MEMS Magnetic Field Sensor Based on Magnetoelectric FeCo/ZnO Thin Films

Jitendra Singh
Smart Sensors Area
CSIR-Central electronics Engineering Research Institute
Pilani, India
jitendra@ceeri.res.in

Ramesh Kumar
Smart Sensors Area
CSIR-Central electronics Engineering Research Institute
Pilani, India
ramfagana123@gmail.com

Ajay Kumar
Smart Sensors Area
CSIR-Central electronics Engineering Research Institute
Pilani, India
karnalajayk@gmail.com

Surajit Das
Smart Sensors Area
CSIR-Central electronics Engineering Research Institute
Pilani, India
surajitceeri@gmail.com

Prateek Kothari
Smart Sensors Area
CSIR-Central electronics Engineering Research Institute
Pilani, India
prateekati@gmail.com

Chelvane J. Arout
Advanced Magnetics Laboratory
Defence Metallurgical Research Laboratory, Kanchanbagh
Hyderabad, India
aroutchelvane@gmail.com

***Abstract*— We have developed a microelectromechanical systems (MEMS) based magnetic field sensor utilizing FeCo/ZnO magetoelectric thin films. The micro-cantilever beam stack consists of Si/SiO$_2$/Pt/ZnO/Pt/FeCo multilayers for self-actuation and sensing of devices. The mechanical resonance frequency of sensor was experimentally observed at 10.45 kHz measured using laser Doppler vibrometer (LDV) The sensor and quality factor was obtained ~593. The sensor lateral dimension was 1360µm×180µm and overall layer stack thickness was 7.9 µm. The packaged device dimension measured was 20mm×10mm. Device sensing performance was measured using a customized magetoelectric measurement set-up and magnetic field sensitivity was 57.6 mV/Gauss in an unshielded environment. The proposed sensor has key advantages such as small size, light weight, low cost, non-invasive and high resolution.**

Keywords—MEMS, magetoelectric, magnetic, sensor

I. INTRODUCTION

Magnetic field sensors are essential components of modern devices and serving human society for many decades. For example, magnetic field sensors have vast applications in computer memory, hard disk, non-contact switching, navigation and linear/angular position sensing. Further, magnetic field sensors found useful applications in robotics and automation industry because of contact less and remote sensing and actuation. The new emerging application of magnetic sensor is related to mobile phones navigation which is also related to electronic compass.

Based on working principle, there are various types of magnetic field sensors like search coil, flux-gate, optically pumped, nuclear precession, SQUID, hall effect, magneto-resistive, magneto-diode and fiber-optic magnetometers. With recent development of new materials and devices, magnetic sensors can be based on magetoelectric effect.

Detection of low level ac magnetic signal (nano-tesla) is a major challenge from technology point of view. Emergence of micro-electro-mechanical systems (MEMS) has made it possible to fabricate small size and light weight magnetic sensing devices. Usually, magnetic sensors are bulky and therefore, use of such sensors is very limited. Small size, high sensitive magnetic field sensors are required to monitor such low level magnetic signals. MEMS magnetic field sensors based on magnetic nanocomposites can be possible alternate in bio-sensing. Further, MEMS based sensors has key advantages like small size, light weight, low cost, non-invasive and high resolution. MEMS magnetic sensors shows high sensitivity at their mechanical resonance frequency. Therefore, MEMS based magnetic field sensors has huge potential for bio-magnetic signal detection and navigation.

Modern design and fabrication method has allowed to realize efficient sensors with enhanced functionalities. Detection of low level magnetic signal (pico- and femto-tesla) is a major challenge from technology point of view. Emergence of micro-electro-mechanical systems (MEMS) has made it possible to fabricate small size and light weight magnetic sensing devices. Usually, superconducting interference devices (SQUID) are employed for low level magnetic field detection. SQUID based sensors operate at low liquid helium temperature. The major limitation comes from helium cooling which makes them bulky and expensive. Therefore, existing state-of-the-art SQUID sensors are costly and not applicable in limited space. Consequently, use of such sensors is very limited due to higher cost and large size. Small size, high sensitive magnetic field sensors are required to monitor such low level (pico- and femto-tesla) magnetic signals. The sensor must be non-invasive, high spatial resolution and highly sensitive. Further, MEMS based sensors has advantages of small size, light weight, low cost, non-invasive and high resolution. MEMS magnetic sensors can show high sensitivity at their mechanical resonance frequency. Therefore, MEMS based magnetic field sensors has huge potential for bio-magnetic signal detection.

