



Enhancing Z- Axis Accelerometer Sensitivity Through Differential Capacitance

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Abstract: This MEMS capacitive accelerometers are key component in measuring motion and vibration in wide range of systems. The realization z- axis accelerometer for high-precision motion detection is still challenging, owing to parasitic capacitances, ambient noise, and fabrication anomalies. To address this, we propose an improved z-axis accelerometer design that incorporates four additional fixed pads to enhance differential capacitance measurement. These fixed pads provide a stable reference, allowing for more precise detection of capacitance changes in the proof mass. The area of each fixed pad is carefully calculated to be equal to the sum of the anchor area and 1/16th of the proof mass area, optimizing sensitivity and reducing errors. This design leads to increased performance, decreased cross-axis interference, and improved signal stability. Through improving capacitance measurement, our method aspires to support in developing of more precise and reliable MEMS accelerometers for next-generation sensing applications.

Index Terms - Differential Capacitance, Z- axis accelerometer, Sensitivity.

I. INTRODUCTION

MEMS capacitive accelerometers are vital in diverse applications, ranging from wearable devices and smartphone to industrial monitoring and automotive safety systems [1]–[3]. Capacitive accelerometers gains popularity among other accelerometers due to their high precision, low power consumption, and upfront integration with electronic circuits [4]–[6]. These sensors work by measuring changes in capacitance that occur when a suspended proof mass moves in response to external forces, making them highly effective in detecting acceleration [7].

A key challenge in designing capacitive accelerometers is ensuring accurate differential capacitance measurement, which is essential for precise motion detection. Conventional accelerometers measures change in capacitance between suspended proof mass and fixed electrode [8]. Differential capacitive accelerometers have been developed to improve sensitivity and reduce cross-axis effects.

These designs typically employ a suspended proof mass with comb-like structures to create variable capacitances [9]–[10]. Vertical comb electrodes have been used to achieve three-axis sensing capabilities in silicon-on-insulator devices [11]. Highly symmetrical designs, such as mirror-symmetrically suspended proof masses and cantilever beams on both sides of the silicon wafer, have been implemented to enhance performance and decouple sensing modes [10] and [12]. These accelerometers have demonstrated high sensitivities, with reported [10] - [11]. Signal conditioning circuits, including switched capacitor CMOS-ASICs., have been developed to process the output signals [12]–[15]. However, factors like fabrication inconsistencies, environmental noise, and temperature variations can introduce errors in the measurements

[16]-[17]. These advancements have led to improved linearity, reduced cross-axis sensitivity, and enhanced overall performance in capacitive accelerometers

In this study, we propose a new design approach for z-axis accelerometers by incorporating four additional fixed pads to improve differential capacitance measurement. These fixed pads serve as reference points, allowing for more stable and accurate detection of capacitance variations in the proof mass. To ensure optimal performance, the area of each fixed pad is carefully designed to be equal to the sum of the anchor area and 1/16th of the proof mass area. This configuration is expected to enhance the sensitivity of the sensor, minimize noise, and improve overall measurement accuracy [18]- [19].

The significance of this design lies in its ability to reduce fabrication-induced errors, improve the signal-to-noise ratio (SNR), and provide more reliable measurements for high-precision applications. Similar design strategies have been explored in previous studies, showing promising improvements in performance [20]-[23]. Our work builds on these advancements, offering a refined approach that is particularly beneficial for Z-axis motion detection, which is often more challenging to measure accurately than movements along the X and Y axes [24]

In the following sections, we will explore the theoretical basis of the proposed design, discuss its design considerations, and analyze its expected performance improvements. By addressing the limitations of traditional accelerometer designs, this study aims to contribute to the on-going development of next-generation MEMS accelerometers for high-performance sensing applications.

II. DESIGN OF Z-AXIS ACCELEROMETER.

To improve the capacitive sensitivity of the accelerometer, the concept of differential capacitance has been introduced into the design. Fig 1 shows the Schematic design and cross-sectional view of the accelerometer designed with static capacitance.

