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Optical absorption measurement at 1550 nm on a highly-reflective Si/SiO_2 coating stack

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Abstract

Future laser-interferometric gravitational wave detectors (GWDs) will potentially employ test mass mirrors from crystalline silicon and a laser wavelength of 1550 nm, which corresponds to a photon energy below the silicon bandgap. Silicon might also be an attractive high-refractive index material for the dielectric mirror coatings. Films of amorphous silicon (a-Si), however, have been found to be significantly more absorptive at 1550 nm than crystalline silicon (c-Si). Here, we investigate the optical absorption of a Si/SiO_2 dielectric coating produced with the ion plating technique. The ion plating technique is distinct from the standard state-of-the-art ion beam sputtering technique since it uses a higher processing temperature of about 250 °C, higher particle energies, and generally results in higher refractive indices of the deposited films. Our coating stack was fabricated for a reflectivity of $R = 99.95\%$ for s-polarized light at 1550 nm and for an angle of incidence of 44°. We used the photothermal self-phase modulation technique to measure the coating absorption in s-polarization and p-polarization. We obtained $\alpha_s^{\mathrm{coat}} = (1035 \pm 42)$ ppm and $\alpha_p^{\mathrm{coat}} = (1428 \pm 97)$ ppm. These results correspond to an absorption coefficient which is lower than literature values for a-Si which vary from 100 cm^{-1} up to 2000 cm^{-1}. It is, however, still orders of magnitude higher than expected for c-Si and thus still too high for GWD applications.

Keywords: optical absorption, mirror coatings, Si/SiO_2
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(Some figures may appear in colour only in the online journal)

1. Introduction

Highly-reflective (HR) dielectric mirror coatings are essential for interferometric gravitational wave detectors (GWDs). Optical coatings with low optical absorption and low mechanical loss are required [1]. It is expected that mechanical loss in optical coatings will result in a significant thermal noise source in GWDs of the second generation, which are currently under construction [2]. The second generation of GWDs will operate at the well-established laser wavelength of 1064 nm and will use well-established dielectric optical coatings made of alternating layers of silica (SiO_2) and tantala (Ta_2O_5). The test mass mirror HR coatings for the 1st generation LIGO GWDs [3] had a design transmission of 5 ppm [4] and an absorption requirement of $\leqslant 1$ ppm. For the second generation Advanced LIGO GWDs the optical absorption needs to be less than 0.5 ppm [1, 4]. While coatings with the specified absorption requirement were already produced [1], the mechanical loss realized is still above the requirement of $\phi = 5 \times 10^{-5}$ [4], at which tantala contributes most to the coating's mechanical loss [2]. Doping the tantala with titanium reduces the loss by nearly a factor of two, but slightly increases the coating absorption [1]. In addition, titanium doped tantala shows a loss peak at low temperatures [5], where some of the third generation GWDs will operate [6]. Therefore various materials are under investigation to replace tantala within dielectric coatings [7].

Because of its high mechanical Q-factor at cryogenic temperatures [8, 9], crystalline silicon (c-Si) is considered as a test-mass material [7] for future GWDs. c-Si shows a high optical absorption at 1064 nm. Since the absorption decreases rapidly toward higher wavelengths [10], the use of c-Si test masses is planned at a wavelength of 1550 nm, which corresponds to a photon energy below the silicon band gap. Silicon might also be an interesting candidate for a coating material in view of replacing tantala. The high index of refraction of Si of $n_{\mathrm{Si}} = 3.48$ at 1550 nm [11] significantly reduces the number of single layers required to achieve high reflectivities. It also reduces the geometrical thickness of the coating stack, since a single layer has a constant optical thickness of about a quarter of the wavelength. The optical as well as the mechanical loss of the Si films, however, need to be less than the values for tantala. Dielectric coating stacks usually contain amorphous material, and amorphous Si (a-Si) is known to be rather absorptive at 1550 nm [12–14]. In [12] it is reported that annealing of a-Si reduces the absorption coefficient of the material. The a-Si in [12] was produced with radio-frequency sputtering.

