A Review on Optimized Accelerometer Design for High Performance Application

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ABSTRACT

Due to the anisotropic characteristics of the energy resolution in crystal space, piezoresistive effect of doped silicon piezoresistors are used for sensing stress on accelerometer structures. Piezoresistive accelerometers are the most popular and widely used method of acceleration sensing due to their simplicity in fabrication, packaging and inherent ruggedness. Moreover, piezoresistive sensors show excellent DC response and hybrid packaging of the sensor chip with signal processing chip in the same package can be used without any signal loss. The performance of the accelerometer which is characterized by the sensitivity and resolution of the accelerometer has a direct impact on the parameters like the size, doping concentration and temperature coefficient of sensitivity of the piezoresistor, noises, power consumption and temperature sensitivity of the accelerometer. It is quite difficult to determine the accelerometer performance only based on some of those parameters. Among these parameters, doping concentration, stress on the piezoresistor and temperature sensitivity is the major factors that affect the performance of the accelerometer. Hence in this paper we investigate on various methods adopted for enhancement of these performance dependent parameters of the accelerometer.

Keywords

MEMS, Accelerometer, Sensitivity, Doping concentration, Temperature effects, stress, Design Optimization

1. ACCELEROMETER OPTIMIZATION

Piezoresistive accelerometers are the most popular and widely used method of acceleration sensing due to their simplicity in fabrication, packaging and inherent ruggedness. Moreover, piezoresistive sensors show excellent DC response and hybrid packaging of the sensor chip with signal processing chip in the same package can be used without any signal loss. Due to the anisotropic characteristics of the energy resolution in crystal space, piezoresistive effect of doped silicon piezoresistors are used for sensing stress on accelerometer structures.

The silicon piezoresistive accelerometer structure consists of three main components, a heavy proof mass, a frame, and a beam connecting the proof mass and the frame [8]. The proof mass is a rectangular mass supported by the beams, on which the acceleration is applied. The supporting beam hold the proof mass and causes a variation in stress when applied with acceleration, as there is a relative displacement between the proof mass end and the frame end of the beam. The beam is the important part of an accelerometer as the stress on the beam is to be sensed using a piezoresistor placed on the most stressed regions of the beam. These piezoresistors arranged in the form of a Wheatstone bridge can convert the change in resistance to a proportional voltage. The device is to be designed such that maximum output voltage appears for prime axis acceleration and ideally zero output signal for transverse acceleration. The sensitivity of the accelerometer depends on the stress on the piezoresistor, displacement of the beam, piezoresistor coefficient etc.

Silicon piezoresistive accelerometers are based on Newton's second law of motion, in which a change in impulse momentum of a mass is linked to a force acting on the mass. And the change in impulse momentum is proportional to the acceleration the mass is undergoing. The force exerted on the mass by the acceleration results in a mass displacement. This mass displacement is a measure of the acceleration the mass is undergoing. The accelerometer performance can be characterized as static performance which is the sensitivity and dynamic performance which includes bandwidth, damping, etc.

2. STRESS

An acceleration applied on the device causes the bending of the beam supporting the central mass. This beam experiences a stretching or compression as the beam is connected to a fixed frame on the other side. This causes a stress on one side of the beam and a strain on the other side. This phenomenon contributes to two stress components which include compressive stress and tensile stress. As the beam is thin this stress will be more on these beams. This stress on the beam is a measure of the acceleration applied on the central proof mass [3]. A sensor that can effectively measure these stress components and then convert it to an equivalent electrical signal can be used to measure the acceleration. The piezoresistors are used as a sensing element as the resistance values change when the resistance value changes on the application of stress. Hence these piezoresistors needs to be placed in a location where the stress is maximum. Care must be taken to place piezoresistors in a location such that the cross axis sensitivity is minimized while maintaining maximum prime axis sensitivity for the applied acceleration.

