A 3D Packaging Technology for Acoustically Optimized Integration of 2D CMUT Arrays and Front End Circuits

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***Abstract*—As compared to piezoelectric technology, MEMS technology employed for Capacitive Micromachined Ultrasonic Transducer (CMUT) fabrication provides increased compatibility with 3D packaging methods, enabling the possible development of advanced transducer-electronics multi-chip modules (MCM) for medical imaging applications. In this paper, an acoustically optimized 3D packaging method for the interconnection of Reverse-Fabricated 2D CMUT arrays and front end ICs using a wafer-level compatible process is presented. The developed packaging method uses Cu pillars and Sn-Ag solder reflow for electrical interconnection, and patterned Benzocyclobutene (BCB) for mechanical bonding. Process parameters were optimized by analyzing the acoustic behavior of a CMUT supported by a BCB film laying on a silicon substrate using Finite Element Modeling (FEM). Dummy CMUT and ASIC wafers were processed and MCMs were assembled following a chip-to-chip bonding approach using the optimized process parameters. Electrical characterization of the MCMs demonstrated successful contact across the entire fabricated devices. Probe head prototypes were assembled and pulse-echo experiments were carried out using the MCM surface as a reflector to verify the effectiveness of the optimization on the acoustic behavior of the device.**

Keywords—CMUT; 3D packaging; acoustic optimization; Multi-Chip Module; Cu pillars; BCB; Reverse Fabrication Process; FEM.

I. Introduction

MEMS technology employed in Capacitive Micromachined Ultrasonic Transducer (CMUT) [1] fabrication enabled the development of advanced transducer-electronics multi-chip modules (MCM) for medical imaging applications. Interconnection of 2D CMUT arrays and analog front end integrated circuits (IC) using die-level 3D packaging methods was demonstrated earlier [2]. However, no effort was devoted to the study and optimization of the complex acoustic behavior of the resulting assembly. In this paper, we propose an acoustically optimized 3D packaging method, schematically described in Fig. 1, for the interconnection of Reverse-Fabricated [3] 2D CMUT arrays and analog front end ICs [4] using a wafer-level compatible process based on the use of Cu pillars and solder reflow for

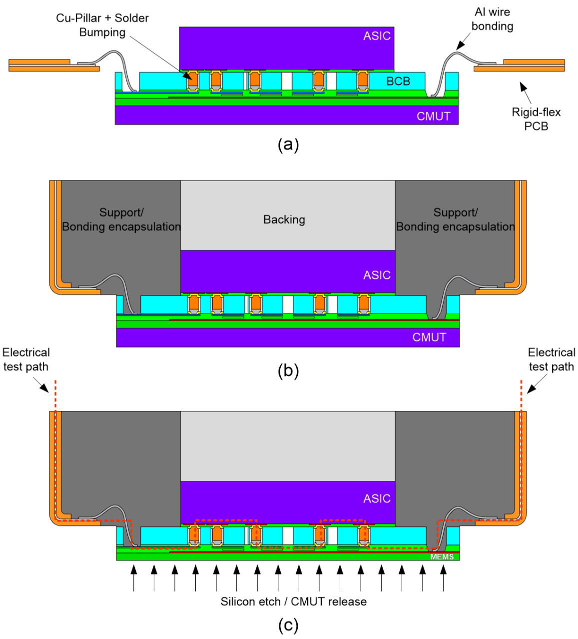


Fig. 1. Packaging process flow: the MCM (a) is connected to external circuits using wire bonding; a backing is applied to the ASIC silicon substrate (b) using an adhesive that encapsulates the wire bonds; the CMUT silicon substrate is etched in order to release the device active surface (c). Test path used in the electrical continuity measurements (c).