In this work we present optical absorption measurements at 1550 nm on a HR Si/SiO_2 coating produced with the ion plating technique. The coating was produced with high particle energies between 30 and 50 eV, a high processing temperature of about 250 °C, and was finally annealed at 400 °C. The coating was fabricated by *Tafelmaier Dünnschicht-Technik GmbH* [15] and optimized for a reflectivity of $R = 99.95\%$ at 1550 nm in s-polarization and an angle of incidence (AOI) of 44°. The ion plating technique is distinct from today's state-of-the-art ion beam sputtering technique since it uses a higher processing temperature, higher particle energies, and generally results in higher refractive indices of the deposited films. The optical absorption of Si-films produced with this technique is not known. Our absorption measurement was performed in a three-mirror ring-cavity setup (see figure 1(*a*)) in s- and p-polarization using the photothermal self-phase modulation (PSM) technique [16, 17]. The actual design of the coating stack was not at our disposal. Therefore, we used a model coating stack [18] that matched our measurement results for the reflectivities in s- and p-polarization. From this model we calculated the absorption coefficient of the Si layers taking into account an effective penetration depth of the laser beam.

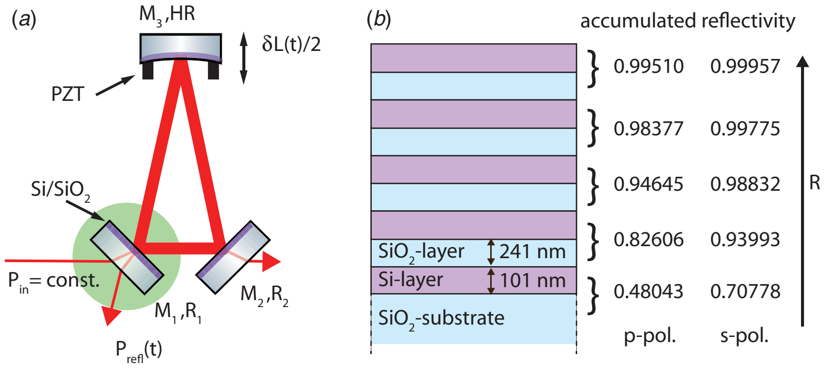

Figure 1. (*a*) Experimental setup of the three-mirror ring-cavity with mirror power reflectivities $R_1 = R_2 = 99.947\%$ (measured in s-polarization) and $R_3 > R_{1,2}$ being close to unity. The cavity length was changed by a piezoactuator (PZT) mounted between the cavity spacer and mirror M_3. The absorption of the coating of in-coupling mirror M_1 (green) was measured in s-polarization and p-polarization at an angle of incidence of 44°. (*b*) Schematic of our dielectric Si/SiO$_2$-coating model that we used to transfer our measurement results to absorption coefficients of the ion plating deposited silicon. By matching the reflectivities to our measurement results, the thickness of the single layers and the reflectivities for the double layers were calculated using [18].

Table 1. Material and geometric parameters of the Corning 7980 mirror substrates and our cavity, respectively, as used to simulate the self-phase modulation and to derive the coating absorption.

Material parameters (at 1064 nm and room temperature)		Cavity geometry parameters	
Index of refraction n	1.48 [19]	Round-trip length L	42 cm
Thermal refr. coeff. $\mathrm{d}n/\mathrm{d}T$	8.45×10^{-6} K^{-1} [19]	Beam waist (radius) w_0	448 μm
Specific heat c	770 J (kg K)$^{-1}$ [20]	Mirror length D	6.35 mm
Density ρ	2201 kg m^{-3} (see footnote no 1)	Mirror radius r	12 mm
Thermal expansion a_{th}	0.52×10^{-6} K^{-1} (see footnote no 1)	AOI	44°
Thermal conductivity k_{th}	1.3 W (m K)$^{-1}$ (see footnote no 1)		

2. Experimental setup and results

The technique of PSM allows coating absorption measurements, if the substrate that carries the mirror coating is used as the incoupling mirror of an optical cavity [16, 17]. For our experiment we used a three-mirror ring-cavity formed by the plane in-coupling mirror M_1 and end-mirror M_2 together with the concave HR coated mirror M_3 (see figure 1(*a*)). All three mirrors had substrates from Corning 7980 glass[1]. All coatings were manufactured by Tafelmaier [15] using the ion plating technique. The coatings of M_1 and M_2 were produced in the same coating run and designed for a reflectivity of $R = (99.95 + 0.01/-0.03)\%$ at an AOI of 44° for a wavelength of 1550 nm and s-polarization. The HR coating of M_3 had negligible transmission compared to the transmissions of M_1 and M_2. The mirror substrate parameters and cavity geometry parameters are presented in table 1.

