Optics Posters

Optics Working Group

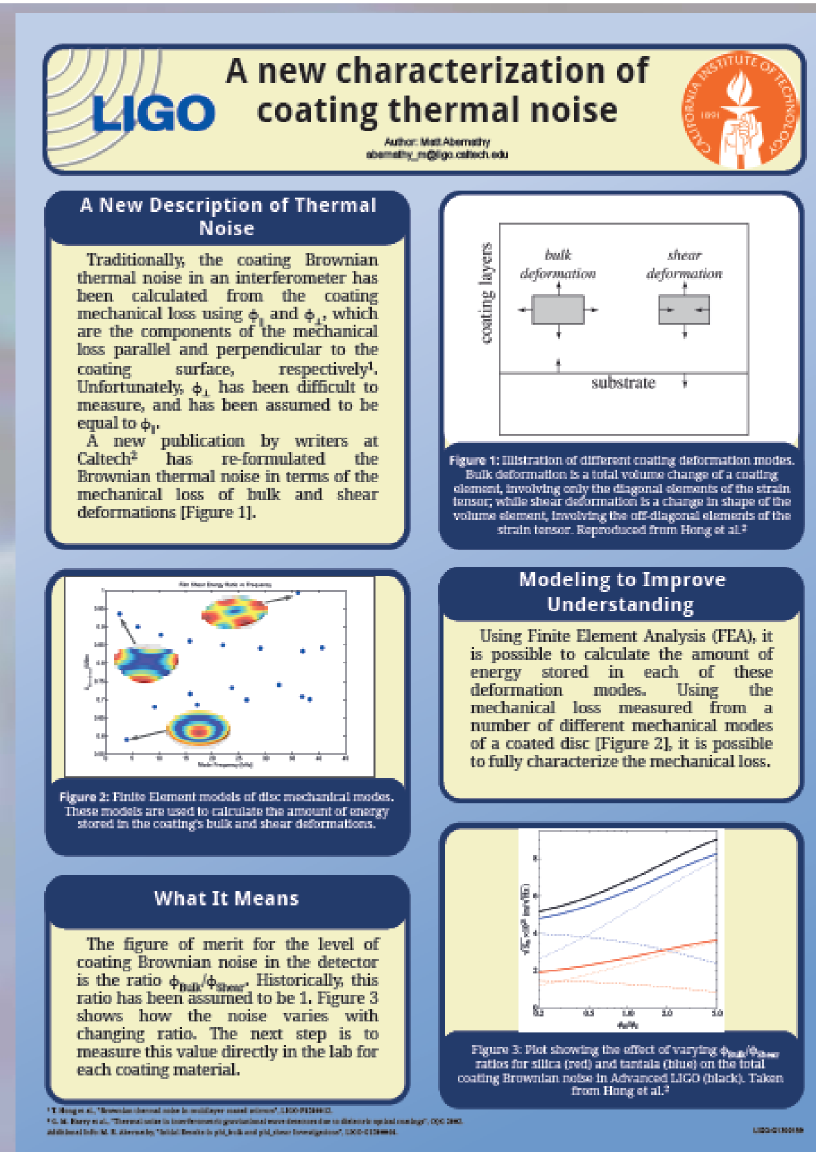
LVC Meeting
Bethesda Maryland
March 18, 2013

G1300310

Bulk and Shear Loss in Coatings

"A New Characterization of Coating Thermal Noise"

Matt Abernathy



Cryogenic Q of Silicon

“Measurement of Q-factors of silicon wafers vibrational modes at low temperatures”

Valery Mitrofanov and Leonid Prokhorov

Measurement of *Q*-factors of silicon wafers vibrational modes at low temperatures

L.G. Prokhorov, V.P. Mitrofanov
Moscow State University

LIGO Scientific Collaboration
LVC meeting, March 2013, LIGO-G1300211.

Motivation

Silicon test masses and silicon suspensions are considered as prospective candidates for the third generation of GW detectors due to very low mechanical loss in crystalline silicon and its other excellent properties [1]. They will operate at the low temperature of about 120 K in order to reduce significantly thermoelastic loss in silicon and associated thermal noise. Internal mechanical losses of silicon single-crystals allowed one to obtain $Q > 10^7$ for the silicon ribbons at these temperatures [2]. The main problem is surface losses because silicon fibers or silicon ribbons have large ratio of the surface to volume, so the losses in their surface layers dominate. It is necessary to realize a technique for silicon ribbons/fibers fabrication and subsequent their treatment which provide low surface losses. It is possible to fabricate silicon ribbons from standard silicon wafers. There are several techniques of etching of silicon used for fabrication of micromechanical structures. Wet or dry etching is likely the most appropriate, because allows obtaining of the smooth surface without defects. Anisotropy of etching allows one to fabricate ribbons from silicon wafer making slots in a wafer with vertical walls.

