Optical and capacitive characterization of MEMS magnetic resonator

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Abstract: In this paper a Lorentz force driven Micro ELectro Mechanical Sytems (MEMS) resonator fabricated on PolyMUMP process with optical and capacitive sensing is presented. The resonator is designed by combining the two poly layers which result in an increase in the thickness of the resonator. Lorentz force generates lateral displacements at low driving voltages which are proportional to the magnetic field and the input current. A displacement of more than 9.8 µm was achieved with a magnetic field of 0.12 T and a driving current of 27 mA. Magnetic sensitivity of 1.41 V/T in air was experimentally measured using permanent magnets and capacitive sensing circuitry. Optical results demonstrate the sensitivity values between 0.090 µm/mT and 0.074 µm/mT.

Keywords: MEMS, PolyMUMP, Lorentz force, capacitive, displacement, MS3110

Classification: Micro- or nano-electromechanical systems

References


1 Introduction

Lorentz force is a popular actuation mechanism to excite Micro ELectro Mechanical Sytems (MEMS) devices. The lorentz force transducer depends linearly on the applied input current perpendicular to the direction of magnetic field. The force induced by a magnetic field can deform the suspended MEMS structures with small stiffness. Depending upon the design and stiffness constant, torsional, lateral and out-of-plane motions can be achieved easily. Lorentz force actuators do not require any special magnetic materials or large area for sensing, these advantages results in small structures, having linear motion, low power consumption, and ideal for large displacement applications [1, 2]. Multiple readout mechanisms have been employed with the Lorentz force sensors which include piezoresistive [3, 4], capacitive [5] and optical ones which are mainly used for out-of-plane detection [6, 7].

Resonant frequency shifts using Lorentz force has also been presented in some designs by applying axial stress which result in an increase in the stiffness of the sensor [8, 9].

In this work we present a MEMS lateral resonator actuated by Lorentz force due to an applied out-of-plane magnetic field. Maximum displacement is measured at the resonant frequency of the MEMS structure. The Lorentz force to displacement change is then detected optically and capacitively. Experimental results shows linear response of the resonator.

2 Resonator design and modeling

The resonator is designed using standard PolyMUMP’s fabrication process [10]. Thickness of the resonator is 4.0 µm including the top gold metal layer which is achieved by combining the two poly layers using the via layer in the design stage. The resonator consists of a center shuttle attached to four parallel beams of equal stiffness and length. The sensing mechanism is designed as a set of two plate parallel capacitor where Poly0 layer is fabricated for the lower capacitor plate on the substrate. Two lower plates are designed for differential and single capacitance
sensing. The displacement of the shuttle increase the overlap area between the plates which results an increase in the total capacitance. The substrate and lower capacitance plates increase damping and parasitic capacitances [11]. The designed gap between the resonator and Poly0 is 2.0 µm. The measured gap through scanning electron microscopy (SEM) is approximate 1.5 µm. FESEM image of the resonator is shown in Fig. 1. Thickness to width aspect ratio are kept equal (i.e. 4.0 µm), this aspect ratio allows the structure to resonate at its first resonant frequency in the lateral direction. Resonator structural parameters are summarized in Table I.

![FESEM image of (a) MEMS resonator and (b) One of the beams and the released shuttle](image)

**Fig. 1.** FESEM image of (a) MEMS resonator and (b) One of the beams and the released shuttle

### Table I. Structural parameters of the resonator

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shuttle length</td>
<td>322 µm</td>
</tr>
<tr>
<td>Shuttle width</td>
<td>180 µm</td>
</tr>
<tr>
<td>Mass of shuttle m</td>
<td>$6.875 \times 10^{-10}$ kg</td>
</tr>
<tr>
<td>Beam length l</td>
<td>418 µm</td>
</tr>
<tr>
<td>Beam width w</td>
<td>4 µm</td>
</tr>
<tr>
<td>Beam metal width</td>
<td>2 µm</td>
</tr>
<tr>
<td>Effective thickness t</td>
<td>4 µm</td>
</tr>
<tr>
<td>Measured gap $z_{ini}$</td>
<td>1.5 µm</td>
</tr>
<tr>
<td>Spring constant k</td>
<td>0.240 N/m</td>
</tr>
<tr>
<td>Calculated resonant frequency f</td>
<td>5.948 KHz</td>
</tr>
<tr>
<td>Damping coefficient $C_{damp}$</td>
<td>$3.753 \times 10^{-7}$ kg/ms</td>
</tr>
</tbody>
</table>
3 Experimental results

