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Capacitive micromachined ultrasonic transducers based on annular cell geometry for air-coupled applications

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ABSTRACT

A novel design of an air-coupled capacitive micromachined ultrasonic transducer (CMUT) with annular cell geometry (annular CMUT) is proposed. Finite element analysis shows that an annular cell has a ratio of average-to-maximum displacement (RAMD) of 0.52–0.58 which is 58–76% higher than that of a conventional circular cell. The increased RAMD leads to a larger volume displacement which results in a 48.4% improved transmit sensitivity and 127.3% improved power intensity. Single-cell annular CMUTs were fabricated with 20-μm silicon plates on 13.7-μm deep and 1.35-mm wide annular cavities using the wafer bonding technique. The measured RAMD of the fabricated CMUTs is 0.54. The resonance frequency was measured to be 94.5 kHz at 170-V DC bias. The transmit sensitivity was measured to be 33.83 Pa/V and 25.85 Pa/V when the CMUT was excited by a continuous wave and a 20-cycle burst, respectively. The receive sensitivity at 170-V DC bias was measured to be 7.7 mV/Pa for a 20-cycle burst, and 15.0 mV/Pa for a continuous incident wave. The proposed annular CMUT design demonstrates a significant improvement in transmit efficiency, which is an important parameter for air-coupled ultrasonic transducers.

1. Introduction

Ultrasound is commonly associated with medical applications, including imaging [1], non-destructive testing (NDT) [2], and special treatments [3,4]. Compared to immersion applications, air-coupled applications are less common, yet they hold important roles in a wide range of products and processes, such as vehicle radars [5], wood and food inspection [6], and flow-meters [7]. Furthermore, air-coupled ultrasound has been increasingly applied to applications of human-computer interaction (HCI) [8], as well as contactless inspection of goods and materials (e.g., electric-packaging materials, art objects, and many composite materials found in aerospace industry). The diverse applications and increasing needs from a large number of industries have led to rapid development of air-coupled ultrasonic transducers [9,10].

The design of air-coupled transducers is challenging for several reasons. Air has low acoustic impedance while the attenuation loss of ultrasound propagation in air is significant. A large impedance mismatch between the transducers and the air results in a high reflection loss, which is detrimental to the transducers' efficiency [9]. On the other hand, the attenuation of acoustic waves in air is significant and increases exponentially as the frequency increases. For instance, at 20 °C and 20% relative humidity, the attenuation factors are 0.9 dB/m, 2.19 dB/m, and 162.4 dB/m at 50 kHz, 100 kHz, and 1 MHz, respectively [11]. The attenuation constrains the transducers to operate in a low-frequency region in order to generate enough acoustic pressure at a certain distance. A low frequency leads to a near natural focal depth for a limited aperture size. As one cannot focus a sound beam at a point beyond the natural focal depth, the implementation of beam focusing in air is limited [1]. Given the limitations, generating a high acoustic pressure, which can compensate for the attenuation and reflection loss, is essential for an air-coupled transducer.

The most widely used ultrasonic transducers are based on piezoelectric lead zirconate titanate (PZT). A corresponding backing layer is required to modify the ringing effect of the PZT while an impedance matching layer is required to increase the transmit efficiency from the active elements to the propagation medium [12]. Ideally, matching layers are required to have low density, low acoustic propagation speed, and low attenuation. Yet, such layers are difficult to realize [13]. In addition, PZT-based transducers are made from bulk materials, which require precision dicing and

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lapping to achieve separate elements and arrays. As a result, batch fabrication is costly.

As a potential replacement technology of piezo-based transducers, micro-electromechanical systems (MEMS)-based ultrasonic transducers driven by electrostatic force have been well studied. Using micro-fabrication technology, capacitive micromachined ultrasonic transducers (CMUTs) can be made with thin plates covering tiny vacuum cavities [14–16]. Given the small cavities, CMUTs are able to have a strong electric field and thus an electromechanical coupling efficiency exceeding that of piezoelectric transducers. A thin plate offers low mechanical impedance, which matches with the acoustic impedance of air and yields a high coupling efficiency. In addition, the silicon process used in CMUTs fabrication is highly compatible with integrated circuits.

Despite the advantages, the output pressure is still a great concern for CMUT air-coupled applications. In order to improve the output pressure, a high DC bias and AC excitation voltage can be used. However, a high voltage may lead to dielectric breakdown of the device. This fundamental design restriction inspired our novel CMUT design based on annular cell geometry (annular CMUT). Even though different membrane configurations and electrode designs of CMUTs for immersion applications have been investigated [17–21], the air-coupled CMUTs reported to date have been primarily focused on circular cell designs [22–26] Optimization aside, seldom research has been conducted on different fundamental cell shapes. Since the geometry plays an important role in the behaviour of a CMUT plate, more investigation about other geometries is prudent. In contrast to a conventional circular plate, an annular plate is clamped at the inner and outer edges, which results in two separate fixed constraints. It has three main advantages over the circular design. First, a higher transmit sensitivity can be achieved due to a larger ratio of average-to-maximum displacement (RAMD) of the plate. Secondly, a higher receive sensitivity can be realized due to an enhanced device capacitance. Thirdly, annular cells with different sizes can be put in a concentric layout for annular-based beam focusing.

