Electrical characterization, crosstalk compensation and experimental examination of AlN-based piezoelectric micro resonators

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Abstract. Aluminum nitride based micro resonators are fabricated and measured with an all-electrical excitation and detection method in this paper. Low resistivity single crystal silicon is used as resonating element, serving simultaneously as bottom electrode for the piezoelectric layer. The elimination of the bottom metal electrodes reduces the number of stacked layers and stress in the cantilever; however, the short circuit connection between drive and sense port silicon grounds induces serious feedthrough capacitance effect. Electrical measurement results indicate that, the resonator output is a superposition of mechanical resonance behavior and electrical crosstalk from feedthrough capacitance. A general equivalent circuit model is derived to analyze the resonator’s electromechanical performance. To eliminate the electrical crosstalk, a compensation solution has been developed, by applying an inverted adjustable voltage to the common bottom electrode. Further experimental investigations of the device under different controlled pressures show that, the output amplitude after compensation is precisely symmetric around the resonance peak, and phase shift of -90° occurs at resonance, indicating that the feedthrough has been adequately cancelled out.

1. Introduction

Piezoelectric micromachined resonators have been widely used in a large variety of applications [1-5]. The active piezoelectric layer provides an input bending stress for the resonator, and another area of the layer can be used to detect the resulting mechanical motion. Aluminum nitride (AlN) thin films are often used in micro devices requiring mechanical excitation and/or detection during operation, since AlN has attractive qualities, like high thermal and chemical stability and full compatibility with conventional silicon technology. By careful control of deposition/sputtering parameters [6], such as plasma power, back pressure level and gas composition, both high piezoelectric coefficients and low intrinsic stress thin films could be achieved. Besides, AlN is also the material of choice for many application scenarios requiring good electrical isolation [7, 8], high chemical inertness and high surface acoustic wave velocity [9, 10].

The electro-mechanical response of piezoelectric AlN materials is complex as it involves a mechanical response, an electrical response, and a mutual coupling between them. Although the piezoelectric phenomenon is non-linear, most applications utilize the operation conditions in which the piezoelectric response is nearly linear. Admittance and/or impedance spectroscopy measurements can...
be used to characterize the frequency response and electromechanical coupling coefficient for transducers [11, 12]. In many cases, the performance of piezoelectric devices is found to be degraded by the electrical crosstalk between the drive port and the sense port [13-17], often due to parasitic elements, mostly feedthrough capacitance. The crosstalk caused by it affects the electrical behavior, or even may completely obscure the mechanical resonance in the worst case, making detection of the resonance peak impossible.

As a result, techniques for reducing/compensating capacitive feedthrough in electrically interfaced piezoelectric resonators are essential. The shape of the piezoelectric layer can be optimized [14], an on-chip compensation capacitor can be introduced by using a dummy twin structure [15], or two separated ground electrodes could be used [16] as to prevent direct capacitive signal transfer through the input and output electrodes. In many work [18-21], low resistivity silicon is used as structure element, serving simultaneously as bottom electrode for the piezoelectric layer. The elimination of extra bottom metal electrodes reduces the number of stacked layers and the stress in the devices, simplifying the fabrication process and increasing the resonance quality factor. However, one major drawback of this type structure is relatively large feedthrough capacitance effect, which tends to obscure electromechanical resonance signal.

In this paper, a piezoelectric micro resonator formed by an AlN layer sandwiched between top metallic electrodes and low resistivity single crystal silicon (SCS) is fabricated. The electrical performance of the micro resonator were found to be a superposition of mechanical resonance behavior and electrical crosstalk from feedthrough capacitance. Based on a derived equivalent circuit model, a crosstalk compensation solution has been developed, and further experimental investigations of the micro device under different controlled pressures have proved the efficiency of the proposed compensation solution.

