PHASE NOISE SUPPRESSION EFFECT AT THE TURNOVER TEMPERATURE IN OVEN CONTROLLED MEMS OSCILLATOR

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ABSTRACT

An obvious phase noise suppression effect is reported for the first time at the turnover temperature of a degenerately phosphorus-doped silicon oscillator. It was reported that the resonant frequency of an N^{++} [100] bulk mode single crystal silicon resonator reached the maximum at a particular temperature, which is called the turnover temperature, and a near zero temperature drift may be obtained by heating the oscillator to the turnover temperature. Our experiments show that both the temperature drift and phase noise reach the minimum at the turnover temperature. More than 20 dB drops of the phase noise has been observed at the turn-over temperature.

INTRODUCTION

Silicon MEMS oscillators are attracting more and more attention due to the advantages of small size, batch manufacture, IC compatibility, superior impact resistance, and electrical performance [1]. One of the most important parameters for the application of MEMS oscillators is the phase noise [2]. The stochastic phase noise leads to broadens the oscillator frequency spectrum and to degrades its electrical performance [3][4]. The phase noise should be as small as possible.

Based on the classical Leeson model [5], the phase noise of an oscillator can be expressed as:

$$L(\Delta f) = \frac{2k_B TF}{P_{sig}}\left[1+\left(\frac{f_0}{2Q\Delta f}\right)^2\right]\left(1+\frac{\Delta f_{1/f^3}}{\Delta f}\right) \qquad (1)$$

where Δf is the offset frequency, f_0 is the resonant frequency, $\Delta f_{1/f^3}$ is an empirical parameter that related with to the flicker noise corner, k_B is the Boltzman constant, T and F is are the absolute temperature and noise factor of the amplifier, respectively, and P_{sig} is the carrier power. Therefore, boosting Q can reduce the phase noise of the oscillator. Considering the limitation of Q [6], quite a few methods have been proposed to suppress the phase noise [7] [8] [9].

In our experiment, an obvious phase noise suppression effect is observed at the turnover temperature of a degenerately phosphorus-doped silicon resonator.

The TCF of the [100]-oriented n^+ silicon resonators is nonlinear, and is equal to zero at the turnover temperature point [10], which can be tuned by the doping level [11]. An oven-controlled degenerately phosphorus-doped silicon resonator was presented by the authors to achieve a high stable frequency [12]. The measurements of the resonator show that both the temperature drift and phase noise reach the minimum at the turnover temperature. More than 20 dB drops of the phase noise has been observed.

DESIGN AND FABRICATION OF THE MEMS RESONATOR

An oven controlled MEMS oscillator is designed, which is schematically shown in Figure 1 [12]. The [100]- oriented length extensional mode resonant structure is degenerately doped with phosphorous to tune the turn-over temperature a bit higher than the upper limit of operating temperature range. The resonator is suspended by heating beams to decrease the thermal conductance. The heating beams also serve as electric leads. During operation, the resonator is electrically heated to the turn-over temperature. The resonator is electrostatically driven and piezoresistive sensing.

The resonator is fabricated on the SOI wafers, with 6μm thick heavily phosphorous doped SOI layers. The resistivity is about 0.001~0.002 Ωcm. The processes are described as follows:

(a) A layer of 6000 Å aluminum is sputtered and patterned. The aluminum covers the surface of the heating beams.
(b) The resonator structure is patterned by deep reactive ion etching.
(c) The resonator is released by etching away the buried oxide with HF vapor.

The SEM of the resonator is shown in Figure 2. The resonator is then packaged in vacuum in a ceramic carrier. The pressure in the ceramic carrier is estimated to be around 1kPa, by comparing the Q after packaging with the Q of the same resonator measured in a vacuum chamber.

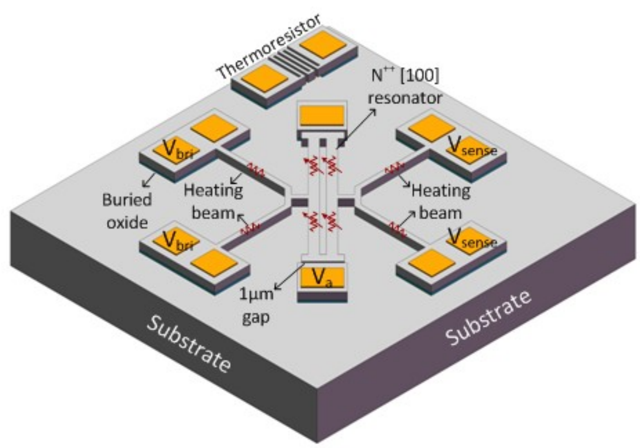

Figure 1 : Schematic diagram of the N^{++} [100] resonator.