The rest of the paper is organized as follows. Section 2 presents the static and dynamic behaviour of an annular CMUT cell through Finite Element Analysis (FEA). A comparison between annular and circular cells is also performed. Section 3 provides the fabrication of the devices using the wafer bonding technique. Section 4 reports the characterization results. Discussion and conclusion are included in Sections 5 and 6.

2. Finite element analysis of an annular CMUT cell

The static and dynamic behaviour of a CMUT plate is determined by the material properties, structural dimensions, and boundary conditions. For a typical vacuum-sealed circular CMUT cell under atmospheric pressure, the maximum static displacement of its plate occurs at the center. However, if the plate is fixed at the center, its active area will become an annular shape while the maximum displacement moves to somewhere between the inner and outer edge. Fig. 1 shows the schematic plot of such an annular-cell CMUT.

The inner and outer radius of the plate are represented by a and b. r and h denote the radial position and the plate thickness. g is the effective cavity depth and can be calculated based on the actual cavity depth g_0, insulating layer thickness t_i, and relative permittivity of the insulating material ε_i using:

$$g = g_0 + \frac{t_i}{\varepsilon_i}. \tag{1}$$

The aspect ratio of the annular plate is defined as:

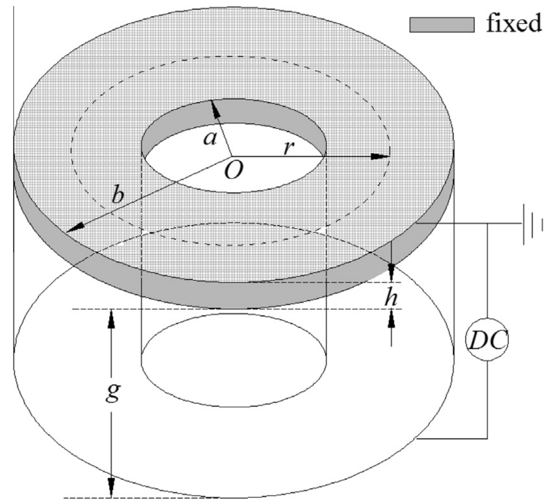

Fig. 1. Schematic of an annular CMUT cell.

$$\tau = \frac{a}{b}. \tag{2}$$

The smaller τ is, the more similar the plate is to a "tent" which is supported at the center. In contrast, the larger τ is, the more similar the plate is to a "ring".

Comsol Multiphysics® (COMSOL Inc) was used to simulate the static and dynamic behaviour of the proposed annular CMUT. When building the finite element model, the following conditions were set: 1. the annular plate was made of highly conductive single crystal silicon which was simplified as a linear and isotropic material; 2. the insulating layer was made of wet thermal silicon dioxide; 3. the top surface of the plate was subjected to one standard atmosphere (atm); 4. the annular cavity was vacuum-sealed with depth of g; 5. the DC bias and AC excitation voltages were applied separately at the silicon plate and bottom surface of the cavity. The physical properties of the materials involved in the model are listed in Table 1.

In the finite element model, five types of forces are involved: the inertia force $F_{inertia}$ caused by the mass of the plate, the restoring force $F_{restore}$ resulting from the boundary conditions, the acoustic force $F_{acoustic}$ induced by the ambient medium, the electrostatic force $F_{electro}$ caused by the DC bias and AC excitation, and atmospheric force F_{atm} due to atmospheric pressure. The dynamic equation can be expressed in terms of the five forces as:

$$F_{inertia} + F_{restore} + F_{acoustic} + F_{electro} + F_{atm} = 0. \tag{3}$$

High-frequency acoustic waves suffer significant attenuation loss in air when the propagation depth is in the order of one meter. As a result, when choosing the operation frequency of an air-coupled transducer, one is forced to make a trade-off between the axial resolution and the penetration depth. This paper sets the transducer's natural resonance frequency to 100 kHz at which the wavelength and acoustic attenuation factor is 3.4 mm and 2.19 dB/m at 20 °C and 20% relative humidity [11]. Given a 100-kHz resonance frequency, the annular CMUT is required to have a large plate width and thickness. Otherwise, the undesired

Table 1
Physical properties of silicon and silicon dioxide used in the model.

Material	Density (kg/m^3)	Poisson's ratio	Young's modulus (GPa)	Relative permittivity
Si	2330	0.27	169	N/A
SiO_2	2200	0.17	70	3.9