Low-Noise CMOS Integrated Sensing Electronics for Capacitive MEMS Strain Sensors

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Abstract

This paper describes a high-performance strain sensing microsystem. A MEMS capacitive strain sensor converts an input strain to a capacitance change with a sensitivity of 26.5 aF per 0.1 με. Low-noise integrated sensing electronics employing a continuous time synchronous detection architecture convert the capacitive signal to an output voltage for further signal processing. The prototype microsystem achieves a minimum detectable strain of 0.09 με over a 10 kHz bandwidth with a dynamic range of 81 dB. The sensing electronics consume 1.5 mA from a 3V supply.

Introduction

High-performance strain sensing system consisting of sensors and interface electronics are highly critical for advanced industrial applications, such as point-stress and torque sensing for ball-bearings, rotating shafts and blades, etc. Stringent performance requirements with a high sensitivity of 0.1 με over a wide bandwidth of 10 kHz and a large dynamic range of 80 dB are demanded for these applications. Conventional strain sensors made of metal foils and semiconductor piezoresistive elements suffer from a limited sensitivity, large temperature dependence and turn-on drift, and are incompatible to standard CMOS integration, thus inadequate for high-performance and low cost applications [1, 2].

MEMS resonant strain sensors [3] have been demonstrated to achieve a high performance by converting an input strain to a change in the device resonant frequency, but requires a large operating voltage of approximately 100 V, thus undesirable for low voltage and low power integrated systems. MEMS capacitive strain sensors, however, are attractive due to a number of key advantages such as high sensitivity, minimum temperature dependence and turn-on drift, low noise, large dynamic range, and potential monolithic integration with low power CMOS electronics [4, 5]. In this paper, low-noise CMOS integrated sensing electronics interfaced with a capacitive MEMS strain sensor is presented to achieve a sensing dynamic range of 81 dB with a strain resolution of 0.09 με over a 10 KHz bandwidth, corresponding to an equivalent displacement resolution of 0.009 $Å/\sqrt{Hz}$, which is twice better than that of state-of-the-art MEMS inertial sensors [6, 7]. The demonstrated performance also represents two orders of magnitude improvement compared to any existing commercial strain sensing technologies.

MEMS Strain Sensor

Figure 1 shows a simplified schematic of a capacitive MEMS strain sensor employed in the prototype system. The device consists of three amplifying buckled beams, critical for improving device sensitivity, with comb fingers positioned at the structural center. An externally applied

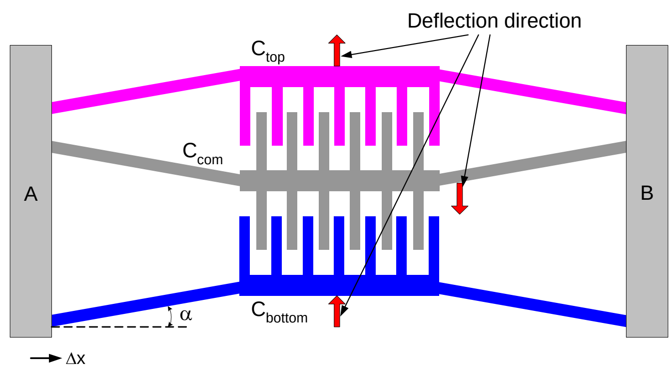

Figure 1. Capacitive Strain Sensor

strain introduces a small lateral displacement, Δx, which will result in an enhanced beams deflection along the vertical axis, upward for the C_{top} and C_{bottom} beams and downward for the center beam, C_{com}. The C_{top} and C_{bottom} electrodes thus form a set of linear differential capacitors (C_s^+ and C_s^-) with respect to the C_{com} electrode, serving as a common reference electrode as shown in the figure. The device sensitivity can be optimized by carefully selecting parameters such as buckling angle (α), finger numbers and thickness, and gap size. Optimized sensors exhibit a buckling angle of approximately 6^o, a structural thickness of 20 μm, a minimum air gap size of 3.6 μm, and a lateral gauge length of 1 mm with 37 sets of center-positioned fingers. The sensors have been fabricated by using DRIE on SOI substrates followed by releasing to free the microstructures [4]. Four fabricated sensors connected in parallel shown in Figure 2 achieve a nominal capacitance value of 0.44 pF with a differential sensitivity of 26.5 aF per 0.1 με, corresponding to a displacement of 1 Å. Mechanical thermal noise, commonly referred to as Brownian motion, for the sensor is estimated several orders of magnitude lower than the minimum detectable

