MEMS BASED PIEZOELECTRIC RATE GYROSCOPE

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***Abstract*: This paper aims at designing and analyzing the model through experimental measurements on piezoelectric rate gyroscope. Conventional MEMS gyroscopes work on the principle of Coriolis force whereas the present work also includes the piezoelectric property of the structural material. The sacrificial etching of the proposed model needs an optimization for the material Quartz. The inclusion of serpentine beams reduces the stress and henceforth enhances the signal conditioning capability of the device through change in capacitance. Numerical simulation of frequencies, displacement, and stress is computed using COMSOL Multiphysics software package. The maximum displacement occurs at 35.652 Hz with the value of 5.02×10^{-9}m and the stress experienced is 2.09×10^{12} N/m^2.**

***Keywords:* MEMS gyroscope, drive tines, Coriolis force, angular acceleration.**

I. INTRODUCTION

At present, miniaturization of commercial products has become a trend since they are easily integrated with other types of devices. The developing branch of modern electronics is MEMS sensors and Actuators. The development of the prototype is expensive and time consuming, whereas the final unit cost of the product is relatively small. The prototype creative involves advanced knowledge, intellectual potential, advanced mathematical, and numerical tools with the supported IT infrastructure which helps in solving complicated mathematical models.

Gyroscope is an instrument used to measure angular velocity and importantly for navigation. Two modes exists in a gyroscope-driving and sensing mode. The design of the gyroscope proposed in this paper is based on the shift of energy from drive tines to sense tines due to Coriolis force that exists between both the modes.MICRO-ELECTRO-MECHANICAL systems (MEMS) gyroscopes used to measure rotation rates and angular displacements are silicon micro-machined. The advantages of MEMS gyroscope include low power consumption, cost-effective, high integration capability, and also mass production. Wide range of application of this device include angular detection for 3-D mouse, stabilization of image for video camera, automobile, robotics and other consumer electronics.

There are three basic types of gyroscope-rotary, vibrating structure, and optical gyroscope. This paper deals with vibrating gyroscope which is a MEMS device that is easily available and affordable. Coriolis force plays a vital role in the principle of operation of this structure. The performance of this model is evaluated in a uniformly rotating reference plane. The rotation rate sensitivity is calculated and the frequency response is computed for this system.

II. WORKING PRINCIPLE

The transfer of Coriolis-induced energy between two vibrational modes of a microstructure is the basis of MEMS vibratory gyroscopes.The operation can be carried out in two modes-matched or split mode.In matched mode,the sense mode and the drive mode operate in the same resonant frequency.Whereas, in split mode,the drive and the sense mode are differed by resonant frequency.In this condition ,the sense mode acts as a primary control that operates like an accelerometer and measures the Coriolis acceleration.

In this proposed tuning fork based gyroscope, in-plane mode is driven by reverse piezoelectric effect. Coriolis force couples both the in-plane and out of plane modes that results in an out of plane motion as shown in fig 1. This out of plane motion is sensed by the piezoelectric effect.

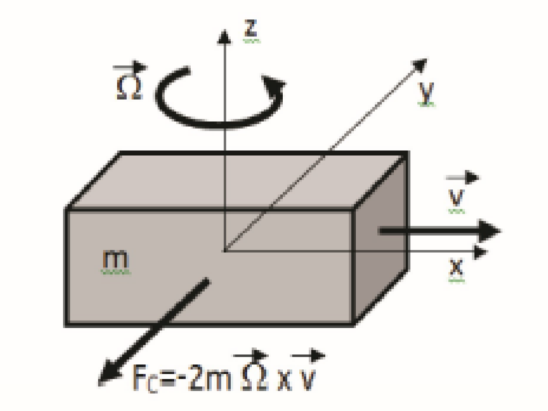

Fig. 1.Gyroscope operational principle [1]