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[1] Corning Inc., USA www.corning.com.

The three mirrors forming the cavity were glued to an aluminum spacer. In the course of our PSM technique, the cavity length was scanned and the shapes of the cavity resonance peaks were recorded. A piezoactuator (PZT) between M_3 and the spacer was used to modulate the cavity round-trip length. To minimize a potential nonlinear motion of the PZT the cavity length was scanned only in a small range around a cavity resonance of approximately 10% of a free spectral range. The modulation voltage was constant for all measurements. To compensate for an remaining nonlinearity of the PZT motion as well as to compensate for a potential PZT hysteresis the actual mirror motion for each modulation frequency and ramp side (expansion or contraction of the PZT) was calibrated using phase-modulation side-bands imprinted on the laser signal via an electro optical modulator before entering the cavity. The resonance peaks for the absorption measurements were detected in reflection of M_1 with a photo diode (PD).

In this setup, the PSM technique provides the absorption of the coating of the in-coupling mirror M_1. While the intra-cavity field builds up, the coating absorbs light. The resulting heat is transferred to the substrate of the incoupling mirror and the in-coupled beam receives a phase shift due to the change of the optical path length through M_1 resulting in a broadening and narrowing of the cavity resonance peak. At the same time absorption in the coatings of all three mirrors result in thermal expansion of the mirrors, which shortens the cavity round-trip length. The measured deformation of the cavity resonance peaks is, however, clearly dominated by the first effect.

A pair of two deformed resonance peaks—one for shortening and one for lengthening the cavity—allowed us to obtain the quantities R_1, $\tilde{R}_2$ and α^{coat}. R_1 is the power reflectivity of in-coupling mirror M_1, whereas $\tilde{R}_2$ is the *effective* reflectivity of M_2 that includes all cavity round-trip losses apart from the transmission of M_1, and α^{coat} is the absorption of the coating of M_1. A measurement of such a pair of resonance peaks we shall call in the following a *single* measurement. To reduce errors due to statistical fluctuations, several single measurements were performed. For every single measurement a Nelder–Mead algorithm varied R_1, $\tilde{R}_2$ and α^{coat}, and thus minimized the deviation between simulated and measured data. The single measurements were carried out with different scan velocities to exclude systematic effects. For p-polarization, in addition to the scan frequency also the input power was varied to exclude intensity-dependent effects that were found in c-Si [21, 22]. The results for our single measurements are shown in figure 3(*a*). The upper light-blue dots show results at an input power of 484 mW, the green circles show the results taken at an input power of 840 mW. Further, the round-trip loss was measured at input powers of 1.5 mW (⧫), 12 mW (▲), 113 mW (•), 484 mW (▼) and 840 mW (■). For p-polarization, the result is $\alpha_{\text{p}}^{\text{coat}} = (1428 \pm 97)$ ppm. The results for the reflectivities are $1-R_{1,\text{p}} = (4717{\pm}212)$ ppm and $1-\tilde{R}_{2,\text{p}} = (7882 \pm 251)$ ppm. Since in p-polarization no power dependence occurred, in s-polarization the input power was kept constant at 367 mW, while the scan frequency was varied between 5 and 500 Hz. Figure 2(*a*) shows resonance peaks (external lengthening: red dots—measurement, orange line—simulation; external shortening: blue dots—measurement, light-blue line—simulation) detected at a scan frequency of 90 Hz, where the two peaks for an external lengthening and shortening of the cavity were identical. A frequency of about 15 Hz was the limit at which the thermal effect was sufficient for fitting α^{coat}. The results of the single measurements for s-pol are presented in figure 3(*a*) (lower, dark-blue dots). The mean value (lower, purple line) and standard deviation (lower, purple dashed lines) of the results from the single measurements is $\alpha_{\text{s}}^{\text{coat}} = (1035 \pm 42)$ ppm. The results for the reflectivities are $1 - R_{1,\text{s}} = (529 \pm 20)$ ppm and $1 - \tilde{R}_{2,\text{s}} = (2902 \pm 103)$ ppm (= round-trip loss). Our measured value of $R_{1,\text{s}}$ is in perfect agreement with the design reflectivity.

