Microelectromechanical Systems (MEMs) Applications – Microphones

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OUTLINE

Introduction, Basics and Tutorial
A Novel Integrated Silicon Capacitive Microphone – Floating Electrode “Electret” Microphone
High-Performance Condenser Microphone with Full Integrated CMOS Amplifier and DC-DC Voltage Converter
A High Sensitivity Polysilicon Diaphragm Condenser Microphone
A MEMS Condenser Microphone for Consumer Applications
A Surface micromachined MEMS Capacitive Microphone with Back Plate Supporting pillars
Implementation of the CMOS MEMS Condenser Microphone with Corrugated Metal Diaphragm and Silicon Back Plate
Commercial Microphones
Akustica AKU1126
INTRODUCTION

Microphone Types
   Electret: output is change in voltage
   Condenser: output is change in capacitance
   Piezoresistive: change in resistance
   Other: accelerometer, optical, piezoelectric, electromagnetic, etc.

Pressures: SPL\textsubscript{DB} – Sound Pressure Level

Diaphragm Calculations: Approximate diaphragm displacement, $\Delta C$, Stress, $\Delta R$

Signal Conditioning: Circuits (Analog or Digital output)

Other: Sensitivity, Frequency Response, etc.
MICROPHONE TYPES

Electret: output is change in voltage

Condenser: output is change in capacitance

Piezoresistive: change in resistance
# PRESSURE UNITS

## Table of Pressure Conversions

- 1 atm = 14.696 lbs/in² = 760.00 mmHg
- 1 atm = 101.32 kPa = 1.013 x 10⁶ dynes/cm²
- 1 Pascal = 1.4504 x 10⁻⁴ lbs/in² = 1 N/m² = 10 dynes/cm²
- 1 mmHg = 1 Torr (at 0°C)

- 1 SPL (Sound Pressure Levels) = 0.0002 dynes/cm²
- Average speech = 70 dB\textsubscript{SPL} = 0.645 dynes/cm²
- Pain = 130 dB\textsubscript{SPL} = 645 dyne/cm²
- Whisper = 18 dB\textsubscript{SPL} = 1.62 x 10⁻³ dyne/cm²

**Example:**

\[70\text{dB}_{\text{SPL}} = 0.645 \text{ dynes/cm}² = 0.0645 \text{ N/m}² = 9.35\times10^{-6} \text{ lbs/in}²\]
**DIAPHRAGM CALCULATIONS**

<table>
<thead>
<tr>
<th>Diaphragm</th>
<th>Deflection ( Y_{\text{max}} = 0.0151 \frac{pL^4(1-Nu^2)}{Eh^3} )</th>
<th>Y_{\text{max}}</th>
<th>6.26E-05 ( \mu \text{m} )</th>
<th>Pressure other units</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P ) = Pressure</td>
<td>( P ) = 1.00E-05 ( \text{lbs/in}^2 )</td>
<td>71 ( \text{dB-SPL} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( D ) = Diameter of round diaphragm or ( L ) = Length of side of square diaphragm</td>
<td>( D ) or ( L ) = 500 ( \mu \text{m} )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( E ) = Youngs Modulus</td>
<td>( E ) = 1.90E+11 ( \text{N/m}^2 )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( Nu ) = Poissons Ratio</td>
<td>( Nu ) = 0.32</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( H ) = Diaphragm Thickness</td>
<td>( H ) = 1.7 ( \mu \text{m} )</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Diaphragm

\( 1 \text{N/m}^2 = 1 \text{Pascal} = 10 \text{dyne/cm}^2 \)

Stress \( = 0.3 \frac{P (L H)^2}{(at \text{ center of each edge})} \)

\( \text{Stress} = 1.79E+03 \text{ Pascal} \)

\( P \) = Pressure

Yield Strength \( = 1.20E+10 \text{ Pascal} \)

\( L \) = Square Diaphragm Side Length

Parallel Plate

Capacitance \( = \frac{e_0 e r A}{d} \)

\( C = 8.6841E-13 \text{ F} \)

\( e_0 = \text{Permittivity of free space} = 8.85E-14 \text{ F/cm} \)

\( e_r = \text{relative permittivity} = 1 \text{ for air} \)

\( A = 1.96E-03 \text{ cm}^2 \)

\( d = \text{distance between plates} \)

\( d = 2.0 \text{ \( \mu \text{m} \)} \)

If round plates, Diameter = 500 \( \mu \text{m} \)

If square plates, Side = 0 \( \mu \text{m} \)

Capacitance Change for \( Y_{\text{max}} \) Deflection \( = 2.72E-17 \text{ F} \)

---

500\( \mu \text{m} \) Diaphragm, 1.7\( \mu \text{m} \) thick, silicon, 2\( \mu \text{m} \) gap

Gives: \( C_0 = 0.87\text{pF} \) and change of \( C_m = 0.027\text{fF} \)
## DIAPHRAGM CALCULATIONS

