SUSTAINED NANO-MECHANICAL OSCILLATION OF A RESONANT-BODY TRANSISTOR BY FREQUENCY-MODULATED HETERODYNE PHASE-LOCKED-LOOP

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Many applications based on resonant nanoelectromechanical systems (NEMS) require monitoring their natural frequency of oscillation over time with high precision, e.g. for gas sensing or nanomechanical mass spectrometry [1]. In this study, we integrated for the first time a very-high frequency, nanomechanical resonant-body field-effect transistor (RB-FET) into a frequency-modulated phase-locked loop (FM-PLL) which operates analog, requires only one frequency source, and simultaneously exploits the low-noise motion detection based on FM-demodulation with resonant transistors [2]. We demonstrate sustained mechanical oscillation of a 120 MHz doubly-clamped nano-resonator (*54* nm thick, *158* nm wide, *2.65* µm long) by using the FM-PLL in vacuum and in air, reaching a frequency stability in the low *ppm*-range at room temperature.

Fig.1 shows a SEM top view of a representative device. The device fabrication was based on a large-scale, silicon-on-insulator (SOI) surface nano-machining process. The initial *37* nm thin device layer was patterned using e-beam lithography. Details on fabrication and co-integration with SOI-CMOS were reported in [3]. The fundamental, flexural mode at $\omega_0/2\pi=121$ MHz was actuated through lateral gate electrodes and *65* nm capacitive air-gaps. We used the RB-FET as efficient FM-demodulator [2] to detect the nanomechanical oscillation on-chip; this technique provides a large signal-to-noise ratio (SNR) and ease of implementation. However, the first-order response does not provide a signal suitable to build a negative feedback loop, due to its symmetry around the resonator centre frequency (see Fig.2). Therefore, most NEMS-PLLs have relied on two-source mixing techniques [4] or digital implementations [5], which required algorithms and computer interface and can limit the measurement bandwidth.

Here, we used a nonlinear effect to create a linear, negative loop-feedback signal. In FM, the bandwidth required to transmit the signal is $\sim 2(\omega_{ref} + \Delta\omega)$, where ω_{ref} is the modulation frequency and $\Delta\omega$ the frequency deviation. When increasing $\Delta\omega$, the FM-bandwidth increased and approached the resonator natural line-width $\omega_0 / Q \approx 120$ kHz. The response became then increasingly nonlinear due to higher-order terms, which arise from the $(\Delta\omega)^n\cos^n(\omega_{ref}t)$ terms (n is the nth order harmonic). The mathematical origin of this nonlinearity was shown in [5]. The odd-terms n=1,3,... showed an amplitude-frequency relation that is asymmetric with respect to the resonator center frequency, and we could use this property to generate a feedback signal (see Fig.3).

The resonator was measured in a vacuum-probe station (Süss Microtech) using a lock-in amplifier (Stanford Research) and an RF signal source with FM-capability. The FM-PLL circuitry is shown in Fig.4. When closing the loop, we observed that a small phase error remained in the loop (parasitic cable capacitances); we used a DC voltage (V_{offset}) in combination with an adder in order to compensate for this error. Interestingly, both the feedback gain and the loop capture range could be controlled via $\Delta\omega$ (Fig.5), which implies an additional degree of freedom for the design of integrated NEMS-PLLs.

When using NEMS as gravimetric sensors, e.g. for measuring a gas concentration, it is useful to introduce the surface mass resolution:

$$\delta\mathcal{M}_s = 2\,\mathcal{M}_{eff} / \mathcal{A}_{eff}\;\delta f / f_0 \approx 1.47\,\delta f / f_0\;t\;\rho \qquad (1)$$

where $\delta f/f_0$ is the fractional frequency stability, ρ the material density, t the thickness and $\mathcal{A}_{eff}$ the effective surface area. The modal mass M_{eff} was estimated $\sim 34x10^{-15}g$ for the fundamental mode (uniform mass loading). Eq.1 underlines that the design of RB-FETs must be carefully considered depending on their final application. We implemented different cc-beam resonator geometries, with the widest resonator showing the best areal mass sensitivity, owing to the largest Q ~ *1000* and output SNR achieved. Fig.6 shows the experimental stability of *2* ppm of the RB-FET resonator integrated in the FM-PLL, with the equivalent mass sensitivity of ~*380* zg/µm^2 (1 zepto-gram=10^{-24} kg). In air (Q ~ *150*), *12* ppm stability was achieved.

We have demonstrated a novel heterodyne feedback loop based on a nonlinear effect in FM-demodulation with a resonant-body transistor. Importantly, the FM-PLL is compatible with the parallel actuation and readout of a large resonator arrays, which remains a crucial aspect for the design of real-world nano-sensors with enhanced the output SNR and capture cross-section [1, 9]. As such, the presented FM-NEMS-PLL could emerge a valuable scheme to realize low-power, low-noise, ultra-sensitive NEMS systems hybridized with CMOS on a single chip.

