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Selective coating deposition on high-Q single-crystal silicon 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, their application as sensors requires the deposition of metallic thin films or dielectric coatings, to set the electrical conductivity, the optical coupling, 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. In this paper, we show a class of resonators used for the investigation of thermal noise statistical properties in non-thermodynamic equilibrium. Design strategies to preserve the silicon Q-factor are discussed.

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Keywords: MEMS bulk-micromaching; thin-films; thermal noise; low-dissipation silicon resonators; vibrations

1. Introduction

The use of single-crystal mechanical oscillators is a powerful tool for different scientific and technological aims. The versatility in the use of these devices is demonstrated by the wide range of applications including, as an example, studies of fundamental physics such as the dissipative properties of thin film [1] or cavity optomechanics [2], but also technological developments in the field of energy harvesting [3], sensor applications, microscopy [4] and so on. Our goal is the study of mechanical thermal noise and internal loss effects occurring when a thermal flow is imposed along the oscillator, namely when the mechanical system is kept out of thermodynamic equilibrium [5–7]. In fact, when the resonator is heated in one of its parts, the energy flux between this energy input and the thermal bath generates correlations, inhomogeneities and large fluctuations which prohibit the use of the tools of equilibrium statistical mechanics [7]. Moreover, dissipative phenomena based on ”phonon transport” could occur when the crystal is moving [8]. For

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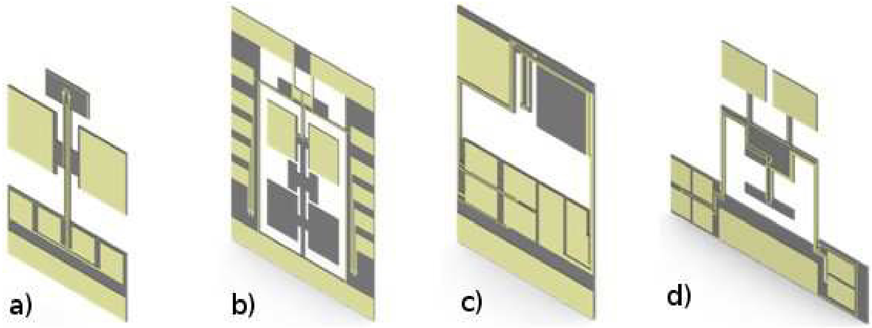

Fig. 1. a) Double Paddle Oscillator (DPO) [9,10], b) Quadruple Paddle Oscillator (QPO) [5], c) Young's modulus resonator (YMR) [11], d) Phonon Transport Resonator (PTR). a) and b) have high Q torsional modes while c) and d) have high Q flexural modes. All devices where fabricated at the Dimes Technology Centre.

these studies we consider mechanical oscillators made from single-crystal silicon, a material with a loss angle as low as 10^{-9} at cryogenic temperatures and frequently used to realize mechanical devices resonating with high quality factor (Q). However, to preserve this low loss in a working device, the oscillator must be supported at its nodal points, to avoid mechanical energy leakages toward the support system, and the addition of any functional element (electrodes for motion detection, thermometers and heaters for the thermal control) must be carefully evaluated. We fabricated a number of low loss oscillators already known in the literature (DPO, QPO, YMR) [5,9–11] and at the same time we developed a novel design, properly optimized to ease the detection of thermal flow effects, called Phonon Transport Resonator (PTR). In these devices a controlled heat flux is applied by integrated heaters/thermometers, and we discuss the strategy applied to keep under control the energy loss introduced by these passive electrical elements. Some details on the fabrication process of the devices will be also provided.

2. Design concepts and fabrication

In figure 1 we show the silicon mechanical oscillators that were used in our measurements. Devices a) and b), already known in literature, are torsional oscillators where the displacement of different parts is carefully balanced to limit the displacement of the suspension points of the device, i.e. the base, thus realizing a configuration in which the device is supported from the nodal points of some resonant modes [5,10,12]. For these mechanical modes the reaction force at the mount point and the consequent clamping losses are minimized. Devices c) and d) exploit the nodal suspension concept to obtain high-Q flexural oscillation modes. The YMR (Fig. 1c), was originally conceived for measurements of internal friction and young's modulus of thin films [11]. The PTR (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 to detect possible dissipative phenomena due to transport of phonons [8]. The PTR is characterized by a high-Q mode in which the central cantilever deflects in opposition to a symmetric deflection of the wings. In these devices the displacement sensing is realized by a capacitive coupling [10].

