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DESIGN AND FABRICATION OF SILICON MICRO-STRUCTURE FOR SEISMOMETER

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Abstract: Seismology is the tool used by geologists to study the interior structure of the planets and seismometers are instruments used to collect data to achieve this objective. A lot of studies are conducted on Earth and highly sophisticated instruments with excellent performance parameters are available. In order to conduct seismic studies of other planetary bodies namely Moon and Mars, seismic instruments are to be made operational there. Conventional seismometers are relatively heavy and large power consuming instruments and hence contradict with the general requirements in planetary missions. This paper describes the approach in developing a bulk micromachined silicon based seismometer to operate over the input range of ± 0.5g with 100 ng/√Hz noise floor and a bandwidth of 50 Hz.

Keywords: Planetary seismology, Seismic instrumentation, MEMS based seismometers, Silicon on Glass

I. INTRODUCTION

The structure of a planet or any celestial body can be understood by studying the seismic waves generated in it due to natural or artificial events. The dynamics of the planet when explored will shed light on the behavior, composition, properties and maybe, even the evolution of the deep interiors of the planet. Seismology provides such a technique to measure and establish the above.

Seismic studies on Earth began several decades ago. The extensive study of the Earth's structure and properties have been undertaken with the aid of a wide network of seismic instruments placed in multiple stations around the world. Instruments from geophones to ultra-high sensitivity instruments have contributed to the current level of knowledge and understanding of the seismology of Earth.

In contrast, there is limited information on the seismic nature of other planets and their satellites. It is for this reason that almost every science mission to the Moon and other planets by various space agencies have contained a seismic payload. But, not every mission has resulted in success with respect to the characterization of the seismic nature of the planets.

The sole success story in the history of planetary and small body seismology is the Moon. The large volume of data generated from the active and passive experiments conducted during the Apollo missions from 1964 to 1974 has contributed to a fair understanding of the structure of the Moon and the different types of seismic activities prevalent[1,2]. Though, the precise measurement of the Moon's core remains to be achieved.

Seismometers are instruments used to detect and quantify motions on the ground including those generated by quakes and volcano eruptions. Seismometers have been used in planetary exploration since the early 1960's with a majority of the seismometers deployed on the Moon. In 1969, the Apollo 11 mission became the first to successfully install completely operational seismometers on any planetary body other than the Earth. They were a tri-axis long period and a short period seismometer. But the total mass of the seismic sensors, readout and signal processing electronics, power and heater units resulted in a very heavy payload. More seismometers were placed on the Moon during the subsequent Apollo missions. These instruments worked as seismic stations on the equatorial region of Moon and collected data for a few years.

After the Apollo era, there has been no mission sent to Moon for seismic studies. Exploiting the progress achieved in diverse fields of technology like seismic instrumentation, computing and signal processing, a rejuvenated interest is shown by various space faring nations in planetary seismology. Some of the missions planned in future with seismology studies as one of the objectives include the Selene 2 of Japan[3], MoonLITE by UK[4] and Luna Glob from Russia[5]. India is planning to conduct seismic studies on Moon during its Chandrayaan 2 mission. The seismometer will be a science payload on the Lander.

Considering the stringent conditions imposed on the mass and power budgets on the instruments due the nature of mission, a MEMS based seismometer is proposed. The target is to realize an instrument with low weight and electrical power requirements but with least possible compromise on the performance parameters. The design and fabrication adopted to successfully realize inertial sensors in our laboratory is the technical knowhow employed to achieve this goal[6]. The target instrument will weigh around 1 kg and consume less than 2 W of electrical power. The noise equivalent acceleration is designed to be around 100 ng/√Hz with capability to measure upto 0.5 g, where g is the acceleration due to gravity, 9.81 ms^{-2}. Since the seismic signals are generally in the low frequency band, the instrument is proposed to have a bandwidth of 0 to 50 Hz.

