Design, Simulate and Performance an Embedded fan-out package for 2-D Ultrasonic Transducer Arrays

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Abstract In this article, the embedded fan-out wafer-level packaging (FO-WLP) for 2-D ultrasonic transducer array with individual electrical connection is proposed. The finite element analysis (FEA) was employed to analyze effects of the package on ultrasonic transducers. The layout of the package was designed based on single-element FEA models. The impedance characteristic of the encapsulated array was measured. The model of encapsulated array was established. The simulation and measured results of the encapsulated array show that the effective electromechanical coupling coefficient is remarkable affected by redistribution layers (RDLs) and passivation layers (PLs).

key words: 2-D ultrasonic transducer array, Embedded fan-out wafer-level package (FO-WLP), Finite element analysis (FEA).

Classification: XYZ (choose one from Table II)

1. Introduction

Ultrasound imaging has been extensively used in clinical diagnostic imaging due to the most convenient, less expensive, and minimal radiation technology among the multitude of imaging modalities. Ultrasonic transducers play a crucial role in offering better resolution and sensitivity[1]. The spatial resolution of the ultrasound image is inversely proportional to the operating frequency of ultrasonic transducers. Commercial high-frequency ultrasound imaging probes are commonly based on single-element transducers or one-dimensional (1-D) transducer arrays. A single-element transducer mechanically scans objects in vivo and the mechanical movement easily induces motion artifacts in images and may be harmful to patients [2, 3, 4, 5, 6, 7, 8, 9]. 1-D transducer arrays offer advantages in imaging comparison with single-element transducers thanks to their capability of electronic scanning and higher image frame rates[1, 3, 10, 11, 12]. However, 1-D array transducers exist drawbacks in building three-dimensional (3-D) images, for 1-D array transducers are required mechanically moving to sweep the two-dimensional (2-D) image into a 3D volume image[13]. With the increasing demand for 3-D imaging in the medical field, 2-D ultrasonic transducer arrays are desired due to their capability of electronic steering and focusing the ultrasound beam to make real-time 3-D images. However, there are little commercial high-frequency 2-D arrays due to limitations in electrical connections of 2-D arrays with many small elements with narrow pitches[14, 15, 16, 17]. Signals of elements in a high-frequency ultrasonic transducer array are generally read out by a flexible printed circuit board (FPCB). Elements in the array connect to the FPCB by a few microns non-conductive epoxy or conductive glues with dicing kerfs. This approach can only be employed to manufacture 1-D arrays or low-frequency 2-D arrays, for a multilayer FPCB is requested to read out each signal of elements in the high-frequency and high-density 2-D array[18, 19, 20, 21, 22, 23, 24]. Unfortunately, the multilayer FPCB induces ringing and crosstalk of the array, especially in high frequency, for the thickness of multilayer FPCBs will reach a few hundred microns with increasing the number of layers of FPCB[25]. Application-specific integrated circuits (ASICs) have been developed to read out signals from ultrasonic transducer arrays to FPCB. However, transmitting and receiving circuits will be complex as the number of elements in the ultrasonic transducer array increases. The arrangement of contact pads on ASICs is restricted by the position of elements in ultrasonic transducer arrays. The design and fabrication of ASICs face great challenges in making balances among the specification of ultrasonic transducer arrays, process capability of ASIC, and circuit design[26, 27].

In this paper, we propose utilizing an embedded fan-out wafer-level packaging (FO-WLP) to fabricate 2-D piezoelectric ultrasonic transducer arrays with individual electrical connections. FO-WLP is capable of manufacturing thin-film circuits with multilayer redistribution layers (RDLs). Signals of elements in a 2-D ultrasonic transducer array are allowed to be unconstrained for the 2-D array size[28, 29]. The embedded FO-WLP can make ultrasonic transducer arrays compatible with FPCB and ASIC pitch requirements and give the flexibility of the design and fabrication of FPCB

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and ASIC. The layout of the package was designed based on finite element analysis (FEA) results. Impedance characteristics of an encapsulated array were measured. Effects of the package on the 2-D piezoelectric ultrasonic transducer arrays were analyzed using FEA.

