Feature

Streamlining the Design of MEMS Devices: An Acceleration Sensor

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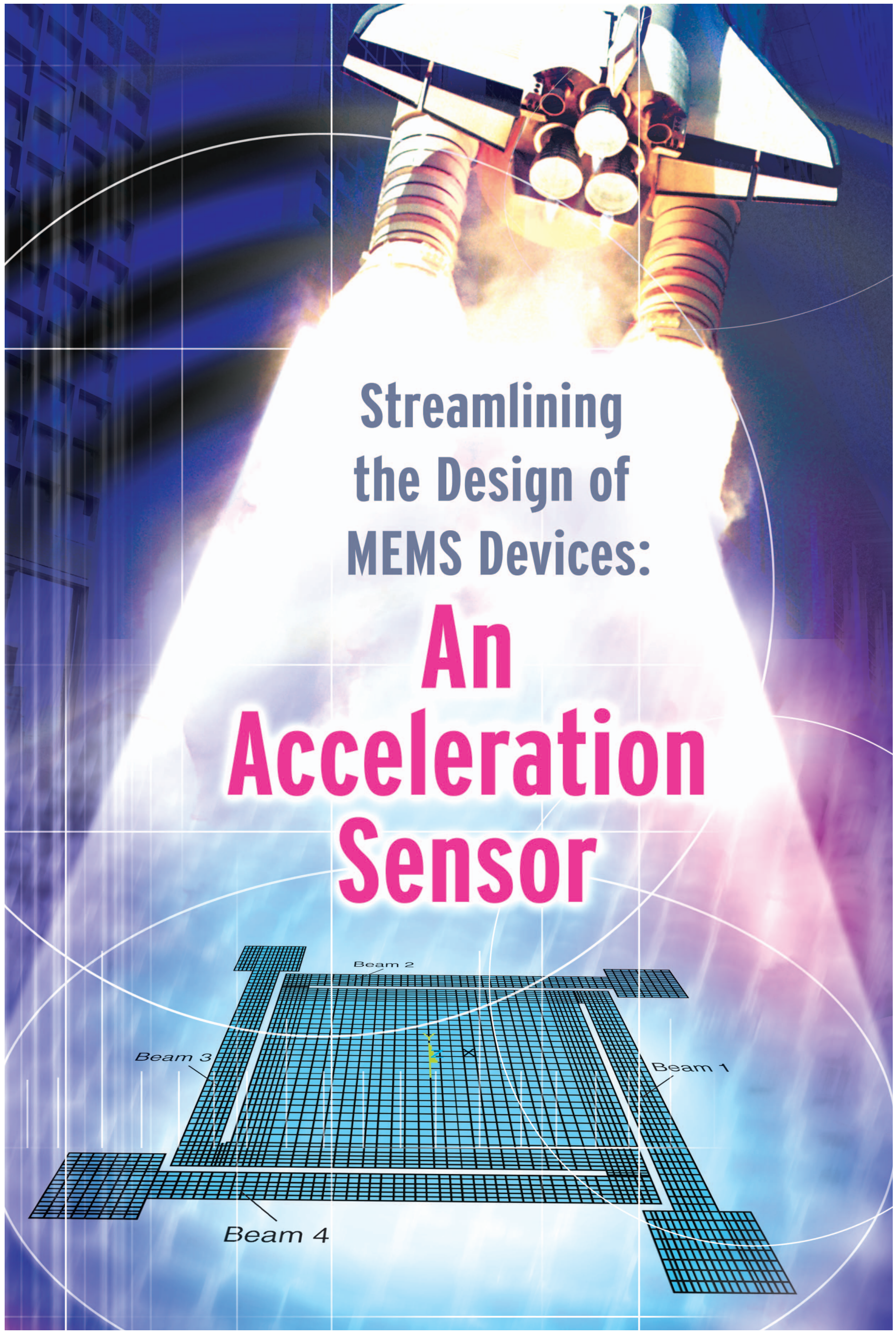
Abstract

A synthesis and optimization process is proposed and applied to the design of a specific MEMS device, namely an acceleration sensor. The design synthesis methodology exploits the fast and accurate simulation of the SUGAR tool (based on modified modal analysis) along with the full simulation capability of ANSYS (based on the finite element method). A three degrees-of-freedom piezoresistive acceleration sensor was designed to validate the proposed design flow. During the course of design, the modified nodal analysis and the finite element methods were combined in optimizing the sensor structure. In the latter, the piezoresistance effect was employed in sensing the acceleration in three dimensions.



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I. Introduction

During the last decades, MEMS technology has undergone rapid development, leading to the successful fabrication of miniaturized mechanical structures integrated with microelectronic components. In order to commercialize MEMS products effectively, one of the key factors is the streamlining of the design process. This paper focuses on the design process leading to a typical MEMS device: a piezoresistive accelerometer.

