ABSTRACT

We report a new Lorentz force magnetic sensor employing a matched pair of silicon micromechanical resonators on the same die. The two resonators are operated as closed-loop oscillators, where the change in oscillation amplitude is used as a measure of the magnetic field strength. The magnetometer, consisting of the two identical oscillators having opposing axes of field sensitivity, produces two similar oscillation amplitudes with nearly identical temperature sensitivities, providing continuous temperature compensation. Differential amplitude modulated (AM) output from the two oscillators reduces the sensor’s offset by a factor of 12 to 26 μT, and suppresses the effect of the resonator’s temperature coefficient of quality factor (TCQ) on the output, reducing the maximum drift error by a factor of 15 to ±0.49 μT, improving the sensor’s bias instability from 86 nT to 26 nT, and increasing the averaging time to reach the bias instability from 1 s to 10 s. With 44-μW power dissipation, the sensor achieves a resolution of 50 nT/√Hz, limited by Brownian noise.

KEYWORDS

MEMS, magnetic sensor, magnetometer, Lorentz force, resonator, micromachined oscillator.

INTRODUCTION

Various types of magnetic sensors have been developed in recent years, including Hall effect sensors [1], magnetoresistive (MR) sensors [2], and MEMS resonant magnetometers [3], [4]. Because Hall effect and MR sensors, presently the dominant technologies used in consumer electronics devices due to their high resolution, are based on magnetic materials, they suffer from magnetic hysteresis and saturation effects that create offset and limit dynamic range. In comparison, silicon MEMS magnetometers using the Lorentz force as the transduction principle offer benefits as they do not require magnetic materials (making them potentially CMOS-compatible), and therefore do not exhibit magnetic hysteresis or saturation. Emerging Lorentz force sensors have already achieved reasonably high sensitivity and low noise floor (<500 nT/√Hz) [5], comparable to, or even better than that of Hall sensors. They can also be co-fabricated with MEMS gyroscopec and accelerometers using a standard silicon MEMS fabrication process, making them attractive to produce single-chip inertial measurement units with lower cost and smaller size.

There are significant research efforts in the last decade trying to improve the sensitivity and resolution of Lorentz force magnetometers, however, their precision is limited primarily by offset. Offset reduces the dynamic range and results in drift error. Considering navigation, a compass requires magnetic sensors that work in the presence of Earth’s magnetic field (ranging from 10 μT to 100 μT) and capable of detecting a magnetic field smaller than 50 nT to achieve 0.1° heading accuracy. In this application, the dominant measurement error of existing low-cost magnetic sensors is drift error, which directly transfers to heading error. Conventional Lorentz force magnetometers have an AM output, and can be operated either off-resonance or at its mechanical resonance. Other groups have demonstrated Lorentz force sensors operated off-resonance to extend the system bandwidth [6], [7], however, they have poor performance due to their low sensitivity to magnetic field. Therefore, AM sensors typically operate at resonance: a MEMS resonator is driven with an ac current with a carrier frequency set to the resonator’s natural frequency (fn), generating an AM Lorentz force (FL) centered at fn when the sensor is exposed to a low-frequency magnetic field. Thus, the motion induced by FL is increased by the resonator’s mechanical quality factor Q, which maximizes the magnetic field sensitivity, resulting in larger signal-to-noise ratio (SNR) and hence better noise performance. MEMS researchers have recently demonstrated AM magnetometers operating at resonance in closed loop to improve sensor performance [8], [9], however, their bias instability is poor due to the presence of high offset, which is significantly sensitive to temperature variations due to the resonator’s TCQ. Here we solve this problem using a closed-loop magnetometer having two identical resonators with opposing axes of sensitivity. Compared to [8], [9], the magnetometer presented here enables a differential measurement that doubles the sensitivity, and cancels the offset and temperature-induced drift, resulting in greater SNR and lower bias instability.

THEORY AND IMPLEMENTATION

A single-resonator magnetometer, shown in Fig. 1, consists of an H-shaped moving body suspended by four folded springs anchored on the substrate. Capacitive electrodes (DR and S) are used to generate electrostatic force Fce, driving the resonator’s in-plane mode into resonance, and to sense the in-plane motion, respectively. During operation, the resonator is put into a positive feedback loop so that it oscillates steadily at its resonance frequency, fc, providing a bias current at fc that is in-phase with Fce. The bias current (ib), injected at contacts IB+ and IB-, interacts with a magnetic field (B) to produce an AM Lorentz force, FL = ib × Le × B, where Le is the effective length of the current path through the resonator. This FL changes the resonator’s amplitude, and the magnetic field strength B is detected from the change in the oscillation amplitude.
Using a second-order model of the resonator, the system dynamics of the Lorentz force magnetometer can be written as

\[ m \ddot{x} + b \dot{x} + kx = F_e \cos(\omega t) + F_L \cos(\omega t) \quad (1) \]

