Voltage-tunable piezoelectrically-transduced single-crystal silicon micromechanical resonators

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Abstract

This paper reports on a new class of high-Q single-crystal silicon (SCS) resonators that are piezoelectrically actuated and sensed, and have voltage-tunable center frequencies. The resonating element is made out of the SCS device layer of a SOI wafer. In a unique manner, piezoelectric transduction was integrated with capacitive fine-tuning of the resonator center frequencies to compensate for any process variations. Quality factor as high as 6200 was measured for the 1.7 MHz first resonance mode of a clamped–clamped beam resonator in 50 mTorr vacuum. Higher order modes of the fabricated resonators were also successfully actuated and demonstrated quality factors larger than 2000 (under vacuum) at frequencies approaching 17 MHz. A 6 kHz tuning range was measured for a 719 kHz resonator by applying a dc voltage in the range of 0–20 V.

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1. Introduction

Advanced consumer electronics such as miniature radios and wristwatch cellular phones pose severe limitations on the size and cost of the frequency selective units contained therein. MEMS resonators are receiving increased attention as building blocks for on-chip integrated filter and frequency references to replace bulky, off-chip ceramic and SAW devices. Several all-silicon resonators with capacitive transduction mechanisms have been reported in literature [1–4], showing high mechanical quality factors and optimal performances in the IF and VHF range. However, in order to reduce the motional resistance of the capacitive resonators for higher frequency applications, sub-100 nm capacitive gap spacing is needed, which can complicate the fabrication process. The piezoelectric film bulk acoustic resonators (FBAR) [5,6] have smaller motional resistance compared to their capacitive counterparts, and hence are suitable for UHF applications. However, they are larger in size, have lower quality factors, and do not have voltage-tunable center frequencies.

This paper reports on a new and simple fabrication technique utilizing SOI wafers to implement single-crystal silicon (SCS) resonators that combine the advantages of piezoelectric and capacitive resonators. The resonating element is substantially made out of SCS, which has a higher inherent mechanical quality factor than bulk piezoelectrics and deposited thin films, whereas actuation and sensing is achieved by piezoelectric means. The high electromechanical coupling offered by the thin zinc oxide film provides for small equivalent motional resistance, hence improving signal to noise ratio. Similar clamped–clamped resonant beams were previously demonstrated in [7] using SiO2 as the resonating element, but low quality factors were reported. The technology described in this paper enables to reach quality factors as high as 6200 at a resonance frequency of 1.7 MHz and is capable of actuating higher order modes of the same beam resonators. The unique feature of this fabrication process, intrinsically related to the choice of the SOI wafer, is the ability to combine piezoelectric actuation mechanisms with electrostatic fine-tuning of the center frequency of the resonator. By applying a dc voltage between the handle layer of the SOI wafer and the resonator body, it is possible to introduce electrical stiffness through the action of the capacitance and reduce the equivalent stiffness of the beam.
inverse of the electromechanical coupling; therefore the mechanical resistance of the resonator depends on the squared shape of the clamped–clamped beam. The equivalent coefficients at the input port are:

$$\eta_{\text{in}} = \frac{dE_{31}T_x}{2} \int_0^L W_s^2(x)\Phi_i'(x)dx$$

$$\eta_{\text{out}} = \frac{dE_{31}T_x}{2} \int_0^L W_o^2(x)\Phi_o'(s)dx$$

(1)

where $d_E$ is the transverse piezoelectric coefficient, $E_{31}$ the modulus of elasticity of zinc oxide, $T_x$ the thickness of the beam, $W_s(x)$ is the electrode width, and $\Phi_i(s)$ is the mode shape of the clamped–clamped beam. The equivalent motional resistance of the resonator depends on the squared inverse of the electromechanical coupling; therefore the values of $\eta_{\text{in}}$ and $\eta_{\text{out}}$ need to be maximized to achieve low values of the motional resistance. The maximum value of the two integrals in (1) occurs for electrode edges placed at the inflection points of the beam mode shape. Such points coincide with 0.224 and 0.776 of the beam length. This concept, derived from analytical considerations, reflects the intuitive idea of maximizing the sensed signal by laying the electrodes over the area where the stress does not change sign.