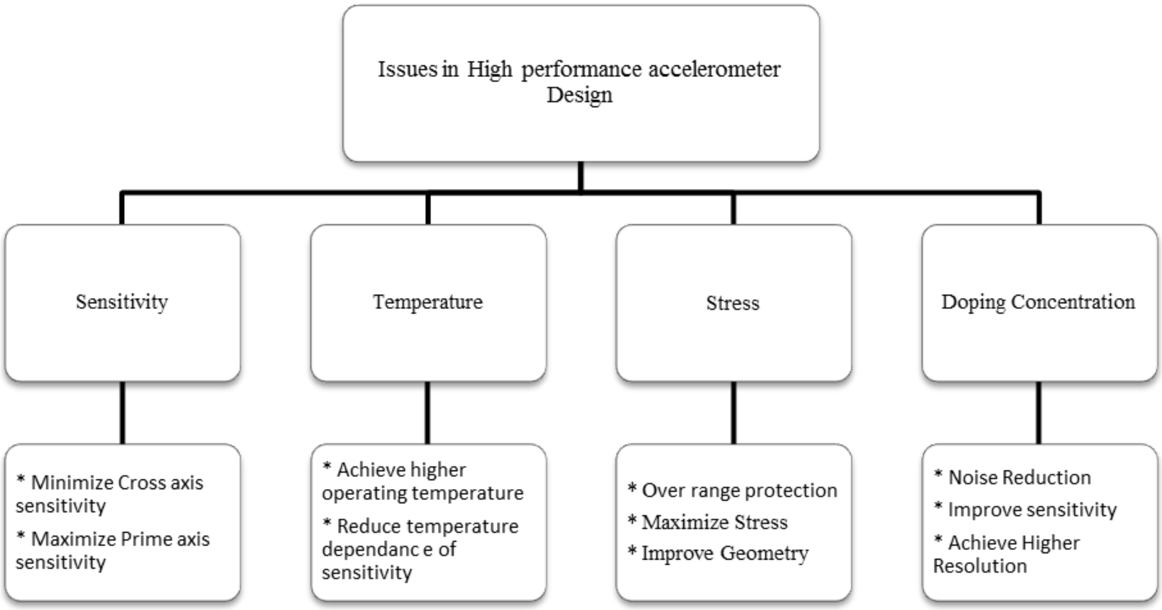

Fig 1: Major issues in high performance accelerometer design

2.1 High-G Piezoresistive Accelerometers

High-G piezoresistive accelerometers [4] utilize an alternate method for protection from over range acceleration. In conventional methods over range stops above and below the structure are used in order to ensure the survival of the accelerometer when the sensor is subjected to excessive accelerations. This is done by bonding of glass or silicon wafers to both sides of the structure. The accelerometer structure is fabricated over a thick layer of an SOI wafer, and the width of the suspension beam is made smaller than the thickness of the same as shown in figure 2. This gives the structure a stiffness in the out-of-plane direction and compliant stiffness in the in-plane direction. When a conductive material is subjected to stress the piezoresistive effect causes a change in resistivity, hence the stress has to be as maximum as possible.

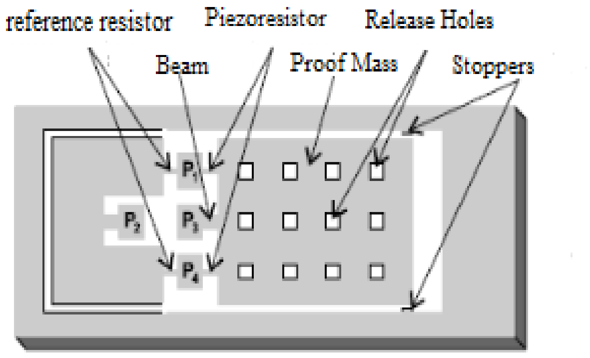

Fig 2: High-G piezoresistive accelerometer structure.

The relation that relates the change in resistance to the relative change in stress can be expressed as

$$\frac{\Delta R}{R} = G\,\frac{\Delta L}{L} \qquad (1)$$

Where ΔR is the change in resistance, ΔL is the change in length of the piezoresistor and G is the gage factor. The sensitivity can also be improved if the proof mass is made larger or the piezoresistors and beams made as thin as possible. SOI wafer with a thin device layer is desirable for better sensitivity of the accelerometer. The presented SOI sensors can be operational up to about 350 ◦C. output characteristics was linear between −13 G and +13 G for *V*in = 5 V. A sensitivity of 0.77 mV G−1 was measured.

