The Micronium—A Musical MEMS Instrument

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***Abstract*—The Micronium is a musical instrument fabricated from silicon using microelectromechanical system (MEMS) technology. It is—to the best of our knowledge—the first musical micro-instrument fabricated using MEMS technology, where the actual sound is generated by mechanical microstructures. The Micronium consists of mass-spring systems that are designed to resonate at audible frequencies. Their displacement is measured by comb drives and is used as the audio signal to drive a loudspeaker. The instrument's sounds are pure sine waves. An extensive set of measurements of individual resonators is presented and discussed. Quality factor measurements at various ambient pressures show that an ambient pressure of 1 mbar results in a note duration of 1 s. The realized frequency deviates considerably from the designed resonator frequency. Measurement results of many resonators are shown to obtain understanding of this deviation. Initial experiments with electrostatic tuning using variable-gap comb drives show a tuning ratio of 5% maximum, depending on the resonator frequency. An audio recording of the instrument is included as a supplementary MP3 file. [2011-0246]**

***Index Terms*—Capacitive displacement sensor, musical instrument, tunable resonators.**

I. Introduction

IN 1997, researchers at Cornell University fabricated the world's smallest guitar, about the size of a human blood cell [1]. Two years later, a microharp was reported by Carr *et al.* [2]. In 2003, laser light was used to strum the "strings" of a nanoguitar [3]. However, no human has heard the sound of these instruments; the strings vibrate at frequencies on the order of tenths of megahertz.

A patent by Yamaha Corporation filed in 1994 describes the use of microelectromechanical system (MEMS) resonators for harmonic synthesis in electronic musical instruments [4]: mechanical resonators produce high-frequency signals that are electronically down-converted to the audio frequency range.

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The paper has supplementary downloadable material, provided by the authors, available at http://ieeexplore.ieee.org, consisting of an MP3 audio recording of the Micronium's performance of "Impromptu No. 1 for Micronium" at the Micromechanics and Microsystems Europe 2010 workshop. The size of the MP3 file is 3.5 MB.

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

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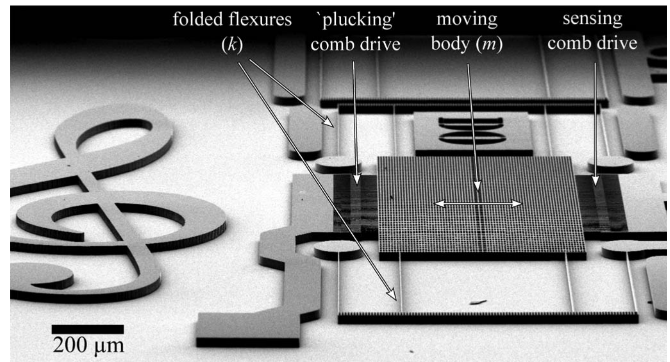

Fig. 1. Scanning electron micrograph of a resonator that generates sound at audible frequencies. The perforated structure is the moving body (mass m), suspended by folded flexures on both sides. The mass is "plucked" by a comb drive on one side, and the mass's displacement is measured by a comb drive on the other side.

We have not found more detailed reports or measurements on Yamaha's design. It is also unclear whether this method has been employed in products. In contrast to Yamaha's design, we have designed a purely mechanical musical MEMS instrument, the *Micronium*, with mechanical resonators at audible frequencies, using electronics only to amplify the mechanical motion. The Micronium consists of micromechanical mass-spring resonators that vibrate at audible frequencies. The resonators are "plucked" using electrostatic comb-drive actuators (see Fig. 1). The resonators generate sound at audible frequencies; however, human ears are not sensitive enough. The instrument's vibrations are sensed by capacitive displacement sensors using comb structures as sensing elements. The measured capacitance change is amplified to drive a loudspeaker. Effectively, the loudspeaker motion is equal to the resonator motion amplified many times. In order to reduce the damping by air, the instrument is placed in a vacuum chamber at around 1-mbar pressure. A control keyboard is used to trigger actuation of the comb drives that "pluck" the resonators.

Because the Micronium generates its sounds mechanically, it has special appeal to musicians. For example, it makes sounds when it is hit (all resonators start vibrating), in contrast to electronic instruments. Both the location and manner in which the instrument is hit determine the sound, which inspired one musician to attempt to "play" the Micronium simply by hitting the vacuum chamber instead of using the control keyboard.

The Micronium was presented during the opening ceremony of the Micromechanics and Microsystems Europe workshop, where it played "Impromptu No. 1 for Micronium" [5]; an audio recording of this performance is included as a supplementary MP3 file, available at http://ieeexplore.ieee.org. In addition to making music, the Micronium finds fruitful application in demonstrating MEMS technology to a very broad audience.

