Applications of CMUT Technology in Medical Diagnostics: From Photoacoustic to Ultrasonic Imaging

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Abstract: ***Transducers have been used for a variety of operations, largely medical imaging for decades using piezoelectric material as conventional techniques. While commercial piezoelectric transducers rely on response to mechanical stress, measurement in the form of change in capacitance is the unique proposition offered by capacitive micromachined ultrasonic transducers (CMUT). CMUTs offer multiplexing capabilities, large scale production, low frequency operation, and integration options making them a go - to for industry leaders towards medical imaging fabrication for applications such as ultrasonic imaging. Polymer substrate based CMUTs have shown to provide versatility in photoacoustic tomography while dual - frequency and multiband CMUTs have provided capabilities of dual - mode imaging on a single array. Such advancements have paved the path into high intensity ultrasound and even ultrasound mediated drug delivery. This review provides an overview of the latest developments in CMUT technology, the principle of operation, advancements with recent findings, and prospects of integrating with artificial intelligence (AI) to maximize efficiency.***

Keywords: CMUT, medical imaging, biosensors, precision medicine, diagnosis, ultrasonic imaging

1. Introduction

3D ultrasonic imaging techniques have revolutionized the realm of medical imaging by providing the freedom to analyze and inspect 2D images in a 360 degree orientation with the assistance of a transducer [1]. The conventional method of detection till date has involved piezoelectric transducers, which cycle changing alternating current (AC) to ultrasound using the shape and size change response of piezoelectric crystals. [2] These transducers however pose obstructions due to large size and space requirements. Using transducers that measure capacitive change in energy allow for a smaller and portable imaging technique. In the 1990s, the fabrication of capacitive micromachined ultrasonic transducers (CMUTs) was made possible with micromachining technology allowing for electrostatic transducer fabrication at micron level operating in megahertz range (mHz) [3]. CMUTs were introduced in the mid - 1990s and were discovered in 1950. Their arrival has provided a more optimal alternative to conventional piezoelectric transducers, especially in the field of medical imaging [4].

CMUTs are silicon - based, micro - electromechanical system devices designed for electrostatic actuation. A CMUT consists of a flexible parallel - plate capacitor suspended over a gap. The CMUT element comprises multiple cells, each consisting of a membrane suspended above a substrate, with a cavity of precisely - defined thickness in between. Both have separate electrodes and typically incorporate thin dielectric layers on the inner surfaces. These devices are fabricated primarily by the Sacrificial Release Process which includes the sequential deposition of silicon nitride, sacrificial polysilicon and aluminum layers. Another popular method of fabricating CMUT is the wafer bonding process which uses a combination of surface machining and silicon on insulator (SOI). Wafer bonding process significantly simplifies the fabrication, improves uniformity and provides control towards the plate thickness, which is now defined by the device layer of the SOI wafer [5].

CMUT technology allows for 360 degree coverage of the localized area, superior to that of a piezoelectric transducer. CMUT technology has advanced into a wider bandwidth operation, enhanced receive sensitivity, tunable frequency response and easy integration with electronics. Conventional piezoelectric transducer array elements consist of bulk resonators which are tiny blocks of ceramic that offer high dielectric strength. CMUTs on the other hand have extremely thin flexural membranes, with thin - film dielectric layers that can withstand significantly higher electric fields. Despite the hurdles of materials, cost and fabrication, CMUT technology offers promising potential benefits that continue to drive sustained research and commercial interest to this day [6]. The CMUT technology is most commonly used in the field of medical science such as ultrasound imaging, ultrasound therapy, high - intensity focused ultrasound (HIFU) etc.

CMUTs have more recently shifted the paradigm of 3D imaging offering an improved lateral and axial resolution, high speed, low cost of fabrication, multiplexing capabilities, higher accuracy, sensitivity and specificity than traditional methods. Most importantly, the capabilities for real time 3D imaging, presenting improved diagnostic applications towards ophthalmology, dermatology and cardiology [7]. Here, we present a brief overview of the principle of operation, recent fabrication advancements, system integration methods and recent technology developments in CMUT research.

