

Design Optimization of MEMS Comb Accelerometer

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Abstract

MEMS (Microelectromechanical Systems) refers to the technology integrating electrical and mechanical components with feature size of 1~1000 microns. MEMS comb accelerometers have been successfully applied for air-bag deployment systems in automobiles. In this paper, the design optimization of a poly-silicon surface-micromachined MEMS comb accelerometer is discussed. The device uses folded-beam structure to enhance the sensitivity. The movable mass is connected to two anchors through folded-beams. There are movable fingers extruding from both sides of movable mass. Each movable finger has left and right fixed comb fingers surrounding it, so that a differential capacitance pair is formed. Any acceleration along the sensitive direction will induce inertial force on movable mass and deflect the beams. Hence the differential capacitance gap will change. By measuring this differential capacitance change, the experienced acceleration can be measured. ANSYS FEM simulation is used to extract the device sensitivity and resonant frequency of the device. By gradually varying the design parameters in ANSYS simulation, the relationship between the device sensitivity and various design parameters is derived. The curves of device sensitivity versus beam width, beam length and mass width are derived and they are in good agreement with theoretical prediction. From the analysis it is concluded that the device behavior strongly depends upon various design parameters. By adjusting design parameters, desired sensitivity can be obtained. Based on the simulation results, a set of optimized design parameters for the comb accelerometer is decided. The ANSYS simulation results show that the device has displacement sensitivity of 3nm/g. The above-proposed MEMS comb accelerometer may be used for many applications, such as automobile airbag deployment and navigations, fabrication sequence of the comb accelerometer is also proposed. The device is to be fabricated using surface-micro machining process with sacrificial layer technique.

I. Introduction

MEMS accelerometers are used to sense the acceleration experienced by a system. They have been good examples for MEMS commercial products and have made their way into most of our daily lives [1]-[3]. The most common uses for MEMS accelerometers are in airbag deployment systems for modern automobiles. In this case accelerometers are used to sense negative acceleration of the vehicle. A processor will analyze the magnitude of the acceleration and decide on whether or not to deploy the airbags in the vehicle. MEMS accelerometers are quickly replacing conventional accelerometers for airbag deployment systems in automobiles. The reason behind this increasing popularity is, the MEMS accelerometers are much smaller, lighter, more reliable and are produced for a fraction of the cost of the conventional bulky accelerometers. Several new innovations in micromachining have been combined to make a commercially available accelerometer for low g (gravity acceleration) applications. One of the successful innovations is straight beam comb accelerometer. The straight beam is anchored at four points. While this sensor is stiff and robust, it is also sensitive to mechanical stress imparted to the die from the package and die amount. The recent innovation of Analog devices Inc. ADXL50 is folded beam comb accelerometer [4]. The folded beam structure is anchored only at two points. The wrap around structure relieves the tension of poly-silicon which makes the beam much less sensitive to package stress. At the same time, the compliance of beam, i.e. the deflection of beam for a given acceleration applied, is increased which enhances the sensitivity. In addition to accelerometers, many other MEMS devices such

as MEMS gyroscopes, digital micromirrors, MEMS optical switches, DNA chips, have been successfully developed and commercialized [5]. MEMS, together with nanotechnology, are believed to be the drive to trigger the next wave of technology revolution.

As MEMS technology continue to grow, MEMS device design optimization is becoming an interesting and important research issue. In order to design a MEMS device to meet the given specifications, the relationship between the device performance and various design parameters must be investigated. Various efforts on MEMS device design optimization and automation have been made. For example, in [6], the design optimization and simulation on a microelectromagnetic pump was discussed. In [7], the mechanical design and optimization of a capacitive micromachined switch was proposed. In [8], an automated approach is used to generating novel MEMS accelerometer configurations. Considering the commercial success of MEMS accelerometers, the design optimization of a folded-beam MEMS comb accelerometer device is discussed in this paper. The relationship between the device sensitivity and the design parameters (such as beam width, beam length, mass width) is analyzed. ANSYS FEM simulation [9] is used to derive the device sensitivity for various design options. Based on the analysis, an optimized design of the MEMS comb accelerometer device is suggested.

II. Device Design

The structure design of a poly-silicon surface-micromachined MEMS comb accelerometer is shown in Figure 1. This device is similar as ADXL 150 accelerometer [4] developed by Analog Devices Inc.