2. Fabrication and experimental setup
Details of test structures are summarized in figure 1, a cross-section schematic and geometry of the micro resonator are drawn in figures 2 and 3. A micrograph of the structure can be found as an insert photo in figure 4, with a thickness, width and length of the silicon beam about 20, 800 and 1200 μm, respectively. The fabrication process was inspired by work reported by Ababneh et al. in our group [6, 22]. The cantilever beam has AlN thin films along the top surface sandwiched between top metallic electrodes and low resistivity (less than 0.1 Ω cm) SCS. AlN is reactively sputter-deposited from an aluminum target in a near vacuum atmosphere filled with rarefied nitrogen gas. Sputtering conditions (such as silicon substrate pre-heating, gas composition, sputtering pressures, plasma power, etc.) are carefully controlled. Piezoelectric coefficients $d_{33}$ and $d_{31}$ in c-axis oriented 500 nm thick AlN films are measured to be approximately 3.0 and -1.0 pm/V [6].

![Figure 1. Image of the test structure and surface morphology of the AlN film.](image1.png)

![Figure 2. Schematic cross section of the micro resonator.](image2.png)
The fabricated cantilever was tested using a HP4395A network analyzer, as schematically drawn in figure 4. The output port of the analyzer is connected to the drive port of the resonator while its output (sensor port) is feedback into the analyzer. By sweeping the actuation frequency across the resonance frequency, one can get the harmonic frequency response of the device.

3. Electrical performance analysis and characterization

3.1. Equivalent circuit model

The electrical behavior of the piezoelectric resonator can be described by an equivalent circuit model. We make the following assumptions: (i) the different modes of resonance of the structure do not interfere with each others, (ii) mechanical and electrical wave propagation phenomena can be ignored, (iii) all electrodes and connecting wires and cables are ideal conductors while the piezoelectric and Si$_3$N$_4$ isolation layers are ideal isolators.

Near the resonance frequency, the mechanical behavior of the structure is well described by a single degree-of-freedom system. In order to simplify the problem, the single modal vibration of the mechanical structure is used to investigate the performance of the piezoelectric resonator. The mechanical resonance is represented in the electrical domain by the series of an inductance $L_m$ (which corresponds to the resonator mass), of a capacitance $C_m$ (which corresponds to the spring constant of the beam), and of a resistor $R_m$ (which corresponds to the parasitic dissipations). The vibration velocity of the bending beam is represented by the current $i$ flowing in the mechanical side and the modal-exciting mechanical force is denoted as a voltage $u$. The electrical representation of mechanical resonance can be described by equation (1):

$$\left(L_m s + R_m + \frac{1}{C_m s}\right)i = u.$$  \hspace{1cm} (1)

The electrical part of the system consists in the resonator's intrinsic capacitances, $C_d$ and $C_s$, between top and bottom electrode layers for drive and sense, and feedthrough capacitance $C_{fs}$, induced from the short circuit connection between drive and sense port silicon grounds. A transformer can be used to couple energy from the electrical domain to the mechanical domain and vice versa.

Figure 5 shows a general equivalent circuit model of the piezoelectric resonator. Once the equivalent circuit parameters are identified (either by finite element analysis [23], analytically [24], or data fitting measurements [25]), the performance of the piezoelectric device can be evaluated by a simulation program such as SPICE or MATLAB.
Figure 5. Schematic structure of a piezoelectric resonator, together with an equivalent circuit model.

The resonator output $U_o$ can be written as a superposition of mechanical resonance behavior $U_M$ (c.f. equation (1)), and electrical crosstalk $U_E$ from feedthrough capacitance: $U_o = U_M + U_E$, with

$$U_M(s) = \frac{1}{\left(R_m s + L_m s^2 + \frac{1}{C_m}\right) C_i} U_i(s),$$

and

$$U_E(s) = \frac{C_R}{C_R + C_i} U_i(s).$$

3.2. Comparison between measurements and model predictions

Figure 6 presents the measured response of the resonator to a 2 Vpp drive voltage at normal atmosphere of the first (flexural) resonance mode, as well as the model predictions based on equations (2 and 3). The resonance frequency $f_r$ is calculated to be 22.48 kHz and quality factor $Q$ is 782. It can be seen that, the electrical performance of the resonator is degraded by the electrical crosstalk, since “anti-frequency” peaks are introduced. The “anti-resonance” peaks’ magnitude difference is about 0.5 mV, much smaller than the crosstalk 1.5 mV, and a maximum phase shift of $18^\circ$ was observed around resonance.

