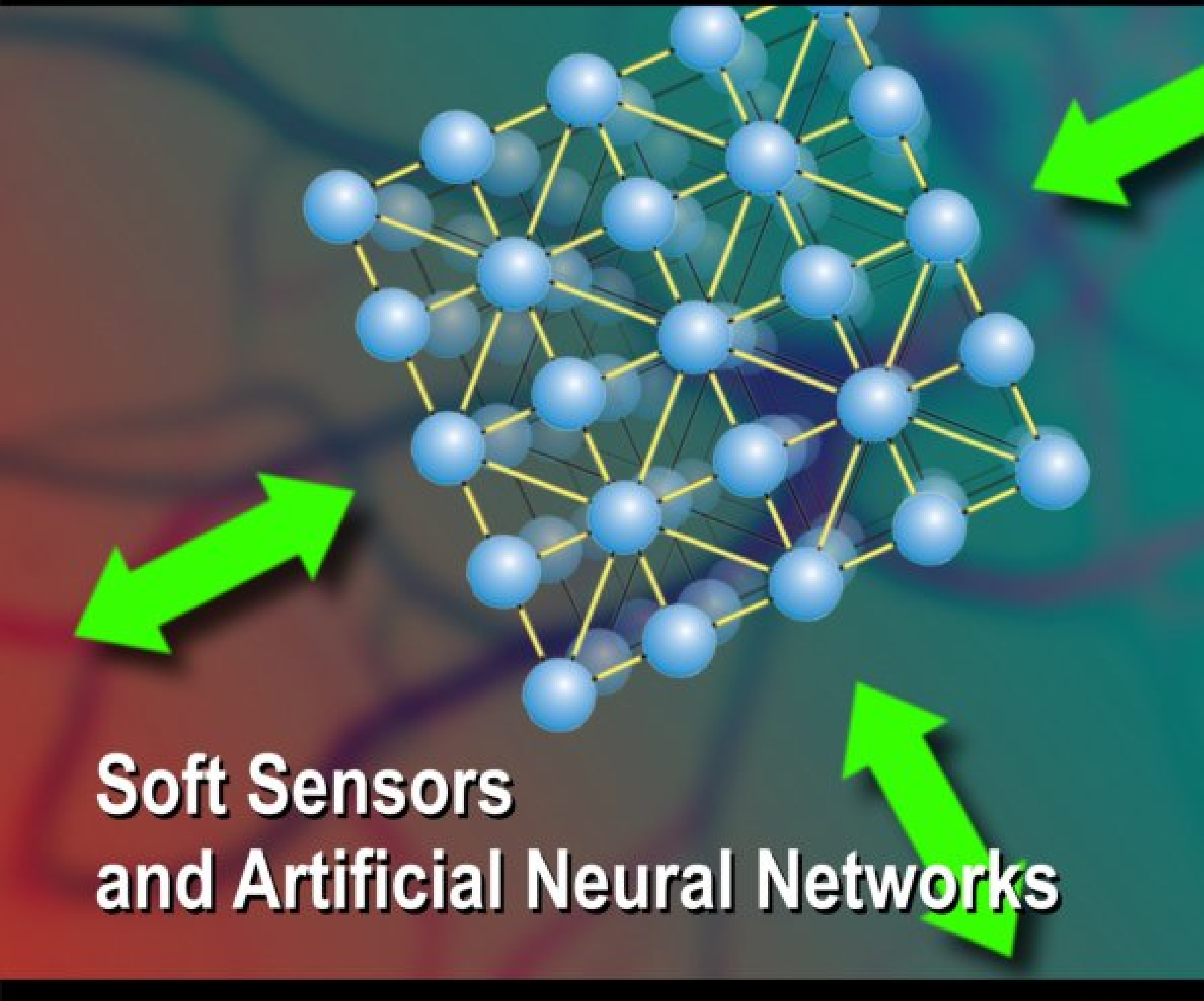
ISSN 1726-5479

SENSORS & TRANSDUCERS

10/12 vol. 145



Soft Sensors and Artificial Neural Networks

International Frequency Sensor Association Publishing

Sensors & Transducers

Volume 145, Issue 10
October 2012

www.sensorsportal.com

ISSN 1726-5479

Sensors & Transducers Journal (ISSN 1726-5479) is a peer review international journal published monthly online by International Frequency Sensor Association (IFSA).
Available in electronic and on CD.

