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A CMOS MEMS Resonant Magnetic field Sensor with differential Electrostatic actuation and Capacitive sensing

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Abstract. This paper is about CMOS MEMS resonant magnetic field sensor in which differential electrostatic actuation, capacitive sensing, resonant frequency, quality factor and sensitivity of interdigitated comb resonator is investigated. Information is embedded in the output signal frequency because it is robust against the interference from other sources during transmission. At damping ratio of 0.0001, resonant frequency of the comb resonator is 4.35 kHz with quality factor 5000 and amplitude 18.45 μm. Sensitivity of the device towards external magnetic field is 9.455 mHz/nT which is 10,000 times improved than recently published data.

Introduction

Magnetic sensors have helped humans in everyday life such as navigation, target detection, compassing, data storage, location sensing, foreign body detection, motion detection, current sensing, disease detection and so on [1]. With the development of micro-electro mechanical systems (MEMS), the MEMS magnetic field sensors not only reduced the production costs, but also covered more tasks than those in macro-sized sensors. In the past couple of decades, the popular principles in MEMS magnetic sensors are Hall Effect, magneto resistance and flux-gate effect, which are cost-effective batch fabrication, easy to integrate with electronics. The renowned limitations of these sensors are their low sensitivity, poor scaling properties, high power consumption and large temperature shifts [2]. In recent years, many novel structures for magnetic field sensing are introduced and analyzed by using suitable technologies. New devices such as resonant magnetic field sensors which use the Lorentz force to actuate the structure, while sensing mechanism is capacitive, are presented by Kadar et al, Emmerich et al, Tucker et al and Bahreyni et al etc [3,4,5]. In order to achieve a large magnitude of actuation, high driving voltages are usually required. To sustain high voltages makes MEMS design difficult. In this paper, differential electrostatic actuation which shows the linear behaviour and capacitive sensing of resonant magnetic sensor is presented in which output is the change in resonant frequency due to axial Lorentz forces, which shows the outside magnetic field [6].

Structural Configuration

Fig. 1 shows a 3D model of the CMOS MEMS magnetic sensor including differential capacitive sensing and differential electrostatic actuating comb fingers. The device has an overall dimension of approximately 780μm × 660μm with a thickness of approximately 45μm. The sensor is equipped with a 280μm × 310μm resonating shuttle, 24 pairs of sensing and 24 pairs of actuation comb fingers. The shuttle is suspended to the substrate through four long beams. CMOS 0.35 μm technology and post-CMOS micromachining is used to design and fabrication the sensor. The 40 micron SCS in the structure is for mechanical support as well as its role as conducting part in the fingers and side wires. Parameters such as the sensor geometric and material properties and their values for sensor design are listed in Table I.

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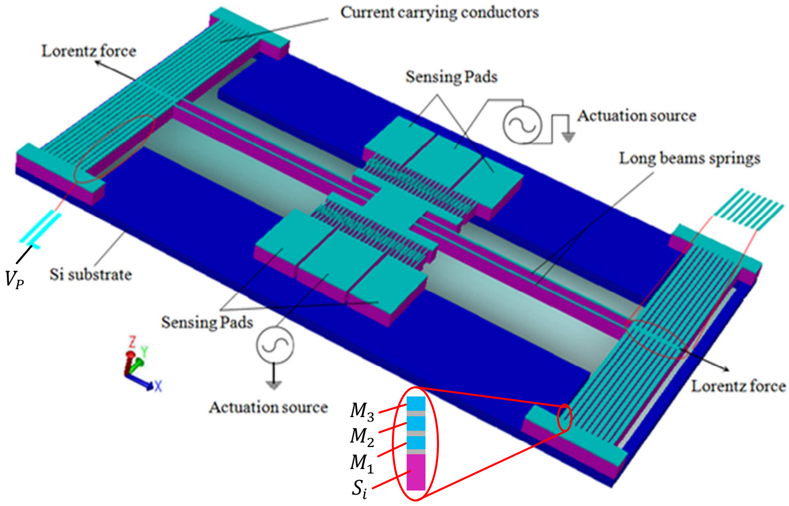

