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A differential resonant micro accelerometer for out-of-plane measurements

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Abstract

This paper reports the theoretical and experimental characterization of a new z-axis silicon resonant micro accelerometer fabricated by the THELMA© surface micromachining technique, characterized by differential sensing and very small dimensions. The working principle of this device is based on the variation of the electrostatic stiffness of two torsional resonators. This work is a prosecution of the research on resonant accelerometers published in [1,2].

Keywords: MEMS; accelerometer; torsional resonators.

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1. Introduction

Resonant micro-accelerometers measure the external acceleration through the frequency variation of resonating parts. Different operating principles can be exploited: in the devices proposed in [1-4] the frequency variation is induced by the presence of axial stresses in resonating beam elements, in [5] the frequency change of parallel beam resonators is due to the variation of the momentum of inertia, in [6-8] the effect of the variation of electrostatic stiffness due to the gap change is used.

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The out-of plane accelerometer proposed in [9] and here studied makes use of the gap sensitive variation of electrostatic stiffness of the torsional resonators and allows for differential sensing. In this work, we present experimental measurements of the device together with a comparison with the analytical predictions. The differential sensitivity, defined as the shift in resonance frequencies corresponding to a 1*g* acceleration, obtained by this device with a proof mass of $440\mu m \times 300\mu m \times 22\mu m$, operated at 2.5V is of 14 Hz/g.

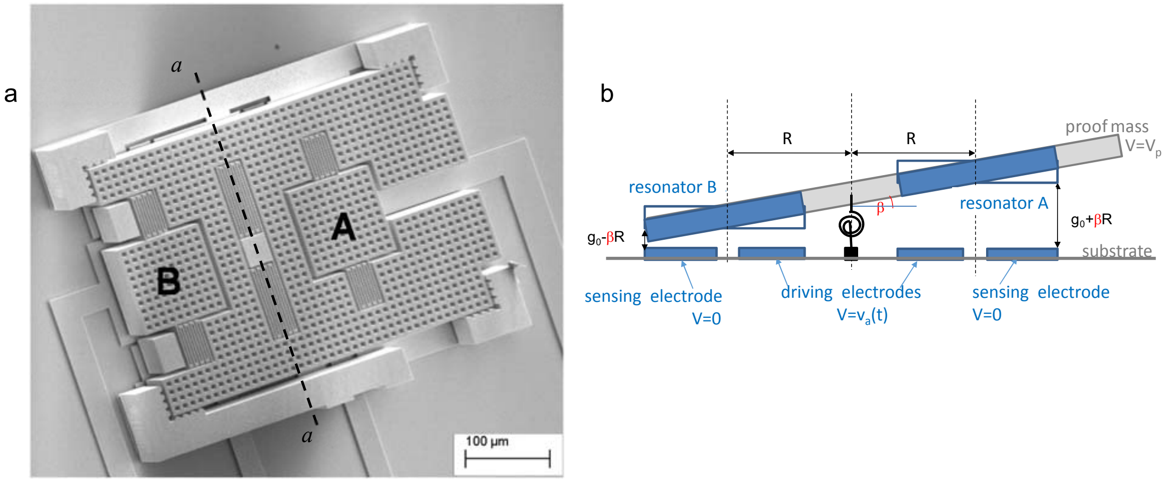

Fig. 1. (a) SEM image of the z-axis accelerometer with two torsional resonators A and B; (b) schematic side view of the electrostatically actuated accelerometer, inclined due to external acceleration.

2. Device operation principle

The proposed accelerometer is composed by a suspended planar proof mass, with out of plane thickness $s = 22\,\mu\text{m}$, attached to the substrate by two folded torsional springs, and by two torsional resonators. Figure 1a shows a SEM image of the accelerometer, fabricated using the THELMA© surface micromachining process of STMicroelectronics [10]: the torsional resonators A and B consisting of a mass of in-plane dimensions $L \times 2b$ and of two folded torsional springs attached to the proof mass are visible. Driving and sensing of the resonators is made by two parallel electrodes attached to the substrate, see Figure 1b. The torsional elements are kept in resonance according to their torsional natural mode. When in the rest position, the mass is at distance g_0 from both the electrodes and the torsional resonator has the nominal frequency f_0