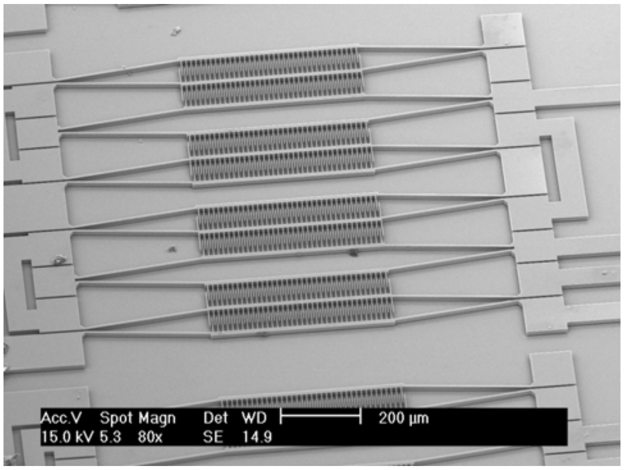

Figure 2. SEM of Fabricated Strain Sensors

signal requirement when operated in air. Therefore, low-noise sensing electronics are critical to interface with the sensor and achieve the overall stringent system performance requirements.

Low-Noise Interface Electronics

Capacitive sensor interface architectures employing switched-capacitor amplifiers typically exhibit an increased noise contribution due to aliasing of the high frequency amplifier thermal noise into the signal band [6, 7, 8]. Continuous time synchronous detection architecture, however, is attractive due to the amplifier low noise performance [9, 10] and is therefore employed in the prototype system, as shown in Figure 3. The MEMS sensors, modeled as differential capacitors, are driven by a clock signal with an amplitude of 1.2 V and are interfaced by a differential charge amplifier, which converts the sensor capacitance change to an output voltage. A clock frequency of 1 MHz is chosen to modulate the sensor information away from the $1/f$ noise of the amplifier, a critical means to achieve a high sensitivity. An input common-mode feedback (ICMFB) circuit is incorporated with the charge amplifier to minimize its input common-mode shift caused by the driving clock; hence, suppressing any offset signal due to the parasitic capacitance mismatch

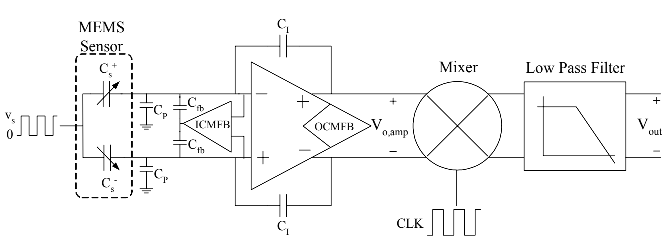

Figure 3. Electronic Strain Sensing Architecture

and drift over time. Feedback capacitors, C_{fb}, of 1.4 pF each are chosen to sufficiently compensate the common mode shift. The charge amplifier output is then mixed by the same clock signal and low-pass filtered to obtain the desired strain information.

The integrating capacitor, C_I, of 1.6 pF is chosen to achieve an output signal range from 20 μV to 200 mV, corresponding to the minimum and maximum input strain of 0.1 με and 1000 με (80 dB dynamic range), respectively. This voltage range is determined by the mixer input signal range due to the DC coupling. The overall parasitic capacitance, C_P, consisting of parasitic capacitances from the sensor interconnect, wire bonding pads, and amplifier input capacitance is estimated to be approximately 3 pF. Therefore, an input referred noise spectral density of 5 $nV/\sqrt{Hz}$ is required for the charge amplifier to achieve the system resolution requirements, i.e. an SNR of approximately 3 at the minimum input strain.

Figure 4 shows the amplifier circuit schematic. A fully differential telescopic architecture was chosen for its low noise and low power performance compared to other architectures such as folded cascode. An output common-mode feedback (OCMFB) circuit consisting of transistors M_{10-15} is required to set the output common-mode voltage level with capacitors C_1 and C_2 stabilizing the feedback loop. The main amplifier input transistors, M_1 and M_2, dominate the amplifier noise performance and are

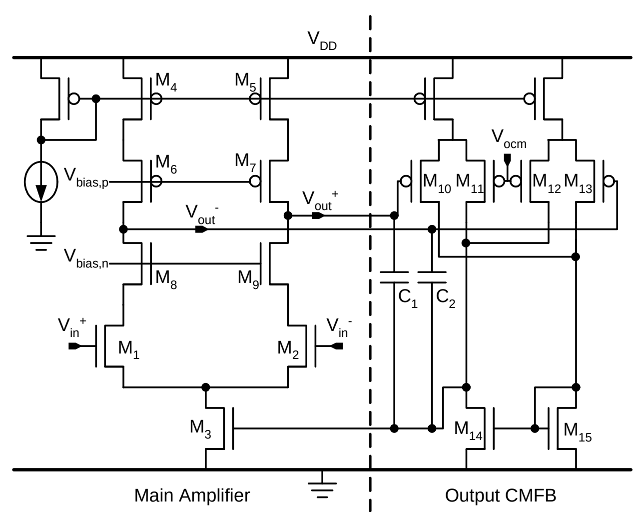

Figure 4. Charge Amplifier Circuit Schematic

designed with a transconductance of 1.3 mS to achieve an input referred noise spectral density of 4.7 $nV/\sqrt{Hz}$ to meet the performance specifications. The amplifier exhibits a DC voltage gain of 73 dB with a unity gain frequency of 50 MHz and consumes a total current of 450 μA from a 3 V supply.