Accelerometers are in great demand for specific applications ranging from guidance and stabilization of spacecrafts to research on vibrations of Parkinson patients' fingers [1], [2]. Generally, it is desirable that accelerometers exhibit a linear response and a high signal-to-noise ratio. Among the many technological alternatives available, piezoresistive accelerometers are noteworthy. They suffer from dependence on temperature, but have a DC response, simple readout circuits, and are capable of high sensitivity and reliability. In addition, it is a low-cost technology suitable for high-volume production [3].

The design flow must correctly address design performance specifications prior to fabrication. However, CAD tools are still scarce and poorly integrated when it comes to MEMS design. This often results in an

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excessively lengthy design cycle [4], [5]. The SUGAR website [6], based at Berkeley, has this to say on the problem: "In less than a decade, the MEMS community has leveraged nearly all the integrated-circuit community's fabrication techniques, but little of the wealth of simulation capabilities. A wide range of student and professional circuit designers regularly use circuit simulation tools like SPICE, while MEMS designers resort to back-of-the envelope calculations…"

One of the goals of this paper is to outline a fast design flow in order to reach multiple specified performance targets in a reasonable time frame. This is achieved by leveraging the best features of two radically different simulation tools: Berkeley SUGAR, which is an open-source academic effort, and ANSYS, which is a commercial product.

SUGAR espouses the philosophy of the venerable IC simulation tool SPICE. It is based on modified nodal analysis (MNA) and provides quick and accurate results at the system level [7], although it does employ some approximations to make the device "fit" within its simulation mechanics.

We used SUGAR to sketch out quickly the structure of the accelerometer. It consists of a center mass connected to four flexure beams comprised of a series of beams and anchors. Design goals for our configuration consist of desired resonant frequencies at the 1st, 2nd and 3rd mode. After iterating in SUGAR to converge towards these goals, an acceptable preliminary design was brought to ANSYS for local optimization at the device level. Then, a stress analysis was performed in order to determine the positions of the doped piezoresistors on the four flexure beams. The overall design and simulation effort using this technique is roughly 20 times shorter than with the built-in optimization function available within ANSYS.

II. Structure and Operation of Piezoresistive Accelerometers

The three-degrees-of-freedom accelerometer always requires small cross-axial acceleration, high and linear sensitivity. We proposed a flexure configuration that is

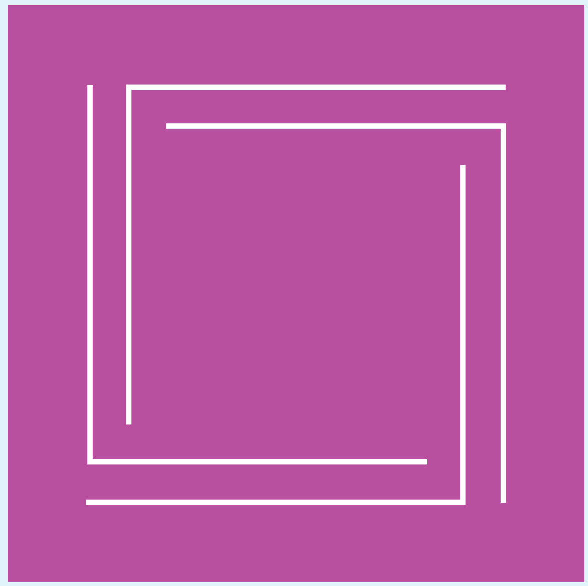

Figure 1. Plane view of the 3-DOF Piezoresistive accelerometer.

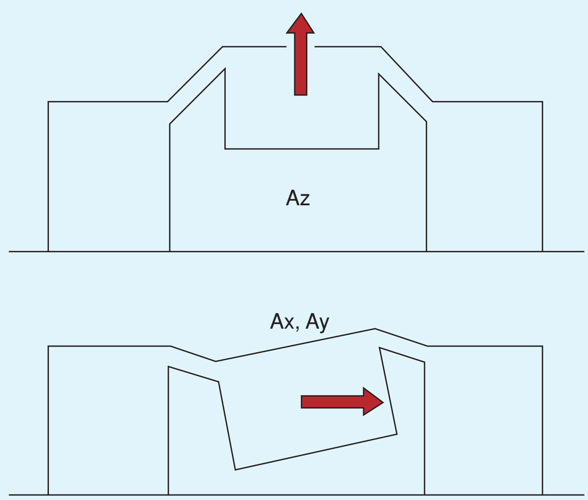

Figure 2. Cross-sectional view of motion along X, Y and Z axes.

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SUGAR is a powerful and flexible tool to perform static, steady-state, and transient analyses of mechanical structures and electrical circuits. SUGAR applies the modified nodal method (MNA) to implement simulation programs using which a MEMS designer can describe a device in a compact netlist format and quickly simulate the device's behavior.

shown in Fig. 1 in order to meet these critical characteristics. Figure 2 shows the cross-sectional view of typical motion along the X, Y and Z axes.

The operation of the device is based on inertia. An external acceleration results in a force being exerted on the mass. This force results in deflection of the proof mass. The acceleration component (Az) causes the mass to move vertically up and down. The second type of motion is caused by the X or Y component of transversal accelerations. The deflection of the proof mass causes stress variations on the four beam surfaces. This phenomenon in turn provokes resistance variations in the piezoresistors embedded on the surface of the beam structure [8], [9].