### 1500um Diaphragm, 1.7 um thick, silicon, 2um gap

Gives: $C_0 = 7.8pF$ and change of $C_m = 20fF$
### DIAPHRAGM CALCULATIONS

**Diaphragm**

\[
Y_{\text{max}} = 0.0151 \frac{P}{L^4} (1 - \frac{E}{\mu}) \cdot \frac{E}{H^3}
\]

- \( Y_{\text{max}} = 3.58 \times 10^{-1} \mu m \)
- \( P = 1.00 \times 10^{-5} \text{ lbs/in}^2 \)
- \( D = 1.7 \mu m \)
- \( L = 1500 \mu m \)
- \( E = 3.00 \times 10^9 \text{ N/m}^2 \)
- \( \nu = 0.00 \)
- \( H = 1.7 \mu m \)

\[\text{Pressure other units}\]

- \( 71 \text{ dB-SPL} \)
- \( 6.89 \times 10^{-2} \text{ N/m}^2 \text{ or Pa} \)

**Stress**

\[\text{Stress} = 0.3 \frac{P}{(LH)^2} \text{ (at center of each edge)}\]

- \( \text{Stress} = 1.61 \times 10^4 \text{ Pascal} \)
- \( \text{Yield Strength} = 0.00 \times 10^0 \text{ Pascal} \)

**Parallel Plate**

\[\text{Capacitance} = \varepsilon_0 \varepsilon_r \frac{\text{Area}}{d}\]

- \( \varepsilon_0 = 8.85 \times 10^{-14} \text{ F/cm} \)
- \( \varepsilon_r = 1 \text{ for air} \)
- \( \text{Area} = 1.77 \times 10^{-2} \text{ cm}^2 \)
- \( d = 2.0 \mu m \)

- \( \text{If round plates, Diameter} = 1500 \mu m \)
- \( \text{If square plates, Side} = 0 \mu m \)

\[\text{Capacitance Change for } Y_{\text{max}} \text{ Deflection} = 1.70 \times 10^{-12} \text{ F}\]

**Diaphragm Calculations**

- 1500um Diaphragm, 1.7um thick, polyimide, 2um gap
- Gives: \( C_0 = 7.8 \text{pF} \) and change of \( C_m = 1700 \text{fF} \)
### DIAPHRAGM CALCULATIONS

#### Diaphragm

<table>
<thead>
<tr>
<th>Deflection ( Y_{\text{max}} = 0.0151 \cdot P \cdot L^4 \cdot (1-Nu^2)/E \cdot H^3 )</th>
<th>( Y_{\text{max}} = ) 1.35E-02 ( \mu \text{m} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P ) = Pressure</td>
<td>( P = ) 9.35E-06 lbs/in²</td>
</tr>
<tr>
<td>( L ) = Length of side of square diaphragm</td>
<td>( L = ) 500 ( \mu \text{m} )</td>
</tr>
<tr>
<td>( E ) = Youngs Modulus</td>
<td>( E = ) 4.00E+09 N/m²</td>
</tr>
<tr>
<td>( Nu ) = Poissons Ratio</td>
<td>( Nu = ) 0.33</td>
</tr>
<tr>
<td>( H ) = Diaphragm Thickness</td>
<td>( H = ) 1 ( \mu \text{m} )</td>
</tr>
<tr>
<td>( P = ) 6.45E-02 Pascal</td>
<td></td>
</tr>
</tbody>
</table>

#### Diaphragm

<table>
<thead>
<tr>
<th>Stress = 0.3 ( P \cdot (L/H)^2 ) (at center of each edge)</th>
<th>Stress = 4.83E+03 Pascal</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P ) = Pressure</td>
<td>Yield Strength = 1.70E+08 Pascal</td>
</tr>
<tr>
<td>( L ) = Square Diaphragm Side Length</td>
<td></td>
</tr>
<tr>
<td>( H ) = Diaphragm Thickness</td>
<td></td>
</tr>
</tbody>
</table>

#### Two Parallel Plates

<table>
<thead>
<tr>
<th>Capacitance = ( \varepsilon_o \varepsilon_r \frac{\text{Area}}{d} )</th>
<th>( C = ) 1.7368E-12 F</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \varepsilon_o ) = Permittivity of free space = 8.85E-14 F/cm</td>
<td></td>
</tr>
<tr>
<td>( \varepsilon_r ) = relative permittivity = 1 for air</td>
<td></td>
</tr>
<tr>
<td>Area = ( 1.96E-03 ) cm²</td>
<td></td>
</tr>
<tr>
<td>N = 1</td>
<td></td>
</tr>
<tr>
<td>d = distance between plates</td>
<td>d = 1 ( \mu \text{m} )</td>
</tr>
<tr>
<td>If round plates, Diameter = 500 ( \mu \text{m} )</td>
<td></td>
</tr>
<tr>
<td>If square plates, Side = 0 ( \mu \text{m} )</td>
<td></td>
</tr>
<tr>
<td>Capacitance Change for ( Y_{\text{max}} ) Deflection = 2.38E-14 F</td>
<td></td>
</tr>
</tbody>
</table>