Figure 5 presents the mixer schematic. A fully balanced switching mixer architecture is chosen to suppress clock feedthrough, critical for minimizing signal compression. M_{9a} and M_{10a} along with an OCMFB circuit are used to set the common-mode output voltage for achieving a large signal swing range. M_{1a} and M_{2a} are designed with a transconductance of 400 µS, thus contributing a negligible noise for the overall system, and achieves a conversion gain of 3.44 with loading resistors, R_1 and R_2, of 11 kΩ. The mixer consumes a total DC current of 200 µA from a 3 V supply.

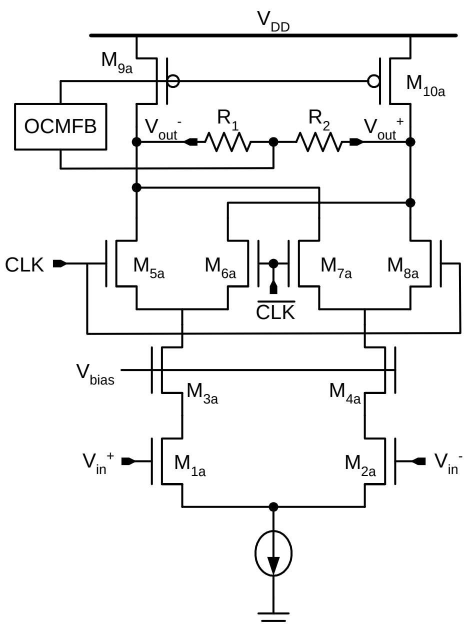

Figure 5. Mixer Circuit Schematic

A second-order low-pass filter (LPF) with a cut-off frequency of 100 KHz is designed to achieve a linear phase characteristic to ensure an un-distorted time-domain signal waveform over the required bandwidth. Figure 6 shows a simplified LPF architecture. Two poles are formed by the RC networks at the mixer and gain stage outputs. The gain stage further amplifies the signal strength for off-chip characterization. Folded cascode amplifier architecture is employed for implementing the gain stage and the output buffers for achieving a large output signal swing.

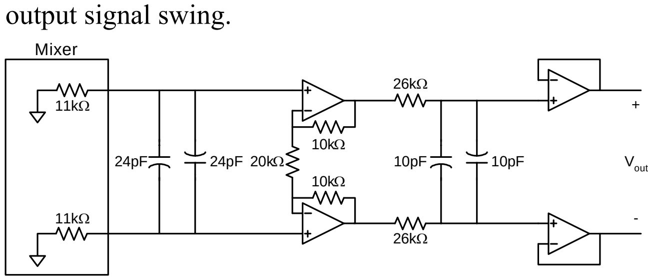

Figure 6. Low Pass Filter Architecture

The sensing electronics are fabricated using a 1.5 µm CMOS process and consume 1.5 mA DC current from a 3 V supply. Figure 7 shows the chip photo with the core electronics occupying an area of approximately 0.6 mm x 1.7 mm.

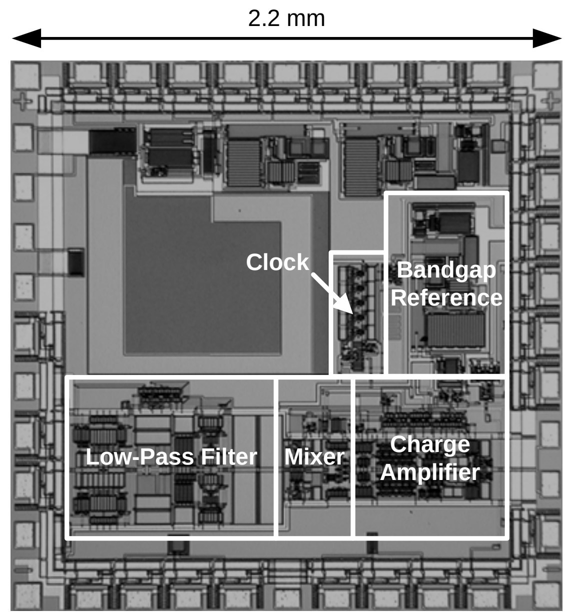

Figure 7. Sensing Electronics Die Photo

Measurement Results

The MEMS sensor chip is wire bonded to the sensing electronics to form the prototype system as shown in Figure 8. The sensor chip is then subjected to a three-point strain testing process for system characterization.