2. Design of package

Prototype ultrasonic transducer array with $20 \times 20$ piezoelectric ceramic elements were employed to demonstrate and assess the feasibility of embedded FO-WLP, as shown in Fig. 1. The ultrasonic transducer array was made of commercial PZT-5H 3203HD piezoelectric ceramic. The size of element in the array is $80 \mu m \times 80 \mu m \times 183 \mu m$. The pitch between each element in the array is $115 \mu m$. Kerfs between each element are filled with epoxy (EPO-TEK 301, Epoxy technology, Inc, MA Billerica, US). 1µm-thick copper films serve as electrodes on top and bottom of ultrasonic transducer arrays. On the top side, the continuous copper film serves as the common ground plane; On the bottom side, the copper film is separated by kerfs extended into the epoxy for 30µm to form independent electrodes.

Fig. 1. A model of the prototype 2-D ultrasonic transducer arrays

Fig.2 shows the schematic cross-section view of the embedded FO-WLP of the 2-D ultrasonic transducer array. From top to bottom, the diagram shows three parts: the ultrasonic transducer array, the double side metallized glass frame with cavity and micro-bumps, and a thin film circuit with RDLs. The ultrasonic transducer array is embedded in the cavity of the frame. The frame and the ultrasonic transducer array are bonded with the thin film circuit by an anisotropic conductive film (ACF). A continuous metal layer is deposited on the surfaces of the frame and on the sidewalls and bottom of the gap between the frame and the ultrasonic transducer array. The ground plane of the ultrasonic transducer array connects to ground pads by the continuous metal layer and micro bumps on the glass frame.

3. Design and simulation of the package

In this section, COMSOL software was employed to simulate the performances of encapsulated ultrasonic transducer arrays. The resonant frequency and the effective electromechanical coupling coefficient are used to assess the effects of the embedded FO-WLP on ultrasonic transducer arrays.

Single-element models with one layer of blind via, RDL, and passivation layer (PL) were established to preliminary study the impact of packaging structures on ultrasonic transducer arrays, as depicted in Fig.3. The PL is a photosensitive polyimide precursor (PIMELTM BL-301, Asahi Kasei, Tokyo, Japan) which can be patterned by photolithography before being cured. The diameter of the blind vias equals the pad to simplify the models. The perfectly matched layer (PML) was set surrounding PL to absorb spurious reflections at the boundary. The width of the PML equals $\lambda_{max}/8$; The distance from the PZT domain to the PML is $\lambda_{max}/4$, where $\lambda_{max}$ is the maximum mechanical wavelength solved in the PL domain. The solid mechanics interface was applied to models. The electrostatics interface was applied to the PZT and the RDL domain. The piezoelectric effect interface was applied to the PZT domain. The excitation voltage was applied on the surface of the copper pillar which connects to the PZT domain. Material properties used in simulations are listed in Table I.

Fig. 2. The schematic cross-section view of the embedded FO-WLP of 2-D ultrasonic transducer array.

As shown in Fig.2, some copper pillars are below the ultrasonic transducer array. The overlapping area between these copper pillars and elements in the array is supposed to be as small as possible, for the great acoustic impedance mismatch between copper (41.6 MRaysl) and piezoelectric ceramics (28.875 MRaysl). As shown in Fig. 3, copper pillars can locate in the two positions.

Fig. 3. The schematic diagram of locations of copper pillars

Fig. 4. Two single-element models of ultrasonic transducers with different location of copper pillars

Impedance characteristics for the two structures are depicted
in Fig.5 (a). The resonant frequency for structure (a) and structure (b) are 6.95MHz and 7.35MHz, respectively. The effective electromechanical coupling coefficient (EEMC) is calculated by the following equation:

\[
K_{ef}^2 = \frac{f_r^2}{f_p^2} - \frac{f_r^2}{f_p^2} f_r
\]  

Where \( f_r \) is the resonant frequency; \( f_p \) is the anti-resonant frequency. The EEMC refers to the capability of converting mechanical and electrical energy into one another. The EEMC for structure (a) and structure (b) are 0.684 and 0.65, respectively. The resonant frequency of structure (b) is higher than structure (a). However, the EEMC of structure (b) is lower than structure (a). Copper pillars were designed as structure (a) to get higher the EEMC.

