Design and simulation of a SOI based mems differential accelerometer

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Abstract

In this paper, the design and analysis of a differential MEMS capacitive accelerometer is presented. The device is designed to be compatible for SOI based fabrication process. The outstanding mechanical and electrical properties of silicon on insulator (SOI) wafers make it popular for high-performance MEMS sensors such as accelerometers. The operating range of the designed device is 0-10g with its sense axis in the in-plane direction. The movable comb fingers attached to the proof mass form capacitors with the fixed electrode fingers. The movable and fixed fingers are spaced with unequal gaps to form the differential capacitive sensing configuration. The base capacitance of this configuration is about 0.77pF and the sensitivity in response to acceleration input is about 0.776 fF/g. The resonance frequency of the structure in the sensing mode is found to be 7.138 kHz.

Keywords: MEMS; Accelerometer; DRIE; CoventorWare®; SOI;

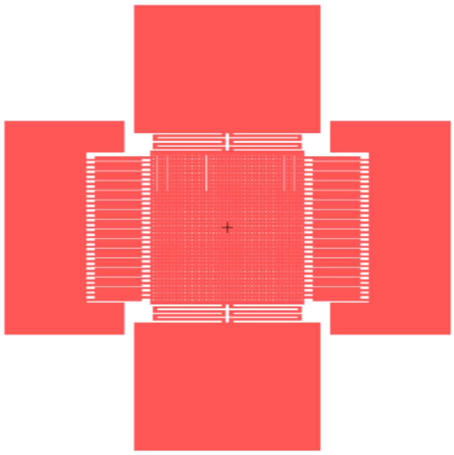
1. Introduction

Accelerometer is used to measure the acceleration, inclination and vibrations of a moving object. Accelerometers have captured a large portion of the MEMS market and emerged as the second largest sold product after Pressure sensors. Micro accelerometers alone have the second largest sales volume after pressure sensors [1]. The miniature accelerometer devices find applications in various areas such as inertial navigation systems for navigational aids, in automobiles for safety air bag deployment, in industries for measurement of machinery vibration and many more. However, the large volume demand for accelerometers is due to their automotive applications, where they are used to activate safety systems, including air bags, to implement vehicle stability systems and electronic suspension [2]. However, the application of accelerometers covers a much broader spectrum where their small size and low cost have even a larger impact. Several accelerometer designs have been reported in different configurations. Some are based on the number of sensing directions it possesses while others are based on the sensing mechanisms such as capacitive, piezo-resistive etc. The most commonly employed acceleration sensors are based on capacitive sensing mechanism due to its almost temperature-invariant nature. However, capacitive sensors are prone to parasitic effects which can be reduced by taking proper care in the design and during packaging. Another important development in capacitive accelerometers is the implementation of the concept of differential sensing. This concept not only increases the sensitivity but also helps in cancelling out the noise.

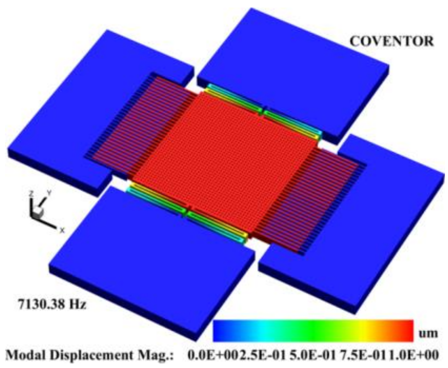
Using the well-established micromachining technology, it is possible to fabricate hundreds of miniature sensors in a single wafer. The technology also offers a wide range of processes to choose from for fabrication of the sensors. The choice of fabrication process is based on the complexity and functional requirements of the sensor. Bulk micromachining and surface micromachining are two basic processes of the micromachining technology. However today, due to the complexity of the structures a combination of both bulk and surface micromachining is employed. Apart from surface and wet bulk micromachining techniques, micro machining by Deep reactive-ion etching (DRIE) is widely employed using SOI wafers for fabrication of the sensors [3-5]. The Deep reactive-ion etching process has proven to be a versatile process, due to its ability to create complex microstructures in several fields such as technology of computer optics [6-8] and others apart from MEMS. Devices fabricated on SOI wafers generally have lower parasitic capacitance, which is vital in capacitive sensors. Further, using the Deep reactive-ion etching process it is possible to etch high aspect ratio structures with nearly vertical sidewalls, which is an important advantage for capacitive structures. DRIE has proven to be a versatile process, due to its ability to create complex microstructures. The advantages of DRIE process are exploited using SOI substrates for fabrication of the sensors [9]. SOI wafers have a well defined device layer with uniform thickness and a buried oxide layer which acts as an insulator as well as an etch stop. Due to these features, the process complexity is reduced to a great extent and it also allows for MEMS and IC integration [3, 4]. Several SOI-MEMS accelerometers have been successfully designed and fabricated. Hence the silicon-on-insulator (SOI) process combines the advantages of DRIE and SOI substrate to precisely fabricate complex structures. In this paper we present the mechanical design and simulation of differential capacitive accelerometer structure using SOI process.

