PIEZOELECTRIC MICRO ULTRASONIC TRANSDUCER (PMUT) WITH FLUIDIC BACKING LAYER AS A SENSING MECHANISM FOR SHORT DISTANCE UNDERWATER MICROPHONE APPLICATION

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2022

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by

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Thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

February 2022

ACKNOWLEDGEMENT

In preparing this thesis, I was in contact with many peoples, researchers, academicians, and practitioners. They have contributed towards my understanding and thoughts. In particular, I wish to express my sincere appreciation to my main project supervisor, Assoc. Prof. Dr. Asrulnizam Abd Manaf, for encouragement, guidance, critics and friendship. I am also very thankful to my co-supervisor Dr. Mohd Ikhwan Hadi Yaacob for their guidance, advices and motivation. Without his continued support and interest, this thesis would not have been the same as presented here. I am also indebted to Universiti Sains Malaysia (USM) for funding this research as well as living expenses through various grants, allowances and incentives. Librarians at USM and fellows at Nanofabrication and Functional Materials (NFM) research group of School of Mechanical Engineering also deserve special thanks for their assistance in supplying the relevant literatures and expertise. My fellow peers of Underwater Robotic Research Group (URRG), USM should also be recognized for their support. My sincere appreciation also extends to all my colleagues and others who have provided assistance at various occasions. Their views and tips are useful indeed. Unfortunately, it is not possible to list all of them in this limited space. I am grateful to my wife and my children, who have supported me continuously until this thesis completed.

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LIST OF ABBREVIATIONS

AIMS	Acoustic Intensity Measurement Systems
Al	Aluminum
AlN	Aluminum Nitrate
ASIC	Application-specific Integrated Circuit
Au	Aurum
BaTiO3:Co	Cobalt-doped Barium Titanate
BEM	Boundary Element Method
CMOS	Complementary Metal Oxide Semiconductor
CMUT	Capacitance Micromachined Ultrasonic Transducer
Cu	Copper
DVL	Doppler Velocity Log
EM	Electromagnetic
FC-84	Fluorinert
FEA	Finite Element Analysis
FEM	Finite Element Model
FFRT	Free-Flooded Ring Transducer
FFT	Fast Fourier Transform
FR4	Flame Retardant 4
FSI	Fluid-Structure Interaction
IDT	Interdigitated Transducer
IMD	Implantable Medical Device
KLM	Krimhotz Leedom Matthaei
MEMS	Micro Electro-Mechanical Systems

MF-PMUT	Multi-frequency Piezoelectric Micromachined Ultrasonic Transducer
OCRR	Open-circuit Receiving Response
OLIM	Omniphobic Lubricant Infused Mold
PCB	Printed Circuit Board
PDMS	Polydimethylsiloxane
PFN	Pulse Forming Network
PI	Polyimide
PML	Perfectly Matched Layer
PMMA	Polymethylmethacrylate
PMUT	Piezoelectric Micro Ultrasonic Transducer
Pt	Platinum
PTFE	Polytetrafluorethylene
PUT	Piezoelectric Ultrasonic Transducers
PVDF	Polyvinylidene Fluoride
PZT5H	Lead Zirconate Titanate
RIE	Reactive Ion Etching
RVS	Receiving Voltage Response
SEM	Scanning Electron Microscope
Si	Silicon
SIL	Sound Intensity Level
Si_3N_4	Silicon Nitride
SiO_2	Silicon dioxide
SPL	Sound Pressure Level
Ti	Titanium
TVR	Transmitting Voltage Response

UT	Ultrasonic Transducer
UV	Ultraviolet
VNA	Vector Network Analyser
ZnO	Zinc oxide
ZrO_2	Zirconium Oxide

LIST OF SYMBOLS

c	Speed of sound
C_o	Unit capacitance
d	Piezoelectric material’s coefficient
D_3	Electric displacement
$d31$	Induced strain in direction 1 per unit electric field applied in direction 3
$d33$	Induced strain in direction 3 per unit electric field applied in direction 3
E	Young's modulus
f_c	Centre frequency
$g33$	Induced strain in direction 3 per unit electric displacement applied in direction 3
$g31$	Induced strain in direction 1 per unit electric displacement applied in direction 3
h	Thickness of dielectric
K^2_{eff}	Effective electromechanical coupling coefficient
m	Volume region between electrodes
p	Area of the electrodes
q	Distance between electrodes
Q	Charges
S_3	Strain along the x-axis
T	Stress
V_{dB}	dB output voltage
V_{rms}	Root mean square voltage

w	Width
ε	Relative permittivity of the piezoelectric material
ε_{33}	Effective dielectric coefficient
ε_o	Vacuum permittivity
λ	Wavelength
ρ	Density
σ_{xx}	Stress component

LIST OF APPENDICES

TRANSDUSER PIEZOELEKTRIK MIKRO ULTRASONIK (PMUT) DENGAN LAPISAN SOKONGAN BENDALIR SEBAGAI MEKANISME PENDERIAAN UNTUK APLIKASI MIKROFON DALAM AIR JARAK DEKAT