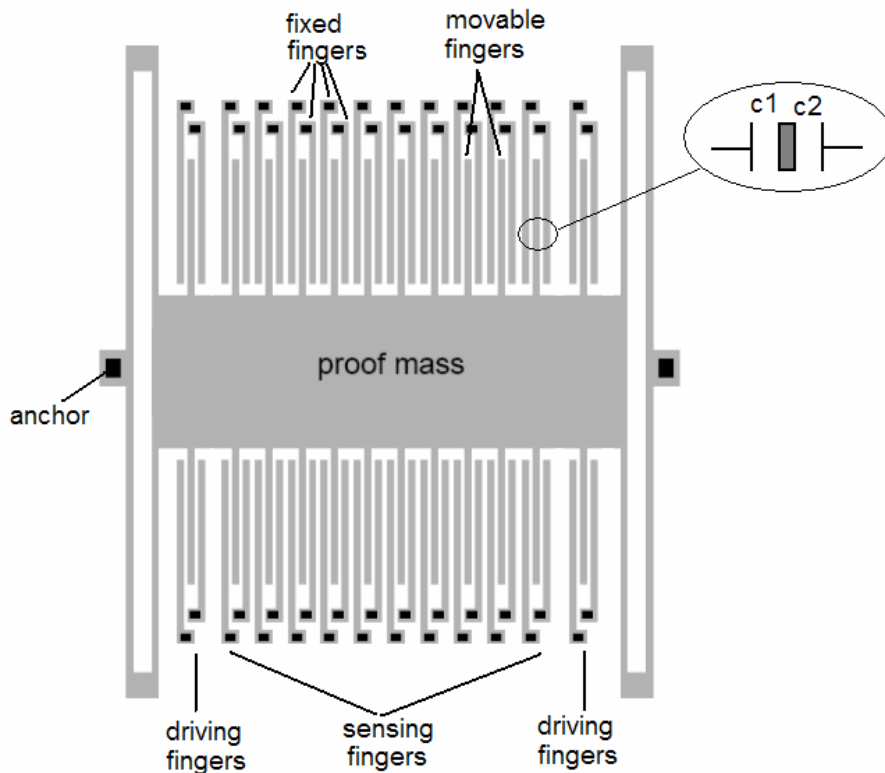


Figure 1. Structure diagram of folded-beam accelerometer

The movable parts of this MEMS comb accelerometer consist of four folded-beams, a proof mass and some movable fingers. The fixed parts include two anchors and some left/right fixed

fingers. The central movable mass is connected to both anchors through four folded beams. There are many movable fingers extruding from the both sides of the central mass. In the right and left side of the each movable finger, there are left and right fixed fingers. The movable fingers constitute the differential capacitance pair C1 and C2 with left and right comb fingers. When there is no acceleration, the movable fingers are resting in the middle of the left and right fixed fingers. In this way, the left and right capacitance pairs C1 and C2 are equal. If there is any acceleration a along horizontal direction parallel to the device plan, the proof mass M_s experiences an inertial force $-M_s \cdot a$ along the opposite direction. As a result, the beams deflect and the movable mass and movable fingers move for a certain displacement x along the direction of the inertial force. The left and right capacitance gaps are changed, hence the differential capacitances C1 and C2 will also be changed. By measuring this small differential capacitance change, we know the value and the direction of the experienced acceleration. This is the working principle of the MEMS comb accelerometer. The comb accelerometer design also supports in-field built-in self-test feature. Among these capacitance pairs, most capacitance groups act as the sensing capacitance and other few capacitance groups act as built-in self-test capacitance. The built-in self-test feature allows the device to be self-tested during in-field usage using electrostatic force. In test mode, when there is no acceleration, a driving voltage V_d is applied to the left or right fixed driving fingers. The electrostatic force will attract the movable fingers toward the left or right direction. By measuring this displacement and comparing with good device response, one knows whether the device is good or faulty [4]. This self-test feature is especially important for the safety critical applications such as automobile airbag deployment.

III. Performance Analysis of the Device

When an acceleration a along the horizontal direction parallel to the device plan is applied to the accelerometer, the beam deflects under the effect of inertial force. The deflection of beam is in opposite direction of the applied acceleration. The displacement sensitivity of the device is defined as the displacement of the movable mass (and movable fingers) per unit gravity acceleration g ($1g=9.8m/s^2$) along devices sensitive direction. The beam-mass structure of the accelerometer can be treated as a simplified spring-mass model. The four folded-beam can be treated as four springs connected in parallel. For each folded-beam, both sections of the beam can be treated as two springs connected in series. Each beam section can be treated as double-clamped beam model.

