Program Digest, 2019 IEEE International Ultrasonics Symposium (IUS)
Glasgow, Scotland, October 6-9, 2019

Ultrasound Transmission through a Flexible Printed Circuit Board Bonded to the Front Side of a Capacitive Micromachined Ultrasonic Transducer Array: Feasibility Study

Chunkyun Seok
Electrical and Computer Engineering
NC State University
Raleigh, NC, USA
cseok@ncsu.edu

Ziad Ali
Electrical Engineering
Stanford University
Palo Alto, CA, USA
ziadaali@stanford.edu

F. Yalcin Yamaner
Electrical and Computer Engineering
NC State University
Raleigh, NC, USA
fyyamane@ncsu.edu

Ömer Oralkan
Electrical and Computer Engineering
NC State University
Raleigh, NC, USA
ooralka@ncsu.edu

***Abstract*—Interconnecting the inner elements of a densely populated ultrasonic transducer array with electronics poses a great challenge when pads are located in the inner area such that they are not easily accessible or wire bonding is not a viable solution. To tackle that challenge, we propose the technique of front-side flip-chip bonding capacitive micromachined ultrasonic transducer (CMUT) arrays to flexible printed circuit boards (FPCBs). As the propagation through the flex material can cause signal attenuation, we measured the pressure reduction for a reference transducer and an experimental CMUT and observed that the reference underwent a 19% pressure reduction while the experimental CMUT experienced a 33% pressure reduction after transmission through the flex. We argue that the difference can be partly attributed to inappropriate underfill in the interface between the CMUT and the FPCB. The proposed packaging approach can potentially provide a versatile interconnecting scheme for densely populated small transducers required in applications such as ultrasound neuromodulation.**

***Keywords*—CMUT, flexible, ultrasound, flip-chip bonding, annular array, wire bonding, interconnect, neuromodulation**

I. Introduction

Researchers have experimentally observed neuromodulation phenomena induced by ultrasound for nearly a century. Particularly in recent years, there has been growing interest in the use of ultrasound for neuromodulation because ultrasonic waves can be non-invasively focused and steered within a small region [1].

Ultrasonic transducers comprise a key part of such systems, and recent advances in microfabrication technologies have enabled the development of micromachined ultrasound transducer arrays with large numbers of elements, challenging the conventional piezoelectric transducers. The annular CMUT array (Fig. 1) demonstrates the versatility of microfabrication techniques in producing diverse transducer shapes. The annular array consists of 8 concentric, independent ring-shaped elements. Due to the concentric structure, the ultrasound beam is naturally focused at the center without needing any acoustic lenses for focusing. Moreover, the axial focus can be electronically controlled using a phased array pulser. Such a system holds great potential as a basic research tool for brain stimulation in small animals [2].

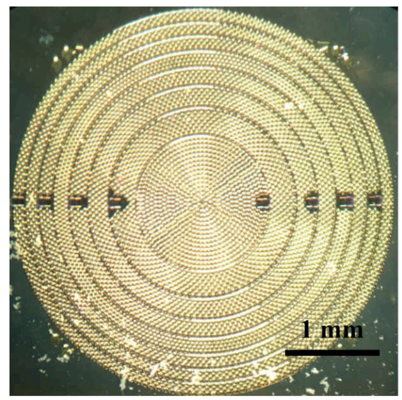


Fig. 1. Eight-ring annular CMUT array with the inner pads on the front side.

However, interconnecting the multiple elements to an electronic system is not trivial because the inner elements of a 2D or annular array are typically hard to reach using a conventional wire-bonding approach. In this work, we review the existing interconnecting approaches for an annular/2D array. We then present our proposed approach to interconnection with front-side flip-chip bonding to FPCB. Also, we investigate the effects of the presence of the flexible material on ultrasound transmission.

II. Interconnecting a CMUT Annular Array

Interconnecting a CMUT annular array to electronics is challenging, especially when inner elements are not readily accessible to a conventional interconnection scheme such as wire bonding.

This work was supported by the National Institutes of Health under Grant EY028456.