The average value of stress on the piezoresistor determines the piezoresistive effect. If the length of piezoresistor is within the range of 6 µm to 30 µm then this average value of stress remain unaffected [10]. The location of stress maximum which is idle for the placement of piezoresistor depend on the geometry of the accelerometer structure. For a fixed doping concentration the relative change in resistance of the piezoresistor varies linearly with the applied stress [11].

2.2 Bulk Micro-machined Silicon Accelerometer

In Bulk micro-machined silicon Accelerometer [12]the static and dynamic behavior of various quad beam accelerometer structures are discussed. When an acceleration is applied on the proof mass the force $F_z = -Ma_z$ acts on the mass which causes the bending of the beam. It is found that both the beam deflection and the angle of rotation at the beam end depend linearly on the force applied to the mass. The force can be divided into two parts $T_{\text{large-deflection}}$ which is the tensile force due to large deflection and T_{stress} which is the lateral force acting on the beam, due to the residual stress бstress. It is found that the tensile stress increases the stiffness while compressive stress decreases the stiffness. For a certain amount of compressive stress, the beam is unstable, as the sign of the reaction force changes making tip displacement larger, until the resulting large-deflection tensile force compensates for the stress force. Even for large values of the compressive stress, the sign of the reaction force is opposite to the tip displacement, which is an unstable behavior of the mass-spring system; the system becomes stable again at larger values of the tip displacement. This results in a hysteresis in the transfer function which needs be avoided. The asymmetric structure is found to be less susceptible to stress compared to the symmetric configurations, because also in this case, the mass will rotate around the z-axis.

3. TEMPERATURE

The temperature influences the mobility and carrier concentration in the respective bands of a piezoresistor which affects the piezoresistive coefficient of the diffused resistor. Temperature affects the accelerometer performance to a great extent. It determines the stability of the accelerometer and hence optimization of the accelerometer’s temperature sensitivity is important. The temperature sensitivity can limit the operation of the accelerometer in a limited temperature range. A large TCR introduces temperature sensitivity to the device performance it is undesirable and needs to be eliminated. It is found that the temperature sensitivity has a great dependence on the doping concentration of the piezoresistor. Leakage currents in piezoresistor limit the operation of the accelerometer sensors to about 150 ◦C. The piezoresistive coefficient also dependents on temperature variations of the environment in which the device operates. Various methods of optimization of accelerometer temperature sensitivity have been proposed in this section.

3.1 Accelerometers with extended temperature range

In the High-G piezoresistive accelerometers with extended temperature range accelerometers [4] silicon-on-insulator (SOI) wafers are utilized to eliminate the pn junctions which causes leakage currents that limits the operation of these sensors to about 150 ◦C. piezoresistors are defined in the device layer and the buried oxide layer isolates them from the proof mass and the support structure, which makes them operational up to temperatures of 400 ◦C. This accelerometer structure is fabricated using a single photo mask, which reduces the number of fabrication steps required. The piezoresistor resistance will change equally with temperature on both sides of the bridge hence no significant change in the output voltage due to temperature occurs. But there exist a slight change in sensitivity because of the temperature dependence of the piezoresistive coefficients of the piezoresistor. Here the sensitivity of the sensor but has a nonlinear temperature dependence that has to be eliminated.

3.2 Piezoresistive effect in *p*-type silicon

Based on “Piezoresistive effect in *p*-type silicon” by T. H. Tan [11] the results show that the temperature coefficient of resistance is greatly influenced by the doping concentration of the p-type silicon piezoresistor. The resistance values were found for different values of temperatures ranging from 30^{0}C to 80^{o}C and the values clearly show that the TCR increases with the increase in doping concentration, hence for a better output response the doping concentration needs to be kept as low as possible. In contrast to the previous works a high piezoresistance value was found for a doping concentration as low as $8\text{x}10^{19}\text{cm}^{-3}$ than 10^{21}cm^{-3} as is proposed by Tufte et al. Also for a piezoresistive accelerometer sensor, a large TCR will introduce temperature sensitivity to the performance of the device which is undesirable and hence care must be taken to maintain the TCR within an affordable range.