**500um Diaphragm, 1um thick, polyimide, 1um gap**

Gives: \( C_0 = 1.7368 \text{pF} \) and change of \( C_m = 23.8 \text{fF} \)
## DIAPHRAGM CALCULATIONS

### Diaphragm

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deflection Ymax</td>
<td>5.07E-03 μm</td>
</tr>
<tr>
<td>Ymax</td>
<td>5.07E-03 μm</td>
</tr>
<tr>
<td>Pressure (P)</td>
<td>1.00E-05 lb/in²</td>
</tr>
<tr>
<td>Co (Capacitance)</td>
<td>7.8pF</td>
</tr>
<tr>
<td>Cm</td>
<td>20fF</td>
</tr>
<tr>
<td>Resonant Frequency (fo)</td>
<td>13,000 Hz</td>
</tr>
</tbody>
</table>

### Diaphragm Properties

- Diaphragm: 1500um, Silicon, 1.7um thick, 2um gap
- Co = 7.8pF
- Cm = 20fF
- Resonant Frequency: fo = 13,000 Hz

### Diameter and Area

- Diameter (D): 1.9 x 10^12 dynes/cm²
- Area (A): 1.77E-02 cm²

### Poisson's Ratio and Young's Modulus

- Young's Modulus (E): 1.90E+11 N/m²
- Poisson's Ratio (ν): 0.32

### Materials Mechanical Properties

\[ f_r = 2\pi \left( \frac{1.015}{d_d} \right)^2 \sqrt{\frac{E \cdot d_d}{12 \cdot \rho \cdot (1 - \nu^2)}} \]

\[ f_r \text{ (Diaphragm Volumn)} = 3.00263E-06 \text{ cm}^3 \]

\[ f_r \text{ (Diaphragm Mass)} = 7.6E-06 \text{ g} \]
**DIAPHRAGM CALCULATIONS**

- **1500um Diaphragm, Polyimide**
- **1.7um thick**
- **2um gap**
- **Co = 7.8pF**
- **Cm = 1.7pF Change**
- **Resonant Frequency**
  - **fo = 2,000 Hz**

### Diaphragm

- **Deflection**
  - \( Y_{\text{max}} = 0.0151P \left(1 - N_u^2\right)/E H^2 \)
  - \( Y_{\text{max}} = 3.58 \times 10^{-3} \) µm

- **Pressure**
  - \( P = 1.00 \times 10^{-5} \) lbs/in²
  - \( 71 \) dB-SPL

- **Diameter of round diaphragm**
  - \( D = 1500 \) µm

- **Length of side of square diaphragm**
  - \( L = 1500 \) µm

- **Young’s Modulus**
  - \( E = 3.00 \times 10^9 \) N/m²

- **Poisson’s Ratio**
  - \( N_u = 0.00 \)

- **Diaphragm Thickness**
  - \( H = 1.7 \) µm

### Parallel Plate

- **Capacitance**
  - \( C = \frac{e_0 e_r A}{d} \)
  - \( C = 7.81 \times 10^{-12} \) F

- **Stress**
  - \( \sigma = 0.3 P \left(1 - H^2\right) \) (at center of each edge)
  - \( \sigma = 1.61 \times 10^4 \) Pascal

- **Yield Strength**
  - \( \sigma_y = 0.00 \times 10^4 \) Pascal

### Electrostatic Force

- \( F_{\text{elec}} = \frac{e_0 e_r V^2}{2d} \)
  - \( F_{\text{elec}} = 1.76 \times 10^{-6} \) N

### Pressure Force

- \( F_{\text{press}} = P \times A \)
  - \( F_{\text{press}} = 1.55 \times 10^{-7} \) N

### Resonant Frequency

- \( f_r = \frac{2\pi}{\sqrt{\frac{E_i r_f^2}{12\rho(1 - v^2)}}} \)

- **Diaphragm Volume**
  - \( V = 3.00263 \times 10^{-6} \) cm³

- **Diaphragm Mass**
  - \( m = 4.06 \times 10^{-6} \) g
SUMMARY

1. Need large thin diaphragms that give enough displacement so that the change in capacitance is 100’s of fF.

2. The resonant frequency needs to be considered. Typically it should be greater than 20,000 Hz (depends on application).

