MODELING AND CHARACTERIZATION OF AN UNSEALED SELF-HEATING MEMS RESONATOR FOR TEMPERATURE COMPENSATION

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ABSTRACT
This paper reports the modeling and characterization of a micromechanical resonator with a built-in heater. The device was modeled analytically as well as by using finite element (FE) simulation. Both the analytical and the FE models agree well with the characteristics measured from the fabricated resonator. These results together show that 5mW of joule heating is sufficient to raise the resonator’s temperature to over 100K above ambient. Such a level of power consumption is orders of magnitude lower relative to commercial ovenized quartz resonators.

INTRODUCTION
Micromechanical resonators have been of interest for realizing integrated on-chip clocks [1] in addition to their application to sensing [2]. These devices hold a number of advantages over quartz in terms of size, technology scalability, and the potential for integration with CMOS. However, in comparison to quartz, silicon shows a strong sensitivity to temperature. One way of addressing this problem is to hold the silicon resonator at an elevated temperature so that it stays constant regardless of changes in the ambient; analogous to an ovenized quartz resonator. Due to the small form factor of the MEMS resonator, the benefit of this approach is lower power consumption and faster response times [3]. In this work, we model (both analytically and also by finite element (FE) computation) and later experimentally characterize an uncapped resonator with built-in heaters. We show herein that good agreement is found between the analytical and FE models together with the measured characteristics of the device.

DEVICE MODELLING
Finite element model
The device reported herein comprises a double-ended tuning fork (DETF) resonator that is flanked on both sides by suspended resistive heater beams. When a current is applied to the heater beams, the temperature of the DETF is raised. Fig 1 shows the FE simulation using COMSOL of the joule heating effect. It can be seen that, as desired, the maximum temperature over the entire device is at the DETF resonator itself.

Analytical model
The heater beams and DETF can each be modeled as resistors as illustrated in Fig 2. The temperature of the DETF over the ambient is given by [3]:

$$\Delta T = \frac{V^2}{R_{el}} \left(\frac{R_{th}}{8}\right)$$

(1)

where $V$ is the voltage applied across the heaters, $R_{el}$ is their electrical resistance, while $R_{th}$ is the corresponding thermal resistance ($R_{th} = L/\lambda A$). $L$ and $A$ are respectively the length and cross sectional area of the beams; $\lambda$ is the thermal conductivity (typically 110 to 140 W/mK).

DEVICE CHARACTERIZATION
The device was fabricated in a foundry SOI MEMS process (Fig 3). Fig 4 shows an optical micrograph of the device. Electrical characterization was performed in a vacuum probe station. Since the device’s temperature of the device cannot be determined directly, we first measure its resonant frequency with varying ambient temperature (through a temperature controller). We then measured the resonant frequency as the voltage applied to the heaters was increased up in steps of 1V up to 7V. By combining the 2 sets of data, we obtain the device temperature as a function of voltage applied to the built-in heater. Fig 5 shows the transmission magnitude measured at 340K. Fig 6 shows the variation of resonant frequency with temperature, which is approximately linear. Fig 7 shows the variation of the resonant frequency as the voltage applied to the heaters is increased. The trend is roughly parabolic since power is equals the square of the voltage. Fig 8 shows the derived variation of DETF temperature with applied voltage from Figs 6 & 7. The simulated and analytical model predictions have also been included in the same figure for ease of comparison. It can be seen that all 3 results agree well with each other. Hence although the device is unsealed, the good agreement in the results indicates that our setup (radiation shield and vacuum) is sufficient to reduce thermal losses due to radiation and convection. These results also show that only 5mW is required to raise the resonator temperature to over 100K above its ambient; useful for temperature compensation.

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REFERENCES

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Figure 1: FE simulation in COMSOL of the joule heating effect in the DETF resonator with built-in heaters.

Figure 2: Equivalent circuit model of the DETF resonator with built-in heaters. $R_H$: Heater resistance, $R_D$: DETF resistance.

Figure 3: Transverse view schematic of the device fabricated using a foundry SOI MEMS process.

Figure 4: Optical micrograph of the fabricated double ended tuning fork (DETF) resonator with built-in heaters.

Figure 5: Electrical transmission (magnitude) of the resonator measured at 340K.

Figure 6: Measured linear variation of resonant frequency with temperature. The temperature coefficient of frequency (TCF) of the device is about -35ppm/K.

Figure 7: Measured parabolic variation in the device resonant frequency with increasing voltage applied to heaters.

Figure 8: Comparison between measured DETF temperature with voltage characteristic against the FE and analytical model predictions. Modeled characteristics have taken into account the uncertainty in the actual thermal conductivity.