Constrained optimum design of 3-DOF micro accelerometers

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ABSTRACT

This paper presents a technique to optimize with constraints, the performance of three-degree of freedom silicon accelerometers. A flexure configuration has been proposed in order to meet requirements of small cross-axial acceleration, high and linear sensitivity. The overall chip dimension is 1.5×1.5×0.5 mm^3 (L×W×T) and the beam size is 950×80×10 μm^3 (L×W×T). The purpose of this constrained optimization process is to achieve the highest sensitivity or resolution while imposing conditions on other parameters. It has been done based on considerations of the junction depth, the doping concentration of the piezoresistor, the temperature, the Signal to Noise Ratio, and the power consumption. Such an optimized accelerometer offers a much better performance compared to others.

Keywords:

Optimization, Piezoresistor, Accelerometer, Constrained, 3-DOF.

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1. INTRODUCTION

Accelerometers are in great demand for many applications ranging from guidance and stabilization of spacecrafts to research on vibrations of Parkinson patients' fingers. Generally, it is desirable that accelerometers have high sensitivity and fine resolution. Among several technological alternatives, silicon piezoresistive accelerometers are noteworthy since it is compatible with microelectronic batch fabrication technology [1], and therefore, the die size and the cost are reduced. There is an extensive research on silicon piezoresistive accelerometer to improve its performance and further miniaturization. However, up to now, there is no available analysis on the impact of physical parameters, such as the size, doping concentration and the temperature coefficient sensitivity of piezoresistor, noise, and power consumption on the sensitivity and resolution.

As we know, the realistic applications create a huge motivation for the widely research of MEMS based sensors, especially accelerometer. In this modern world, applications require new sensors with smaller size and higher performance. Along the line of this requirement, this paper presents an efficient and comprehensive methodology for accelerometer designs.

2. LITERATURE SURVEY

T. Mineta et al. [2] presents the design, fabrication, and calibration of a 3-DOF capacitive acceleration sensor which has uniform sensitivities to three axes. However, this sensor is more complex than the piezoresistive one and is not economical to fabricate with current MEMS technology.

In 1996, Shin-ogi et al. [3] presented an acceleration sensor fabricated on a piezoresistive element with a full Wheatstone bridge circuit and its amplifier running parallel under sensing elements. The accelerometer utilizes lateral detection to obtain good sensitivity and small size. The built-in amplifier has been formed with a narrow width, and showed its stable working.

In 1998, Kruglick E.J.J et al [4] presented the design, fabrication, and testing of multi-axis CMOS piezoresistive accelerometers. The operation principle is based on the piezoresistive behavior of the gate polysilicon in standard CMOS. Built-in amplifiers were designed and built on chip and have been characterized.

In 2006, Dzung Viet Dao et al [5] presented the development of a dual axis convective accelerometer. The working principle of this sensor is based on the convective heat transfer and thermo-resistive effect of lightly-doped silicon. This accelerometer utilizes novel structures for the sensing element which can reduce thermal-induced stress by 93%. Instead of the seismic mass, the operation of the accelerometer is based on the movement of a hot fluid air from a heater in a hermetic chamber. Thus, it can overcome the disadvantages of the ordinary "mechanical" accelerometers such as low shock resistance and complex fabrication process.

In 2011, Li Sui et al [6] proposed design, manufacturing and testing method of the accelerometer array in order to reduce the influence of cross sensitivity. In this way, each independent chip has 2×2 accelerometers, and every two accelerometers have the same structure sizes. So, the accelerometer array has two different measurement ranges.

In 2013, M. Messina et al. [7] presented design of a novel single square millimeter 3-axial accelerometer for head injury detection of racing car drivers. By exploiting the electro-mechanical features of nanowires as nanoscale piezoresistors, the nominal sensor sensitivity is overall boosted. However, authors did not concern to any optimization process to even improve this sensor's performance.

In this paper, we examine the optimum structure of piezoresistive accelerometers. We proposed a configuration for the flexure-beam structure in order to meet requirements of high resolution, as well as high and linear sensitivity. The structure proposed is quite simple but it is very useful to illustrate our optimization process. Consequently, we can apply to every complicated accelerometer structures.