First, the theoretical design of the instrument is explained, followed by fabrication details and characterization of the instrument. An extensive set of measurements of individual resonators is presented and discussed, providing valuable information for future musical MEMS instrument designs.

II. Theory and Design

The Micronium consists of individual resonators for each note, similar to a xylophone. A resonator, shown in Fig. 1, is a mass that is suspended by folded flexure springs, such that the mass is restricted to move in one direction. The resonance frequency depends on the mass m and the spring stiffness k of the folded flexure suspension; by adjusting the length of the springs and the width of the mass, each resonator is designed to resonate at a specific note frequency within the C-major scale (the white keys on a piano).

Each resonator is actuated ("plucked") by a comb drive on one side of the mass, slowly pulling the mass to one side and then releasing it so it starts oscillating. The comb drive on the other side of the mass is then used to measure the displacement by measuring the comb-drive capacitance. The measured change in capacitance is amplified and is used to drive a loudspeaker to make the resonator vibration audible to humans.

It is important to note that the actuating comb drive only briefly "plucks" the resonator and does not drive the resonator with, e.g., a sine wave. A single comb drive could be used to both actuate and sense the resonator; however, this would considerably complicate the measurement circuitry.

A. Resonator Theory

Each resonator behaves according to the well-known differential equation

$$m\frac{d^2x}{dt^2} + \gamma\frac{dx}{dt} + kx = F_{\mathrm{comb}} \tag{1}$$

where m is the mass of the resonator, x the displacement, γ the coefficient of viscous damping by air, k the suspension spring constant, and F_{comb} the comb-drive force. The solution of (1) is the expected comb-drive displacement x after excitation,

$$x(t) = Ae^{-\alpha t}\cos(2\pi f_1 t) \tag{2}$$

with amplitude A and damping $\alpha = \gamma/2m$, assuming a release with zero initial velocity and acceleration. The free resonance frequency f_1 for an underdamped system is

$$f_1 = \frac{1}{2\pi}\sqrt{\frac{k}{m} - \alpha^2} \approx f_0\left(1 - \frac{1}{8Q^2}\right) \tag{3}$$

with $2\pi f_0 = \sqrt{k/m}$, and $Q = \pi f_0/\alpha$. The approximation is correct for low damping. Tailoring the mass and spring constant, resonators with different resonance frequencies are made. In order to obtain resonance frequencies in a range from 440 Hz to 1400 hertz, large structures are needed compared with common MEMS structure sizes: the spring lengths range from 0.5 mm to 0.9 mm and the mass areas range from 0.6 mm^2 to 1 mm^2.

The duration of a note after being excited/struck is proportional to the quality factor Q and inversely proportional to the resonance frequency. A piano string has a quality factor much larger than 1000. It is hard to obtain high quality factors for MEMS structures because of unfavorable scaling laws. For a mass-spring-damper-system resonator, the quality factor equals

$$Q = \frac{\sqrt{mk}}{\gamma}. \tag{4}$$

When the dimensions of the mass are scaled with an arbitrary factor l, the mass scales cubically, $m \propto l^3$. The spring constant should scale proportionally to the mass in order to maintain the same resonance frequency, hence $k \propto m$. The viscous damping is proportional to the area of the mass, $\gamma \propto l^2$. Consequently, the quality factor scales with l; reducing the dimensions of the system results in a proportionally reduced Q-factor. In general, at equal resonance frequencies, a smaller mass-spring oscillator will experience more damping and will sound a shorter note than a larger oscillator. To solve this issue of small MEMS instruments, we decrease the air damping γ by placing the instrument in a vacuum chamber. Ambient pressures below 2 mbar significantly increase the Q-factor, because the mean free path of the air molecules becomes larger than the gap sizes of our resonators [6].

B. Instrument Design

The instrument design consists of 24 resonators at 12 different frequencies, two resonators for each frequency, spread across four 7 mm × 7 mm chips. The instrument is designed such that the notes form part of a C-major diatonic scale (the white keys on a piano: C, D, E, F, G, A, and B). Note A of the fourth octave on a modern 88-key piano, called A4, is tuned to 440 Hz [7]. The note frequencies follow from:

$$f(n) = 2^{\frac{n}{12}} \times 440 \text{ Hz} \tag{5}$$

with $n \in \{0, 2, 3, 5, 7, 8, 10, 12, 14, 15, 17, 19\}$ indicating the number of semitones above A4 [7]. A semitone is the musical interval between two adjacent notes on a piano, for example between C and C$^\sharp$.

