

Design and Simulation of MEMS Vibration Sensor for Launch Vehicles

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Abstract

The prime intention of a launch vehicle is nothing more than to place the satellite in the designated orbit or a particular point in the space in a safe and secure manner. So an important task in that sort of a mission is to safely keep the satellite intact even under the extreme stresses and thermal conditions as well as during the severe vibrations and shock levels. And this paper deals with the design of a mems based vibration sensor to sense and measure the vibration induced in a launch vehicle during different stages of a mission. This paper is truly based on a summer internship project which I have pursued under the guidance of Mrs. Sheena Abraham (SCI/ENGR SF/ALDF/APG/ AVIONICS) at VSSC/ISRO Thiruvananthapuram. This paper covers the design of the sensor structure, a consolidated outline of the proposed fabrication methodology, couldn't elaborate it because of the word limit, and later it progresses with the numerical analysis and ends with a FEM simulation using ANSYS software which substantiates the practicality of the so proposed design. And hence a novel design which can withstand a maximum acceleration of 100g and a working frequency of 2 KHz, on keeping the resonant frequency at 20 KHz, was found as a result of the detailed study.

Keywords: MEMS, Vibration Sensor, Accelerometer, FEM, ANSYS.

1. Introduction

Shock and vibration perturbation in any mechanical or electrical device is an ongoing problem that engineers face. So as to analyze and examine the vibration levels in a

Launch Vehicle thousands of such accelerometers will be put in use. And miniaturizing such accelerometers will surely benefit us with the reduction of total weight of the Launch Vehicle as whole. This paper concerns with design of one such accelerometer/ Vibration sensor with the FEM simulation of the structure using ANSYS software.

2. Problem Statement

The intention of this project was to realize a design of *MEMS Vibration Sensor for Launch Vehicle*. As the title suggests the sensor has to be based on MEMS technology as well it has to prove the practicality and robust performance. The design criterion were; the sensing action has to be realized with a piezoelectric material, where the sensor has to have a square shaped diaphragm structure and the working frequency would be of around 20 KHz, so as the resonant frequency shouldn't be less than 20 KHz, also the sensor/diaphragm has to withstand a maximum acceleration of about 100g.

3. Design and Proposed Fabrication Methodology

Vibration sensor is nothing but an accelerometer, since vibration is a mode of acceleration, measuring the vibration levels of a body or system is same as measuring the proper acceleration on it. In this work a square shaped diaphragm of edge length 4mm was used, also it got a seismic/proof mass of square shape of edge length 2mm is meant to attach at the bottom centre portion of the diaphragm.

The piezoelectric materials under consideration were PZT-5H and Zinc Oxide. The fabrication process explains the method in which the design can be realized.

The starting substrate is a 4 inch diameter, (100) n-type (resistivity $> 1-10 \Omega\text{cm}$) double sided polished silicon wafer. The process demands only 3 masks, a front to back alignment and 2 DREI steps. The three mask levels consist of electrode definition, backside accelerometer frame (die) definition and backside proof mass area definition. At first a $0.5 \mu\text{m}$ thick silicon dioxide, thermally developed, has to be grown. A bottom electrode Ti/Pt (20 nm/150 nm) has to sputter on to the SiO_2 layer. After that a $0.5 \mu\text{m}$ ZnO has to be sputtered on top the bottom electrode. The top electrode is Cr/Au (20 nm/120 nm) which can be deposited by electron beam and thermal evaporation respectively. In the alternative design, on considering the PZT-5H, it has to be made on a layer on top of Ti/Pt by using SolGel process or chemical solution deposition approach for a thickness of $0.6 \mu\text{m}$. All these process until now can be performed by blanket process.

By adopting photolithography process as well as a two stage DRIE process the final structure of the sensor can be created which is as show in the fig: 1.

A 'two order packaging' has to be done for this sensor, namely first order and second order. First Order Packaging could be accomplished by using organic adhesives, such as BU-8 or BCB, as well as a lid made up of silicon itself. The lid will ensure a vacuum around the diaphragm, so that the load acted upon the diaphragm will

be purely inertial. In the Second Order Packaging the silicon substrate can be attached on to a metal base by using Si-Au eutectic bonding process. Electrical connections are made using a metal feed-through and glass-to-metal seals.

