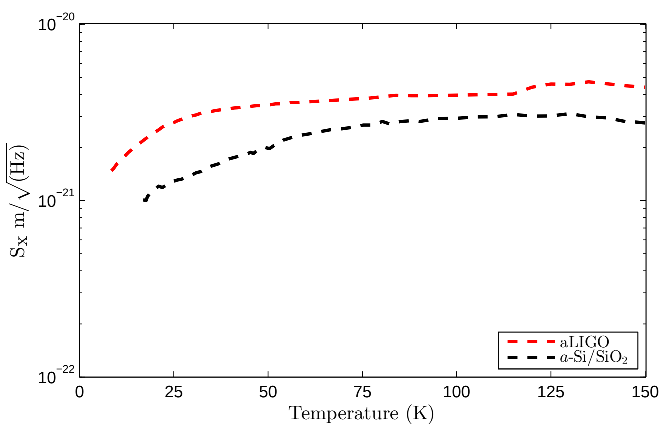

FIG. 10. Brownian thermal noise at 100 Hz as a function of temperature for an Advanced LIGO coating (red) compared with the Brownian thermal noise for an as-deposited a-Si/SiO$_2$ coating (black).

ACKNOWLEDGMENTS

We are grateful for the financial support provided by SUPA, STFC (ST/L000946/1 'Investigations in Gravitational Radiation') and the University of Glasgow. IWM is supported by a Royal Society Research Fellowship. SR holds a Royal Society Wolfson Research Merit Award. SP is supported by the NSF through grant PHY-1307423. We are also grateful to the International Max Planck Partnership for Measurement and Observation at the Quantum Limit for support. We would like to thank our colleagues in SUPA, the LSC, Virgo and KAGRA Collaborations for their interest in this work. This article has LIGO document number LIGO-P1500080-v1.

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