Design and characterization of an air-coupled capacitive ultrasonic sensor fabricated in a CMOS process

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Abstract
This work presents a CMOS micromachined capacitive sensor for detection of acoustic pressure transmitted through the air. The microstructure has a suspended plate of 65 µm in diameter that produces a sensing capacitance of 35 fF and a resonant frequency of 1.2 MHz. The post-CMOS fabrication can effectively reduce the parasitic capacitance to enhance the signal-to-noise ratio. The measured input-referred circuit noise is 0.35 µV Hz^1/2 at 40 kHz. The measured sensor output is 3.5 µV under a dc bias of 10 V, equivalent to a capacitance change of 1.7 × 10^{-2} aF. The corresponding electrode displacement and acoustic pressure are 4.1 × 10^{-2} Å and 1.3 Pa, respectively.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Ultrasound is used in a wide variety of applications, most notably in medical imaging [1, 2] and nondestructive evaluation [3]. The research on capacitive micromachined ultrasonic transducers (cMUT) [4] has been increasingly popular over the past ten years, as they are capable of providing lower mechanical impedances and a better impedance matching to the fluid medium than those of the conventional bulk piezoelectric transducers. The electromagnetic coupling behaviors of cMUT in air [5–8] and fluid [9, 10] have both been studied in the prior published work. Capacitive-type thin-film transducers have been batch fabricated with a uniform quality at low cost by the similar processes used for making integrated circuits.

From the signal-processing standpoint, it is desirable to achieve monolithic integration of the signal-conditioning circuits such that the tasks for signal routing and multiplexing of a sensor array can be conveniently achieved on a single chip. Prior examples include transducers combining electrothermal actuation and piezoresistive sensing [11–13], and electrostatic actuation and capacitive sensing [14]. Rufer [11] reported thermally-actuated dielectric membranes fabricated by a backside silicon etch in a 0.8 µm CMOS process. And by using an intermediate CMOS micromachining process, polysilicon membranes [14] were fabricated by using silicon dioxide as the sacrificial material for structural release. The integration of capacitive sensing electronics is important for promoting the measured signal-to-noise ratio; otherwise it can be negatively impacted by the large parasitic capacitance in a two-chip solution, with the sensing capacitance commonly in the order of tenths to hundreds of fF. The advantage of integration is well evidenced by the success of many highly sensitive capacitive inertia sensors [15, 16].

This paper would focus on exploring the sensing capabilities of an air-coupled capacitive ultrasonic sensor fabricated in a conventional CMOS process [17]. Prior work has generally concerned the 1D or 2D sensor arrays with external sensing circuits, in which the signal-to-noise ratio is promoted by connecting multiple sensing elements in parallel.
to form a large sensing capacitance. The study on a single sensing element provides the knowledge for making a sensor array in the future. Different from the intermediate CMOS micромachining process adopted in [14], our devices are fabricated after the completion of the CMOS process such that the foundry does not need to alter the existing fabrication procedure.

2. Device fabrication

The TSMC 0.35 μm two-polysilicon four-metal (2P4M) CMOS process is used for sensor fabrication. The process flow in figure 1 shows the development of a released microstructure in cross-section. After completion of the CMOS foundry process, most of the die area, including the bond pads, is covered by the top passivation layer except for the openings beside the structure for release etch. As shown in figure 1(b), we perform a sacrificial wet etch of stacked metal (aluminum) and via (tungsten) layers through the openings by using a mixed H2SO4/H2O2 (2:1) etchant, with the dielectric layers for etch protection. The top movable electrode for capacitive sensing is formed after the sacrificial metal-3 layer is removed. To avoid stiction due to liquid remaining between the movable and fixed electrodes, the die is immersed in isopropyl alcohol (IPA) followed by a hotplate bake. Then a reactive ion etch using the CHF3/O2 plasma is performed to remove the passivation remaining on top of the structure and bond pads (figure 1(c)).

According to the processing steps, the shape of the suspended microstructure is defined by the passivation openings. The use of large-size vias for the sacrificial metal etch is against foundry design rules but acceptable for fabrication. The etching rates of tungsten via and aluminum layer are about 0.04 μm/min and 1.5 μm/min, respectively.