Sensors & Transducers Journal

Contents

Volume 145
Issue 10
October 2012

www.sensorsportal.com

ISSN 1726-5479

Research Articles

Authors are encouraged to submit article in MS Word (doc) and Acrobat (pdf) formats by e-mail: editor@sensorsportal.com
Please visit journal’s webpage with preparation instructions: http://www.sensorsportal.com/HTML/DIGEST/Submition.htm

International Frequency Sensor Association (IFSA).

Sensors & Transducers Journal, Vol. 145, Issue 10, October 2012, pp. 86-95

Sensors & Transducers

ISSN 1726-5479

http://www.sensorsportal.com

A Piezoresistive Acceleration Sensor: from System to Physical Levels

Tran Duc TAN
University of Engineering and Technology (UET), VNUH,
E3 building,144 Xuan Thuy, Cau Giay, Hanoi, Vietnam
Tel.: +84437547709
E-mail: tantd@vnu.edu.vn

Received: 23 February 2012 /Accepted: 22 October 2012 /Published: 31 October 2012

Abstract: In this paper, we focus to design and simulation of a piezoresistive accelerometer using three different soft-wares corresponding to three different levels: system, device, and physical ones. At the system level, MATLAB software was utilized to model a simple mechanical damping system. At the device level, we have used SUGAR/MATLAB to investigate the basic behaviors of 3-DOF accelerometer. Consequently, the ANSYS finite-element software has been used to design and simulate the advance properties of a 3-DOF piezoresistive accelerometer. At this level, we would also perform optimization process for the fabrication step. *Copyright © 2012 IFSA.*

Keywords: Piezoresistive, Accelerometer, MEMS.

1. Introduction

Accelerometers are in great demand for specific applications ranging from guidance and stabilization of spacecraft to research on vibrations of Parkinson patients' fingers [4]. Generally, it is desirable that accelerometers exhibit a linear response and a high signal-to-noise ratio [1]. Although piezoresistive accelerometers suffer from the dependence of temperature, they have DC response, simple readout circuits, ability to meet the requirement of high sensitivity, high reliability and low cost in addition to the potential for mass production [2].

Simulation is used to predict the performance of a design. Accurate modeling and efficient simulation can save time and cost. In the past years, much progress has been archived in the field of MEMS design and simulation. Any MEMS device should be modeled at all levels [3]. However, it is hardly to find software supported modeling at all the levels. Consequently, individual software can be used at each level and the data can be transfer easily between two levels. In this paper, the comprehensive research on modeling and simulation of a 3-DOF accelerometer utilizing MEMS technology has been presented.

2. Working Principle of Piezoresistive Accelerometer

Piezoresistive accelerometer is a typically open-loop system that utilizes the material advance of silicon. Apart from using the excellent mechanical properties of silicon for the accelerometer structure, another interesting property of this material, the piezoresistive effect is also utilized for detecting the deformation of this structure from which acceleration can be derived [1].

The operation of the device is based on Newton's second law of motion. An external acceleration results in a force being exerted on the mass. This force results in a deflection of the proof mass. When a vertical acceleration (*AZ*), i.e. *Z* component, applies to the sensor the mass will move vertically up and down. Similarly, when the *X* or *Y* component of transversal acceleration acting on the sensor, the mass will move laterally. The deflection of the proof mass causes stresses in four beams, resulting in resistance variation of the piezoresistor doped on the surface of the beam structure [2]. This variation was converted into electrical signals by using three imbalance Wheatstone bridge circuits. These Wheatstone bridge circuits were built by interconnecting twelve p-type piezoresistors. These p-type piezoresistors were chosen to diffuse on the surface of these four beams because they can provide the maximal resistance variations. These piezoresistors were aligned with the crystal directions <110> and <1 0> of n-type silicon (100). These piezoresistors were designed to be identical and fabricated by diffusion method.

3. Modeling Level

Modeling levels mentioned in [3] is useful to classify the various kinds of MEMS design tools. In the scope of this work, three modeling level were focused: system level, device level and physical level. At the system level, MATLAB was utilized to simulate an open-loop accelerometer working as a second order damped system. SUGAR tool was used in the device level to quickly model the structure of the sensor with a proof mass, beams and anchors. To fully exploit the characteristic of this piezoresistive accelerometer, the ANSYS software was applied at the physical device modeling.