ABSTRAK

Transduser ultrasonik mikro Piezoelektrik (PMUT) adalah penting untuk aplikasi mikrofon bawah air (hidrofon). Hidrofon biasanya digunakan untuk mendengar atau menerima sebarang isyarat akustik di bawah air. Beberapa kajian telah mendokumentasikan bahawa PMUT berfungsi sebagai hidrofon bawah air dengan sensitiviti penerimaan rendah dan lebar jalur operasi yang sempit. Isyarat akustik yang diterima dengan sensitiviti penerimaan rendah tidak tepat kerana gangguan oleh isyarat yang tidak diingini. Transduser akustik dengan lebar jalur sempit telah dilaksanakan resolusi rendah untuk pengimejan akustik bawah air. Transduser lebar jalur sempit ditangkap untuk frekuensi tertentu sahaja dan sukar untuk menangkap isyarat akustik pada frekuensi jarak jauh. Dalam pengimejan, adalah penting transduser boleh menerima isyarat untuk pelbagai frekuensi yang panjang. Objektif kajian ini untuk meningkatkan transduser kepekaan penerimaan rendah dan meluaskan jalur lebar frekuensi sempit di bawah air ultrasonic transduser. Objektif seterusnya adalah PMUT yang direka menggunakan struktur piezoelektrik mod d33, membran lenturan dan lapisan sokongan cecair. Kemudian, PMUT dengan parameter pembolehubah ketebalan membran, jarak antara elektrod, bahan piezoelektrik dan bahan lapisan sokongan cecair telah disimulasikan oleh COMSOL Multifizik 5.0 untuk mengoptimumkan PMUT. Seterusnya, PMUT telah direka menggunakan parameter PMUT yang dioptimumkan daripada hasil simulasi yang dianalisis untuk mendapatkan prestasi optimum dan kekerapan yang disasarkan. Lembaran titanate zirkonate plumbum (PZT5H) sebagai bahan piezoelektrik, litar fleksibel dengan elektrod planar, lapisan nipis polydimethylsiloxane (PDMS), bekas PDMS dan minyak kastor digunakan dalam fabrikasi PMUT. Ketebalan PZT5H, lapisan nipis PDMS, elektrod tembaga (Cu), poliimid (PI) dan bekas PDMS diukur menggunakan mikroskop elektron pengimbas (SEM) dan metrologi fokus tak terhingga G4. Lapan (8) reka bentuk dengan parameter PMUT yang berbeza telah direka dan diuji untuk aplikasi bawah air. Ujian bawah air disimulasikan menggunakan tangki akuarium dengan dimensi 760 mm × 360 mm, hidrofon komersial (UNDT-500 kHz) dan PMUT. Kaedah Pulse-echo digunakan untuk mencirikan isyarat penerima dan menganalisis menerima transduser. Kekerapan sasaran transduser adalah dalam lingkungan 300 kHz hingga 800 kHz. PMUT dengan minyak kastor sebagai lapisan sokongan cecair, mempamerkan prestasi optimum seperti sensitiviti penerimaan tinggi 2.8 dB rel 1 V/μPa, lebar jalur frekuensi lebar 325 kHz dan kekerapan resonan 575 kHz dalam skop kerja. PMUT dengan lapisan sokongan cecair telah berjaya disimulasikan, direka, diukur dan diuji dalam kajian ini. Reka bentuk PMUT berjaya mendapat isyarat penerimaan dengan sensitiviti penerimaan yang tinggi dan lebar jalur frekuensi lebar yang luas.

PIEZOELECTRIC MICRO ULTRASONIC TRANSDUCER (PMUT) WITH FLUIDIC BACKING LAYER AS A SENSING MECHANISM FOR SHORT DISTANCE UNDERWATER MICROPHONE APPLICATION

ABSTRACT

Piezoelectric micro ultrasonic transducer (PMUT) is vital for underwater microphone (hydrophone) applications. Hydrophone is generally used for listening or receiving any acoustic signal in underwater. Several studies have documented that PMUT served as underwater hydrophone with low receiving sensitivity and narrow operation bandwidth. The received acoustic signals with low receiving sensitivity are not accurate due to interference by unwanted signal. Acoustic transducers with narrow bandwidth were effected low resolution for underwater acoustic imaging. Narrow bandwidth transducers were captured for certain frequency only and it were difficult to catch acoustic signal at a long range frequency. In imaging, it is important the transducers can receive the signal for a long range of frequencies. The objectives of this study to increase the low receiving sensitivity transducer in the range of 300 kHz to 800 kHz and widen the narrow frequency bandwidth underwater ultrasonic transducer. Subsequently objectives are a PMUT designed using *d33* mode piezoelectric structure, flexural membrane and fluidic backing layer. Then, A PMUT with the variable parameters of membrane thicknesses, distances between electrodes, piezoelectric materials and fluidic backing layer materials were simulated by COMSOL Multiphysics 5.0 to optimize the PMUT. Next, the PMUT was fabricated using the optimized parameters of PMUT from analysed simulation result to obtain optimum performance and targeted frequency. Lead zirconate titanate (PZT5H) sheet as piezoelectric material, flexible circuit with planar electrodes, thin layer of polydimethylsiloxane (PDMS), PDMS container and castor oil were used in fabrication of PMUT. The thickness of PZT5H, thin layer of PDMS, copper electrodes (Cu), polyimide (PI) and PDMS container were measured using scanning electron microscope (SEM) and alicona infinite focused metrology G4. Eight (8) designs with different parameters of PMUTs were fabricated and tested for underwater application. Underwater testing was simulated using an aquarium tank with dimension of 760 mm × 360 mm × 380 mm, commercial hydrophone (UNDT-500 kHz) and PMUT. Pulse-echo method was used to characterize the receiving signal and analyse receiving transducer. The target frequency of the transducer was in range of 300 kHz to 800 kHz. The PMUT with castor oil as fluidic backing layer, exhibited optimum performance such as high receiving sensitivity of 2.8 dB rel 1 V/μPa, wide frequency bandwidth of 325 kHz and resonant frequency of 575 kHz within the scope of work. The PMUT with fluidic backing layer was successfully simulated, fabricated, measured and tested in this study. A design PMUT was successful obtained a receiving signal with high receiving sensitivity and wide frequency bandwidth.

CHAPTER 1

INTRODUCTION

1.1 Background

Underwater acoustic transducer was developed for marine instrumentation system, underwater acoustic communication system and navigating system. Sonar systems utilize underwater acoustic transducer to generate a sound pulse, often referred as “ping”, and then listen for reflection (echoes) of the pulse. The pulse reflect off a target, and return to the ship. By calculating the speed of the sound in water, and the time for the sound to travel off the target and back, and the distances between the submarine and the target can be computed. With that method, the submarine or autonomous underwater vehicles (AUV) can measure the depth of vehicle and the distance between seabed the submarine. The application of ultrasonic transducer system is shown in Figure 1.1.