II. SEISMOMETERS

2.1 Working Principle

Seismometers operate on the principle of inertia – stationary objects remain stationary unless an external force is applied to them. They generally consist of a heavy proof mass suspended with a thin flexure that is anchored to a frame. The frame is rigidly mounted to the Earth. When there is displacement of Earth due to quakes, the mass thus tends to remain stationary while the frame moves. Seismometers used in earthquake studies are designed to be highly sensitive to ground movements. The output of the sensor is a physical variable corresponding to the input and is generally in terms of voltage in modern instruments. Such a configuration is represented by a spring-mass-dashpot system as shown in Figure 1.

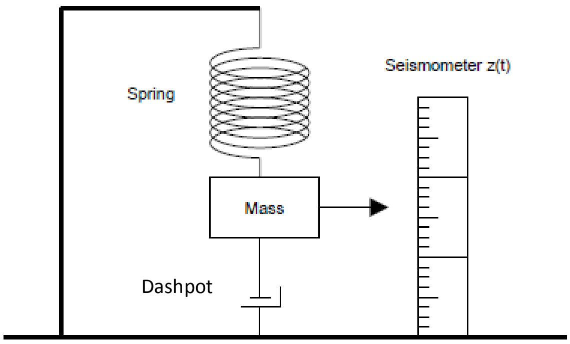

Fig.1: Mechanical inertial seismometer represented by the Spring-Mass-Dashpot system (*Ref. Instrumentation in Earthquake Seismology, Jens Havskov*)

2.2 Conventional Seismometers

Seismometers are classified into different types on various concepts such as the frequency range of operation, sensing principle and readout mechanism. Hence there are long period, short period and broadband seismometers, horizontal and vertical seismometers, Faraday law, inductive and capacitive type detectors and so on. Conventional seismometers for Earth bound applications are very high performing instruments with nano-g resolutions or even better. This performance is achieved by having heavy proof mass suspended by thin flexures. The readout electronics and signal processing modules are highly sophisticated. These requirements make them heavy (3 to 15 Kg) and has high power consumption. The operating ranges of temperature are between -40 to +65 ^{O}C in most of the cases and are designed to survive shock levels of around a few tens of g.

2.3 Advantages and Disadvantages

Conventional seismometers have several disadvantages such as large weight and occupy a large volume. The size and weight restrictions limit their use in many applications, which has led to the development of miniaturized seismometers. The key concern while miniaturizing seismometers is the sensor noise exceeding the ambient noise. Seismometers intended for lunar seismic studies face constraints from the harsh environment that is unique to space missions like ambient temperature, radiation and mechanical shock and vibration. The advantages of MEMS structures help in addressing these design challenges faced in ensuring the space qualification of the proposed seismometer. With the application of MEMS technology the seismic device will have enhanced resistance to incident radiation, lower power consumption, very low weight and higher reliability. But, this is at the cost of the sensitivity of the device. However, a suitably designed MEMS structure with low noise readout electronics can overcome this drawback to a large extent.

2.4 Scope of MEMS based Seismometers

With the technological innovations in materials, design, fabrication and the development of MEMS technology, the goal to realize a Seismometer weighing less than 1 kg and consuming power less than 2W can be achieved. Hewlett Packard has recently reported a seismic grade MEMS accelerometer with ultra-high resolution seismic sensing having a power spectral density of less than 100 ng/√Hz over a bandwidth of DC- 200 Hz[7]. The device has linear response to ± 150 mg and sensitivity of over 25 V/g. This sensor detects change in capacitance when an array of electrodes patterned on an in-plane moving proof mass displaces relative to a stationary array of electrodes across a fixed gap.
The work reported in the current paper employs an in-plane moving proof mass and a capacitive sensing principle. Here, it is the gap between the interdigitated combs that changes leading to a corresponding change in capacitance. The details of design and the approach in fabricating the designed structure is explained in the following sections.

III. DESIGN

3.1 Basic structure and sensing principle

The sensor will be made using bulk micromachining of single crystal silicon supported on glass, otherwise known as the Silicon on Glass (SoG) architecture. The main feature of the structure is a proof mass suspended by folded cantilever beams, with comb electrodes projecting out of the proof mass at right angles. The schematic representation of the structure is shown in Figure 2.

