TEMPERATURE COMPENSATION OF A MEMS RESONATOR USING QUALITY FACTOR AS A THERMOMETER

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ABSTRACT

Silicon MEMS resonators have great potential for on-chip high frequency signal applications. This paper compares methods of sensing the temperature of an encapsulated silicon MEMS resonator and using this temperature measurement to stabilize the temperature, and hence the resonant frequency, of the resonator. The use of external Pt RTDs, integrated Si thermistors, and the use the Quality factor (Q) of the resonator are explored. Use of the Q as a temperature sensor is explored in detail as it is a nearly ideal temperature sensing method. Characterisations of the temperature sensors and preliminary temperature control results are presented.

1. INTRODUCTION

Micromachined silicon resonators fabricated in Micro-Electro-Mechanical Systems (MEMS) technologies are of increasing interest for potential applications in on-chip high frequency signal manipulation, integrated circuit clock generation, and other applications based on a stable frequency reference signal. Silicon is a preferred material for high performance microresonators because of its high mechanical stiffness, excellent fatigue resistance, and compatibility with integrated circuit (CMOS) technology. Recent work in our group on wafer-scale encapsulation [1, 2, 3] has shown that it is possible to fabricate silicon MEMS resonators inside a robust, low-pressure encapsulated cavity using a CMOS-compatible process. Unfortunately, these silicon resonators exhibit a typical temperature coefficient of frequency (TCf) of -30 ppm/°C due to the softening of the silicon with increasing temperature. Practical applications for portable frequency references, such as tactical radio frequency hopping or navigation beacons, require frequency references with TCf values << 1 ppm/°C [4]. Achieving low resonator TCf requires some form of temperature compensation, by controlling the temperature of the device directly or by other means. In all cases, some method of accurately sensing the temperature of the device is required.

The state-of-the-art technology for portable frequency references is ovenized quartz crystal oscillators (OCXOs). These are large (25 cm^3) enclosures which require several Watts of power to operate. Our team is working to develop active temperature compensation methods based on control of the resonator temperature within the wafer-level encapsulation - a MEMS equivalent to an OCXO - that will provide state of the art performance. Success in such a temperature control approach depends on accurate knowledge of the temperature of the resonator. An ideal thermometer would be one that is fully integrated with the MEMS resonator, dissipates no power, and is accurate and stable for the long-term applications. If a suitable thermometer can be developed, then a compensation system can be implemented which applies feedback control to maintain the thermometer output at a fixed value, making calibration unnecessary.

To address this need, we have explored the use of several potential thermometers: a second chip with a Platinum RTD, a silicon thermistor integrated into the MEMS resonator, and the temperature coefficient of the quality factor of the resonator (TCQ). Of these three options, the Temperature Coefficient of the Q is certainly the most interesting. The Q(T) signal is a direct measure of the temperature of the resonator. In an oscillator system, Q(T) can be measured without additional power dissipation at the resonator simply by measuring the amplitude of the oscillation signal. Resonator Q has been shown to be very stable within our wafer-level packaging [5], and the Q and the Temperature Coefficient of the Q can be engineered within our process, as described in a separate paper at this conference [6, 7].

The resonators used in this work are double-ended tuning forks (DETF) that are fabricated in our epi-seal wafer-scale encapsulation process which has been described previously [3]. The process has been modified slightly to accommodate silicon resistors for heating the encapsulated devices.

2. THERMOMETER SELECTION

We have considered three types of thermometers for measuring the temperature of the resonator: external platinum resistor temperature detectors (RTD), integrated silicon thermistors, and the resonator Quality factor. Our initial goal is to achieve frequency stability of approximately 1 ppm/°C. Given a TCf of -30 ppm/°C, we require a thermometer with a resolution of < 1/30 °C.

