Sensors and Actuators A 243 (2016) 66–70

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

A 9.45 MHz micromechanical disk resonator with movable electrodes for gap reduction

Xinyi Li[a,*], Jingfu Bao[a], Yulin Huang[a], Yuan Ling[b], Yingbin Zheng[b], Yijia Du[b]

[a] School of Electronic Engineering, University of Electronic Science and Technology of China, 2006 Xiyuan Ave, Chengdu 611731, China
[b] Institute of Electronic Engineering, China Academy of Engineering Physics, Mianyang, Sichuan 621900, China

ARTICLE INFO

Article history:
Received 29 January 2015
Received in revised form 5 March 2016
Accepted 9 March 2016
Available online 17 March 2016

Keywords:
MEMS resonator
Insertion loss
Gap reduction
Quality factor

ABSTRACT

A micro-electromechanical wine glass modal disk resonator with movable electrodes is presented in this paper. The movable electrodes were driven by electrostatic force for gap reduction to reduce insertion loss. By reducing the gap from 2.5 μm to 0.5 μm, the insertion loss improved from −104 dB to −81 dB at the same bias voltage of 20 V. However, unstable movable electrodes caused the quality factor to decrease from 920,000 to 27,200.

1. Introduction

Micro-electromechanical system (MEMS) resonators are small in size and exhibit CMOS compatibility, thus making them one of the most promising candidates for integrated oscillators in the future [1]. Quality factors of electrostatic MEMS resonators could reach as high as four million, comparable with those of conventional quartz crystal resonators [2]. However, one of the defects for the capacitive MEMS resonators is its high motional resistance, which results in large insertion loss. The transfer characteristics of capacitive MEMS resonators significantly depend on the dimensions of capacitive transduction gaps [3].

Capacitive gaps with high aspect ratio have been studied to achieve high transfer efficiency. In 2005, Lin and Nguyen [4] presented solid dielectric gaps with low motional resistance. Ayazi and Pourkamali [5] proposed a high-aspect-ratio poly and single crystalline silicon fabrication process with high-aspect-ratio capacitive gaps (as high as 460) in 2007. Clark Nguyen et al. [6] utilized atomic layer depositions to fill the gaps of released resonators in 2008 and achieved effective gap spacing as small as 32 nm. However, these methods would introduce extra complicated fabrication processes.

Movable structures have been utilized to obtain narrow gaps without extra fabrication processes [7,8]. However, the vibrating modes in these reported works were chosen as width-extensional modes without high quality factors for original resonators (without movable structures). In this work, two 9.45 MHz wine glass mode disk resonators with normal fixed electrodes and movable electrodes are investigated. By driving the movable electrodes with electrostatic force, a 0.5 μm gap is achieved using the commercial SOIMUMPs process from MEMSCAP, whose designed technological strip width is 2 μm. The comparison of the measured insertion loss and Q for both resonators at the same DC driving voltage indicates that the structure of movable electrodes could obtain a low insertion loss for 23 dB but at the risk of reducing the Q.

2. Design and fabrication

2.1. Design of disk resonator

The overall diagram of the resonator with movable electrodes is shown in Fig. 1. The resonator includes a disk resonator, four movable electrodes with folded supporting beams, and eight fixed stopping blocks.

The disk resonator in this work is designed to operate in wine glass mode, and the radius of the disk R is 185 μm. The eigenfrequency of the wine glass modal shape for a disk could be calculated by solving the mode frequency equation [9]:

$$\left[\psi_2\left(\frac{\zeta}{\xi}\right)-2-q\right]\left[2\psi_2(\zeta)-2-q\right]=(nq-n)^2, \quad (1)$$

* Corresponding author.
E-mail address: kimilee56@gmail.com (X. Li).

http://dx.doi.org/10.1016/j.sna.2016.03.010
0924-4247/

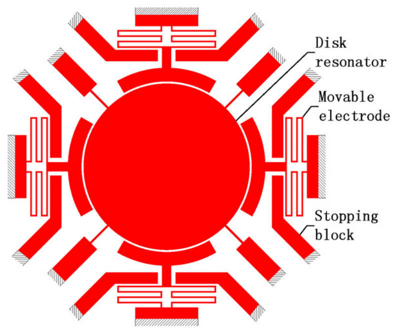

Fig. 1. Schematic diagram of the whole structure.

where

$$q = \frac{\zeta^2}{2n^2-2}, \quad \zeta = R\sqrt{\frac{2\rho\omega_0^2(1+\sigma)}{E}}, \quad \xi = \sqrt{\frac{2}{1-\sigma}}, \qquad (2)$$

where R is the radius of the disk, E is Young's modulus of the material, $\omega_0 = 2\pi f_0$ is the angular frequency, n is the order of the mode, σ is Poisson's ratio, and ρ is the density of the material. For the single crystal silicon, the typical parameters of the material are $E = 180$ GPa, $\sigma = 0.23$, and $\rho = 2330\ \mathrm{kg/m^3}$. The resonance frequency is also confirmed by finite element software simulation (Fig. 2).

