Design of Spring-Supported Diaphragm Capacitive MEMS Microphone

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Abstract

In this research project, the design and performance optimization techniques of a microelectromechanical (MEMS) condenser microphone will be studied and described using several established plate theories and numerical analysis. MEMS microphone is shown to have been increasingly popular to be used in various consumer electronic products especially in the mobile phone industry and hearing aid devices. Thus, it is important for the microphone designers to be able to design and improve a microphone's performance given sets of design constraints in the shortest time possible while reducing the overall overhead cost associated with the mass production exercise.

The proposed new spring-supported diaphragm MEMS microphone has a higher open-circuit sensitivity, sufficiently high pull-in voltage, adequate frequency response in the audio range bandwidth, and uses fewer fabrication masks to reduce the overall production cost and possibly reduce the production rejection rate. The mathematical modelling of the proposed spring diaphragm has been described in detail to relate its performances with several of its structural dimensions such as spring width and length, diaphragm area, air gap distance, and diameter of backplate holes. Coventor FEM software has been used to simulate the mechanical performances of the final structure and to verify the mathematical modelling derived for the proposed spring microphone.

Numerical results from Matlab and Coventor FEM software show that the proposed spring diaphragm has about 100 times higher sensitivity compared with the edge-clamped diaphragm microphone of the same diaphragm area. Various numerical performance analysis graphs have been presented and used to obtain the optimized microphone parameters by taking the points where the open-circuit sensitivity will be the highest, operating bandwidth of at least 20kHz, and the pull-in voltage threshold is at least 3 times its bias voltage.

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Declaration

This thesis contains no material which has been accepted for the award of any other degree or diploma, except where due reference is made in the text of the thesis. To the best of my knowledge, this thesis contains no material previously published or written by another person except where due reference is made in the text of the thesis.

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Table of Contents

List of Figures

List of Tables

List of Acronyms

Abbreviation	Description
FEM	Finite Element Modeling
FEA	Finite Element Analysis
MEMS	Microelectromechanical system
MOS	Metal Oxide Semiconductor
MPW	Multi Projects Wafer
PECVD	Plasma-Enhanced Chemical Vapor Deposition
PSG	Phosphosilicate Glass
SEM	Scanning Electron Microscope
SPL	Sound Pressure Level

Glossary of Symbols

Symbol	Description
a	acceleration
A	effective plate area
b	damping coefficient
c	sound velocity
C_0	initial capacitance
C_{a}	air gap compliance
C_g	time varying capacitance
C_{m}	mechanical compliance
C_{o}	microphone initial capacitance
C_{s}	microphone stray capacitance
d	distance
E	modulus of elasticity
ε_0	electric permittivity of vacuum
ε_r	capacitor dielectric constant
f	sound pressure frequency in Hertz
F	Force
F_{net}	net force
F_{s}	sound pressure force
h	diaphragm thickness
h_g	air-gap thickness

Glossary of Symbols

Symbol	**Description**
I	electrical current
k	spring constant
k_{B}	Boltzmann constant
L	inductance
L_{b}	beam length
L_p	acoustic pressure level
L_{s}	spring length
m	mass
M_{m}	lumped effective mass
n	number of backplate holes
ΔP	sound pressure force
ρ	polysilicon density
ρ_{o}	density of air
q	capacitor charge
r_{h}	hole radius
R	resistance
R_{g}	air gap viscosity loss
R_{h}	backplate holes viscosity loss
S	open-circuit sensitivity
S_{e}	electrical sensitivity

Glossary of Symbols

Symbol	Description
S_m	mechanical sensitivity
S_N	A-weighted mechanical thermal noise
T	absolute temperature (in Kelvin)
μ_o	viscosity of air
v	Poisson's ratio
V_b	bias voltage
V_m	diaphragm velocity
V_o	output voltage
w_1	diaphragm's center deflection
w_b	beam width
w_d	diaphragm length and width
w_s	spring width
Δw	deflection of a microphone diaphragm
x	displacement
$\dot{x}$	mass velocity
Z_t	total impedance
Z_C	complex impedance of a capacitor
Z_L	complex impedance of an inductor
Z_R	complex impedance of a resistor

