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Effect of Electroplated Gold Film on the Performance of a Piezoresistive Accelerometer with Stress Concentrated Tiny Beams

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Abstract

Background/Objective: In the recent times, piezoresistive accelerometers have been extensively explored with the primary focus on the optimization of its sensitivity and measurement bandwidth. In this paper, the design of an in-plane deflection mode accelerometer sensor has been devised with selective deposition of gold metal on the top and both the sides of the proof mass. **Methods/Statistical Analysis:** The micromachined silicon accelerometer constitutes of stress concentrated tiny piezoresistor beams and a central cantilever beam to support the proof mass. In order to improve the electromechanical response of the sensor, selective deposition of the gold metal layer was performed on the top and both the sides of the proof mass. The design and modeling of the sensor has been performed utilizing a Finite Element Model (FEM) software simulation tool IntelliSuite®. **Findings:** Compared to the conventional designs reported in the literature, accelerometer sensors with stress concentrated tiny beams and gold layer selectively deposited on the proof mass have shown an improvement in the electrical sensitivity and the FOM (product of the sensitivity and square of the resonant frequency). Simulation results demonstrate that the accelerometer structure with gold layer atop of the proof mass has a better sensitivity and FOM than the conventional design without gold by 28.26% and 27.43% respectively. Similarly, the accelerometer structure with gold on both sides of the proof mass has shown an improvement in the sensitivity by 57.82% and the Figure Of Merit (FOM) by 29.70% compared to the structure without gold layer. **Conclusion/Improvements:** It has been demonstrated that the performance metrics of piezoresistive accelerometer sensors with stress concentrated tiny beams can further be improved by selective deposition of metal gold layer on the proof mass of the accelerometer structure.

Keywords: Accelerometer Sensor, Electroplated Gold, In-plane Deflection, Piezoresistive Read Out, Resonant Frequency, Sensitivity

1. Introduction

Over the years, MicroElectroMechanical Systems (MEMS) based accelerometers have found numerous applications in the field of robotics, aerospace, auto-mobile, defense to cite a few[1,2]. Treatise encompasses various sensing schemes which are utilized to convert the net mechanical deformation of the accelerometer structure into an equivalent electrical signal. Typical readout methods include piezoresistive[3], capacitive[4], tunneling[5], piezoelectric[6], vibrating/resonant mode[7,8], etc. Even though, various readout mechanisms have been devised, piezoresistive readout has the inherent advantages like simple interface circuitry, better linearity, high sensitivity and cost effectiveness compared to other sensing schemes. However, one serious limitation of a cantilever-mass accelerometer is its narrow bandwidth which arises mainly due to its lower resonant frequency[9-11].

This limitation was overcome with a double clamped beam-mass accelerometer to improve the resonant frequency[11], however, at the cost of its sensitivity. In both the aforementioned examples, the product of sensitivity and

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resonant frequency remains constant even though there was an improvement in the magnitude of constituent individual quantities. Therefore, the lower value of the product of the sensitivity and the resonant frequency makes the applicability of the piezoresistive accelerometers inefficient, especially for the high performance applications. A possible solution to overcome this problem is to improve both the sensitivity and resonant frequency simultaneously. To accomplish a higher magnitude of product of the sensitivity and resonant frequency, an accelerometer structure with two tiny beams and a central supporting beam was proposed[12]. Further improvement in the performance was obtained by modifying the distance between the central supporting cantilever beam and the tiny beams, which resulted in pure axial-deformation[20].

In this paper, we present the design and modeling of an stress concentrated tiny beam piezoresistive accelerometer. An improvement in the figure of merit defined as product of the prime axis sensitivity and square of the resonant frequency, FOM = $s.f_o^2$ is achieved by selectively electroplating the gold metal on the proof mass of the accelerometer structure. This work is based on the improvement in the performance of a piezoresistive accelerometer obtained with gold (Au) atop reported elsewhere[13-16]. Au[17, 18] is preferred to any other metal like Cu[19] due to its inertness i.e. it is nobler than Cu and it is compatible with IC fabrication process flow. An in-depth analysis of the parameters has been performed by selectively depositing the gold layer on top and both faces of the proof mass structure. The numerical simulations were carried out using the Computer Aided Design (CAD) software tool IntelliSuite®. From the simulation results it has been demonstrated that the piezoresistive accelerometer structure with gold gives better performance metric than conventional designs of stress concentrated tiny beam piezoresistive accelerometer reported in the literature.