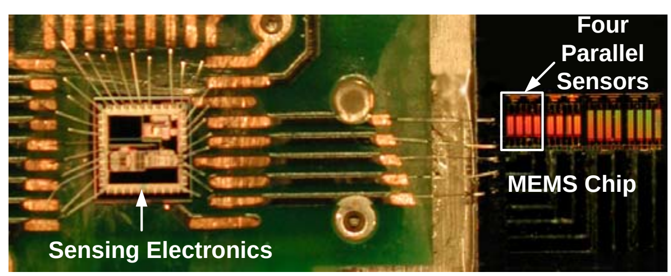

Figure 8. Prototype System Testing Board

Figure 9 shows the measured output voltage versus an applied input strain, indicating that the prototype system can achieve a maximum input signal of 1000 µε, corresponding to an output voltage of 420 mV, with a linearity of 1.5% of full scale. Figure 10 presents the measured output noise spectral density, demonstrating that the microsystem achieves a low noise level of 375 $nV/\sqrt{Hz}$, which is equivalent to a minimum detectable signal of 37.5 µV over a 10 KHz bandwidth, thus an 81 dB dynamic range. Considering the mixer conversion gain and noise from the mixer and low pass filter, the predicted noise performance is within 1 dB of the measurement results. A further reduced electronic noise floor is expected with improved CMOS technologies. The low frequency tone and 1/*f* noise are contributed by the measurement equipment.

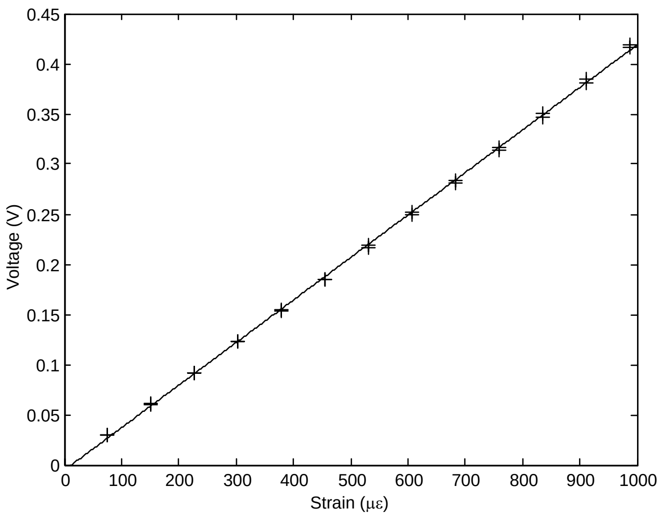

Figure 9. Output Voltage vs. Input Strain

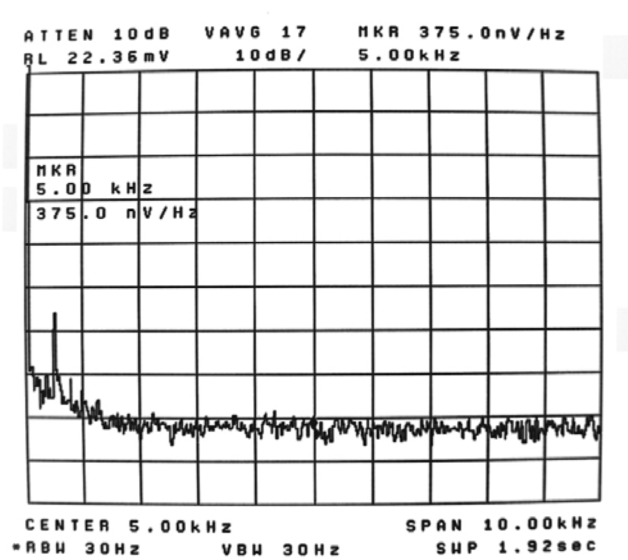

Figure 10. Output Noise Spectral Density

Conclusion

A high-performance strain sensing microsystem has been demonstrated. A MEMS capacitive strain sensor with amplifying buckled beams improves the device sensitivity. A low noise continuous time synchronous detection circuit is interfaced with the sensor to achieve an overall stringent system performance requirement. The prototype system demonstrates a strain sensing resolution of 0.09 με over a 10 kHz bandwidth with 81 dB dynamic range, corresponding to a minimum detectable displacement of 0.9 Å.

Acknowledgement

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