New electrostatically excited Silicon resonator vibrating in a thickness extensional mode

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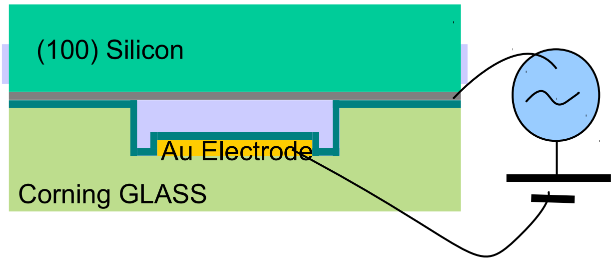
This paper presents a new micro-mechanical BAW resonator built in Silicon, using an electrostatic excitation. The device is based on a one-port design with a 1µm gap to apply the superimposition of static bias voltage and dynamic excitation to the silicon plate. A thickness extensional mode is exploited, yielding a frequency operation near 10 MHz with a standard 400µm thick Si plate. The micro-fabricated resonator was tested in one-port configuration using a network vector analyzer. As expected theoretically, the electromechanical coupling factor and many resonator features, including the quality factor Q, change with the DC bias polarisation. A Q factor near 9000 have been observed with a coupling close to the ones usually observed for Quartz resonators.The resonator was tested in air at different temperatures between 0°C and 100°C and the TCF was found at -28ppm/°C. We are currently investigating a new appropriate composite structure in order to reducing this value. The stabilization of a RF oscillator using this resonator is still under development. Another approach is also reported based on the exploitation of a low frequency mode (fundamental flexural mode). The characterization of the mode is achieved and the operation of an oscillator stabilized using it is demonstrated

Introduction

This paper presents a new micro-mechanical BAW resonator built in Silicon, using an electrostatic excitation. The device is based on a one-port design with a 1µm gap to apply the superimposition of static bias voltage and dynamic excitation to the silicon plate. A thickness extensional mode is exploited, yielding a frequency operation near 10 MHz with a standard 400µm thick Si plate. The resonator presented in the paper is based on a single p-doped (100) Silicon plate bonded onto a Corning® glass substrate by using the anodic bonding technique. The glass layer is machined to create the electrostatic gap mandatory for the electrical excitation. The micro-fabricated resonator was tested in one-port configuration using a network vector analyzer (Rohde &Schwarz). Analyzing the frequency response of the resonator for various DC bias voltages yields to prove that the electromechanical coupling factor and many resonator features, including the quality factor Q, change with the DC bias polarization, as expected theoretically. Once compensating the static capacitance, the Q factor near 9000 have been observed with a promising coupling w.r.t. quartz resonator values. By principle, the proposed design allows for a further optimization of the Q factor using energy trapping techniques. The resonator was tested in air at different temperatures between 0°C and 100°C and the Temperature Coefficient of Frequency (TCF) of the resonator was experimentally found equal to -28ppm/°C which fairly corresponds to the actual TCF sensitivity of the longitudinal elastic wave in Silicon. A new appropriate composite structure is currently investigated to reduce this value. The stabilization of a RF oscillator using this resonator is still under development. As a consequence, another approach has been tested at much lower frequency, based on the fundamental flexural mode of the silicon plate. This approach has allowed to demonstrate the possibility for building an effective oscillator based on the proposed structure. In that case, a positive CTF was measured, showing that both Silicon and Glass contribute to the exploited vibration.