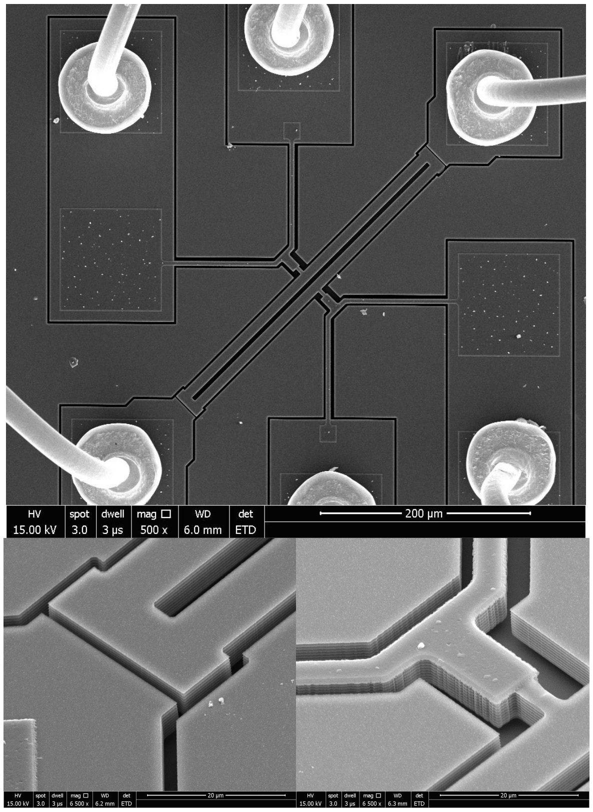

Figure 2: The SEM of the resonator.

MEASUREMENTS OF THE RESONATOR AND PHASE NOISE SUPPRESSION

Resonant frequency, quality factor and turn-over temperature

The resonant frequency and the Q factor is characterized with a network analyzer. The resonator itself is used as a piezoresistor and connected with a resistor to form a Wheatstone half-bridge, as shown in Figure 3.

The resonant frequency of the LE mode is measured to be 10.495 MHz and the quality factor is 201540 at 25°C, as shown in Figure 4. The excitation voltage of the Wheatstone half-bridge is as low as 0.2V to suppress the self heating during the measurements.

The TCF of [100]-oriented n^+ silicon resonators is nonlinear. The relation between the resonant frequency and the temperature is measured with Vcc=0.2V and shown in Figure 5. The turn-over temperature is estimated to be 109°C for the resonator used in this paper. The resonant frequency at the turn-over temperature is about 10.49968MHz, while the Q factor is about 364320, which is larger than the Q factor at room temperature.

The resonator can be electrically heated by the excitation voltage of the Wheatstone half-bridge. The resonant frequency-excitation voltage curves are measured at different ambient temperatures, as shown in Figure 6. As it is expected that the maximum resonant frequencies at different ambient temperatures are approximately equal, though small drifts with the ambient temperature have been observed. The small drifts may be caused by the residue gas in the carrier.

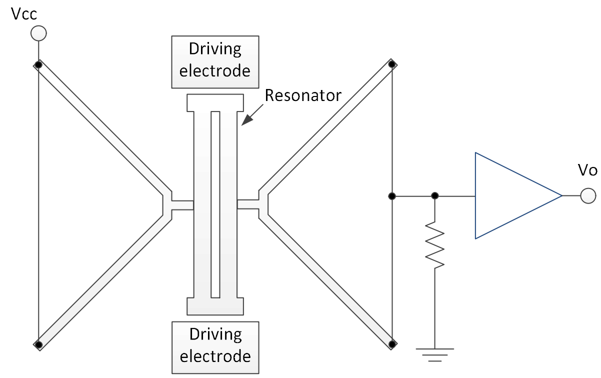

Figure 3: The measurement setup.