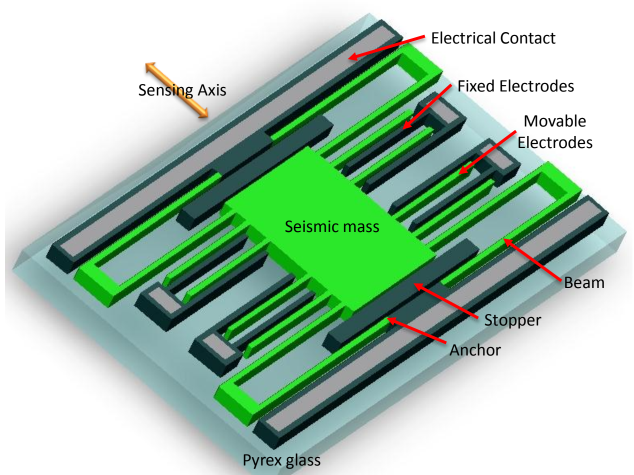

Fig. 2: Schematic representation of the seismometer structure

The cantilever beams are anchored to the outer casing at its four respective ends. The proof mass with electrodes is movable and is designed to be sensitive to ground vibration in one direction, marked as sensing axis in Figure 2. Sensitivity in one direction is due to the rectangular cross-sectional shape of the suspension beam. The low width of the beam compared to the length and thickness makes it more compliant in the sensing direction, and hence more sensitive to applied forces along that direction.

Corresponding to the movable electrodes, an equal number of fixed electrodes are placed in complementary positions so as to create a parallel-plate capacitive structure between the two sets of electrodes.

When there is a deflection due to an external vibration, the proof mass along with the electrodes attached to it moves. This results in a change in the separation between the movable and fixed electrodes. Consequently, there is a corresponding change in the capacitance, which is inversely proportional to the distance of separation.

The electrodes are arranged to derive a differential change in capacitance values from various arms of electrodes as shown in the Figure. This variation in capacitance against input acceleration is read out using a differential amplifier circuit where capacitance change is converted to voltage output. The output is further amplified and conditioned to obtain the final output from the seismometer.

3.2 Design process

The main design considerations for the microstructure presented here are (i) Mechanical sensitivity (ii) Electrical sensitivity (iii) Dynamic behavior of the structure (iv) Brownian Noise Equivalent Acceleration (BNEA) (v) Shock survivability of the structure (vi) Feasibility of fabrication

While designing a microstructure, the dimensions are optimized considering the feasibility of fabrication. It is important to select a range of dimensions that are practically realizable by lithography and etching in the available facility. The final dimensions, however, are optimized by detailed mechanical, electrostatic and electromechanical analysis.

The deflection of the proof mass can be obtained by solving the equation of motion of the structure, by considering it as a spring-mass-damper system.

$$m\frac{\partial^2 x}{\partial t^2} + c\frac{\partial x}{\partial t} + kx = m\frac{\partial^2 u}{\partial t^2} \qquad (1)$$

where m is the proof mass, c the damping constant, k the stiffness of the cantilever suspension structure and u is the ground displacement. Mechanical sensitivity is defined as the deflection of the proofmass ‘x’ per unit ‘g’ of acceleration. The mass of the structure and its mechanical stiffness determines the mechanical sensitivity as given by the classical spring equation, which is also the solution to the equation (1) approximated for very low frequencies of operation compared the natural frequency of the structure. The dimensions of the suspension beam play a huge role here, because they directly impact the deflection achieved, and hence the mechanical sensitivity.

One of the most important criteria in the design of seismometers is to minimize the Brownian noise of the mechanical structure. This is the most dominating source of noise in microstructures. The Brownian noise equivalent acceleration has been reported by several authors, expressed in g/√Hz, by the equation (2)[8].

$$BNEA^2 = \frac{4k_B Tc}{m^2 g^2} = \frac{4k_B Tf}{mQg} \qquad (2)$$

where k_B is the Boltzmann constant, c the damping constant, T the temperature, Q the quality factor and f is the natural frequency of vibration.