3.1 Optical measurement

The resonator pads were wire bonded to a printed circuit board (PCB) and a permanent magnet was placed under the board, providing a static magnetic field. Sinusoidal signal with driving currents ranging from 19–27 mA are applied to the resonator. The imposed magnetic flux density on the resonator is about 0.12 T. Fig. 2(a) shows the optical photograph at initial position. Fig. 2(b) shows the resonator motion in the lateral direction. An optical microscope is used to measure the displacement and resistance of the resonator is monitored by a digital multimeter. Testing setup is shown in Fig. 3. The optical measurements are carried out at the experimental resonant frequency maximum displacements are observed at 6.1 KHz. The percentage difference between the calculated and experimental values is 1.98% this difference is due to the fabrication tolerances. Relationship between the displacement of the resonator and the flowing current with a fixed magnetic flux density of 0.12 T is given in Fig. 4(a).

![Fig. 2](image1.png)

(a) Optical image of the resonator at rest, (b) resonator in motion at resonance frequency

![Fig. 3](image2.png)

Fig. 3. Testing setup. Inset shows the permanent magnet placed under the PCB
3.2 Capacitance measurement

Capacitance detection is carried out by a commercially available capacitive readout circuit MS3110 of Irvine sensors. The general purpose MS3110 CMOS IC is a low noise capacitance to analog voltage converter. The MS3110 readout works either in a differential capacitor pair or a single capacitance configuration setup [12]. In this work, single capacitance configuration is used by connecting the resonator shuttle and one of the lower plates designed using Poly0. The capacitance to voltage output of the device is experimentally measured as a response to the change in the current flowing through the resonator. The readout circuit provides a biasing voltage to the resonator through its input pins $V_b = 1.124 \text{ V}$. This biasing voltage reduces the spring constant of the resonator and the effect is called “spring softening”. The spring softening effect reduces the resonant frequency of the resonator and the experimental resonant frequency found from capacitive measurement is 5.8 KHz. The percentage difference between the resonant frequency found by capacitance measurement and the calculated is 3.12%. Schematic of the sensor, its working principle and electrical connections with the readout circuit is given in Fig. 5.

Fig. 4. (a) Dependence of displacement on input current with a magnetic flux density of 0.12 T, (b) measured displacement values over a range of magnetic flux densities

Fig. 5. Schematic diagram of the resonator and the capacitive sensing circuitry
The capacitance to voltage circuitry provides change in output voltage as a response to change in external magnetic flux density. Fig. 6(a) shows a linear response of output voltage measured at fixed input currents with changing magnetic flux densities. The capacitance change due to overlapping of the resonator and the lower plate is calculated from the output voltage response of the sensing circuitry, Fig. 6(b) shows measured capacitance with change in the external magnetic flux densities. The initial overlap of the resonator and the lower plate is 30 µm which provides capacitance values in femto Farads. Fig. 6(c) shows the dependence of the resonator resistance on the applied current, the resistance remains unchanged over a range 0–27 mA with slight drifts due to measurements (44 ± 0.5 Ω). The top metal layer gets destroyed when the resonator is operated at more than 27 mA. At higher currents the double thickness polysilicon layer remains unaffected but the total resistance of the resonator increase. The overlap displacement is also calculated by the output voltage change measured by the circuitry, Fig. 6(d) shows a comparison of displacements calculated by the capacitance and optically measured mechanisms. The displacement comparison show a good agreement between optically measured and calculated values with a 1.08% difference.

4 Conclusion

A Lorentz force MEMS resonator is developed in this work. The resonator is designed using standard PolyMUMP process and it shows a linear response to the magnetic flux density and current. The resonator provides two type of sensing
mechanisms i.e. optical and capacitive. The resonator provides a magnetic field sensitivity of 1.41 V/T. The lower gap distance between the resonator and lower plates increase the damping effect but provides large capacitance output. The displacement and capacitance response of the resonator can be increased by operating in vacuum condition which will reduce air damping effect significantly.

Acknowledgments

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