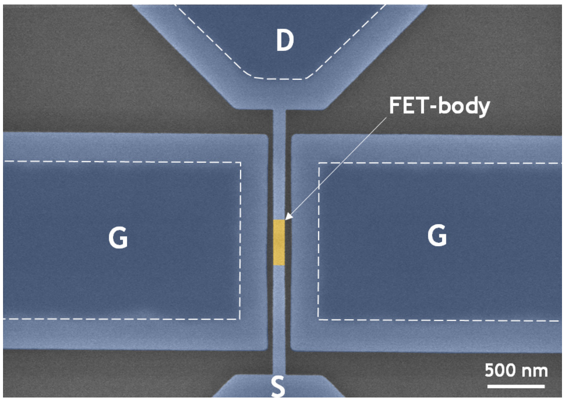

Fig.1: *Top-view SEM image (false color) of the $n^{+}pn^{+}$ RB-FET with lateral drive electrodes. The dashed lines indicate the buried ox ide beneath the SOI device layer.*

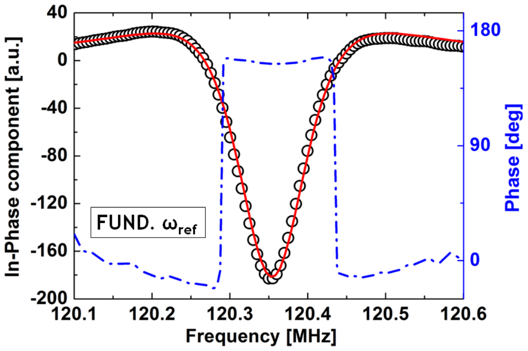

Fig.2: *The mechanical resonance at f_0=120.35MHz is shown as in-phase component of the drain current detected at* $\boldsymbol{\omega_{ref}}$. *The right axis shows the phase response.*

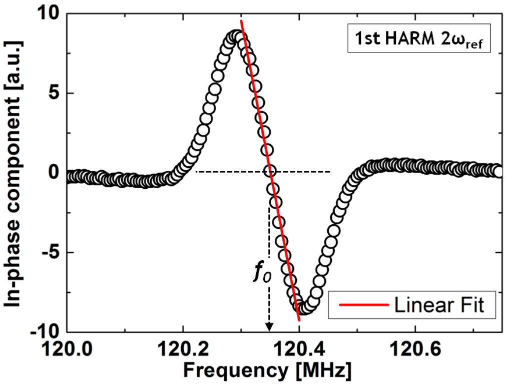

Fig.3: *The 1^{st} harmonic of the in-phase component detected at* $\boldsymbol{2\omega_{ref}}$ *is used to provide a negative loop feedback signal and lock onto the resonance at $f_0=\omega_0/2\pi$.*

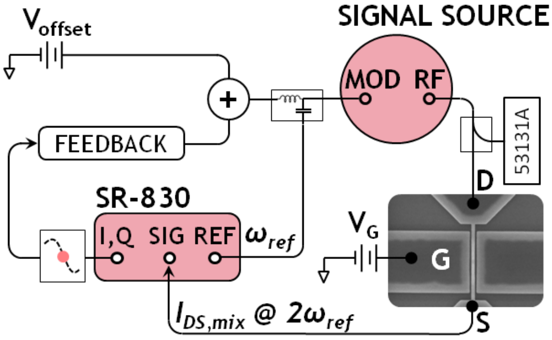

Fig.4: *The circuit schematic of the single-source FM-NEMS-PLL (ω_{ref} =8kHz, V_G =10V). The signal source generates the FM-signal cos(ωt+ $\Delta\omega/\omega_{ref}$sin $\omega_{ref}t$).*

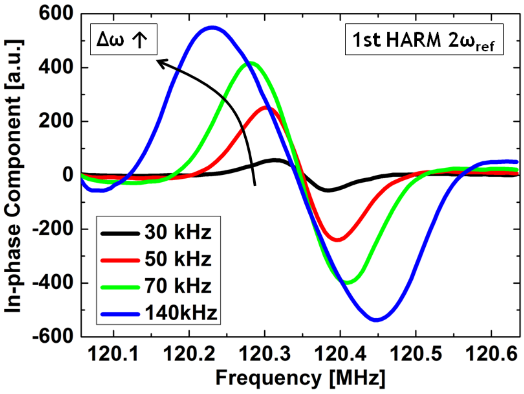

Fig.5: *The amplitude response of the detected 1^{st} harmonic as function of the frequency deviation $\Delta\omega/2\pi$. The loop capture range is reached at the point where the slope of the signal falls to zero.*

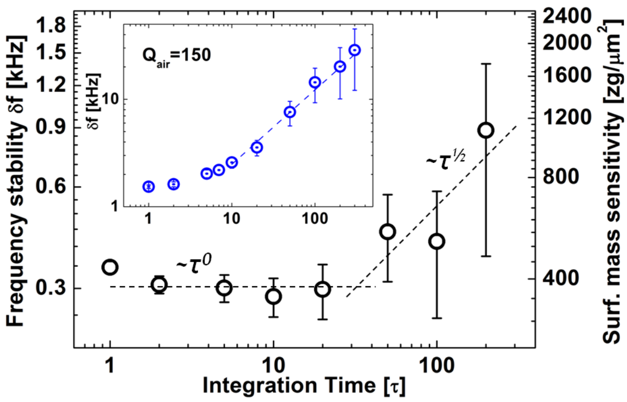

Fig.6:*Experimental frequency stability and corresponding surface mass sensitivity vs. the integration time (295K, in high vacuum) for a cc-beam measuring 158nm x 2.65µm (W x L). The drive power is -26 dBm and the deviation $\Delta\omega/2\pi$=70 kHz. The inset shows the frequency stability of ~12 ppm measured at ambient conditions (P_{in}= -18 dBm).*

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