A FAST-STARTUP SELF-SUSTAINED THERMAL-PIEZORESISTIVE OSCILLAROR WITH >10^6 EFFECTIVE QUALITY FACTOR IN THE AIR

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ABSTRACT

This paper reports a self-sustained thermal-actuation piezoresistive-detection oscillator with boosted startup time and quality (Q) factor in the order of a million. A high Q-factor is an essential property for resonant sensors to achieve a high signal to noise ratio. It is demonstrated that the thermal-piezoresistive effect can increase the Q-factor. We obtained an effective Q-factor up to 1.06 million operating in air with direct-current induced self-oscillation. Furthermore, a fast startup time is achieved when stimulating the self-sustained oscillator with a current just below the threshold of self-oscillation requirements. The experimental results show that the startup time can be decreased by a factor of ~3 by initially thermally pre-expanding the actuating nanobeam compared to a cold-startup condition.

KEYWORDS

Oscillator, MEMS, thermal-piezoresistive, quality factor, self-oscillation.

INTRODUCTION

Microelectromechanical (MEMS) oscillators have been emerging as alternatives to replace quartz time references [1] and to develop various sensing applications [2]. Normally, to establish self-oscillation, an electronic control loop is required with a resonator to provide the functions of harmonic actuation and frequency tracking; this increases the system complexity. Recently, a self-sustained technique that combined piezoresistive detection and thermal actuation with only a direct current (dc) input was proposed [3], and developed [4][5]. In [3], thermal expansion/cooling alternatively dominates the resistance of the nanobeam since the nanobeam was with a negative piezoresistive coefficient. At the same time with the self-sustaining process, the energy of the input current compensates the dissipation caused by the motion of the resonator, which results in a significant improvement on the effective quality (Q) factor. The Q-factor is a measure of the energy dissipation in a specific working mode, and is a critical parameter to improve the signal to noise ratio (SNR) of force sensors, phase noise of oscillators and noise rejection of filters [6]. In previous work, we have already introduced a mass sensor with two coupled resonators using the thermal-piezoresistive principle with a Q-factor of ~95k in atmospheric environment [7]. However, associated with a high effective Q-factor, the startup time of the oscillator usually increases as well, limiting the applications that require periodic oscillator startup [8].

In this paper, in addition to Q enhancement, we found that the thermal-piezoresistive effect can also effectively tune the startup time. If the oscillator starts from an initially pre-expanded state via injecting a current with marginally lower level than the self-oscillation threshold, called ‘warm startup’ in the following, the startup time can be decreased by a factor of more than three, compared to switching on from zero current directly to self-oscillation (cold startup).

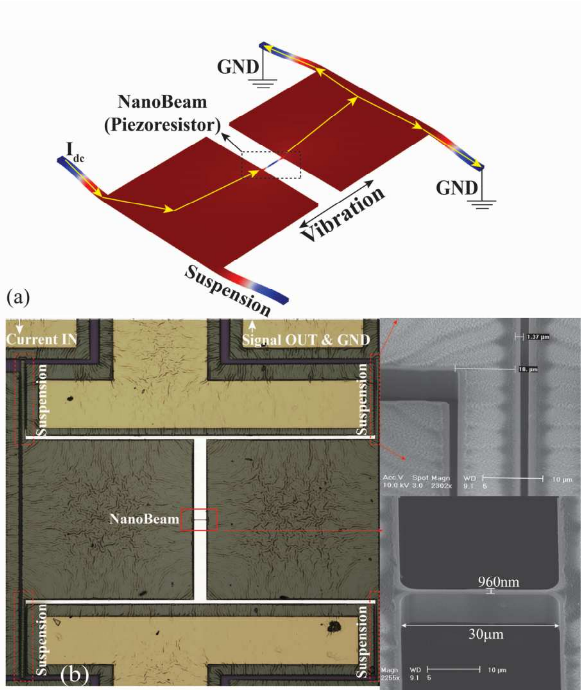

Figure 1: (a) Finite element analysis of the resonator indicating the in-plane vibration mode. Yellow arrows show the current flow direction. (b) optical (left) and SEM (right) images of the oscillator.

