Silicon-based, low-g microelectromechanical systems inertial switch for linear acceleration sensing application

Zhuang Xiong, Fengtian Zhang, Yingdong Pu, Bin Tang, Jie Yang, Chao Wang

Institute of Electronic Engineering, China Academy of Engineering Physics, Mianyang 621999, People's Republic of China
E-mail: xiong.zhuang@caep.cn

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Most of the microelectromechanical systems inertial switches developed in recent years are intended for shock and impact sensing above 40 g. These switches are fabricated based on non-silicon surface micromachining with multiple steps of electroplating. In this reported work, a silicon-based low-g inertial switch typically used for linear acceleration sensing was conceived, designed and fabricated. The developed inertial switch consists of a high volume proof mass and low stiffness spiral spring, and is fabricated in a specially designed double-buried layer silicon-on-insulator wafer, with standard silicon micromachining. The measurement results show that the threshold value is about 7.42 g and the stiffness is about 1.5 N/m, in accordance with the finite element method calculation.

1. Introduction: A microelectromechanical systems (MEMS) inertial switch can use the acceleration to trigger a safety mechanism to prevent damage from a sudden impact during operation of the inertial system when the applied acceleration exceeds the threshold level of the inertial switch [1]. Owing to their small size, low cost batch production and low power consumption, MEMS inertial switches show great potential to be widely used in toys, accessories, automotive, military weapons and industrial applications [2–5]. There has been substantial literature published on all-metal MEMS inertial switches which were fabricated based on non-silicon surface micromachining and with multiple steps of electroplating technology [6–9]. However, these were all designed for shock or impact sensing, with a threshold value above 40 g. On the other hand, the low-g inertial switch, typically ranging from 1 to 30 g, is usually used for linear acceleration sensing. According to the static state equation $a = kd/m$ (where a is the acceleration threshold, k is the spring constant and d is the moving distance of the proof mass), a low-g inertial switch design should consist of a high volume proof mass and a low stiffness spring. However, the high volume proof mass to be achieved with a large number of electroplating processes is not practical considering that the induced residual stresses might cause unexpected structure deformation.

Yoo *et al.* [10] proposed a low-g switch that made use of the advantageous properties of liquid-metal droplets (e.g. mercury) in a mictrostructured channel. The threshold value of the liquid-metal switch could vary from 5 to 20 g. However, mercury is a toxic material and sensitive to the surrounding temperature, which might result in possible security and reliability problems. To provide a more safe and reliable low-g MEMS inertial switch, a kind of silicon-based switch has been conceived, designed and fabricated by the present authors. The standard silicon micromachining technology was used for fabrication. A double-buried layer silicon-on-insulator (SOI) wafer, with a spiral spring design, was applied for producing the high volume proof mass and low stiffness spring.

2. Structure design: The silicon inertial switch consisted of a square proof mass held at diagonal positions by spiral springs (Fig. 1). The holding points were located at the central part along the thickness of the proof mass to maintain structural mechanical balance. The springs were designed in a spiral shape, with thin thickness, to reduce the stiffness and favour the flexible movement of the proof mass under the applied load. The top surface of the proof mass was layered with a Ti/Pt/Au metal stack to make a moveable electrode.

An assembled design sketch is illustrated in Fig. 2. The switch was sealed by two glass layers. The bottom glass layer was patterned with two fixed electrodes which could be connected to external signal processing electronics.

The distance between the moveable electrode and fixed electrodes keeps the switch OFF in the static state. When subjected to a sufficient amount of acceleration over the threshold level along the sensing direction, the proof mass will move towards the bottom glass layer and the moveable electrode will collide with the fixed electrodes, thus forming a closed electrical path.

Therefore, the distance between the proof mass and the fixed electrodes is the main factor that defines the threshold value of the switch. Considering that the threshold value of the first switch prototype is designed as 8 g, a quick FEM static analysis (ANSYS) was applied to investigate the moving distance of the proof mass (asophisticated analytical model will be reported elsewhere). The geometric parameters used for the current design are shown in Table 1 and the material properties are defined as: Young's modulus = 130 GPa; density = 2330 kg/m^3 and Poisson ratio = 0.23.

According to the simulation results shown in Fig. 3, when subjected to 8 g acceleration, the movement of the proof mass is around 150 µm. The simulated stiffness of the entire spring-mass system along the sensing direction is about 1.45 N/m.

