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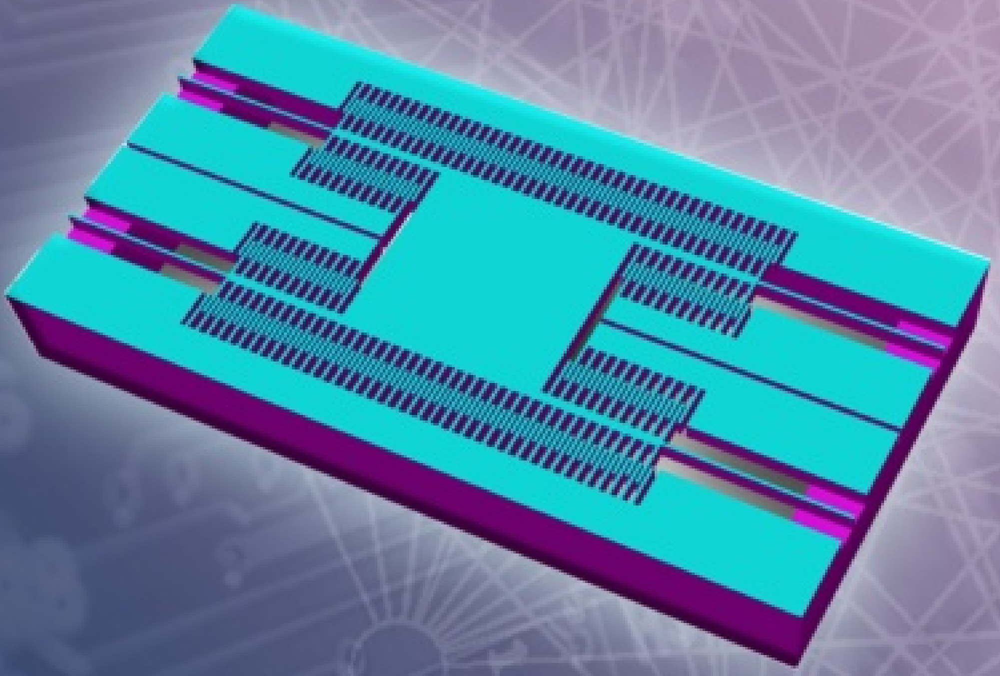

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Modeling and Layout Design of Resonant Lateral Comb Magnetic Sensor

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Abstract: This paper covers the modeling and layout design of CMOS resonant lateral comb magnetic sensor capable of measuring magnetic field in the nanotesla range. The actuation mechanism of this sensor is based on differential electrostatic along with Lorentz force and sensing is piezoresistive. Cadence virtuoso is used to create the layout of resonant magnetic sensor according to design rules of MIMOS Bhd. All CMOS layers i.e. three metal and two poly layers are used in the structure to fabricate the magnetic sensor to enhance the sensitivity. At sensor output, without any amplification its sensitivity is 1.4807 μV/μT at 0.001 damping ratio with quality factor 500 and resonant frequency 9.35 kHz. *Copyright © 2012 IFSA.*

Keywords: MEMS resonators, Interdigitated fingers, Lorentz force, Differential electrostatic actuators and PZR sensing.

1. Introduction

Magnetic field sensors are very important now days in our daily lives due to their involvement in automotive industry, navigation, target detection, compassing, oceanographic and biomedical fields. Search coil, Hall Effect, fluxgate and Superconducting Quantum Interference Device (SQUID) are much more power consuming, big in size and require cryogenic environment. During movement of ionic currents of nerve and cardiac tissue, bio-electromagnetic activities are generated in the range from 100 fT to 0.1 nT. Some research groups in the past periods tried to fabricate MEMS based magnetic sensors according to the new biomedical requirements as high sensitivity and resolution, small in size and low power consumption. These sensors are based on Hall Effect, magneto resistance and flux-gate effect, which are cost-effective batch fabrication, easy to integrate with electronics but well-known restrictions of these sensors are their low sensitivity, poor scaling properties and large temperature shifts [3]. These days, many novel MEMS magnetic sensors for eye-catching position are offered and analyzed by using appropriate technological innovation. Some new resonant devices are proposed by Beroulle et al, Herrera-May et al, and Farooq Ahmad et al in which the Lorentz force is used to actuate the structure, and piezoresistive is the sensing mechanism [4-6]. To experience a large scale of actuation, great driving voltages are usually required. To maintain high voltages makes MEMS design complicated. In this paper, differential electrostatic actuation which has the straight line behaviour and piezoresistive sensing is provided, in which differential change due to Lorentz force in amplitude of resonating sensor shows the external magnetic field [7].

