9 MHz Vibrating Body FET Tuning Fork Oscillator

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***Abstract*— A 9.4MHz micro-electromechanical oscillator based on a Vibrating Body Field Effect Transistor (VB-FET) is presented in this work. The tuning fork VB-FET used in this work provides a high quality factor of 9400 in the open-loop configuration and a low equivalent resistance. This performance makes the VB-FET an interesting candidate for fully integrated oscillator. An oscillator based on the tuning fork VB-FET is characterized.**

***Index Terms*— MEMS, Resonator, Transistor, Tunable Oscillator, Tuning Fork, Phase Noise**

I. Introduction

Quartz resonators are currently the most widely used devices for timing and frequency reference applications in electronic systems, with their main limitation being the incompatibility with CMOS process technology and difficulties of integration derived from this incompatibility. Silicon based resonators promise a higher degree of integration with smaller resonator dimensions and lower power consumption and attract therefore a lot of interest. This has led to performances of micro-electromechanical (MEM) resonators on par with quartz resonators [1] or even better. Electrostatic transduction is widely used for MEM resonators, but scaling of such devices faces some practical problems. The main limitations comes from the decreasing signal levels and the increasing parasitics in these devices. To overcome these issues the concept of Resonant Gate [2], [3], [4] and Vibrating Body [5] FETs have been proposed. The built-in amplification of VB-FETs increases the signal level, effectively transforming the resonator into an active device.

In this paper we demonstrate a feedback oscillator at 9.4MHz based on an active tuning fork VB-FET resonator and discuss the main challenges for design and performance.

II. The VB-FET

An SEM image of a VB-FET tuning fork resonator is shown in Fig. 1a, where the tines of the tuning fork are 3μm wide and 40μm long. The fundamental mode shape of the tuning fork in the flexurale mode shown in Fig. 1b is obtained by modal analysis using the ANSYS simulation software. In the center of the two tines, where the displacement is maximal, a FET body is placed to sense the displacement of the tines. The body region of the FET is indicated in Fig. 1a with white squares.

A cross section through the body region is shown in Fig. 2, illustrating the concept of the fixed gate and the mobile body. The charge modulation takes place on the lateral side

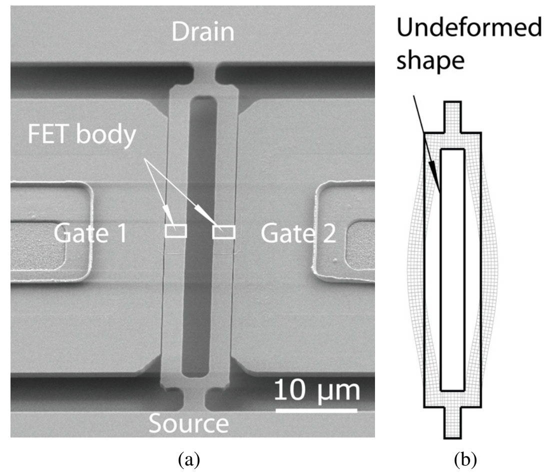

Fig. 1: a) SEM image of a VB-FET tuning fork resonator. The resonators beams are 40μm long and 3μm wide and the FET is placed in the center of the beams with a active gate area of $L_{chan} = 1\mu$m and $W_{chan} = 1.25\mu$m. b) The mode fundamental mode shape of the tuning fork resonator and it's undeformed shape simulated using ANSYS.

of the FET, facing the gate electrode. Implants and thermal oxidation (20nm oxide thickness) define along the beam the source, channel and drain regions of the VB-FET. While the length of the channel can be designed by CAD and is 1μm in this case, the width of the channel is 1.25μm, limited by the substrate thickness. The transistor body is n^- low doped while the drain and source regions are highly doped n^+ , which results in a normally-on transistor (non-zero current at $V_G = 0V$) and a modulation of the conductivity by accumulation of electrons $V_{G1,2} > 0$. An air gap between gate and beam of 180nm has been measured by microscopy, determining the electrostatic actuation as well as the electric field dependent detection of the VB-FET. Additional to the field effect based current modulation, capacitive currents and a modulation of the current in the beam by the piezoresistive effect is possible, but the dominant effect in the current device is the field effect modulation in the channel region.

