CONTACTLESS ELECTROMAGNETIC INTERROGATION OF A MEMS-BASED MICRORESONATOR USED AS PASSIVE SENSING ELEMENT

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ABSTRACT

This paper reports an innovative contactless MEMS-based microresonator actuated by an external time-varying magnetic field. The actuation principle is based on the interaction between the eddy currents and the magnetic field generated by an external inductor driven by a sinusoidal current; the system response is sensed via an inductive pick-up based on a high permeability material (100-µm of diameter) in order to detect the micromachined system resonance. The working principle and the experimental set-up are here described and some preliminary results are reported for a BESOI (Bulk and Etch Silicon On Insulator) crab-leg device.

KEYWORDS

Contactless MEMS, crab-leg microresonator, BESOI technology.

INTRODUCTION

Passive sensing elements that can be remotely interrogated arouse interesting applications in different fields such as harsh environments, hermetic or protective spaces, human body. Hostile, hazardous and not accessible places are incompatible with the active electronics or with the cabled measurement systems. Moreover contactless readout strategy can be adopted to measure physical quantities of interest like viscosity, temperature, pressure, from a sensor located in a risky and unsafe environment. The literature presents a lot of contactless sensors, focused toward MEMS approach, for various application fields, in order to detect different target quantities: bent beam MEMS temperature sensors have been developed to measure high temperature in harsh environments with a remote sensing based on a transponder [1], a MOEMS inertial sensor based on a suspended mass and "transparent materials" [2], the LVDT readout strategy has been used to detect a fluid viscosity or a tilt of a not accessible container and incompatible with active electronics [3], or sensors to measure the thickness of a ferromagnetic metal strip and based on a magnetic approach [4]. The previous works are based on different remote sensing strategies (optical, Linear Variable Differential Transformer, magnetic) in order to extrapolate the measurand information adopting a wireless system. This paper reports an innovative contactless MEMS-based microresonator actuated by an external time-varying magnetic field. The actuation principle of the microresonator is based on the interaction between the eddy currents (generated on a conductive surface) and the magnetic field forced by an external inductor and driven using a sinusoidal signal; the system response can be analyzed adopting a remote sensing, based on pick-up coils. This principle, previously tested on a conductive and non-magnetic cantilever [5] (a piezoelectric bimorph cantilever covered by two aluminum sheets) and in some preliminary MEMS approach [6, 7], represents an interesting result in view of MEMS and standard microelectronic realizations. It is possible in fact to use standard materials as conductive surface (metal, doped silicon, etc.) avoiding sputtering of magnetic material or invasive post-processing depositions. In this paper a contactless microresonator sensor (a four beams suspended MEMS mass, with crab-leg springs configuration) has been designed, using the heterogeneous beam theory and fabricated by adopting a BESOI technology (Bulk and Etch Silicon on Insulator), whereas a miniaturized inductor having a 100-µm magnetic core diameter, has been used to stimulate efficiently a suspended mass and to detect its oscillations. The working principle and the experimental set-up are here described and some preliminary results show the performances and validate the principle of a MEMS contactless device.

THE CONTACTLESS WORKING PRINCIPLE

In this section a brief overview of the contactless actuation principle and remote readout strategy is presented; more details can be found in [5, 8, 9]. The contactless actuation principle is based on the interaction between the eddy currents induced on a conductive plate and a time-variable external magnetic field. Forcing a periodic bias current $I_e(t)$ at frequency f_e in the solenoid, a periodic magnetic field $B_e(t)$ is generated (Fig. 1a); the magnetic field induces an eddy current density J_e in the conductive plate and correlated with its electrical impedance. The interaction between the eddy currents and the radial component of the magnetic field (B_{er}) spreads a Lorentz force per unit of volume that moves the conductive beam in the z direction. The force along the z axis, can be expressed as follow [6]:

$$F_z = \frac{1}{2}k(\omega)\left[B_{er}\sin(\phi) + B_{er}\sin(2\omega t + \phi)\right] \quad (1)$$

This expression shows: 1) A constant force component correlated to the conductor plate impedance phase (ϕ).
2) A force component that evolves with 2ω frequency, where ω represents the excitation bias frequency; finally the system will oscillate with twice excitation frequency. The Fig. 1b shows the schematic diagram of the detection principle: a periodic bias current $I_p(t)$ at frequency f_p, generates a periodic magnetic field $B_p(t)$; the magnetic field induces an eddy current density J_s in the conductive plate and generates a magnetic field B_s which is modulated by the beam motion. The oscillations generate an amplitude modulation on the carrier bias and the information can be extracted using the sensing coils A and B (Fig. 1c) with a frequency domain readout strategy. In absence of a conductive passive beam, only the carrier bias frequency appears; furthermore in presence of the cantilever beam two spectral components will appear as consequence of the motion of the beam ($f_p \pm f_r \equiv f_p \pm 2f_e$).

