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研究課題名（和文） Development of crystalline mirrors for high precision measurements of space and time

研究課題名（英文） Development of crystalline mirrors for high precision measurements of space and time

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研究成果の概要（和文）：時間や周波数で距離を高精度に測定するためには、高フィネス光共振器を使用するが、その感度は鏡への熱雑音により制限される。本研究の目的とは、熱雑音低減のための結晶性コーティング鏡を開発することである。我々は、成膜用結晶成長の分野を研究する研究所や産業との議論を通じて適切な基材と成膜技術を調査した。その後GaAsウェハにGaAs/AlAs複層被膜を被着させたサンプルを作成し、評価した。最終的に、サファイア基材にGaAs/GaAlAs被膜を被着し、直径2インチの鏡を作成、評価した。最終形の鏡は、僅かな粗は認められるものの、極めて低い表面粗度（<1Å）と光散乱損失量（<6ppm）で作成された。

研究成果の概要（英文）：High precision measurements of distances, time or frequency, use high finesse optical cavities. Their sensitivity are limited by the mirror thermal noise. The purpose of this research has been to develop new mirrors based on crystalline coatings in order to decrease the thermal noise. First we investigated possible materials and deposition techniques through discussions with laboratories and industries working in the field of crystal coatings growth. We then have produced and characterized several samples made of GaAs/AlAs multilayers coatings deposited on GaAs wafers. Finally we have produced and characterized a two inches mirror made of a GaAs/GaAlAs coating deposited on a sapphire substrate. Despite a few defects, the final mirror has a very low roughness (<1 A) and a very small optical scattering (<6ppm).

研究分野： Gravitational wave astronomy

キーワード： Coatings　Crystals　Absorption　Scattering

１．研究開始当初の背景

1. Background of research

High precision measurements of distances, time or frequency, use high finesse and low loss optical cavities. These devices are used in several fields including in particular gravitational wave detection and optical atomic clocks but also quantum opto-mechanics and cavity quantum electro-dynamics. Nowadays the performances of these measurements are limited by the thermal noise affecting the mirrors which compose the optical cavities.

According to the fluctuation-dissipation theorem, the position of any mechanical system, affected by some energy dissipation process, will fluctuate. This fluctuation is known as thermal noise. In the case of high quality mirrors detailed studies have shown that the main cause of energy dissipation resides in the reflective multilayer coating deposited on the mirror surface.

２．研究の目的

2. Purpose of research

Coatings with low optical absorption (< 1ppm) are produced by means of ion beam sputtering. These materials have excellent optical properties but their mechanical losses are limiting the performances of high precision optical cavities. Measurements show that the majority of amorphous materials have losses of the order of 10^{-4} and that these losses do not improve when the temperature is decreased.

The situation is different for single-crystals which, in general, have lower mechanical losses which decrease further at cryogenic temperature. This observation pushes the development of optical coatings based on crystalline materials. The purpose of this research is to investigate present coatings made of amorphous material and develop new mirrors based on crystalline coatings in order to decrease the thermal noise and to improve the sensitivity of these optical sensors.

３．研究の方法

3. Method of research

The research has been focus on the investigation of crystalline coatings for optical applications.

To this purpose we started with having discussions with experts in the field of crystalline coatings growth, both from the industry and from the academic community mainly from Japan, France and the US. Once the most promising solution was identified we produced and characterized samples in collaboration with other academic groups. Finally we identified an industrial partner to produce the first large crystalline coating deposited on a sapphire crystal. In parallel we also investigated the performances of coatings developed for the LIGO and Virgo mirrors.

４．研究成果

4. Research Achievements

Single crystals coatings have been developed by research laboratories and industry mainly for application in the micro-electronics industry. They are used to produce semiconductor devices such as transistors, semiconductor lasers, LED, etc. For this reason in the first phase of the project we had extensive discussions with experts in the field of crystalline coatings growth. This includes discussions with research groups in France (CNRS/LPN, CNRS/CRHEA and CEA) and in Japan (University of Tokyo). We also had discussions with the industry in Japan (NTT, QDlaser) in France (SoITech) and in the US (CMS).