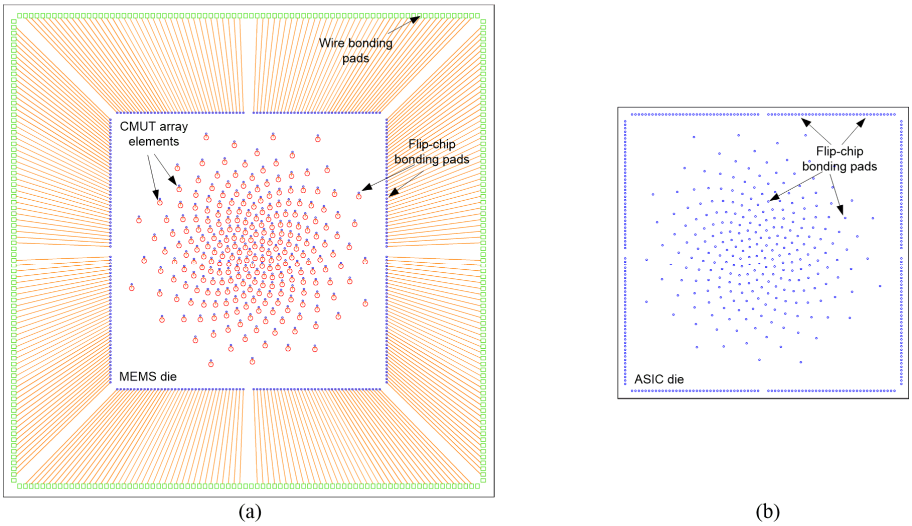


Fig. 2. Shape and layout of the main features of the (a) CMUT die and of the (b) ASIC die. The flip-chip bonding pads are used to connect the 256 CMUT array elements to the ASIC, and to route the ASIC signals towards external circuits by means of the wire bonding pads located on the MEMS die.

electrical interconnection, and partially cured and patterned Benzocyclobutene (BCB) for mechanical bonding [5]. Finite Element Modeling (FEM) was used to analyze the acoustic behavior of the CMUT supported by a BCB film laying on a silicon substrate fixed to a backing. The effect of the BCB film resonant vibration and of the backing material on the two-way frequency response of the CMUT was investigated in order to optimize the 3D-packaging process parameters. Dummy CMUTs and ICs, i.e. actual-sized chips provided only with one metal layer and electrical interconnection pads, were then fabricated and processed using the optimized parameters, and MCMs [Fig. 1(a)] were assembled using a chip-to-chip bonding approach. The layout of both dummy devices, shown in Fig. 2, was designed in such a way that the pads were positioned following a 256-element spiral array [6] configuration. They were interconnected in pairs to form conductive paths accessible from the outside for electrical testing, as conceptually illustrated in Fig. 1(c). Electrical continuity measurements were performed to monitor the electrical and mechanical stability of the MCM during the entire packaging process. Probe head prototypes were assembled and pulse-echo experiments were carried out using the MCM surface as a reflector to verify the effectiveness of the optimization on the acoustic behavior of the device.

II. Acoustic Optimization

A 2D axisymmetric FEM model of a spatially periodic Reverse-Fabricated CMUT cell, designed for wideband operation around 7 MHz in immersion, was built using ANSYS APDL (Ansys Inc., Canonsburg, PA, USA). The model allowed activating an arbitrary number of material layers supporting the CMUT, each with its mechanical properties. The boundary condition for the back surface of the model was selectable between “fully clamped” or “absorbing”. The front face of the CMUT was coupled to an infinitely extended fluid with the acoustic characteristics of water. For each simulation, two pre-stressed harmonic anal-

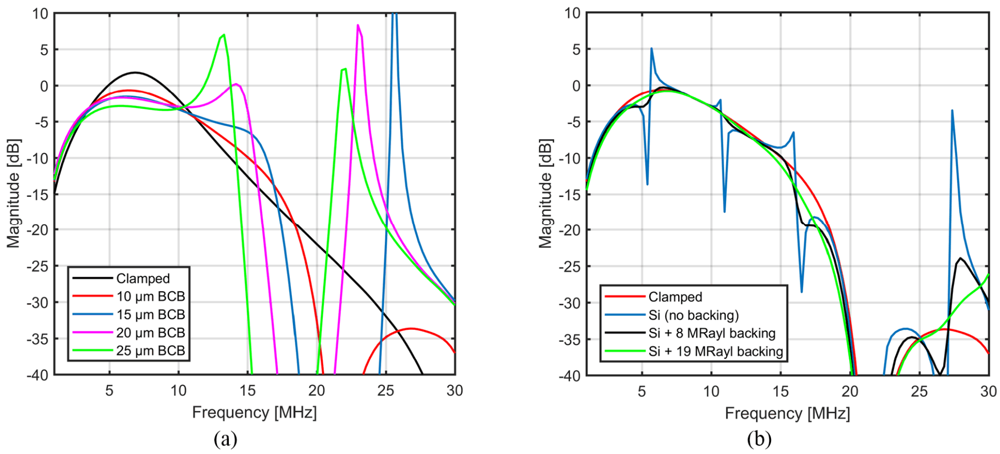


Fig. 3. FEM simulation results: (a) two-way frequency response of the CMUT supported by a BCB layer of various thicknesses laying on an infinite Si substrate; (b) two-way frequency response of the CMUT supported by a 10µm-thick BCB layer laying on a 750µm-thick Si substrate in different backing conditions.