The final input to output admittance $Y_{\text{in}}$ of the SCS resonator with piezoelectric transduction can be expressed as:

$$Y_{\text{in}} = \frac{2.49 \cdot d_{31}E_pT_x(W/L)^2s}{M + (M/Q)s + K_1}$$

where $M_1$, $K_1$, and $Q$ are respectively the modulus of elasticity, the natural resonance frequency of the beam, and $s$ is the Laplace variable. The fabrication process has three masks. The resonator die was etched in the middle span of the beam, therefore reducing the effective covering of the resonator body by the piezoelectric and enhancing the mechanical Q of the resonator. Such a solution has resulted in a 100% increase in the Q of the resonators as confirmed by the experimental results.

When an ac voltage is applied to the drive electrode, the active piezoelectric film is producing a distributed moment, which causes the beam to deflect. Such a deformation is sensed by the piezoelectric material on the opposite side of the beam. The admittance model of a doubly-clamped piezoelectric beam resonator was taken into account during the design phase [8]. The electromechanical coupling coefficients at the input port $\eta_{\text{in}}$ and at the output port $\eta_{\text{out}}$ of the resonator, with the assumption that the thickness of the piezoelectric layer is negligible compared to the thickness of the beam, are expressed by [8]:

$$\eta_{\text{in}} = \frac{dE_{31}T_x}{2} \int_0^L W_s^2(x)\Phi_i'(x)dx$$

$$\eta_{\text{out}} = \frac{dE_{31}T_x}{2} \int_0^L W_o^2(x)\Phi_o'(s)dx$$

(2)
The thickness of 4 μm. The beam thickness is defined by the thickness of the device layer. A cavity is opened underneath the beam by isotropic etching of the buffer oxide layer in HF/H2O. This unconventional step, aimed at the release of the structures in an intermediate step of the process, was made necessary by the presence of ZnO, which is easily attacked by any type of acid [9]. The cavity underneath the beam provides for the 1 μm gap that is used for capacitive fine-tuning of the micro-beam center frequency.

The active piezoelectric film is sputter-deposited on the silicon substrate. Zinc oxide was selected because of its well-established process recipe [10] and ease of integration with current microelectronics. The low-temperature fabrication process makes these devices post-CMOS compatible. A temperature of 250 °C for the silicon substrate, a pressure of 6 mTorr, an Ar to O2 mix ratio of 0.5, and a power of 300 W were used as deposition parameters. The piezoelectric film has a thickness of 0.3 μm and shows strong c-axis orientation, as confirmed by the XRD data shown in Fig. 3. Zinc oxide was patterned by wet etching using ammonium chloride (NH4Cl). NH4Cl was selected because it has a very slow etch rate (50 Å/s) and enables the definition of small features without severe lateral undercut.

The aluminum top electrode (1000 Å) is defined by the third mask using lift-off. The thickness of the ZnO and Al layers have been kept small to avoid any detrimental effects on the quality factor and resonance frequency of the resonators due to stacked layers of different materials.

Fig. 4 shows top-view of a SCS piezoelectrically-transduced clamped-clamped beam resonator. The input and output signal pads are electrically isolated from the silicon substrate by the piezoelectric ZnO film, which exhibits a resistivity value higher than 10^8 Ω cm if an Ar to O2 mix ratio of 0.5 is used during the deposition phase. Fig. 5 is a close-up view of a SCS piezoresonator, showing the zinc oxide film sandwiched between the low resistivity silicon and the top aluminum electrodes. ZnO was etched away in the middle of the beam to increase the quality factor of the resonator.

It should be mentioned that the oxide undercut extending into the clamping region of the beams causes a downshift in the resonance frequency of the resonators.
the resonance frequency of the smaller beams. A thorough FEM analysis was conducted using ANSYS to predict the effect of the oxide undercut as well as the deposited thin films on the resonance frequency of the fabricated resonators. The following sections will present the measurement results and their comparison with ANSYS simulation results.

