

## Displacement mechanical amplifiers designed on poly-silicon

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### ABSTRACT

Using Poly-Silicon, the implementation of novel Displacement-amplifying Compliant Mechanisms (DaCM), in two geometries of accelerometers, allows for remarkable improvements in their operation frequency and displacement sensitivity, with different proportions. Similar DaCM's geometries were previously implemented by us with Silicon. In all mentioned cases, the geometries of DaCM's are adjusted in order to use them with Conventional Capacitive Accelerometer (CCA) and Capacitive Accelerometer with Extended Beams (CAEB), which operate in-plane mode, (y-axis). It should be noted that CAEB shows improvements (95.33%) in displacement sensitivity compared to ACC. Simulations results, carried out using Ansys Workbench software, validate the system's performance designed with Poly-Silicon. Finally, a comparison with the similar systems, previously designed with Silicon, is also carried out.

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## 1. INTRODUCTION

Micro-accelerometers are devices used to measure acceleration (or g-force)/deceleration, velocity, gravity, position, vibration and shock. About their use in several, areas such as: Engineering, Biology, Industry, Building and structural monitoring, Medical applications, Navigation, Transportation, Volcanology, Consumer Electronics, Motion input, Orientation sensing, Image stabilization, and Device integrity; information can be found in [1]. Another classification, in accordance with their applications by disciplines, is made in academic and consumer-driven [2].

About specific applications, one of the most explored area corresponds to accelerometers on smartphones. In [3], description and evaluation of a system that use phone-based accelerometers to perform human activity recognition are presented. Useful knowledge about habits of users were obtained, just by having them carry cell phones in their pockets. A comprehensive survey of the recent advances in activity recognition with smartphones's sensors is presented in [4]. The potential of mobile activity recognition is attributed to its applications according to the targeted beneficial subjects: (1) applications for the end users such as fitness tracking, health monitoring, fall detection, behavior-based context-awareness, home and work automation, and self-managing system; (2) applications for the third parties, such as targeted advertising, research platforms for the data collection, corporate management, and accounting; and (3) applications for the crowds and groups, such as social networking and activity-based crowd-sourcing [4].

About detection of falls, in [5] a novel algorithm to map the tri-axial accelerometer data streams to bit patterns and mines the frequent bit pattern occurring for normal activities like sitting/standing, lying and walking within a time-sensitive sliding window. Fall have significant peak acceleration and it is detected by setting most significant bit of bit pattern.

On the other hand, in [6], seismic signal of moving targets were successfully measured by a microacceleration measurement system and applied neural networks to the recognition of seismic signals for vehicle targets. About monitoring of power turbines, in [7], it is considered that another approach that is gaining interest among users is to mount accelerometers on the bearing housings, inside the machine, when the power turbine uses rolling element bearings.

In [8], a technological development is described, which involves the detection of hand tremors and cardiac pulse monitoring, by means of a portable physical device. The alarm is implemented by sending an SMS (Short Message Service), to the cell phone of the pre-established contacts, and also by means of an audible alarm installed in the physical device.

Several Apps for health monitoring have been developed, which take their measurements or data, from accelerometers. Other ones can measure and display seismic signals. Some game Apps are played by tilting the device. It is necessary to mention that other sensors could be involved in the measurements. Distributed micro-accelerometers, gyros, force and tactile sensors are used in the design of a novel wearable force and motion capture suit [9].

About mechanical amplifiers, a wide field of research is given by mechanical displacement amplifiers integrated with a piezoelectric (PZT) actuator, for applications such as precision stages in biological manipulations and in high-accuracy devices for optical fibers alignments [10]. PZT actuators can produce large forces [11], but they have relatively short motion ranges (typically about 15–20  $\mu\text{m}$ ) that are not sufficient for many engineering applications [10]. This disadvantage can be overcome by the use of a displacement amplification mechanism.