Gyroscope consists of two tuning forks that are coupled together by a suspension structure. As shown in the figure 2, the drive tines are driven in their resonant frequency. Whereas, sense tines are in the out of plane motion which is designed to have distinct resonant frequency. The Coriolis force acts on the structure within the rotating frame which is an outcome of the vibration of drive mode in the in-plane direction. This results in the excitation of sense mode in the out of plane motion. The Coriolis force is illustrated in the equation 1.

$$F_{cor} = -2\Omega\rho\times\frac{\delta u}{\delta t} \qquad (1)$$

Where Ω is the angular acceleration and ρ is the density of material, *u* is the local velocity of the structure. The parameter that corresponds to the out of plane motion of the drive tines is the angular velocity according to the equation given above. In the case where angular velocity of the rotating frame is parallel to the in-plane axis of the piezoelectric gyroscope, the Coriolis force is maximum. This force results in the out of plane motion of the drive tines. This in turn has an effect on the supporting suspension which leads to motion in the sense mode in the out of plane direction.

The gyroscope can be viewed as mass spring damper system with two degrees of freedom. Where one DOF is the drive direction and the other is the sense direction as shown in the fig 2.

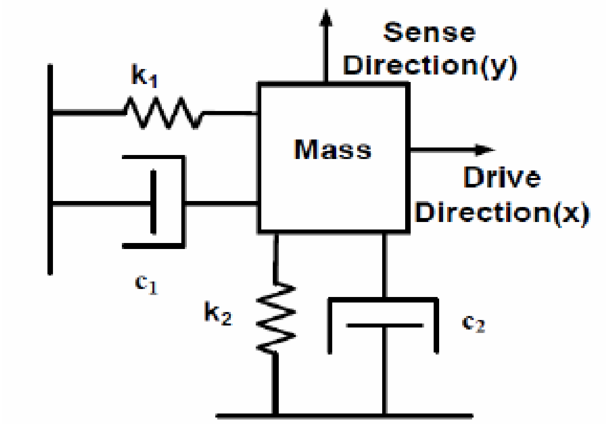

Fig. 2.Two- degrees of freedom mass spring damper system [1]

From Newton's second law of motion,

$$\sum F = ma \qquad (2)$$

$$\sum F = m\frac{\partial^2 x}{\partial t^2} \qquad (3)$$

The forces acting on the mechanical system are the spring forces Fs, damping force Fd, and the actuation force Fel.

$$F_s = -kx \qquad (4)$$

$$F_d = -c\frac{\partial x}{\partial t} \qquad (5)$$

Equation (3) becomes,

$$F_{el} = m\frac{\partial^2 x}{\partial t^2} + c\frac{\partial x}{\partial t} + kx \qquad (6)$$

Where,
m = mass of the body;
F_{el} = Actuation force on the drive direction;
c = Damping co efficient;
k = Spring constant.

Thus the equation for a 2 DOF gyroscope is obtained as,

$$F_{r,x} = F_{i,x} + 2m\Omega\dot{y} + m\Omega^2 x + m\Omega' y \qquad (7)$$

$$F_{r,y} = F_{i,y} - 2m\Omega\dot{x} + m\Omega^2 y - m\Omega' x \qquad (8)$$

III. FABRICATION

Various design methods and fabrication processes have been explored to improve the certain performance metrics especially bias instability and ARW to increase MEMS gyroscopes robustness. Silicon-on-glass fabrication technique to reduce parasitic capacitances.

Silicon-on insulator (SOI)-wafer-based silicon-on-glass (SOG) micromachining process is used to fabricate gyroscope. The process flow of fabrication is shown in the fig 3.Firstly,glass wafer is prepared by the formation of anchors (a) followed by interconnect metallization (b).Then, the pattern of device layer is imprinted on the SOI wafer using DRIE. Etch stop layer that is required during the fabrication is formed by the buried oxide of SOI layer. Without applying a bias to the patterned SOI layer, process which is similar to standard silicon-glass anodic bonding is used to anodically bond the SOI and the glass wafers (c).In the end, structures are released by dissolving handle layer and buried oxide of the wafer (d).There is an added advantage of more stable process condition by performing DRIE on SOI wafer instead of recessed glass wafer.

