Mechanical losses of oscillators fabricated in silicon wafers

L.G. Prokhorov and V.P. Mitrofanov

Faculty of Physics, Moscow State University, Moscow 119991, Russia

E-mail: prokhorovlg@phys.msu.ru and mitr@hbar.phys.msu.ru

Abstract. Investigation of mechanical dissipation in silicon ribbons is important for the development of low noise silicon test mass suspension of the future interferometric gravitational wave detectors. Ribbon-like oscillators were fabricated in commercial silicon wafers using the anisotropic chemical wet etching technique. Results of measurement of the mechanical loss of such oscillators in the temperature range from 90 K to 300 K are presented. Suppression of thermoelastic loss down to 2×10^{-7} at a temperature of about 124 K is observed.

PACS numbers: 04.80.Nn, 62.40.+i

1. Introduction

The interferometric gravitational wave detectors of the second generation (Advanced LIGO, Advanced VIRGO) are planned for commissioning in the near future [1, 2]. The next generation of detectors is now under discussion. Single crystalline silicon test masses suspended by silicon ribbons operated at low temperature are considered as prospective candidates for the third generation of GW detectors due to very low mechanical loss in crystalline silicon and its excellent thermal and optical properties at wavelength around 1.5 μm [3]. The mechanical loss is a crucial parameter determining thermal fluctuation in the test mass and its suspension [4, 5]. At the temperature of about 124 K the thermal expansion coefficient of silicon crosses zero so the thermoelastic loss and thermoelastic noise also approach zero. In order to calculate the thermal noise of the test mass suspension one needs to know the minimal value of the mechanical loss that can be achieved in the suspension ribbons. This value can be determined experimentally by measuring the Q-factor of the silicon mechanical oscillator having a vibration mode shape that is close to the mode shape of the suspension ribbon. One of the main problems is to minimize clamping loss of this oscillator. Bending modes and various dissipation mechanisms of silicon cantilevers were studied in [6]. The cantilevers had a thick 'clamping block' at one end, which was designed to minimize the loss of energy into the support structure. Reduction of clamping loss can be also realized by choosing the optimal geometry of the oscillating system [7]. Very low clamping loss was

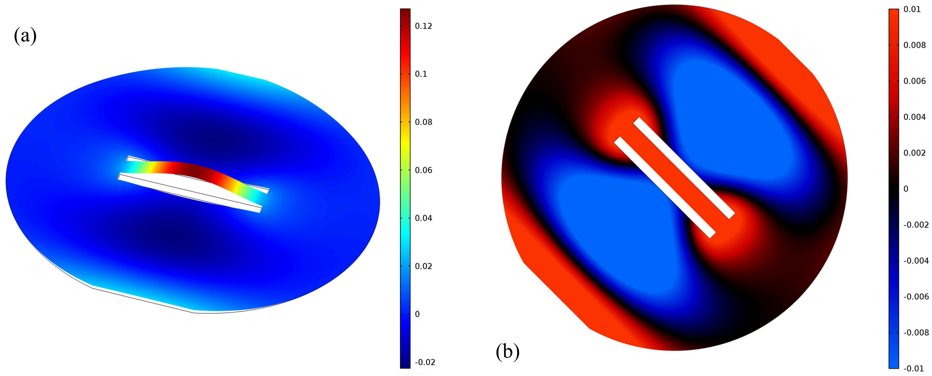

Figure 1. Shape of the oscillator's first bending mode obtained by the computer simulation *(a)* Distribution of the wafer displacement where the color scale has a range limited by small displacements (the nodal areas are black) *(b)*.

obtained in silicon mechanical resonators with a tuning fork structure and additional dynamic balancing [8]. Another important dissipation mechanism in silicon ribbons and oscillators is the surface loss which can dominate due to a large surface to volume ratio in ribbons. Surface loss obstructs the attaining maximal Q-factor which was obtained for bulk silicon mechanical resonators [9]. Surface loss depends on surface preparation techniques [10]. A wide variety of fabrication techniques has been developed to make silicon micromechanical structure [11]. In this paper, we present results of measurements of mechanical losses for oscillators fabricated as doubly clamped ribbons in silicon wafers by means of anisotropic chemical wet etching. Fabrication of the oscillator in a silicon wafer allows us to reduce the clamping loss by using the mounting of the wafer in nodal points of its vibration. The measurements were carried out in the temperature range from 90 K to 300 K.

