Lamination of capacitive micromachined ultrasonic transducer on a piezoelectric array: process and evaluation

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***Abstract*—Harmonic imaging plays a crucial role in medical ultrasound imaging, where the transducer probes are required to emit low-frequency ultrasonic waves into the tissues, and receive reflected signals at the higher, typically the second harmonic of the transmitted wave. We have designed a unique probe with a high-frequency capacitive micromachined ultrasonic transducer (CMUT) on top of a low-frequency piezoelectric array for harmonic imaging. This paper presents a lamination process between CMUT and piezoelectric array using epoxy. The bond-line between the two components was thoroughly investigated using mechanical and electrical methods. The resulting bond-line thickness was less than 2 µm, and shear strength fell within the range 4.8 – 5.1 MPa. Additionally, electrical impedance measurement of all elements in the low-frequency array exhibited resonance shifts before and after bonding, providing further insight into the bonding process.**

Keywords—harmonic imaging, piezoelectric array, dual frequency, capacitive micromachined ultrasonic transducer.

I. Introduction

Harmonic imaging (HI) is a technique employed in medical ultrasound imaging to enhance image quality and diagnosis accuracy. The HI technique utilizes the non-linear properties of the tissues, which distort the transmitted wave as it propagates, generating higher harmonics of the transmitted fundamental frequency. Transducer probes for HI are mostly based on piezoelectric materials. These traditional transducers are operated by thickness vibration mode of the piezoelectric layer under an electrical excitation. A drawback of piezoelectric material is its high acoustic impedance, which is the product of density and longitudinal sound speed, around 35 MRayl, in contrast to 1.5 MRayl for water and human tissue. To compensate for the impedance mismatch, one or more quarter wavelength matching layers are added to the transducers. The matching layers secure a broad bandwidth for the piezoelectric transducers. The number of matching layers is normally limited to two due to production complexity and lower sensitivity. The matching layer is typically composed of particle-loaded epoxy with an optimal specific acoustic impedance. In this work, a single matching layer with an acoustic impedance 7.3 MRayl is utilized. The piezoelectric array is formed by dicing the piezoelectric plate, creating an array configuration to allow steering and focusing of the beam, necessary for imaging.

Over the last three decades, in parallel with piezoelectric technology, significant advancements have made in the development of CMUTs [1]. A CMUT cell consists of a thin membrane suspended on a cavity, two electrode layers, and a passivation base. The top membrane, which can range in thickness from nanometers to a few micrometers, is typically made of an elastic material, such as silicon nitride (Si_xN_y) or polymer. The CMUT operates based on the principle of capacitance. The two electrodes separated by the cavity, form a capacitor. In operation, a bias voltage is applied to maintain static charges on both electrodes. In transmission mode, when an electrical excitation is applied, the fluctuation of electrostatic force between the electrodes causes the membrane to vibrate. This vibration generates ultrasonic waves for transmission. In receiving mode, the membrane vibrates in response to incoming waves, resulting in a change in the capacitance between the electrodes. This vibration in capacitance generates an electrical signal that can be processed to extract information about the received waves. CMUTs offers high receiving sensitivity, flat bandwidth, high frequency operation and good integration with microelectronics. They can be designed in many shapes, which satisfy a wide range of applications from medical imaging to industrial inspection. However, one of the challenges in integrating CMUTs with conventional electronics is the requirement for high bias voltages, often in range of hundreds of volts. The fabrication process for CMUTs is complex and requires extremely well-controlled microfabrication techniques. In transmit, CMUTs typically generates lower acoustic intensity compared to piezoelectric probes. However, advancements in CMUT design and fabrication continue to address the challenges, making CMUTs an attractive technology for various ultrasonic applications.

In previous work, a unique single-element probe design was demonstrated, incorporating a high-frequency CMUT on top of a low-frequency piezoelectric element for harmonic imaging [2]. The piezoelectric transducer was responsible for transmitting acoustic signals at low frequencies, while the CMUT received the reflected waves at high frequencies. This design offered a combination of strong transmit sensitivity and linearity from the piezoelectric transducer, along with the broad bandwidth and configurability provided by the CMUT. The focus of this paper is on the development of a hybrid CMUT-piezoelectric transducer array, which introduces new challenges. To minimize crosstalk between elements of the piezoelectric array, air-filled kerfs were implemented. The lamination process between the piezoelectric array and the CMUT die was accomplished using the epoxy, Epotek 301-2 [3]. This epoxy is a biocompatible adhesive which can be cured within a wide range of conditions, from room temperature to 80°C. The epoxy layer was positioned between the matching layer of the low frequency array and the silicon nitride layer of the CMUT, without entering deeply into the kerfs of the array. The bond-line was characterized through cross-sectional inspection. The mechanical strength was tested using a shear tester. Additionally, electrical impedance measurements were performed on each piezoelectric element to investigate whether the bonding was successful.

