A CMOS MEMS CAPACITIVE DIFFERENTIAL FLOW SENSOR FOR RESPIRATORY MONITORING

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ABSTRACT

This work presents a CMOS (complementary metal oxide semiconductor) micromachined capacitive differential flow sensor for respiratory monitoring. Airflow induces a pressure change on the suspended sensing plate and causes a capacitance change with respect to the electrodes. The microstructure fabricated by post-CMOS metal etch occupies an area of 320 × 230 μm^2 and has differential sensing capacitances of 190 fF. Output waveform of consecutive breaths was successfully measured with an output noise of 140 μV for a measuring bandwidth of 0.5 Hz, which was equivalent to a minimum detectable capacitance change and airflow velocity of 6.2 aF and 4.3 mm/sec, respectively.

KEYWORDS: Complementary metal oxide semiconductor, Capacitive flow sensor.

INTRODUCTION

Respiratory monitoring is important for early detection and diagnosis of potentially dangerous conditions such as sleep apnea and sudden infant death syndrome. Current detection methods include measurements based on transthoracic impedance, blood O_2/CO_2 concentrations, airflow induced differential pressure, chest or abdominal circumference, photoplethysmography, and electrocardiography. Compared to conventional air-flow measurement methods, our goal is to develop a miniaturized flow sensor system-on-chip which can be conveniently carried by patients for long-term respiratory monitoring. MEMS flow sensors are typically implemented based on heat transfer [1] and momentum transfer [2-3] of the mass flow. Previously we have developed a single-ended capacitive flow sensor in a CMOS process based on momentum transfer [4]. This work presents a differential type which can more efficiently reject common-mode interferences. Capacitive sensitivity is enhanced due to a small gap between sensing electrodes in this study. Sensor noise is also significantly reduced by suppressing the parasitic effect through monolithic integration, leading to enhanced sensor resolution.

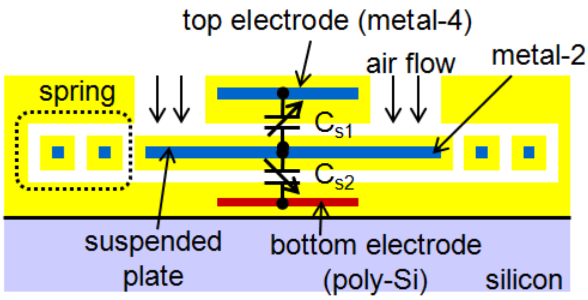

Figure 1: Cross-sectional view of the capacitive differential flow sensor.

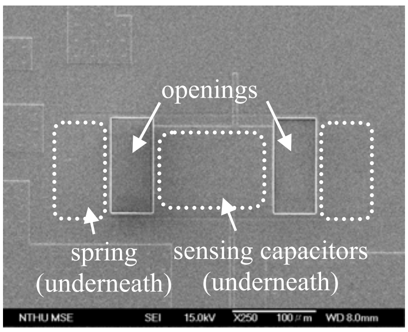

Figure 2: SEM of the capacitive differential flow sensor.

METHOD

The capacitive differential flow sensor was fabricated by taking advantage of the multiple metallization layers in a two-polysilicon-four-metal 0.35-μm CMOS process. After completion of the CMOS process, a sacrificial wet etch was performed to remove the stacked metal/via layers for structural release [4]. The dielectric layers in CMOS were used for etch protection. As shown by the cross-sectional view in Fig. 1, the movable structure contains the metal-2 layer. The differential sensing capacitors are formed by the metal-4/metal-2 and metal-2/polysilicon layers as represented by C_{s1}

and C_{s2}, respectively. Scanning electron micrograph of the fabricated device is illustrated in Fig. 2. Pressure induced by momentum change of air flow vertical to the chip is detected by a suspended microstructure which contains the metal-2 layer sandwiched between intermetal dielectric thin films. This symmetrical composition (thickness ~ 2.64 μm) is intended to minimize the overall structural curl caused by individual thin-film strain gradient. The suspended microstructure has an electrode of 150 × 100 μm^2 and four meandering springs. The total area of the sensor is 320 × 230 μm^2. Airflow produces a pressure on sensor surface due a momentum change ($P = \rho v^2$; ρ is mass density of air and v is the airflow velocity). The pressure is estimated to be 1.2 Pa for a normal breathing flow velocity of 1 m/sec. The simulated natural frequency and spring constant of the microstructure in Fig. 3 are 17.9 kHz and 2.03 N/m, respectively. The sensing capacitance and sensitivity are simulated to be 190 fF and 1.2 fF/Pa, respectively. The capacitive readout shown in Fig. 4 uses the chopper technique to modulate the slow-varying breathing signal to 500 kHz and then performs demodulation and low-pass filtering to obtain the baseband signal. The parasitic capacitance at the sensing node is minimized by placing the readout near the microstructure. The overall sensitivity is calculated to be 27 mV/Pa or 32 mV/(m/sec).

