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A micromachined voltage controlled oscillator using the pull-in mechanism of electrostatic actuation

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Abstract: This study presents a microelectromechanical voltage controlled oscillator based on the pull-in electromechanical contact of an electrostatic actuator. Micromachining process of nickel electroplating on a silicon substrate was used to develop an electrostatic torsion plate mechanism (200 μm × 200 μm in area, 15 μm in thickness) that could be mechanically movable (0.1 rad) by the electrostatic torque of applied voltage. An electromechanical stopper was designed underneath the movable plate such that the effective drive voltage was discharged upon the electrostatic pull-in contact. Peripheral electrical circuits were designed to compose a ring oscillator, in which the temporal response of electrostatic mechanism determined the oscillation frequency. The frequency became tunable as a function of the drive voltage. Frequency tuning range of 4.39∼9.6 kHz was experimentally observed using the control voltage of 7.4∼10.6 V.

Keywords: MEMS, voltage controlled oscillator, electrostatic actuator, pull-in
Classification: Micro- or nano-electromechanical systems

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1 Introduction

MEMS (microelectromechanical system) resonators are under intensive research and development for the compatibility with the silicon microelectronics technology and are replacing the quartz resonators upwards of several hundreds MHz [1]. Silicon resonator array of multiple frequency bands or of frequency tuning capability are also under development for potential applications in the multi-band mobile phone system in the GHz range [2]. Most of those MEMS resonators today use the electrostatic coupling for mechanical excitation and detection thanks to the simplicity of mechanism but the small electrical current associated with the faint capacitance change, which generally decreases with reducing the physical dimensions of resonator, needs a delicate current amplifier based on the high-speed analog circuit technology. Microelectromecanical resonators of lower frequency range in the order of kHz, on the other hand, have potential applications such as an optical bar-code scanners and spatial light modulator within the endoscope sensor heads [3]. It also requires electrical circuit that is usually composed by using external discrete capacitors.

In a view to compose a MEMS oscillator without deploying a complicated drive/detection circuits, frequency transition phenomena based on the electrostatic pull-in have been investigated [4]. A simple electrostatic cantilever was electrically biased to induce mechanical deflection, and was released upon the electrostatic pull-in contact onto the discharge electrode; the electromechanical process was repeatedly continued as long as the cantilever was electrically biased. A significance of this work was a potential to bring a MEMS device to be a core component within the contemporary microelectronics. However, it has been questioned about the stability of the frequency and the accessibility to tap the electrical signal. The cantilever oscillation was governed by the stray-capacitance of the micromechanical structure made

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in the SOI (silicon-on-insulator) layer, and extracting the current from the oscillating microstructure was also found to alter the time constant of the oscillation.

We have recently developed a novel approach of MEMS self-oscillating circuitry based on the electrostatic pull-in mechanism. A simple CMOS (complimentary metal-oxide-semiconductor) digital buffer and level-shifter circuits were used to detect the electrostatic pull-in contact and to sustain the electromechanical oscillation in the ring-oscillator loop. In this letter, we report the structure and the fabrication of the CMOS-compatible MEMS resonator, and give results of the voltage-controlled oscillator (VCO) operation.

2 Self-oscillation based on electrostatic pull-in

The structure of the micromachined VCO is composed of an electrostatic torsion plate, a pair of torsion beams, and a set of electrical CMOS circuit of the pull-in detector and the voltage level-shifter as shown in Figure 1. At the initial condition, where no voltage is applied to the drive electrode, the contact electrode (also as a mechanical stopper) at the circuit node A is free from the torsion plate. Upon throwing in the power to the circuitry, the voltage at node A is elevated to high due to the pull-up voltage V_{dc} through the external resistor $R_{external}$. This makes a high level of the inverter output at node C, and the drive electrode is positively charged by the level-shifter output. The applied voltage makes the electrostatic attractive torque on the torsion plate, which is fully brought into the contact electrode. At this moment, the potential at node A is pulled down to the electrical ground level