Regarding the materials for the multilayer coatings and the substrate we considered the following solutions:

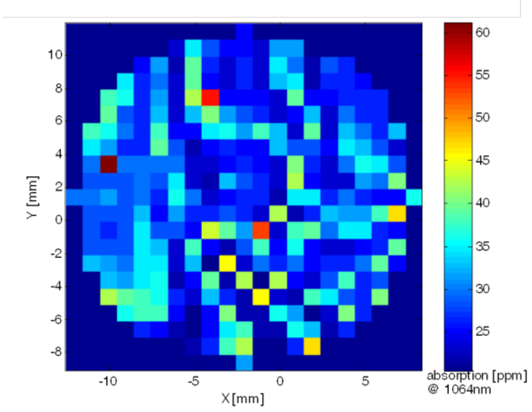
1. GaAs/AlAs grown on GaAs substrate and transferred onto sapphire, silica or silicon substrates
2. GaAs/AlAs grown on off-axis Ge substrate and transferred onto sapphire, silica or silicon substrates
3. GaAs/AlAs grown on silicon substrate
4. GaN/AlN grown on sapphire substrate
5. GaP/InP grown on silicon substrate

Solution 4 would be very interesting since it would allow to have the crystal directly grown on high quality optical substrate such as sapphire, the material used by the KAGRA project. Unfortunately the low lattice matching between GaN and AlN and the low index of refraction contrast makes the development of high reflectivity mirrors difficult with these materials. Solution 2, 3 and 5 are all affected (at different level) by the development of dislocations in the crystal. These dislocation are very problematic for high quality optical coatings with low absorption and low mechanical dissipation such as the ones that we want to develop. In conclusion solution 1 appears as the most promising. The main limitation in this case will be the size of the GaAs substrate that is limited to 6” at present and that will limit the size of the coating. This is relevant for application in gravitational wave detectors. With more time and funds available solution 2 appears to be the most promising alternative to increase the size of the coatings in case the size of GaAs wafer cannot be increased.

Regarding the coating growth technique both Molecular Beam Epitaxy (MBE) and Metalorganic Chemical Vapor Deposition (MOCVD) were investigated. While MBE is expected to ensure the best material purity, with MOCVD one can deposit coatings on larger substrates with a better uniformity. Given that efforts are ongoing in the industry to improve the purity of materials produced with MOCVD we decided to try both.

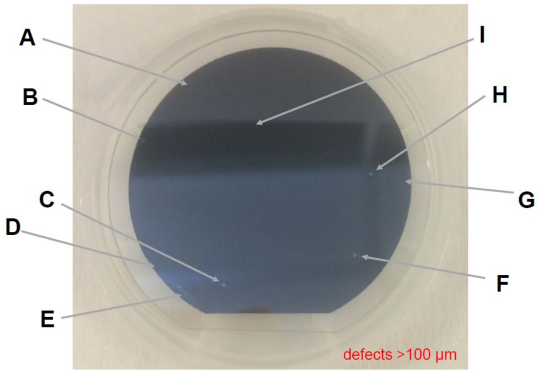
Based on the conclusions described above we started a collaboration with CNRS to produce and characterize several test samples made of GaAs/AlAs multilayer coatings deposited on GaAs substrates. All sample were 2 inches in diameter. We produced both samples made by MOCVD and samples made by MBE. The multilayer coatings were composed by 31 doublets providing a coating with a transmissions ranging from 140 ppm to 500 ppm at a wavelength of 1064 nm.

For these samples we measured the optical properties namely the optical absorption and the optical scattering. We found that both the optical absorption and the scattering were considerably lower on the sample made by MBE. In the case of MBE the best absorption we measured was 28 ppm ppm while in the case of MOCVD we measured 225 ppm. In the case of the absorption measurement, we suspect that the best absorption measurement could have been limited by the residual absorption inside the substrate itself probably due to the residual transmission of the coating. For the scattering we measured 80 ppm on the sample made by MBE and 3500 ppm on the sample made by MOCVD. Here below we show the absorption measurements as a function of the position on a sample made by MBE.