4. Measurement results

The fabricated microresonators were tested in a custom-built vacuum chamber capable of pressures as low as 10μTorr. A low noise JFET source-follower with a gain stage was used to interface with the resonators. The frequency spectra of the resonators were captured using Agilent 4395A network analyzer. As expected, higher quality factors were obtained from the SCS piezoresonators in which the zinc oxide is etched away from the middle of the beam. Fig. 6 shows a typical frequency response taken from the network analyzer for a 100μm long, 20μm wide clamped–clamped beam resonator. This MEMS resonator has a center frequency of 1.72 MHz and shows a quality factor of 6200 at a pressure of 50 mTorr, which was the highest Q measured. Clamped–clamped beams of identical...
dimensions in the basic configuration (with ZnO in the middle, as shown in Fig. 1a) showed Q’s of about two times smaller than the ones without ZnO (in the order of 3000).

4.1. Higher order modes

The fabricated SCS piezoresonators were operated in their high order flexural modes to achieve higher frequencies. The responses of a 200-μm long beam in two high order modes are shown in Fig. 7. A Q of 5300 was measured at 3.29 MHz with no substantial decrease from the first mode quality factor. The quality factors for higher order modes, at 4.87 and 6.7 MHz, are ~3000 and 2400, respectively, approximately half the Q of the first mode. Fig. 8 shows the highest resonance frequency (16.8 MHz) achieved by actuating a 50-μm long SCS piezoresonator in its higher order mode with a quality factor of ~2600 in vacuum. The relatively high values of quality factor measured for these devices in the 1–20 MHz range, when compared to the values reported in [7], confirm the optimal choice of SCS as the resonator structural element. Actuation voltages as low as 0.7 mV (minimum value enabled by the network analyzer) can excite the microresonators, showing a dynamic range of at least 45 dB.

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\[ \text{Q} \sim 3000, \text{Q} \sim 2400 \]

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**Fig. 6.** Response of a 100-μm long, 20-μm wide SCS piezoresonator showing a Q of ~6200 at a resonance frequency of 1.72 MHz.

**Fig. 7.** Response of a 200-μm long resonator actuated in high order modes. The table summarizes the FEM analysis results in which the effect of buffer oxide undercut on the resonant frequency was taken into account.

**Fig. 8.** Response of a 200-μm long resonator actuated in its higher order mode with a quality factor of ~2600 in vacuum.
Pressure dependence of the loaded quality factor of the resonators was analyzed. Fig. 9 shows the experimental data for two clamped-clamped beams, 100 and 200 μm long, with the same width of 20 μm. These results agree with [11], showing that the value of the quality factor tends to drop at higher pressure for higher frequency beams.

4.2. Electrostatic fine-tuning

Fig. 10 shows the comparison between the measured and the theoretical frequency-tuning characteristic for a 200 μm long resonator, obtained by changing the dc voltage applied between the handle layer of the SOI wafer and the body of the resonator from 0 to 20 V. This feature, uniquely related to this specific fabrication technology, enables the combination of the piezoelectric transduction mechanism with capacitive fine-tuning of the resonance frequency. This technique provides an electrostatic tuning range of 6 kHz for a 719 kHz resonator. The uncertainty in the exact dimensions of the resonator and the amount of the buffer oxide undercut could account for the small mismatches between the theoretical and experimental curves.

5. Finite element modal analysis

A finite element modal analysis of the structure was completed in ANSYS. The model consists of the resonator beam, the device layer oxide undercut region, the zinc oxide, and the aluminum electrodes (Fig. 11). The interface between the materials is assumed to be structurally ideal, and the model is assumed to be perfectly clamped at the surrounding areas of the undercut region. The silicon beam, zinc oxide, and aluminum used in the ANSYS model.

Table 1

<table>
<thead>
<tr>
<th>Material</th>
<th>Parameter</th>
<th>Value (GPa)</th>
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<tbody>
<tr>
<td>Silicon</td>
<td>Stiffness</td>
<td>$C_{11}$ 166</td>
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<tr>
<td></td>
<td></td>
<td>$C_{12}$ 64</td>
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<tr>
<td></td>
<td></td>
<td>$C_{14}$ 80</td>
</tr>
<tr>
<td></td>
<td>Density</td>
<td>2330 $^a$</td>
</tr>
<tr>
<td>Zinc oxide</td>
<td>Stiffness</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>$C_{12}$ 121.1</td>
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<td></td>
<td></td>
<td>$C_{13}$ 105.1</td>
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<td></td>
<td></td>
<td>$C_{33}$ 210.9</td>
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<td></td>
<td></td>
<td>$C_{44}$ 42.47</td>
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<tr>
<td></td>
<td>Density</td>
<td>5676 $^a$</td>
</tr>
<tr>
<td>Aluminum</td>
<td>Stiffness</td>
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<tr>
<td></td>
<td>Poisson ratio</td>
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</tr>
<tr>
<td></td>
<td>Density</td>
<td>2700 $^a$</td>
</tr>
</tbody>
</table>

$^a$ The values are in kg/m$^3$. 

