Report on

MEMS Magnetic Field Sensors with Integrated Powder-Based Permanent Magnets

submitted by

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DECLARATION

We hereby declare that the material that we are now submitting for evaluation under the report title"MEMS Magnetic Field Sensors with Integrated Powder Based Permanent", which is entirely our own work and has not been plagiarized from the work of others, except where such work has been cited and mentioned throughout the text of this report.

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1 Abstract

Electrical current can be easily sensed with magnetic field sensors without disrupting the electrical circuit. MEMS sensors are particularly appealing since they can be manufactured precisely and in huge quantities. In this work, piezoelectric resonators triggered by the interaction of integrated permanent magnets are used to create MEMS magnetic field sensors by following F. Niekiel's research paper[1]. The detailed physics of cantilever based magnetic field sensor is studied in this report. The sensor fabrication process also discussed in this report. We made model of this MEMS magnetic field sensor in the COMSOL multi-physics software by following fabrication process described in the paper[1]. The model made from scratch in COMSOL is novelty of this project. We also studied the magnetic field of permanent magnet attached to the cantilever tip. This report also covers the experimental setup and sensitivity measurement. This MEMS based magnetic field sensor reports lowest limit of detection with $7.2\frac{pT}{\sqrt{Hz}}$ - $8.5\frac{pT}{\sqrt{Hz}}$.

2 Introduction

The development of Microelectromechanical System (MEMS) devices has become more important over the past few decades for fusing technologically feasible sensor miniaturization with fabrication techniques. A sensor is a device that recognizes several physical inputs, reacts to them, and transforms them into analogue or digital forms. These fluctuations are transformed by the sensor into a shape that can be used as a marker to check the device variable. Due to its small size, low power consumption, good performance, and batch manufacturing, MEMS exhibits excellent feasibility in miniaturizing sensors.

Electrical current measurement is an essential requirement in many fields that affect our daily lives. The exact and precise measurement of electrical current provides the basis for applications in consumer electronics, power electronics, and healthcare applications, in addition to its fundamental use in metrology. The demand for current sensors with even better performance is increasing, particularly in the context of our supply and usage of electrical energy, such as in the context of smart grids and electric mobility. Utilizing the magnetic field produced by current is the most effective approach to detect it. Thus, Magnetic field sensor provide us a convenient way for electrical current sensing. To advance in the technological sphere, these magnetic field sensors must be miniaturized.

There are two types of MEMS based sensors, e.g. The Encircling based sensor and Proximity based sensor as shown in Figure (1).

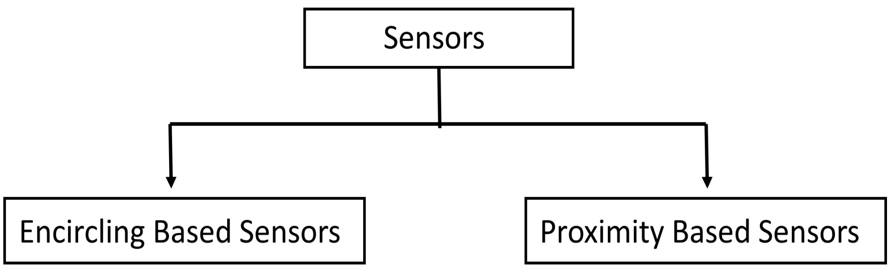

Figure 1: Types of Sensors

Encircling based sensor uses Rogowski coil [2] and current transformer [3]. It is dependent on the availability of a conductor that is geometrically encircled. Encircling sensors are useful for examining Eddy current measurements [4]. Proximity based sensors measure the magnetic field at one or more points in the vicinity of the conductor. In order to detect absolute current levels with great precision, proximity-based sensors placed high demands on knowing the precise relative position of the conductor while relaxing the geometrical restrictions of the conductor. The benefit of proximity-based sensors is that they can measure electrical current without making contact with a conductor, allowing us to sense current without interfering with electronic circuits.The proximity-based approach can be implemented using a variety of magnetic field sensors, such as Hall effect sensors, magnetoresistive sensors, and flux gate sensors [5].

