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In-plane and Out-of-plane MEMS Motion Sensors Based on Fringe Capacitances

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Abstract

New MEMS motion sensors have been developed. These prototypes are based on a sensing technique that exploits the fringe capacitance between two co-planar electrodes designed over a thin oxide layer covering a grounded wafer substrate. A relevant fraction of the electric-field streamlines, generated by the readout voltage applied between the electrodes, develops in the air (or vacuum) volume over the electrodes. A grounded suspended mass moving within this volume modifies the streamlines configuration, causing relative changes in the capacitance between the electrodes as large as the ~80% of the initial value. Two types of devices based on the described concept have been designed and built in an industrial surface micromachining process, to sense acceleration in the direction both parallel and orthogonal to the substrate surface. The realized devices have been tested and a sensitivity of ~0.9 fF/g and ~0.2 fF/g has been obtained for the in plane and for the out-of-plane structures respectively.

Keywords: MEMS, inertial sensors, fringe field sensors.

1. Introduction

The operating range of a voltage-biased MEMS parallel-plate sensor is limited by the pull-in instability [1]. The problem becomes relevant when, keeping constant the biasing voltage, either the elastic stiffness of the suspended part is lowered or the gap between the plates is diminished, in order to increase the sensitivity-to-area ratio. Solutions proposed to avoid this problem often rely on the development of electronic readout circuits based on feedback controls, which help minimizing the electrostatic readout forces [2]. Another approach consists in exploiting different sensing principles, like resonant sensing: in such a case, the displacement of a suspended part determines variations in the stiffness of a resonator. The consequent resonance frequency change gives information on external forces [3]. In this work a new sensing principle based on fringe field capacitances is studied. A set of suitably designed co-planar electrodes constitutes the sensing element, while a suspended mass subject to external acceleration moves over the fringe field area modifying the steady capacitance value. Similar methods have been used in other types of sensors, such as tactile sensors [4], where a flexible dielectric membrane is moved towards a set of sensing planar electrodes by an external force, for instance a user's finger in touch-screen displays. In the literature only few attempts to use the fringe field effect for motion sensing applications have been reported [5] and none of them was realized with an industrial surface micromachining technique, as in the present work. First, FEM simulations have been

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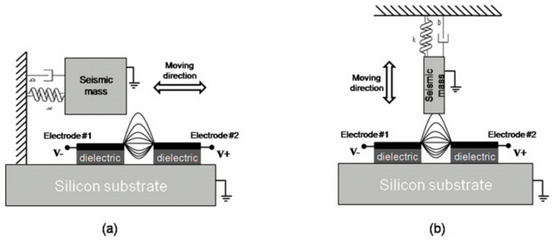

Figure 1: (a) Schematic illustration of an in-plane fringe field motion sensor (IP-FF) (b) Schematic illustration of an out-of-plane motion sensor (OP-FF).

performed on elementary structures to identify the achievable performance and the design constraints. Based on the obtained simulations results, in-plane and out-of-plane fringe field accelerometers have been designed and built in the STMicroelectronics surface micromachining ThELMA process. Finally, the devices have been tested and their performance has been compared with the expected theoretical behavior.

2. Device working principle

Consider a basic structure like the one schematically depicted in Fig. 1a, where two thin electrodes are designed, isolated with a thin dielectric layer, on top of a grounded silicon substrate. The capacitance between the two electrodes is mainly determined by the electric-field streamlines configuration generated in the surrounding air volume as a consequence of potential difference applied to the electrodes. A grounded seismic mass moving over the two electrodes can intercept a fraction of the electric-field lines, changing the capacitance value. In Fig. 1a,b both in-plane and out-of-plane fringe field structures (IP-FF and OP-FF respectively) are schematically sketched. The intrinsic advantage evidenced by these two sensing configurations is in that the suspended structure never moves toward a plate biased at a different voltage, because the stiffness in the sensing direction is decoupled from the stiffness in the pull-in direction. For in-plane structures the stiffness in the vertical direction can be design to be very high (see Fig.1a); for out-of-plane structures the suspended mass moves over (or at worst between) the sensing plates with a high stiffness in the horizontal direction (see Fig.1b). The mechanical constraints and the readout voltage can be thus tailored with larger freedom to the application, without risks of pull-in.