3. The fabrication technology: single wafer, CMOS compatible, low temperature, surface MEMS process.

4. Electrical output signal processing …

5. Desired specifications: Sensitivity of few 10’s of mV/dB_{SPL} more is better, free field (not including packaging acoustic effects) frequency response up to 20KHz flat or increasing with frequency,
A Novel Integrated Silicon Capacitive Microphone—Floating Electrode “Electret” Microphone (FEEM)

Quanbo Zou, Zhimin Tan, Zhenfeng Wang, Jiangtao Pang, Xin Qian, Qingxin Zhang, Rongming Lin, Sung Yi, Haiqing Gong, Litian Liu, and Zhijian Li

Abstract—A novel principle “electret” microphone, i.e., floating electrode electret microphone, is proposed and implemented in this study. Single-chip fabrication and corrugation technique are used in the design and fabrication of the microphone. The floating electrode is encapsulated by highly insulated materials to ensure that there is no electric-leakage passage between the floating electrode and the electrodes of the microphone. Net-free electronic charges (not “bonded” charges as in traditional electret) in the floating electrode can excite the electric field, which is similar to that of the traditional electret. The floating electrode can be easily charged by use of the “hot” electron technique, available using the avalanche breakdown of the p⁺–n junction. Therefore, the electret microphone is rechargeable, which can greatly increase the lifetime of the device. The preamplifier has been on-chip integrated in a junction-field-effect transistor (JFET) source-follower type with resistors by use of ion implantation. Electret charges are bonded in a deep potential trap, thus, this microphone can operate at a high temperature (as high as 300°C) and has high stability and reliability. Experiments show that the prototype has a 3-mV/Pa sensitivity and a larger than 21-kHz frequency bandwidth in a 1 mm × 1-mm diaphragm area. Microphone performance can be further improved by optimized process and design. The fabrication is completely integrated-circuit (IC) compatible, hence, the microphone shows promise in integrated acoustic systems. [304]

Index Terms— Corrugated diaphragm, electret microphone, integrated microphone, micromachining, single-chip fabrication.
ELECTRET MICROPHONE

Introduction
1. States that a condenser microphone requires an external bias voltage for operation, while electret microphone does not.
2. States that electret structures historically used conductors in Teflon FEP which is not compatible with IC/MEMS fabrication. Polysilicon conductors in SiO2 have shown decay time constants of 400 years in EEPROM applications.
3. States that the fabrication technology described here is superior to other MEMs electret approaches which glue two wafers together.
4. Electrical output signal is voltage making signal processing straightforward.

Output Capacitance
Charged floating conductor
Top plate diaphragm
Fixed bottom plate
Output Voltage
Substrate
Top plate diaphragm
ELECTRET MICROPHONE

Fig. 1. Floating electrode electret configuration.

Fig. 2. Equivalent circuit of the FEEM.
Fig. 4. (a) Microphone corrugation placement. (b) The charging and discharging configuration: top view. (c) Cross-section view.
ELECTRET MICROPHONE

4” wafers, 500 µm, (100), n-type, 2 ohm-cm, Backside polished

Deposit oxide (7000 Å) and nitride (2000 Å)

Etch from back of wafer leaving 40 µm thick silicon layer.

Fabricate JFET’s for amplifier circuit.

Etch V groove corrugation from front of wafer, almost but not through the 40 µm thick silicon layer

Ion implant P+ areas for hot-electron injection charging of floating polysilicon gate

Grow 5000 Å oxide followed by 2000 Å polysilicon for floating electrode, dope poly, and cover with low stress silicon nitride
ELECTRET MICROPHONE

Next a sacrificial layer of LTO phosphosilicate glass is deposited totaling 2.7 µm in thickness.

A poly layer 8000 Å thick is deposited for the diaphragm, and doped by ion implant, followed by a 2000 Å silicon nitride layer, a 1050 C nitrogen anneal is used to reduce stress.

Contact cuts are plasma etched and metal is deposited and patterned.

The back of the wafer is Reactive Ion Etched (RIE) to open up the V groove prior to sacrificial oxide etch in Buffered HF while the front of the wafer is protected with photoresist.
ELECTRET MICROPHONE

Fig. 5. Process flow of the FEEM microphone.
ELECTRET MICROPHONE
Fig. 8. Measured microphone sensitivity ($S$) versus $V_D$ at different $V_P$.

Fig. 9. Measured frequency response of the microphone.
Conclusion:

An electret integrated microphone has been proposed and developed.

The charge on the floating gate is generated by hot-electron injection, thus, the microphone is rechargeable, giving long life.

Sensitivity of ~3mV/Pa (measured) or ~30mV for average speech.

Frequency response >21KHz (measured).

The operation temperature can be as high as 300 C.
High-Performance Condenser Microphone with Fully Integrated CMOS Amplifier and DC–DC Voltage Converter

Michael Pedersen, Wouter Olthuis, and Piet Bergveld

Abstract—The development of a capacitive microphone with an integrated detection circuit is described. The condenser microphone is made by micromachining of polyimide on silicon. Therefore, the structure can be realized by postprocessing on substrates containing integrated circuits (IC’s), independently of the IC process. Integrated microphones with excellent performances have been realized on a CMOS substrate containing dc–dc voltage converters and preamplifiers. The measured sensitivity of the integrated condenser microphone was 10 mV/Pa, and the equivalent noise level (ENL) was 27 dB(A) re. 20 μPa for a power supply voltage of 1.9 V, which was measured with no bias voltage applied to the microphone. Furthermore, a back chamber of infinite volume was used in all reported measurements and simulations. [338]

Index Terms—Capacitance transducers, integrated electronics, microphones, polyimide films, voltage multipliers.
Introduction

1. Fabrication is low temperature (<300 C) making this process compatible with post processing of CMOS Amplifier.

2. Both the diaphragm and the backing plate are made of polyimide coated with Cr/Pt/Cr metal and use an aluminum sacrificial layer.