An especially interesting type of magnetic field sensors for proximity-based current detection is offered by microelectromechanical systems (MEMS). The great degree of downsizing, reproducibility, and precision in high volume production as well as packaging to system level solutions make MEMS particularly attractive for magnetic field sensors, even though they can also be produced on a larger scale.

In this report, we worked on a proximity-based sensor that is based on a cantilever-mounted permanent magnet by following F. Niekiel et. al. 's research paper [1]. A cantilever-shaped resonator has permanent magnets installed at the tip for excitation via magnetic field interaction. The resonator is mechanically excited by the interaction of the permanent magnet with the magnetic field, which produces a force proportional to the gradient of the field. The mechanical excitation is transformed into an electrical signal that serves as the sensor output via a piezoelectric layer. To increase the sensitivity for magnetic field signals close to the resonance frequency, a resonator structure's mechanical resonance can be used. These sensors have the benefit of being passive, meaning that no additional power is needed to produce the readout signal. We used COMSOL to create the sensor model while adhering to the [1] fabrication process and study the physics of cantilever based magnetic field sensor.

3 Theoretical Model

In this section, the theoretical concept of a proximity sensor based on a cantilever is thoroughly discussed. The sensor is made up of a micromechanical cantilever with a permanent magnet at the tip and a piezoelectric layer in the bending area. As seen in the figure (2), the cantilever's tip with the permanent magnet is free to move while the other end is fixed to the substrate.

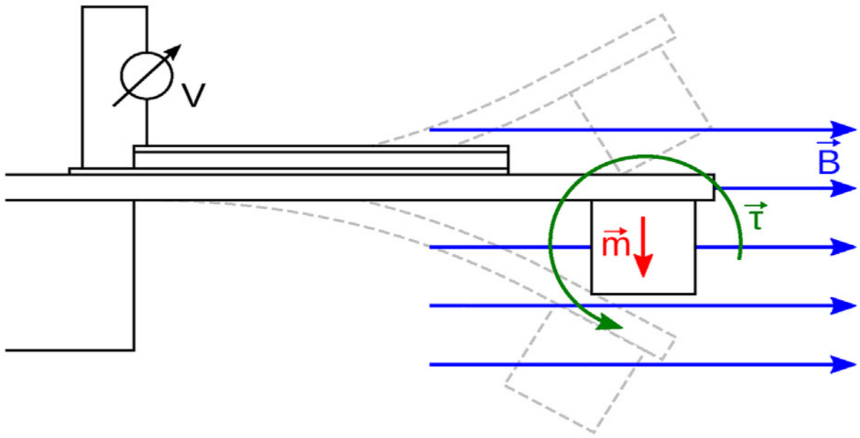

Figure 2: MEMS magnetic field sensor based on a piezoelectric cantilever triggered by magnetic interaction on a tip integrated permanent magnet. (Image Ref. [1])

The permanent magnet has a magnetic moment $\vec{m}$ that experiences a torque in the magnetic field $\vec{B}$.

$$\vec{\tau} = \vec{m} \times \vec{B} \tag{1}$$

The cantilever bends as a result of the torque. This bending stresses the piezoelectric layer, changing its polarisation and causing a voltage signal V to be monitored across the layer thickness. The excitation torque fluctuates in time in accordance with a magnetic field that is time-varying (for example, one produced by an alternating electrical current). When operating close to the resonance frequency, the mechanical resonator's resonance amplifies the signal produced by the sensor.

We take the following assumption in order to simplify the theoretical model. As long as the permanent magnet is modest in comparison to the change in the magnetic field, the reduction of the permanent magnet to a single magnetic moment causes minor deviations. Here, only the non-deflected geometry is included in the force and torque calculations, which is applicable in the case of small deflections. For larger deflections, the force and torque dependence on deflection must be considered, as well as the changing orientation of the magnetic moment. The piezoelectric layer and the required spatial extent to incorporate the permanent magnets are neglected in favour of the cantilever being simplified to demonstrate a constant bending stiffness with load operating on the tip.

In this report, We discussed about two configurations (A and B) by taking magnetic moments into consideration as shown in the figure (3).