In general, we try to maximize the sensitivity and the resolution while minimizing the influence of noise. Unfortunately, these optimum characteristics are in opposition with each other. This means we have to deal with a multi-objective optimization problem, also called Pareto optimization [8], whose complexity is high when considering the three acceleration components concurrently. The purpose of this optimization process is to achieve high sensitivity or resolution while imposing conditions on other parameters [9]. It is performed with consideration given to the junction depth, the doping concentration of the piezoresistor, temperature, noise, and the power consumption. To the best of our knowledge, no application of such a systematic optimization procedure to a 3-DOF accelerometer has been reported in the open literature. Results obtained by our approach show that the sensitivity of the optimized accelerometer is improved while the resolution is higher than that of previously reported fabricated devices.

3. WORKING PRINCIPLE

High sensitivity and small cross-axis sensitivity are important requirements for the 3-DOF accelerometer. We proposed a configuration as shown in Fig. 1 to meet these critical characteristics. It consists of a proof mass connected to four surrounding beams, which are fixed to the outer frame at the centers.

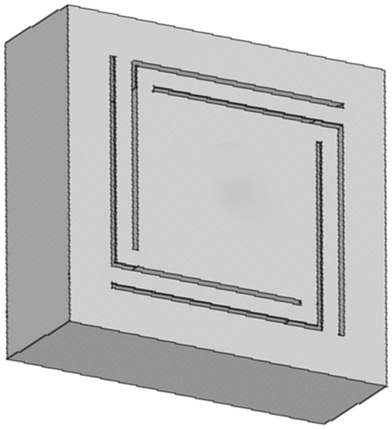


Figure 1: 3D model of the 3-DOF piezoresistive accelerometer

An external acceleration results in a force exerted on the mass which results in a deflection of the proof mass. When a vertical acceleration (AZ) applied to the sensor, the mass moves up or down vertically. Similarly, when the X or Y component of transversal acceleration is acting on the sensor, the mass moves laterally. The deflection of the proof mass causes stresses in the four beams, resulting in resistance variation of the piezoresistors on the surface of the beam structure [10]. This variation is then converted into electrical signals by using three imbalance Wheatstone bridge circuits which are built by interconnecting twelve p-type piezoresistors. These piezoresistors are chosen to diffuse on the surface of these four beams because they can provide the maximal resistance variations and are aligned with the crystal directions <110> and <11*0> of n-type silicon (100). The piezoresistance effect is known to be caused by the anisotropic characteristics of the energy resolution in crystal space. In the silicon material, there are only three independent piezoresistive coefficients π_{11}, π_{12}, and π_{44}. The longitudinal piezoresistance coefficient π_l is defined in the case the stress parallels with the direction of the electric filed and current flow. Similarly, the transverse piezoresistance coefficient π_t is defined in the case the stress is perpendicular to the direction of the electric filed and current flow. In directions <110> and <11*0> of n-type silicon (100), we can express these two coefficients using three independent coefficients π_{11}, π_{12}, and π_{44} in the following equation:

$$\pi_l = \frac{1}{2}(\pi_{11} + \pi_{12} + \pi_{44})$$
$$\pi_t = \frac{1}{2}(\pi_{11} + \pi_{12} - \pi_{44}) \tag{1}$$

From simulation results in Fig. 3, we found that two normal s σ_2 and σ_3 are rather smaller compared to σ_1. To eliminate the cross-talk effect, we should avoid placing piezoresistors near the fixed end and the start of the beam. Thus, we can calculate the relative change of resistance due to the normal stress by the following equation:

$$\frac{\Delta R}{R} = \pi_l \sigma_l + \pi_t \sigma_t \tag{2}$$

4. DESIGN AND ANALYSIS USING APPROACH

A simple and efficient technique of designing accelerator sensors was proposed by us in [11]. It consists of sequentially combining the use of the 2 available softwares SUGAR and ANSYS; SUGAR is based on the modified nodal analysis technique (MNA) while ANSYS is based on the finite element method (FEM). Given the required ranges and the beam dimensions, SUGAR quickly estimates the dimension of the sensor. Subsequently, ANSYS computes the stress distribution in the flexure beam. In order to maximize the sensitivities of the three acceleration components, it is necessary to eliminate their cross-axis sensitivities. This is done by placing piezoresistors at appropriate positions accordingly to the obtained stress distribution. The designed sensing chip is finally analyzed by ANSYS.

