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⁸⁹⁷ Evaluation of wafer bonded CMUTs with rectangular membranes featuring high fill factor

Serena H. Wong, Mario Kupnik, Xuefeng Zhuang, Der-Song Lin, Kim Butts-Pauly, and B.T. Khuri-Yakub

Abstract

Increasing fill factor is one design approach used to increase average output displacement, output pressure, and sensitivity of capacitive micromachined ultrasonic transducers (CMUTs). For rectangular cells, the cell-to-cell spacing and the aspect ratio determine the fill factor. In this paper, we explore the effects of these parameters on performance, in particular the nonuniformity of collapse voltage between neighboring cells and presence of higher order modes in air or immersed operation. We used a white light interferometer to measure nonuniformity in deflection between neighboring cells. We found that reducing the cell-to-cell spacing could cause bending of the center support post, which amplifies nonuniformities in collapse voltage to 18.4% between neighboring cells. Using a 2-D finite element model (FEM), we found that for our designs, increasing the support post width to 1.67 times the membrane thickness alleviated the post bending problem. Using impedance and interferometer measurements to observe the effects of aspect ratio on higher order modes, we found that the (1,3) modal frequency approached the (1,1) modal frequency as the aspect ratio of the rectangles increased. In air operation, under continuous wave (CW) excitation at the center frequency, the rectangular cells behaved in the (1,1) mode. In immersion, because of dispersive guided modes, these cells operated in a higher order mode when excited with a CW signal at the center frequency. This contributed to a loss of output pressure; for this reason our rectangular design was unsuitable for CW operation in immersion.

Keywords

CMUTs; rectangular membranes; HIFU; output pressure; receive sensitivity; mode shapes

I. Introduction

Transducers with high sensitivity and output pressure are essential in acoustic applications such as nondestructive evaluation, imaging, and therapeutics. For instance, in pulse-echo and photoacoustic imaging, higher sensitivity improves detection of incoming pressure waves [1]-[3], thus increasing image quality. For pulse-echo imaging, high transmit output pressures increase the penetration through tissue and the signal-to-noise ratio of the image. In therapeutic applications, such as high intensity focused ultrasound (HIFU), greater output pressures deposit more energy in tissue for faster heating [4]. All these applications motivate the design of transducers to maximize sensitivity and output pressure.

For capacitive micromachined ultrasonic transducers (CMUTs), achieving high sensitivity and output pressure relies on maximizing a cell's average output displacement. Several research groups have previously suggested dual electrode structures [5], nonuniform membrane configurations [6]-[8], and modifying the fill factor and cell shape [9] as possible design approaches to increase average output displacement. In particular, Huang, et al. showed that modifying cell shapes from square to rectangle to tent improved transmit efficiencies by 46%

and 44% and receive efficiencies by 43% and 65%, respectively. He attributed the increase in efficiencies to be caused by the increase in fill factor between different shapes [9].

The fill factor is defined as the ratio of the total active area, which is equal to the cavity area, to the total area of the device [10], [11]. Increasing the fill factor increases the device area that is free to move compared to the perimeter of the cell that is clamped, thus increasing the cell's total average displacement. In practice, increasing the fill factor can cause pitfalls such as amplification of nonuniformities between neighboring cells and an increased presence of higher order modes. In particular, these higher order modes can be detrimental in imaging applications because broadband pulses can easily excite them, which causes ringing that degrades the image resolution [12].

Of the three shapes Huang studied, rectangles demonstrated an improved fill factor and performance, while maintaining robustness to single-point fabrication defects. Many research groups have also developed models and fabricated rectangular cells because of this improvement. Using simulation tools, they investigated cell response as a function of cell width and length. Analytical tools have been developed that can predict the collapse voltage and primary resonant frequency [13], [14]. Finite element analysis (FEA) has also been used to calculate modal frequencies of rectangles with regard to dimensions [11], [15] and orientation with respect to the crystal axes [16]. Using these models as a guideline, research groups have fabricated rectangular cells for air and immersion applications including microphones, lamb wave transducers, and imaging transducers [17]-[20].