3.1. System Level Modeling

Modelling at the system level is simple and time consuming is short. We can do simulation at system level by using hardware description language or model based method [3]. In this work, the MATLAB-SIMULINK, a model-based tool, is utilized to model simple behaviours of an accelerometer.

From a system point of view, there are two major classes of silicon micro-accelerometers: open-loop and force-balanced accelerometers [4]. In this paper, the behaviour of only open-loop accelerometers will be described and its steady state, frequency, and transition response will be studied analytically. The force-balanced accelerometers are not the subject of this paper. The reason is that this paper intends to focus to the piezoresistive sensing method which is applied mainly for the open-loop accelerometer type, whereas in the force balanced one the capacitive sensing method is needed to be used.

The equation of motion of the proof mass m can be thus written as:

$$m\frac{d^2x}{dt^2} = F(t) - kx - b\frac{dx}{dt}, \tag{1}$$

where *F(t)* is the external force, *k* is the spring constant of the suspension and *b* is the damping coefficient of the air and any other structural damping.

Fig. 1 shows the SIMULINK model of an open loop accelerometer which was derived from the mechanical simulation of the accelerometer. This high level model can be utilized to analyze the frequency and transient responses of the sensor.

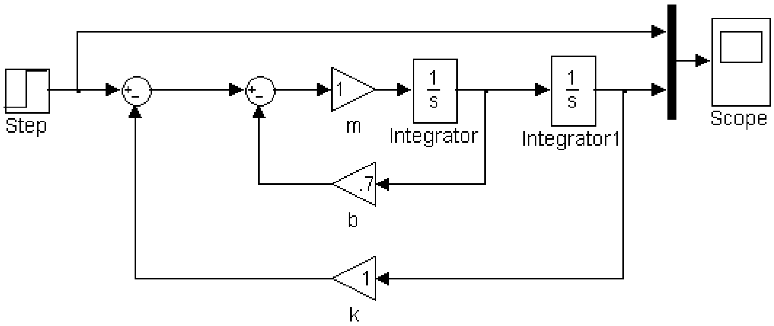


Fig. 1. The SIMULINK model of the open-loop accelerometer.

The transient responses in the time domain with various damping are shown in Fig. 2 when the acceleration input is a step function.

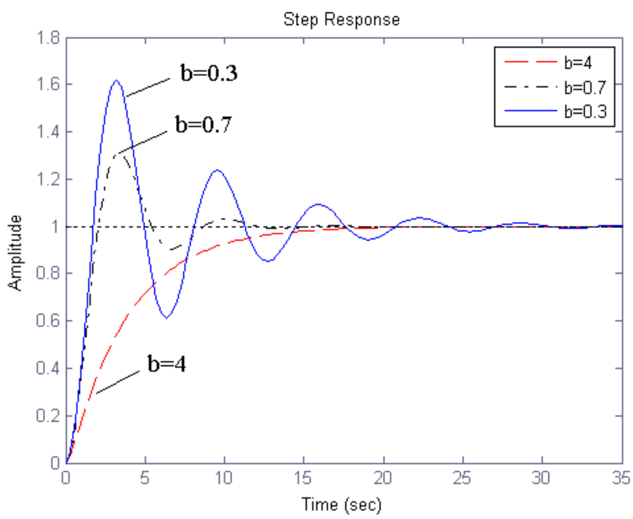


Fig. 2. Transient responses of the accelerometer with various damping coefficients.

The accelerometer should be operated in the low frequency region of the Fig. 3 due to the fact that the response is almost constant. In this linear region, the magnitude of the response is inversely proportional to the square of the resonant frequency. Therefore, the mechanical resonant frequency is a very important parameter determining the performance of the sensor. At the next section, the device level modelling, we can quickly investigate the dependence of the resonant frequency on geometry parameters and material properties of the sensor.

