

Miniaturized Ultrasound Imaging Probes Enabled by CMUT Arrays with Integrated Frontend Electronic Circuits

B. (Pierre) T. Khuri-Yakub, Ömer Oralkan, Amin Nikoozadeh, Ira O. Wygant, Steve Zhuang, Mustafa Gencel, Jung Woo Choe, Douglas N. Stephens, Alan de la Rama, Peter Chen, Feng Lin, Aaron Dentinger, Douglas Wildes, Kai Thomenius, Kalyanam Shivkumar, Aman Mahajan, Chi Hyung Seo, Matthew O'Donnell, Uyen Truong, and David J. Sahn

Abstract— Capacitive micromachined ultrasonic transducer (CMUT) arrays are conveniently integrated with frontend integrated circuits either monolithically or in a hybrid multichip form. This integration helps with reducing the number of active data processing channels for 2D arrays. This approach also preserves the signal integrity for arrays with small elements. Therefore CMUT arrays integrated with electronic circuits are most suitable to implement miniaturized probes required for many intravascular, intracardiac, and endoscopic applications. This paper presents examples of miniaturized CMUT probes utilizing 1D, 2D, and ring arrays with integrated electronics.

I. INTRODUCTION

In conventional ultrasound imaging systems that utilize 1D transducer arrays for 2D cross-sectional imaging the frontend transmit/receive (T/R) electronic circuits are typically located in the main processing unit. The transducer array is packaged in the form of a hand-held probe. Each element in the array is connected to a dedicated frontend channel through a long (~2 m) coaxial cable.

This conventional scheme has not been practical for transducer arrays with increased number of elements such as the 2D arrays with over 2000 elements. All major ultrasound system providers today offer 2D matrix arrays for 3D imaging. All these 2D matrix probes house a portion of the beamforming electronics next to the array so that the number of cables between the system and the transducer can be minimized and the acquired data can be processed by the existing imaging systems without having the need for thousands of active electronic channels. Placing the frontend electronics next to the array also improves the signal

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Ö.O., A.N., I.O.W., S.Z., M.G., J-W.C., and P.T.K-Y. are with the E. L. Ginzton Laboratory, Stanford University, Stanford, CA 94305, USA (e-mail: ooralkan@stanford.edu).

D.N.S. is with the University of California, Davis, CA 95616, USA.

A.D.L.R. and P.C. are with St. Jude Medical, Irvine, CA 92618, USA.

F.L., A.D., D.W., and K.T. are with the General Electric Global Research Center, Niskayuna, NY 12309, USA.

K.S. and A.M. are with the University of California, Los Angeles, CA 90095, USA.

C.H.S. and M.O. are with the University of Washington, Seattle, WA 98101, USA.

U.T. and D.J.S. are with the Oregon Health and Science University, Portland, OR 97239, USA.

TABLE I
 SUMMARY OF INTEGRATION METHODS OF CMUTS WITH SUPPORTING FRONTEND CIRCUITS

Monolithic	Co-processing (e.g., Eccardt et al. [1])	Post-processing (e.g., Noble et al. [2], Daft et al. [3], Gurun et al. [4])
Multichip	Chip-to-chip bonding (e.g., Wygant et al. [5])	Bonding on a flexible intermediate substrate (e.g., Nikoozadeh et al. [6])
		Bonding on a rigid intermediate substrate (e.g., Wodnicki et al. [7])

integrity.

Ultrasound imaging catheters for intracardiac and intravascular applications also benefit from close integration of frontend electronic circuits with transducer arrays. This approach helps with preserving the signal integrity and in some cases also to minimize the number of cables. Catheter-based applications impose additional constraints on the physical size of the transducer-electronics assembly and the total power consumption of the electronic circuits.

One of the great promises of the capacitive micromachined ultrasonic transducer technology has been the convenient and compact integration of electronic circuits with transducer arrays for both large-area 2D arrays and miniature probes.

This paper reviews different approaches that enable close integration of CMUT arrays with supporting electronic circuits. Following this brief review we present integration examples including 2D arrays designed for intracavitary imaging and 1D and ring arrays for intracardiac imaging.

II. INTEGRATION OF CMUT ARRAYS WITH SUPPORTING FRONTEND ELECTRONIC CIRCUITS

Several methods developed for a variety of micro-electro-mechanical systems (MEMS) applications have also been used to integrate CMUT arrays with electronic circuits. These methods can be categorized in two main groups: monolithic and multi-chip (hybrid) approaches. As summarized in Table I, monolithic integration can be realized by building CMUTs and electronics at the same time or building CMUTs on finished electronics wafers. For

multichip (hybrid) integration on an intermediate substrate may or may not be used.