Resonator principle

The capacitive actuation is widely used in MEMS, and particularly recent advances have been achieved for the development of RF devices capable to compete with quartz-based Bulk Acoustic Wave (BAW) resonators. Different vibrating modes can be electrostatically-excited in different kinds of Silicon-based structures: flexural modes for clamped-clamped beams and disks [1], circular and elliptic modes for disks [2], width and length-extensional modes for rectangular plates and bars [3], [4], [5]. In the present work, a longitudinal bulk acoustic wave is excited by electrostatic forces in Silicon in a similar way to what is achieved in Film Bulk Acoustic Resonators (FBARS) based on C-axis AlN self supported films. The main motivation of this approach is to get rid of strong geometrical dependence of the resonance (as for example in shape mode resonators or vibrating beams) and to get a full advantage of the crystal quality acting as the best filter for the mode selection. Using a reduced dimensionality principle then is expected to provide the best way for an effective control of the resonance frequency. The device architecture is reported in fig.2 . It consists of a Silicon pate bounded onto a glass substrate on which a gap has been formed and electrodes have been deposited, allowing for the electrostatic actuation to be implemented. This device is then expected to operate as a classical Bulk Acoustic Wave (BAW) resonator, the DC voltage being used to fixed the operating point and to control the coupling factor (the thinner the gap, the higher the electromechanical coupling). Actually, the operation of the resonator can be represented using a Butterworth-Van Dyke equivalent circuit for a given value of DC voltage. One can easily demonstrate that for a thickness of about 400 µm for a (100) silicon plate used as resonator, the operating frequency will arise a little above 10,5 MHz (the longitudinal mode in silicon propagates with a phase velocity of 8900 m.s^{-1})



Basic concept of the Bragg Mirror: a) the structure b) calculated admittance response

Figure 2: Basic principle of a cMUT exploiting the fundamental flexural mode of a Si-plate actuated by a DC-bias voltage plus an AC excitation

Technology development

The resonator presented in the paper is based on a single p-doped – conductive – (100) Silicon plate bonded onto a Corning® glass substrate by using the well-known anodic bonding technique. The glass layer is machined to create the electrostatic gap mandatory for the electrical excitation, as explained above.

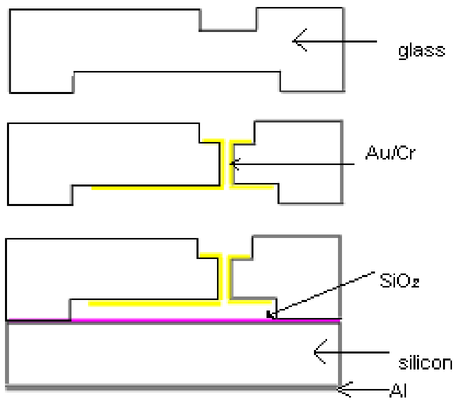


Figure 3: Principal technology steps for the fabrication of the bulk acoutic wave electrostatic resonator: – 1 fabrication of the gap and the protection groove for anodic bonding – 2 manufactruign the via and metallisation for contacting the leectrode within the gap – 3 anodic bonding and top side metallization

A classical 60% electrode surface compared to the plate diameter has been considered to optimize the excitation. To avoid any electrical breakdown, the Al electrode onto silicon has been passivated using a thin PECVD SiO_2 film. The fabrication process uses four masks and several processes outlined in fig.2. In a first step, the glass wafer is micro-machined using DRIE Bosch process to realize two cavities on its both sides: the 1-micron deep cavity completes the electromechanical transduction (fig.4) while another 100-µm deep cavity, on the second side of the wafer, is intended to act as a protection against the electrical discharges during the anodic bonding. This precaution was revealed necessary after unsuccessful tests.

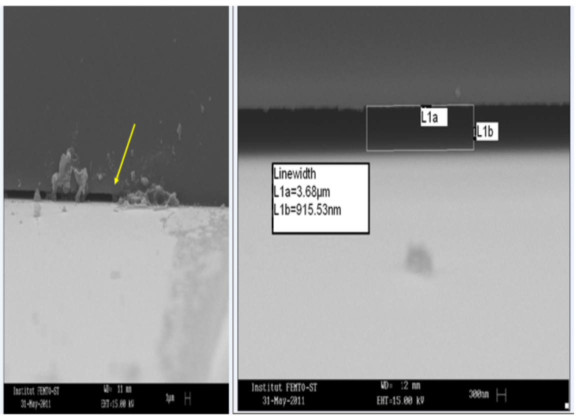


Figure 4: Close views of the gap after the anodic bonding process, showing the capabilities for sub-micron gap manufacturing.

The two glass sides are connected by means of a hole drilled by ultrasonic micro-machining. Subsequently, a gold/chromium layer is sputtered inside the hole and over the bottom of the cavities, thus patterning the top electrode and the electric via. The last steps consist in the anodic bonding between the glass and the Silicon passivated wafers, the deposition of the bottom (ground) Aluminium electrode and a rapid thermal annealing.

Implementation and characterization

Some details of the resonator geometry are presented in fig. 6, whereas fig. 6 shows a picture of a manufactured device with the connecting wires.