2. Experimental procedure

Mechanical oscillator is fabricated in a 3 inch diameter, 360 μm thick, double side polished, n-type $< 100 >$ oriented commercial single crystal silicon wafer (the electrical resistivity is about 4 Ohm·cm). The oscillator is designed as a ribbon clamped at both ends. It is formed by two parallel slots etched in the silicon wafer. They have a length of 30 mm and a width of 2 mm. The ribbon's width is 4 mm. The protective mask is formed using photolithographic technique in 1.2 μm-thick SiO_2 layers grown by thermal oxidation on each side of the wafer. 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 cut into the wafer. Anisotropic wet etching in a KOH solution (30% concentration by weight in water) at the temperature of 80°C was used. One can find the detailed description of this technique in [12]. The shape of the oscillator's first bending mode obtained by computer simulation is shown in figure 1*(a)*.

Schematic of the experimental setup is presented in figure 2. The silicon wafer is

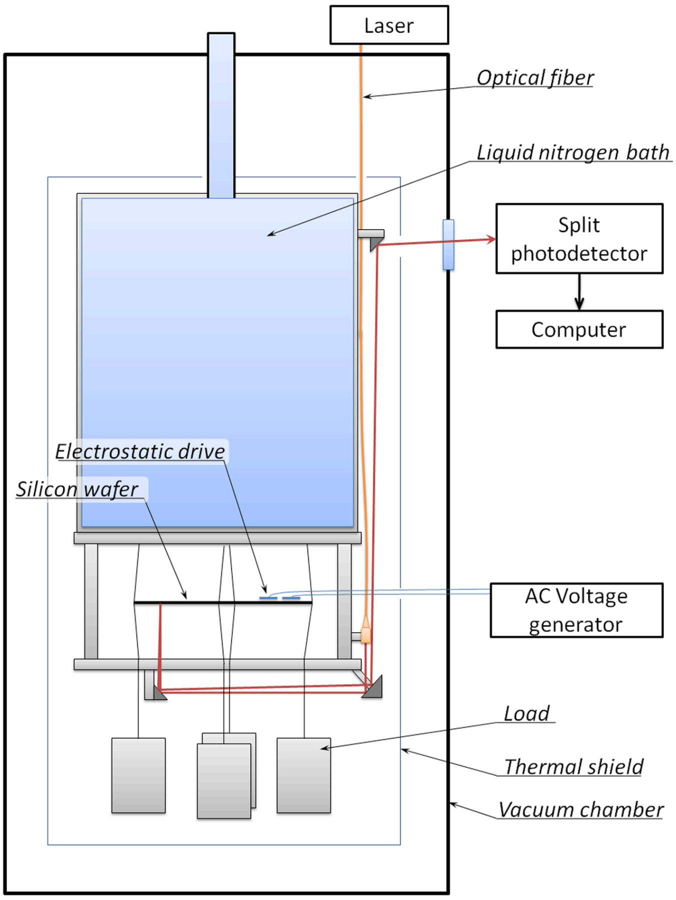

Figure 2. Schematic of the experimental setup.

suspended in a special frame attached to a dewar with liquid nitrogen mounted inside the vacuum chamber. The wafer is clamped by 4 nichrome wires of 100 μm diameter. A load of $\approx$ 200 g is hanged from the each wire in order to provide the constant tension in the process of cooling. The wires contact the wafer in nodal points of the wafer vibration. Spatial distribution of the wafer displacement along the normal of the wafer surface is shown in figure 1*(b)*. In order to clearly display the nodal areas of the wafer, the color scale has a range limited by small displacements. Slight nonsymmetry of the displacement distribution is caused by two dissimilar reference flats cut into the standard wafer indicating the crystallographic planes and the doping type.

Resonant excitation of the oscillator's vibration is realized using the electrostatic drive. The electrostatic drive plate is placed a few millimeters over the vibrating ribbon. The amplitude of the excited mode of the ribbon's vibration 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 system of mirrors is detected by a split photodiode outside the vacuum chamber.

The ring-down time τ of the vibrational mode is determined by exciting the

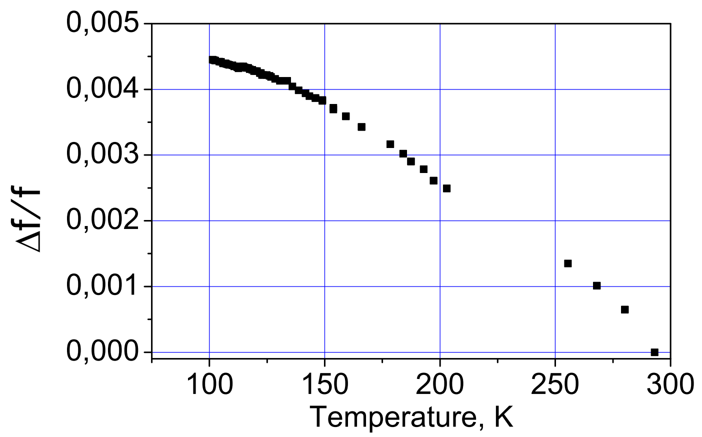

Figure 3. Temperature dependence of the fractional frequency shift of the silicon oscillator.