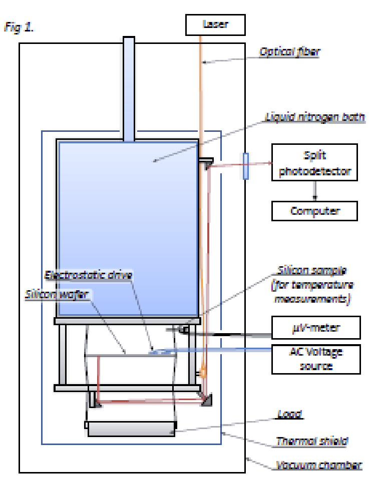
The losses in silicon ribbons can be determined by measuring the *Q*-factors of mechanical oscillators formed on the base of the ribbons. It is necessary to clamp the oscillator so that the clamping losses are negligible. In work [3] the thicker block at one end of the thin flexure was fabricated in order to reduce clamping losses of thin silicon flexure. We suppose to test other versions of clamping structure in order to measure dissipation in silicon ribbons which is not associated with clamping losses. It is proposed to fabricate the mechanical oscillator in the silicon wafer by means of etching and to clamp the wafer with the fabricated oscillator attaining the minimal clamping losses.

In this work we investigate mechanical losses of vibrational modes of silicon wafers suspended by wires at temperatures 100K – 300K.

Experimental setup.

Schematic of the setup is shown in Fig.1. The dewar with liquid nitrogen is mounted inside the vacuum chamber. The silicon wafer is suspended inside a special frame which is attached to the dewar bottom. We use 100 µm diameter nichrome wire for the wafer suspension. In order to provide the constant wire tension in the process of cooling the weight is hung on the wire end. The additional piece of silicon wafer with attached thermocouple is used to measure the temperature. Resonant excitation of the wafer vibrational modes is realized by the electrostatic drive. Optical sensor is used to monitor the vibration amplitude of the wafer modes. Local bending of the wafer produced by its vibration results in deflection of the laser beam reflected from the silicon wafer which passes through the mirror system and is detected by a split photodiode set outside the vacuum chamber. *Q*-factor of the mode is determined measuring the decay time of the mode free vibration.

Fig 1.



Results of measurements

The main measurements were carried out for 3 inch diameter 320 µm thickness double side polished commercial *n*-type single-crystal silicon <111> wafer doped with antimony (the electrical resistivity is 0.02 Ohm·cm). Several vibrational modes are measured. The temperature dependence of the relative variations of the modes frequencies is shown in Fig. 2.

We use two regimes of measurement of temperature dependence of the mode's *Q*-factor. In the first one the *Q*-factor is measured in process of cooling of the wafer after the dewar was filled with liquid nitrogen. The cooling of the wafer is realized by radiative heat transfer at the pressure of about 3×10^{-6} Torr in the vacuum chamber. In the second regime the *Q*-factor is measured in process of heating of the wafer which was cooled preliminary by means of exchange gas-nitrogen at the pressure of about 3×10^{-3} Torr in the vacuum chamber.

The temperature dependence of loss for two vibrational modes of the silicon wafer is shown in Fig.3. The dependences were measured in process of heating of the wafer.

Estimates of thermoelastic loss were made using calculations for silicon beam with rectangular cross section and the same thickness as the thickness of the wafer used in our measurements

Fig 2.

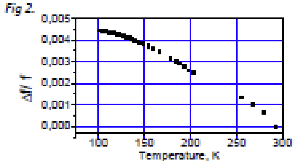
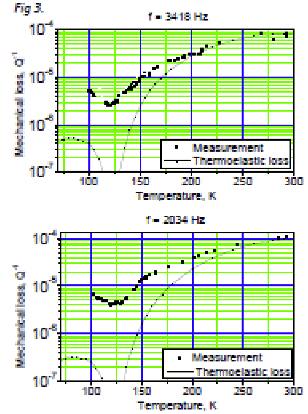


Fig 3.



