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PIEZOELECTRIC MICROMACHINED ULTRASONIC TRANSDUCER (pMUT) USING ADHESIVE WAFER BONDING FOR UNDERWATER APPLICATIONS



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JAMILAH WARDAH BINTI HARUN

SULTAN IDRIS EDUCATION UNIVERSITY

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SULTAN IDRIS EDUCATION UNIVERSITY

2024



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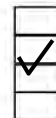
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ABSTRACT

The objective of this study is to design and develop a piezoelectric micromachined ultrasonic transducer (pMUT). The developed pMUTs are then characterized and verified for underwater applications. PDMS and epoxy thick films are deposited using the spin-coating technique. The wafer bonding method is employed to adhere to the functional and structural layers. Bonding quality is analysed using FESEM images while material interaction is studied using EDS analysis. Electrical characterization is carried out on all developed pMUTs using impedance analysis. Finally, the receiving and transmitting responses are determined and verified using the pulse-echo technique in a freshwater tank. All pMUTs are successfully constructed, with overall thicknesses ranging from 880 to 980 μm . PDMS and Epoxy thick films are uniformly deposited at 1000 rpm. A strong bonding between the piezoelectric active layer and the silicon substrate is observed using PDMS as an adhesive, with a minimum thickness of 26.42 μm and a maximum of 64.76 μm . It is verified that the speed of sound is measured at 1333.3 ms^{-1} using the developed pMUT. At an operating frequency of 100 kHz, the DUT utilizing PDMS adhesive demonstrated 66% higher sensitivity in receiving mode and 71% more sensitivity in transmitting mode compared to the DUT using epoxy. PDMS adhesive has also contributed to a wider operating frequency while epoxy adhesive carries a dead-space below 80 kHz of operating frequency. In conclusion, pMUTs for underwater applications can be fabricated using the wafer bonding method. The performance of all developed pMUTs has been measured through mechanical characterization, electrical analysis, and underwater verification. It is found that the proposed wafer bonding method simplifies the fabrication of pMUT. The usage of PDMS as an adhesive has contributed to increased sensitivity while maintaining operating bandwidth.





TRANSDUSER ULTRASONIK DIMIKROMESIN PIEZOELEKTRIK (pMUT) MENGUNAKAN CANTUMAN WAFER UNTUK APLIKASI DALAM AIR

ABSTRAK

Objektif kajian ini adalah untuk merekabentuk dan membangunkan transduser ultrasonik dimikromesin piezoelektrik (pMUT). pMUTs yang dibangunkan akan melalui perincian dan pengesahan untuk aplikasi dalam air. Kaedah salut-putar digunakan untuk mendepositkan saput tebal PDMS dan epoksi. Kaedah cantuman wafer digunakan untuk melekatkan lapisan struktur dan lapisan penderiaan. Kualiti cantuman dianalisa menggunakan imej FESEM manakala tindakbalas bahan akan dikaji menggunakan analisis EDS. Perincian elektrik pula dijalankan ke atas semua pMUT yang dibangunkan menggunakan analisis impedans. Akhir sekali, tindakbalas penerimaan dan penghantaran ditentukan serta diperincikan di dalam tangki air tawar melalui kaedah denyut-gema. Kesemua pMUT telah berjaya dibina pada ketebalan keseluruhan di antara 880 ke 980 μm . Filem tebal PDMS dan epoksi didepositkan dengan sekata pada 1000 rpm. Cantuman yang baik antara lapisan aktif piezoelektrik dan substrat silikon dapat diperhatikan dengan menggunakan PDMS sebagai pelekat, pada ketebalan minimum 26.42 μm dan maksimum 64.76 μm . Kelajuan bunyi juga telah disahkan pada 1333.3 ms⁻¹ menggunakan pMUT yang telah dibangunkan. Pada frekuensi 100 kHz, peranti yang menggunakan PDMS didapati 66% lebih sensitif dalam mod penerimaan dan 71% lebih sensitif dalam mod penghantaran, berbanding peranti yang menggunakan epoksi. PDMS juga didapati menyumbang kepada kelebaran jalur operasi berbanding epoksi yang tidak memberikan reaksi di bawah frekuensi 80 kHz. Kesimpulannya, kaedah cantuman wafer boleh digunapakai untuk membina pMUT bagi aplikasi dalam air. Perincian mekanikal, analisis elektrik dan pengesahan bawah permukaan air telah dijalankan untuk menentukan prestasi kesemuapMUT yang telah dibangunkan. Kaedah cantuman wafer yang dicadangkan didapati mampu meringkaskan proses pembuatan pMUT. Selain itu, penggunaan PDMS sebagaibahan pelekat telah menyumbang kepada peningkatan sensitiviti tanpa menjejaskan kelebaran jalur operasi.



