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Lorentz Force Magnetic Sensor based on a Thin-Film Piezoelectric-on-Silicon Laterally Vibrating Micromechanical Resonator

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Abstract

We present a unique MEMS magnetometer based on a laterally-vibrating Thin-film Piezoelectric-on-Silicon (TPoS) resonator. This is the first time that the piezoelectric effect has been explored for the detection of magnetic fields among CMOS-compatible resonant devices. Strong electromechanical coupling provided by the Aluminium Nitride (AlN) layer, enhances sensitivity to allow operation in air as opposed to vacuum. A Lorentz force in the presence of a magnetic field excites the in-plane vibration mode. No amplifier circuit has been used at the output of the magnetometer. Our proof-of-concept device has been operated at a resonant frequency of 33.27MHz, and shows a measured sensitivity of 0.42µA/T despite a sub-optimal quality factor (Q) of 432 in air.

Keywords: Thin-Film Piezoelectric-on-Silicon (TPoS); micromachined resonant magnetic field sensor; microelectromechanical systems (MEMS); lateral vibration mode.

1. Introduction

Magnetic field sensors have earned their place in different applications starting from navigation in early stages to speed detection, position sensing, current detection, vehicle detection, direction finding (electronic compass) and brain function mapping [1]. Hall-effect magnetic sensors and magnetoresistive sensors are commonly used in portable electronic applications [2, 3]. Hall-effect sensors are beneficial in terms of low cost, and capable to detect
magnetic fields ranging from 10µT to 1T [4]. The drawback of Hall-effect sensors is that they require higher power consumption to achieve better resolution [4]. Magnetoresistive sensors require special magnetic materials in their fabrication process, although these sensors are capable of detecting magnetic fields over a wide range (0.1nT to 0.1T) [4]. Nowadays, consumer electronic products incorporate advanced multi degree of freedom (DOF) Inertial Measurement units (IMUs) [5]. A 9 DOF IMU unit integrates a 3-axis accelerometer, a 3-axis gyroscope, and a 3-axis magnetic sensor [5]. The capability to incorporate all the sensors together allows realization of compact sensing units. Being free from magnetic materials, micromachined (MEMS) magnetometers are potentially compatible with CMOS fabrication and free from magnetic hysteresis [2]. Micromachined resonant magnetic field sensors typically detect magnetic fields by means of magnetic field-induced Lorentz force excitation at the resonant frequency of the device in order to maximize sensitivity [5]. Capacitive [2-5] and piezo-resistive [6] readout interfaces have been employed to electromechanically convert the mechanical vibration into an electronic output. Both require vacuum to reach high quality factors and their resonant frequencies are typically low and thus limited by flicker noise. In this work, we experimentally demonstrate a proof-of-concept of exciting the lateral bulk mode at 33.27MHz of a TPoS resonator to detect magnetic fields under ambient conditions.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>( L )</td>
<td>Length of the resonator body</td>
</tr>
<tr>
<td>( I_{AC} )</td>
<td>Input AC drive current</td>
</tr>
<tr>
<td>( B_z )</td>
<td>Out-of-plane magnetic field</td>
</tr>
<tr>
<td>( F_y )</td>
<td>In-plane component of the Lorentz force</td>
</tr>
<tr>
<td>( Q )</td>
<td>Mechanical quality factor of the resonator</td>
</tr>
<tr>
<td>( k )</td>
<td>Spring constant of the resonator based on the resonant mode shape</td>
</tr>
<tr>
<td>( x )</td>
<td>Displacement of the resonator</td>
</tr>
</tbody>
</table>

2. Sensor Design and Modeling

The proposed device has been fabricated using a foundry AlN-on-SOI MEMS process. Fig. 1(a) shows an optical micrograph of the fabricated device, while Fig. 1(b) shows a schematic of the cross-section seen across line section AA’ labelled on Fig. 1(b). The top metal (Al) layer is insulated from the silicon device layer (10µm-thick) by a 0.5µm-thick piezoelectric AlN layer. The resonator is based on a rectangular plate that is supported at each corner by tethers that carry the AC drive currents \( (I_{AC}) \). The AC drive currents are applied at the resonant frequency of 33.27MHz along the metal tracks in opposite directions via a differential-pair of AC input voltages.

