Abstract—This letter presents a micromachined silicon Lorentz force magnetometer, which consists of a flexural beam resonator coupled to current-carrying silicon beams via a microleverage mechanism. The flexural beam resonator is a force sensor, which measures the magnetic field through resonant frequency shift induced by the Lorentz force, which acts as an axial load. Previous frequency-modulated (FM) Lorentz force magnetometers suffer from low sensitivity, limited by both fabrication restrictions and lack of a force amplification mechanism. In this work, the microleverage mechanism amplifies the Lorentz force, thereby enhancing the sensitivity of the magnetometer by a factor of 42. The device has a measured sensitivity of 6687 ppm/(mA·T), which is two orders of magnitude larger than the prior state-of-the-art. The measured results agree with an analytical model and finite element analysis. The frequency stability of the sensor is limited by the quality factor ($Q$) of 540, which can be increased through improved vacuum packaging.

Index Terms—Frequency modulation, magnetometers, microelectromechanical systems (MEMS), sensor phenomena and characterization

I. INTRODUCTION

MAGNETOMETERS are widely used in many applications, such as current measurement, navigation, and traffic control [1]. Emerging MEMS magnetometers based on Lorentz force sensing are low cost, low power, CMOS compatible, and can be directly integrated with MEMS accelerometers and gyroscopes, making them attractive for many applications. One class of Lorentz force magnetometers relies on amplitude modulated (AM) readout where the resonator’s amplitude varies in proportion to the external magnetic field. An AC excitation current applied to the resonator modulates the low-frequency magnetic field, generating a Lorentz force centered at the excitation current’s frequency, $f$. Setting $f = f_n$, the resonator’s natural frequency, the resulting displacement is amplified by the quality factor ($Q$) of the resonator. It was demonstrated that a high-$Q$ single-structure 3-axis Lorentz force magnetometer could achieve a noise-equivalent field of 30 nT/√Hz [2], which is 10 times better than that of existing Hall-effect sensors. Many efforts have been made to increase the sensitivity by maximizing $Q$ [3, 4], however, higher $Q$ reduces the sensor’s bandwidth. Also, the sensitivity is temperature-dependent due to the temperature dependence of quality factor.

A second class of Lorentz force magnetometers, based on frequency-modulated (FM) readout, has recently been developed [5, 6] and possesses many advantages over conventional AM magnetometers, including no trade-off between $Q$ and bandwidth, improved sensitivity stability over temperature, and large dynamic range. FM readout can be accomplished with very high resolution and low power consumption: Izyumin et al. recently demonstrated a 0.2 ppb/√Hz frequency-to-digital converter requiring only 50 μW of power [7]. FM magnetometers can be realized either by using the Lorentz force to create axial tension on a MEMS resonator, thereby changing its resonant frequency [5], or by applying a quadrature Lorentz force to an electrostatically excited MEMS oscillator [6]. Previous axially-loaded magnetometers have sensitivities not exceeding 33.9 ppm/(mA·T) [6], which require a frequency resolution better than 0.1 ppb to measure 1 μT, making this sensor less promising for compass applications. In this letter, we

Fig. 1. SEM of the fabricated Lorentz force magnetometer (left) and the simulated mode shape using COMSOL (right). Assuming an overetch of 80 nm, the simulated resonant frequency is 23.8 kHz.
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In previous work, the flexural beam is connected directly to the middle of the crossbar, which has no leverage mechanism. This structure resembles an “H”. The sensitivity of the H-shaped magnetometer, defined as the relative change in the resonant frequency over the input magnetic field per mA of excitation current, can be estimated by [5]:

$$S = \frac{\delta f}{I_b d_B} = \frac{0.015 L_d}{E H W^2} L_c \quad [\text{ppm/(mA·T)}],$$

where $E$ is the Young’s modulus of silicon, $L_d$ and $W_d$ are the length and width of the resonator, and $L_c$ is the length of the current-carrying flexure. Due to the fact that the Lorentz force is a distributed force rather than a point force, the actual sensitivity is about 15% lower than this estimation. The sensitivity can be increased by increasing $L_c$ and $L_d$ by decreasing $H$ and $W_d$ at the cost of increased device size and resistance.