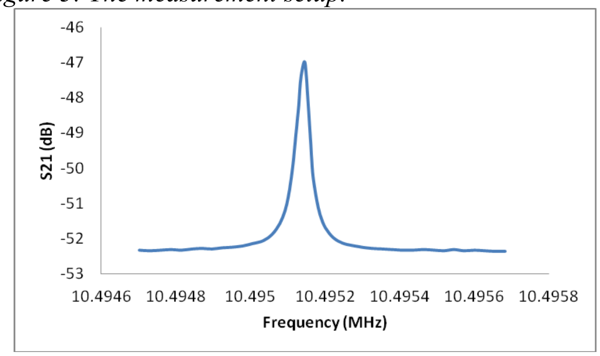

Figure 4: The amplitude-frequency curve of the LE mode at 25℃.

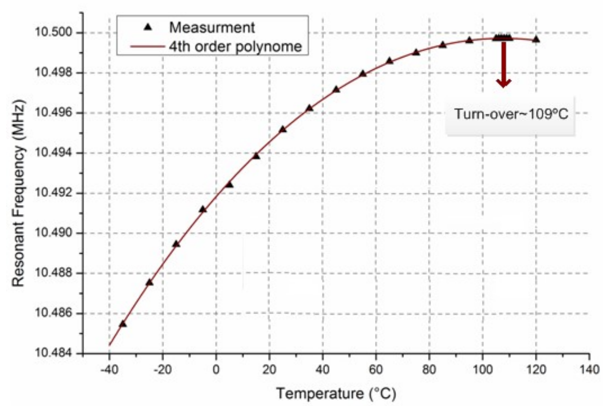

Figure 5: The resonant frequency-temperature curve.

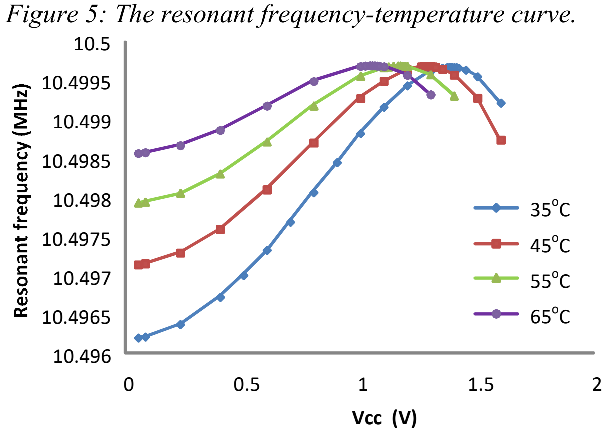

Figure 6: The resonant frequency versus the excitation voltage of the Wheatstone half-bridge at different ambient temperatures.

Phase noise suppression effect

The phase noise of the resonator is measured at different conditions. An obvious phase noise suppression effect is observed at the turnover temperature.

The resonator is electrostatically excited by an AC signal (Keysights 33519B) coupled with a 20V DC bias. The resonator is electrically heated by the excitation voltage of the Wheatstone half bridge and the piezo- resistive signal is measured with the setup shown in Figure 3 at room temperature. The output signal is analyzed by the source analyzer (Keysights E5052B) to obtain the phase noise curve.

For each excitation voltage, the frequency of the driving signal is swept and the corresponding phase noise curves are recorded. Figure 7 shows the smoothed phase noise curves at Vcc=1.3V. The frequency sweep is indicated by the the phase lag between the input and output signal, ϕ. When the amplitude of the output signal reaches the maximum, the phase lag between the input and output signal is about 1.21π. Figure 8 compares the measured and smoothed phase noise curves at Vcc=1.3V and $\phi=1.21\pi$.

At room temperature, the resonator is measured with eight different excitation voltages: 1.3, 1.35, 1.37 1.39, 1.4, 1.42, 1.45, and 1.5 V. The resonant frequency reaches the maximum when Vcc=1.4V. The phase noise at different excitation voltages are compared in Figure 9, in which all the curves are smoothed. The phase noise versus the excitation voltage at the 10 Hz, 100 Hz, and 1 kHz offsets are compared in Figure 10. It can be obtained from the figure that when the excitation voltage increases from 1.3 to 1.4 V, the phase noises at the 10 and 100 Hz offsets drop 24.9 dB and 19.2 dB, respectively. When the excitation voltage increased from 1.4 to 1.5 V, the phase noises at the 10 and 100 Hz offsets rise more 27.5 dB and 22.5 dB, respectively.

The phase noise suppression effect is not caused by the change of the Q factor with the temperature. The Q factors at different excitation voltages are measured and shown in Figure 11. The Q factor increases monotonically with the excitation voltage.

The phase noise suppression effect may be caused by the very low TCF around the turn-over temperature, which suppress the frequency fluctuation caused by the thermal fluctuation. Though the physics behind the effect is not clear yet.