Platinum RTDs

Platinum resistor temperature detectors are widely used for temperature measurement applications and commercial Pt RTDs are easily available at low cost. Platinum is extremely stable and it has a nearly linear temperature coefficient of resistance (TCR) over a wide temperature range. For our experiments, we used a Omega F3105 Pt RTD [8], which has a nominal resistance of 100 ohms, and a HP 34420A

Nanovoltmeter to measure the RTD. The Nanovoltmeter uses a four-wire measurement and built-in calibration and conversion features to provide temperature readings with better than 0.01°C accuracy twice a second.

The primary disadvantage of the RTD is that it is physically separate from the resonator. Figure 1 is a photograph of a resonator assembled on an oscillator circuit board with an RTD inside the device package. Even with the minimum separation between the resonator and the RTD, the steady state temperature signal can differ from the temperature of the resonator by tenths of a degree and the transient reading by even more. The RTD signal is, however, used as our measurement of the ambient temperature of the thermal chamber environment during resonator testing.

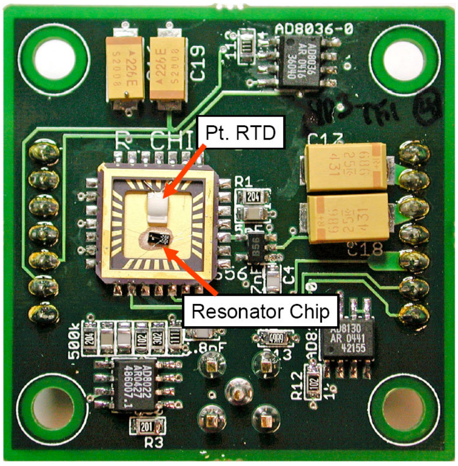

Figure 1: Photograph of Oscillator Circuit Board with Pt RTD and Resonator Assembled in the IC Package. The circuit board measures 3.75 cm on a side.

Silicon Thermistors

In order to accurately measure the temperature of the resonator, the sensor needs to be as close as possible to the device. As the wafer-scale encapsulation process involves extremely high temperatures (1000 °C), the choice of materials that can be integrated in the encapsulated process is limited. Silicon resistors are already integrated into the encapsulation for the purpose of heating the ovenized enclosure, and so using them for temperature sensing is an obvious choice. However, the measurement of integrated silicon thermistors presents some challenges. For example, if we want to maintain a 200 °C temperature difference between the ovenized enclosure and the ambient temperature with 5 mW of power, than we must dissipate < 25 µW of power in the thermistor to keep the introduced temperature error < 1 °C. Silicon TCR values are non-linear, depend on doping, and are typically on the order of 1%. In order to dissipate less than 25 µW, a 10 kΩ thermistor in a voltage divider will require a bias voltage of < 0.7 V. For a TCR of 1%/°C, this implies measurement of changes in voltage of ~ 50 µV. This is not impossible, but difficult, and thermocouple effects, resistor noise, etc. have not been considered. So silicon thermistors are a possibility, but far from ideal.

Quality Factor (Q)

Quality factor of a resonator is defined as the energy stored in a system divided by the energy dissipated per radian. Many energy dissipation mechanisms may contribute to the measured Quality factor of a resonator. These mechanisms add in parallel, so that if any one contribution is much larger (i.e., Q value is much smaller) than the others, it will dominate the result, as given in Equation 1.

$$\frac{1}{Q_{total}} = \frac{1}{Q_{air}} + \frac{1}{Q_{TED}} + \frac{1}{Q_{anchor\,loss}} + \frac{1}{Q_{others}} \qquad (1)$$

The total Q value of the resonators described in this work is dominated by thermoelastic dissipation (TED) [9]. TED is a complex phenomenon, and it has several types of temperature dependence, which can be modeled accurately for our resonator designs [6]. In the case of the tuning forks discussed here, the TCQ is approximately 85/°C, or about 1% F.S./°C.