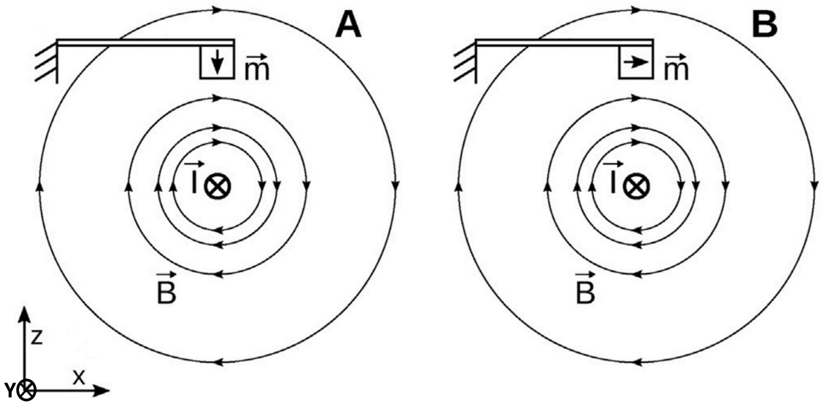

Figure 3: Configurations that use the torque (A) or force (B) produced by magnetic interaction to measure the current flowing through a conductor. (Image Ref. [1])

The current $\vec{I}$ is assumed to flow through the origin of the coordinate system, as depicted in (3). Magnetic fields produced by current-carrying wire are perpendicular to the current's flow. Let's assume that, as illustrated in figure (3), the cantilever's tip is placed on the z axis with a distance of z. We can find the magnetic field at cantilever's tip using the Biot-Savart law.

$$\vec{B}(z) = \begin{pmatrix} \frac{\mu_0 I}{4\pi z} \\ 0 \\ 0 \end{pmatrix} \tag{2}$$

Now, We can discussed about torque and force experience by cantilever tip for the both magnetic moments configurations.

3.1 Case: A

As shown in the figure (3), Consider the magnetic moment direction in the negative z axis.

$$\vec{m}_A = \begin{pmatrix} 0 \\ 0 \\ -m \end{pmatrix} \tag{3}$$

The torque can be calculated using Equation (1). So the torque experience by the cantilever is given by,

$$\vec{\tau}_A(z) = \begin{pmatrix} 0 \\ -\frac{\mu_0 I m}{2\pi z} \\ 0 \end{pmatrix} \tag{4}$$

Similarly, we can express force experience by the cantilever as follows,

$$\vec{F}_A(z) = \nabla(\vec{m}.\vec{B}(z)) = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} \tag{5}$$

It is assumed that the cantilever has a length l and a constant bending stiffness EI along its length. The left end of it has a fixed support, whereas the right end is free. The permanent magnet's spatial extent is not taken into account as the force or torque loads only affect the rightmost edge. It is possible to determine the bending moment M(x) along the cantilever at a distance x from the left end side using structural analysis.

$$M(x) = \vec{\tau}_A(z) = -\frac{\mu_0 I m}{2\pi z}\hat{y} \tag{6}$$

The differential equation for tiny deflections can be used to determine the beam deflection W(x) of the cantilever.

$$\frac{d^2}{dx^2}W_A(x) = -\frac{M(x)}{EI} \tag{7}$$

We can solve equation(7),

$$\int \frac{d^2}{dx^2}W_A(x)dx = \int \frac{\mu_0 I m}{2\pi z EI}dx$$
$$\int \frac{d}{dx}W_A(x)dx = \int \left(\frac{\mu_0 I m}{2\pi z EI}x + C\right)dx$$
$$W_A(x) = \frac{\mu_0 I m}{2\pi z EI}x^2 + Cx + D$$

We get following deflection equation using boundary condition $W_A(0) = 0$ and $\frac{d}{dx}W_A(0) = 0$,

$$W_A(x) = \frac{\mu_0 I m}{2\pi z E I} x^2 \tag{8}$$

For thorough study, we can calculate elastic energy U for bending cantilever using,

$$U = \int_0^l \frac{M^2(x)}{2EI} dx \tag{9}$$

So, The elastic energy of cantilever for this configuration,

$$U_A = \frac{\mu_0^2 I^2 m^2 l}{8\pi^2 E I z^2} \tag{10}$$

3.2 Case: B

We can follow the similar calculations as discussed for case A. Here, Magnetic moment is pointed along the x axis as shown in the figure (3).

