2023 IEEE 36th International Conference on Micro Electro Mechanical Systems (MEMS) | 978-1-6654-9308-6/23/$31.00 ©2023 IEEE | DOI: 10.1109/MEMS49605.2023.10052375

HIGH SENSITIVITY MEMS Z-AXIS ACCELEROMETER WITH IN-PLANE DIFFERENTIAL READOUT

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ABSTRACT

This paper reports the innovative design and a preliminary experimental characterization of a miniaturized *z*-axis accelerometer. For the first time in a MEMS accelerometer, a motion conversion mechanism is implemented to allow an electrostatic readout based on in-plane comb fingers, thus overcoming the main limitations of out-of-plane parallel plate detection, e.g. nonlinearities, trade-off between sensitivity and full-scale range, pull-in, etc. The first prototype fabricated by exploiting the features of the Thelma-Double fabrication process shows an experimental sensitivity of 12.9 fF/g which agrees well with numerical predictions computed by considering nominal geometric dimension of the sensor.

KEYWORDS

MEMS, *z*-axis accelerometer, motion conversion, high-sensitivity, differential readout, comb fingers.

INTRODUCTION

Since the early 1990s, a large variety of *z*-axis electrostatic accelerometers have been proposed [1]-[2]. They mainly belong to two families exploiting either translational or rotational motion depending on the possibility to manufacture top and bottom electrodes through the different techniques adopted for fabrication. Due to the out-of-plane nature of such sensors, parallel-plate based differential readout has been usually implemented with consequent compromise between sensitivity, linearity and full-scale [3].

Only few designs able to implement a readout system based on capacitors with varying overlap have been proposed so far. In [4], for example, a force rebalance readout is proposed by combining lateral comb fingers electrodes (used for sensing) with a parallel plate capacitor located beneath the proof mass (used to electrostatically pull-down the mass in closed-loop operation). In [5]-[6] *z*-axis accelerometers with asymmetric vertical comb fingers are presented as valid solution to overcome limitations of parallel-plates based readout schemes. In [7], regular comb fingers are instead employed to measure the out-of-plane displacement of the proof mass induced by external acceleration in a non-differential way.

However, innovative, compact and high-performance solutions compatible with standard MEMS fabrication processes are still required to allow an efficient and differential readout of out-of-plane accelerations. To this purpose, the idea to design proper suspension springs able to convert an out-of-plane (in-plane) force into an in-plane (out-of-plane) displacement developed in the last years for MEMS actuators seems very promising.

The first out-of-plane (in-plane) to in-plane (out-of-plane) motion-conversion mechanism in MEMS actuators has been introduced by Ando et al. [8]-[9]. They exploited slanted cross-section beams to obtain an out-of-plane motion as consequence of an imposed in-plane force. Thanks to the non-symmetric cross-section, indeed, this spring provides intrinsic coupling between out-of-plane and in-plane movements [10]. The main drawback of their solution is related to the complex fabrication process it requires. Slanted cross-sections can indeed be realized in MEMS through anisotropic wet etching that is however not suitable for rectangular cross-sectioned comb fingers needed for actuation. To solve this problem, Hotzen et al. [11]-[12] proposed a different motion conversion mechanism based on ladder-shaped suspension springs which are more compatible with MEMS mass-production despite preserving the ability to generate out-of-plane motion as consequence of an applied in-plane force.

Here we start from the idea presented in [11]-[12] and we propose an innovative design for the suspension springs of a *z*-axis accelerometer able to convert the out-of-plane translation of the proof mass induced by the inertial force in an in-plane motion of the external frames where readout comb fingers are located.

The resulting design represents the first prototype of a new generation of high sensitivity *z*-axis MEMS accelerometer with in-plane differential readout fully compatible with a commercial fabrication process, i.e. Thelma-Double by STMicroelectronics [13]-[14].

MECHANICAL DESIGN

In Fig. 1a, a schematic and simplified view of the proposed suspension spring is reported for the sake of clarity. From the structural perspective, it consists of two elongated springs fabricated on the first (EPI 1) and second (EPI 2) polysilicon layers, respectively and connected through auxiliary blocks built with full silicon thickness (EPI 1 + EPI 2). Thanks to the non-symmetric cross-section, a force applied along the *z*-direction on one side of the spring, will cause a displacement along both the *z*- and the *y*- directions [10]. If a proof mass is then connected on one side of such springs and an external frame properly constrained to move only along the *y*-axis direction, is attached on the other side, a *z*-axis accelerometer with in-plane differential readout can be obtained.

In Fig. 1b, a 3D-view of the proof-mass suspension spring here proposed is reported together with the definition of the main geometric quantities whose dimensions are collected in Table 1. With respect to the simplified scheme shown in Fig. 1a, auxiliary masses (colored in grey in Fig. 1b) can be seen. They only guarantee fabricability of the structure through the Thelma-Double process without playing any structural role.

