Design and Characterization of a Fully Differential MEMS Accelerometer Fabricated Using MetalMUMPs Technology

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ABSTRACT

This paper presents a fully differential single-axis accelerometer fabricated using MetalMUMPs process. The unique structural configuration and common-centriod wiring of the metal electrodes enables a fully differential sensing scheme with robust metal sensing structures. CoventorWare was used in sensor design. The MUMPS foundry fabrication process of the sensor allows for high yield, good process consistency. The sensitivity was measured as 0.8 mV/g prior to off-chip amplification. Dynamic characterization of the sensor was performed using a vibration shaker with a high-end commercial calibrating accelerometer as reference.

Keywords: Accelerometer, MetalMEMPs, Capacitive Sensor, Fully Differential Sensing.

1. INTRODUCTION

One of the current trends in physical sensor technology is hybrid approach rather than monolithic integration, for optimal sensing element, dedicated electronics and overall low cost. Electroplated metal as sensing structural material has been attempted for robust sensors. Recently a microgyroscope fabricated using a customized nickel plating process has been reported [1]. For process controllability and overall low cost of MEMS elements, foundry services are preferable. Among the many MEMS foundry services, MUMPs provides relatively mature technologies for a variety of MEMS materials including metal. Although MetalMUMPs technology has been widely used for various types of actuators [2], due to the limitation of design rules, only few types of sensors have been exploited using this process [3]. In this reported displacement sensing scheme, a capacitive half-bridge sensing circuit is constructed using sidewall capacitance formed by nickel electrodes.

In this paper, a MetalMUMPs capacitive accelerometer employing in-plane sensing mechanism has been designed, fabricated and characterized. To validate the unique sensing mechanism, no conditional circuit is integrated on the chip in this work. Instead, a commercially universal capacitive readout IC MS3110 from Irvine Sensor was used in device characterization. Common-centroid wiring of the symmetrically partitioned sensing capacitor groups allows a fully differential sensing scheme and offset cancelation for large sensitivity.

2. DEVICE DESIGN AND SIMULATION

Fig. 1 shows a 3D model of the fabricated fully differential accelerometer. The sensor has an overall dimension of approximately 1.6 mm × 1.2 mm in size with a thickness of approximately 20 mm. The proof mass is anchored through the four folded springs that suspend the proof mass symmtricly. MetalMUMPs technology has been used for sensor design and fabrication. The schematic cross-section of the released structure is illustrated in Fig. 2 which shows MetalMUMPs layers used in this project and their spatial locations. The critical technological parameters of MetalMUMPs technology is summarized in Table 1 [2].

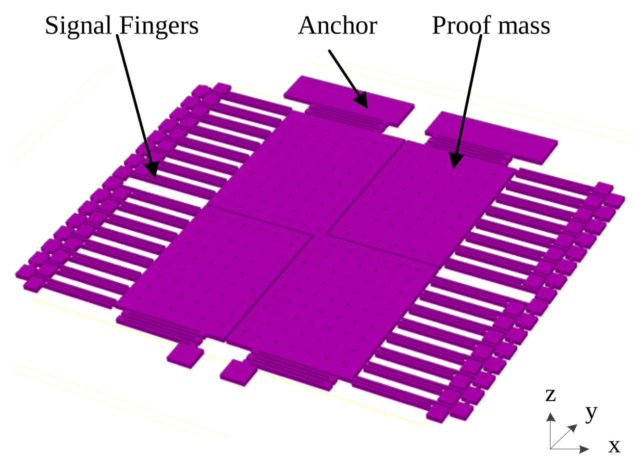


Fig.1. 3-D model of the fully differentialaccelerometer.

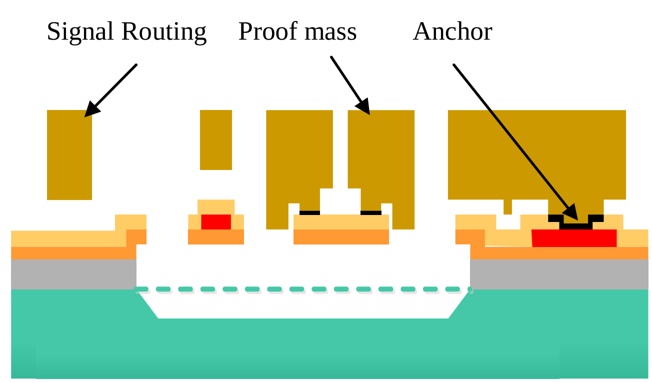


Fig.2. Cross-sectional view of the structures of a released accelerometer.