$$\vec{m}_B = \begin{pmatrix} m \\ 0 \\ 0 \end{pmatrix} \tag{11}$$

Torque experience by cantilever in this configuration is given as,

$$\vec{\tau}_B(z) = \vec{m}_B \times \vec{B}(z) = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} \tag{12}$$

Similarly, Force can be calculated by,

$$\vec{F}_B(z) = \nabla(\vec{m}_B.\vec{B}(z)) = \begin{pmatrix} 0 \\ 0 \\ -\frac{\mu_0 I m}{2\pi z^2} \end{pmatrix} \tag{13}$$

Force is dominated over the torque for this configurations. Using structural analysis, one can find bending moment M(x) along the cantilever at a distance x from the left end.

$$M(x) = \vec{F}_B(l - x) = -\frac{\mu_0 I m}{2\pi z^2}(l - x) \tag{14}$$

We can find the deflection W(x) equation using the equations (7) and (14).

$$W_B(x) = \frac{\mu_0 I m}{4\pi z^2 E I} x^2 \left(l - \frac{x}{3}\right) \tag{15}$$

From equation (9), we can find elastic energy of bending cantilever for this configuration,

$$U_B = \frac{\mu_0^2 I^2 m^2 l^3}{24\pi^2 E I z^4} \tag{16}$$

3.3 Interpretations from the calculations

With the permanent magnet, the cantilever's tip experienced the greatest deflection. The cantilever beam experiences increased stress as the deflection increases. voltage signal produced by piezoelectric material as a result of cantilever stress. Equation (8) and (15) allows us to compare the deflection at the cantilever tip for both configurations.

$$\frac{W_A(l)}{W_B(l)} = \frac{3}{2}\frac{z}{l} \tag{17}$$

According to equation (17), as long as $l < 1.5z$, the bending of the tip for configuration A is greater than that of configuration B. In order to get larger cantilever defection with configuration A, the length of the cantilever must be less than 1.5 times the distance from the wire to the tip. Additionally, elastic energy assists in the generation of more sensitive signals. Equations (10) and (16) allow us to compare elastic energy.

$$\frac{U_A}{U_B} = 3\left(\frac{z}{l}\right)^2 \tag{18}$$

As shown in Eq. (18), configuration A should have a higher elastic energy due to the interaction with the magnetic field than configuration B as long as $l < \sqrt{3}z \approx 1.73z$. Due to the increased elastic energy generated by the magnetic interaction, which would cause a larger peak displacement and ultimately a higher piezoelectric output voltage. Configuration A is anticipated to perform better than configuration B in the sensor application for $l/z < \sqrt{3}$.

4 Fabrication

A crucial step in the development of MEMS sensors is fabrication. In the realm of MEMS, a variety of fabrication techniques are employed. One should use a fabrication approach that will shorten production time and lower manufacturing costs for MEMS sensors. In this section, we went into great detail on the fabrication procedure for the suggested MEMS magnetic field sensors.

The steps in the fabrication process are as follows:

- The powder magnet based magnetic sensor is fabricated on silicon wafer.
- The passive layer of the cantilever is created by depositing an 18 μm thick chemical-mechanical polished (CMP) poly-crystalline silicon layer on top of an oxidized silicon substrate. A 1 μm thick oxide layer is created by low pressure chemical vapour deposition to achieve isolation (LPCVD), As shown in figure (4a).
- A piezoelectric thin film stack composed of an evaporated Ti/Pt bottom electrode (20 nm/100 nm thick)
- The active layer of the cantilever is formed by depositing 2 m of reactively sputtered AlN and The top electrode is created by a 100 nm thick sputtered Mo.
- A layer of silicon nitride that is 1μm thick and was applied via plasma-enhanced chemical vapour deposition (PECVD) serves as protection and passivation
- Thermal evaporation is used to install a 500 nm thick Cu layer extra, which will serve as a sacrificial layer in a subsequent stage.
- Deep cavities are carved into the silicon substrate (several 100 μm) through the poly-crystalline silicon layer using deep reactive ion etching (DRIE) to integrate the powder-based permanent magnets as shown in figure (4b)
- The cavity is lined with a 100 nm thick ALD Al_2O_3 and a 500 nm thick PECVD silicon oxide layer.
- Utilizing a doctor blading process, NdFeB powder with a particle size range of 4.5 to 6.5 μm is used integrate the magnetic material by filling the cavities.
- In a following ALD stage, the powder is agglomerated, depositing an Al_2O_3 layer to solidify the magnet over the whole depth of the cavity.
- Another PECVD silicon oxide layer is used to protect the top surface of the

