Applied Physics Letters

RESEARCH ARTICLE | MARCH 13 2023

Substrate-transferred GaAs/AlGaAs crystalline coatings for gravitational-wave detectors

Special Collection: Gravitational Wave Detectors

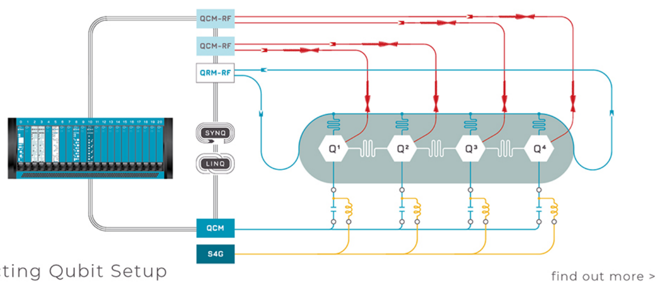
G. D. Cole ; S. W. Ballmer ; G. Billingsley ; S. B. Cataño-Lopez ; M. Fejer; P. Fritschel; A. M. Gretarsson ; G. M. Harry ; D. Kedar ; T. Legero ; C. Makarem ; S. D. Penn ; D. H. Reitze ; J. Steinlechner ; U. Sterr ; S. Tanioka ; G.-W. Truong ; J. Ye ; J. Yu

Check for updates

Appl. Phys. Lett. 122, 110502 (2023)
https://doi.org/10.1063/5.0140663

View Online
Export Citation
CrossMark

QBLOX
Integrates all Instrumentation + Software for Control and Readout of
Superconducting Qubits
NV-Centers
Spin Qubits



Superconducting Qubit Setup
find out more >

AIP Publishing

26 December 2023 22:12:06

Applied Physics Letters PERSPECTIVE scitation.org/journal/apl

Substrate-transferred GaAs/AlGaAs crystalline coatings for gravitational-wave detectors

Cite as: Appl. Phys. Lett. **122**, 110502 (2023); doi: 10.1063/5.0140663
Submitted: 29 December 2022 · Accepted: 22 February 2023 ·
Published Online: 13 March 2023

View Online Export Citation CrossMark

G. D. Cole,[1,a)] S. W. Ballmer,[2] G. Billingsley,[3] S. B. Cataño-Lopez,[1] M. Fejer,[4] P. Fritschel,[5] A. M. Gretarsson,[6] G. M. Harry,[7] D. Kedar,[8] T. Legero,[9] C. Makarem,[3] S. D. Penn,[10] D. H. Reitze,[3] J. Steinlechner,[11,12] U. Sterr,[9] S. Tanioka,[2] G.-W. Truong,[1] J. Ye,[8] and J. Yu[9]

AFFILIATIONS

[1]Thorlabs Crystalline Solutions, Santa Barbara, California 93101, USA
[2]Department of Physics, Syracuse University, Syracuse, New York 13244, USA
[3]LIGO Laboratory, California Institute of Technology, Pasadena, California 91125, USA
[4]Stanford University, Palo Alto, California 94309, USA
[5]LIGO Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts 02142 USA
[6]Department of Physics, Embry-Riddle Aeronautical University, Prescott, Arizona 86301, USA
[7]Department of Physics, American University, Washington, DC 20016, USA
[8]JILA, National Institute of Standards and Technology and University of Colorado, Boulder, Colorado 80309, USA
[9]Physikalisch-Technische Bundesanstalt, 38116 Braunschweig, Germany
[10]Department of Physics, Hobart and William Smith Colleges, Geneva, New York 14456, USA
[11]Maastricht University, 6200 MD Maastricht, The Netherlands
[12]Nikhef, 1098 XG Amsterdam, The Netherlands

Note: This paper is part of the APL Special Collection on Gravitational Wave Detectors.
[a)]**Author to whom correspondence should be addressed:** gcole@thorlabs.com

26 December 2023 22:12:06

ABSTRACT

In this Perspective, we summarize the status of technological development for large-area and low-noise substrate-transferred GaAs/AlGaAs (AlGaAs) crystalline coatings for interferometric gravitational-wave (GW) detectors. These topics were originally presented as part of an AlGaAs Workshop held at American University, Washington, DC, from 15 August to 17 August 2022, bringing together members of the GW community from the laser interferometer gravitational-wave observatory (LIGO), Virgo, and KAGRA collaborations, along with scientists from the precision optical metrology community, and industry partners with extensive expertise in the manufacturing of said coatings. AlGaAs-based crystalline coatings present the possibility of GW observatories having significantly greater range than current systems employing ion-beam sputtered mirrors. Given the low thermal noise of AlGaAs at room temperature, GW detectors could realize these significant sensitivity gains while potentially avoiding cryogenic operation. However, the development of large-area AlGaAs coatings presents unique challenges. Herein, we describe recent research and development efforts relevant to crystalline coatings, covering characterization efforts on novel noise processes as well as optical metrology on large-area (~10 cm diameter) mirrors. We further explore options to expand the maximum coating diameter to 20 cm and beyond, forging a path to produce low-noise mirrors amenable to future GW detector upgrades, while noting the unique requirements and prospective experimental testbeds for these semiconductor-based coatings.

© 2023 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/). https://doi.org/10.1063/5.0140663

I. INTRODUCTION

Thermal noise in high-reflectivity optical interference coatings is a limiting noise source in precision interferometric systems. The pioneering theoretical work on thermal noise by Callen and Greene[1] was introduced to the gravitational-wave (GW) community by Saulson[2,3] as well as Braginsky and collaborators.[4] In 1998, Levin[5] identified coating thermal noise (CTN) as a potential limiting noise source for gravitational-wave detectors. Harry *et al.*[6] measured the

© Author(s) 2023

elastic loss in the Initial laser interferometer gravitational-wave observatory (LIGO) coatings and confirmed that CTN would limit the sensitivity of Advanced LIGO.[7] A collaboration of Syracuse, Glasgow, Stanford, and the LIGO Lab determined the source of the loss to be the high-index material[8] and designed the coating[9] used in Advanced LIGO to make the first direct detection of these ripples in space–time.[10]