The Q of a resonator can be measured by recording the response of the resonator to a range of frequencies around its resonance and measuring the 3 dB bandwidth of the peak. However, this method is relatively slow, and prone to errors related to the resolution of the measurement over a wide frequency range. Typically, the measurement of Q by this method will have an error of up to ±5%. The Q can also be inferred from the amplitude of the resonator response at resonance. In our electrostatic resonators, the amplitude of the motion of the resonator beams is a function of Q and the drive (stimulus) and bias voltages, as in Equation 2.

$$x = \frac{CV_{bias}V_{drive}}{kg_0}Q \qquad (2)$$

Here, x is the displacement of the resonator, C is the capacitance of the actuator gap, g_0 is the initial gap width, k is the mechanical stiffness of the resonator, Q is the quality factor, and the V terms are voltages applied to the resonator. The resulting output current, I, at frequency ω_0, is given by:

$$I = \frac{\omega_0 C V_{bias} x}{g_0} \quad \text{(for } g_0 >> x\text{)} \qquad (3)$$

In our oscillator system, the resonator motion is directly reflected in the amplitude of the oscillator output signal. The key features of the oscillator circuit developed by our group are illustrated in Figure 2. The transimpedance amplifier converts the output current, I, into a voltage signal. The feedback signal that drives the resonator is applied by a unity-gain clamping amplifier whose purpose is to ensure that the voltage driving the resonator has a constant amplitude, independent of the resonator feedback signal.

The driving voltage and the bias voltage are constant, so the output signal amplitude depends only on resonator Q, and so the signal amplitude indicates the temperature of the device.

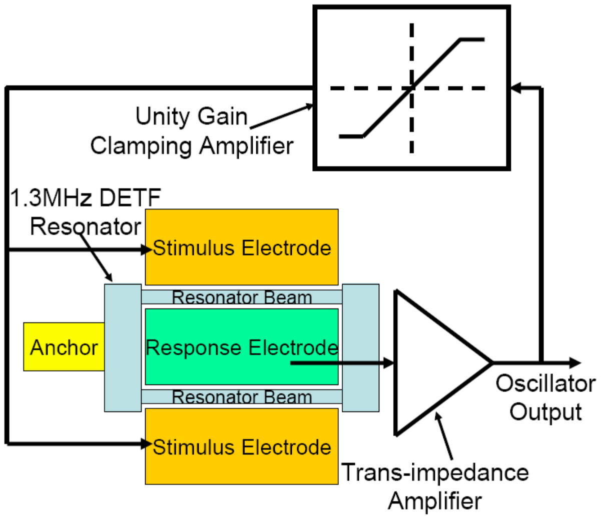

Figure 2: Oscillator Circuit Schematic. The resonator stimulus signal is maintained at a constant level by the clamping amplifier,

Typical Q values as a function of temperature are shown in Figure 3. An RMS detector can convert the signal amplitude into a DC voltage signal which is easily measured to determine the temperature. With this method, the thermometer output is approximately 12.5 mV/°C, and so for 0.03 °C change, we need to detect a change of 400 µV, an order of magnitude better than Si thermistors.

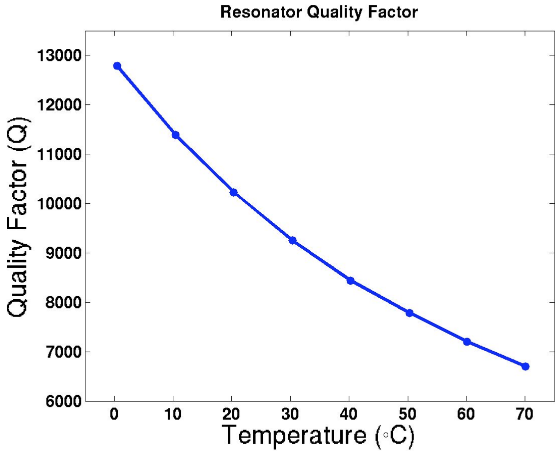

Figure 3: Resonator Quality Factor vs. Temperature for a 1.3 MHz DETF resonator.

3. EXPERIMENTAL RESULTS

To test the thermometers, an oscillator like the one shown in Figure 1 was assembled using a 1.3 MHz DETF and placed in a thermal chamber. A HP 53132A counter was used to measure the frequency of the resonator, and a AD8361 RMS detector was used to measure the amplitude of the oscillator output signal. The measurement setup is shown in Figure 4. The measurements were controlled by a computer through a GPIB interface.