Fig. 8. Response of a 50 μm long microresonator actuated in a high order mode. A quality factor of ~2600 is obtained at 16.8 MHz.

Fig. 9. Plot of 100 and 200 μm long beams quality factors vs. pressure.

Fig. 10. Electrostatic fine-tuning characteristic for a 719 kHz piezoresonator: comparison between experimental and theoretical curves. Theoretical curve is based on electrostatic force derivation in parallel plate capacitor theory.
and aluminum electrode is tightly meshed with hexahedral SOLID186 elements, the undercut region is meshed with tetrahedral SOLID186 elements, and transitional pyramid elements are used at the interface. The material properties used in the model are listed in Table 1. The eigenmodes and eigenvalues (Fig. 11) from this modal analysis confirm and validate the test results. These results show that the oxide undercut introduces additional modes and alters the mode shape and natural frequencies (especially in higher order modes). The undercut can be easily minimized through process optimization for a particular geometry of interest.

6. Conclusions

The design, fabrication and testing of voltage-tunable, piezoelectrically-transduced, high-Q single-crystal silicon resonators on SOI substrates were reported in this paper. High mechanical quality factors ranging from 5400 to 6000 were demonstrated for the resonators in which the zinc oxide film was etched away in the middle area of the beam. The experimental results confirmed the optimal choice of SCS as the resonating material. Higher order modes were actuated showing the ability of reaching resonance frequencies as high as 16.8 MHz with a quality factor of ~2600. The advantages of piezoelectric transduction mechanisms were combined with electrostatic fine-tuning of the resonance frequency. A tuning range of 6 kHz was obtained for a 719 kHz resonator by applying a dc voltage in the range of 0–20 V.

Acknowledgements

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References

Biographies

Gianluca Piazza was born in Broni, Italy in 1977. In 2001, he received the Laurea degree with high honors in electrical engineering from the Politecnico di Milano and the MS degree in electrical engineering from the University of Texas at Austin where he conducted research focused on piezoelectric materials for civil engineering applications. In January 2002, he joined the Georgia Institute of Technology where he worked on the application of piezoelectric materials to micromechanical resonators. He is currently with the University of California, Berkeley where he is pursuing his PhD degree in electrical engineering working on thin-film piezoelectric materials for RF MEMS. His research interests concentrate on MEMS, piezoelectric materials for RF MEMS and the integration of MEMS with CMOS. Mr. Piazza received the Studentenkreis fellowship from Siemens (1998-2000).

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Gavin K. Ho was born in Vancouver, Canada in 1980. He received the McGill degree and BAEc degree with distinction in mechanical engineering from the University of British Columbia, Canada in 1996. Following, he joined the Georgia Institute of Technology where he is currently pursuing a PhD degree in Electrical Engineering. Mr. Ho was the recipient of the UBC Letson Prize in 2001 and the Col. Oscar P. Cleaver Award from the Georgia Institute of Technology in 2002. His research interests include the physics of loss mechanisms in MEMS resonators and MEMS resonator design for signal processing applications.

Farrokh Ayazi was born in 19 February 1972. He received the BS degree in electrical engineering from the University of Tehran, Iran, in 1994, and the MS and the PhD degrees in electrical engineering from the University of Michigan, Ann Arbor, in 1997 and 2000, respectively. He joined the faculty of Georgia Institute of Technology in December 1999 where he is currently an assistant professor in the School of Electrical and Computer Engineering. Prof. Ayazi’s current research interests are in the areas of integrated MEMS, RF MEMS, VLSI analog integrated circuits, integrated microsystems, MEMS inertial sensors, and microfabrication technologies. Prof. Ayazi is the recipient of the Georgia Tech College of Engineering Cutting Edge Research Award for 2001-2002. He received a Rackham Predoctoral Fellowship from the University of Michigan for 1998-1999.