In the following, the influence of potential errors in the simulation input parameters on our results is analyzed. Therefore, we simulated the influence of the individual parameters

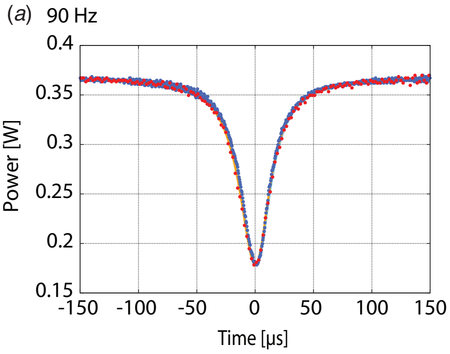

Figure 2. Cavity resonance peaks in s-pol for scan frequencies of 90 Hz and 5 Hz using the same scan amplitude and input light power measured on the reflected light. While at 90 Hz(*a*) no thermal effect occurs and the peaks are identical for lengthening and shortening of the cavity, at 5 Hz (*b*) for an external lengthening of the cavity the broad peak (red dots: measurement, orange line: simulation) forms, for an external shortening the narrow peak (dark-blue dots: measurement, light-blue line: simulation) forms. From this thermal effect the coating absorption was derived.

Table 2. Influence of potential errors in the simulation input parameters (listed in table 1) on our absorption result.

Parameter	Influence of potential errors on our absorption result
n, $\mathrm{d}n/\mathrm{d}T$	Error negligible, literature values known to high precision [19]
a_{th}	Error negligible [17]
c, ρ	Uncertainties affected absorption result approximately linearly
k_{th}	Change by 10% affected result by about 4%
D, r	Errors do not affect absorption result for $D, r \gg w_0$, which is valid for this setup
L	A measurement error was estimated to be $<1\%$ and was thus negligible
AOI, w_0	Calculated from L, errors were therefore negligible

listed in table 1 on our result beginning with the material parameters, which we took from the literature. The errors of the refractive index n as well as of the thermal refractive coefficient $\mathrm{d}n/\mathrm{d}T$ were found to be negligible [19]. An error of the thermal expansion ath was also negligible since $\mathrm{d}n/\mathrm{d}T$ by far dominates the phase shift of the laser beam [17]. Changes of the specific heat c and density ρ affected the absorption result approximately linearly. A change by 10% of the thermal conductivity kth affected the result by about 4%. Potential errors in the cavity geometry parameters were also found to be negligible. The mirror length D and mirror radius r did not affect our absorption result for $D, r \gg w_0$, which is valid for our setup. A measurement error of the round trip length L of 420 mm was estimated to be $<1\%$ and was thus negligible as well. AOI and beam waist w_0 were based on L and potential errors in these quantities were also negligible. We thus conclude that the standard deviation of our measurements also includes potential errors of the input parameters if we assume that the errors of the parameters are statistically independent. A summary of the error analysis can be found in table 2.

3. Discussion and conclusion

For our dielectric Si/SiO$_2$ coating produced with ion plating, absorption values of $\alpha_{\mathrm{s}}^{\mathrm{coat}} = (1035 \pm 42)$ ppm and $\alpha_{\mathrm{p}}^{\mathrm{coat}} = (1428 \pm 97)$ ppm were measured. These values are orders of

