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Summary

Novel three axis SOI capacitive accelerometer have been designed for low-G detection. The accelerometer has a mass over 400μm thickness formed by dicing saw using bulk silicon substrate. The mass can be formed in high aspect ratio of nearly infinity using a dicing blade in width of 500μm, it promise high sensitivity for each axis acceleration and small sensor size of 2.5mm by 2.5mm. The characteristics were simulated with FEM for two structures which mass was supported with thin straight beams or spiral beams. The capacitor electrodes were designed in clover-leaf structure using SOI structure. The electrode forms a differential capacitor for X,Y axis, which is effective to reduce noise or temperature dependence. The structure can be also applied for microgyroscope etc.

Keywords: capacitive accelerometer, three axis, high aspect ratio, dicing saw ,SOI

1 INTRODUCTION

Many silicon micromachining accelerometers have been developed and used for automotive industry such as airbags. Their typical measurement range is 0-50g with a resolution 1mg and chip-size of around 5mm by 5mm. However, more sensitive multi-axis accelerometers are required for a number of interesting applications in automotive motion control systems, airplane and biomedical field. These require the range of 0-2g and resolution of 1μg. Features of small size, low-cost are also important because a number of accelerometers are used in the precise control system.
A three-axis silicon accelerometer can be satisfy the requirements because of productivity with micromachining technology. So that bulk micromachining accelerometers and surface micromachining accelerometers were developed recently [1]-[7]. However, it is difficult to detect 1μg using polysilicon surface micromachining technology because of its small mass of μgram. Though capacitive bulk micromachining accelerometers have higher sensitivity, anistropic etching process is necessary for the formation of mass and beam structure, which forms (111) side-walls at peripheral of sensor. As the result, sensor chip-size is tend to be large especially using thick(over 400μm) wafers. And the lateral axis sensitivity become small in comparison with the virtual axis sensitivity[4][7], so that some accelerometers adopt a glass bonded mass structure although it raises process complexity and sensor cost[3][5].
High aspect ratio mass structure solves the problem. Anistropic etching using (110) silicon plane, LIGA, deep trench R.I.E. process were candidates for high aspect mass structure, but these process require high running cost and long process time. Thus, these process results low throughput and high cost.
In this paper, a dicing saw was first used for the mass structure formation because it formed a high aspect ratio(nearly infinity) mass with high throughput and low running cost. A dicing blade in width of 500μm was used for the fabrication process. This paper describes the concept, design analysis and fabrication process of the accelerometer with the dicing process.

2 DESIGN

2.1 Structure

The structure of three axis accelerometer is shown in Fig.1. The accelerometer has glass-silicon structure which size is designed 2.5mm by 2.5mm. The accelerometer has a thick mass of over 400μm thickness formed by dicing saw with bulk silicon substrate. The mass is supported by thin straight beams or spiral beams.

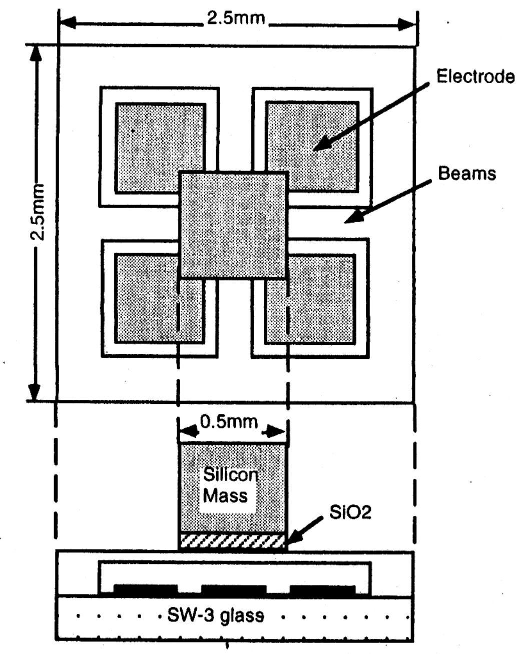


Fig.1. Structure of three axis accelerometer.

The beams are formed by single crystal silicon which raises reliability because it does not have hysteresis or creep. Z-axis accelerometer is formed between mass and metal electrode on glass substrate. Clover-leaf structure is attached to the mass to form X,Y axis capacitor in minimum sensor chip-size. X,Y accelerometer is formed between clover-leaf structure and metal electrode on glass which is illustrated in Fig.2. The equivalent circuit of three-axis accelerometer is written as Fig.3. The mass forms a common electrode, and X,Y axis accelerometers are constructed with a differential capacitor which is effective to reduce noise or temperature dependence.