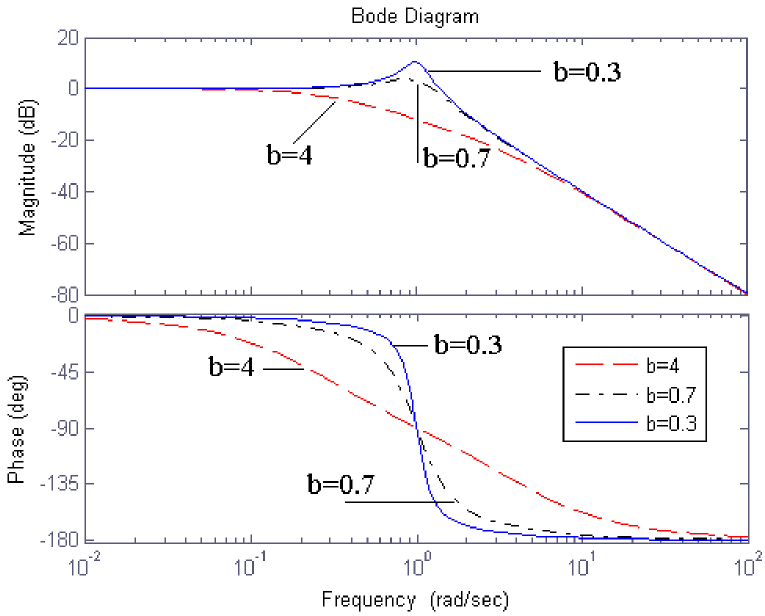


Fig. 3. Frequency response with various damping coefficient *b*.

3.2. Device Level Modeling

Nodal analysis method has been widely used at this level. Nodal analysis decomposes the structure into N-terminal devices [5]. Each device is modeled by ordinary differential equations (ODEs) whose the coefficients are parameterized by device geometry and material properties. In this paper, SUGAR tool was utilized to quickly sketch out the structure of the accelerometer. Our desired structure comprises a square-shaped mass, anchors, and flexure beams as shown in Fig. 4. The mass is a rigid plate, i.e. it is sufficiently thick to be treated as a rigid element. In this design, the dimension of the sensor die is fixed to 1.5×1.5×0.5 mm^3 and the outer frame is fixed to 200 µm. The die size of the sensor is quite small in order to use in up-to-date applications and the outer frame must be wide enough to perform wire bonding.

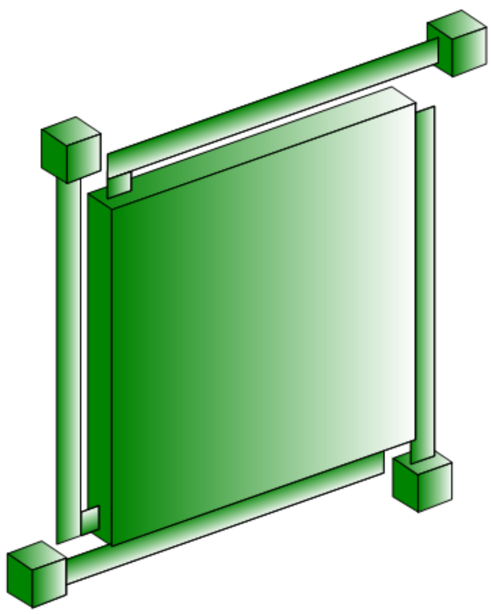


Fig. 4. Simulated structure obtained by SUGAR.

As mentioned in this previous section that resonant frequency is an important parameter. Here we have got two specification constraints are imposed on the structure to be designed: (1) the natural frequency in the Z direction must be about 1500 Hz and (2) the natural frequency in the *X* (or *Y*) direction must be about 100 kHz. These values would define the effective bandwidths of the accelerometer which are suitable for such typical applications as automotive, medical and vibration monitoring applications.

The best SUGAR design shown in Table 1 is brought to the Finite Element Method (FEM) process. ANSYS software, a Finite Element Analysis (FEA) based tools – although complex – yield more complete and precise numerical results and especially are more flexible in choosing the device geometry.

Table 1. Sensor geometry parameters.

Parameters	Size
Mass	845×845×400 μm^3
Beam	975×80×10 μm^3
Die size	1.5×1.5×0.5 mm^3
Outer frame width	200 μm

3.3. Physical Level Modeling

Most of MEMS devices have been simulated at physical level by using FEM software [6]. Finite element methods (FEM) can be defined as techniques used for finding approximate solutions of partial differential equations (PDE) or integral equations. The method is relied on reducing the differential equations to linear equations or a system consisted of ordinary differential equations. Above all other considerations, the most important aspect of FEA in our physical level is the analysis of the stress distribution in the flexure beams [7]. Based on this distribution, piezoresistors are positioned to eliminate cross-axis sensitivities and to maximize the sensitivity to the three acceleration components.
In order to perform stress analysis, an appropriate meshing is need. Note that all the geometry parameters from Table 1 and material properties were transferred easily from device level to this physical level. Fig. 5 shows the mesh generation for analysis. Based on the stress, piezoresistors are placed to eliminate the cross-axis sensitivities and to maximize the sensitivities to three components of acceleration.

