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DESIGN AND FABRICATION OF THE MICRO-ACCELEROMETER USING PIEZOELECTRIC THIN FILMS

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This paper discusses the design and the fabrication procedure of a novel design of microaccelerometer. The proposed design consists of a seismic mass suspended with quadri-beams and the patterned displacement transducers using piezoelectric thin films. The electromechanical system model is presented to illustrate the interactions of material characteristics, amplification circuit designs, and microstructure geometry. The micromachining processes of the microstructure are proposed. Due to the anisotropic property of the wet etching process, the geometry of the microstructure presents a particular configuration. Major manufacturing concerns are presented. For a 1900μm × 1900μm microstructure, analytical predictions show the natural frequency around 23 KHz and the pre-amplification sensitivity of 0.03 (mV/g). The analytical results coincide with the FEM analysis.

Keywords: Microsensor; Piezoelectric; Accelerometer; Sensor Design; MEMS.

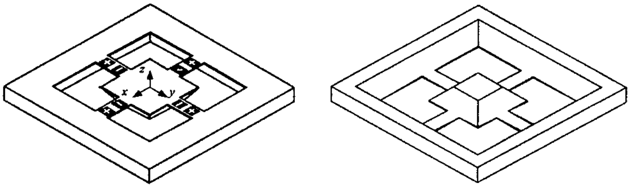
INTRODUCTION

MEMS technology has successfully applied silicon micromachining to the fabrication of different types of microaccelerometer. Electric and mechanical subsystems can now be integrated into one chip, which facilitates the applications with space constraints. The miniaturization of sensors not only reduces the manufacturing cost but also improves the operational bandwidth and reliability. Successful examples mainly appear in automotive industry such as control of airbags and suspension systems. Potential markets also exist in the areas of biomechanics and aerospace technology.

Piezoelectric accelerometers have the advantages of easy integration with existing measuring systems[1]. Due to the excellent dynamic performance and linearity, they have been widely used in condition monitoring systems to measure machinery vibration. Two types of piezoelectric micro- accelerometers are reported based on the fabrication approach. The piezoelectric accelerometers using surface micromachining technology are more cost effective due to its relatively simple fabrication [2]. On the other hand, the piezoelectric accelerometers using bulk micromachining technology usually have a lower detection level that is suitable for precision measurement [3].

DESIGN OF MICROACCELEROMETER

The proposed microaccelerometer consists of a quadri-beam suspension, a seismic mass, and the displacement transducers using piezoelectric thin films as illustrated in FIGURE 1. Due to the symmetry of the beam suspension, the seismic mass vibrates along the *z*-axis with negligible motions in other directions. Two transducers are attached to each suspension beam. One is near the fixed end and the other is near the seismic mass. In the first vibrating mode, the stresses of the inner and the outer transducers due to bending of the beam are in the opposite directions. On the other hand, the stresses due to unexpected noises, such as accelerations in the horizontal directions, and the tensions of the deflective beams, are in the same direction. The upper electrodes of the outer transducers are connected with the lower electrodes of the inner transducers, and vice versa, as shown in FIGURE 1(a). This design not only increases the sensitivity, but also compensates the noise effects.



(a) Front View (b) Back View

FIGURE 1. A 3D view of the piezoelectric microaccelerometer

The system modeling of the accelerometer can be divided into two subsystems. The mechanical subsystem converts the acting acceleration $\ddot{z}_i$ into the relative displacement z_s of the seismic mass and the sensor base. The electric subsystem then picks up z_s and transforms to the output voltage e_o of the piezoelectric transducer. The Laplace function of the system model is as follows [4]:

$$\frac{e_o(s)}{\ddot{z}_i(s)} = S_T \cdot \frac{\tau s}{\tau s+1} \cdot \frac{\omega_n^2}{s^2+2\zeta\omega_n s+\omega_n^2} \tag{1}$$

where $S_T=K_q/(C\omega_n^2)$ is the sensor sensitivity, $\omega_n=\sqrt{K/M}$ is the resonance frequency of the microstructure, M is the seismic mass, K is the spring stiffness of the suspension beams, ζ is the damping ratio, K_q is the charge output of unit seismic displacement, τ is the time constant of the electric subsystem, and C is the equivalent capacitance of the electric subsystem.

The typical range of the accelerometer frequency response, using ±5% as an accuracy requirement, is between $3/\tau$ and $\omega_n/5$. The low frequency response is limited by the time constant τ while the high frequency range is limited by the mechanical resonance ω_n. The piezoelectric characteristic K_q/C and the structure characteristic $1/\omega_n^2$ determine the accelerometer sensitivity. Tradeoffs exist between high frequency response and sensitivity. The sensitivity S_T is mainly related to the dimensions of the beam suspension and the seismic mass. The parameter designs will depend on the features of performance desired for specific applications.

FABRICATION PROCEDURE

The fabrication procedure is proposed in FIGURE 2. The microstructure is bulk machined using KOH wet etching, and the transducer pattern and the suspension beams are surface machined using lift-off and Buffered Oxide Etchant (BOE) etching.

When using bulk-micromachining techniques, the seismic mass is shaped like a truncated pyramid, as shown in FIGURE 1(b), due to the anisotropic etching of silicon in KOH. Corner compensation in the design of photo mask such as FIGURE 3 has to be used to realize the shape of the mass [6]. The etching rate in the 100 direction of silicon in 20% KOH solution fairly coincides with the results reported in the literature [5].

$$R = R_0 \exp(-E_a / k_B T) \tag{2}$$

where R_0=1.23 × 10^{10} ($\mu m/h$), activation energy E_a=0.57(eV), k_B is the Boltzmann constant (1.38066 × 10^{-23} JK^{-1}), and T is the absolute temperature. Etching time can then be estimated to create the required height of the seismic mass.