II. METHOD

A. Piezoelectric array fabrication

The piezoelectric stack had dimensions 16.3 x 11.0 mm^2, and consisted of a PZT (Lead Zirconate Titanate) ceramic with an acoustic matching layer on top. The matching layer was composed of alumina and tungsten powder loaded epoxy. The construction of the stack involved a bonding process. Initially, the piezoelectric layer was bonded to the matching layer using glue DP 460 (3M, Minnesota, USA). Subsequently, the stack was bonded to a flex circuit using the same adhesive. The curing condition for the glue was set to 60°C for 2 hours. Alignment of the layers and flex during the bonding process was secured by employing a bonding tool. This tool helped to maintain precise alignment between the layers, ensuring the accurate bonding and integration of the stack and the flex circuit.

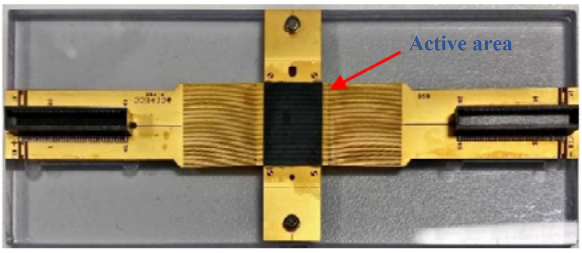

Fig. 1 Piezoelectric array on a flex. Active area, 16.3 x 11.0 mm^2, is diced with 160 µm pitch and 30 µm kerf.

The stack was diced into an 1D array using a 30 µm thick blade, as shown in Fig. 1. The resulting kerfs, measured less than 40 µm, and the elements were uniform, as depicted in Fig. 2. In addition, a dummy array was fabricated, which only contained the acoustic matching layer. This dummy array was specifically intended for destructive testing, such as cross-sectional inspection and shear testing. Prior to the lamination process, the top surface of the array, including dummy array, was activated using 200W oxygen plasma treatment for a duration of 60s right before the lamination process.

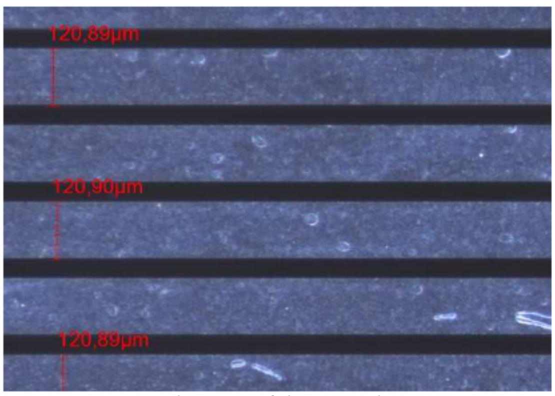

Fig. 2 Some elements of the piezoelectric array

B. Dummy CMUT die

The dummy CMUT dies with dimension 15.4 x 15.4 mm^2 were fabricated with Si_xN_y structure on the top of a Si-handler, as illustrated in Fig. 3. The CMUT structure had a thickness of 8 µm, while the die had a thickness of 350 µm. Before the lamination process, the CMUT dies were cleaned using iso-propanol and dried completely. Subsequently, the top surface of the dummy CMUT was subjected to a 200W oxygen plasma for 60s. This oxygen plasma process ensured the removal of any contaminants, provided an activated surface for next steps, and promoted adhesion during the lamination process.

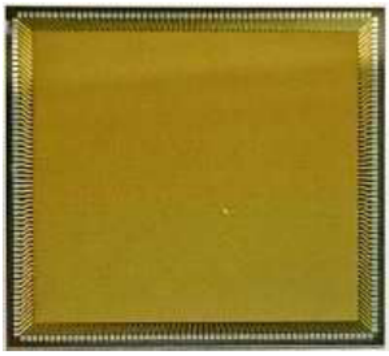

Fig. 3 Dummy CMUT die, size 15.4x15.4 mm^2.

