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Study On Design and Fabricate a Mems Piezoresistive Accelerometer with Very Low Cross-Axis Sensitivity for Aircraft Sensing Application

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Abstract – MEMS accelerometers are widespread in various applications like inertial sensing applications, indoor robotic navigation, microsurgery, volcanology and also in defense applications. Though various sensing mechanisms are available piezoresistive is still popular due to its simple fabrication and packaging techniques. An incessant development has been made in the growth of piezoresistive accelerometers which has led to various innovations in design, fabrication, packaging and testing. The present thesis focuses to study on MEMS piezoresisitve accelerometer that deals with simulation analysis of quad beam MEMS piezoresistive accelerometer, etch time optimization using a novel corner compensation structure and a detailed discussion on realization of piezoresistive accelerometer with proof mass edge aligned flexures. To determine the device performance two structures quad beam piezoresistive accelerometer with and without gold were analyzed. Damping characteristics were estimated by analyzing different structures of fixed-fixed quad beam piezoresistive accelerometer using a high performance Finite Element processor (Altair Hypermesh) and analysis by means of OptiStrucut module. To analyze the undercutting behavior in fixed-fixed quad beam piezoresistive accelerometer the etch time characteristics were estimated. A study has been done to determine the etching time of different compensation structures using KOH and TMAH etchants using Anisotropic Crystalline Etching Simulator (ACES). To improve the cross axis sensitivity in the device the flexures are made in aligned with the proof mass edges in the present study.

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INTRODUCTION

"Small is Beautiful." The fact of this statement is discussed in economic and communal circles, but when it comes to technology, there is no debate; small is beautiful because small is fast, small is cheap, and small is profitable. Feynman termed the word "miniaturization" in science and technology for our time. The technology which combines miniaturization in electronics and mechanical engineering structures is micro-electro mechanical systems (MEMS). MEMS is the technology to realize very small devices and made up of components between 1 to 100 micrometers in size. MEMS devices generally range in size from 20 micrometers to a few millimeters. These devices started finding practical applications once they could be fabricated using modified semiconductor device fabrication technologies such as bulk micromachining, surface micromachining, wafer bonding and electroplating to name a few (Madou M J et al., 2012). The application of of MEMS spans over a wide range of devices like accelerometers, gyroscopes, microphones, wearable devices and biomedical devices.

An accelerometer measures the acceleration it experiences relative to a freefall. Accelerometer devices detect both the magnitude and the direction of the acceleration as a vector quantity, and is used to sense orientation, vibration and shock of various device (Mac Donald G. A., 1990). An accelerometer behaves as a damped mass on a spring and experiences an external force such as gravity, the mass is displaced until the external force is balanced by the spring force. An accelerometer fabricated by a MEMS process are mechanically similar to traditional accelerometers, but only fabricated on a micrometer scale. Advantages of MEMS sensors are small in size, light weight, low cost and low power and their ability to monolithically fabricate signal conditioning circuitry on the same die, resulting in improved sensor performance and reduced sensor costs. Accelerometers are in great demand for many applications including biomedicine, airbag, inertial navigation, acoustic emission, seismometer, machine vibration monitoring, guidance and stabilization of the spacecraft"s, etc.

CLASSIFICATION OF ACCELEROMETERS

It is desirable that accelerometers have high sensitivity and fine resolution. Various sensing techniques like capacitive, piezoelectric, tunneling, piezoresistive are used for acceleration measurement.

Performance of a capacitive accelerometer is superior due to its high sensitivity, good dc response, low temperature sensitivity and low power dissipation. Capacitive accelerometers have several attractive features: In most micromachining technologies no or minimal additional processing is needed, capacitors can operate both as sensors and actuators. However, the structural configuration of the capacitive accelerometer is much more complicated than the piezoresistive devices. Moreover, capacitive accelerometer needs on-chip integration with associated signal conditioning circuits and reduces noise. Irrespective of the base material, capacitive accelerometer relies on the variation of capacitance when the geometry of the capacitor is changing. Acceleration is detected by a change of distance or change of overlapping area of the two electrodes due to the inertial force (Rocha L A et al., 2011, Sankar A R et al., 2011, Zhou X et al., 2015). Figure 1.1 shows the model of a capacitive accelerometer.