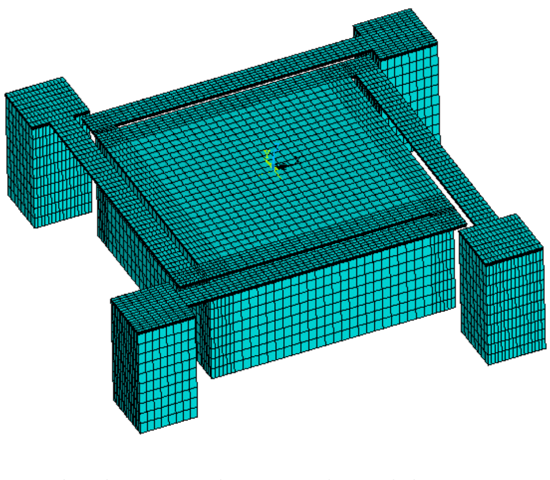


Fig. 5. The dense mesh generation of the FEM model.

Fig. 6 shows the stress distribution in the X-oriented, Y-oriented and Z-oriented of the first beam caused by the acceleration Az. Clearly, the stress distribution in the direction along the beam is much larger than the others'.

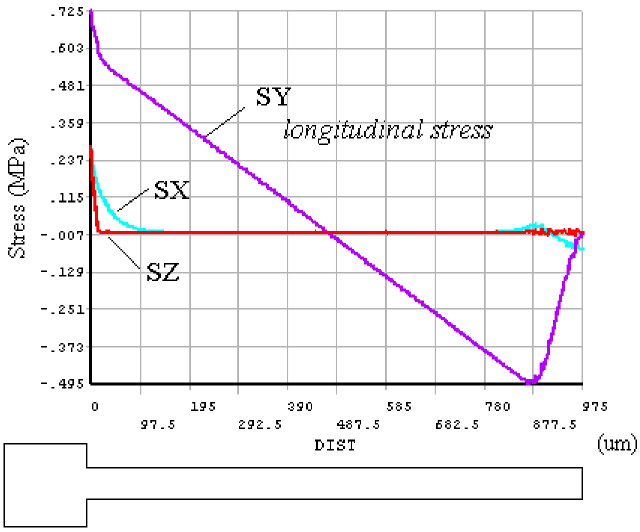


Fig. 6. The stress distribution on the first beam.

Based on the stress distribution in the flexure beams, twelve piezoresistors are placed to maximize the sensitivities to three components of acceleration and eliminate the cross-sensitivity. The sensing principle of the sensor is based on the characteristic of the p-type piezoresistor. These identical piezoresistors are diffused on the surface of the beams to form three Wheatstone bridges as shown in Fig. 7.

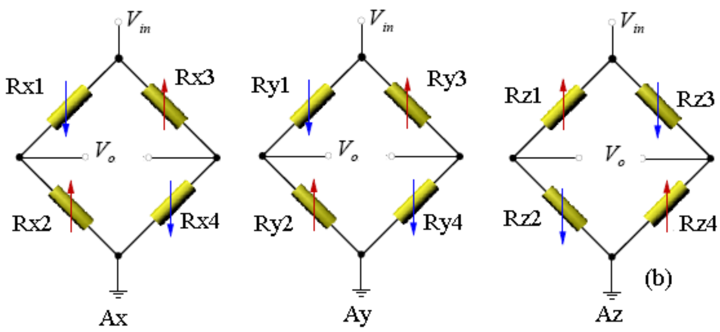


Fig. 7. Three Wheatstone bridges.

With an input voltage V_{in}, the output voltage V_{out} can be expressed as a function of resistances of four piezoresistors R_1-R_4:

$$V_{out} = \frac{1}{4}\left(\frac{\Delta R_1}{R_1} - \frac{\Delta R_2}{R_2} - \frac{\Delta R_3}{R_3} + \frac{\Delta R_4}{R_4}\right)V_{in}, \quad (2)$$

Table 2 summarizes the increase (+), decrease (-), or invariable (0) in resistance of piezoresistors due to application of accelerations Ax, Ay, and Az.

