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Design Optimization for an SOI MOEMS Accelerometer

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Abstract- With optimization being vital, the design optimization of a silicon-on-insulator (SOI) micro-opto-electro-mechanical systems (MOEMS) accelerometer is discussed in this paper. This process has enabled a simplistic design that employs double-sided deep reactive ion etching (DRIE) on SOI wafer to be able to attain high sensitivity of 294 $\mu\text{W}/\text{G}$ with a calculated proof mass displacement of 0.066 $\mu\text{m}/\text{G}$ which was close to ANSYS simulated results of 0.061 $\mu\text{m}/\text{G}$. Optimization has also enabled an in-depth study of the effects of the different variables on the overall performance of the device.

Keywords- Micro-Opto-Electro-Mechanical Systems (MOEMS), double-sided deep reactive ion etching (DRIE), seismic motion detection, design optimization

I. INTRODUCTION

Optimization is crucial in ensuring that devices developed would have enhanced performance, sensitivity, while minimizing the amount of resources required. (Kelley 2010) One field that places a strong emphasis on optimization is the micro/nano-electro-mechanical systems (MEMS/NEMS) field. Devices developed using this technology have high overhead costs and the main way to reduce such costs would be to mass produce them. At the same time, these devices are on the micro/nano scale. This inevitably implies that the devices have high space constraint.(Bhansali and Vasudev 2012; Gad-el-Hak 2005) Optimization in this case saves valuable resources through prior analysis like in thermal and fluid flow,(Mohammadi and Pironneau 2010; Von Arx et al. 2000) structural and mechanical, (Huang et al. 2001; Zhang et al. 2001) electrical and optical, (Choi et al. 2006; Samuelson et al. 2012) process(Bose et al. 2013) and sometimes chemical(Ranjan et al. 2013) too. With this in mind, it is also important to consider practicality at the same time as it is still required to transform designs into reality too. This is determined through the requirements and limitations of the device, which would have to be determined according to industry standards.

In this paper, the design optimization process of an optical MEMS (MOEMS) would be discussed.(Teo et al. 2016) This process involves the analysis of the effects of multiple variables that would contribute to the overall performance of the device, which is fabricated using double sided deep reactive ion etching on an SOI wafer. The schematic diagram of how the device works is given in Fig. 1. The proof mass (red portion) is supported by four thin cantilever beams that are extended from the frame (blue portion) of the MEMS layer. The entire MEMS

Fig. 1. Schematic diagram of the MOEMS device where (a) shows the position of proof mass at rest and (b) is the position of the proof mass under external acceleration. This acceleration causes a change in the intensity of incident light picked up by the photodiode sensor due to the inertial force experienced by the proof mass. (c) is a CAD drawing of the MEMS layer with a zoom in on the cantilever beam (inset)

Table 1. List of MOEMS developed in order of resonant frequency

Author	Sensitivity ($\mu\text{m}/\text{G}$)	Res. Freq. (Hz)
Zandi, K. (Zandi et al. 2010)	0.0025	1670
da Costa Antunes, P. F. (da Costa Antunes et al. 2009)	0.011	39
Borinski, J. W. (Borinski et al. 2001)	0.041	2000
SIMULATED DEVICE	0.061	2106
Schröpfer, G. (Schröpfer et al. 1998)	0.14	1176
Doyle, C. and G. F. Fernando (Doyle and Fernando 2000)	1.1	592
Krishnamoorthy, U. (Krishnamoorthy et al. 2008)	20	1131
Llobera, A. (Llobera et al. 2004)	34.3	85
Loh, N. C., M. A. Schmidt (Loh et al. 2002)	39	80

Fig. 2. Variables of interest for device (a) Top view, (b) Sectional view, (c) Isometric view of square hole in device layer with table of variables

layer is fabricated using an SOI wafer where the device layer would be the layer with the beams and the handle layer would be the main bulk of silicon that acts as the proof mass and frame. The most crucial part of the MOEMS seismic motion detector device is in the design and fabrication of this layer. This is the main portion that would be discussed in this paper. As mentioned previously, there are limitations during optimization, the device target is set to 2000 Hz for its 1st resonant frequency, and 0.10 μm in-plane displacement. This frequency is set to enable a linear readout for detection below 500 Hz, which is in line with Sabatier and Ekimov (2006). A

list of past devices with their mechanical sensitivities and resonant frequencies are also given in Table 1 as a means of comparison.

The device mentioned in this paper makes use of a simple proof mass that requires optimization to enhance its detection capabilities. The general method of detection for the device works based on the deflection of the proof mass upon an external exertion force acting on it. This force is then translated to the inertial force that causes the deflection of the proof mass from the CMOS layer photodetector below as observed in Fig. 1. With the deflection, the light passing through the proof mass

Fig. 3. ANSYS simulation results showing effects of different variables. Standardized variables used, Mass width = 1000 μm, Mass Length = 2000 μm, Beam width = 5 μm, Gap width = 30 μm, Beam length = 100 μm, Device layer thickness = 30 μm, Handle layer thickness = 500 μm, Strip length = 900 μm, Number of strips = 25. acceleration = 19.62 m/s², unless otherwise stated in graphs.