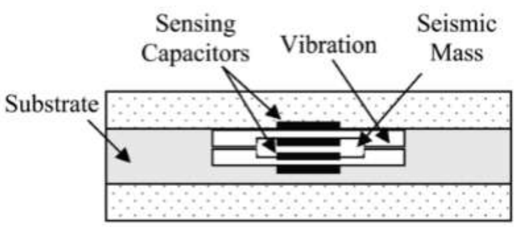

Figure 1.1 Model of a capacitive accelerometer

Piezoelectric accelerometers are made up of piezo ceramics (e.g., lead zirconate titanate) or single crystals (e.g., quartz, tourmaline) which produce an electrical charge when stressed. When the seismic mass experiences a vibration, piezoelectric accelerometer generates an electric charge signal proportional to the induced acceleration (Wang T et al., 2017). A model of a piezoelectric accelerometer is shown in Figure 1.2. Piezoelectric accelerometers are widely accepted as the best choice for measuring absolute vibration. They are unmatched in terms of their upper frequency range, low packaged weight and high temperature range.

Tunneling accelerometers are sought to measure very fine perturbations such as detecting and identifying submarines. Tunneling tips have been utilized to increase the resolution and sensitivity of the device. By utilizing a feedback control circuit to maintain a constant tunneling gap between tip and counter-electrode, the accelerometer is able to measure minute displacement readings (Liu C H et al., 2001).

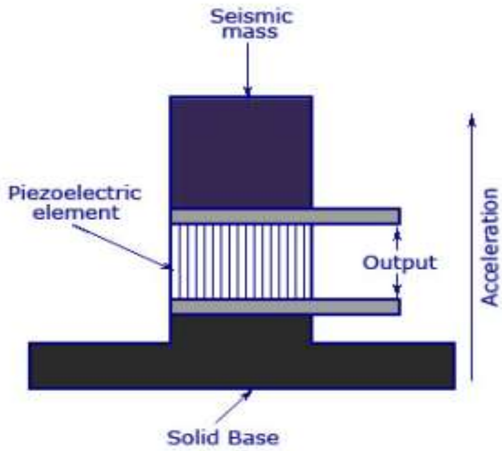

Figure 1.2 Model of a piezoelectric accelerometer

The system to measure the acceleration is shown in figure 1.3. Though the tunneling accelerometer offers high sensitivity, the damping mechanisms are very complex due to the complexity of the structure.

In piezoresistive accelerometers, miniature silicon resistors are embedded at maximum stress locations in a suspended beam to sense the input acceleration. The sensing mechanism utilizes the change of resistivity of the embedded resistors to sense the acceleration (Rockstad H K et al., 1996). Required damping of a piezoresistive accelerometer can be obtained by changing the gap between the moving proof mass and top or bottom glass lids that are static. No complex process steps are required in achieving the required damping, since changing the gap between moving and fixed cover plates does not affect the device sensitivity. However, the main drawbacks of the piezoresistive sensing method are large temperature sensitivity and low overall sensitivity.

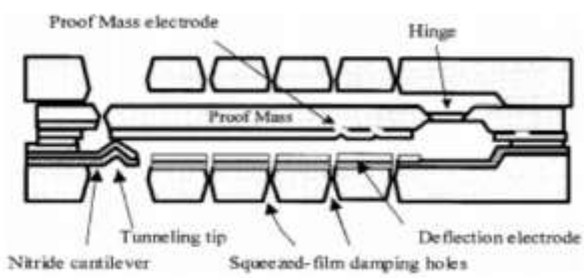

Figure 1.3 Model of a tunneling accelerometer (Liu C H et al., 2001)

Moreover, piezoresistive sensors show excellent DC response and hybrid packaging of the sensor chip with signal processing chip in the same die can be used without any signal loss. Figure 1.4 shows the classification of various accelerometers with their performance features.