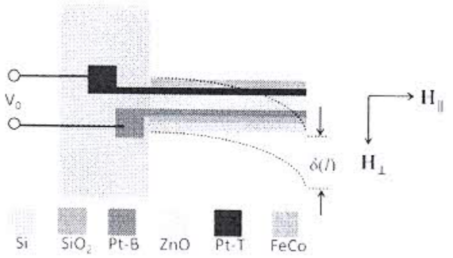

Fig. 1: Schematic sketch of fabricated MEMS magnetic sensor.

TABLE I: Material properties of various layers used in fabrication process.

Layer	Young Modulus (GPa)	Density (Kg/m^3)	Poisons ratio (υ)	Thickness (μm)
Si	160	2330	0.28	5.0
SiO$_2$	73.1	2750	0.17	1.0
Pt	168	21450	0.38	0.2
ZnO	211	5680	0.3	1.8
FeCo	152	7860	0.27	0.5

The proposed sensor is based on magetoelectric effect. Basically, magetoelectric (ME) layer are composed of piezoelectric and magnetostrictive bilayer thin films. When ME bilayer is subject to magnetic field, length elongation along the magnetic field direction and strain is produced in magnetostrictive layer. This strain is transferred to adjacent piezoelectric layer and results to output voltage. The ME bilayer structure is deposited on a micro-machined micro-cantilever structure for high sensitivity. In fact, stress is relieved by bending of cantilever and this results to output voltage. Higher cantilever defection is desirable for high sensitivity of sensor. The output voltage response is described in terms of ME voltage coefficient (α) as

$$\alpha = \frac{\partial E}{\partial \lambda} . c . \frac{\partial \lambda}{\partial H} = \frac{V_{out}}{t.H} \left[\frac{V/m}{A/m}\right] \qquad (1)$$

Where, E is electric field across the piezoelectric ZnO layer, λ is strain produced in FeCo layer, c is coupling coefficient and V_{out} is output voltage across ZnO layer of thickness t. These sensors show very high sensitivity and capable to measure magnetic fields in the of pico-tesla range. Figure 1 shows the schematic sketch of a proposed MEMS magnetic sensor. The layer stack consists of multilayers with specific role of each layer. The sensor is designed for a 10.45 KHz mechanical resonance frequency and accordingly geometric parameters are selected. Table 1 shows the mechanical properties and various layers' parameters used in the fabrication process.

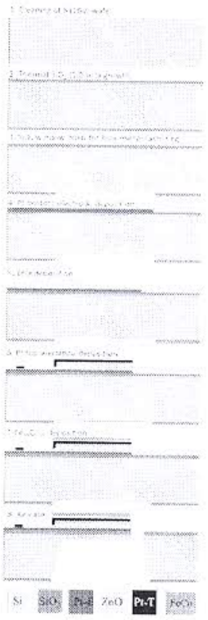

Fig.2: Fabricated process steps of MEMS magnetic sensor.

II. EXPERIMENTAL PROCEDURE

Magnetic sensors were fabricated on a 3-inch diameter double side polished Si(100) wafer using a bulk micromachining process. Fabrication of magnetic sensor consists of multiple mask level process steps as shown in figure 2. Initially, Si wafers were cleaned using a standard chemical process (step 1) and loaded in thermal oxidation furnace for growth of silicon dioxide 1.0 μm thickness using a dry-wet-dry process (step 2). Silicon dioxide (SiO$_2$) layer at the back side of wafer was structured using buffered oxide etch BOE (step 3). Using double sided mask aligner (MA6), back side alignment (BSA) was performed and bottom electrode Ti/Pt was patterned by a lift-off process (step 4). This was followed by deposition of 1.2 μm thick, ZnO layer deposition using a sputter deposition process and patterned by wet chemical etching process (step 5). Next, top electrode Ti/Pt was deposited and patterned using lift-off process to complete the device circuit (step 6). Subsequently, magnetostrictive FeCo sensing layer was deposited on a micro-cantilever by a lift-off process (step 7). Finally, micro-cantilever was released using a combination of wet and dry etch process (step 8).

III. RESULTS AND DISCUSSION

Figure 3(a) shows the optical image of packaged MEMS magnetic sensor. Sensor die was fabricated using a fabrication procedure as described in experimental section. This sensor die was mounted on a alumina substrate which have a patterned gold electrodes for electrical output. Electrode connection were done by wire bonding method and sensor output signal was collected on these electrodes for measurement. Figure 3(b) shows the scanning electron microscope (SEM) image of a fabricated sensor. The micro-cantilevers are clearly visible in the SEM image. Release cantilevers are anchored at the one end of structure. It is visible that cantilevers are un-deformed and indicate that constituent material has nearly no stress or minimal stress.

