Low-loss silicon optics for cryogenic gravitational wave detectors

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Introduction

The silica/tantala (SiO_2/Ta_2O_5) coatings and silica test masses currently used in aLIGO are unsuitable at cryogenic temperatures due to their high mechanical loss. Crystalline silicon (cSi) test masses and amorphous silicon (aSi) coatings are promising alternatives, but their optical properties are not fully characterised yet.

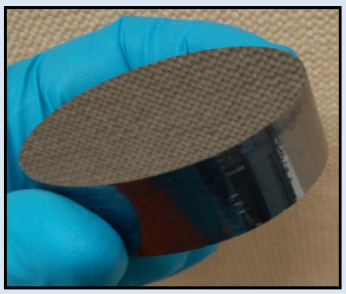

Figure 1: Bulk Indium-doped crystalline Si

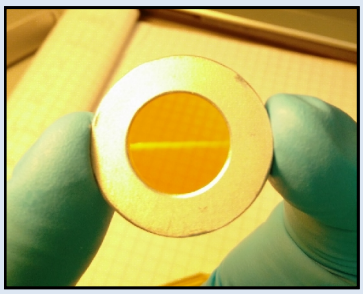

Figure 2: Ion beam sputtered amorphous Si film

Bulk crystalline silicon

- Residual dopants and impurities cause relevant optical absorption at the 1550 nm telecom wavelength even in high resistivity samples
- Temperature affects the dopants' degree of ionisation. Absorption changes then, because neutral atoms, ions and free carriers contribute to absorption differently
- Available theoretical models for such contributions don't fully explain observations
- Direct transmission measurements to probe absorption dependence on temperature in highly doped cSi.
- Photothermal deflection[1] technique is able to detect absorption down to a few ppm

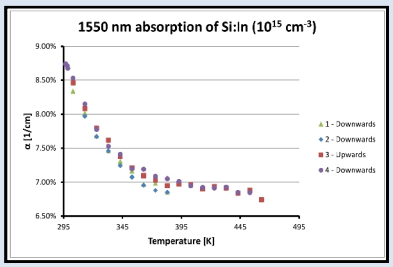

Figure 3: The curve labels refer to whether the curves have been taken heating or cooling the sample (to spot hysteretic effects)

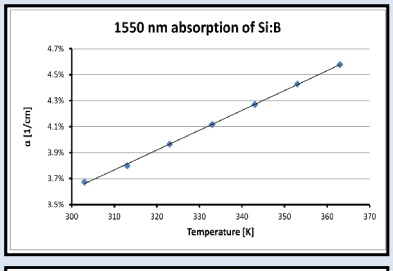

Figure 4: The dependence is completely linear for B dopants, because the B atoms have already ionised completely at a lower temperature.

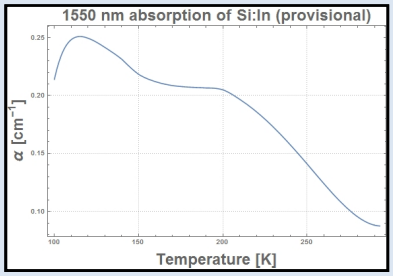

Figure 5: Photothermal deflection is a relative measurement. To obtain absolute values for the absorption, data must be normalised via a computational procedure whose reliability we are still testing.

[1] V. Loriette, C. Boccara, *Absorption of low-loss optical materials measured at 1064 nm by a position-modulated collinear photothermal detection technique*, Applied Optics (2003)

Amorphous silicon coatings

- Lower mechanical loss than tantala at low temperatures
- Higher refractive index. This helps beating thermal noise by reducing the number of bilayers and their geometrical thickness
- Optical absorption still too high to completely replace tantala (but multimaterial solutions may be already possible – see companion poster "Amorphous Silicon for Highly-Reflective Mirror Coatings"). To match GWD requirements, absorption in aSi has to be further reduced [2]
- Other crucial parameters, including mechanical loss, scattering and homogeneity, need more R&D
- Such parameters are thought to be dependent on the microscopic structure of the amorphous material, which can be probed via Raman scattering
- While annealing is used to improve absorption, the evolution of the amorphous structure can be studied as a function of annealing temperature

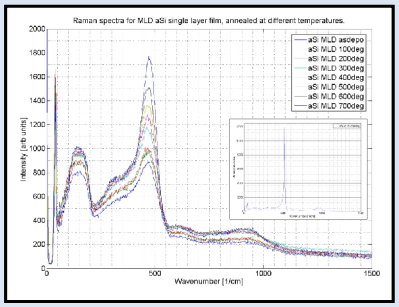

Figure 6: Evolution of Raman spectrum with annealing temperature for ion beam sputtered aSi. Inset: 800 °C sample, highly crystallised.

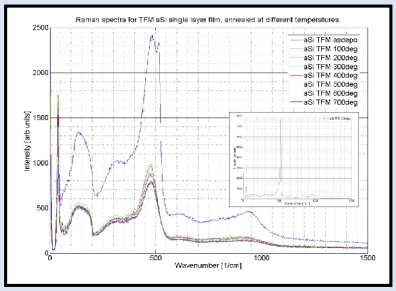

Figure 7: Evolution of Raman spectrum with annealing temperature for ion plated aSi. Inset: 800 °C sample, highly crystallised.

