High resolution microresonator-based digital temperature sensor

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A digital temperature sensing technique using a complementary metal oxide semiconductor (CMOS) compatible encapsulated microresonator is presented. This technique leverages our ability to select the temperature dependence of the resonant frequency for micromechanical silicon resonators by adjusting the relative thickness of a SiO_2 compensating layer. A dual-resonator design is described that includes a pair of resonators with differential temperature compensations so that the difference between the two resonant frequencies is a sensitive function of temperature. The authors demonstrate a temperature resolution of approximately 0.008 °C for 1 s averaging time, which is better than that of the best CMOS temperature sensors available today. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2768629]

Complementary-metal-oxide-semiconductor (CMOS)-compatible micromechanical resonators have shown the potential of being used in precision timing and frequency reference application.[1–3] However, the frequency of silicon resonators varies strongly with temperature.[4,5] This characteristic of a silicon resonator, which is disadvantageous in general, can be used to measure temperature. However, the biggest problem lies in measuring the temperature-dependent frequency without using any external frequency references. In this work, we present a novel dual-resonator design with a composite $Si-SiO_2$ structure,[6] which provides a temperature-dependent signal and a reference for measuring the signal. This concept for digital thermometry relies on the application of the basic mechanics of resonator design, as well as the materials physics that provides different temperature coefficients of stiffness for silicon and SiO_2.

In this design, we build a pair of resonators with different cross-sectional dimensions, but with similar frequencies, by scaling the lengths. After formation of an oxide compensation layer over all surfaces, we obtain a pair of resonators with similar frequencies but with different temperature coefficients of frequency. The difference frequency between these two references has a much higher sensitivity to temperature, and it can be "internally counted" using one of the resonators as a reference.[7,8] Taken together, the physics of compensated microresonators and the ultrastable resonator encapsulation process provides path toward a unique, CMOS-compatible digital temperature sensor with potential for much better performance than existing digital temperature sensors based on diode thermometers.

A candidate dual-resonator design having two mechanically coupled double-ended tuning fork (DETF) type resonators is shown in Fig. 1. These DETF resonators consist of composite resonator beams of silicon (Si) and silicon dioxide (SiO_2). The thickness of the thermally grown SiO_2 coating over the Si beam is approximately 0.33 μm for both resonators (Fig. 1). The silicon-to-oxide ratio of the beams for the two DETF structures is designed to achieve two different temperature coefficients of frequency[6] (TCf), while keeping the two frequencies close together. These devices were fabricated using a CMOS-compatible wafer scale encapsulation process.[9,10] A scanning electron microscopy view of the thermally grown SiO_2 coating over the Si beam can be referred in recent publication.[6] The two reference frequencies, f_1 and f_2, from the dual resonator are mixed to form the difference frequency or beat frequency, f_{beat}, as shown in Fig. 2. There are, of course, many analog and digital methods for obtaining the beat frequency signal. In our experiment, the frequency mixing is performed using a four-quadrant analog multiplier AD734. The multiplication of the two oscillator signals at frequencies f_1 and f_2 yields signals at frequencies f_1+f_2 and f_1-f_2 as per Eq. (1). The difference frequency f_1-f_2 is called the beat frequency and is obtained after discarding the higher frequency through the second order low-pass filter (Fig. 2),

$$\cos(2\pi f_1 t)\cos(2\pi f_2 t) = \frac{1}{2}[\cos\{2\pi(f_1+f_2)t\} + \cos\{2\pi(f_1 - f_2)t\}]. \tag{1}$$

The temperature dependence of f_1, f_2, and f_{beat} can be expressed as

$$f_1(T) = f_1(T_0) + a_1\Delta T + b_1\Delta T^2 + \cdots , \tag{2}$$

$$f_2(T) = f_2(T_0) + a_2\Delta T + b_2\Delta T^2 + \cdots , \tag{3}$$

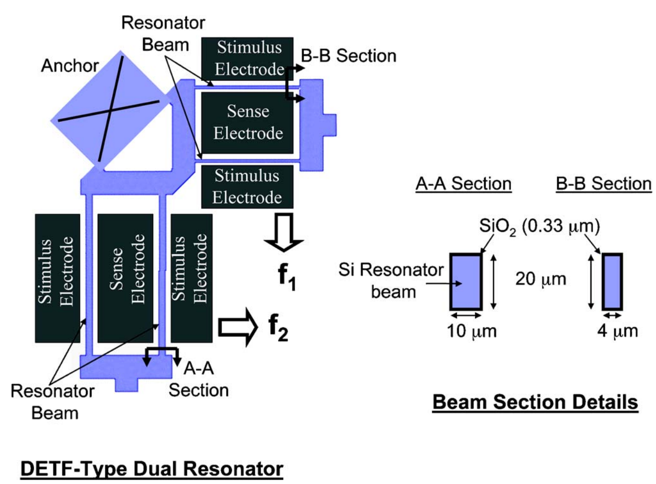

FIG. 1. (Color online) Dual resonator design showing the cross sections of the two resonators.