NSTI-Nanotech 2011, www.nsti.org, ISBN 978-1-4398-7139-3 Vol. 2, 2011

Layers	Thickness(µm)
Isolation Oxide	2.0
Oxide 1	0.5
Nitride 1	0.35
Poly	0.7
Oxide 2	1.1
Nitride 2	0.35
Anchor Metal	0.035
Metal	20

Table 1 Typical MetalMUMPs Layers Thickness

Other parameters such as the sensor geometric and material properties and their values for sensor design are listed in Table 2.

Symbol	Description	Value
E	Nickel's Young's Modulus (GPa)	214
$L_m \times W_m$	Proof mass length and width (µm×µm)	1000×1300
L_s	Sensing finger length (µm)	300
t	Structure thickness (µm)	20
L×W	Springs length and width (µm×µm)	1200×8
g	All sensing finger gaps (µm)	8.0
N	Number of sensing fingers	16×4

Table 2 Geometric and material properties

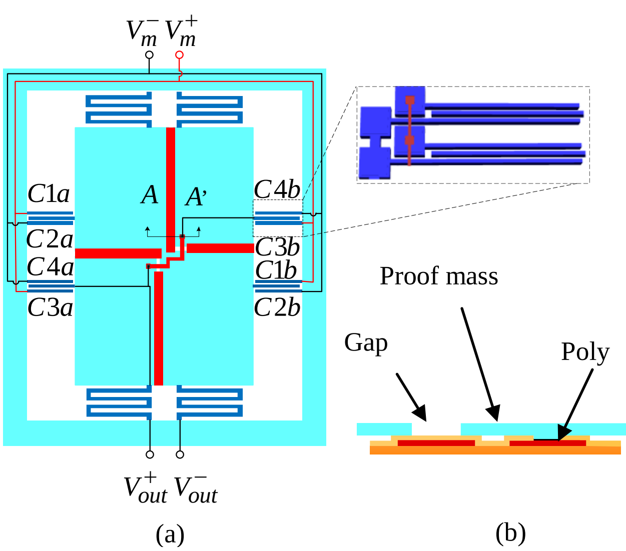


Fig.3. (a) Fully differential configuration of the accelerometer and (b) AA' cross-sectional view.

As shown in Fig. 3(a), to realize fully differential sensing scheme by use of the design rules and material arrangements amply, the metal proof-mass is separated into three pieces which are mechanically connected underneath using the combined layers including nitride, polysilicon and oxide. The two diagonal pieces (upper right and lower left) are connected using polysilicon layer to form a differential output node while the whole large piece is the other output node. Fig. 3(b) shows the cross-sectional view of the combined layers, proof mass and the gap. The gap between the two diagonal pieces and the whole large piece are used for electrical disconnection [4].

An enlarged picture of comb fingers viewed from backside shown in Fig. 3(a) includes comb fingers and anchor of comb fingers. As shown in the picture, the anchor of comb fingers can be classified to two types, anchor without polysilicon and anchor with polysilicon. For the first type, electrical signal generated by capacitance change goes through metal. For the other type, electrical signal goes though the polysilicon which is under the metal layer.

A fully differential sensing bridge is formed by wiring the comb fingers in a common-centroid manner as shown in Fig. 3(a). *C1a*, *C3a*, *C1b* and *C3b* are connected together to V_m^+ while *C2a*, *C4a*, *C2b* and *C4b* are connected together to V_m^-. The electrical equivalent circuit of the sensing bridge is shown in Fig. 4 (Assuming the proof mass is moving forward).

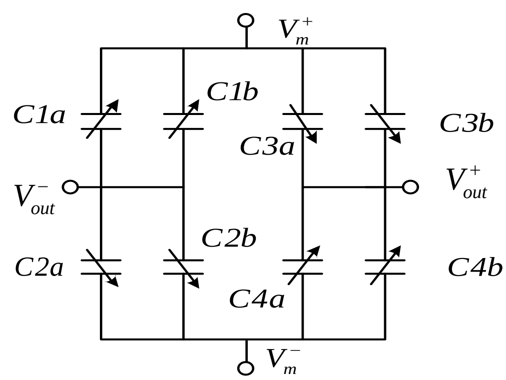


Fig.4. Electrical equivalent circuit for the common-centroid configuration of the sensing capacitors.