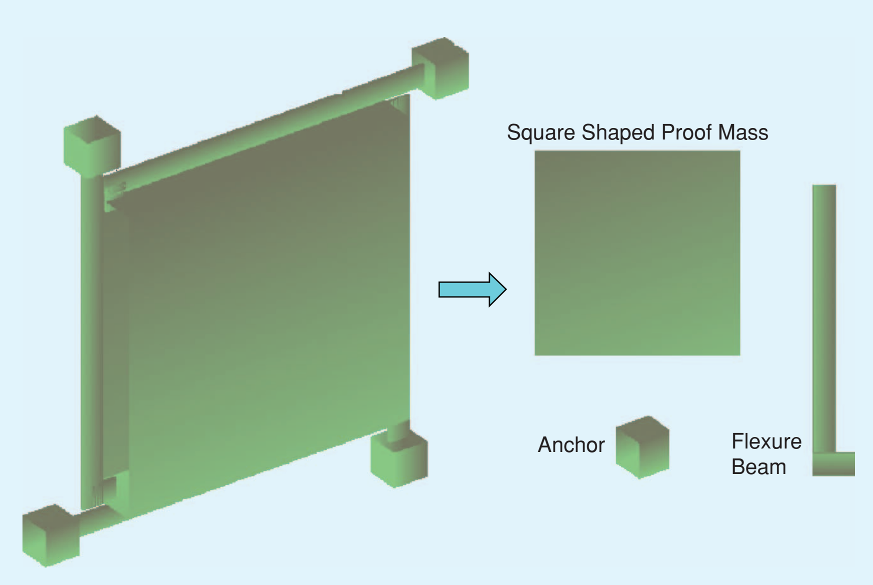

Figure 3. Separating the elements from the flexure structure.

Such variations are converted into electrical signals by using three Wheatstone bridge circuits. They are simple and it is possible to integrate electronic circuitry directly on the sensor chip for signal amplification and temperature compensation. These bridges were built by interconnecting twelve p-type piezoresistors because of their large gauge factor. These were chosen for diffusion on the surface of the four beams because they can provide maximal resistance variations in bending when compared to any point in the beam. They were aligned with the crystal directions $< 110 >$ and $< 1\bar{1}0 >$ of n-type silicon (100). They were designed to be identical and fabricated via the diffusion method.

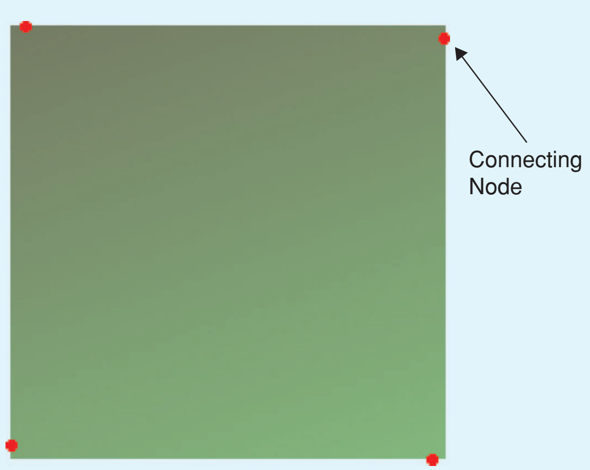

Figure 4. Connectivity of the proof mass.

The phenomenon where resistance of crystal material varies when subjected to mechanical stresses is called the piezoresistance effect. It is caused by the anisotropic characteristics of the energy resolution in the crystal space. In silicon material, piezoresistance is fully characterized by three independent coefficients π_{11}, π_{12} and π_{44}. The longitudinal piezoresistance coefficient π_l corresponds to the case where the stress is parallel to the direction of the electric field. Similarly, the transverse piezoresistance coefficient corresponds to the case where the stress is perpendicular to the direction of the electric field. In the directions $< 110 >$ and $< 1\bar{1}0 >$ of n-type silicon (100), we can determine these two coefficients as a function of independent coefficients π_{11}, π_{12} and π_{44} as follows:

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

From the simulation results in Fig. 12 (section 3), we found that the two normal stresses σ_2 and σ_3 occasionally have non-negligible values when compared to σ_1. Such cross-sensitivity will negatively affect the sensitivity of the sensor. To counter this effect, piezoresistors should be positioned away from the ends of the beam where the cross-sensitivity is strongest.

Thus, the piezoresistive effect of conventional single crystal piezoresistors can be expressed as follows:

$$
\frac{\Delta R}{R} = \pi_l \sigma_1 \qquad (2)
$$

Where $\Delta R/R$ is the relative change of resistance due to the normal stress $\sigma_i(\mathrm{i} = 1, 2, 3)$ and shear stress $\tau_j(\mathrm{j} = 4, 5, 6)$. Note that the resistance changes due to the effects of dimensional

The modeling techniques and efficient analysis in SUGAR allow the creation of designs and the production of simulation results much faster than with conventional CAD software.