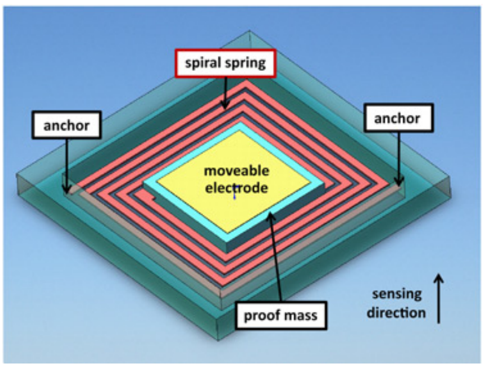

Figure 1 *Schematic representation of the proposed MEMS inertial switch*

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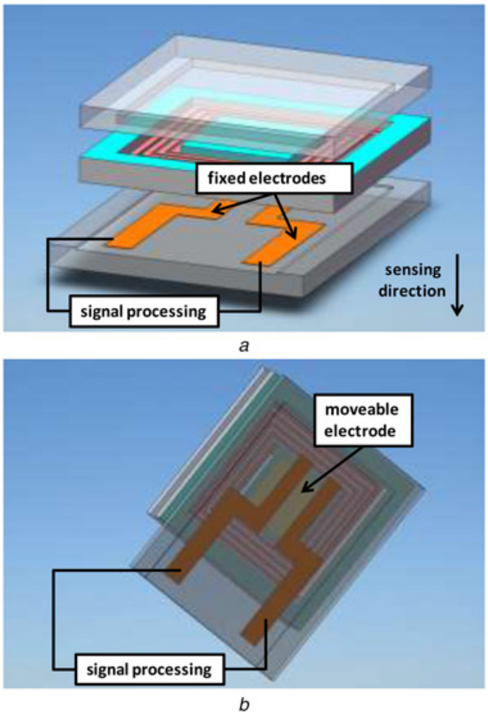

Figure 2 *Schematic representation of the assembled switch design*
a Switch is sealed with a top and bottom glass layers
b View from back side

3. Fabrication: The MEMS inertial switch was fabricated with a special design double buried (100) *n*-type SOI wafer (top device layer 135 µm, middle device layer 30 µm, handle layer 300 µm and BOX layer 0.7 µm), with standard silicon micromachining technology. As illustrated in Fig. 4*a*, a 2.5 µm thick SiO_2 layer was first grown on both sides of the wafer by thermal oxidation. The SiO_2 layer was then patterned and the silicon was etched in KOH solution (Fig. 4*b*). The etch depth on the handle layer was

Table 1 Designed geometric parameters of the inertial switch

Component	Value, µm
proof mass length	2000
proof mass thickness	300
spring width	130
spring thickness	30
distance between springs	70

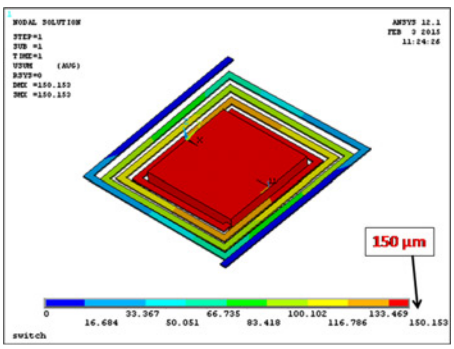

Figure 3 *ANSYS simulation result of the MEMS switch when subjected to 8 g acceleration*