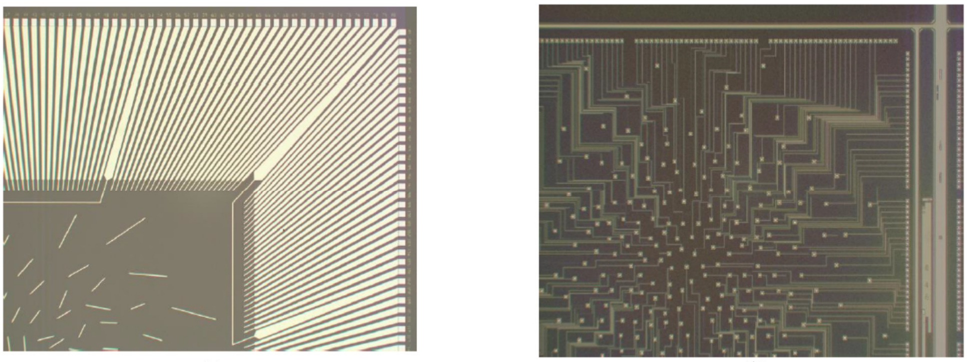

(a) (b)

Fig. 4. Optical microscopy of the CMUT (a) and ASIC (b) dummy dice. Electrical interconnections between pad pairs are visible on both dice.

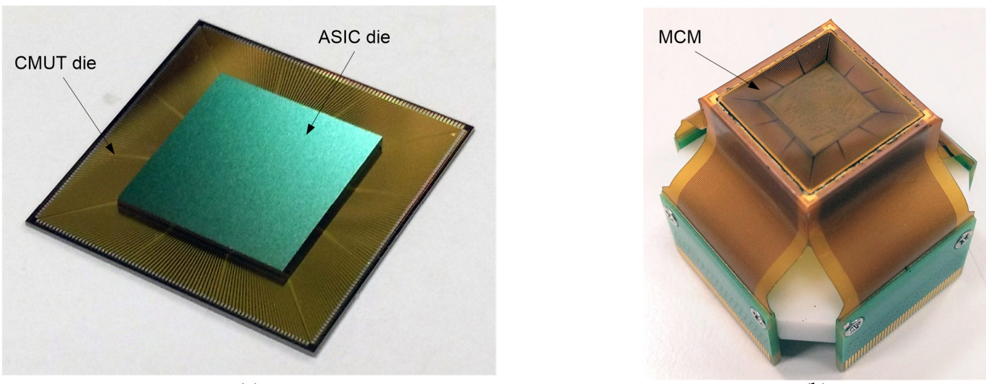
yses with the CMUT biased at 90% of the collapse voltage were run to compute the two-way frequency response with low-impedance electrical loading condition in reception (charge readout).

A first set of simulations was carried out by modeling the CMUT supported by a BCB film laying on a 750 μm-thick silicon substrate with absorbing boundary condition activated at the back surface. Fig 3(a) shows the frequency response computed for different values of the BCB thickness. As can be seen, the fundamental thickness-mode resonant vibration of the BCB film causes a peaking effect that alters the frequency response of the transducer as the film thickness increases. A thickness of 10 μm was chosen as a good compromise between the effect on the acoustic behavior of the transducer and the practical processability of the BCB as a bonding layer.

A second set of simulations was performed, starting from the partially optimized configuration, to analyze the effect of the backing material on the silicon substrate resonant vibration [7]. Fig. 3(b) shows the results achieved without any backing, and with two backing materials characterized by different acoustic impedance values. As can be seen, the thickness-mode resonances of the silicon substrate fall inside the transducer band, seriously impairing the transducer performance. The peaks introduced by the silicon substrate vibration can be partially damped by using epoxy-based compounds, typically used for acoustic backing applications, with a specific acoustic impedance (Z_a) of 8 MRayl. By using a higher specific acoustic impedance material, such as Aluminum (Z_a=19 MRayl) that is better matched to silicon, the peaks are fully damped out as long as the back-propagated energy may be completely absorbed in the backing.