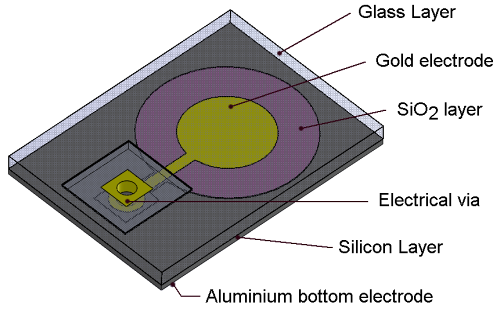


Figure 5: Detailed scheme of the internal structure of the resonator

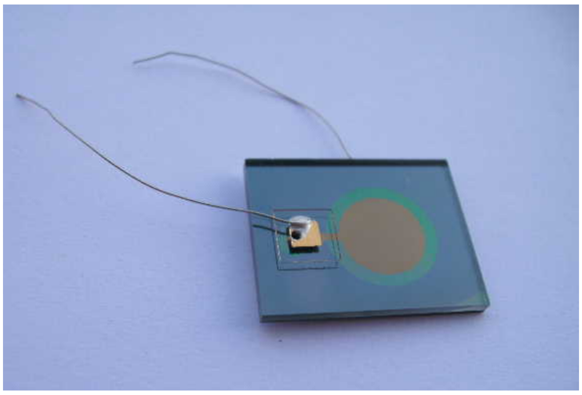


Figure 6: View of the manufactured resonator emphasizing the backside connection (Au via crossing the glass substrate)

The micro-fabricated resonator was tested in one-port configuration using a network vector analyzer (Rohde &Schwarz). Figure shows the frequency response of the resonator for various DC bias voltages. The electromechanical coupling factor and many resonator features, including the quality factor Q, change with the DC bias polarisation, as expected theoretically. After the static capacitance compensating, the Q factor near 9000 have been observed with a promising coupling w.r.t. quartz resonator values. By principle, our design will permit a further optimization of the Q factor with help of energy trapping.

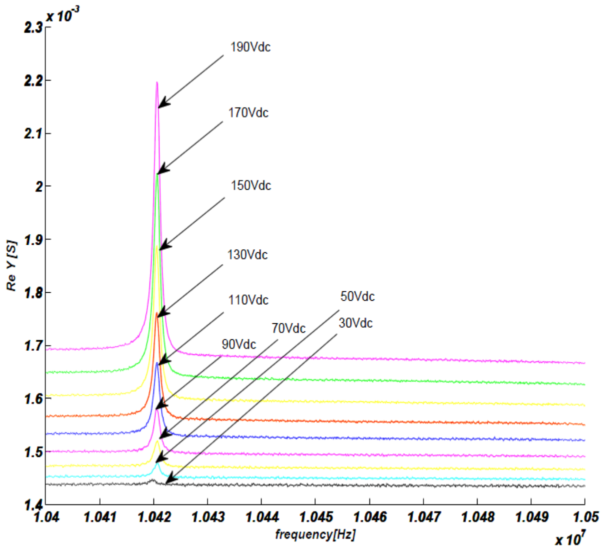


Figure 7: Evolution of the electrical admittance of the resonator vs DC voltage

The resonator was tested in air at different temperatures between 0°C and 100°C and the TCF was found at -28ppm/°C. We are currently investigating a new appropriate composite structure in order to reducing this value. The stabilization of a RF oscillator using this resonator is still under development.

Alternative solution – flexural mode

As mentioned above, the longitudinal mode solution needs more effort to allow for its insertion in an oscillator loop. Therefore, an alternative approach was developed to illustrate the interest of RF devices based on capacitive forces. Rather low DC-bias voltages (between 40 and 60V) are needed to allow for electromechanical coupling compatible with the expected application (k_s^2 in excess of 1%). An oscillator is stabilized using such a resonator and the possibility for electronic control of the oscillator frequency is demonstrated. Finally, the sensitivity of the oscillator to mass deposition is tested and compared with theoretical predictions. The optimization of the structures is discussed as a conclusion. This work then contributes to develop such a solution, particularly for deposited/adsorbed mass detection and measurement.

