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Silicon Micromechanical Resonators for RF-Applications

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Abstract

The small size and integrability make the silicon micromechanical rf-resonators attractive components for future wireless communication devices. In particular, we show that using the microresonators one can construct oscillators exhibiting low phase noise and good long-term stability. Such compact solutions challenge conventional quartz crystals in frequency reference applications.

1. Introduction

Silicon micromechanical devices have obtained considerable recent interest due to their potential in creating compact frequency-selective components for wireless applications [1]. In this paper, we focus on generating a frequency reference using such microresonators. Conventionally, the frequency in reference oscillators is derived from the mechnical resonance in quartz [2]. However, the macrosize quartz components appear bulky in the modern highly-integrated transceiver architectures. The potential size reduction and integrability form the key advantages of silicon microresonator technology.

Two fundamental challenges of the microresonators are (*i*) to store enough mechanical energy and suppress dissipations in the small resonator volume to obtain the required spectral purity, and (*ii*) to obtain sufficient long-term precision of the frequency despite the large surface-area-to-volume ratio which makes the microresonators prone to instability mechanisms such as surface contamination.

Our analysis, complemented by measurement results, shows that the low phase noise (meeting GSM-specifications) and the ppm-level long-term stability are indeed achievable in the microresonators using a sophisticated resonator design. In particular, we show that these goals can be met using a two-dimensional bulk-acoustic-wave resonator while e.g. flexural-mode resonators are typically subject to much inferior performance.

2. Resonator Design

Figure 1 illustrates the prototype design for a silicon micromechanical resonator showing eigenfrequency $f_r = 13.1\,\text{MHz}$ [3]. The component is made on silicon-on-insulator (SOI) wafer using deep reactive ion etching (DRIE). The hydrofluoric release is done through $1.5\,\mu\text{m}$ diameter holes, arranged in a 39×39 square matrix to perforate the resonator plate. The resonator dimensions are $320\,\mu\text{m} \times 320\,\mu\text{m} \times 10\,\mu\text{m}$. T-shape corner anchors are applied to minimize energy leakage to the substrate.

The resonator is operated in a two-dimensional bulk acoustic vibration mode which can be described as the square extending/contracting [Fig. 1(b)]. In this mode, the square sides move in unitary phase without significant bending. This is in contrast with the well-known Lamé-mode [4] in which the resonator edges move in anti-phase and show appreciable

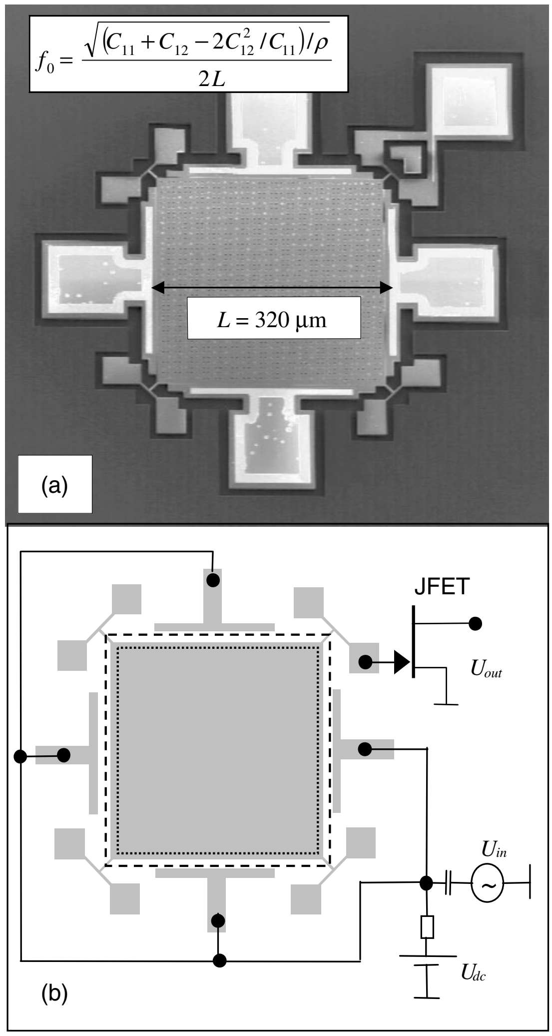

Fig. 1. (a) A scanning electron microscope view of the square-extensional bulk acoustic mode resonator ($f_0 \sim 13.1\,\text{MHz}$) . (b) A schematic illustration of the vibration mode shape and electromechanical coupling configuration using narrow gaps ($d = 0.75\,\mu\text{m}$).

bending. Our resonator also shows the Lamé-mode at 12.1 MHz which was detected using a two-electrode configuration. Using the symmetrical four-electrode configuration shown in Fig. 1(b) the Lamé-mode is not excited. As the resonator operation is based on propagation of longitudinal bulk acoustic waves, the condition for the fundamental resonance frequency results from the standing-wave condition $f_0 = v_s/\lambda = v_s/2L$, where v_s is the speed of sound and λ is the wavelength.