3. Sensor design

The released microstructure as shown in figure 2 has four support beams connected to the anchors. The circular plate is 65 μm in diameter and the support beams are 20 μm in both width and length. The suspended structure consists of one metal and one dielectric layer to produce a total thickness of about 1.9 μm.

The out-of-plane spring constant of the suspended structure is an important parameter for calculating the measured sensitivity in terms of the applied acoustic pressure. The spring constant calculated by finite-element simulation [18] as shown in figure 3 is 1070 N m⁻¹. Young’s moduli of aluminum and silicon dioxide used in the simulation are...
where \( m \) is the mass, \( b \) is the damping coefficient, \( k \) is the spring constant, \( F_c \) is the electrostatic force between the electrodes and \( P(t) \) is the acoustic pressure. The equation becomes a classical parallel-plate actuator that achieves a maximum displacement,

\[
x_p = \frac{g_0}{3} + \frac{\varepsilon_0}{3\varepsilon_d} h.
\]

when the acoustic pressure is not considered. The expression reduces to one third of the air gap at pull-in when the dielectric thickness is zero. The pull-in voltage at \( x_p \) can also be derived as given by

\[
V_{pi} = \sqrt{\frac{8k g_0^2}{27\varepsilon_o A}}.
\]

Similarly with no dielectric layer, the expression reduces to

\[
V_{pi} = \sqrt{\frac{8\varepsilon_o A^2}{27\varepsilon_o A}}.
\]

The negative spring constant induced by the electrical field gradient at any displacement \( x_o \) within the pull-in position is given by

\[
k_e = -\frac{2}{(1 - x_o/g_0) + h\varepsilon_0/\varepsilon_d} k.
\]

By substituting parameters into equations (3) and (4), the calculated pull-in displacement and pull-in voltage are 0.38 \( \mu \)m and 128.6 V, respectively.

By applying a voltage \( V(t) = V_{DC} + V_{ac} \sin(\omega t) \) between the electrodes, the electrical admittance at each frequency is calculated by using the ratio of the current in the capacitor and the applied voltage. We assume the static displacement is small such that

\[
x = \frac{\varepsilon_o A V_{DC}^2}{2k (h\varepsilon_0/\varepsilon_d + g_0)^2}.
\]

Thus the capacitance becomes

\[
C = \frac{\varepsilon_o A}{h\varepsilon_0/\varepsilon_d + g_0} + \frac{\varepsilon_o A}{h\varepsilon_0/\varepsilon_d + g_0} \frac{x}{h\varepsilon_0/\varepsilon_d + g_0} = C_0 + C_0 \frac{x}{h\varepsilon_0/\varepsilon_d + g_0}.
\]

The dynamic displacement associated with the force at the frequency \( \omega \) is given by

\[
x(t) = \frac{\varepsilon_o A}{(h\varepsilon_0/\varepsilon_d + g_0)^2} \left| \frac{V_{DC} V_{ac}}{|k - m\omega^2 + j\omega|} \right| \sin(\omega t)
\]

where the transformer ratio is

\[
n = \frac{\varepsilon_o A V_{DC}}{(h\varepsilon_0/\varepsilon_d + g_0)^2}.
\]

70 GPa and 75 GPa, respectively. The top and bottom sensing electrodes are the metal-4 and metal-2 layers, respectively, in the 2P4M CMOS process, which are covered by the inter-metal dielectric layers and separated by an air gap of 0.64 \( \mu \)m. The capacitance is expressed as

\[
C = \frac{\varepsilon_0 A}{h\varepsilon_2 + (g_0 - x)}
\]

where \( \varepsilon_0 \) is the permittivity of air, \( \varepsilon_d \) is the permittivity of silicon dioxide, \( A \) is the electrode area, \( h \) is the total dielectric thickness, \( x \) is the upper electrode displacement and \( g_0 \) is the initial air gap. The initial capacitance value is 35 fF by simulation [18].