2. Mechanical design and operation

The structural design of a SOI based DRIE-micro machined MEMS comb accelerometer is shown in Fig.1. The movable parts of this MEMS comb accelerometer consist of four folded-beams, proof mass and movable fingers. The fixed parts include two anchors and 2 sets of fixed comb fingers, one each on either sides of the movable proof mass. The central movable mass is connected to both anchors through four folded beams. U-beams are used in the design to increase the flexibility such that the device responds to lower g levels, resulting in finer resolution. The central proof mass has several comb fingers on either sides which overlap with the fixed comb fingers in the same plane, such that each movable finger has a fixed finger on either sides. The movable finger constitutes the differential capacitance pair with the left and right fixed comb fingers. When there is no acceleration, the movable fingers are in the rest position between the left and right fixed fingers. In this condition, the left and right capacitance pairs have some constant value. In the event of an acceleration a in the sensing direction parallel to the device plan, the proof mass M experiences an inertial force, $M \cdot a$, *in* the opposite direction. As a result, the beams deflect and the movable proof mass experiences a linear displacement in a direction opposite to the direction acceleration. As the proof mass moves, the movable fingers attached to the proof mass also move, causing a change in the gap with the left and right fixed fingers. Hence the capacitance also changes. By measuring and calibrating this small differential capacitance change with reference to external acceleration, the magnitude and direction of the experienced acceleration can be known. This is the working principle of the MEMS comb accelerometer. Some design considerations have been taken into account for fabrication compatibility. The proof mass is provided with large anchors so that it can be electrically isolated from the fixed comb fingers by creating trenches in silicon. The gap between the fixed and movable fingers is designed such that the oxide etchant has easy access to etch the underlying buried oxide to release the structure. The proof mass is provided with perforations for the purpose of damping and for sacrificial release of the structure. Care should be taken in the mechanical design to avoid features of varying sizes which would otherwise hamper the release process. Accordingly the structure is designed and the dimensional parameters of the beams, proof mass and other features of the structural layer are given in Table-1.



(a)



(b)

Fig. 1. (a) Device layout; (b) FEM Simulation: Fundamental mode in y-direction.

3. SOI fabrication process

The proposed fabrication process involves just two lithography steps. In this process silicon-on-insulator wafer with 15 μm device layer, 4 μm buried oxide layer and 675 μm handle layer is used as the starting material (Fig. 5). The process is based on Deep reactive Ion etching to realize high aspect ratio structure and finally the structure is released by sacrificial etching of the buried oxide using Vapor phase etching. The process begins with the deposition of Cr/Au to a thickness of 200Å/2000Å on the silicon device layer using sputtering process. Subsequently, lithography and etching is carried out selectively to realize the metal pads for wire bonding. The pads are located on the four proof mass anchors and on all the four stationary comb anchors. The device layer of the SOI wafer shall have low resistivity such as 0.01 ohm-cm, for better electrical connectivity from the anchors to the movable fingers. This is followed by Lithography of the structural layer and subsequently baking is done to harden the resist before it undergoes DRIE process. Next, silicon is etched up to buried oxide using controlled process parameters. At the end of this step, the structural layer is formed with the necessary metal pads. The structural layer is then released by sacrificial etching of buried oxide using Vapor phase etching process. The etching is time based and ensures perfect release of the structure while limiting the undercut to a minimum.

Table 1. Parameter values used for calculations

Parameters	Values
M	2.7844×10^{-8} kg
Frequency (ω)	7130.38 Hz
Perforation size	8 μm
Young's Modulus	185 GPa
Beam length	350 μm
Beam width	10 μm

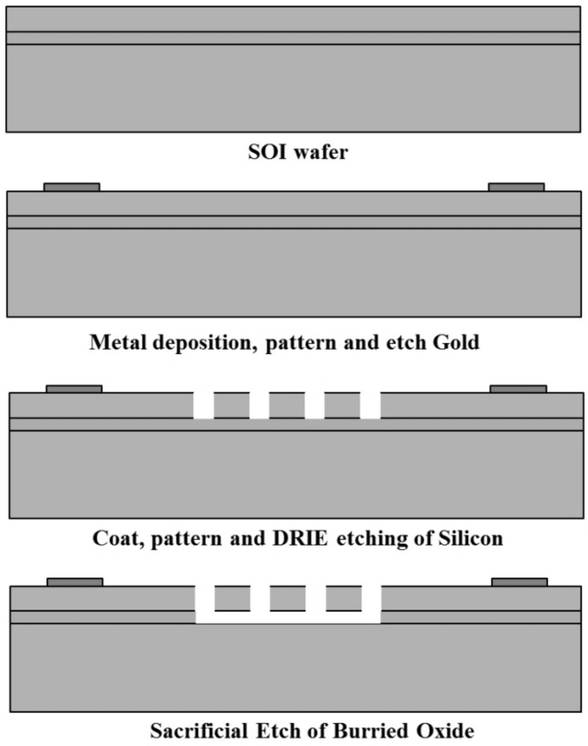


Fig.2. Fabrication steps of SOI MEMS accelerometer.