2. Operational Theory

A schematic of the sensor is shown in Fig. 1. The resonating shuttle is suspended to anchor pads by means of four long beams with eight polysilicon piezoresistors implanted in most sensitive regions of the long beams near the anchor pads. Shuttle fingers are interdigitated with the fingers of stator. Metal 1, 2 and metal 3 in the shuttle as well as stator fingers are interconnected through VIAs filled by tungsten plugs. when an AC input voltages are applied to the fixed stator combs 180 out of phase and the suspended shuttle is biased by V_P (Polarization voltage) through metal 3, a differential electrostatic (push-pull) force between shuttle fingers and the fixed stator comb fingers is generated that consequently causes the vibration of resonator.

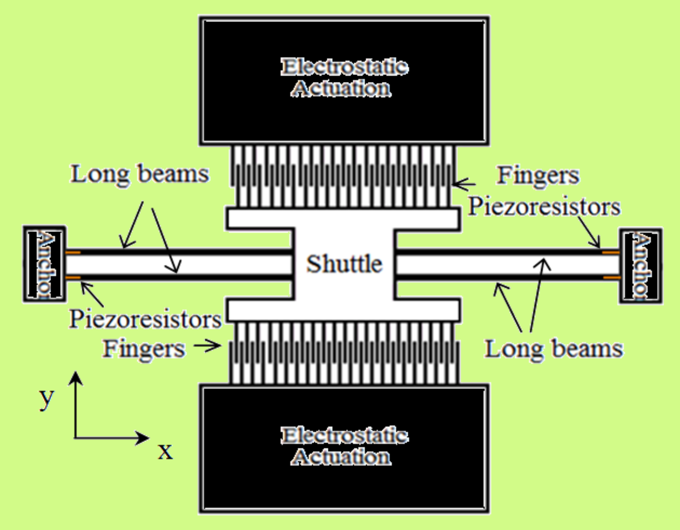

Fig. 1. Schematic of magnetic resonant PZR sensor.

Piezoresistors experience the maximum stresses, resulting in the maximum resistance change in PZR when the applied drive voltage frequency matches to the mechanical natural frequency of the shuttle [6]. In the presence of external magnetic field, Lorentz force increases amplitude of resonating shuttle because AC is flowing through metal 1 and metal 2 in the long beams through central shuttle with same fundamental frequency of the shuttle. This differential change in amplitude of resonating shuttle produces the differential stress values in the piezoresistors, which is read out through Wheatstone bridge circuit in the form of voltages. Differential change in the amplitude of voltages through the Wheatstone bridge circuit shows the strength of external magnetic field.

3. Modelling of the Sensor

3.1. Damping of a Comb Drive Resonator

There are lot of damping mechanisms those contribute to energy loss in micromachined resonators. The important source of loss of energy is friction between the micromachined structure and the gaseous environment. According to the different damping mechanisms, the air damping force for a comb resonator consists of many components. The main damping force components are the following.

3.2. Slide-film Damping Force on the Bottom

As the gap distance d_p between the moving shuttle and the substrate is much smaller than δ (effective decay distance), the damping force is of Couette-flow type and can be expressed as

$$F_1 = \mu \frac{A_p}{d_p} \dot{x} = C_1 \dot{x} \, , \tag{1}$$

where A_p is the effective area for the damping calculation, including the areas of the shuttle and beams. The etch hole region is also included in A_p as the dimension of the etch hole is usually small so that no lateral flow of air exists in the hole. This is usually the most important force component of all the force components μ is the viscosity of the air.

3.3. Slide-film Damping on the Top

Suppose the structure is far away from any objects above it. The damping force above the moving parts of the structure is of Stokes-flow type. The damping force component is

$$F_2 = \mu \frac{A_p}{\delta} \dot{x} = C_2 \dot{x} \, , \tag{2}$$

where δ is the effective decay distance: $\delta = \sqrt{2\mu / \rho_{air}\omega}$; and ρ_{air} is the density of air.