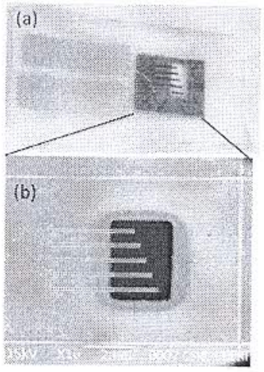

Fig.3: (a) Sensor die packaged, (b) SEM image of released sensors.

Electric field induced out of plane displacements and resonant frequency measurement were done using micro system analyser (MSA) from M/s. Polytec laser Doppler vibrometer (LDV). This provides real-time dynamic characterization at designed frequencies with a displacement resolution in the pico-meter (pm) range. Scanning LDV is a non-contact measurement method for real time vibrational behaviour. It also measures vibration velocity and displacement at any point on sample. LDV relies on frequency shift of back scattered light from a moving object.

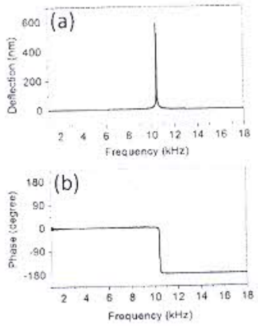

Fig.4: (a) Deflection of sensor and, (b) Phase response.

The actuating sample reflects light from laser beam and Doppler frequency shift gives precise information about the vibrating cantilever due to ZnO layer actuation. Figure 4(a) shows cantilever deflection amplitude with frequency variation and resonance peak was observed at 10.45 kHz resonance. Figure 4(b) shows the phase response and it is observed that phase change of 180° observed at mechanical resonance. The cantilever lateral dimension was 1360μm×180μm as measured by SEM. The quality factor (Q) is measure of device performance and defined as $Q=f_r/\Delta f$, where f_r is resonance frequency and Δf if full width half maxima (FWHM) at resonant peak. Quality factor Q~593 was obtained for 1380μm length cantilever. Further, it is observed that deflection amplitude was 588 nm. Experimentally observed mechanical resonance frequency was found at 10.45 kHz and it is in good agreement with theoretically calculated 10.5 kHz resonance frequency of a cantilever beam. Resonance frequency first harmonics of a cantilever is given as

$$f = \frac{1}{2\pi}\frac{\lambda^2}{L^2}\sqrt{\frac{\sum E_n I_n}{\sum m_n}} \qquad (2)$$

Where L is length of micro-cantilever, E_n is Young's modulus, I_n is moment of inertia and m_n mass per unit length. Various layer used in the fabrication process are their layer properties are listed in Table 1.

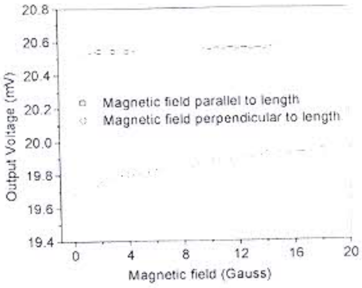

Fig.5: Measured sensing performance of sensor along the cantilever length direction and perpendicular.

Sensor performance was measured using a magetoelectric measurement set-up which consist of Keithly 2430 1kW Pulse source meter, Signal recovery 7265 Lock-in amplifier, Dual channel power amplifier 2000W MOSFET, Keithly 2100 6 ½ Digital Multimeter, F.W Bell 7010 Gaussmeter and ac, dc Helmholtz coils and gauss probe. Sensor was placed in ac magnetic field and actuated using Helmholtz coils. DC magnetic field was increased 0-15 Gauss range and output voltage response was measured as shown in Fig.5. Here, DC magnetic field was applied parallel to cantilever length and also perpendicular. When DC magnetic field was applied perpendicular to cantilever length and output voltage was 19.72 mV measured. It is noticed that output voltage (20.51mV) is higher when magnetic field is parallel to length direction. Sensor output response increases with increase in dc magnetic field. It is perceived that output voltage was higher in when magnetic field is parallel to length of micro-cantilever due to high actuation force.

IV. CONCLUSIONS

MEMS micro-cantilever based magnetic field sensor was realized and characterized. The micro-cantilever beam consist of $Si/SiO_2/Pt/ZnO/Pt/FeCo$ multilayers for sensing and actuation. The mechanical resonance frequency of sensor was found at 10.45 kHz which was measured using laser Doppler vibrometer (LDV). The sensor lateral dimension was 1360μm×180μm and overall layer stack thickness was 7.9 μm. Device sensing performance was measured using a customized magetoelectric measurement set-up and high magnetic field sensitivity 57.6 mV/Gauss was obtained in an unshielded environment. The proposed sensor is very promising and have key potential advantages such as small size, light weight, low cost, non-invasive and high resolution.

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