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Design and simulation of mass sensors based on horizontally actuated silicon cantilevers

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ABSTRACT

Two designs for a mass sensor based on polysilicon cantilevers for hybrid integration with CMOS circuitry are introduced. The change of deposited mass on the cantilever is measured through the detection of frequency or settling-time shifts in the cantilever oscillation, which is horizontally produced by an interdigitated comb capacitor structure. Interdigitated comb actuators are preferred over parallel plates due to their larger displacement which is not a function of the gap between electrodes. Also, using the interdigitated comb as sensor port, the capacitive change is increased and the nonlinearity before pull-in effect is reduced. Therefore, the signal detection is improved, reducing readout electronics design effort. The preliminary results obtained are validated through finite element analysis and electrical simulations in SPICE. Mass–frequency changes of 3.43 pg/Hz and 6.71 pg/Hz are predicted for these designs with natural frequencies of 11.461 kHz and 8.465 kHz respectively. Also, settling time variations of 1.69 ms/ng and 0.7 ms/ng were obtained.

1. Introduction

Silicon-based micro cantilevers are extensively studied and used as inertial sensors due to their simple design, which can be effectively predicted by analytical expressions. Polysilicon is used due its manufacturability and properties for actuation in a micro scale. These structures have proved their usefulness in a wide range of applications, including mass change detection which is important for Lab-on-chip devices [1–6].

In cantilever-based mass sensors, the changes of a deposited mass are measured through the oscillation frequency shift, since their dynamic behavior is directly affected by such mass changes [7,8]. A classical approach is to use cantilevers electrostatically actuated by parallel plate capacitors defined in such a way to produce vertical displacements, normal to the substrate. In this case the electrostatic force induced is a function of displacement, which tends to be difficult to control, and the capacitance change is small and highly nonlinear.

Sensitivity of cantilevers is improved by increasing its oscillation frequency. However, high frequencies are related to bad signal to noise ratio (SNR), requiring challenging electronic circuit interface designs [9], especially for hybrid integration schemes. This worsens when complex circuitry and control strategies to avoid system instability are required [8]. Usually this is addressed by monolithic integration of electronics [10] but this could lead to incompatibility between manufacturing processes.

Standardized fabrication processes, like SUMMiT-V of Sandia National Laboratories, are preferred due to their intrinsic compatibility with microelectronics processes which ensures a high yield in fabricated devices. This process is a surface micromachining technology based on thin five layers of polysilicon, alternated with four sacrificial oxide layers [11]. However, the small gaps between structural layers restrict the vertical motion, even more when dimples are used to prevent stiction.

2. Sensor design

This work proposes two novel designs of cantilever-based mass sensors horizontally actuated, compatible with SUMMiT-V, which can be operated in free oscillation or in resonance. In free oscillation, the cantilever will be deflected to an initial displacement and then released. Therefore, the structure in free oscillation will be used to detect the shift in dynamic parameters, such as frequency, to measure the deposited mass in a container defined in the free end of the structure.

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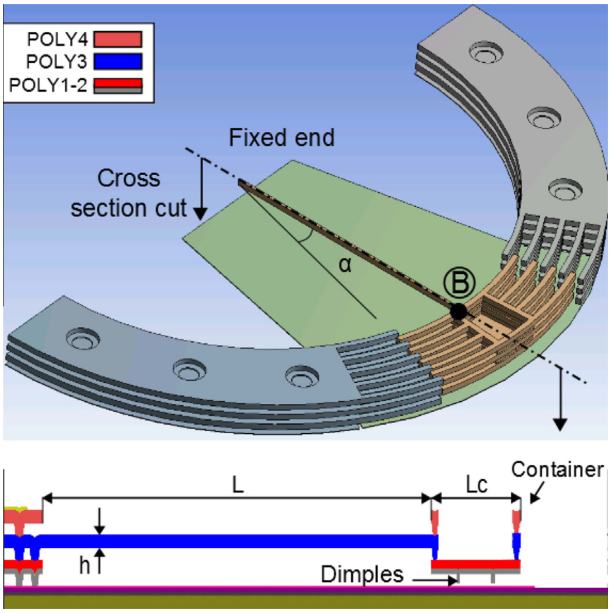

Fig. 1. Design specifications of mass sensor using vertical interdigitated comb capacitors.

Beam movement is produced by using an interdigitated comb of capacitor electrodes which provide a large capacitance suitable for electrical signal detection and relatively large actuation forces, without restricting the oscillation amplitude. The main goal is to enable several detection schemes, suitable for an effective electronic integration which could require less design effort. System performance is improved without reducing the beam-width below the technological limit of 1 µm [11].