Fig.1. 3D model of the CMOS-MEMS magnetic sensor

Table. 1

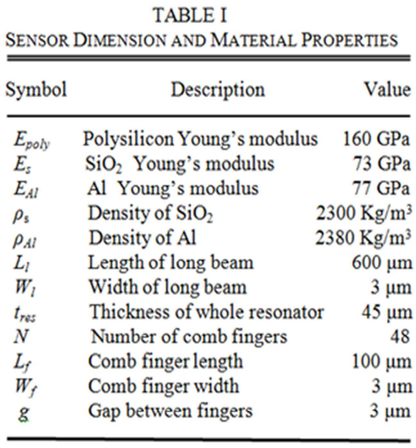

TABLE I
SENSOR DIMENSION AND MATERIAL PROPERTIES

Symbol	Description	Value
E_{poly}	Polysilicon Young's modulus	160 GPa
E_s	SiO_2 Young's modulus	73 GPa
E_{Al}	Al Young's modulus	77 GPa
ρ_s	Density of SiO_2	2300 Kg/m³
ρ_{Al}	Density of Al	2380 Kg/m³
L_l	Length of long beam	600 µm
W_l	Width of long beam	3 µm
t_{res}	Thickness of whole resonator	45 µm
N	Number of comb fingers	48
L_f	Comb finger length	100 µm
W_f	Comb finger width	3 µm
g	Gap between fingers	3 µm

Shuttle fingers are interdigitated with the fingers of stator. Fringe capacitance formed by the multiple metal layers on neighbouring shuttle and stator comb fingers is exploited. The electromechanical behaviour of the device is

$$m\ddot{y} + c\dot{y} + k_y y = F_y(t) \tag{1}$$

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. When a dc-bias VP (Polarization voltage) is applied to the suspended shuttle fingers through metal 3 where the finger metals 1, 2 and metal 3 are interconnected through vias and an ac input voltages are applied to the fixed stator combs 180 out of phase. The result is a differential electrostatic (push-pull) force between shuttle fingers and the fixed stator comb fingers that consequently causes the vibration of resonator. 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_a is the ac voltages and ω_a is the actuation frequency of ac signal. The minimum device voltage for the push–pull actuation is calculated as

$$V_d = V_P + 2V_a \tag{2}$$

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

$$F_y(t) = \frac{1}{2}\frac{\partial C}{\partial y}(V_2^2 - V_1^2) = 2\frac{\partial C}{\partial y}V_P V_a \sin(\omega_a t) \tag{3}$$

where C is the combs static capacitance. Then, the steady-state solution of Eq.1 is

$$y_{(t)} = \frac{\partial C}{\partial y}\frac{2V_P V_a}{\sqrt{(k_y - m\omega_a^2)^2 + c^2\omega_a^2}}\sin(\omega_a t - \theta) \tag{4}$$

where θ is phase shift and $\theta = \tan^{-1}[c\omega_a/(k_y - m\omega_a^2)]$ [6]. The fundamental frequency of the device is determined using Rayleigh method, which is given by

$$f_d = \frac{1}{2\pi}\sqrt{\frac{4\left(\frac{Ewt^3}{l^3}\right)}{\rho_{av}(V_{vol(shuttle)} + V_{vol(s\ beams)})}} \tag{5}$$

When the frequency of the applied drive voltage is equal to the mechanical fundamental frequency of the resonator, motion of the shuttle reach their maximum values (resonance) [7]. As shown in Fig. 2 in which only one set of sensing or actuation capacitors is illustrated, stator comb fingers, which are connected to substrate, use metal 1,2 and metal 3 together as one, capacitor electrodes. In between the stator fingers is a shuttle comb finger. The shuttle comb finger also uses all three metal layers as one electrode. They are connected by the very densely placed interconnected vias.

