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Ultra-sensitive NEMS magnetoelectric sensor for picotesla DC magnetic field detection

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We report a highly sensitive NEMS DC/low frequency magnetic field sensor consisting of an AlN/FeGaB resonator, with a ∆E effect-based sensing principle. Unlike previously reported magnetic field detection schemes, such as observing induced magnetoelectric voltage, or monitoring impedance, we designed a system to directly measure the reflected output voltage from the sensor as a function of magnetic field. The AlN/FeGaB resonator shows a resonance frequency shift of 3.19 MHz (1.44%), which leads to a high DC magnetic field sensitivity of 2.8 Hz/nT and a limit of detection of 800pT in an unshielded, room temperature and pressure, lab environment.

Recently, MEMS magnetic field sensors have been of great interest due to their possible applications in magnetic anomaly detection, magnetoencephalography (MEG), and magnetocardiography (MCG).1 In these applications, magnetic field sensors should be able to detect magnetic fields in the picotesla range at DC or low frequencies (<10 Hz). Sensors based on various mechanisms have been reported, but low values of sensitivity and complex actuation requirements and/or sensing mechanisms limit the application of these devices.2 Magnetic field sensors utilizing magnetostrictive/piezoelectric magnetoelectric composites have been widely studied in the recent years.3,4 In such composites, the piezoelectric and magnetostrictive phases are mechanically coupled; thus, the strain induced in the magnetostrictive phase transfers to the piezoelectric phase, enabling the detection of magnetic field. More specifically, two detection mechanisms have been reported in magnetoelectric MEMS magnetic sensors: one is to measure directly induced magnetoelectric voltage and the other is to monitor admittance changes of the resonator. In an FeCoSiB/aluminum nitride (AlN) thin film cantilever heterostructure, magnetic field was sensed by strain induced magnetoelectric voltage.5 However, 1/f noise is the dominant noise source at DC or low frequencies, so the sensitivity of the sensor was limited. In magnetoelectric magnetic sensors using a high frequency contour mode AlN resonator, the admittance of the resonator was monitored by a network analyzer under different magnetic fields, with shifts of the admittance resonance peaks reflecting changes in the DC field.6

In this work, we fabricated and tested AlN/FeGaB resonator magnetic field sensors. The advantages of an AlN piezoelectric resonator are high working frequency, high quality factor, and high power efficiency. Coupled with highly magnetostrictive and magnetically soft magnetic FeGaB material, such a sensor can potentially detect extremely small magnetic fields.

We present a unique experimental method to obtain the resonance frequency of the sensor. An ultra-high frequency lock-in amplifier was used to directly measure the sensor’s reflected output voltage. This approach was easier and more convenient than measuring admittance (e.g., with a network analyzer).7 The magnetic field sensitivity and limit of detection to static DC magnetic field of the AlN/FeGaB resonator magnetic field sensor were explored.

Figure 1 shows the 3-dimensional schematic of the Nanoelectromechanical systems (NEMS) resonant magnetic field sensor. Piezoelectric AlN film is sandwiched between a magnetostrictive FeGaB layer and interdigital electrodes (IDE). IDE is utilized to excite and sense the contour-extensional mode of vibrations in the AlN film. The Young’s modulus of the FeGaB layer, $E_m$, changes under external magnetic fields due to the ∆E effect of magnetostrictive materials. Thus, the equivalent Young’s modulus of the resonator, $E_{eq}$, is affected. Al2O3 layers were used as interlayers in between FeGaB layers to decrease eddy current losses at RF frequency. They are not shown in Figure 1.

Figure 1. 3D schematic of NEMS AlN resonant magnetic sensor. From top to bottom, the materials for each layer are magnetostrictive layer, piezoelectric layer, and interdigitated electrodes.

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The resonance frequency of the sensor is given by Equation (1)

\[ f = \frac{1}{2w_0} \sqrt{\frac{E_{eq}}{\rho_{eq}}}, \]  

where \( w_0 \) is the pitch between electrode fingers and \( \rho_{eq} \) is the equivalent density of the device. \( E_{eq} \) and \( \rho_{eq} \) can be calculated by \( E_{eq} = \Sigma E_i \nu_i \) and \( \rho_{eq} = \Sigma \rho_i \nu_i \), respectively, where \( E_i \) is the Young’s modulus, \( \rho_i \) is the density, and \( \nu_i \) is the volume ratio for each layer in the device.

