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Numerical and Experimental Investigation on Contactless Resonant Sensors

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Abstract

This paper reports numerical and experimental investigation on a BESOI-MEMS device. The implemented contactless actuation principle exploits Lorentz forces exerted on a conductive-non magnetic surface of the sensor, deriving from interaction between the eddy currents and the radial magnetic field, both generated by a sinusoidally driven external inductor. Both excitation and readout strategies are performed remotely via a magnetic strategy; moreover, the conceived sensor has been first numerically studied by using CoventorWare™2008, then the device prototype has been fabricated and a preliminary experimental campaign has been performed to characterize the system in terms of variation of its resonance frequency.

Keywords: Contactless MEMS, crab leg microresonator, BESOI technology, numerical and experimental investigation.

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1. INTRODUCTION

The use of a sensor element totally passive, consisting of a resonant structure that can be excited and interrogated without contact, appears promising for measurements of different physical quantities [1, 2, 3, 4] especially in unsafe environments. Through the innovative contactless principle described here, it is possible to derive the measurand information without cables connection or active systems.

Moreover this methodology represents an interesting approach for passive microresonators realization by using only standard MEMS materials (i.e. metal layer for the conductive sensor plate, and the others as structural materials), without supplementary highly polluting materials or deposition of magnetic alloys.

The transduction contactless working principle, previously studied by the authors [5, 6, 7] consists on an actuation principle based on Lorentz force source and a detection principle realized by a carrier signal and a pick-up coil in a differential configuration.

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The Fig. 1 shows the contactless schematic principle applied in a crab leg microresonator:

- Forcing a periodic bias current at pulsation ω_e in the realized solenoid faced to the resonator, a periodic magnetic field is generated. The magnetic field induces an eddy current density in the conductive plate. The interaction between the eddy currents and the radial component of the magnetic field (B_r) spreads a Lorentz force per unit of volume that moves the conductive beam in the z direction. The force along the z axis (F_z), can be expressed as follow [7, 8]:

$$F_z=0.5\cdot k(\omega_e)[B_r\cdot \sin(\phi)+B_r\cdot \sin(2\omega_e t+\phi)] \tag{1}$$

The force expression evinces a constant force component correlated to the conductor plate impedance phase (ϕ), and a component that evolves with a pulsation of $2\omega_e$. Adopting an excitation pulsation of $\omega_e=\omega_r/2$, where ω_r represents the mechanical resonance pulsation of the device, the system will oscillate at resonance frequency.

- The detection principle is based on a periodic bias current at pulsation ω_p forced in a solenoid. The magnetic field induced, creates an eddy current density in the conductive plate and generates a magnetic field B_s. The oscillations generate an amplitude modulation on the carrier bias and the information can be extracted using the two sensing coils with a frequency domain readout strategy. In absence of a conductive passive beam, only the carrier bias frequency appears; on the contrary, in presence of the cantilever beam two spectral components will appear as consequence of the motion of the beam ($\omega_p\pm\omega_r = \omega_p\pm 2\omega_e$).

This working principle can be applied to different families of micromachined devices, like cantilever beams, bridges, suspended masses with springs, crab leg structures, etc..

The next section shows numerical and experimental investigation of an inertial suspended mass, with four springs in a crab leg configuration. This structure offers major robustness respect to a simple cantilever beam and also, it is possible to integrate a consistent inertial mass; this represents an advantage in terms of Lorentz force actuation because a big proof mass implies a low resonance frequency and neglectable skin effects.