Table 2. Resistance changes due to application of accelerations.

	Rz_1	Rz_2	Rz_3	Rz_4	Ry_1	Ry_2	Ry_3	Ry_4	Rx_1	Rx_2	Rx_3	Rx_4
Ax	-	-	+	+	0	+	+	0	-	+	-	+
Ay	-	0	+	0	-	+	-	+	0	+	+	0
Az	+	-	+	-	-	-	-	-	-	-	-	-

To predict the other characteristics of the piezoresistive sensor [8], multi-physics analyze are needed in the 2nd phase. Coupling to the structural – piezoresistive analysis, the resistors volumes are modeled using the piezoresistive option of the coupled-field solid SOLID227 and the structural part of the beam is modeled using SOLID92. The resistors are connected into a Wheatstone bridge arrangement by coupling the VOLT degrees of freedom on area sides of the resistors. The applied acceleration 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. 8.

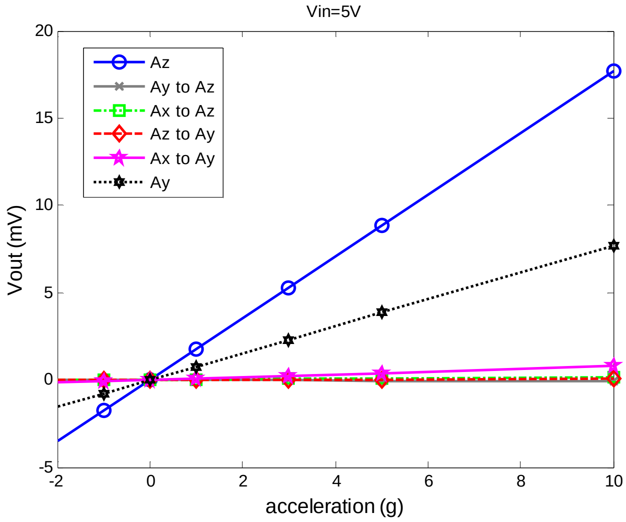


Fig. 8. The sensing and crosstalk voltages obtained by the ANSYS.

The analysis of noise is very necessary for design and fabrication. In practice, the sensitivity is affected by these following effects: the intrinsic noise due to damping, the noise from the measuring circuit, residual calibration errors and drift problems, etc. In the scope of this paper, we consider the noise voltage for the detection circuit consists of thermal (Johnson), flicker noise, and thermo-mechanical noise [9].

Cross axis sensitivity is another important characteristic. The sensor should be sensitive in one axis only. Misalignment of the device can lead to cross-axis sensitivity. But the sensor can also have an intrinsic cross axis response.

Using measuring circuit and good calibration technique, we can reduce electric noises to quite low values but the Johnson, flicker and thermo-mechanical noise. The performance of the sensor can be summarized in Table 3 with the input voltage V_{in} is 5 V.

Table 3. Performance parameters of the sensor.

	Sensitivity (mV/V/g)	Johnson noise per 1 piezoresistor (μV)	Flicker noise (μV)	Resolution (mg)
Ax, Ay	0.152	0.513	0.036	1.353
Az	0.336	0.415	0.031	0.495

The sensing chip was fabricated by micromachining process (see Fig. 9). Starting material is a multi layers SOI wafer. Thermal diffusion is performed to form p-type Si, EB lithography and RIE to create piezoresistors, metallization process to make interconnection, and deep RIE to define the beam and proof mass [10].

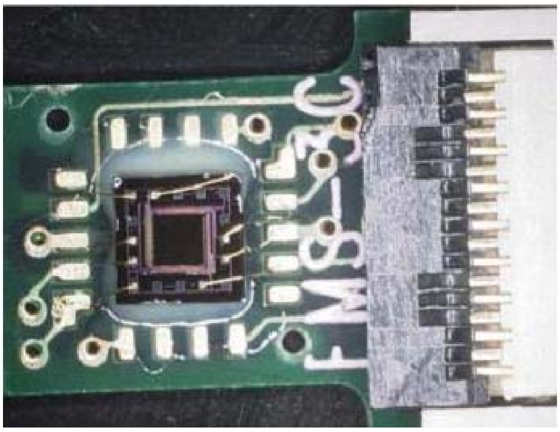


Fig. 9. The sensing chips after bonding.

