Balance-approach For Mechanical Properties Test of Micro Fabricated Structure

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ABSTRACT

A simple and effective method using a balance to measure micro force and corresponding deflection is presented. The method is proved to be very practical in testing the force-deflection behavior of silicon cantilever, in which the Young's modulus of the material can be calculated, and in investigating the static performance of bulk micromachined capacitive accelerometers. The balance approach for micro force-displacement measurement is very attractive for its easiness in operation, low cost and higher resolution.

Keywords micromechanism the Young's modulus capacitive accelerometer

1. INTRODUCTION

The thickness of the material used in MEMS(Micro Electro Mechanical System) is in the order of micron . Since the properties of material in such dimensions may be greatly different from those of bulk material, it's very necessary to test the mechanical characteristics of the microfabricated structures. For this purpose, an instrument which can measure micro force and displacement in the orders of μN and μm respectively is required. Nanoindentation method[1] applies a micro force through a coil and magnet assembly or piezoelectric drives. The corresponding micro displacement is measured by capacitive sensors. Though high resolutions of load and displacement can be achieved, it remains some drawbacks including the complexity of the apparatus and the special requirements for the specimen. Threshold-voltage method[2] can also measure micro force and displacement, but it can only be applied to the conductive suspended thin film. A novel approach for micro force-deflection measurement[3] is presented, in which a balance is utilized to measure the force and displacement ingeniously. The balance approach is proved to be very effective during testing the force-deflection behavior of silicon cantilevers and the static characteristic of bulk micromachined capacitive accelerometers. The Young's Modulus of single crystal silicon in <110> orientation is then calculated to be E=160GPa. The balance measurement system is very useful to measure the mechanical properties of micromachined structures which are suitable to this apparatus.

2. MEASUREMENT SETUP

The measurement setup consists of a TG328-A balance, a rigid probe and a microscope, as shown in Fig.1. The probe can be adjusted in X, Y and Z direction precisely. The measurement setup is fixed on a quake-proof platform to avoid the influence of the surroundings.

During the measurement, the specimen was located in the left scale-pan of the balance. A certain amount of counterweights are added to keep the balance in equilibrium. Adjust the probe right in contact with the specimen without any force. The balance still remains in equilibrium. Then a little more counterweights T (with an unit of mg) are added in the right scale-pan. The balance inclines, so that the left pan is elevated. Therefore, a force is applied on the specimen by the rigid probe, and the specimen is pressed down. With the increase of the inclination of the balance, the force acting on the specimen also increase to counterbalance the increased counterweights T. When the optical scale reading varies a certain amount of Δ (with an unit of mg), the balance comes to a new equilibrium. Since the probe is rigid, the elevation of the left scale-pan equals to the deflection of the cantilever at the press point of the probe. A certain variation of the optical scale reading corresponds to a certain elevation of the left scale-pan, which can be calculated from the size of the balance. If the elevation of the left scale pan corresponding to a variation of 0.1mg in the optical scale reading is s μm, the deflection h_s of the cantilever at the press point of the probe can be calculated as following

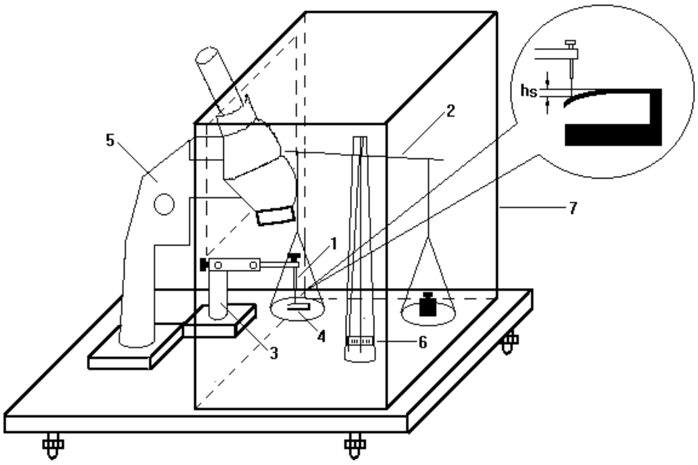


Fig.1 Schematic diagram of micro force displacement measurement system 1. probe 2.balance 3.probe-platform 4.specimen(cantilever) 5.microscope 6.optical scale 7.frame