For the past 20 years, a concerted research effort has sought to reduce CTN by identifying coating materials exhibiting both low levels of optical and elastic losses. The first decade of this work is summarized in Ref. 11 and ultimately led to the development and manufacturing of the mirrors used for the detection of gravitational waves as well as those slated for future upgrades.[12,13] In the Advanced LIGO interferometers, CTN limits the achievable strain sensitivity in the most sensitive frequency band around 100 Hz.[14] Similarly, this noise source impacts the stability of ultrastable optical resonators, placing a limit on the minimum linewidth achievable in lasers employed for cutting-edge optical atomic clocks.[15,16] This was initially explored in cavity-stabilized laser systems owing to theoretical work by Numata,[17] followed by measurements on cm-length reference cavities by Notcutt and colleagues.[18] Exploratory efforts focusing on alternative materials with these same requirements were also carried out with micrometer-scale systems in the burgeoning field of cavity optomechanics.[19] Early work in this area ultimately led to the development of the substrate-transferred GaAs/AlGaAs (AlGaAs) crystalline coatings as described herein. A key motivation of these efforts is the potential for significant performance enhancements in GW detectors, owing to the low elastic losses and correspondingly low Brownian noise of these mirrors. As shown in Fig. 1, in a model LIGO-based interferometer employing crystalline mirrors, the achievable strain sensitivity at 100 Hz is $1.1 \times 10^{-24}/\sqrt{\mathrm{Hz}}$, representing a 3.6× improvement over the Advanced LIGO design target at the same frequency ($4.0 \times 10^{-24}/\sqrt{\mathrm{Hz}}$).[14] This results in a significant enhancement in the astrophysical reach for a binary neutron star merger, from 175 Mpc for the current design target to 600 Mpc for this proposed upgrade with AlGaAs-based crystalline coatings—yielding a factor of ∼40 increase in detection rates.

In this Perspective, we provide a detailed account of the status of AlGaAs-based crystalline coatings as a solution to the coating Brownian noise problem. We begin with a brief historical overview of suspended crystalline multilayers in cavity optomechanics experiments starting in 2007. We then discuss the transition of this technology to precision metrology applications with the development of centimeter-scale substrate-transferred AlGaAs coatings for ultrastable optical reference cavities. Recent findings from key partners at national metrology labs point to novel noise processes in these coatings at cryogenic temperatures. Exploring size scaling, we cover preliminary results for crystalline coatings at diameters up to 10 cm, with discussions relevant to expanding to 20 cm and beyond, covering the optical properties of these single-crystal films in terms of their absorption, scatter, birefringence, and surface uniformity. Given the opacity of AlGaAs coatings at visible wavelengths, alternative lock acquisition schemes must be defined; one potential solution is presented here. Next is an overview of experimental testbeds that would enable detailed metrology of large-area crystalline mirrors. Finally, a brief overview of paths forward in terms of research and funding requirements is presented.

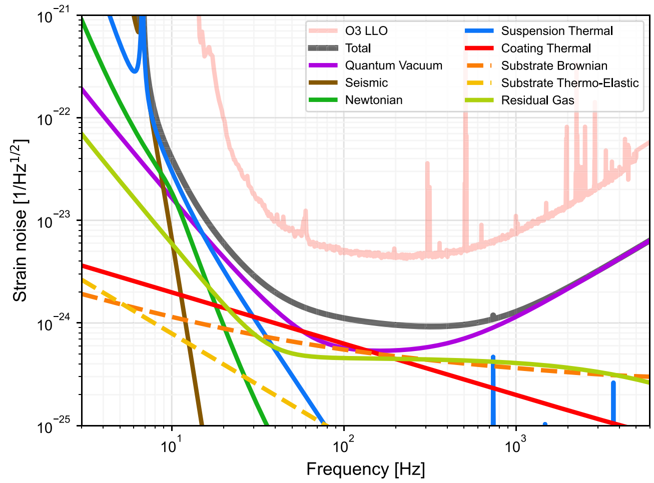


FIG. 1. Target strain sensitivity, as limited by fundamental noise sources, for a potential upgrade to the LIGO interferometers using AlGaAs crystalline coatings operating at room temperature. The CTN curve (red) is calculated using a mechanical loss angle of 6.2×10^{-6}, based on direct thermal noise measurements at MIT,[20] and a beam radius of 5.5 cm on the end test masses (ETMs) and 4.5 cm on the input test masses (ITMs); these beam sizes are compatible with a 30 cm diameter AlGaAs coating. The test masses are 100 kg fused silica (substrate noises), suspended with fused silica fibers (suspension thermal noise). The quantum vacuum noise derives from 1.5 MW of laser power in each arm cavity (1.06 μm wavelength), combined with 10 dB of effective vacuum squeezing at all frequencies, which is realized using a narrow linewidth filter cavity that appropriately rotates the squeezing angle as a function of frequency. The noise due to residual gas in the vacuum system arises from damping of the suspended test masses at frequencies below 50 Hz, and from scattering of the laser beams in the 4 km arms at frequencies above 50 Hz. The Newtonian noise is due to density perturbations in the earth close to the test masses, producing fluctuating gravitational forces. The seismic noise, in contrast, is the earth vibration that couples through the seismic isolation and test mass suspensions. The "Total" noise curve for this upgrade, shown in gray, is compared with the performance of the LIGO Livingston Observatory (LLO), light pink, recorded during its third observing run, O3 (April 2019 to March 2022).[21]

II. SUSPENDED ALGAAS MULTILAYERS FOR CAVITY OPTOMECHANICS

AlGaAs-based monocrystalline multilayers were first pursued as high-performance micromechanical resonators for cavity optomechanics experiments. This compound semiconductor material platform has historically been employed for microwave devices as well as for micro-cavity-based optoelectronics devices. It was not until 2008 that measurements of the intrinsic elastic losses of AlGaAs were performed, revealing a unique combination of low optical and mechanical losses.[22] The realization of low elastic losses, represented by the mechanical loss angle, ϕ (or conversely, the mechanical quality factor, $Q = \frac{1}{\phi}$), is paramount to reaching the quantum regime in cavity optomechanics. Amorphous ion-beam sputtered (IBS) multilayers, while capable of high reflectivity, exhibit Q values at the few thousand level (corresponding ϕ of a few $\times 10^{-4}$).[8] In comparison, crystalline multilayers, owing to their improved structural order, show a significant improvement, with measured Q values in the range of ∼20 000 to >200 000 (ϕ at the low 10^{-5} level or below).[22–25] The low Q values in IBS-deposited optical coatings presented a major roadblock in these efforts. This can be understood by the Qf product, with f being the

26 December 2023 22:12:06

© Author(s) 2023

mechanical eigenfrequency of the resonator. This product must exceed the thermal decoherence rate, yielding the condition $Qf > k_B T_{bath}/h$ (where k_B is the Boltzmann constant, T_{bath} is the system temperature, and h is Planck's constant), for the system to survive at least a single oscillation before a thermal phonon causes decoherence. This is a necessary requirement to prepare nonclassical states of motion.[26,27] Given the significantly reduced elastic loss and resulting low thermal noise, high-Q AlGaAs-based micromechanical devices have been instrumental in studying fundamental aspects of quantum-limited interferometry,[28,29] even without meeting the aforementioned condition.