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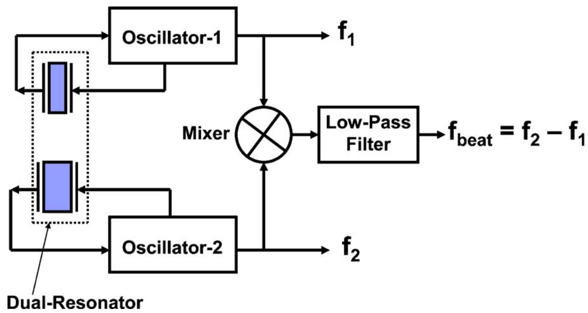

FIG. 2. (Color online) Illustration of the beat frequency generation technique.

$$f_{\rm beat}(T) = f_{\rm beat}(T_0) + (a_1 - a_2)\Delta T + (b_1 - b_2)\Delta T^2 + \cdots , \tag{4}$$

where a's and b's are constants representing temperature sensitivities of f_1 and f_2, T_0 is a reference temperature, and $\Delta T = T - T_0$. The fractional change in beat frequency is given as

$$\frac{\Delta f_{\rm beat}(T)}{f_{\rm beat}(T_0)} = \frac{(a_1 - a_2)}{f_{\rm beat}(T_0)}\Delta T + \frac{(b_1 - b_2)}{f_{\rm beat}(T_0)}\Delta T^2 + \cdots . \tag{5}$$

From the measured data of $f_{\rm beat}$ (Fig. 3), using quadratic curve fit, it is observed that the first order term of Eq. (5) is approximately 360 ppm as compared to 0.069 ppm for second order term for the temperature range of −40 to 120 °C. Therefore, the fractional change in beat frequency after ignoring the higher order terms is given as

$$\frac{\Delta f_{\rm beat}(T)}{f_{\rm beat}(T_0)} = \frac{(a_1 - a_2)}{f_{\rm beat}(T_0)}\Delta T = c_1 \Delta T, \tag{6}$$

where c_1 is the first order TCf (ppm/°C) of the beat frequency.

According to Eq. (6), to obtain a beat frequency with a large temperature sensitivity, the difference in TCf of f_1 and f_2 should be as large as possible and at the same time the beat frequency should be as small as feasible. The dual resonator described in this work produces reference frequencies f_1 and f_2 of approximately 1.37 and 1.45 MHz, respectively, resulting in a beat frequency $f_{\rm beat}$ of approximately 75 kHz. The resonator with frequency f_1 is passively temperature compensated to first order, while the resonator with frequency f_2 has a larger TCf of −17 ppm/ °C. We obtain a pair of resonators with the same frequency but with different TCfs by scaling one design with respect to the other and growing the same thickness of oxide on both.[6] Since the

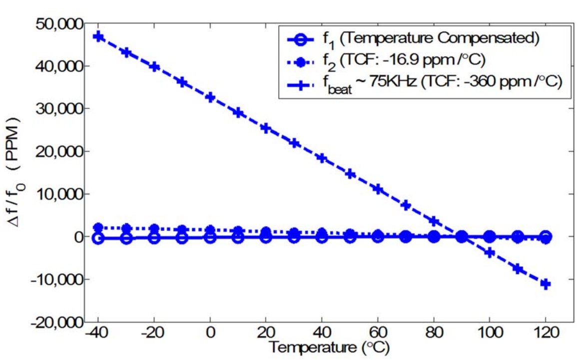

FIG. 3. (Color online) Temperature dependence of f_1, f_2, and $f_{\rm beat}$.

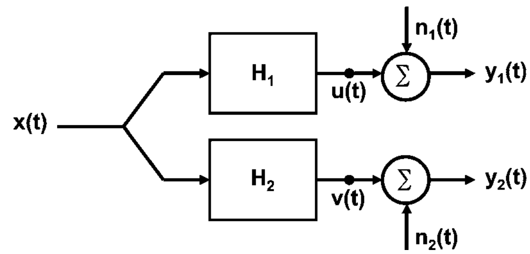

FIG. 4. Block diagram showing the modeling of correlation technique.

frequencies of the dual resonator are close together, the beat frequency is exceptionally sensitive to temperature changes, as per Eq. (6), and nearly linear, as shown in Fig. 3, with a TCf of approximately −360 ppm/ °C.