3.4. Slide-film Damping of the Sidewalls

The slide damping force of the side walls is

$$F_3 = \mu \frac{A_s}{d_s} \dot{x} = C_3 \dot{x} \, , \tag{3}$$

where A_s is the area of the sidewalls of the movable fingers and d_s is the gap distance between the sidewalls and the fixed fingers. Here we have assumed that: $d_s << \delta$. The total damping force on the moving shuttle consists of F_1, F_2 and F_3 [8].

$$F = F_1 + F_2 + F_3 = (C_1 + C_2 + C_3)\, \dot{x} \tag{4}$$

3.5. Spring Constant

Mechanical behaviour of the sensor is analyzed by the calculation of the spring constant of the flexural beams. Equation for the static bending of a beam is.

$$k_b = \frac{F}{y_{dis}} = \frac{12EI}{l^3} = \frac{Ewt^3}{l^3}, \tag{5}$$

where k_b is the spring constant of the individual beam and I, t, l and w are the moment of inertia, thickness, length and width of the beam respectively.

$$k_y = Nk_b = N\frac{Ewt^3}{l^3}, \tag{6}$$

where k_y is the spring constant of whole sensor in y direction; E is the Young's modulus of elasticity; N is the number of beams attached to the shuttle [9].

3.6. Resonant Frequency

Resonant frequency of the magnetic sensor is determined using Rayleigh method, which is easy to use in the structures with varying distributions of mass and stiffness [10].

$$f_r = \frac{1}{2\pi}\sqrt{\frac{4\left(\frac{Ewt^3}{l^3}\right)}{\rho_{av}(V_{vol(shuttle)}+V_{vol(s\ beams)})}} \tag{7}$$

3.7. Electrostatic Actuation

The driving voltages applied for the push–pull comb drive are $V_1=V_p-V_a\sin(\omega_a t)$ on one pair of the comb drive and $V_2=V_p+V_a\sin(\omega_a t)$ on the other pair of comb drive, where V_p is the dc bias, V_a is the ac voltages, and ω_a is the actuation frequency of ac signal. The minimum system voltage for the push–pull actuation is calculated as

$$V_s = V_p + 2V_a \tag{8}$$

The corresponding net electrostatic force excited in the y direction, is

$$F_y(t) = \frac{1}{2}\frac{\partial C}{\partial y}(V_2^2 - V_1^2) = 2\frac{\partial C}{\partial y}V_p V_a \sin(\omega_a t), \tag{9}$$

where C is the comb capacitance.

3.8. Mechanical Behavior

The electromechanical behaviour of the device is shown by equation (10):

$$m\ddot{y} + c\dot{y} + k_y y = F_y(t), \tag{10}$$

where m is the effective mass of the system; c the damping factor; y the resonator displacement; k_y is the effective spring constant of system in y direction, and $F_y(t)$ is the net electrostatic force. Then, the steady-state solution equation (10) is [1].

$$y_{(t)} = \frac{\partial C}{\partial y}\frac{2V_P V_a}{\sqrt{(k_y - m\omega_a^2)^2 + c^2\omega_a^2}}\sin(\omega_a t - \theta) \tag{11}$$

where θ is the phase shift and

$$\theta = tan^{-1}[c\omega_a /(k_y - m\omega_a^2)] .$$

3.9 Lorentz Force Contribution

The net electrostatic actuation force produces a bending moment over the long flexural beams, straining these beams as well as the active piezoresistors located on them. Lorentz force adds the differential change in bending moment and this maximum bending moment *(M)*, and the longitudinal strain (ε) over the long flexural beams are obtained by:

$$M = [F_y(t) + F_L]l \tag{12}$$

$$M = \frac{2\sigma_{max}}{t} I \tag{13}$$

$$\epsilon_{max} = \frac{6[F_y(t) + F_L]l}{Ewt^2} , \tag{14}$$

where l is the distance between a fixed end of the long flexural beam to the centre of the shuttle; E is the elastic modulus of the silicon, w and t are the width and thickness of the long flexural beams, respectively. This strain changes the active piezoresistors resistance (R_1 and R_2) that modifies the output voltage of the Wheatstone bridge. The variation of the active piezoresistors resistance (ΔR) is determined by:

$$\Delta R = G \epsilon R \tag{15}$$

where $R = R_1 = R_2$, and G is the gauge factor of the active piezoresistors. The ratio of the output voltage (V_{out}) to the bias voltage (V_{bias}) of the Wheatstone bridge for the proposed microdevice is expressed as:

$$\frac{V_{out}}{V_{bias}} = \frac{\Delta R}{2R} . \tag{16}$$

The external magnetic field is converted to an electrical signal through the Wheatstone bridge.