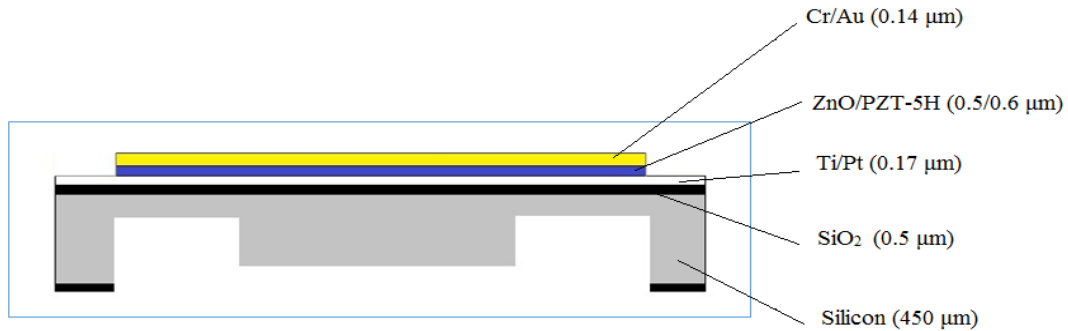


Fig. 1: Final Structure of the sensor after deposition and etching stages.

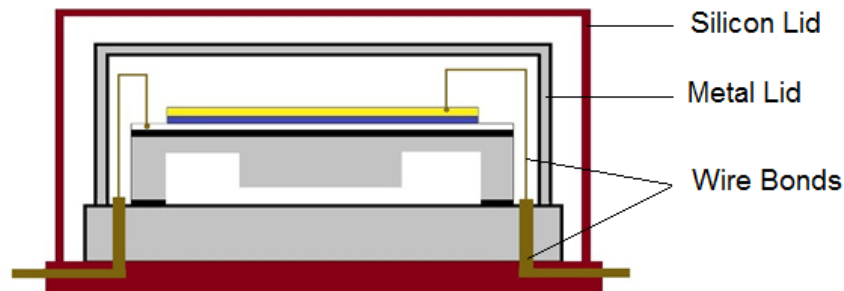


Fig. 2: Sensor with complete package (with electrical connections).

The electrical connections can be achieved through ‘Wire Bond’ technology, by using gold wires. The lead outs can be taken out through the silicon substrate and it will get in contact with the connection pads at the metal base, as shown in the above figure.

4. Results and Discussions

The findings of the hand calculations for the sensor structure and its electro-mechanical properties are mentioned in this section. As mentioned in the abstract the design requirements were, to have a resonance frequency of about 20Khz and the maximum acceleration in which the sensor will be put into will be 100 g. On analyzing the structure, it came to know that the maximum deflection and the maximum stress will be acted upon at the centre of the diaphragm structure with the corresponding values of 1.25 pm and 23.41 MPa, also it would be able to possess a natural frequency of 21.2 KHz with a spring constant (K) of 13.210 KN/m.

From the electro-mechanical angle of approach; charge, voltage as well as its related aspects are different for the two configurations say ZnO configuration as well as PZT-5H configuration. For the ZnO configuration the charge developed and charge sensitivity are $-1.6215e^{-14}$ C and $-1.714e^{-15}$ C respectively at the same time

corresponding values of its counterpart are $1.513e^{-13}$ C and $1.543e^{-14}$ C respectively and that is a favorable aspect for PZT-5H than ZnO, but when we compare the voltage developed in the ZnO configuration of about 0.199 mV than $6.27\mu\text{V}$ of PZT-5H configuration along with an added advantage of the lower capacitance value of $8.44e^{-11}$ F than $1.83e^{-8}$ F, hence ZnO shows more compatibility than PZT-5H. Also from a manufacturing point of view PZT-5H is not so commonly preferred because of the risks in using lead based materials in the laboratories.

To substantiate above mentioned structural analysis and the electro-mechanical outcomes, which is driven by the former, an FEM analysis has been done using the ANSYS Workbench, and the details are given in following section.

4.1 Modal analysis using ANSYS software

The structure in which the study was carried on, the ‘membrane–proof mass’ structure, was analyzed using the FEM model in ANSYS software (version 11). Which concluded with satisfactory results shows not that far agreement with the outcomes from the hand calculations. Two configurations for the sensor structure were put for the study, one ‘*without the proof mass*’, means it will act as simple thin film/plate and the second configuration evaluates the final and proposed design of the sensor the ‘*membrane–proof mass*’ structure. The deflection is through the Z-axis and since the membrane is fixed over the frame/die as per the design the boundary conditions for a ‘fixed end thin plate’ will prevail in this study. The plots are as follows.

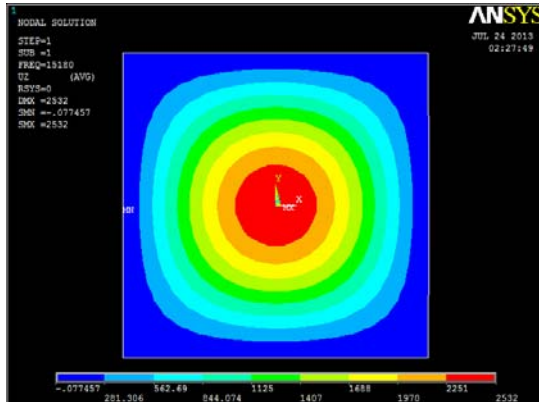


Fig. 4.1: Diaphragm without proof mass.