where \( m, b, k, \) and \( x \) are the effective mass, damping coefficient, stiffness, and displacement, respectively. \( F_e \) and \( F_L \) are the baseband components of the electrostatic force and Lorentz force. In closed-loop AM operation, the resonator is actuated by both \( F_e \) and \( F_L \), where \( F_e \) is created from the voltage output of the oscillator loop’s sustaining amplifier. This loop ensures that \( F_e \) is generated at the resonator’s natural frequency (\( f_n \)) and provides a frequency reference for the bias current generator (\( i_{ac} \)) as well. Because \( i_{ac} \) has the same frequency and phase as the oscillation signal, \( i_{ac} \) produces \( F_e \) centered at \( f_n \) and in-phase with \( F_e \). For a dc magnetic field (\( B \)), the steady-state oscillation amplitude at \( f_n \), resulting from both \( F_e \) and \( F_L \) acting on the moving body of the resonator, can be derived from Eq. (1) as

\[ x = x_e + x_L = \frac{F_e Q}{k} + \frac{F_L Q}{k}, \quad \text{where} \quad F_e = V_{ac} V_b \frac{C_0}{g} \quad (2) \]

where \( V_b \) and \( V_{ac} \) are the amplitudes of the dc bias and ac electrostatic driving voltages applied to the resonator, and \( C_0/g \) is the capacitive displacement sensitivity. In Eq. (2), the displacement terms, \( x_e \) and \( x_L \), are induced by the electrostatic force \( F_e \) and Lorentz force \( F_L \), respectively. Because \( F_e \) is in-phase with \( F_L \) at \( f_n \), it creates offset in the sensor’s output that is many times larger than the sensor’s noise floor. Any change with temperature in the parameters contributing to \( x_e \) produces unpredictable offset drift that introduces low-frequency noise including 1/f, 1/f² and 1/f³ noise in the sensor’s output, increasing bias instability. From Eq. (2), the parameters of \( x_e \) related to geometry (\( C_0 \) and \( g \)) and the applied voltages (\( V_{ac} \) and \( V_b \)) are independent of temperature to first-order, while the other parameters (\( Q \) and \( k \)) are temperature-dependent. In silicon MEMS resonators, the stiffness \( k \) has a small temperature coefficient of roughly \(-60 \text{ ppm/°C}\) determined by the Young’s modulus of silicon. In comparison, \( TCQ \) is much greater: roughly \(-10,000 \text{ ppm/°C}\) when thermoelastic dissipation is the dominant energy loss mechanism [10]. Overall, \( TCQ \) is the primary factor that produces offset drift in AM readout of silicon resonators operated as closed-loop oscillators.

To suppress the offset and drift error induced by temperature due to the resonator’s \( TCQ \), we propose an all-silicon Lorentz force magnetometer composed of two identical 1.6×0.8 mm² resonators, designed to operate near 50 kHz, and integrated onto the same die. The SEM image of the dual-resonator sensor and its parameters are shown in Fig. 2 and Table 1, respectively. The device is fabricated in 40-µm-thick <100> single-crystal silicon and vacuum sealed at approximately 1 Pa using an epi-seal encapsulation process [11] that provides high \( Q (=12,000) \) and is compatible with CMOS manufacturing. A highly-doped silicon wafer with resistivity of \( \sim 1 \text{ mΩ·cm} \) is used to reduce the resistance of the current-carrying flexures.

### Table 1: Sensor parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Resonator 1</th>
<th>Resonator 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Frequency, ( f_n )</td>
<td>47220 Hz</td>
<td>47305 Hz</td>
</tr>
<tr>
<td>Quality Factor, ( Q )</td>
<td>11760</td>
<td>12940</td>
</tr>
<tr>
<td>Drive/Sense Capacitance, ( C_0 )</td>
<td>327 fF</td>
<td>327 fF</td>
</tr>
<tr>
<td>Capacitive Gap, ( g )</td>
<td>1.3</td>
<td>1.3 µm</td>
</tr>
<tr>
<td>Effective Length, ( L_e )</td>
<td>1200 µm</td>
<td>1200 µm</td>
</tr>
<tr>
<td>Effective Stiffness, ( k )</td>
<td>2000 N/m</td>
<td>2000 N/m</td>
</tr>
<tr>
<td>Proof mass, ( m )</td>
<td>22 µg</td>
<td>22 µg</td>
</tr>
<tr>
<td>Device Thickness, ( t )</td>
<td>40 µm</td>
<td>40 µm</td>
</tr>
<tr>
<td>Resistance, ( R_{flex} )</td>
<td>20 Ω</td>
<td>20 Ω</td>
</tr>
</tbody>
</table>
where the subscripts 1 and 2 represent resonator 1 and 2, respectively. The displacement sensitivity $S$ can be derived from Eq. (3) as

$$S = \frac{\partial x_{\text{out}}}{\partial B} = 2L_i \frac{Q}{k}$$

(4)

The offset from electrostatic force is removed and the sensitivity is doubled. The resulting displacement is converted into a voltage signal using capacitive sensing, and the final sensitivity, in $V/T$, is determined by multiplying $S$ by the displacement-to-voltage scale factor.