To apply and to control the thermal flow, we integrate Pt and Au patterned thin film layers on both sides of the wafer. Platinum serpentines of thickness of 120 nm with a resistance of about 1 kΩ at room temperature are deposited on properly selected areas of the devices, with the dual function of temperature sensors (RTD or Resistance Temperature Detector) if connected to a low-power circuit (10 mW) for a 4-wire measurement of resistance, or heaters if connected to power supply (up to 1 W) (Fig. 2a). Gold thin films paths of thickness 150 nm, with a resistance approximately an order of magnitude lower than the RTD, are used as electrical connections. To allow the capacitive coupling, a grounded thin film of gold is also deposited on the moving parts of the mechanical oscillator that are sampled by a capacitive displacement sensors. Finally, in order to maintain the electrical connections isolated from the silicon substrate, the deposition of a thin film of thermal SiO_2 is integrated in the fabrication process of the devices. The unavoidable degradation of the quality factor resulting from the deposition of metal and (especially) dielectric coatings must be kept under control by a proper choice of their position over the oscillator and of their thickness. In fact, for each modal shape, the total loss is obtained as the sum of the silicon substrate loss and the film loss. The latter is

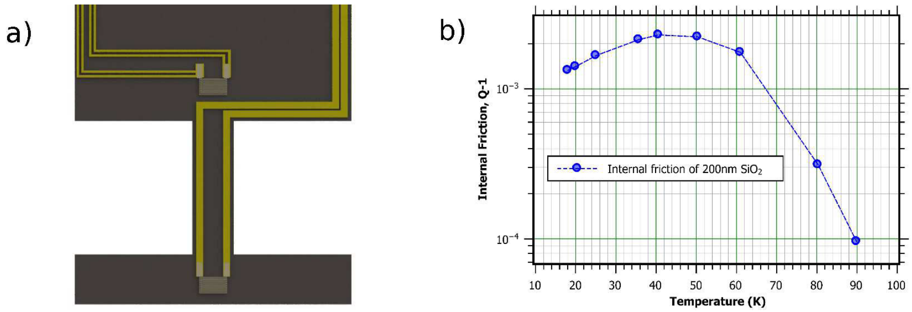

Fig. 2. a) Details of the Pt and Au structured thin film layers. The Pt serpentines are placed on appropriate points to allow an accurate control of the heat flow over the cantilever. The serpentine at the top is used as temperature sensor and it is connected to a circuit for a 4-wire measurement of resistance whereas that one at the bottom is used as heater and it is connected to a high-power circuit (max. 1W) . On the opposite side of the cantilever the use of the two serpentines is inverted so as to have in correspondence of the same points of the cantilever both a thermometer and a heater. This allows, with an appropriate feedback control, to maintain a constant and controllable heat flux through the cantilever. b) Internal friction of 200 nm thermal deposited SiO_2 film. The data are derived from the measurement of the internal friction versus temperature of the bare silicon oscillator (in the specific case the YMR resonator of Fig. 1c) and of the coated oscillator. A Finite Element Model is used to compute the ratio between the elastic energy stored in the coating and in the device (E_{film}/E_{sub}) during the oscillation of the high Q mechanical mode.

proportional to the intrinsic loss of the film weighted by the ratio between the total elastic energy stored in the film (E_{film}) and in the substrate (E_{sub}) [1]:

$$Loss_{total} = Loss_{sub} + (E_{film}/E_{sub})\,Loss_{film} \quad (1)$$

At cryogenic temperatures the internal friction of the metal films (Pt and Au), even though being greater than that of the bare silicon oscillator [13], is negligible in our resonators. On the other hand, the dissipative contribution of the electrical insulation substrate of SiO_2 between the silicon and the metal film is potentially more relevant as it can show a loss angle up to 10^{-3} at 50 K [1].