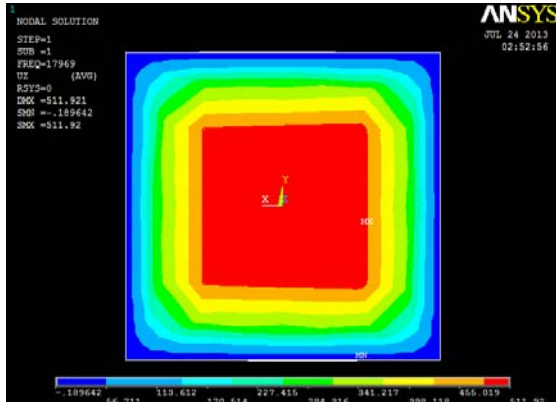


Fig. 4.3: Diaphragm with proof mass.

From the plot itself we can have a good idea about the deflection, also it has to be noted that there was a good level of increase in the Natural frequency, so as the resonant frequency, of the structure or the sensor. The value show is 17969 Hz, means it’s almost equals to 18 KHz. Also, from the FEM analysis, it is clear that the resonant frequency got shifted from 15180 Hz to 17969 Hz, which means on attaching the proof mass the natural frequency of the diaphragm/membrane structure got increased by more than 300 Hz. And that shows a considerable advantage from the design point of view. The theoretical calculation that carried out by keeping the resonant frequency as

20 kHz, and the numerical simulation; FEM analysis, showed a descent agreement with the former. And hence that analysis gives promising performance for the proposed design—the ‘membrane–proof mass’ design.

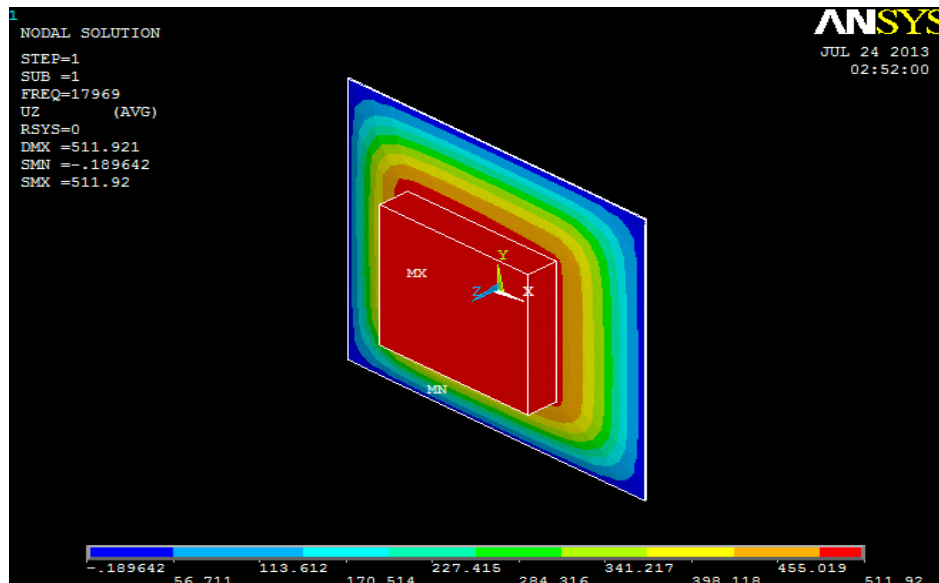


Fig. 4.3: Isometric view of Diaphragm with proof mass Structure.

5. Conclusion

The piezoelectric MEMS bases Vibration sensor/accelerometer, combining a ‘diaphragm–proof mass’ design and high yielding piezoelectric material Zinc Oxide film demonstrate good sensitivity $1.714 \times 10^{-15} \text{ C/g}$ and can deliver assured performance in the proposed working frequency of 2 kHz, since the resonant frequency found was about 18 kHz. The design of the sensor is in a manner that the transverse sensitivity will be negligible. Furthermore, the diaphragm design doesn’t require the etching through the silicon to release the diaphragm, unlike any beam type structures, therefore the fabrication process is simplified and yield is enhanced. Also it shows that the resonant frequency will vary with the force as well as the thickness of the diaphragm. And as a concluding remark, the descent agreement of the FEM analysis with the theoretical calculations shows promising utility and robust performance of the sensor.

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