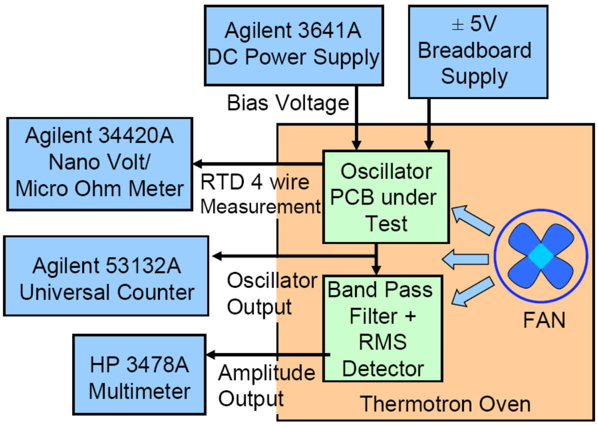

Figure 4: The Measurement Setup for Thermometry Tests. All of the circuit components were placed inside the oven.

The first task was to determine the resonator's response to temperature. The thermal chamber temperature, as measured by the on-board RTD, is allowed to stabilize at 10 °C intervals, and 50 frequency measurements are taken at each temperature. The results are shown in Figure 5.

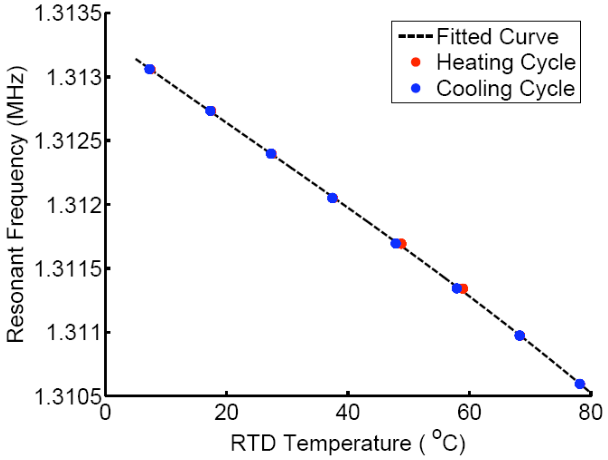

Figure 5: Resonant Frequency vs. Ambient Temperature. A single heating and cooling cycle is plotted. Each point on the graph is actually a cluster of 50 measurements taken at that temperature.

The amplitude of the oscillator output was then measured and compared to the output frequency. The result, shown in Figure 6, is a reflection of the resonator characteristics plotted in Figure 3. The RTD sensor is physically separate from the resonator, and because of this we expect there to be a time lag between the temperature signal and the change in resonant frequency. This can be minimized with careful packaging, as discussed above, but the response still suffers in comparison to the measurement of output amplitude, as shown in Figure 7.

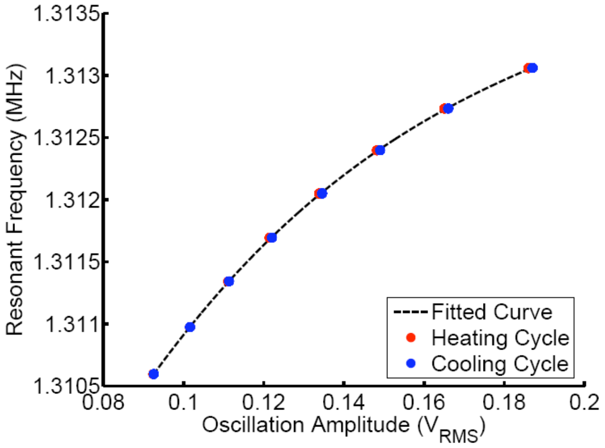

Figure 6: Resonant Frequency vs. Oscillator Output Amplitude. As in Figure 5, each point on the graph is a cluster of 50 points.