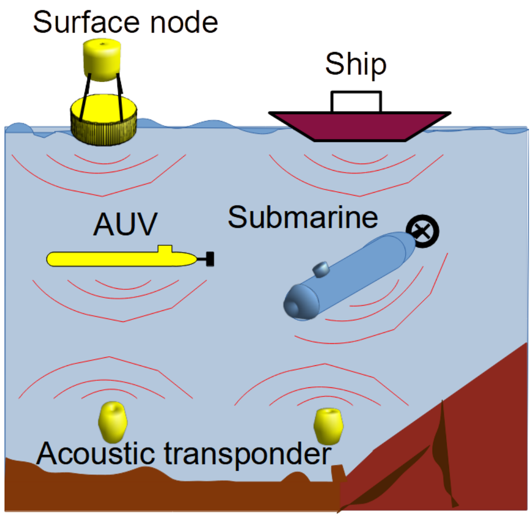

Figure 1.1 Application of ultrasonic transducers in oceanographic engineering and marine

Piezoelectric micro ultrasonic transducer (PMUT) was consist of piezoelectric material as sensing element, top electrode as a generating voltage or transfer the energy to piezoelectric material generating wave and bottom electrode as a ground. Membrane was consist of piezoelectric material, top electrode and bottom electrode. When PMUT applied for underwater, some materials were added as membrane to improve the transmitting signal, receiving signal and frequency bandwidth. Ultrasonic signal is travel in different speed at different medium. Furthermore, the energy of ultrasonic signals were absorbed by medium during travel and it directly proportional to the frequency of signal. If higher frequency is applied, the medium will absorb more energy. The schematic drawing of piezoelectric micromachined ultrasonic transducer (PMUT) designed by Bernstein et al. 1996 is shown in Figure 1.2.

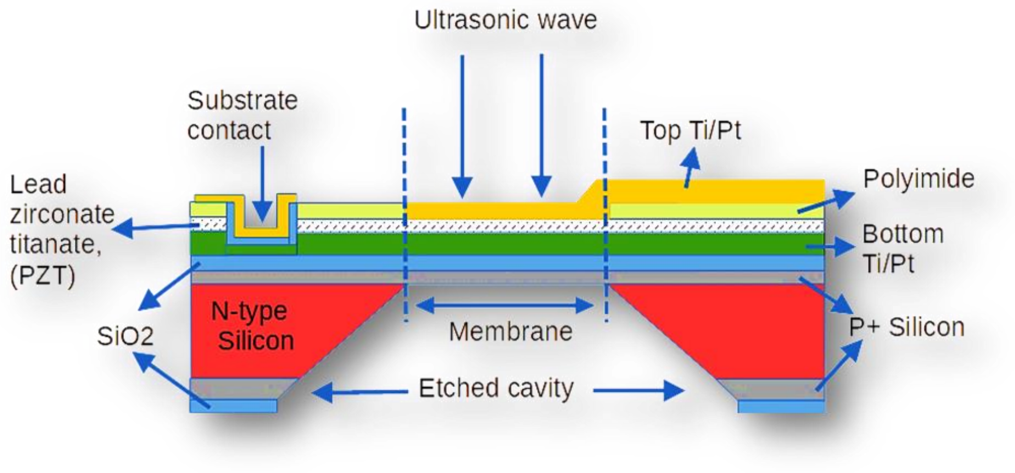

Figure 1.2 D31 mode polarization method modelled by Bernstein et al. 1996

Underwater sound transducers were found in the range of frequency of 1 Hz to 10 MHz and worked at two meters or below from the surface or operated at full depth of ocean depended on their applications (Woollett. 1970). The size and weight of transducers were much related on operating frequency and power to transmit the signal. The transducers usually serve as projectors and receivers, however, if transducers solely served as receivers, it usually in small size and light.

For underwater sound system, one of the criteria that must be consider was attenuation characteristics of ocean. This characteristic was related to operating frequency of transducers and distance of transmission (Tao Wang et al., 2015a). The transmission acoustic signal in seawater has low-pass characteristic where a high-frequency roll-off rate with increase of distance (Bakaric et al. 2021). Underwater sound transducers were transmitted and received the signal using two type method, i.e. communications and echo ranging. "Ping" method has been used in underwater communication to transmit and receive the information. Sonar was the device to transmit and receive the information (Jiang et al., 2019). Ultrasonic transducer used pulse-echo method and time of flight method to project the images (Caliano et al. 2005; Caronti et al. 2006; Wang et al. 2010).Ultrasonic transducers work at different frequencies and amplitudes for underwater applications. High frequency ultrasonic transducers have a short length detection and useful for imaging applications. The frequency operation was range in between 100 kHz to 2 MHz (Sutton, 1979; Tao Wang et al., 2015a). For underwater communication application, a low frequency ultrasonic transducers have been applied. The frequency operation was range in between 10 Hz to 15 kHz (Jiang et al., 2019; Martins et al., 2012). The membrane size of the piezoelectric material is inversely proportional to its operating frequency (Woollett at al. 1970). Thus, it defined that high frequency transducer has small membrane and low frequency transducer has large membrane.

Previous studied, backing layer has been developed in ultrasonic transducers to expand their operating operations, but limited to low frequency transmitting ultrasonic transducers in the range 10 Hz to 15 kHz (Z. Zhang et al. 2019). Then, for MEMS-based ultrasonic transducers were limited to high frequency applications. Receiving ultrasonic transducers are required for wide range applications to receive a strong signal in reducing noise. Backing layer is one of the solution to improve the wide ranges of frequencies operation. Broadband ultrasonic transducers were improved the imaging resolution (Tao Wang et al. 2015a). Receiver piezoelectric ultrasonic transducers without backing layer has narrow bandwidth and gave low resolution to image applications (Zhang and Liang. 2018). Figure 1.3 shows the piezoelectric ultrasonic transducer without backing layer and with backing layer.