III. SUBSTRATE-TRANSFERRED ALGAAS COATINGS FOR PRECISION METROLOGY

The low-noise potential of these suspended micromirrors motivated the development of centimeter-scale reflectors based on substrate-transferred AlGaAs multilayers.[30] Production considerations for these single-crystal coatings have been covered in detail elsewhere.[31] Given lattice matching constraints in epitaxial (crystal) growth, direct deposition is not possible, and, thus, separate growth, microfabrication, and bonding are necessary to generate the coated optic. For low-loss macroscopic mirrors, optical quality is paramount. Each stage of the production process has the potential for defects, with the epitaxial growth stage contributing the largest share of imperfections. Since 2012, crystalline coatings, typically 5–20 mm in diameter, transferred to planar, and curved bulk fused silica substrates have been realized. Other substrate materials have been successfully implemented including Si and Al_2O_3 (sapphire) for cryogenic reference cavities as well as SiC, diamond, and YAG, for high-power laser systems. Optimized crystalline coatings with a radius of curvature as tight as 10 cm have demonstrated excess losses (scatter + absorption) below 2 ppm, with absorption as low as ~0.5 ppm observed between 1 and 1.5 μm. More recently, excess losses < 10 ppm have been demonstrated for mirrors operating near 4.5 μm.[32,33] The maturation of cm-scale crystalline coating production in the past decade has put this technology on par with IBS in terms of optical losses in the near-infrared spectral region while exceeding the state-of-the-art in the mid-infrared (wavelengths from 2 to 5 μm). Standard mirrors are now commercially available, finding applications in cavity-stabilized lasers and in cavity-enhanced spectroscopy.[34]

A. Novel noise sources in cryogenic reference cavities

In time-and-frequency metrology, where high-finesse reference cavities employing crystalline coatings are becoming ubiquitous, the noise of AlGaAs multilayers has been closely studied and compared against theory. Room temperature cavity-stabilized lasers employing these coatings have been demonstrated to operate near the thermal noise floor,[35,36] while turn-key systems capable of a fractional frequency instability $<5 \times 10^{-16}$ are commercially available.[37] As the metrology community pushes optical oscillators to lower instabilities, the research focus has shifted to cryogenic systems. Progress on cryogenic reference cavities has matured to the point where the dominant noise contribution is CTN from the amorphous mirrors,[38] making them ideal testbeds for probing low-temperature noise sources in AlGaAs coatings.

Two independent studies using silicon cavities with AlGaAs coatings at 1.5 μm have pioneered crystalline coating characterization at cryogenic temperatures. In both systems, the expected contributions from technical noise, and spacer and substrate thermal noise are well below the expected coating thermal noise (one cavity is 21 cm long and held at 124 K),[39] and the other is a 6 cm long cavity operated at 4 and 16 K.[40] Interestingly, both systems have revealed hitherto unknown noise sources that can be manipulated by the polarization of the probe beam. Although it is well-known that coating birefringence leads to a static frequency splitting between orthogonal polarizations of the TEM_{00} mode, the cryogenic testbeds additionally observe dynamic frequency fluctuations of the two polarization components that are anti-correlated. Additionally, the magnitude of this effect increases with the intracavity optical power. The resulting noise level is far above the coating thermal noise floor (20–40 dB depending on the cavity and the temperature), and the power spectral density acquires a slope steeper than 1/f. Both birefringent modes of the cavity exhibit similar levels of frequency noise for equivalent optical conditions. However, if the two modes are addressed simultaneously, the anti-correlated frequency fluctuations can be averaged and suppressed,[39,40] as in Fig. 2. The residual noise after cancelation no longer scales with intracavity optical intensity, though it is still above the expected thermal noise level. This noise source is coherent between a TEM_{10} and TEM_{00} beam, implying a longer spatial correlation length than the spot size of ~1 mm. The source of this "global" noise is not yet understood, and further investigations are ongoing. It also remains to be seen whether these measured noise scalings persist at higher frequency, as these cavities are optimized for the frequency range of 1 Hz and below, lower than the frequency band where coating thermal noise is relevant for Advanced LIGO, roughly 30–300 Hz.

It is important to note that the observed birefringence in crystalline coatings is an "extrinsic" effect, as 100-oriented GaAs is optically symmetric. The current conjecture is that non-uniform strain relaxation, upon cooling from the growth temperature drives the symmetry breaking.[41] The coatings are grown at elevated temperature (~600 °C), leaving a compressive residual stress of ~100 MPa upon cooling. It is possible to tailor the strain by alloying the multilayer with In or P (e.g., GaAsP, InGaP, InGaAs, etc.).[42] Careful measurement of the optomechanical properties of these materials would be necessary. The observed birefringence, measured from cavity mode splitting and corresponding to the accumulated difference in phase on reflection between the fast and slow polarizations, $\Delta\theta = \theta_f - \theta_\theta$, is all within a similar range, roughly 2×10^{-3} radians, and is temperature and substrate independent. Furthermore, thermal cycling does not affect the mode splitting in cryogenic crystalline coatings.

Beyond studies of the static and dynamic (fluctuating) components of birefringence, there is a need to investigate potential thermally induced effects. Owing to the anisotropic nature of AlGaAs coatings, radial thermal gradients will induce shear strains in the crystal. Assuming the mirror is a flat, half-infinite disk and the coating face is parallel to the [001] crystal plane, if we choose the x and y coordinate axes to lie in the [010] and [100] planes, respectively, then the magnitude of the induced birefringence is largest along lines at ±45° to the coordinate axes. In addition, the orientation of the principal axes varies with azimuthal angle across the face of the mirror. Assuming a 100 μm diameter perfect absorber and a mirror irradiance at the level of Advanced LIGO, the effect may be similar in magnitude to the static birefringence seen in AlGaAs multilayers; several point absorbers could combine to impart a significant effect and must be investigated further.