The equivalent circuit in Fig. 4 can be further simplified as shown in Fig. 5 where *C1* = *C1a* + *C1b*, *C2* = *C2a* + *C2b*, *C3* = *C3a* + *C3b* and *C4* = *C4a* + *C4b*. Referring to Fig. 5, the output voltage is given by

$$V_S = \frac{2C_S}{2C_S + C_p} \cdot V_m \cdot \frac{x}{x_0} \tag{1}$$

and the overall sensitivity, V_S / a_{in} is given by

$$\frac{V_s}{a_{in}} = \frac{4C_s}{2C_s + C_p} \cdot \frac{1}{\omega_n^2} \cdot \frac{V_m}{x_0} \tag{2}$$

where $V_S = V_{out}^+ - V_{out}^-$, C_S is the sensing capacitance, C_P is the parasitic capacitance formed by wiring metal beams and polysilicon, etc.; V_m is the modulation voltage; x is the displacement of the proof mass under acceleration; x_0 is the

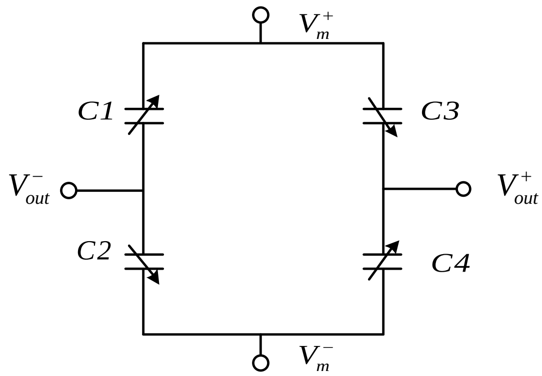


Fig.5. Simplified equivalent circuit of the sensor.

orginal gap between two sensing fingers and ω is the resonant frequency given by

$$\omega = 2\pi f = \sqrt{\frac{k}{m}} \tag{3}$$

where k is the spring constant of the suspension system. These folded springs can be modeled as fixed-fixed beams with spring constant given by

$$k = \frac{N}{n}\left(\frac{12EI}{L^3}\right) \tag{4}$$

where I is the moment of inertia of the rectangular beam cross section given by

$$I = \frac{tW^3}{12} \tag{5}$$

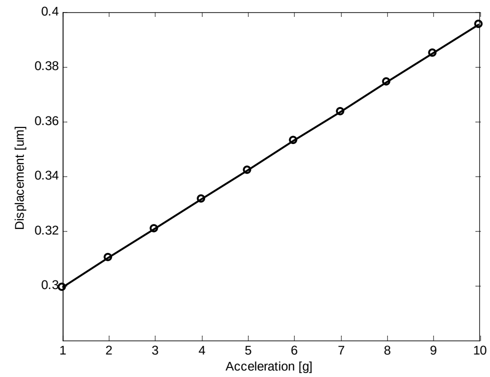
and E is the Young's Modulus of the senser structrue Nickel; t, L and W are the beam thickness, length and width, respectively; N denotes the total number of springs suspending the mass, and n is the number of folds per spring.

The accelerometer presented in this project has 2-turn folded-beams on both ends. The two springs are in parallel configuration in y-axis. Therefore, the total spring constants are given by

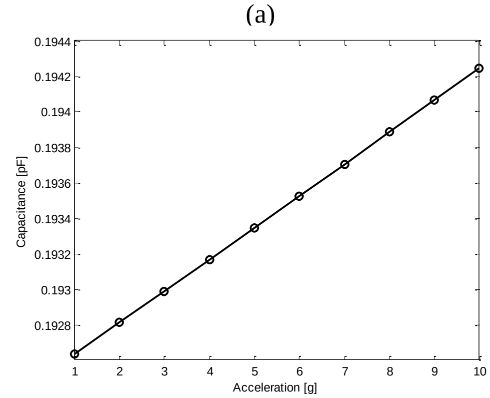
$$k = \frac{4Etw^3}{3L^3} \tag{6}$$

From Eqn. (6), the resonant frequency is calculated as ~ 3 kHz and the overall sensitivity is further estimated as 0.75 mV/g.

CoventorWare, a FEA simulator dedicated to MEMS device design is used in the structural and electrical design of the fully differential accelerometer. Linear responses are observed for both the displacement and capacitance change as shown in Fig. 6. A capacitance sensitivity of ~ 0.16 fF/g has been obtained. Based on these simulaiton, with an external modulation voltage of 2.25 V, a mechanical sensitivity of 3.6 mV/g has been deduced (This may be because of the edge effect). From the modal simulation, the sensor structure demonstrates a resonant frequency of approximately 3.1 kHz, which is within 10% of the calculated value.



(a)



(b)

Fig.6. CoventorWare simulation results for displacement (a), and capacitance change (b), both under acceleration ranging from 1 to 10 g

3. DEVICE FABRICATION

The MetalMUMPs technology has been utilized for the fabrication of the accelerometer through MEMSCAP.The proof mass made by Nickel is cut into three pieces to create electrical disconnection while these pieces are connectted underneath to generate mechanical connection. Nickel which has considerably good electrical and elastic properties as primary structural material and electrical interconnect layer is built on top of polysilicon and nitride with a deep, KOH-etched trench underneath [2]. Doped polysilicon is used as mechanical structures and electrical routing. Silicon nitride is used in this project as an electrical isolation and mechanical connection layer. Fig. 7 shows the plan view of the optical image of a released sensor.