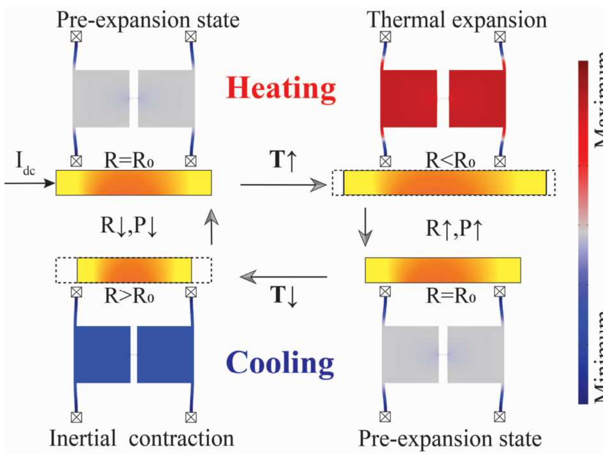

Figure 2: Positive heating and cooling feedback loop of the oscillator. R is the resistance of the nanobeam, T the temperature and P the Power. T is proportional to power. In the self-oscillation regime, thermomechanical movements due to noise provide the starting alternating fluctuation, while for the open-loop sweep measurements, an AC drive from the lock-amplifier acts as the initial actuation.

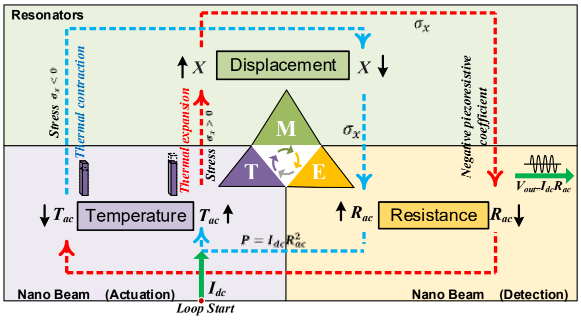

Figure 3: Illustration of the thermal(T)-electric(E)-mechanical(M) interaction and self-sustaining loop of the oscillator.

Device description

The developed device is constructed with two movable plates supported by four suspensions and connected by a nanobeam (Fig. 1(a)). The device was fabricated using a silicon-on-insulator (SOI) wafer, with the 10 µm-thick device layer having a negative piezoresistive coefficient and resistivity of 0.01-0.02 Ohm-cm. The fabrication process is described in previous work [9]. SEM images of the device are shown in Fig. 1(b). The measured nanobeam width is ~960 nm and the length is ~30 µm, as shown in Fig. 1(b). Fig. 1(a) also indicates the current flow.

The movement of the oscillator results from the periodical thermal expansion and contraction of the nanobeam. The FEM simulation results of the oscillator are summarized in Fig. 2. A direct current (I_{dc}) flowing through the nanobeam pre-expands the nanobeam having a resistance of R_0 to a pre-expansion state. Ambient positive resistance fluctuations (from thermomechanical movements) cause further expansion and decrease the resistance ($R<R_0$) due to the negative piezoresistive coefficient. Consequently, the Joule heating power ($P=I_{dc}^2R$) is reduced and the temperature decreases, resulting in the nanobeam being contracted back to the pre-expansion state. The inertia of the plates moves the nanobeam into a contracted state with $R>R_0$, after which the heating power starts to increase, and the beam expands again until going into another heating/cooling cycle. In addition to this short intuitive explanation, Fig. 3 illustrates the principle of the thermal-electric-mechanical interaction. A more detailed description can also be found in [7]. The nanobeam plays the role of both actuating the resonator and detecting the movement as well. The expansion and contraction of the nanobeam is finally transferred to an alternating voltage based on the equation of $V_{out}=I_{dc}R_{ac}$, which can be directly monitored by an oscilloscope.