The mesh used for the analysis is shown in Fig. 2. The corresponding results for longitudinal and transverse stress distributions caused by the acceleration AZ on the first beam are shown in Fig. 3. We clearly observe that the stress along the beam is much more important than in the transverse direction.

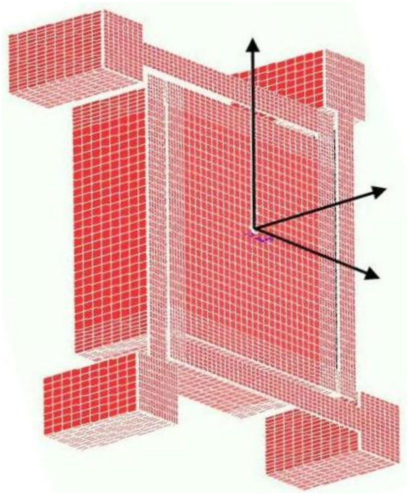


Figure 2: The dense mesh generation of the FEM model.

As mentioned above, the optimal positions where to place piezoresistors are determined by the obtained stress distribution. The Table 1 describes the sensor behavior. To sense the tree acceleration components, we proposed in [11] a structure composed by three Wheatstone bridges which are formed by interconnecting the beams over which twelve identical p-type piezoresistors are shallowly diffused.

Table 1: Resistance values changes with three components of acceleration

	Rx1	Rx2	Rx3	Rx4	Ry1	Ry2	Ry3	Ry4	Rz1	Rz2	Rz3	Rz4
AX	↓	↓	↓	↓	↓	↓	↓	↓	↑	↓	↑	↓
AY	0	↑	↑	0	↓	↑	↓	↑	↓	0	↑	0
AZ	↓	↑	↓	↑	0	↑	↑	0	↓	↓	↑	↑

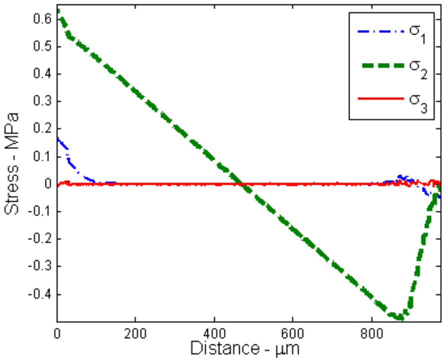


Figure 3: Stress distribution of a beam caused by vertical acceleration AZ.

5. OPTIMIZATION OF RESOLUTION AND SENSITIVITY OF THE 3-DOF ACCELEROMETER

Figure 4 shows the flowchart of the sensitivity/resolution optimization process. This process is implemented via a MATLAB program. The structure of this 3-DOF accelerometer is fixed with specific dimensions and two parameters, that is, resistor length and impurity concentration were used as independent variables. An important constraint imposed in the optimization process is the power consumption. Indeed, in various types of applications which require wireless sensors, such as structure health monitoring or patient monitoring, low power consumption is a crucial requirement [12].

At specific power consumption of a full bridge Wheatstone circuit, we have got series of input voltages, noises, sensitivities, and resolutions varied by a set of constraint parameters listed in Table 2. Note that the cross-sectional area of the piezoresistor is fixed to 2µm×1.5µm (W×T) and structure parameters of the accelerometer were mentioned in Table 2.

Table 2: Parameters constraints for optimization process

Parameters	Values	
	Min	Max
Length of piezoresistor *L*	6 µm	30 µm
Diffused concentration *N*	1.26×10^{17} atoms cm^{-3}	3×10^{20} atoms cm^{-3}
Input voltage V_{in}	1 V	6 V

It seeks to provide the best compromise among objectives. Different optimal designs are found for which one objective can not be improved without degradation in one of the other objectives [13]. In the hyperspace of the Pareto front, there is no point that provides an improvement compared to any other with respect to both the sensitivity and the minimum detectable acceleration (resolution). Thus, we have got two approaches: maximizing the sensitivity and minimizing the noise (i.e. best resolution).