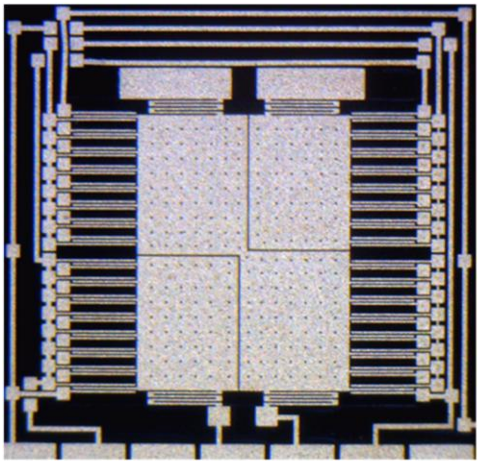


Fig.7. Image of a released sensor.

4. DEVICE CHARACTERIZATION

In device characterization, a universal capacitive readout IC MS3110 with 2.25 V modulation voltage from Irvine Sensor was used. An external bandpass filter with a gain of ~37 dB was employed for further signal conditioning. Preliminary dynamic tests were conducted using a LMT-100 shaker from Ling Electronics. In the measurements, a Type 8692B50 PiezoBeam accelerometer from Kistler was used as a reference. Fig. 8 shows the test setup and the mounting board on which the device under test (DUT) is assembled with the reference accelerometer. The DUT is packaged in a 68 pins J-Bend Leaded Chip Carrier. The board is screwed to the threaded pole of the shaker.

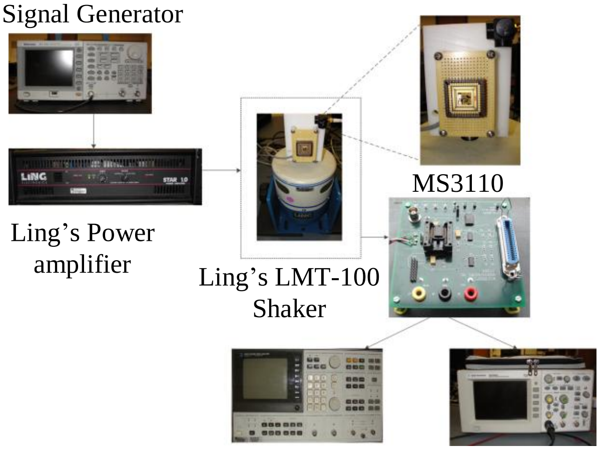


Fig.8. Test setup with inset showing the PCB where the DUT and reference accelerometer are mounted.

Figure 9 shows the comparison of the output waveforms between the fabricated sensor and the reference accelerometer. Prior to the test, the reference accelerometer was calibrited using a hand-held shaker that can provide standard 1 g acceleration at 159.1 Hz. In the test, the excitation was a sinusoidal acceleration with amplitude of 1.4 g and frequency of 110 Hz. Under these conditions, the sensor demonstrated a sensitivity of ~64 mV/g (0.8 mV/g without external gain).

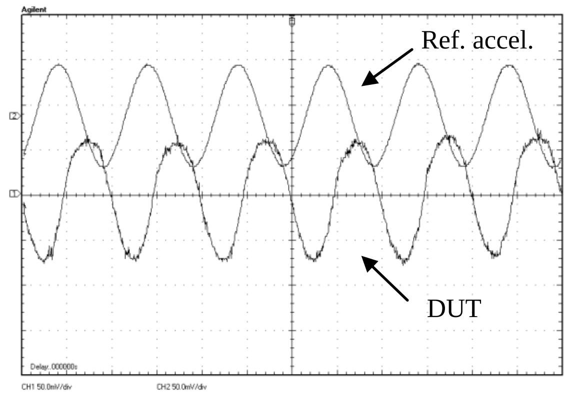


Fig. 9. Capacitance and reference accelerometers response to 1.4g acceleration

5. CONCLUSION

A capacitive accelerometer enabled by MetalMUMPs foundry technology has been designed, fabricated and characterized in this project. The device features fully differential sensing scheme with a unique common-centriod capacitance configuration. In simulation results, linear responses for both displacement and capacitance are observed. With a ~37 dB external amplification gain, the accelerometer achieves a sensitivity of ~ 64 mV/g. Without amplification, the device demonstrates a mechanical sensitivity of 0.8 mV/g.

ACKNOWLEDGEMENTS

The project is partially supported by NSF for Adelia Wong's REU research at Oakland University. The authors would also like to MicroStar LLC for support of device fabrication.

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