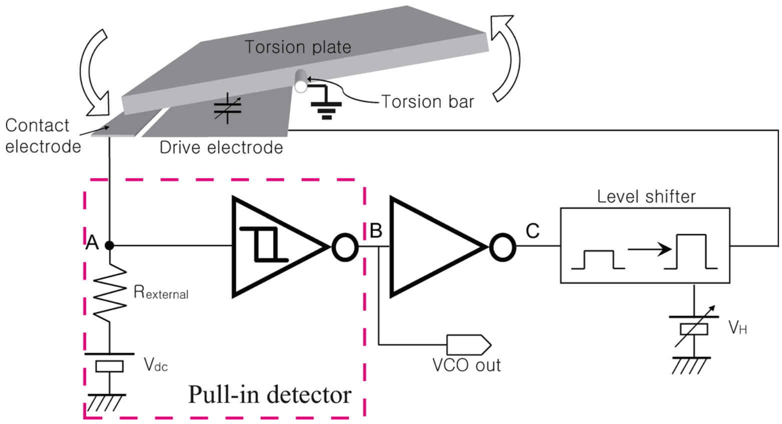

Fig. 1. Schematic drawing of a ring oscillator with a level-shifter. The motion of the torsion plate is detected by the pull-in contact of the pull-up voltage, and inversely amplified to the drive voltage. Oscillation frequency is controlled by the transient rising time of the electrostatically driven plate, i.e., by the output voltage level of the level shifter, V_H. Output frequency is tapped from the output of the Schmitt triggered inverter (node B).

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through the torsion plate that is electrically grounded at the anchor. This triggers the lowering of voltage at node C, and the torsion plate is released in time. As a result, the procedure is repeated to leave the torsion plate oscillating.

The electrical inverters and the torsion plate compose a ring oscillator, whose oscillation frequency is governed by the temporal response of rise and fall of each stage. Amongst of all, the MEMS torsion plate has the longest time constant due to the large mass and small mechanical spring constant, and hence the mechanical response time determines the overall oscillation frequency of the oscillator. Here, the transient response time of the torsion plate from the rest position to the contact was accelerated by increasing the amplitude of voltage applied to the drive electrode. Consequently, the oscillating frequency could be controlled by the level-shifter output and the total system worked as a voltage controlled oscillator (VCO).

The pull-in detector was composed of an external resistance $R_{external}$ (10 kΩ), a DC voltage source V_{dc} (2 V to 3 V), and a Schmitt triggered inverter (74ACT14) as illustrated in the dashed-box in Figure 1. The Schmitt trigger inverter was used to remove the electrical "chattering" associated to the multiple impact of the plate on the mechanical contact. It was also designed to impedance-convert the output from the pull-up resistance and to give clear digital input of 0 or 5 V to the subsequent level-shifter. The output voltage level of the level shifter was controlled by the dedicated power supply V_H, which was used as the control voltage to the MEMS VCO.

3 Fabrication

The micromechanical torsion plate structure was developed by the electroplating microfabrication process illustrated in Figure 2 (a). (1) Metal layers of Cr (100 nm) and Au (200 nm) were vacuum deposited on the SiO_2 surface insulator (50 nm) of a silicon substrate (380 μm). The deposited metals were patterned into the anchor, the drive electrodes, and the interconnections by the wet etching with photoresist patterns (Shipley S1805, 0.5 μm thick). Cr etching HY-solution and $KI+I_2$ based gold etchant were used. (2) After putting another photoresit mould patterns (AZ P4620, 8 μm thick), sacrificial patterns of copper (1.2 μm thick) was deposited by electroplating. In the following step (3 and 4), nickel microstructures were formed by the electroplating process using a thick photoresist mould (double coat AZ P4620, 20 μm thick total). In step (5), the photoresist mould was removed in acetone, and the copper sacrificial layer was selectively etched with respect to the structural nickel in an etching acid of 1:1:14 of acetic acid, hydrogen peroxide (H_2O_2), and deionized water at room temperature [5]. In order to avoid in-process stiction, the rinse water after the etching was repeatedly replaced with isopropylalcohol (IPA) of low surface tension force. The contact resistance between the torsion plate tip and the contact electrode could be lowered by applying a short-time gold plating on the nickel before the IPA-finished rinse. A SEM image of the completed device is shown in Figure 2 (b).

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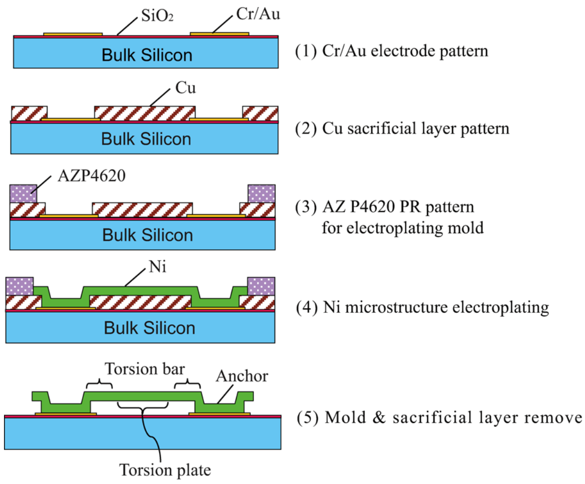
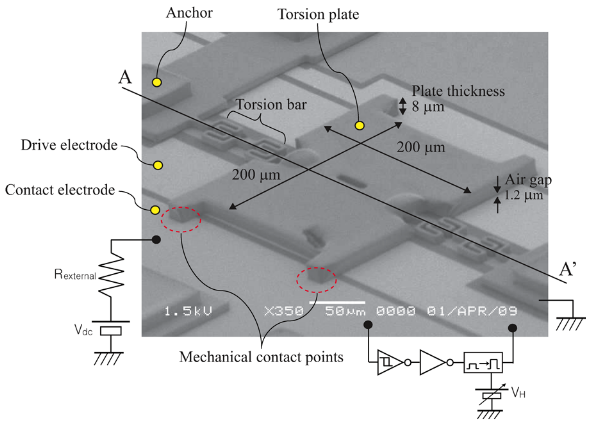