Assume for each section of the folded-beam, the beam width and length are W_b and L_b separately. The width and length of central proof mass are W_m and L_m separately. The device thickness (thickness of the poly-silicon layer) is t . There are totally N_f finger groups, among which there are N_s sensing finger groups and N_d driving finger groups ($N_f=N_s+N_d$). For each movable finger, the finger width and length are W_f and L_f separately. When there is no acceleration, the capacitance gap between each movable finger and its left (right) fixed fingers is d_0 . The density ρ and Young's modulus E of poly-silicon material are given as below.

The density of poly-Si is $\rho = 2.33 \times 10^3 \text{ kg} / \text{m}^3$

Young's modulus of poly-Si is $E = 1.70 \times 10^{11} \text{ Pa}$

When there is no acceleration, the static sensing capacitance of the MEMS comb accelerometer is

$$C_{10} = C_{20} = C_0 = \frac{\varepsilon \cdot N_s \cdot L_f \cdot t}{d_0} \quad (1)$$

where ε is the dielectric constant of air.

Assume there is acceleration along left direction horizontally, the movable mass experiences an inertial force toward right by x , as shown in Figure 2. Assume small deflection approximation ($x \ll d_0$), the left (right) capacitances C_1 (C_2) are changed to

$$C_1 = \frac{\varepsilon \cdot N_s \cdot L_f \cdot t}{(d_0 + x)} = \frac{\varepsilon \cdot N_s \cdot L_f \cdot t}{d_0 \cdot (1 + x/d_0)} \approx \frac{\varepsilon \cdot N_s \cdot L_f \cdot t}{d_0} \cdot \left(1 - \frac{x}{d_0}\right) \quad (2)$$

$$C_2 = \frac{\varepsilon \cdot N_s \cdot L_f \cdot t}{(d_0 - x)} = \frac{\varepsilon \cdot N_s \cdot L_f \cdot t}{d_0 \cdot (1 - x/d_0)} \approx \frac{\varepsilon \cdot N_s \cdot L_f \cdot t}{d_0} \cdot \left(1 + \frac{x}{d_0}\right) \quad (3)$$

The differential capacitance change ΔC is

$$\Delta C = C_1 - C_2 = \frac{2\varepsilon \cdot N_s \cdot L_f \cdot t}{d_0} \cdot \left(\frac{x}{d_0}\right) = 2C_0 \cdot \left(\frac{x}{d_0}\right) \quad (4)$$

From above equations we can see that for small deflection approximation, differential capacitance change is directly proportional to the displacement x of the movable fingers. Further, for small deflection (beam deflection angle $< 5^\circ$), we can treat the accelerometer as simplified spring-mass model. Assume the total sensing mass of the accelerometer as M_s , the inertial force $F_{inertial}$ experience by the sensing mass for acceleration a along sensitive direction is

$$F_{inertial} = -M_s \cdot a \quad (5)$$

Assume the total spring constant of the beams as K_{total} , the displacement x of the movable mass can be calculated as

$$x = \frac{F_{inertial}}{K_{total}} = -\frac{M_s \cdot a}{K_{total}} \quad (6)$$

From equations (4) and (6), we can see that the differential capacitance change ΔC of the accelerometer is directly proportional to the experienced acceleration a . Thus by measuring the differential capacitance change, the acceleration can be measured.

The resonant frequency f_0 of the spring-mass system is given by

$$f_0 = \frac{1}{2\pi} \sqrt{\frac{K_{total}}{M_s}} \quad (7)$$

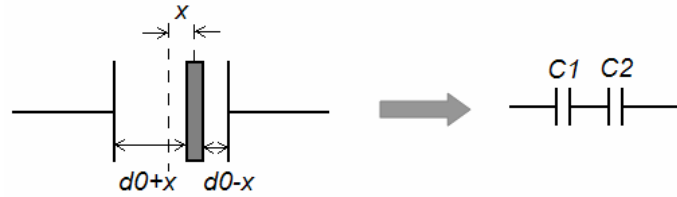


Figure 2. Differential capacitance of MEMS comb accelerometer

The sensing mass M_s of the accelerometer, includes the seismic mass and all the movable fingers attached to it, can be expressed as follow [10]