Single-element models with the varying diameter of copper pillars, diameter of blind vias, thickness of blind vias, width of RDLs and thickness of RDLs were established and simulated. The packaging design must refer to design rules of the wafer-level packaging foundry to ensure the yield of the process. Table I shows design rules of the wafer-level packaging foundry. According to the design rules, when the pitch of adjacent pads is 115\( \mu \)m, the maximum diameter of blind vias is 50\( \mu \)m, and the line width and spacing of RDLs is 20/22.5\( \mu \)m. Thus, the resonant frequency and the EEMC of ultrasonic transducers varying with the diameter of blind vias from 30\( \mu \)m to 50\( \mu \)m were simulated. As shown in Fig.5(b), the resonant frequency slightly decreases with the increase of blind vias in diameter; the EEMC slightly increases with the increase blind vias in diameter.

Table I. The material properties used in simulations.

| Material   | Item               | Symbol | Value                  |
|------------|--------------------|--------|------------------------|
| PZT-5H     | Elastic constants short circuit | \( E_s \), \( E_t \), \( E_p \) | 85 \( GPa \) |
|            | Density            | \( \rho \) | 7500 \( kg/m^3 \) |
|            | Mechanical Quality Factor | \( Q_m \) | 50 |
|            | Electrical loss tangent | \( \sigma_{el} \) | 0.02 |
|            | Piezoelectric charge | \( \zeta \) | \(-520 \times 10^{-12} \) C/N |
|            | Dielectric constant | \( \varepsilon \) | 40 |
| Copper     | Density            | \( \rho \) | 8960 \( kg/m^3 \) |
|            | Elasticity modulus | \( E \) | 120 \( GPa \) |
|            | Poisson ratio      | \( \nu \) | 0.3 |
| Epo-tek 301| Density            | \( \rho \) | 11500 \( kg/m^3 \) |
|            | Dielectric constant | \( \varepsilon \) | 4 |
|            | Longitudinal velocity | \( V_L \) | 2650 \( mm/s \) |
|            | Shear velocity     | \( V_S \) | 1833 \( mm/s \) |
|            | Poisson ratio      | \( \nu \) | 0.16 |
| PL         | Density            | \( \rho \) | 11000 \( kg/m^3 \) |
|            | Elasticity modulus | \( E \) | 3.3 \( GPa \) |
|            | Poisson ratio      | \( \nu \) | 0.2 |
| Glass      | Density            | \( \rho \) | 24800 \( kg/m^3 \) |
|            | Elasticity modulus | \( E \) | 74.3 \( GPa \) |
|            | Poisson ratio      | \( \nu \) | 0.23 |
| ACF        | Density            | \( \rho \) | 24800 \( kg/m^3 \) |
|            | Elasticity modulus | \( E \) | 7 \( GPa \) |
|            | Poisson ratio      | \( \nu \) | 0.31 |
| Solder cap | Density            | \( \rho \) | 5763 \( kg/m^3 \) |
|            | Elasticity modulus | \( E \) | 41.6 |
|            | Poisson ratio      | \( \nu \) | 0.31 |

Fig. 5. The impedance curves for the two structures

Table II. The design rules of the foundry

| Item                        | Standard (\( \mu \)m) |
|-----------------------------|-----------------------|
| Line/Space (L/S)            | 20/15                 |
| Diameter of Vias (Dv)       | 30                    |
| Via land (VL)               | Dv±20                 |
| Thickness of Via (Tv)       | 5                     |
| Thickness of RDLs (TR)      | 3                     |
| Diameter of bump (Db)       | 50                    |