The resolution of the beat frequency temperature sensor is measured using a correlation technique,[11–13] because the expected resolution was below the stability of our measurement oven and beyond the performance of thermometers commonly available in the laboratory. We use this technique because it is the only approach that allows characterization of references that are more accurate than the common references available in our laboratory. This technique is described elsewhere, and only the results are summarized here.

The beat frequencies of two different dual-resonator devices, with the same design, were simultaneously measured while operated side-by-side inside an oven. A schematic diagram representing the above scenario is shown in Fig. 4, where the input $x(t)$ is the temperature inside the oven causing the same temperature effect in both devices. The output of the two devices $y_1(t)$ and $y_2(t)$ contains the inherent noises $n_1(t)$ and $n_2(t)$ of the sensors, respectively. By estimating the cross correlation between the two output measurements, the inherent noise can be extracted. The true resolution of the temperature sensor is limited by its inherent noise.

The inherent noise in device 1 is estimated as

$$\sigma_{n_1 n_1} \approx \sigma_{y_1 y_1}(1 - \rho_{y_1 y_2})^{1/2}, \tag{7}$$

where $\sigma_{y_1 y_1}$ is the deviation in the output signal of device 1 and $\rho_{y_1 y_2}$ is the correlation coefficient between the measured signals of the two devices. Measurements of $f_{\rm beat}$ of both devices were taken over a period of 10 h. As can be seen in Fig. 5(a), both signals are tracking the variations in the temperature inside the oven (~0.3 °C), and that most of the variations in the individual signals are present in both sensors. Since the resonator based oscillators can have various types of noise other than white noise, an IEEE recommended Allan deviation[14] has been used to calculate the deviation in the measurements. The classical standard deviation for such measurements depends on the number of data points and hence may not converge.[14] However, if the oscillator exhibits only white noise then the Allan deviation and the classical standard deviation will give the same result. The Allan deviation, for an averaging time τ of one second, can be estimated as

$$\sigma_y(\tau) = \sqrt{\frac{1}{2(N-1)}\sum (y_{i+1} - y_i)^2}, \tag{8}$$

where y_i are the discrete frequency measurements averaged over time τ. Ignoring the dead time between the two consecutive measurements, the Allan deviation for multiple τ can be evaluated by simply averaging the consecutive fre-

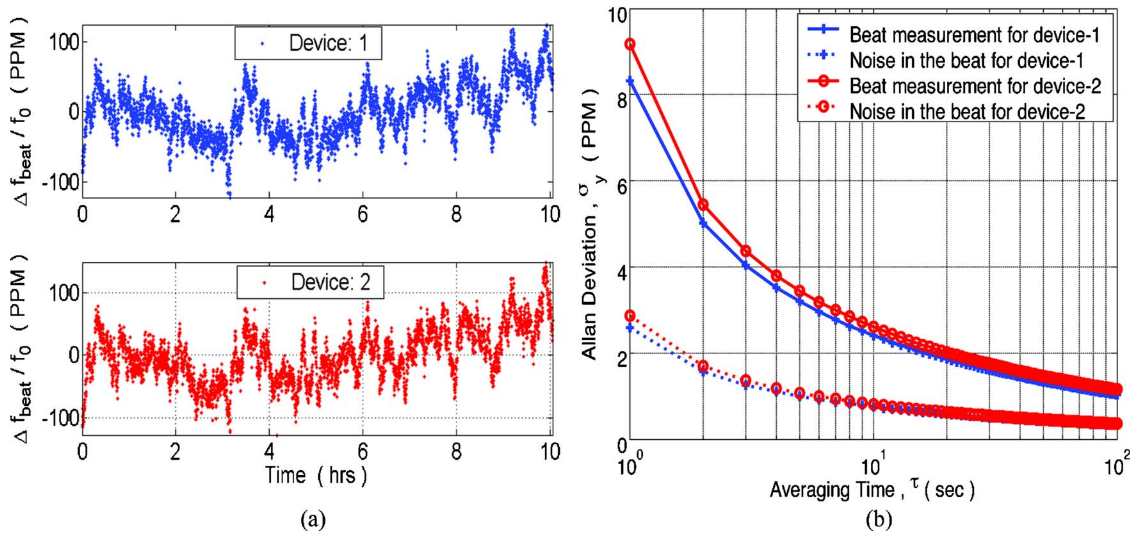

FIG. 5. (Color online) (a) Measurement of the beat frequencies of two different devices at a nominally constant temperature. (b) Evaluation of the Allan deviation of the measured beat frequency data and its noise.

quency data, as shown in Fig. 5(b). The correlation coefficient of the two beat frequencies is calculated to be 0.90. From Eq. (7) we can compute the noise component of the beat frequency as a function of averaging time τ, as shown in Fig. 5(b). By knowing the sensitivity of the beat frequency and its noise component, the resolution of the dual-resonator beat frequency thermometer can be evaluated and is illustrated in Table I. From these measurements, we find that the resolution of the beat frequency thermometer is 0.008 °C for a 1 s averaging time and as low as 0.0023 °C for a 10 s averaging time.