$$h_s = \Delta \times 10s \quad \mu\text{m/mg} \tag{1}$$

For the setup used in this work, a 0.1mg variation in the optical scale reading corresponds to 14.38μm elevation of the left scale pan, i.e. s=14.38. On the other hand, the micro force F applied on the cantilever is

$$F = (T - \Delta) \times 9.8 \quad \mu\text{N/mg} \tag{2}$$

The error of the balance measurement system in displacement measurement comes mainly from the bending of the “rigid” probe, the deformation of the scale-pan and the elasticity of the contact between the beam and the scale pan. All these factors may lead to that the measured value of displacement tends to be larger than the actual value. To solve this problem, one may adjust the probe right in contact with the scale-pan instead of the specimen without any force. Then add counterweights continuously, the corresponding variations of the optical scale reading, which are the systematic error of the balance measurement system, can be measured, so that the main error can be deducted from the total value of the displacement measured on the specimen.

3. CANTILEVER FORCE-DEFLECTION TEST WITH BALANCE MEASUREMENT SYSTEM

3.1. PRINCIPLE OF MEASUREMENT

As shown in Fig.2, cantilever deflects under the action of a force F. The length, width and thickness of the cantilever are L′, b and h respectively. The distance from the root A of the cantilever to the press point B is L. In the case of small deformation, the differential equation of the deflection y of the cantilever is[4]

$$-EIy'' = M(x) = -F(L - x) \tag{3}$$

where E is the Young’s moudulus of the material, M is the bending moment, I is the inertia moment of the cantilever, which can be calculated by the following equation

$$I = \frac{1}{12} bh^3 \tag{4}$$

The boundary conditions are

$$y|_{x=0} = 0 \tag{5}$$

$$y'|_{x=0} = 0 \tag{6}$$

therefore, the deflection curve can be obtained, as following equation

$$y(x) = \frac{1}{EI}(FL \cdot \frac{x^2}{2} - \frac{1}{6}Fx^3) \tag{7}$$

The deflection at the press point B is

$$y_B = y\Big|_{x=L} = \frac{FL^3}{3EI} \tag{8}$$

So the deflection of the cantilever at the press point is directly proportional to the force F. If the force and corresponding deflection of a cantilever is known, the Young's modulus of the material can be calculated from equation (8).

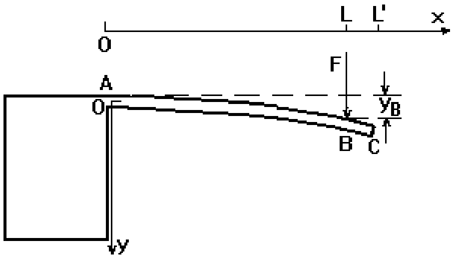
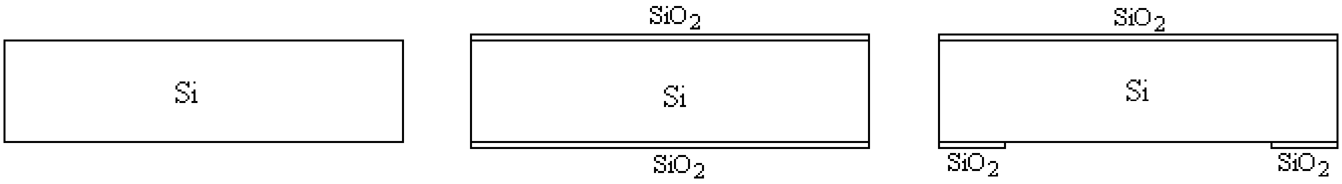


