Temperature Control of CMOS Micromachined Sensors

Hasnain Lakdawala* and Gary K. Fedder†
Department of Electrical and Computer Engineering* and The Robotics Institute†
Carnegie Mellon University, Pittsburgh, PA 15213, USA
phone: (412) 268 4403 fax: (412) 268 3890 email: [hasnain,fedder]@ece.cmu.edu

ABSTRACT
In this paper, we describe a methodology for temperature stabilization of CMOS micromachined sensors. Temperature stabilization of a z-axis accelerometer, fabricated in a 0.5µm Agilent CMOS process is demonstrated. The accelerometer motion is sensed by a vertical comb drive designed by controlling the rotor and stator curvature. The polysilicon layer of the CMOS process has been utilized for heating the device structure to a constant temperature, that is higher than the maximum ambient operating temperature. The capacitance detection circuits have temperature independent gain. The D.C. bias stability of the accelerometer improved from 1.9 G/°C, to 42 mG/°C, and the sensitivity stability improved from 60% to 18% over a temperature of 70°C after temperature control.

INTRODUCTION
Effort has been underway to integrate three axis accelerometers and gyroscopes on a single chip, to create an integrated inertial measurement unit (I-IMU). The integration of this functionality will provide a cost effective solution for many augmented GPS applications. CMOS micromachining technology [1] has the potential to deliver an I-IMU. Accelerometers and gyroscopes in all three axes have been demonstrated in this technology [2][3][4].

One important consideration in designing microstructures made using the metal and the dielectric layers of CMOS process is the presence of residual stress gradients, that cause structures to curl out-of-plane, and in-plane [5][6]. Design techniques for compensation of curl, helps improve nominal device performance. However, due to the large difference in thermal expansion coefficients of the aluminum (23µ/K) and the oxide (0.4µ/K) layers, the curl is function of temperature. The out-of-plane curl can cause variation in D.C. bias output and sensitivity of CMOS micromachined inertial devices. The situation is complicated by the dependence of in-plane curl variation with temperature due to misalignments of the metal masks during the foundry CMOS fabrication.

In this paper, we describe a temperature compensation technique that aims to keep the temperature of the device constant using integrated polysilicon resistors of the CMOS process embedded in the device structure. Keeping the device at a constant temperature rather than keeping the entire chip leads to lower power consumption and reduces packaging difficulties [7]. A Z-axis accelerometer sensitive to out-of-plane accelerations has been used as a test-bed for demonstration of the temperature control scheme. Unlike prior CMOS micromachined accelerometer designs this device has an inherently large D.C. bias sensitivity to temperature.

Z-AXIS ACCELEROMETER
A cross-section of the CMOS micromachined device is shown in Figure 1 [1]. An SEM of the z-axis accelerometer is shown in Figure 2. The accelerometer is a spring-mass system, and force acting on the mass due to external acceleration is balanced by a spring force. The spring is designed to be compliant in the out-of-plane direction, while being stiffer in the x and y modes. The spring is designed using the thinner metal 1,2 beams, and made compliant in out-of-plane by increasing the number of meanders. The increased length of the spring also increases the thermal isolation between the rotor and the stator. The spring constants for the spring are k_x = 0.198 N/m, k_y=1.93 N/m and k_z=2.12 N/m. The rotor is suspended from a stiff frame that ensures that curl of the stator fingers can be controlled and the device is thermally isolated. The motion of the mass is detected by a change in capacitance between fixed set of fingers (stator combs), and the moving set of comb fingers (rotor combs). To maximize the sensitivity of the device, the area of the combs is maximized, 75% of the device area (500 µm x 500 µm) is occupied by comb fingers. The capacitance sense mechanism is sensitive to out-of-plane changes, while rejecting capacitance changes due to in-plane motion.

Out-of-plane comb drive
A cross-section of an out-of-plane comb drive is shown in Figure 3. A z-offset is introduced between the rotor and the stator by exploiting the differences in
curvature of the rotor and the stator. The capacitance change due to a small z-displacement by parallel plate approximation is

\[ \Delta C_{accn} = \frac{\varepsilon_0 L_t}{g} \Delta z_{ov} \]  

(1)

where \( C_{accn} \) is the capacitance of the accelerometer, \( L_t \) is the total length of the combs, \( g \) is the gap between the fingers, and \( z_{ov} \) is the initial overlap of the fingers. This expression does not account for the fringing fields and the actual capacitance must be computed from finite element modeling. A plot of the capacitance and capacitance sensitivity per micron of z displacement is shown in Figure 4. The maximum sensitivity is achieved when the combs are just engaged, and the design of the comb fingers aims to achieve this maximal sensitivity position. The curl was designed using simulation techniques described in [5]. An iterative finite element simulation for placement of the stator combs [8] was employed to achieve the best z-offset. Figure 2(b) illustrates the structural curl of the rotor and the stator such that the rotor combs are mostly below the stator combs.