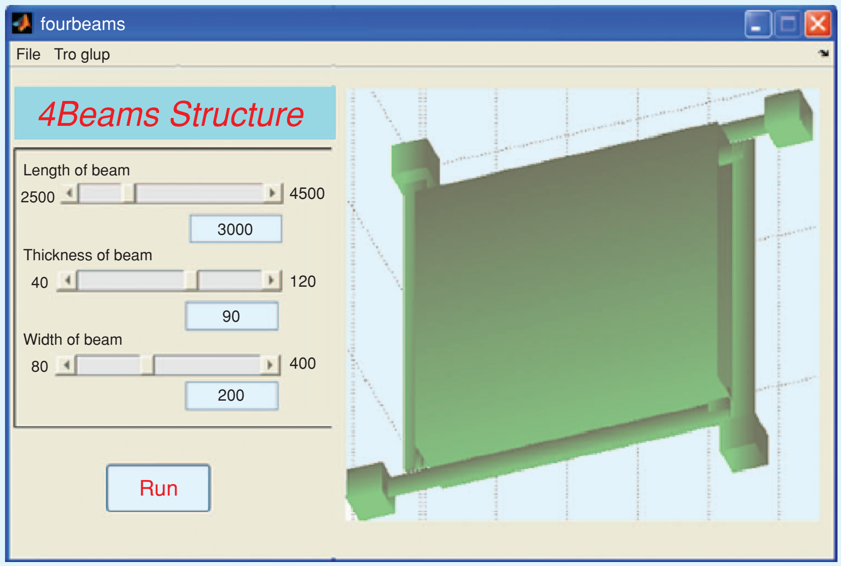

Figure 5. GUI of the four-beam structure.

Table 1.
Parameter constraints for accelerometer.

Proof Mass			
Parameter		***Value***	
Max thickness		400 μm	
Min thickness		150 μm	
Max area		500 μm^2	
Min area		200 μm^2	
Flexure Beam			
Longer Spring		**Shorter Spring**	
Parameter	***Value***	***Parameter***	***Value***
Max thickness	100 μm	Max thickness	100 μm
Min thickness	10 μm	Min thickness	10 μm
Max width	200 μm	Max width	200 μm
Min width	60 μm	Min width	60 μm
Max length	480 μm	Max length	200 μm
Min length	240 μm	Min length	10 μm

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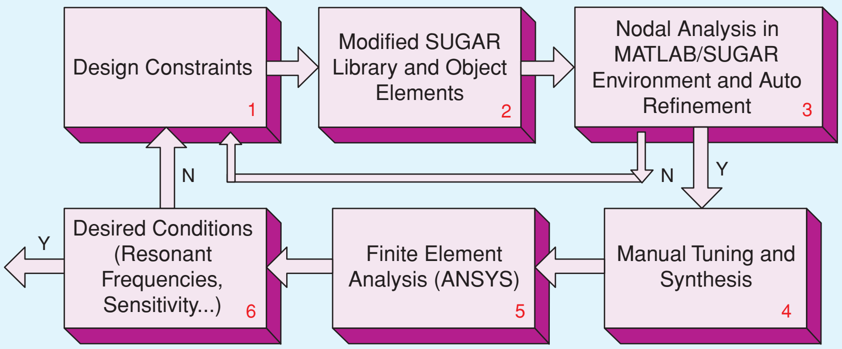

Figure 6. Flow chart of the optimizing design.

changes have been neglected as those are normally more than one order of magnitude smaller than the resistance change due to resistivity variations alone [8], [9].

III. Optimization by Using Sugar and ANSYS

SUGAR is a powerful and flexible tool to perform static, steady-state, and transient analyses of mechanical structures and electrical circuits. SUGAR applies the modified nodal method (MNA) to implement simulation programs using which a MEMS designer can describe a device in a compact netlist format and quickly simulate the device's behavior [10]. SUGAR abstracts the MEMS structures in terms of three basic elements: beams, gaps, and anchors. It builds ordinary differential equations (ODE) models for each. The overall system of equations can be formulated according to the node connectivity information provided in the input file, and solved using nodal analysis.

Our desired structure comprises a square-shaped mass, anchors, and flexure beams as shown in Fig. 3. 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 $1.5 \times 1.5 \times 0.5$ mm^3 and the outer frame is fixed to 200 μm. Thus, the mass and the beams are evolved to achieve the design requirements. The connectivity of the center mass is represented by the four

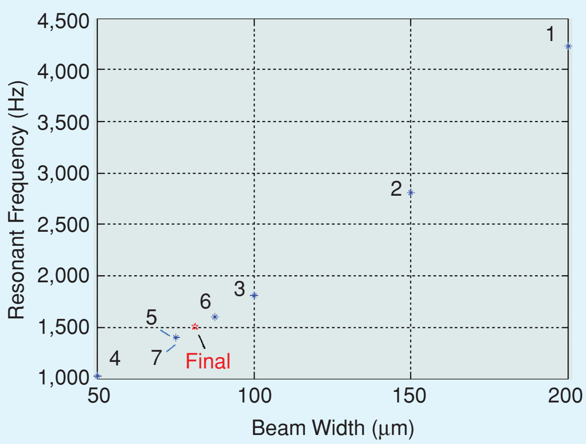

Figure 7. Determining the optimum beam width when the thicknesses of the beam and mass are fixed to 10 μm and 400 μm, respectively.

