

Parametric Amplification of Acoustically-Excited Micromechanical Oscillators Using Fringing Electrostatic Fields

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Summary. We present an experimental demonstration of parametric amplification of acoustically excited bulk micromachined single-crystal silicon cantilevers. We used electrostatic actuation by fringing fields for the parametric pumping of vibrational oscillations. The omnidirectional acoustic pressure served as a non-contact source for linear harmonic driving. We show that acoustic actuation is a convenient and versatile tool for dynamic characterization of micromechanical devices. This excitation method is suitable for wafer level dynamic testing, and could serve as an alternative to commonly used piezoelectric actuators. Our results suggest that this amplification approach may have applications in a wide variety of micromechanical devices, including resonant sensors, microphones and hearing aids.

Introduction

Parametric amplification plays an important role in resonant micro and nanoelectromechanical (MEMS/ NEMS) sensors due to its ability to increase the amplitude of vibrations and squeeze noise, thereby improving sensitivity [1-4]. In MEMS/NEMS structures parametric pumping of an external harmonic signal was demonstrated using electrostatic [1,2], piezoelectric [3] and magnetic actuation. The use of electrostatic actuation for direct harmonic driving [2] introduces a nonlinearity that alters the spectral characteristics of the structure. While integration of piezoelectric materials allows linear actuation and high vibrational amplitudes [3], the method requires deposition of additional layers, complicating the fabrication process. These layers may also induce undesirable residual stresses. To achieve parametric amplification in conjunction with a commonly used linear harmonic forcing by an external piezoelectric actuator [1,4], an additional electric signal is required at the electrode. In a laboratory environment, the piezo mounted devices cannot be electrically connected with micro manipulator probes. System testing requires wire bonding and packaging. Consequently, inertial excitation of micro structures is not suitable for wafer level testing.

In this work we use electrostatic forces associated with fringing fields for parametric pumping, and omnidirectional acoustic pressure as a source for non-contact linear harmonic mechanical excitation. In the MEMS/NEMS arena, investigations into the acoustic actuation were primarily motivated by the development of microphones and hearing aids [5]. Several groups have reported on resonant acoustic excitation of optical micro scanners [6] or micro cantilevers [7]. Here, we use acoustic fields for the mechanical excitation of a parametrically amplified device.

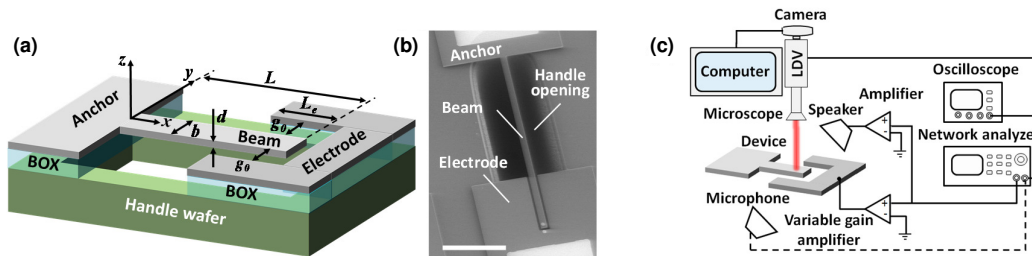


Fig. 1: (a) Schematics of the device. (b) Scanning electron micrograph of the fabricated device. The scale bar is $100 \mu\text{m}$. Measured dimensions of the structure are $L = 296.13 \pm 0.60 \mu\text{m}$, $b = 15.13 \pm 0.60 \mu\text{m}$, $L_e = 97.27 \pm 0.60 \mu\text{m}$, $g_0 = 5.61 \pm 0.60 \mu\text{m}$. The estimated measurement error was based on the pixel-to-micrometer conversion factor of the scanning electron micrographs and a one-pixel uncertainty in determining feature dimensions. (c) Schematics of the experimental setup.

Device Architecture

Our device [8] consists of a cantilever of a nominal (as designed) length $L = 300 \mu\text{m}$, width $b = 16 \mu\text{m}$ and thickness $d = 3 \mu\text{m}$, Fig. 1(a). A planar side electrode of length $L_e = 100 \mu\text{m}$ is located symmetrically at two sides of the beam, at a distance $g_0 = 5 \mu\text{m}$. To allow large unobscured vibrations in the out-of-plane (z) direction, an opening was created in the substrate under the beam. Since both the cantilever and the electrode are fabricated from the same wafer layer, due to symmetry, the resultant electrostatic force is zero in the initially undeformed configuration. In the deformed state, the distributed electrostatic force, arising from asymmetries of the fringing fields, acts in a direction opposite to the beam's deflection and serves as a restoring force. Application of a time-dependent voltage to the electrode results in a modulation of an effective stiffness and in parametric amplification of the beam. Using deep reactive ion etching (DRIE), cantilevers and electrodes were fabricated from a $\approx 3 \mu\text{m}$ thick single crystal silicon device layer using a silicon on insulator wafer. DRIE was used also to etch a cavity within the handle wafer. The devices were released using a vapor hydrofluoric acid process. A fabricated device is shown in Fig. 1(b).