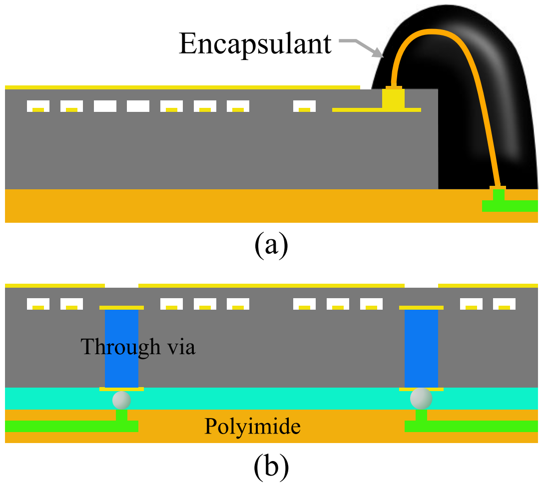


Fig. 2. (a) Fan-out interconnects with wirebonding. (b) Through-wafer-via interconnects with flip-chip bonding.

A. Related Work

Fig. 2 shows two common approaches to interconnecting CMUT arrays to electronics. The first method [Fig. 2(a)] is to fan out the interconnects to the edge of the array and expose pads for wire bonding [3]. Wires can be then connected from a substrate to the pads at the edge of the array, without crossing over the active elements. This interconnecting approach is asymmetric because the interconnects should cut through the rings in only one direction, not to break the rings in half. Also, the surface structure becomes more asymmetrical after the wires are encapsulated, which is not ideal for device-tissue interfaces.

The through-wafer via approach with flip-chip bonding is an ideal solution for interconnecting a 2D array to electronics [4]. The interconnection is done at the backside of the device, not hindering ultrasound propagation. However, forming the through vias involves additional complicated process steps, which is costly.

B. Front-Side Flip-Chip Bonding on an FPCB

In this work, we bonded a FPCB on to the front-side of a CMUT. Fig. 3 illustrates a scheme for the front-side flip-chip bonding process.

We used a dual circular-shaped single-element CMUT for demonstration purposes (Fig. 4). The extra CMUT element on the opposite side of the device under test ensures bonding stability. The assembly process is as follows. A large number of 150-µm diameter Sn62Pb36Ag02 solder balls (EasySpheres, Powell Butte, OR, USA) were dunked in solder flux (SMD291NL, Chip Quick, Ancaster, ON, Canada). The flux-coated solder balls were then picked and placed manually on the pads of the FPCB using the tip of a razor blade. The FPCB with the solder balls was then reflowed in an oven. Next, the reflowed solder balls were retouched with the flux. Finally, the CMUT was flipped, aligned with the solder balls, and then reflowed in the oven for bonding. The semi-transparent glass substrate of the CMUT enabled us to align the pads with the solder balls easily without the help of any special flip-chip bonding tools. It should be noted that the FPCB had pre-cut lines with a small portion of the material left uncut. These pre-cut lines aid in taking off the piece of the FPCB to make an opening for the following experiment (no flex material on the CMUT) without damaging the devices.

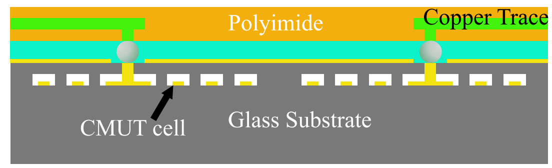


Fig. 3. Schematic cross-section of the front-side FPCB interconnect

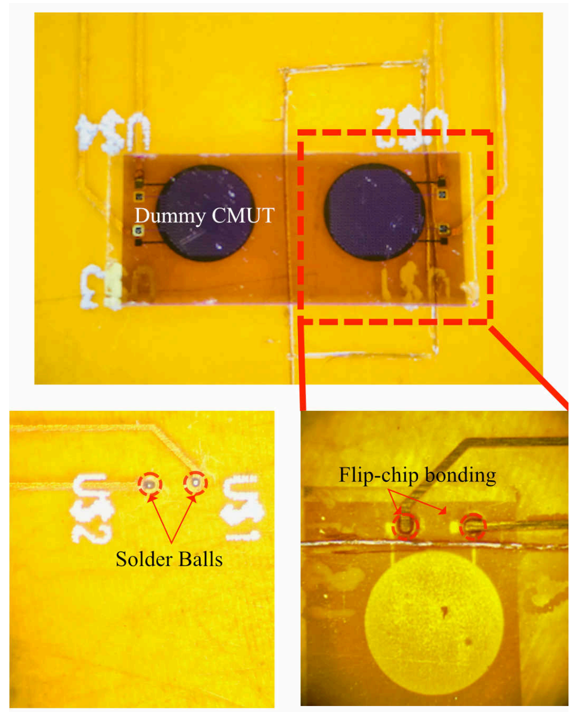


Fig. 4. Optical image of a flip-chip bonded dual CMUT (top), solder balls attached to an FPCB after reflow (bottom left), and the zoomed-in active CMUT (bottom right).