Pulsed-laser-deposited (PLD) ferroelectric PZT films have been synthesized using $La_{0.5}Sr_{0.5}CoO_3$ as buffer layers. The crystal structure of the PZT films is remarkably influenced by the characteristics of the buffer layers. The buffer layers show different tendencies to develop low index orientations, and therefore vary the ferroelectric properties of the PZT films. The material of the electrode films uses chromium or nickel.

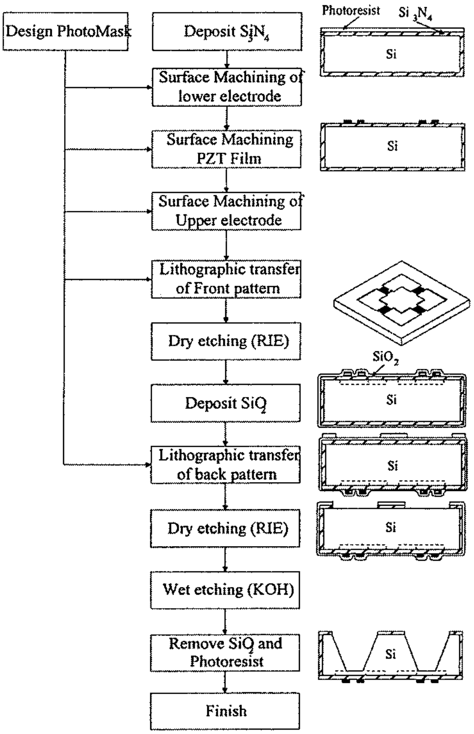


FIGURE 2. Fabrication procedure of the microaccelerometer

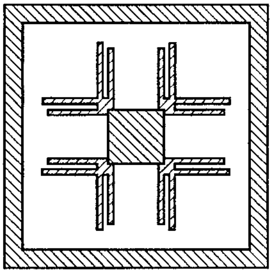


FIGURE 3. Schematic view of the Si_3N_4 photo mask for KOH etching of the seismic mass

FEM ANALYSIS OF FREQUENCY RESPONSE

This paper uses ANSYS 5.3 to verify the frequency response of the accelerometer. Table 1 shows the dimensions of the numerical example. The piezoelectric transducers are arranged as in FIGURE 1(a) starting from $l/10$ to $4l/10$ and from $6l/10$ to $9l/10$, where l is the length of the suspension beam. The material properties of the thin film PZT layer have not yet been determined and hence the values of the bulk PZT 52/48 are used in the analysis.

Table 1. Microstructure dimensions of the piezoelectric accelerometer

Length of beam suspension	l	500
Width of beam suspension	b	180
Thickness of beam suspension	h	20
Width of seismic mass	l_{Mt}	900
Thickness of seismic mass	h_M	400
Thickness of PZT film	h_p	0.3
Thickness of electrode	h_e	0.2

Units: μm

The frequency response of the accelerometer is shown in FIGURE 4. The modeling result gives the undamped resonance frequency 22552 (Hz) that is very close to the peak frequency 22922 (Hz) obtained from the FEM analysis. The modeling and the FEM estimated preamplification sensitivities are 0.029 (mV/g) and 0.030 (mV/g) respectively.

The theoretical minimum detectable signal, a_{min}, due to Brownian noise can be found as follows [7]:

$$a_{\min} = \sqrt{\frac{4k_B T \omega_n}{MQ}} \tag{3}$$

The seismic mass is about 0.418(mg). Assume the quality factor of the mechanical subsystem Q=1/(2ζ)=0.707, the detection level at room temperature is 9×10^{-5} ($\mathrm{ms^{-2}/Hz^{1/2}}$). The noise needs to be added by the readout electronics noise.

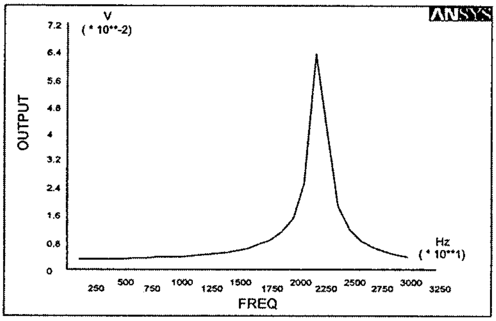


FIGURE 4. Frequency Response of the microaccelerometer

CONCLUSION

This paper presents the electromechanical model of the piezoelectric microaccelerometer that illustrates the interactions of material characteristics, amplification circuit design, and structure geometry. Discussions of sensor performance tradeoff are presented. The comparisons of the resonance frequency and the frequency response show that the system modeling agrees well with the FEM results. The proposed model provides good estimates of sensor behavior and can be readily applied to parameter design where design iterations are required.

References

[1] P.L. Chen, R.S. Muller, R.D. Jolly, G.L. Halac, R.M. White, A.P. Andrews, T.C. Lim, and M.E. Motamedi, *IEEE Trans. Electron Devices*, **29**, 27 (1982).
[2] D.L. DeVoe and A.P. Pisano, *Transducers '97*, Chicago, 1205, (1997).
[3] R. de Resus,J.O. Gullov, and P. Scheeper, *J. Micromech. Microeng.* **9**, 123 (1999).
[4] J. Yu and C. Lan, *Proc. of the 1999 IEEE International Conf. on Multisensor Fusion and Integration for Intelligent Systems*, Taipei, 99 (1999).
[5] S.M. Sze, *Semiconductor Sensors*, John Wiley & Sons, Inc., 47 (1994).
[6] W. Lang, *Materials Science and Engineering*, **R17**, 1 (1996).
[7] T.B. Gabrielson, *IEEE Trans. on Electron Devices*, **40**, 90, (1993).