The general layout of an instrument chip is shown in Fig. 2. Both the suspension spring stiffness k and the moving body mass m of the resonators are adjusted to obtain the desired resonance frequencies. The spring stiffness of the folded flexure suspension equals [8]

$$k = \frac{2Ehb^3}{L^3} \tag{6}$$

where E is the effective Young's modulus of silicon, h the spring height, b the spring width, and L the spring length. The effective mass of the resonator m_{eff} is equal to the moving body mass, including comb-drive fingers, plus the folded flexure truss mass, neglecting the mass of the spring beams. Because the folded flexure trusses move only half the distance of the moving

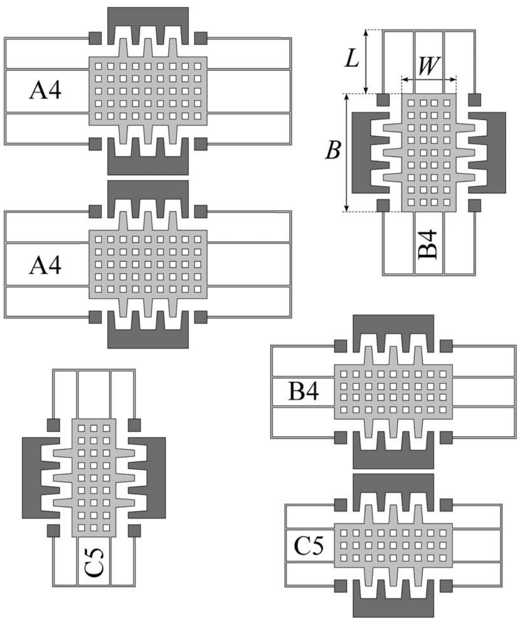

Fig. 2. Layout of the 7 mm × 7 mm instrument chips (not drawn to scale). Six resonators fit on one chip. Four chip types are designed to fit 12 different note frequencies: chips c_1, c_2, c_3, and c_4 contain notes (A4, B4, C5), (D5, E5, F5), (G5, A5, B5), and (C6, D6, E6), respectively. The comb drives and length B are equal for all resonators, only the spring length L and mass width W are varied to tune the resonance frequencies. All structures have a height h of 50 μm, and the used spring width b equals 3 μm.

body, only half their mass contributes to the effective mass. The moving body and trusses need to be perforated because of the used fabrication process. The perforation consists of 5 μm × 5 μm squares with 3 μm silicon beams in between. This results in an area reduction R_{perf} of approximately 0.6

$$R_{\mathrm{perf}} \approx \frac{8^2 - 5^2}{8^2} \approx 0.6. \tag{7}$$

The moving body has height h, width W, and length B. Referring to Fig. 2, $B = 1.2$ mm is fixed for all resonators, and W is adjusted. The area of a perforated truss A_{truss} is equal to 32 μm × (W + 333 μm). The total area A_{fingers} of the comb-drive fingers on both sides of the resonator equals 3.84×10^{-8} m. We find for the effective mass

$$m_{\mathrm{eff}} = \rho_{\mathrm{Si}} h \cdot \left[A_{\mathrm{fingers}} + R_{\mathrm{perf}}(WB + A_{\mathrm{truss}})\right]. \tag{8}$$

The layout of the instruments chips is shown in Fig. 2. The 50 μm thick device layer of the silicon-on-insulator wafer used in the fabrication process determines height h of the comb drives, springs, and masses. The smallest trench that can be etched is 3 μm wide, defining the gap g between comb-drive fingers. Each comb drive contains 60 finger pairs, and the initial overlap x_0 equals 30 μm. The spring width b is 3 μm, which is the smallest beam width that can be fabricated reliably. The mass width W and spring length L of the resonators are listed in Table I.

C. Capacitive Read-Out

By measuring the capacitance of a comb drive connected to the mass, the displacement of the mass is determined. The

TABLE I
DESIGN TARGET FREQUENCIES f_0 OF THE INSTRUMENT NOTES AND THE RESULTING DESIGN PARAMETERS FOR THE SPRING LENGTH L AND MOVING BODY SIZE W. THE PARAMETERS ARE ROUNDED TO INTEGER MICROMETERS, THEREFORE, THE TARGET FREQUENCIES DEVIATE (±0.05% OR LESS) FROM THE IDEAL FREQUENCIES $f(n)$ GIVEN BY (5)

Note	f_0 (Hz)	W (μm)	L (μm)
A4	440.1	846	910
B4	493.9	845	843
C5	523.3	702	859
D5	587.4	700	796
E5	659.3	700	737
F5	698.7	700	709
G5	784.0	551	706
A5	879.7	551	654
B5	987.9	552	605
C6	1047.0	552	582
D6	1174.7	552	539
E6	1318.8	552	499