$$M_s = \rho t (W_m L_m + N_f W_f L_f) \quad (8)$$

Spring constant K_b of one section of beam can be calculated by

$$K_b = \frac{12EI_b}{L_b^3} \quad (9)$$

where I_b is the inertial momentum of the beam:

$$I_b = \frac{1}{12} W_b t^3 \quad (10)$$

Two sections of a folded-beam have equal length and are connected in series. Hence the spring constant K_{fold} of one folded-beam is

$$K_{fold} = \frac{1}{2} K_b = \frac{6EI_b}{L_b^3} \quad (11)$$

Four folded beams are connected in parallel and have the same size. Thus, the total spring constant K_{total} of the device is given by

$$\begin{aligned} K_{total} &= K_{fold1} + K_{fold2} + K_{fold3} + K_{fold4} \\ &= 4K_{fold1} = \frac{24EI_b}{L_b^3} = \frac{2EW_b t^3}{L_b^3} \end{aligned} \quad (12)$$

The displacement sensitivity S_d of the device along the sensitive direction can be expressed as

$$S_d = \frac{M_s g}{K_{total}} = \frac{\rho t (W_m L_m + N_f W_f L_f) L_b^3}{2EtW_b^3} \quad \text{m/g} \quad (13)$$

Based on the above sensitivity analysis we can draw the following conclusions.

- (1) From Equation 6 we can conclude that the sensitivity of the folded-beam comb accelerometer is inversely proportional to the third power of the beam width W_b , that is, $S_d \propto (1/W_b^3)$. The device sensitivity changes rapidly with the beam width. In other words, beam width of the folded beam accelerometer is a highly sensitive parameter to adjust the sensitivity of the device. A folded beam accelerometer of desired sensitivity can be designed by adjusting beam width. Theoretically we can narrow down the beam width W_b to achieve very high device sensitivity. However, there is always a bottom limit for the beam width set by the minimum line width in a fabrication process. If the beam width is too narrow (e.g. less than $2\mu\text{m}$), it will become very challenging to fabricate the beam because the beam is extremely fragile and can be easily broken. This will greatly reduce the fabrication yield. Thus there is a trade-off between them and we can not shrink the beam width unlimitedly. In order for high sensitivity, we may rely on adjusting the other design parameters (such as beam length, mass width) as well.
- (2) Sensitivity of the folded beam accelerometer S_d is directly proportional to the third power of beam length. That is, $S_d \propto L_b^3$. However, increasing the beam length will also increase the overall device area.
- (3). Sensitivity of the folded beam accelerometer S_d is directly proportional to the mass width and mass length. That is, $S_d \propto W_m$ and $S_d \propto L_m$.

IV. Device Design Optimization

The above theoretical analysis predicts the relationship between device sensitivity and various design parameters (such as beam width, beam length, mass width and length). However, the theoretical analysis is based on the simplified spring-mass model. In order for a more accurate analysis, ANSYS FEM simulation [9] is required to simulate the device sensitivity for various design options. Based on ANSYS simulation, the relationship between device sensitivity and various design parameters are extracted. The results can be very helpful for guiding the device design optimization. In order to extract the relationship between device sensitivity and each individual design parameters, first the beam width of the suggested accelerometer is varied while keeping other design parameters (beam length, mass width and length, etc.) unchanged. Similarly, the relationships between device sensitivity and

beam length as well as mass width are also extracted. ANSYS model (after meshing) for an optimized design of the MEMS comb accelerometer is shown in Figure 3. We used ANSYS command line programming to build the device model and perform the ANSYS simulation. Here only the movable parts (folded-beams, movable mass and movable fingers) and the anchor are shown in the figure. The fixed comb fingers are not involved in the displacement of the movable parts, thus they are not shown in the figure.