4. DOPING

The optimization of the piezoresistor is important for achieving a better accelerometer output by reducing the cross axis sensitivity and increasing the sensitivity. The piezoresistors are formed by doping the silicon with a p-type or n-type impurity on the silicon substrate. These piezoresistors have an excellent response to stress as compared to other types of piezoresistor. The doping is characterized by two major factors junction depth and doping concentration. Doping concentration influences the accelerometer performance hence the determination of an optimal doping concentration is very important accept in the accelerometer design. Both these factors play an important role in determining the piezoresistive coefficient of the piezoresistor.

4.1 Six degree of freedom piezoresistive accelerometer

The six degree of freedom accelerometer [9] proposed by Ranjith Amarasinghe is fabricated using a symmetric quad beam structure, having two symmetrically bonded identical seismic mass. The device is intended to measure 3 components of linear acceleration and three component of angular acceleration as in [2], [6]. Here in the design twelve boron doped p-type single crystalline piezoresistors are used. The piezoresistors are formed from the masked diffusion method that lies on very thin surface layer. Hence only two piezoresistive coefficients need to be considered which are π_{11} and π_{12}. As in p-type piezoresistor the resistance decreases on compressive stress and increases on tensile stress. This resistance variation is converted into corresponding electrical signal with the help of six imbalanced Wheatstone bridge circuit. The piezoresistors are fabricated on the surface of the beam structure which is aligned with the crystal direction <110> of silicon (001) symmetrically. This configuration helps in measuring the six acceleration components and also eliminates cross talk. The fabrication of piezoresistor was done by boron diffusion process followed by a drive-in process to send boron ions deeper into Si substrate. The doping concentration was optimized to 5×10^{19} atoms cm^{-3} in order to reduce temperature sensitivity of piezoresistors. The average value of sensitivity for linear and angular X,Y,Z acceleration components were found to be 0.116mV(Vg)^{-1}, 0.103mV(Vg)^{-1}, 1.774mV(Vg)^{-1}, $2.544\text{mV(Vrad/s}^{2})^{-1}$, $1.964\text{mV(Vrad/s}^{2})^{-1}$, $0.124\text{mV(Vrad/s}^{2})^{-1}$ respectively for a power supply of 5V.

4.2 Design of high Sensitivity MEMS Sensor

In the Design of high Sensitivity MEMS Sensor [1] the design parameters involved in the sensor optimization are discussed with a consideration on the effect of doping concentration on various performance issues of the device. The experimental studies show that longitudinal piezoresistive coefficient (π_l) depends on the doping concentration and the operating temperature. Within a normal atmospheric temperature range the π_l decreases with the increase in the doping concentration for a doping concentrations above 10^{17} atoms/cm^3. However for doping levels below 10^{17} atoms/cm^3, the value of π_l was found to be nearly constant. The Johnson noise depends only on geometry and doping level when a step dopant profile is used for the piezoresistor. The *1/f* noise in piezoresistive sensors is found to vary inversely with the carrier concentration in the piezoresistor. Noise in the piezoresistor can be reduced by heavily doped piezoresistors with deep sections; while considering the sensitivity lightly doped piezoresistors with shallow sections are preferred. Therefore an optimal doping concentration is found as a function of the piezoresistors volume and the measurement bandwidth. The piezoresistors were fabricated with doping concentration is 5×10^{19} atoms/cm^3 at a junction depth of 1 μm. Johnson noise is found to increase as the operating temperature increases up to doping level of 10^{19} atoms/cm^3 beyond which it is found to be temperature independent. Also increasing the doping level beyond 5×10^{18}atoms/cm^3 helps in reducing the noise dependence on the operating temperature which improves the sensor performance. It was observed that increasing the doping level lowers the output signal and which in turn reduces the sensitivity. At high doping levels (more than 1019 atoms/cm3) the output signal of the device gets stabilized making it temperature-independent. Even though low doping concentrations favor sensitivity, stable sensor resolution requires a high doping concentration which is greater than 10^{19} atoms/cm^3.