(a) Fabrication steps viewing from A to A' using electroplated copper (sacrificial) and nickel (structural).



(b) SEM image of the completed torsion plate structure.

Fig. 2. Development of the electrostatic torsion plate.

The fundamental electromechanical behaviors of the device such as the dc and the frequency responses have been reported elsewhere [7].

4 Experimental results

The developed MEMS torsion plate device was wirebonded in a ceramic package and mounted on a testing bed made of a universal printed circuit board (PCB) together with other peripheral circuits such as a Schmitt triggered inverter (74ACT14) and a level shifter (MC14504BCBPG, Onsemi) [6]. Figure 3 (a) to (c) show the experimentally obtained waveforms measured at different control voltage levels. Each plot contains the VCO input voltage level (top), the VCO output signal (middle) and the electromechanical displacement of the torsion plate measured at the tip by using the laser Doppler vibrometer (bottom). For each operation, the level shifter voltage was increased to a point of pull-in voltage (typically 7.4 V), where the torsion plate started oscillation at 4.39 kHz. By increasing the voltage to 7.8 V, 8.1 V, and 10.6 V, the output frequency was observed to shift higher to 6.3 kHz, 7.8 kHz, and 9.6 kHz, respectively. The output frequency results were plot as a func-

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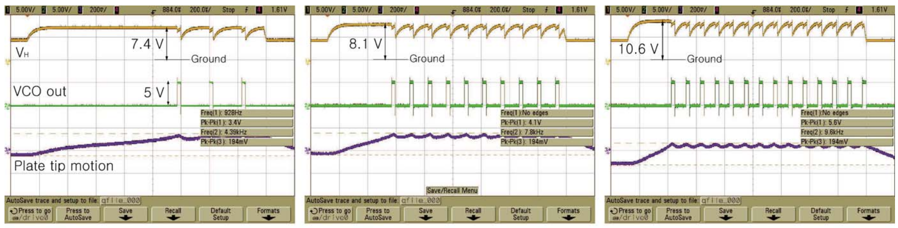
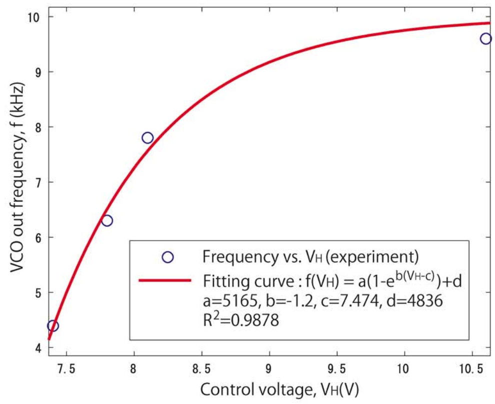


(a) 4.39 kHz at 7.4 V (b) 7.8 kHz at 8.1 V (c) 9.6 kHz at 10.6 V.



(d) VCO output frequency as a function of V_H.

Fig. 3. Experimental results of MEMS VCO operation.

tion of voltage as shown in Figure 3 (d). The output frequency asymptotically increased with the voltage. The behavior was found to fit the inversed exponential curve (shown in the Figure 3 (d) inset), which was derived from a theoretical analysis presented elsewhere [7].

5 Conclusion

We reported a microelectromechanical self-oscillating resonator using the electrostatic pull-in mechanism and a simple CMOS driver circuitry for the first time to develop a compact MEMS VCO. Frequency tuning range of 4.39 to 9.6 kHz was controlled with voltage range in 7.4 to 10.6 V within a relatively small device size (MEMS footprint 300 μm $\times$ 300 μm, CMOS circuit footprint equivalent to a chip electronics of 100 μm $\times$ 100 μm). From device process and circuit design points of view, this results indicated that the MEMS pull-in oscillator was compatible with the full scale integration of CMOS-MEMS. Detail study of the MEMS VCO model and the mixed-signal analysis are under investigation and reported soon elsewhere.

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