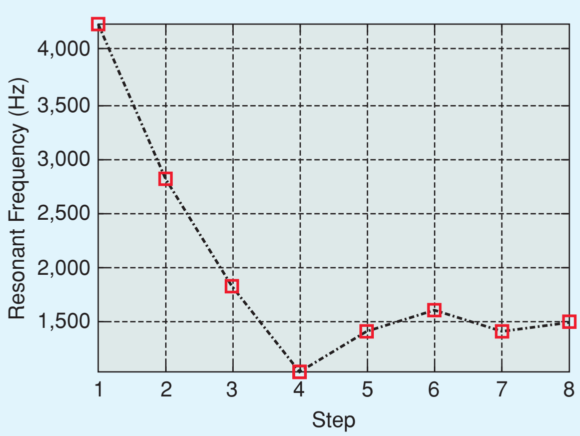

Figure 8. The convergence of the design process in the 3rd block.

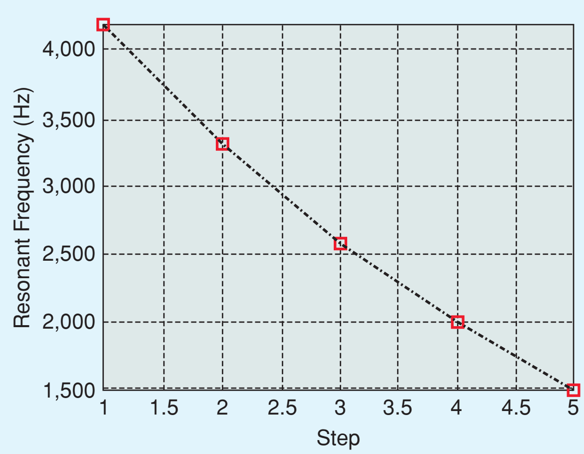

Figure 9. Convergence of design parameters (resonant frequency) showing how sensitive the time expenditure is to the initial value of the step size.

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nodes shown in Fig. 4. Positions of these connecting nodes are determined by parameters of the beams.

The MEMS designer can easily modify various process parameters such as Young's modulus, Poisson's ratio, the residual stress, and the coefficient of thermal expansion in the process file [7].

The modeling techniques and efficient analysis in SUGAR allow the creation of designs and the production of simulation results much faster than with conventional CAD software [4]. Furthermore, its graphical user interface (GUI) provides convenient interactive visualization capabilities (see Fig. 5).

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. Furthermore, a set of parameter constraints is listed in Table 1. Note that the actions of various parameters are interdependent.

A MEMS device can have a surface structure or a bulk structure. Our case study accelerometer adopts the bulk-type structure. Figure 6 shows the mostly (90%) automated synthesis flow that was used to evolve the final design. In the first three steps, an automatic refinement procedure is employed where the step size of a given parameter is varied adaptively. For example, the step size of the beam's width (λ) is initially set at 50 μm. When the resonant frequency overshoots across the desired frequency, we move back to the previous step point and scale back the step size in order to reach the optimum point (see Fig. 7).

Figure 7 shows the resonant frequency variation in terms of the beam width when we fixed the beam thickness to a minimal value and the proof mass thickness to a maximal value in order to get the maximum sensitivity. These extreme values are based on process constraints, i.e. design rules. The beam width was iteratively refined in order to make the first resonant frequency reach the desired value. We can see that the resonant frequency decreases rapidly when the beam width decreases. It takes 8 iterations to reach the optimum value and the process overshoots twice.

Figure 8 shows again that the design process converges in eight steps. Theoretically, we can get the exact desired

Table 2.
Sensor parameters after manual tuning and synthesis block.

	Size
Mass	$845 \times 845 \times 400 \mu m^3$
Beam	$975 \times 80 \times 10 \mu m^3$
Die Size	$15 \times 15 \times 0.5 \mu m^3$
Outer Frame Width	$200 \mu m$

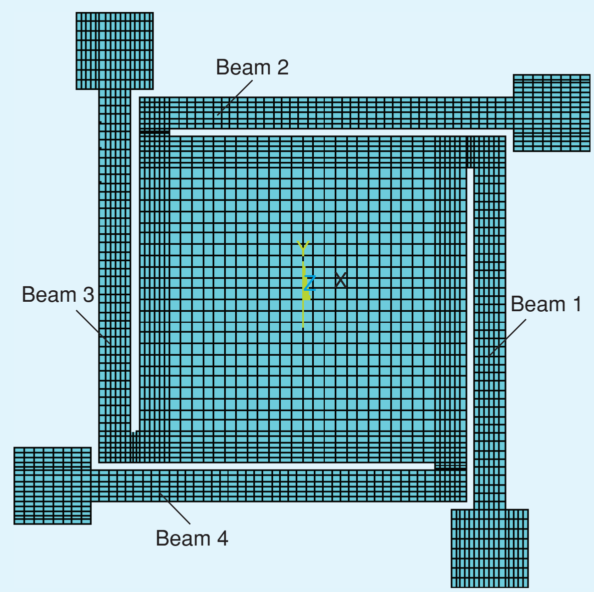

Figure 10. The dense mesh generation of the FEM model.