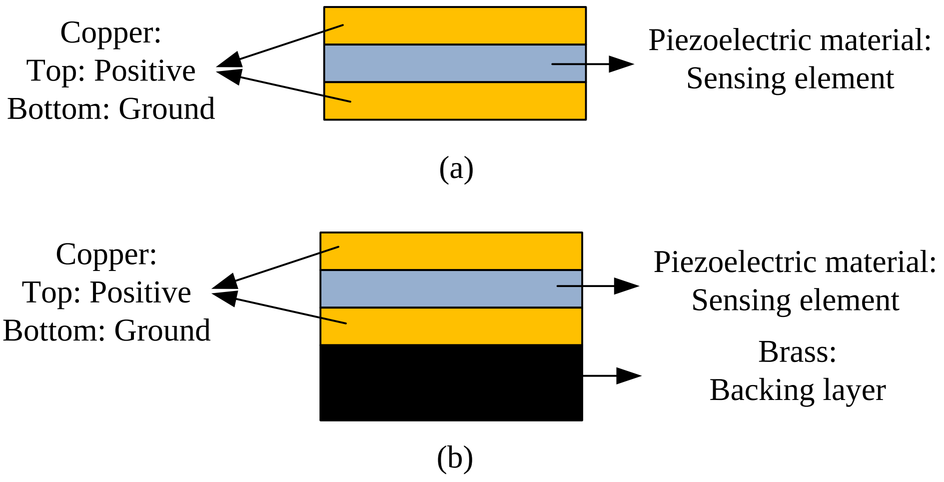

Figure 1.3 Piezoelectric ultrasonic transducer, (a) without backing layer and (b) with backing layer

Previous studies of backing layer in piezoelectric ultrasonic transducers were used high absorption solid material for example brass, wood and carbon. However, these materials are suitable for bulky size transducers and not suitable for small size transducers. Fluidic backing layer such as castor oil has high viscosity and high absorption coefficient is targeted to solve the problem.

Sensitivity of transducers is one of the important criteria that must transducers have in giving a reliable and stable value of signal detection. Several methods have been introduced to improve the sensitivity of piezoelectric ultrasonic transducers. Piezoelectric coefficient is one of the methods has been introduced to improve the sensitivity of transducers. Piezoelectric coefficients, d_{ij} are defined with double subscripts, with the first subscript indicating the direction of the electrical field associated with the applied voltage or produced charge and the second subscript indicating the direction of the mechanical stress or strain. Different material of piezoelectric has different value of piezoelectric coefficients. In designing of piezoelectric ultrasonic transducers, two types of piezoelectric coefficients have been approached. Thickness mode piezoelectric ultrasonic transducers used piezoelectric coefficients, d_{31} orientation to express the output based on stress or strain given to the piezoelectric, while in-plane mode piezoelectric ultrasonic transducers used piezoelectric, d_{33} orientation to express the output. The sensitivity of receving transducers is based on gap between electrodes. The d31 mode PMUT is designed based on sandwiched of electrodes, meanwhile the d33 mode is designed based on in-plane of electrodes. Hence, the d33 mode design is possible to increase the receiving sensitivity based on the design gap of in-plane of electrodes. Figure 1.4 shows how the piezoelectric coefficient method was applied in designing piezoelectric ultrasonic transducer.

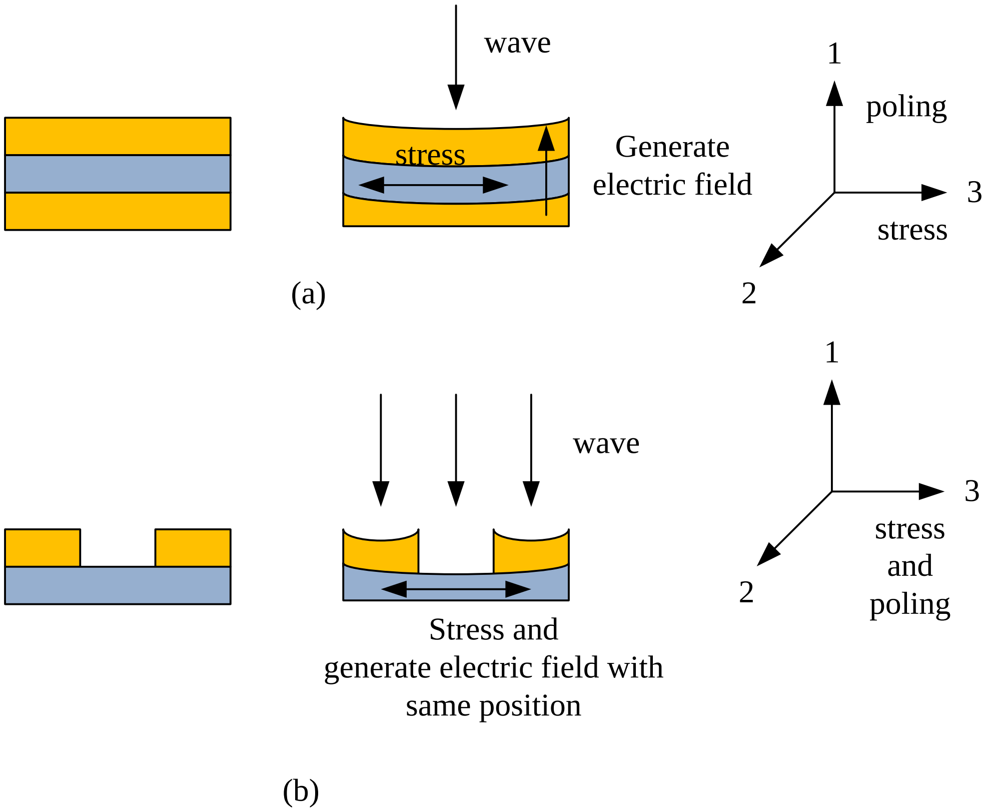

Figure 1.4 Piezoelectric coefficient method approach in piezoelectric ultrasonic design, (a) d31 mode, and (b) d33 mode

A structure-acoustic boundary is setup around transducers to realize the transformation from transducer stress to sound field pressure. Stress from piezoelectric membrane has been obtained from force exerted per unit area in the material. The maximum stress allowable to the piezoelectric membrane also depended on elasticity of piezoelectric material. In this design used PZT5H, the target of stress membrane is around 5 x 10^{10} Pa.

The others challenges in the development of ultrasonic transducers are the transducers capable of withstanding ocean bottom pressure (Choi et al. 2010; Sung et al., 2013), and development of algorithms to solve problems regarding attenuations, signal scattering (Guillermic et al. 2018), reflecting or absorbing (Martins et al. 2012). Normally, sonar transducer can act as transmitter and receiver, and if it served as a simple receiver, it will be designed in small size and light weight (Sung et al. 2013).

For transmitter purposes, the directivity of transducer is a priority requirement, and it is difficult to develop transmitters that function at high frequency because due to high attenuation. High attenuation requires high power sonar to project an ultrasonic signal. The far-field zone is a zone that the signal can obtain good receiving signal. The distance of far-field zone is inversely proportional to wavelength of signal propagation. Then, wavelength is proportional to speed of sound and inversely proportional to frequency. If frequency increase, then the far-field zone is decrease.