4.3 3-DOF Micro Accelerometer

In this paper a 3-DOF Micro Accelerometer [10] structure optimization is presented. Here the main areas of optimization were the junction depth, the doping concentration of the piezoresistor and power consumption. The device is made up of a proof mass connected to four surround beams, which are fixed to the outer frame at the centers. Twelve identical p-type piezoresistors shallowly diffused on the surface forms three imbalance Wheatstone bridge circuits that convert the mechanical stress into an equivalent electrical signal. An average value of stress on each piezoresistor determines the piezoresistive effect. It is found that the sensitivity decrease with the impurity concentration and the beam length. The length of piezoresistor becomes insensitive in the range of 6 μm to 30 μm as it has less effect on average value of stress. An optimum doping concentration was selected to be 1×10^{17} atoms cm^{-3}below which an instability in ohmic contact results. However the optimum resolution can be achieved with the doping concentration of 9×10^{18} atoms cm^{-3}

5. SENSITIVITY

An accelerometer is a transducer that converts mechanical acceleration into an equivalent electrical signal. The sensitivity gives the relationship between the input signal, which is the stress on the accelerometer to the equivalent electrical signal as its output. For a given accelerometer the major parameters that need to be estimated is the sensitivity. For an accelerometer one has to achieve maximum prime axis sensitivity and small cross axis sensitivity[5]. Some of the major factors that affect the sensitivity include structure and the positions of piezoresistors on the accelerometer, the length, the cross-sectional area, and doping concentration of the piezoresistor. A major optimization on the sensitivity can be achieved by selecting an appropriate structure of the accelerometer.

5.1 Skew symmetric cantilever accelerometer

Skew symmetric cantilever accelerometer [7] is intended to solve the transverse sensitivity problem and the resistor fabrication problem by changing the structure of the accelerometer. The accelerometer consist of a proof mass, cantilever beam and a supporting rim. The upper and lower portions of proof mass are symmetric with respect to the plane of cantilever beam having an offset in the direction of the beam. The figure 3 shows the skew symmetric accelerometer structure. The given skew symmetric accelerometer design provides a sensitivity of 65μVg^{-1}V^{-1} and the nonlinearity was about 4%. The device is thought to be insensitive to cross axis sensitivity but a 2.3% transverse sensitivity was measured for the device due to manufacturing imperfections and axis misalignment.

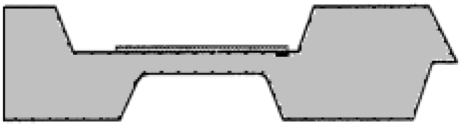

Figure 3: Skew symmetric Cantilever beam accelerometer structure

5.2 Accelerometer with proof mass edge aligned flexures

For the accelerometer with proof mass edge aligned flexures [14] the main objective is to obtain a low cross axis sensitivity while maintaining high prime axis sensitivity. This optimization is achieved by improving the device stability. The accelerometer is designed such that the piezoresistors are placed at the two ends of the beams which support the heavy proof mass, where the maximum stress appears. Thus eight piezoresistors form a fully active Wheatstone bridge circuit that gives a maximum output voltage for z-axis acceleration and ideally zero output voltage for transverse acceleration along X and Y directions. The accelerometer structure is shown in the figure.