To minimize the damping effects of the insulation coating we have first measured the internal friction of the 200 nm SiO_2 layer obtained by thermal oxidation during fabrication. With the aid of a Finite Element Model we calculated the strain energy stored on the film and on the substrate (E_{film}/E_{sub} of Eq. 1) during the oscillation of the high Q mechanical mode and then, by measuring at various temperatures the internal friction of a fully coated oscillator ($Loss_{total}$) and of an uncoated oscilator ($Loss_{sub}$), we obtained the internal friction of the SiO_2 film (Fig. 2b). With this data and starting again from the Finite Element analysis of the strain energy on the surface of the device, we have outlined the optimal design for the structured thin film layers in order to minimize the ratio E_{film}/E_{sub}. In this procedure, we essentially avoid the deposition of the film of SiO_2 insulating layer over the parts of the device that are mostly strained during the oscillatory motion in a sort of ”selective coating” [14–16]. The expected quality factor for a PTR resonator at different SiO_2 layers is shown in figure 3a), while figure 3b) shows the mode where measurement where performed.

The silicon resonators are developed by using MEMS bulk micromaching. The starting wafer is a 300 ±5 μm <100> high resistivity (> 1 kΩ-cm) (Czochralski) double-side polished wafer having low roughness. Low-Pressure Chemical Vapor Deposition thermal oxide layers of thicknesses ranging from 100-300 nm are grown at 1100 °C. Dry etching of the oxide layer is done for the selective coating deposition. The 120 Pt and 150 nm Au layers are evaporated over a 15 nm Ta and Cr adhesion layer, respectively. The metallizations are patterned by lift-off (Fig. 2 a)) to obtain resistors and interconnections. A 4 μm Plasma Enhanced Chemical Vapor Deposition oxide is used as masking layer for the Deep-Reaction Etching. This oxide is removed at the end of the process by BHF 1:7 to release the structures.

3. Conclusions

In high-performance silicon oscillators having low energy losses, damping due to deposited passive elements must be taken into account even though their thickness is small. In this work, we show how FEM simulations of damping can guide the design of a resonant device. First, we have measured the loss factor of the coatings. Then we use these

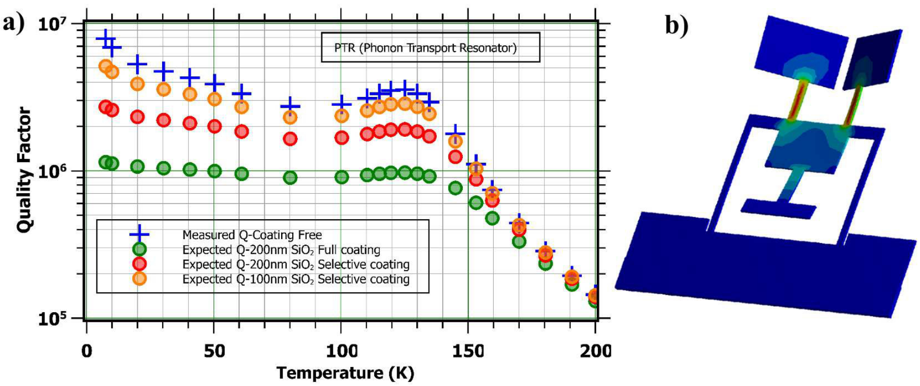

Fig. 3. a) Expected quality factor for a PTR resonator with different SiO_2 coatings (full coating or selective coating) compared with that measured for a device free of coating. In a selective coating the shape of the coating is chosen to avoid the deposition over the parts of the device that are mostly strained during the oscillatory motion. In addition to this, it is obviously advantageous also the use of a thinner layer of SiO_2. In the best case, below 100K the quality factor is reduced of 30% compared to the bare device. At higher temperatures the loss of the coatings becomes negligible with respect to the thermoelastic loss in the substrate. b) Distribution of strain for the high Q flexural mode of the resonator.

data to set the optimal shape and thickness of the deposition. This technique is applied to a new flexural silicon low loss resonator to be used as testbed for fundamental physic research investigating thermal noise statistical properties.

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