About accelerometers performance, in order to obtain the acceleration value, accelerometer has a moving mass connected to suspension beams. When there is an external acceleration, the mass is displaced from its initial position. The magnitude of this displacement is proportional to the magnitude of the acceleration and inversely proportional to the rigidity of the suspension beams [12]. These devices stand out due to their high sensitivity of displacement or high operation frequency [13].

On the other hand, Displacement-amplifying Compliant Mechanisms (DaCM) have the ability to transform the applied displacement at the input into an amplified version of it, obtained at the output of the system. It uses elastic deformation of its members to transform or transfer an input displacement, force or energy to the output. DaCMs are amenable for microfabrication because they do not have joints and thus most of them are available in one piece. Due to, no wear, backlash or friction associated with joints. Furthermore, they make use of 2D geometry with uniform thickness and hence they can easily be lithographically patterned and microfabricated. In [14], the DaCM was developed with an interdigitated accelerometer. DaCM's allow amplification or gain of mechanical signals due to the simple assembly of its parts, such as rigid beams connected by bolts [15].

DaCMs were first used to amplify the output of piezoelectric stack actuators. Piezo-electric material has become increasingly popular in positioning devices due to its accuracy and ease of use [16]. These stacks generate high forces but small displacements of around 10  $\mu\text{m}$  for a 1 cm stack.

In this paper, two systems conformed by an accelerometer and a DaCM, are designed in Poly-Silicon, in order to identify their performance and to compare them with the corresponding individual accelerometer response. Subsequently, their performance will be compared with those presented in [17], to validate our scaled models, using Poly-Silicon.

## 2. RESEARCH METHOD

The ensitivity of displacement of a capacitive accelerometer can be calculated from Equation (1) [18].

$$S_x = ma/k \quad (1)$$

Where  $m$  is the mass of the system,  $a$  is the acceleration,  $x$  is the sensitivity of displacement and  $k$  is the stiffness constant or spring constant, given by Equation (2).

$$k = Et(wb/lb)^3 \quad (2)$$

Where  $E$  is the Young's modulus of material,  $t$ ,  $w_b$  and  $l_b$  are the thickness, wide and length of the suspension beams, respectively.

The accelerometer will have an adequate displacement sensitivity corresponding to each acceleration value, as long as no resonance frequencies are present. This is due to, as it is well known, before any resonance frequency is generated, the device will operate in accordance with the design requirements, under which it was developed. For this reason, it is recommended to design devices for high operating frequencies, in order to avoid low resonance frequencies.

In this work, an improvement in the displacement sensitivity and operation frequency with the DaCM implementation, is presented in accordance with simulation results. The complexity of the implemented system makes also complex its theoretical analysis as well.

Operation frequency of an accelerometer can be calculated, by Equation (3), [18].

$$f = (1/2\pi)(NEtw_b^3/mlb^3)^{1/2} \quad (3)$$

Where  $N$  is the number of suspension beams.

All designs and simulations were realized considering the in-plane mode.

### 3. RESULTS AND ANALYSIS

#### 3.1. Structures implemented in poly-silicon

The purposes of this paper are: Improve the displacement sensitivity and operation frequency of the Conventional Capacitive Accelerometer (CCA) made in Poly-Silicon, using extended beams (CAEB) and, compare the simulated performance of the systems formed by each accelerometer and the corresponding DaCM, designed in Silicon [17] with similar systems designed with Poly-Silicon (Section 3.2.).

