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Does greater piezo-resistive transduction give rise to higher anchor loss in a square-extensional mode micromechanical resonator?

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ABSTRACT

The square-extensional (SE) mode resonator was used as the timing element in one of the first demonstrations of a MEMS oscillator meeting the GSM specification for phase noise. Crucial to its high *Q* was the use of T-shaped tethers in the anchoring design, which could also be used as piezo-resistors that could provide higher transduction. In this work, we examine the relationship between *Q* and corresponding piezo-resistive transduction efficiency, affected by changes in the compliance of the T-shaped tether anchoring design. Does a high *Q* necessarily mean a lower piezo-resistive transduction factor as an unavoidable performance tradeoff? Our measurement results, corroborated by finite element simulations, suggest that *Q* and the related piezo-resistive transduction factor are not opposed to each order in the SE mode resonator. In fact, the two indicative metrics of performance exhibit similar trends to the other with respect to changing the compliance of the anchoring design.

1. Introduction

As a timing element, silicon-based micro-mechanical resonators possess a number of attractive traits such as having a small form factor and a possible route toward integration with integrated circuit fabrication technology [1]. Among the possible vibration modes, bulk mode resonators have received increasing attention since they offer a number of advantages over flexural mode resonators. Since the stiffness of bulk mode resonators are typically higher than those of flexural mode resonators, this leads to higher frequencies for the same order of dimensions. This in turn translates to better frequency versus transduction scaling characteristics in bulk mode resonators compared to flexural mode resonators [2]. Given the same order of resonant frequency, owing to a larger stiffness and size, this leads to higher energy storage capacity which results in higher *Q* in bulk mode resonators compared to flexural mode resonators [3,4]. This larger energy storage capacity also allows a higher power handling capability prior to the onset of non-linearity for bulk mode resonators compared to flexural mode resonators [5].

Among the various bulk mode resonator structures and mode shapes reported to date in the literature, it was the square-extensional (SE) mode resonator that was used in one of the earliest demonstrations of a micro-mechanical resonator meeting the GSM specification for phase noise [6,7]. The SE mode is illustrated in Fig. 1, and can be described as a square-plate expanding and contracting symmetrically on all 4 sides. The SE mode resonator reported by Kaajakari had a quality factor (*Q*) of 130,000 and a resonant frequency of 13 MHz. SE mode resonators with yet higher *Q* have been reported since. One example is a 2.2 MHz resonator with a *Q* of over 1 million [8,9]. In all these implementations of the SE mode resonator, T-shaped tethers placed at each corner were used to anchor the suspended square-plate to the substrate. As can be seen from Fig. 1, the corners of the square-plate correspond to anti-nodes in the SE mode. As such, T-shaped tethers help reduce energy dissipation to the anchors through a compliant cap section of the tether, which is described in Fig. 2. This in turn increases *Q*, which is desirable for both sensing and low phase noise oscillator applications.

It can be seen from Fig. 3 that as the square-plate expands and contracts, the central stems of the T-shaped tethers are subjected to axial stress. This axial stress arises from the reaction forces imposed by the cap section of the tether and the corner of the square-plate. Lin used these axially stressed stems as piezo-resistors in order to significantly enhance the electromechanical conversion efficiency at the output port [10]. It would then intuitively seem that increasing the stiffness of the cap would increase the axial stress stems resulting from greater resistance of the motion of the square-plate. This greater axial stress in the tether's stem would then enhance the piezo-resistive conversion efficiency.

It was previously observed that the compliance of the cap section in the tether had some influence in determining *Q* [11]. It was found that a more compliant cap section came with a higher *Q*. The

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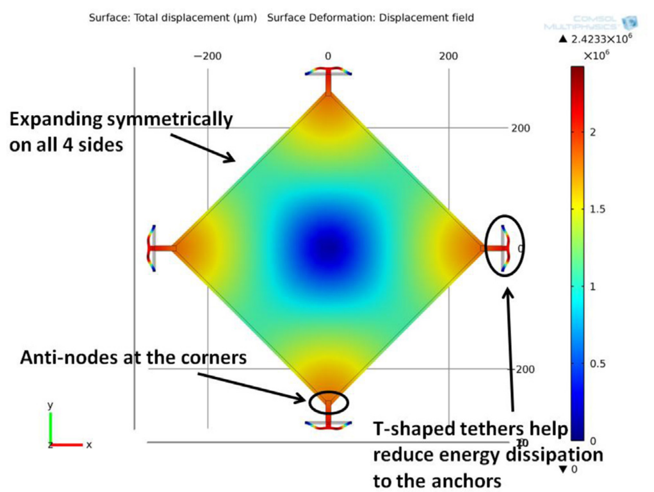

Fig. 1. Top view illustration of the square-extensional (SE) mode by finite element (FE) simulation in COMSOL.

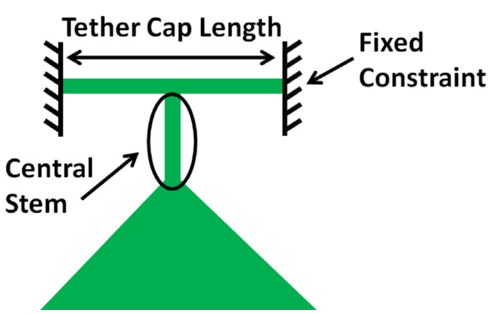

Fig. 2. Zoom-in schematic of a T-shaped tether with annotations to the parts of the tether.

comparison was only limited to two devices, of which their lateral dimensions were not even the same. Hence from the view of design, it would be interesting to empirically see the effect of *Q* when the compliance of the tether is gradually varied while the dimensions of the square-plate were kept the same.