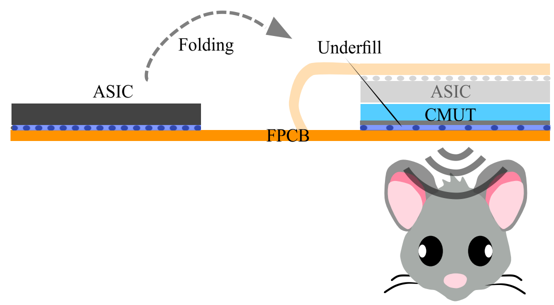


Fig. 5. Folding the FPCB enables a small-form-factor system.

This front-side flip-chip bonding approach with flexible interconnect substrate has several benefits despite an expected partial loss in intensity: (1) the flip-chip bonding allows interconnections to access the inner elements of an array, (2) the flex material automatically encapsulates the CMUT surface, and (3) the flex circuit is useful for various applications that demand

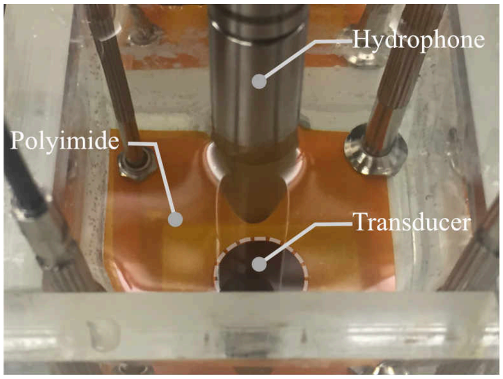


Fig. 6. Hydrophone scan set-up for the commercial focused piezoelectric transducer with a polyimide film on top.

a small form factor (Fig. 5) or conformality for a certain structure such as wearable/implantable devices.

III. Experimental Results and Discussion

In the following experiment, we investigated the effects of a layer of the flex material (polyimide) on transducers, mainly focusing on intensity/pressure (Fig. 6).

A. Commercial Focused Ultrasonic Transducer

First, we used a commercial piezoelectric 5-MHz focused ultrasound transducer. The transducer was attached at the bottom of a water tank through a hole. We placed a 3D-printed spacer (4.9-mm height) inside the water tank. A layer of 76-µm thick polyimide film (Kapton) was used in lieu of a flex-circuit material. The flex film sat on the top of the spacer with all four corners pressed against the spacer with heavy loading to prevent bubble formation and to ensure the polyimide film remained flat and in place.

Finally, we drove the transducer with a three-cycle tone burst at 5-MHz, with 10-Vpp amplitude. The pressure pattern was scanned at a distance of 19 mm above the polyimide material with a hydrophone (HGL-0200, Onda Corp., Sunnyvale, CA) (Fig. 7). The maximum pressures with and without the polyimide film are 83.6 and 102.6 in an arbitrary unit, respectively, indicating that the flex material caused a 19% reduction in pressure.

B. Single-Element CMUT Transducer

The front-side flip-chip bonded CMUT assembled as described in Section II.B, which shares a cell structure similar to the annular CMUT array, was used to examine the effects of the flex material. Before the CMUT was immersed in an oil tank, we let oil flow through the gap between the CMUT and the FPCB to underfill the gap for better coupling. The CMUT was biased at a DC voltage of 40 V and excited with the same sinusoidal bursts used for the commercial transducer. To experiment without the flex material, we started the pressure scan with the flex material on. Then, the flex material was taken off using the pre-cut lines, making an opening above the CMUT surface.

Fig. 8 shows the scanned pressure patterns for the CMUT with and without the flex material. The maximum pressures with and without the polyimide film are 17.8 and 26.6 in an arbitrary unit, respectively, indicating that the flex material contributed to a 33% reduction in pressure. Table I summarizes the measured results.