In previous studied, piezoelectric material for example zinc oxide (ZnO) (Ito et al., 1995), aluminum nitrate (AlN) (Mastronardi et al. 2014), lead zirconate titanate (PZT)(Ozaki et al. 2014), and polyvinylidene fluoride (PVDF) (AlMohimeed et al. 2018), were the among the favourite piezoelectric materials used in the design of ultrasonic transducers. ZnO was used in thin film single element transducers for acoustic microscopy (Ito et al. 1995). ZnO thin film is suitable for high frequency ultrasonic transducer and which is in the range of 100 MHz to 1 GHz (Ito et al. 1995; Sharp et al. 2004; Zhang et al. 2012). Normally the methods of piezoelectric ultrasonic transducers have been applied in biomedical imaging or medical imaging (Zhou et al. 2011) and immersion (Yaacob et al. 2010) will study back for underwater applications. The limitation of ZnO is their lowest sensitivity to PVDF and AlN (Sarkar et al. 2018). While, PVDF offers several advantages, such as low acoustic impedance, lower fabrication cost and mechanical flexibility compared to PZT. However, it has limitation in receiving sensitivity where PVDF has lower piezoelectric coefficient (d_{33}) compared to PZT (Martins et al., 2012) which PZT5H has ability to produce more voltage than PVDF. A large number of studied on AlN have been conducted for high frequency ultrasonic transducers that more than 4MHz and suitable for biomedical imaging (Lu et al. 2015). Pop et al., (2018) was designed PMUT with

AlN for underwater application. The results showed that the resonant frequency occurred at high frequency exceeding 1 MHz. The operating frequency is not suitable for long range underwater communication (10 to 15 kHz) (Stojanovic and Preisig, 2009) but suitable for short range underwater imaging (100 kHz to 2 MHz) (Sutton, 1979). Other limitations are the fabrication process of AlN and ZnO was complex and need sophisticated laboratory. AlN and ZnO need to fabricate in laboratory due to it did not present in sheet type such PZT and PVDF materials. These PZT and PVDF have been used in large scale applications due to their availability and price. PZT material is more dominant in underwater ultrasonic transducer design compared to other material due to its high piezoelectric properties.

PZT5H has been studied by (Rouffaud et al., 2015). Yun et al., (2014) and designed an acoustic transducers using PZT with three matching layer and backing layer for underwater navigation. The transducers was obtained wide frequencies bandwidth ranging from 800 kHz to 1400 kHz at the receiving part. However, the receiving sensitivity was low at -187.3 dB re 1V/µPa and below expectation which is easily affected by environmental noise. The ultrasonic transducer design with PZT materials still needs to be improved in terms of sensitivity and bandwidth. The target studies is used design of piezoelectric coefficient, *d33* in PZT5H, added suitable matching layer and fluidic backing layer in designing piezoelectric ultrasonic transducers.

1.2 Problem Statement

Current receiving ultrasonic transducer has narrow frequency bandwidth and effect to low resolution image

In underwater imaging application, ultrasonic transducers must have high resolution capability (Lu et al., 2016b). Current studied on backing layer for underwater ultrasonic transducers were applied for low frequency below 100 kHz and high frequency more than 4 MHz. Furthermore, all backing layer application for transmitting ultrasonic transducers studied. Some piezoelectric ultrasonic transducers used high attenuation solid material (Hodnett and Zeqiri. 2009) for example steel (Wang et al. 2021; Zhang and Liang. 2018), brass (Savoia et al. 2016), and wood in designing backing layer and applied for low frequency application that less than 100 kHz. Their transducers size are also in bulky form. Several piezoelectric ultrasonic transducers were designed using fluidic material such air (Pham and Nguyen, 2017; Røed et al. 2019) and oil for applied in small size transducers. Normally, micro size piezoelectric ultrasonic transducers used high absorption epoxy to widen the frequency bandwidth, however their applications were more to high frequency transducers (Nolan et al. 2005). Most of the studies on ultrasonic transducers with high resolution and wide bandwidth capability work at high frequency more than 2 MHz. All these studied on backing layers were applied in transmitting ultrasonic transducers. Underwater acoustic imaging signals are operated in the range of frequency 100 kHz to 1.2 MHz. Receiving piezoelectric ultrasonic transducer need to design for the range in between 100 kHz to 1.2 MHz. In this studies the transducer is designed for the range of 300 kHz to 800 kHz. This is the target bandwidth of the transducer.

Output signal easily influenced by environmental noise due to low sensitivity piezoelectric ultrasonic transducers.

Environment noise easily interrupt the receiving ultrasonic signal if the receiving transducer sensitivity is low (Sung et al. 2017). When the transducers were reduced the size, the sensitivity of transducer was decreased. Some transducers need to design extra amplifier to amplify the output signal, however the noise signal was also increased and the power consumption increased due to power up amplifier component. Filtering circuit is also need to design to remove the noise has been increased (Sung et al. 2016). Some design of piezoelectric ultrasonic transducers need complex fabrication to enhance the transducers sensitivity. Fabrication of transducers with partially-etched need a sophisticated machine to fabricate transducers and enhanced receiving sensitivity (Li et al. 2017; Wang et al. 2017). A simple piezoelectric ultrasonic transducers need to design for receiving part with high receiving sensitivity.

1.3 Objective

The main objective of the study is to design and develop the piezoelectric micromachined ultrasonic transducer (PMUT) based fluidic backing layer particularly used for receiving underwater acoustic signal. Specifically, three objectives that support main objective are as follow:

i. To design, simulate and fabricate the simple structure of a planar electrode based PMUT with fluidic container;

ii. To analyse the most suitable fluidic for the purpose of frequency bandwidth enhancement;

iii. To characterize the fabricated PMUT device for underwater application.