The electrical behavior of the resonator can be explained by redrawing the response in a polar diagram in the complex plane, as shown in figure 7, wherein $U_M$ is illustrated as a resonant circle (a high $Q$ factor of the resonance indicates a large circle), and $U_E$ introduces an offset of resonant circle toward the third quadrant. With increasing frequency $f$, the magnitude of $U_o$ reaches a minimum first and then a maximum (as called “anti-peaks”). Meanwhile, the phase shift $\Phi$ in the frequency interval around resonance is smaller than expected $180^\circ$ in an ideal resonance behavior.
Figure 6. Measured and analytically derived response of the AlN based piezoelectric resonator at normal atmosphere.

Figure 7. Measured and analytically calculated polar diagram of the resonator's response, the right circle shows the ideal resonance polar diagram.

4. Crosstalk compensation and readout

Experimental resonator responses were found to match well with model predictions. However, the overall performance of the resonators was lower than expected, with a phase lag at resonance of only 18° for the 22.48 kHz device. This is primarily due to a relatively large feedthrough capacitance in the tested device, which obscures the electromechanical signal. It can be predicted that, as the system damping increases, the crosstalk stays almost constant but the resonance becomes weaker, to certain extent, the crosstalk and electrical noise will completely obscure the resonator's electromechanical signal finally, thus calling for crosstalk compensation.

Since the electrical crosstalk has no phase shift with respect to the input voltage (cf. equation (3)), a compensation technique can be developed, by minus one portion of the input voltage (which dummy equals to the crosstalk) from the resonator output, to extract the resonance signal. This technique is schematically shown in figure 8 a). A drive voltage $U_i$ is applied to the drive electrode, the bottom electrode is connected with a voltage $-kU_i$ from an inverted voltage amplifier, where $k$ is the adjustable
gain of the amplifier and theoretically equals $C_{ft}/C_s$. After the compensation of electrical crosstalk, a charge amplifier can be used to amplify the resonator output signal. Figure 8 b) shows a photograph of the compensation-readout circuit.

Further measurements of the device under different controlled pressures have carried out to investigate the efficiency of the proposed compensation solution. The device was measured in a vacuum chamber under back pressures ranging from atmospheric conditions ($\approx 1000$ mbar) down to low vacuum (0.1 mbar) obtained with a rotary vane pump. Figure 9 illustrates the measured resonator response without any circuit treatment under 1000, 100, 10, 1 and 0.1 mbar pressures. For comparison, Figure 10 shows the resonance signal after the circuit treatment using compensation. The output amplitude after electrical compensation is precisely symmetric around the resonance peak, and a phase shift of $-90^\circ$ occurs at resonance. From these two figures it can be seen that, the electrical crosstalk in the resonator has been adequately cancelled out and the quality of the resonator output signal is much improved.

Figure 9. (a) Measured amplitude and phase curves as well as (b) polar plots of original resonator output under 1000, 100, 10, 1 and 0.1 mbar pressures.
5. Conclusions

Micromachined resonator employing AlN active piezoelectric film has been designed and fabricated. Low resistivity SCS is used as resonating element, serving simultaneously as bottom electrode for the piezoelectric layer, to reduce the number of stacked layers and stress in the micro resonator. The elimination of the bottom metal electrodes, on one hand, reduces the number of stacked layers and stress in the cantilever; on the other, the short circuit connection between drive and sense port silicon grounds induces feedthrough capacitance effect which tends to obscure the resonator’s electromechanical signal. Electrical characterization of the resonator is performed and find that, the electrical performance of the resonator is degraded by the electrical crosstalk, since the crosstalk introduced “anti-frequency” peaks and heavily buried the mechanical resonance.

An equivalent circuit model describing the electromechanical behavior of the resonator was developed, with predicted performance matching well with experimental results. A compensation solution for crosstalk has been investigated, by the resonator output minus a dummy signal which equals to the crosstalk, to extract the resonance signal. It is electrically realized by using an adjustable inverted voltage amplifier to apply a compensation voltage to the SCS bottom electrode. This solution is very flexible with respect to individual precise adjustment. Further validation examples are investigated and the results demonstrate the accuracy of the proposed equivalent circuit modeling method and its efficiency of the proposed compensation solution.

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