RESULTS

The dual-resonator magnetometer, shown in Fig. 2, is characterized in open loop by applying a 10 V dc bias voltage to the resonator body with no bias current. The frequency response is obtained by sweeping the frequency of a constant-amplitude voltage signal applied to the driving electrode to electrostatically excite the resonator, and measuring the corresponding output amplitude from the sense electrode. Although the two matched resonators are integrated onto the same die, fabrication imperfections result in a difference between the quality factors ($Q$) and resonance frequencies ($f_0$) of the two resonators (Fig. 4).

Fig. 4. Frequency responses of the two resonators at 10V bias.

All other experiments were conducted with 10 V dc bias and 1.1 mA current flowing through the 20 Ω flexure resistance of each resonator, resulting in 44 µW power dissipation by Joule effect in the magnetometer. We use a pair of Helmholtz coils to generate magnetic field for measuring the sensor’s sensitivity. Fig. 5 depicts the output vs. input magnetic field. The offset is suppressed by a factor 12 to 5.4 mV (corresponding to 26 µT), and the differential sensitivity is doubled (to 207 V/T), in good agreement with the estimated sensitivity of 200 V/T calculated with a gain of 20 used in the electronics. Because both resonators are excited with the same ac actuation voltage, the 5.4 mV residual offset is mainly due to the difference in $Q$ between the two resonators.

Fig. 5. Measured sensitivity of the devices. The resulting differential sensitivity is doubled, and the offset is reduced from ~30 mV (300 µT) to 5.4 mV (26 µT).

The temperature variation causes a change in each resonator’s quality factor, $Q$. Fig. 6 shows the measured $Q$ for each resonator over a temperature range from 10 °C to 50 °C. Both resonators showed very similar $TCQ$ of approximately 3.4, obtained from the curve fit to the data in Fig. 6. The $1/T^{3.4}$ dependence of $Q$ is mainly due to thermoelastic dissipation. For each resonator, the $TCQ$ is about -11,500 ppm/°C near room temperature, where the magnetometer was tested.

Fig. 6. Measured temperature dependence of quality factor ($Q$) of resonator 1 and 2.

The sensor’s output was recorded over 8-hours in a magnetically-shielded environment without temperature control. Fig. 7 shows the measured offsets of resonator 1 and 2 and the differential output with the mean value subtracted. The two oscillator outputs fluctuate with the ~4.2 °C temperature variation during this period due to $TCQ$, but the differential output shows little temperature sensitivity. The maximum drift error of both oscillators is ±7.2 µT, and is reduced to ±0.49 µT through differential measurement of the two oscillator amplitudes. Because the ±7.2 µT drift error is consistent with a ~4.2 °C temperature variation during the test, all drift can be mainly attributed to the resonator’s $TCQ$.
The actuation voltage (assuming both resonators have an amplitude) rather than driving them with the same driving voltage allows the resonators into the same displacement, thereby reducing the maximum drift error by a factor of 15 in the differential output.

Differential outputs, showing that the $1/f$ noise in the residual offset. Fig. 9 depicts the measured noise spectra of the resonator 1 and differential outputs, showing that the $1/f$ and $1/f^2$ noise on the resonator output is significantly suppressed as a result of differential sensing. The offset-related $1/f$ and $1/f^2$ noise density of the differential output can be further reduced by driving the resonators into the same displacement amplitude rather than driving them with the same actuation voltage (assuming both resonators have a similar $TCQ$ and different $Q$). Furthermore, the resonator’s white noise is dominated by the thermomechanical (Brownian) noise of 70 nT/√Hz, which is reduced to 50 nT/√Hz with differential sensing.

**CONCLUSIONS**

In this paper, we have described a closed-loop micromechanical Lorentz force magnetic sensor using simultaneously-operated two matched resonators on the same silicon die. Sensor operation is demonstrated using a differential AM readout. With the proposed differential AM operation, the magnetic field sensitivity is doubled, whereas the offset and temperature-induced drift error from the offset is significantly suppressed. The magnetic sensor demonstrated in this work has a measured offset of 26 µT, resolution of 50 nT/√Hz, and exhibits a 26 nT bias instability at 10 s averaging time. These results make the device suitable for use in navigation system as a compass.

**ACKNOWLEDGEMENTS**

This work was supported by the DARPA grant “Precise Robust Inertial Guidance for Munitions (PRIGM),” managed by Dr. Robert LuTwak, Contract # N66001-16-1-4023. Work was performed in part at the Stanford Nanofabrication Facility, supported by the National Science Foundation under Grant ECS-9731293.

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