# Capacitive Micromachined Ultrasonic Transducer Arrays for Integrated Diagnostic/Therapeutic Catheters

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**Abstract.** In recent years, medical procedures have become increasingly non-invasive. These include endoscopic procedures and intracardiac interventions (e.g., pulmonary vein isolation for treatment of atrial fibrillation and plaque ablation for treatment of arteriosclerosis). However, current tools suffer from poor visualization and difficult coordination of multiple therapeutic and imaging devices. Dual–mode (imaging and therapeutic) ultrasound arrays provide a solution to these challenges. A dual-mode transducer can provide focused, noncontact ultrasound suitable for therapy and can be used to provide high quality real-time images for navigation and monitoring of the procedure. In the last decade, capacitive micromachined ultrasonic transducers (CMUTs), have become an attractive option for ultrasonic imaging systems due to their fabrication flexibility, improved bandwidth, and integration with electronics. The CMUT's potential in therapeutic applications has also been demonstrated by surface output pressures as high as 1MPa peak to peak and continuous wave (CW) operation. This paper reviews existing interventional CMUT arrays, demonstrates the feasibility of CMUTs for high intensity focused ultrasound (HIFU), and presents a design for the next-generation CMUTs for integrated imaging and HIFU endoscopic catheters.

**Keywords:** capacitive micromachined ultrasonic transducer, HIFU, imaging, intracardiac endoscopic
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## INTRODUCTION

Since the early 1990s [1], CMUT research has concentrated on fabrication [2], characterization [3], modeling [4,5,6], and more recently, applications in medicine [7,8]. Fabricated using silicon micro-machining methods that provide uniformity and sub-micron accuracy, CMUTs have distinct advantages over other ultrasonic transducers. They can be fabricated for a broad range of frequencies (10 kHz – 60 MHz). Arrays with widely varying geometries and with sizes between 100 μm and 5.4 cm have also been demonstrated. Additionally, CMUTs typically have larger bandwidth than comparable piezoelectric transducers. Because CMUTs are fabricated using a silicon micromachining process, they are easily integrated with electronics, either monolithically or by flip-chip bonding.

A CMUT is essentially a vacuum-gap capacitor in which the top membrane is free to move with applied voltage (Fig. 1). Currently the dominant methods of fabrication are the sacrificial nitride process and silicon wafer bonding process [2]. To transmit and receive ultrasonic waves, a DC voltage is first applied to the membrane, which causes it to deflect downward. An additional AC voltage moves the membrane about the operation point, which is determined by the DC voltage, and launches pressure waves into the medium. Conversely, a pressure applied to the membrane causes vibration that results in a detectable current.

### SIMPLIFIED CROSS-SECTION OF CMUT

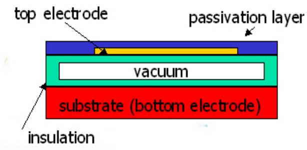

**FIGURE 1.** A simplified cross-section of a CMUT.

Imaging CMUTs are designed for wide bandwidth and sensitivity using simplified electrical models or finite element analysis (FEA). The gap height and the thickness, size, and shape of the membrane are optimized for these characteristics and a desired frequency range. A 64-element annular ring array and a 16 x 16 2-D array have been developed for intracardiac and endoscopic catheters (Fig. 2). Demonstrations of the wide bandwidth and 2-D and 3-D image quality (Fig. 3), as well as integration of electronics by flip-chip bonding [9] and the trench process [10], illustrate the powerful capabilities of CMUT technology. Integration of electronics presents several advantages, including the ability to 1) multiplex many channels to reduce signal lines and size of the device, 2) reduce degradation of the output acoustic power and receive sensitivity, and 3) aid data acquisition and processing for 3-D volumetric imaging. Pulse-echo and photoacoustic images as well as 3-D images have been shown to exhibit good image quality (Fig 3).

### CURRENT INTERVENTIONAL IMAGING CMUTS

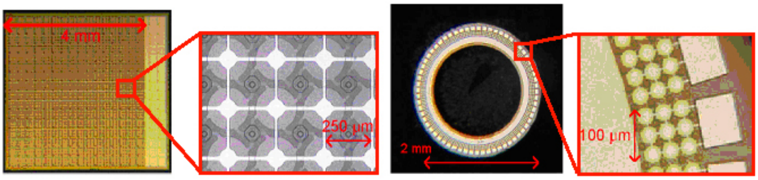

**FIGURE 2.** 4 mm, 16 by 16, 2-D array (left) and 2 mm, 64-element annular ring array (right) used for endoscopic and intra-cardiac applications, respectively [11].