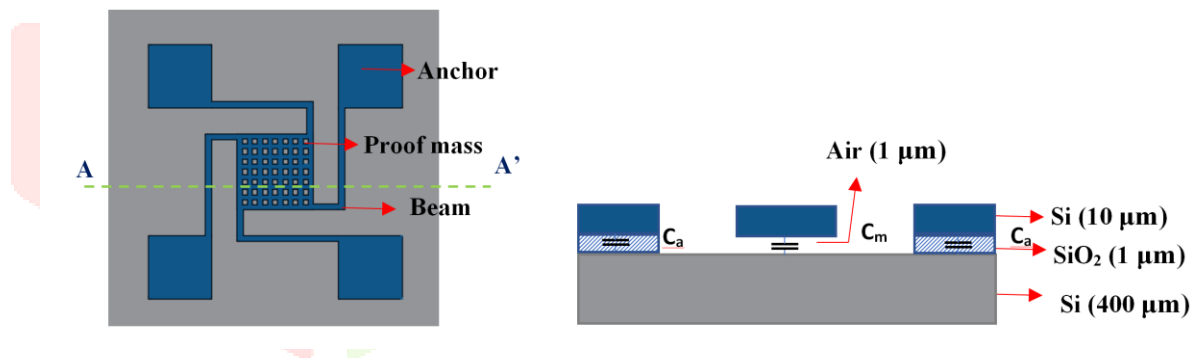


Figure 1 Schematic of z axis accelerometer (a) top view (b) cross sectional view

The following set of equations show the calculation of the overall capacitance of the device under static condition.

$$\text{Apparent area of the Proof mass} = m_s^2$$

$$\text{True Area of the proof mass due to perforations} = m_s^2 * m_{sf}$$

$$\text{Gap between the device layer and the handle layer is } d = 1 \mu\text{m}$$

$$\text{Relative permittivity of air} = 1$$

$$\text{Static capacitance in the proof mass } C_m = \frac{\epsilon_0 \epsilon_r A_p}{d} \dots\dots 1$$

$$\text{Area of the Anchor} = (m_a)^2$$

$$\text{Total Area of the Anchors } A_a = 4 * (m_a)^2$$

$$\text{Relative permittivity of silicon dioxide} = 3.9$$

$$\text{Static capacitance in the Anchor } C_a = \frac{\epsilon_0 \epsilon_r A_a}{d} \dots\dots 1$$

$$\text{Total static capacitance } C_o = C_m + C_a \dots\dots 32$$

MEMS z- axis Accelerometers are parameter design considered for the analysis are tabulated in Table 1. The results of the z- axis accelerometer for designed parameter is shown in Table 2. The total static capacitance of 9.255pF for the designed dimension.

Table1: Dimensions for accelerometer design

S.No	Parameter	Dimensions
1.	Proof Mass	Length 300 μm
		Width 300 μm
		Thickness 10 μm
2.	Perforations	Length 20 μm
		Width 20 μm
		Thickness 10 μm
3.	Flexures	Length 500 μm
		Width 25 μm
		Thickness 10 μm
4.	Air gap	Thickness 1 μm
5.	Material	Silicon<100>

Table 2: Design parameter and result for z- axis accelerometer

Area Proof mass (μm^2)	Area Perforation in proof mass (μm^2)	Area of perforated proof mass (μm^2)	Static capacitance in proof mass (pF)	Area of each Anchor (μm^2)	Static Capacitance in Anchor (pF)	Total Static Capacitance (pF)
300X300	49x20x20	70400	0.623	250X250	8.632	9.255

III. STRUCTURAL MODIFICATIONS IN Z- AXIS ACCELEROMETER

In new design to realize differential capacitance in the z-axis accelerometer, four fixed pads were introduced. The proof mass capacitance variation is measured in relative to the fixed capacitance of these pads. The area of each fixed pad's is designed to be the sum of the anchor area and 1/16th of the proof mass area. To facilitate differential capacitance, the structural modifications were implemented in the mask design as illustrated in Fig 2. The schematic representation of the differential capacitance is illustrated in Fig 3. The parameter g_{fx} represents the gap between the fixed pads and the beams, and its size is constrained by the fabrication process.

