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Design and fabrication of a tuning fork shaped voltage controlled resonator with additional tuning electrodes for low-voltage applications

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Abstract

In this work a silicon voltage-controlled microelectromechanical tuning-fork resonator with electrostatic actuation and separate frequency tuning electrodes is presented. The released device is fabricated using a silicon-on-insulator (SOI) wafer by a 2-step process involving only Focused Ion Beam (FIB) masking and Cryogenic Deep Reactive Ion etching (DRIE). This process is ideal for rapid prototyping, as the time to turn a design into the final device is only a few hours. The design of the resonator is optimized to accommodate the restrictions of the fabrication process, to maximize the frequency tunability and to minimize the biasing voltage. Separating tuning and driving electrodes enables the resonance frequency adjustment by over 10000 ppm ($f_{\text{central}} > 1.5$ MHz, quality factor $Q \approx 2000$) with a tuning voltage of 12 volts.

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1. Introduction

Silicon MEMS resonators have a huge potential in replacing quartz crystal devices in frequency reference applications, especially when high integration level and low power consumption are required [1]. The main obstacle is the temperature instability of silicon which is challenging to compensate mechanically [2]. One way to overcome this difficulty is to measure the temperature and compensate the frequency drift accordingly using an electronic interface. This requires highly tunable resonators to be available.

The tuning of capacitively coupled MEMS is usually done by adjusting the DC-voltages on driving/reading electrodes. Due to the electrostatic spring softening, the resonance frequency decreases when the DC voltage is increased. This method, however, has a side effect, as the output signal level strongly depends on the bias voltage. This issue can be resolved by the means of the electronic driving circuit, but with the cost of the increased complexity and power consumption.

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In this work, a single-ended tuning fork component which has separate signal and tuning electrodes is demonstrated and characterized. The separate electrodes make it possible to perform frequency tuning with little interference with the output signal level. The component design is verified using finite element modeling (FEM) simulations. The device is fabricated by using a recently developed rapid micromachining technique.

The performance of the components was further improved by metallization and ALD encapsulation without significantly affecting the dynamics of the resonator, nevertheless, the total fabrication time stayed below one day.

2. Design and simulation

The goal of the design was to produce a component with maximum tunability and minimum required DC voltage within the restrictions of the fabrication process (Table 1). Three topographies of the resonators were analyzed: clamped-free (CF) beam, clamped-clamped (CC) beam and bulk acoustic wave (BAW) component. For the system level analysis, theory described in [3] was utilized.

Table 1. The set of requirements and restrictions

| Properties                        | Available values | Properties                        | Available values |
|-----------------------------------|------------------|-----------------------------------|------------------|
| Operational frequency $f$         | 1-2 MHz          | Output current $I_{\text{out}}$    | Maximize         |
| Maximum bias voltage $V_{\text{DC}}$ | < 30 V          | Minimum gap width $d$              | > 500 nm         |
| Tunability of the component $@V_{\text{tuning}}=V_{\text{DC}}$ | > 10 000 ppm    | Maximum width of released structure $w$ | < 5 μm          |
| Quality factor $Q$                | Not important    | Height of the moving parts of the component $h$ | < 2.5 μm         |

Based on the results of the optimization process one can see that from all 3 topologies BAW is less favorable for this application, as it can not be significantly tuned, considering tuning voltage and the width of the coupling gap. From CC and CF – beams a clamped-free topology was chosen to minimize the mechanical nonlinearities and to let the electrostatic spring softening effect prevail maximizing the tunability. The component is also made very small ($w_{\text{cantilever}} \approx 1 \mu$m) since at a fixed bias voltage $V_{\text{DC}}$ and gap width $d$, smaller components lead to stronger motional current.

A tuning fork type resonator is very promising in terms of separating tuning and driving mechanisms (Fig 1a). The resonator is actuated and detected on the left branch of the fork whereas the frequency tuning is introduced by the electrostatic spring softening on the right branch of the component. This design decouples the actuation DC bias $V_{\text{DC}}$ from the tuning voltage $V_{\text{tuning}}$ thus greatly simplifying the design of control electronics. The structure was simulated using COMSOL Multiphysics to insure that the resonance frequency is within limits ($F_{\text{in-phase}} = 1.7 \text{ MHz}$, $F_{\text{anti-phase}} = 2.2 \text{ MHz}$), and first and second eigenfrequencies are well apart (Fig 1b, 1c). No process originated non-idealties are taken into account at this point, leading to the fact that the measured values are somewhat lower than the simulated ones.