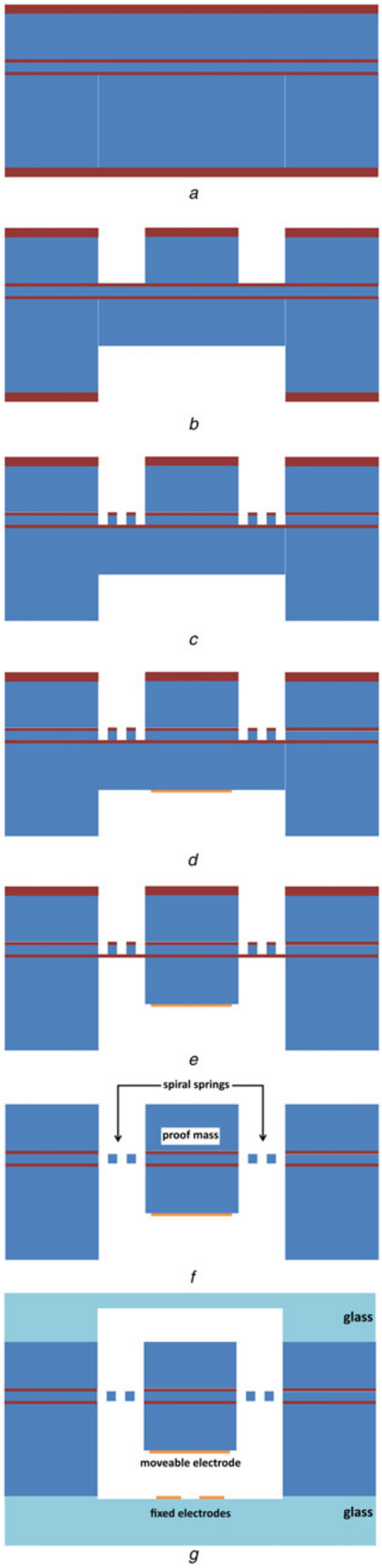

Figure 4 *Fabrication process of the silicon-based inertial switch*

controlled within a vicinity of about 150 µm, which is the distance between the moveable electrode and fixed electrodes. The revealed BOX layer was then patterned and the 30 µm thick spiral spring was fabricated by deep reactive-ion etching (DRIE)

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(Fig. 4*c*). After the moveable electrode (Ti/Pt/Au) deposition on the back side (Fig. 4*d*), another DRIE process was applied to reveal the back side of the proof mass (Fig. 4*e*). The MEMS switch was finally released after removing the excessive SiO_2 layers in BHF (Fig. 4*f*).

The switch was then bonded with two 400 µm thick Pyrex 7740 glass wafers (Fig. 4*g*). The fixed electrodes on the bottom glass layer were chosen as a Ti/Pt/Au metal stack. The top glass layer was etched to about 100 µm to avoid possible contact between the surface of the proof mass and the glass wafer during the bonding process.

Scanning electron microscope (SEM) pictures of a fabricated device (the silicon part) are shown in Fig. 5. The proof mass is well suspended by the released spiral spring. A closer view of the spring location is shown in Fig. 5*b*. The sidewall of the proof mass is vertical and the spiral springs are well shaped.

4. Test results: A home-made centrifugal testing setup was built to investigate the acceleration sensing capability of the MEMS inertial switch. The testing setup mainly consisted of a rotating plate, rpm controller and a device holder (Fig. 6). The acceleration amount can be set from 1 to 30 g. The two fixed electrodes on the bottom glass layer were connected to a DC power source and a resistor. When the applied acceleration reaches the threshold value, the moveable electrode touches the fixed electrodes and turns on the detection circuit. The whole system is computer controlled, recording the time-varying acceleration signal and the ON/OFF states of the switch.

In the centrifugal experiment, each test device was placed in the same position (i.e. a 150 mm radius of rotation). Fig. 7 shows the relationship between the ON/OFF state and the applied acceleration of one device. For the first test, the threshold value was measured to be about 8.38 g. A total of six experiments were performed and the threshold value for each test was 8.38, 7.61, 7.47, 7.42, 7.43 and 7.42 g. The threshold value was finally stabilised at about 7.42 g.

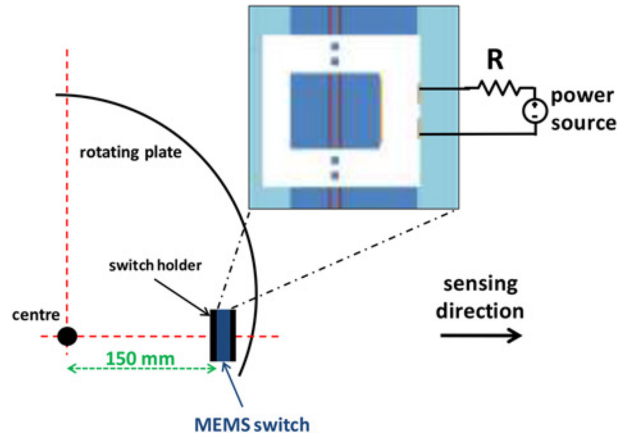

Figure 6 *Schematic representation of centrifugal experiment*

This phenomenon is probably because of the strain releasing process inside the spiral springs.

To verify the stiffness of the MEMS switch, a precise control of the applied load and also the displacement of the proof mass are required. Therefore, a nanoindentation (TI900 TriboIndenter, HYSITRON) test was employed. The test sample consists of only the silicon part. The spherical tip was vertically positioned at the centre of the proof mass. The load was applied during 4 s to its maximum value and unloads to zero during 4 s. A total of three loading tests were performed and the maximum force applied was 4, 6 and 8 µN, respectively. Fig. 8 shows the force–displacement curve of the test sample.

