Frequency tunable resonant magnetoelectric sensors for the detection of weak magnetic field

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Abstract
This paper reports on frequency tunable MEMS magnetoelectric (ME) sensors. Different designs are studied in respect to ME voltage coefficient and frequency tunability. Compared to state-of-the-art ME sensors, the presented ME resonators display a highly reversible and linear frequency tuning, enabled by applying a DC voltage to piezoelectric actuators. A frequency shift of up to 0.2 Hz V\(^{-1}\) is demonstrated for a sensor with a limit of detection of 128 pT/Hz\(^{0.5}\) at resonance frequency of 13 kHz. This sensor type is of particular interest for vector field sensors and sensor arrays in bio-magnetic applications, where sensors with either identical resonance frequencies or precisely defined frequency spacing are required.

Keywords: MEMS, magnetoelectric sensor, piezoelectric, frequency tuning

Some figures may appear in colour only in the online journal

1. Introduction
MEMS sensors based on magnetoelectric (ME) composites have attracted great interest due to their capability to detect magnetic fields in the pT regime at low frequencies, showing a high potential in applications like biomagnetic field detection, magnetic particle imaging and antennas [1–5]. According to the current state of the art, superconducting quantum interference devices (SQUIDs) are the most commonly used ultra-high sensitive low-field magnetometers in biomedical applications like magneto-encephalography or -cardiography (MEG, MCG) [6]. However, the arrays of SQUIDs in MEG or MCG applications require a costly cooling system with liquid helium to minimize the instrumental noise and a shielded room for operation [7, 8]. Due to their bulky cooling system, SQUID sensors have a greater distance to the bio-magnetic source (i.e. the human brain or the human heart) than the room temperature sensors [7] and thus require a significantly better sensitivity for the same measurement task. Due to the aforementioned limitations of SQUIDs, MEMS ME sensors with small size, showing a high sensitivity in biomagnetic field detection at room temperature, are of particular interest [1, 9].

MEMS sensors based on ME composites are comprised of mechanically coupled magnetostrictive and piezoelectric materials. The presence of a magnetic field leads to a change in the strain of the magnetostrictive layer which is transferred to the piezoelectric material via the mechanical coupling. An electrical voltage across the piezoelectric layer is thus generated [10, 11]. As a figure of merit of ME sensors, ME voltage coefficient \(\alpha_{\text{ME}}\) describes the change of the electric field in dependence of the magnetic field strength given by equation (1) [9]:

\[
\alpha_{\text{ME}} = \frac{U_{\text{ME}}}{l_{\text{piezo}} \cdot H_{\text{ac}}}
\]

where \(U_{\text{ME}}\) is the voltage output of the sensor, \(l_{\text{piezo}}\) is the thickness of the piezoelectric layer and \(H_{\text{ac}}\) is the applied alternating excitation magnetic field.

As the ME effect provides a high sensitivity already at room temperature, a cooling system can be omitted. MEMS ME sensors can be vacuum encapsulated using wafer-level packaging (WLP) technology which protects the sensors during handling and from environmental influences [12]. Moreover,
The vacuum environment significantly reduces the laminar damping resulting in a higher quality factor Q [13, 14]. For the use in medical applications, WLP MEMS ME sensors have small size and thus can easily be assembled in flexible sensor arrays adapted to different diagnostic requirements.

Resonant thin film ME sensors exhibit a significant enhancement of the ME coefficient in resonance over a narrow bandwidth [15]. To enable wideband measurement and allow these sensors to measure low frequency signals, frequency conversion through AC magnetic [16, 17] or electric fields [17, 18] has been developed. For specific applications, the development of vector field sensors and sensor arrays requires either identical resonance frequencies or precisely defined frequency spacing. For instance, to detect the artificial magnetic signal of deep brain stimulation, the resonance frequency of ME sensor has to be tuned to the stimulus frequency of brain pacemaker or its higher harmonics [19]. To build up tuning fork ME sensors which are designed to reduce the acoustic noise, ME sensors with identical resonance frequencies are required [20]. These are just a few examples for which tunable sensors are a great help or even an enabler. It is therefore very important to fabricate sensors with exactly reproducible resonance frequencies. However, manufacturing tolerances typically in the order of a few percent cannot be avoided and are far above the tolerable range in such applications which is the bandwidth Δf of the sensor. For high Q, the bandwidth of ME sensors Δf = f_0/Q is typically in the per mill range or below. Thus, there is a need to develop ME sensors with the ability to tune their resonance frequency. Few resonance frequency tuning methods for ME sensors have been reported. Röbisch et al presented a ME sensor based on shape memory alloy substrate whose frequency is tuned by changing the microstructure of the substrate via temperature [21]. Petrie et al discussed a technique to tune the resonance frequency by applying an in-plane tensile force via a suspended weight [22]. Wang et al studied a frequency shift method for ME sensor via an inductor–capacitor (LC) circuit [23].