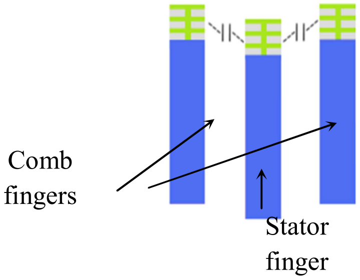

Fig.2. Illustration of the capacitance change

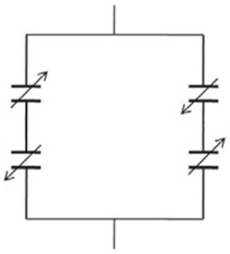

Fig.3. Simplified equivalent circuit of the sensor

Upon application of magnetic field, Lorentz force (axial force) modifies the stiffness of the long beams, which is given by

$$k_b{}' = \frac{EI\gamma^3}{\gamma l - 2\tanh\frac{\gamma l}{2}} \qquad \text{where } \gamma = \sqrt{F_{axial}/EI} \tag{6}$$

and consequently, the resonant frequency of the shuttle changes. This change in resonant frequency, which is proportional to the square root of the change in stiffness constant, is observed with the help of differential capacitive sensing. When shuttle moves towards right, the capacitance among right fingers of shuttle and stator increases and left decreases and vice versa when shuttle moves towards left. To achieve differential sensing and offset cancellation, common-centroid wiring is used to connect the capacitors having the same changing trend together, e.g. right fingers. The same total capacitance with opposite changing trend can be reached. Referring to the equivalent circuit in Fig. 3 and by ignoring the parasitic effect, the output capacitance is

$$C = 4 \times \frac{\varepsilon_0 l_0 t}{d} \tag{7}$$

Device fabrication and simulation

CoventorWare simulation software is used in this study to fabricate the differential electrostatically actuated comb structure and capacitivelly sensing mechanism and to perform finite element simulations. The device is fabricated by using standard processes of 0.35 micron (two ploy-crystallinesilicon and three metals) 2P3M CMOS fabrication technology [8]. To increase capacitive actuation area all three metal layers are connected together through via holes filled with tungsten plugs. Electrical connection of fingers to the surrounding is made through metal 3. Metals (1, 2 and 3) of stator fingers are also connected with each other through via holes filled with tungsten plugs. As a post processing micromachining step, back side selective DRIE process is done that produced a thin SCS (single crystal silicon substrate) membrane of ~ 40 µm, as illustrated in Fig.4. Anisotropic SiO_2 RIE is then performed on the front side to open the patterns of shuttle and long beams as shown in Fig. 4. (b). Next, silicon DRIE process is used to etch through the substrate, as shown in Fig. 4 (c). 40 µm single crystal substrate attached with thin film (~5 µm) is then doped to make it conductor.

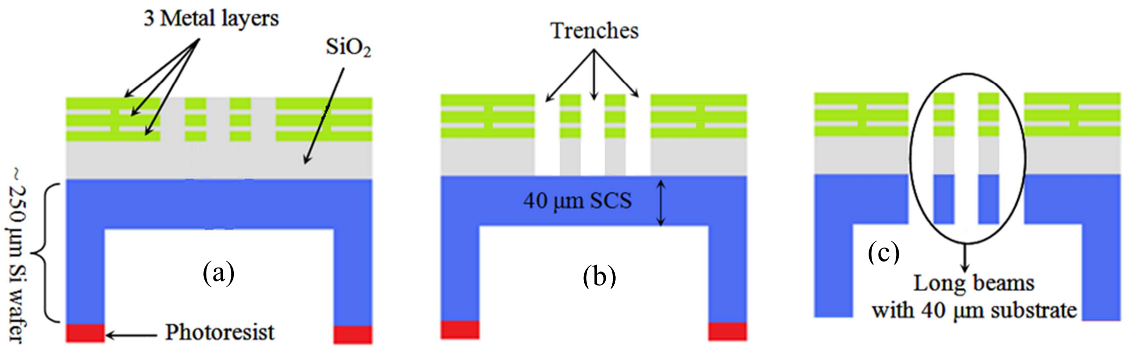

Fig. 4. Post CMOS Process flow for structure released.

The simulations are conducted using a mechanical domain solver, MemMech and a CoSolveEM from CoventorWare. Appropriate meshing is conducted on the solid model using a Manhattan parabolic type mesh structure. Unnecessary part of the device which is the anchor is not meshed so as to reduce the computational load.