III. Electrical Device Characteristics

A. Static characteristics

Measurements of the $I_D - V_D$ and $I_D - V_G$ characteristics of the tuning fork VB-FET are shown in Fig. 3. A symmetric gate voltage ($V_{G1} = V_{G2}$) is applied for these measurements,

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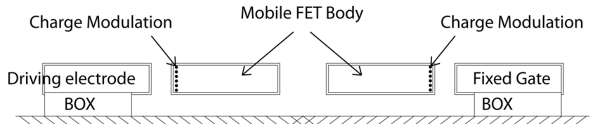
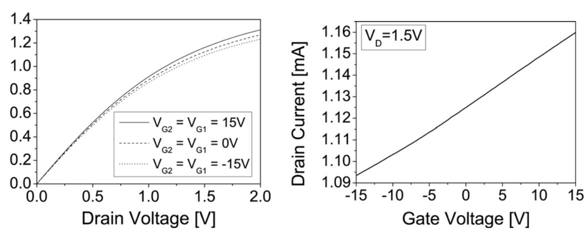


Fig. 2: Cross section of tuning fork VB-FET, the charge modulation take place on the lateral side-walls facing the two gate electrodes.

effectively each channel contributes 50% of the measured drain modulation. A depletion mode FET like behavior is observed in these measurements, where the FET can not be turned off completely due to the size of the body region. As a consequence the $I_D - V_D$ characteristic is strongly dominated by the current through the VB-FET body and the gate voltage has only a limited influence on drain current. The current measured for the $V_D = 1.5V$ is 1.1mA with $V_{G1,2} = 0$ and a variation of 2μA per volt is achieved. The transconductance is in the order of 2.2μS at $V_G = 15V$. The rather high current is due to the size of the n-type body in this depletion mode VB-FET. Saturation and self heating is observed for higher V_D, impacting the mechanical and the electrical properties of the device.



(a) (b)

Fig. 3: a) Experimental $I_D - V_D$ and b) $I_D - V_G$ characteristics of a tuning fork VB-FET ($L_{beam} = 40\mu$m, $W_{beam} = 3\mu$m, $L_{chan} = 1\mu$m). The gate voltage is applied on both gates ($V_{G1} = V_{G2}$).

B. Dynamic characteristics

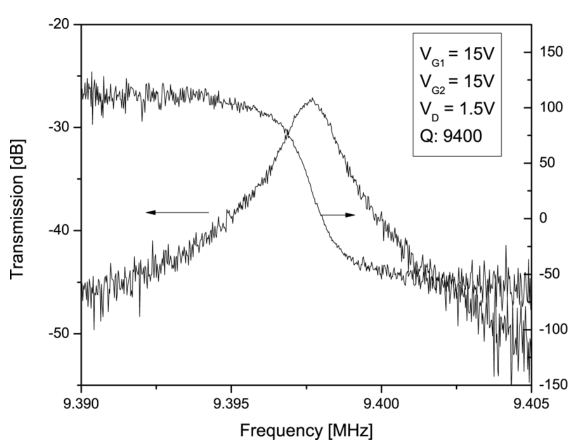


Fig. 4: Magnitude and phase of the scattering transmission parameter for a tuning fork VB-FET resonator.

1) Linear operation: Magnitude and phase of a tuning fork VB-FET with $V_G = 15V$ as measured with a vector network analyzer (VNA) is reported in Fig. 4. All measurements are done in a vacuum (< 10^{-5}mbar) and at room temperature. The study of the temperature sensitivity of the resonance frequency of the resonator or oscillator is beyond the scope of this paper. In these measurements, the excitation signal is applied on gate 1 only, while both gates are used to modulate the drain current. A quality factor of 9400 is obtained from Fig. 4 using the 3dB method. The measured phase has a change of 180° around the resonance with a transmission peak at resonance of -27.5dB measured on a 50Ω load.