Table 2. List of device designs

	Mass Length (μm)	Mass Width (μm)	Beam Width h (μm)	Beam Length (μm)	Device Layer Thickness (μm)	Handle Layer Thickness (μm)	Gap Width h (μm)	Strip Length (μm)	No. of Strips	1 st Resonant Frequency (Hz)			In-plane Displacement (μm)			Brownian Equivalent acceleration on noise ($nG/\sqrt{Hz}$)	Sensitivity from ANSYS (μm/G)
										Theory	ANSYS	% Diff	Theory	ANSYS	% Diff		
Device D	2000	1000	8	300	30	500	30	900	20	2354.69	2397.50	1.82	0.09	0.09	-2.28	88.30	0.040
Device E	2000	1800	7	210	30	500	30	1500	25	2492.32	2504.40	0.49	0.08	0.08	-0.24	67.82	0.040
Device F	2000	1800	7	220	30	500	30	1200	25	2253.70	2265.08	0.51	0.10	0.10	0.15	63.88	0.049
Device G	2000	1800	6	240	30	500	30	1500	25	2076.41	2106.51	1.45	0.12	0.11	-1.36	70.40	0.061
Device H	2000	1800	7	240	30	500	30	1300	20	1930.60	1971.62	2.12	0.13	0.13	-2.80	60.86	0.065

from the top side would be reduced and thus resulting in the decrease in light intensity input.

II. THEORY

The displacement of the proof mass is determined according to the spring-mass-damper equation,

$$\sum F_{acting\ on\ proof\ mass} = 0 \quad (1)$$

$$m\ddot{x} + c\dot{x} + kx = F_o \sin \omega t \quad (2)$$

where the mass of the proof mass, m , the damping constant, c , the spring constant of the beams, k , all determine the displacement, x , through the use of the force, F_o , and induced frequency of the system, ω . The displacement amplitude of the proof mass, X , and natural frequency, ω_n , can then be simplified into

$$X = \frac{F_o}{\sqrt{(k - m_{mass}\omega^2)^2 + (c\omega)^2}} \quad (3)$$

and,

$$\omega_n = \sqrt{\frac{k}{m_{mass}}} \quad (4)$$

III. DEVICE DESIGN

For the incorporation of these equations into the designing process, each variable had to be broken down into its relative constituents as observed in Fig. 2. For k , the value is determined by the beams that would hold the proof mass in position, which in this case would be four cantilever beams. Straight cantilever beams were used as simulations revealed it to be of the best balance between stress and cross axial sensitivity when compared with triangular or serpentine beams. These four beams are cantilevers that would enhance in-plane motions and reduce out-of-plane motions and are given according to these set of equations.

$$k = 4k_{beam}$$

$$k_{beam} = \frac{12EI}{B_L^3} \quad (5)$$

$$I = \frac{bh^3}{12} = \frac{t_{dev}B_W^3}{12} \quad (6)$$

$$\therefore k = \frac{4Et_{dev}B_W^3}{B_L^3} \quad (8)$$

For the fabrication of this device, the buried oxide (BOX) layer of the SOI has a minimal effect of the mass and would be neglected. The value for the m_{mass} as given in equations 3 and 4 are as follows.

$$m_{mass} = \rho \times V_{mass} \quad (9)$$

which becomes,

$$(10)$$

$$m_{mass} = \rho[(M_L \times M_W - G_W \times G_L \times N)t_{sub} + (M_L \times M_W - (G_W \times N + S_W \times (N - 1)) \times G_L)t_{dev}]$$

With this value for m_{mass} , equation 4 can then be broken down as follows.

$$\begin{aligned} \omega_n &= \sqrt{\frac{\frac{4Et_{dev}B_W^3}{B_L^3}}{\rho[(M_L \times M_W - G_W \times G_L \times N)t_{sub} + (M_L \times M_W - (G_W \times N + S_W \times (N - 1)) \times G_L)t_{dev}]} \\ &= \sqrt{\frac{4Et_{dev}B_W^3}{\rho[(M_L \times M_W - G_W \times G_L)t_{sub} + (M_L \times M_W - (G_W + S_W) \times G_L)t_{dev}]B_L^3}} \quad (11) \end{aligned}$$

Through these set of equations, it is observable that the main contribution for the improved performance of the device would be the beam length, B_L , beam width, B_W , and volume of proof mass, V_{mass} . There however were a few limitations that had to be considered during the optimization process. Some examples would be the thickness of the SOI wafer, the size of the proof mass, and the minimal beam width. The SOI wafer used in this case had the thicknesses kept at 500 μ m for the handle layer and 30 μ m for the device layer. The buried oxide layer was only 2 μ m thus the mass of that section is overlooked.

Using these set of equations, two approaches were adapted for optimization. The first method is the theoretical approach which makes use of the equations mentioned above, and the second is through the use of ANSYS simulation software. After a comparison of both results, a final experiment will be carried out using the fabricated device to determine the accuracy of the results.