- Two sets of aSi films from vendors MLD and Tafelmaier were probed (figs. 6 and 7)
- Collaboration with UWS: find best way to deposit aSi (companion poster: "Ultra-low loss aSi coatings using novel ECR ion beam deposition.")

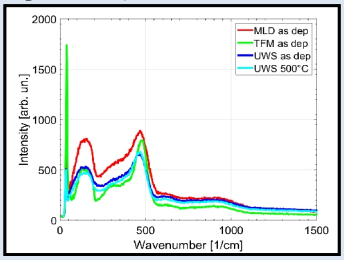

Figure 8: Comparison between Raman spectra of as-deposited films from different manufacturers. In cyan the spectrum of the lowest absorbing sample so far.

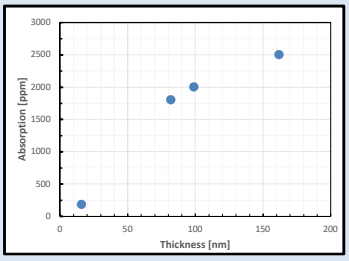

Figure 9: The thickness of the coating affects the absorption, because the transmitted fraction of light changes if the geometrical thickness is close to λ/4 or λ/2.

[2] J. Steinlechner et al., *Optical absorption of ion-beam sputtered amorphous silicon coatings*, Phys. Rev. D (2016)

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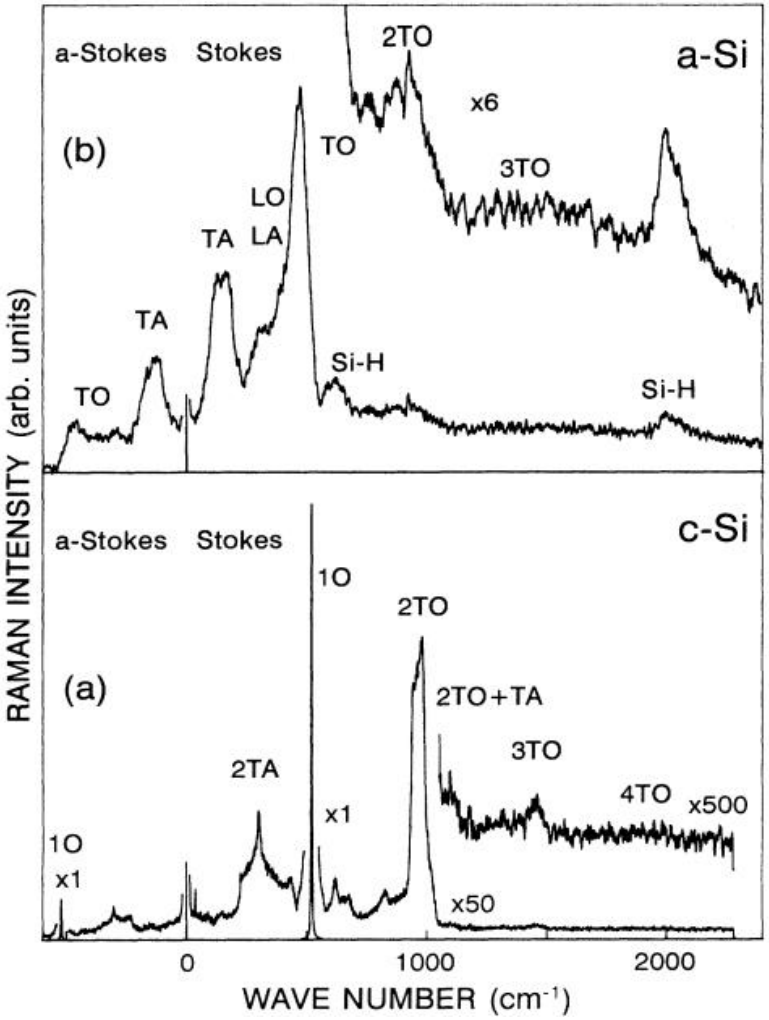
How to read an aSi Raman spectrum?



A. Zwick and C. Carles

Physical Review B (1993) 48-9

- The spectrum is characteristic of a highly disordered material: it is composed of broad bands. Two prominent structures are ascribed to first-order scattering by vibrational modes, corresponding to TA (50-200 cm^{-1}) and TO (440-520 cm^{-1}) phonons in cSi.

- The shoulder on the lower energy tail of the TO band (250-440 cm^{-1}) has been ascribed to LA- and LO-like modes.

- At 2000 cm^{-1} is shown the Si-H bond-stretching band, and the corresponding bending or wagging around 60 cm^{-1}.

- In addition, second-order features can also be observed, particularly the 2TO centred at 960 cm^{-1}. Not so easily noticed is the presence of the 2LA and TO+TA, since their contribution is practically hidden by the Si-H band.