The resonant frequency and the EEMC of ultrasonic transducers varying with the thickness of blind vias, the thickness of RDL, and the width of RDL were simulated, respectively. As shown in Fig.5 (c), (d) and (e), the resonant frequency and the EEMC are almost constant, when the thickness of blind vias, the thickness of RDL, the width of RDL are from 6\( \mu \)m to 10\( \mu \)m, 3\( \mu \)m to 7\( \mu \)m, 20\( \mu \)m to 40\( \mu \)m, respectively. The resonant frequency and the EEMC of ultrasonic transducers varying with the diameter of copper pillar were simulated. The height of copper pillars equals their diameter. The resonant frequency and the EEMC are almost constant as depicted in Fig.5 (f).

The simulation results show that the width of RDLs, the thickness of blind vias, of RDLs, and of copper pillars have little effect on performances of ultrasonic transducers in the range of the simulation. The diameter of blind vias which directly connects to the ultrasonic transducer has a relatively higher effect on ultrasonic transducers.

The layout of embedded FO-WLP 2-D ultrasonic transducer arrays was designed based on the simulation results. The
layout is shown in Fig.6 (a). The schematic cross-section of the embedded FO-WLP 2-D ultrasonic transducer array is shown in Fig.6 (b). The thickness of the glass frame is 173μm. The encapsulated ultrasonic transducer array contains three RDLs (M1, M2, and M3), four passivation layers (P1, P2, P3, and P4), and three vias (V1, V2, and V3). The vias are 30μm in diameter. The thickness of each passivation layer is 5μm. The thickness of M1 is 5μm and of M2 and M3 is 3μm. The contact pads (M1) are 50μm in diameter. The line width and spacing of M2 and M3 are 20μm and 15μm. The V1 through P2 connects M1 to pads of the M2. The diameter of pads on the M2 is 60μm. The V1 through P3 connects M2 to pads of the M3. The pads of the M3 are 70μm in diameter. The V3 through P4 connects the M3 to copper pillars. The diameter of copper pillars is 50μm.

**4. Measure and discussion**

The embedded RDL-first FO-WLP was employed to manufacture the 2-D ultrasonic transducer arrays. In this process, RDLs and ultrasonic transducer arrays were manufactured, respectively. The Curie temperature of the PZT-5H is 225°C. The curing temperature of PLs is 230°C. RDL-first process avoided PZT-5H suffering from high curing temperature of PLs and losing its piezoelectric properties. ACF with low curing temperature was employed to form electric connections between RDLs and ultrasonic transducer arrays. The curing temperature of ACF is 120°C. The encapsulated ultrasonic transducer array is shown in Fig.8. The thickness of the thin-film circuit is around 25μm.

**Fig. 6.** (a) The layout of the embedded FP-WLP (b) The schematic cross-section view of the embedded FO-WLP of 2-D ultrasonic transducer array

An encapsulated array with complete RDLs and vias was established to analyze the impacts of the package on the array. A quarter symmetric model was established to reduce the number of meshes, as shown in Fig.7. Symmetric boundary conditions were applied to symmetry planes. The shell interface was performed to simulate the metal layer. The electrostatics interface was applied to the ultrasonic transducer array, epoxy, PLs, RDLs and copper pillars. The excitation voltage was applied on the surface of copper pillars connecting to measured elements in the array, respectively.