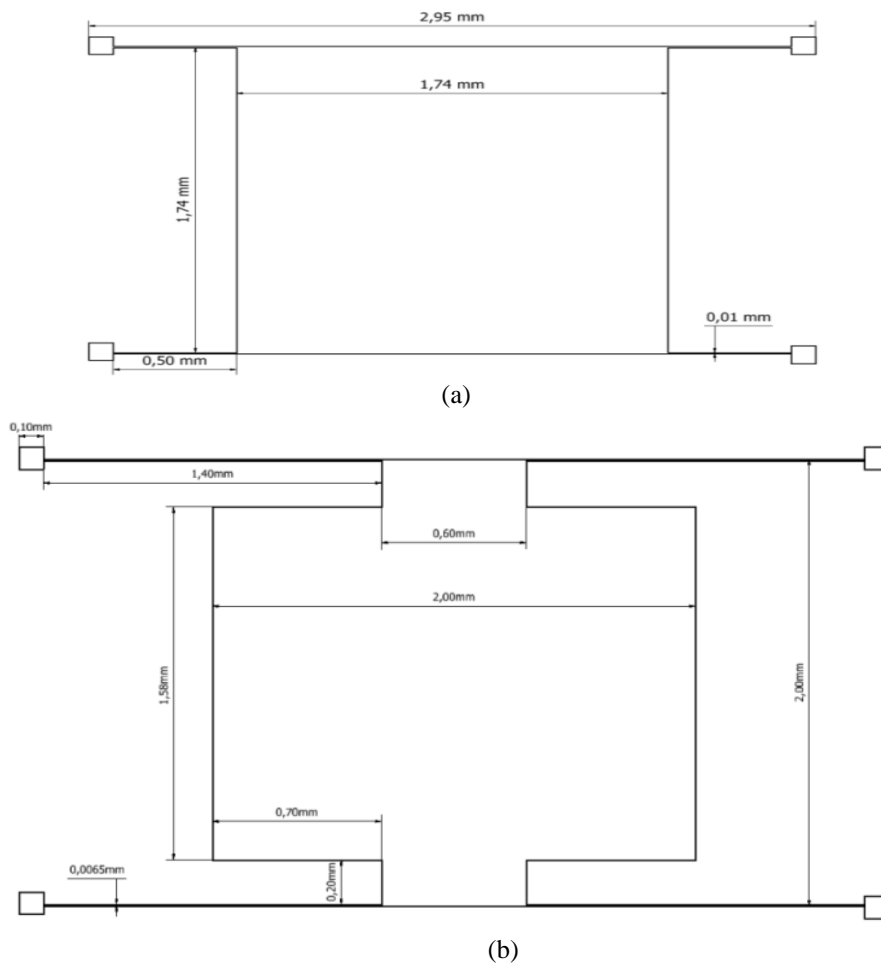


Figure 1. Dimensions of (a) CCA and (b) CAEB

Silicon properties properties are shown in Table 1. The dimensions of the CCA and CAEB designed in this material are shown in Figure 1. For CAEB, beams are extended, without excessively reduce the value of the mass, in accordance with sensitivity Equation (1).

Table 1. Properties of Poly-Silicon [19]

Property	Value
Density ( $\rho$ ), kg/m <sup>3</sup>	2320
Thermal expansion coefficient ( $\alpha$ ), 1/°C	$2.6 \times 10^{-6}$
Young's Modulus ( $E$ ), Gpa	160
Poisson ratio, (dimensionless)	0.22

To obtain displacement sensitivity and operation frequency for CCA and CAEB, Equations (1) and (3), were used Table 2. In order to validate the analytical values, 1 g (9.81 m/s<sup>2</sup>) is applied in the simulations the error between theoretical and simulated values are lower than 2% while for CAEB, the error is lower than the 1%.

Table 2. Values of CCA and CAEB Parameters In-Plane Mode

Parameter	CCA			CAEB		
	Theoretical Value	Simulated Value	Error	Theoretical Value	Simulated Value	Error
Displacement sensitivity, $S_x$	0.056 $\mu\text{m/g}$	0.057 $\mu\text{m/g}$	1.78%	1.23 $\mu\text{m/g}$	1.22 $\mu\text{m/g}$	0.81%
Operation frequency, $f$	2,093 Hz	2,087 Hz	0.3%	447.9 Hz	451.22 Hz	0.74%

A comparison of performance between CCA and CAEB, is shown in Table 3. It is observed that the largest value of displacement sensitivity corresponds to CAEB, but, for the case of operation frequency, the largest value is of CCA.