A. Co-Processing

A BiCMOS process using 16 masks has been used with only minor modifications including an additional photolithography step and sacrificial layer etching to fabricate CMUTs side-by-side with electronic circuits on the same substrate [1]. Although this method offers a cost-effective means of integration, it has two major limitations: 1) The transducer element area is shared by electronic circuits or interconnects. 2) The device dimensions in the vertical direction are limited by the film thicknesses available in the process used to make electronic circuits.

B. Post-Processing

Another monolithic integration technique is to make the electronic circuits first using a foundry process and then build CMUTs on top of finished electronics by further processing, which includes surface passivation, planarization, opening of contacts to electronics, and further successive thin film deposition and etching steps to define the CMUT membranes [2, 3, 4]. This approach has good area utilization. However, processing techniques for making CMUTs are still limited, mainly due to temperature constraints set by the existing metal lines on the electronics.

C. Independently Processing

By making CMUTs and electronic circuits on two separate substrates one can use optimized process flows for each component. CMUTs, in this case, need through-wafer via interconnections from the front side of the substrate to the back side. Deep reactive ion etching (DRIE) enables these vias in silicon. CMUT arrays can then be bonded directly on electronics [5] or on an intermediate substrate, which can be flexible [6] or rigid [7]. Direct bonding usually requires that the electronics die area be greater than the CMUT die area. Using an intermediate substrate makes the size of the CMUT and electronics dice independent. Both components can be tiled to obtain larger arrays. Flexible substrates are preferred for catheter applications because of the smaller form factor they offer through bending.

III. 2D CMUT ARRAYS WITH INTEGRATED FRONTEND ELECTRONIC CIRCUITS

We developed two generations of frontend integrated circuits for 16x16-element 2D CMUT arrays for 3D intracavitary imaging applications such as endoscopic, endorectal, or endovaginal imaging.

A. Synthetic Aperture System

The first generation frontend integrated circuit (IC) we designed comprised a 25-V pulser, a T/R switch and a low-noise preamplifier for each transducer element in the array [Fig.1(a)] [5]. Both the 2D CMUT array and the frontend IC had a pitch of 250 μm . Using Sn-Pb eutectic solder bumps the two components were directly bonded together [Fig.1(b)]. Although each transducer element had their

dedicated T/R frontend circuitry, only one channel was programmed to be active at a time for simplicity and hence classical synthetic aperture imaging was performed with this first-generation prototype.

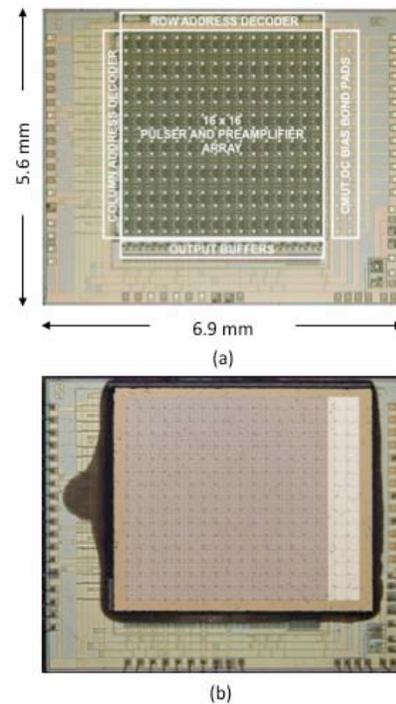


Fig. 1 (a) Custom-designed frontend IC for the 3D synthetic aperture system. (b) A 16x16-element, 250- μm pitch, 2D CMUT array bonded on frontend electronics.

B. Full-Transmit X-Receive System with Integrated Beamforming Hardware

The second-generation frontend IC we designed for the 16x16-element 2D array included digital circuitry to perform the functions of a transmit beamformer on the chip [Fig.2(a)] [8]. With this IC 224 elements can be simultaneously fired in transmit and 16 elements can be used at a time for receive. We use a beamforming scheme, which we developed to reduce the frontend hardware complexity with minimum compromise from image quality. In this scheme the 32 diagonal elements in the array constitute the receive aperture and the remainder of the array constitutes the transmit aperture. A preamplifier is provided for each of the 32 receive elements. To interface to a 16-channel data acquisition system, 16 of the 32 receive elements are active at a time. Sixteen buffers drive the cable capacitance in receive. A high-voltage pulser and an 8-bit shift register are provided for each of the 224 transmitting elements. The timing of each pulser is determined by delay information stored in the shift register. When transmitting, a particular pulser fires when a global counter equals the pulser's stored delay value. For each new beam, delay information is loaded into the delay shift registers by 16 parallel lines. This scheme also reduces the number of cables between the backend system and the frontend. We bonded a 16x16-

element 2D CMUT array operating at 2.5 MHz directly on this frontend IC and used this prototype for imaging several phantoms in 3D (Fig.3).