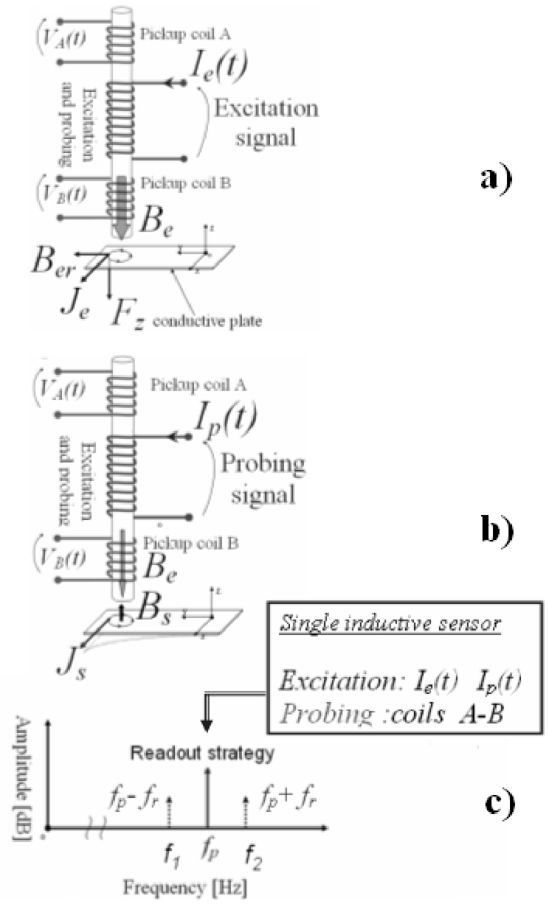

Figure 1: a) Schematic diagram of the excitation principle. b) Schematic diagram of the detection principle. c) Frequency domain response: carrier frequency (f_p) and the effect of the beam modulation (f_1, f_2).

THE DESIGN OF THE SOI PROTOTYPE

A reference microresonator device is presented in Fig. 2. It is composed of a suspended mass supported by a four crab-leg beams. The passive micromachined device has been developed by adopting the BESOI (Bulk and Etch Silicon on Insulator) custom technology realized at the Centro Nacional de Microelectronica (CNM), Spain. A Silicon On Insulator (SOI) wafer based on 15 µm upper silicon layer and 450 µm thick of substrate with 2 µm of buried oxide has been used and a backside DRIE etching procedure has been performed to suspend plates or masses. A surface micromachining deposition has been conducted on top of the 15 µm silicon layer. Fig. 3 shows the BESOI cross-sectional area.

The device has been designed using the heterogeneous beam theory in accordance with the different stacked materials offers by the BESOI process. The main difficulty of elastic characteristics estimation concerns the heterogeneous composition of a beam section. Using the mechanically equivalent shape (having a Young's modulus E_n), the beam inertia's moment I_n can be expressed as follow:

$$I_n = b \times \sum \left[\frac{E_i}{E_n}\frac{t_i^3}{12} + t_i \frac{E_i}{E_n}(h_n - h_i)^2 \right] \quad (2)$$

Where b is the width of the beam, E_i, t_i, h_i represent the Young's modulus, thickness and the neutral axis position for the ith element respectively. Equation (2) allows studying a heterogeneous device in an equivalent homogeneous domain. For a four beams suspended mass, the resonant frequency can be expressed as.

$$f_r \cong \frac{1}{2\pi}\sqrt{\frac{4k}{M}} = \frac{1}{2\pi}\sqrt{\frac{48E_{\max}I_n}{l^3M}} \quad (3)$$

where k is the elastic constant of a single beam, furthermore E_{max} is the maximal value of the stack materials Young's modulus, l and M represent the length of the beam and the inertial mass.

