Lorentz force magnetometer using a micromechanical oscillator

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This paper presents a Lorentz force magnetometer employing a micromechanical oscillator. The oscillator, actuated by both electrostatic force and Lorentz force, is based on a 370 μm by 230 μm silicon micromechanical resonator with quality factor (Q) of 13 000. This field-sensitive micromechanical oscillator eliminates the need for an external electronic oscillator and improves magnetometer’s stability over temperature. The resonator uses no magnetic materials and is encapsulated using an epitaxial polysilicon layer in a process that is fully compatible with complementary metal-oxide-semiconductor manufacturing. The sensor has a magnetic field resolution of 128 nT/rt-Hz with 2.1 mA bias current. © 2013 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4826278]

Many different types of magnetometers have been developed in recent years, including Hall-effect sensors, magneto-resistive (MR) sensors, and Lorentz force magnetometers. Lorentz force magnetometers can be fabricated in a standard silicon microelectromechanical systems (MEMS) fabrication process without any post processing or magnetic materials. As a result, they offer benefits over MR and Hall-effect sensors as they do not require magnetic materials and have no magnetic hysteresis. High sensitivity, low cost, low power, and direct integration with MEMS accelerometers and gyrosscopes make the Lorentz force magnetometer, a very attractive option in consumer electronic devices that already contain these MEMS inertial sensors. Lorentz force magnetometers can generally be categorized into two operating types. The first type is actuated only by Lorentz force and has an amplitude modulated (AM) output. The sensor is excited with an oscillating bias current at a carrier frequency ω, producing an AM Lorentz force centered at ω when the sensor is exposed to a low-frequency magnetic field. The amplitude of the resulting motion is used as a measure of the magnetic field strength. To maximize the field sensitivity, the carrier frequency is set to the sensor’s natural frequency so that the motion is amplified by the mechanical quality factor, Q. However, in prior work, sensors were operated in an open-loop mode with an external frequency source used to generate the carrier frequency, adding complexity and making it difficult to ensure that the carrier frequency is identical to the resonator’s natural frequency. Any difference between these frequencies results in reduced sensitivity. Because the natural frequency is temperature dependent and the half-power bandwidth of the resonator is inversely proportional to Q, such an open-loop sensor is impractical unless the resonator has a relatively low Q and therefore relatively low sensitivity to magnetic field. The second type has a frequency modulated (FM) output and is actuated only by electrostatic force. The Lorentz force creates tensile or compressive stress on the spring of resonator, which shifts the resonant frequency and results in a FM output. Most of these sensors operate in closed-loop as oscillators. A phase-locked loop (PLL) or frequency counter is required for readout.

However, this type of magnetometer has poor performance due to their low sensitivity.

Here, we demonstrate a closed-loop Lorentz force magnetometer with AM readout driven by both electrostatic force and Lorentz force. The magnetometer resonates in plane and measures out-of-plane (z-axis) magnetic field. Instead of using an external oscillator, the resonator is connected in a self-sustaining loop as an oscillator, whose frequency tracks the resonator’s natural frequency. This configuration greatly simplifies the detection electronics as an external oscillator and PLL is not required. Compared to a magnetometer with FM readout, the operation mode demonstrated here amplifies the Lorentz force by Q, increasing the sensitivity so thermomechanical noise-limited resolution can easily be achieved. The all-silicon resonator device is fabricated in a silicon encapsulation process that results in very high Q (=13 000) and is compatible with complementary metal oxide semiconductor (CMOS) manufacturing. The resonator has a magnetic field resolution of 128 nT/rt-Hz with 2.1 mA bias current and 2.3 V bias voltage measured at room temperature. Assuming a horizontal Earth’s field of 10 μT, the angle resolution is 0.6°.

Fig. 1 shows the MEMS magnetometer, which consists of a 370 μm by 230 μm moving structure suspended with four folded springs anchored on the substrate. The structural layer is composed of 40-μm-thick highly doped single crystal silicon. The inset of Fig. 1 shows the SEM image of the magnetometer. The resistance measured across contacts IB+ to IB− is 300 Ω for each flexure. During operation, an ac bias current is applied between these contacts, as indicated by the red arrows. Parallel plate capacitors with nominal gap of 0.7 μm are connected to electrodes DR and S for in-plane capacitive driving and sensing. The magnetometer is wafer-level vacuum sealed at less than 1 Pa to reduce damping and increase the quality factor (Q).

