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Temperature dependent dissipation in silicon mechanical resonators

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Two main designs were suggested for the 3-rd generation of LIGO detectors [1]. The Blue design is centered around the choice of silicon mirrors which operates at the temperature of about 120 K. The thermal expansion coefficient of silicon goes to zero at $T \approx 18$ K and $T \approx 125$ K. In this notes we present our knowledge and experience about temperature dependent dissipation in silicon mechanical resonators.

More than 30 years ago Professor's V.B. Braginsky group was developing cryogenic bar gravitational wave detector fabricated from a silicon single crystal. The main feature of this detector was its high mechanical quality factor. It was important to obtain a maximal Q for a silicon mechanical resonator. The silicon resonator was a cylinder with a diameter of 77.5 mm and a length of 604 mm, with the [111] axis parallel to the cylinder axis. Its mass was about 6 kg. Silicon was weakly doped with phosphorus and had a resistivity of ≈ 1 kOhm cm at room temperature. The ends surfaces and the barrel of the cylinder were polished with diamond pastes in order to reduce surface losses. The resonator was suspended by a loop of 0.3 mm-diameter polished molybdenum wire and was placed into a vacuum chamber inside a liquid helium cryostat. A fundamental longitudinal mode with a resonant frequency of 7420 Hz at room temperature was excited in the silicon cylinder by means of electrostatic actuator. A capacitive sensor was used to detect the resonator's vibration. Q-factor was calculated from the measured decay time of the resonator's free vibrations. The resonant frequency of the silicon crystal depends on its temperature. Such dependence was determined at the preliminary experiment with a thermocouple attached to the silicon cylinder. When Q-factor temperature dependence was measured the resonator's temperature was determined measuring its resonant frequency. The loss factor Q^{-1} of the silicon cylinder fundamental longitudinal mode as a function of temperature is shown in Fig.1.

Reduction of the resonator's surface losses and the suspension losses allowed us to obtain $Q = 1.4 \times 10^8$ at room temperature and $Q = 1.9 \times 10^9$ at $T \approx 5$ K. In Fig. 1 one can see peaks of losses at temperatures of about 120 K and 20 K. Notice that these peaks of losses are in the temperature ranges of zero value of the silicon thermal expansion coefficient. The temperature dependent dissipation in silicon resonators have been reported by other authors.