3.10. Sensitivity

The microsensor sensitivity *(S)* is calculated as the ratio of the output voltage variation to the range of the applied magnetic field.

$$\frac{V_{out}}{V_{bias}} = \frac{\Delta V_{out}}{\Delta B_z}, \qquad (17)$$

where ΔB_z is the external magnetic field range [6].

4. Layout Design in Cadence Virtuoso

CMOS resonant lateral comb magnetic sensor is designed layer by layer in Cadence virtuoso layout editor including pads and routing. For the specific design, biasing and routing of the sensor selective part of each (Metallic and polysilicon) layer is used. This configuration is explained in next few screenshots of the window of Cadence virtuoso. Transverse and longitudinal polysilicon PZR are designed using poly 1 and poly 2 in the each long beam near the anchor parts as shown in Fig. 2.

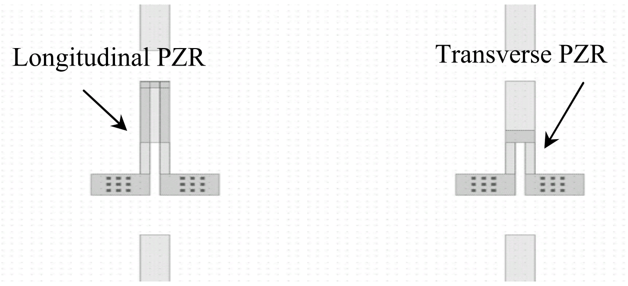

Fig. 2. Schematic of embedded Transverse and longitudinal PZR.

Pattern of metal 1 used in the resonant lateral comb magnetic sensor is shown in Fig. 3.

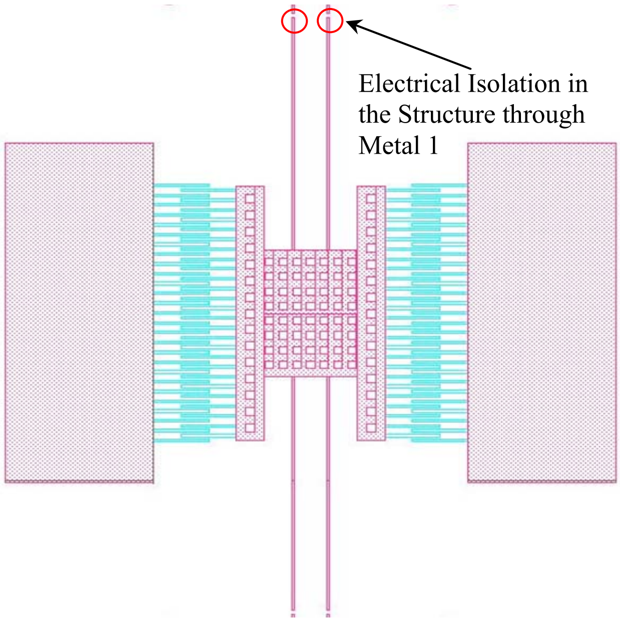

Fig. 3. Schematic of sensor with metal 1 only.

This metal is used in long beams, central shuttle, shuttle fingers and stator fingers. The routing of PZR is done through metal 1 that is why a trench is given before and after the PZR in metal 1 to isolate this region from rest of the sensor part as well as differential electrostatic actuation part of the sensor is routed to the pads using this same metal 1 layer as shown in Fig. 4.

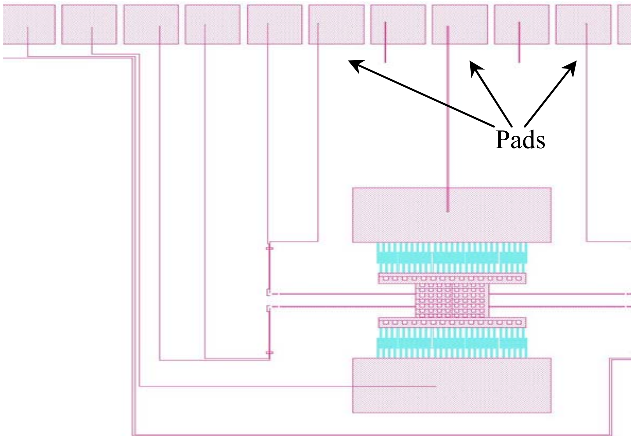

Fig. 4. Schematic of routing part of the sensor with metal 1.