The device is characterized in open-loop by applying a dc bias voltage to both the IB+ and IB− electrodes with no bias current. Voltage applied to the driving electrodes is used to electrostatically drive the resonator, and capacitive sensing electrodes are used to sense the motion. A digital lock-in amplifier (Zurich Instruments HF2LI) is used to sweep the
frequency of the excitation signal applied to DR, while the amplitude and phase of the motional current is recorded with an transimpedance amplifier (TIA). The fabricated device has a natural frequency $f_n = 105.9$ kHz when compared to 107.2 kHz predicted from FEM simulation. The difference is due to line width reduction from the silicon etching process. The sensor has a measured $Q$ of 13 000 and a 3 dB bandwidth of 4 Hz $= f_n/2Q$.

Fig. 2 shows the block diagram of the closed-loop system. The circuit is designed with discrete components on a printed circuit board (PCB). The oscillator loop, drawn in black, consists of a TIA that converts the resonator’s motional current into a voltage signal, followed by a limiting amplifier. Conceptually, the resonator is put into a positive feedback loop so that oscillation starts due to thermomechanical noise. The oscillation signal grows until it reaches the limiting voltage, which prevents the resonator from being driven to its nonlinear region. Oscillation occurs at $f_n$, the frequency at which the phase shift around the loop is 0°, with the oscillation amplitude controlled by the limiter voltage. The loop shown in blue indicates the bias current generation. Once the oscillation stabilizes, a voltage buffer is used to provide ac bias current for the magnetometer. The ac bias current has the same frequency and phase as the oscillation signal. The voltage buffer also provides a dc bias voltage on the moving mass of the resonator, which is necessary for capacitive driving and sensing.

The resonator’s response to the electrostatic and Lorentz force is modeled by the following equation of motion:

$$m\ddot{x} + b\dot{x} + kx = F_E + F_L,$$

where $m$ is the effective mass, $b$ is the damping coefficient, and $k$ is the stiffness. $F_E$ is the electrostatic force from capacitive driving, which is given by

$$F_E = \frac{1}{2} \frac{dC}{dx} (V_{DC} + V_{AC} \sin \omega t)^2 \approx \frac{1}{2} \frac{C_0}{g} V_{DC}^2 + \frac{C_0}{g} V_{DC}V_{AC} \sin \omega t + \frac{1}{2} \frac{C_0}{g} V_{AC}^2 \sin^2 \omega t,$$

where $C_0$ and $g$ are the capacitance and air gap of the parallel-plate electrodes, and $V_{DC}$ and $V_{AC}$ are the amplitudes of the dc and ac voltages applied to the resonator. When $\omega = \omega_n = 2\pi f_n$, the second term drives the resonator at its resonance. The first term and third term create a dc force and an ac force at twice the resonance frequency. Since a high $Q$ resonator has small gain at $2\omega_n$, these terms are neglected in the following analysis.

$F_L$ is the $x$-axis Lorentz force produced by a $z$-axis magnetic field $B\cos\omega_1t$ acting on the $y$-axis current $I\cos\omega_1t$ flowing through the resonator. The Lorentz force appears as sidebands centered around the carrier frequency $\omega_n$

$$F_L = 1/2B\ell I [\cos(\omega_n + \omega_1)t + \cos(\omega_n - \omega_1)t],$$

where $B$ is the applied field, $I$ is the bias current amplitude, and $L$ is the resonator’s effective length for Lorentz force generation, extracted as 250 $\mu$m from FEM simulation. To extract the effective length, a body force is applied to the structure for a given bias current and magnetic field to replicate the Lorentz force. The effective length is extracted from the resulting displacement.

For a dc magnetic field $(\omega_1 = 0)$, the resulting steady-state oscillation amplitude at $\omega_n$ is given by

$$x = Q \frac{g}{k} V_{DC}V_{AC} + Q \frac{B\ell I}{k}.$$

The first term is induced by the electrostatic force, and the second term is induced by Lorentz force. The electrostatic drive amplitude $V_{AC}$ is held constant by the voltage limiter; therefore, this component of the oscillation amplitude is ideally constant. The second term is dependent on magnetic field strength $B$, and the displacement sensitivity can be derived as
\[ S_x = \frac{\partial x}{\partial B} = \frac{QLI}{k}. \] (5)

To avoid oscillation at parasitic high-frequency modes, the bias current is generated from the output of the TIA rather than the output of the voltage limiter, which contains various harmonics of the \( \omega_x \), carrier. As a result, the sensitivity \( S_x \) is slightly nonlinear because the bias current varies with applied magnetic field. To ensure that this nonlinearity is negligibly small, the electrostatic oscillation is set to amplitude that is 2 to 3 orders of magnitude larger than the amplitude produced by the maximum Lorentz force.