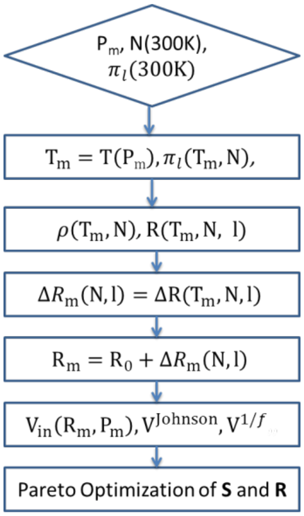


Figure 4: The flowchart of the sensitivity/resolution optimization process

The mechanical sensitivities of each components of acceleration can be respectively expressed as:

$$S_{stress}^{i} = \frac{\sigma_l^i}{a_i} \tag{3}$$

where S^i_{stress} is the mechanical sensitivity and σ^i_l is longitudinal stress induced by the i^{th} acceleration component a_i. The electrical sensitivity can be given by:

$$S_i = \frac{V_{out}}{a_i} = \frac{\Delta R}{R} V_{in} = \pi_l S_{stress}^{i} V_{in} \tag{4}$$

where S_i and V_{out} are the sensitivity to the i^{th} acceleration component and the output voltage, respectively.
Eq. (4) can be rewritten:

$$S_i \approx \frac{1}{a_i} \pi_l^i \sigma_l^i V_{in}^i \qquad i = X, Y, Z \tag{5}$$

We can see the role of the sensitivity when we apply an acceleration to the sensor that results in stress redistribution, leading to the variation of the piezoresistors, giving rise to an output voltage that depends on the input acceleration as shown in Fig. 5 [6]. Such cross-sensitivity will negatively affect the sensitivity of the sensor.

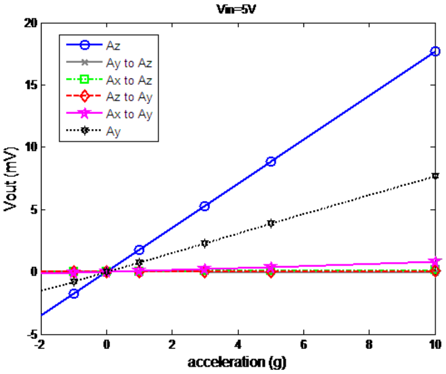


Figure 5: The sensing and crosstalk voltages obtained by the ANSYS program

Eq. (5) shows that the sensitivity depends not only on the structure and the positions of the piezoresistors, but also on the length, the cross-sectional area, and doping concentration of the piezoresistor. In general, temperature affects the piezoresistive coefficient through a change in the mobility and carrier concentration (N) in the respective bands [14, 15]. The dependence of the piezoresistive coefficient on the impurity concentration at a given temperature (T) can be obtained by multiplying the piezoresistive factor P(N,T) by the PR coefficient at room temperature (T_0) as follows:

$$\pi(T)=\pi(T_0)P(N,T) \tag{6}$$

where the piezoresistive factor is:

$$P(N,T)=\frac{300}{T}\frac{F'_{s+0.5}\left(E_F/KT\right)}{F_{s+0.5}\left(E_F/KT\right)} \tag{7}$$

where K is the Boltzmann constant, T is temperature, and $F_{s+0.5}$ is the Fermi integral [15].The temperature strongly determines the value of π(N,T). The higher it is, the smaller is the effect. Also larger concentration decreases the value of the piezoresistance coefficient. A MATLAB program was built to calculate the dependence of the PR coefficient impurity concentration at different temperatures (see Fig.6). Experimental measurements of piezoresistive coefficients can also be found in [16]. To extend the range of the problem, the piezoresistance effect nonlinearity in p-Si was mentioned in [15, 17].

