Aluminum Gallium Arsenide as a High-Reflectivity Coating Material for Interferometric Gravitational-wave Detectors

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Abstract: Substrate-transferred single-crystal semiconductor heterostructures are effective as low-thermal-noise optical coatings for small beams. We discuss developing GaAs/AlGaAs coatings at a size scale relevant to interferometric gravitational wave detectors such as LIGO.

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1. Introduction, Background, and Requirements

Gravitational wave detectors like LIGO [1] and Virgo [2] are optical instruments designed to detect waves predicted in Einstein's General Theory of Relativity. They have had recent success by detecting gravitational waves from black hole and neutron star systems [3–5]. When these detectors reach their design sensitivity [6] around 2021, they will be limited by thermal noise [7] from the mirror coatings on the test masses [8]. Thermal noise is the random motion of atoms and is determined by temperature, material Young's moduli, beam size of the readout laser, and the mechanical loss of the coating, the ratio of the imaginary to the real part of the Young's modulus. Most of these quantities are known for coating materials or easily determined. The exception is mechanical loss, which must be measured.

Substrate-transferred single-crystal aluminum gallium arsenide/gallium arseninde ($Al_xGa_{1-x}As/GaAs$) (AlGaAs) multilayer Bragg stacks have proved effective as optical coatings for precision measurement applications [9]. AlGaAs coatings are grown on gallium arsenide wafers using molecular beam epitaxy. They then can be moved to substrates of various materials including fused silica glass where they adhere without use of intermediate materials. As an interference coating, the reflectivity can be modified by changing the layer count, the individual layer thicknesses and in this system specifically, by adjusting aluminum content in the low refractive index AlGaAs layers.

The Advanced LIGO test masses are 40 kg optics made from fused silica, 34 cm diameter and 20 cm thick. These optics have an ion beam sputtered coating of titania-doped tantala [10] and silica. Future interferometeric gravitational wave detectors with increased sensitivity to see further into the universe require lower coating thermal noise.

2. Measurements, Modeling, and Future Plans

Direct measurements of thermal noise from AlGaAs mirrors have been made in the quantum measurement community [8, 9]. The beam size in these experiments is typically tens of microns to one millimeter, which increases the thermal noise and makes it possible to measure in a laboratory setting. Thermal noise consistent with more than a factor of two improvement over current LIGO mirror materials has been observed in these experiments. Confirmation of this result within the gravitational wave detection community is in progress.

The mechanical quality factor of silica disks coated with AlGaAs have been measured to determine mechanical loss. These have been reported as a single value, although the samples are alternating layers of GaAs and AlGaAs and each material separately has multiple loss angles. Initial measurements yielded loss angles of $\phi \approx 5 \times 10^{-4}$. Improvements to coating uniformity and to the coating transfer process for coatings sizes up to ~ 75 mm in diameter, have lowered the loss angle to $\sim 2 \times 10^{-5}$, which is comparable to the best loss observed in direct thermal noise measurements [9].

AlGaAs is a crystal with three independent loss angles. Each of these loss angles serves as a source of thermal noise. The full implications of these mutliple loss angle for both interpretation of Q measurements and prediction of thermal noise is being analyzed. An open source computational tool that numerically solves the elastic problem to predict Brownian thermal noise from crystalline coatings has been developed. This code has successfully reproduced known results on amorphuous coatings and correctly scales with beam size, coating thickness, and coating diameter.

The principle engineering challenge to use of AlGaAs coating on gravitational wave detectors is the size. The largest AlGAs coating to date is 20 centimeter diameter, while more than 30 centimeters is needed, with excellent optical and mechanical properties across the whole diameter. Samples for optical tests at the LIGO Laboratory at Caltech are being prepared for measurement the summer of 2018. Samples suitable for mechanical loss measurements will also be prepared from the same deposition run to measure Q on low defect AlGaAs. Q samples with just AlGaAs and GaAs will also be measured for mechanical loss, to determine how much each individual material contributes to thermal noise. Modeling and theory efforts on the full crystalline nature of AlGaAs's stiffness matrix continue as well.

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