The Brownian (thermomechanical) noise of the resonator is given by

\[ F_B = \sqrt{4k_bTb}, \] (6)

where \( k_b \) is the Boltzmann constant, \( T \) is temperature, and \( b \) is the damping coefficient. Using (3) and (6), the Brownian-noise equivalent magnetic field is given by

\[ B_{\text{min}} = \frac{\sqrt{4k_bTb}}{IL}. \] (7)

The output noise of the sensor is dominated by Brownian noise with careful design of the detection electronics.\(^{15}\) From (7), the minimum detectable field in this case is proportional to \( b \), which can be minimized by operating the resonator in vacuum, thereby increasing the resonator’s \( Q \). This also has the effect of reducing the resonator’s motional impedance, which makes the oscillation circuit less sensitive to stray capacitance.

Experiments in the closed-loop configuration were conducted by connecting the TIA output to a digital lock-in amplifier (Zurich Instruments HF2LI), which tracks the oscillation frequency and measures the amplitude of the oscillation signal. All experiments were conducted with 2.3 V dc bias on the moving mass and 2.1 mA bias current, and with the sensor operating at room temperature without temperature control. A Helmholtz coil was used to characterize the sensitivity of the magnetometer. Fig. 3 shows the amplitude spectrum of the sensor’s output in response to 4 Hz 40 \( \mu \)T ac magnetic field, which is similar to the strength of Earth’s field. The –19.2 dBV oscillation signal appears at 0 Hz offset from the carrier frequency \( f_c = 105.9 \) kHz, which is equivalent to 36 nm of displacement. The magnetic test signal appears as sidebands at 4 Hz offset from \( f_c \). Note here that the single crystal silicon resonator has a temperature coefficient of frequency (TCF) of approximately –30 ppm/°C.\(^{16}\) If the resonator is operated open-loop with a fixed excitation frequency, a 1.7°C temperature change will shift the natural frequency by 4 Hz (equal to the resonator’s 3 dB bandwidth), thereby reducing the sensitivity significantly. However, closed-loop operation ensures that the excitation frequency tracks the natural frequency, thereby maintaining maximum sensitivity.

The sensitivity of the magnetometer was measured by applying magnetic field ranging from 4 \( \mu \)T up to 400 \( \mu \)T, as is shown in the inset of Fig. 3. The magnetometer has a measured sensitivity of 12.06 V/T for dc magnetic field, which compares well with the theoretical sensitivity of 11.9 V/T.

To show that closed-loop operation maximizes the magnetometer’s sensitivity over temperature, the sensor was heated using an infrared lamp and a thermocouple (NI-USB-TC01, National Instruments) was mounted next to the magnetometer to record the temperature. Fig. 4 shows the measured scale factor over temperature. In open-loop operation, the scale factor is reduced to 3.7% of the initial value at 27°C, mainly due to the significant drift of the resonant frequency (~22 Hz), while in closed-loop, it remains 91% of the initial value. From (5), the temperature dependence of the closed-loop sensitivity can be attributed to the temperature dependence of \( Q \) and \( I \). Since the bias current \( I \) is proportional to the closed-loop oscillation amplitude in our setup, it is also proportional to \( Q \), and as a result

\[ S_x \propto Q^2 \propto \frac{1}{T^2}. \] (8)

where \( \gamma \) is the temperature coefficient of quality factor (TCQ).\(^{17}\) The value of \( \gamma \) is approximately 3.5 based on the observed temperature-dependence of the scale-factor.
the values predicted by a theoretical model, and the observed temperature. Measured sensitivity and resolution agree with the oscillator’s time constant, $Q = \frac{Q}{Q_{0}} = 39 \text{ ms}$. The zero-field oscillation amplitude is 77.80 mV and varies by $\pm 0.35 \text{ mV}$ in response to the $\pm 40 \mu T$ input, corresponding to a magnetic field sensitivity of 12.37 V/T. The measured resolution is 128 nT/rt-Hz, close to the theoretical limit of 110 nT/rt-Hz. Although the oscillation amplitude is stable over the time scale shown in Fig. 5, for longer measurement times, the sensor’s resolution is limited by drift in the oscillation amplitude.

In conclusion, we demonstrate a closed-loop Lorentz force magnetometer using a micromechanical oscillator. Electrostatic force is used to close the oscillation loop, providing a frequency reference for Lorentz force generation. The method proposed in this work has the advantage of tracking the resonator’s natural frequency without an external oscillator, thereby maintaining maximum sensitivity over temperature. Measured sensitivity and resolution agree with the values predicted by a theoretical model, and the observed noise-equivalent magnetic field, 128 nT/rt-Hz, is comparable to or better than the performance of silicon Hall sensors currently used as electronic compasses in consumer electronics.

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FIG. 5. Sensor response to a $\pm 40 \mu T$ dc magnetic field over 60 s. The magnetic field is reversed with a period of 6 s. The oscillation amplitude is 77.80 mV without magnetic field applied, and it varies by $\pm 0.35 \text{ mV}$ when the external $40 \mu T$ field is applied.