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Electrical detection of multiple resonant modes in a CMOS–MEMS cantilever

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Abstract

The design, implementation and test of a monolithically integrated CMOS-mechanical resonator based on a metal cantilever are presented. Several resonant modes including fundamental and first higher mode have been electrically characterized with the embedded CMOS circuitry. Test results provide measures of both lateral and vertical modes of vibration of the metal cantilever. The experimental resonant modes found have been corroborated by finite element method (FEM) simulations.

Keywords: CMOS–MEMS; Resonant cantilever; Cantilever-based-sensors

1. Introduction

Since several years it has been shown that cantilevers can be used for sensing a variety of magnitudes such us temperature, humidity or mass. In particular, the use of vibrating cantilevers as a mass sensor has been proven to be a promising solution to achieve sensitivities in the range of 10^{-18} g [1]. When a mass is deposited on the surface of a cantilever, assuming that the spring constant remains unaltered, a shift on the resonance frequency of the cantilever allows determining the increase in mass that has occurred. Eq. (1) shows the dependence of the resonance frequency (f_0) on the effective mass (m_{eff}) and spring constant (k)

$$f_0 = \frac{1}{2\pi}\sqrt{k/m_{\mathrm{eff}}} \tag{1}$$

It has been studied how the sensitivity increases with the frequency of operation of the cantilever. Two different approaches can be followed to obtain this improvement in the sensitivity. The first one consists on the reduction of the dimensions of the mechanical structure. A smaller cantilever will always provide a higher value for the resonance frequency but, as a drawback, it makes more difficult the process of fabrication as well as the detection of the movement. The second approach consists on taking benefit of the use of higher frequency modes of resonance of the cantilever, which at the same time provide higher quality factors. It has been reported on the literature that mass sensitivity increases at least one order of magnitude when higher modes of vibration are used [2].

This paper is focused on the characterization of a monolithically integrated CMOS–MEMS based on a cantilever shaped resonating structure embedded in a CMOS read-out circuitry. The detection of the movement is performed using electrostatic actuation and capacitive read-out of the generated motional current. Within this approach we have been able to obtain both lateral and vertical modes of cantilever resonances. Experimental results have been analysed and corroborated with Coventor simulator tool.

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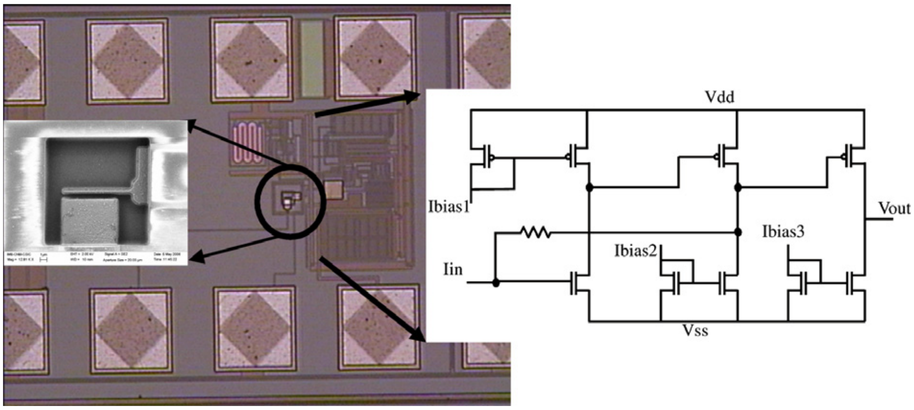

Fig. 1. Optical image of the full system composed of the released cantilever and the amplifier. The insets represent a scanning electron microscope (SEM) image of the released cantilever and the implemented transimpedance amplifier in charge of detecting the output current.

2. System design

2.1. MEMS resonator: fabrication and principle of operation

The mechanical resonator consists of metal cantilever electrically actuated by an electrode (driver) placed in plane and separated by a sub-micrometric gap. The CMOS–MEMS system has been implemented in a commercial technology (0.35 μm AMS CMOS), adding a mask-less wet etching process to release the MEMS cantilever [3]. Cantilever and driver are fabricated using as structural layer the top metal layer available in the technology, while the sacrificial layer is the underneath stack of silicon oxide layers. In order to allow a direct post-processing, the CMOS design includes a pad cut over the resonator area. In this way, the resonator structure is kept free of the addition of any other layer over it. The rest of the chip area is covered by the passivation layer, a silicon nitride film deposited by Plasma Enhanced Chemical Vapor Deposition (PECVD) that protects the circuitry during the post-process.