Considering that the switch is subjected to elastic deformation, the unloading force curve should recover the shape of the loading

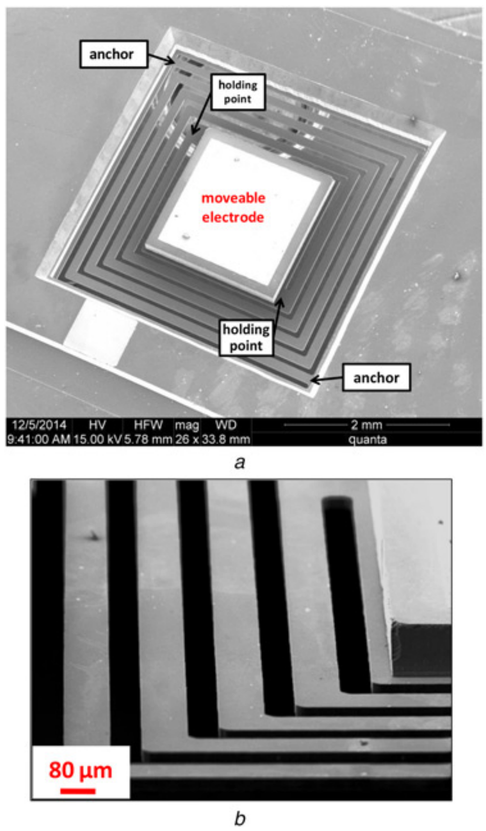

Figure 5 *SEM pictures*
a Overview of the MEMS switch
b Closer view at spiral springs location

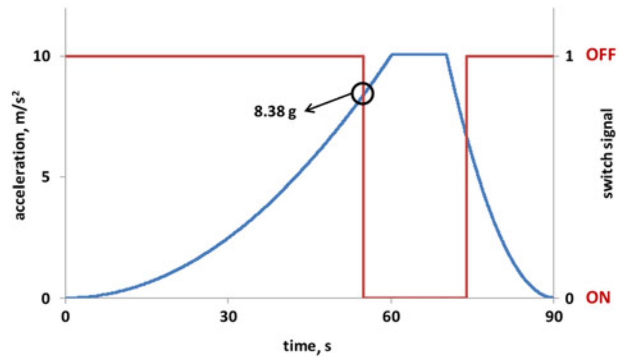

Figure 7 *Centrifugal experiment result of the MEMS switch*
Switch turns to ON state at 8.38 g

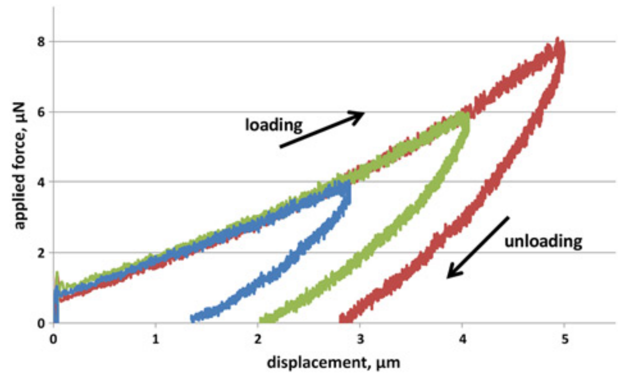

Figure 8 *Force against displacement curve of the MEMS switch*

force curve which, however, was not the case as seen from Fig. 8. This phenomenon was probably because the low stiffness spring requires a relatively long time to return to its initial position. The stiffness can be approximately obtained by calculating the gradient of the loading slope. The average stiffness of the three tests was about 1.5 N/m. The measured stiffness was slightly higher than the calculated value which is mainly because of the dimensional changes during the fabrication process (i.e. lithography, DRIE etc.). Other sources, such as the uncertainties in the material's properties, could also create errors in calculation.

5. Conclusion: A silicon-based low-g MEMS inertial switch for linear acceleration sensing application has been designed, fabricated and tested. The fabrication is based on a double buried SOI wafer with standard silicon micromachining. Centrifugal testing was performed and the threshold value measured is about 7.42 g. A nanoindentation test showed that the stiffness was about 1.5 N/m, which is close to the simulation result. Further study will focus on improving the structure design and simplifying the fabrication process to enhance the production yield.

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7 References

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