1

Introduction

1.1 Introduction

A microphone is a device used to convert an acoustic energy into an electrical energy. The resulted electrical energy will then be amplified by means of an electronic circuitry and normally feeds back into another energy conversion device such as a speaker to transform the energy back into its original form. Microphones have been widely used to record several acoustical signals such as human speech, music, and environmental noise for various applications including telecommunication, media storage, and medical. A high performance and small size microphone to reproduce a high-quality sound signal is increasingly demanded in telecommunication and medical applications such as mobile phones and hearing aid devices [2]. Due to the increasing demand for smaller technological devices, the internal components of these devices must use as small component size as possible to make the devices more compact, lighter, and possibly cheaper. The smaller component size demands have led to the use of microelectromechanical system (MEMS) technology using silicon micromachining to build various millimeter and micrometer size components and devices such as a microphone, accelerometer, and pressure sensor.

Many commercial portable devices today needs to consume as low electrical power as possible to prolong its power supply life. A high-performance capacitive microphone normally needs a high voltage and power to boost its sensitivity. In order to use a lower operating voltage while maintaining the high sensitivity, the mechanical sensitivity of the microphone has to be exploited and improved. The microphone's performance parameters and their corresponding equations are thoroughly discussed in Chapter 2. There have been several research works carried out to increase the mechanical sensitivity starting from the use of a corrugated diaphragm, the use of a low-stress polysilicon diaphragm, and the use of a spring type diaphragm. However, very little significant work has been done to explain the detailed modelling of various spring type diaphragm structure and its relationship with the electrical properties of the capacitive microphone. The scientific work in this thesis is therefore trying to explain the behaviour of a new variation of spring-supported diaphragm microphone by investigating its mechanical and electrical characteristics via mathematical modelling development and numerical analysis using finite element analysis software. The microphone model with several different structure dimensions will then be fabricated on top of a silicon wafer using PolyMUMPs processes which utilize three layers of doped polysilicon material with several micrometers space between each of them. Only the first two polysilicon layers will be used to form a capacitive spring microphone in this project.

1.2 Research Objectives and Scope

The need for a smaller, lower cost, lower power consumption, but high-performance microphone using MEMS technology is increasing as previously described. Since smaller size condenser microphones will result in smaller operating capacitance, thus having a lower open circuit sensitivity. The commonly used methods to increase its sensitivity is either increasing its bias voltage or reducing its diaphragm stiffness to increase its mechanical deflection. However, the needs for a low voltage and a lower power consumption device means that the option to use a higher bias voltage is not favourable. This means that the only option to increase the microphone's sensitivity is to reduce its diaphragm stiffness. There have been several works done on reducing the diaphragm stiffness including the use of corrugated diaphragms and different types of spring diaphragms. However, there is a limit to how much softer the diaphragm or the spring needs to be designed since the attractive force caused by the electrostatic charge between the capacitor plates will pull the diaphragm completely towards its backplate when the bias voltage has exceeded its pull-in voltage threshold. So, a microphone which uses a higher bias voltage needs a stiffer diaphragm compared to the microphone with a much lower bias voltage.

The work described in this thesis is based on a newly designed spring-supported diaphragm condenser MEMS microphone. In order to fully understand and optimize the performance of the newly designed microphone, it is important to describe its behaviour by means of any form of mathematical modelling, and be able to simulate and analyze its theoretical characteristics to fine tune the model. The mathematical modeling for a spring diaphragm microphone in this thesis is derived based on several lumped mechanical and acoustic parameters in analogy to the electronic components which forms a closed circuit diagram. A variable output voltage expression of the resulted circuit diagram will then be used to describe and analyze the behaviour of the spring diaphragm microphone. The main objectives and scope of this thesis are therefore to describe the behaviour of the spring-supported diaphragm microphone mathematically and numerically, identify its advantages and limitations, and to use the knowledge to design a miniature capacitive microphone with higher sensitivity, better performance, lower power consumption, and possibly lower cost.