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LIST OF ABBREVIATIONS

AlN	Aluminum Nitride
AFM	Atomic force microscope
AuNP	Gold Nanoparticles
BHF	Buffered-hydrofluoric acid
CAREF	Central advanced research enabler facility
DUT	Device under test
EDP	Ethylenediamine pyrocatechol
EDS	Energy dispersive X-ray Spectroscopy
EDX	Energy dispersive X-ray
FEA	Finite-element analysis
FESEM	Field emission Scanning electron microscope
LCR	Liquidity coverage ratio
LTO	Low-temperature oxide
MUTs	Micromachined ultrasound transducers
PDMS	Polydimethylsiloxane
pMUTs	Piezoelectric micromachined ultrasound transducers
PNF	Proprioceptive neuromuscular facilitation
PZT	Lead zirconate titanate
SAW	Surface acoustic wave





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SEM	Scanning electron microscope
SIO	Silicon on insulator
Si ₃ N ₄	Silicon Nitride
SiO ₂	Quartz
ZnO	Zinc Oxide



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CHAPTER 1

INTRODUCTION



Curie, J. and Curie, P. made the initial discovery of piezoelectricity in single crystals in 1880. However, it wasn't until 1917 that it was used in underwater acoustic applications. That's when physicist Paul Langevin used quartz, a piezoelectric crystal, in his hydrophone as part of his study into creating underwater acoustic transducers for finding submarines. Later, his sound projector also used a quartz transducer. The idea that dictates the distribution of electric polarization and illustrates how a piezoelectric field responds to electrical stress by producing depolarization waves can be used to explain the piezoelectric capabilities of a material. The internal polarization force balances the crystal strain force when the system is in equilibrium. The emitting depolarization field will provide a rebalancing force to maintain the initial equilibrium





if this equilibrium is disturbed by the application of an external electric field or an external mechanical load.

Mechanical stress will happen if the external force comes from an electric field (applied voltage), but an electric field will be created if the external force comes from a mechanical displacement (vibration). The term for this phenomenon is known as piezoelectricity (Motamedi, 1994, p. 521).

A transducer is a device that changes one form of energy into another. In receiving mode, an acoustic transducer transforms the mechanical energy of sound waves into electric energy, while in transmitting mode, it transforms electrical energy into sound waves. Micromachined ultrasonic transducers (MUTs) have recently undergone substantial development for a variety of uses.

The MUTs that employ piezoelectric principles fall under the category of piezoelectric MUTs (pMUTs). Due to the decreased impedance of pMUTs, more energy input might be possible. It is simple to create arrays using MUT that have high element density, small element size, and high resonant frequency (Li, Ren, Fan, & Wang, 2017). The sensitivity of the single-element transducers has a big impact on a MUT array's characteristics. Sensitivity is significantly influenced by the structure of the pMUT and the piezoelectric film.

Piezoelectric ceramics made of lead zirconate titanate (PZT) are the most common active materials used in underwater acoustic transducers, while composites that combine the advantages of ceramics and polymers are gaining more attention (Li,





Deng, & Carlson, 2012). This study suggested using the wafer bonding technique to create an immersion-application PZT-based piezoelectric micromachined ultrasonic transducer.

An active layer consisting of electrode PZT is adhered to the structural layer of the silicon wafer using commonly used adhesive Polydimethylsiloxane (PDMS). PDMS stands out as a favored elastomeric substance in scientific and engineering fields, especially within biomedical engineering, owing to its widespread availability, transparency, biocompatibility, and ease of manufacturing (Duffy, McDonald, Schueller, & Whitesides, 1998). Epoxy is another potential adhesive material that on the other hand, is chosen for its superior strength, rigidity, and strong adhesive capabilities. The development phase includes a spin-coating method to apply adhesive at various thicknesses. Each prototype has undergone structural, electrical, and underwater characterizations. The structural analysis includes the elemental composition of the material as well as the thickness of each material layer observed by a field emission scanning electron microscope (FESEM).

One of the most crucial parts of the pMUT's construction is the adhesive layer. When analyzing the two polymers that will be the subject of this study's emphasis, flexibility stands out as a key distinction in the material choice for the adhesive layer. Energy is produced by pMUT through vibration.