Piezoresistive accelerometer

Piezoresistive accelerometer was the first silicon accelerometer realized using micro machined technology (Roylance L M et al., 1979). Piezoresistive accelerometers are the most popular and widely used method of acceleration sensing due to their simplicity in fabrication, packaging and inherent ruggedness.

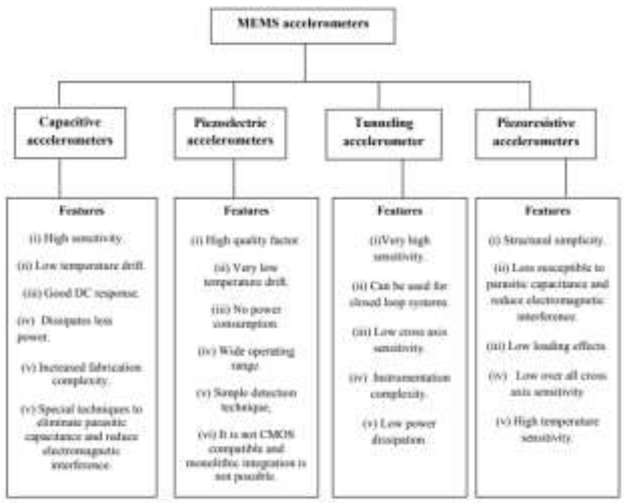

Figure 1.4 Classification of various MEMS accelerometers

CHARACTERISTICS OF PIEZORESISTIVE ACCELEROMETERS

The first batch fabricated accelerometer made use of the piezoresistive property and was initiated by Roylance and Angell in 1979. The device is 3mm long with a mass of 0.02g. The accelerometer was able to measure accelerations ranging from 0.001g to 50g. His work motivated several researchers to develop various silicon based micro-machined piezoresistive accelerometers (Roylance L M et al., 1979).

Configuration of the piezoresistive accelerometers

Piezoresistive accelerometer consists of a heavy seismic mass (M) attached to a fixed frame through a spring of stiffness (K). When acceleration is applied, the mass stays in rest and the spring stretches to get sufficient energy which makes the mass to move. When there is a steady acceleration, the mass tends to move either away or towards the frame; while in oscillation the mass will tend to move in both directions. The acceleration can be measured by measuring the stress in the spring. The two forces acting on the accelerometer are restoring force and damping force. Acceleration acting on the mass causes damping force to act, which in turn causes the mass to move up or down until the restoring force of the beam suspension equals the inertial force. In Figure 2.1, 'M' represents the mass of the system; 'K' represents the spring Constant 'X' represents displacement and 'D' represents damping Constant. The desired properties of micro-accelerometers are high sensitivity, high resolution, good linearity, low offset, low drift, low cross-axis sensitivity, low temperature sensitivity, wide operation range and frequency response, high accuracy, precision and high signal/noise ratio (Roylance L M et al., 1979).

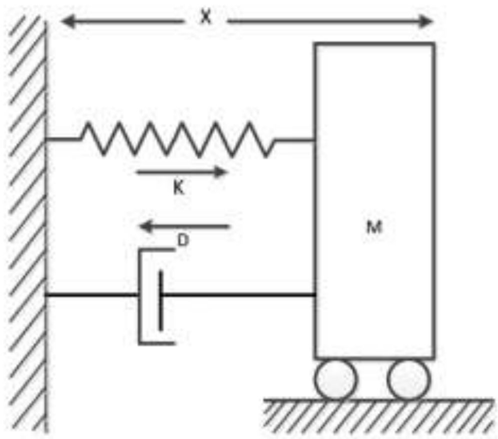

Figure 2.1 Pictorial view of suspended beam mass structure

Design of piezoresistive accelerometers

Kampen et al. reported the mechanical behavior of the static and dynamic properties of bulk micro-machined accelerometers (Van Kampen R V et al., 1998). The static characteristics are the properties of the system after all the transient effects have settled to their final or steady state; and is determined by the mass and the stiffness of the beam suspension which includes sensitivity, accuracy, precision, linearity, etc. The stiffness of a material in a particular direction depends on (i) the number of flexures (ii) geometrical dimension on the flexures and (iii) the position of the flexures (Sankar A R et al., 2012).