1.4 Research Scope

This study focuses on the development of a transducer that can receive ultrasonic signal underwater for medium frequency, between 300 kHz to 800 kHz. The frequency range for underwater acoustic imaging is 100 kHz to 2 MHz (Sutton, 1979). While the underwater acoustic communication was cover in the frequency range of 10 to 15 kHz (Stojanovic and Preisig, 2009). The distance ranges for transmitting ultrasonic transducers are 40 mm and the depths range for transmitting ultrasonic transducers are

30 mm. This is due to high frequency underwater applications where high attenuation occur during signal propagation in water medium. The far-field zone is inversely proportional to frequency of the signal. If frequency of the zone is increase then the far-field region is reduced. The far-field region is the zone where the ultrasonic signal in a very good strength. This study is focused on receiving transducer which it received an ultrasonic signal from transmitting transducers and the signal strength depended on transmitting signal. The development of this receiving transducers are focused on sensitivity and wide frequency bandwidth detection. This also covers the characterization and calibration of ultrasonic transducer in distance range of 40 mm. This distance range was selected based on previous researchers 1 mm to 500 mm (Siwapornsathain and Lal, 2001; Song et al., 2015).

The simulation of ultrasonic transducer is carried out using COMSOL MultiPhysics 5.0 to determine the parameters of ultrasonic transducer for the frequency range 25 kHz to 1500 kHz with step of 25 kHz and underwater testing. The simulation includes loading of fluid pressure. The simulation is conducted on three different materials, namely AlN, ZnO, PVDF, Q and PZT5H with the same thickness and other configurations. These materials are well known in literature owing to their capabilities in electromechanical coupling, dielectric property and density. These materials have been used in the form of thin films for acoustic sensing for commercial designs. The simulations are used as guideline to develop a single ultrasonic transducer.

For experimental part, PMUTs that made of PVDF and PZT5H were tested and calibrated for receiving sensitivity, frequency bandwidth and resonant frequency. Nevertheless, the hydrostatic pressure of the transducer is not considered in this study.

The pulse-echo method was conducted on the ultrasonic transducers. The commercial hydrophone was used to project the ultrasonic signal and the PMUT received the signal and tested for receiving sensitivity and frequency response. The testing on transducers were in receiving part which is in the range of frequency 25 kHz to 1500 kHz with step of 25 kHz.

1.5 Thesis Organization

Chapter 1 provides an overview about sonar and ultrasonic transducer used in underwater application. Problem statements, research objectives, and research scope are also presented including the summary of contribution.

Chapter 2 provides the literature review on the design of ultrasonic transducers using *d31* and *d33* polarization methods, as well as piezoelectric material, backing layer, calibration and pulse echo method.

Chapter 3 highlights the methodology used in this study, which includes structure and performance of PMUT. This chapter starts with COMSOL MultiPhysics FEA simulation using pressure acoustic and frequency domain, solid mechanics, and electrostatics on PMUT. The methodology to simulate *d33* mode and fluidic backing layer implemented in the PMUT design is also described. Simple fabrication and process setup are explained in this chapter. Lastly, the experimental setup to characterize the PMUT design is included.

Chapter 4 presents the results and discussion obtained from the simulation, fabrication and experiment. It discusses the findings obtained from the FEA including material selection, resonant frequency tuning and sensitivity determination. These chapter also discusses the fabrication of fluidic container using mould. The determination of thickness of the fluidic container, PZT5H, flexible circuit, and top layer PDMS are also obtained. Then, the effects of vibration and temperature on transducer are discussed. Lastly, the characterization of PMUT with fluidic backing layer are obtained and discussed.

Chapter 5 presents the conclusion of this study and provides recommendation for future studies.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

There are several studies on underwater piezoelectric micromachined ultrasonic transducers (PMUT) which include underwater transducer arrays, hydrophone, transponders, and underwater sound projector. The overall design for underwater acoustic transducer is based on the thickness or d33 mode to induce the output voltage. The underwater PMUT uses piezoelectric material as electro-acoustic transduce to transmit and receive acoustic signals. The design of PMUT depends on the application of the transducer. The backing system was used to improve bandwidth of underwater PMUT. Several studies on the design of acoustic transducers has used d33 mode and backing layer systems are highlighted in this chapter.

2.2 Design and Principles

Design and principles of micromachined ultrasonic transducer was discussed methods have been used by researchers. Methods used by researchers in designing electrode circuitry, namely d33 mode polarization has been discussed. Next, principles of backing layers are discussed at the end of subsection.

2.2.1 D33 Mode Polarization

D_{33} mode polarization was referred to axes of piezoelectric polarization direction. The axes, x_3 was referred to axis parallel to piezoelectric film plane, the x_1 was referred to axis perpendicular to piezoelectric film plane, and the x_2 was determined by right-hand coordinate rule. Figure 2.1 shows the PMUT operated in d33 mode. Ultrasonic wave came from the top to PZT membrane and create stress to the membrane at x_3 direction, and then electric field distribution was created at x_3 direction from positive potential to negative potential. This is called d33 mode operation, Wang et al., (2007a). The voltage generated, V at terminal is shown in equation 2.1.

$$V = \frac{Q}{C} = \frac{D_3}{\varepsilon} G \tag{2.1}$$

The electrical charge, Q induced at terminal was caused by electric displacement, D_3 and the effective electrode area, A_e shown in equation 2.2.

$$Q = D_3 A_e = D_3 L t \tag{2.2}$$

Then the capacitance, C is calculated by

$$C = \varepsilon \frac{A_e}{G} = \varepsilon \frac{tL}{G} \tag{2.3}$$

where ε is permittivity of piezoelectric material, t is thickness of piezoelectric material, L is total length of electrodes and G is electrode gap.

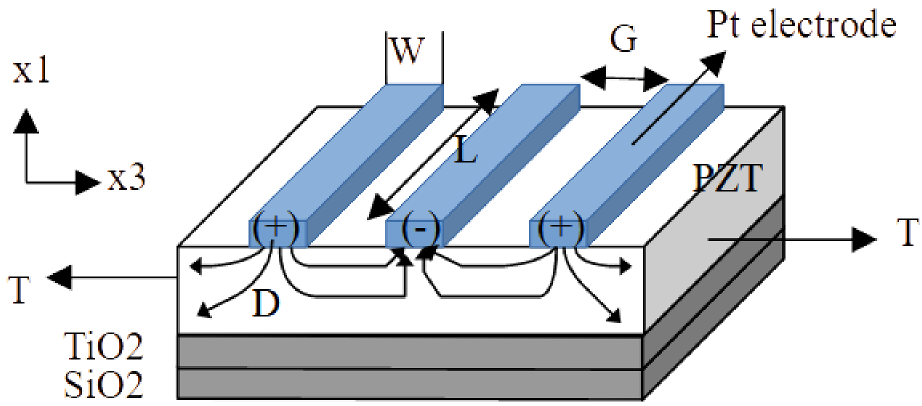

Figure 2.1 Schematic structure of the in-plane polarized PMUT: Electric field distribution

.