2. Device Details

The deformation or movement of the mechanical structure of an accelerometer can either be in the in-plane or out-of-plane direction. In accelerometers, the relative thickness of the proof mass and the central supporting beam determines whether the deflection is in the in-plane or out-of-plane direction. In accelerometers with equal thickness of the proof mass and the central beam, an in-plane motion is seen whereas, when the thickness of the central beam is less than the proof mass, it is likely to deform in the out-of plane direction. Generally, the in-plane structures have a higher magnitude of the resonant frequency and sensitivity compared to out-of-plane structures.

Figure 1 shows the schematic diagram of a piezoresistive accelerometer structure considered for present analysis[20]. The accelerometer (structure-1) consists of a central supporting beam, proof mass and two tiny piezoresistive beams. To utilize the axial stress, the two tiny piezoresistive beams are placed on either side of the central supporting beam. The axial deformation of the tiny beams results in a higher magnitude of the resonant frequency and sensitivity of the accelerometer[7].

The dimensions of the accelerometer structure were derived from the structures reported in the literature[20]. The device dimensions are given as follows: (a) proof mass: 2600μm (E) x 2600μm (D) x 528μm (T), (b) beams: 1840μm (H) x 400μm (F) x 528μm (T), (c) central supporting beam: 200μm (S) x 60μm (W) x 528μm (T),(d) tiny piezoresistive beams: 50μm (l) x 3μm (b) x2μm (h). The proof mass thickness was chosen to be T = 528μm, since, it is the maximum thickness of a 4 inch Silicon On Insulator (SOI) wafers.

When acceleration is applied along the Y-direction, the tiny beams experience a uniform stress. More importantly due to the careful positing of the tiny beams, the two piezoresistive tiny beams experience atleast 50% higher stress compared to that of the central beam of the structure. To analyze the impact of the selective deposition of gold on the proof mass, firstly, an electroplated gold film of 20μm thickness is deposited on top surface of the proof mass (structure-2). To further analyze the effect of the selective deposition of the gold layer on the performance, gold layer is deposited on both the top and bottom faces (structure-3) of the proof mass. The cross-sectional view (along two cut planes) of the accelerometer

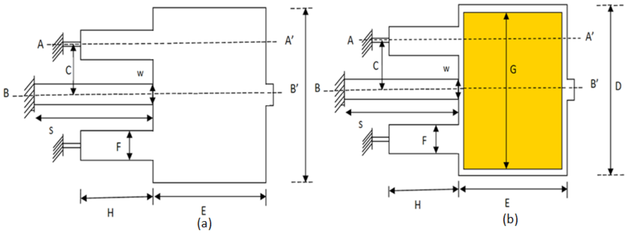

Figure 1. Top view of an accelerometer with tiny beams, **(a)** without the gold layer and **(b)** with the gold layer on the proof mass.

structure without and with gold (on top and both sides) layers are shown in Figure 2.

The dynamic range of the designed accelerometer rages from 0.25g to 25,000g. The dynamic range of the sensor can be varied by careful design of the length and width of the central supporting cantilever beam.

3. Results and Discussion

The modeling and numerical simulation of the piezoresistive accelerometer structures were performed utilizing the various modules of a Finite Element Model (FEM) CAD simulation software tool IntelliSuite®. The virtual fabrication of the sensor with appropriate process parameters were performed in the IntelliFAB® module. An optimal mesh was selected to optimize the sensitivity of the sensor and computation time of the simulations. Silicon On Insulator (SOI) wafer (100) was used as the substrate to virtually fabricate the proof mass, beams and central supporting beam. Boron was ion- implanted throughout the thickness (2μm) in silicon to form the tiny piezoresistive beams aligned along the <110> direction. The schematic of the virtually fabricated piezoresistive accelerometer without the selective deposition of electroplated gold is shown in Figure 3.

Figure 4 shows the schematic of the sensor with electroplated gold deposited on both faces of the proof mass. The static and dynamic analysis for evaluating the deformation of the structure, the electrical sensitivity and resonant frequency were performed in the Thermo-electro-mechanical (TEM®) module. The electrical, mechanical and thermal parameters used in the simulation were: an applied input voltage, V = 5V, surface doping concentration = 5E18 (cm^{-3}), piezoresistive coefficient, $\Pi_{44} = 1.38 \times 10^{-9}$ Pa^{-1} at a temperature of 25°C.