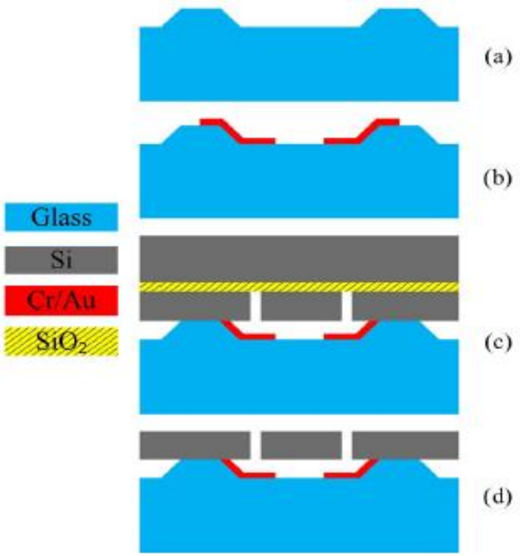

Fig. 3.Process flow of the SOI-wafer-based SOG micromachining process. [2]

Piezoelectric sensors are fabricated using reactive ion etching to detect the vertical motion induced in the sensor. Sensors fabricated with RIE shows bigger sensitivity as compared to the present close-type sensors. A third direction motion is induced by Coriolis force which is perpendicular to direction of rotation and the driven motion. This motion in a MEMS device is sensed by structures like comb, beam, ring or disc. Comb structure is fabricated on single crystalline silicon (SCS) by using TMAH or KOH etching for bulk micromachining and reactive ion etching (RIE) for surface micromachining.

In this paper, surface micromaching process which is reactive ion etching is discussed. Micro-structures with comparatively larger height and smaller gap are preferred for fabrication since the performance of the device is enhanced by the increase in the electrostatic force that exists between the elements.

IV. DESIGN

The anchors are connected to serpentine structure which is in turn attached to proof mass which consists of holes of the dimension mentioned in the table 1.Holes present in the proof mass helps in reducing the stress enacted on the structure during the fabrication process.Comb drives placed on either sides of proof mass with pitch of 0.8 um is connected to fixed vertical structures.

V. GEOMETRY

At the anchors, the structure is fixed, while the proof mass along with rest of the structure is free to move. Electrostatic actuation of the proof mass takes place by applying voltage to the comb drive. The vibration of proof mass in x-direction contributes to drive mode. With the application of Coriolis force, vibration of the structure takes place in perpendicular direction which is sense mode.

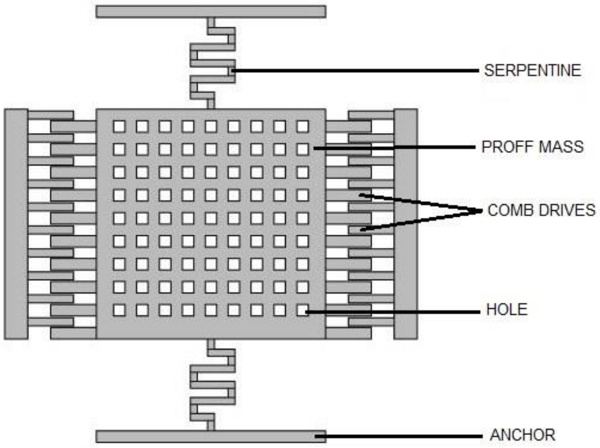

Fig. 4.Geometry of the designed gyroscope.

Table. 1
Dimensions of the structure.