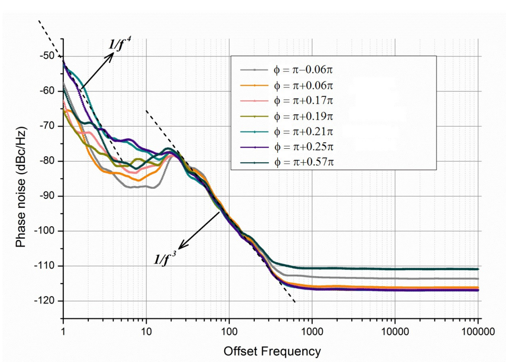

Figure 7: The phase noise curves at Vcc=1.3V with the frequency of the driving signal sweep, which is indicated by the the phase lag between the input and output signal.

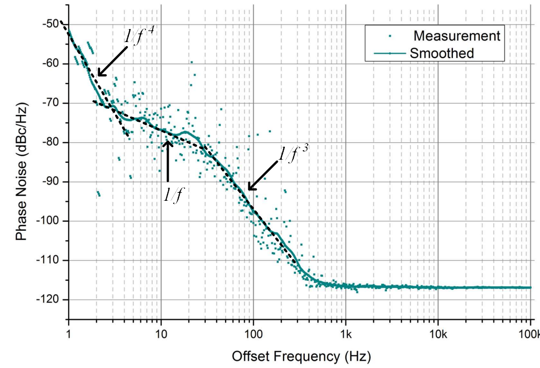

Figure 8: The measured and smoothed phase noise curves at Vcc=1.3V and $\phi=1.21\pi$.

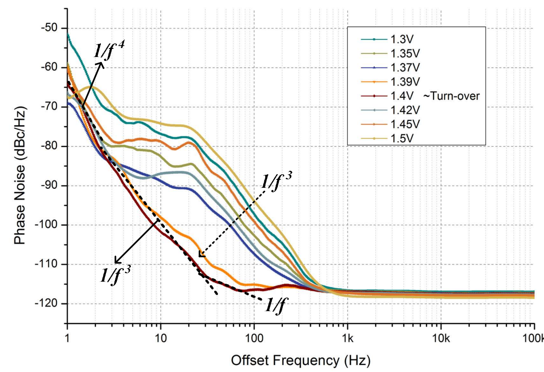

Figure 9: The phase noise at different excitation voltages.

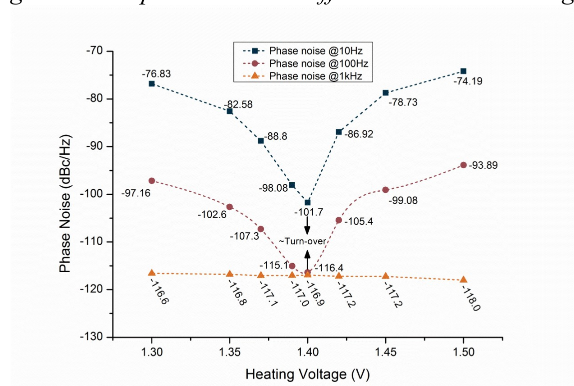

Figure 10: The phase noise values as the function of the excitation voltage at the 10 Hz, 100 Hz, and 1 kHz offsets

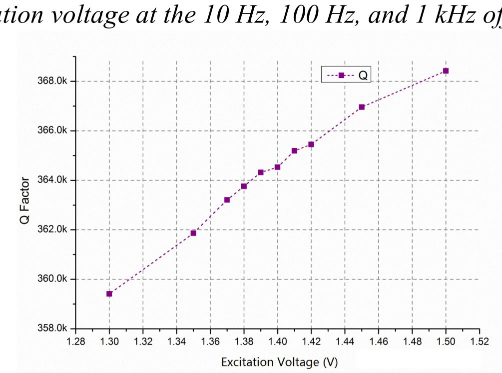

Figure 11: The Q factor of the resonator at different excitation voltages.

CONCLUSIONS

This paper presents the phase noise suppression effect at the turnover temperature in a degenerately phosphorus-doped silicon oscillator, where the phase noises at the 10 and 100 Hz offsets drop 24.9 dB and 19.2 dB, respectively. The phase noise suppression effect is not caused by the change of the Q factor with the temperature. The very low TCF around the turn-over temperature may play a role in the phase noise suppression effect, though the physics behind the effect is not clear yet.

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