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Low-temperature mechanical losses of oscillators fabricated in silicon wafers

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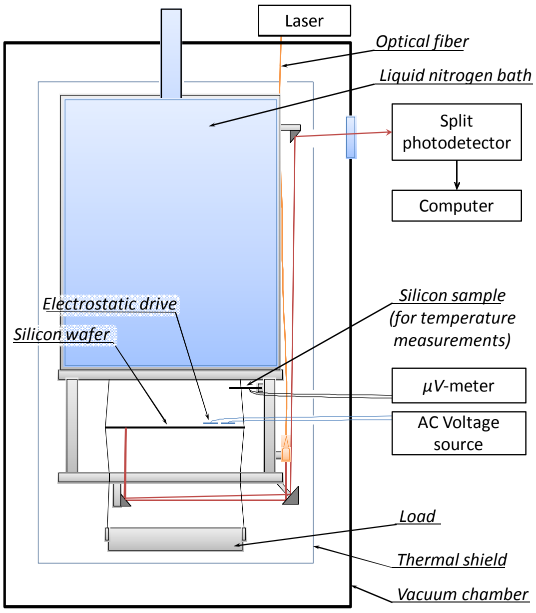
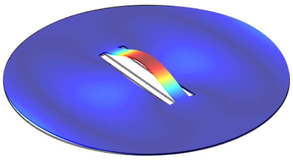
Introduction

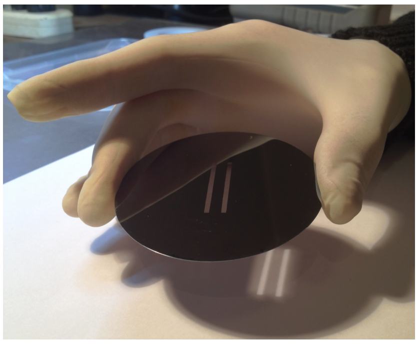
The Blue Design of the Advanced LIGO upgrade program is based on crystalline silicon core optics suspended by silicon fibers or ribbons using cryogenic operation at about 120 K. At this temperature the thermal expansion coefficient (TEC) of silicon crosses zero, so the thermoelastic losses and thermoelastic noise also approach zero. Silicon fibers or silicon ribbons have a large surface-to-volume ratio, so the losses in the surface layer dominate. It is necessary to realize a technique for silicon ribbons/fibers fabrication and their subsequent treatment which provide low level of the surface losses. It is possible to fabricate silicon ribbons from standard silicon wafers using anisotropic chemical wet etching. Anisotropy of etching allows one to fabricate ribbons from a silicon wafer making slots in a wafer with flat walls. Such a technique is realized in our lab. The losses in silicon ribbons can be determined by measuring the Q-factors of mechanical oscillators formed on the base of the ribbons. The simplest version of such an oscillator can be designed as a doubly clamped ribbon. The shape of its fundamental bending mode obtained by computer simulation is shown below. Fabrication of the oscillator in a silicon wafer allows reducing the clamping losses if one clamps the wafer in nodal points of vibrations.

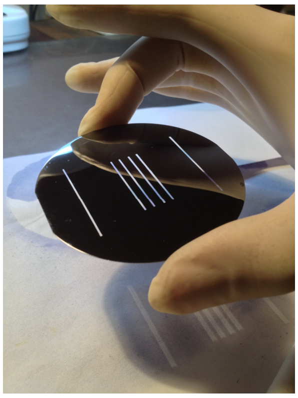


Manufacturing of silicon oscillators

The oscillator was fabricated from a 3 inch diameter, 360-µm thick, double side polished, commercial n-type <100> oriented single crystal silicon wafer (the electrical resistivity is about 4 Ohm·cm). 1.2 µm-thick SiO_2 layer was grown by thermal oxidation on each side. After cleaning the wafer was warmed up at 120˚C (removing of adsorbed water) and then coated with a positive photoresist. To form the strips on the photoresist layer, the wafer was put in contact with a mask printed on a transparent film. It is important to carefully align the strips, so that they are parallel to the crystal axis <110> which is denoted by the reference flat specially cut into the wafer. The photoresist was then exposed for 20 min by the UV lamp. After developing in 1 % KOH solution for 1 min, the wafer was rinsed, dry and hardbaked at 140˚C for 20 min. The bare SiO_2 was then stripped by etching in buffered oxide etch (BOE). In order to eliminate the residual photoresist, the wafer was cleaned by acetone. The silicon etching was then performed in a KOH solution (30% concentration by weight in water) at 80˚C. The measured etch rate was about 1 µm/min. The residual SiO_2 layer was removed by BOE. The wafer was then rinsed and dry. Oscillators fabricated in the silicon wafers are shown below.

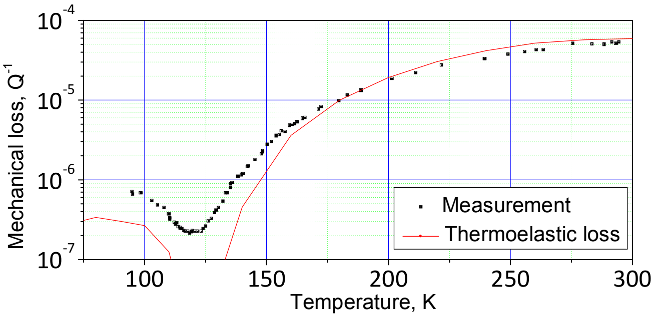






Results of measurements

We have measured the temperature dependence of resonant frequency and Q-factor of the silicon oscillator – doubly clamped ribbon. The ribbon length is 30 mm, width – 4mm. The silicon wafer is suspended inside a special frame attached to a dewar with liquid nitrogen mounted inside the vacuum chamber. The wafer is inset between 4 nichrome wires of 100 µm diameter stretched with suspended loads. Resonant excitation of the oscillator vibration is produced using the electrostatic drive. The vibration amplitude is monitored by the optical sensor. Local bending of the ribbon produced by its vibration results in deflection of the laser beam reflected from the ribbon surface. The reflected beam passed through the mirror system is detected by a split photodiode set outside the vacuum chamber. The lower mode of bending vibration of the ribbon has a resonant frequency f = 2390 Hz and Q = 1.6×10^4 at room temperature. The temperature dependence of measured and calculated loss Q^{-1} for this mode of the silicon oscillator is shown at the plot. One can see that around room temperatures the measured loss factors are slightly less than calculated according to Zener's theory. This can be explained by uncertainties of thermal and elastic parameters of silicon taken from literature as well as more complicated structure of deformations of the ribbon near its ends in contrast to the model of true doubly clamped beam.



Discussion and Future plans

We present results of measurements of dissipation in silicon ribbons fabricated on the base of standard silicon wafers. The limit of Q determined by thermoelastic damping at temperatures near zero TEC of silicon is likely not reached as yet. It is necessary to improve the etching technique for obtaining very high quality of the etched surfaces of silicon and low surface losses. In order to have possibilities of detailed search of losses in silicon ribbons at the level of low than 10^{-7}- 10^{-8} at low temperatures the clamping losses need to be reduced significantly as well. Also we plan to fabricate the oscillators having other configurations and lower resonant frequencies.

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