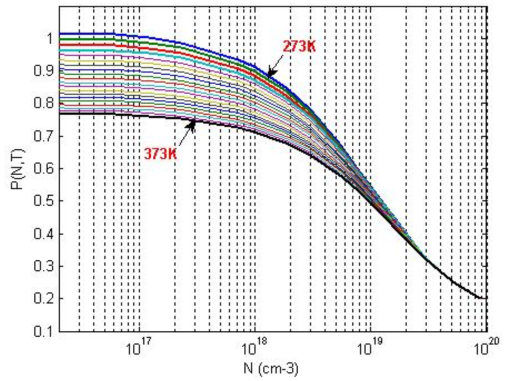


Figure 6: Piezoresistance factor P(N, T) as a function of impurity concentration and temperature for p-Si

In fact, the doping concentration N should be calculated as average concentration due to its variation with diffusion length (i.e. the thickness of the piezoresistor). Figure 7 shows the Gaussian distribution of the doping profile which is in agreement with experimental results [18].

The temperature of piezoresistors is decided by power consumption [19]. The steady state temperature rise of the self-heating piezoresistor (T_{ss}) is as follows:

$$T_{ss}=\frac{P}{4\pi dk}\left[1+\frac{2k}{hR}\right]\approx\frac{P}{2\pi dhR} \tag{8}$$

where P is the power consumption of each piezoresistor, d represents the thickness of the beam, h represents the heat transfer coefficient, and R represents the width of the beam, respectively.

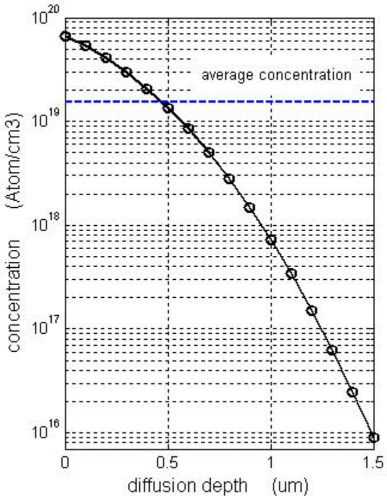


Figure 7: Gaussian distribution of doping profile

At a specific power consumption, the mathematical representation of the optimization problem is the maximization of three objective functions $S_i(x)$ denoted as:

$$S_i^{\max}(x)=\underset{x=L,N,T,Vin}{Max}S_i(x) \qquad i=X,Y,Z \tag{9}$$

or

$$S_i^{\max}(x)=\frac{1}{a}\underset{x=L,N,T,Vin}{Max}\pi_l^i\sigma_l^iV_{in}^i \qquad i=X,Y,Z \tag{10}$$

The sensitivity varies significantly with the beam length. The piezoresistive effect on each piezoresistor is determined through the average value of stress. However, changing the length of the piezoresistor from 6 μm to 30 μm does not affect this average stress value. The value of σ_i^1 can be fixed when the geometric structure is specific [11]. Thus, (10) can be rewritten as:

$$S_i^{\max}(x)=\frac{1}{a}\sigma_l^i\underset{x=L,N,T,Vin}{Max}\pi_l^iV_{in}^i \qquad i=X,Y,Z \tag{11}$$

It is also observed that the sensitivity decreases monotonically with the impurity concentration. With constant power, high input voltage, in conjunction with high resistance values for the piezoresistors, is needed to increase the sensitivity. Thus, the solution to maximize three sensitivities (S_x, S_y, S_z) concurrently can converge to a unique set of results (see Fig. 8).

For the AZ acceleration component at a specific power consumption of 7.7 mW, we found that the optimum length of piezoresistors and doping concentration are of 30μm and 1.26 × 10^{17} atoms cm^{-3}, respectively. Concentrations below 10^{17} atoms cm^{-3} are not practical due to instable Ohmic contact. The optimal sensitivity we can achieve is 1.91 mV/g (i.e. 0.37 mV/V/g). At that optimal point, the resolution is 0.53mg, the resistance of the piezoresistor is 3.5kΩ, the input voltage is 5.1V, and the temperature is 305K.