Entity	Dimension
Proof mass	100×100×1 um
Comb Drive	5×5×1 um
Anchor	100×5×1 um
Pitch	0.8 um
Hole	5×5×1

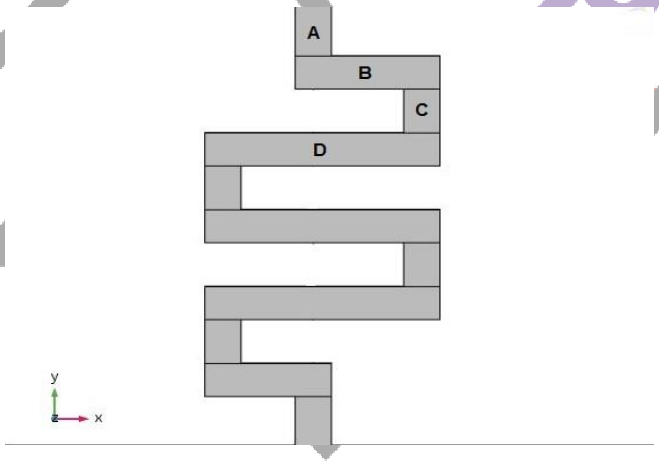

Fig 4. Serpentine Structure.

Table. 2
Dimensions of the serpentine structure.

Block	Dimension
A	3×4.5×1
B	12×3×1
C	3×4×1
D	19.5×3×1

1. *Mesh*

A relatively coarse mesh is used for the designed piezoelectric gyroscope. A very fine mesh is generally used to achieve accurate frequency response but it is time consuming to process a very fine mesh. A coarse mesh is applied to the structure as shown in the fig 5.

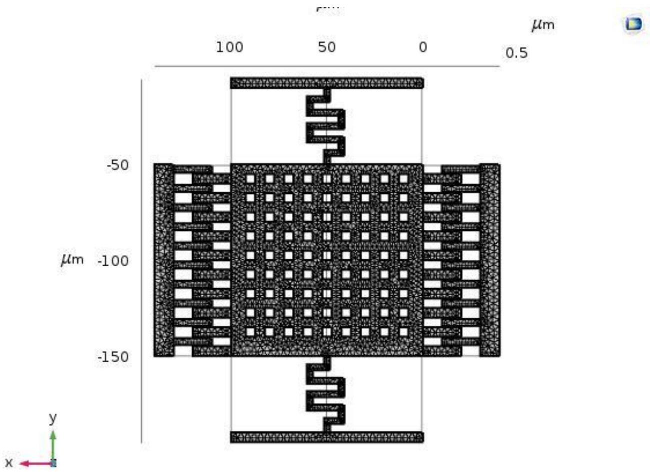

Fig.5. Mesh applied to the design.

2. *Material*

Quartz is a well-known piezoelectric material. Piezoelectric materials become electrically polarized when strained. From a microscopic perspective, the displacement of charged atoms within the crystal unit cell (when the solid is deformed) produces a net electric dipole moment within the medium. In certain crystal structures, this combines to give an average macroscopic dipole moment and a corresponding net electric polarization. Material that is used to build this piezoelectric gyroscope is Quartz LH(1978 IEEE).

Table. 3
Parameters of the design

Property	Variable	Value	Unit
Young's modulus	E	169e9	Pa
Poisson's Ratio	Nu	0.29	1
Density	Rho	2320	kg/m^3
Relative Permittivity	EpsilonrSij=0	{4.428,4.634}	1

VI. SIMULATION AND RESULTS

A. Stress of piezoelectric rate gyroscope

For any electromechanical device, the values of stress are critical values. According to Hooke's law stress is directly proportional to strain with proportionality constant as young's modulus of the material. The distribution of stress throughout the structure is shown in the fig 6. Maximum stress is experienced at electrodes. The value of maximum stress experienced is 2.09×10^{12} N/m^2 in this model.