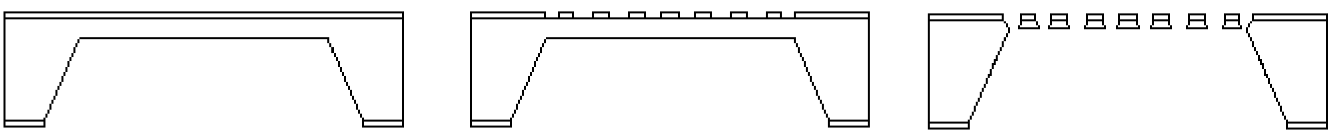
Fig.2 A cantilever deflects under the pressure of a probe

3.2. EXPERIMENTAL RESULTS

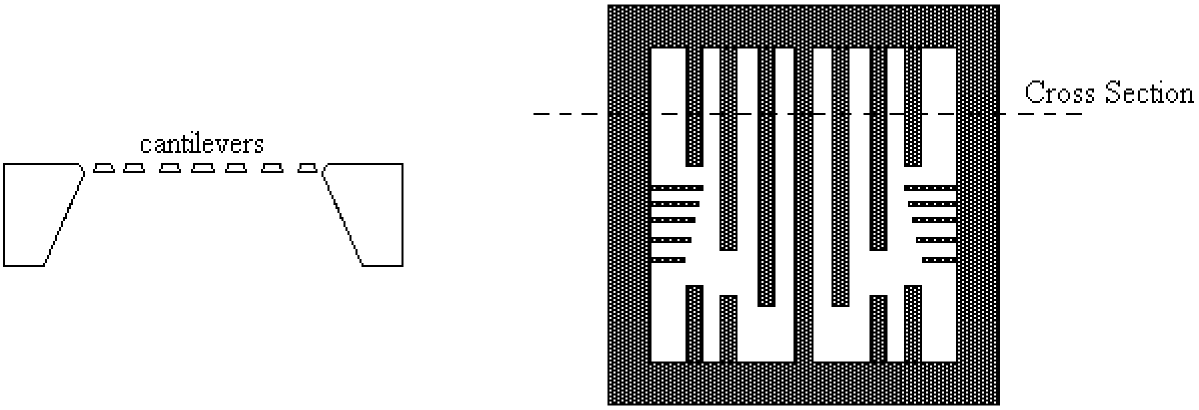
The technology processing for the cantilever fabrication is schematically shown in Fig.3. Both-side-polished (100) orientation silicon wafers with 10Ω·cm resistivity were oxidized at 1150℃in steam to grow 1μm oxide film. Then square windows with about 10mm edge were opened photographically on the back side and etched in 30% KOH solution at 40℃to form square silicon membrane with a double thickness as that of the expected cantilever. At third step, patterned various cantilevers in the upper side of the wafers photographically and etched in 30% KOH solution at 40℃ again until the cantilevers were released. Finally, got rid of the SiO_2, the single crystal silicon cantilevers were obtained.



(a). silicon wafer (b). oxidation (c). open square window
photographically



(d). first anisotropic etching (e). pattern cantilevers photographically (f). second anisotropic etching



(g). get rid of SiO_2 (h). pattern of cantilevers

Fig. 3 Cross-sectional view of the fabrication sequence for cantilevers

In this experiment, single crystal silicon cantilevers of various sizes are fabricated. Since anisotropic etching technology is adopted, the shape of cross section of the cantilever is an isosceles trapezoid with 54.7° base angle instead of a rectangle[5]. Three silicon cantilever samples are tested with the balance measurement system. The force-deflection curves of the cantilevers are obtained, as shown in Fig. 4.

The Young's modulus of the material is also extracted from the force-deflection curve of the silicon cantilevers, as listed in Table 1. In the table, L′ and h are the length and thickness of the cantilever respectively. L is the distance from the root of the cantilever to the press point of the probe. "d" is the width of the upper side of the cantilever cross section.