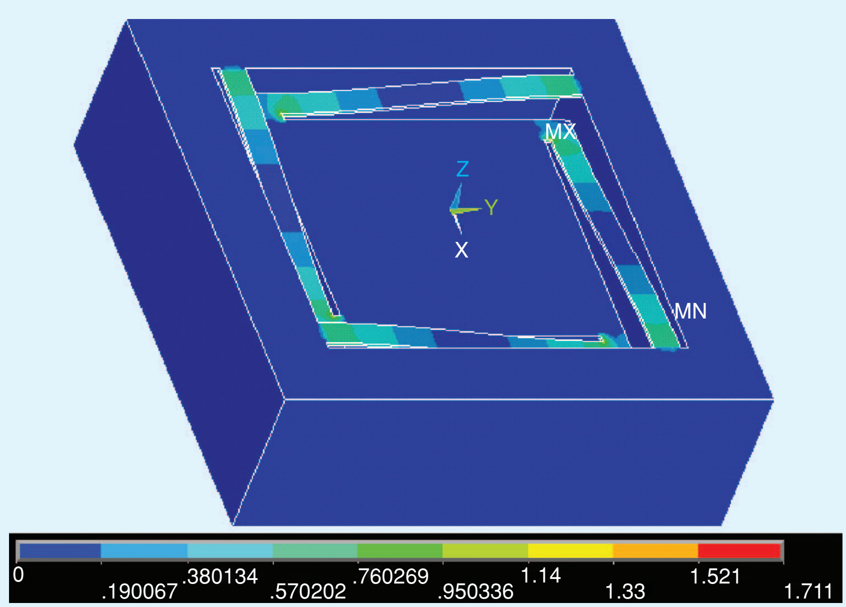

Figure 11. The stress distribution on the beams caused by the acceleration Az.

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The sensor is fabricated with five photo masks corresponding to piezoresistor patterning, contact hole opening, interconnection wiring, crossbeam forming, and deep reactive ion etching from backside.

resonant frequency, but this is not very meaningful because there is a divergence of approximately 5% between SUGAR and reality.

The initial value of the step size in this algorithm should be chosen wisely. Figure 9 depicts a case with no overshoot where the final result is reached in just 5 steps. This was accomplished by simply reducing the initial step size with respect to Fig. 8.

The best designs resulting from the 4th block (Table 2) are brought to the Finite Element Method (FEM) process. Finite Element Analysis (FEA) based tools—although

Table 3.
First three resonant frequencies of the structure.

Mode	Frequency (Hz)	Description
1	1506	Vibration in Z direction
2	98470	Vibration in X direction
3	98470	Vibration in Y direction

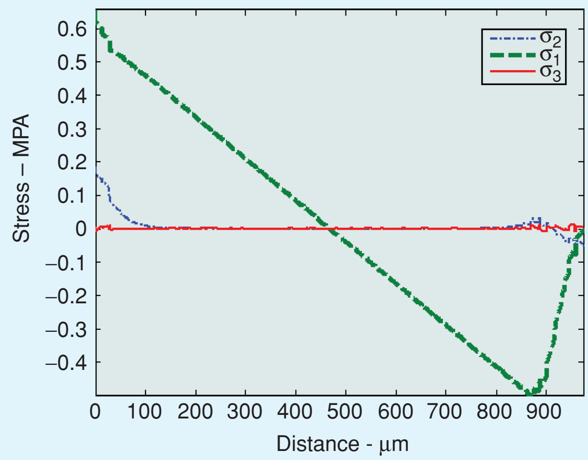

Figure 12. The stress distribution on the first beam.