magnets before the passivation of the electrodes is opened and rewired using a 1 μm thick sputtered AlCu metallization patterned by wet etching. (figure (4c))

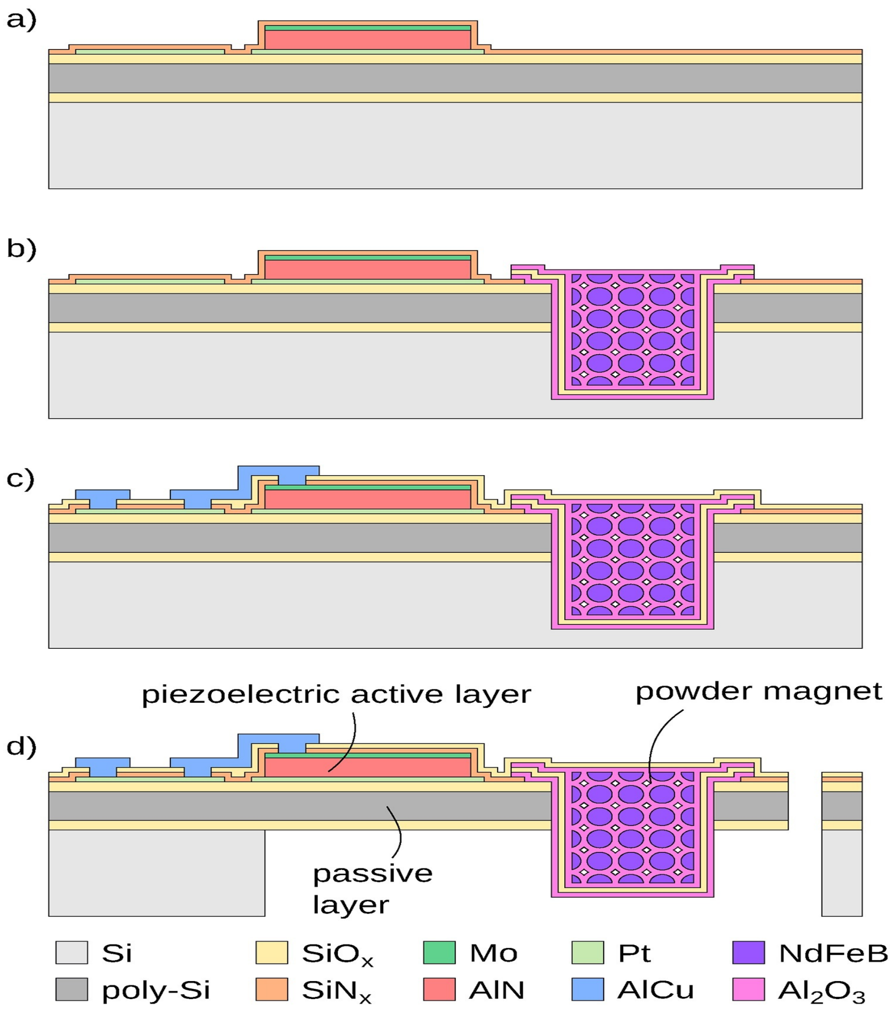

Figure 4: The technology used to create MEMS magnetic field sensors with integrated powder-based permanent magnets is shown schematically in cross sections: (a) The final piezoelectric layer stacks on the passive polycrystalline silicon layer protected by a silicon nitride layer, (b)integration of powder-based permanent magnets in cavities etched into the substrate, solidified by ALD Al_2O_3, (c) wiring the piezoelectric layer stack following the installation of an extra SiO_2 layer to protect the permanent magnet. (d) DRIE releasing the cantilever from the front and back. The piezoelectric active AlN layer and the passive polycrystalline silicon utilised have thicknesses of $2\mu m$ and $18\mu m$, respectively. (Image Ref. [1])

- The cantilever resonator is finally structured using DRIE. First, the frontside oxide and poly-crystalline silicon layers are etched to determine the cantilever's shape. The silicon substrate is finally etched from the back, stopping on the buried oxide and the material lining the magnet cavities. The cantilever is then freed, as shown in figure (4d).