The measured transmission response of the square-extensional resonator is shown in Fig. 2. For the measurement the device was placed in a laboratory vacuum chamber ($p < 0.01\,\text{mbar}$). The resonance is very narrow ($Q = 130\,000$), which originates fundamentally from the small material dissipations in silicon. Due

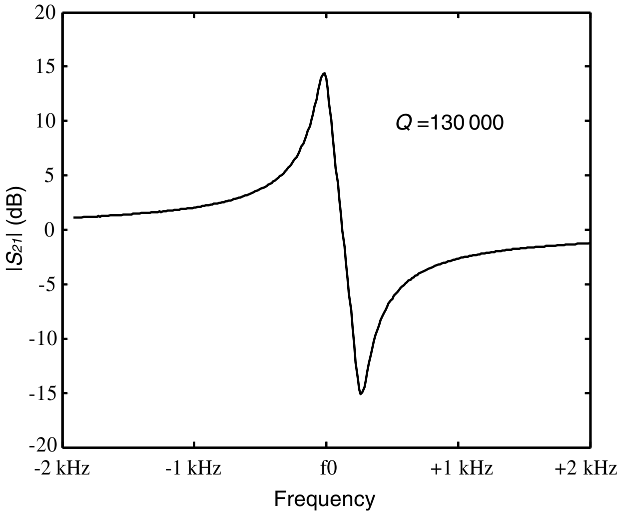

Fig. 2. Measured transmission response of the square-extensional resonator (f_0 = 13.1 MHz, U_{dc} = 100 V). The Q-value of the resonance is 130 000.

to the bulk acoustic wave operation the role of surface effects remains low. The Q-value of the resonance was determined using a simulation model developed for the microresonator [8, 9].

3. Theoretical Oscillator Phase Noise

The good frequency selectivity of the resonator offers a promise of a low-noise oscillator application. However, in order to realize a good signal-to-noise ratio, the resonator must also be capable of sufficient energy storage. The single sideband phase noise [5, 6] for an *ideal* oscillator (sustaining amplifier noise neglected) can be estimated as

$$L_{\Delta f} = \frac{1}{4\pi}\frac{k_B T}{E_{vib}}\frac{f_0}{Q\Delta f^2}, \tag{1}$$

where f_0 is the oscillation (carrier) frequency, Δf is the frequency offset from f_0, and E_{vib} is the mechanical vibration energy. The oscillator short-term frequency stability characterized by $L_{\Delta f}$ corresponds to the ratio of the phase noise power spectral density at Δf to the vibration power. Eq. (1) shows that $L_{\Delta f}$ is fundamentally set by the ratio $k_B T/E_{vib}$. Thus, the more vibration energy the resonator can store, the better is the separation from thermal noise. Eq. (1) also shows that $L_{\Delta f}$ is inversely proportional to Q, reflecting importance of the filtering action of the resonator.

Figure 3 shows the calculated $L_{\Delta f}$ for the square-extensional resonator assuming a vibration amplitude x_{vib} = 1 nm. The phase noise decays 20 dB per decade of the frequency offset due to the $1/\Delta f^2$ term in Eq. (1). At the offset Δf = 1 kHz the calculated result is $L_{\Delta f} = -146$ dBc/Hz. This corresponds to an excellent oscillator performance–for example the typical specification for the frequency reference in GSM-mobile phones is −130 dBc/Hz. The calculated result thus shows that already at 1 nm vibration amplitude the square-extensional resonator is capable of producing low-noise mechanical oscillatory motion meeting the typical communication specifications. Furthermore, the measurement of the nonlinearity in the prototype resonators have revealed that at least an order of magnitude larger vibration amplitudes are feasible [8].

Figure 3 also shows the calculated phase noise for a typical flexural mode "bridge" resonator at the same eigenfrequency and the same vibration amplitude (dimensions w = 4 µm, L = 44 µm,

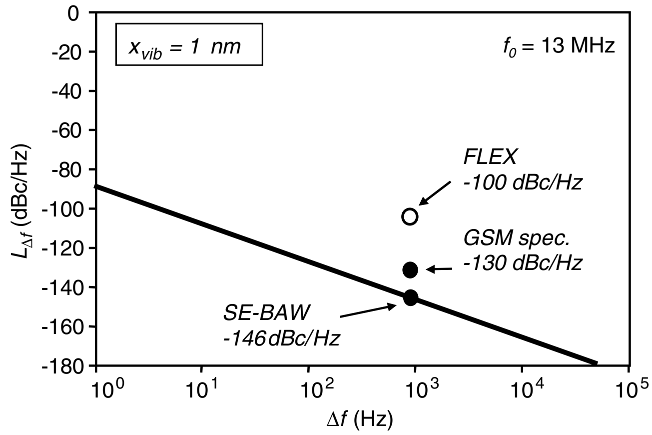

Fig. 3. Calculated single-sideband phase noise $L_{\Delta f}$ for the square extensional resonator (solid line) at x_{vib} = 1 nm. For comparison, the calculated result for a flexural mode bridge resonator [7] and the GSM specification are shown. The calculated results correspond to an idealized oscillator in which the thermal noise is the only noise mechanism (the sustaining amplifier noise is neglected).

h = 8 µm, Q = 1500) [7]. At Δf = 1 kHz the calculated phase noise is only 100 dBc/Hz. This result illustrates the fundamental difficulty in reaching good signal-to-noise performance using the small-sized flexural mode resonators.