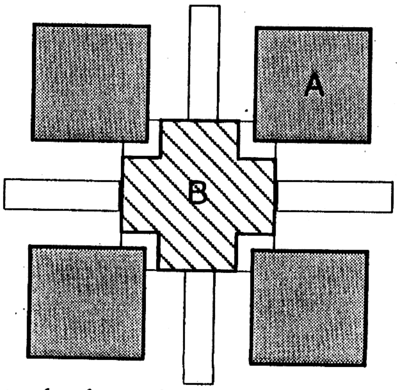


Fig.2. Electrode shape for each axis.

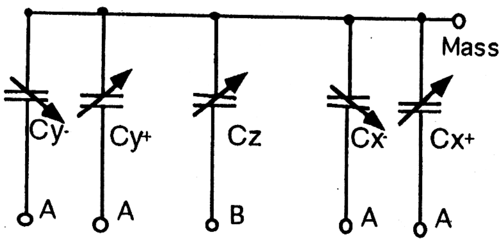


Fig.3. Equivalent circuit of three axis accelerometer.

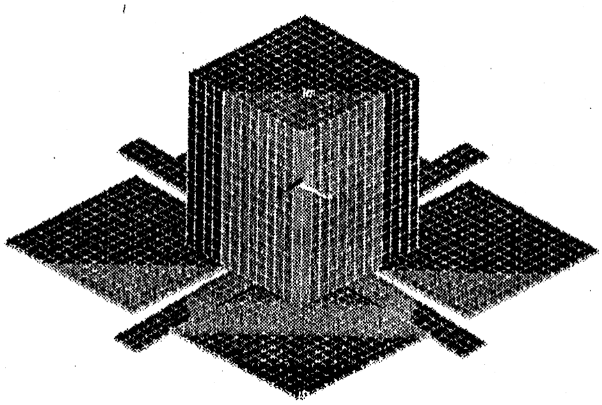
2.2 FEM simulation

FEM analysis was performed for the structure which mass was supported with thin straight beams or spiral beams. Figure 4 shows the simulation models of accelerometers. The width and thickness of beams were selected 100μm and 10μm respectively. The gap between mass and electrodes was 2μm. The sizes of clover-leaf structure are 560μm by 560μm for Fig.4 (a) and 350μm by 350μm for Fig.4 (b). The displacements by each axis acceleration were obtained from FEM results, and the capacitance changes were calculated as Table 1. The capacitance change can be increased rapidly if thinner beam1s width or thickness were selected. Interesting results were obtained as follows.

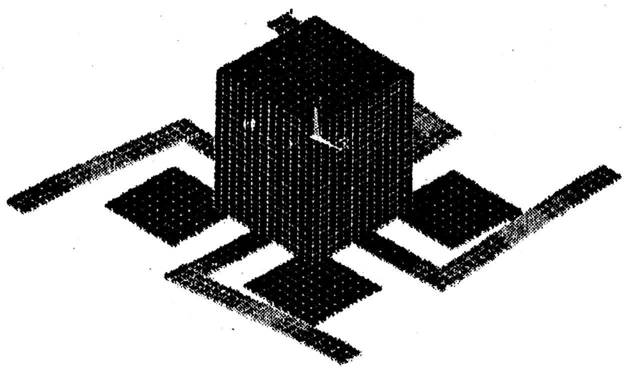
1) Same initial capacitance for each axis were obtained for accelerometer (a).

2) Same capacitance changes for each axis were obtained for accelerometer (a) with 610μm mass thickness, so that uniform axial sensitivity were obtained in the case.

3) X,Y axis initial capacitance and capacitance change were half of them of Z axis accelerometer in (b) with 610μm. As X,Y axis accelerometers forms a differential capacitor, uniform axial sensitivity can be obtained by using a adequate circuit. From the reset, if a high aspect ratio mass in thickness of over 600μm can be formed, three-axis accelerometer with uniform axial sensitivity will be fabricated with single silicon mass.



(a) Accelerometer with straight beams.



(b) Accelerometer with spiral beams.

Fig.4. FEM simulation models of accelerometers.

Table 1. Simulated characteristics for each sensors.

Thickness of mass	425μm		610μm	
sensor type	(a)	(b)	(a)	(b)
X,Y initial capacitanceCx[pF]	1.4	0.64	1.4	0.64
capacitancechange dC[fF/G]	5.4	6.6	11	14
ratio dC/Cx [%]	0.38	1.0	0.78	2.1
Z initial capacitanceCz[pF]	1.3	1.1	1.3	1.1
capacitancechange dC[fF/G]	6.8	36	9.4	51
ratio dC/Cz [%]	0.52	3.3	0.72	4.7

3 SENSOR FABRICATION

3.1 Mass formation with dicing saw

Dicing saw was used for the high aspect mass formation because the aspect ratio of diced walls was nearly infinity, and the price of dicing saw and its running cost is much lower than LIGA or deep R.I.E. process. The process time depends on the cutting speed, but if a multi-blade is used for dicing, the throughput can be increased according to the number of blade. So that the dicing process has high throughput and low running cost.