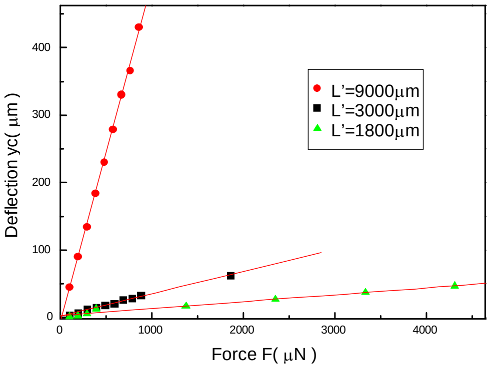


Fig. 4 Force-deflection behavior of silicon cantilevers

Table 1. Young's modulus extracted from the force-deflection behavior of cantilevers

Sample No.	h (μm)	d (μm)	L' (μm)	L (μm)	Force (μN)	Deflection (μm)	Young's modulus E(GPa)
1	37	500	9000	8550	100	58	162.0
2	37	300	3000	2625	1000	28	156.7
3	37	100	1800	1500	1000	13	164.8

In conclusion, from measurement of the force-deflection behavior of silicon cantilevers with the balance measurement system, Young's modulus of single crystal silicon material in <110> orientation is deduced to be $E_{si<110>}$=160GPa, which is very close to that widely accepted: $E_{si<110>}$=170GPa [6] and $E_{si<110>}$=167GPa [7].

4. STATIC PERFORMANCE TEST OF CAPACITIVE ACCELEROMETER WITH BALANCE MEASUREMENT SYSTEM

Silicon micromachined capacitive accelerometers have been developed rapidly in recent years for its high sensitivity, high stability and low temperature coefficients. Various designs have been proposed for bulk micromachined silicon capacitive accelerometers, such as cantilever design[8], two-beam design[9] and eight-beam design[10], etc. To test the performance of a capacitive accelerometer, special instruments are required. The micro force-displacement balance measurement system can be applied to measure the static performance of the bulk micromachined capacitive accelerometer before the device is packaged. Two kinds of accelerometers, cantilever-designed and four-beam-designed, are tested by the balance measurement system in this work and it is proved to be very practical for its easiness and high precision. Here the sensitivity of bulk micromachined capacitive accelerometer is defined as the displacement of mass center of the seismic mass per g, where g is the acceleration of gravity.

4.1. STATIC PERFORMANCE TEST OF CANTILEVER CAPACITIVE ACCELEROMETER

4.1.1. PRINCIPLE OF MEASUREMENT

A cantilever capacitive accelerometer is schematically shown in Fig. 5. The mass of the seismic mass is m. The length of the cantilever and the cantilever-mass assembly are L_1 and L_2 respectively. When the mass experiences an inertial force ma, a is the acceleration, the cantilever deflects. Neglecting the mass of the cantilever, the equation of deflection y in coordinate system in Fig.5 is

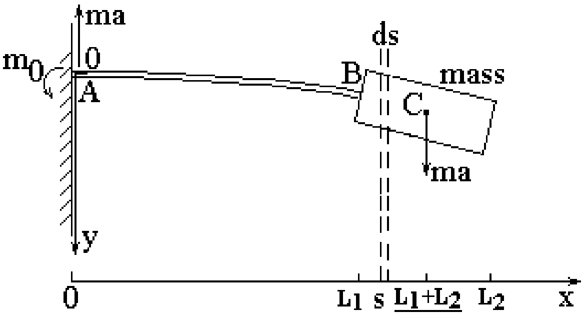


Fig.5 Schematic diagram of cantilever capacitive accelerometer

$$-EI_1y''=M_1(x)=-m_0+m\cdot a\cdot x \qquad 0\le x\le L_1 \tag{9}$$

$$-EI_2y''=M_2(x)=-m_0+m\cdot a\cdot x-\int_{L_1}^{x}\rho b_2h_2a(x-s)ds \qquad L_1\le x\le L_2 \tag{10}$$

where E is the Young’s modulus of the material, I_1 and I_2 are the inertia moments of the cantilever and the mass respectively, M is the total bending moment, m_0 is the bending moment acting on the cantilever from the wall, b_2 and h_2 are the width and thickness of the seismic mass respectively, s is the distance between the root of the cantilever and the differential element ds. From the boundary conditions

$$y\big|_{x=0}=0 \tag{11}$$

$$y'\big|_{x=0}=0 \tag{12}$$

$$y''\big|_{x=L_2}=0 \tag{13}$$

we have

$$y'=\frac{ma}{2EI_1}\left[(L_1+L_2)x-x^2\right] \qquad 0\le x\le L_1 \tag{14}$$

$$y=\frac{ma}{12EI_1}\left[3(L_1+L_2)x^2-2x^3\right] \qquad 0\le x\le L_1 \tag{15}$$