The presence of an out-of-plane magnetic field \( (B_z) \) generates a Lorentz force pair in opposite directions \( (F_y) \) that excites the lateral vibration mode shown in Fig. 2(a). The Lorentz force can be mathematically expressed as,
\[ F_y = LI_{AC} \times B_z \] (1)

The Lorentz force induced displacement is amplified by the mechanical quality factor \((Q)\) of the resonator [3]. By equating the mode shape of the resonator off-resonance to that at resonance, the displacement of the resonator can be expressed as,

\[ x = \frac{F_y}{k} Q \] (2)

The in-plane vibration mode of the resonator has an associated lateral stress profile. As such, the modulated stress in the piezoelectric layer electromechanically couples to an output resonant motional current through the piezoelectric effect. The motional current is sensed from the output patch electrode (Fig 1(a)). The sensitivity of the device is defined by the ratio of the output motional current to the applied magnetic field. We performed finite element analysis (FEA) in COMSOL multiphysics using a two step process in order to determine the sensitivity of the device. We first evaluated the resonant frequency of the device for the concerned lateral vibration mode (Fig 2(a)) using an eigenfrequency study. As can be seen from Fig 2(a), addition of the tethers at the corner of the rectangular plate causes distortion of the vibration mode shape from the desired mode shown in Fig 2(b). In the second step, a distributed line force was applied to the sides of the plate in a frequency-domain study. The resultant stress-induced motional currents were computed, based on which we derived a sensitivity of 0.33μA/T. On this note it is worth noting that the corner tethers reduce \(Q\) while the consequent mode distortion reducing piezoelectric coupling, the net effect is a reduction in the sensitivity.

![Fig. 2. (a) Lateral vibration mode of the TPoS MEMS Magnetometer simulated by FEA using COMSOL (colour-coded contours denote the relative magnitude of displacement); (b) Desired vibration mode shape described by uniform displacement along the length of the plate that will improve electromechanical coupling by over one order of magnitude.](image)

3. Measurement and Discussion

The fabricated device was wire-bonded to a customized printed circuit board, and the external connections to the network analyzer were made through SMA connectors. Electrical characterization of the device was performed using a network analyzer. No amplifier circuit was used at the output stage of the measurement setup. We first measured the electrical transmission \((S_{21})\) of the device in air with no external magnetic field applied, to find the piezoelectric drive offset of the device. To calibrate the sensitivity of the device, we measured the electrical transmission characteristics of the device under the same driving conditions, but with a range of magnetic fields applied. Fig. 3(a) illustrates the change in \(S_{21}\) measured with an external field of 102mT relative to the unwanted piezoelectric drive offset. Fig. 3(b) shows the resulting linear calibration plot (converted from \(S_{21}\) with offset removed) with a best fit regression line that defines the device sensitivity. The calibrated unamplified sensitivity of 0.42μA/T is in good agreement with the corresponding FE simulation result of 0.33μA/T.
Fig. 3. (a) Measured transmission magnitude of the TPoS magnetometer with and without a magnetic field applied; (b) Measured output current (converted from $S_{11}$ and after removing the offset current) as a function of applied magnetic field strength; slope of best fit line defines the calibrated sensitivity.

4. Conclusion

In this work, we have designed, fabricated and electrically characterized a TPoS micromechanical resonator where the piezoelectric effect has been employed to provide a strong electromechanical readout interface. Despite its sub-optimal quality factor of 432 in air and non-ideal vibration mode shape, the device shows a measured sensitivity of 0.42 μA/T, which agrees well with our finite element model. We envisage that existing results can be realistically improved by a few orders of magnitude through design modifications (particularly with the support structures) to improve both $Q$ and electromechanical coupling while also reducing the piezoelectric drive offset.

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References