26 December 2023 22:12:06

© Author(s) 2023

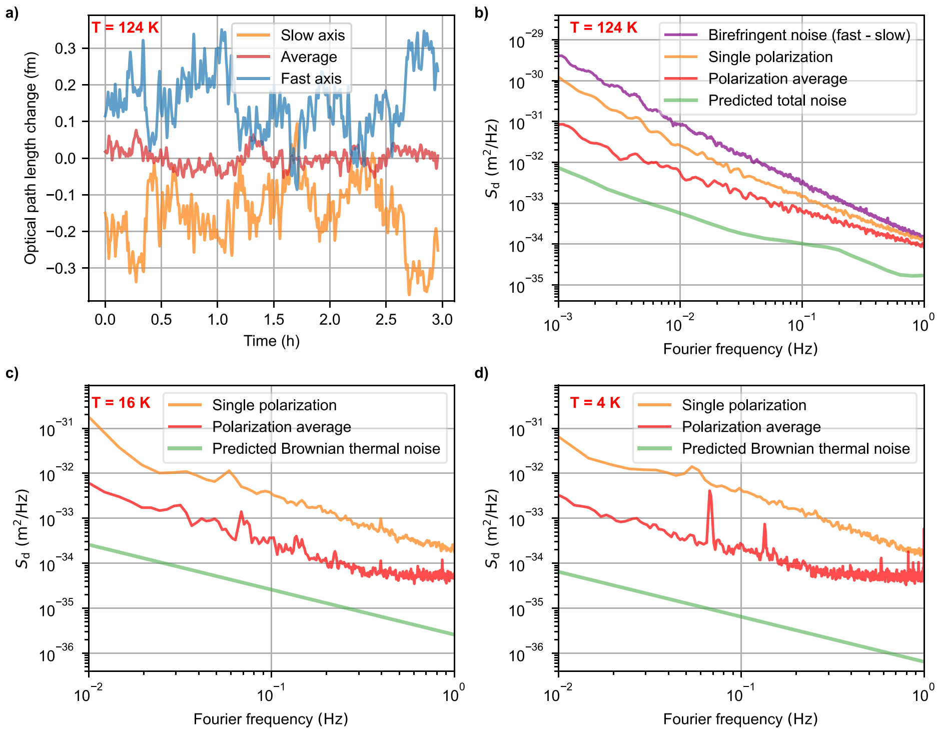


FIG. 2. Potential non-Brownian CTN observed in ultrastable cryogenic Si reference cavities with AlGaAs coatings. (a) Optical path length fluctuations of a 21-cm long Si cavity measured for the two polarization eigenmodes of the TEM_{00} resonance (blue and orange). (b) Power spectral densities, S_d, of the length fluctuations of the cavity. The plot in this panel includes the birefringent noise (purple), the noise of an individual polarization eigenmode (orange) as well as the average of the two polarizations (red). The sum of technical noise and the measured Brownian thermal noise limit for the TEM_{00} mode (green) is included for comparison. (c) and (d) Power spectral densities of the length fluctuations of a 6-cm long Si cavity at 16 (c) and 4 K (d). Shown are the frequency stability of the individual polarization eigenmodes (orange), the average of two polarization eigenmodes (red), and the predicted Brownian thermal noise (green). As explained in the main text, while the average polarization can be used to suppress the birefringence fluctuations, the residual noise remains above the expected CTN level for these systems. Reproduced with permission from Yu *et al.*, arXiv:2210.15671 (2022). Copyright 2022 Author(s), licensed under a Creative Commons Attribution 4.0 License.

26 December 2023 22:12:06

IV. LARGE-AREA ALGAAS COATINGS FOR FUTURE GRAVITATIONAL-WAVE DETECTORS

Challenges with large-area mirror production are being tackled to extend the application of crystalline mirrors from advanced reference cavities to GW detection. Studies on 2 in. and 3 in. (50.8 mm and 76.2 mm) diameter test mirrors have yielded: (i) mean absorption < 1 ppm, (ii) mean total integrated scatter (TIS) < 10 ppm, and (iii) coating thickness variation (rms) < 100 ppm.[43,44] Ongoing efforts involve the production of 10 cm and ultimately 20 cm diameter test mirrors, the latter representing the largest continuous crystalline coatings that can currently be produced, limited by the availability of base substrates for epitaxial growth. In terms of the observed optical properties in large coatings, there appears to be a greater number of scattering centers compared with the best IBS coatings, but the background total integrated scatter level away from larger (>20 μm) scatterers is comparable. These scattering centers may be caused by "oval defects" arising from spitting of the gallium source during deposition, generating crystallites that locally disrupt the structure. It is not known whether these defects are absorbing; thus, distinguishing pure scattering centers from local absorbers is an important task. Both are a source of optical loss but have different impact on interferometer. Similarly, a bidirectional reflectance distribution function analysis of larger point defects will be useful for estimating the effect of rare but large scatterers vs frequent but small scatterers on interferometer scatter noise.

Recent results from Caltech include surface maps and scattering data from the first 10 cm diameter AlGaAs coating. In this prototype, the coating is transferred to a 10-mm thick planar synthetic fused silica substrate, see panel (a) of Fig. 3 for photographs of the completed test mirror. Surface figure measurements were made on the bare substrate before coating and also on the final coated mirror. After coating, the surface appears to have gained 4 nm of astigmatism, and the radius of the coated substrate changed by −784 m, with a corresponding sagitta change of 270 nm (convex), both measured over an 80 mm diameter aperture. The requirements on 34 cm diameter × 20 cm thickness test masses are a change of less than 0.5 nm for astigmatism and higher order terms. The observed changes in the surface figure of the 10 cm diameter test mirror could be caused by non-uniformity of the coating or by stress imparted on the 10 mm thick substrate. Further study will be needed to separate these effects, particularly given the thin nature of the test substrate, noting that the results could be quite different for an AlGaAs coating applied to a 200 mm thick test mass if stress is the main driver. Panels (b) and (c) of Fig. 3 show the results of the scattering measurements performed on this test structure. The mean TIS is somewhat higher than for the smaller samples mentioned earlier. This is due to an increased number of relatively strong scatterers indicated by red points [Fig. 3(c)]. Excluding these large scattering centers, the mean total integrated scatter of this initial test mirror was approximately 2 ppm higher than equivalent measurements on an Advanced LIGO end test mass, with a point scatterer density of 86 cm^{-2}. Additional 10 cm diameter test mirrors are currently in production to ascertain the repeatability in optical performance of these first large mirrors.