Table 3. Comparison of Simulated Parameters of CCA and CAEB

Parameter	CCA	CAEB	Improvement
Displacement sensitivity, $S_x$	0.057 $\mu\text{m/g}$	1.22 $\mu\text{m/g}$	CAEB 95.33%
Operation frequency, $f$	2,087 Hz	451.22 Hz	CCA 78.38%

For DaCM implementation, the accelerometer's mass will be reduced at a half of its original size, in order to improve both, displacement sensitivity and operation frequency. Figure 2 shows the dimensions of CCA and CAEB, with the integration of the DaCM, respectively. As it can be observed, the accelerometer's height is halved, compared to the CCA and CAEB, respectively Figure 1. Geometries of DaCMs are different.

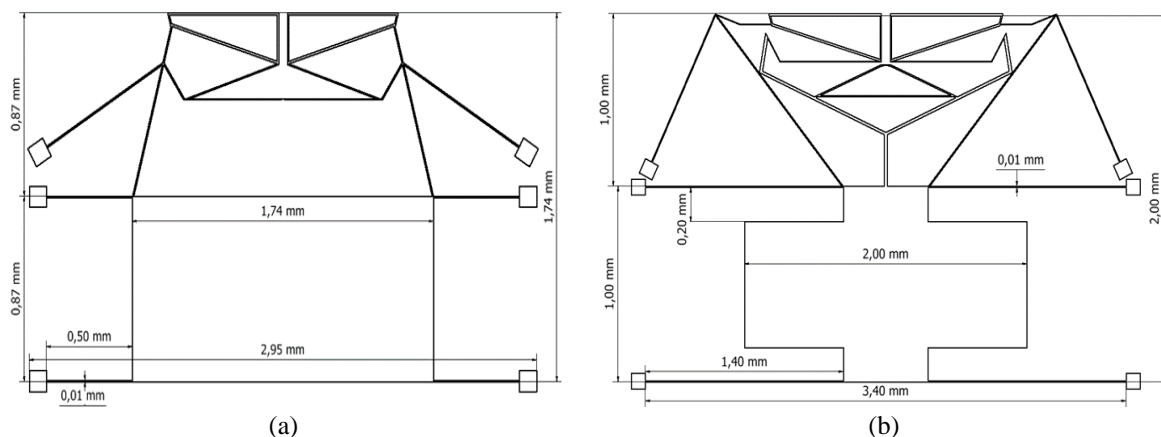


Figure 2. Dimensions of (a) CCA and (b) CAEB with DaCM, respectively

Simulations were carried out as in the cases previously shown. Figure 3 and Figure 4 show the simulated result of the displacement sensitivity and the operation frequency for CCA and CAEB, respectively.

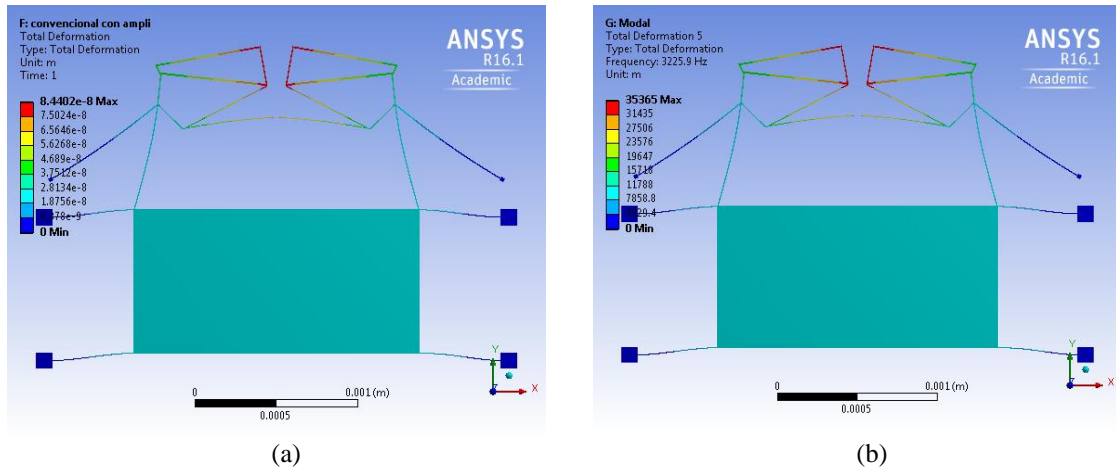


Figure 3. (a) Displacement sensitivity and (b) operation frequency of CCA with DaCM