IV. INTRACARDIAC ECHOGRAPHY CATHETERS WITH CMUT ARRAYS WITH INTEGRATED FRONTEND ELECTRONIC CIRCUITS

We developed two types of forward looking intracardiac echography (ICE) catheters to provide guidance during electrophysiological (EP) interventions.

A. Forward-Looking Microlinear Arrays for Real-Time Cross-Sectional Imaging

The first device we developed for forward-looking ICE applications is a 24-element microlinear array operating at

10 MHz center frequency with a fractional bandwidth of 100%. The element pitch is 63 μm . The array measures 1.7 mm by 1.3 mm and employs doped-polysilicon filled through-wafer via interconnects [Fig.4(a)]. This array was bonded on one side of a custom flexible printed circuit board (PCB). The 24-channel electronics die providing each transducer element with a T/R switch, a low-noise preamplifier and an output buffer was bonded on the back side of the flexible PCB [Fig.4(b)]. With this IC the transmit pulses with amplitudes up to ± 50 V were provided from the imaging system (GE Vivid7), which is connected to the flex assembly by microcoaxial cables. A thin layer of Polydimethylsiloxane (PDMS) provided electrical insulation on the front side of the array.

The final catheter packaged in a 9-F shaft [Fig.4(c)] was tested successfully in an animal study recently providing forward-looking cross-sectional images up to 4-cm depth (Fig.5).

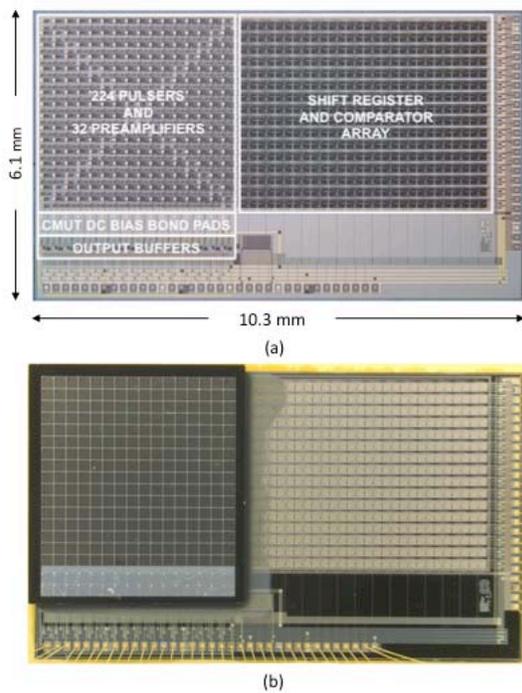


Fig.2. (a) Custom-designed frontend IC for the full-transmit X-receive imaging system. (b) A 16x16-element, 250- μm pitch, 2D CMUT array bonded on frontend electronics.

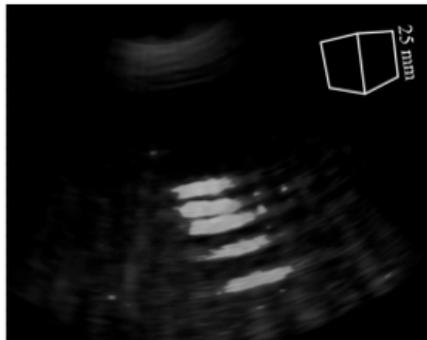


Fig.3. 3D rendered image of a nylon wire phantom obtained with a 2.5-MHz 2D CMUT array

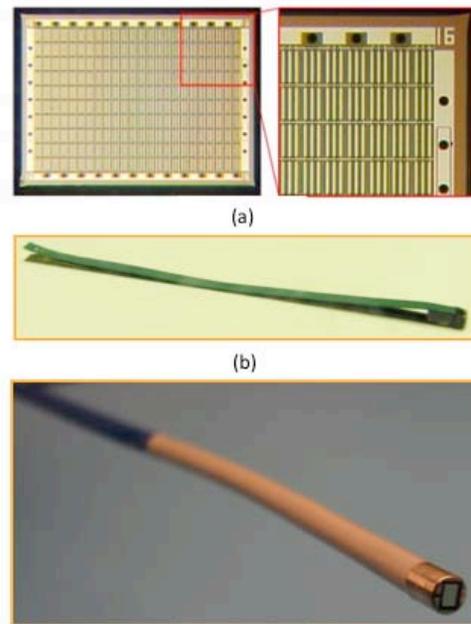


Fig. 4. (a) 24-element CMUT microlinear array. (b) The flex assembly with CMUT microlinear array bonded on side and the frontend IC on the other. (c) The final 9F catheter with forward-looking microlinear CMUT array.