Given the excellent imaging properties of the CMUTs already demonstrated, we will first show experimental results illustrating the potential of HIFU CW operation. We will also show a design for a next-generation dual-mode CMUT for an endoscopic catheter with imaging at 3 MHz and ablation at 2 MHz.

**PULSE-ECHO and 3D IMAGING**

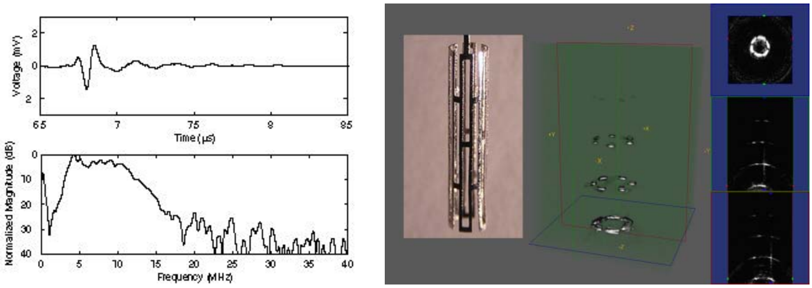

**FIGURE 3.** Typical pulse-echo response and frequency response of the CMUT ring array (left). 3-D image (right) of a stent taken by the 64-element annular ring array; a picture of the stent is shown on the left for comparison [11].

## DUAL-MODE STRATEGIES

CMUTs are especially advantageous for dual-mode arrays because fabrication methods allow production of transducers of different designs to be interspersed on the same wafer. Electronics integration enables switching between imaging and ablation array elements and reduces the size of the device.

Requirements for a HIFU transducer are different than for an imaging transducer. Imaging transducers operate in pulsed mode at higher frequencies (3 - 50 MHz) for better spatial resolution and require large bandwidth and sensitivity. HIFU requires lower frequencies (~500 kHz – 5 MHz) for deeper penetration into tissue. Design of arrays with focusing gain is important for HIFU; if designed with a focusing gain of 10, a CMUT with a peak CW surface pressure of 1 MPa can generate the hundreds of $W/cm^2$ required at the focal point for ablation. Thus, transducers operating with narrow bandwidth in CW mode at a specific frequency with 1 – 2 MPa surface output pressure are adequate for HIFU. These requirements determine separate approaches for dual-mode imaging. In one approach, imaging and therapeutic arrays are fabricated as separate devices on the same silicon die to optimize for each respective application. In the second approach, one array is used interchangeably for imaging and ablation. Since imaging and therapeutic considerations must be balanced, this leads to a design with higher resonant frequency. Imaging is performed at the resonant frequency to increase sensitivity, while ablation is performed at a frequency at the low end of the pass band.

## FEASIBILITY OF CMUT FOR HIFU

To evaluate the feasibility of CMUTs for HIFU, we took typical imaging transducers and operated them in continuous wave operation. We immersed a 1.8 mm by 0.66 mm device in vegetable oil for electrical isolation. We then positioned a hydrophone 1 cm from the surface of the transducer. After using a series inductor to match the device to 50 ohms, we connected the CMUT to a function generator and DC bias supply. The DC voltages were swept from 50 to 100% of the collapse voltage of the CMUT, and AC voltages were selected so that the overall voltage did not exceed 200 V, to prevent dielectric breakdown of the oxide. The input voltage was measured over the CMUT and recorded. Pressure measurements obtained from the hydrophone were corrected for attenuation and diffraction and then plotted versus applied AC and DC voltages given in Fig. 4. These imaging devices were designed with center frequencies near 7 MHz, so we operated them off-resonance at 3 MHz to illustrate the dual-mode operation methodology.