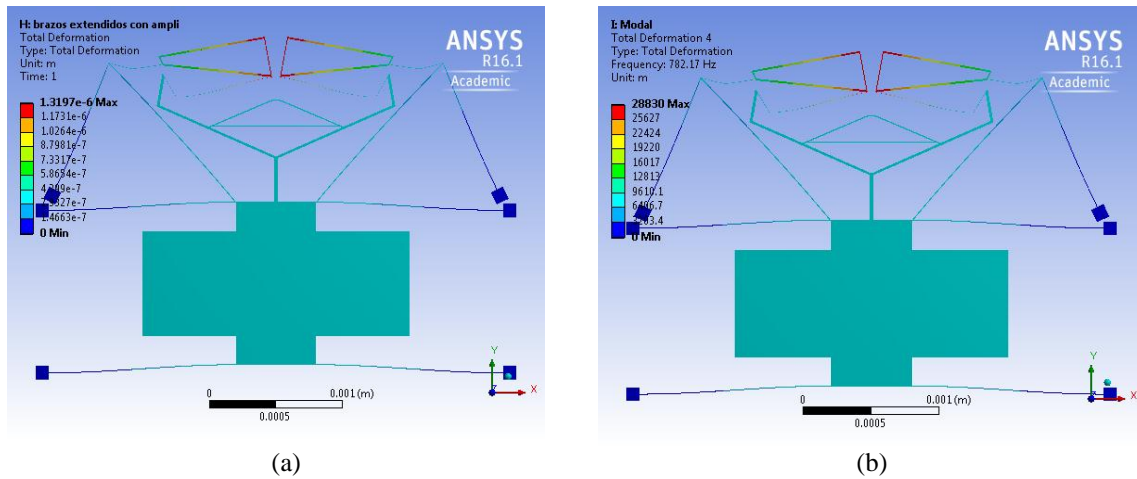


Figure 4. (a) Displacement sensitivity and (b) operation frequency of CAEB with DaCM

Table 4 shows a comparison of the results obtained by simulation between the individual CCA and the CCA with DaCM. As it can be observed, the improvements in displacement sensitivity and in operation frequency are near to 50%.

Table 4. Comparison of Simulation Results for CCA’s Simulated Parameters, with and without DaCM

Displacement Sensitivity			Operation Frequency		
CCA	CCA with DaCM	Improvement with DaCM, %	CCA	CCA with DaCM	Improvement with DaCM, %
0.057 $\mu\text{m/g}$	0.084 $\mu\text{m/g}$	47	2,087 Hz	3,225.9 Hz	54

Table 5 shows the comparison of the results obtained by simulation between the single CAEB and the CAEB with DaCM. In this case, both parameters show increments, but in different proportion, very significant only for the case of operation frequency.

Table 5. Comparison of Simulation Results for CAEB's Parameters, with and without DaCM

Displacement Sensitivity			Operation Frequency		
CAEB	CAEB with DaCM	Improvement with DaCM, %	CAEB	CAEB with DaCM	Improvement with DaCM, %
1.22 $\mu\text{m/g}$	1.31 $\mu\text{m/g}$	7	451.22 Hz	782.17 Hz	73

### 3.2. Comparison between poly-silicon and silicon structures

In this section, a comparison of simulated parameters for structures implemented with Poly-Silicon here implemented; with similar structures designed and simulated in Silicon [18], is performed. Table 6 shows a comparison of the displacement sensitivity in CCA and CAEB without DaCM and with the integration of these in Poly-Silicon and Silicon.