Metal 1 and 2 are isolated by SiO_2. Pattern of metal 2 used in the resonant lateral comb magnetic sensor is shown in Fig. 5. This metal is also used in long beams, central shuttle, shuttle fingers and stator fingers.

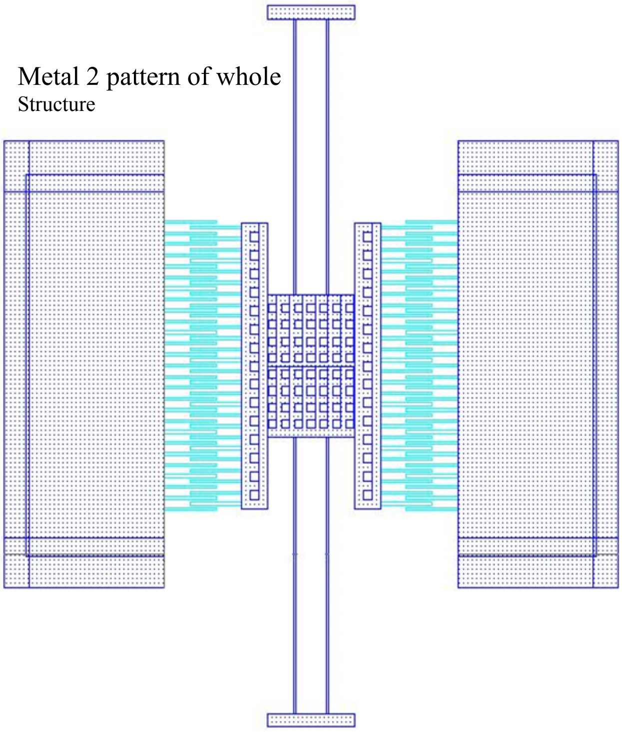

Fig. 5. Schematic of sensor with metal 2 only.

Fig. 6 shows routing of the dc biasing part in differential electrostatic actuation of the sensor to the pads using metal 2. This metal 2 wire is not attached to the pads because sensor can be connected to the pads through metal 1 only so via 1 is used to connect metal 2 to metal 1.

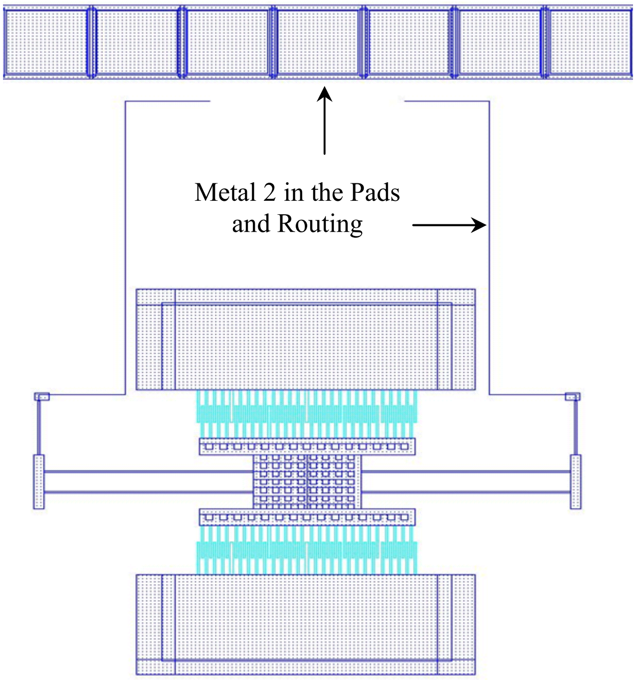

Fig. 6. Schematic of routing part of the sensor with metal 2.

There are some dummy structures in metal 3 pattern to control the etch rates means approximately same etch rate in each trench. Metal 3 is used as mask to the whole sensor structure during DRIE which is shown in Fig. 7.