The proposed *z*-axis accelerometer is schematically shown in Fig. 2a. It consists in a rectangular proof mass

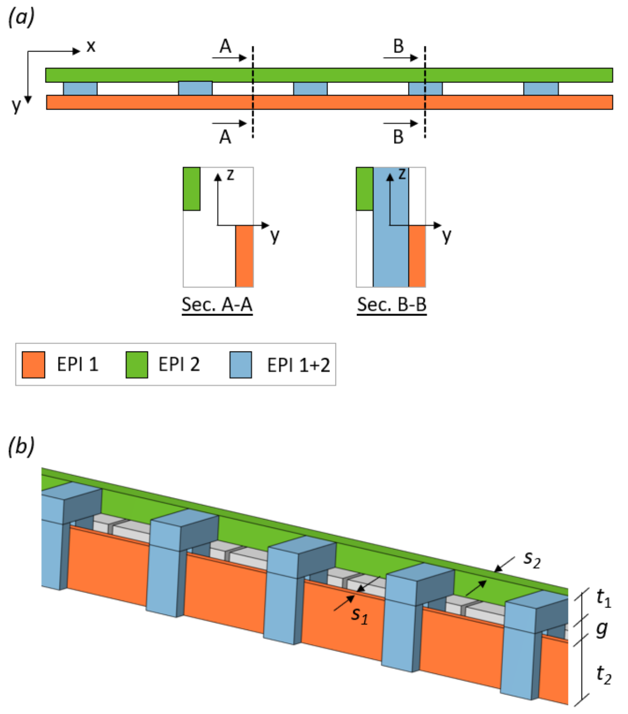

Figure 1: (a) Schematic in-plane view of the proposed suspension spring with non-symmetric cross-sections. It consists of two elongated springs fabricated on the first (EPI 1) and second (EPI 2) polysilicon layers, respectively and connected through auxiliary blocks built with full silicon thickness (EPI1 + EPI2). (b) 3D view of the spring configuration implemented in the proposed z-axis accelerometer.

Table 1: Geometric nominal dimensions of the proposed non-symmetric cross sectioned z-axis accelerometer proof mass suspension springs.

s_1	1.7 µm	t_1	20 µm
s_2	3.0 µm	t_2	8.2 µm
l_1	1440 µm	g	1.8 µm
l_2	1440 µm		

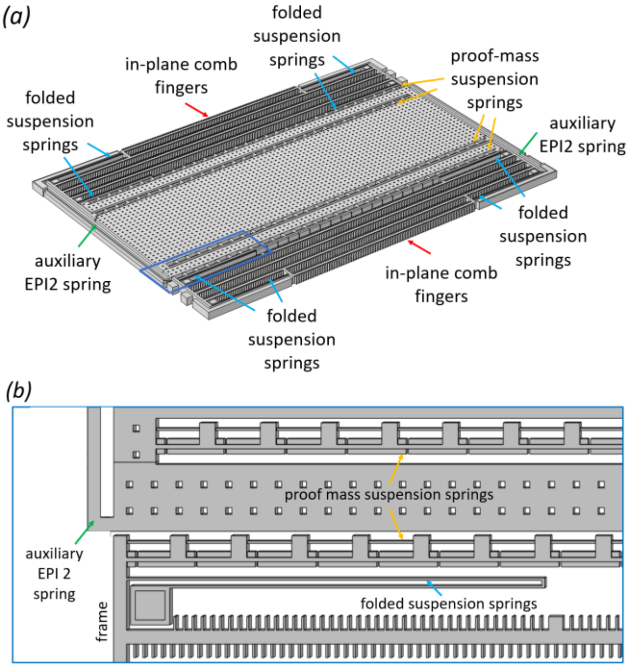

Figure 2: (a) Schematic view of the proposed z-axis accelerometer. (b) Close-up view of the bottom-left corner of the proposed z-axis accelerometer.

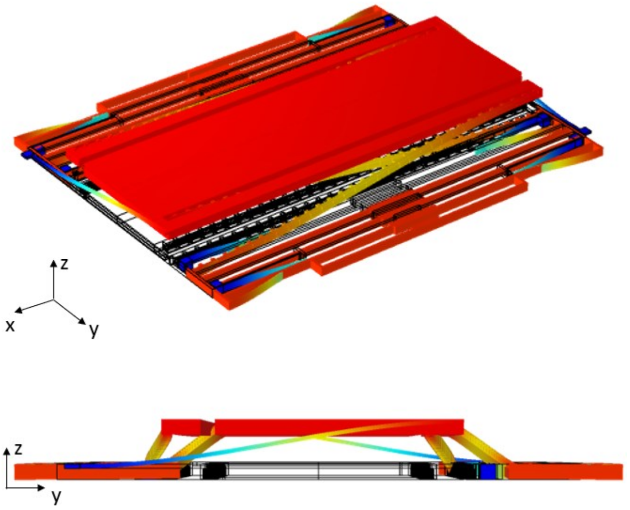

Figure 3: Modal shape function of the first mode of the structure. The normalized displacement field is shown in color.