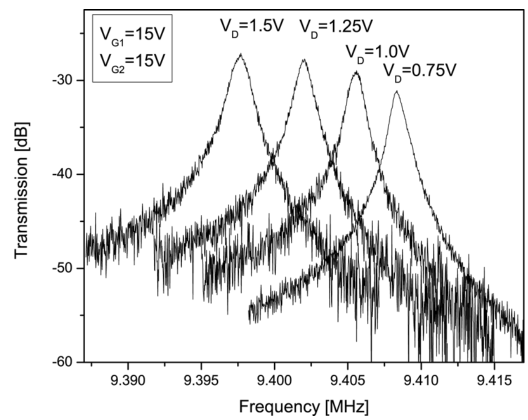


Fig. 5: Frequency spectrum of the tuning fork resonator with V_D as parameter.

The influence of V_D on the transmission characteristics is illustrated in Fig. 5. As expected for any FET device, V_D influences strongly on the transconductance and therefore on the transmission characteristics of the device. The impact of the gate voltage on the transmission characteristics is shown in Fig. 6, where V_{G1} is held constant and V_{G2} is changed between 12V and 15V. The change in the electrical spring is quite small (dominant spring constant due to V_{G1}) and the resonance frequency can be tuned very subtle. The tuning range in the presented structure is roughly 200ppm/V, allowing compensation of fabrication process related frequency variations. The signal amplitude at resonance is almost unchanged in this case, due to a minor dependence of the transconductance on V_G.

2) Non-linear operation: Fig. 7 shows the frequency characteristics of a tuning fork resonator (different die) with drive power ranging from -60dBm to -20dBm. Strong non-linear behavior is observed starting from approx. -40dBm and the increase of the applied power leads to a strong reduction of the transmission peak at resonance. The bending of the resonance frequency towards lower frequencies corresponds well with the theory of damped-forced Duffing systems [6].

IV. Oscillator Operation

The oscillator setup is given in Fig. 8, using a band-pass amplifier to sustain the oscillation. The filtering removes excessive noise at low frequency without reducing the gain at the frequency of interest. Both poles of the band-pass amplifier are designed to be at slightly lower frequencies than the

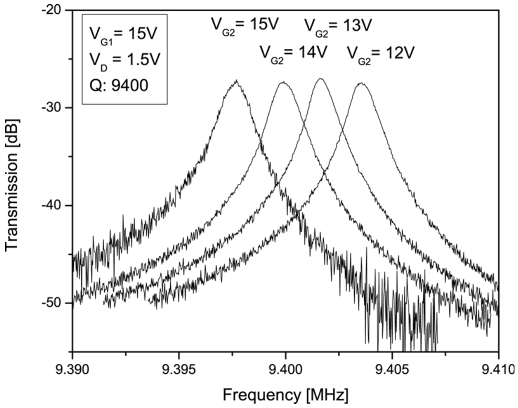


Fig. 6: Frequency spectra of the tuning fork VB-FET with V_{G2} as parameter ($V_{G1} = cst.$). The VB-FET vibrates at a constant amplitude, minimizing the change of the resonance peak and allowing a subtly frequency tuning.

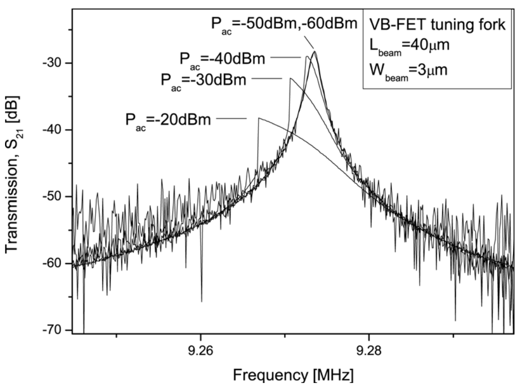


Fig. 7: Frequency spectra for a tuning fork VB-FET with the applied ac power as parameter. Bifurcation of the frequency-amplitude relation is observed for -40dBm limiting the power level in the oscillator for linear operation.

resonance frequency of the VB-FET. The sustaining amplifier is connected to the resonator by cables, as the resonators are operated inside a vacuum chamber. The gate and drain voltages are applied to the VB-FET using commercial bias-T (L_1, C_1, L_2, C_2). To avoid loading the sustaining amplifier with 50Ω impedance of the spectrum analyzer, a buffer amplifier was used for open and closed-loop measurements.