Figure 5 shows the diagram of mass formation on bulk silicon wafer. Width of 1mm must be grinding to form sensor structure. There are many blades which width from 0.03mm to 2mm in metal bond blade by DISCO Co.. A 1mm width blade can be also used for grinding, however, a thick blade loses thickness accuracy and chipping was occurred during dicing. So that a blade of 500μm width was selected for the fabrication process.

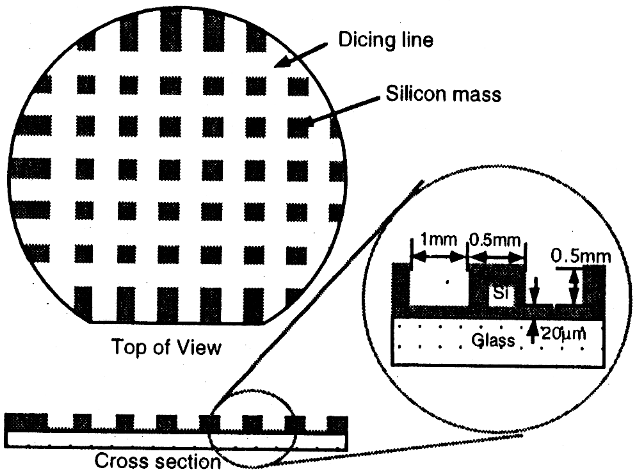


Fig.5. Diagram of mass formation by dicing saw.

Dicing was tested using 400μm silicon wafer at rotor speed of 30000r.p.m and stage speed of 1mm/sec with a blade of BIA801SD1500N100M42(DISCO Co.). Figure 6 shows the photograph of diced wafer with the blade. Although some chippings were observed on the corner of mass, a cube structure of 500μm width was successfully formed by dicing saw. The roughness of diced surface was 3μm. The aspect ratio of mass was nearly infinity. From the result, a high aspect silicon mass can be effectively formed by dicing saw.

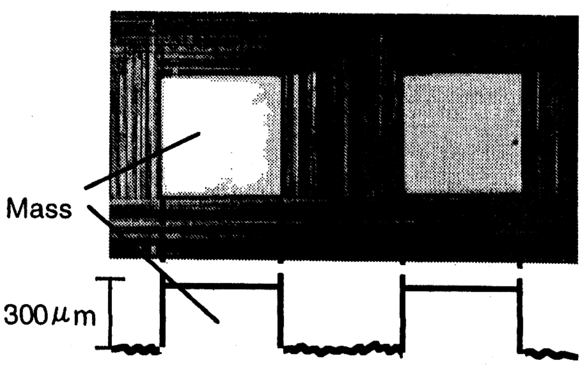


Fig.6. Photograph of silicon mass formed by dicing saw with a blade of 500μm width.

3.2 Fabrication process

The three axis accelerometer was designed with FEM results and CAD system, and it was now under development. The fabrication process was designed as follows.

(a) Starting material was n-type SDB-SOI wafer. Top layer was 12μm n-type($10^{15}cm^{-3}$) single crystal silicon, middle di-oxide layer was 0.5μm and 1μm thickness. Substrate was n-type ($10^{15}cm^{-3}$) wafer in thickness of 425μm and 610μm.

(b) The SOI wafer was oxidized and etching pattern was aligned with double-side mask aligner. The silicon di-oxide was etched for next anisotropic etching process.

(c) The SOI wafer was etched by TMAH solution at 85°C in depth of 2μm. The depth determine the gap of sensor capacitor. Then, the SOI wafer was oxidized again. The silicon beams and electrodes were etched with a conventional reactive ion etching(R.I.E.) system with SF_6 gas. Middle di-oxide layer acts as etching stop layer for R.I.E. process. Figure 8 (a) shows the photograph of the sensor after R.I.E. process.

(d) Aluminum was sputtered on SW-3 glass(IWAKI Co.) and patterned to form electrode for each axis.

(e) The wafer and glass were anodically bonded, which photograph is shown in Fig.8 (b).

(f) The bonded wafer was diced with a 500μm width blade remaining 20μm thick silicon layers. Then the bonded wafer was diced to individual chips.