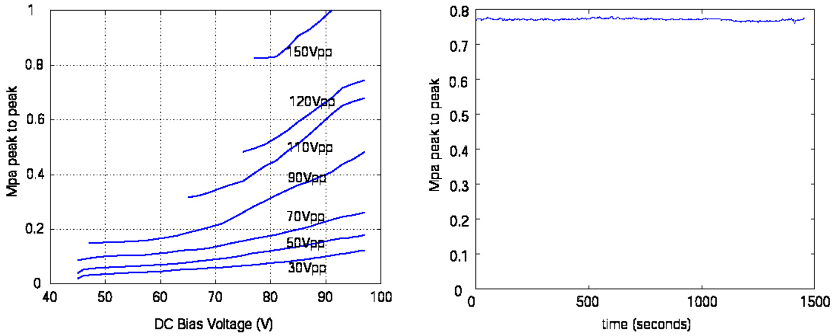
**7MHz IMAGING TRANSDUCER USED IN HIFU MODE**

**FIGURE 4.** A wafer-bonded device has been demonstrated to produce output pressures as high as 1 MPa (left). The device also achieved 0.7 MPa peak-to-peak consistently in continuous wave mode with 80 V bias voltage and 130 Vpp AC voltage (right). The slight decrease in output pressure with time is probably caused by oxide charging.

The output pressure increases for bias voltages close to the collapse voltage because the gap between the electrodes is small at these voltages, and thus the electric field is high. Though these CMUTs were designed with imaging in mind, they were shown to exhibit pressures as high as 1 MPa peak to peak and were operated in CW operation at 0.7 MPa peak to peak for 25 min. The major limitations of current CMUTs are the breakdown of the insulating layers from the high voltages and the failure of metal traces from high current densities. Increasing the thickness of the insulation layers and interconnects can greatly improve performance.

## NEXT GENERATION HIFU/IMAGING TRANSDUCERS

New dual-mode transducers have been designed to operate in conventional mode with a resonant frequency that is in the imaging frequency range (3 - 50 MHz), but they can also be operated at lower frequencies in HIFU mode. In order to achieve the increased pressures needed for HIFU operation, these transducers have larger gap size, 0.2 - 0.3 μm, to generate larger displacements and velocities. In addition, a heavy gold electrode serves as a weight to increase the output pressure. The thick gold allows a more piston-like transducer behavior, which increases the average displacement of the membrane. It also allows separate control of the mass and spring constant of the membrane; increasing the mass allows larger pressure waves to be launched into the medium. We used an axisymmetric model in ANSYS to simulate a CMUT with design parameters shown in Fig. 5. The CMUT membrane and electrode are modeled by PLANE82 elements; TRANS126 elements transfer electrical to mechanical energy. A fluid column of FLUID29 elements was constructed, and the average pressure was calculated to be at least 2 MPa peak-to-peak. The simulated frequency response of this transducer exhibited good imaging qualities with an output of 7.5 kPa/V and 90% fractional bandwidth at 80% of the collapse voltage.

### PRESSURE OUTPUT AND BANDWIDTH

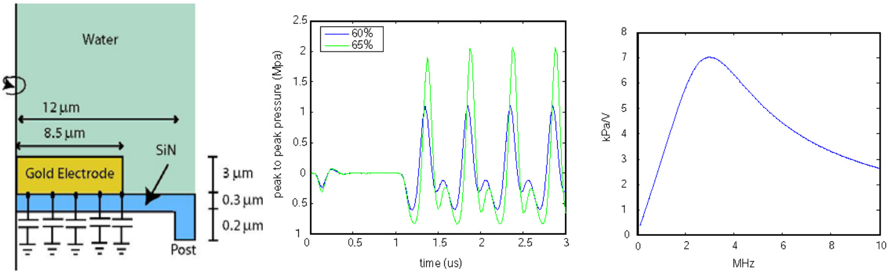

**FIGURE 5.** A dual-mode endoscopic CMUT transducer was modeled in ANSYS (left). A maximum output pressure was calculated to be in excess of 2 MPa peak-to-peak at 2 MHz (center). With a bandwidth of ~90% and the sensitivity 7.5kPa/V, the transducer can image at 3 MHz (right).

## CONCLUSION

Current 2-D and annular ring array CMUT catheters have demonstrated the image quality, fabrication methods, and integration of electronics necessary for successful interventional devices. Experiments with current imaging CMUTs have shown that CMUTs are capable of delivering higher pressures in continuous wave operation. With these promising results, a dual-mode CMUT can be designed for endoscopic imaging and ablation.

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