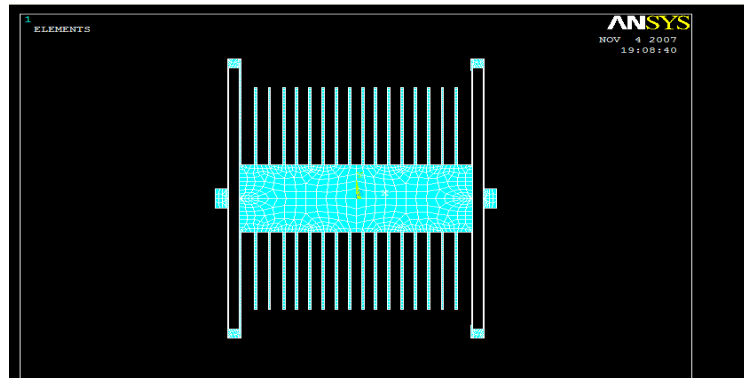


Figure 3. Model of optimized design

Based on ANSYS simulation, the relationship between the device sensitivity and the beam width (while other design parameters are fixed) is shown in Figure 4.

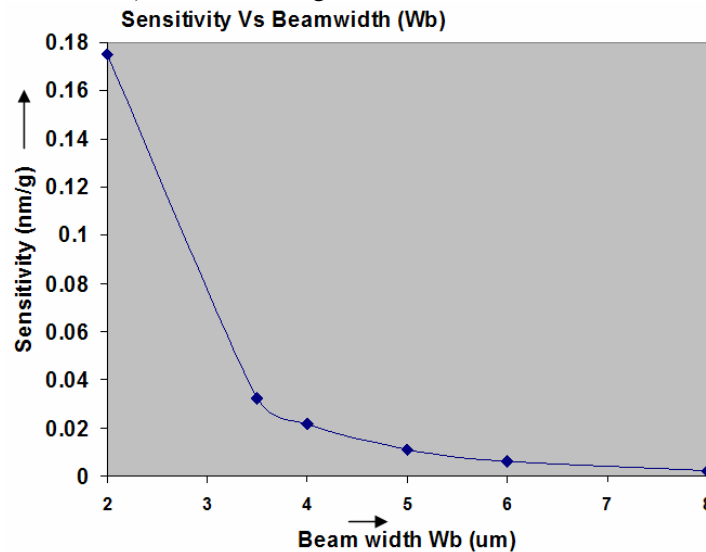


Figure 4. The relationship between device sensitivity and beam width for MEMS accelerometer

As shown in Figure 4, we can see that the displacement sensitivity of the device increase rapidly with the decreased beam width. This is in good agreement with the previous theoretical analysis that the device sensitivity is inversely proportional to third power of beam width, that is, $S_d \propto (1/W_b^3)$. This proves that the beam width is the most effective parameter to adjust the device sensitivity. If we can shrink the beam width to half of the original width, the sensitivity can be increased by approximately 8 times.

Based on ANSYS simulation results, the relationship between the device sensitivity and beam length L_b is plotted, as shown in Figure 5. In Figure 5, the sensitivity of the device increases with the beam length. The sensitivity analysis predicts that sensitivity is directly proportional to the third power of beam length, that is, $S_d \propto L_b^3$. From Figure 5, we can see that the trend of the curve from simulation results matches theoretical expectation well.

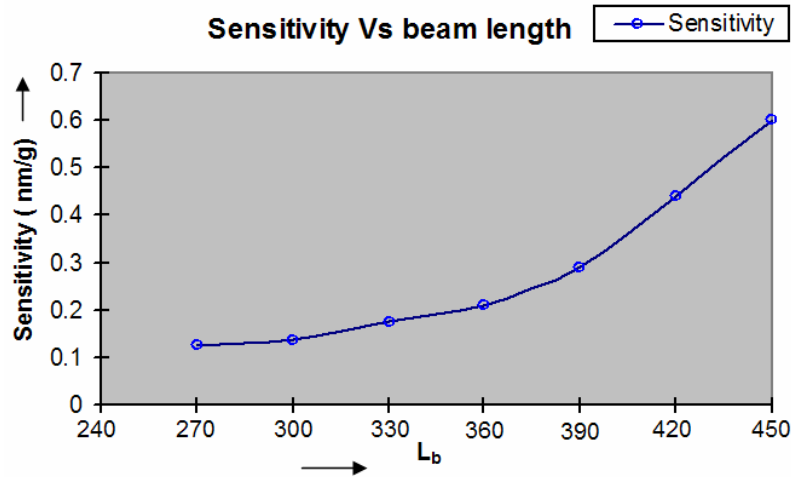


Figure 5. The relationship between sensitivity and beam length of the comb accelerometer

Further, the relationship between displacement sensitivity S_d and mass width W_m is also simulated with ANSYS for various designs. The curve of device sensitivity versus mass width is shown in Figure 6. The sensitivity analysis predicts that the sensitivity of the device is directly proportional to the mass width, that is, $S_d \propto W_m$. As we can see from Figure 6, the relationship between sensitivity and mass width is approximately linear. This proves the correctness of the theoretical analysis.