Equation 1.1 represents the vertical displacement of the mass subjected to normal acceleration.

$$\Delta Z = -\frac{Ma_z}{K_z} \qquad 1.1$$

Equations (1.2) & (1.3) represent mass subjected to lateral acceleration causing rotation in 'X and 'Y' axes direction.

$$\theta_x = -\frac{Ma_y Z_c}{K_{\theta y}} \qquad 1.2$$

$$\theta_y = -\frac{Ma_x Z_c}{K_{\theta x}} \qquad 1.3$$

The properties of the system transient response to the input are called dynamic characteristics of the device. The resonant frequency and damping determine the dynamic characteristics. It includes zero, first and second order systems (Van Kampen R V et al., 1998). The resonant frequency is governed by the Eigen values of the system and it is given in Equation (1.4),

$$f_z = \frac{1}{2\pi}\sqrt{\frac{K_z}{M}} \qquad 1.4$$

where 'M' is the mass of the proof mass, 'az' is acceleration along the z-axis, 'ay' is acceleration along the y-axis, 'ax' is acceleration along the x-axis, 'Zc' is the distance between the 'Kɵx' is the spring constant of the flexure along 'X' axis, 'Kɵy' is the spring constant of the flexure along 'Y' axis, 'Kz' is the spring constant of the flexure along 'Z' axis.

RESEARCH OBJECTIVE

This research work aims to design and fabricate a MEMS piezoresistive accelerometer with very low cross-axis sensitivity for aircraft sensing application.

It also focuses to solve the undercut issues which happen during micromachining and the problems related to wet anisotropic etching.

RESEARCH METHODOLOGY

A single cantilever proof mass structure shown in figure 3.1 (a), was introduced by Roylance et al., in 1979. It deflects the 200µm thick proof mass for accelerations acting perpendicular to the proof mass plane. The stress was measured using p-type resistors diffused in the beam. However, the cross axis sensitivity measured was around 10% and the device is used for medium g accelerometers. In 1991, Tschan et al., developed a two beam accelerometer in which the beams are located at one side of the proof mass as shown in figure 46 3.1 (b). Though the cross axis sensitivity is slightly less as compared to single cantilever proof mass structure, the prime axis sensitivity is reduced by 50% and not suitable to be used for high performance applications. A two beam accelerometer also called as torsional double beam structure is similar to a bridge type two beam structure and is designed by placing two beams in a balanced manner at the centre of two opposite edges.

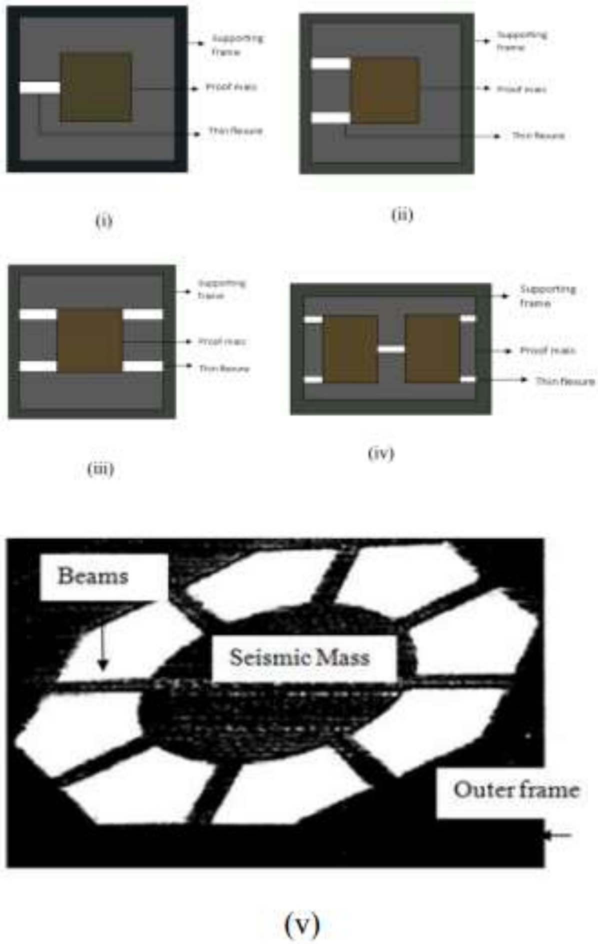

Figure 3.1 Structural Configuration of (i) single beam structure (ii) double beam structure (iii) quad beam structure (iv) twin mass five beam structure (v) eight beam structure