Summary and future work

The mechanical dissipation in silicon wafer which we measure at the temperature range near 120 K is mainly associated with clamping losses. We plan to improve the wafer suspension and to measure the dissipation in silicon oscillators fabricated in the wafers.

Acknowledgements

The authors are grateful to NSF and Caltech for support of this research under grant PHY-0967049 and to Stan Whitcomb for his invaluable help.

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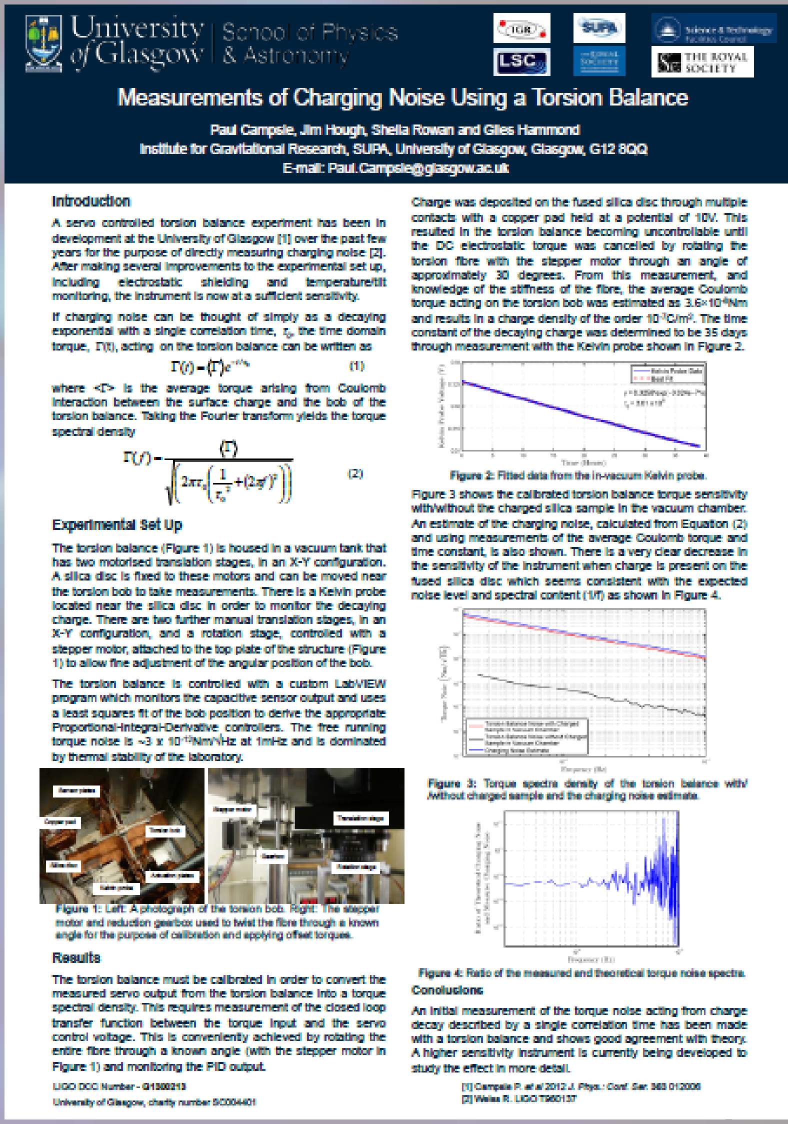
3. R. Nawrodt et al., submitted to Class. Quantum. Grav.

Charging Noise

"Measurements of Charging Noise with a Torsion Balance"

Paul Campsie, Giles Hammond, James Hough, Sheila Rowan



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Measurements of Charging Noise Using a Torsion Balance

Paul Campsie, Jim Hough, Sheila Rowan and Giles Hammond
Institute for Gravitational Research, SUPA, University of Glasgow, Glasgow, G12 8QQ
E-mail: Paul.Campsie@glasgow.ac.uk

Introduction

A servo controlled torsion balance experiment has been in development at the University of Glasgow [1] over the past few years for the purpose of directly measuring charging noise [2]. After making several improvements to the experimental set up, including electrostatic shielding and temperature/tilt monitoring, the instrument is now at a sufficient sensitivity.