To further improve the sensitivity, we introduce a microleverage mechanism, shown in the inset of Fig. 2. The distributed Lorentz force can be treated as an equivalent point load $F_p$, which acts at the center of the crossbar to generate the same deflection, $x$. The force applied to the input of the lever system, $F_{in}$, is given by $F_p = k_p x$, where $k_p$ is the stiffness of the beam to a point load. $F_{in}$ generates a moment about the fulcrum, and an additional moment on the lever arm is generated by the Lorentz force resulting from current flowing through the lever arm itself. Combined, these moments generate an force, $F_{out}$, on the resonant beam, which shifts its resonant frequency. Because an ideal fulcrum cannot be fabricated using the existing MEMS fabrication technology, the maximum amplification is dependent on the fabrication restrictions and microleverage topology [9]. We designed the microleverage system and device geometry using both FEM and analytical models. The distance from the fulcrum to the flexural beam, $L_1$, 7 μm, is chosen to be about 100X smaller than the distance from the fulcrum to the lever input, $L_2$ in order to maximize the overall sensitivity of the system. Simulation of the leverage mechanism shows that it amplifies the sensitivity of the magnetometer by a factor of 42 relative to the same design in absence of the lever mechanism.

**II. DEVICE DESCRIPTION AND MODELING**

The Lorentz force magnetometer consists of a flexural beam resonator with a microleverage mechanism. The 1.2 mm by 0.68 mm device is fabricated out of 40 μm-thick single-crystalline silicon, and wafer-level vacuum sealed to a second wafer using eutectic bonding. Fig. 1 shows an SEM image of the sensor and the mode shape, simulated using COMSOL (finite element analysis). The resonant frequency of the flexural beam resonator is simulated to be 23.8 kHz assuming 80 nm overetch of the silicon beam. Fig. 2 shows the working principle of the magnetometer. A DC excitation current $I_b$ flows through the 542 Ω device resistance, $R_{LES}$, which generates a Lorentz force in the presence of a magnetic field. This twists the lever arms, applying an axial load to the flexural beam resonator, therefore shifting its resonant frequency. The resonator is electrostatically transduced using 30 comb fingers on each side of the flexural beam, resulting in a capacitance change over displacement ($dC/dx$) of 10.6 nF/m. A DC bias voltage $V_p$, which is required for electrostatic actuation and capacitive sensing, is applied on top of the excitation current. The device dimensions are shown in Table I.

<table>
<thead>
<tr>
<th>Device Geometry</th>
<th>Value (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness of Device, $H$</td>
<td>40</td>
</tr>
<tr>
<td>Length of Crossbar, $L_c$</td>
<td>1000</td>
</tr>
<tr>
<td>Width of Crossbar, $W_c$</td>
<td>3</td>
</tr>
<tr>
<td>Length of Fulcrum Beam, $L_f$</td>
<td>40</td>
</tr>
<tr>
<td>Width of Fulcrum Beam, $W_f$</td>
<td>2</td>
</tr>
<tr>
<td>Length of Flexural Beam, $L_d$</td>
<td>500</td>
</tr>
<tr>
<td>Width of Flexural Beam, $W_d$</td>
<td>3</td>
</tr>
<tr>
<td>Fulcrum to Flexural Beam, $L_2$</td>
<td>7</td>
</tr>
<tr>
<td>Fulcrum to Lever Input, $L_1$</td>
<td>730</td>
</tr>
</tbody>
</table>

demonstrate a novel FM magnetometer design which builds on the structure developed in [5], but utilizes a microleverage mechanism, such as previously employed in [8] to amplify the tension produced by Lorentz force, thereby enhancing the sensitivity by more than two orders of magnitude to 6687 ppm/(mA·T).