Table 6. Comparison of Displacement Sensitivity and Operation Frequency Simulated Values for CCA and CAEB, with and without DaCM

Material	Displacement sensitivity, $\mu\text{m/g}$					
	CCA	CCA with DaCM	Improvement with DaCM, %	CAEB	CAEB with DaCM	Improvement with DaCM, %
Silicon	1.12	1.72	53	10.77	<b>13.18</b>	47
Poly-Silicon	0.057	0.084	22	1.22	<b>1.31</b>	7
				Operation frequency, Hz		
Silicon	471.05	<b>711.52</b>	51	152	245.38	61
Poly-Silicon	2,087	<b>3,225.9</b>	54	451.22	782.17	73

#### About displacement sensitivity:

For Silicon, with the implementation of DaCM, the displacement sensitivity, compared with the individual accelerometers has a similar increment, near to 50%, but nominal value is bigger for the case of CAEB with DaCM. When Poly-Silicon is used, the sensitivity increment is bigger in the case of CCA with DaCM, but, CAEB values remain bigger.

Poly-Silicon implementation is suggested to provide a displacement sensitivity below 1  $\mu\text{m/g}$ , and for operating frequencies range from 450 up to 3,200 Hz.

#### About operation frequency:

For Silicon, with the implementation of DaCM, the increment of operation frequency is bigger for CAEB with DaCM, but nominal value is bigger to CCA with DaCM. When Poly-Silicon is used, the increment of operation frequency with DaCM is bigger for the case of ACBE, by 54%, but the biggest nominal value is for the case of CCA with DaCM.

In general, for the materials under analysis, bigger values of displacement sensitivity corresponds in general to CAEB with DaCM, but for the case of operation frequency, bigger values correspond to CCA with DaCM. About the size of the structures, the dimensions in the XY-planes are shown in Table 7. Areas of the systems accelerometer-DaCM in silicon are equivalent, but in Poly-Silicon, are lightly bigger for the case of CAEB with DaCM.

Table 7. Comparison of Dimensions

Material	Dimensions					
	CCA XY-plane [mm]	CCA with DaCM XY-plane [mm]	Area [mm <sup>2</sup> ]	CAEB XY-plane [mm]	CAEB with DaCM XY-plane [mm]	Area [mm <sup>2</sup> ]
Silicon	11.2, 7	11.2, 7	78.4	11.2, 7	11.2, 7	78.4
Poly-Silicon	2.95, 1.74	2.95, 1.74	5.133	3.6, 2	3.6, 2	7.2

## 4. CONCLUSIONS

In general, the implementation of DaCM structures requires modification in their geometries and in the accelerometer's mass. It was considered that the system did not exceed the area of each individual accelerometer.

About the comparison of the accelerometers with DaCM, designed with Poly-Silicon and Silicon, the conclusions are:

It is suggested the implementation with Silicon to obtain a sensitivity of displacement in a range of 1 to 13  $\mu\text{m/g}$ , and for a range in operating frequencies of 150 to 710 Hz. The implementation with Poly-Silicon is suggested in order to provide a displacement sensitivity below 1  $\mu\text{m/g}$ , and for a range in operating frequencies of 450 to 3,200 Hz.

From the comparison performed, it is also concluded that the behavior of the structures in both materials is similar, although the results are greater for the sensitivity of displacement when Silicon is used, while the higher operation frequency corresponds to the case of Poly-Silicon, for CAEB and CCA with DaCM, respectively. This fact is due to the mass involved is smaller than in the case of Silicon, as it is required by the design rules.

The size of the systems implemented in Poly-Silicon, are approximately one-third smaller than those implemented in Silicon. Systems' sizes do not surpass that of the accelerometers analyzed independently. The shape of the DaCM is adjusted in each case, according to limitation on area, and the desired performance.

About the practical impact of DaCM, due to increases in displacement sensitivity or operating frequency, it may not be necessary to use an external amplifier. As future work, the design of new DaCM geometries for geometries of other accelerometers could also be performed.

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