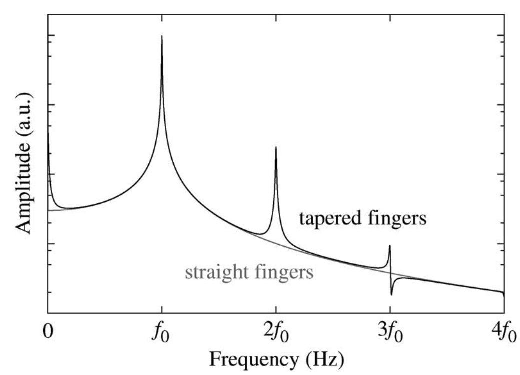

Fig. 3. Fourier transform of the simulated capacitance of comb drives with straight and tapered fingers for an exponentially decaying sinusoid displacement. The nonlinear capacitance versus displacement of tapered fingers gives rise to higher harmonics proportional to the sinusoid displacement amplitude.

measured capacitance is used as the audio signal. In addition to ease of fabrication, the use of a comb drive allows us to adjust the timbre of the note, by modifying the comb-drive finger shape. For straight comb-drive fingers, the capacitance is proportional to the displacement [8]. However, the capacitance of a comb drive with tapered fingers depends nonlinearly on the displacement x

$$C_{\mathrm{tapered}} = 2N\epsilon_0 h \frac{x + x_0}{g - (x + x_0)\tan\theta} \tag{9}$$

where N is the number of fingers, h is the comb-drive height, x_0 and g are the initial overlap and gap between fingers, respectively, and θ the angle of the tapering [9]. This nonlinearity gives rise to higher harmonics in the audio signal, resulting in a more interesting tone. The upper bound on the angle θ is set by fabrication limits; for maximum effect, the maximum angle of $\theta = 0.72°$ is used in our designs, such that the reduced gap between fingers can still be reliably fabricated. The angle is small because of the relatively large overlap x_0 between combs. Fig. 3 shows the Fourier transform of the simulated capacitance of straight and tapered fingers using (2) for a sinusoidal displacement x. In addition to the fundamental, higher harmonics are present in the capacitance of the tapered fingers. The relative amplitude of the higher harmonics depends on the displacement amplitude A. Although the addition of higher harmonics by a modified comb-drive finger shape defeats the goal of purely mechanical tone generation, it may be desirable to give the instrument a more interesting musical character (the relative strengths of higher harmonics give instruments their unique sound).

D. Tuning

Two methods of tuning the resonance frequency are softening the suspension stiffness by lowering its Young's modulus by heat and reducing the effective spring constant by applying a dc offset voltage on the comb drives that induces a negative "electrostatic stiffness."

Thermally tuning the resonance frequency of resonators takes advantage of the temperature dependence of the Young's modulus and the thermal expansion of silicon [10], [11]. Heating the springs by running an electrical current through them, the Young's modulus is decreased [12], resulting in a lower resonance frequency. Silicon expands when heated, which can induce compressive or tensile strain, depending on the geometry, leading to a change in resonance frequency [10]. Initial experiments on the Micronium's resonators indicate that the resonance frequency can be decreased by 5% in air. Cooling by convection of the surrounding air, and therefore the tuning result, depends on the ambient pressure [10]. Currently, the chip design and measurement setup are unsuited for electrothermal tuning experiments, and no experiments have been done at 1 mbar yet.

An electrostatic spring stiffness can be created by applying a constant offset voltage on the comb drives. The effective spring constant k_{eff} is equal to the derivative of the total force on the mass with respect to x. When a constant voltage is applied on one of the comb drives, the effective spring constant is equal to

$$k_{\text{eff}} = \frac{\partial F}{\partial x} = k - \frac{1}{2}\frac{\partial^2 C}{\partial x^2}V^2. \tag{10}$$

For straight comb-drive fingers, $\partial^2 C/\partial x^2$ vanishes. However, the tapered finger shape used in our instrument results in an electrostatic force that is a function of position, and the effective spring constant becomes a function of applied voltage V and x

$$k_{\text{eff}} = k - \epsilon_0 NhV^2\left(\frac{2\tan\theta}{(g-(x+x_0)\tan\theta)^2}\right) + \epsilon_0 NhV^2\left(\frac{2(x+x_0)\tan^2\theta}{(g-(x+x_0)\tan\theta)^3}\right). \tag{11}$$

At a constant voltage, the electrostatic force increases for increasing x, corresponding to a negative nonlinear spring constant, decreasing the resonance frequency of the resonator. Note that, because the effective spring stiffness depends on x, the exact frequency decrease depends on the amplitude of motion. Moreover, the nonlinear spring stiffness may introduce harmonics. Because k is larger for resonators at higher frequencies than for resonators at lower frequencies, and because the electrostatic spring stiffness change is additive, the relative frequency decrease at equal offset voltage will be lower for resonators at high frequencies.