C. Lamination process of CMUT on a piezoelectric array

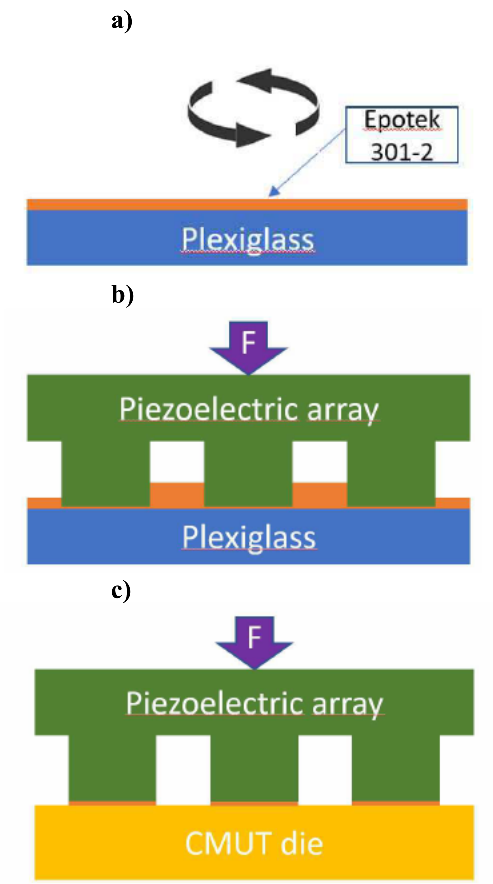

Fig. 4 Lamination process of a piezoelectric array on a CMUT die. a) Spin- coating of Epotek 301-2 on a plexiglass; b) The piezoelectric array is up-side-down on the epoxy film; c) The piezoelectric array is transferred to attach on a CMUT die.

The lamination process ensured the bonding and integration of the piezoelectric array with the CMUT die using the epoxy film as an adhesive layer. The process consisted of three main steps. Firstly, a plexiglass substrate was activated by oxygen plasma, at a power of 200W for a duration of 200s. This oxygen plasma was necessary to make the substrate hydrophilic before spin coating process. A thin film of Epotek 301-2 was deposited onto the plexiglass substrate using spin coating, as shown in Fig. 4a. To achieve 30 µm thick epoxy layer, the spinning speed was set to 1000 RPM, lasting for 60s. In the second step, the piezoelectric array was pressed onto the wet epoxy film to ensure proper wetting of the surface, as depicted in Fig. 4b. The pressing step lasted for 60s. Finally, the piezoelectric array, along with the wet epoxy on the top surface, was transferred onto a CMUT die, as shown in Fig. 4c. The array and the CMUT die were pressed together and left to cure at room temperature for a period of 3 days.

D. *Evaluation of the bond-line*

In the first prototype, which featured a real piezoelectric array, electrical impedance measurement was conducted. Electrical impedance of a PZT element is represented as a complex number, $Z = R + j*X$. The reactance, represented by X, encompasses the capacitance and inductance components of the transducer. The value of X influences the phase of electrical impedance, which indicates the phase shift between electrical input and output signals. At low frequencies, the impedance is predominantly capacitance, indicated by a large negative X. Resistance R should dominate around resonance. R indicates power dissipation, either within the transducer or as acoustic radiation. The value of electrical impedance depends on various factors, such as material properties, physical dimensions, layer structure and electrical connections. To access these electrical characteristics, the impedance of each active element in the array was measured both before and after the lamination process by an E4990A Impedance Analyzer (Keysight, California, USA).

For the second prototype, a dummy array without flex was utilized. The dummy array featured the same matching material on the surface as the first prototype to maintain consistency. The prototype was diced, allowing cross-sectional inspection under optical microscopy. Subsequently, a shear test was conducted using a 4000 Plus Bondtester (Nordson Dage, Ohio, USA). The purpose of the shear test to evaluate the strength of the structure.

III. Results and discussion

A. *Bond-line thickness*

A thin film of Epotek 301-2 coating, measuring 30 µm in thickness, was successfully achieved by a specific spinning schedule and the wetting properties of the plexiglass surface. Plexiglass was chosen as the substrate material because it facilitated the maintenance of a thin epoxy layer over extended periods of time. Si wafer and glass substrates were also tested, but they did not exhibit the same level of uniformity in maintaining a wet Epotek 301-2 epoxy film after spinning. Even when subjected to the same oxygen plasma activation, the epoxy would tend to shrink towards the center region on these substrates. Therefore, the use of plexiglass proved to be more suitable for obtaining the desired uniformity in the wet epoxy film.

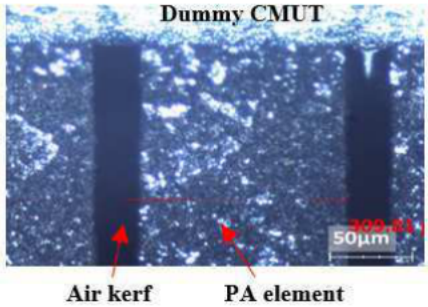

Fig. 5 Cross-sectional view of the bond-line between matching material and dummy CMUT

During cross-sectional inspection, it was observed that the air kerfs had uniform widths. There was no delamination after the dicing process, as depicted in Fig. 5. The Epotek 301-2 layer applied was of sufficient thickness to uniformly cover the entire sample surface without excessive epoxy infiltrating into the kerfs. The air kerfs in the piezoelectric array serve the purpose of reducing crosstalk effects between active elements.

