A HIGH SENSITIVITY POLYSILICON DIAPHRAGM CONDENSER MICROPHONE

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ABSTRACT

This paper presents the analysis, design, fabrication, and testing of a condenser microphone utilizing a thin low-stress polycrystalline silicon diaphragm suspended above a p+ perforated back plate. The microphone is fabricated using a combination of surface and bulk micromachining techniques in a single wafer process without the need of wafer bonding. The device shows sensitivities of -34 dB (ref. to 1 V/Pa) for 2 mm diaphragms with bias of 13 V and -37 dB for 2.6 mm-wide diaphragms at 10 V in good agreement with expected performance calculations.

INTRODUCTION

Many types of small-sized microphones can be constructed using silicon micromachining techniques at low cost; therefore these devices are promising for consumer electronics. Three types of silicon microphones have been developed: piezoelectric, piezoresistive, and capacitive-type [1]. Capacitive microphones show the highest sensitivity while maintaining a low power consumption. Diaphragms can be made of metal [2], p+ doped silicon [3,4], silicon nitride [5], polyimide and metal [6], and TFE [7]. The most successful devices use silicon as the diaphragm material because of its low intrinsic stress. This stress is very important because it determines the diaphragm sensitivity and its resistance to warpage. These silicon devices use a bulk micromachined p+ diaphragm with a bonded or electroplated stationary electrode.

In this paper we use low-stress polysilicon as the diaphragm electrode and a p+ etch-stop silicon plate as the back plate electrode as shown in Fig. 1. The device consists of an n-type silicon substrate, a phosphorus doped polysilicon diaphragm, a p+ perforated back plate, and the metal contacts. This arrangement permits the use of thinner diaphragms with reasonably low stress and does not require any bonding techniques.

In the sections below an electrical analog circuit is constructed to determine the microphone sensitivity. Optimal diaphragm edge width, thickness, and air gap are next determined for maximum sensitivity subject to pull-in voltage and processing constraints. Figure 2 shows a top view of a polysilicon diaphragm microphone with 2 mm diaphragm.

SENSITIVITY ANALYSIS

The performance of the microphone depends on the size and stress of the diaphragm. Other parameters, such as air gap distance and the bias voltage, also affect the sensitivity. The response of the capacitive microphone can be calculated using the equivalent analog electrical network of Fig. 3. The acoustic force $F_{\text{sound}}$ and flow velocity $u_m$ are modeled as equivalent voltage and current sources, respectively. The radiative resistance is $R_e$ and air mass $M_f$. The diaphragm mechanical mass is $M_m$ and its compliance $C_m$. The air gap and back vent losses are represented by viscous resistances $R_g$ and $R_{bt}$, and the air gap compliance
where \( D \), \( T \), and \( \rho \) are the flexural rigidity, tensile force per unit length, and mass per unit area of the diaphragm, respectively. For the first fundamental mode, we can assume the deflection of the square diaphragm is

\[
W(x, y, \tau) \approx A \sin \frac{\pi x}{a} \sin \frac{\pi y}{a} e^{-j2\pi f \tau}
\]

where \( a \) is the diaphragm width. Substitution of Eq. (2) in Eq. (1) yields the first resonant frequency for the diaphragm

\[
f_{\text{res}} = \sqrt{\frac{1}{\rho} \left( \frac{D \pi^2}{a^4} + \frac{T}{2a^2} \right)}
\]

The acoustic impedance of the air in contact with the vibrating diaphragm is represented by a radiative resistance and mass. For a square diaphragm, these are approximated by [5]

\[
R_e = \frac{\rho_o a^4 \omega^2}{2\pi c}, \quad M_r = \frac{8\rho_o a^3}{3\pi \sqrt{\pi} a^2}
\]

where \( \rho_o \) is the air density, \( c \) is the sound velocity, and \( \omega \) is the angular vibration frequency (2\( \pi f \)).