Considering these factors and the feasibility of fabrication, the structure with proof mass dimensions 8 mm x 6 mm x 0.27 mm supported by four folded beams is designed. The suspension beam has horizontal length of 6.35 and 4.35 mm. The width and thickness of the suspension beams are 75 and 150 µm respectively. The BNEA is calculated to be around 40 ng/√Hz.

The design ensures large deflection in the sensing direction alone. Such a design helps to minimize the cross axis sensitivity of the instrument.

Modal analyses have been done using the CoventorWare FEM solver in order to ensure optimum mode separation. The first mode of vibration is along the sensing directions and higher modes have impact on the cross axis sensitivity of the instrument. The frequencies of vibration for the first three modes are 294, 457 and 798 Hz. Figure 3 summarizes the modal analysis results. The solver has also been used to numerically compute the deflection of the mechanical structures and compare with the analytically generated values.

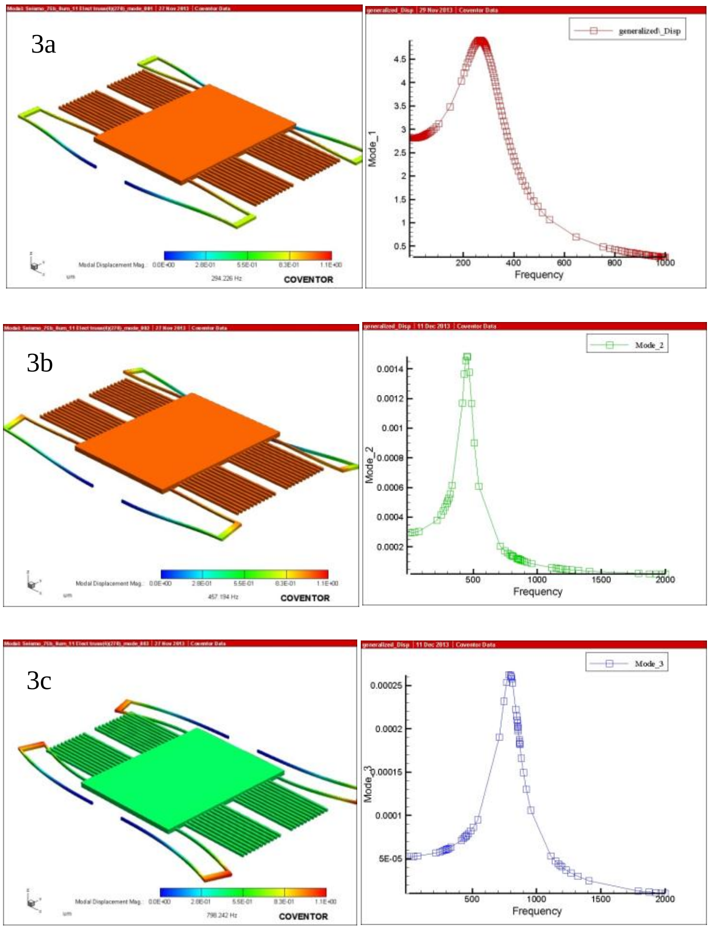

Fig. 3: First three modes of vibration. 3a shows the vibration along sensitive direction and 3b and 3c are next two higher modes of vibration.

Electrically, since the sensing principle is capacitive, there are certain constraints that need to be met with respect to electrical parameters. The dead capacitance C_0 (capacitance observed when there is no deflection) needs to be maintained less than 30 pF, and the change in capacitance ΔC is preferred to be greater than 10 pF. These design requirements are obtained from the readout electronics design proposed for the first prototype instrument. The electrical sensitivity is defined as the change in capacitance per unit g input acceleration. The area of overlap between electrodes and the separation between them determines dead capacitance. ΔC directly depends on the mechanical sensitivity. There are 44 pairs of electrodes with overlap length of 3.5 mm and depth of 150 µm. The gap between electrodes is fixed at 8µm. The electrodes are distributed as four sets.

Electrostatic and electromechanical FEM analyses was performed in order to compute the values of C_0 and ΔC and verify the analytically calculated values. The result is shown in Figure 4.