1.3 Capacitive MEMS Microphone Development

This section reviews the development of capacitive MEMS microphone and their performances so far. The need for a better performance spring-supported diaphragm microphone will be highlighted.

Capacitive MEMS microphone consists of two charged plates which produce a variable voltage across its plates when one of its plates (diaphragm) vibrates with sound pressure. The sensitivity of the microphone is characterized by its electrical and mechanical sensitivities. The microphone's electrical sensitivity is directly dependent on its bias voltage and plate area, but inversely dependent on the plates' gap (air gap) distance. Therefore, the higher the bias voltage used between the diaphragm and backplate, the higher the sensitivity would be, and the larger the plate area, the higher the sensitivity. However, the main objective of the current application for mobile consumer devices such as mobile phones and hearing aids requires the microphone to be as small as possible. This would also mean that the microphone will use the least material possible to reduce its total cost and possibly make the earth greener by having less waste. Even though a higher bias voltage could increase the microphone's sensitivity, however, this is not favourable since most current consumer devices need to use the least battery power as possible, thus limits the bias voltage that could be used. The most common voltage used in consumer electronics and digital electronics is between 3 Volt and 5 Volt.

Consequently, the microphone's mechanical sensitivity is directly dependent on the stiffness of the diaphragm (softer diaphragm will have more deflection). Even though the diaphragm could be made much softer to get a higher mechanical sensitivity, too soft diaphragm suffers from a higher chance of breaking, and limits the bias voltage that could be used due to the electrostatic force pulling the diaphragm towards the backplate. Therefore, it is always a challenge to design a high sensitivity microphone given all the constraints to find the balance between high sensitivity, small size and low power device.

A high sensitivity capacitive microphone can be designed by adjusting several parameters:

- A higher bias voltage is applied between the plates to increase the electrical sensitivity. However, the pull-in voltage threshold will limit the highest bias voltage that could be applied. The electrostatic force resulted from the bias voltage will attract the diaphragm to touch the backplate if the voltage has exceeded the pull-in voltage threshold.

- A smaller air gap is used to increase the capacitance. A larger capacitance value will result in a larger open circuit voltage of the microphone for the same diaphragm deflection. However, a small air gap (several micrometers) introduces a squeeze-film damping to the microphone's diaphragm which will reduce its mechanical sensitivity and affect its frequency response.

- A larger plate area is used to increase the capacitance. However, many consumer applications today needs a small size microphone, thus its plate area must be designed to be as small as possible.

- A softer diaphragm plate is used to increase the mechanical sensitivity. A softer diaphragm along with a low residual stress diaphragm will allow it to have a large deflection with sound pressure. However, a softer diaphragm will result in a lower resonance frequency (lower operating bandwidth) and higher thermal noise. Thus, the diaphragm stiffness needs to be designed according to the operating bandwidth and minimum noise requirements.

In 1983, Royer *et al.* [3] was the first to fabricate a piezoelectric MEMS microphone using zinc oxide and silicon micromachining technique along with MOS buffer amplifier. The technique was then used to fabricate a capacitive MEMS microphone as demonstrated by many researches [4–30]. Table 1.1 shows the development of various types capacitive MEMS microphones for the past 24 years.

Table 1.1: Development history of various capacitive MEMS microphones.