2. Discussion

2.1 Principle of Operation

The ultrasonic imaging works on the principle of Doppler effect as shown in Figure 1. The transmitting ray falls on the surface of the tissue or blood vessel and forms an angle of incidence which is then used to calculate the blood flow [8]. CMUT uses acoustic doppler velocity measurement to detect doppler shifts at different velocity and frequency intervals [9]. Delving deep into the blood - flow measurement, CMUT can act both as a transmitter and receiver. The transmitter is used to generate ultrasound waves that interact with the moving blood. The receiver on the other hand collects the frequency shifted waves due to the Doppler effect [10] as shown in Figure 1. The angle between the transmitted wave and the direction of blood flow is called the angle of incidence, which is usually maintained around 60 degrees to minimize velocity calculation errors [11]. Velocity of the blood flow can be calculated using the Doppler equation:

$$V = \frac{cf_D}{2f_0 cos\theta}$$

where,
V = blood velocity
c = speed of sound in the medium (typically 1540 m/s in soft tissue)
f_D= Doppler shift frequency (difference between transmitted and received frequencies)
f_0= transmitted ultrasound frequency
θ = angle between the ultrasound beam and direction of blood flow

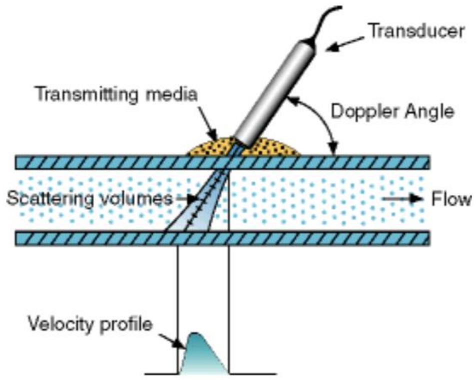

Figure 1: Doppler effect principle of operation.

The conventional technique for CMUT fabrication is performed using complementary metal - oxide - semiconductor (CMOS) technology which allows for a permanent bonding of the electronics and hardware components on the wafer by an exchange of two transistors: (1) the N - Channel metal - oxide - semiconductor field - effect transistor (MOSFET) and (2) the P - channel MOSFET [12]. Using silicon, an insulating layer of thin materials such as silicon dioxide are deposited. After this, photolithography is used to mask patterns onto the substrate using a photoresist mask and UV light. The wafer is cleaned using reactive ion etching (RIE) and the entire process takes place in a clean room setting to prevent contamination. Thousands to millions of microsized CMUT cells come together with CMOS chips to generate enough power to drive these cells and read them. The CMUT layer is integrated monolithically over the CMOS substrate resulting in a single chip. This allows multiplexing of very large 2D arrays operating at large frequencies which is not possible with conventional bulk piezoelectric transducers [13].

2.2 Applications

2.2.1 Integrated systems

One of the advantages that CMUT offers is easy integration with electronic circuits. Close integration of ultrasonic transducer arrays and supporting integrated circuits is highly desired in many applications, especially for transducer arrays with small elements such as in 2 - D arrays and arrays for use at the end of a catheter [14].

Several microelectro - mechanical systems (MEMS) techniques have been adapted to integrate CMUT arrays with electronic circuits. These can be widely divided into two categories, Monolithic and Multichip integration: Monolithic integration involves fabrication of CMUT and the electronic circuit together, thus does not require any additional assembly or bonding. This type of integration is highly compact by combining the transducer and circuit components on a single monolithic chip. A distinctive integration option for CMUTs had been the monolithic approach where the CMUT array is built directly on top of the electronic circuitry, ensuring a cohesive fusion within the components [15]. Multichip integration on the other hand involves fabrication of the CMUT array and electronic circuit separately. Interconnections are made via flip - chip bonding or other intermediate substrates. This type of integration allows easy optimization of CMUT and circuitry as they are fabricated independently of each other.