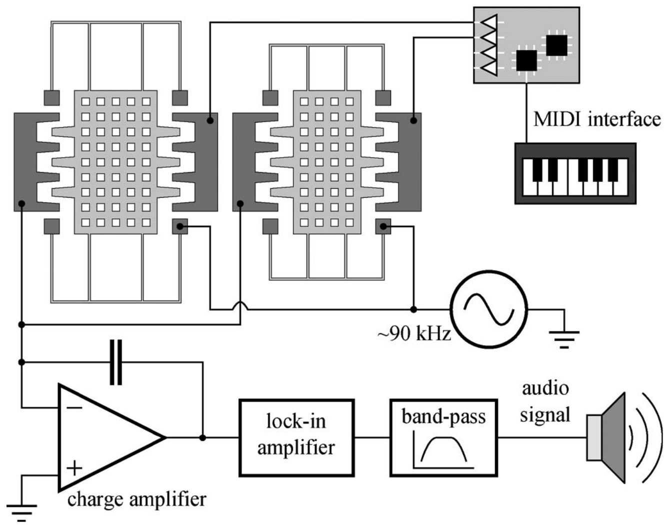

Fig. 4. Simplified drawing of the used measurement setup. The displacement of a resonator is measured from the comb-drive capacitance, using a charge amplifier circuit and lock-in amplifier. In total, 12 resonators are connected in parallel to one charge amplifier circuit (only two resonators are drawn). The resonators are actuated by high-voltage amplifiers that are controlled through a MIDI interface.

III. Fabrication Details and Measurement Setup

The instrument chips are fabricated from one (1 0 0) single-crystal highly boron-doped silicon-on-insulator wafer, with a 50 μm thick device layer and an oxide thickness of 3 μm. The structures are made by deep reactive-ion etching (DRIE) [13]–[15], after which the (movable) structures are released by HF vapor phase (VHF) etching [16] of the oxide layer. The VHF etching is isotropic and also etches oxide under the structures. The resonator masses have large areas and require perforation in order to release them. The VHF etch time is tuned such that thin beams and perforated structures are released, and large (unperforated) structures are not.

The measurement setup, partly shown in Fig. 4, consists of two charge amplifiers [17], each sensing 12 resonators in parallel, two lock-in amplifiers (Stanford Research Systems SR830), and an additional amplifier with bandpass filter. The output of the bandpass filter is used as audio signal and is connected to an amplifier with a loudspeaker, or to a microphone input of a PC soundcard for measurements. The sine waves used for sensing the capacitance changes with the lock-in amplifiers have a frequency around 90 kHz with an amplitude around 400 mV; the precise values are chosen such that audible noise, which is partly due to external disturbances and therefore varies for each venue, is minimized. The charge amplifiers function best at high frequencies, and the measurement frequency is therefore chosen close to the 100-kHz bandwidth of the lock-in amplifiers.

The resonators are actuated by a programmable microcontroller that controls D/A-converters followed by high-voltage amplifiers. At rest, the applied voltage is zero. A note is

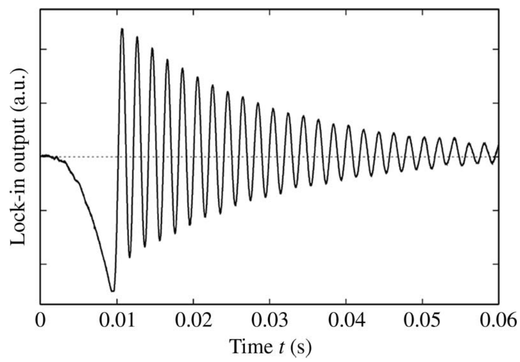

Fig. 5. Recorded lock-in output signal of an "A4 resonator" at an ambient pressure of 37 mbar upon pressing the keyboard key. The negative ramp at the start shows the "plucking" of the note, pulling the resonator back before it is released (remember that the lock-in output is approximately equal to the resonator displacement). The actuation voltage ramp stops just before 10 ms, and the resonator starts oscillating according to (2).

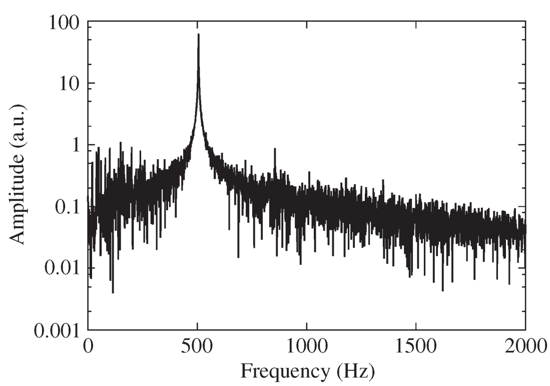

Fig. 6. Fourier transform of the audio signal of an "A4 resonator," showing one resonance peak (506 Hz). There is no visible effect of the nonlinear capacitance versus displacement of the tapered comb-drive fingers.