Four straight supporting beams are placed at the four nodal points of the vibrating modal shape to minimize the energy dissipation through the anchors. The length of the tethers is 55 μm, which is optimized for minimum energy loss.

2.2. Design of electrodes

The equivalent circuit for a MEMS resonator comprises an RLC series resonant circuit and a parasitic feedthrough capacitance. The energy dissipated in vibrating is equivalent to the energy consumed in the resistor. The motional resistance value of the MEMS resonator can be expressed by the following [3]:

$$R_x = \frac{v_i}{i_0} = \frac{m_e\omega_0}{\varepsilon_0^2 {A_e}^2 V_p^2} \cdot \frac{d_0^4}{Q}, \qquad (3)$$

where m_e is the equivalent mass of the MEMS resonator, ω_0 is the angular frequency, ε_0 is the vacuum permittivity, A_e is the relative area of the coupling capacitor, V_p is the bias DC voltage between electrodes and resonator, Q is the quality factor of the resonator, and d_0 is the width of the gap between electrodes and resonator. d_0 has the highest order, and its value considerably influences motional resistance.

Fig. 3 shows the detailed structure of the folded movable beam, the design parameters of which are given in Table 1. The electrostatic force F_e is generated by the DC bias voltage V_p and would pull the electrodes toward the resonator. The gap between the electrodes and fixed stopping blocks g_2 is 0.5 μm narrower than the gap between electrodes and resonator g_1. Therefore, the electrodes will stop upon contact with the stopping blocks instead of the resonant body. Thereafter, the gap between electrodes and resonator after the change would be as follows:

$$g_0 = g_1 - g_2. \qquad (4)$$

By using the folded beams, the spring constant of the movable electrodes can be decreased such that a low pull-down DC voltage for driving will be enough. To calculate the pull-down DC voltage, the elastic coefficient of the whole electrode structure should be obtained. An equivalent elastic model made of three springs is built (Fig. 4). For convenient calculation, the folded beams could be divided into three parts. k_1 is the spring constant of a clamped–clamped beam, and the force is applied on the middle part. Both k_2 and k_3 are the spring constants of the three cascaded cantilever beams combined.

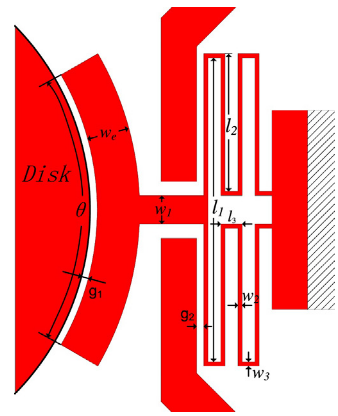

Fig. 3. Simplified identification of folded movable electrode.

Table 1
Design parameters.

Parameter	Value (designed)
Gap between electrode and resonator, g_1	2.5 μm
Gap between stopping block and beam2, g_2	2.0 μm
Radian of the electrode, θ	60°
Width of electrode, w_e	30.0 μm
Width of beam1, w_1	20.0 μm
Length of beam2, l_1	220.0 μm
Width of long folded beams, w_2	2.0 μm
Length of folded beams, l_2	98.0 μm
Width of short folded beams, w_3	4.0 μm
Length of short folded beams, l_3	13.0 μm

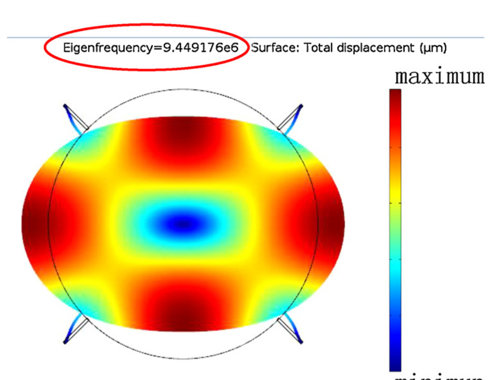

Fig. 2. Simulation of wine glass mode disk resonator.

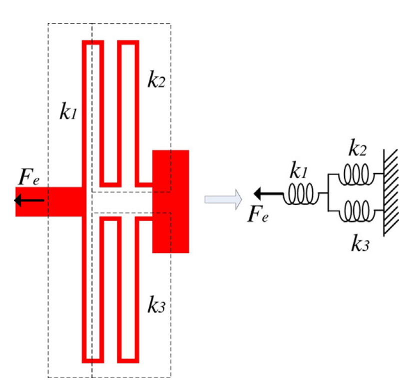

Fig. 4. Equivalent elastic model.