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Compact heterodyne NEMS oscillator for sensing applications

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ABSTRACT

We present a novel topology of heterodyne nanoelectromechanical self-oscillator, aimed at the dense integration of resonator arrays for sensing applications. This oscillator is based on an original measurement method, suitable for both open loop and closed loop operations, which simplifies current down-mixing set-ups. When implemented on-chip, it will allow the reduction of the size and power consumption of readout CMOS circuitry. This is today the limiting factor for the integration density of NEMS oscillators for real-life applications. Here we characterize this method in both open-loop and closed-loop, and evaluate its frequency stability.

1. State of the art

The implementation of Nanoelectromechanical systems (NEMS) arrays is of importance for a variety of applications: parallel sensing circumvents the small capture area of individual sensors [1], allows different functionalization for selective sensing [2] and enables applications requiring spatial mapping. Therefore, the dense integration of NEMS oscillators (*i.e.* resonators in closed loop) is desirable for a wide range of applications, where it is important to individually track the frequency response of each resonator in real time. In this sense, the monolithic co-integration of the NEMS resonators with CMOS circuitry for data processing represents a low-power and compact solution [3], with potential to achieve a very good density of integration.

Even though CMOS-NEMS co-integration has clear advantages, the factor limiting the density of integration is nowadays the area of the circuitry required to read the response of the resonator, typically much larger than that of the sensor itself [4,5]. Moreover, the fabrication of the NEMS arrays themselves is still challenging: few works have addressed this issue, and those which have comprise a small number of resonators (typically less than 10) or use external optical transduction [1,6–8]. For this reason, until now all-electrical closed loop operation with individual addressing has been attempted either with single devices [9,10] or with arrays sharing a single feedback loop and time-multiplexed addressing [11,12]. Another layer of complexity is added in mass sensing applications, where simultaneous operation of at least two resonance modes of each resonator is required [13,14]. Therefore, in this case, at least two self-oscillating loops per resonator are needed, which imposes stringent conditions in terms of gain and bandwidth of the feedback loop due to the frequencies of higher modes.

Existing closed loop topologies include the homodyne self-oscillating scheme, the most simple and probably the most widely used [5,10]. In this topology, the frequency of the signal at any point of the loop is that of the resonator's, in the order of tens to hundreds of MHz. This poses several problems: the parasitic capacitances have an important effect at high frequencies, degrading the operation of the oscillator; and high frequency operation involves constraints in terms of complexity and power consumption of the analogue circuitry. In contrast, a Phase-Locked Loop (PLL) [11] or a heterodyne oscillator scheme [15] helps to circumvent this cut-off issue by working at low frequencies, but they imply a more complex—and therefore, area-consuming—circuitry. For this reason, neither of them represents an ideal candidate for the dense integration of NEMS arrays.

In a previous work [16] we presented the initial proof of concept of a novel down-mixing measurement method for NEMS resonators, which potentially presents a reduced power consumption with no important increase in circuit footprint, aimed at the dense

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integration of individually addressed sensor arrays. In closed loop configuration it provides advantages with respect to traditional schemes: a reduced bandwidth of the feedback signal and at the same time robustness relative to parasitic capacitances without increasing the complexity of the circuit. The first stage of the amplifier is usually one of the largest elements of the feedback loop, and has a power consumption determined by the product of its gain and bandwidth. The technique we propose allows a decrease of three orders of magnitude of the amplifier bandwidth with respect to a homodyne oscillator, while maintaining the gain in the same order of magnitude. Hence it reduces the power consumption of the readout and feedback circuitry and eliminates the need of a mixer (with the corresponding gain in circuit footprint), facilitating a dense integration of CMOS-NEMS arrays.

Here we present a significant step further towards the implementation of this technique for real-life applications: we demonstrate its experimental feasibility for NEMS-Mass Spectrometry (NEMS-MS) applications, which requires robustness and dual mode operation of doubly-clamped beam resonators. Robustness is a key parameter of the circuit for the integration of large arrays, in order to overcome the variability of the circuit components and mechanical resonators. Here we study this parameter by determining the range of operation of the feedback loop, through an examination of its response as a function of its phase shift (Fig. 5b). The experimental demonstration of the new technique is more challenging with doubly-clamped beam resonators than with cantilevers such as those used in [13], as the output voltage is almost an order of magnitude lower. We demonstrate the suitability of this scheme for measuring doubly-clamped NEMS resonators which have been used for sensing applications [13,14]. This was performed for the first and second modes of resonance independently as this is a requirement to deduce both mass and position of single particles landing at the surface of the NEMS (Fig. 7a). Finally, we show a method to use the set-up in real-time mass sensing applications without the need to double the feedback loop, by employing a time-multiplexed measurement of the first two modes of resonance (Fig. 7b).