FeGaB is used as the magnetostrictive material in the design of our NEMS resonator magnetic sensor due to its high magnetostrictive properties and \( \Delta E \) effect. 250 nm FeGaB film was sputter-deposited onto silicon strips with dimensions of 35 mm \( \times \) 3.5 mm \( \times \) 150 \( \mu \)m. The magnetostrictive properties of those samples are calculated following Klokholm’s cantilever method.\(^8\) When a bias magnetic field is applied perpendicular to the magnetic film’s easy axis, the resulting magnetostrictive strain in the film forces the bilayer cantilever structure into a bending deflection; this deflection is linearly proportional to the magnetostrictive constant. Here, we utilized a high precision fiber-optical sensor with sensitivity of 4.6 nm/mV to detect this deflection. A saturation magnetostriction constant \( \lambda_s \) of 70 ppm and a maximum change of over 150 GPa \( E_m \) were obtained. Such vast changes in \( E_m \) will result in a large shift of resonance frequency of the device.

The piezoelectric AlN resonator was fabricated by a five-mask microfabrication process. A 50 nm thick platinum (Pt) film was deposited by sputtering and patterned by lift-off on top of a high resistivity silicon wafer. Then, a 250 nm thick AlN film with stress of \(-62\) MPa and full width at half maximum (FWHM) of 1.53° was deposited by OEM Group, Inc. \( \text{H}_3\text{PO}_4 \) was used to etch the AlN film to expose the bottom Pt IDE. Next, a 100 nm thick gold (Au) film was evaporated and patterned to form probing pads electrically connected to the IDE. The shape of the resonator was defined by inductively coupled plasma (ICP) etching. Then, FeGaB/Al\(_2\)O\(_3\) multilayers were deposited by sputtering and patterned by lift-off. During deposition, a 650 Oe bias magnetic field was applied along the width direction of the resonator to align the magnetic domains. Finally, the resonator plate was released by XeF\(_2\) isotropic etching of the silicon substrate. A 10 nm thick Al capping layer was used to protect the magnetostrictive layers from XeF\(_2\) during release. Figure 2 shows an optical image of the NEMS resonator magnetic field sensor.

The fabricated NEMS resonator magnetic field sensor was tested in an RF probe station under a DC magnetic field applied by a solenoid coil along the length of the device. An ultra-high frequency (UHF) lock-in amplifier (Zurich Instruments, Switzerland) and a directional coupler (Mini Circuits, USA) were used to apply and test the RF signal. The measurement setup is illustrated in Figure 3.

For AlN NEMS resonator sensor applications reported previously, a network analyzer was used to monitor the admittance of the device.\(^6,7\) Extra calculations and analysis were needed to present the parameter of interest. Here, we used the UHF lock-in amplifier to directly observe the reflected output voltage as a function of frequency or applied magnetic field. The output voltage signal from the UHF lock-in amplifier was applied to the AlN film, and the reflected voltage was measured by the input port. At resonance, more power was absorbed by the resonator, with less power reflected, so a downward peak was observed. Using this simplified test process, the reflected output voltage of the sensor corresponding to the applied magnetic field could be directly measured.

Various thicknesses of FeGaB films were deposited to compare the resonance frequency of the resonator magnetic sensors, as shown in Figure 4. The Young’s modulus of FeGaB film has not been reported yet. Here, we used a non-linear curve fitting function in Origin 9.0 to find the Young’s modulus of FeGaB film. The effect of anchors on resonance frequency of the resonator was neglected. The dashed line in Figure 4 shows the fitted curve to the experimental data by Equation (1) and the parameters listed in Table 1. It was found that the Young’s modulus of FeGaB film \( E_m \) was 215 GPa. Because FeGaB film has a lower Young’s modulus, but higher density, than AlN film, thicker
FeGaB film simultaneously decreased the value of $E_{eq}$ and increased the value of $q_{eq}$ of the device. Thus, the device resonance frequency decreased.

When under bias DC magnetic field, the value of $E_m$ changes according to the $D_E$ effect induced by magnetostriction in FeGaB films. This change of $E_m$ affects $E_{eq}$, and as a result, the resonance frequency of the resonant magnetic field sensor shifts. The output voltage of the device was recorded for various DC magnetic fields, as the driving frequency of the UHF lock-in amplifier was swept from 223 MHz to 228 MHz, as shown in Figure 5. When the DC magnetic field was increased, the magnetic domains were rotated towards the field direction. This process leads to higher energy loss, resulting in a broader bandwidth of curves, which represents lower quality factor $Q$ of the device. As the DC magnetic field was further increased, the reorientation process of magnetic domains was completed. Thus, the $Q$ factor of the curves became higher again.