If charging noise can be thought of simply as a decaying exponential with a single correlation time, τ_0, the time domain torque, $\Gamma(t)$, acting on the torsion balance can be written as

$$\Gamma(t) = \langle\Gamma\rangle e^{-t/\tau_0} \quad (1)$$

where $\langle\Gamma\rangle$ is the average torque arising from Coulomb interaction between the surface charge and the bob of the torsion balance. Taking the Fourier transform yields the torque spectral density

$$\Gamma(f) = \frac{\langle\Gamma\rangle}{\sqrt{\left(2\pi\tau_0\left(\frac{1}{\tau_0^2}+(2\pi f)^2\right)\right)}} \quad (2)$$

Experimental Set Up

The torsion balance (Figure 1) is housed in a vacuum tank that has two motorised translation stages, in an X-Y configuration. A silica disc is fixed to these motors and can be moved near the torsion bob to take measurements. There is a Kelvin probe located near the silica disc in order to monitor the decaying charge. There are two further manual translation stages, in an X-Y configuration, and a rotation stage, controlled with a stepper motor, attached to the top plate of the structure (Figure 1) to allow fine adjustment of the angular position of the bob.

The torsion balance is controlled with a custom LabVIEW program which monitors the capacitive sensor output and uses a least squares fit of the bob position to derive the appropriate Proportional-Integral-Derivative controllers. The free running torque noise is ~3 x 10^{-12}Nm/√Hz at 1mHz and is dominated by thermal stability of the laboratory.

Figure 1: Left: A photograph of the torsion bob. Right: The stepper motor and reduction gearbox used to twist the fibre through a known angle for the purpose of calibration and applying offset torques.

Results

The torsion balance must be calibrated in order to convert the measured servo output from the torsion balance into a torque spectral density. This requires measurement of the closed loop transfer function between the torque input and the servo control voltage. This is conveniently achieved by rotating the entire fibre through a known angle (with the stepper motor in Figure 1) and monitoring the PID output.

Charge was deposited on the fused silica disc through multiple contacts with a copper pad held at a potential of 10V. This resulted in the torsion balance becoming uncontrollable until the DC electrostatic torque was cancelled by rotating the torsion fibre with the stepper motor through an angle of approximately 30 degrees. From this measurement, and knowledge of the stiffness of the fibre, the average Coulomb torque acting on the torsion bob was estimated as 3.6×10^{-8}Nm and results in a charge density of the order 10^{-7}C/m². The time constant of the decaying charge was determined to be 35 days through measurement with the Kelvin probe shown in Figure 2.

Figure 2: Fitted data from the in-vacuum Kelvin probe.

Figure 3 shows the calibrated torsion balance torque sensitivity with/without the charged silica sample in the vacuum chamber. An estimate of the charging noise, calculated from Equation (2) and using measurements of the average Coulomb torque and time constant, is also shown. There is a very clear decrease in the sensitivity of the instrument when charge is present on the fused silica disc which seems consistent with the expected noise level and spectral content (1/f) as shown in Figure 4.

Figure 3: Torque spectra density of the torsion balance with/without charged sample and the charging noise estimate.

Figure 4: Ratio of the measured and theoretical torque noise spectra.

Conclusions

An initial measurement of the torque noise acting from charge decay described by a single correlation time has been made with a torsion balance and shows good agreement with theory. A higher sensitivity instrument is currently being developed to study the effect in more detail.

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[1] Campsie P. et al 2012 J. Phys.: Conf. Ser. 363 012006
[2] Weiss R. LIGO T960137

Epoxy and Silica Mechanical Loss

"Mechanical Loss Measurement of TRA-DUCT 2902 Epoxy and Shear and Bulk Mechanical Loss of Silica"

Jonathan Newport, Danika Balas, David Beyea, Alexandra France, Steve Penn, Raymond Robie – American University (and HWS)

Mechanical Loss Measurements of TRA-DUCT 2902 Epoxy and Shear and Bulk Mechanical Loss of Silica

Jonathan Newport[1], Danika Balas[1], David Belyea[1], Alexandra France[1], Steve Penn[2], Raymond Robie[1], Gregory Harry[1]

[1]American University, [2]Hobart and William Smith Colleges

We measured the mechanical loss of TRA-DUCT 2902 conductive epoxy and bare silica disks. Both were analyzed to determine separately the shear and bulk components of mechanical loss. The epoxy is of interest as a way of attaching tuned mass dampers to Advanced LIGO test masses to help mitigate parametric instability. Measuring the shear and bulk components of silica mechanical loss are a first step towards designing coatings with partial cancellation of shear and bulk thermal noise. *LIGO-G1300163*