oscillator at the resonant frequency f, then turning off the excitation voltage and measuring the decay time τ of the vibration amplitude. The quality factor is then given by the relation $Q = \pi f \tau$. Measurements are carried out in vacuum under residual pressure of about 10^{-6} Torr. Cooling of the wafer is achieved through radiation between the wafer and cold walls of the cryostat as well as the heat conduction through the suspension wires. Q-factor is measured as a function of the mode frequency that changes due to the temperature dependence of the silicon Young's modulus and the ribbon's geometrical sizes. The temperature dependence of the change of the mode frequency is determined in preliminary measurements performed with a thermocouple attached to the silicon wafer. It is shown in figure 3. Time required to cool the wafer from room temperature to 90 K is about 5 hours. We measure Q-factors in the process of cooling or heating of the wafer. Usually the both temperature dependences coincide.

3. Results of measurements and discussion

The lower modes of bending vibration of the ribbon oscillator have resonant frequencies $f_1 = 2386$ Hz, $f_2 = 7318$ Hz, $f_3 = 12664$ Hz. A good agreement between frequencies calculated using finite element simulation and measured resonant frequencies is found. The temperature dependence of mechanical loss factor Q^{-1} for these modes was measured in the temperature range from 90 K to 300 K. The loss has a minimal value at a temperature of ≈124 K. This testifies that the thermoelastic loss is really suppressed. The best value of the $Q \approx 5 \times 10^6$ was obtained for the first bending mode (see figure 4). In this figure, the temperature dependence of the calculated thermoelastic (TE) loss factor is shown by the solid line. We use the approximate expression for the thermoelastic loss factor obtained by Zener for flexural vibrations of thin rectangular

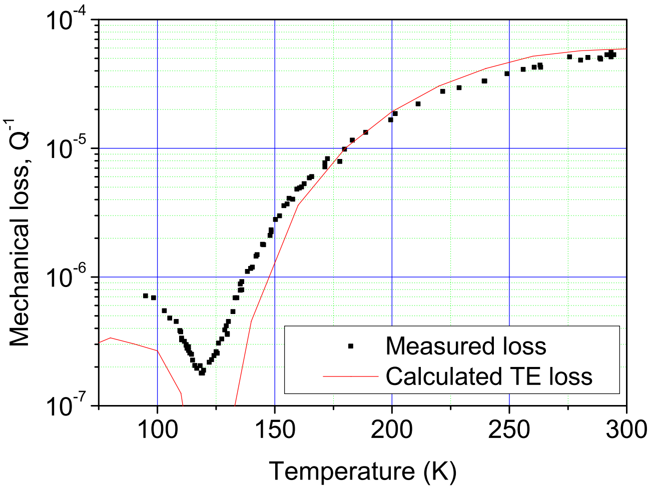

Figure 4. Temperature dependence of the measured loss factor (dots) and calculated thermoelastic loss factor (solid line) for the first bending mode of the ribbon oscillator at $f \approx 2386$ Hz.

beam [13]. It is also possible to use the more exact expression [14] or a finite element simulation model to calculate the thermoelastic loss. One can see a good agreement between the measured and calculated values of loss in the temperature range of ≈170-300 K. Below ≈170 K other loss mechanisms dominate. Notice that the second and the third bending modes of the ribbon oscillator have the considerably lower Q than the first one. We can explain this fact taking into account that the nodal points of the wafer vibrations for the first and the other bending modes of the ribbon do not coincide. In addition, the distance between the nodal points of the wafer vibration decreases with increase of the oscillator frequency. This makes difficult the accurate determination of the nodal points and setting of clamping wires into these points.

It is interesting to compare the best value of the Q-factor obtained for the ribbon oscillator with the Q measured for silicon resonators of large size [9]. In such resonators the surface and clamping losses are lower than the bulk loss determined by dissipation in material. One can see a peak at temperatures of about 120 K on the temperature dependence of losses [9]. The peak value of loss Q^{-1} is about 3×10^{-8}. The occurrence of peak in the temperature dependence of Q^{-1} can indicate existence of relaxation process associated with defects or impurities in the crystal structure of the material. There are several hypotheses about physical mechanisms of this loss [15, 16, 17] but there is no reliable evidence suggesting these mechanisms. The maximal achievable Q of mechanical resonators fabricated from perfect single crystals is determined by the phonon-phonon loss according to Akhiezer's mechanism [13]. Calculation of the phonon-phonon loss requires knowledge of behavior of silicon phonon spectrum and the Grüneisen parameters which also have the peculiarity in the vicinity of the temperature of zero thermal expansion. The loss associated with the surface along with clamping loss determine the Q of the ribbon oscillators at a temperature of about 124 K obtained in the present work. The surface losses can be reduced by improving the etching technique and using special treatments of the ribbon surface.