- A 2 T strong magnetic field is used to align the magnetic moments of the individual magnetic powder particles out of plane in order to create a powder-based permanent magnet with a certain magnetization.

The powder-based magnetic sensor created utilising the aforementioned fabrication procedure is shown in Figure (8).

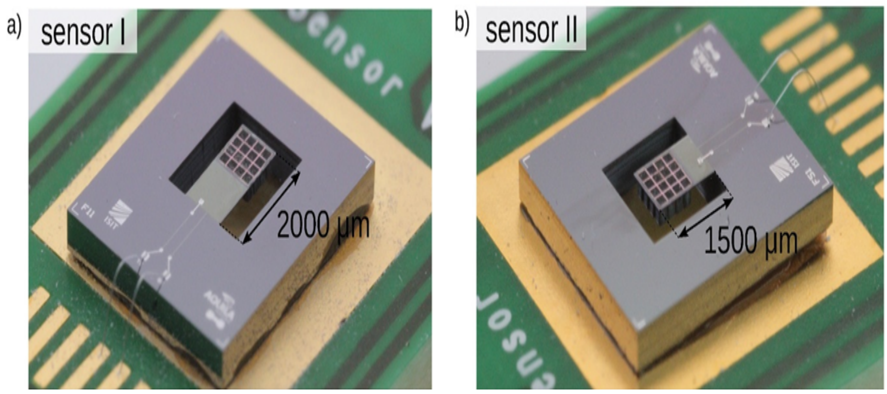

Figure 5: Images of the manufactured devices: sensor I in (a) and sensor II in (b). At the tip of the cantilevers, arrays of 4 x 4 powder magnets of (180 x 180 x 390) μm^3 are integrated over an area of (1000 x 1000) μm^2. For sensors I and II, the piezoelectric bending areas are 1000 μm and 500 μm long, resulting in total lengths of 2000 μm and 1500 μm, respectively. (Image Ref. [1])

A 1000 μm wide cantilever is a feature of both sensor designs. According to the previously stated fabrication method, an array of 4 $\times$ 4 permanent magnets is positioned at the cantilever's tip over a surface area of (1000 x 1000) μm^2. To reduce the possibility of fracture brought on by thermally induced stress during processing, an array of magnets is favoured over a single big magnet. Each magnet has dimensions of about (180 x 180 x 390) μm^3, which results in a total volume of powder loaded per cantilever of 0.20 mm^3. The length of the bending piezoelectric structure between the clamping to the substrate and the permanent magnets differentiates sensor I and sensor II. It is 1000 μm long for sensor I, but only 500 μm long for sensor II, resulting in total cantilever lengths of 2000 μm and 1500 μm, respectively.

5 COMSOL Simulation and Results

In this section, We discussed about COMSOL model of cantilever based magnetic field sensor. This model is made by following fabrication process as described in the previous section. Since, Niekiel[1] has not mention about any software based sensor model, The model shown in figure 8(b) is novelty of this project.