Through this paper, two approaches are described. The first design incorporates a horizontal actuator with a circular comb drive configuration to increase the electrostatic force, as shown in Fig. 1, where the capacitor plates are perpendicular to the substrate. However, since cantilever bending does not follow a circular path, its motion amplitude has to be restricted with a beam stop to avoid electrical short circuit.

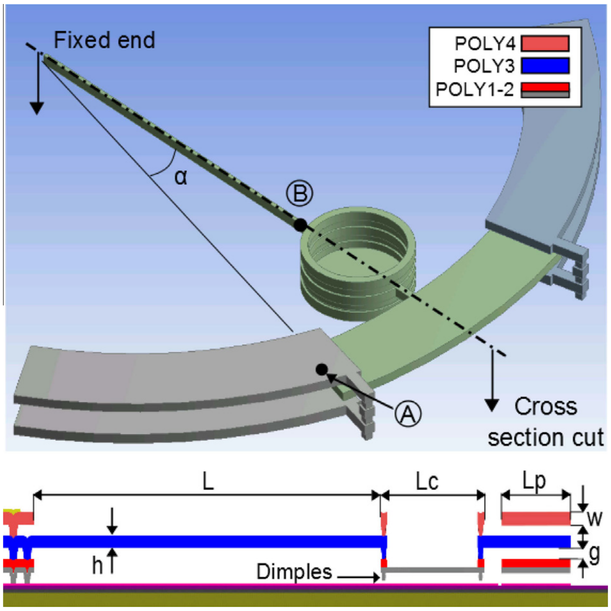

Fig. 2. Design specifications of mass sensor using horizontal interdigitated comb capacitors.

Consequently, a second design, is shown in Fig. 2, consists of an actuating capacitor with the plates parallel to the substrate and separated by the same gap (associated with the sacrificial oxide layers, which are removed upon the release of the structures [11]) above and below the moving electrode. Hence, the motion amplitude of the moving electrode does not have to be restricted.

3. Theoretical background

The structure is divided in two sections for its study. The first is an elastic section defined from the fixed end of the beam and point B, shown in Figs. 1 and 2, where its uniform width ends. Then, beyond this point, a rigid section is assumed since no important deformation is expected. To perform the initial displacement the electrostatic actuator will produce a force $\vec{Fe}$ which can be approximated from Eq. (1) [12,13]:

$$\vec{F_e} = \frac{n\varepsilon w}{2}V^2\left\{\left(\frac{1}{g+x}+\frac{1}{g-x}\right)\hat{i}+(d0+\Delta d)\left(\frac{1}{(g+x)^2}-\frac{1}{(g-x)^2}\right)\hat{j}\right\} \tag{1}$$

where ε is the permittivity of air, n is the number of fingers, V is the applied voltage, w is the width of the electrodes and g is the gap between electrodes, x is the lateral displacement, $d0$ is the initial electrode overlap and Δd is the longitudinal displacement. As a result of the actuation force at point A, shown in Figs. 1 and 2, in the rigid section a moment Mb is produced in point B. This assumption reduces to the problem of a simple cantilever beam, which can be characterized through the Euler–Bernoulli equation. In consequence, the deflection δ_y can be calculated by using Eq. (2):

$$\delta_y = \frac{F_e x^2}{2EI}\sum_{i=1}^{n} d_i + nL(1-\cos\alpha) \tag{2}$$

where E is the Young modulus, I is the second moment of area, L is the length of elastic section, α is the angle between the beam in equilibrium position and the tangent to the end of circular electrodes, which is useful to define the direction of the applied force F_e, d_i is the difference between elastic section radius and the electrode radius measured from the fixed end and x is the point along the elastic section where the deflection will be calculated. For the deflection in point B $x = L$. As it can be observed, Eq. (2) can be applied to n number of electrodes. Hence, for the first approach (Fig. 1) $n = 4$ and for the second (Fig. 2) $n = 1$. Since a cantilever can be modeled by a mass-spring-damper system [14], the natural oscillation frequency achieved when the voltage is turned off after the device has reached the desired deflection, can be calculated with the following expression [12]:

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m_0+m'}} \tag{3}$$

$$k = \frac{3EI}{(L+0.75(Lc+Lp))^3}$$

where m_0 is the effective mass of the structure and m' is the deposited mass to be detected. It is assumed that the extra mass will only affect the frequency response. In consequence, the mass sensitivity due to a frequency shift can be calculated as follows:

$$Sm = \frac{k}{2\pi^2 f_n^3} \tag{4}$$