**Fig. 7.** (a) The quarter symmetric model of the encapsulated array with complete RDLs (b) The model of RDLs

An impedance analyzer (6500B, Wayne Kerr, West Sussex, U.K.) and a probe table were employed to measure impedance characteristics of the encapsulated ultrasonic transducer array. Each probe connected to the impedance analyzer using 1.5m coaxial cables, respectively. Calibration was performed at probes to eliminate the influences of coaxial cables and the impedance analyzer. The encapsulated array was placed on a silicon gel carrier and the top of the encapsulated array contacted the carrier. When measured the encapsulated array, one probe touched one of the ground bumps, and the other one touched the signal bump of an element in the encapsulated array. The measured elements are marked in Fig.9. The measured and simulated impedance characteristics were shown in Fig.10. The measured resonant frequency of elements 57, 79, and 134 in the encapsulated array are 7.85MHz, 8.345MHz, and 8.3MHz, respectively. The measured EEMC of elements 57, 79, and 134 in the encapsulated array are 0.311, 0.190, and 0.410, respectively. The simulated resonant frequency of elements 57, 79, and 134 are 8.39MHz, 8.48MHz, and 8.42 MHz, respectively. The simulated EEMC of elements 57, 79 and 134 are 0.380, 0.282, and 0.551, respectively. The simulated resonant frequency of elements 57, 79, and 134 are 0.54, 0.156, and 0.12 higher than the measured results, respectively. The simulated...
Fig. 9. The layout with being marked elements 57, 79 and 134

EEMC of elements 57, 79, and 134 are 0.069, 0.092, and 0.141 higher than the measured results, respectively. Measured and simulated results show that the EEMC of elements 57 and 79 with long RDLs are lower than element 134 due to the electrical coupling induced by the electromagnetic induction between RDLs. Some of the input energy is consumed by the electrical coupling, leading to a decrease in the EEMC.

The magnitudes of measured resonant impedance of elements 57, 79, and 134 are 5.392KΩ, 12.665KΩ, 5.537KΩ, respectively. The magnitudes of simulated resonant impedance of elements 57, 79 and 134 are 10.06KΩ, 12.205KΩ, 8.634KΩ, respectively. The magnitudes of measured resonant impedance of elements 57 and 134 are 4.688KΩ and 3.094KΩ lower than the simulated resonant impedance, respectively. The magnitudes of measured resonant impedance of the element 79 is 0.46KΩ higher than the simulated resonant impedance.

The differences in the resonant frequency and the magnitudes of impedance between simulations and measurements are caused by manufacturing errors. The resonant frequency and the magnitude of impedance relate to the mass and damping of the encapsulated array, respectively.[30] A stylus profilometer (Alpha-Step®-D-600, KLA-Tencor Corp, Milpitas, California) was used to measure thicknesses of M1, M2, and M3 during the manufacturing process. Average measured thicknesses of M1 and M2 are 0.3μm and 0.33μm thinner than the simulated model, and of M3 are 0.81μm thicker than the simulated model. The measured thickness of PLs is 1.05μm thinner than the simulated model. Vias with solid copper cylinders were built in the simulation, while vias in the measured array were not fully filled with copper due to the process capability, as shown in Fig.8 (b). These factors result in the differences in the mass of the thin-film circuit between the measured array and the simulated model. In addition, material properties were provided by suppliers. The difference in material properties between actual values and standard values used in the simulation also lead to differences in mass and damping between the measured array and simulated model.

Fig. 10. (a) The impedance curve of element 57 (b) The phase curve of element 79 (c) The impedance curve of element 79 (d) The phase curve of element 134 (e) The impedance curve of element 134

Two obvious sub-peaks appeared near the resonant peak in the measured impedance curves; Two weak sub-peaks can be observed in the simulated impedance curves. As shown in Fig.9, peaks are marked by arrows. For the measured array was placed on a silicon gel carrier during measuring, the silicon gel carrier forms a reflection boundary condition in front of the encapsulated array. Sub-peaks became obvious and were close to the resonant peak. In the measured impedance curves, continuous weak vibrations appeared in the low frequency due to bad contact between the probe and solder caps with smooth hemispheric shape.

5. Conclusion

The embedded FO-WLP as a promising technology for 2-D ultrasonic transducer array with individual electrical connection was proposed in this work. FEA was employed to analyze the impacts of the package on the ultrasonic transducer array. Single-element models were established to analyze the impacts of packaging structure on ultrasonic transducers from solid mechanics of view. The layout of the package was designed based on the simulation results of single-element models. Impedance characteristics of the encapsulated array were measured. The model of encapsulated array with completed RDLs was established to analyze the impedance characteristic of the encapsulated array. The simulated and measured results show that the EEMC is remarkable affected by RDLs and PLs.