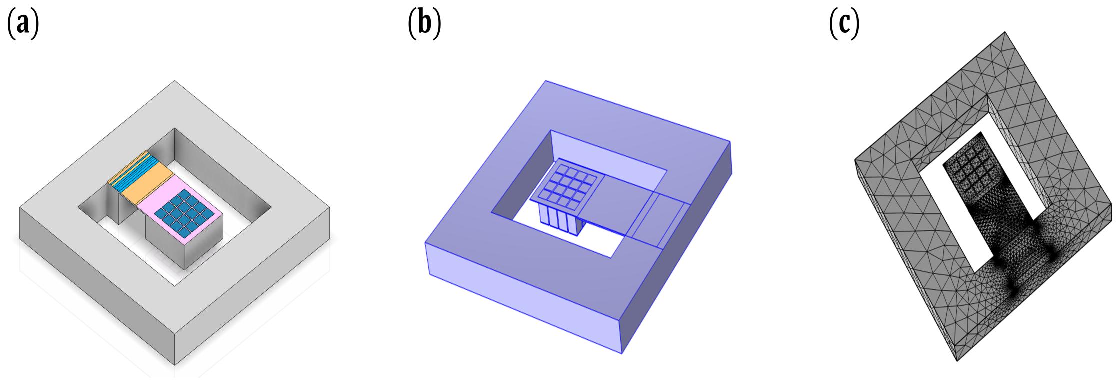

Figure 6: (a) Magnetic field sensor model made in Autodesk Inventor (b) Magnetic field sensor with material made in COMSOL software (c) The COMSOL model with trigonal mesh is applied to study physics of the magnetic field sensor.

Figure 8(a) shows the model of magnetic field sensor made in Autodesk Inventor. Initially, we were thought about importing this inventor file in COMSOL and produce the results. But, COMSOL took whole geometry as one unit. So we could not apply any physics on this model. Then we made model in the COMSOL software from the scratch using the fabrication process as show in the figure 8(b). Sensor geometry is built in COMSOL which includes a magnetic sensor with cantilever of 2000 μm length to sense the fields from nearby target. we added NdFeB permanent magnetic material half part of the cantilever which serves as tip of the cantilever, whenever the sensor is bought to any nearby magnetic fields the cantilever starts bending and to detect the bending in the cantilever we added piezoelectric material stack (which consists of bottom platinum and middle AlN and top Mo) on the remaining half part of the cantilever and whenever it detects any change in

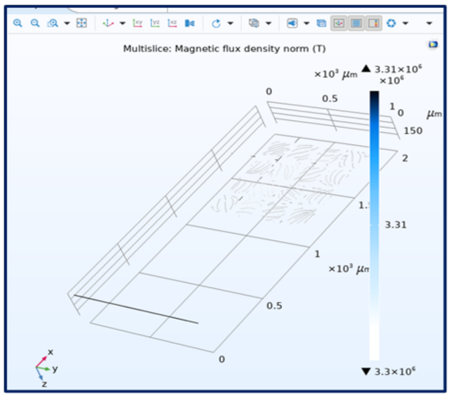

Figure 7: The magnetic field of NdFeB at the bottom of the cantilever tip.

displacement which is coming from bending of the cantilever tip it will generate voltage accordingly. The Magnetic field of permanent magnet at the bottom of the cantilever is studied in the COMSOL as shown in the figure 7. But, We facing the mesh problem while the study of the deflection profile with respect to magnetic field generated by the current and voltage profile generated by the piezoelectric material.
Here, we explain the practical magnetic field sensitivity measurement as discussed in [1].