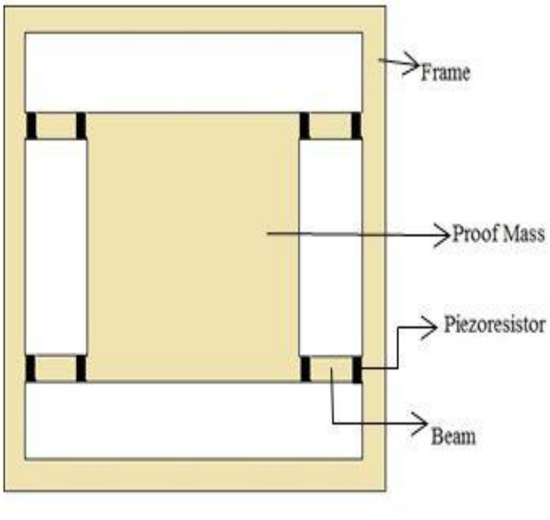

Figure 4: Accelerometer with proof mass edge aligned flexures

The device consist of a proof mass front side 3360 μm long, 3500 μm wide with 270 μm thickness, the flexures 1200 μm long 250 μm wide × 30 μm and thick and the piezoresistors 200 μm long 20 μm wide and 2 μm thick [13]. The beam root problem associated with the wet anisotropic etching is eliminated by shifting the vertical edges of proof mass towards its center. By making stiffness high along a particular direction we can achieve a low cross axis sensitivity along that direction. In the above structure as the four flexures that are oriented parallel to X-axis, the cross-axis sensitivity along X-axis is very less. Now the cross axis sensitivity along Y direction can be reduced by placing the flexures in-line with the proof mass edges. The vertical edges of the proof mass are shifted inwards by around 90 µm in order to avoid the beam root problems. For a devices with shifted proof Mass edges the prime-axis sensitivity along Z-axis was found to be 572µV/g/5V along with a cross-axis sensitivities along X and Y axes of 0.24% and 0.46% of prime axis sensitivity. By this approach a 63% reduction in cross-axis sensitivity along Y-axis is achieved with no much variation in the prime-axis and cross-axis sensitivity along X-axis. A nonlinearity of around 0.5% FS or lesser was observed for this structure. Through this approach a cross-axis sensitivity of 0.62% FS of the prime-axis sensitivity, which is comparatively lesser than already reported devices is achieved without using any additional manufacturing coast.

6. CONCLUSION

Some of the major design constraints of the accelerometer structure including the doping, stress, effect of temperature and sensitivity were analyzed based on the various accelerometer designs proposed by various authors. Based on this analysis it is found that these parameters play a major role in the performance optimization of the accelerometer.

Table 1: Variation of sensitivity as a Function of doping Concentration

Accelerometer	sensitivity (mV/Vg)	Doping Concentration (atoms cm$^{-3)}$
3-DOF Micro Accelerometer	≈0.2	1×10^{17}
Six degree of freedom Piezoresistive	1.774	5×10^{19}
High performance silicon piezoresistive Z-axis	.111	5×10^{18}

Table 2: Temperature coefficient of resistance as a function of doping concentration

Doping concentration(cm^{-3})	TCR(/^{0}C)
1×10^{19}	0.000771
7.6×10^{19}	0.000890
1.2×10^{20}	0.001543
1.3×10^{20}	0.001757

Table 3: Prime Axis and Cross axis sensitivities of different accelerometer structures

Accelerometer	Prime axis sensitivity (mV/Vg)	Cross axis sensitivity (%)
Skew-symmetric cantilever beam	0.065	2.3
Novel vertical beam structure	0.11	2
Quad beam with Proof mass edge aligned flexures	0.111	0.62

The stress profile of the accelerometer structure is important as it is important to position the piezoresistor in maximum stressed regions of the structure for a better performance. A better performance is observed for the accelerometer structure when fabricated over a thick layer of an SOI wafer as proposed by E Jesper Eklund[4]. Also it is found that temperature influences the mobility and carrier concentration in the respective bands of a piezoresistor which affects the piezoresistive coefficient of the diffused resistor. Table 1 gives the sensitivity and doping concentration of various accelerometer structures. Also the leakage currents in piezoresistor limit the operation of the accelerometer sensors to about 150 ◦C. By using a buried oxide layer to electrically isolate the device the sensors can be made operational to a temperature of up to 400◦C. The table 2 shows the variation of the temperature coefficient of resistance as a function of doping concentration. In the case of doping profile of piezoresistor an optimum value has to be selected such that the required sensitivity is achieved while compromising the noise in the piezoresistor. Also from table 3 it can be observed that a large variation of sensitivity can be achieved by the structural modifications.

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