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# Low loss single-crystal silicon mechanical resonators for the investigation of thermal noise statistical properties☆

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ABSTRACT

Silicon resonators are widely used in a large class of applications including sensing and actuation, signal processing and energy harvesting. Very often, the application for which these sensors are designed requires the deposition of thin films or coatings, in order to modify the optical coupling, the electrical conductivity or other physical–chemical properties of the device. Invariably coatings degrade the quality factor ($Q$) of resonance by increasing the amount of energy dissipated during vibration. Generally this is an unwanted effect. In fact, developing strategies for controlling damping due to film deposition is vital for the design of high-performance resonators requiring low energy losses. In this paper, we present the results of our strategy for damping control applied to a class of high-$Q$ silicon resonators used for the investigation of thermal noise statistical properties in non-thermodynamic equilibrium both at room temperature and cryogenic temperatures.



## 1. Introduction

The use of single-crystal mechanical oscillators is a powerful tool for different scientific and technological enterprises. The great versatility of these devices is demonstrated by their effectiveness in a very wide range of applications including, as an example, studies of fundamental physics such as the dissipative properties of thin films also at ultra-cryogenic temperatures [1] or quantum effects in cavity optomechanics [2], but also technological developments in the field of energy harvesting [3], sensor applications and microscopy [4]. Furthermore, the rapid developments and innovations that have been achieved in recent years in the microfabrication and the study of materials have allowed the realization of mechanical devices of sizes up to nanoscale and shape optimized for particular studies or applications (membranes, whispering galleries, stings, pillars, see for example [2]). Our interest in this field is focused on the realization of silicon oscillators as the core devices to investigate the mechanical thermal noise and the internal dissipation effects occurring when a thermal flow is imposed along the oscillator, namely when the mechanical system is kept out of thermodynamic equilibrium [5]. This research aims to reproduce experimental configurations similar to those encountered in gravitational wave (GW) detectors, where the vibrations of the test masses are monitored continuously to single out signals induced by a passing GW. The effects of thermal gradients applied on the test mass by the measuring system, which is an usual condition especially in the interferometers [6], are not yet fully characterized, and this knowledge is important for the design of the next generation of detectors [7]. In particular, the fibers which suspend the mirrors of the interferometer must extract the light power dissipated into the mirror substrate and coating, as well as the additional thermal loads usually applied on the back side of the mirror to balance the thermal lensing effects induced by this non-uniform thermal source [8]. The energy flux between this energy inputs and the thermal bath generates correlations, inhomogeneities and large fluctuations which potentially prohibit the use of the tools of equilibrium statistical mechanics [9]. Previous results have made evident that, as far as the elastic behavior is concerned, a solid-body subject to steady-state thermal differences is equivalent to the same body in equilibrium at the average temperature [10], whereas the energy separately associated with low-frequency normal modes depends

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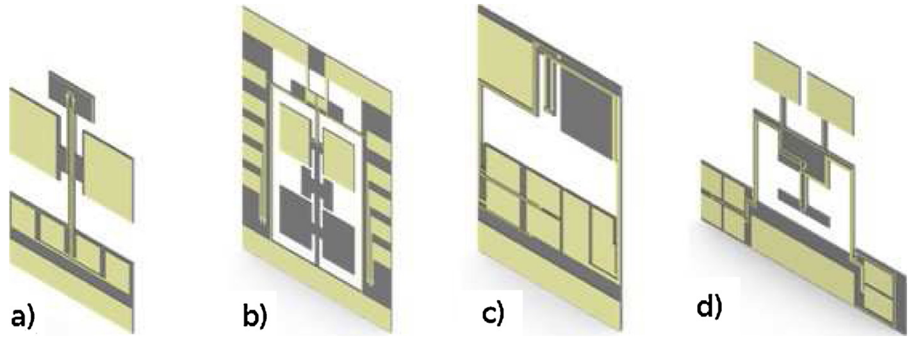


**Fig. 1.** Overview of the silicon low-loss mechanical oscillators used for our measurements. All oscillators are supported from the nodal points of the resonant mode (nodal suspension), in order to minimize the reaction forces at the mount point and to obtain a clamping loss almost independent from the mechanical impedance of the holder and its internal dissipation. (a) Double Paddle Oscillator [21], (b) quadruple paddle oscillator (QPO) [10], (c) Young's modulus resonator (YMR) [22], (d) Phonon transport resonator (PTR). (a) and (b) have high $Q$ torsional modes while (c) and (d) have high $Q$ flexural modes. In particular the novel design (d) has a higher sensitivity in the transduction of the displacement, because of its lower effective mass (about one order of magnitude smaller than the flexural mode of the design c). All resonators where fabricated at the Dimes Technology Centre.

strongly on the heat flux, and decouples noticeably from temperature [11]. Moreover, the dynamic behavior of an oscillating crystal could be modified by an applied thermal gradient, leading to dissipative phenomena based on "phonon transport" when the crystal is moving [12]. The characterization of this phenomenon could have a significant role in the performances of future devices for precision measurements.