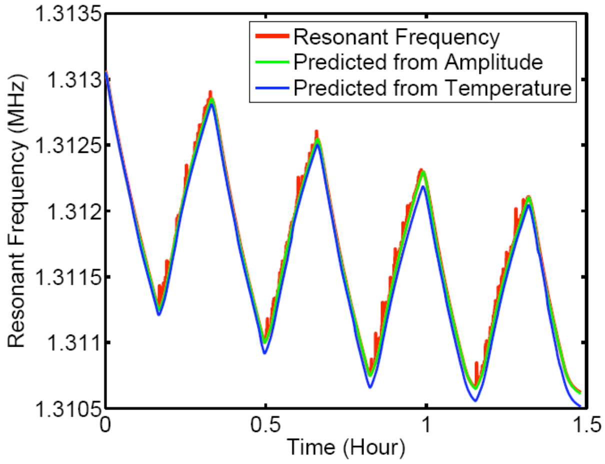

Figure 7: Transient response of the resonant frequency and temperature measurement. The temperature measurements have been converted to predicted temperature using the data from Figures 5 and 6.

As a demonstration of the use of Q as a thermometer for temperature compensation, a "micro-ovenized" DETF resonator was operated in a feedback loop using the 3dB Q measurement as the temperature sensor. The results are plotted in Figure 8. The controller maintained the resonator frequency around the setpoint, although there was significant noise due to the errors and time delays involved in the measurement of Q.

4. CONCLUSIONS

The use of resonator Q as a thermometer has great potential. The Q(T) signal is nearly the ideal thermometer: it is directly integrated with the device of interest, introduces no temperature error, is easily detectable, and consumes no power. We expect the use of Q(T) to enable ppb-level oscillator temperature compensation in future devices.

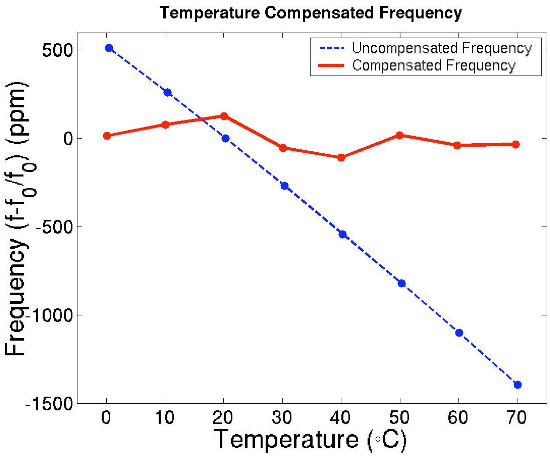

Figure 8: Temperature Compensated Frequency of a Resonator. The variation in compensated frequency is due to errors and time lag in the measurement of Q by the 3dB bandwidth method.

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REFERENCES

[1] Candler, R.N., et al., *Single wafer encapsulation of MEMS devices.* IEEE Transactions on Advanced Packaging, **26**(3), 2003.

[2] Partridge, A., et al. *New thin film epitaxial polysilicon encapsulation for piezoresistive accelerometers*. at MEMS '01, 2001. Interlaken, Switzerland.

[3] Candler, R.N., et al. *Hydrogen diffusion and pressure control of encapsulated MEMS resonators*. at TRANSDUCERS '05, 2005.

[4] Vig, J.R., *Quartz Crystal Resonators and Oscillators for Frequency Control and Timing Applications - A Tutorial*, 2005.

[5] Kim, B., et al. *Frequency stability of wafer-scale encapsulated MEMS resonators*. at TRANSDUCERS '05, 2005.

[6] Kim, B., et al. *Temperature Dependence of Quality Factor in MEMS Resonators*. at MEMS '06, 2006. Istanbul, Turkey.

[7] Candler, R.N., et al. *Impact of slot location on thermoelastic dissipation in micromechanical resonators*. at TRANSDUCERS '05, 2005.

[8] Omega Engineering Inc., *F3105 Thin Film RTD Elements*, 2005.

[9] Candler, R.N., et al. *Investigation of Energy Loss Mechanisms in Micromechanical Resonators*. at TRANSDUCERS '03, 2003. Boston, MA USA.