Recently, monolithic integration of piezoelectric micromachined ultrasonic transducers (PMUT) with CMOS electronics have been achieved by virtue of their shared advantage: their compatibility of micromachining processes with CMOS processes. Monolithic integration has been regarded as the gold standard due to the compactness of the resulting system and the elimination of extra integration steps associated with multi - chip approaches. Multichip integration has been applied in linking 2 - D CMUT arrays to the electronics. Methods such as flip - chip bonding with solder reflow, inclusion of gold stud bumps and anisotropic conductive films (ACF) or thermo - compression bonding are usually applied in multi chip fabrication processes. These integration methods are common but not unique to CMUTs and have been applied to piezoelectric matrix arrays with great success as well.

2.2.2 Environment

Over the course of recent developments, CMUT has also emerged as a strong candidate for a micro mechanical resonant - chemical sensor system [16]. Low - power gas sensor designs have been made based on CMUT technology for environmental monitoring. The core of these designs lie in the vibrating structure suspended over a vacuum - sealed cavity exhibiting a higher quality factor compared to cantilevers with similar detection areas. Each resonator is composed of hundreds of cells connected in parallel, which ensures robust operation. CMUTs have also been demonstrated as chemical sensors with high sensitivity and high resolution for the detection of chemical warfare agents.

Paper ID: SR24619062609 DOI: https://dx.doi.org/10.21275/SR24619062609

As the emphasis is on the sensor's ability to detect chemical agents, power consumption was not the primary constraint. The CMUT is functionalized with polyisobutylene (PIB), which is sensitive to specific volatile organic compounds (VOCs) such as toluene. When the functionalized device is exposed to a VOC, the additional mass of the absorbed analyte on the resonant structure causes a shift in the resonant frequency which can be detected downstream. The CMUT resonators have been fabricated using a novel process based on anodic bonding and the final CMUT structure consists of a vibrating plate, which is composed of a layer of single - crystal silicon, a layer of silicon nitride, and a patterned metal bottom electrode deposited inside a vacuum sealed, sub - micron cavity. As a result, a low power resonant chemical sensor based on CMUTs are able to detect the specific gasses such as VOCs and carbon dioxide, which are indicators of air quality and environmental hazards. Another example of environmental monitoring is Inkjet printing [17] in which CMUTs are used in the fabrication of functionalized sensors for detecting gasses and enhancing air quality via real - time monitoring. Inkjet printers are used to deposit specific materials on the CMUT surface to create functional sensors. Examples include polyethyleneimine (PEI) which is used as a functional material on the surface of CMUTs, proven to be fully functional for carbon dioxide detection by the measurement of the PEI functionalized CMUT mechanical impedance. The CMUTs have also played a significant role in air applications [18], but have been underestimated for long, due to their lack of sensitivity for non - destructive testing applications [19]. The first research article on CMUT in the field of gas sensing was published in 2007, which showed the top electrode was coated with a sensitive polymer in order to detect the molecule of interest, by increasing the vibrating plate mass and thereby decreasing the resonant frequency when absorbing these gas molecules. Exploring further, we come upon the ability of air coupled CMUTs to monitor binary gas mixtures [20]. This method consists of sensing simultaneously the variations of both the ultrasonic velocity and the ultrasonic attenuation. The most common approach for gas sensing is based on the resonance frequency variations of an acoustic oscillator covered by specific chemical coating to detect particular gas molecules from the environment. As an advancement in MEMS based technology, an air - coupled transducer based on CMUTs was proposed. CMUTs have a notable frequency bandwidth that admits very low emitted pulse duration and also allows monitoring the ultrasonic attenuation in the gas over a large range of frequencies. Therefore, the concept of using air - coupled CMUT without sensitive coating for monitoring binary mixture of gasses was proposed and successfully demonstrated.

