Chapter 1
INTRODUCTION

The conjoining of silicon IC processing and micromachining techniques during 1980s marked the advent of Micro Electro Mechanical Systems (MEMS) technology and resolved many problems of critical space applications pertaining to weight, reliability, power consumption and cost. MEMS is a major step towards the ultimate miniaturisation of machines and devices. MEMS promises to revolutionize nearly every product category by bringing together silicon-based microelectronics with micromachining technology, making possible the realization of complete System-On-a-Chip (SOC).

MEMS is the integration of mechanical elements, sensors, actuators and electronics on a common silicon substrate through micro fabrication technology. While the electronics is fabricated using Integrated Circuit (IC) process sequences, the micromechanical components are fabricated using compatible "micromachining" processes that selectively etch away parts of the silicon wafer or add new structural layers to form the mechanical and electromechanical devices. Although the term MEMS is not restricted to silicon micromachining, most of today’s MEMS technology is based on silicon. Silicon micromachined inertial accelerometer is of particular importance because it offers the possibility of integrating sensor and signal processing circuit on the same chip, thereby permitting the construction of a smart sensor/ Integrated MEMS.

Design of MEMS is a challenging and currently active research topic. Micro accelerometer is a MEMS having wide range of applications in automobiles for measurement of acceleration and related parameters. It can also be used in satellite launch vehicles. The most important characteristics needed for navigational grade accelerometers viz. sensitivity, repeatability, accuracy, stability and reliability can be met perhaps only by micromachined devices. At present, five conventional servo accelerometers are used in satellite launch vehicle Inertial Navigation systems (INS). They weigh about 500 gms each. Substantial reduction with respect to weight, volume and cost can be achieved by using MEMS devices in place of the presently used servo-accelerometers. The cost saving in lieu of weight reduction alone is estimated to
be about Rs 20 lakhs per launch assuming a launch cost of Rs 10 lakhs per Kg. Due to inherent accuracy and repeatability of integrated circuits, MEMS accelerometers are all set to replace their conventional counterparts in the immediate future.

Design, performance analysis and optimization of silicon micromachined navigational grade accelerometer with particular emphasis of its use in satellite launch vehicles is the motivation of this thesis work.

Efforts are made to achieve the navigational performance by controlling the design parameters both at physical device and at system levels. Extensive design and analysis of the microstructure is carried out using ANSYS (shell element SHELL63). Mesh convergence study has been made and total number of elements has been arrived at. Initially, a typical simple symmetrical suspension structure (4 beam-support) has been chosen and based on the structural analysis viz, deflection analysis, frequency analysis, stress analysis and cross axis sensitivity study, dimensions of the accelerometer for launch vehicle Inertial Navigation System (INS) have been optimized. For optimizing the geometry of the microstructure, several other suspension structures that can be used in bulk micromachined accelerometers are also analyzed. The beams are assumed to be rigidly fixed. The same number of elements are assumed in all cases. After the first iteration, simple beam configuration from the centre of four sides of the proof mass has been selected as the best option. Subsequently, single folded and double folded configurations are also analysed.

Coventor Ware software tool which supports both physical and system level approaches to design MEMS has been used for further analysis. Structural analysis carried out hitherto with ANSYS has been repeated with Coventor Ware. Both results are matching closely indicating design perfection. With Coventor Ware, structural analysis has been carried out on various cross sections of the proof mass which are obtained from both wet and dry etching processes. Also study has been carried out with various suspension schemes (beams formed at the top and from the centre of the proof mass thickness). It is found that the dry etched proof mass with beams formed from the center of the proof mass thickness is the best option for navigational use from both performance and fabrication point of view. Thus the symmetrical geometry with simple beams at the centre of each side formed from the middle of the proof mass thickness with dry etching has been arrived at as the best choice and design
constants have been finalized for the launch vehicle inertial navigation application with a range of ± 20 g and bandwidth of 200 Hz.

Subsequently mechanical noise of the designed microstructure has been analysed and the vacuum level at sealing has been tuned to achieve the required quality factor/damping ratio. The noise level has been kept as low as possible to obtain the required resolution. The open-loop model of the accelerometer has been simulated in the MatLab Simulink with the designed parameters and its performance analysed. The step response and Bode plots have been plotted and analysed for various damping ratios. The performance of the designed accelerometer has been predicted. Capacitive pick-off sense methodology has been chosen. A high sensitive, high performance differential capacitance pick-off circuit has been designed, keeping the noise as low as possible. The circuit has been simulated in Microsim PSPICE and results are analyzed. The designed circuit can be implemented in CMOS technology which can be integrated into the same silicon chip with the micro structure, at a later stage, leading to Integrated MEMS.

The non-linearity at the capacitive pick-off output is improved by digital compensation. Non-linearity has been characterized, algorithm designed and validated. Compensator module has been implemented in FPGA and its performance verified. MIL-STD-1553B Bus Interface circuit has been designed to make accelerometer output compatible to bus oriented system.

This thesis is organised in 10 chapters. First chapter being introduction, the second chapter presents an overview of MEMS and Microsystems, materials, fabrication process and micromachining techniques. The third chapter focuses on inertial accelerometers and the requirements of inertial navigation system for launch vehicles. Also it presents the capacitive pick-off micromachined accelerometers, modeling and analysis.

The fourth chapter concentrates on the micro structure. Extensive design and analysis of the micro structure is carried out with the help of ANSYS Multi Physics FE package so as to achieve the performance required for use in launch vehicle inertial navigation system with a range of ±20 g and bandwidth of 200 Hz and the results are presented.

Also the performance of various microstructure geometries has been studied.
Deflection, frequency and stress analyses are performed and sensitivity study has been carried out by varying the beam dimensions to select the best option for ±20 g / 200 Hz accelerometer and the results are presented.

In the fifth chapter Coventor Ware Finite Element tools have been used to design, model and characterize the mechanical microstructure. Also structural analyses carried out hitherto with ANSYS have been repeated with Coventor Ware. Accelerometer design has been completed with capacitive sensing transduction circuits and noise analysis has been carried out. The performance of the designed accelerometer has been predicted and results presented.

Sixth chapter focuses on transduction circuitry. A high performance differential capacitance readout circuit capable to meet the high resolution and stability requirements and which can be implemented in CMOS technology is designed and analyzed. The designed circuit has been simulated in PSPICE and performance evaluated.

In chapter seven, non-linearity of capacitive transduction circuit is modeled as a third order polynomial. The algorithm for solving the polynomial is developed with a view to implement in ASIC with the ultimate goal of realizing an integrated smart accelerometer for navigation purpose. The algorithm is coded in VHDL, simulated, synthesized and implemented in FPGA and evaluated. Test results match closely with the simulation.

Chapter eight deals with the design and implementation of 200 Hz filter and design of MIL-STD-1553B Bus Interface circuit. A second order digital filter is designed for a bandwidth of 200 Hz. The algorithm of the digital filter has been developed in C language, simulated and verified. Also in this chapter, MIL-STD-1553B Bus Interface circuit has been designed to plug the accelerometer output to MIL-STD-1553B Bus system.

In chapter nine, packaging aspects of MEMS are addressed.

The thesis concludes with the results of the study and scope for future work. Some of the results of these investigations have been published as per the details given below:


3. “Comparative study on various Microstructure configurations for Navigational grade MEMS Accelerometer” at the National Symposium on Instrumentation held at CUSAT Cochin pp 404 – 409 (2005).


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