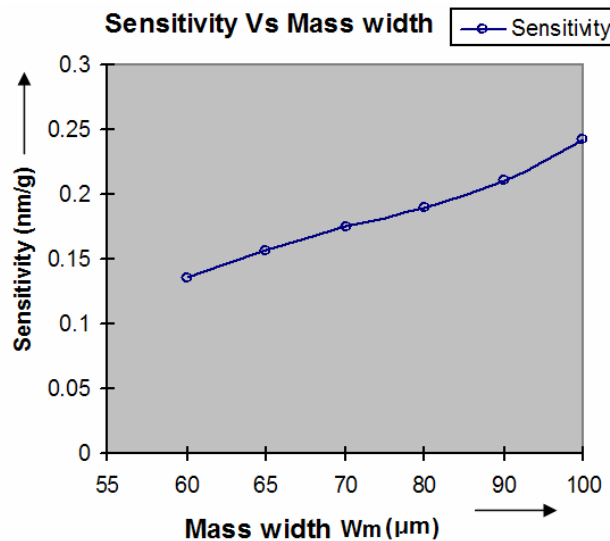


Figure 6. The relationship between sensitivity and mass width of the comb accelerometer

From the above simulation results, we can see that the device sensitivity can be adjusted by design parameters such as beam width, beam length, mass width and mass length. Among these parameters, the beam width is the most effective parameter to adjust the device sensitivity without increasing the overall

device area. However, the minimum beam width is limited by the minimum line width we can achieve in the surface-micromachining process. Thus sometimes we may combine other parameters (such as beam length, mass width and length) to further improve the device sensitivity. Generally we would prefer larger device sensitivity so that it is easy to detect the signal due to the acceleration change. However, the simplified spring-mass model for the beam-mass system is valid only for small deflection approximation. Further, the device linearity between acceleration input and differential capacitance change will be degraded if the maximum displacement of the movable fingers exceeds 5% of the capacitance gap. Thus we need to have a trade-off between the device sensitivity and linearity for the design optimization.

Based on the above analysis and simulation, an optimized design of MEMS comb accelerometer for balanced device sensitivity and linearity is achieved. The optimized design parameters are shown in Table 1. ANSYS simulation shows the proposed accelerometer design has displacement sensitivity of 3nm/g. It can be used for general applications such as automobile airbag deployment system.

Table 1. Optimized design of a MEMS comb accelerometer

Design Parameters	Dimensions/Performance
Beam Width W_b	2 μ m
Beam length L_b	290 μ m
Mass Width W_m	70 μ m
Mass length L_m	350 μ m
Movable finger width W_f	4 μ m
Movable finger length L_f	160 μ m
Fixed finger width W_{ff}	4 μ m
Fixed finger length L_{ff}	200 μ m
Total Number of Driving fingers N_d	8
Total Number of sensing fingers N_s	24
Device thickness t	4 μ m
Capacitance gap d_0	2 μ m
Gap d_1 between two driving or sensing Finger groups.	4 μ m
Gap d_2 between driving and sensing finger groups	6 μ m
Anchor Size	20 μ m \times 20 μ m
Outermost device area	460 μ m \times 630 μ m
Static capacitance C_0	0.068pF
Sensing mass M_s	0.42 μ g
Spring constant K_{total}	1.784N/m
Resonant frequency f_0	10.38kHz
Displacement sensitivity S_d	3nm/g

V. Device Fabrication

The designed device is to be fabricated with poly-silicon surface-micromachining process. The movable microstructures (folded-beams, movable mass and movable fingers) are to be released with BSG (Boron Silicate Glass) sacrificial layer technique. In order to avoid the stiction problem in surface-micromachining, super-critical CO₂ drying [11] is used after wet-etching of the BSG sacrificial layer. Due to the compatibility of surface-micromachining with VLSI fabrication processes, the comb accelerometer can be integrated with CMOS signal-sensing circuitry on a single chip using CMOS-MEMS process [12]. Considering the possible high-temperature process in MEMS structure fabrication, a post-CMOS process

is preferred. That is, the MEMS microstructure will be fabricated first, and CMOS circuitry will be fabricated later. In this way, the aluminum interconnect in CMOS circuitry will not be damaged due to the high-temperature process in MEMS fabrication. The fabrication flow chart of the MEMS microstructure of the comb-accelerometer is shown in Figure 7.