In order to characterize the movement of the cantilever, an electrostatic actuation and capacitive read-out is performed. In particular, a DC voltage plus AC excitation voltage is applied to the driver electrode. The resulted electrostatic force due to the AC signal, induces the oscillation of the cantilever at the excitation frequency. If the frequency matches the resonance frequency of the cantilever, a maximum oscillation is achieved. The oscillation generates a change in the capacitance formed by the driver electrode and the cantilever that can be quantified by measuring the induced output current through the cantilever [4]. Eq. (2) corresponds to the measured output current (assuming $V_{\mathrm{Dc}} \gg V_{\mathrm{Ac}}$)

$$I \cong V_{\mathrm{DC}} \frac{\partial C}{\partial t} + C_0 \frac{\partial V_{\mathrm{AC}}}{\partial t} \tag{2}$$

where C_0 is the static capacitance between driver and cantilever.

2.2. CMOS Amplification circuit

The configuration proposed is based on the integration of the capacitive current generated by the vibrational movement of the resonator by using the intrinsic capacitance of a CMOS amplifier. An inverter amplifier structure, in particular, a common source one has been selected. The structure is formed by an inverting amplifier followed by a source-follower for enhancing the bandwidth of the full amplifier. In order to polarize the amplifier, a PMOS transistor has been used as a resistor (Fig. 1).

In order to maximize the gain of the amplifier, both, the amplifier input transistor and the PMOS polarizing device have been designed trying to minimize its parasitic capacitances, which are in charge of integrating the current generated by the movement of the cantilever. Moreover, the input node has been designed with a high input impedance so that the motional current will go mainly to the integrator capacitor.

Finally, an output buffer stage has been designed to drive the 50 Ω input impedance of the network analyzer. It consists on a basic source follower. To reduce power consumption at the output stage, the full amplifier is AC coupled to the network analyzer by means of an external capacitive coupling. With the designed amplifier, a high transimpedance gain of 1 MΩ is achieved at 6 MHz.

3. Experimental results

3.1. Mechanical resonator

Fig. 1 shows an optical image of the full system composed of the released cantilever and the implemented amplifier. A scanning electron microscope (SEM) image of a released metal cantilever is presented in the inset. The cantilever is 10 μm long by 650 nm wide, with a gap between the driver electrode and the cantilever close to 1 μm. The 15 ∗ 15 μm pad window designed to allow an easy post-process of the structure can be clearly observed.

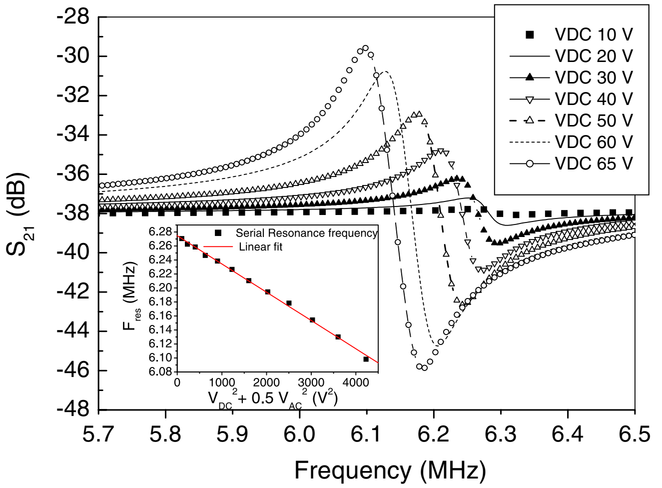

Fig. 2. Transmission spectrum (S_{21}) under air conditions for the first lateral mode showing the spring softening effect on the resonant cantilever for different DC applied voltages. The inset represents the resonant frequency versus the DC applied voltage. The experimental linear fit gives a slope of 40.37 Hz/V^2 and a natural resonant frequency of 6.27 MHz, according the theoretical ones.

3.2. Full CMOS–MEMS system characterization

The electrical signal coming from the CMOS–MEMS is acquired using a network analyzer (Agilent E5100A). A bias-tee (Mini-Circuits ZFBT) has been used to apply simultaneously the AC and DC voltage to the driver.

Fig. 2 shows the transmission spectrum of the first lateral mode obtained under air conditions for different DC voltages (from 10 to 65 V) and an AC voltage corresponding to a power of −10 dBm. It can be observed an increment of the quality factor when higher DC voltages are applied. In particular, the quality factor increases from 15 at 20 V to 75 at 65 V. A displacement of the spectrum to lower frequencies for higher DC voltages, due to the spring constant softening effect [4], is also shown in Fig. 2. In particular, the inset represents the dependence between the resonance frequency and the DC voltage obtained from Fig. 2. From the measurements, a natural frequency of 6.27 MHz and a slope of 40 Hz/V^2 are obtained. We have performed calculus in order to corroborate the experimental dependence. The natural resonant frequency for the fundamental in-plane resonant mode is obtained solving the movement equation and it is given by

$$f_n = \frac{1}{2 * \pi} \alpha_n^2 \frac{w}{l^2} \sqrt{\frac{E}{12\rho}} \tag{3}$$

where ρ is the mass density, E is the Young's modulus, l the length, w the width and α_n is different parameter for each resonant mode ($\alpha_1 = 18{,}751$ and $\alpha_2 = 46{,}941$ for the fundamental and first higher mode respectively) [5].