**TEMPERATURE INDEPENDENT CIRCUITS**

The accelerometer output is measured by chopper stabilized capacitance-sense circuits that have constant gain with temperature, and cancel D.C. offset drifts due to temperature. The circuit topology is shown in Figure 5. The clock generation circuits are included on chip. The D.C. voltage at the input is reset using an NMOS transistor compensated to reduce charge injection. No D.C. voltage across the device is applied by the sense circuit. The output of the circuit after low-pass filtering can be written as

![Figure 2: (a) SEM of a Z axis accelerometer curl, and (b) the room temperature structural curl of the device showing the z-offset between the rotor and the stator.](image)

![Figure 3: Cross-section of an out-of-plane comb driver. All metal layers of the beam are at the same potential.](image)

![Figure 4: Variation of (a) out-of-plane capacitance, (b) capacitance sensitivity as a function of gap and vertical displacement.](image)

![Figure 5: Schematic of the capacitance sense circuits implemented in the 0.5µm CMOS process.](image)
\[
V_{out} = \frac{A_o \Delta C_{accn} \Delta V_{mod}}{C_{accn} + C_r + C_p}
\]  

(2)

where, \(\Delta V_{mod}\) is the total modulation voltage, \(A_o\) is the circuit gain, \(C_r\) is the reference capacitance, and \(C_p\) is the total parasitic capacitance at the sense node. The D.C drift of the circuits was measured to -170 \(\mu V/^{\circ}C/V\) (~18m\(G^{\circ}C/V\)), and no measurable change in circuit gain was seen until 104\(^\circ\)C. The bandwidth of the circuit is limited to 1.1 kHz with an off-chip low pass filter. The dynamic range of the circuit is 3.8V, which corresponds to about 200G, is important to accommodate the large capacitance change due to temperature change. An identical z-constrained accelerometer has been used as reference capacitor. This provides a first order cancellation of thermal effects.

INTEGRATED HEATER DESIGN

Separate polysilicon heaters were embedded in the stator, rotor and the rotor comb fingers to heat the device uniformly. Each resistor was heated by independent electrical control. The heat loss from the device is dominated by thermal conduction to the substrate through air. The presence of temperature gradients across the device are not desirable as the structural curl is then affected by the ambient temperature. The dimensions of the polysilicon heaters within the device structure were optimized using a finite difference modeling technique and modified Levenberg algorithm [9] to ensure the most uniform temperature distribution. The nominal resistance of each resistor is between 0.5-1k\(\Omega\), for optimal power transfer in a 5V supply design. The average temperature of the heaters was monitored by measurement of the resistance. The polysilicon has a temperature coefficient of resistance (TCR) of 0.0049 /K, with a tolerance of +/-10%. The TCR was measured by calibration of the polysilicon heater against an on-chip temperature measurement circuit. The measured temperature distribution due to rotor heating is shown in Figure 6. The thermal time constant of the device is about 3 ms, which is much smaller than the time constant of ambient temperature change. This greatly simplifies the controller design.

Figure 6: The temperature distribution due to rotor heating. Additional heaters need to be added for uniform temperature distribution.

ACCELEROMETER CHARACTERIZATION

The mechanical response of the accelerometer was characterized by electrostatic actuation of the comb fingers. The response is shown in Figure 7 [10]. The dominant mode of the sensor was out-of-plane at 4.4 kHz (5.22 kHz from simulation). The sensitivity of the transducer before circuit gain is 0.13mV/G/V (for \(\Delta V_{mod}=1V\)), and 9.3mV/G after on-chip amplification. The noise floor was about 2mG/\(\sqrt{Hz}\), and performance is limited by the circuit noise. The linearity of the device was better than 3% over 20G input range. The cross axis sensitivity was 32 dB, and was limited by the test setup.

TEMPERATURE CONTROL

The stator, rotor and the rotor comb heaters were independently controlled to achieve a uniform distribution across the device. To evaluate full three heater control, a PC-based control scheme was developed. The reference and the device heaters were simultaneously heated to the same temperature. Each heater resistance was kept constant to the value corresponding to the set temperature using a Kiethley source meter, controlled using Labview. The chip was wire-bonded in a 40-pin DIP socket, and was heated using a strip heater. The chip temperature was monitored by on chip temperature measurement circuit. The printed circuit board was mounted on a shaker table with 1 G peak to peak acceleration at 230 Hz. The D.C. bias level and sensitivity of the device were measured at different chip temperatures.

Various temperature control schemes were implemented, to investigate the power performance trade-off. These schemes were:

1. Rotor heater control
2. Stator heater control
3. Rotor and stator heater control
4. Full rotor, rotor comb and stator control.

The variation of device capacitance and sensitivity with rotor heating at different device temperatures is shown in Figure 8. The capacitance reaches a peak, and the sensitivity reached a minimum at about 140\(^\circ\)C. At higher rotor temperatures the capacitance begins to reduce, and sensitivity begins to increase, as the mismatch increases. The maximum

Figure 7: Mechanical frequency response of the Z accelerometer, with dominant z mode at 4.4kHz.
safe temperature for heating is about 200°C. Beyond this temperature the aluminum begins to get grainy, and leads to device failure.

The best D.C. bias and sensitivity control was obtained when all the heaters were operational, with the rotor and the rotor comb heater maintained to the same temperature. A plot of D.C. bias and sensitivity for stator temperature of 130°C and a rotor temperature of 90°C is shown in Figure 9. The total power required for full control of the heaters is about 35mW at room temperature. The D.C. bias stability of the accelerometer improved from 1.9 G/°C, to -42 mG/°C, and the sensitivity stability improved from 60% to 18% over a temperature of 70°C after temperature control. The performance is limited by the temperature gradients across the device, induced in part by the inability to accurately determine the temperature of the device (the controller only measures an average over the whole polysilicon heater).

CONCLUSIONS

A temperature control scheme utilizing the polysilicon layer of the CMOS process has been shown to improve the temperature performance of CMOS micromachined z-axis accelerometer. The methodology developed can be applied to any CMOS sensor to improve temperature stability and optimize the device curling.

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