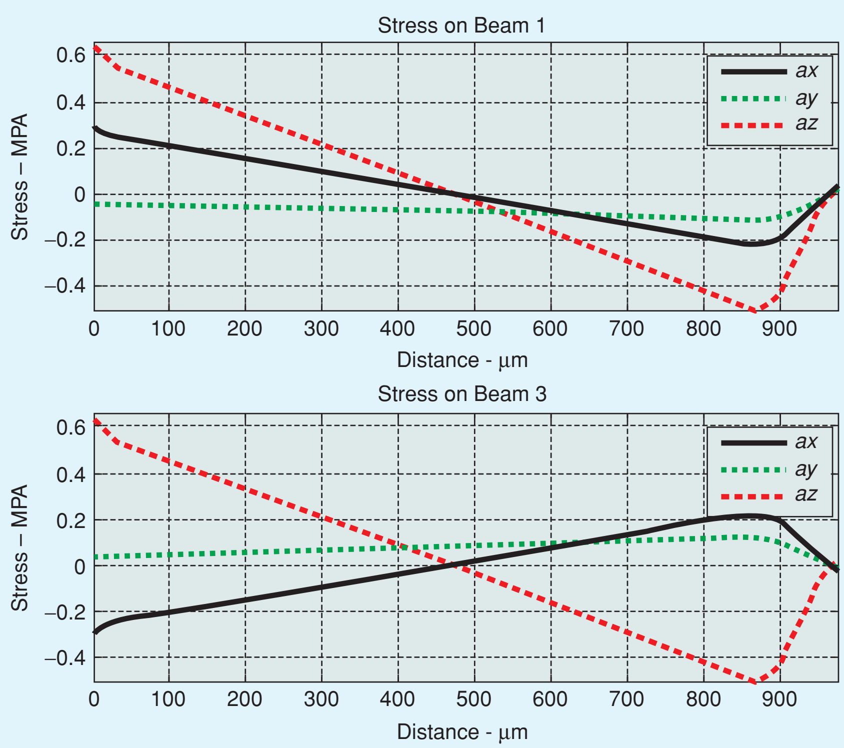

Figure 13. The stress distribution on beams 1 and 3 in three directions.

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Above all other considerations, the most important aspect of FEA in our design process is the analysis of the stress distribution in the flexure beams. Based on this distribution, piezoresistors are positioned to eliminate cross-axis sensitivities and to maximize the sensitivity to the three acceleration components.

complex—yield more complete and precise numerical results and especially are more flexible in choosing the device geometry.

SUGAR is a simplified simulation method and is therefore prone to imprecisions of various kinds. The main source of error in our case stems from beam overlap. In exchange for much faster simulation speed, SUGAR does not include the actual conditions at the end of the beam. Instead, SUGAR assumes a fixed connection exactly at the node point. In fact, when two beams connect at an angle, especially an acute angle, there is some physical overlap in their areas (see Fig. 3—flexure beam) within the SUGAR model. This problem can be avoided in ANSYS by joining all the beam polygons into a single polygon through a union operation, such that overlapping areas are subsumed.

Above all other considerations, the most important aspect of FEA in our design process is the analysis of the stress distribution in the flexure beams. Based on this distribution, piezoresistors are positioned to eliminate cross-axis sensitivities and to maximize the sensitivity to the three acceleration components.

Now, we will consider the stress states on the surface of the beams due to each individual component of force and moment applied separately. Note that all calculations are based on the isotropic material assumption. Figure 10 shows the mesh generation for analysis and the stress distribution on the beam is shown in Fig. 11. There are several solvers available in ANSYS for modal analysis and the Block-Lanczos solver was used for this case. The frequencies from the first to third mode obtained by FEM are listed in Table 3.

Figure 12 shows the stress distribution along the X, Y and Z orientations of the first beam caused by an acceleration Az. Clearly, the stress distribution which is aligned with the direction along the beam is much larger than the others. Figure 13 shows the stress analysis results along the 1st and the 3rd beams when the sensor is subject to acceleration in the three directions (X, Y and Z). From this figure, we can pinpoint the optimal locations for the piezoresistors in order to sense accelerations Ax and Az without cross-talk. By the same token, the acceleration Ay can be sensed via four piezoresistors on the 2nd and the 4th beams.

The lithographic fabrication process requires precise photo masks to accurately create micro-scale patterns and structures. In this paper, the sensor is fabricated with five photo masks corresponding to piezoresistor patterning, contact hole opening, interconnection wiring, crossbeam forming, and deep reactive ion etching from backside. The mask layout design was drawn using L-EDIT software (see Fig. 14).

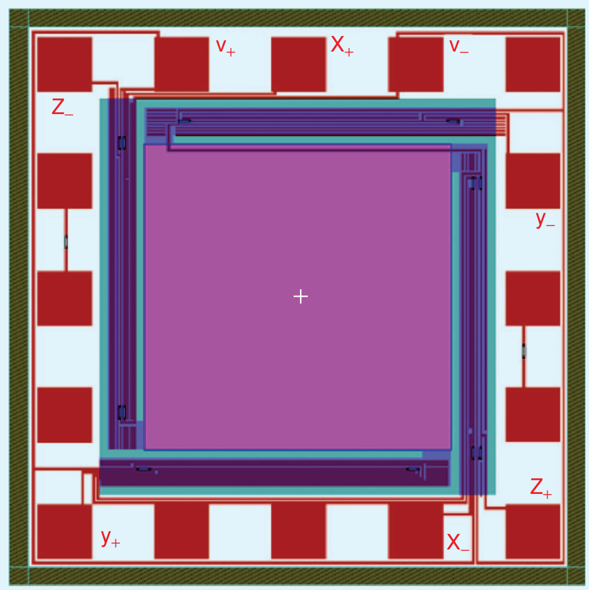

Figure 14. The mask layout of the accelerometer.