Given the lack of commercially available options, scaling to AlGaAs coating diameters beyond 20 cm will entail the growth of custom GaAs boules for waferization. Sticking with traditional wafer geometries, 30 cm diameter would be an obvious choice as a next step. In terms of multilayer epitaxy, production molecular beam epitaxy systems have demonstrated sufficiently good optical performance and

© Author(s) 2023

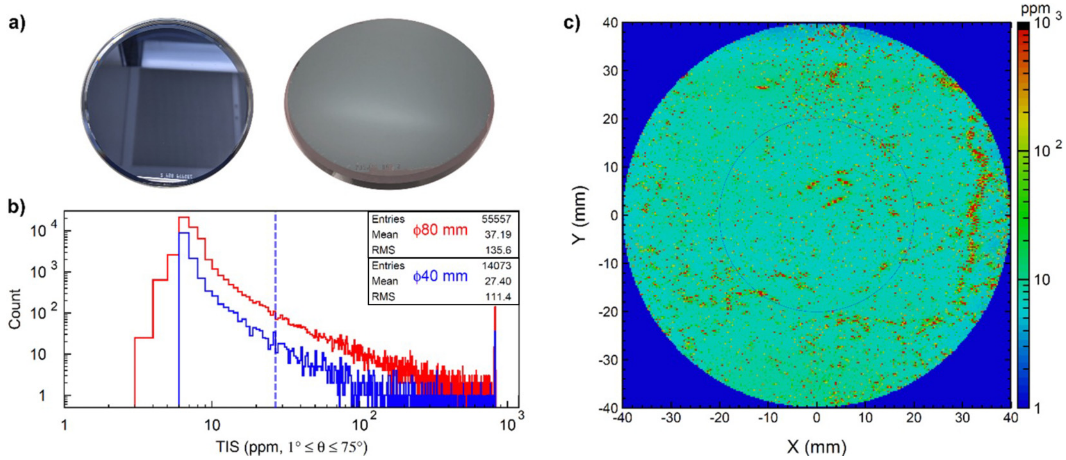


FIG. 3. Optical characterization of a first 10 cm diameter test mirror with substrate-transferred AlGaAs coatings. (a) Photographs of the mirror backside (left), viewing the bond interface through the 10-mm thick fused silica substrate, and mirror frontside (right) following substrate and etch stop removal, leaving only the GaAs/AlGaAs multilayer on the fused silica substrate. (b) Histogram of the TIS for apertures of 40 mm diameter (blue) and 80 mm diameter (red). The vertical dashed line shows the mean TIS for the 40 mm diameter aperture. The legend gives the means and standard deviations of both histograms. (c) Scatter map obtained via an integrating sphere raster-scanned over the mirror surface. The thin blue circle shows the 40 mm diameter inner aperture referenced in panel (b).

uniformity[31,44] and would not require customization. A dedicated system will be necessary to produce high-performance prototype and deliverable optics capable of meeting the strict optical specifications of GW detectors.[45] At the bonding stage, commercial vendors have demonstrated the production of silicon-on-insulator wafers up to 45-cm diameter.[46] However, such systems are typically limited to a total bonded thickness of a few mm, while GW-relevant optics exhibit high mass (∼40 kg) and much greater thickness (∼20 cm), entailing modified tooling and unique challenges in production.

If sufficiently large mirrors with the desired performance metrics can be produced, it will then be necessary to explore impacts on the overall system operation. For instance, given the narrow bandgap of the high-index GaAs layers, traditional cavity arm locking with frequency-doubled 532 nm light is no longer an option;[47] thus, alternative locking schemes must be developed. Given the long-wavelength transparency of AlGaAs, a dichroic coating with sufficient reflectance at both 1064 nm and an auxiliary wavelength of 2128 nm may be used. The auxiliary 2128 nm beam would be generated from the 1064 nm beam, which is phase-locked to the main laser, using a degenerate optical parametric oscillator (DOPO) instead of a conventional frequency doubling.[48] If low-noise dichroic AlGaAs coatings can be produced, then a locking system can be realized with minimal risk. In principle, such a coating design is possible, and based on recent optical loss measurements, at 4.5 μm, absorption at the 1 ppm level or less is expected for wavelengths near 2 μm.[32,33]

Possible options for installing AlGaAs-coated input and end test masses (ITMs and ETMs) as an upgrade to the existing 4 km Advanced LIGO interferometers will require minimum coating diameters of 21–22 cm to exceed current requirements on coating thermal noise. Thus, the use of 20 cm GaAs wafers for both test masses is not possible without radical modifications, and custom boules are needed. However, mixed mirror sizes could be employed to avoid this, with larger IBS-coated ITMs focusing a smaller spot onto AlGaAs-coated ETMs. Such a design is limited by the size of the beam splitter but has the advantage of keeping the power-recycling and signal-recycling cavity designs mostly unchanged (though it would require reshaping the anti-reflective side of the ITM to form a lens). Similar "mixed mirror" solutions leveraging 20 cm diameter AlGaAs will be evaluated for noise, alignment stability, resonances of higher order modes in the arms, sideband resonances in the arms, etc. These designs have the potential to serve as technology demonstrators for next-generation instruments.

As with cutting-edge ultrastable laser efforts, third-generation GW detectors such as the Einstein Telescope (ET) are proposing to incorporate cryogenics. To maintain compatibility with available growth substrates, the ET low frequency interferometer could potentially implement similar mixed mirror designs, including cooled ETMs with a 13 cm beam and 70 cm diameter IBS coatings and ITMs having a 4 cm spot size with 20 cm diameter AlGaAs coatings (with or without cryogenic cooling). With cryogenic cooling, this geometry could employ ultrapure float-zone silicon substrates for the ITMs, which are currently available up to 20 cm diameter.

A. Relevant testbeds for large-area crystalline coatings

Open questions relevant to AlGaAs in future GW detectors may go beyond that which can be answered in table-top experiments. These include (a) an accurate wideband (frequency) measurement of coating noise over the span of 10 Hz to 1 kHz; (b) successful production of larger than "lab-scale" mirrors, spanning substrate procurement, polishing, and bonding, to integration with relevant suspension systems; and (c) investigations of large-area coating performance when integrated in a complex and sensitive system at high laser power. Several platforms will be available within the gravitational-wave community in the near-term for such efforts:

(i) A key aim of the 10 m prototype at the AEI in Hannover, Germany,[49] operating at 1064 nm and room temperature, is to investigate and overcome the standard quantum limit.[29]

26 December 2023 22:12:06

© Author(s) 2023

Low-noise AlGaAs-coated 4.8 cm diameter mirrors have been proposed for this system.