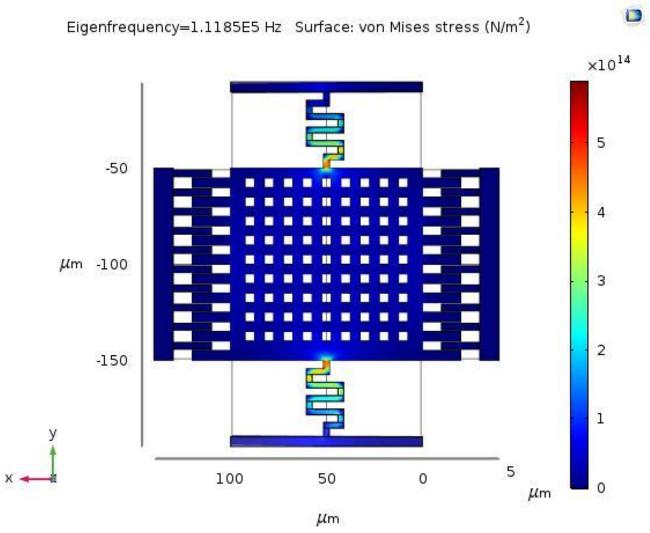

Fig. 6. Stress pattern of the design.

B. Eigen frequency analysis of gyroscope

Eigen frequencies are distinct frequency values at which the model vibrates. The deformation of a structure into a particular shape called Eigen mode takes place when it is vibrating with Eigen frequency.

Various Eigen frequency of this model are shown in the table 4.

Table .4

Frequency at different modes.

MODE	FREQUENCY (Hz)
1	13.712
2	35.652
3	1.0287E5
4	1.0639E5
5	1.1185E5
6	1.5997E5
7	2.3161E5

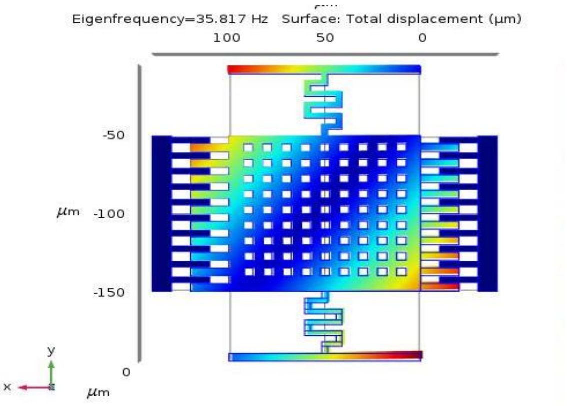

Fig. 7. Displacement of the proof mass

C. Displacement with respect to frequency

The displacement versus frequency plot of the model is shown in the figure 6.The maximum displacement occurs at 35.652 Hz with the value of 5.02×10^{-9} m as shown in the fig 7.

A force of 100 N/m^2 is applied on the piezoelectric structure which linearly results in the displacement of the gyroscope. A point graph of displacement with respect to frequency is plotted by taking two points on the proof mass linearly as shown in the fig 8.

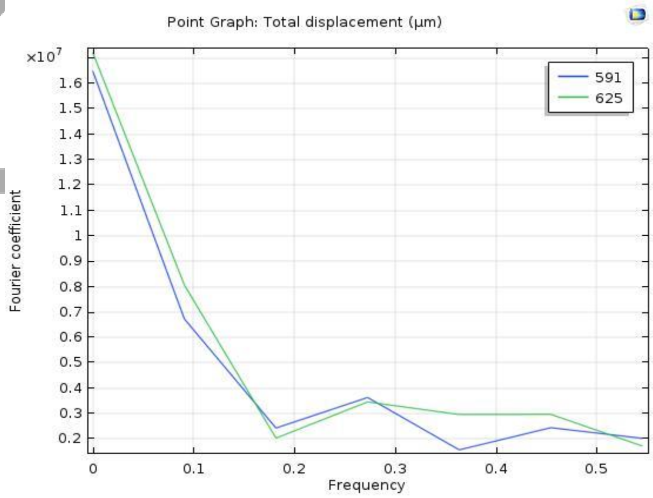

Fig.8. Displacement point graph.

VII. CONCLUSION

A comprehensive model of gyroscope is designed and simulated using COMSOL Multiphysics 5.3a. The results show the performance of the device with perforated proof mass. It was found that the device showed a improved displacement on applying force. When the device was operated at its natural frequency it showed displacement of 5.02×10^{-9} m.

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