The diaphragm compliance is equal to the average diaphragm deflection divided by the applied force. From the energy method, it is approximately

\[
C_m = \frac{32\pi^2}{\pi^2(2\pi^2 D + \alpha^2 T)}
\]

The equivalent mass element \( M_m \) is derived from the kinetic energy of the square diaphragm under the uniform loading. It can be written as

\[
M_m = \frac{\pi^4 (2\pi^2 D + \alpha^2 T)}{64T}
\]

The viscosity loss in the air gap \( R_g \) and its compliance are [5, 8]

\[
R_g = \frac{12\mu a^2}{\pi \rho \eta a^2} \left( \frac{\alpha^2}{2} - \frac{\ln \alpha}{4} - \frac{3}{8} \right)
\]

The pull-in voltage for a clamped rectangular elastic plate under tension is approximately [9]

\[
V_P \approx \frac{64}{7} \sqrt{\frac{E t^3 \delta^5}{3(1 - \nu^2) \varepsilon_0 a^2}} \left( 1 + \frac{2}{9} (1 - \nu^2) \frac{\sigma_R a^2}{E t^2} \right)
\]

where \( E \) is the Young’s modulus of the polysilicon diaphragm (\( \approx 1.3 \times 10^{11} \text{ Pa} \)), and \( \nu \) is Poisson’s ratio (\( \approx 0.18 \)). From Eq. (13), the pull-in voltage is also dominated by \( T \) as \( t \rightarrow 0 \). If \( t < 0.01a \), \( V_P \) reduces to

\[
V_P \approx \frac{64}{7} \sqrt{\frac{2}{45}} \sqrt{\frac{T d^5}{\varepsilon_0 a^2}}
\]

where \( \eta \) is the hole density in the backplate, \( \alpha \) is the surface fraction occupied by the holes, \( \eta \) is the air viscosity coefficient, \( d \) is the average air gap distance, and \( \rho_o \) is the air density. Finally, the viscosity loss of back plate holes is approximated as [8]

\[
R_h \approx \frac{8 \mu h a^2}{\pi \eta a^4}
\]

where \( h \) is the back plate height and \( r \) is the radius of hole.

Then, the sensitivity of the microphone is the output voltage under the presence of the acoustical pressure loading, or

\[
S = \frac{V_0}{P} = \frac{V_o a^2}{3 jwZ_t}
\]

where \( P \) is the sound pressure, \( V_h \) is the bias voltage between two electrodes, and \( Z_t \) is the total equivalent impedance of the circuit.

\[
Z_t = R_e + jw(M_r + M_m) + \frac{1}{jwC_m}
\]

\[
+ \frac{R_g + R_h}{1 + jw(R_g + R_h)C_a}
\]

The sensitivity of the microphone is hence a function of the frequency. A goal in our design is the maximization of sensitivity subject to fabrication and bias voltage constraints.

**OPTIMIZATION**

Six design variables are considered: diaphragm edge width, diaphragm thickness, air gap distance, back plate thickness, hole edge width, and the surface fraction occupied by the holes. At low frequencies, the sensitivity of the microphone is approximated as

\[
S_0 \approx \frac{32V_o a^2}{\pi^3 T d}
\]

since the tension in the diaphragm dominates its compliance as the diaphragm thickness \( t \rightarrow 0 \). For the poly-Si diaphragm \( T = \sigma_R t \) is the tensile force, and \( \sigma_R \approx 20 \text{ MPa} \). The pull-in voltage for a clamped rectangular elastic plate under tension is approximately

\[
V_P \approx \frac{64}{7} \sqrt{\frac{E t^3 \delta^5}{3(1 - \nu^2) \varepsilon_0 a^2}} \left( 1 + \frac{2}{9} (1 - \nu^2) \frac{\sigma_R a^2}{E t^2} \right)
\]
Therefore the sensitivity is related to the pull-in voltage by

\[ S_0 \approx \frac{\kappa}{\varepsilon_0} \left( \frac{V_p}{V_F} \right) d^2 \]  

where \( \kappa \) is a constant. For maximum sensitivity we must select the maximum gap distance \( d_{\text{max}} \). The device capacitance must also be maximized

\[ C_{\text{mic}} = \frac{\varepsilon_0 a^2}{d_{\text{max}}} \]  

Therefore the maximum width \( a_{\text{max}} \) is selected. With now \( a \) and \( d \) known, the diaphragm thickness \( t \) is determined from Eq. (14)

\[ t \geq \frac{2205 V_F^2 \varepsilon_0 a_{\text{max}}^2}{8192 \sigma_R d_{\text{max}}^3} \]  

Using \( d_{\text{max}} = 4 \mu m \), \( a_{\text{max}} = 3 \mu m \), and \( V_F = 12 \) V, then \( t \geq 2.4 \mu m \). In our design we adopted the maximum thickness of 3 \( \mu m \) which satisfies all the constraints.