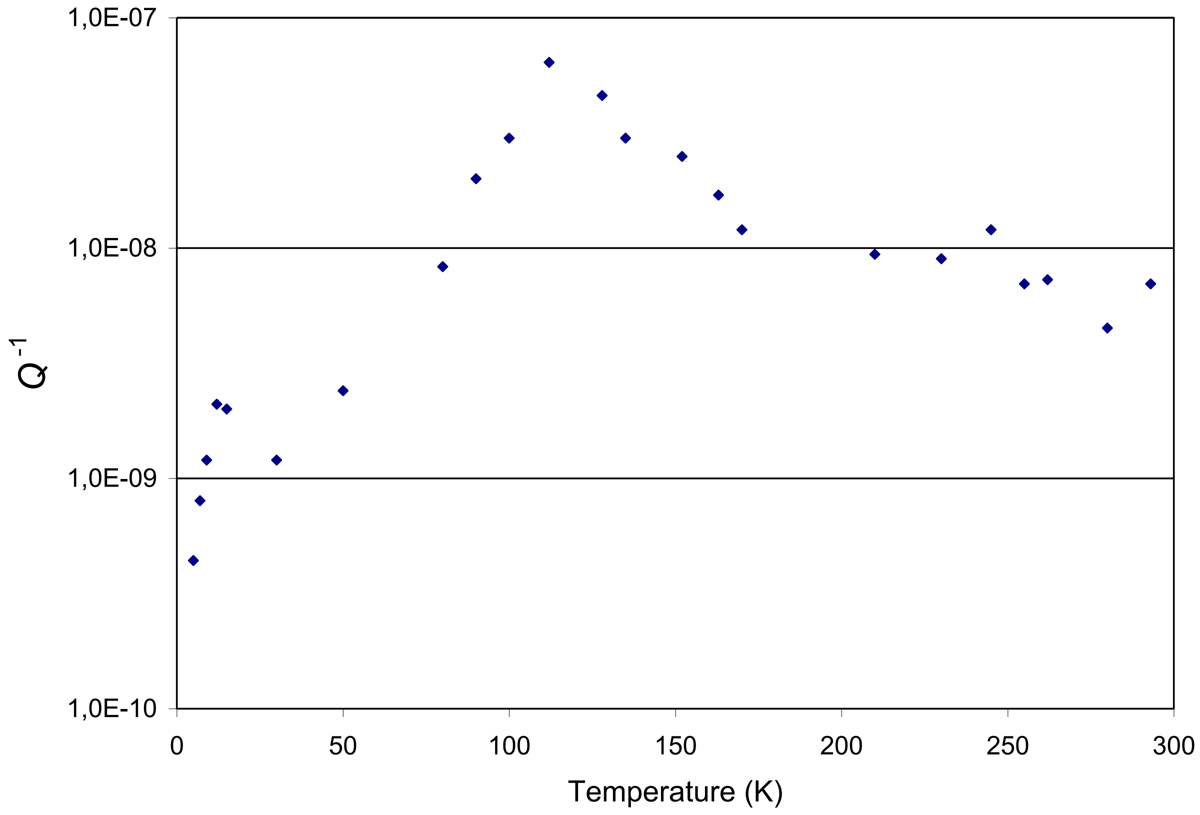

Fig.1. Loss factor Q^{-1} of the silicon resonator vs. temperature

The general picture of measured losses Q^{-1} in various silicon resonators at the kHz frequency range is shown in Fig. 2. The curves #3[2], # 4[3] and #5[4] show results of measurements for three silicon resonators which have various characteristic sizes: of order 10 cm, 100 μm and 1μm, respectively. Results of measurements obtained by Moscow group are shown for comparison. They marked by the curve #2. One can see the general tendency of increasing of losses with reduction of the resonator size. This indicates surface losses mechanisms in the resonators. For the large size resonators (curves #2 and #3) the surface losses do not screen the material losses at the interesting temperature of about 120 K. They appear as a peak of losses. There are several hypotheses about physical mechanisms of these losses [5,6,7]. But as we know, so far there is no reliable evidence for these mechanisms. Also there is not enough information about dependence of these losses on type of impurities and their concentration in silicon crystal. Nevertheless, mechanical losses in silicon at the temperature range near 120 K are not so high and do not block usage of silicon as a material of the test masses- mirrors in LIGO-3 detectors.

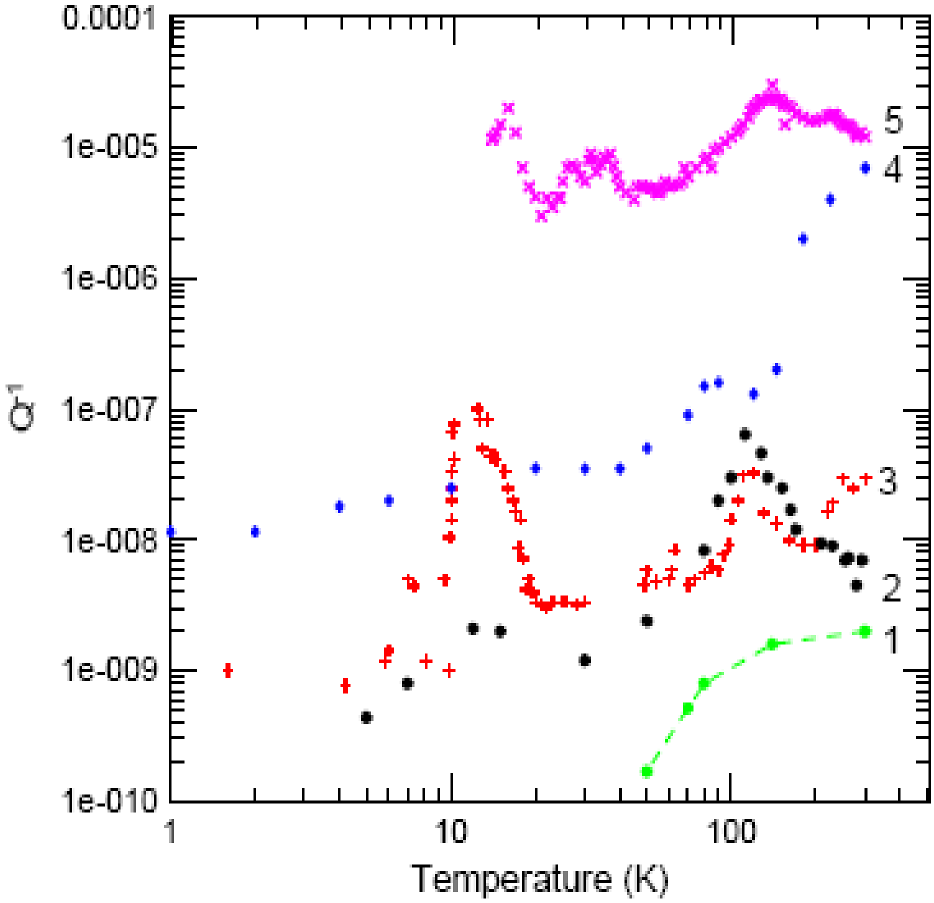

Fig.2. Measured dissipation Q^{-1} in silicon oscillators of kHz frequency band

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