4. Measured Oscillator Phase Noise

For a practical oscillator that produces an electric output, one still has to realize an electric coupling to the low phase noise mechanical motion of the square-extensional resonator depicted in Figure 3. As the effective noise temperature T_a of modern amplifiers is well below 300 K, it is theoretically possible to detect the mechanical motion without contributing significant additional noise. However, this requires the amplifier to be matched to the impedance of the resonator. As the resonator impedance is a strong function of frequency near the resonance as seen in Fig. 2, perfect noise-matching is impossible to achieve to cover *all* frequency offsets. To evaluate the noise contribution from an amplifier, we have build an oscillator using the JFET-detection of the prototype resonator (Fig. 1) [9, 10]. The phase noise measured from the prototype oscillator is shown in Fig. 4. The measured data

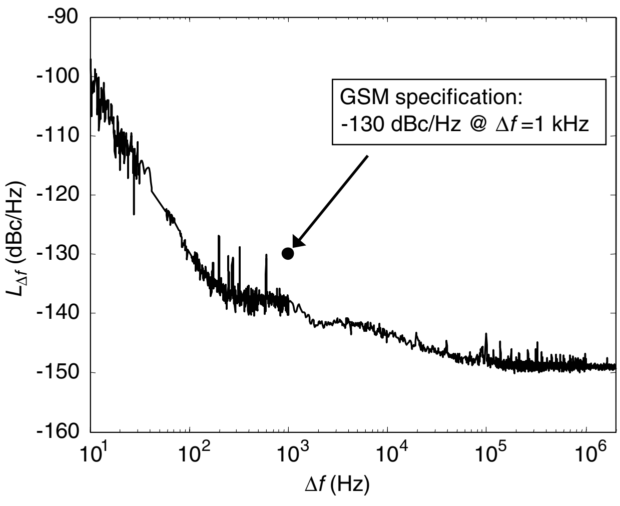

Fig. 4. The measured single-sideband phase noise of the prototype oscillator based on the square-extensional resonator. The coupling voltage was U_{dc} = 70 V. The data was recorded using the Agilent E5500 phase noise measurement system.

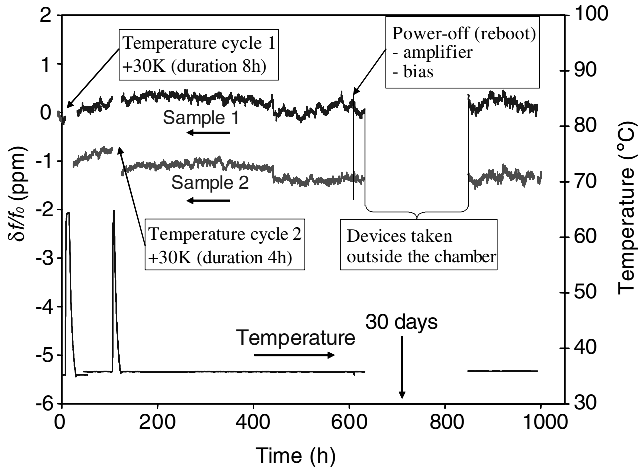

Fig. 5. The measured long-term frequency stability of two vacuum-encapsulatd BAW-resonator samples. Temperature-induced variations are removed from the data. During measurement the samples have been subject to two elevated temperature cycles and to being removed from the measurement setup.

shows that it is feasible to create a practical micro-oscillator that shows phase noise performance well meeting the typical wireless communication standards.

5. Long-Term Stability

In addition to the spectral purity (low phase noise), the long term frequency stability is a central requirement for a reference oscillator. Figure 5 shows the measured frequency variation from two vacuum-encapsulated bulk-acoustic mode resonators [9]. The resonance frequencies were determined at 15 minute intervals by measuring the transmission responses. The measurement was carried out in a temperature-stabilized climate chamber. The temperature inside the measurement chamber was recorded using a Pt100-sensor. Based on the measured temperature and the measured temperature-dependence of the resonance frequencies, the remaining temperature-induced variations are removed in the data shown in Figure 5.

The result shows that the two resonators have well maintained a ppm-level accuracy during the first 40 days monitoring period. During the measurement, the resonators were subjected to two temperature cycles ($+30\,\mathrm{K}$) and to 200 hour removal from the measurement chamber. The second resonator sample shows a minor ($\sim -1\,\mathrm{ppm}$) frequency shift due to the temperature cycles.

6. Conclusion

Our work demonstrates that using silicon microresonators one can construct oscillators that exhibit low phase noise and good long-term stability. When compensated for the temperature-dependence of the resonance frequency (typically $-30\,\mathrm{ppm/K}$), such compact solutions challenge the conventional quartz crystals in frequency reference applications.

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