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**Figure 4:** Calculated sensitivity frequency response for a 2.6 mm microphone

![Sensitivity Frequency Response](image)

Using these values for \( t \) and \( d \), the calculated frequency response for a 2.6 mm microphone at different biases is shown in Fig. 4. The sensitivity decays in the high frequency range due to the viscous loss in the air gap and back vent holes. The calculated resonant frequency of this device is about 25 KHz.

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### FABRICATION

The simplified 10-mask fabrication process of the microphone is shown in Fig. 5. On (100) \( n \)-type silicon wafers, a 1 \( \mu m \) thick wet oxide is first grown at 1100 \( ^\circ \)C for three hours. This oxide layer is then patterned and etched in the buffered HF (5:1 BHF) for 12 minutes serving as a mask for the deep boron diffusion. A deep \( p^+ \) boron diffusion is next introduced into the silicon from a solid source at 1175 \( ^\circ \)C for 15 hours, followed by a 20-minute wet oxidation at 1000 \( ^\circ \)C. The thick boron diffusion forms the stationary back electrode and the measured thickness is about 13 \( \mu m \). The oxide was then stripped in a 1:1 HF:H_2O solution for 4 minutes.

A 2 \( \mu m \)-thick layer of LPCVD low-temperature oxide (LTO) is deposited at 420 \( ^\circ \)C for 4 hours and patterned in 5:1 BHF for 23 minutes. This oxide provides isolation for the two electrodes. A 0.3 \( \mu m \)-thick layer of low-stress LPCVD SiN is deposited at 875 \( ^\circ \)C. This layer is patterned and etched in hot phosphoric acid for 3 hrs. using a 0.5 \( \mu m \) layer of LTO as a mask. This nitride layer protects the passivation oxide from a subsequent the sacrificial etch. A 4 \( \mu m \)-thick LTO sacrificial layer is next deposited defining the air-gap electrode spacing. This oxide is patterned and etched 5:1 BHF for about 20 minutes.

Next, a 2 \( \mu m \)-thick layer of LPCVD low-stress polysilicon is deposited at 588 \( ^\circ \)C. This material showed an unannealed tensile residual stress of about 100 MPa. The deposition is followed by a phosphorus ion implantation of 7x10^{15} \text{ cm}^{-2} at 50 \text{ KeV}. The remaining 1 \( \mu m \)-thick layer of polysilicon is next deposited. The polysilicon is next annealed at 1050 \( ^\circ \)C for 1 hour to redistribute the diaphragm dopants and remove as much residual stress as possible. The poly layer is next patterned and etched first using RIE with 20:5 SF_6:O_2 sccm, at 40 mT, and 60 W for 15 minutes, followed by a wet etch in 950:500:50 HNO_3:H_2O:NH_4F for 25 minutes.

A 0.6\( \mu m \)-thick LTO mask is deposited and patterned in BHF for 7 min. to define the contact area of the back plate. The nitride over the contact area is then etched in hot phosphoric acid for 3 hours. A second 0.5\( \mu m \)-thick LTO layer is deposited followed by a 0.2 \( \mu m \) Al evaporation. The LTO protects the front side of the wafer during the backside etch and the metal is used to pattern the back-to-front alignment key. The backside oxide is patterned and etched in...
5:1 BHF for about 8 minutes. The wafer is then anisotropically etched in EDP for 8 hours at 110 °C. After striping the protective LTO in 5:1 BHF for 20 min., the wafers are dried. Cr and Au are next evaporated forming the contact pads with thickness of 50 and 400 nm. The metal is next patterned and wet Au and Cr etchants for 4 and 1 min., respectively.