3. Backside etching is done with deep trench plasma etch tool and stops on the Cr/Pt/Cr metal
Backside hole can be etched in KOH or with plasma etching

Fig. 1. Cross-sectional view of the polyimide condenser microphone.
SIGNAL CONDITIONING

Co = Average value of C
Cm = amplitude of C change
C = Co + Cm sin (2πft)
V is constant across C

Vo = - i R

i = d (CV)/dt
i = V Cm 2 π f cos (2πft)

Vo = - 2πf V R Cm cos (2πft)

amplitude of Vo
CONDENSER MICROPHONE

Fig. 4. Fabrication process of the integrated condenser microphone. (a) Standard CMOS processing and deposition of Cr/Pt/Cr diaphragm electrode and polyimide diaphragm. (b) Deposition of Al sacrificial layer and Cr/Pt/Cr backplate electrode. (c) Deposition of polyimide backplate and Cr etchmask on the back of substrate. (d) Etching of sacrificial layer and substrate.
Fig. 5. Chip photograph of polyimide condenser microphone with integrated CMOS detection circuit.
CONDENSER MICROPHONE

~2mV/Pa at 5V bias or ~ 20mV for average speech

Fig. 7. Measured microphone sensitivity versus supply voltage using external biasing.

Fig. 9. Measured frequency response of the integrated microphone with a supply voltage of 1.9 V.
Conclusion:

CMOS compatible microphone process

Low temperature process

Sensitivity ~2mV/Pa at 5V bias

Frequency response flat to f > 20KHz
To be presented at the 1998 MEMS Conference, Heidelberg, Germany, Jan. 25-29 1998

A HIGH SENSITIVITY POLYSILICON DIAPHRAGM CONDENSER MICROPHONE

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Center for Integrated Sensors and Circuits
Department of Electrical Engineering and Computer Science
University of Michigan, Ann Arbor, MI 48109-2122, USA

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.

Figure 1: Cross section of the polysilicon diaphragm condenser microphone
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.

Figure 2: Top view of poly-Si diaphragm microphone

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 $v_m$ are modeled as equivalent voltage and current sources, respectively. The radiative resistance is $R_r$ and air mass $M_r$. 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 $R_h$, and the air gap compliance
POLYSILICON DIAPHRAGM MICROPHONE

Figure 3: Equivalent electrical circuit of the condenser microphone

by $C_a$ [4].

The diaphragm compliance depends on its flexural rigidity and tension. The flexural rigidity depends on the diaphragm thickness and the tension is determined by the polysilicon residual stress. The diaphragm deflection $W$ can be approximated by the following differential equation:

$$-D\nabla^4 W + T\nabla^2 W = \rho \frac{\partial^2 W}{\partial \tau^2},$$  \hspace{1cm} (1)

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

$$W(x, y, \tau) \approx A \sin \frac{\pi x}{a} \sin \frac{\pi y}{a} e^{-j2\pi f \tau}$$  \hspace{1cm} (2)

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

$$C_a = \frac{d}{\rho_c c^2 \alpha^2 a^2}$$  \hspace{1cm} (8)

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

$$R_h \approx \frac{8uha^2}{\pi nr^4}$$  \hspace{1cm} (9)

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

$$S = \frac{V_o}{P} = \frac{V_b a^2}{jw d Z_t}$$  \hspace{1cm} (10)

where $P$ is the sound pressure, $V_b$ is the bias voltage between two electrodes, and $Z_t$ is the total equivalent impedance of the circuit.

$$Z_t = R_r + jw(M_r + M_m) + \frac{1}{jw C_m} + \frac{R_g + R_h}{1 + jw(R_g + R_h)C_a}$$  \hspace{1cm} (11)

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.
POLYSILICON DIAPHRAGM MICROPHONE

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

(3)

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]

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

(4)

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

\[ C_m = \frac{32a^2}{\pi^6 (2\pi^2 D + a^2T)} \]  

(5)

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

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

(6)

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

\[ R_g = \frac{12u a^2}{n d^3 \pi} \left( \frac{\alpha}{2} - \frac{\alpha^2}{8} - \frac{\ln \alpha}{4} - \frac{3}{8} \right) \]  

(7)

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

\[ S_o \approx \frac{32V_o a^2}{\pi^6 T d} \]  