A. Open-Loop Characterization

The feedback loop is discontinued at the output of the sustaining amplifier in order to measure the frequency spectra in the open-loop configuration, shown in Fig. 9. The VB-FET itself is no longer loaded by 50Ω, which considerably improves the transmission peak, as the current to voltage conversion is now done on the VB-FET itself, which has a higher drain-source impedance of around 2.5kΩ at 1.5V. The measured open-loop gain is 2.9dB for the given biasing conditions with a phase of approx. -30° at the resonance. The zero phase condition is fulfilled for a slightly lower frequency.

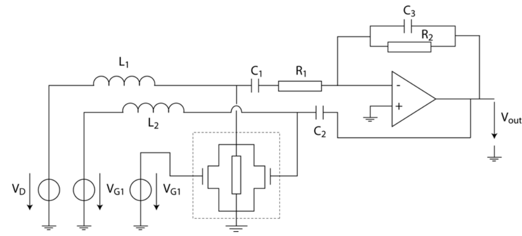


Fig. 8: Schematic of the discrete element circuit used for the oscillator. The VB-FET resonator is represented inside the small box (dashed line).

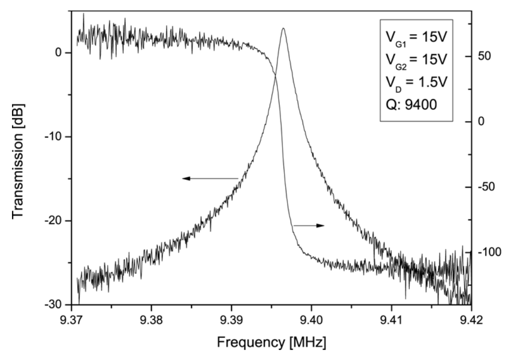


Fig. 9: Open-loop transfer characteristics of the oscillator circuit measured with a VNA. A gain of 2.9dB is measured under the given biasing conditions.

B. Oscillator performance

The closed loop operation was performed using the setup as shown in Fig. 8, with the VB-FET resonator being inside the vacuum prober. Fig. 10 shows the oscillator output frequency spectra under operating conditions of $V_{G1,2} = 15V$ and $V_{G1,2} = 14.5V$. The center frequency and the observed frequency shift correspond well to the measured frequency spectra of the resonator presented above. In these measurements relatively strong side-peaks were observed at a frequency offset of approx. 320 and 990 Hz. It was found, that these side-peaks are a function of the applied voltages

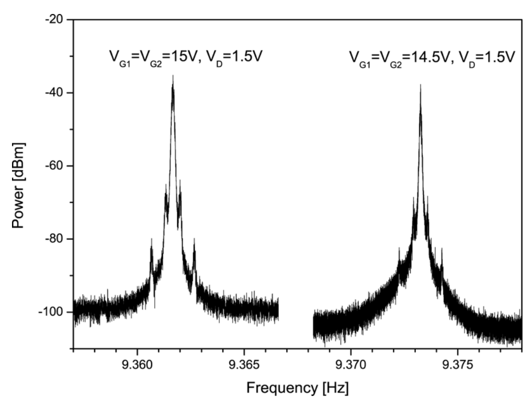


Fig. 10: Measured oscillator spectra of the tuning fork VB-FET with a drain voltage of $V_D = 1.5V$ and gate voltages of $V_{G1,2} = 15V$ and $V_{G1,2} = 14.5V$.

and therefore directly of the gain in the oscillator loop.