Table 4.
Resistance values changes with three components of acceleration (where $0 < c_1 < c_2 \ll b$ (100 times)).

	$\Delta Rx_1/R$	$\Delta Rx_2/R$	$\Delta Rx_3/R$	$\Delta Rx_4/R$
Ax	b	−b	−b	b
Ay	$-c_1$	$-c_2$	c_1	c_2
Az	a	−a	a	−a
	$\Delta Ry_1/R$	$\Delta Ry_2/R$	$\Delta Ry_3/R$	$\Delta Ry_4/R$
Ax	$-c_1$	$-c_2$	c_2	c_2
Ay	b	−b	−b	b
Az	a	a	a	−a
	$\Delta Rz_1/R$	$\Delta Rz_2/R$	$\Delta Rz_3/R$	$\Delta Rz_4/R$
Ax	−b	b	−b	b
Ay	−b	b	−b	b
Az	−a	a	a	−a

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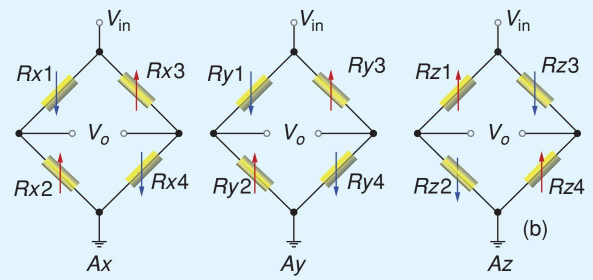

Figure 15. Three Wheatstone bridges.

Based on the stress distribution in the flexure beams, twelve piezoresistors are placed to maximize sensitivity to the three acceleration components and minimize cross-sensitivity. The behavior of the sensor is captured in Table 4 based on the characteristics of the p-type piezoresistor [11]. The resistance decreases when the sensor is exerted by a compressive stress and increases when it is exerted by a tensile stress. These identical piezoresistors are diffused on the surface of the beams to form three Wheatstone bridges as shown in Fig. 15.

When the structure is in a balanced state, the output voltage is zero. When the sensor is undergoing acceleration, the Wheatstone bridges become unbalanced and a voltage appears at their output. When the sensor is submitted to acceleration in an arbitrary direction, the output is given by:

$$\begin{aligned} V_1 &= \frac{1}{4}\left(\frac{\Delta Rx1}{Rx1} - \frac{\Delta Rx2}{Rx2} - \frac{\Delta Rx3}{Rx3} + \frac{\Delta Rx4}{Rx4}\right) \\ V_2 &= \frac{1}{4}\left(\frac{\Delta Ry1}{Ry1} - \frac{\Delta Ry2}{Ry2} - \frac{\Delta Ry3}{Ry3} + \frac{\Delta Ry4}{Ry4}\right) \\ V_3 &= \frac{1}{4}\left(\frac{\Delta Rz1}{Rz1} - \frac{\Delta Rz2}{Rz2} - \frac{\Delta Rz3}{Rz3} + \frac{\Delta Rz4}{Rz4}\right) \end{aligned} \tag{3}$$

When the sensor is only submitted to the Az acceleration component, the output can be easily found from equation (3) and Table 4, i.e.,

$$\begin{aligned} V_1 &= 0 \\ V_2 &= 0 \\ V_3 &= \frac{\Delta Rz_1}{Rz_1} V_{in} = a \end{aligned} \tag{4}$$

When the sensor is strictly reacting to the Ax acceleration component, we have

$$\begin{aligned} V_1 &= 0 \\ V_2 &= \frac{c_2 - c_1}{2} \to 0 \\ V_3 &= 0 \end{aligned} \tag{5}$$

Likewise, we can write

$$\begin{aligned} V_1 &= \frac{c_2 - c_1}{2} \to 0 \\ V_2 &= 0 \\ V_3 &= 0 \end{aligned} \tag{6}$$

when only the Ay component is applied.

This proposed design flow was successfully applied to a specific 3 degrees-of-freedom accelerometer. The sensor structure is a cubic seismic mass suspended with symmetric single crystal silicon beams to an outer frame. The piezoresistance effect in silicon was exploited to measure stress on the flexure beams and thus achieve 3-axis acceleration sensing.

IV. Conclusion

This paper presented a hierarchical MEMS design synthesis and optimization process developed for and validated by the design of a specific MEMS accelerometer. The iterative synthesis design is largely based on the use of a MNA tool called SUGAR in order to meet multiple design specifications. After some human interactions, the design is brought to FEM software such as ANSYS for final validation and further optimization (such as placement of the piezoresistors in our case study). The optimal configuration was reached by exploiting the advantages of both types of simulations. The piezoresistance effect was applied to this structure in order to sense the acceleration in three dimensions. This sensor is currently being fabricated. The future work includes the test and characterization of the physical part, as well as quantifying and understanding any discrepancies with the simulation results.

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