Sensor characterization and discussion

To improve the noise performance of the device, it is designed in such a way to actuate in the linear region of operation. Differential electrostatic actuation is adapted by applying 10 V as dc bias on the central shuttle and 3 mV ac on the actuation pads that are 180 out of phase. At value of damping ratio 0.0001, theoretical value of amplitude is 18.15 µm while simulated value, from harmonic analysis of MemMech is 18.45 µm. From CoSolveEM value of amplitude is 17. 5 µm. Theoretical value of resonant frequency is 4.412 kHz while simulated is 4.35 kHz which is shown in Fig.5. These small differences in calculated and simulated values are due to large size of meshes. For output signal, differential capacitive sensing is adopted because signal strength is doubled as compared to the normal capacitive sensing. The value of current generated by capacitance variation in the sensing fingers is 16.06 nA.

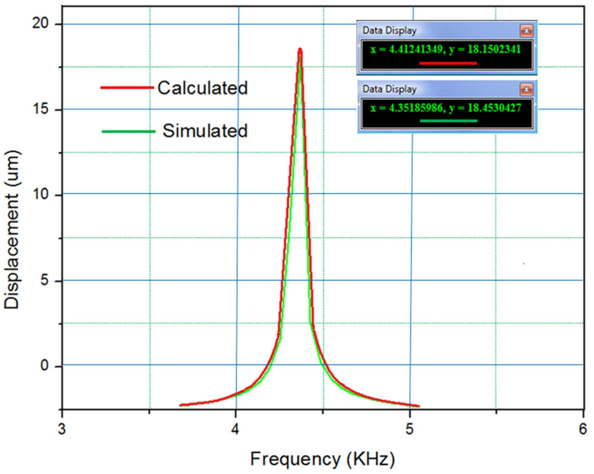

Fig.5. Displacement of shuttle vs. frequency

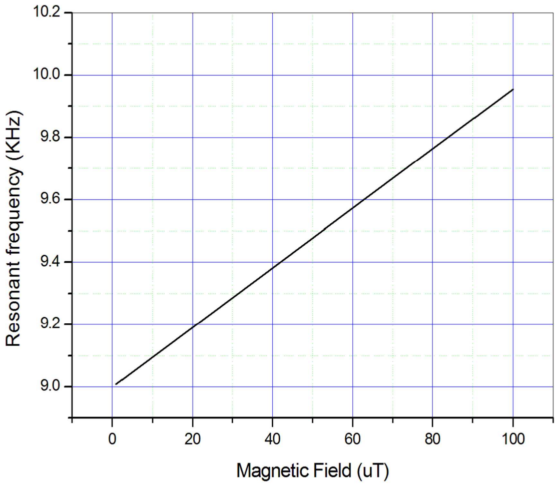

Fig. 6. Sensor responses to external magnetic field

When the sensor is exposed to the external magnetic field along z- axis, Lorentz forces in the side ten wires modify the stiffness of long beams, while each wire carrying 40 mA current i.e. 10 mA current through M1, M2, M3, and 40 micron conducting silicon separately. The values of Lorentz forces, those are opposite in direction, corresponding to the magnetic field of 1 to 100 µT are the ones to change the resonant frequency of the sensor. The sensitivity of the sensor is 9.455 mHz/nT which is shown in Fig.6. Bahreyni and Shafai reported the device sensitivity 0.330 µHz/nT using MUMPs technology and 69.6 nHz/nT using MicraGEM technology. This sensor sensitivity is nearly 10,000 times enhanced than reported one. Reasons for the improvement in the sensitivity are (a) the use of CMOS technology with DRIE as post processing sensitivity enhancing tool, (2) the use of ten wires as compared to the one and each wire have four separate paths to carry the current i.e. M1, M2, M3 and doped 40 micron Si substrate that is acting as support to CMOS layers also. On each side of the resonator, Lorentz force is enhanced by 40 times that is responsible to change the resonant frequency of the device.

Summary

The analytical and simulated results for a CMOS MEMS resonant magnetic field sensor with differential electrostatic actuation and capacitive sensing are discussed in this paper. There is close agreement between them. The sensor uses a mechanical resonator whose fundamental resonant frequency is modified by the Lorentz force generated from the interaction of the sensor structure and the external magnetic field. At damping ratio of 0.0001, resonant frequency of the comb resonator is 4.35 kHz with quality factor 5000. Sensitivity of the magnetic field sensor is 9.455 mHz/nT which is 10,000 times better than recently reported data. Without amplification output current is 16.06 nA.

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