2. NEMS resonator and open loop drive mixing topology

The nanomechanical resonators used here are monocrystalline silicon beams, fabricated in the top layer of a silicon-on-insulator wafer (Fig. 1a). They are fabricated with hybrid DUV/e-beam lithography followed by dry etching at wafer level. They are highly doped with boron, in order to have a good electrical conductivity. Two different resonator topologies are used: single-clamped (Fig. 1b) or clamped-clamped beams [13]. For both of them, the actuation is performed electrostatically from a nearby driving electrode. The motion of the resonator is detected by two differential piezoresistive nanogauges [17]. This transduction method provides a large dynamic range, it is efficient at high frequencies [18] and rejects the common mode of the readout signal. The measurements are performed under vacuum (10^{-5} mbar) and at room temperature.

The measurement topology presented here in open loop configuration is described in Fig. 2. This setup is an alternative to the conventional down-mixing scheme [19]: here the mixing is performed by the quadratic voltage-to-force relationship of the electrostatic actuation ($F_{el} \propto V_{Drive}^2$), simplifying the set-up by avoiding the need for mixers, splitters and a circuit branch to generate the reference lock-in signal. This is a significant experimental advantage, even with discrete elements, as one of the main disadvantages of down-mixing set-ups is their complexity with respect to homodyne configurations. In order to actuate the resonator, we combine two signals at different frequencies, sent to the drive electrode: $V_{Drive} = V_B \cos 2\pi f_B + V_M \cos 2\pi f_M$. The first signal is a biasing signal at a high frequency f_B (in the order of magnitude of the resonance frequency, here tens of MHz), while the second one is at a low-measurement frequency f_M (in the range of kHz). As the electrostatic force is proportional to the square of the driving voltage, we obtain:

$$F_{Drive} \propto (V_B \cos 2\pi f_B + V_M \cos 2\pi f_M)^2 = (V_B \cos 2\pi f_B)^2 + (V_M \cos 2\pi f_M)^2 + V_B V_M \cos 2\pi (f_B + f_M) + V_B V_M \cos 2\pi (f_B - f_M), \quad (1)$$

where the last two components are at frequencies $f_B + f_M$ and $f_B - f_M$. The other components are at frequencies far away from resonance, and therefore do not affect the motion of the resonator importantly. The resonator is then in resonance when its resonance frequency f_0 is equal to the sum or the difference of f_B and f_M.

For the detection of the motion of the resonator, we feed the same bias voltage to the nanogauges with inverted polarities

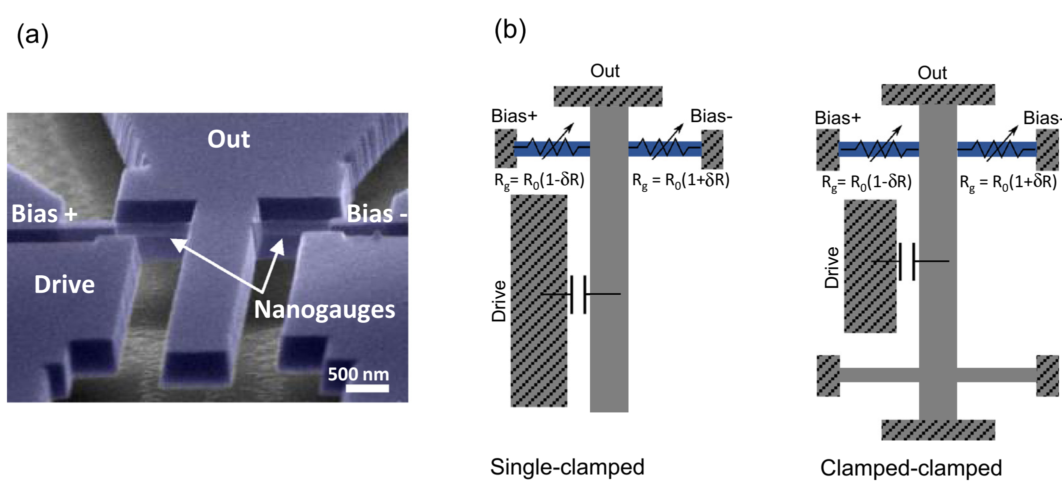

Fig. 1. Nanomechanical resonators. (a) Scanning electron microscope image of a single-clamped NEMS resonator used for the measurements. It is patterned in the crystalline layer (coloured in violet) of a silicon-on-insulator wafer. It is 3.2 μm long, 300 nm wide and 160 nm thick. The nanogauges are 1 μm long and 100 nm wide. The actuation is performed electrostatically through a drive electrode, and the motion is transduced by two piezoresistive nanogauges. (b) Schematic of the single-clamped and clamped-clamped nanomechanical resonators. The striped parts are fixed to the substrate, and the nanogauges are coloured in blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)