Table 3.1 Device dimensions of the sensor

Parts of the device sensor	Parameter	Dimensions (µm)
Proof mass	Length	3500
	Breadth	3500
	Thickness	270
Flexure	Length	1200
	Breadth	250
	Thickness	20
Electroplated Gold	Length	2500
	Breadth	2500
	Thickness	20
Piezoresistors	Length	200
	Breadth	20
	Thickness	2

A twin mass with five beam structure as shown in figure 3.1 (iv), was fabricated by C Burrer et al., which has two proof mass with beam connecting the two proof mass. The figure of merit is high compared to other structures nevertheless it occupies more space. An eight beam by Jun Hwan Sim et al. has eight beams with four beams placed at the top side of the proof mass and other four beams placed in the bottom surfaces. Though the cross axis sensitivity is reduced by 50% compared to quad beam structure, micromachining the device without any undercut is quite difficult. Figure 3.1(v), shows the configuration of an eight beam structure. The device specifications considered for study is given in Table 3.1,

RESULTS AND DISCUSSION

The above results are analyzed using ACES simulator to determine the etch time consumption for different etchants at its corresponding etchant concentration and temperature.

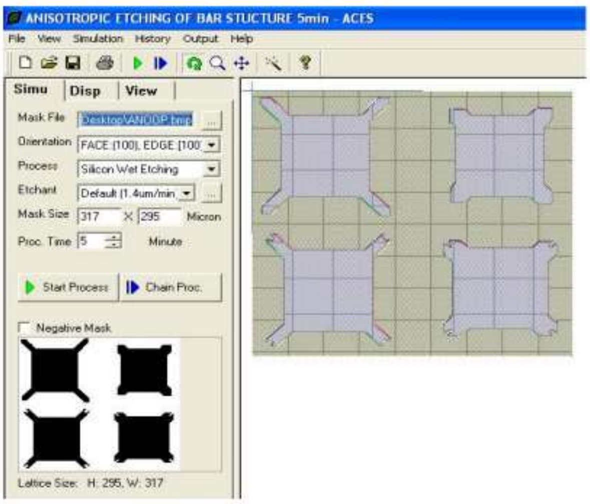

Figure 4.10 Screen shot of ACES window before the etch time optimization

From the experimental analysis made by Seidal H et al., it is observed that the etchant concentration is inversely proportional to the etch rate and the temperature is directly proportional to the etch rate (Seidal H et al., 1987, Madou M J et al., 2012). Xuefeng D et al. analyzed the characteristics of square mask file which has 300µm length and 300µm breadth using TMAH etchant (Xuefeng D et al., 2005). He used a triangular strip (a small pad for corner compensation structure) along (100) direction for 60 minutes by simulating the etching process using a cellular automata method. The present study focuses to study the etching time of different compensation structures using KOH and TMAH etchants using Anisotropic Crystalline Etching Simulator (ACES). ACES takes the values of etchant concentration, temperature, the mask file, and the mode of etchant as its input and the processing time is evaluated as soon as perfect corner is obtained at the 84 edges of the corner. The size of the mask has a length of 317µm and a breadth of 295 µm. Figure 4.10 shows the screen view of the ACES window.

CONCLUSION

This present research work aspires to study and design very low crossaxis sensitivity MEMS piezoresistive accelerometer. This thesis has addressed the following topics of research (i) the simulation analysis of etch time optimization in bulk silicon MEMS devices using novel structures, (ii) realization issues of the sensor using wet anisotropic etching based bulk micromachining, and (iii) investigation of fixed quad beam accelerometer and its damping analysis.

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