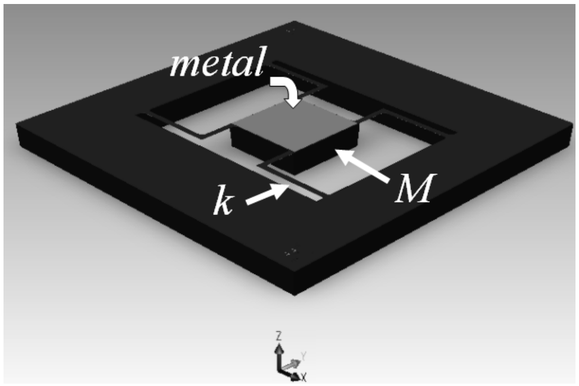

Figure 2: 3D schematic of the passive microresonator studied.

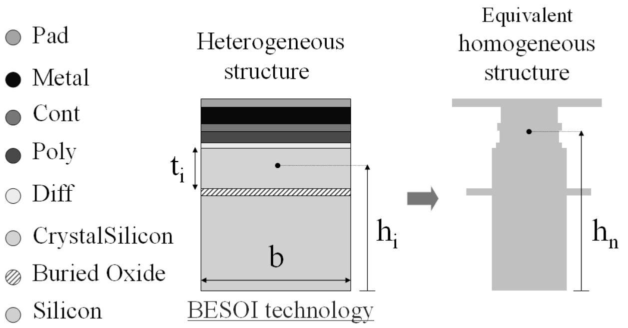

Figure 3: BESOI cross-sectional area and the equivalent homogeneous structure extracts using the heterogeneous beam theory.

EXPERIMENTAL RESULTS

A prototype of contactless electromagnetic microresonator based on BESOI technology (Bulk and Etch Silicon on Insulator) and used as passive sensing element will be here presented. The micromachined sensor is represented by four crab-leg beams with a suspended mass 1600 µm x 1600 µm x 467 µm of silicon and 1 µm of metal plate used like conductive surface (Fig. 4). A frequency of ~ 420 Hz has been estimated by the heterogeneous beam theory, in the perspective of an experimental analysis. The contactless sensing element is realized adopting an external inductor based on 100-µm FeSiB amorphous ferromagnetic core material; two superimposed primary coils are used as excitation and probing coils while two secondary coils represent the pick-up coil (Fig. 5a). The conditioning circuit is shown in Fig. 5b: an operational amplifier (V/I configuration) has been used to drive the primary coil of the inductor with a sinusoidal excitation signal ($V_e (t)$) having an amplitude of 900 mV_{pp} @ 225 Hz and a probing bias ($V_p \ (t)$) of 6.5 V_{pp} @ 1.087 MHz; the secondary coils have been connected in differential configuration and applied through two high pass filters, to an instrumentation amplifier. Fig. 6a shows the experimental setup: a microtranslator has been used to move the sensing platform composed by the inductive sensor and a supplementary laser sensor. The MEMS die has been fixed in the bottom of the setup.

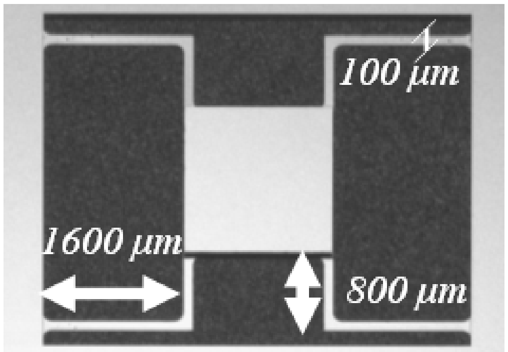

Figure 4: Microresonator based on BESOI (Bulk and Etch Silicon on Insulator) technology (bottom view).

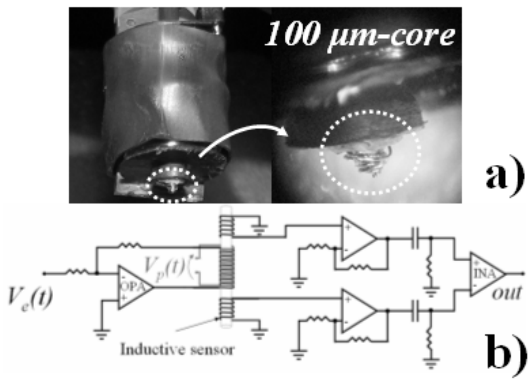

Figure 5: a) Microscope picture of the inductive sensor based on 100-µm core diameter. b) Conditioning circuit.

The resonant frequency estimated through experiments, by using the inductive sensing corresponds to ~ 450 Hz. Fig. 7a shows the magnetic response around the point of interest (f_p-f_r=1.087 MHz-450 Hz) with a resonant frequency shift dictated by the presence of different quantities of paint deposited on the top surface of the resonator. A sample mass of ~ 220 µg has been estimated through the model inversion (3). Furthermore, the decreasement of the resonant frequency has been compared with the values obtained by optical sensing. Coherence between both readout strategies has been detected as shown in fig. 7b.