4. Optimum Design Consideration

The performance of piezoresistive accelerometers presented in previous section depends on several physical parameters such as junction depth, doping concentration of the piezoresistor, temperature, noise, and power consumption. However, the fabricated accelerators have some imposed fabrication conditions. It would be interesting to know how their performance is compared to the ideally optimum ones which will be fabricated for next generations.

We examine the optimum structure of piezoresistive accelerometers. In general, we try to maximize the resolution while minimizing the influence of noise. Unfortunately, we have to deal with a multi-objective optimization problem, also called Pareto optimization [11] in which the complexity may be triple when we have to consider to three components of acceleration concurrently. Despite the fact that this optimization consideration is quite natural for any designer in this field, in my knowledge however, there are not any comprehensive researches reported yet in the open literature.

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

$$S_i^{\max}(x) = \frac{1}{a}\sigma_l^i.\underset{x=L,N,T,Vin}{Maximize} \quad \pi_l^i V_{in}^i \qquad i = X, Y, Z \,, \tag{3}$$

It is also observed that the sensitivity decrease monotonically with the impurity concentration.

Resolution is defined as the noise divided by the sensitivity. It defines the lower end of the dynamic range which piezoresistive accelerometer can resolve in the presence of noise. The optimization problem is formulated in terms of objective functions based on performance parameters: sensitivity, noise, and resolution.

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

$$R_i^{\min} = \frac{2a}{\sigma_l^i} \underset{x=L,N,T,Vin}{Minimize} \frac{\sqrt{4k_B T B_i R + \frac{\alpha V_{in}^2}{N} \ln\left(\frac{f_{\max}^i}{f_{\min}^i}\right)}}{\pi_l^i V_{in}^i}, \qquad (4)$$

where $B_i = f_{\max}^i - f_{\min}^i$.

From the equation (4) we can see that if we chose a unique bandwidth for three acceleration components (by using low-pass filters) we can get the same solution for three resolutions (R_x, R_y, R_z) concurrently (see Fig. 10).

The details solution can be summarized as following:

- 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 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 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 piezoresistor is 370 **Ω**, and the input voltage is 1.7 V, respectively.

The optimization was applied to an available structure of acceleration sensor fabricated by micromachining process. Obviously, the new design gives higher resolutions at lower power (see Table 4). Work on the fabrication of this optimized accelerometer is in progress.

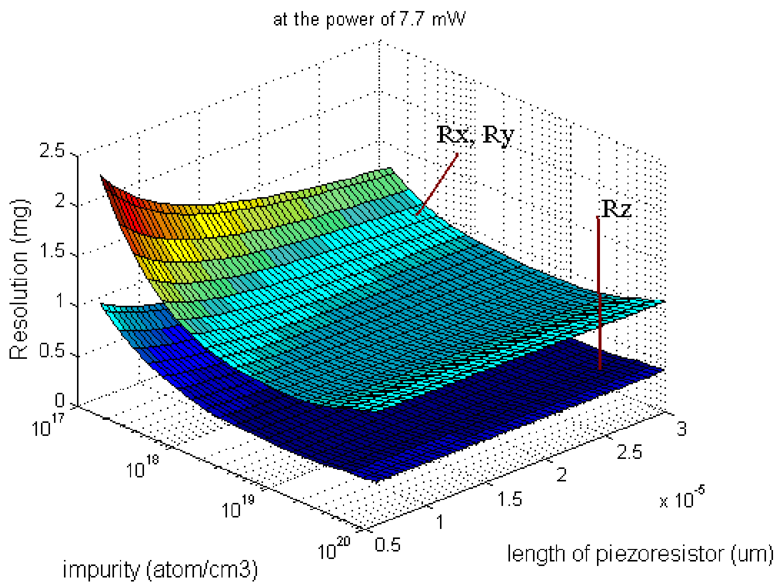


Fig. 10. Variation of resolution for different piezoresistor lengths and doping concentrations.

5. Conclusions

This paper presents a comprehensive simulation in three design level of a MEMS based piezoresistive accelerometer. We also have been successful in optimization of the sensor's resolution. The complexity was triple reduced by utilizing the frequency constraint. The Pareto optimization was implemented with the considerable concern of piezoresistors' dimensions, the doping concentration of the piezoresistor, the temperature, the noise, and the power consumption. This analysis is necessary to improve and optimize the performance of the device.