2.3 Clinical applications

CMUT has played a key role in advancing the field of medical imaging and therapy. Over the past two decades of extensive research and development of new innovative microfabrication methods, CMUT based integrated circuits have shown an immense potential for medical applications [21]. Some of the factors that make CMUT stand out include high levels of integration giving rise to low cost point of care devices, higher resolution in imaging and higher sensitivity at a compact scale. CMUT's versatility can be showcased in their imaging capabilities, 1 - D array allows electronic focusing and steering of ultrasonic beams within an azimuthal plane resulting in a 2 - D cross - sectional image. Similarly, 2 - D transducer array allows electronic focusing and steering of ultrasonic beams both in azimuthal and elevational directions to enable real - time 3 - D imaging. Recently, several major ultrasound system manufacturers have introduced 2 - D array based 3 - D imaging platforms to the market [22]. These systems employ electronic multiplexing and beamforming circuitry next to the transducer array to reduce the number of active electronic channels, so that the standard backend systems with limited number of channels can be used for image formation. CMUT also has great potential for therapeutic ultrasound which is guided by magnetic resonance imaging (MRI), it is a non - invasive treatment that potentially reduces mortality, lowers medical cost, and widens accessibility of treatments for patients [23]. Modern improvements in the design and fabrication of CMUTs, have made them competitive, with piezoelectric transducers for use in ultrasound applications. Some of these advancements include propagation of mechanical impedance in liquid medium. Since in CMUTs, the mechanical impedance of the membrane is smaller than the acoustic impedance of water, ultrasound waves are able to travel at a much faster rate, a key medium used in ultrasound imaging [24]. Because of this, CMUTs are often described as 'overdamped systems' with wide bandwidth and are equipped with effective transmission into water. Since therapeutic ultrasound applications frequently excite transducers at a single frequency, a wide bandwidth is not critical, but could be beneficial for applications such as dual - mode ultrasound, where the same transducer is used for imaging. CMUTs also play a promising role in underwater imaging [25].

2.4 Ultrasonic imaging

CMUT technology used in photoacoustic imaging (PAI), also called as optoacoustic imaging, is a promising medical imaging technology that combines contrast information of optics with the spatial resolution of acoustics [26]. PAI uses a two - dimensional array of CMUT with integrated front - end electronics and it has been extensively studied for the imaging of humans and small animals. Potential clinical applications for PAI include detection of cancerous tissue, functional and molecular imaging. In PAI, the target tissue is illuminated with short laser pulses that cause brief heating of absorbing structures like blood vessels. Rapid heating induces a thermoelastic expansion which generates ultrasonic waves that are detected by an ultrasound transducer. Advantages of CMUT technology in PAI include the ease of integration with electronics, ability to fabricate large arrays with arbitrary geometries, wide - bandwidth arrays and high frequency arrays [27]. CMUT has also been implemented on intravascular ultrasound (IVUS) which is another medical imaging methodology that uses a specifically designed catheter with a miniaturized ultrasound probe attached to the distal end. This allows the observation of blood vessels and its surrounding blood column, providing insights into the inner wall of blood vessels in active individuals [28].

2.5 Challenges

While CMUT offers a number of advantages, it has always been in competition with piezoelectric transducers [29]. Achieving output surface pressures to match that of commercial - grade piezoelectric transducers has been a primary challenge for CMUTs. Piezoelectric transducers generally outperforms CMUTs on these metrics and achieve greater signal - to - noise ratio (SNR) and imaging penetration depth. Piezoelectric transducers manufacturing involves going through a harsh environmental and durability testing, yielding a rugged probe that can sustain performance over a decade or more of frequent clinical use. CMUTs on the other hand are extremely thin flexural membranes, with thin - film dielectric layers that must withstand very high electric fields resulting in low durability. Another CMUT processing concern is ensuring consistent CMUT cells across a wafer during the surface - machining and sacrificial - release processes. Since different process steps involve varying temperatures and the materials have different coefficients of thermal expansion, membranes may exhibit a “bowing” effect, which creates variation for all cells near the center versus the edge of the wafer. Without tight process controls, this bowing can cause changes in the cavity gap height from its intended value, and thus resulting in a CMUT voltage collapse, leading to inconsistent operation and performance on a given wafer. A key fundamental challenge for CMUTs is their inherently nonlinear response - the electric force on CMUT membrane is proportional to the square of the applied voltage, so pressure pulses output from a CMUT tend to include higher - order harmonic components. Moreover, due to temperature constraints set by the existing metal lines on the electronics, processing techniques for fabricating CMUT are still limited [30]. To summarize some more recent developments of cMUT technology, its advantages and challenges are listed in Table 1.