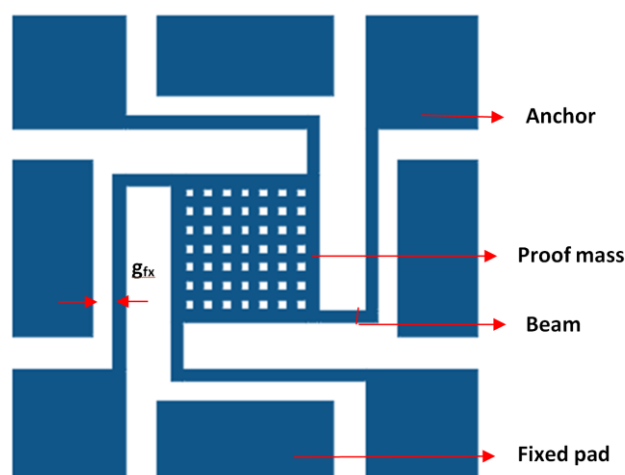


Figure 2 Schematic of z axis accelerometer after structural modification

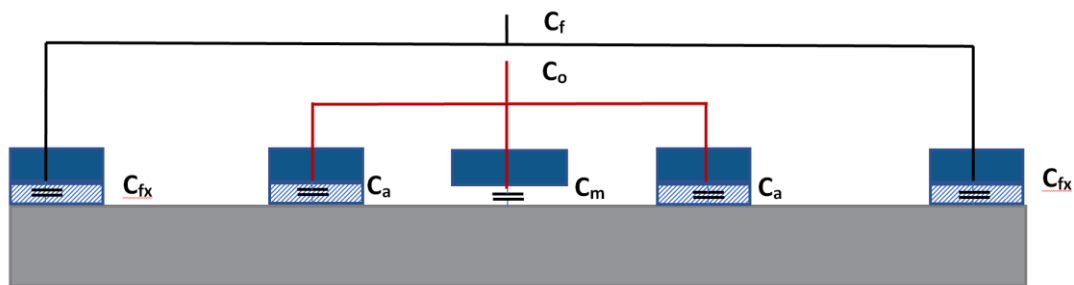


Figure 3 Differential capacitance of z axis accelerometer

The capacitance in the fixed pads $C_f = 4 \times C_{fx}$

The differential capacitance $C_d = C_f - C_o$

Area of the balancing capacitance $C_f = 4 \times C_{fx}$

Therefore area of the balancing capacitance is

$$\text{Static capacitance in the Anchor } C_{fx} = \frac{\epsilon_0 \epsilon_r A_{fx}}{d} = A_{fx} = \frac{C_{fx} d}{\epsilon_0 \epsilon_r} \dots\dots 4$$

Hence $A_{fx} = L_{fx} W_{fx}$

Where L_{fx} is the length of the balancing capacitance

W_{fx} is the width of the balancing capacitance

Table 3: Design parameter and its result for modified z- axis accelerometer

Design	Capacitance in Fixed Pad C_f (pF)	Capacitance of fixed Pads (pF)	Area of fixed pad A_{fx} (μm^2)	Gap between beams and pad g_{fx} (μm)	Width of the fixed pad W_{fx} (μm)	Length of fixed Pad L_{fx} (μm)
Design 1	9.255	2.314	67005	25	200	268
Design 2	9.255	2.314	67005	20	205	327
Design 3	9.255	2.314	67005	15	210	319
Design 4	9.255	2.314	67005	10	215	312

The dimensions of the fixed pad were analysed for different g_{fx} values, as presented in Table 3. The design results indicate that for a g_{fx} of 25 μm , the fixed pad measures $200 \times 268 \mu\text{m}^2$. Similarly, for a g_{fx} of 20 μm , the dimensions are $205 \times 327 \mu\text{m}^2$, for g_{fx} of 15 μm , they are $210 \times 319 \mu\text{m}^2$, and for g_{fx} of 10 μm , the fixed pad measures $215 \times 312 \mu\text{m}^2$. The capacitance values remain the same across all designs, indicating that the modifications in dimensions aim to optimize other performance parameters rather than capacitance itself. As the gap between the beams and the pad (g_{fx}) decreases, the width (W_{fx}) increases, while the length (L_{fx}) varies. The total area (A_{fx}) remains constant, meaning adjustments in width and length compensate for each other. The smaller gap sizes (g_{fx}) can improve sensitivity but may introduce fabrication challenges due to tight tolerances. The trade-off between width and length ensures that the area remains constant, likely helping maintain mechanical stability while optimizing performance. The consistent capacitance values suggest that these design adjustments primarily influence structural parameters rather than electrical properties.

IV. CONCLUSION

The integration of fixed pads in the design of the Z-axis accelerometer has successfully enabled the realization of differential capacitance measurement. By providing stable reference points, these fixed pads enhance the accuracy of capacitance variation detection in the proof mass, improving overall sensor performance. The optimized pad dimensions and gap adjustments ensure better signal stability, reduced cross-axis interference, and enhanced sensitivity. This design advancement contributes to the development of high-precision MEMS accelerometers, making them more reliable for applications requiring accurate Z-axis motion detection. Further optimization and experimental validation can refine the design for improved efficiency and

manufacturability. By inclusion of fixed pads in design we were able achieve differential capacitance in z – axis accelerometer.

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