4. Results and Discussion:

FEM simulation has been carried out using CoventorWare® MEMS design and Analysis software suite. The device is modeled using the SOI process in the process editor and layout editor tools of CoventoWare®. The proof mass thickness is modeled as 15 μm and the gap between the movable finger with left and right fingers is 2 μm and 3 μm. Frequency analysis has been carried out and it is found that the fundamental mode in the sensing direction occurs at a frequency of 7.13 kHz. Hence, the device can be conveniently used for automobile applications. The mode shape corresponding to this frequency is shown in Fig. 1(b). Parametric study was carried out to determine the displacement of the proof mass for different acceleration inputs. The plot of displacement versus acceleration is shown in Fig. 3. It can be seen in the plot that the proof mass has a linear movement all-through the designed acceleration range. The maximum displacement of the proof mass at 10g acceleration is found to be about 50 nm. Coupled electro-mechanical analysis was carried out to determine the change in capacitance of the capacitors formed by the fixed and movable fingers in response to external acceleration. The variation in capacitance on the left capacitive comb fingers and the right capacitive comb fingers is plotted and shown in Fig. 4. It can be seen that the magnitude of change in capacitance on the left fixed fingers and right fixed fingers is the same but opposite in nature i.e. one shows an increasing trend in capacitance while the other shows a decreasing trend. The differential capacitance change per g is found to be 0.776 fF and the full scale output at 10g acceleration is about 7.7 fF, at the sensor level. This can be further amplified and converted to a voltage output using suitable conditioning electronics.

5. Conclusion

The design and fabrication process of a SOI based MEMS differential capacitive accelerometer with u-beams is presented. The considerations in mechanical design for fabrication compatibility with SOI process are discussed. The device is designed with u-beams for in-plane motion in the acceleration range of 0-10g. FEM simulations have been carried out to determine the resonant frequency, proof mass displacement and capacitance change. The resonance frequency of the structure is found to be 7.13 kHz, characterized by in-plane motion in the sensing direction. The concept of differential sensing with unequal gaps between the movable and fixed fingers has been implemented and the sensitivity of the device is found to be 0.776 fF/g. The maximum displacement of the proof mass is found to be about 50 nm at 10g acceleration. The process flow for fabrication of the acceleration sensor on SOI wafers using a simple two mask process is explained.

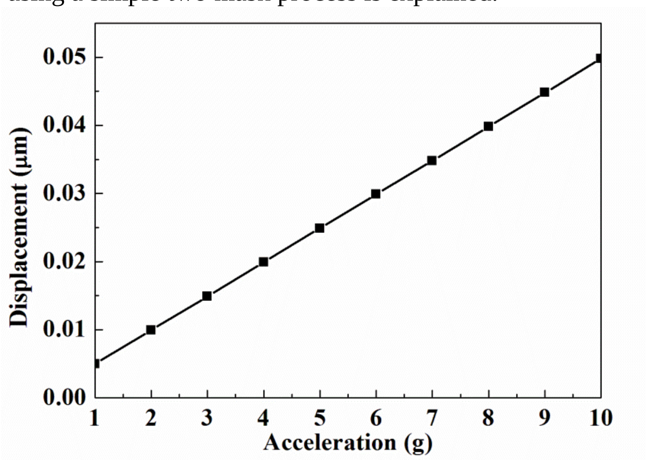


Fig. 3. Acceleration vs. displacement plot.

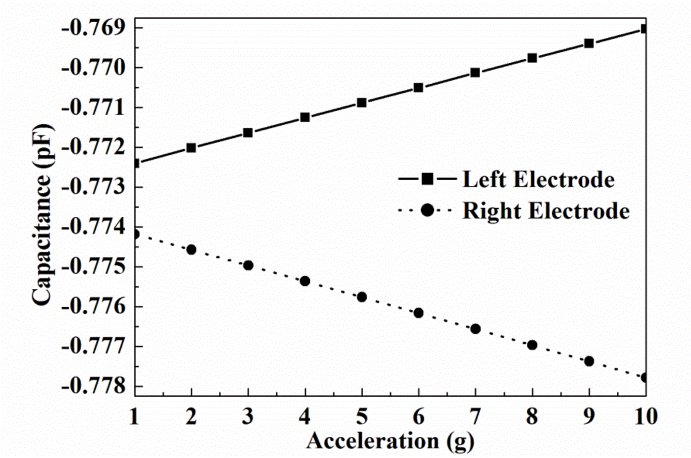


Fig. 4. Acceleration vs. capacitances plot.

Acknowledgements

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