Table 1 summarizes the performance of the three structures. It can be observed that, with the selective

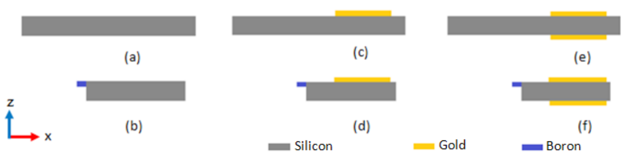

Figure 2. Cross-sectional view of different accelerometer structures under investigation: structure-1, **(a)** along AA' **(b)** along BB', structure-2 **(c)** along AA' **(d)** along BB', structure-3 **(e)** along AA', and **(f)** along BB'.

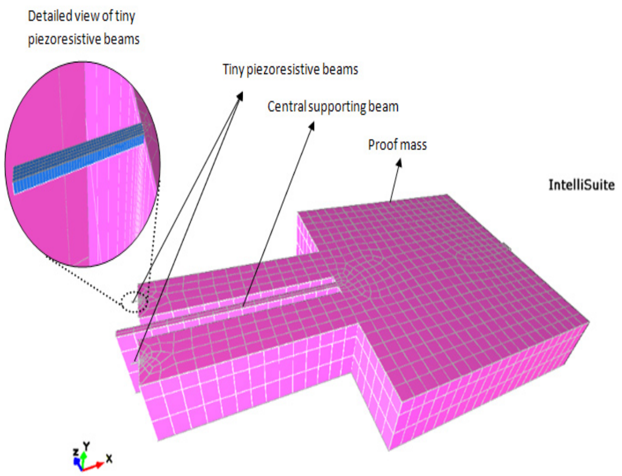

Figure 3. Schematic of virtually fabricated accelerometer (Structure-1) in IntelliSuite® software.

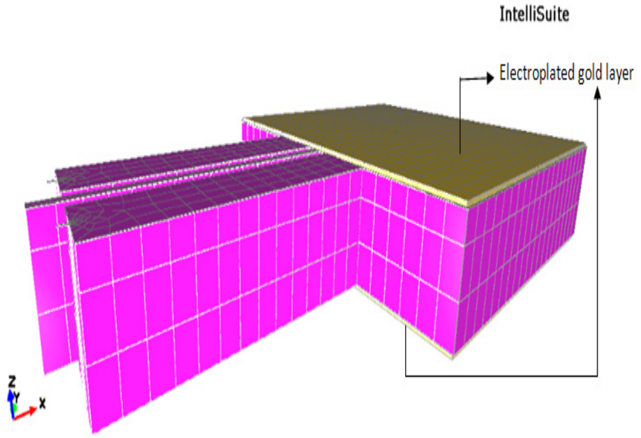

Figure 4. Schematic of the accelerometer (structure-3) with electroplated gold deposited on both faces of the proof mass.

Table 1. Effect of gold on the sensitivity of tiny beam piezoresistive accelerometer

Acceleration	Sensitivity (ΔR/R) (E-3)		
	Structure-1	Structure-2	Structure-3
0g	–	–	–
0.5g	11.5	14.8	18.1
1g	23	29.5	36.3
1.5g	34.5	44.2	54.3
2g	46	58.9	72.2

deposition of the gold layer on the proof mass, there is an improvement in the sensitivity. For instance, at an input of 1g, the structure-2 with gold atop of the proof mass shows an improvement in the sensitivity by 28.26% compared to structure-1. Similarly, with deposited gold on both faces of the proof mass the sensitivity further improves by 57.82% compared to the structure without gold. The improvement in the sensitivity can be attributed to the increase in the mass of the proof mass due to the electroplated gold. The increase in the mass results in a higher structural deformation for a given acceleration which results in an increase in the stress experienced by the piezoresistor, which in turn is translated into a higher sensitivity.

Figure 5 depicts graphically the performance of the three accelerometer structures under investigation. It is evident that the sensitivity of the sensor increases when gold is deposited on the proof mass. There exists a linear relationship between sensitivity and acceleration for a range of 0 to 2.5g.