The thickness of the bond-line was found to be less than 2 µm, which is much smaller than acoustic wavelength of 500 µm. Therefore, the acoustic effect of such a thin bond-line can be considered negligible.

To ensure the integrity of the active elements, the pressing force was carefully controlled to minimize the thickness of the bond-line. Applying high force could potentially cause damage to the active elements. The force exerted on the entire surface, equivalent to 10 bar pressure, remained consistent in both step 2 and step 3 of the lamination process. Traces of Epotek 301-2 on the dummy CMUT exhibited minimal variation in adhesion strength over a large area, as shown in Fig. 7.

B. *Shear strength*

The shear strength of the bond-line was measured within the range 4.8 – 5.1 MPa, as shown in Fig. 6. The surface roughness and flatness of the matching layer played a crucial role in achieving a strong adhesion and uniformity of the bond-line. The strong adhesion of the bond-line ensures good acoustic transmission through the interfaces.

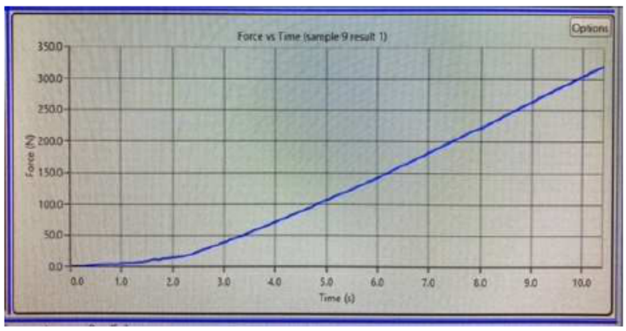

Fig. 6 Shear strength curve

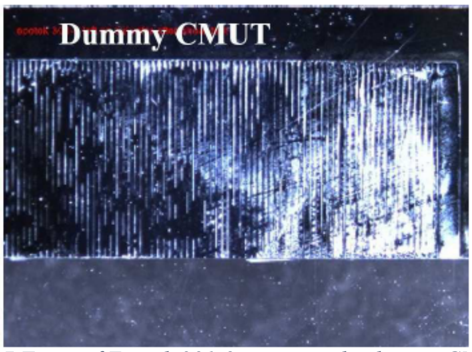

Fig. 7 Trace of Epotek 301-2 epoxy on the dummy CMUT after shear test

C. *Electrical impedance measurment*

The electrical impedance of each element on the array was measured within the range 1 – 10 MHz using connectors on the flex. The absolute value of electrical impedance spectrum exhibited a clear change after lamination with the CMUT die, as illustrated in Fig. 8. The impedance spectra show the resonance-antiresonance structures characteristic for a piezoelectric plate. Prior to lamination (blue curve), two such structures are seen in the impedance spectrum. The resonance frequencies are at the minima of these curves, i.e., at 3.6 MHz and 6.1 MHz. However, after lamination (red curve) a strong resonance is seen at 5.1 MHz, along with two weak resonances at 1.5 MHz and 6.5 MHz. These shifts in the resonance frequencies were a result of the presence of the CMUT die on the top of the matching layer. The Si-handler layer of the die creates acoustic mismatch with the matching layer and the tissue, which is undesirable. Consequently, wave reverberation and crosstalk between elements occur inside the transducer.

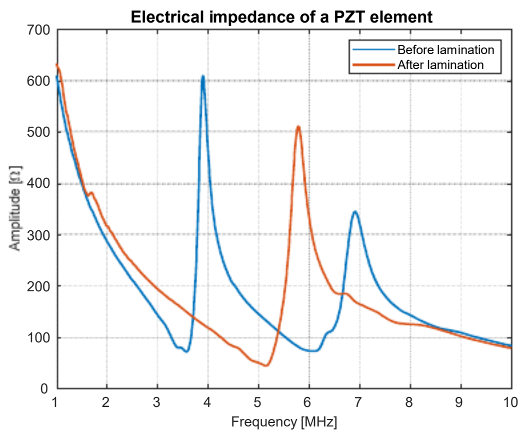

Fig. 8 Electrical impedance of a PZT element before and after lamination to the CMUT die

IV. Conclusion

A lamination process for a hybrid CMUT-piezoelectric ultrasound transducer was developed and successfully performed. The method uses traditional materials and equipment. Two different prototypes underwent shear testing, microscopic examination, and electrical impedance measurement. The strong and thin bond-line achieved ensured excellent acoustic transmission properties. Importantly, the epoxy did not enter the kerfs, thereby avoiding additional acoustic crosstalk in the low-frequency array.

The results validate the assembly process for constructing a new generation of ultrasonic transducer with the potential to improve image quality for medical diagnosis.

The resultes have also demonstrated the need for a thin silicon substrate layer, i.e., the necessity of removing or thinning down the Si handler layer.

Acknowledgment

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