Experimental Setup

The schematics of the experimental setup is illustrated in Fig. 1(c). The device was mounted on the chuck of a wafer prober. Using micro manipulator probes, the beam was set to ground with the electrodes set at a potential supplied by a voltage source. The cantilever was acoustically actuated by a speaker placed at a distance of ≈ 5 cm from the device. The sinusoidal, zero offset, voltage signal provided by a network analyzer was split into two channels. The first channel, connected to a fixed $\times 20$ gain amplifier, supplied to the speaker a peak-to-peak voltage signal (V_{spkr}) ranging from ≈ 3 V to ≈ 10 V. The second channel, connected to a variable gain (up to $\times 150$) voltage amplifier, supplied a signal to the electrode. The out-of-plane response of the beam was measured using a laser Doppler vibrometer (LDV) operated in a velocity acquisition mode. The output of the LDV was fed back into the network analyzer. The velocity time history of the LDV output was monitored by an oscilloscope. During our speaker calibration, the acoustic signal was monitored by a microphone. The measured resonant frequency of the speaker was $39.68 \text{ kHz} \pm 6.63 \text{ Hz}$ (mean \pm one standard deviation). The uncertainties were estimated from a Lorentzian functional fit to the measured spectra.

Results

First, the electrode was disconnected from the voltage source and vibrations of the beam were induced acoustically. Two resonant peaks were registered, associated with the speaker and the cantilever resonances, Fig. 2(a). To distinguish between the spectral outputs of the speaker and the beam, the re-scaled response of the speaker was subtracted from the LDV output, Fig 2(a). Acoustically excited amplitudes of the cantilever were estimated using the velocity time history (insert in Fig. 2(a)). In our frequency tuning, experiment, a harmonic voltage of $V_{spkr} \approx 5$ V was applied to the speaker. The signal frequency was swept from ≈ 43 kHz to ≈ 47 kHz for ≈ 25 s. Simultaneously, a steady-state dc voltage V_{dc} was applied to the electrode. We demonstrate that by applying a steady dc voltage the fundamental beam frequency can be tuned up to $\approx 2.5\%$, Fig. 2(b). Finally, voltage signals $V_{spkr} \cos(\omega t)$ and $V_{ac} \cos(\omega t)$ were applied simultaneously to the speaker and to the electrode, respectively. In this scenario, the beam undergoes direct harmonic acoustic forcing and parametric excitation by the electrostatic force. Since the electrostatic force is proportional to the square of the voltage, the parametric signal is at the frequency of 2ω and the case of a degenerate parametric pumping [1-4] is realized. Results shown in Fig. 2(c) indicate that the application of the electrostatic force at the voltage values below the parametric resonance threshold [3,4] allows amplification of the acoustically induced vibrations.

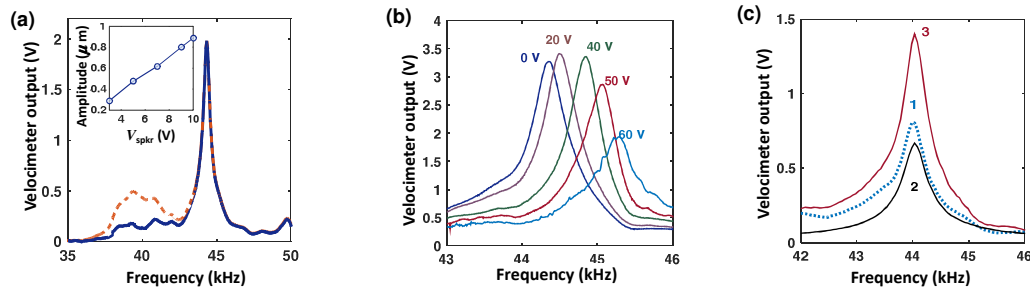


Fig. 2: (a) Frequency response of the beam excited by the speaker at $V_{spkr} \approx 9$ V before (dashed) and after (solid line) extraction of the microphone output. Two peaks at $39.61 \text{ kHz} \pm 6.63 \text{ Hz}$ and $44.34 \text{ kHz} \pm 1.98 \text{ Hz}$ correspond to the speaker's and to the beam's resonances, respectively. Insert shows the beam's resonant amplitude at different V_{spkr} . The amplitude uncertainty, estimated by sinusoidal fitting to the time history data is 15 nm. (b) Frequency response of the beam at different values V_{dc} (numbers) of the voltage applied to the side electrode; speaker voltage is $V_{spkr} \approx 5$ V. (c) Parametric amplification: 1 – acoustic excitation; 2 – electrostatic excitation; 3 – combined acoustic and electrostatic excitation. $V_{spkr} \approx 600 \text{ mV}$, $V_{ac} \approx 30 \text{ V}$.

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