(12)

since the tension in the diaphragm dominates its compliance as the diaphragm thickness \( t \to 0 \). 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 is [9]

\[ V_P \approx \frac{64}{7} \sqrt{\frac{E t^3 d^3}{5(1 - \nu^2)\varepsilon_o a^4} \left(1 + \frac{2}{9} (1 - \nu^2) \frac{\sigma_R a^2}{E t^2}\right)} \]  

(13)

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 \( t \to 0 \). If \( t < 0.01a \), \( V_P \) reduces to

\[ V_P \approx \frac{64}{7} \sqrt{\frac{2}{45}} \sqrt{\frac{T d^3}{\varepsilon_o a^2}} \]  

(14)
Therefore the sensitivity is related to the pull-in voltage by

\[ S_o \approx \frac{\kappa}{\varepsilon_0} \left( \frac{V_b}{V_P} \right) d^2 \]  

(15)

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

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

(16)

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

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

(17)

Using \( d_{max} = 4 \mu m \), \( a_{max} = 3 \) mm, and \( V_P = 12 \) 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.

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

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.
POLYSILICON DIAPHRAGM MICROPHONE

FABRICATION

The simplified 10-mask fabrication process of the microphone is shown in Fig. 5. On (100) n-type silicon wafers, a 1 μm thick wet oxide is first grown at 1100 °C for three hours. This oxide layer is 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 °C for 15 hours, followed by a 20-minute wet oxidation at 1000 °C. The thick boron diffusion forms the stationary back electrode and the measured thickness is about 13μm. The oxide was then stripped in a 1:1 HF:H2O solution for 4 minutes.

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

Next, a 2 μm-thick layer of LPCVD low-stress polysilicon is deposited at 588 °C. This material showed an unannealed tensile residual stress of about 100 MPa. The deposition is followed by a phosphorus ion implantation of 7×10^{15} cm^{-2} at 50 KeV. The remaining 1 μm-thick layer of polysilicon is next deposited. The polysilicon is next annealed at 1050 °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 SF6:O2 sccm, at 40 mT, and 60 W for 15 minutes, followed by a wet etch in 950:50:50 HNO3:H2O:NH4F for 25 minutes.

A 0.6μm-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 0.5μm-thick LTO layer is deposited followed by a 0.2 μm Al evaporation. The LTO protective 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...
POLYSILICON DIAPHRAGM MICROPHONE

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 60x60 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 ACOI7012 free-field microphone is used as the reference microphone. Both microphones are connected to an HP ACOP4012 preamplifier with an internal 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.

![Graph showing capacitance versus bias voltage](image1.png)

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

![Graph showing frequency response](image2.png)

Figure 12: Experimental frequency response of a 2.6 mm microphone
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.

Figure 13: Frequency response of a 2 mm microphone

Figure 14: Frequency response of a 3 mm microphone
POLYSILICON DIAPHRAGM MICROPHONE

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.

ACKNOWLEDGEMENTS

This work was supported by the Defense Advanced Research Projects Agency (DARPA) under contract DABT63-C-0111. We thank the staff and graduate students of the UM Center for Integrated Sensors and Circuits for their helpful assistance during the device fabrication.

References


MEMS CONDENSER MICROPHONE


A MEMS CONDENSER MICROPHONE FOR CONSUMER APPLICATIONS

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2 Pixtronix, Inc., Andover, MA, USA
3 Analog Devices, Inc., Greensboro, MA, USA

ABSTRACT

This paper describes the design, fabrication, testing, and characterization of a MEMS microphone fabricated at Analog Devices. The device consists of a polysilicon diaphragm suspended over a single crystal silicon backplate fabricated on silicon on insulator (SOI) wafers. The MEMS microphone has been successfully fabricated and tested in an anechoic chamber. The microphone is fabricated using a process that is compatible with inexpensive high volume production using unit processes that are currently used to fabricate inertial sensors. Details of the design, fabrication, and electrical and acoustic characterization of the microphone will be presented.
MEMS CONDENSER MICROPHONE

Figure 3: SEM of microphone diaphragm and spring.

Figure 4: Photograph of backside of microphone die (left) next to frontside of die (right).

Figure 5: Photograph of MEMS microphone.

Figure 6: Photograph of MEMS microphone in 8 lead LCC package.
MEMS CONDENSER MICROPHONE

Figure 7: Schematic of discrete circuit used to readout the changing capacitance of the sensor.