(ii) The Gingin prototype in Western Australia[50] will investigate high-power effects in silicon mirrors at a wavelength near 2 μm. This is a three-phase project: (1) buildup of a 7 m Fabry-Perot cavity at 5 W laser power and 3 mm beam diameter with interchangeable fused silica and silicon mirrors, (2) construction of a 72 m Fabry-Perot cavity using silicon mirrors with 10 cm diameter AlGaAs coatings and $\sim$1 cm beam diameter, and (3) an increase in the laser power to 23 kW in the arm cavities, which will operate at 123 K. This system can be used to explore the impact of point absorbers, wide angle scattering, thermal distortions and birefringence of coated and uncoated silicon substrates, and possibly electro-optic and non-linear effects at high laser power.

(iii) There are currently two cryogenic prototypes under development, the ET-pathfinder in Maastricht, Netherlands[51] and a cryogenic upgrade to the 10 m prototype in Glasgow, UK,[52] with the aim of testing technologies for low-temperature operation of future GW detectors. Parameters such as 1.5 and 2 μm laser wavelengths at temperatures of $\sim$120 and $\sim$15–20 K are planned, using Si substrates for the mirrors. These systems could be ideal platforms to test large-area AlGaAs coatings beyond ongoing efforts with cm-scale reference cavities.

These platforms will be instrumental in confirming the viability of AlGaAs coatings in these unique astronomical instruments.

V. SUMMARY AND OUTLOOK

We have outlined the historical background in the initial development of, as well as the current status and potential paths forward for, AlGaAs-based crystalline coatings. These unique coatings exhibit promising optomechanical properties for enhanced sensitivity in GW detection and, thus, demand further investigation. We end by noting that the cost and timeline to realize the large-diameter production capabilities above (custom base wafers, epitaxy, and bonding) are comparable to the development of other important subsystems such as seismic isolation[53] and quantum squeezing,[54] which is an appropriate comparison in that coating thermal noise is the limiting noise in the most sensitive frequency band of second-generation GW detectors.[7] This can also be compared to potential budgetary savings realized by putting off or even eliminating the need to develop cryogenics for future detectors.[55,56] A proposed timeline (available to LIGO, Virgo, and KAGRA members) has been developed that would allow GW-relevant AlGaAs coatings to be realized within a span of 5 years. This will allow for AlGaAs to be considered for upgrades to the Advanced LIGO detectors.

ACKNOWLEDGMENTS

This research was supported by the National Science Foundation through the following grant awards: American University (Nos. PHYS-2012017 and PHYS-2011787), Caltech (No. PHY-1764464), HWS (Nos. PHY-1912699, PHY-2011688, and PHY-2208079), M.I.T. (No. PHY-1764464), Embry-Riddle Aeronautical University (No. PHY-2110598), and Syracuse University (Nos. PHY-2011723 and PHY-2207640). J. Steinlechner acknowledges the support of ETpathfinder (Interreg Vlaanderen-Nederland), E-TEST (Interreg Euregio Meuse-Rhine), the Province of Limburg, and the NWO Talent Programme Vidi 2020, Project No. VI.Vidi.203.062. D. Kedar and J. Ye acknowledge support from NSF PHY-1734006, NIST, and AFRL. T. Legero, U. Sterr, and J. Yu acknowledge support by the Project 20FUN08 NEXTLASERS, which has received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 Research and Innovation Programme. A portion of this work was performed in the UCSB Nanofabrication Facility, an open access laboratory.

AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Garrett David Cole: Writing – review & editing (equal). **Thomas Legero:** Writing – review & editing (equal). **Camille Makarem:** Writing – review & editing (equal). **Steven Penn:** Writing – review & editing (equal). **David Reitze:** Writing – review & editing (equal). **Jessica Steinlechner:** Writing – review & editing (equal). **Uwe Sterr:** Writing – review & editing (equal). **Satoshi Tanioka:** Writing – review & editing (equal). **Gar-Wing Truong:** Writing – review & editing (equal). **Jun Ye:** Writing – review & editing (equal). **Jialiang Yu:** Writing – review & editing (equal). **Stefan Ballmer:** Writing – review & editing (equal). **GariLynn Billingsley:** Writing – review & editing (equal). **Seth B. Cataño-Lopez:** Writing – review & editing (equal). **Martin M. Fejer:** Writing – review & editing (equal). **Peter Fritschel:** Writing – review & editing (equal). **Andri M. Gretrasson:** Writing – review & editing (equal). **Gregory M. Harry:** Writing – review & editing (equal). **Dhruv Kedar:** Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

1H. B. Callen and R. F. Greene, "On a theorem of irreversible thermodynamics," Phys. Rev. **86**, 702 (1952).
2P. R. Saulson, "Thermal noise in mechanical experiments," Phys. Rev. D **42**, 2437 (1990).
3G. I. González and P. R. Saulson, "Brownian motion of a mass suspended by an anelastic wire," J. Acoust. Soc. Am. **96**, 207 (1994).
4V. B. Braginsky, V. P. Mitrofanov, and V. I. Panov, *Systems with Small Dissipation* (University of Chicago Press, 1985).
5Y. Levin, "Internal thermal noise in the LIGO test mass: A direct approach," Phys. Rev. D **57**, 659 (1998).
6G. M. Harry, A. M. Gretarsson, P. R. Saulson, S. E. Kittelberger, S. D. Penn, W. J. Startin, S. Rowan, M. M. Fejer, D. R. M. Crooks, G. Cagnoli, J. Hough, and N. Nakagawa, "Thermal noise in interferometric gravitational wave detectors due to dielectric optical coatings," Class. Quantum Gravity **19**, 897 (2002).
7B. P. Abbott, R. Abbott, T. D. Abbott, *et al.*, "GW150914: The advanced LIGO detectors in the era of first discoveries," Phys. Rev. Lett. **116**, 131103 (2016).
8S. D. Penn, P. Sneddon, H. Armandula, J. C. Betzwieser, G. Cagnoli, J. Camp, D. R. M. Crooks, M. Fejer, A. M. Gretarsson, G. M. Harry, J. Hough, S. E. Kittleberger, M. J. Mortonson, R. Route, S. Rowan, P. R. Saulson, and C. C.