Several methods that make use of polymer adhesive have been developed, mostly for device packaging. The adhesive layer should be suitable in terms of both function and characteristics. The specifications are met by the two polymers used as





adhesives, PDMS and epoxy. Both types of polymers adhere to silicon-based ceramics. In the electronics sector, PDMS is a high-performance material that is frequently employed. This elastomeric polymer has a turnable hardness and great flexibility. Excellent qualities are required for these features for vibration to work. A dielectric polymer is PDMS which can be utilized as a heat-dissipation material in electronic components due to its excellent thermal conductivity. On the other hand, electrical circuit components and electronic gadgets are frequently coated and enclosed with epoxy. It is a thermosetting adhesive with long-lasting, solid bonding. Typically, it protects an item from harmful environmental influences and vibrations. An electrical insulator is epoxy. However, it turns conductive when it contacts copper. Compared to PDMS, it has a low heat conductivity.



possessing unique qualities extensively utilized in the micro-electric industry, proves to be incredibly fascinating. These resources have the potential to enhance the overall performance of pMUTs, a prospect that can be assessed comprehensively through thorough studies.

A time-consuming and delicate deposition method is needed to fabricate pMUT layer by layer. Several strategies will be thought up, and streamlining the entire process will be the main objective. The range of application is limited to the adhesive layer's various thicknesses. Hence, spin coating is the most appropriate technique for this research since it is simple to create a homogenous coating that can be accomplished at various thicknesses.





The following step involves utilizing FESEM to characterize the coating quality and required thickness based on spin speed. In addition, any chemical reactions that took place can be seen. The energy dispersive x-ray (EDX) analysis is a method of elemental analysis connected to electron microscopy that is frequently employed. It is based on the production of distinctive x-rays that indicate the existence of elements present in the samples. Researchers employed scanning electron microscopy (SEM), which has several benefits including being simple to use, requiring little to no sample preparation, and operating quickly. In essence, SEM may make images by focusing an electron beam across a surface. The interaction between the beam's electrons and the sample results in a variety of signals that can be used to gather data (surface topography and composition).



While developing piezoelectric transducers, measuring electrical impedance is a crucial step. All electrical characteristics of the transducer are provided, along with comparisons to expectations. Frequently, transducers are bonded to a substrate at megahertz frequencies. This is the case, for instance, with plate transducers, which eventually grow too thin and delicate to be used on their own. The electrical impedance of the transducer might vary significantly depending on the substrate's presence. When the attenuation of waves in the substrate is low and the end faces of the bounded substrate are flat and parallel to the transducer, this occurs. These changes have nothing to do with the properties of the transducer and are caused by the acoustic waves reflecting off the ends of the substrate.

In this research, impedance analysis is used in electrical characterizations to identify the appropriate electrical circuit for each device. Designing the electric





matching circuit that connects the driving or receiving circuit to the transducer is known as electrical impedance matching. Moreover, the shape and electrical characteristics of the wire and transducer must be designed. Impedance matching is accomplished by a variety of devices placed in between an energy source and a load. Engineers use transformers with transmission lines, resistors, inductors, capacitors, and other components to match electrical impedances. It is very certainly necessary to match the impedances between a source, transmission line, and load when working with digital or analog signals. To ensure that a signal sent down the line is perceived as the same signal at the receiver, impedance matching is crucial in transmission lines.

Impedance mismatching can cause pulse distortion and signal reflection because of even a slight mistake. The window of error shrinks as the frequency rises.

Therefore, maximum power transfer becomes crucial at higher frequencies. If the impedance is exactly matched, the circuit operates correctly and effectively. Due to signal reflection, there are numerous negative effects in the circuit if the impedance is not properly matched. The transmitted signals coincided with these reflected waves. Moreover, it may result in data delays, phase distortion, and a decrease in the signal-to-noise ratio.

In electrical and electronic applications, a load's power input is a crucial variable. In DC circuits, the load is represented by a resistor with R_L ohms of resistance. Like this, we may represent it in AC circuits by using a complicated load with an impedance of Z_L ohms.

According to the maximum power transfer theorem, the DC voltage source





will only supply the variable load resistor with the greatest amount of power when the load resistance is equal to the source resistance. Like, according to the Maximum Power Transfer Theorem, the AC voltage source will only provide the variable complex load with the greatest amount of power when the load impedance is equal to the complex conjugate of the source impedance.