We have considered an aluminium cantilever of 650 nm wide, 10 μm long, 700 nm hight with a Young's modulus of 77 GPa, a mass density of 2230 kg/m^3 and a gap of 1 μm. The analytical values of the natural resonance frequency (Eq. (3)) and the slope [4] are 6.17 MHz and 51.4 Hz/V^2 respectively which are in the same range that the experimental ones previously reported.

Fig. 3 shows the measured transmission spectrum S_{21} (both magnitude and phase) for a fixed DC polarization voltage for three different resonant modes: two in-plane or lateral resonant modes (fundamental and first higher mode) and the fundamental vertical mode. The resonance frequencies of these modes are 6.285 MHz (Fig. 3a), 6.64 MHz (Fig. 3b) and 38.55 MHz (Fig. 3c) respectively. By comparing the obtained magnitude between the first higher mode and the fundamental in the lateral resonant mode, it is seen a clear reduction in the read-out signal

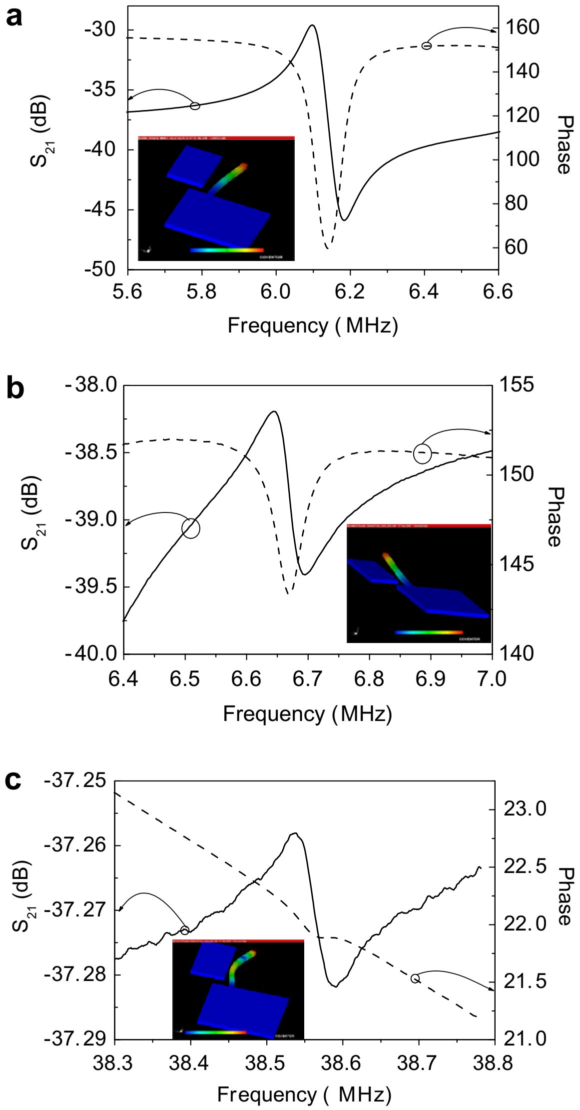

Fig. 3. Transmission spectrum (S_{21}) under air conditions for three different resonant modes. (a) corresponds to the first lateral mode, when a DC voltage of 65 V and −10 dBm are applied. (b) corresponds to the first vertical mode, when a DC voltage of 65 V and −10 dBm are applied. (c) shows the second lateral mode when a dc voltage of 30 V and −10 dBm are applied. The insets illustrate qualitatively the movement of the cantilever, obtained by FEM simulations from Coventor.

(from 3 dB at the resonance peak for the fundamental frequency to 0.03 dB for the first higher mode). This effect is due to the electrical read-out used, which accounts for a change on the capacitance between driver and cantilever. In fact, the movement of the second lateral mode presents two nodes, almost compensating the variation of capacitance during the resonance. In this way the induced output current through the cantilever is smaller than for the fundamental mode in which there is a net movement of the tip of the cantilever and thus a higher variation of the capacitance (see Eq. (2)).