3. FEM simulation

In order to investigate the feasibility of accelerometers based on the proposed sensing principle, FEM simulations have been performed on the elementary structures of Fig. 1a,b under the technology constraints of the ThELMA process. The sensing electrodes can be realized with a 670 nm thin polysilicon layer (shortly TPL) and integrated on top of a silicon oxide layer (2.4 μm) deposited over a silicon substrate; the seismic mass can be realized with a 15 μm thick epitaxial polysilicon layer (so on EPL). The gap between the TPL and the EPL layer is of 1.8 μm. Simulations, performed with the *Comsol 3.5* software, have been used to evaluate the variation of capacitance between two adjacent TPL electrodes while a grounded seismic mass (EPL) is moved over the fringe field area. The electrodes length (400 μm) is considered to be far larger then the lateral pitch (34 μm), thus 2D simulation can be performed with good approximation. Fig. 2a reports the simulation results for the IP-FF elementary cell, which is schematically represented in the close-up. This elementary cell is constituted by two TPL electrodes and a 23 μm wide EPL suspended mass. The plot of Fig. 2a evidences a relative capacitance variation $\Delta C_{FF}/C_{FF}$ around the 80%, where $C_{FF} = 0.9fF$ is the capacitance when the seismic mass is at $x = 0$, as indicated in the close-up. A good linear behavior is obtained for $-1.5\ \mu m \leq x \leq +1.5\ \mu m$, where the capacitance variation with respect to the mass displacement has a coefficient $\Delta C_{FF}/\Delta x$ of 0.16 fF/μm. The mean linearity error, defined as the ratio of the capacitance deviation from the linear behavior and the effective ΔC_{FF}, is within the 5 % over this range. In Fig. 2b, the simulations for the OP-FF elementary cell are reported. The OP-FF cell differs from the IP-FF one only in the moving mass which is now 2.3 μm wide and free to

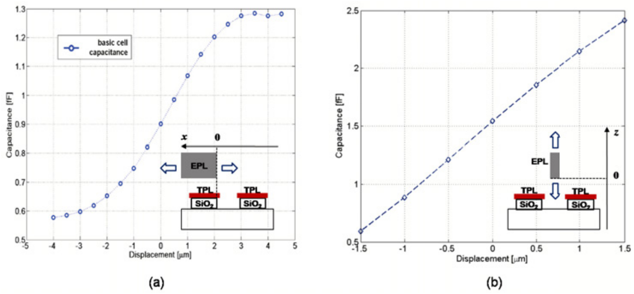

Figure 2: 2D simulation results showing the capacitance variations caused by a grounded seismic mass moving over the fringe field area (a) capacitance-displacement plot of the IP-FF elementary cell, schematically represented in the close-up (TPL electrodes length of 385 μm) (b) capacitance-displacement plot of the OP-FF elementary cell, schematically represented in the close-up (TPL electrodes length of 780 μm).

move in the direction orthogonal to the substrate only. A linear behavior is evidenced within the range of -1 μm $\leq$ x $\leq$ + 1 μm , characterized by a capacitance variation of 0.63 fF/μm and a mean linearity error of 5 %. The results obtained on the elementary cells have been used to design two test devices, useful for a first experimental validation.

4. Experimental results

4.1. IP-FF accelerometer

To build the in plane accelerometer, 12 of the IP-FF elementary cells described in the previous section were implemented in a parallel configuration. The total capacitance variation of the device is the sum of the capacitance variation of each elementary cell. Fig. 3a reports a SEM image of the realized device. The EPL suspended mass is formed by holed strips, suitably placed above the correspondent fringe field capacitance in the position determined through simulations. These EPL strips are joint together in a single suspended structures by an external frame that is anchored to the substrate with a system of compliant springs. The TPL electrodes are arranged in an interdigitated planar configuration, forming two sensing electrodes underneath the moving EPL strips. The presented IP-FF accelerometer has been designed to have a nominal elastic stiffness $k = 0.075N/m$ and two self-test actuators have been integrated on-chip in order to test the device with accelerations larger than 1 g. The realized device has been tested with the low-noise platform for MEMS/NEMS capacitive sensors presented in [6]. Fig. 3b, reports the experimental change of the in-plane fringe capacitance as a function of the actuator voltage. From these measured data both the capacitance vs. acceleration and capacitance-displacement plots can be obtained. A very good experimental agreement with the theoretical prediction is shown in Fig. 3c and a sensitivity of 0.9 fF/g is evidenced in Fig. 3d.