Acknowledgements

This work was partly supported by University of Engineering and Technology (UET-VNUH).

References

[1]. Middelhoek S.. Noorlag D. J. W.. Signal conversion in solid-state transducers, *Sensors and Actuators*, Vol. 2, 1992, pp. 211-228.
[2]. Yozo Kanda, Piezoresistance Effect of Silicon, *Sensors and Actuators*, A28, 1981, pp. 83-91.
[3]. Stephen D. Senturia, Microsystem Design, *Kluwer Academic Publishers*, 2001.
[4]. Myer Kutz, Mechanical Engineers' Handbook: Instrumentation, Systems, Controls, and MEMS, *John Wiley & Sons,* 2006.
[5]. Clark J. V., Bindel D., Kao W., Zhu E., Kuo A., Zhou N., Nie J., Demmel J., Bai Z., Govindjee S., Pister K. S. J., Gu M., Agogino A., Addressing the needs of complex MEMS design, in *Proceedings of the 15th IEEE International Conference on Micro Electro Mechanical Systems*, Las Vegas, NV, USA, 2002, pp. 204 – 209.
[6]. Mukhiya R., Adami A., Bagolini A., Zen M., Kal S., FEM Based Design and Simulation of Bulk Micromachined MEMS Accelerometers with Low Cross Axis Sensitivity, *EuroSim,* Italy, 2006, pp. 1- 5.
[7]. Megson T. H. G., Structural and stress analysis, *Planta tree Publisher*, 1996.
[8]. C. Pramanik, S. Banerjee, D. Mukherjee, and H. Saha, Development of SPICE Compatible Thermal Model of Silicon MEMS Piezoresistive Pressure Sensor for CMOS-MEMS Integration, in *Proceedings of the 5th IEEE Conference on Sensors*, 2006, pp. 761 – 764.
[9]. Gabrielson, Mechanical-Thermal Noise in Micromachined Acoustic and Vibration sensors, *IEEE Transactions on Electron Devices*, Vol. 40, 5, 1993, pp. 903 – 909.
[10]. Ranjith Amarasinghe, Dzung Viet Dao, Toshiyuki Toriyama, and Susumu Sugiyama, Simulation, fabrication and characterization of a three-axis piezoresistive accelerometer, *Smart Material and Structure*, Vol. 15, 2006, pp. 1691-1699.
[11]. Hailiang Zhao, Tsu-Tian Lee, Research on multiobjective optimization control for nonlinear unknown systems, in *Proceedings of the 12th IEEE International Conference on Fuzzy Systems*, 2003, pp. 402 – 407.

____

Guide for Contributors

Aims and Scope

Sensors & Transducers Journal (ISSN 1726-5479) provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because of it is a peer reviewed international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per year by International Frequency Sensor Association (IFSA). In additional, some special sponsored and conference issues published annually. *Sensors & Transducers Journal* is indexed and abstracted very quickly by Chemical Abstracts, IndexCopernicus Journals Master List, Open J-Gate, Google Scholar, etc. Since 2011 the journal is covered and indexed (including a Scopus, Embase, Engineering Village and Reaxys) in Elsevier products.

Topics Covered

Contributions are invited on all aspects of research, development and application of the science and technology of sensors, transducers and sensor instrumentations. Topics include, but are not restricted to:

- Physical, chemical and biosensors;
- Digital, frequency, period, duty-cycle, time interval, PWM, pulse number output sensors and transducers;
- Theory, principles, effects, design, standardization and modeling;
- Smart sensors and systems;
- Sensor instrumentation;
- Virtual instruments;
- Sensors interfaces, buses and networks;
- Signal processing;
- Frequency (period, duty-cycle)-to-digital converters, ADC;
- Technologies and materials;
- Nanosensors;
- Microsystems;
- Applications.

Submission of papers

Articles should be written in English. Authors are invited to submit by e-mail editor@sensorsportal.com 8-14 pages article (including abstract, illustrations (color or grayscale), photos and references) in both: MS Word (doc) and Acrobat (pdf) formats. Detailed preparation instructions, paper example and template of manuscript are available from the journal's webpage: http://www.sensorsportal.com/HTML/DIGEST/Submition.htm Authors must follow the instructions strictly when submitting their manuscripts.

Advertising Information