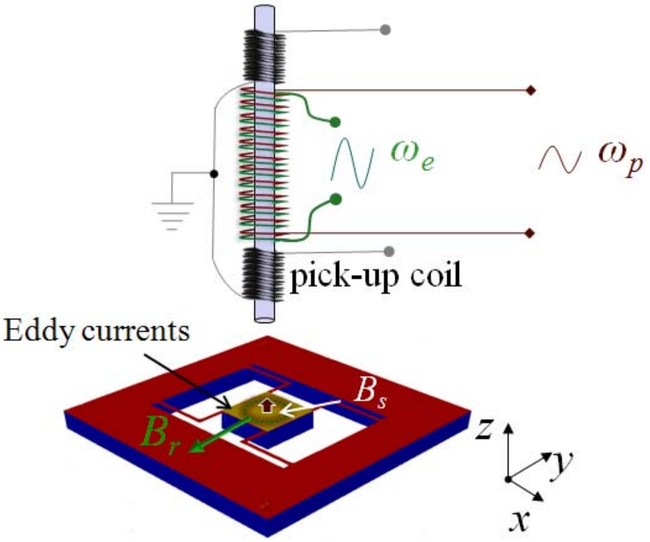

Fig. 1. Schematic diagram of the contactless principle in a four silicon beams with a suspended inertial mass (crab leg structure).

2. INVESTIGATION ON A BESOI CRAB LEG MICRORESONATOR

The micromachined investigated device is a suspended mass supported by a four crab leg beams, realized by using a BESOI (Bulk and Etch Silicon on Insulator) process, realized at the Centro Nacional de Microelectronica (CNM) of Barcelona, Spain.

A Silicon On Insulator (SOI) wafer based on 15 µm c-Si layer and 450 µm carrier substrate with 2 µm of buried oxide, has been processed with a front and back side DRIE etching technique. Functional materials as metal and polysilicon have been added as shown in Fig. 2. Furthermore a doping c-silicon procedure based on $POCl_3$ (with a concentration of ~10^{20}) has been used to increase the Lorentz forces effect. A silicon suspended mass of 1600 µm x 1600 µm x 467 µm has been designed with four silicon springs (100 µm width and a length of 800 + 1600 µm for the segment anchored to the central proof mass and the one anchored to the substrate, respectively).

The physical behaviour of the micromachined sensor has been investigated by using CoventorWare™ 2008, based on a Finite Element Method (FEM) analysis. The Fig. 3a shows the 3D model mesh realized by using an adaptive 2nd order tetrahedrons architecture.

The MemMech tool has been used to analyze the resonance frequency along the z axis, a resonant frequency of about 500 Hz has been estimated by using the Lanczos solution method as shown in Fig. 3b. The resonance frequency agrees with previously analytical studies realized with the heterogeneous beam theory [8]. Fig. 3c shows the displacement along the easy axis in absence of applied load to the plate surface of the microresonator, a maximal value of about 0.3 µm has been detect around the center of the conductive plate.

The experimental investigation has been performed using a proper designed coil to move and to sense the device oscillations. In order to increase the detection quality, a FeSiB amorphous ferromagnetic microwire, prepared by the rotating water spinning method and having nominal diameter of 100 µm has been selected as the core of the coil. Two superimposed primary windings are used as excitation and probing coils, respectively, while two lateral windings, in differential configuration, represent the output pick-up coil. The excitation and probing signals are applied by means of a voltage-current converter amplifier, while the pick-up coil signal has been analyzed by using two high pass filters and an instrumentation amplifier. Fig. 4a shows the experimental setup and Fig. 4b shows the realized microresonator. A sinusoidal excitation signal having an amplitude of 900 mV_{pp} and a probing bias of 6.5 V_{pp} @ 1.087 MHz have been used. The frequency range around $f_r/2$ has been experimentally analyzed, where f_r ($\omega_r/2\pi$) represents the mechanical resonance frequency of the structure. A resonant frequency of about 450 Hz has been experimentally estimated. Fig. 4c shows the frequency spectrum of the magnetic readout signal around the point of interest (f_p-f_r=1.087 MHz-450 Hz) with a gaussian values distribution as consequence of the resonance frequency deviation.

As a future step an extensive experimental campaign and a simulation MemHenry/MemMech CoventorWare™ 2008 based will be realized.