Neglecting the deformation of the seismic mass, the deflection of the mass-center C is

$$y_c=y\Big|_{x=L1}+y'\Big|_{x=L1}\cdot\left(\frac{L_2-L_1}{2}\right)=\frac{ma}{12EI_1}(L_1^{\ 3}+3L_1L_2^{\ 2}) \tag{16}$$

The theoretical sensitivity S_{th} of the capacitive accelerometer can be calculated:

$$S_{th} = \frac{mg(L_1^3 + 3L_1L_2^2)}{12EI_1} \tag{17}$$

Applying a force F on the mass center of the seismic mass with the balance measurement system is equivalent to the situation that an equivalent acceleration a=F/m is experienced. Measure the corresponding deflection of the mass center y_C, the actual sensitivity of the accelerometer is

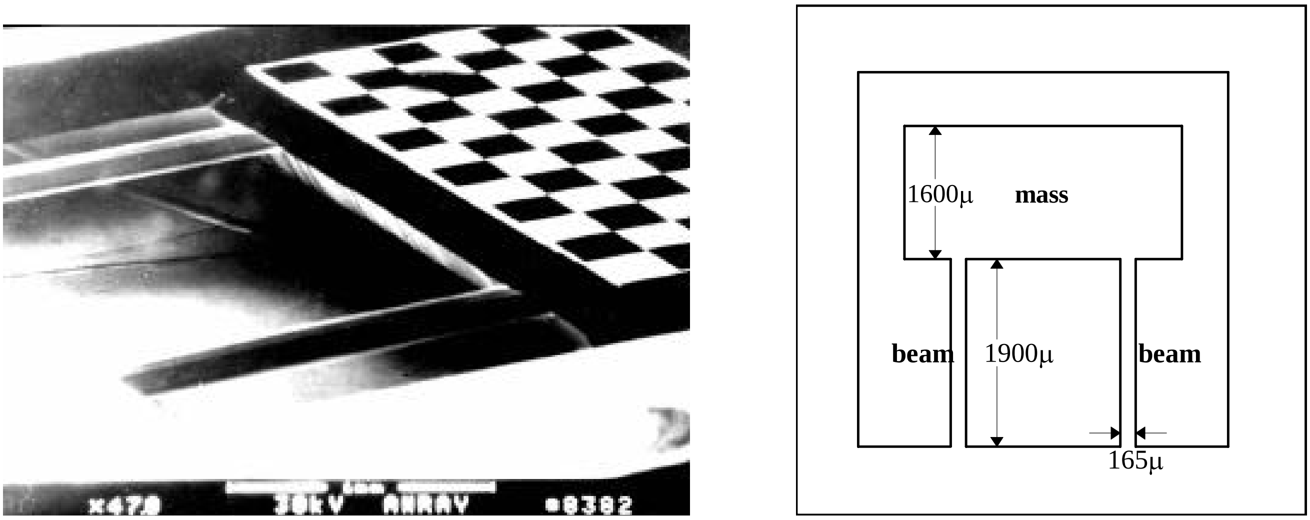
$$S_{act} = \frac{mgy_c}{F} \tag{18}$$

At the same time, the Young's modulus of the material can be extracted:

$$E = \frac{F}{12I_1y_C}(L_1^3 + 3L_1L_2^2) \tag{19}$$

4.1.2. EXPERIMENTAL RESULTS

The cantilever capacitive accelerometer measured in this work[11] is shown in Fig.6. The mass of the seismic mass with rectangular air-damping holes is m=3.36mg. The length, width and thickness of the cantilever are 1900μm, 165μm and 11μm respectively. The length of the seismic mass (L_2-L_1) is 1600μm. The two cantilevers are equivalent to one cantilever of double width.