"plucked" by ramping the applied voltage in several milliseconds up to the actuation voltage V_{act} and subsequently rapidly reducing the applied voltage back to zero. The ramp prevents sounding a note upon the increase of the applied voltage. This "plucking ramp" simulates manually pulling back the resonator and releasing it, similar to plucking a string, as can be seen at the start of the audio signal in Fig. 5. The height of the actuation voltage V_{act} is determined by the velocity parameter received in the MIDI messages from the MIDI keyboard; the harder a key is pressed on the keyboard, the larger V_{act} and the louder the note will sound. The value for V_{act} is limited by the snap-in voltage of the most compliant resonator. A maximum value of 29 V is sufficiently far from this limit.

IV. Results

Fig. 5 shows a recorded lock-in amplifier output signal of an "A4 resonator." As expected from (2) and (9), the signal is a decaying sine wave. The Micronium's sounds are very pure. The Fourier transform of the audio signal from an "A4 resonator" is shown in Fig. 6. There is only one sharp peak visible, at 506 Hz. The signal contains no higher harmonics.

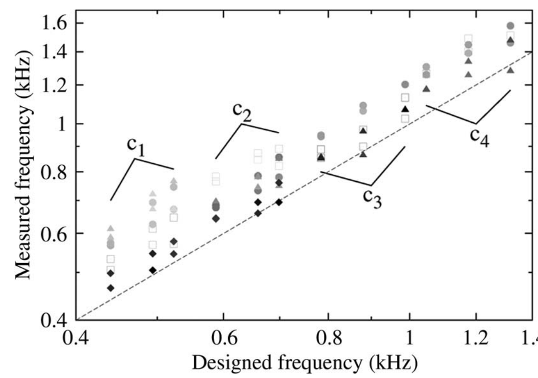

Fig. 7. Measured resonance frequencies of 83 resonators versus their designed resonance frequencies, all from the same silicon wafer. Note that the x and y axes are logarithmic. The dashed line shows when the measured frequency equals the design. Within a group c_i, equal symbols are used for resonators from the same chip. The open squares represent the 24 resonators used in the Micronium. The grayscale value indicates the distance to the center of the wafer for each resonator; resonators with darker points lie closer to the center, see Fig. 8.

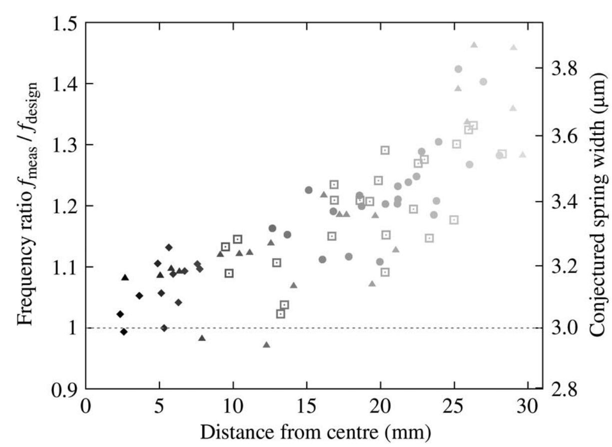

Fig. 8. Ratio of measured and designed resonance frequencies from Fig. 7, as a function of distance from the center of the wafer. A larger than designed spring width would result in a higher resonance frequency. The right y-axis indicates the spring width corresponding to the frequency ratio on the left y-axis.

The measured resonance frequencies of 83 resonators from 14 chips are shown in Fig. 7. For each design frequency, there is a large spread in measured frequencies. Almost all resonators resonate at a higher frequency than their design predicts (up to 5 semitones higher).

Fig. 8 shows the data from Fig. 7, plotting the ratio between the measured and designed frequency as a function of distance from the center of the wafer. On average, the resonance frequency is 18% higher than expected. Resonators that are closer to the center of the wafer deviate less from the design than resonators that lie farther from the center. The increase in frequency is explained by a larger than designed spring width. Scanning electron microscope (SEM) measurements on the springs show very strong tapering for chips far away from the center of the wafer. For example, an "A4 resonator" at 25 mm distance from the center with a 1.4 times increased frequency has a spring width of 2.8 μm and 4.4 μm at the top and bottom, respectively. To estimate the extent of the tapering, the right

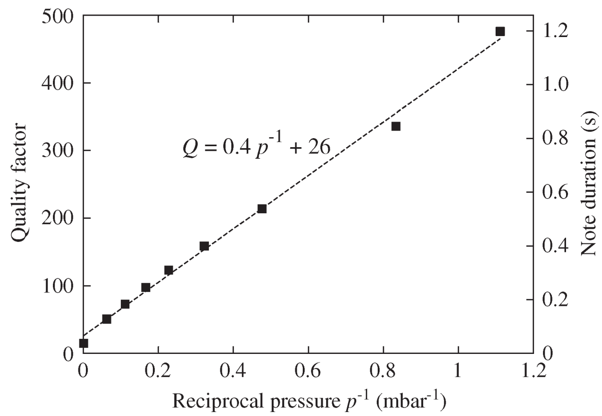

Fig. 9. Quality factor measurements of an "A4 resonator" (506 Hz) at different pressures. The quality factors are obtained from fitting an exponentially decaying sinusoid to the measured audio signal. The dashed line fits the data with $Q(p) = ap^{-1} + b$, where $a = 0.40(1)$ and $b = 26(5)$. The right y-axis indicates the apparent note duration $(4\alpha^{-1})$.