In the future, the impedance characteristic of the encapsulated ultrasonic transducer array can be optimized by ASICs. The embedded FO-WLP can integrate ASICs with 2-D ultrasonic transducer array at the same time.
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References

[1] K. K. Shung and M. Zippuro: “Ultrasound transducers and arrays,” IEEE Engineering in Medicine & Biology Magazine 15 (1997) 20 (DOI: 10.1109/51.544509).

[2] Gichard F D., Auth D C: “Development of a Mechanically Scanned Doppler Blood Flow Catheter,” Ultrasounds Symposium (1975) 18 (DOI: 10.1109/ULSYSM.1975.196455).

[3] J. M. Cannata, J. A. Williams, et al.: “Development of a 35-MHz piezo-composite ultrasound array for medical imaging,” IEEE Transactions on Ultrasonics Ferroelectrics & Frequency Control 53 (2006) 224 (DOI: 10.1109/TUFFC.2006.1588408).

[4] Holm H H., Kristensen J K., et al.: “A new mechanical real time ultrasonic contact scanner,” Ultrasound in Medicine & Biology 2 (1975) 19 (DOI: 10.1016/0301-5629(75)90037-X).

[5] Evans, J. L., et al.: “Arterial imaging with a new forward-viewing intravascular ultrasound catheter, I. Initial studies,” Circulation 89 (1994) 712 (DOI: 10.1161/01.CIR.89.2.712).

[6] K. H. Ng, et al.: “Arterial imaging with a new forward-viewing intravascular ultrasound catheter. II. Three-dimensional reconstruction and display of data,” Circulation 89 (1994) 718 (DOI: 10.1161/01.CIR.89.2.718).

[7] M. Tan, et al.: “A Front-End ASIC With High-Voltage Transmit Switching and Receive Digitalization for 3-D Forward-Looking Intravascular Ultrasound Imaging,” IEEE Journal of Solid State Circuits 53 (2018) 2245 (DOI: 10.1109/JSSC.2018.2828826).

[8] L. Gatzoulis, et al.: “Three-dimensional forward-viewing intravascular ultrasound imaging of human arteries in vitro,” Ultrasound in Medicine & Biology 27 (2018) 2245 (DOI: 10.1016/S0301-5629(10)00371-4).

[9] Jr. Black W. C. and D. N. Stephens: “CMOS chip for invasive ultrasonic imaging,” IEEE Journal of Solid-State Circuits 29 (1994) 1381 (DOI: 10.1109/4.328640).

[10] J. H. Cha and J. H. Chang: “Development of 15MHz 2-2 piezo-composite ultrasound linear array transducers for ophthalmic imaging,” Sensors and Actuators A: Physical 217 (2014) 39 (DOI: 10.1016/j.sna.2014.06.024).

[11] Y. Lin and K. Grosh: “Topology optimization of the kerf fillings in linear phased arrays for therapy,” Journal of the Acoustical Society of America 112 (2002) 1968 (DOI: 10.1121/1.1510531).

[12] E. S. Ebbini and C. A. Cain: “A spherical-section ultrasound phased array applicator for deep localized hyperthermia,” IEEE Transactions on Biomedical Engineering 38 (1991) 634 (DOI: 10.1109/10.83562).

[13] S. W. Smith and H. G. Pavy, “High-speed Ultrasound Volume Imaging System: Part I: Transducer Design and Beam Steering,” IEEE Transactions on Ultrasonics Ferroelectrics & Frequency Control 38 (1991) 100 (DOI: 10.1109/58.68466).

[14] G. Caliano, et al.: “Design, fabrication and characterization of a capacitive micromachined ultrasonic probe for medical imaging,” IEEE Transactions on Ultrasonics Ferroelectrics & Frequency Control 52 (2005) 2259 (DOI: 10.1109/TUFFC.2005.1563268).

[15] O. Oralvan, et al.: “Capacitive micromachined ultrasonic transducers: next-generation arrays for acoustic imaging,” IEEE Transactions on Ultrasonics Ferroelectrics & Frequency Control 49 (2002) 1596 (DOI: 10.1109/TUFFC.2002.1049742).