For these studies we consider mechanical oscillators made from single-crystal silicon, a material with a loss angle ($\sim 1/Q$ at resonance) as low as $10^{-9}$ at cryogenic temperatures. The feature of having low intrinsic loss entails the possibility to build mechanical devices resonating with high quality factor ($Q$ value) defined by the loss angle of the resonant mode:

$$Q^{-1} = \frac{\Delta E}{2\pi E} \tag{1}$$

where $\Delta E$ is the energy dissipated during one cycle of vibration, and $E$ is the maximum elastic strain energy during the vibration cycle. This point is extremely important as there are several reasons why a high quality factor is often a critical parameter for various applications, especially for those requiring high-precision sensing:

- according to the fluctuation-dissipation theorem, the spectral power of the displacement noise induced by the thermal bath at temperature T depends on the $Q$ value. For instance in the simple case of a unidimensional velocity-damped harmonic oscillator with mass $m$ resonating at angular frequency $\omega_0$ it is described by [13]:

$$S_{xx}(\omega) = \frac{4k_B T}{mQ} \frac{\omega_0}{\left(\omega^2 - \omega_0^2\right)^2 + (\omega^2\omega_0^2/Q^2)} \tag{2}$$

  where $x$ is the position of the oscillator. We recall that the quality factor is related to the viscous damping factor $\eta$ as $Q = m\omega_0/\eta$. Prediction for thermal noise for more realistic mechanical models can be made by generalizing such model
- if the oscillator is used to measure a small periodic force at resonance, a high $Q$ factor helps to overcome the background noise of the system used to measure the oscillation, since the resulting oscillation amplitude is proportional to Q. We point out that the relevant quality factor is determined by intrinsic loss phenomena within the oscillator, as the increase of the quality factor by feedback techniques does not improve the optimal resolution of the measurement [14]
- a low loss mechanical system represents the best playground for fundamental studies as for example the measurements of the dissipative effects of functionalization layers [1,15] or the detection of quantum phenomena in the behavior of systems involving macroscopic objects [16–18]
- a high $Q$ permits lower power consumption, higher frequency selectivity and higher efficiency for MEMS\NEMS systems [19]

Even if damping mechanisms can be of different nature [20], some general rule must be followed to preserve low losses in a working device. First, the oscillator must be supported at its nodal point (nodal suspension) to avoid mechanical energy leakages toward the support system, and, second, the addition of any functional element (electrodes for motion detection, thermometers and heaters for the thermal control) must be carefully evaluated. We produced a number of low loss oscillators already known in the literature (DPO, QPO, YMR) [10,21,22] and at the same time we developed a novel design, called phonon transport resonator (PTR), properly optimized to ease the detection of thermal flow effects. The following sections discuss the methods we implemented for the application of a controlled heat flux on these devices and the strategy used to keep under control the energy dissipation introduced by the passive elements necessary for the thermal control. Some details on the fabrication process of the devices will also be provided.

## 2. Design rationale

In Fig. 1 we show the silicon mechanical oscillators that we have used in our measurements. The first two (Fig. 1a and b), already known in the literature, are torsional oscillators characterized by high quality factor mechanical modes obtainable by means of a balancing of the torsion of the "head" device's in respect to a longitudinal axis, and the "wings" in respect to a transverse axis [10,21]. This balance allows to considerably limit the displacement of the suspension points of the device, i.e. the base, thus realizing a configuration in which the device is supported at the nodal points of some mechanical modes. For these mechanical modes the reaction force exerted by the support and then the clamping losses are minimized. The devices shown in Fig. 1c and d exploit nodally suspended high-$Q$ flexural oscillation modes designed with the same technique of nodal suspension. The YMR or Young's modulus resonator (Fig. 1c), was originally conceived for measurements of internal Friction and Young's Modulus of thin films [22], while the PTR or phonon transport resonator (Fig. 1d), represents a new design expressly developed by the authors to allow the study of the effects of a controlled thermal gradient applied on the oscillating masses and particularly to highlight the possible dissipative phenomena due to transport of phonons [12]. The PTR is characterized by a high-$Q$ mode in which the central cantilever deflects in opposition to a symmetric