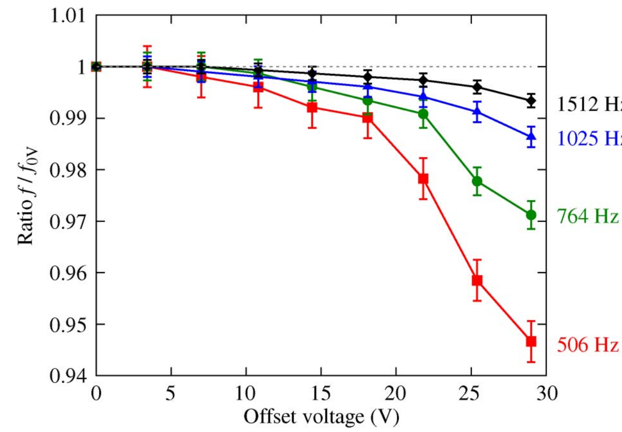

Fig. 10. Ratio between the resonance frequency with an applied offset voltage on the plucking comb drive and the resonance frequency without offset voltage, for four resonators. The resonance frequency without offset voltage is indicated on the right next to each graph. The lines connecting the measurement points are guides to the eye.

y-axis in Fig. 8 indicates the spring width corresponding to the frequency ratio on the left y-axis, if a rectangular spring cross-section is assumed and all other parameters are kept constant. Note that because of the tapered geometry, the actual average spring width is smaller than this conjectured spring width.

The damping α and quality factor Q are determined by fitting an exponentially decaying sinusoid to the audio signal; Fig. 9 shows the quality factor of an "A4 resonator" for different ambient pressures. The apparent note duration can be approximated by $4\alpha^{-1}$ and is proportional to the quality factor. Without the vacuum chamber ($p = 1$ bar), only a very brief oscillation of less than 20 ms was measured. The duration of the note is greatly increased at a reduced pressure. The quality factor and note duration are proportional to the reciprocal of the ambient pressure, on the investigated range from 1000 mbar to 1 mbar. A close linear fit to the measurements can be made with $Q(p) = ap^{-1} + b$, where $a = 0.40(1)$ bar and $b = 26(5)$.

Tuning of the resonance frequency is measured by applying a constant offset voltage V_{offset} on the plucking comb drive. The actuation signal on the plucking comb drive is modified to incorporate the offset voltage. The modified plucking signal starts at V_{offset}, is ramped up to 29 V in several milliseconds, is rapidly decreased to zero, and finally after 11 ms, it is set back to V_{offset}. No offset is applied to the sensing comb drive. Fig. 10 shows measurements of the resonance frequencies of four resonators as a function of the applied offset voltage on the plucking comb drive, relative to the resonance frequency without offset voltage. Applying an offset decreases the resonance frequency; a decrease of more than 5% is obtained for the 506-Hz resonator at 29 V. The relative decrease depends on the original resonance frequency: the higher the resonance frequency, the smaller the relative decrease.

V. Discussion

The Micronium has a very clean and pure sound. The Fourier spectrum of the audio signal of each resonator shows one large and sharp peak. Although the capacitive read-out of the resonator displacement is nonlinear, the displacement amplitude is not large enough for higher harmonics to appear in the audio signal. Early measurements using a pulsed excitation and with a larger displacement amplitude did show a higher harmonic at double the resonance frequency. For reliability reasons, the excitation waveform was changed to the ramped shape reducing the displacement amplitude. Simulations confirm that the presence of harmonics is strongly influenced by the displacement amplitude. The displacement amplitude is determined by the maximum allowed ramp voltage that must be chosen sufficiently below the snap-in voltage. In addition to electronic instruments, we did not find other musical instruments that generate pure sine waves without harmonics. Although a xylophone generates many harmonics, many people find the Micronium to sound similar to a xylophone.