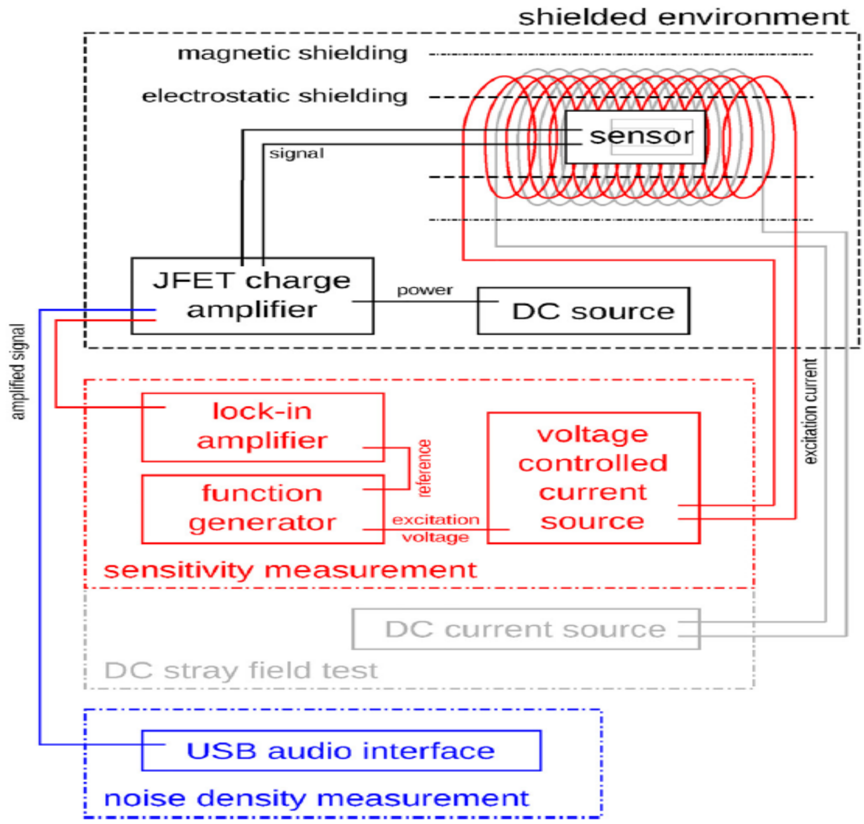

Figure 8: The magnetic field sensitivity measurement setup.

When the sensor is brought close to the coil, the field coming out of the coil tends to cause bending in the cantilever tip because there is a permanent magnet at the tip. In the experiment, we have a lock-in amplifier for measuring the output from the piezoelectric sensor, set of function generators, and VCVS (voltage controlled voltage source). To prevent interference from other fields, the magnetic sensor used for measurement is housed in a hardwood box with a Mu (nickel-iron alloy) coating. The USB audio interface receives the output from the amplifier and converts it to digital form for noise density measurement.

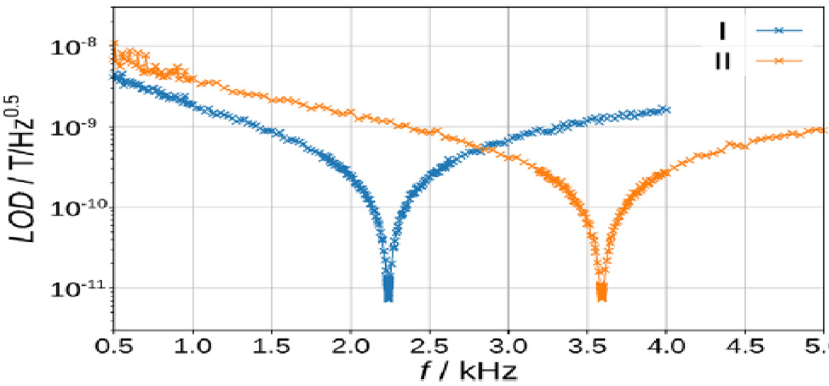

Figure 9: Experimental result of sensitivity measurement of magnetic field produced by the current.

The sensitivity measurement can be done using this setup. The paper reported the 7.2 $pT/\sqrt{Hz}$-8.5 $pT/\sqrt{Hz}$ sensitivity for magnetic field generated by the current caring wire in the printed circuit board, which is lowest limit of detection (LOD) reported till now. the experimental result is shown in figure 9.

6 Conclusion

The thorough study of the physics for cantilever based magnetic field sensor is discussed in this project report. According to our interpretation of the equations, torque-excited cantilever structures should outperform force-excited cantilever structures in homogeneous magnetic fields for cantilever lengths smaller than $\sqrt{3}$ times the distance between sensor and conductor. Based on this interpretation, we made model of the cantilever based magnetic field sensor using the COMSOL multi-physics software. We studied magnetic field of permanent magnet (NdFeB) at the bottom of the cantilever tip using this model. But, we could not solve the meshing problem arising during the deflection measurement and voltage profile generated by piezoelectric material. The benefits of MEMS based magnetic field sensors are to sense electric currents without disrupting the electrical circuit. MEMS sensors are particularly appealing since they can be manufactured precisely and in huge quantities. High sensitivity of cantilever based magnetic field sensor opens door for development in aerospace, biomedical, geological exploration, and vehicle detection.

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