In this paper, we present two vacuum encapsulated tunable ME sensors with integrated piezoelectric actuators (figure 1(II) and (III)) [24]. A standard design cantilever ME sensor using the same fabrication technology is presented as a reference (figure 1(I)). It is the first time that a low-stress polycrystalline silicon (poly-Si) layer as a substrate is integrated into ME sensors using surface micromachining process. As the amorphous magnetostrictive material FeCoSiB used in this work is temperature sensitive and its crystallization happens at a temperature above 350 °C [25], a wafer level AuSn transient liquid phase (TLP) bonding process [12] with low bonding temperature of 330 °C is applied.

The paper is organized as follows: first, the sensor concepts are discussed in section 2. In section 3, the fabrication and the measurement setup are presented. Then the characterization results of the tunable sensors are discussed and compared to the reference sensor in section 4. Finally a conclusion is given.

2. Sensor concepts

Simplified schematic illustrations of the ME sensors are sketched in figure 1. The reference (sensor I) is a clamped-free cantilever with a poly-Si layer (12 μm) as substrate and ME composites consisting of AlN (1 μm)/FeCoSiB (2 μm). In the previous technology, ME sensors are designed based on a 650 nm thin SiO₂ substrate [11, 13]. These sensors face problems like low quality factor Q and undesired bending of the structure due to residual stress in the functional layers. Here, a 12 μm thick low-stress poly-Si substrate is integrated to ME sensors using surface micromachining process as we have extensive in-house processing experience of polycrystalline silicon. The introduction of the poly-Si layer increases the Q factor and reduces the impact of the stress from other layers on ME sensors. It also reduces the requirements for adjusting the intrinsic mechanical stress of the ME functional layers. Moreover, a great design flexibility is given by a stiff elastic substrate providing the possibility to realize mechanically coupled resonators. The deposited magnetostrictive layer has a magnetic easy axis along the short axis of the cantilever (figure 1(I)). Applying a magnetic bias field H_{bias} and an alternating magnetic field H_{ac} pointing to the long axis of...
1. the cantilever shifts the operating point in the magnetostriction curve. At optimal magnetic bias field $H_{bias}$, where the derivative of the magnetostriction with respect to the applied magnetic field reaches its maximum, a maximum ME voltage coefficient is reached [9].

Sensor II is a double-side clamped coupled resonator. The middle beam with a stack of poly-Si/AlN/FeCoSiB is used as the magnetic field sensing element for piezoelectric readout. The outer piezoelectric actuator beams consist of poly-Si and the piezoelectric layer (AlN). An applied DC voltage to the outer beams leads to a displacement of the piezoelectric layer via the inverse piezoelectric effect. As the piezoelectric layer is coupled to a thick poly-Si layer with high stiffness, a stress induced by the displacement is generated in the outer beams. As all three beams are mechanically coupled and clamped on both sides, the displacement-induced stress is transferred to the whole structure. The resonance frequency is tuned by changing the stress in the structure via the applied voltage. In comparison to sensor I, a reduced sensitivity but a distinct frequency shift is expected for sensor II because the double-sided clamped structure limits the bending but also reduces stress relaxation.