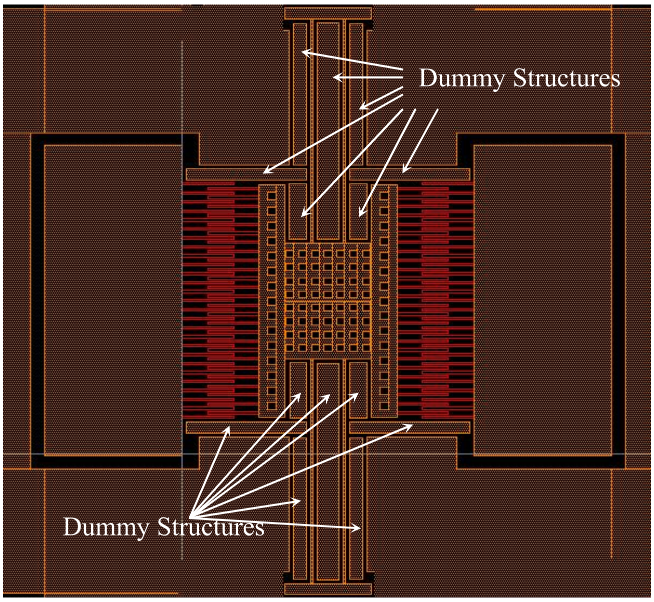

Fig. 7. Schematic of the sensor with metal 3 as mask.

To connect electrically metal 2 and 3 via 2 is used but metal 2 is used to bias central shuttle with dc polarization voltages that is connected to the pad through metal 1 along with via1.

5. Results and Analysis

5.1. Resonant Frequency

To get the frequency response of the resonant lateral comb magnetic sensor it is swept in the resonance neighborhoods of the theoretically calculated by equation (7). The dynamic characteristics when a periodic (sinusoidal) force of amplitude 73.75 *nN* is applied on the sides of shuttle are shown in Fig. 8.

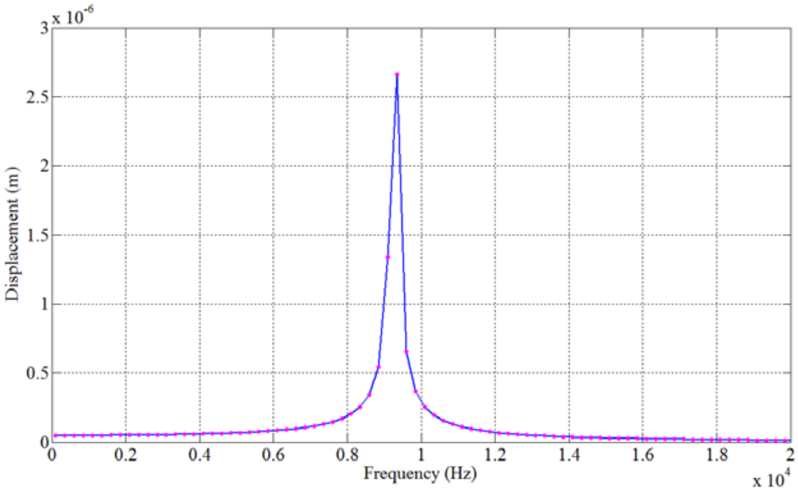

Fig. 8. Displacement of shuttle vs. frequency.

The resonant frequency is determined from the graph of displacement as a function of frequency. Fig. 8 shows the value of maximum displacement is 2.662 µm at damping ratio 0.001, 3 dB below the maximum displacement (70 % of maximum displacement) is 1.86 µm, f_1 is 9.340 kHz, f_2 is 9.359 kHz, frequency band width $\Delta f_{3dB}\ (f_2 - f_1)$ is 18.7 Hz and the resonant frequency is 9.35 kHz. Using these values quality factor is found to be 500.

5.2 Damping Analysis of Comb Resonator

Due to $d_s << \delta$ (effective decay distance δ=17.34 µm) Couette damping is dominant and is equal to 5.34×10^{-8}. The value of Squeeze film damping is small i.e. 2.436×10^{-13} due to end faces of the fingers of comb resonator. Top and bottom slide damping have negligible values.

5.3. Lorentz Force Contribution

Differential electrostatic actuation is used to actuate the sensor at its resonance frequency. At resonance under differential electrostatic actuation, its amplitude is 2.662 µm. When the sweep of external magnetic field from 1 nT to 100 µT is applied to the sensor Lorentz force contributed in the enhancement of amplitude of the sensor because 30 mAmp current is passing through the sensor. This relationship is very important in the calculation of strain produced where the PZR are embedded. Fig. 9 shows the rise in amplitude is linearly proportion to external magnetic field means there is regular and continuous increase in the amplitude. This increase in amplitude is responsible to produce strain at the most sensitive regions of the sensors. The maximum strain produced corresponding to the magnetic sweep of 1 nT to 100 µT is shown in Fig. 10.