Experimental results in the open-loop setup

The device was first tested with an open-loop setup to characterize the natural frequency and quality factors in the ambient environment. The test setup of the open-loop sweep is shown in the inset in Fig. 4(c). A Zurich lock-in amplifier was employed to provide the sweep signal and to analysis the output voltages. A bias tee was used to isolate the alternating and direct current signals. The amplitude-frequency responses of the oscillator with different injection currents are shown in Fig. 4(a). For $I_{dc}<5.7$ mA,

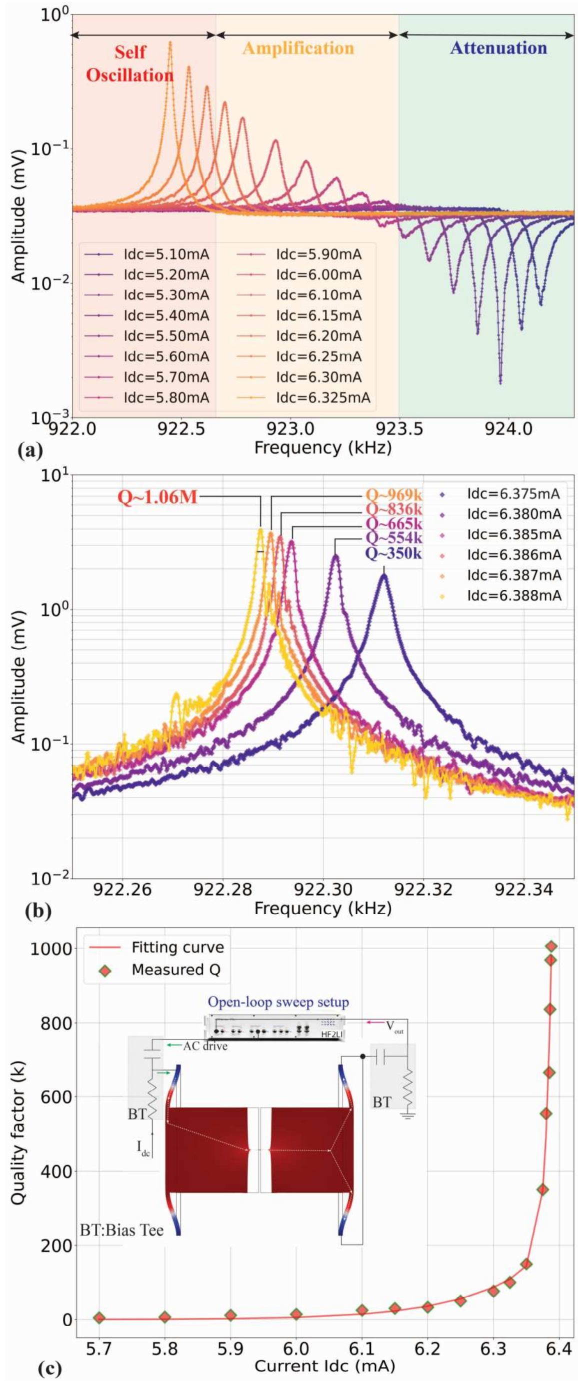

Figure 4: Measured frequency responses and Q-factors of the device. (a) Amplitude-frequency responses versus DC currents with AC drive of 2mV from a Zurich lock-in amplifier HF2LI. (b) Amplitude-frequency responses versus DC currents in the self-oscillation regime with AC drive of 0.1mV from the lock-in amplifier. (c) Measured Q-factors versus injected currents. The inset figure in (c) indicates the electrical setup when measuring the Q-factor using the open-loop frequency sweep method.

the oscillator works in an attenuation regime so that dips but not peaks are appearing during the oscillation. For $I_{dc}>5.7$ mA, resonance peaks are visible, with a resonant frequency between 922 and 923 kHz; this is defined as the amplification regime. With the increase of the current, the