III. Fabrication

A critical aspect in 3D-packaging of large dice with thin die-to-die separation is related to the surface topography. Dummy wafers, provided only with one metal and one dielectric layer, mimicking the final steps of the actual fabrication processes, were designed to test and optimize the flip-chip-bonding pads lateral dimensions and passivation thicknesses. Actual-sized dummy CMUTs and ASICs wafers were fabricated. The two devices were first processed at a wafer level. Sn-Ag-capped Cu-pillars were fabricated on the dummy ASIC wafers, whilst a BCB film was spun, partially cured, and patterned on the CMUT wafers. The partially processed wafers were diced and transferred to the flip-chip bonding facility. Chip-to-chip bonding was then performed by aligning the CMUT and ASIC dice, and by applying heat and pressure in order to induce the solder reflow and to complete the curing of the BCB. A successfully assembled MCM prototype is shown in Fig. 5(a). Several MCMs were assembled and further processed following the CMUT Reverse Fabrication Process packaging procedure described in



(a) (b)

Fig. 5. (a) MCM prototype realized by flip-chip bonding of a CMUT die and an ASIC dummy die, and (b) probe head prototype obtained by electrically interconnecting the MCM to a rigid-flex PCB using wire bonding and by etching the CMUT silicon microfabrication substrate.

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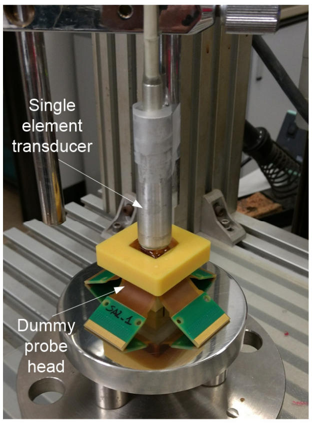
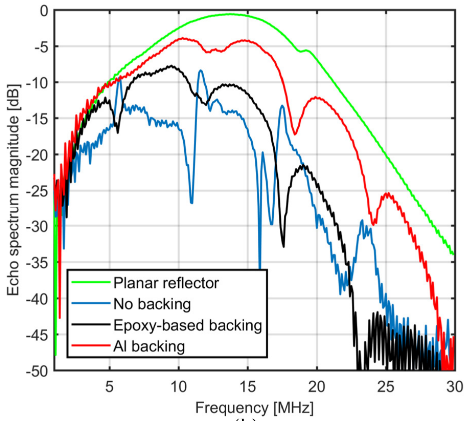


(a)



(b)

Fig. 6. Acoustic characterization of the assembled probe heads: (a) a 12MHz single-element CMUT is used to perform pulse-echo measurements using the MCM surface as a reflector; (b) the FFT magnitudes of echo signals show the effect of the different acoustic backings on the MCM spurious vibration.

[8]. Fig 5(b) shows a photo of one of the resulting probe head prototypes. Various probe heads were assembled with different backing materials in order to test three particular backing conditions: no backing, tungsten-alumina-doped epoxy (Z_a=8 MRayl), and pure aluminum (Z_a=19 MRayl).

IV. Experimental Characterization

Electrical continuity measurements were performed on all the pad pairs before and after silicon etching to monitor the electrical and mechanical stability of the MCM during the entire packaging process. A 100% yield was observed in all the processed and tested devices.

Acoustic characterization was carried out by performing pulse-echo measurements using a broadband 12MHz single-element CMUT [9] placed in front of the probe head [Fig. 6(a)]. The single element transducer and the MCM surface were coupled through a 10mm-thick water layer contained by a silicone gasket. The MCM was acoustically excited by means of a broadband pressure pulse generated and propagated into the water layer towards the device surface by driving the single-element CMUT with a 10ns 16V broadband electrical pulse. The mechanical response of the MCM to the incident pressure pulse was measured by collecting the echo signals reflected by the MCM surface using the single-element CMUT and an oscilloscope. Fig. 6(b) summarizes the obtained results: the FFT magnitudes of the echo signals produced by a stainless steel planar reflector and by the front surface of the probe heads provided with different acoustic backings are plotted and compared. As can be seen, the spurious vibration of the MCM in the frequency band of interest (i.e. 5 to 10 MHz) is effectively damped by the aluminum backing, which is characterized by a specific acoustic impedance close to that of silicon.

V. Discussion and Conclusion

A 3D-packaging technology for the wafer-level integration of 2D CMUT arrays and front end ICs was proposed. FEM was used to analyze the acoustic behavior of MCMs based on the proposed packaging approach, and to optimize the process parameters. MCMs and probe head prototypes were successfully fabricated. Electrical and acoustic characterization results supporting the proposed optimization were presented.

Acknowledgment

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