Reducing the gate voltages to $V_{G1} = 14V$ and $V_{G2} = 13.7V$ results in the frequency spectrum shown in Fig. 11 ($V_D = 1.5V$). Under these conditions, the side-peaks are no longer present. An amplitude of 20mV is measured using an oscilloscope (Fig. 12a), also showing the sinusoidal shape of the output signal. Fig. 12b shows the phase noise extracted from Fig. 11. A high level of $1/f^3$ noise is observed for this oscillator and a noise floor set by the amplifier noise is found at approximately -74dBc/Hz. The low amplitude of 20mV is among the reasons for the high relative noise, but it does not explain the $1/f^3$ noise observed. In the literature a similar $1/f^3$ noise component was reported for MEM resonators [7][8] and explained by aliasing of $1/f$ noise into the oscillator phase noise. This is probably the case for the current oscillator, as the resonator is driven in its non-linear regime. Nonlinear operation is confirmed by comparing the drive level in the oscillator with the measurement presented above. It is assumed, that the VB-FET resonator is limiting the gain in the feedback loop to 0dB through its non-linear behavior. In future oscillators, an additional non-linear element needs to be used, to adjust the gain of the sustaining amplifier and keep the resonator below the onset of non-linearity.

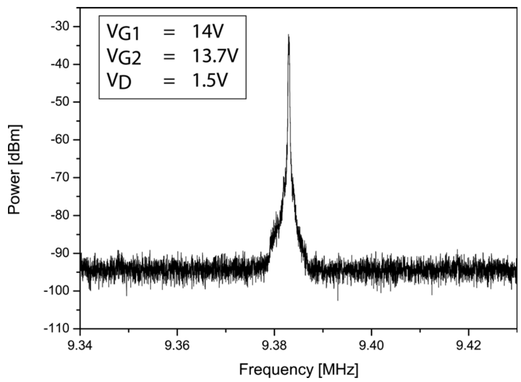
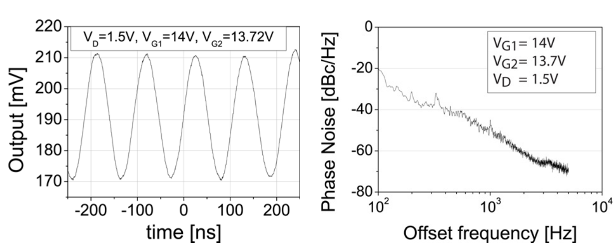


Fig. 11: Measured oscillator spectrum of the tuning fork VB-FET with a drain voltage of $V_D = 1.5V$ and gate voltages of $V_{G1} = 14V$ and $V_{G2} = 13.7V$.



(a) (b)

Fig. 12: a) A sinusoidal signal with an amplitude of 20mV is measured at the output of the sustaining amplifier under a polarization of $V_D = 1.5V, V_{G1} = 14V$ and $V_{G2} = 13.7V$. b) The phase noise of the oscillator was extracted under the same conditions from Fig. 11. A strong $1/f^3$ noise component is observed.

V. Conclusion

The performance of Vibrating Body Field Effect Transistors (VB-FETs) has been detailed for a tuning fork resonator operating at 9.4MHz. It is shown, that fully CMOS compatible oscillators can be built using the active tunable MEM resonators with high quality factor of 9400. The main advantage of this device comes from its built-in gain, compared to capacitive resonators, relaxing the demand for high gain sustaining amplifiers. This development eventually drives the miniaturization of MEM resonators further, as it allows higher signal levels and better control of the parasitics in smaller devices. The realized proof-of-concept oscillator based on discrete components has an output amplitude of 20mV at a frequency of 9.4MHz, dictated by the VB-FET resonator. Further improvements of the sustaining amplifier are needed to improve the oscillator characteristics to a level comparable with quartz resonators. Moreover, future work concerns the identification of VB-FET specific integrated oscillator design, which should exploit its unique intrinsic gain and low output impedance features. The VB-FET could enable future applications in both communications and sensing.

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