connected through four non-symmetric cross-sectioned springs (Fig. 1) to two external frames suspended from the substrate through standard rectangular cross-sectioned folded springs. The proof mass, the two auxiliary frames and the folded suspension springs are fabricated such as to have a EPI1+EPI2 out-of-plane thickness. Comb fingers electrodes are located inside the two external frames for the in-plane readout of the *z*-axis external acceleration. Two additional suspension springs made in EPI2 are finally connected to the proof mass to avoid unwanted spurious torsional modes at low frequencies while not penalizing the desired movement of the structure.

In Fig. 2b, a close-up view of the bottom-left corner of the proposed accelerometer is shown for the sake of clarity. Proof mass and external frames suspensions springs are shown together with a portion of the auxiliary EPI 2 spring. Stators allowing the differential in-plane readout of the *z*-axis acceleration are not reported in Fig. 2b for simplicity, while holes in the proof mass are necessary to guarantee the structure release through the adopted MEMS fabrication process.

The first mode of the structure is computed in COMSOL Multiphysics through a modal analysis and reported in Fig. 3: it consists in a simultaneous translation of the proof mass in the *z*-direction and of the two external frames in the *y*-direction. The natural frequency of the first mode of the proposed structure computed numerically by considering nominal geometric dimensions is 2100 Hz as reported in Table 2.

When an external acceleration acts on the accelerometer, the proof mass translates in the *z*-direction according to the first mode of the device shown in Fig. 3, thanks to the inertial force. The nearly 1:1 motion conversion ratio between the *z*-axis movement of the proof mass and the y-axis displacement of the external frames is achieved through a proper optimization of the non-symmetrical cross-sections of the proof mass suspension springs. The optimal design of the folded suspension springs guarantees instead the pure translational motion along the y-axis direction of the external frames and thus a differential readout through comb fingers electrodes located in them.

By considering nominal dimensions of the proposed MEMS accelerometer, a sensitivity of 14.4 fF/g is numerically estimated. The full-scale range of the proposed accelerometer in the present realization is limited to 17g by the gap between the proof mass and the substrate, i.e. 1.8 µm, and can in principle be improved by releasing such constraint during fabrication.

Finally, from a set of nonlinear static analyses performed in COMSOL Multiphysics, we numerically demonstrate a nonlinearity below 1%, i.e. 0.37%, for external accelerations in the range 0-50g. Note that numerically estimated nonlinearities take into account both geometric contributions deriving from large displacements of both the proof mass and the auxiliary frames and electrostatic contributions coming from spurious unwanted out-of-plane displacements of comb fingers during the regular functioning of the proposed accelerometer. Out-of-plane displacements of the external frames induced by the non-symmetric cross-sectioned springs' response are minimized by design, but are in principle different from zero and must be taken into account in the nonlinearity estimation.

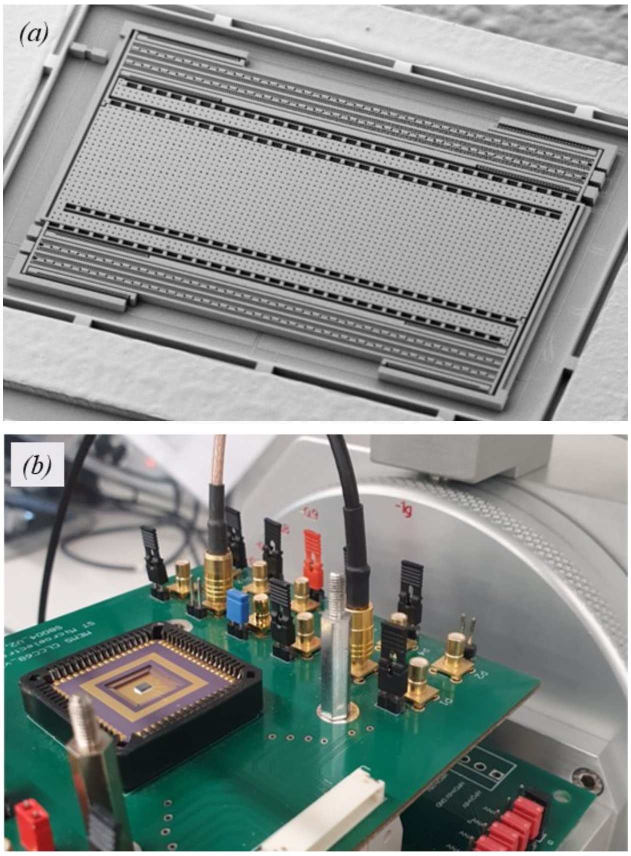

Figure 4: (a) SEM image of the z-axis accelerometer fabricated through the Thelma-Double process of STMicroelectronics. (b) Experimental set-up: the MEMS is wire-bonded to a ceramic carrier, mounted on a PCB and then on a mechanical support able to rotate from the -1g condition to the +1g condition.