**III. MEASUREMENT AND DISCUSSION**

To measure the frequency response of the flexural beam resonator, a digital lock-in amplifier (Zurich Instruments HF2-LI) is used to generate the electrostatic drive voltage $V_{drive}=50$ mV, resulting in an estimated mean-square amplitude of displacement $x=58$ nm. The sensing current $I_{sense}$ is amplified using a trans-impedance amplifier and demodulated. A triple output power supply is used to generate $V_p=6$ V and $I_b=4$ mA. We use a commercial Hall-effect gaussmeter (FW Bell 5180) to calibrate the magnetic field that is applied to the sensor.

We first place a magnet above the device to generate $z$-axis magnetic field. The measured frequency responses for -66 mT, 0 mT, and 66 mT are shown in Fig. 3. With zero bias current, the measured resonant frequency is 22.6 kHz with $Q$ of 540, but due to stress induced by thermal expansion, the frequency...
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Fig. 3. Measured frequency responses of the magnetometer. Measurements were collected by applying -66 mT, 0 mT, and 66 mT z-axis DC magnetic fields.

Fig. 4. Measured frequency shift versus input magnetic field for various bias currents. Frequency shift is measured using a digital PLL, and both absolute frequency change and relative frequency change are shown.

...drops to 21.92 kHz when a 4 mA current is applied. To characterize the frequency shift as a function of input magnetic field, we used an electromagnet to generate a magnetic field ranging from -8 mT to 8 mT for various bias currents. The results are shown in Fig. 4. The measured sensitivity is 6687 ppm/(mA·T), close to the 6820 ppm/(mA·T) sensitivity simulated by COMSOL. Our analytical model, however, overpredicts the sensitivity by 25% due to the non-ideality of the fulcrum. Assuming a fixed device of 1.2 mm by 0.68 mm, an optimization study of the device geometry shows that the sensitivity can be further improved by 17%. Also, since the sensitivity is inversely proportional to $H$, the sensitivity can be further improved by a factor of 4 if a 10 μm device layer is used; therefore we believe that a sensitivity of 31295 ppm/(mA·T) can be achieved.

The short term noise floor of the sensor, which was experimentally measured by examining the FFT of the output in the absence of applied external field, is 20 μT/√Hz (0.5 ppm/√Hz). Considering only the thermal noise contributed by the flexural beam resonator, the minimum detectable frequency change can be calculated [10]:

$$\frac{df}{fn} = \frac{k_b T B}{2\pi f Q X^2 k} \text{[ppm]},$$

where $k_b$ is Boltzmann’s constant, $T$ is absolute temperature in Kelvin, $B$ is the measurement bandwidth and $k$ is the spring constant of the flexural beam resonator ($k=19.8$ N/m). The theoretical minimum detectable frequency change is found to be 0.029 ppm for a 1 Hz bandwidth, which is about 17 times lower than our measured noise floor. We believe electronic noise dominates the noise floor in the setup. Table II compares this work to recent works on Lorentz force magnetometers with frequency output.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>This Work</th>
<th>Zhang et al. [5]</th>
<th>Li et al. [6]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excitation Current</td>
<td>DC Current</td>
<td>DC Current</td>
<td>AC Current</td>
</tr>
<tr>
<td>Device Length</td>
<td>1200 μm</td>
<td>800 μm</td>
<td>250 μm</td>
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<tr>
<td>Sensitivity</td>
<td>6687 ppm/(mA·T)</td>
<td>33.9 ppm/(mA·T)</td>
<td>5200 ppm/(mA·T)</td>
</tr>
</tbody>
</table>

IV. CONCLUSION

In this letter, we have designed, fabricated and modeled an FM Lorentz force magnetometer with a microleverage mechanism. The magnetometer is demonstrated to have a sensitivity two orders of magnitude higher than previous work, thanks to the microleverage mechanism and carefully chosen device dimensions. The resolution of the sensor, which is high enough to show great potential for many applications, can be further improved by increasing the quality factor, as well as increasing the oscillation amplitude.

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REFERENCES