Figures 3 and 3 illustrate the actual operation of one of the fabricated devices, with a clear control of the frequency and coupling coefficient along the DC-bias voltage value (several hundred of ppm/V).

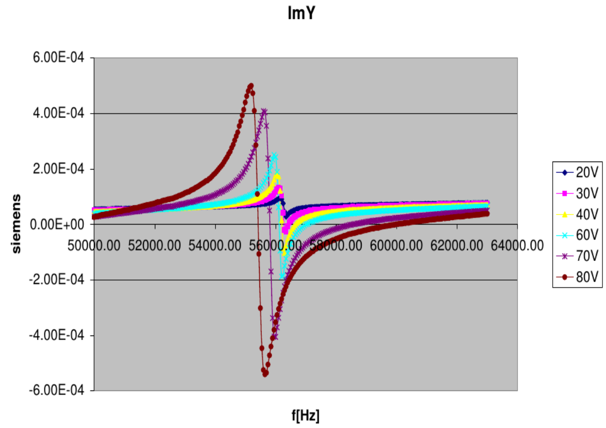


Figure 8: Harmonic susceptance of the low frequency flexural mode for various DC-bias voltages

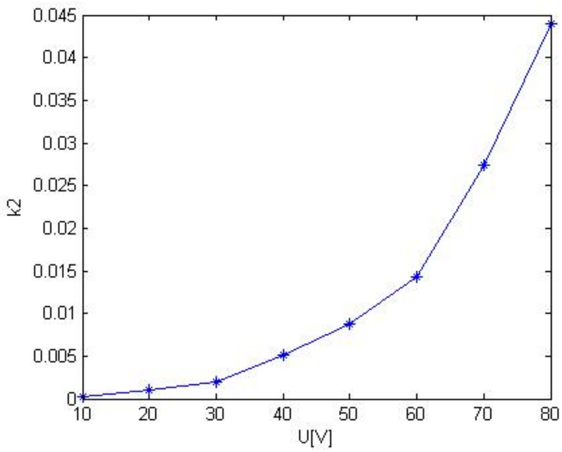


Figure 9: Electromechanical coupling dependence of the low frequency flexural mode vs DC-bias voltage

An oscillator has been stabilized using this mode and the possibility for detecting frequency changes due to mass deposition/adsorption atop the resonator has been finally tested (fig.3). The estimated experimental sensitivity of the whole system fits well with theoretical estimation based on finite element analysis.

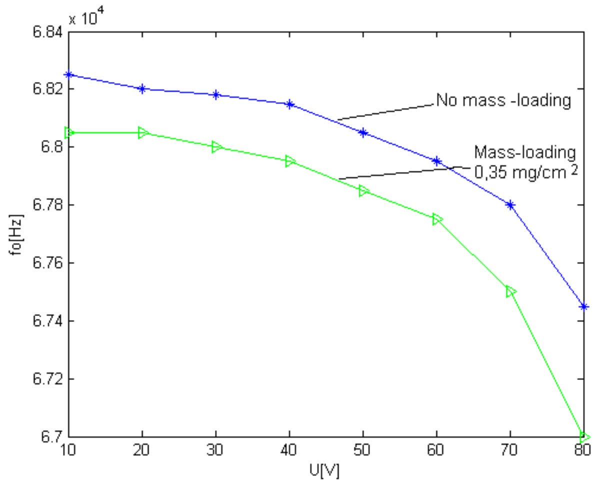


Figure 10: First estimation of the gravimetric sensitivity of an oscillator stabilized using the flexural mode resonator exposed in the previous figures

Conclusion

In this paper, we have presented a new kind of radio-frequency bulk acoustic wave resonator has been proposed. The excitation is achieved on one side of a silicon plate using electrostatic forces across a submicron gap. Resonance near 10 MHz have been demonstrated with Q factor near 10 000. Although the resonator reveals rather sensitive to temperature, more work is engaged to develop 0 TCF devices. Furthermore, the same structure has beem exploited for achieving a low frequency oscillator succesfully. In that case, the thermal sensitivity was found positive, which indicates that silicon as well as glass contributes to the whole vibration (the TCF of glass is known to be strongly positive). Many dgree of freedoms then are considered to improve both devices, yielding an interesting alternative to standard piezoelectric BAW devices.

References

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