For the AX or AY acceleration component, we also found that the optimum length of piezoresistors and doping concentration are of 30 μm and 1.26 × 10^{17} atoms cm^{-3}, respectively. The optimal sensitivity we can achieve is 0.89 mV/g (i.e. 0.17 mV/V/g). At this point, the resolution is 1.27 mg, the resistance of piezoresistor is 3.5 kΩ, the input voltage is 5.1 V, and the temperature is 305 K.

Figure 9 shows the variation of sensitivities of the acceleration components with length of piezoresistor for different power consumptions. Obviously, at a higher power, sensitivity can be increased in spite of higher noise.

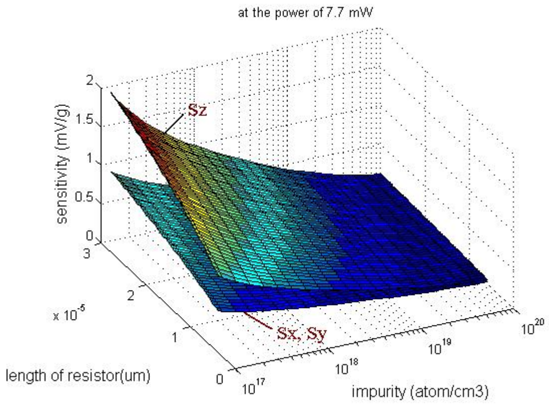


Figure 8: Variation of sensitivity with respect to different piezoresistor lengths and doping concentrations at power of 2.6mW

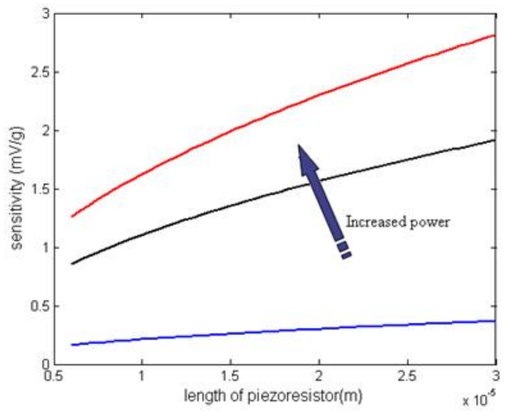


Figure 9: Variation of sensitivity for different power consumptions

Resolution is defined as the noise divided by the sensitivity, i.e. [7]

$$R_i=\frac{V_i^{noise}}{S_i}\qquad i=X,Y,Z \tag{12}$$

or

$$R_i=\frac{2\sqrt{\left(V_i^{Johnson,rms}\right)^2+\left(V_i^{1/f}\right)^2}}{\frac{1}{a}\pi_l^i\sigma_l^iV_{in}^i}\qquad i=X,Y,Z \tag{13}$$

There are two typical noise sources affecting all piezoresistive sensors, including the Johnson noise $V_i^{Johnson,rms}$ and flicker noise $V_i^{1/f}$ [20]. The noises depend on the bandwidth of the sensor, the temperature, the geometry of the piezoresistor, the doping concentration and also the thickness of the beam.

The mathematical representation of the optimization problem is the minimization of three objective functions $R_i(x)$ denoted as

$$R_i^{\min}(x)=\underset{x=L,N,T,Vin}{Min}R_i(x)\qquad i=X,Y,Z \tag{14}$$

or

$$R_i^{\min}(x)=\frac{2a}{\sigma_l^i}\underset{x=L,N,T,Vin}{Min}\frac{\sqrt{\left(V_i^{Johnson,rms}\right)^2+\left(V_i^{1/f}\right)^2}}{\pi_l^iV_{in}^i} \tag{15}$$

or

$$R_i^{\min}(x)=\frac{2a}{\sigma_l^i}\underset{x=L,N,T,Vin}{Min}\frac{\sqrt{4k_BTB_iR+\frac{\alpha V_{in}^2}{N}\ln\left(\frac{f_{\max}^i}{f_{\min}^i}\right)}}{\pi_l^iV_{in}^i} \tag{16}$$

where k_B= 1.38 × 10^{-23} J/K is Boltzmann's constant, T is the resistor temperature, R is the resistance value of the piezoresistor, and B is the measured bandwidth B_i= f_{imax}- f_{imin}. The bandwidth can be determined by many parameters such as the sampling frequency, analog filtering, the resonant frequency of the mechanical structure, or losses in the wires, etc [21].