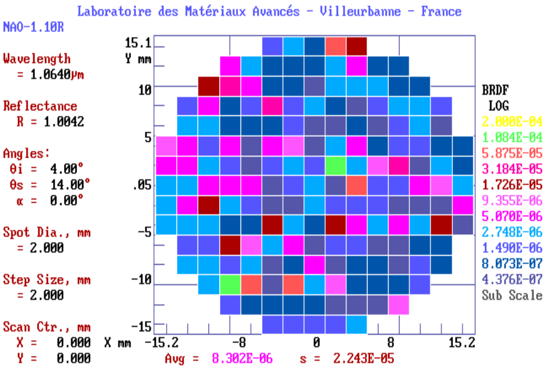
To investigate the origin of the mirror scattering we measured the scattering from a GaAs wafer without coating and found it to be well below the scattering from the wafer with the coating. We then checked the number of defects. Also in this case the MBE sample was of better quality then the MOCVD one, with a smaller density of defects. We measured about 160 defects/cm^2. We found that this density of defects is compatible with the measured scattering.

Based on this results we decided to start the production of a crystalline coating made of 35.5 doublets of GaAs/Al$_{0.92}$Ga$_{0.08}$As deposited on a GaAs wafer and then transferred onto a sapphire substrate. For this last step we worked with the company CMS (US). The sapphire substrate was a two inches micro-polished wafer having a residual roughness of about 1 Angstrom.



The visual inspection of the mirror shows that apart from about nine large defects the coating appears clean and properly bonded to the substrate. The measurement of the mirror roughness gives a value of about 1 Angstrom compatible with that of the original substrate. The picture above shows the sapphire substrate with the crystalline coating deposited on its surface. The arrows point to the defects larger than 100 µm. The picture below shows one of the defects. The origin of the defects remains to be investigated. The two most probable hypothesis are: 1) a defect on the back of the coating when the latter is separated from the original GaAs wafer, or 2) a defect on the sapphire substrate which create a defect in the bonding.

Given the index of refraction of the GaAs and of the Ga$_{0.08}$Al$_{0.92}$As layers the expected transmission is about 10 ppm. The measurement we made show an average transmission of about 6 ppm.



In order to qualify the optical quality of the mirror, we measured its scattering. The measurement is shown above. On average the scattering is about 6 ppm over the central 35 mm diameter of the mirror. This is a very good result, comparable to best results one can obtain with conventional high quality mirrors made with amorphous coatings. Finally we looked into the density of defects. Compared to the previous sample we found a much lower number of defects corresponding to a density of about 80 per cm^2 most of which concentrated on the outer region of the mirror.

In parallel with this work we also continued to investigate the mechanical quality factor of high quality coatings that have been used for the mirrors of the gravitational wave detectors Advanced LIGO and Advanced Virgo and will also be used for the baseline KAGRA. These measurements confirmed that at room temperature the mechanical losses of the coating and the corresponding mirror thermal noise will be the one of the main limitation to the sensitivity of gravitational wave detectors such as Advanced LIGO and Advanced Virgo and that the development of large crystalline coatings remain one of the most promising path to improve the sensitivity of laser interferometer gravitational wave detectors.

５．主な発表論文等
（研究代表者、研究分担者及び連携研究者には下線）

5. Papers and presentations
(underline PI and Co-investigators’ names)

〔雑誌論文〕（計 1 件）

[papers in journals] (total no.)

Massimo Granata, Emeline Saracco, Nazario Morgado, Alix Cajgfinger, Gianpietro Cagnoli, Jérôme Degallaix, Vincent Dolique, Danièle Forest, Janyce Franc, Christophe Michel, Laurent Pinard, Raffaele Flaminio
Mechanical loss in state-of-the-art amorphous optical coatings
Physical Review D 93 1 012007-(1-16) (2016)
10.1103/PhysRevD.93.012007
Peer reviewed

〔学会発表〕（計 1 件）

[presentations in academic conferences] (total no.)

Tatsumi, D., Aso, Y., Somiya, K., Schnabel, R., Flaminio, R.
R&D to improve the KAGRA sensitivity
Japan Physical Society
2016/09/25 - 2016/09/28
Osaka City University, Osaka, Japan

６．研究組織

6. Research organization

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