To increase sensitivity, sensor III is designed as a clamped-free structure consisting of three parallel cantilevers. All three beams have exactly the same stack with the reference (sensor I) to achieve a comparable performance. To enable tuning, the actuators (outer cantilevers) and the sensing element (inner cantilever) are coupled via a poly-Si bar at the tip of the cantilevers. Similarly, the output voltage of the centre beam responding to the AC magnetic field is recorded, and the outer beams are used as piezoelectric actuators. The resonance frequency of sensor III can be tuned by applying a voltage to the outer beams to change the beam stiffness.

3. Experimental methods

3.1. Sample fabrication

ME sensors have been fabricated using a surface micromachining process. All three ME sensors presented in this paper are manufactured on the same wafer. The process flow of the device is presented in figure 2.

The process of the device wafer starts with the deposition of a polished 12 µm thick low stress poly-Si layer on an oxidized Si wafer. After the deposition of an additional PECVD SiO$_2$ isolation layer (650 nm), the bottom electrode with 20 nm Ti and 100 nm Pt is evaporated and structured by a lift-off process. The next step is to sputter deposit 1 µm piezoelectric layer of AlN and 100 nm Mo as top electrode. The wet etching of AlN is performed in tetramethylammonium hydroxide (TMAH) at 82 °C using the structured Mo as a hard mask (figure 2(1)). A low stress passivation layer SiN$_x$ with a thickness of 1 µm is introduced after the deep reactive-ion etching (DRIE) of poly-Si for the cavity openings (figure 2(2)). Dry etching is used to define the openings of SiN$_x$ to the electrodes, enabling the connection to the contact pads via Au conductors. The bond frames with a thickness of 4 µm Au are electroplated at the same time with the contact pads and contact lines (4 µm) using Ti/Au as electrode plating base (figure 2(3)). A stack of Ta (10 nm)/FeCoSiB (2 µm)/Ta (50 nm) is sputter deposited under a magnetic field and structured by ion beam etching. After a 100 nm Cr layer is sputtered to protect
the cap wafer and the device wafer are diced in sequence. At the beginning of the process, the wafer and the device are diced in sequence. After the alignment of the cap and the device wafer, the wafers are brought into contact at 330 °C for 30 min and cooled down. The whole bonding process takes place under a pressure of 5 × 10^−3 mbar.

The vacuum encapsulation is performed using a wafer-level AuSn TLP bonding process [12]. The temperature and the chamber pressure during the bonding process are plotted in figure 3. After the alignment of the cap and the device wafer, the bonding process begins. The bonding parameters are 600 nm SiO2 deposited on the cap wafer substrate, with 4 μm Au and 3 μm Sn electroplated using a Ti/Au plating base. The Ti getter material is deposited into the cap wafer cavities by lift-off procedure.

The cap wafer cavities are etched by KOH using PECVD SiN as a hard mask. Followed by the removal of the hard mask, the wafer is etched using a KOH solution. After 6 h of etching, sensor I and II are completely released, while in the case of sensor III, one third of the middle beam is still fixed to the substrate (compared to the dotted line in figure 1(III)). A longer etching time is not preferred here because there is a high risk that the structures might be destroyed. Even though the inner beam of sensor III is not completely released in this case, the performance of the sensor is not expected to change significantly except a higher resonance frequency.