Year	Author	Diaphragm Size (Type)	Air-gap (μm)	Sensitivity (mV/Pa)	Bias Voltage (V)	Bandwidth
1992	Scheeper *et al.* [6]	1.5mm x 1.5mm (silicon nitride flat diaphragm)	1.1	2.0	16.0	100 Hz - 14 kHz
1993	Bergqvist, J. [31]	2.0mm x 2.0mm (monocrystalline silicon flat diaphragm)	2.3	2.4	10	20 kHz
1996	Zou *et al.* [8]	1.0mm x 1.0mm (multilayer corrugated diaphragm)	1.0	14.2	25	100 Hz - 16 kHz
1998	Hsu *et al.* [9]	2.0mm x 2.0mm (polysilicon flat diaphragm)	4.0	20	13	25 kHz
1998	Pedersen *et al.* [10]	2.2mm x 2.2mm (polyimide flat diaphragm)	3.6	10	14	100 Hz - 15 kHz
2000	Torkkeli *et al.* [11]	1.0mm x 1.0mm (low stress polysilicon flat diaphragm)	1.3	4.0	2.0	10 Hz - 12 kHz
2000	Li *et al.* [13]	1.0mm x 1.0mm (single deeply corrugated diaphragm)	2.6	9.6	5.0	100 Hz - 19 kHz
2002	Rombach *et al.* [15]	2.0mm x 2.0mm (polysilicon flat diaphragm, dual backplate)	0.9	13	1.5	20 kHz
2003	Tajima *et al.* [17]	2.0mm x 2.0mm (crystalline silicon flat diaphragm)	24	4.5	48	75 Hz - 24 kHz
2003	Scheeper *et al.* [16]	1.95mm radius (silicon nitride flat diaphragm)	20	22	200	47 Hz - 51 kHz
2005	Liu *et al.* [21]	0.23mm radius (flat diaphragm, dual backplate)	2.0	0.28	18 (AC)	180 kHz
2006	Kim *et al.* [22]	0.5mm radius (flexure hinge diaphragm)	2.5	0.2 μm/Pa	16	20 kHz

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Table 1.1 – *Continued from previous page*

Year	Author	Diaphragm Size (Type)	Air-gap (μm)	Sensitivity (mV/Pa)	Bias Voltage (V)	Bandwidth
2007	Goto *et al.* [24]	2.0mm x 2.0mm (crystalline silicon flat diaphragm)	10	6.7	48	30 Hz - 20 kHz
2009	Ganji *et al.* [29]	0.5mm x 0.5mm (perforated aluminum flat diaphragm)	1.0	0.2	105	20 kHz
2011	Esteves *et al.* [32]	0.5mm x 0.5mm (perforated aluminum flat diaphragm)	2.0	17.8	1.0	8 kHz
2011	Chan *et al.* [33]	0.5mm radius (polysilicon rigid diapgrahm with spring backplate)	2.0	12.63	–	20 Hz - 20 kHz
2012	Hur *et al.* [34]	1.0mm radius (polysilicon flat diaphragm)	3.0	8.3	12	20 Hz - 27.4kHz
2012	Lee *et al.* [35]	0.3mm radius (aluminum flat diaphragm)	2.8	4.12	10.4	80 kHz
2013	Ahmad-nejad *et al.* [36]	0.5mm x 0.5mm (perforated polysilicon flat diaphragm)	1.0	7.1	2.3	70 kHz
2014	Grixti *et al.* [37]	0.675mm x 0.675mm (perforated polysilicon flat diaphragm)	2.0	8.4	6.0	28 kHz
2015	Lo *et al.* [38]	0.3mm radius (polysilicon diaphragm with planar interdigitated sensing electrodes)	–	0.99	–	1 kHz - 20 kHz
2015	Kim *et al.* [39]	0.3mm radius (polysilicon spring diaphragm)	4.0	12.0	10	37 kHz
2016	Zawawi *et al.* [40]	0.68mm x 0.68mm (silicon carbide flat diaphragm)	3.0	4.3 μm/ 20 μPa	–	70 kHz

In 1992, Scheeper *et al.* [6] had proposed and demonstrated a new condenser microphone design which consists of a plasma-enhanced chemical vapor deposition (PECVD) silicon nitride film and can be fabricated using the sacrificial layer technique. The sacrificial layer will form the required air-gap for the microphone. The technique in etching sacrificial layer to form the air-gap will reduce the needs for critical wafer alignment and high temperature treatment during bonding of the diaphragm and backplate wafer plate [4]. Even though the new microphone was fabricated on a single wafer without using any bonding technique, the microphone has a relatively low sensitivity (about 2 mV/Pa) using a bias voltage of 16 V. An adequate sensitivity of about 10 mV/Pa should be achieved for audio applications such as hearing aid devices [6].