26 December 2023 22:12:06

© Author(s) 2023

Vassiliou, "Mechanical loss in tantala/silica dielectric optical coatings," Class. Quantum Gravity **20**, 2917 (2003).
[9]G. M. Harry, M. R. Abernathy, A. E. Becerra-Toledo *et al.*, "Titania-doped tantala/silica coatings for gravitational-wave detection," Class. Quantum Gravity **24**, 405 (2007).
[10]B. P. Abbott, R. Abbott, T. D. Abbott *et al.*, "Observation of gravitational waves from a binary black hole merger," Phys. Rev. Lett. **116**, 061102 (2016).
[11]*Optical Coatings and Thermal Noise in Precision Measurement*, edited by G. Harry, T. P. Bodiya, and R. DeSalvo (Cambridge University Press, 2012).
[12]L. Pinard, C. Michel, B. Sassolas, L. Balzarini, J. Degallaix, V. Dolique, R. Flaminio, D. Forest, M. Granata, B. Lagrange, N. Straniero, J. Teillon, and G. Cagnoli, "Mirrors used in the LIGO interferometers for first detection of gravitational waves," Appl. Opt. **56**, C11–C15 (2017).
[13]M. Granata, A. Amato, G. Cagnoli, M. Coulon, J. Degallaix, D. Forest, L. Mereni, C. Michel, L. Pinard, B. Sassolas, and J. Teillon, "Progress in the measurement and reduction of thermal noise in optical coatings for gravitational-wave detectors," Appl. Opt. **59**, A229–A235 (2020).
[14]J. Aasi, B. P. Abbott, R. Abbott *et al.*, "Advanced LIGO," Class. Quantum Gravity **32**, 074001 (2015).
[15]D. G. Matei, T. Legero, S. Häfner, C. Grebing, R. Weyrich, W. Zhang, L. Sonderhouse, J. M. Robinson, J. Ye, F. Riehle, and U. Sterr, "1.5 μm lasers with sub-10 mHz linewidth," Phys. Rev. Lett. **118**, 263202 (2017).
[16]E. Oelker, R. B. Hutson, C. J. Kennedy, L. Sonderhouse, T. Bothwell, A. Goban, D. Kedar, C. Sanner, J. M. Robinson, G. E. Marti, D. G. Matei, T. Legero, M. Giunta, R. Holzwarth, F. Riehle, U. Sterr, and J. Ye, "Demonstration of 4.8×10^{-17} stability at 1 s for two independent optical clocks," Nat. Photonics **13**, 714 (2019).
[17]K. Numata, A. Kemery, and J. Camp, "Thermal-noise limit in the frequency stabilization of lasers with rigid cavities," Phys. Rev. Lett. **93**, 250602 (2004).
[18]M. Notcutt, L.-S. Ma, A. D. Ludlow, S. M. Foreman, J. Ye, and J. L. Hall, "Contribution of thermal noise to frequency stability of rigid optical cavity via Hertz-linewidth lasers," Phys. Rev. A **73**, 031804 (2006).
[19]M. Aspelmeyer, T. J. Kippenberg, and F. Marquardt, "Cavity optomechanics," Rev. Mod. Phys. **86**, 1391 (2014).
[20]S. Gras and N. Demos, MIT, personal communication.
[21]A. Buikema, C. Cahillane, G. L. Mansell *et al.*, "Sensitivity and performance of the Advanced LIGO detectors in the third observing run," Phys. Rev. D **102**, 062003 (2020).
[22]G. D. Cole, S. Gröblacher, K. Gugler, S. Gigan, and M. Aspelmeyer, "Monocrystalline $Al_xGa_{1-x}As$ heterostructures for high-reflectivity high-Q micromechanical resonators in the megahertz regime," Appl. Phys. Lett. **92**, 261108 (2008).
[23]G. D. Cole, I. Wilson-Rae, M. R. Vanner, S. Gröblacher, J. Pohl, M. Zorn, M. Weyers, A. Peters, and M. Aspelmeyer, "Megahertz monocrystalline optomechnaical resonators with minimal dissipation," in *23rd IEEE International Conference on MEMS*, Hong Kong, China, 24–28 January 2010 (IEEE, 2010), pp. 847–850.
[24]G. D. Cole, Y. Bai, M. Aspelmeyer, and E. A. Fitzgerald, "Free-standing $Al_xGa_{1-x}As$ heterostructures by gas-phase etching of germanium," Appl. Phys. Lett. **96**, 261102 (2010).
[25]G. D. Cole, "Cavity optomechanics with low-noise crystalline mirrors," in *SPIE Optics & Photonics, Optical Trapping and Optical Micromanipulation IX*, San Diego, CA, 12–16 August 2012 (SPIE, 2012).
[26]W. Marshall, C. Simon, R. Penrose, and D. Bouwmeester, "Towards quantum superpositions of a mirror," Phys. Rev. Lett. **91**, 130401 (2003).
[27]Y. Chen, "Macroscopic quantum mechanics: Theory and experimental concepts of optomechanics," J. Phys. B **46**, 104001 (2013).
[28]J. Cripe, N. Aggarwal, R. Lanza, A. Libson, R. Singh, P. Heu, D. Follman, G. D. Cole, N. Mavalvala, and T. Corbitt, "Measurement of quantum back action in the audio band at room temperature," Nature **568**, 364 (2019).
[29]T. Cullen, R. Pagano, J. Cripe, S. Sharifi, M. Lollie, S. Aronson, H. Cain, P. Heu, D. Follman, N. Aggarwal, G. D. Cole, and T. Corbitt, "Surpassing the standard quantum limit using an optical spring," arXiv:2210.12222 (2022).
[30]G. D. Cole, W. Zhang, M. J. Martin, J. Ye, and M. Aspelmeyer, "Tenfold reduction of Brownian noise in high-reflectivity optical coatings," Nat. Photonics **7**, 644 (2013).
[31]G. D. Cole, W. Zhang, B. J. Bjork, D. Follman, P. Heu, C. Deutsch, L. Sonderhouse, J. Robinson, C. Franz, A. Alexandrovski, M. Notcutt, O. H. Heckl, J. Ye, and M. Aspelmeyer, "High-performance near- and mid-infrared crystalline coatings," Optica **3**, 647 (2016).
[32]G. Winkler, L. W. Perner, G.-W. Truong, G. Zhao, D. Bachmann, A. S. Mayer, J. Fellinger, D. Follman, P. Heu, C. Deutsch, D. M. Bailey, H. Peelaers, S. Puchegger, A. J. Fleisher, G. D. Cole, and O. H. Heckl, "Mid-infrared interference coatings with excess optical loss below 10 ppm," Optica **8**, 686 (2021).
[33]G.-W. Truong, L. W. Perner, G. Winkler, S. B. Cataño-Lopez, C. Nguyen, D. Follman, O. H. Heckl, and G. D. Cole, "Transmission-dominated mid-infrared supermirrors with finesse exceeding 200 000," arXiv:2209.09902 (2022).
[34]B. J. Bjork, T. Q. Bui, O. H. Heckl, P. B. Changala, B. Spaun, P. Heu, D. Follman, C. Deutsch, G. D. Cole, M. Aspelmeyer, M. Okumura, and J. Ye, "Direct frequency comb measurement of OD + CO → DOCO kinetics," Science **354**, 444 (2016).
[35]S. Herbers, S. Häfner, S. Dörscher, T. Lücke, U. Sterr, and C. Lisdat, "Transportable clock laser system with an instability of 1.6×10^{-16}," Opt. Lett. **47**, 5441 (2022).
[36]M. Kelleher, F. Quinlan, M. L. Kelleher, and F. J. Quinlan, NIST (personal communication).
[37]M. Brekenfeld, B. Rauf, S. Saint-Jalm, G. D. Cole, G.-W. Truong, M. Lessing, A. Fricke, M. Fischer, M. Giunta, and R. Holzwarth, "Rack-mounted ultrastable laser system for Sr lattice clock operation," in Conference on Lasers and Electro-Optics (CLEO), San Jose, CA, 15–20 May 2022.
[38]J. M. Robinson, E. Oelker, W. R. Milner, W. Zhang, T. Legero, D. G. Matei, F. Riehle, U. Sterr, and J. Ye, "Crystalline optical cavity at 4 K with thermal noise limited instability and ultralow drift," Optica **6**, 240 (2019).
[39]J. Yu, D. Kedar, S. Häfner, T. Legero, F. Riehle, S. Herbers, D. Nicolodi, C. Y. Ma, J. M. Robinson, E. Oelker, J. Ye, and U. Sterr, "Excess noise in highly reflective crystalline mirror coatings," arXiv:2210.15671 (2022).
[40]D. Kedar, J. Yu, E. Oelker, A. Staron, W. R. Milner, J. M. Robinson, T. Legero, F. Riehle, U. Sterr, and J. Ye, "Frequency stability of cryogenic silicon cavities with semiconductor crystalline coatings," arXiv:2210.14881 (2022).
[41]M. Bückle, V. C. Hauber, G. D. Cole, C. Gärtner, U. Zeimer, J. Grenzer, and E. M. Weig, "Stress control of tensile-strained $In_{1-x}Ga_xP$ nanomechanical string resonators," Appl. Phys. Lett. **113**, 201903 (2018).
[42]G. D. Cole, P.-L. Yu, C. Gärtner, K. Siquans, R. Moghadas Nia, J. Schmöle, J. Hoelscher-Obermaier, T. P. Purdy, W. Wieczorek, C. A. Regal, and M. Aspelmeyer, "Tensile strained $In_xGa_{1-x}P$ membranes for cavity optomechanics," Appl. Phys. Lett. **104**, 201908 (2014).
[43]M. Marchiò, R. Flaminio, L. Pinard, D. Forest, C. Deutsch, P. Heu, D. Follman, and G. D. Cole, "Optical performance of large-area crystalline coatings," Opt. Express **26**, 6114 (2018).
[44]P. Koch, G. D. Cole, C. Deutsch, D. Follman, P. Heu, M. Kinley-Hanlon, R. Kirchhoff, S. Leavey, J. Lehmann, P. Oppermann, A. K. Rai, Z. Tornasi, J. Wöhler, D. S. Wu, T. Zederbauer, and H. Lück, "Thickness uniformity measurements and damage threshold tests of large-area GaAs/AlGaAs crystalline coatings for precision interferometry," Opt. Express **27**, 36731 (2019).
[45]G. Harry and G. Billingsley, "Fused silica, optics, and coatings," in *Advanced Gravitational-Wave Detectors*, edited by D. Reitze, P. Saulson, and H. Grote (World Scientific, 2019), Vol. 2.
[46]McGrath, "EV group to ship 450-mm wafer bonding tool," EE Times (2011).
[47]A. Staley, D. Martynov, R. Abbott *et al.*, "Achieving resonance in the advanced LIGO gravitational-wave interferometer," Class. Quantum Gravity **31**, 245010 (2014).
[48]C. Darsow-Fromm, M. Schröder, J. Gurs, R. Schnabel, and S. Steinlechner, "Highly efficient generation of coherent light at 2128 nm via degenerate optical-parametric oscillation," Opt. Lett. **45**, 6194 (2020).
[49]C. Gräf, S. Hild, H. Lück, B. Willke, K. A. Strain, S. Goßler, and K. Danzmann, "Optical layout for a 10 m Fabry–Perot Michelson interferometer with tunable stability," Class. Quantum Gravity **29**, 075003 (2012).
[50]C. Zhao, D. G. Blair, P. Barrigo *et al.*, "Gingin high optical power test facility," J. Phys.: Conf. Ser. **32**, 368 (2006).
[51]A. Utina, A. Amato, J. Arends *et al.*, "ETpathfinder: A cryogenic testbed for interferometric gravitational-wave detectors," Class. Quantum Gravity **39**, 215008 (2022).
[52]K. D. Skeldon, D. A. Clubley, B. W. Barr, M. M. Casey, J. Hough, S. D. Killbourn, P. W. McNamara, G. P. Newton, M. V. Plissi, D. I. Robertson, N. A. Robertson, K. A.