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sensor. From the preliminary investigations, the maximum ME voltage coefficient was achieved at a magnetic bias field \( \mu H_{\text{bias}} \) of 0.8 mT for sensor I, 0.5 mT for sensor II and 0.9 mT for sensor III. Operating at their optimal bias fields, the ME coefficients of all three sensors at resonance (when driven with an excitation magnetic field \( \mu H_{\text{ac}} \) of 1 \( \mu T \)) are shown in figure 6. It can be seen that all sensors show the highest ME coefficient at their mechanical resonance. The resonance frequencies \( f_{\text{res}} \) of 8200 Hz, 11 195 Hz and 13 043 Hz are measured for sensor I, II and III respectively. The resonance frequencies differ for all three sensors as they differ in designs. Considering the manufacturing tolerances, the resonance frequency of sensor I is in good agreement with finite element analysis (FEA) calculation (only considering the mechanical part of the sensor geometry). In contrast, the resonance frequencies of sensor II and III differ slightly from FEA results. This might due to the intrinsic stresses in the layers (most prominent in the magnetic layer). In resonance, the ME coefficients of 661 V cmOe\(^{-1}\) for sensor I, 22 V cmOe\(^{-1}\) for sensor II and of 424 V cmOe\(^{-1}\) for sensor III have been measured. A relative error of 5\% is estimated for all three sensors from repeated measurements. It is mainly caused by the uncertainties of the magnetic fields generated by the coils and positioning, i.e. aligning the sensors within the coils. The Q factors of about 1800, 1600 and 1900 are determined from the bandwidth for sensor I, II and III, respectively. Among all devices, sensor II has a significantly smaller ME coefficient due to the limited bending of its double-side clamped structure. Between the clamped-free cantilevers with the same length, sensor I has a higher ME coefficient than sensor III which is related to its lower resonance frequency, resulting in a higher amplitude and thus higher ME coefficient under the same excitation magnetic field. In comparison to similar ME sensors from Marauska \textit{et al} [11, 13] and Yarar \textit{et al} [27], higher quality factors are achieved for all sensors. This fact can be explained mainly by the following two reasons. The sensors are vacuum encapsulated and the vacuum environment significantly reduces the air damping and thus enhances the quality factor [13, 14]. Secondly, a poly-Si substrate is integrated to the ME sensors, reducing the oscillation losses in resonance due to the ideal elastic properties of this material and a high Q is thus obtained. Other design related loss mechanisms such as anchor losses are crucial for an in-depth comparison of the different sensor types, but are outside the scope of this work.

The voltage noise density \( E \) of the investigated sensors is measured and shown in figure 7. The noise of the audio
Figure 6. ME coefficient $\alpha_{ME}$ at the mechanical resonance (1st bending mode). Sensor I has a ME coefficient of 661 V cmOe$^{-1}$ at 8200 Hz with a Q of 1800. Sensor II has a ME coefficient of 22 V cmOe$^{-1}$ at 11 195 Hz with a Q of 1600. Sensor III has a ME coefficient of 424 V cmOe$^{-1}$ at 13 043 Hz with a Q of 1900.

Figure 7. Voltage noise density spectra of sensor I, II and III were recorded at optimal magnetic bias field $|\mu H_{bias}| = 0.8$ mT, 0.5 mT and 0.9 mT, respectively. The noise of the audio interface is recorded as a reference. The noise density at resonance is determined as 101 nV/Hz$^{0.5}$ for sensor I, 100 nV/Hz$^{0.5}$ for sensor II and 54 nV/Hz$^{0.5}$ for sensor III. A comparison of measured and calculated noises [28] of sensor I is shown in the inset plot.

The intrinsic sensor noise can be derived. The calculated values of $E_{model}(f_{res})$ are in good agreement with measurements (figure 7 inset) not only for the single cantilever structure (sensor I, $E_{model}(f_{res}) = 105$ nV/Hz$^{0.5}$) but also for the more complex structures (sensor II and III, $E_{model}(f_{res}) = 96$ nV/Hz$^{0.5}$ and 40 nV/Hz$^{0.5}$, respectively).

From the values of the voltage noise density $E(f_{res})$ and ME voltage coefficient $\alpha_{ME}(f_{res})$, the limit of detection (LOD) can then be derived [9]:

$$\text{LOD}(f_{res}) = \frac{E(f_{res})}{t_{piezo} \cdot \alpha_{ME}(f_{res})}$$  \hspace{1cm} (2)

Therefore, the LOD for sensor I is 153 pT/Hz$^{0.5}$, 4.6 nT/Hz$^{0.5}$ for sensor II and 128 pT/Hz$^{0.5}$ for sensor III. As all three sensors have been fabricated from the same wafer, $t_{piezo}$ is the same for all sensors so that the relative changes in
LOD are given by the ratio of the noise to ME coefficient only. High $\alpha_{ME}$, lowest noise and in total best LOD are measured for sensor III. Although sensor I has the highest ME coefficient, the increase in noise yields a reduced LOD. The worst LOD is found for sensor II as expected.

To study the frequency tuning behaviour, an additional DC voltage is symmetrically applied (same voltage to both outer cantilevers) to the piezoelectric actuators of the tunable sensors II and III. All other measurement parameters are kept the same.