(a). SEM photograph (b). geometry diagram

Fig.6 Fabricated cantilever capacitive accelerometer

Taking the Young's modulus of silicon in <110> orientation as $E_{Si<110>}$=170GPa, from equation (17), the theoretical sensitivity of the capacitive accelerometer is 33.8 μm/g. Using the balance measurement system, the deflection of the mass center corresponding to an average load of 100μN on the mass center is found to be 109μm. So from equation (18), the actual sensitivity of the capacitive accelerometer is 35.9 μm/g, which is larger by only 6% compared with S_{th} . The Young's modulus of the cantilever material can also be deduced, and it is 160.2GPa.

The theoretical and measured static performance of the cantilever capacitive accelerometer are in accordance with each other well, as shown in Fig.7.

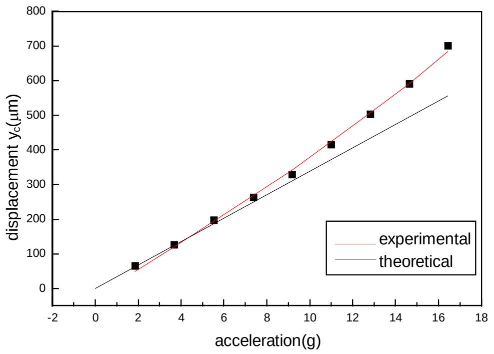


Fig.7 Static performance of cantilever capacitive accelerometer

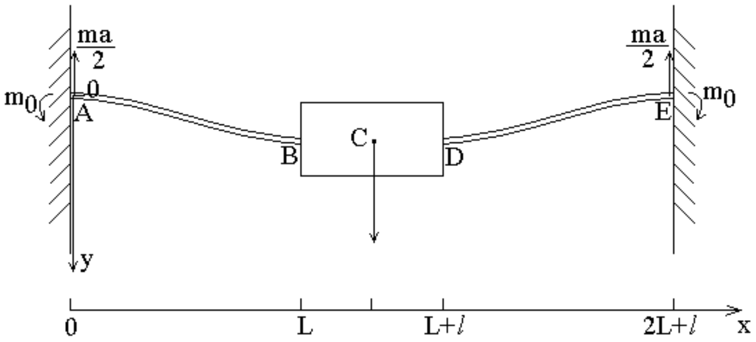


Fig.8 Schematic diagram of four-beam capacitive accelerometer

4.2. STATIC PERFORMANCE TEST OF FOUR-BEAM CAPACITIVE ACCELEROMETER

4.2.1. PRINCIPLE OF MEASUREMENT

An equivalent diagram of four-beam capacitive accelerometer is shown in Fig.8. The mass of the seismic mass is m. When the mass experiences an inertial force ma, the beams deflect. The length of the beam and mass are L and *l* respectively. Neglecting the mass of the beam, the equation of deflection y of the beam in coordinate system in Fig.8 is

$$-EIy'' = M(x) = -m_0 + \tfrac{1}{2} m \cdot a \cdot x \tag{20}$$

where E is the Young's modulus of the material, I is the inertia moment of the beam, M is the total bending moment, m_0 is the bending moment acting on the beam from the wall.

The boundary conditions are

$$y\big|_{x=0} = 0 \tag{21}$$

$$y'\big|_{x=0} = y'\big|_{x=L} = 0 \tag{22}$$

We have

$$m_0 = \tfrac{1}{4} m \cdot a \cdot L \tag{23}$$

$$y'(x) = \frac{ma}{4EI}(Lx - x^2) \tag{24}$$

$$y(x) = \frac{ma}{24EI}(3Lx^2 - 2x^3) \tag{25}$$

Neglecting the deformation of the seismic mass, the deflection of the mass center C is