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{K_m - K_e}{\rho J_{mass}}} \quad \text{with} \quad K_m = \frac{2GJ}{l}, \; K_e = \frac{2\varepsilon_0 L}{3g_0^3} V_p^2 \left(b^3 - c^3\right) \tag{1}$$

where: ρJ_{mass} is the centroidal mass moment of inertia of the rigid mass, ρ is the mass density, J is the torsional momentum of inertia of the springs, l is the total length of one of the folded torsional springs, G is the shear elastic modulus of polysilicon, ε_0 is the vacuum dielectric constant, V_p is the polarization voltage applied to the mass, $2c$ is the distance between the sensing and driving electrodes. The values of the geometrical data are reported in Table 1.
When an external out-of-plane acceleration a_z is applied, the proof mass rotates around the axis *a-a* and the gap between the resonators and the electrodes changes as shown in Figure 1b; this induces the variation of the electric stiffness and, hence, of the frequency. The angle of rotation is proportional to the acceleration and it is expressed as:

$$\beta = \frac{3}{2}\frac{m a_z R_G}{G s \bar{t}^3}\bar{l} \tag{2}$$

where R_G is the distance between the *a-a* axis of rotation of a proof mass and the center of gravity of the same mass, $\bar{l}$ is the total length of one folded torsional spring attaching the mass to the substrate and $\bar{t}$ is its in-plane thickness. In particular, a first resonator element approaches the substrate and its gap reduces to $g_0 - R\beta$ while the other resonator element moves away from the same substrate and its gap increases to $g_0 + R\beta$, R being the distance between the *a-a* axis and the torsional resonator's axis of rotation. The torsional resonators changes their natural frequencies according to (1) because of their electrostatic stiffness variation. Combining the readings f_A and f_B of the two torsional resonators, the following expression, allowing for the measure of the external acceleration a_z, is obtained:

$$f_A - f_B \approx 3 f_0 \frac{K_e}{K_m - K_e} \frac{R}{g_0} \beta = \frac{9}{2} f_0 \frac{K_e}{K_m - K_e} \frac{R}{g_0} \frac{m R_G}{G s \bar{t}^3} \bar{l}\, a_z \tag{3}$$

3. Results

The tested device is packaged at a pressure of 1 mbar with the wafer-to-wafer bonding technique. The MEMS is directly wire-bonded to an electronic board housing two trans-impedance amplifiers to read the currents flowing out of the two resonators. With no external acceleration applied in the sensitive direction, the resonances were evaluated from the peaks of the spectral responses of the resonators, and analytically converted in inclination angles of the resonators; the spectral responses were obtained applying a small oscillating voltage on one electrode and biasing the proof mass with a constant voltage. Figure 2a shows the measured resonance frequencies of the two resonators as a function of the applied voltage V_p and the theoretical predictions obtained with the identified over etch which slightly differs for the two resonators (0.317 µm for resonator A and 0.321 µm for resonator B). Figure 2b shows the comparison between the experimental and theoretically predicted resonant curves of resonator B at different polarization voltage.

Figure 3 reports the motional current as a function of the frequency at rest and subject to external accelerations of ±1 g: a sensitivity of the single resonator around 7 Hz/g, which leads to a differential sensitivity of 14 Hz/g, is measured. This sensitivity is in good agreement with the predicted one, see Table 2, and proves the potentiality of the proposed device.

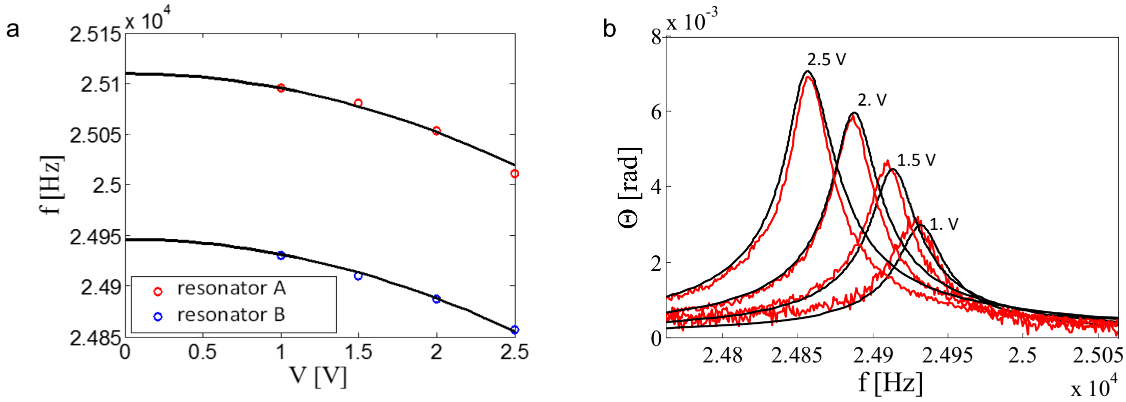

Fig. 2. (a) Resonance frequency as a function of the polarization voltage: experimental data and theoretical predictions of the torsional resonators labeled A and B in Figs. 1a and b; (b) experimental and analytically predicted resonance curves of torsional resonator B at different polarization voltage. Identified quality factor Q=870

Table 1. Material and geometrical data of the fabricated accelerometer.