A temperature sensor with such resolution can be exploited for various in-chip applications. However, one of the most important applications is the temperature compensation of the microresonator to achieve sub-ppm frequency stability. The temperature compensation is done by sensing the temperature of the resonator and then stabilizing the frequency by using feedback control logic. Since the dual-resonator beat frequency thermometry is inherent to the resonator, this technique of temperature sensing is ideal for the temperature compensation of microresonators. Similar techniques have been used in the past to achieve the frequency stability of the order of 10^{-9} in the quartz resonators.[7,8]

Significant improvements in the performance of this sensor are possible by designing high-frequency low phase-noise dual resonators, resulting in a sensor resolution of better than 0.001 °C, which would enable significant improvements in temperature compensation of a very wide spectrum of analog and digital systems. It is also possible to enhance the temperature sensitivity of the beat frequency by more closely matching the initial frequencies of the two resonators. In the example demonstrated here, the mismatch between frequencies is of the order of 6% and arises from fabrication uncertainties in our process. A more stable process executed in a CMOS manufacturing line can be expected to achieve frequency matching to better than 1%, resulting in a very high temperature sensitive beat frequency, leading to improved performance of the sensor in measuring the smallest change in temperature above its resolution.

TABLE I. Allan deviation and resolution of the beat frequency measurements.

			σ_y for the noise (ppm)		Resolution (°C)	
	f_{beat} (kHz)	TCf_{beat} (ppm)	τ=1 s	τ=10 s	τ=1 s	τ=10 s
Device 1	75	360	**2.9**	0.81	0.0081	0.0023
Device 2	62	330	2.6	0.75	0.0079	0.0023

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[1]C. T.-C. Nguyen, IEEE Trans. Ultrason. Ferroelectr. Freq. Control **54**, 251 (2007).
[2]V. Kaajakari, J. Kiihamaki, A. Oja, S. Pietikainen, V. Kokkala, and H. Kuisma, Sens. Actuators, A **130–131**, 42 (2006).
[3]C. T.-C. Nguyen and R. T. Howe, IEEE J. Solid-State Circuits **34**, 440 (1999).
[4]M. J. Madou, *Fundamentals of Microfabrication*, 2nd ed. (CRC, New York, 1997), pp. 204–207.
[5]R. Melamud, M. A. Hopcroft, C. M. Jha, B. Kim, S. A. Chandorkar, R. N. Candler, and T. W. Kenny, The 13th International Conference on Solid-State Sensors, Actuators, and Microsystems, Seoul, Vol. 1, pp. 392–395.
[6]R. Melamud, B. Kim, S. Chandorkar, M. A. Hopcroft, M. Agarwal, C. M. Jha, and T. W. Kenny, Appl. Phys. Lett. **90**, 1 (2007).
[7]S. S. Schodowski, *Proceedings of the 43rd Annual Symposium on Frequency Control* (IEEE, New York, 1989).
[8]J. R. Vig, IEEE Sens. J. **1**, 1 (2001).
[9]R. N. Candler, M. A. Hopcroft, B. Kim, W. T. Park, R. Melamud, M. Agarwal, G. Yama, A. Partridge, M. Lutz, and T. W. Kenny, J. Microelectromech. Syst. **15**, 1446 (2006).
[10]R. N. Candler, W.-T. Park, H. Li, G. Yama, A. Partridge, M. Lutz, and T. W. Kenny, IEEE Trans. Adv. Packag. **26**, 227 (2003).
[11]A. Barzilai, T. VanZandt, and T. W. Kenny, Rev. Sci. Instrum. **69**, 7 (1998).
[12]J. S. Bendat and A. G. Piersol, *Random Data: Analysis and Measurement Procedures*, 2nd ed. (Wiley, New York, 1986), pp. 117–120 and 534–536.
[13]J. S. Bendat and A. G. Piersol, *Engineering Applications of Correlation and Spectral Analysis* (Wiley, New York, 1980), pp. 43–48 and 154–159.
[14]D. A. Howe, D. W. Allan, and J. A. Barnes, Proceedings of the 35th Annual Symposium on Frequency Control, 1981, pp. 1–47.