Table 2 summarizes the performance factors for a piezoresistive tiny beam accelerometer with and without gold. It is evident that with selective deposition of the gold layer on the proof mass of the accelerometer, there is a significant increase in the sensitivity of the sensor. For instance, the sensitivity of structure-2 and structure-3 increases by 28.26% and 57.82% respectively compared to the structure without gold. This increase in the electrical sensitivity can be attributed to the increase in the stress experienced by the piezoresistors which is mainly due to the increase in the mass of the structure as explained previously. However, the increase in the mass reduces the resonant frequency of the structure. More importantly, even though, the FOM depends on the square of the resonant frequency of the structure, there is still an improvement in the FOM of structure-2 and structure-3. Figure 6 represents graphically the improvement in the FOM of the structure-2 and structure-3 with gold. It can be observed that the FOM improves by 27.43% and 29.70% respectively for structure-2 and structure-3 compared to the structure without gold.

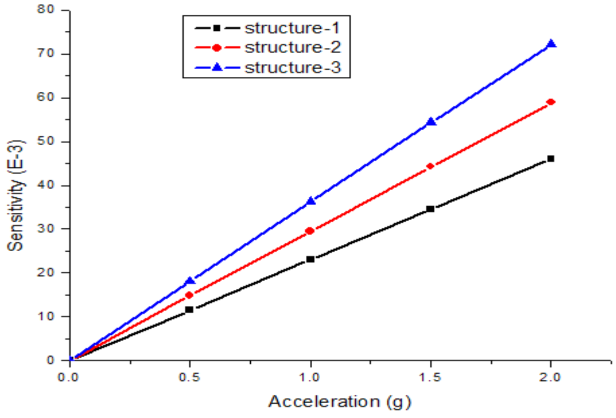

Figure 5. Variation in the sensitivity for the three structures over a range of acceleration from 0 - 2.0g.

4. Conclusion

This paper presents a micromachined silicon accelerometer with a couple of tiny piezoresistive beams and a central beam coated selectively with electroplated gold. A systematic analysis has been carried out to optimize the sensitivity and the FOM ($s.f_o^2$). Compared

Table 2. Effect of gold on the performance factors of the tiny beam piezoresistive accelerometer

Configuration	Sensitivity(E-3)	Frequency (kHz)	Figure of merit (FOM=$s.f_0^2$) (kHz^2)
Structure-1	23	1.112	29.084
Structure-2	29.5	1.005	29.882
Structure-3	36.3	0.908	29.948

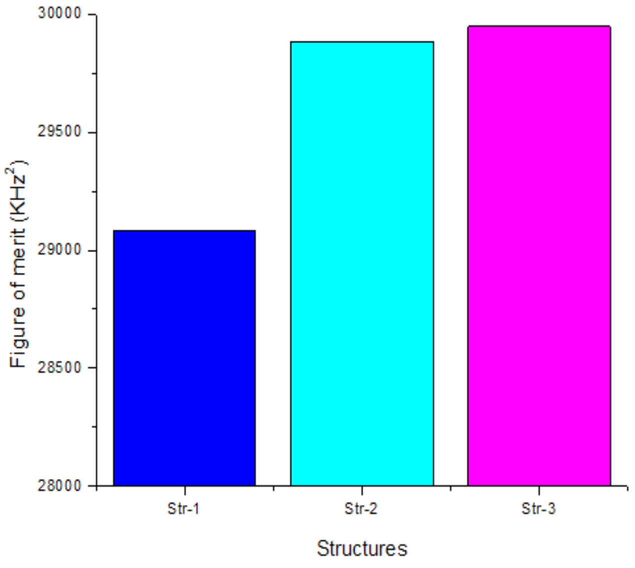

Figure 6. Comparison of figure of merits of various structures.

to the conventional design without the gold layer, accelerometer structure with gold layer on top and both sides of the proof mass demonstrated an improvement in the sensitivity by 28.26% and 57.82% respectively. Furthermore, the structures with gold on top and both sides of the proof mass showed an improvement in the FOM by 27.43% and 29.70% respectively. Therefore, an appreciable increase in the performance of the accelerometer is achieved by selective deposition of the gold on the proof mass. To conclude, we have presented a method to improve the sensitivity and FOM of a micromachined silicon accelerometer with tiny piezoresistive beams.

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