Figure 8: Graph of microphone response to 94dB input sound pressure level at 1 kHz using discrete readout circuit.
MEMS MICROPHONE WITH BACKPLATE SUPPORT

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Abstract—We present a new surface micromachined MEMS capacitive microphone with improved frequency response and high sensitivity. The proposed MEMS microphone has a top back-plate with a bottom sensing membrane and the back-plate is supported by supporting pillars which are anchored to the bottom of the deep back chamber. The back-plate supporting pillars increase the stiffness of the back-plate and prevent deformation. A present surface micromachined MEMS capacitive microphone is fabricated using fully CMOS compatible processes. It has a thin metal membrane of 500 μm diameter, a sensing air gap of 2.5 μm and seven back-plate supporting pillars. A 100 μm deep back chamber is formed by xenon difluoride dry etching of silicon substrate. As a result, the proposed microphone shows a flat frequency response and high open-circuit sensitivity. It shows a measured zero-bias capacitance of 1.0 pF and a pull-in voltage of 11.0 V, and an open-circuit sensitivity of 10.37 mV/Pa on a DC bias of 6.0 V.
MEMS MICROPHONE WITH BACKPLATE SUPPORT

Figure 1. Schematic view of the proposed surface micromachined MEMS capacitive microphone with back-plate supporting pillars.
### MEMS MICROPHONE WITH BACKPLATE SUPPORT

#### TABLE II. MEASURED DATA OF THE FABRICATED MEMS MICROPHONE

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero-bias Capacitance, $C_0$ (pF)</td>
<td>1.00 ± 0.05</td>
</tr>
<tr>
<td>Pull-in Capacitance, $C_p$ (pF)</td>
<td>1.64 ± 0.14</td>
</tr>
<tr>
<td>Pull-in Voltage, $V_p$ (V)</td>
<td>11.0 ± 1.2</td>
</tr>
<tr>
<td>Bias voltage, $V_b$ (V)</td>
<td>6.0</td>
</tr>
<tr>
<td>Open-circuit sensitivity (mV/Pa)</td>
<td>10.37</td>
</tr>
<tr>
<td>$f_0$ of back-plate with supporting pillars (kHz)</td>
<td>236.5 ± 0.6</td>
</tr>
<tr>
<td>$f_0$ of back-plate w/o supporting pillars (kHz)</td>
<td>87.5 ± 7.4</td>
</tr>
<tr>
<td>Membrane displacement@1 kHz (nm)</td>
<td>13.5 ± 0.3</td>
</tr>
</tbody>
</table>
In this paper, a novel surface micromachined MEMS capacitive microphone with back-plate supporting pillars was designed, fabricated and characterized. The proposed MEMS microphone has a top back-plate with a bottom sensing membrane and the back-plate is supported by supporting pillars which are anchored to the bottom of the deep back chamber. The back-plate supporting pillars increase the stiffness of the back-plate and prevent deformation after removing sacrificial layer. We fabricated the microphone by using fully CMOS compatible fabrication process. The membrane diameter is 500 μm and the sensing gap is 2.5 μm. Seven supporting pillars are fabricated within back chamber and support the top back-plate through the membrane venting holes. A 100 μm deep back chamber is formed by xenon difluoride dry etching of silicon substrate. The fabricated top back-plate with supporting pillars shows a resonant frequency of 236.5 ± 0.6 kHz. As a result, the proposed microphone shows a flat frequency response and high open-circuit sensitivity. It shows a measured zero-bias capacitance of 1.0 pF and a pull-in capacitance of 1.64 pF on a pull-in voltage of 11.0 V. The calculated open-circuit sensitivity is 10.37 mV/Pa on a DC bias of 6.0 V.
MEMS Applications – Microphones

MEMS CMOS MICROPHONE – METAL DIAPHRAGM

Implementation of the CMOS MEMS Condenser Microphone with Corrugated Metal Diaphragm and Silicon Back-Plate

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Received: 21 April 2011; in revised form: 30 May 2011 / Accepted: 31 May 2011 /
Published: 10 June 2011

OPEN ACCESS

Sensors
ISSN 1424-8220
www.mdpi.com/journal/sensors
Abstract: This study reports a CMOS-MEMS condenser microphone implemented using the standard thin film stacking of 0.35 µm UMC CMOS 3.3/5.0 V logic process, and followed by post-CMOS micromachining steps without introducing any special materials. The corrugated diaphragm for the microphone is designed and implemented using the metal layer to reduce the influence of thin film residual stresses. Moreover, a silicon substrate is employed to increase the stiffness of the back-plate. Measurements show the sensitivity of microphone is $-42 \pm 3$ dBV/Pa at 1 kHz (the reference sound-level is 94 dB) under 6 V pumping voltage, the frequency response is 100 Hz–10 kHz, and the S/N ratio >55 dB. It also has low power consumption of less than 200 µA, and low distortion of less than 1% (referred to 100 dB).
MEMS CMOS MICROPHONE – METAL DIAPHRAGM

Figure 1. The proposed CMOS MEMS microphone design.