[16] Changheng Liu, F. T. Djuth, Qifa Zhou, and K. K. Shung: “Micromachining techniques in developing high-frequency piezoelectric composite ultrasound array transducers,” IEEE Transactions on Ultrasonics Ferroelectrics & Frequency Control 60 (2013) 2615 (DOI: 10.1109/TUFFC.2013.2860).

[17] S. W. Smith and E. D. Light: “Two-dimensional array transducers using thick film connection technology,” IEEE Transactions on Ultrasonics Ferroelectrics & Frequency Control 40 (1993) 727 (DOI: 10.1109/58.248217).

[18] S. S. Corbett, T. R. Clary, and J. P. Yarno: the United States Patent US8585049 A (1999).

[19] J. D. Plummer, J. D. Meindl, and M. G. Maginness: “An ultrasonic imaging system for realtime cardiac imaging,” Solid-State Circuits Conference. Digest of Technical Papers. 1974 IEEE International (1974).

[20] G. Schiavone, et al.: “A highly compact packaging concept for ultrasound transducer arrays embedded in neurosurgical needles,” Microsystem Technologies 23 (2017) 3881 (DOI: 10.1007/s11522-015-2775-1).

[21] C. Y. Park, J. H. Sung, and J. S. Jeong, “Design and fabrication of ultrasound linear array transducer based on polarized inverion technique,” Sensors & Actuators A Physical 280 (2018) 484 (DOI: 10.1016/j.sna.2018.08.008).

[22] M. Lukac, et al.: “Performance and Characterization of New Micromachined High-Frequency Linear Arrays,” IEEE Transactions on Ultrasonics Ferroelectrics & Frequency Control 53 (2006) 1719 (DOI: 10.1109/TUFFC.2006.1058).

[23] T. Manh, et al.: “Microfabrication of stacks of acoustic matching layers for 15MHz ultrasonic transducers,” Ultrasonics 54 (2014) 614 (DOI: 10.1016/j.ultras.2013.08.015).

[24] N. E. Cabrera-Munoz, et al.: “Forward-looking 30-MHz phased-array transducer for peripheral intravascular imaging,” Sensors & Actuators A Physical 280 (2018) 145 (DOI: 10.1016/j.sna.2018.07.035).

[25] N. E. Cabrera-Munoz, et al.: “Forward-looking 30-MHz phased-array transducer for peripheral intravascular imaging,” Sensors & Actuators A Physical 280 (2018) 145 (DOI: 10.1016/j.sna.2018.07.035).

[26] A. Bhuyan, et al.: “3D volumetric ultrasound imaging with a 32×32 CMUT array integrated with front-end ICs using flip-chip bonding technology,” IEEE International Solid-state Circuits Conference Digest of Technical Papers (2013).

[27] C. Chen, et al.: “A Pitch-Matched Front-End ASIC With Integrated Subarray Beamforming ADC for Miniature 3-D Ultrasound Probes,” IEEE Journal of Solid-State Circuits 53 (2018) 3050 (DOI: 10.1109/JSSC.2018.286429).

[28] S. W. Yoon, “Ultrathin 3D FO-WLP eWLB-PoP (Embedded Wafer-Level Ball Grid Array-Package-on-Package) Technology,” 2015 10th International Microsystems, Packaging, Assembly and Circuits Technology Conference (IM-PACT)(2015) 77 (DOI: 10.1002/9781119313991.ch4).

[29] M. Brunnbauer, et al.: “An Embedded Device Technology Based on a Molded Reconfigured Wafer,” 56th Electronic Components and Technology Conference 2006 IEEE (ECTC) (2006) 547 (DOI: 10.1109/ECTC.2006.1645702).

[30] R. Krimholtz, et al.: “Understanding Impedance Response Characteristics of a Piezoelectric-Based Smart Interface Subjected to Functional Degradations,” Complexity 2021 (2021) 24 (DOI:10.1155/2021/5728679).