By conducting many frequency sweeps, each under a different DC magnetic field, more voltage response curves, like the examples in Figure 6, were collected, and the resonance frequency for each DC field value was calculated by a Matlab program. Figure 6 shows the resulting resonance frequency changes as a function of DC bias magnetic field in the range between 0 and 150 Oe. It can be seen that as the magnetic field increases from 0 Oe to 8.82 Oe, the resonance frequency decreases from 225.71 MHz to a minimum value of 223.53 MHz, indicating that the value of $E_m$ is minimal at this field. This field of 8.82 Oe corresponds to the position where the piezomagnetic coefficient $d_m = d_k/dH$ is highest, where the magnetic domains in the FeGaB films are easily rotated by the magnetic field. When the DC magnetic field was further increased, the resonance frequency of the sensor increased and saturated at 49.05 Oe, with a maximum resonance frequency of 226.72 MHz. The total shift of resonance frequency in the sensor with FeGaB film was 3.19 MHz, or 1.44%. Under a DC bias field of 12 Oe, the AlN/FeGaB resonator magnetic field sensor has a sensitivity of 2.8 Hz/nT.

To investigate the smallest magnetic field that could be detected by the resonator magnetic field sensor, defined as limit of detection (LOD), a second coil was driven by a precision current source (Keithley 6220) to apply an extremely small change of DC magnetic field. The oscillator and demodulator of the UHF lock-in amplifier were fixed at 225.8 MHz, which is near the resonance frequency of the sensor under a bias field of 12 Oe, and the bandwidth was set to 1 Hz. The sensor response at 225.8 MHz was recorded, with the noise level in the unshielded lab environment being $1.8 \times 10^{-6}$ V. A standard lab table without vibration isolation was used.

Figure 7 shows the output voltage of the resonator magnetic sensor under small changes of DC magnetic field. The output voltage of the sensor at 225.8 MHz decreased, as the amplitude of the DC magnetic field decreased. When the DC magnetic field was smaller than 800 pT, the change of output voltage of the sensor was overwhelmed by noise and could not be detected.

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**TABLE I. Parameters of the resonator magnetic field sensor.**

<table>
<thead>
<tr>
<th>Materials</th>
<th>Young’s modulus (GPa)</th>
<th>Thickness (nm)</th>
<th>Density ($kg/m^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AlN</td>
<td>350$^a$</td>
<td>250</td>
<td>3260</td>
</tr>
<tr>
<td>Pt</td>
<td>168</td>
<td>50</td>
<td>21400</td>
</tr>
<tr>
<td>Al</td>
<td>70$^a$</td>
<td>10</td>
<td>2700</td>
</tr>
<tr>
<td>FeGaB</td>
<td>215$^b$</td>
<td>100–350</td>
<td>7600</td>
</tr>
</tbody>
</table>

$^a$Cited from Ref. 9.

$^b$Nonlinear curve fitting from data in Figure 4.

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**FIG. 4.** The resonance frequency of FeGaB/AlN magnetic sensor as a function of thickness of FeGaB films. The dash line shows the fitted curve by Equation (1); the red dots show the experimental results. The Young’s modulus of FeGaB film was found to be 215 GPa.

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**FIG. 5.** The measured output voltage curves of the FeGaB/AlN resonator magnetic field sensor under different DC magnetic fields. The increase of bandwidth at resonance frequency is due to the energy loss in the reorientation process of the magnetic domains.

**FIG. 6.** The resonance frequency of the resonator magnetic field sensor under various DC magnetic fields. The maximum shift of resonance frequency is 3.19 MHz, by a ratio of 1.44%. The magnetic field sensitivity was 2.8 Hz/nT at 12 Oe DC bias field.
not be observed. Thus, we can conclude that the LOD of our resonator magnetic sensor is 800 pT. Compared to the previous report, in which a sweeping of the bias field was used to measure LOD,\(^7\) we obtained the LOD in a static DC magnetic field.

To further improve the LOD of the sensor, the choice of fixed frequency and bias field can be analyzed and optimized. We believed that the device was most sensitive at 225.8 MHz but did not investigate this thoroughly. Also, the noise level of \(1.8 \times 10^{-6} \text{ V}\) was much higher than \(4nV/H\), the voltage noise of the UHF lock-in amplifier. By identifying and reducing sources of noise, the LOD could be further improved.

We reported an ultra-miniaturized, power efficient, high-sensitivity, and high-resolution NEMS AlN/FeGaB resonator magnetoelectric magnetic field sensor. Our testing setup enabled direct measurements of reflected output voltage and the monitoring of resonance peak shifts corresponding to changing magnetic field. As varying strengths of DC magnetic fields were applied, the resonance frequency of the magnetic field sensor changed by a maximum of 3.19 MHz, or 1.44 %, resulting in a high magnetic field sensitivity of 2.8 Hz/nT. An experimental limit of detection of 800 pT in static DC magnetic field was achieved. These results indicate the potential of this sensor for detecting extremely low levels of magnetic field.

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