The cantilever was designed to generate strain on PZT thin film and electrodes was configured for d33 mode. The voltage, *V* was induced based on equation shown in equation 2.4,

$$V = \sigma_{33} g_{33} L_3 \qquad (2.4)$$

where σ_{33} is stress at x3 direction, g_{33} is piezoelectric coefficient and L_3 is gap of electrodes, Park et al., (2009). A double spiral electrode was designed and piezoelectric material was polled by d33 mode. The double spiral design is shown in figure 2.2 (a). The poling field induced by spiral electrode has a distribution in the diaphragm. The material properties in the diaphragm are anisotropic and nonuniform. The double spiral electrodes, V1 and V3 were fabricated on top of piezoelectric material, PZT wafer and another double spiral electrodes, V2 and V4 were fabricated aligned with V1 and V3 under the bottom of PZT wafer. The PZT wafer was poled and the electrical field was distributed all the area of PZT wafer. It is shown in figure 2.2 (b). The receiving sensitivity of double spiral transducer was measured inside an anechoic chamber. The maximum sensitivity of ultrasonic transducer for air medium was 19.95 mV/Pa at frequency of 13.71 kHz.

Another studied conducted by Bernstein et al. (2000) was used d33 mode method. This ultrasonic transducer design was worked for frequency at 3 MHz. The d33 mode has been implemented in the design to increase the receiving sensitivity. In this method, all transducer electrodes were placed in one-plane direction (planar orientation). The receiving sensitivity increases based on the equation 2.5. The generated voltage, *V* depends on spacing between positive and ground electrodes, *l*.

$$V = \sigma_{xx} \, . \, l \, . \, g33 \qquad (2.5)$$

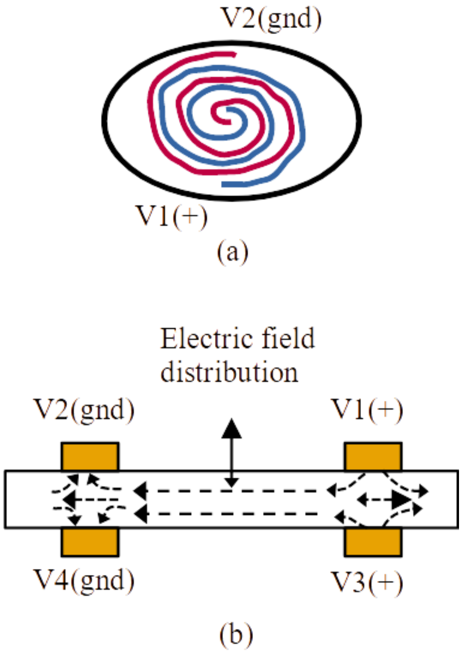

Figure 2.2 Design structure of double spiral electrodes, (a) top view double spiral design, and (b) electrical field distribution after polled by d33 mode

In PZT specification, the piezoelectric voltage coefficient, *g33* is twice higher than the *g31*. This is another advantages of *d33* mode polarization method. σ_{xx} is stress of transducer membrane when ultrasonic waves hit the membrane. The *d33* mode polarization method is shown in figure 2.3.

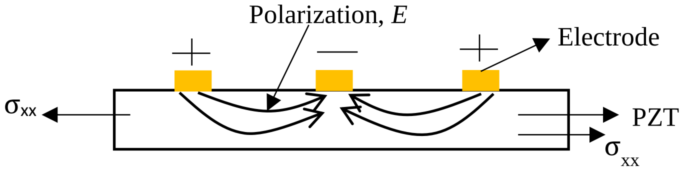

Figure 2.3 *D33* mode polarization method of ultrasonic transducer

Sonar transducer was fabricated on 100 mm diameter silicon wafer with 290 µm thickness. The sonar was designed with ring electrodes and the electrodes were radially poled. It worked in *d33* mode polarization. The transducer consisted of 2 µm silicon oxide (SiO2), 0.5 µm zirconium oxide (ZrO2), 3 µm PZT, 3 µm polyimide and Ti/Pt/Au metal layer. The transducer has receiving sensitivity of -210 dB ref V/µPa and resonant frequency of 3.8 MHz. Furthermore, Mescher et al. (2002) made several improvement to the previous device developed by Bernstein et al. (2000). The transducer was improved in terms of operating range of 1-5 MHz.

Zhu et al. (2007) was developed micro-acoustic device based on *d33* mode for ultrasonic transducer applications. The transducer was designed with a square diaphragm clamped at four edges and a multi-layer membrane consisting of Pt/PZT/TiO2/SiO2. The electrodes were patterned in interdigital transducer (IDT) and formed a square ring-shaped. This square ring-shaped electrodes radially poled and polarized in-plane direction. The frequency ranges for transmitting and receiving ultrasonic transducer were 100 Hz to 200 kHz. The width of the electrodes was 60 μm and the space between the electrodes was 20 μm. The membrane size was 1000 x 1000 x 3 μm^3, while the thickness of the PZT film was 1.8 μm. The PZT was polarized along in-plane direction at 100 kV/cm. The measured resonant frequency was around 44 kHz for air testing condition. The electromechanical coupling factor was calculated at 0.22. The maximum sensitivity was around 11 mV/Pa, and the ultrasonic radiating performance was in the range of 5 kHz to 60 kHz. Another measured elements were the maximum acoustic pressure of 90 mPa, the resonant frequency of 43.8 kHz and the output sound pressure level (SPL) of 73 dB.

