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A CMOS MEMS Accelerometer with Bulk Micromachining

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Summary: Due to the lack of important seismic mass, CMOS-FSBM cantilevers have never been carefully considered for inertial sensing. This paper demonstrates that such beams can be used for acceleration measurement. A dedicated cantilever has been designed and fabricated. experimental results have demonstrated a sensitivity of about 22.4 mV/g.

Keywords: CMOS MEMS, Accelerometer.

1 Introduction

When using Front-side Bulk Micromachining (FSBM) as a low-cost fabrication approach, the obtained suspended structures do not feature important seismic mass while both CMOS design rules and wet etching do not allow for capacitive detection. Nevertheless, we have recently demonstrated that the very low noise level in polysilicon gauges allows a theoretical resolution of about 0.5g [1]. We have then designed a test chip to verify the performances of such CMOS cantilevers used as inertial sensors. In this paper we intend to present the mechanical structure and its analytical model that has been validated by FEM simulations. Then, mixed mode simulations of the sensor with its circuitry are reported. Finally, encouraging experimental results that confirm the expected performances are presented.

2 Sensing principle and modeling

The proposed sensor is based on a “T-shaped” cantilever beam that provides a good mass/stiffness ratio with this fabrication approach. The acceleration is measured by means of two embedded strain gauges that convert the vertical displacement of the mechanical structure into resistance variations. A fabricated device is illustrated in Figure 1 with a SEM image of the proposed sensor and its associated CMOS electronic circuitry.

Figure 2 illustrates design parameters of the dedicated beam. As vertical dimensions are imposed by the CMOS fabrication process, design parameters are the size of the plate ($W_p \times L_p$) and the size of the beam ($W_b \times L_b$) plus the design and the location of the polysilicon strain gauges. Two different cantilevers have been fabricated with a single variation of one design parameter: the width W_b of device A is twice the one of device B. The sensitivity of device B is therefore expected to be twice the sensitivity of device A. Dimensions of both structures are summarized in table 1.

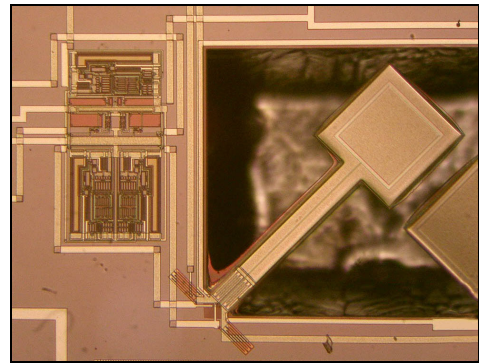


Figure 1. SEM picture of the T-Shaped beam and its electronic circuitry.

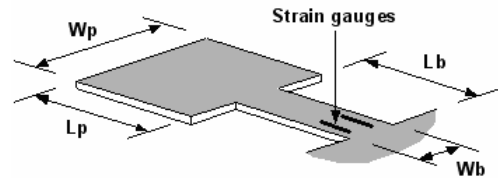


Figure 2. Design parameters of the proposed accelerometer.

Table 1. Dimensions of the “T-Shaped” structures

	Device A	Device B
$L_b \times W_b$ (μm)	480 \times 80	480 \times 40
$L_p \times W_p$ (μm)	280 \times 280	280 \times 280

The cantilever beam is modeled by a second order mechanical system including a spring k , a mass M and a damper D . The actual model considers a uniformly loaded beam. This model is used to compute accurately the equivalent stiffness, mass and damping factor.

3 Design environment

We have implemented an analog-HDL description of the sensor in order to simulate the behaviour of the sensor concurrently with the electronic circuitry.

The on-chip electronic circuit is a programmable instrument amplifier with three possible values of the gain (20\110\1000).