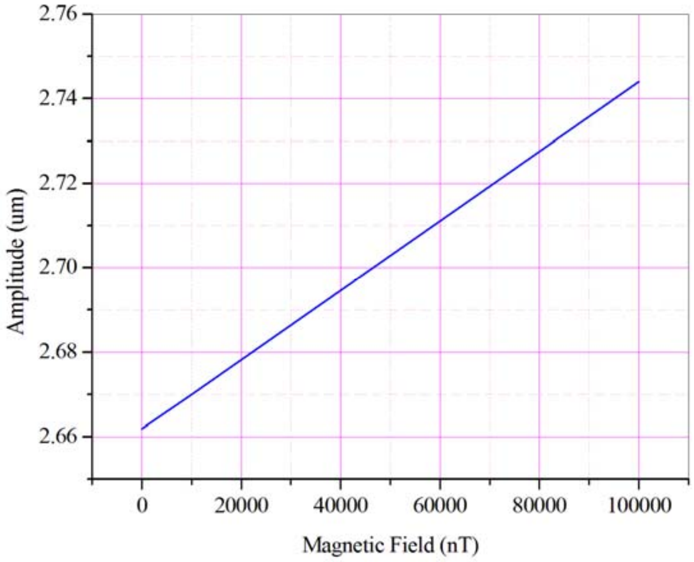

Fig. 9. Amplitude of the sensor vs. applied magnetic field.

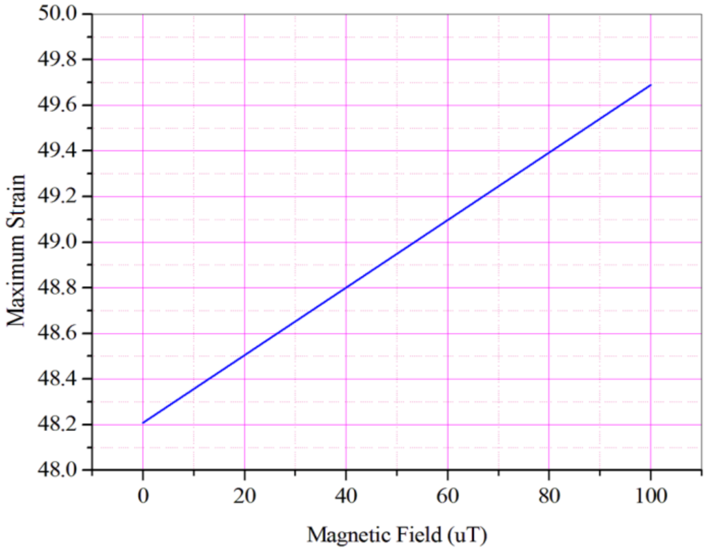

Fig. 10. Strain gradient of the sensor vs. applied magnetic field.

Relative change in resistance of PZR during the exposure of the sensor to the external magnetic field is shown in Fig. 11 which shows that there is no any nonlinearity between ΔR/R and external magnetic field.

5.4. Sensitivity Analysis

The sensing mechanism of this sensor is PZR. The change in the resistance of PZR is converted into voltages by using Wheatstone bridge. Without any amplification of the output voltages the sensitivity of the sensor from the Fig. 12 is 1.4807 µV/µT. This value is improved 179.3 % and 267.4 % from Berroulle *et all* [4] and Herrera-May *et all* [5] respectively.