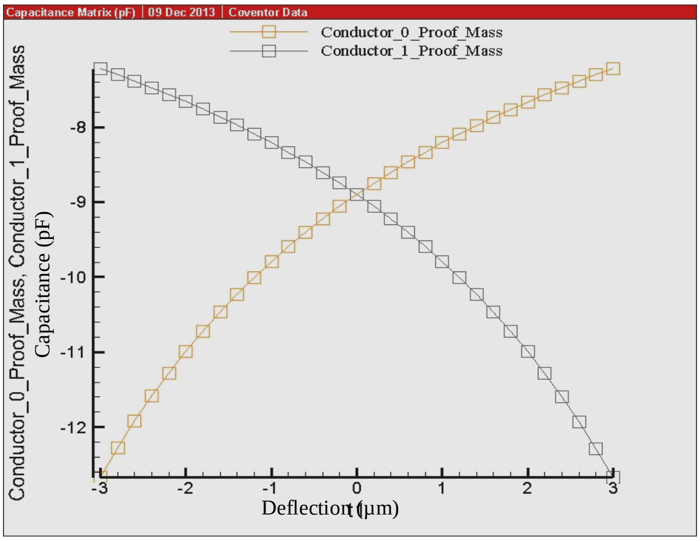

Fig. 4: Electromechanical analysis showing the electrical sensitivity of the structure per arm

IV. FABRICATION

The structures are fabricated from double side polished 100 mm diameter, low resistivity silicon wafer. The starting thickness is 380 µm. The support wafer is 500 µm thick, borosilicate glass having both sides polished to optical finish. We are using three masks to realize the seismometer structure with five levels of photolithography. The key process step in silicon wafer processing is the dry etching with standard Bosch process using the machine from SPTS. High aspect ratio etching is used to define the comb electrodes. The bonding of silicon wafer to glass is carried out using anodic bonder from AML. Aluminum contacts are defined on the wafer by sputtering with Nanomaster sputter system. The patterned wafer is annealed at 475 ^{O}C to make the contact linear and low resistance in nature. The devices are singulated by trenching the wafer stack using dicing machine from ADT. After every stage of silicon etching, the photoresist that is used as the masking layer is removed using plasma ashing system from PVA Tepla. The fabrication process flow is summarized in Figure 5.

(a) Starting Wafer, Silicon 380 µm thick, both sides polished, P type

(b) Dry plasma etching using SF_6, 10-15 µm deep

(c) High Aspect Ratio etching using SF_6 and C_4H_8 followed by bonding the processed side of Si wafer to Borosilicate Glass

(d) Electrical contact definition by Aluminum sputtering, patterning and annealing

(e) Final release of the structure with SF_6 and C_4F_8 plasma etching

Fig. 5: Fabrication process flow for realizing seismometer sensor structure at LEOS

The pilot fabrication round has been completed and we have realized the structures meeting the targeted specifications close to 75% of the designed values. A photograph of the device is shown in Figure 6. The sensor chip dimension is around 16 x 14 mm.

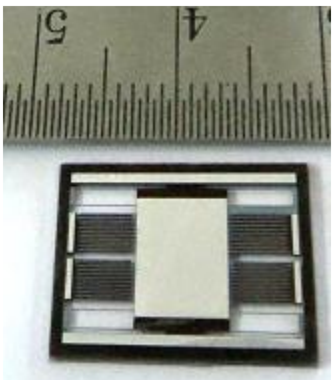

Fig. 6: Bulk micromachined seismometer sensor chip with silicon on glass architecture fabricated at LEOS

V. CONCLUSION

A bulk micromachined silicon sensor structure with silicon on glass architecture is designed and fabricated to realize a seismometer for lunar seismic studies. The instrument with this sensor is meeting the mission requirements in terms of weight, power, vibration/shock and radiation survival. The sensors obtained from first round of fabrication are being integrated to the readout electronics. Detailed performance analysis will be conducted and the results will be reported in future. The reasons of initial sensor chips not in close agreement with the targeted specifications are being analyzed. Based on the outcome of this analysis, design and processes modifications will be implemented in the future rounds of fabrication till the resultant devices exceed 95% targeted specifications.

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