In order to increase the sensitivity without using a high bias voltage, a mechanical sensitivity could be increased. This can be achieved by reducing the diaphragm stiffness and stress by reducing its thickness or using a softer material such as polysilicon [9, 11, 15, 27, 28], polyimide [10], and aluminium [29]. Other than using a softer diaphragm to increase its deflection, a corrugated diaphragm [7, 8, 14, 41, 42] and a spring type diaphragm [22, 23, 26] has been used to reduce the diaphragm's initial stress.

The use of a corrugated diaphragm in a capacitive microphone has been demonstrated by Scheeper *et al.* [7] in 1994 and followed by several other researchers [8, 14, 41, 42]. Scheeper *et al.* [7] has fabricated a silicon nitride diaphragm of 2 mm x 2 mm with a diaphragm thickness of 1 μm and having 8 circular corrugations. Corrugations on the diaphragm are used to reduce the initial stress of a clamped diaphragm depending on the diaphragm fabrication process. Scheeper *et al.* [7] showed that a measured mechanical sensitivity of a diaphragm with 4 μm corrugation depth is 25 times larger than the mechanical sensitivity of a flat diaphragm with equal size and thickness. Moreover, the corrugated diaphragm has been shown experimentally to have a larger linear range than a flat diaphragm and a reduced influence of thermal stress.

Hsu *et al.* [9] demonstrated a capacitive microphone using a square low-stress polysilicon diaphragm without having any corrugations. The 2 mm^2 square diaphragm microphone was fabricated and tested to have a sensitivity of 20 mV/Pa using a 13V bias voltage. The use of a low-stress polysilicon diaphragm in capacitive microphone was further demonstrated by Torkkeli *et al.* [11] in 2000. The fabricated 1 mm^2 square microphone had only about 2 Mpa residual stress, and achieved a sensitivity of 4 mV/Pa using a bias voltage of only 2 V.

The use of polyimide (plastic type diaphragm) in capacitive microphone fabrication has been introduced by Pedersen *et al.* [10] in 1998. Polyimide diaphragm can be fabricated using a low-temperature fabrication process directly on substrates containing integrated circuits without causing any damage to the circuits itself. The fabricated 2.2 mm by 2mm square polyimide diaphragm microphone had a sensitivity of 10 mV/Pa using an equivalent bias voltage of 14 V. The actual device was using only 1.9 V power supply, but the input voltage was amplified by the built-in DC-DC voltage converter to supply a bias voltage of 14 V to the microphone plates.

In 2006, Kim *et al.* [22] had designed and fabricated a spring type diaphragm capacitive microphone. The circular aluminum diaphragm consists of three circular slits and bridges near its edge to form a spring-like structure. The fabricated 0.5 mm radius circular diaphragm resulted in a center diaphragm deflection about 250 times higher than the equal size edge clamped flat diaphragm. Another spring type diaphragm microphone was designed and fabricated by Weigold *et al.* [23] at Analog Devices in 2006. The measurement using a low noise amplifier circuit yields a sensitivity of about 4.47 mV/Pa.

The other possible method to increase the microphone sensitivity is to reduce the air gap between the capacitor plates. The air gap for a typical MEMS condenser microphone is within several micrometers thick. This very small air gap introduces a squeeze-film damping to the microphone's diaphragm which will reduce its mechanical sensitivity during high frequency operation [43]. Since the smaller air gap will increase an air-streaming resistance at high frequency operation [43–49], perforated holes on the backplate are often used to enable the air to pass through the holes thus increase the