Receiving piezoelectric ultrasonic transducer was based on vibration or wave to generate the output voltage. Piezoelectric accelerometer is based on piezoelectric direct effect which depend on vibration and convert it into voltage. Zhou et al. (2016) was design piezoelectric accelerometer based on d33 mode. The interdigital transducer (IDT) electrode was fabricated on the surface of PZT thin film to perform d33 mode operation and generate voltage. Cantilever with PZT film would deformed and induced high electric field. The working operation similar to figure 2.2 when to generate the output voltage with d33 mode. The voltage sensitivity obtained by d33 mode piezoelectric accelerometer was 4.55 mV/g.

(Rahaman et al., 2019; Rahaman and Kim, 2019) was introduced combination AlN and d33 mode in the acoustic transducer design. The combination of these two has eliminated sensor noise which AlN with low dielectric loss has minimized thermal mechanical noise and d33 mode has enhanced the transducer sensitivity with increase of IDT electrodes gap. Two designs have been studied and the difference between these two were torsional beam length. The first design called "mic335" obtained sensitivity of 3.29 mV/Pa and second design called "mic280" obtained sensitivity of 3.41 mV/Pa. The torsional beam length can improve more sensitivity in d33 mode.

Lu et al. (2014) developed the first PMUT compatible with CMOS. AlN is a piezoelectric element that has a low dielectric constant and high receiving sensitivity used as sensing element. Silicon dioxide (SiO_2) is a passive layer with a thickness of 0.8 μm and AlN has a thickness of 0.75 μm. PMUT has a diameter of 25 μm and the centre frequency of water is loaded at 20 MHz. The d33 mode membrane used ring-type electrode to induce electric field with the structure of in-plane poling scheme. The in-plain strain is induced by d33 effect. The magnitude of d33 coefficient has two times higher than d31 coefficient. Moreover, the d33 mode diaphragm has a sensitivity twenty times higher than the d31 mode diaphragm. Later, Shen et al. (2013) designed an acoustic transducer with spiral shape. This spiral shape was used d33 mode concept to generate the electric field. The transducer consisted polymethylmethacrylate (PMMA) with thickness of 2.5 mm, epoxy, PZT thickness of 127 μm, and Au thickness of 300 nm. The diaphragm has radius of 3 mm and receiving sensitivity of 16.95 mV/Pa. The resonant frequency for the transducer was 13.71 kHz.

Lu et al. (2020) designed PMUT based on thin-film lithium niobate ($LiNbO_3$). The electrodes based lateral field excitation (LFE) were fabricated on 36° Y-cut $LiNbO_3$ thin-films for high figure of merits. PMUT showed high in electromechanical coupling (K^2) of 4.2%, and high quality factor (Q) in vacuum of 2605 and air of 264 at 7.6 MHz. The arrangement of LFE electrodes are similar to previous studies such as IDT and spiral methods where the LFE electrodes fabricated on upper of piezoelectric material. It would made the PMUT worked in d33 mode operation to induce the electric field. PMUT designed with LFE electrodes at the top, followed by single layer of $LiNbO_3$, silicon dioxide (SiO_2) layer, silicon (Si) layer at the edge, and air under $LiNbO_3$ membrane. The resonant frequency for PMUT was 7.6 MHz. The dynamic displacement was measured using a Polytec vibrometer OFV-5000 of 20.2 nm/V.

Table 2.1 Summary of D33 mode polarization

Author	**Shape**	**Piezoelectric Material**	**Polarization**	**Additional Features**	**Output Performance**
Wang et al. (2007a)	Interdigital Electrodes (IDE)	PZT thin film	*d33* mode	Flexural membrane with all the edge were clamped	Claimed obtain high sensitivity. Value of sensitivity not mention.
Park et al. (2009)	Double Spiral Electrode	PZT wafer	*d33* mode	-	Maximum sensitivity of ultrasonic transducer for air medium was 19.95 mV/Pa at frequency of 13.71 kHz
Bernstein et al. (2000)	Ring	PZT	*d33* mode	Four diaphragms with Quad designs per unit cell, Two or three diaphragms with “racetrack” designs per unit	FEA results: Quad with receiving sensitivity of -209 dB ref V/µPa, “racetrack” of -211.5 dB ref V/µPa , and Nona of -213.2 dB ref V/µPa.

				cell, Nine diaphragms with Nona per unit cell.	Testing: MONO150 transducer design has receiving sensitivity was at – 210 dB ref V/µPa and resonant frequency was at 3.8 MHz.
Mescher et al. (2002)	Shell	PZT	*d33* mode	New piezoelectrically-actuated MEMS-based micro shell, dome structure membrane.	Quad85: Receiving sensitivity was at -248 dB re 1 V/µPa, resonant frequency was at 5.6 MHz, and frequency bandwidth was at 1.78%.
Zhu et al. (2007)	Square-ring IDT	PZT	*d33* mode	Multi-layer membrane, Pt/PZT/TiO_2/SiO_2 structure, interdigitated electrodes in square-ring shaped.	The maximum acoustic pressure was at 90 mPa and resonant frequency was at 43.8 kHz. The output sound pressure (SPL) measured that time was at 73 dB.
Zhou et al. (2016)	Rectangle IDT	PZT	*d33* mode	A pair of IDT electrodes on PZT thin films.	In simulation result, the resonant frequencies for *d33* and *d31* mode polarization were

					closed to each other where the resonant frequency for *d33* mode was 13.48 kHz and *d31* mode was 13.34 kHz.
(Rahaman et al., 2019; Rahaman and Kim, 2019)	IDT	AlN	*d33* mode	Combination AlN and IDT	Eliminate sensor noise, increase sensitivity, "mic335" obtained sensitivity of 3.29 mV/Pa, "mic280" obtained sensitivity of 3.41 mV/Pa, Torsional beam length was increase more receiving sensitivity.
Lu et al. (2014)	Ring-type Electrode	AlN	*d33* mode	-	High sensitivity, value not given.
(Shen et al. 2013)	Spiral	PZT	*d33* mode	Double spiral electrode on both side top and bottom of PZT,	The receiving sensitivity of 16.95 mV/Pa. The resonant frequency for this transducer is 13.71 kHz.

Lu et al. (2020)	IDT	$LiNbO_3$	*d33* mode	IDT on top of $LiNbO_3$	PMUT has electromechanical coupling of 4.2%, quality factor in vacuum of 2605 and air of 264, and displacement sensitivity of 20.2 nm/V