The equivalent circuit of a cMUT is represented by a two-port network as shown in figure 4, where the electrical domain (voltage and current) is represented at one port and the mechanical domain (force and velocity) at the other. The mechanical impedance \( Z_m \) is defined as the ratio of the acoustic pressure over the membrane velocity. For a circular membrane, \( Z_m \) can be expressed analytically in terms of the Bessel functions [4]. For our case, the impedance is obtained by finite-element simulations [18] in which the pressure as a function of frequency is applied to the suspended plate and the displacement is calculated accordingly with the operating condition close to vacuum. Figure 5 shows that the impedance drops to the minimum value at the mechanical resonant frequency of 1.2 MHz.

The lumped-parameter model of single degree of freedom is used to describe the motion of the suspended plate under acoustic pressure. The equation of motion for the displacement \( x(t) \) is

\[
m \frac{d^2 x}{dt^2} + h \frac{dx}{dt} + k x = F_c + P(t) A
\]
as shown in figure 4. The current into the capacitor terminals is

\[ i(t) = C \frac{dV}{dt} + V \frac{dC}{dt} \approx C_0 V_{ac} \omega \cos(\omega t) + n \frac{dx}{dt}. \] (11)

Thus the electrical admittance at each frequency can be obtained as the ratio of the current into the capacitor and the applied voltage.

The quality factor of the suspended plate is associated with the squeeze-film damping and the radiation loss as given by

\[ Q = \frac{1}{Q_{spool}} \left( \frac{1}{Q_{vibr}} \right). \] (12)

A detailed analysis on the quality factor can be found in [5]. The polysilicon diaphragm of the work has a measured \( Q \) of 50 that is predominantly determined by squeeze-film damping for the operation at atmospheric pressure. The associated equivalent damping coefficient is about \( 4 \times 10^{-6} \text{ N s m}^{-1} \). Here we use this value to approximately estimate the equivalent noise displacement produced by the Brownian motion. The root spectral density of the thermomechanical noise \( F_b \) is given by

\[ F_b = \frac{\sqrt{4k_B T b}}{\sqrt{2}} \] (13)

where \( k_B \) is Boltzmann’s constant, \( T \) is the temperature in Kelvin and the unit of \( F_b \) is \( \text{Hz}^{1/2} \). The value of \( F_b \) is 2.6 \( \times \) \( 10^{-13} \text{ N Hz}^{1/2} \) at room temperature, producing an equivalent noise displacement of \( 2.4 \times 10^{-10} \text{ m Hz}^{1/2} \) for the structure with a spring constant of 1070 \( \text{N m}^{-1} \).

The sensing circuit as shown schematically in figure 6 contains two p−channel source followers that provide a voltage gain close to one. The circuit area is 130 \( \mu \text{m} \times 40 \mu \text{m} \) and can be placed directly beneath the sensor. The use of PMOS input transistors helps to reduce the flicker noise at low frequencies. The first source follower uses a small-size input transistor to provide a small input capacitance with the value comparable to that of the sensing capacitance. Despite large transistors are commonly used in a conventional low-noise circuit design for reducing the transistor thermal noise and flicker noise; in this case, they also reduce the sensed signal owing to the increased gate capacitance [16]. To our advantage, the interconnect capacitance can greatly be reduced as the sensing circuit can be placed beneath the sensor. Our process also features a smaller parasitic capacitance from the bottom electrode to the substrate than that of the CMOS polysilicon micromachined process [14]. The latter uses a doped well structure as the bottom electrode, which has a large depletion capacitance with respect to the substrate.

The dc path at the circuit input is provided by the transistor M5 operated in the subthreshold region. The second source follower with a larger input transistor is used for driving the output pad. For signal detection at the acoustic frequency \( \omega_{ac} \), a dc voltage is applied at the top electrode of the sensing capacitor to produce the displacement current, \( i_s = V_{DC} \frac{dC}{dt} \). The sensing capacitance based on a small sinusoidal change is

\[ C(t) = C_0 + C_0 \frac{x}{(h x_0/\varepsilon_d + g_0)} \sin(\omega_{ac} t). \] (14)

The displacement current, after flowing into the input capacitance \( C_{in} \), produces a sensed voltage given by

\[ v_s = \frac{x}{(h x_0/\varepsilon_d + g_0)} \frac{C_0}{C_{in}} V_{DC}. \] (15)