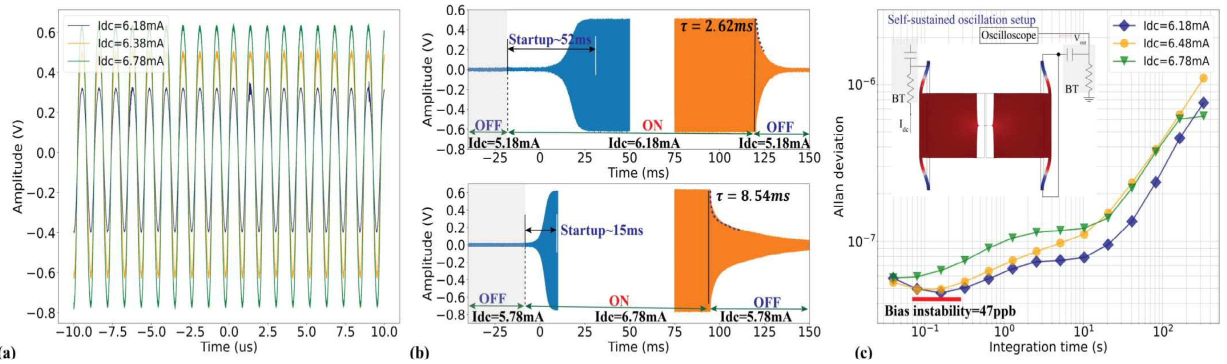

Figure 5: Self-oscillation performance. (a) Oscillation cycles of the device with different DC currents. (b) Startup and ringdown processes for two different current levels. (c) Allan deviation measurements of the oscillator with three different DC currents. The inset figure in (c) indicates the electrical setup of the self-oscillation measurements.

vibrating peak amplitude is raising as well, which means that the effective Q-factor is improving as well because the background basis is almost constant. The minimum Q-factor is ~2k when I_{dc}=5.700 mA. In the above tests, the drive AC signal from the lock-in amplifier was fixed at 10 mV.

If I_{dc} is larger than a threshold of ~6 mA, the device enters the self-oscillation regime, which means that oscillation is observable even without any harmonic drive signal input. A close-up view of the responses in the self-oscillation regime is shown in Fig. 4(b). In this region, the Q-factor is boosted from 350×10^3 @ I_{dc}=6.375 mA to 1.06×10^6 @ I_{dc}=6.388 mA. The optimized Q-factor is more than 500 times higher than the lowest value in the amplification regime. A summary of the Q-factors in the amplification and self-oscillation regimes versus the input current (I_{dc}) is shown in Fig. 4(c). It can be seen that the Q-factor first increases slowly, and then erupts exponentially in the self-oscillation regime. A micro-Ampere level current difference will result in significant changes on the vibration amplitudes and Q-factor.

Experimental results for the self-oscillation setup

The self-oscillation setup is rather simple as only a current source and an oscilloscope are needed, as the inset figure in Fig. 5(c) shows. The oscillation waveforms of the oscillator with different stimulation currents are shown in Fig. 5(a), reproducing the results of the open-loop test that the vibration amplitude (output voltage) is increasing with an increase of the input current. The startup time of the oscillator is an important performance metric for applications requiring periodic oscillator startup for power savings [10]. Unfortunately, when working in the self-oscillation regime, the effective Q-factor can be pumped up to an ultra-high value, which makes the oscillator turn on slowly, as the startup time of an oscillator is normally proportional to the Q-factor and inversely proportional to the oscillation frequency [10].

In our experiments, the measured startup time is 52 ms when switching the oscillator on with I_{dc} between 5.18 and 6.18 mA (cold startup). On the contrary, the startup time is reduced to 15 ms when starting between 5.78 and 6.78 mA (warm startup), as shown in Figure 3(b). The startup time would be much longer if we directly start from 0 mA, yet, here we do not provide this data because there is a high risk of burning the nanobeam when there is a drastic bias current change.

The Allan deviations of the oscillator under different input current are collected and shown in Fig. 5(c). The best frequency bias instability is 47 ppb, as shown in Fig. 3(c). It can be concluded that although the effective Q factor has significantly been improved with the increase of the bias current, the bias instability cannot be improved to a comparable level. This is reasonable because the frequency resolution (represented by the bias instability) is primarily determined by the inherent mechanical Q-factor but not the effective Q-factor [6].

CONCLUSION

In summary, we have demonstrated an oscillator working in the ambient environment with a Q-factor as high as 1 million operating in atmospheric conditions. A further Q-factor increase can be expected by raising the stimulating current below the threshold at which the nanobeam is burned. In addition, the startup time can be reduced when pre-expanding the nanobeam somewhat lower to the requirements of self-oscillation. However, when increasing the current, the thermal noise of the oscillator increases as well, which influences only the effective Q-factor while the mechanical Q-factor does not change significantly and thus the frequency resolution cannot be improved much. Even though, this work will facilitate the development of resonant sensors and timing devices requiring a simple electrical setup and fast startup properties for a wide range of applications.

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