Table 1: Advantages of CMUT in recent applications.

Study	Type of Application	Description	Advantages	Challenges
I. O. Wygant et al [31]	Ultrasound imaging	Non - invasive medical imaging technique that uses high - frequency sound waves to visualize internal body structures.	Non - ionizing, safe, cheap, portable, high frequency, high output pressure for good image quality	Connecting 2D array elements to front - end electronics, acoustic impedance mismatch leading to weaker output signal
Srikant. V. et al [27]	Photoacoustic Imaging	Hybrid imaging modality that combines optical and ultrasound techniques, leveraging optical contrast and ultrasound propagation for deep tissue imaging.	Ease of integration with electronics, large 2D arrays, arbitrary geometries, wide bandwidth, high frequency, optical contrast with deep penetration	Manufacturing and assembling miniature components for endoscopic applications
Fesenko, P. et al [32]	Biometric devices	Technologies for personal identification and authentication based on unique biological characteristics, such as fingerprints, iris, or facial features.	Good combination of accuracy, size, and price. Ideal compatibility with capacitive fingerprint sensors	Performance degradation with sweaty/dirty fingers, lower accuracy for high - security applications
Wang, J. et al [33]	Intravascular Ultrasound Imaging	Imaging technique that uses a catheter - based ultrasound probe to visualize the interior of blood vessels, particularly for diagnosing coronary artery diseases.	Provides vital information for coronary disease diagnosis, can be fabricated into arrays with less complications, easy integration with CMOS	Limitations of traditional piezoelectric transducers acting as transmitter and receiver
Salim, M et al [34]	Immersion Applications	Applications where the transducer is submerged or loaded with a fluid or solid medium, such as sonar, flow metering, and non - destructive testing (NDT).	Wide - band transducers benefit applications like air, flow metering, NDT, sonar	Bandwidth and size constraints for low - frequency transducers, especially in space - limited UUVs

2.6 Integrating Artificial Intelligence with CMUT

CMUTs offers a promising pathway towards integration with artificial intelligence (AI) and internet of things (IoT) to enable advanced sensing and monitoring applications. These miniaturized sensor structures operate on electrostatic principles enabling the transmission and detection of ultrasonic waves. Manufactured using semiconductor technology, they offer great flexibility in sensor design with high precision and reproducibility for single and multi - channel systems [35]. In the field of AI integrated CMUT arrays can be applied for chemical vapor detection and analysis. It involves functionalization of three chemically sensitive layers within a CMUT resonant devices 1) phenyl - selective peptide, 2) colloids of single - walled nanotubes and peptide and, 3) polystyrene - co - allyl alcohol which can be used to detect specific volatile organic compounds (VOC). Such sensors are essential for home healthcare and workplace safety because VOCs are environmental pollutants that may critically affect human health. These arrays are further used to obtain a large dataset that captures the unique fingerprint of a chemical texture. Also, the compact size and wireless capabilities of CMUT make them well - suited for IoT applications. A portable VOC sensor system has been demonstrated using CMUT array with wireless readout circuitry. Other than chemical sensing, CMUTs can also be used for structural health monitoring by embedding them in materials and structures. CMUTs combined with advanced sensing methodologies can be applied in lab - on - a - chip applications allowing intricate analyses and detection within miniaturized devices [36] [37].

3. Conclusion

CMUTs have emerged as a promising alternative to piezoelectric transducers with advantages such as ease of use, integration with electronics, high frequency bandwidth and fabrication capabilities. Integrating AI with CMUT can result in innovative sensing and monitoring applications in various fields such as environment, healthcare, industrial, etc. As CMUTs continue to be a topic of research and development, challenges such as acoustic impedance, temperature constraints and nonlinear response characteristics will need to be dealt with. Overall, the unique capabilities of CMUTs pose a promising solution for a wide range of ultrasound - based applications.

Supplementary Material
Not applicable

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