Parameter	Value	Parameter	Value	Parameter	Value	Parameter	Value
G	61.5 GPa	$L=2b$	105 µm	$\bar{l}$	388 µm	R_G	82.23 µm
m	3.64 µg	l	301 µm	$\bar{t}$	2 µm	R	110 µm

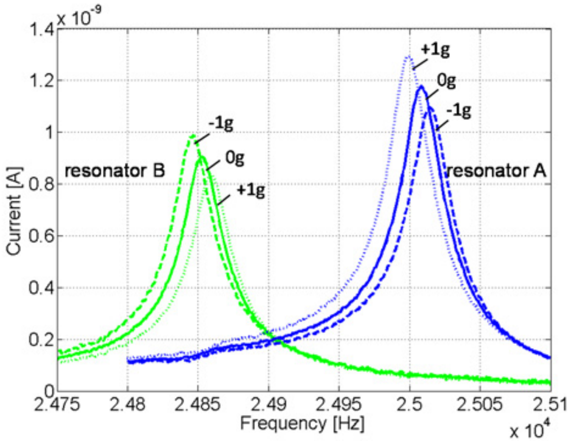

Fig. 3. Experimental resonance curves of torsional resonators *A* and B with different external accelerations. Polarization voltage 2.5V.

Table 2. Frequency of resonators and sensitivity of the device.

Resonator	Frequency @0g, 2.5V	Sensitivity experiments	Sensitivity theory
A	25008 Hz	- 7.0 Hz/g	- 7.1 Hz/g
B	24852 Hz	6.5 Hz/g	7.2 Hz/g

4. Conclusions

A new out-of-plane resonant accelerometer has been studied and tested. The experimental results exhibit good agreement with the theory and show a sensitivity of the device of 14 Hz/g. The differential reading enables detection of the external acceleration even in the presence of eigenstresses due e.g. to temperature variations.

References

[1] C. Comi, A. Corigliano, G. Langfelder, A. Longoni, A. Tocchio, B. Simoni, A resonant micro-accelerometer with high sensitivity operating in an oscillating circuit, J. Microelectromech. Syst., 19 (2010) 1140-115.

[2] A. Caspani, C. Comi, A. Corigliano, G. Langfelder, A. Tocchio, Compact biaxial micromachined resonant accelerometer, J. Micromech. Microeng. 23, (2013) 105012.

[3] D. Pinto, D. Mercier, C. Kharrat, E. Colinet, V. Nguyen, B. Reig, S. Hentz, A small and high sensitivity resonant accelerometer, Proc. Chemistry, 1 (2009) 536-539.

[4] S.X.P. Su, H.S. Yang, A.M. Agogino, A resonant accelerometer with two-stage microleverage mechanisms fabricated by SOI-MEMS technology, Sensors, 5 (2005) 1214-1223.

[5] O.Tabata, T.Yamamoto, Two-axis detection resonant accelerometer based on rigidity change, Sensors and Actuators 75 (1999) 53–59.

[6] H.C. Kim, S. Seok, I. Kim, S-D. Choi, K. Chun, Inertial-grade out-of-plane and in-plane differential resonant silicon accelerometers (DRXLs), Proc. Transducers '05, Seoul, Corea, June 5-9 (2005) 172-175.

[7] S. Sung, JG. Lee, T. Kang, Development and test of MEMS accelerometer with self-sustained oscillation loop, Sensors Actuators 109 (2003) 1–8.

[8] B. Lee, C. Oh, S. Lee, Y. Oh, K. Chun, A vacuum packaged differential resonant accelerometer using gap sensitive electrostatic stiffness changing effect. Proc MEMS2000 Miyazaki, Japan, January 23-27 (2000) 352 – 357.

[9] C. Comi, A. Corigliano, A. Ghisi, S. Zerbini, A resonant micro accelerometer based on electrostatic stiffness variation, Meccanica 48 (2013), 1893–1900.

[10] A. Corigliano, B. De Masi, A. Frangi, C. Comi, A. Villa, M. Marchi, Mechanical characterization of epitaxial silicon through on chip tensile tests. Journal of Microelectromechanical Systems, 13 (2004) 200-219.