For example, the sensed voltage is 87 \( \mu \text{V} \) when \( x \) is 0.01 nm, \( V_{DC} \) is 10 V and \( C_0 \) is equal to \( C_{in} \). Note that the dielectric layers covered on electrodes provide a much higher breakdown electrical field (\( \sim 1000 \text{ V} \mu\text{m}^{-1} \)) than that of the electrodes with a pure air gap (\( \sim 3 \text{ V} \mu\text{m}^{-1} \)). This implies a breakdown does not happen for an applied \( V_{DC} \) value below the pull-in voltage; otherwise the produced current would charge the input capacitor and eventually saturate the circuit output. For the air-gap electrodes made of pure conductors, a transimpedance amplifier can be used to avoid integration of the breakdown current over a long time.

4. Experiment

The static displacement of the suspended plate as shown in figure 7 was measured by an optical profiler as the voltage between the electrodes gradually increased. The figure shows that the measured displacement falls approximately between the curves predicted by the finite-element analysis [18] and the lumped-parameter model.
The frequency response of the sensing circuit was measured by an Agilent 4395A network analyzer, which supplied sinusoidal voltages of gradually increased frequencies to the one end of the sensing capacitor and measured the circuit output simultaneously to establish the transfer function. Figure 8 shows a measured gain of $-7.5$ dB, which indicates a measured $C_{in}$ of 48 fF based on a simulated sensing capacitance of 35 fF. The equivalent resistance of the subthreshold transistor was adjusted by the gate-to-source voltage, and the value can be more $G_{source}$ as shown by the lower corner frequency of the frequency response.

For electromechanical characterization, the pressure produced by a 40 kHz acoustic emitter was air coupled to the sensor chip separated by a distance of 1 cm. By applying 10 V to the top sensing electrode, the output spectrum was measured at a resolution bandwidth of 1 Hz as shown in figure 9. The peak value at 40 kHz is 3.5 $\mu$V and the noise floor is about 0.35 $\mu$V Hz$^{1/2}$. Figure 10 shows the sensor output by gradually increasing the dc voltage on the electrode to 100 V. The measured linearity could be affected by the trapped charges in the dielectric thin films on the electrodes. The sensed voltage increases accordingly due to the increased displacement current. HSpice simulation was used for the calculation of the corresponding capacitance changes. The measured value of 3.5 $\mu$V at 10 V was equivalent to a capacitance change of $1.7 \times 10^{-2}$ aF and a plate displacement of $4.1 \times 10^{-2}$ Å. The corresponding force and pressure acting on the suspended plate are 4.3 nN and 1.3 Pa, respectively, based on the spring constant of 1070 N m$^{-1}$.

By increasing the gate-to-source voltage of the subthreshold transistor to reduce its equivalent resistance, the total impedance at the circuit input decreased accordingly and caused a reduction of the sensor output. Figure 11 shows the output decreases from 9.8 $\mu$V to 0.9 $\mu$V for $V_{GS}$ values from 0.1 V to 0.7 V, respectively.

5. Discussion and conclusion

In this paper, we propose a convenient post-CMOS micromachining process for making capacitive ultrasonic sensors at the die level. The suspended microstructure with a high stiffness in the out-of-plane direction can be successfully released without stiction during the wet etch. The capacitive sensitivity is enhanced with the electrodes separated by a sub-$\mu$m air gap defined by the sacrificial metal layer; in addition, monolithic integration of the sensing circuit effectively reduces the parasitic effect which would otherwise negatively impact the minimum detectable signal. Capacitance change of much less than 1 aF has been successfully detected.

The static measurement in figure 7 indicates that the spring-constant simulation is acceptable although the residual stresses of thin films are not considered. The dielectric layers on electrodes prevent electrical breakdown when a high dc
voltage is applied for capacitive sensing. However, the sensed signal and the sensitivity could be affected by the trapped charges in the dielectric layers. The modulation technique using an ac bias can be applied to resolve this issue. The sensor measurement was conducted at the acoustic frequency of 40 kHz because commercial air-coupled emitters do not operate in the MHz range. Therefore the sensed signal is not enhanced by the quality factor of the device as being operated at the resonant mode.

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