Fig. 1. a) Schematic view of the resonator. The signal is applied and read on the left and tuning is made on the right side of the device. DC-coupling resistors prevent the cross talk through biasing circuits. b) COMSOL simulation of the in-phase mode, $F_{\text{in-phase}} = 1.7 \text{ MHz}$ c) COMSOL simulation on the anti-phase mode $F_{\text{anti-phase}} = 2.2 \text{ MHz}$. 
3. Fabrication

Fig 2 shows the fabrication process of the resonator. We start with an SOI wafer and mask the device geometry by local Ga⁺ doping with FIB and finally fabricate the component with cryogenic DRIE. The release of the suspended structures is done using the notching effect by continuing etching after the oxide layer is reached. When buried silicon oxide is exposed and charged, the electrostatic field bends the ions sideways. For this effect to appear the coupling gap should be between 500 nm < d < 2000 nm [4]. For some of the test components, also two optional steps have been performed. First step includes oxide removal, aluminum evaporation (25 nm) and sintering to insure proper contact from bonding wires to silicon and to decrease the feed-through capacitance of the component. The second step is the component encapsulation by atomic layer deposition (ALD) in Al₂O₃ (35 nm), slowing down the processes such as native oxide formation on Si and helping to prevent stiction. The optional steps prolong the fabrication time by approximately 3 hours, but the total fabrication time is still below 5 hours. Fig 3a shows the overview of the final component without optional steps and Fig 3b illustrates the main dimensions of the beam.

![Fabrication Process Diagram](image_url)

4. Characterization and results

Electrical measurements show that the quality factor in the in-phase mode (the intended mode of operation) is over Q > 3000 (Fig 4a) at 29 V DC for the uncoated component. Coating decreases the Q-factor to ca. \( Q = 2000 \), but the signal level is a few dB stronger and the anti-resonance is almost extinguished. Extra mass of the metallic coating brings also the resonance frequency down by about 10%.

The frequency tuning was performed by sweeping the bias \( V_{DC} \) and the tuning \( V_{tuning} \) voltages between 3 V and 29 V. The results are shown in Fig 4b. Both frequency control mechanisms exhibit similar dependency of the tuning voltage.

Fig 6 shows the amplitude and the quality factor (Q) dependencies of the \( V_{DC} \) and \( V_{tuning} \). In Fig 5a it can be seen that the amplitude is highly dependent on \( V_{DC} \) (dash line), but there is only a small decrease (< 5 dB) in amplitude when \( V_{DC} \) is applied. The decrease of amplitude can be explained by a change of a Q of the system due to the energy losses into the de-coupling resistors on the tuning side, which is supported by Fig 5b.
Fig. 4: a) Frequency response of the component indicating the quality factor of $Q > 3000$ for uncoated and $Q > 1500$ for coated components. The bias $V_{DC} = 29$ V, $V_{tuning} = 0$ V. Input power after attenuator $P_{in} = -50$ dBm. b) Frequency shift by applying $V_{DC}$ (dashed curve) and by tuning via $V_{tuning}$, multiple points at each $V_{tuning}$ are taken at various $V_{DC}$.

Fig. 5: a) transmission amplitude for coated component for various $V_{DC}$ and $V_{tuning}$. $V_{tuning}$ does not significantly affect the amplitude (horizontal lines), while exhibiting a quadratic dependency on $V_{DC}$ (dashed line). b) Measured quality factors of a coated component at various $V_{DC}$ and $V_{tuning}$.

5. Summary

In this work is shown a design and a fabrication method for a capacitively coupled voltage controlled resonator with separate biasing and tuning electrodes. The electrode separation results in good frequency tunability ($> 10,000$ ppm) without hampering the signal strength (variation < 5 dB) which in turn simplifies interface electronics.

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