Because the resonator frequencies deviate from their design, more notes can be played than the designed 12 notes (24 resonators, indicated by open squares in Fig. 7). By carefully selecting the closest note for each resonator frequency, the instrument can play 16 notes spanning almost two octaves (C to A) that are reasonably in-tune without tuning. The eight unused resonators are either close to notes that are already represented by the 16 chosen resonators, or are too much out-of-tune. On the instrument's range from C to A, six notes are missing (low octave: F, F$^\sharp$; high octave: C$^\sharp$, D$^\sharp$, F, G$^\sharp$). The available notes allow many tunes to be played on the Micronium.

The note duration is proportional to the reciprocal of the ambient pressure on the investigated range, in qualitative agreement with Okada *et al.* [6, eq. (7)]. A piano-like sustain pedal could be simulated by controlling the pressure from 10 mbar to 1 mbar or lower. The note durations are different for each note. In order to equalize the durations, control of the quality factor of individual resonators is required, in contrast to the "global" control by modifying the ambient pressure. While the ratio of k and m is fixed for each resonator, the product of k and m can be tailored for a desired quality factor [see (4)]. The perforation geometry of the resonator bodies influences the damping by air [6]. This effect can be used to tailor the note duration of individual notes, by carefully choosing different perforation geometries and ratios during design.

The increase in resonance frequency from the designed frequency is larger for resonators that are farther from the center of the wafer. This is mainly caused by a strongly tapered spring cross-section resulting in a larger than designed spring width. Because the springs are only 3 μm thin and the spring stiffness depends on the cube of the width, the resonance frequency is very sensitive to the obtained spring width and the etch profile (compared to a change in spring length or mass area). The etch rate at the center of the wafer is higher than on the periphery, explaining the larger spring width for resonators farther from the center (see Fig. 8). These deviations can be solved by optimizing the fabrication process and taking the spring tapering into account during design. However, because of intrinsic uncertainties in fabrication, particularly the DRIE process, there remains a large uncertainty in the resonance frequencies after fabrication. Resonators of exactly equal design and positioned next to each other on the wafer have resonance frequencies that differ by as much as 18%. To obtain a playable instrument, either measuring and choosing a specific resonator for each note, or tuning of the resonators is necessary.

Note in Fig. 2 that the A4 resonators have the same orientation, in contrast to the B4 resonators and the C5 resonators. Resonators from the same chip with the same orientation (the first column in each group c_i in Fig. 7) generally show less spread than resonators from the same chip but with different orientation (the second and third columns in each chip type c_i in Fig. 7). Also, the spread in obtained resonance frequencies seems independent of the designed frequency or distance from the center of the wafer. However, more statistical data are required to draw conclusions regarding these observations of the frequency spread.

There are several methods of tuning the resonance frequencies, but the setup only allowed tuning by applying an offset voltage on the plucking comb drive. The tapered finger shape leads to a nonlinear electrostatic spring stiffness; the effective spring stiffness with an offset voltage decreases for increasing displacement. This means that for a sustained note, the frequency should increase as the volume decreases. This effect, however, is small and has not been heard during the measurements. The larger relative decrease in frequency for low notes than for high notes, seen in Fig. 10, is explained by the additive character of the electrostatic spring stiffness change ($k = k_{\mathrm{springs}} + k_{\mathrm{electrostatic}}$). The maximum tuning voltage is limited by sideways pull-in, limiting the tuning range. For the lowest note (506 Hz) a 5% lower frequency was obtained. However, for a high note at 1512 Hz, less than 1% change was obtained at an equal offset voltage. Because a 6% decrease in frequency corresponds to one semitone, a tuning range of 6% is desired in order to tune the resonator's frequency precisely to the nearest piano note frequency.

Large permanent frequency adjustments can be realized through mass fine-tuning performed by depositing additional material on the moving body. Another possible tuning method is to electrostatically pull on the folded-flexure trusses in the direction perpendicular to motion, similar to the "axial tuning" proposed by Yao and MacDonald [18]. Because the trusses move inward (in the direction of the mass) when the mass is displaced, pulling the trusses outward will increase the resonance frequency. Because there is no snap-in possibility, very high voltages can be used with this method.

VI. Conclusion

We successfully designed and realized a musical instrument using MEMS technology that resonates at audible frequencies. The generated tones are decaying sine waves without higher harmonics and sound similar to a xylophone. Viscous damping by air is relatively large for microresonators at audible frequencies, resulting in a short tone. A vacuum around 1 mbar is required for a note duration around 1 s. The frequencies of the fabricated notes are higher than expected (18% on average, but up to 46%), and there is a spread of up to 5 semitones ($\sim$34%) in obtained frequencies between resonators with identical designs. The frequency increase is larger for resonators farther from the center of the wafer, indicating that the increase is caused by thicker than designed springs. The instrument notes' frequencies can be tuned down by applying a constant offset voltage on the plucking comb drive. The frequency of the lowest note (506 Hz) can be decreased by 5% (almost one semitone). More research is needed to increase the tuning range, particularly for the higher frequencies.

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