4. Conclusion

We investigated losses of mechanical ribbon-like oscillators fabricated in commercial silicon wafers using the anisotropic chemical wet etching technique. The goal of this research is development of low noise ribbon suspension for the silicon test masses of the next generation of gravitational-wave detectors. To reduce clamping loss the wafer is clamped between nichrome wires contacting the wafer in the nodal points of the wafer vibrations, which are determined using the computer simulation model. Measurement of the temperature dependence of the loss for bending modes of the ribbon oscillator have shown decrease of loss factor down to 2×10^{-7} at a temperature near 124 K. In order to attain the ultimate value of the Q-factor determined by phonon-phonon damping it is necessary to reduce surface loss by improving the technique of ribbon fabrication.

Acknowledgments

The authors would like to thank Rana Adhikari, Eric Gustafson, Stan Whitcomb, Nicolas Smith and Zach Korth for helpful discussions. This work was supported by the Russian Fund of Fundamental researches under grant 14–02–00399 and the United States National Science Foundation and Caltech under grant PHY–1305863.

References

[1] Harry G M (the LIGO Scientific Collaboration) 2010 Advanced LIGO: the next generation of gravitational wave detectors *Class. Quantum Grav.* **27** 084006
[2] Acernese F *et al* 2015 Advanced Virgo: a second-generation interferometric gravitational wave detector *Class. Quantum Grav.* **32** 024001
[3] Adhikari R X 2014 Gravitational radiation detection with laser interferometry, *Rev. Mod. Phys.* **86** 121–51
[4] Nawrodt R, Rowan S, Hough J, Punturo M, Ricci F and Vinet J-Y 2011 Challenges in thermal noise for 3rd generation of gravitational wave detectors *Gen. Rel. Grav.* **43** 593–622
[5] Hammond G D, Cumming A V, Hough J, Kumar R, Tokmakov K, Reid S and Rowan S 2012 Reducing the suspension thermal noise of advanced gravitational wave detectors *Class. Quantum Grav.* **29** 124009
[6] Reid S, Cagnoli G, Crooks D R M, Hough J, Murray P, Rowan S, Fejer M M, Route R and Zappe S 2006. Mechanical dissipation in silicon flexures *Phys. Lett. A* **351** 205–11
[7] Spiela C L, Pohl R O and Zehnder A T 2001 Normal modes of a Si (100) double-paddle oscillator *Rev. Sci. Instrum.* **72** 1482–91
[8] Zotov S A, Simon B R, Prikhodko I P, Trusov A A and Shkel A M, 2014 Quality Factor Maximization through Dynamic Balancing of Tuning Fork Resonator *IEEE Sensors Journal* **14** 2706–14

[9] McGuigan D F, Lam C C, Gram R Q, Hoffman A W, Douglas D H and Gutche H W 1978 Measurements of the mechanical Q of single-crystal silicon at low temperatures *J. Low Temp. Phys.* **30** 621–9

[10] Nawrodt R, Schwarz C, Kroker S, Martin I W, Bassiri R, Brückner F, Cunningham L, Hammond G D, Heinert D, Hough J, Käsebier T, Kley E-B, Neubert T, Reid S, Rowan S, Seideland P and Tünnermann A 2013 Investigation of mechanical losses of thin silicon flexures at low temperatures *Class. Quantum Grav.* **30** 115008

[11] Kovacs G T A, Maluf N I and Petersen K A 1998 Bulk micromachining of silicon *Proc. IEEE* **86** 1536–51

[12] Haiberger L, Jäger D and Schiller S 2005 Fabrication and laser control of double-paddle silicon oscillators *Rev. Sci. Instrum.* **76** 045106

[13] Nowick A S and Berry B S 1972 Anelastic Relaxation in Crystalline Solids Academic, New York

[14] Lifshitz R and Roukes M L 2000 Thermoelastic damping in micro-and nanomechanical systems *Phys. Rev. Lett. B* **61** 5600–9

[15] Yasumura K Y, Stowe T D, Chow E M, Pfafman T, Kenny T W, Stipe B C and Rugar D 2000 Quality Factors in Micron- and Submicron-Thick Cantilevers *Journal of microelectromechanical systems* **9** 117–24

[16] Haucke H, Liu X, Vignola J F, Houston B H, Marcus M H, and Baldwin J W 2005 Effects of annealing and temperature on acoustic dissipation in a micromechanical silicon oscillator, *Appl. Phys. Lett.* **86** 181903

[17] Wanser K H and Wallis R F 1981 Anomalous thermoelastic effect in silicon *Solid State Communications* **39** 607–10