EXPERIMENTAL RESULTS

The z-axis accelerometer has been fabricated through the Thelma-Double fabrication process of STMicroelectronics [13]-[14] in polysilicon (E= 160GPa, ν=0.23, ρ = 2330 Kg/m^3) and its Scanning Electron Microscope (SEM) image is reported in Fig. 4a. The z-axis accelerometer footprint is 1524 µm x 980 µm.

The sensor is then wire-bonded on a ceramic carrier and mounted on a Printed Circuit Board (PCB) which has the only function of redirecting the electrical signals from the MEMS transducer to capacitance meter.

The PCB containing the accelerometer under study is then mounted on a mechanical support able to rotate from the +1g to the -1g condition as shown in Fig. 4b.

In Fig. 5 the differential capacitance variation between the movable mass and two sense stator electrodes is reported for different levels of external accelerations in the range -1g - +1g. By fitting the curve, a sensitivity of 12.9fF/g is obtained, which well agrees with numerical predictions summarized in Table 2.

Table 2: Numerical predictions computed in COMSOL Multiphysics by considering nominal geometric dimensions of the accelerometer and experimental results.

	Numerical Predictions	**Experimental Measurements**
Natural Frequency [Hz]	2100	2300
Sensitivity [fF/g]	14.4	12.9
Linearity [@50g]	0.37%	N.A.

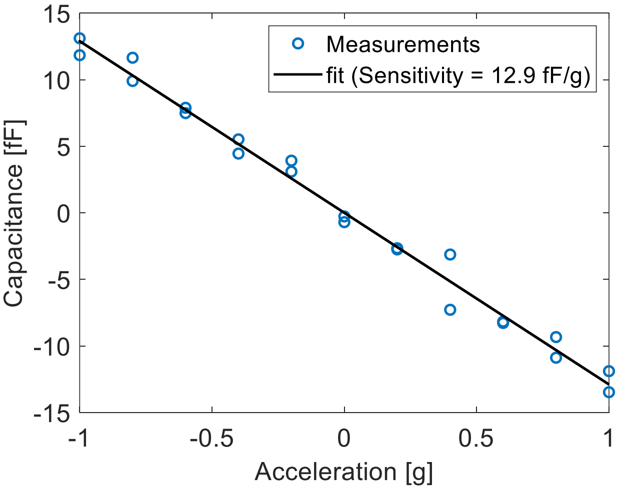

Figure 5: Experimental differential capacitance variation measured on the z-axis accelerometer here proposed when an external acceleration in the range -1g - +1g is applied by rotating the mechanical support to which the PCB is mounted. Linear fitting employed to determine the sensor sensitivity.

A frequency response measurement, not reported here for the sake of brevity, has been also performed by applying a bias voltage on the MEMS *z*-axis accelerometer here proposed, an alternate current signal on one set of electrodes and performing the readout on the other set of electrodes originally designed for the differential readout of the *z*-axis acceleration. The experimental resonant frequency of the first mode (Fig. 3) of the fabricated device is equal to 2300 Hz. It is slightly higher than the one numerically predicted in Table 2, thus suggesting the presence of fabrication imperfections, i.e. over etch and pre-stresses, not correctly catched by the actual model based on nominal geometric dimensions of the mechanical structure.

CONCLUSIONS

A novel high-sensitivity *z*-axis MEMS accelerometer with in-plane differential readout fully compatible with a commercial fabrication process, i.e. Thelma-Double by STMicroelectronics, has been designed, fabricated and preliminary tested.

It shows an experimental sensitivity of 12.9 fF/g which is in good agreement with theoretical estimation computed by considering nominal geometric dimensions of the accelerometer. The small discrepancy between numerical predictions and experiments can be ascribed to fabrication imperfections, i.e. over etch and pre-stresses, not taken into account in the model.

A very promising 0.37% of nonlinearity in the acceleration range 0-50g has been also estimated through numerical analyses and will be experimentally validated in future works.

The proposed accelerometer, thanks to the exploitation of the motion conversion capability of non-symmetric cross-sectioned beams opens the way to a new class of *z*-axis MEMS high-sensitivity accelerometer with in-plane differential readout.

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