$$y_c = y|_{x=L} = \frac{maL^3}{24EI} \tag{26}$$

So the theoretical sensitivity of the four-beam capacitive accelerometer is

$$S_{th} = \frac{mgL^3}{24EI} \tag{27}$$

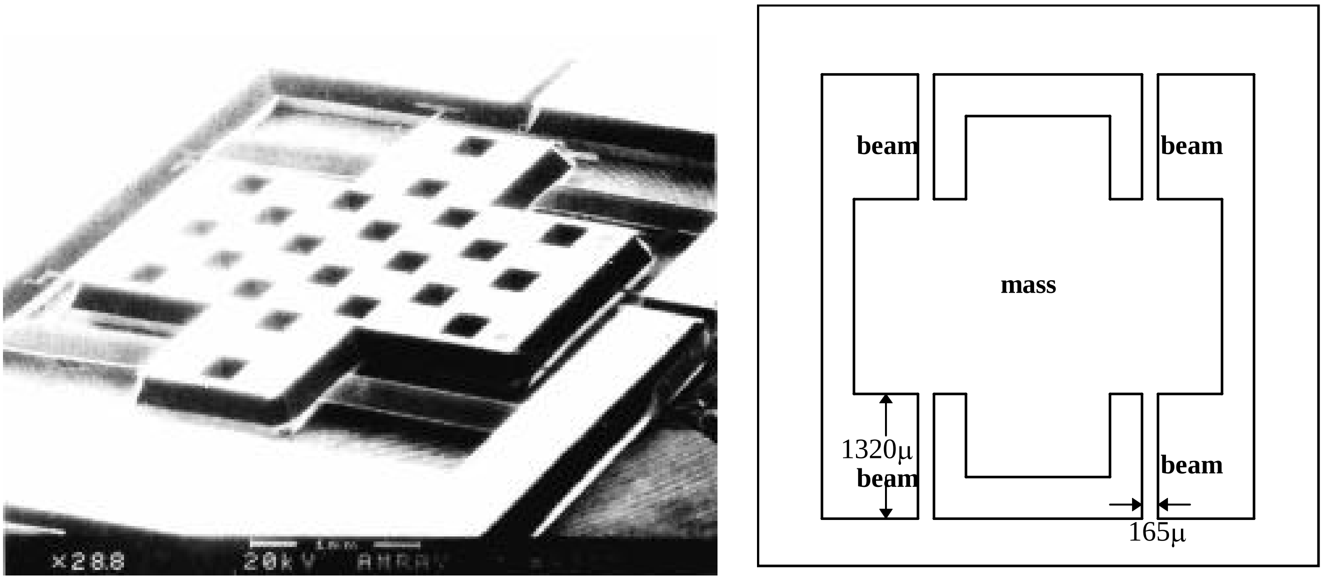
Applying a force F on the mass center of the seismic mass with the balance measurement system is equivalent to the situation that an equivalent acceleration a=F/m is experienced. Measure the corresponding deflection of the mass center, the actual sensitivity of the accelerometer is

$$S_{act} = \frac{mgy_c}{F} \tag{28}$$

At the same time, the Young's modulus of the material can be calculated:

$$E = \frac{F}{24Iy_c} L^3 \tag{29}$$

4.2.2. EXPERIMENTAL RESULTS



(a). SEM photograph (b). geometry diagram

Fig. 9 Fabricated four-beam capacitive accelerometer

The four-beam capacitive accelerometer measured in this work[11] is shown in Fig. 9. The mass of the seismic mass with rectangular air damping holes is 4.2mg. The length, width and thickness of the beam are 1320μm, 165μm and 20μm respectively. The four beams are equivalent to two beams of double width. Taking the Young's modulus of single crystal silicon in <110> orientation $E_{si<110>}$ as 170GPa, from equation (27), the theoretical sensitivity of the capacitive accelerometer is 0.10 μm/g. Using the balance measurement system, the average deflection of the mass center corresponding to an average load of 1000μN is found to be 2.7 μm. So the actual sensitivity of the capacity accelerometer is 0.11 μm/g, which is larger by only 10% compared with S_{th}. The Young's modulus of the silicon material can also be deduced, and it is also equal to about 160GPa.