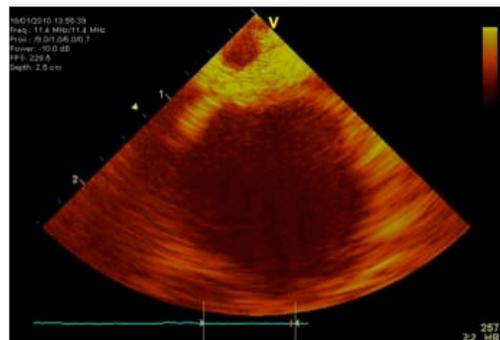


Fig. 5. A 2D image obtained with the CMUT ML array in-vivo in a pig heart.

B. Forward-Looking Ring Arrays for Volumetric Imaging

The second type of the ICE catheters we developed is based on a 10-MHz, 64-element CMUT ring array [Fig.6(a)]. The electronics we used along with this array has the same circuit topology as the one used with the microlinear array. However, in this case 8 channels are grouped on one die and 8 ICs were used to address the entire array. The CMUT ring array and the 8 ICs were bonded on an 8-legged flexible printed circuit board. A compact assembly was achieved by folding the legs of the flex circuit on a support structure [Fig.6(b)]. Microcoaxial cables connected this assembly to the imaging system. A programmable imaging platform (Verasonics, Redmond, WA) was used to reconstruct real-time volume images on multi-plane display with the option of off-line 3D rendering.

The initial prototype was packaged in a 12-F catheter shaft [Fig.6(c)] and was used for imaging several phantoms (Fig. 7).

The ring catheter provides a 4.5-F inner lumen that can be used to introduce therapeutic devices such as RF ablation catheters. Optical fibers can be inserted into the inner lumen to enable photoacoustic imaging.

V. CONCLUSION

We have demonstrated several prototypes of miniaturized ultrasound probes using CMUT arrays with integrated electronics. The use of standard silicon microfabrication techniques in CMUT manufacturing enables densely populated transducer arrays with arbitrary geometries. These arrays can be conveniently integrated with supporting

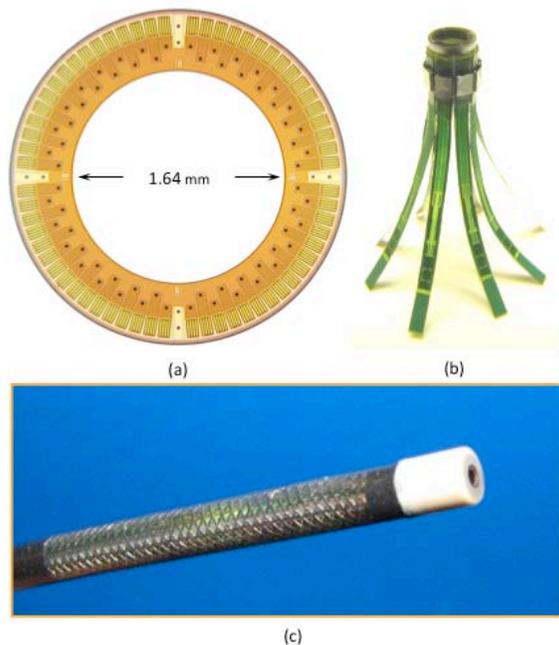


Fig. 6. (a) 64-element CMUT ring array. (b) Flex assembly with the CMUT array and eight 8-channel frontend ICs. (c) The final 12-F catheter.

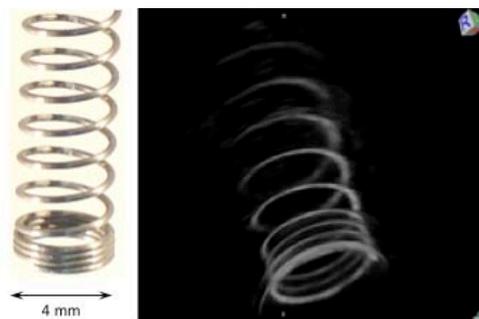


Fig. 7. 3D rendered image of a metal spring obtained with the CMUT ring array.

electronic circuits monolithically or in the form of a multichip module to reduce the number of cables between the probe and the system and also to preserve signal integrity. Results presented in this paper show that CMUT technology has the potential to enable many applications in ultrasound imaging and therapy that were not possible with the conventional piezoelectric transducers.

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