26 December 2023 22:12:06

© Author(s) 2023

Strain, and H. Ward, "Performance of the Glasgow 10 m prototype gravitational wave detector operating at λ=1064 nm," Phys. Lett. A **273**, 277 (2000).
[53]F. Matichard, B. Lantz, K. Mason *et al.*, "Advanced LIGO two-stage twelve-axis vibration isolation and positioning platform. Part 1: Design and production overview," Precis. Eng. **40**, 273 (2015).
[54]E. Oelker, G. Mansell, M. Tse, J. Miller, F. Matichard, L. Barsotti, P. Fritschel, D. McClelland, M. Evans, and N. Mavalvala, "Ultra-low phase noise squeezed vacuum source for gravitational wave detectors," Optica **3**, 682 (2016).
[55]S. Hild, M. Abernathy, F. Acernese *et al.*, "Sensitivity studies for third-generation gravitational wave observatories," Class. Quantum Gravity **28**, 094013 (2011).
[56]See the ET Design Study Update at https://apps.et-gw.eu/tds/?call_file=ET-0028A-20_EinsteinTelescopeScienceCaseDe.pdf for details on the required CTN reductions for ET-LF and ET-HF, outlining targets 10× and 4× below Advanced LIGO respectively; compared to current IBS multilayers, large-diameter AlGaAs coatings are anticipated to meet these requirements without the expense and risk of employing cryogenic detectors.

26 December 2023 22:12:06

© Author(s) 2023