The last characterization focuses on the estimation of the pMUT's sensitivity or receiving and transmitting responses using the ultrasonic pulse-echo method in a water tank. A sonar transducer can be performed to transmit and/or receive sound waves. To emit or receive acoustic energy in the desired directions, directional beams are generated by arrays of individual transducer elements, which are the standard for sonar transducers. Many sonar systems use a distinct transducer on each array for producing sound projector and receiving sound hydrophone, while some sonar systems employ the same transducer for both functions.

1.2 Research Backgrounds

Recently, PMUT for underwater sensing applications has grown in popularity, and over the past few years, an overview of this developing technology has been thoroughly addressed (Akhbari, Sammoura, & Lin, 2016). Basic pMUT structures are often created by sandwiching an active or functional layer made of a thin layer of piezoelectric material between two electrodes. Within an active layer, energy transitions from mechanical to electrical to mechanical take place. A structural layer typically supports the active layer. Layers that are both active and structural are combined to create the



membrane.

The membrane is clamped on the edges of the piezoelectric material, which when it tries to contract or expand causes a deformation that pushes the membrane out of the horizontal plane, displacing the medium nearby and generating a pressure wave. The electrostriction process is sensed by a piezo active layer, but the parameters that relate to frequency will depend only on the design and materials that are chosen.

Less studies have recently concentrated on using PZT as the active component in pMUT, which tunes its resonant frequency to suit underwater applications. The majority of pMUTs functioned at a set resonance, and only modern designs allow for the modification of the resonance frequency. Today, a wide variety of commercially accessible materials, including platinum, gold, copper, and titanium, are available for use as connections and electrodes in microfabricated devices. Each of these materials has a unique performance.

The vibration membrane of the pMUT is made of a silicon-on-insulator (SOI) wafer. This work demonstrates the manipulation of adhesive materials and their thickness. The monitored outcome includes operational bandwidth, resonance frequency, and transmit and receive replies. Changes in structural parameters will be shown to have an impact on resonance frequency, electromechanical coupling coefficient, and acoustic impedance in addition. In this study, pMUT thickness is adjusted to tune the resonance frequency. More research will be done on the model to examine overall performance after the model dimension is established.



Acoustic sensors used for underwater applications are highly dependent on the operating frequency. This is because the operating frequency will determine the phenomenon that will occur in the propagation of sound waves in the water. The arrangement of molecules in the medium plays the most important role in determining the propagation pattern of sound waves because sound waves are arranged periodically between compression and rarefaction pressure. Therefore, the frequency will affect how much attenuation will occur on the propagation of sound waves in water. The higher the frequency, the higher the attenuation that will occur. Several phenomena including reflection, absorption, diffraction, interference, and reverberation may cause this attenuation. Because of this, most sonar operates at frequencies below 200 kHz and only certain applications will sonar operate above 200 kHz. In addition, the operating frequency also greatly affects the propagation distance of sound waves under the surface of the water. Due to high attenuation, high frequencies cannot propagate as far as waves at lower frequencies.

For echo sounder applications, for example, the commonly used operating frequency is between 20 kHz and 250 kHz. The latest CHIRP technology on sonar can use frequencies up to 400 kHz for water depths less than 50 m. there is always a trade-off between frequency and distance for this sonar application. If high resolution is the priority, then the propagation distance has to be reduced. If propagation distance becomes a priority, then the overall resolution of the system must be sacrificed. For example, the measurement of the depth of the seabed at a depth of 200 m cannot be done at high resolution as with CHIRP technology because for penetration as far as 400 meters (the round trip of sound waves at a depth of 200 m), only signals at a frequency of less than 50 kHz are used. On the other hand, the details of bottom profiling on





CHIRP can only be carried out at a depth of less than 50 m because the details can only be revealed by manipulating high frequencies.

Several other factors need to be emphasized during the construction and design of underwater acoustic sensors. Among them is the operating depth of the sensor. Operating depth will determine the amount of hydrostatic pressure that will be applied to the sensor including the cable connected to the sensor. Operating depth specifications must be clearly stated in the datasheets in addition to the specific pressure test that needs to be done on the sensor which is usually carried out in the pressurizing chamber. For this study, the targeted operating depth is only 1 meter, therefore the housing design aspect for the sensor is not the focus of discussion. The shape of the housing also sometimes describes the ability of a sensor to withstand hydrostatic pressure. For example, a sensor capable of operating at a depth of 100 meters will use a spherical housing while sensors for a depth of fewer than 100 meters usually use a cylindrical housing. The material used in the housing also plays a role in protecting against hydrostatic pressure.