The theoretical and measured static performance of the four-beam capacitive accelerometer are in accordance with each other well, as shown in Fig.10.

From the above two experiments, it can be concluded that the balance measurement system is also a good approach for testing the static performance of silicon bulk micromachined capacitive accelerometer.

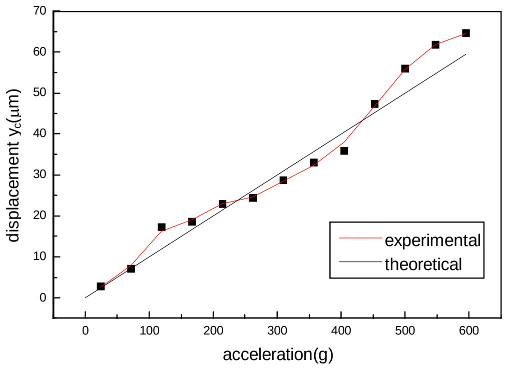


Fig.10 Static performance of four-beam capacitive accelerometer

5. CONCLUSIONS

The balance measurement system utilizing a balance ingeniously to measure both micro force and the corresponding displacement exhibits excellent performances in resolutions of force and displacement. The balance measurement approach can be applied to the measurement of the force-deflection behavior of a cantilever to extract the Young's modulus of the material. It can also be used to test the static performance of bulk micromachined capacitive accelerometers. There still may be many other applications for the balance measurement system to test various mechanical properties of micro fabricated structures. The balance measurement approach has been experimentally proved to be very practical and reliable. It is very attractive for its easiness in operation, low cost and high precision. It may become very useful means to measure the mechanical properties of micromachined structures and materials.

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REFERENCES

1. G.M.Pharr and W.C.Oliver, "Measurement of Thin Film Mechanical Properties Using Nanoindentation", MRS Bulletin, 17(7), pp.28-33, 1992.
2. Quanbo Zou, Litian Liu and Zhijian Li, "Study of Techniques for Measuring Residual Stress in Micromachined Films", Chinese Journal of Semiconductors, 16(7), pp.509-516, 1995.
3. Deren Lu, Wenyu Zhu, Gang Rong, Chinese Practical Novel Patent Bulletin, Patent No. ZL93225564.7, 10(4), pp.180, 1994.1.26.
4. Ben'an Xu and Xiuzhi Li, *Material Mechanics*, pp.225-230, Shanghai JiaoTong University Press, Shanghai, 1988.
5. K.E.Peterson, "Silicon as a Mechanical Material", *Proceedings of the IEEE*, 70(5), pp.420-457, 1982.
6. J.C.Greenwood, "Silicon as a Mechanical Material, Fabrication Techniques", *Silicon Based Sensors*, IOP short meetings No.3, pp.1-13, Institute of Physics, London, 1986.
7. Xixin Qu, *Electronic Component Material Handbook*, pp.352, Electronic Industrial Press, Peking, 1989.
8. S.Suzuki, S.Tuchitani, K.Sato, S.Ueno, Y.Yokota, M.Sato and M.Esashi, "Semiconductor Capacitance-type Accelerometer with PWM Electrostatic Servo Technique", Sensors and Actuators, A21-A23, pp.316-319, 1990.
9. F.Rudolf, A.Jornod, J.Bergqvist and H.Leuthold, "Precision Accelerometers with μg Resolution", Sensors and Actuators, A21-A23, pp.297-302, 1990.
10. H.Seidel, H.Riedel, R.Kolbeck, et al, "Capacitive Silicon Accelerometer with Highly Symmetrical Design", Sensors and Actuators, A21-A23, pp.312-315, 1990.
11. Qiang Zou, Baoqing Li, Xingguo Xiong, Bin Xiong, Deren Lu and Weiyuan Wang, "Structure Design and Fabrication of Symmetric Capacitive Force-Balance Micromaching Silicon Accelerometer", *Proceedings of SPIE'97*, 3223, To be published, Austin, 1997.