CONCLUSIONS AND FUTURE WORK

The preliminary results here presented evince the possibility to adopt a four beams crab-leg suspended mass BESOI-based as contactless electromagnetic microresonator. The heterogeneous beam theory has been used to design the MEMS device and to analyze the dynamic behavior. In order to excite the suspended mass and to sense the motion, an external inductor based on 100-µm ferromagnetic core material has been used; the small core diameter gives high performance in term of spatial resolution and therefore in the capability of pointing a very small target as the MEMS device considered here. The resonant frequency estimated through experiments corresponds to ~ 450 Hz in accordance with the theoretical model. Moreover in order to analyze the frequency shift an experimental estimation of the resonance frequency, ranging the excitation bias frequency has been conducted; a variation of about 18 Hz has been detected as consequence of about ~ 220 µg of paint.

The possibility of using a contactless microresonator MEMS-based with an inductive approach both for excitation and readout has been demonstrated here. The system has been studied via analytical models and experimentally verified by using an optical feedback.

As a future step the optimization of the overall system is planned, in particular accurate Finite Elements Simulations will be performed for the integrated device and an extensive experimental campaign will be realized.

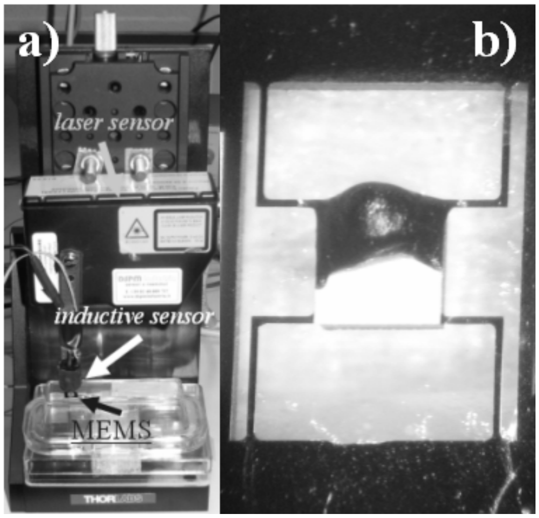

Figure 6: a) Experimental setup. b) Microscope picture of the realized crab-leg microresonator and on the surface the deposited paint (top view).

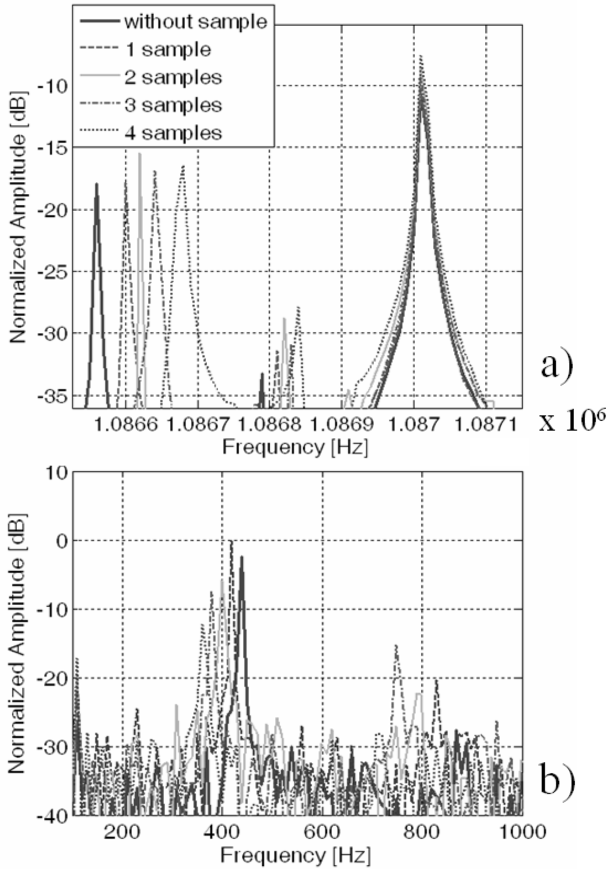

Figure 7: a) Experimental evaluation of the resonant frequency shift as consequence of different quantities of paint. The response has been considered around f_p-f_r *=1.087 MHz-450 Hz and the spectrum is normalized to its maximum value of amplitude. b) Optical response around the resonant frequency.*

CONTACT

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