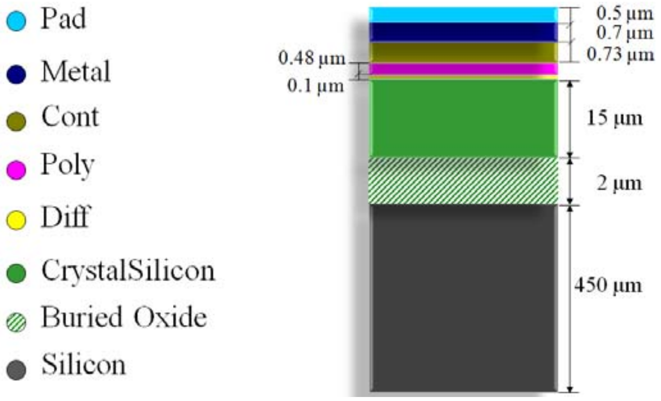

Fig. 2. Cross sectional area of the Bulk and Etch Silicon on Insulator (BESOI) technology used.

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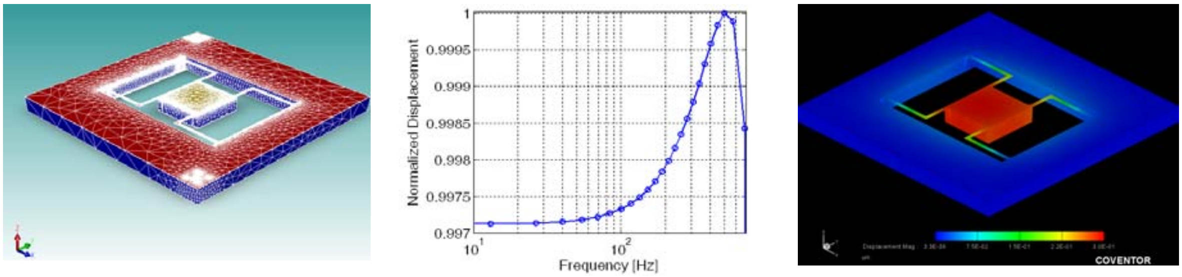
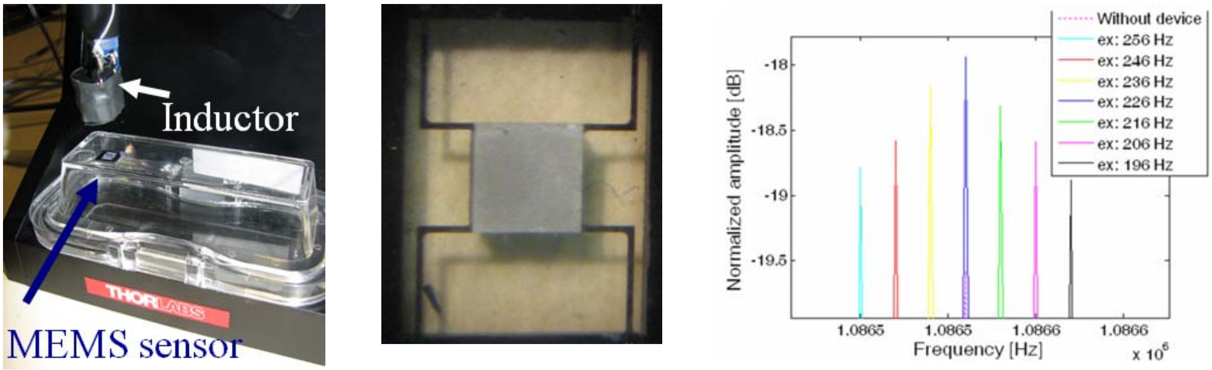


(a) (b) (c)

Fig. 3. (a) Tetrahedrons-based model mesh, (b) harmonic response along the z axis (normalized to its maximum value), (c) displacement color map in absence of applied load to the plate surface of the microresonator.



(a) (b) (c)

Fig. 4. (a) Experimental setup, (b) microscope picture of the BESOI crab leg device realized, (c) experimental result: the central spike represents the contribution at the resonance. An analysis around this value has been conducted by varying the excitation bias frequency. A sinusoidal waveform has been maintained during the experimental campaign.