The ME coefficient of sensor II response to the applied voltage in resonance is plotted in figure 8. The resonance frequency of sensor II can be tuned as expected when a DC voltage is applied. With an increasing DC voltage from $-100 \text{ V}$ to $100 \text{ V}$ (the bottom electrode is defined as ground), the resonance frequency of sensor II increases from $11.149 \text{ Hz}$ to $11.243 \text{ Hz}$. The same qualitative tuning effect is found for sensor III. The resonance frequency shift of sensor II and III with the applied tuning voltage is shown in figure 9. It reveals that both sensors show a linear tuning of the resonance frequency in the investigated voltage range. Sensor II has a frequency shift coefficient of $0.41\%$ per $100 \text{ V}$ which is about three times larger than the sensor III with a frequency shift of $0.14\%$ per $100 \text{ V}$. Since sensor III has a clamped-free structure, the pre-stress on the structure generated by the applied voltage is partially released through displacement. Therefore, in comparison to sensor III, sensor II has a higher stress concentration on its double side clamped structure, resulting in a larger frequency shift. In particular, both sensors exhibit a highly reversible and hysteresis-free frequency tuning behavior, which is due to the linearity of the piezoelectric material AlN.

The measurement results of sensor I (reference sensor), II and III are summarized in table 1. It can be seen that sensor III has the best LOD which is by a factor of 36 lower compared to sensor II. Although sensor I has the highest ME coefficient of $661 \text{ V cmOe}^{-1}$, the LOD of sensor III is as good as the standard ME sensor. The frequency shift coefficients of $0.5 \text{ Hz V}^{-1}$ and of $0.2 \text{ Hz V}^{-1}$ are measured for sensor II and III respectively. However, the difference of the frequency shift coefficient between sensor II and III is not too large. As a result, sensor III with frequency tuning property shows an excellent performance comparable to the standard cantilever ME sensor.

| Sensor | $|\mu_{HAC}|$ (mT) | $f_{res}$ (Hz) | $\alpha_{ME}(f_{res})$ (V cmOe$^{-1}$) | $E(f_{res})$ (nV/Hz$^{0.5}$) | $Q$ | LOD($f_{res}$) (pT/Hz$^{0.5}$) | $\Delta f$ (%/(100 V)) | $\Delta f$ (Hz/V) |
|--------|----------------|------------|---------------------------------|-----------------|-----|----------------|------------------|----------------|
| I      | 0.8            | 8200       | 661                             | 101             | 1800 | 153             | –                | –               |
| II     | 0.5            | 11195      | 22                              | 100             | 1600 | 4563            | 0.41             | 0.5             |
| III    | 0.9            | 13043      | 424                             | 54              | 1900 | 128             | 0.14             | 0.2             |

In comparison to the tunable ME sensors from Röbisch et al [21] and Wang et al [23], the presented sensor III has several distinct advantages in spite of a slightly higher limit of detection and a smaller frequency tuning. Based on its linear frequency tuning effect, the applied voltage, which can tune the resonance of the sensor to match the targeted frequency of the proposed applications, can be easily estimated. Due to its small size it can be easily assembled in flexible sensor arrays adaptable to different diagnostic requirements enabling better localization. In addition, it is suitable for mass production using MEMS technology.

**5. Conclusion**

In this study, we presented two vacuum encapsulated MEMS ME sensors with highly reversible quasi-linear frequency tuning effect. The presented frequency tuning method via integrated piezoelectric actuators can be easily controlled and is highly reproducible. Sensor II has a high frequency tuning coefficient of about $0.5 \text{ Hz V}^{-1}$ with a LOD of $4.6 \text{ pT/Hz}^{0.5}$ while sensor III has a LOD of $128 \text{ pT/Hz}^{0.5}$ with a frequency tuning coefficient of about $0.2 \text{ Hz V}^{-1}$. In addition, the performance of sensor III for magnetic field sensing is not significantly affected by introducing piezoelectric tuning, which...
enables ME sensors for measuring very weak magnetic fields with a precise control of the filter frequency (resonance). In summary, the combination of excellent performance for magnetic field detection and frequency tuning in a ME sensor was demonstrated which is highly beneficial for the development of vector field sensors and sensor arrays.

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