From (12) we can see that if we choose a unique bandwidth for the three acceleration components (by using low-pass filters) we can get the same solution for three resolutions (R_x, R_y, R_z) concurrently [22]. The variation of the resolution with specific power consumption for different doping concentrations and different piezoresistor lengths is shown in Fig. 10.

The optimization of the sensitivity involves an impurity concentration different from that obtained with the optimal resolution. The reason is that the optimal resolution values are achieved by the compromise between sensitivity and noise that depends to many parameters such as bandwidth, power, doping concentration, etc. The optimal resolutions for all three acceleration components can be reached at a piezoresistor length of 30 µm. From these results above, a trade-off between high sensitivity and high resolution is necessary to determine the doping concentration within the range from 1.26×10^{17} atoms.cm^{-3} to 4.47×10^{18} atoms.cm^{-3}.

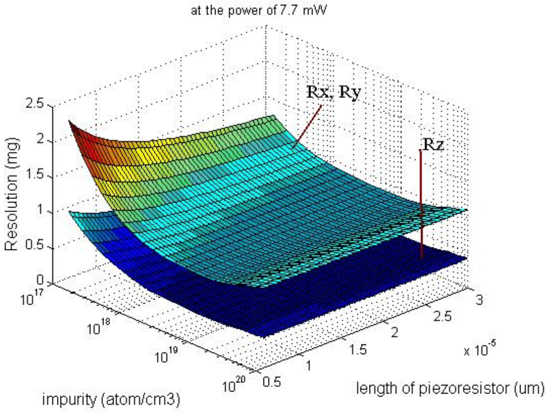


Figure 10: Variation of resolution with respect to different piezoresistor lengths and doping concentrations

For the AZ acceleration component at a specific power consumption of 7.7 mW, the optimal resolution we can achieve is 0.33 mg. At this point, impurity concentration is 4.47×10^{18} atoms cm^{-3},the sensitivity is 0.61 mV/g (i.e. 0.36 mV/V/g), the resistance of the piezoresistor is 370 Ω, the input voltage is 1.7 V, and the temperature is 305 K, respectively.

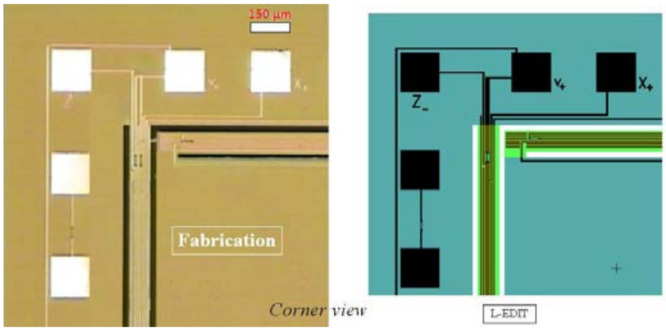
For the AX or AY acceleration component, the optimal resolution we can achieve is 0.86 mg at an impurity concentration of 4.47×10^{18} atoms cm^{-3}. At this point, the sensitivity is 0.28 mV/g (i.e. 0.17 mV/V/g), the resistance of the piezoresistor is 370 Ω, and the input voltage is 1.7 V, respectively.

This optimization procedure has been applied to design an accelerometer with all physical parameters given, except the concentration and the power which are two parameters we used to obtain the optimum performance for the designed accelerometer.