Table 1. The important design parameters and dimensions of the microphone.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diaphragm diameter</td>
<td>800 μm</td>
</tr>
<tr>
<td>Diaphragm density</td>
<td>2,500 kg/m³</td>
</tr>
<tr>
<td>Diaphragm thickness</td>
<td>1.1 μm</td>
</tr>
<tr>
<td>Young's module of diaphragm</td>
<td>21.2 GPa</td>
</tr>
<tr>
<td>Diaphragm stress</td>
<td>41.63 MPa</td>
</tr>
<tr>
<td>Effective diameter of backplate</td>
<td>800 μm</td>
</tr>
<tr>
<td>Backplate thickness</td>
<td>40 μm</td>
</tr>
<tr>
<td>Initial air gap</td>
<td>4.2 μm</td>
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<tr>
<td>Air hole diameter</td>
<td>20 μm</td>
</tr>
<tr>
<td>Air hole quantity</td>
<td>350</td>
</tr>
<tr>
<td>Hole ratio</td>
<td>22%</td>
</tr>
<tr>
<td>Air density</td>
<td>1.8 kg/m³</td>
</tr>
<tr>
<td>Viscosity of air</td>
<td>$1.73 \times 10^{-5}$ N-s/m²</td>
</tr>
<tr>
<td>Bias voltage</td>
<td>6 V</td>
</tr>
<tr>
<td>Parasitic capacitor</td>
<td>0.7 pF</td>
</tr>
</tbody>
</table>
This study presents the design of a CMOS-MEMS microphone consisting of a corrugated diaphragm that is 800 µm in diameter, and having a rigid thick back-plate mainly formed by the silicon substrate. Moreover, the tests demonstrate the performance features of the device such as sensitivity and frequency range. The microphone has flat frequency response from 100 Hz to 10 kHz, and sensitivity of $-42 \pm 3$ dBV/Pa at 1 kHz (the reference sound-level is 94 dB). Moreover, the microphone has current consumption of less than 200 µA, the S/N ratio of over 55 dB, and low distortion of <1% (refer to 100 dB). In short, this study demonstrates the possibility of implementing the CMOS MEMS microphone by establishing and integrating the standard CMOS and post-CMOS release processes in an open CMOS foundry. This could be a critical step for the mass production of MEMS devices in such a CMOS foundry.
COMMERCIAL MICROPHONES

Akustica
Analog Devices
Boesch
Emkay Sisonic
Futurlec
Infineon
Knowles
Motorola
STMicroelectronics
TI
Others
**Akustica AKU230**
It uses a free-floating diaphragm, and a capacitive sensing based on a silicon circuit combining the MEMS process on the ASIC process in a single die. This microphone targets high end consumer applications: notebooks, laptops...

**Epcos T4060**
Manufactured in the EPCOS “Chip Size MEMS Package” technology, the component targets high end consumer applications: mobile phones, MP3 players and digital cameras.

**Knowles SPU0410LR5H**
It uses free floating diaphragm with capacitive sensing. It is the 4th generation of MEMS microphones from Knowles. This device is found in high volume consumer applications: cell & smart phones (iPhone4)...

**Analog Devices ADMP421**
It uses a free floating diaphragm and a capacitive sensor and offers a full integration of a MEMS microphone & ASIC. It targets high end consumer applications: tablets, smart phones.

**AAC Acoustic iPhone 4**
This MEMS Microphone uses a free floating diaphragm & a capacitive sensing and offers a full integration of a MEMS microphone and ASIC, both provided by Infineon. It is for consumer applications: cell & smart phones...

**STM MP45DT01**
The MP45DT01 microphone uses a MEMS die manufactured by Omron using a free floating diaphragm, and a capacitive sensing. It is for high-end consumer applications: note book, tablets...

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**Yole Developpement**

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AKU1126 MICROPHONES

AKUSTICA

September 2009

AKU1126 Single-Chip Analog Microphone

GENERAL DESCRIPTION

The AKU1126 is the world's smallest, analog-output microphone that uses standard semiconductor packaging technology and materials. While other microphones degrade in performance as they shrink in size, the AKU1126 maintains superior performance in an ultra-small form factor.

The AKU1126's gain select feature, accessed by use of a single external resistor, allows the microphone to be used in both near-ear applications as well as far-field applications - such as speaker phones or headsets - without the use of additional amplifiers.

The AKU1126 is the first microphone product to leverage Akustica's 1mm x 1mm CMOS MEMS microphone die - a monolithic solution which integrates the acoustic transducer and accompanying electronics in a single chip of silicon. In contrast to other silicon microphones, Akustica's one die approach eliminates the need for inter-die wirebonds, allowing for smaller, higher performance, more reliable products.
AKU1126 MICROPHONE
AKU1126 MICROPHONE
REFERENCES


1. What is the difference between a condenser microphone and an electret microphone?

2. Why are there holes in the backing plate in a MEMS microphone?

3. Use the Diaphragm spreadsheet to calculate the capacitance change and resonant frequency for a capacitive microphone with the following: 1000um diameter silicon diaphragm, 1.5um gap. You may pick the other parameters you need.

4. The Paper above from Analog devices uses a plate held by springs. Estimate the capacitance change for sound pressures for normal speech.

5. Grad Students Only: Find another publication describing the fabrication of a MEMs pressure sensor (or microphone). Describe the fabrication sequence in your own words. Attach a copy of the paper.