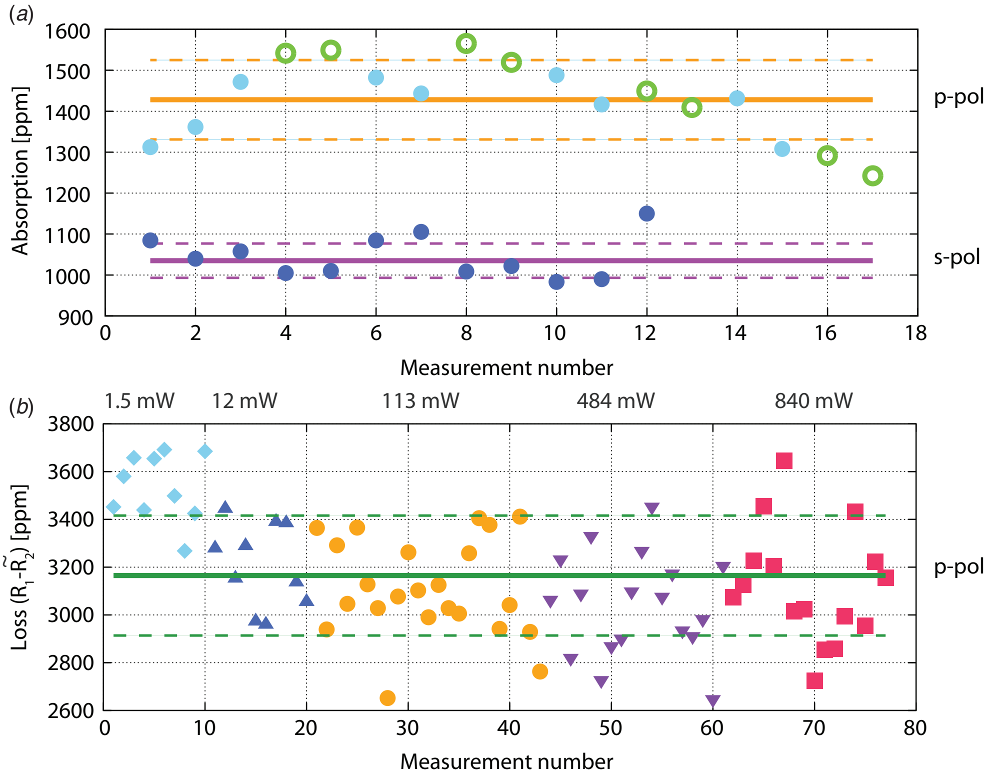

Figure 3. (*a*) Single measurement results for the coating absorption of mirror M_1 in p-pol (upper, green circles: 484 mW input light power, upper light blue dots 840 mW input light power) and s-polarization (lower, dark blue dots). Several measurements were performed for each polarization varying the scan frequency and in p-polarization additionally the input power. The solid lines show the mean values and the dashed lines the standard deviation of the individual results. (*b*) Results of the single measurements for the cavity round-trip loss $((1-\tilde{R}_2)-(1-R_1))$ in p-polarization: At each of the cavity input powers 1.5 mW (♦), 12 mW (▲), 113 mW (●), 484 mW (▼) and 840 mW (■) several single measurements were performed.

magnitude higher than the optical absorption of state-of-the-art SiO_2/Ta_2O_5 coatings being in the ppm regime [17, 23].

To transfer our results to an absorption coefficient for the deposited silicon layers, the layout of the actual dielectric Si/SiO_2 coating stack is required. Since the actual design was not at our disposal, we used a model coating stack that matched our measurement results for the reflectivities in s- and p-polarization of $R_{\mathrm{meas,\,s/p}} = 0.999\,47/0.995\,28$ using [18]. $R_{\mathrm{sim,\,s/p}} = 0.999\,57/0.995\,10$ was the best matching set that could be achieved. Figure 1(*b*) shows a schematic of the simulated coating stack including the thicknesses per single layer. The simulated reflectivity after each double layer is given on the right side in figure 1(*b*). Since the individual double layers transmit only a fraction of the laser power, the absorption coefficient needs to be based on an effective penetration depth, here given in units of double layers

$$\begin{aligned} D_{\mathrm{eff,s}} = 1 &+ (1-0.707\,78) + (1-0.939\,93) + (1-0.988\,32) \\ &+ (1-0.997\,75) + (1-0.999\,57) = 1.366\,65, \end{aligned}$$

where the numbers are taken from figure 1 for s-polarized light. As the result, effectively 1.37 double layers are transmitted twice by 100% of the input power. Assuming the absorption in the SiO_2 layers to be negligible [17, 23], this results in an absorption coefficient of $1035\,\text{ppm}/(2 \times 1.37 \times 1.02 \times 101\,\text{nm}) = (37 \pm 2)\ \text{cm}^{-1}$ for the silicon layers. The factor 1.02 is a correction of the layer thickness due to the AOI differing from 0°. Correspondingly, for p-polarization the absorption coefficient is $(39 \pm 3)\ \text{cm}^{-1}$. Both results are in good mutual agreement.

Our absorption coefficient of $\alpha_{\text{si}}(1550\ \text{nm}) \approx 40\ \text{cm}^{-1}$ found for the ion plated silicon layers of our coating stack is lower than values of $100\ \text{cm}^{-1}$ up to $2000\ \text{cm}^{-1}$ reported for a-Si [12–14], while for c-Si the absorption coefficient is only in the order of a few ppm cm^{-1} up to a few hundreds ppm cm^{-1} at 1550 nm [10, 21, 24]. Our result reveals a rather modest reduction of optical absorption for Si layers deposited by ion plating instead of the ion beam sputtering technique, and the coating investigated has an absorption that is still far too high for test mass mirrors in GWDs.

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