After calibration of the model to fit experimental results we have calculated the resolution by means of a noise simulation. When integrating the input noise from DC up to the cantilever resonant frequency, we obtain a resolution of 1.7g for a system based on T-Shape A and 0.89g for a system based on T-Shape B. Given that most of the observed noise comes from the implemented amplifier (Op-Amp based) [2], this resolution can be improved by designing a dedicated low-noise amplifier.

4 Experimental Results

The experimental setup is shown in figure 3. The packaged test chip is attached to a one-axis shaker which can apply sine-wave vibrations with magnitudes ranging from 0.1g up to 20g at various frequencies up to 200Hz. Shocks can be also applied in a range from 200g to 2000g.

The output signal of the test chip is captured by an oscilloscope, the latter being triggered by means of the shaker built-in accelerometer.

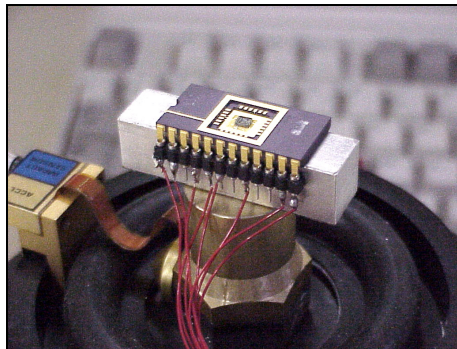


Figure 3. Close-up view of the test chip attached to the shaker.

This setup has been used to study the sensor response to both shocks and sine wave accelerations. The results are partially presented hereafter.

Figure 4 displays experimental results for the test chip under a 20g sine-wave accelerations at 100Hz. The thin curve is the T-Shape B response while the thick curve correspond to T-Shape A.

The sensitivity of both fabricated sensors is reported in figure 5 with the amplifier gain set to 1000. Regarding the response to a sinusoidal input, a sensitivity of about 14.1mv/g has been observed for T-Shape A and 22.4mV/g for T-Shape B. Resolution has been evaluated around 1g at 100Hz.

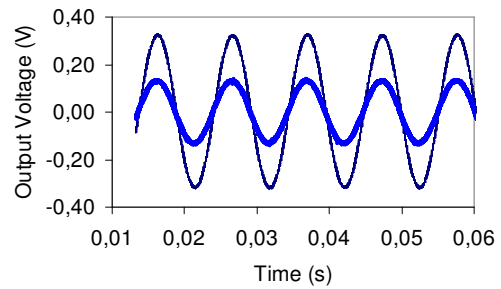


Figure 4. Sensor response to a 20g vibration @ 100Hz.

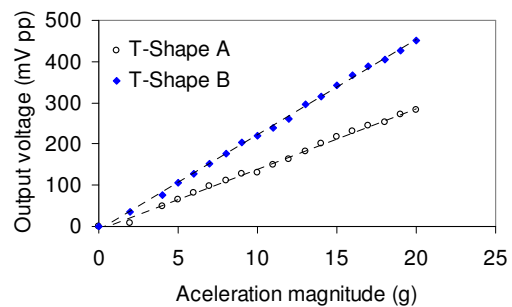


Figure 5. Sensitivity of the two devices to 100Hz vibrations.

5 Conclusion

In this paper, we intend to demonstrate that FSBM CMOS mechanical structures can be used to manufacture low-cost accelerometers. Based on first theoretical and experimental results, it appears that the poor sensitivity of the mechanical structure itself is compensated by a low noise level. It is therefore possible to increase the performance level by means of dedicated on-chip electronics. A sensitivity of 22.4mV/g has been measured on a test vehicle with a resolution of about 1g. Since both sensitivity and resolution can be improved by design, and because the fabrication process is cheap and fully industrialized, we believe that this sensing solution should be considered for out-of-plane (z-axis) acceleration measurement, in association with already reported comb-drives or convection heat transfer devices for other directions.

References

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2. T.B. Gabrielson; *Mechanical-Thermal Noise in Micromachined Acoustic and Vibration Sensors*, IEEE Transaction on Electron Devices, Vol. 40, n°5, May 1993.