IV. SIMULATION RESULTS AND COMPARISON

ANSYS simulation results of the different variations, B_L , B_W , V_{mass} show a general trend that when the displacement of the proof mass decreases, the

Fig. 3), correlating well with equations mentioned above. As such, an optimal point would be at a point where the two curves intersect, however this would also be determined according to the requirements of the device itself, which would be to have a resonant frequency of approximately 2000 Hz and a maximized in-plane displacement of approximately 0.1 μm . Based on the ANSYS simulations, it is observed that by varying the overall SOI wafer thickness and number of strips, the trend produced is a relatively linear one. On the other hand, the variation of the beam length and beam width causes an exponential trend instead. This goes to prove that the critical parameters in this case would be the beam length and width, whereas the volume of proof mass would be less critical. A list of designs are gathered in Table 2 which give the specifications of each design and the results obtained through ANSYS and theoretical calculations. For the out-of-plane displacement, ANSYS results show a maximum deflection of 0.006 μm for Design H which showed an in-plane displacement of 0.130 μm .

Fig. 4. Microscope images of each device after fabrication shows defined features that agree well with intended designs

Amongst all the designs mentioned here, this design has the highest out-of-plane displacement which would not affect the detection by the CMOS layer as the LED used would be of a collimated beam nature.

By comparing the theoretical and ANSYS results, a maximum of 2.8% difference was observed for the in-plane displacement and a 2.1% difference for the 1st resonant frequency, showing high accuracy of simulation results. A Brownian equivalent acceleration noise level was also calculated to be at a maximum of $88 \text{ nG}/\sqrt{\text{Hz}}$ amongst the five designs, and a simulated sensitivity of a maximum of 0.065 μm/G . Using these different device designs, fabrication was carried out to test the feasibility of fabrication and also to confirm on the theoretical and simulated results

V. FABRICATION AND EXPERIMENTAL SETUP

The prototype developed makes use of an SOI wafer with 30 μm device layer thickness and 500 μm handle layer thickness. This wafer thickness is according to the developed designs as given in Table 2. Standard photolithography procedures were carried out with etching on the top and bottom sides of the wafer using deep reactive ion etching (DRIE) to allow fabrication accuracy of the beam structures.

Experiments were carried out to determine the results of the optimization and to determine the feasibility of fabrication. It is highly critical to do so as thin beams are used to support the bulky proof mass. An 850nm IR Laser Module (MM850-5, US-Lasers Inc.) is fixed on a wafer holder with a photodiode power sensor (S121C, ThorLabs) attached below it positioned similar to the schematic diagram in Fig. 1. The photodiode power sensor used is different from the one mentioned in Fig. 1 as the main objective of this paper is the design optimization of the MOEMS layer. A reference accelerometer (Miniature Single Axis Piezoelectric Accelerometer Model No. 353B15) is also used for calibration and comparison. The wafer holder moves in a forward-backward motion attached to a rotary motor producing a maximum force of 10.42N.

VI. EXPERIMENTATION RESULTS

After fabrication, various designs were tested and they have shown to provide similar results, as such, one design was chosen to be discussed for this section of the paper. The design used would be Design G. Based on the experimental results

Fig. 5. Experimental observations obtained from device at quiescent state from 0 to 50 seconds and motor excitation from 50 seconds onwards.

Fig. 6. Output of device compared with acceleration measured by reference accelerometer

Fig. 5, it can firstly confirm that the proof mass was structurally sound and could be used for experimentation. This goes to show that the design of the device would not cause any issues during fabrication, which is a realistic design. Secondly, the MOEMS layer was able to effectively capture the changes in acceleration when the piston motor was initiated as in Fig. 5. A 3 second delay was purposely given in the graph to show background noise level, which was at $558 \mu\text{W}$. As the acceleration increased on the wafer holder, there was an increase in the intensity detected by the photodetector up to a peak which was at the maximum point of the piston arm. Subsequently the intensity dropped up to a point where there were irregularities in the intensity detection. This was a result of the motor limitation which made it unable to provide a constant torque when the piston arm was retracted. However, the motor still worked well at the other stages of the rotation cycle thus it can still be used. The overall device detected intensity compared with the acceleration readout from the reference accelerometer shows a sensitivity of $294 \mu\text{W/G}$ (See Fig. 6) with a calculated proof mass displacement of $0.066 \mu\text{m/G}$ which was similar to that calculated in the simulations with an error of less than 10%. The noise level obtained experimentally was higher than the Brownian NEA as obtained in Table 1. This was due to the combination of the background light level, detection circuit, experimental setup and light source noise, which could not be separately measured without adequate equipment. However, further details on noise level measurement can be found which would provide deeper insight in the noise measurement. (Bochobza-Degani et al. 2003; Papin et al. 2012)

VII. CONCLUSION

The design optimization process for a new MOEMS proof of concept device used in seismic motion detection has been discussed. By incorporating the design optimization process, the effects of each variable was studied and a series of designs were developed. Experiments were carried out with one of the devices and results obtained have shown the experimental proof mass displacement to be similar to the sensitivity calculations in ANSYS finite element modelling simulations.

VIII. ACKNOWLEDGMENT

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