In short, a stiffer cap section would seem to benefit the piezo-resistive electromechanical conversion efficiency while a more compliant cap section would benefit *Q* (by reducing anchor loss). It would then appear that some trade-off would exist between higher

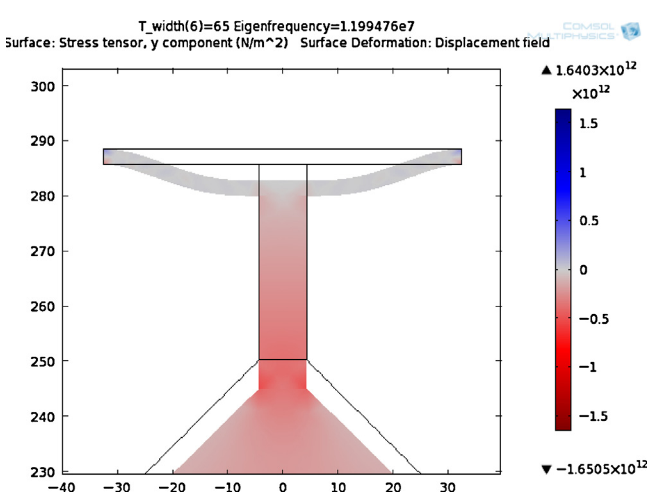

Fig. 3. FE simulation showing the axial stress in the central stem of the tether, which thereby acts as a built-in piezoresistors.

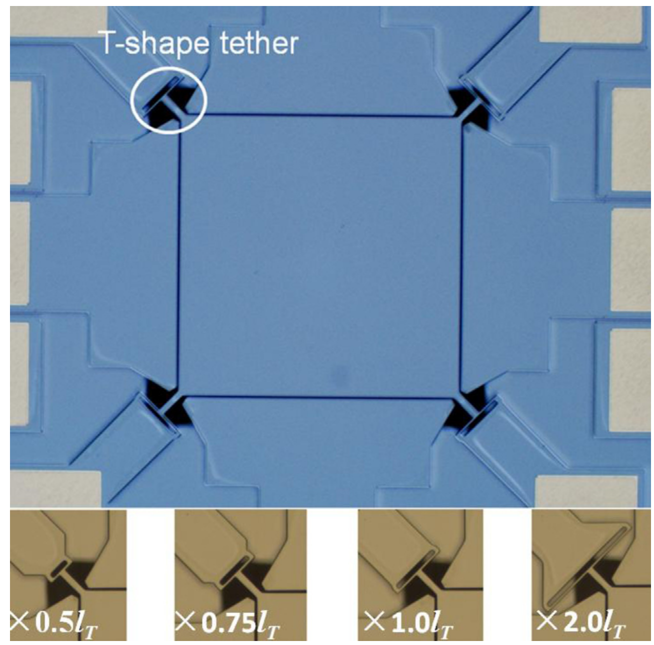

Fig. 4. Optical micrograph of the fabricated square-plate resonators showing the variation in the tether cap length from one device to the other.

Q (through reducing anchor loss) and higher piezo-resistive electromechanical conversion efficiency in relation to the compliance of the cap section in the tether. In this work, we investigate whether such a trade-off of higher piezo-resistive transduction versus *Q* actually exists. The results of this study would be a useful reference in the design of high *Q* SE mode resonators with the capability of employing piezo-resistive sensing to boost transduction.

In this work, we vary the length of the cap section (as defined in Fig. 2) so as to change the compliance of the cap section gradually between devices. The dimensions of the square-plate in each device have been kept the same to allow for closer comparisons. In Section 2, the devices investigated in this work are described in greater detail. In Section 3, the results from electrical characterization of the S21 transmission of fabricated devices are presented. We show that the measured frequencies are well matched to those predicted by finite element (FE) analysis. Then in Section 4, correlations between *Q* and piezo-resistive transduction efficiency are drawn as well as discussed. We have also used the method of perfectly matched layers (PML) to compute the anchor loss in our devices. The computed anchor limited *Q* agrees well with our measurements. Our results surprisingly reveal that the effect of the tether's compliance on *Q* and piezo-resistive conversion is contrary to a trend that indicates a trade-off.

2. Device description

In this work, four square-plate resonators of the same length (360 μm) with T-shaped tethers of different lengths for the cap section were fabricated on the same die using a standard SOI MEMS process without any additional doping to assess their impact on both *Q* and piezo-resistive conversion efficiency. The variations between the lengths of the cap sections were referenced to a standard tether cap section length of 65 μm by factors of 0.5, 0.75, 1.0 and 2 as shown in the optical micrographs of the fabricated devices (Fig. 4). The dimensions of the tether stems are all fixed at a length of ∼35.5 μm and width of ∼8.6 μm width. The widths for the tether caps are also fixed at ∼2.8 μm. Note that for fixed beam anchored resonators (i.e. just the stem only), the ideal beam length should be a quarter-wavelength to minimize anchor loss. This