Finally, the device is released in concentrated HF for 1 hour. In this operation, the HF removes the sacrificial LTO from the backside while the wafer front is protected by the SiN layer. After rinsing the samples thoroughly, the chips are diced and wire bonded to a DIL metal package.

Figures 6-9 shows SEM pictures of the fabricated microphone. Figure 6 shows the top view of a 2.6×2.6 mm² device. Contacts for both polysilicon diaphragm and back plate are at opposing sides of the device. Figure 7 shows a close up view of the polysilicon diaphragm edge. The p+ back plate is made slightly larger that the diaphragm to account for misalignments and uncertainties on the wafer thickness during the back side etch. The shallow squares of the back-plate holes are visible at the front of the diaphragm due to the oxide step created during the deep boron diffusion. Figure 8 shows microphone backside. The back plane shows the periodic 60×60 μm² hole array that provide a back vent for the polysilicon diaphragm. Figure 9 shows a close up of the back plate holes after the sacrificial oxide etch. The 4 μm air gap is clearly visible. The curvature of the holes is a result of the deep boron diffusion. The p+ back plate is 13 μm-thick.

MEASUREMENTS

The capacitance of the microphone was measured as a function of the applied bias using an HP 4284A precision LCR meter. Figure 10 shows the measured capacitance versus bias voltage of the microphone with a 2.6 mm diaphragm. At zero bias the microphone exhibits a 16.2 pF capacitance in close agreement to the calculated result. The capacitance increases as the bias voltage increases. The pull-in voltage is about 10 V.

In order to test the sensitivity of the microphone, the device was placed in the sound isolation box shown Fig. 11. The interior of the box is covered with SONEX prospec polyurethane composite foam providing a barrier to external noise and internal sound absorption. The microphone is driven with a speaker connected to a HP33120A waveform generator. The condenser or reference microphone is connected to a preamplifier which converts the capacitor variation to the voltage output. A calibrated ACOJ7012 free-field microphone is used as the reference microphone. Both microphones are connected to an HP ACOP4012 preamplifier with an input impedance of 2.5 GΩ. The preamplifier is connected an HP ACOP9200 microphone power supply which provides an internal DC polarization voltage of 200 V for the reference microphone. For the device condenser microphone, the bias voltage is adjusted externally. The output voltage is recorded using an HP3561A dynamical signal analyzer.
The measurement starts with the calibration of the reference microphone using a HP ACOP511E calibrator, which exhibits a standard sound level of 1 Pa at 1 KHz. The characteristics of the speaker are next determined using the reference microphone. Next the reference microphone is replaced by the condenser microphone and the bias voltage is adjusted to a desired level. The sensitivity of the microphone is obtained by subtracting the reference response from the device response plus the calibration output level.

![Capacitance vs Bias Voltage](image)

**Figure 10**: Measured capacitance versus bias voltage of a 2.6-mm wide microphone

![Block Diagram](image)

**Figure 11**: Block diagram of the microphone measurement setup

Figure 12 shows the frequency response of a 2.6 mm-wide microphone at three different bias voltages. With a bias voltage of 10 V, the microphone exhibits a sensitivity between -44 and -36 dB from DC to 10 KHz. The sensitivity decreases 5 to 8 dB when using a 5 V bias. These measurements are in close agreement with the calculated values of Fig. 4 with a residual stress of 20 MPa.

Figures 13-14 show the highest sensitivity achieved for diaphragm widths of 2 and 3 mm. With a bias voltage of 13 V, the 2 mm-wide microphone has a sensitivity between -32 and -42 dB. The 3 mm-wide microphone shows a high sensitivity between -37 and -47 dB for a bias voltage of 9 V.
SUMMARY

This paper presents the design and fabrication of condenser microphone using a low-stress polysilicon diaphragm suspended above a p+ perforated back plate. The microphone performance matches expected calculated values yielding a sensitivity of about -34 dB. The microphone dimension is optimally designed to achieve the highest sensitivity. The device is fabricated using a single wafer process without need of wafer bonding.

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References