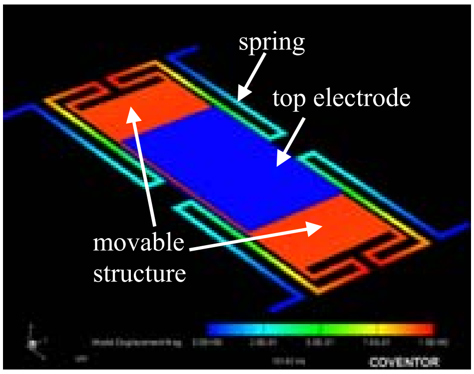

Figure 3: Finite-element simulation of the microstructure for flow sensing.

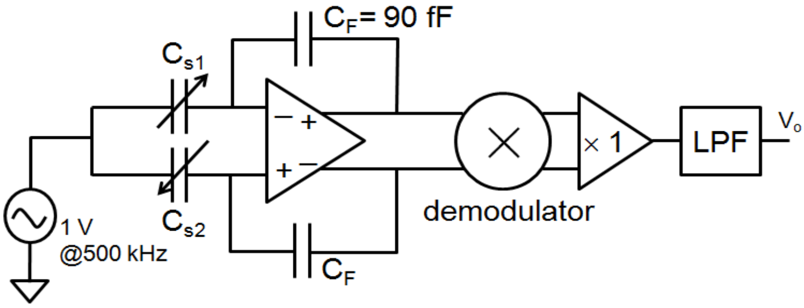

Figure 4: Sensing circuit of the differential capacitive flow sensor.

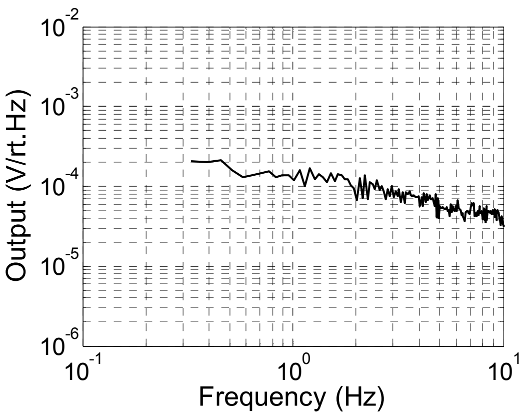

Figure 5: Measured output noise of the capacitive readout.

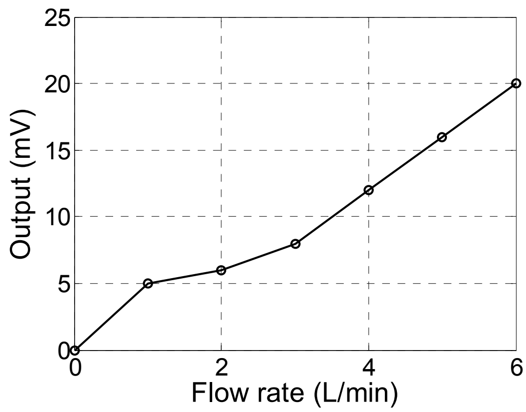

Figure 6: Measured output change with respect to flow rate.

EXPERIMENTAL

The bandwidth of the sensing pre-amp was measured to be 1 MHz, which is larger than the modulation frequency of 500 kHz. The readout noise as shown in Fig. 5 was measured by a dynamic signal analyzer (Agilent 35670A). The measured readout noise below 1 Hz was about 2×10^{-4} V/Hz$^{1/2}$ as shown in Fig. 5, producing an equivalent noise voltage of about 140 μV for a respiratory rate as fast as 0.5 Hz. This value corresponds to a minimum detectable capacitance change and airflow velocity of 6.2 aF and 4.3 mm/sec, respectively, based on the calculated sensitivities. The readout output with respect to the flow rate was measured with a sensitivity of 3.33 mV/(L/min) as shown in Fig. 6. Fig. 7 shows the measured waveform of a subject's nasal respiration when the sensor was placed about 10 cm beneath the subject's nose.

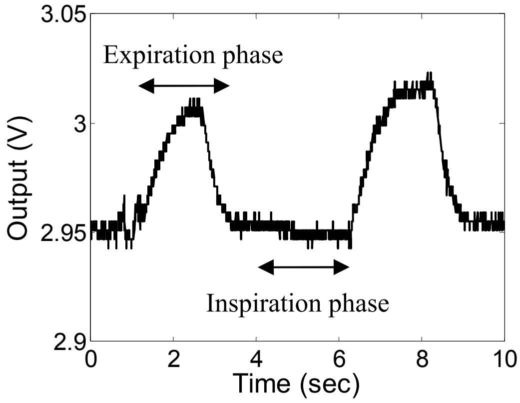

Figure 7: Measured output waveform of consecutive breaths.

CONCLUSION

A convenient post-CMOS micromachining process is used to fabricate a novel capacitive flow sensor with differential sensing capability. Highly sensitive detection is demonstrated through monolithic sensor integration to suppress the parasitic effect. It is very promising to use the CMOS MEMS approach to implement a miniaturized sensor system-on-chip for long-term respiratory monitoring.

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