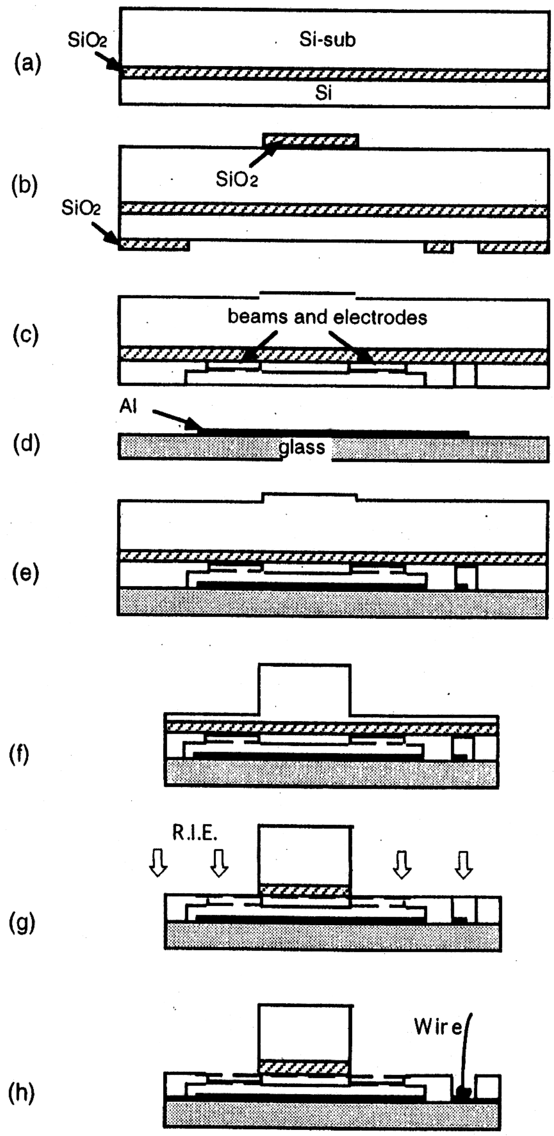
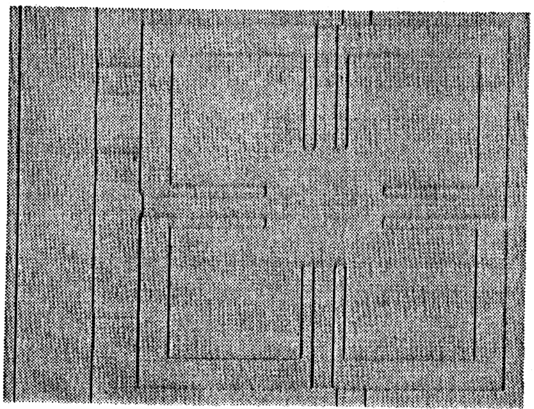


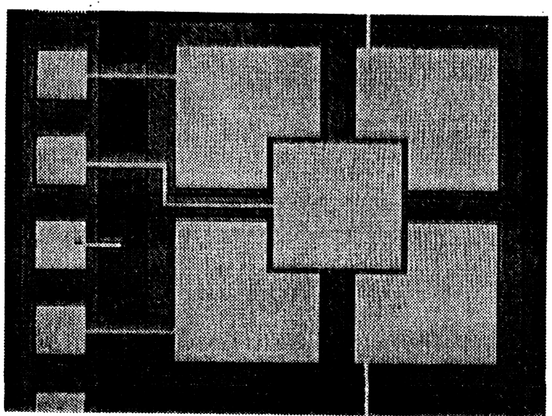
Fig.7. Fabrication process of accelerometer.

(g) Remained silicon layer and middle silicon di-oxide layer were etched R.I.E. system with CF_4 gas. The accelerometer structure was released with dry process so that so that sensor did not break or stuck to substrate during the release process. This process promise high yields and high performance.

(h) Finally, gold wires were bonding to aluminum pad.



(a) After R.I.E. process of Fig.7 (c)



(b) After anodic bonding process of Fig.7 (e)

Fig.8. Photograph of a developing accelerometer.

CONCLUSION

Novel three axis SOI capacitive accelerometer have been designed for low-G detection. A thick mass over 400μm thickness can be successfully formed by dicing saw with aspect ratio of nearly infinity. Sensor size was designed 2.5mm by 2.5mm using the high aspect mass structure. The thin straight beams or spiral beams were formed by single crystal silicon which raises the reliability. The capacitor electrodes are formed in clover-leaf structure using SOI structure. From the FEM simulation, it promise same sensitivity for each axis acceleration. The electrode forms a differential capacitor for X,Y axis, which is effective to reduce noise or temperature dependence. Sensor structure was released by R.I.E. process so that sensor did not break or stuck to substrate. This process promise high yields and high performance. The structure can be also applied for microgyroscope etc.

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