To corroborate the resonance frequencies found in the electrical test, we have solved the movement equations of a vibrating cantilever, also for the vertical mode. In this case, it is necessary to replace in Eq. (3) the dimension w (width) by t (thickness). In our case, a thickness of 700 nm has been used to compute the frequency of the vertical resonant modes. The theoretical resonant frequencies obtained from the equations are 6.17 MHz, 38.64 MHz for the lateral modes and 6.64 MHz for the vertical mode which are in good agreement with the obtained experimental ones.

In order to further study and explain the overall movement and electrical characterization of the CMOS–MEMS cantilever, FEM analysis simulations (using Coventor tool) have been carried out. The cantilever, according with the metal structure provided by the technology (AMS) is not simply a one metal aluminium layer, instead it is implemented with a double layer of Al and TiN with thickness of 532 nm and 30 nm respectively. The big differences on the Young's modulus and mass densities for the Al (77 GPa and 2230 kg/m^3) and for the TiN (600 GPa and 5220 kg/m^3) made difficult the analytical evaluation of the mechanical behaviour of the cantilever in all its resonant modes. Therefore, a bi-layer cantilever with a 600 nm wide, 10 μm long and a gap of 1 μm has been simulated. Taking into account these characteristics, the obtained simulated frequencies are 6.38 MHz and 39.4 MHz for the fundamental and first higher mode in plane resonant modes and 6.69 MHz for the fundamental vertical mode, values which are very similar to the experimental ones. The simulated dependence of the resonance frequency (for the fundamental lateral mode) versus the DC voltage presents the expected quadratic dependence versus the applied voltage, giving a value of 23 Hz/V^{2}for the slope which is in the same range that the 40.37 Hz/V^{2}obtained by the electrical test (see Fig. 2). In the cases of the vertical resonant mode (fundamental) and first higher mode of the resonant lateral mode, the experimental dependence of the resonant frequency with the applied DC voltage is almost negligible as has been also found from the Coventor simulations. In this way we can state that the CMOS–MEMS system is capable of a full characterization of the cantilever movement with several resonant modes.

Fig. 4 shows the measured transmission spectrum S_{21},(magnitude), for a DC voltage of 20 V under vacuum conditions (5.5 e−3 mbars). By comparing both air and vacuum electrical characterization, it is seen how the damping is reduced, increasing the quality factor of the resonator in its two first fundamental resonance modes. In particular, quality factors around 380 and 90 are achieved for both the first lateral and vertical modes respectively, using a VDC of 20 V.

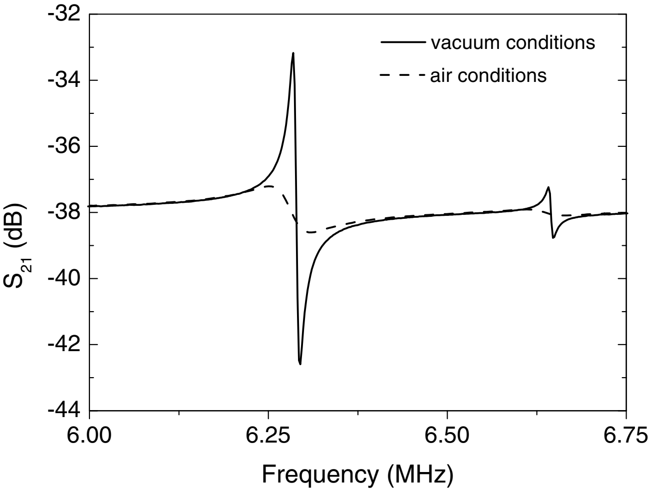

Fig. 4. Transmission spectrum S_{21} (magnitude) under vacuum (5.5 e−3 mbars) and air conditions for the first lateral and vertical modes respectively when a dc voltage of 20 V and −10 dBm are applied. An increase of the quality factor is observed in both cases.

Some conclusions can be extracted from the complete electrical characterization we have reported in this paper. In fact, the analysis of the different obtained behaviour of these modes allows to predict higher resolution in terms of mass due to higher resonant frequencies of the first higher mode [2]. However, we have proved that the electrostatic transduction does not allow to see the increase of the quality factor of these modes even in vacuum. In this way we can state that the electrostatic transduction based on a capacitive read-out is absolutely useful in terms of accuracy and integrability for the fundamental resonant mode contrary to other results obtained and reported in the literature which use other transduction techniques. Due to the full integration of the read-out circuit with the cantilever, the characterization of the MEMS is simple, without the need of any other additional setup.

4. Conclusions

A complete CMOS–MEMS system based on a resonant metal cantilever has allowed to electrically characterize several resonant modes. Three different resonant modes have been measured, in air and vacuum conditions, corresponding to the fundamental and first higher frequency in the lateral mode and the fundamental in the vertical mode. The results have been corroborated using FEM simulations.

Acknowledgement

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