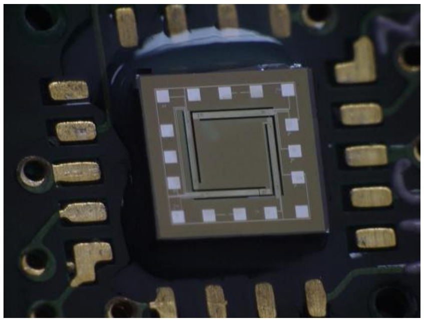
At Ritsumeikan Lab, accelerometers based on our proposed structure [11] were fabricated using the procedure described in [10]. The dimensions of the fabricated sensors are shown in table 3, suitable for many emerging applications. In the first experiment [23], the impurity concentration was controlled at about 5.10^{19} atoms cm^{-3}. The vertical sensitivity in this case is too low, and equal to 0.342mV/g with V_{in}=5.1 V; this value of V_{in} would give a power of 7.7 mW as mentioned above. With the desire of improving of the sensor's performance, in a subsequent experiment (see Fig. 11), the concentration was reduced in order to increase the sensor's sensitivity. It is important to note that concentration below 10^{17} atoms cm^{-3} is not practical due to the instable Ohmic contact [24].

Table 3: Sensor Parameters for fabrication process

	Proof mass	Beam	Outer frame width	Die size
Size (L×W×T)	845×845×400 μm^3	975×80×10 μm^3	200 µm	1.5×1.5×0.5 mm^3



(a)



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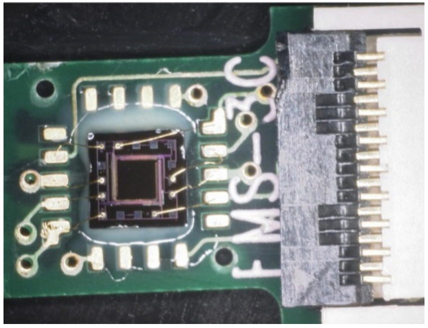

(c)

Figure 11: Micrographs of a fabricated chip: (a) A corner view of the layout and the fabricated sensor; (b) the sensor before bonding; (c) the sensor after bonding.

Fig. 12 shows the results of the AZ acceleration component for this second experiment along with the theoretical results of the optimum structure presented in this paper. Obviously, the new optimum design yields higher sensitivity at lower power.

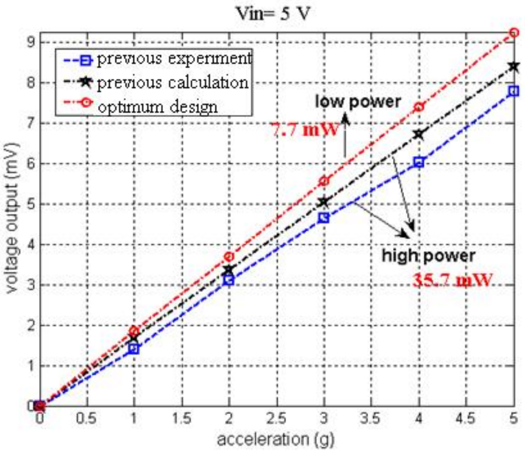

Figure 12: Comparisons among previous experiment, previous calculation [20], and new proposed design

Table 4 summarizes the optimal results on the sensitivity and resolution of the sensor. By applying our optimization procedure, we can both enhance the sensitivity or the resolution.

Table 4: Sensor Parameters for fabrication process

	Ax, Ay		Az	
	Previous calculation	Optimum design	Previous calculation	Optimum design
Sensitivity (mV/g)	0.76	0.89	1.68	1.91
Resolution (mg)	1.35	0.86	0.49	0.33

7. CONCLUSION

3-DOF micro-accelerometers using the structure that we have previously proposed [11] were successfully fabricated at the MEMS Laboratory of Ritsumeikan University. This success shows that our proposed structure is practical and can be easily optimized by varying the doping concentration, in designing high performance sensors.

This paper presents such an optimization procedure that uses two performance parameters: sensitivity and resolution. The complexity is triply reduced by utilizing the frequency constraint. Two Pareto optimization procedures, namely sensitivity maximization and resolution minimization, were implemented in MATLAB with adequate consideration given to junction depth, doping concentration of the piezoresistor, temperature, noise, and power consumption.

Based on our previous experience of fabrication, we can say that 3-DOF micro-accelerometers designed with the optimization technique presented in this paper can be implemented without difficulty. One important characteristic of this optimized sensor is the low power consumption. This characteristic shows that our proposed method is useful in practice and can be easily applied to designing high performance sensors.

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