4.2. OP-FF accelerometer

The OP-FF accelerometer has been realized through a tilting structure, embedding 6 of the OP-FF elementary cells described in section 3. The capacitance variation can be expressed as the sum of each elementary cell, weighted by its effective displacement in the z-direction along the device length. A SEM image of the realized device is reported in Fig. 3e. Similarly to its in-plane counterpart, this device has been realized with EPL strips joint together by an external frame and with interdigitated TPL electrodes. The overall tilting stiffness is design to be $k_\theta = 11 \cdot 10^{-9} Nm$ and a self-test actuator allows to test the device with more than 1g of acceleration. The device has been tested with the same platform used for the IP-FF structure and the results are reported in Fig. 3f, g, h. A discrepancy between measured data and the theoretical prediction is evidenced in the capacitance-displacement plot of Fig. 3g, and a sensitivity of 0.22 fF/g is obtained in Fig. 3h.

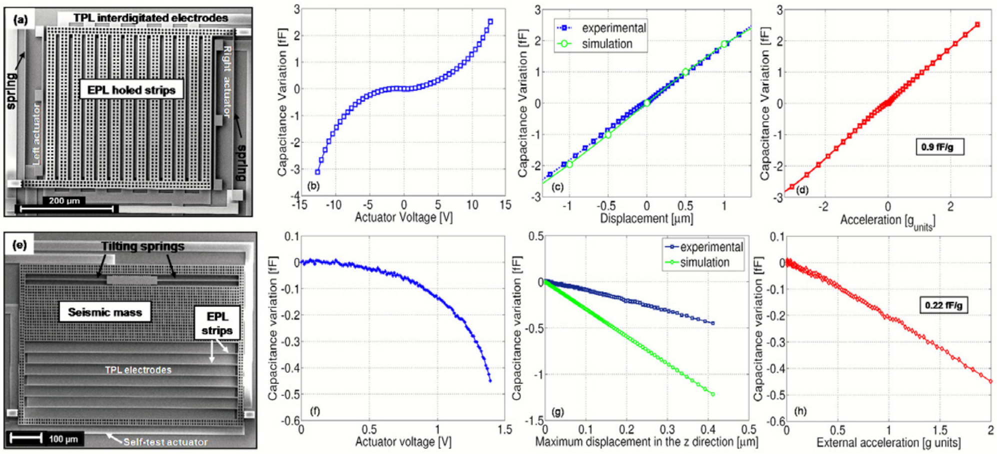

Figure 3: (a), (b), (c), (d) report respectively the SEM image of the IP-FF accelerometer and the relative experimental results (e), (f), (g), (h) report respectively the SEM image of the OP-FF accelerometer and the relative experimental results.

5. Conclusion

A novel motion sensing principle based on the fringe field effect has been presented and validated through the comparison between FEM simulations and experimental results. Two test devices have been realized with an industrial surface micromachining process, both for in-plane and out-of-plane motion sensing. The experimental characterization of the in-plane device showed good agreement with the simulations prediction and a sensitivity of 0.9 fF/g is demonstrated. Further investigations on the out-of-plane device, which showing a sensitivity of 0.22 fF/g does not fulfill the expected performance, are needed. The variance of many process parameters - such as the over-etch underneath the seismic mass or the over-etch on the tilting-springs width - can be studied to explain the unexpected device behavior. The proposed devices do not suffer from pull-in instability; they can be therefore coupled to a standard time-continuous readout electronics, with no need for reducing the biasing voltage or using switching circuits.

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