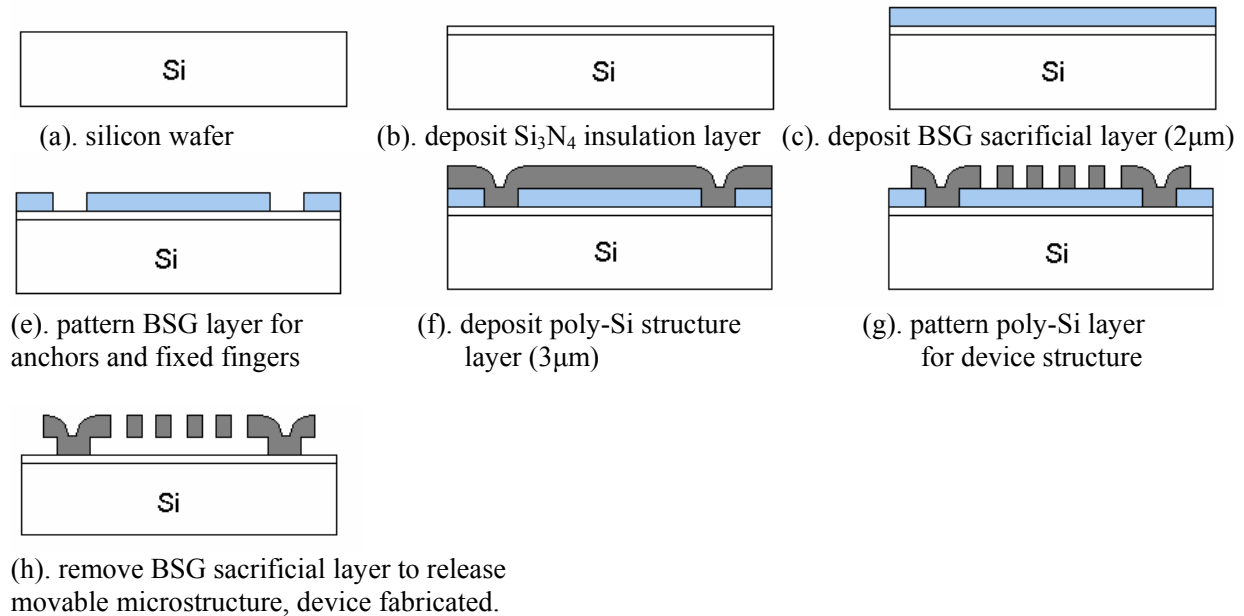


Figure 7. Fabrication flow chart for the MEMS comb accelerometer

VI. Conclusions and Future Work

In this paper, the design optimization of a poly-silicon surface-micromachined MEMS comb accelerometer with folded beam structure is studied. A simplified spring-mass model is used to predict the device sensitivity. Based on the theoretical analysis, ANSYS simulation was used to extract the relationship between the device sensitivity and various design parameters, such as beam width, beam length and mass width. Simulation results demonstrate that the device sensitivity increases rapidly with beam width. Thus the beam width can be a very efficient design parameter to adjust the device sensitivity. Further, increasing beam length or mass width can also improve the device sensitivity, but with the overhead of increasing the overall device area. In other words, by adjusting design parameters a device having desired sensitivity can be achieved. Based upon this analysis, an optimized folded-beam comb accelerometer is designed. Simulation results show that the device has a sensitivity of 3nm/g . The proposed accelerometer device can be implemented for $\pm 50\text{g}$ automobile airbag applications.

The future work is to further improve the performance of the proposed comb accelerometer device by using novel structure design. For example, the spring constant of the beams can be further reduced by using some more compliant flexure structures (e.g. four-fold beam). The sensing mass can be further increased by using bulk-micromachining such as DRIE etching. Both efforts can further increase the device sensitivity. We will look into how to achieve optimized design with these design improvements.

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