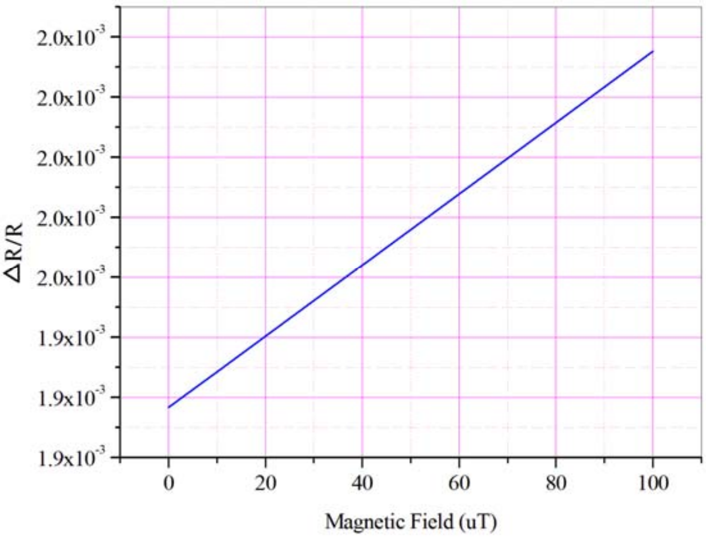

Fig. 11. ΔR/R of the PZR vs. applied magnetic field.

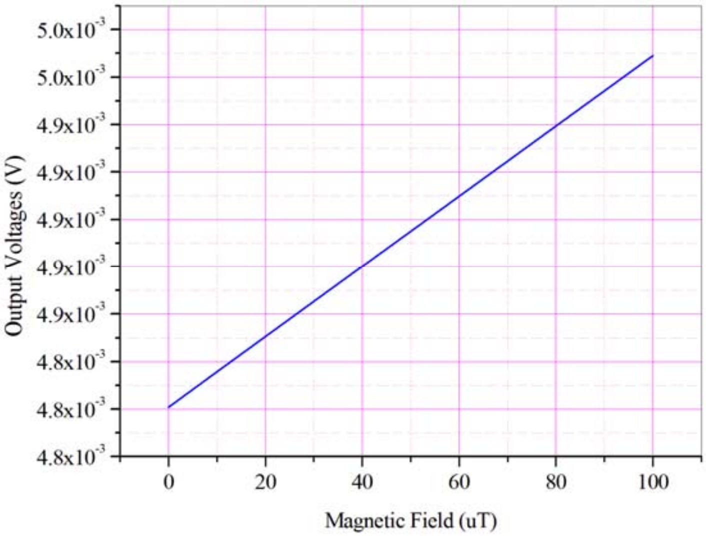

Fig. 12. Output voltages vs. applied magnetic field.

6. Conclusion

Modeling and layout design of CMOS resonant lateral comb magnetic sensor is presented. A thorough analysis of the device is done in terms of damping, spring behavior of long beams, resonant frequency, differential electrostatic actuation and PZR sensing. The sensitivity of the sensor is 1.4807 µV/µT which is improved 179.3 % and 267.4 % from Berroulle *et all* and Herrera-May *et all* respectively. The enhancement in the sensitivity is due to CMOS technology with DRIE as post processing tool.

Acknowledgment

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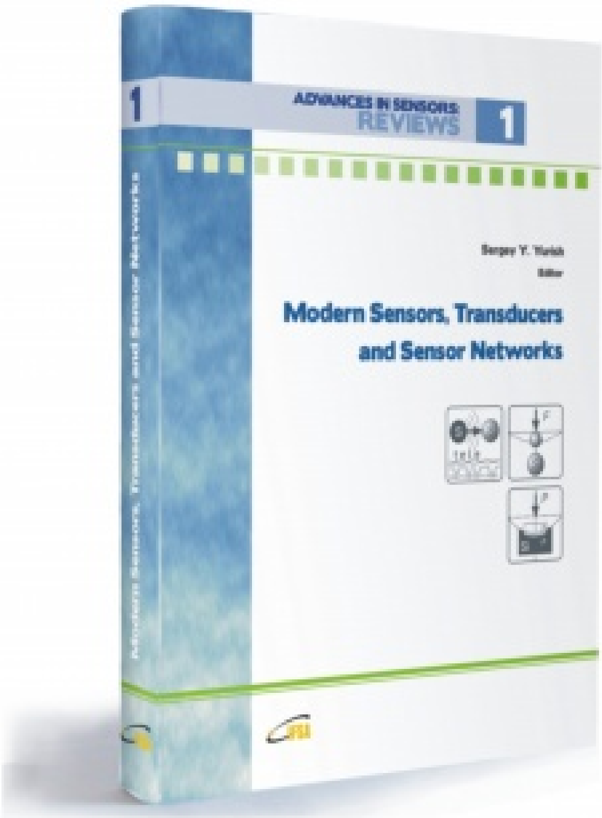

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