Typically, there is more than one material that will be used for underwater acoustic sensor housings. It depends on the role of the part, for example, a hard metal material will be used to protect the piezoelectric element that is easily broken but a rubber-based material is used on the wavefront to provide impedance matching for transmission and reception. The material used in the wave front depends on the thickness and the material used as an active material where the electro-acoustic process occurs. The material that is usually used to protect the sensor structure is based on bronze alloy or copper alloy. For the wavefront, butyl rubber is used as an impedance-





matching layer.

1.3 Problem Statements

Several approaches are implied by the fabrication of pMUT to obtain results and applications. Several researchers employ complex and time-intensive methods when applying layers of piezoelectric coatings onto substrates. It is intriguing to offer simple solutions to get the same result. The concept of discovering a solution for an identical attitude to the underwater application is influenced by the successful application of pMUT on terrestrial platforms. The problem statements that underpin this research can be distilled as follows from earlier works of literature:



- i) To attain the appropriate thickness for the intended operating frequency for current excellent materials like PZT, a tedious and delicate deposition process that repeatedly incorporates sol-gel, spin coating, sintering, and high voltage polarizing is needed (Shilpa1, Sreelakshmi & Ananthaprasad, 2016). It takes a while to build a pMUT layer by layer, and if the appropriate operating frequencies and responses are not obtained, the process of building the pMUT will be resumed.
- ii) A huge number of commercially available PZT transducers are designed for terrestrial purposes and are not suitable for submersion. Terrestrial applications differ significantly from those designed for underwater use due to the distinct acoustic properties and environmental conditions they are optimized for. These



differences necessitate unique designs and considerations in construction and operation to ensure optimal performance in their respective mediums.

- iii) Little information is reported on the pMUT's underwater calibration and testing protocol's standard operating procedure using a simple fabrication technique. For bulk underwater transducers, there are a lot of written publications available.

1.4 Research Objectives

The objective of this research is to propose a simplified approach in developing pMUTs using wafer bonding for underwater applications below 200kHz of operating frequency that include:

- i) To utilize the in-house spin coating for the deposition of adhesive layering.
- ii) To fabricate pMUT with PDMS and epoxy using a wafer bonding technique on the silicon substrate (Si/PZT) employing PZT as an active transduction material.
- iii) To characterize pMUT's structure of different adhesive materials on bonding.
- iv) To evaluate the performance of the pMUT's encapsulation's electrical characteristics.



- v) To compare how well the pMUT performs underwater with different adhesivematerials.

1.5 Research Questions

The research questions are as follows:

- i) Can an on-the-shelf PZT disc be utilized as an active element for immersion pMUT?
- ii) Will the wafer bonding method and in-house spin coating provide sufficient bonding strength for the pMUT to operate at a frequency of up to 200 kHz?
- iii) What is the effect of packaging and encapsulation on the electrical properties of thepMUT?
- iv) What is the transmit sensitivity, receiving sensitivity, operating bandwidth, and resonant frequency of the pMUTs?
- v) Which adhesives contributed to the higher efficiency of pMUT?



1.6 Research Scopes

This research is carried out within these scopes:

- i) Only two types of adhesive material were studied namely PDMS and industrial epoxy as these two adhesives are commonly used for wafer bonding.
- ii) Piezoelectric PZT discs used in this research are supplied by a single manufacturer to maintain the consistency of the findings. All the available discs on the shelf are not specifically designed for underwater use; they are primarily intended for terrestrial applications.
- iii) Underwater calibration is carried out in the freshwater water tank and the separation distance is set to less than 1m due to the tank-size limitation. The reported findings for transmitting voltage response (TVR) and open circuit receiving the response (OCRR) is in the physical dimensional unit of V/Pa and Pa/V respectively rather than in standardized unit of dB re 1V/ μ Pa at 1 m and dB re 1 μ Pa/V at 1 m.

1.7 Thesis Outline

This thesis consists of five chapters. Chapter one of this thesis discusses the introductory, problem statements, objectives scopes, and limitations of this study.



In chapter two, the entirety of the pertinent literature is organized into three key categories: commonly used materials, designs or architectures, and characterizations of pMUTs. Based on structural, electrical, and undersea analyses, the characterization parts were sub-categorized.

All the methodologies used in this study are classified and organized according to the study's goals in chapter three of the methodology section. Methodologies are matched with the objectives of the research.

The findings about physical characterizations, electrical characterization data, and acoustics characterization results are presented separately in chapters four and three, respectively, along with considerations that are pertinent to each. At the end of every sub-chapter is a discussion of relevant results.

The fifth and final chapter summarizes the findings and suggests a course of action for this investigation.