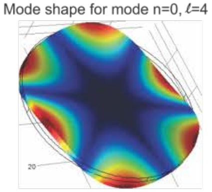
Shear and Bulk Mechanical Loss in Silica

Theory: We modeled the mechanical loss in silica starting with the technique of Penn *et al*, Physics Letters A **352,** (2006) 3, but expanded to allow for a loss angle associated with the shear modulus, ϕ_{shear}, and bulk modulus, ϕ_{bulk}.

$$\phi_{substrate}(f_n) = a_n\,\phi_{shear}\,f_n^{0.77} + (1-a_n)\,\phi_{bulk}\,f_n^{0.77}$$

where $\phi_{substrate}$ is the mechanical loss of the silica substrate (excluding surface effects), n is normal mode number, f_n is the normal mode frequency, a_n is the fraction of elastic energy of the normal mode in shear deformation, and ϕ_{shear} and ϕ_{bulk} are loss angle coefficients to be determined from experimental data.

Mode shape for mode n=0, ℓ=4



Measured Q Values

Mode	Frequency	Q	a_n
n=0, ℓ=1	2699.3 Hz	2.17×10^7	0.935
n=0, ℓ=3	6148.5 Hz	1.90×10^7	0.898
n=1, ℓ=1	9438.3 Hz	1.32×10^7	0.656
n=0, ℓ=4	10612 Hz	0.92×10^7	0.876

Silica Results

The two modes n=1, ℓ=4 and n=0, ℓ=4 have the widest spread in their shear and bulk energy ratios. Using these two modes, we find

$$\phi_{shear} = 9.8 \times 10^{-11}$$
$$\phi_{bulk} = 4.5 \times 10^{-12}$$

Predicted and Measured Q's

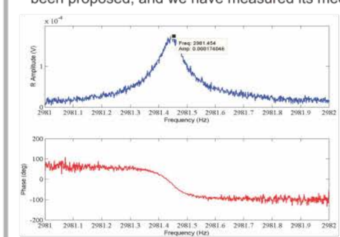
Using the values found to the left for ϕ_{shear} and ϕ_{bulk} we predict the Q's for the n=0, ℓ=1 and n=0, ℓ=3 modes and compare with measured values.

	$Q_{predicted}$	$Q_{measured}$
n=0, ℓ=1	2.47×10^7	1.93×10^7
n=0, ℓ=3	1.36×10^7	1.90×10^7

Mechanical Loss of TRA-DUCT 2902 Epoxy

Theory: Exchange of energy between optical and acoustical modes, parametric instability, is a potential problem in high power operation of Advanced LIGO. Tuned mass dampers, designed to reduce the modal Q's of test masses have been proposed to solve this problem. These dampers could be held to the test masses with epoxy. Excess thermal noise from the epoxy is a concern. To predict the level of thermal noise, mechanical loss of epoxy must be measured. TRA-DUCT 2902 conductive epoxy has been proposed, and we have measured its mechanical loss.

Sample showing epoxy (silver), suspension bob and exciter (blue).



Amplitude and phase shift of n=0, ℓ=1 mode.

Measured Q Values

Mode	Frequency (Hz)	Q	Energy % in Epoxy
n=0, ℓ=1	2707.5	1.76×10^4	0.11
	2981.5	2.07×10^4	0.09
n=1, ℓ=0	4137.5	1.63×10^4	0.11
n=0, ℓ=3	6157.6	4.11×10^4	0.09
	6312.8	5.49×10^4	0.08
n=1, ℓ=1	9457.8	2.15×10^4	0.07
Shear	37071.2	9.51×10^4	0.04
	37155.1	8.64×10^4	0.04

Epoxy Results

$$\phi_{shear,epoxy} = 4 \pm 1 \times 10^{-2}$$

This mechanical loss is about a factor of 2 better than was used in the model in G1001023. However, it may still be too high to avoid excess thermal noise in Advanced LIGO.

Future Plans: On the shear and bulk loss project, expand the model to include surface loss, measure additional modes including higher bulk energy, and anneal substrates. Once silica is understood, coatings like titania-tantala, AlGaAs, and Si_3N_4 will be measured.

On the epoxy project, measure additional epoxies including MasterBond EP30-2, Hysol TRA-BOND, and natural resin from Australia. Also measure higher frequencies to determine any frequency dependence of the epoxy loss.

Coatings and Materials

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