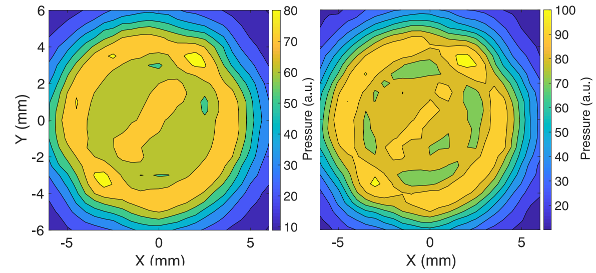
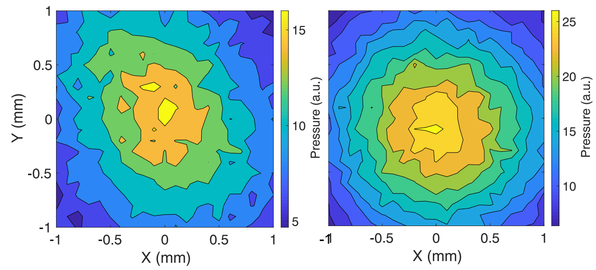


Fig. 7. Measured pressure pattern with (left) and without (right) a polyimide film on.



Fi.g 8. Measured pressure pattern with (left) and without (right) an FPCB on.

TABLE I. Measurement Summary

	Pressure (a.u.)		Reduction (%)
	with flex	**w/o flex**	
Commercial transducer	83.6	102.6	19
CMUT	17.8	26.6	33

C. Discussion

Because the thickness of the FPCB stack-up is very thin (approximately 100 µm), the propagation loss through the flex material should be negligible. However, the two interfaces—oil-to-flex (interface 1) and flex-to-oil (interface 2)—along the path of ultrasound waves have a non-negligible contribution to the pressure loss. The acoustic impedance (Z_{Oil}) of the vegetable oil is 1.4 Mrayl, and the acoustic impedance ($Z_{Polyimide}$) of polyimide is 3.61 Mrayl [5] indicating the measured loss could be due to reflections at the interfaces. However, a more thorough analysis is required as the film thickness is smaller than the acoustic wavelength in oil. The greater loss in the experiment with the CMUT is possible because the gap between the CMUT and the FPCB might not be properly underfilled.

IV. Conclusion

In this work, we developed a front-side flip-chip bonding technique to interconnect inner elements of a CMUT array, such as an annular array, to a FPCB. The pressure losses due to the presence of the flex material in front of the transducer surface were measured to be 19% and 33% for the commercial transducer and the CMUT, respectively. With a properly underfilled gap between the CMUT and the FPCB, we expect around a 19% transmission loss. This loss can be overcome by using such a system described in [6], eventually generating sufficient intensity at the target region to excite neural activities.

ACKNOWLEDGMENT

This work was performed in part at the NCSU Nanofabrication Facility (NNF) and the Analytical Instrumentation Facility (AIF) at NC State University. Both NNF and AIF are members of the North Carolina Research Triangle Nanotechnology Network (RTNN), which is supported by the National Science Foundation (Grant ECCS-1542015) as part of the National Nanotechnology Coordinated Infrastructure (NNCI). AIF is also supported by the State of North Carolina.

REFERENCES

[1] O. Naor, S. Krupa, and S. Shoham, “Ultrasonic neuromodulation,” *J. Neural Eng.*, vol 13, no. 3, pp. 031003, May 2016.

[2] H. Kim, et al., “Miniature Ultrasound Ring Array Transducers for Transcranial Ultrasound Neuromodulation of Freely-Moving Small Animals,” in *Brain Stimulation*, 10.1016/j.brs.2018.11.007, Dec. 2018.

[3] O. Farhanieh, et al., "Integrated HIFU Drive System on a Chip for CMUT-Based Catheter Ablation System," in *IEEE Transactions on Biomedical Circuits and Systems*, vol. 11, no. 3, pp. 534-546, June 2017.

[4] A. Moini *et al.*, "Fully Integrated 2D CMUT Ring Arrays for Endoscopic Ultrasound," in *Proc. IEEE Ultrason. Symp*, Tours, 2016, pp. 1-4.

[5] *Material Properties Tables*, NDT Education Resource Center, Iowa State University. [Online]. Available: https://www.nde-ed.org/GeneralResources/MaterialProperties/UT/ut_matlprop_plastics.htm

[6] C. Seok, F. Y. Yamaner, M. Sahin, and Ö. Oralkan, "A Sub-Millimeter Lateral Resolution Ultrasonic Beamforming System for Brain Stimulation in Behaving Animals," in *Proc. IEEE EMBC,* 2019, to be published.