While maximizing fill factor has been a common design rule for increasing average output displacement, we found that there is a limit to increasing the fill factor before performance is compromised. In this paper, we will discuss the parameters that affect rectangular fill factor, the cell-to-cell spacing and aspect ratio. First, we study the effect of cell-to-cell spacing on nonuniformity by observing differences in collapse voltage between neighboring cells. We used a 2-D finite element model (FEM) to analyze these effects and design an adequate cell-to-cell spacing. Second, we discuss the effects of aspect ratio on higher order modes in the dynamic response of the cells, measured with an impedance analyzer and laser interferometer. We examine the modal frequencies of the (1,1) and (1,3) mode as a function of aspect ratio. Finally, we examine continuous wave (CW) excitation in air and immersion to demonstrate the modes of operation.

II. CMUT cell design - Fill Factor Considerations

Cell shape greatly affects the fill factor of a device. Circles have a low fill factor even when placed in a close packed structure (Fig. 1 a). Replacing circles with hexagons increases the fill factor (Fig. 1 b). Rectangles (Fig. 1 c) introduce an extra degree of freedom, the length, which further increases fill factor. Finally, tent CMUTs have the greatest fill factor and active area because the whole membrane is free to move, except where the tent posts are located (Fig. 1 d).

CMUT cells are designed for an operation frequency by choosing a combination of membrane thickness and cell radius or width [11], [21]. If we compare cells with different shapes that have the same center frequency, we find that the circle has the smallest fill factor, followed by hexagons, rectangles, and tents. To illustrate this, we assumed a minimum, constant support post width of $5\text{ }\mu\text{m}$ and calculated the fill factor for shapes depending on the cell diameter or width (Fig. 2). For an example comparison, we chose a membrane thickness of $6\text{ }\mu\text{m}$ and a desired center frequency of 6 MHz in air. For these specifications, the circle's radius should be $62.5\text{ }\mu\text{m}$, the square's side should be $112.5\text{ }\mu\text{m}$, and the rectangle's width should be $92.5\text{ }\mu\text{m}$. This translates to fill factors of 83.9%, 91.5%, and 94.8% for the circle, square, and rectangle, respectively. Even as the diameter of the circle increases, the upper limit for the fill

factor of the circle is close to 90%, while that of rectangles is near 100% (Fig. 2). While tents have the greatest fill factor, near 100%, this configuration suffers from the lack of sub-cell isolation, which makes it vulnerable to processing defects. Rectangular cells show a better compromise of fill factor while maintaining robustness to fabrication-related defects [9].

For a rectangular shape, there are two methods of increasing the fill factor, decreasing the cell-to-cell spacing (support post width) and increasing the aspect ratio of the rectangle. Care must be taken when designing these parameters as performance may be sacrificed because nonuniformities are amplified or higher order modes begin to dominate the response. The support post width should be chosen as small as possible to maximize fill factor while maintaining enough stiffness to prevent amplification of nonuniformities between neighboring cells, thus providing mechanical cell-to-cell isolation. In addition, the aspect ratio needs to be chosen to minimize the excitation of higher order modes.

III. Methods

A. Fabrication

The direct-fusion, wafer-bonding process enables fabrication of long rectangular shapes that are not easily formed using the sacrificial-release process [22]. Cavities are first etched on a prime wafer; then, a silicon-on-insulator wafer, with an active layer that has the appropriate membrane thickness, is fusion bonded to the cavities [22]-[24] (Fig. 3). Highly conductive silicon is used as the membrane, which eliminates the need for metal as a top electrode. This process allows flexibility in the shapes that can be fabricated, but also creates additional design parameters that need to be explored.

Using the wafer-bonding process, we fabricated rectangular cells for medical imaging and therapeutics in the 1-5 MHz range. Designs A and B (Table I) were used as examples to examine the effects of support post width rigidity on cell-to-cell uniformity. Rectangles of varying aspect ratios with constant width (Table I, designs C-E), were used to examine higher order modes. These three designs were patterned into 3-by-3 mm transducers for testing.

B. Measurements

Measurements were made to examine the behavior of the rectangular cells with different support post widths and aspect ratios in air and immersion.

We investigated nonuniformity effects influenced by support post width by observing the deflection of cells under applied DC voltages (SRS PS310, Stanford Research Systems, Stanford, CA). We measured the static deflection of neighboring cells with a white light interferometer (NewView 200, Zygo Corporation, Sunnyvale, CA) for DC bias voltages from 10 V up to the collapse voltage.

The effects of aspect ratio on higher order modes were studied by analyzing the electrical input impedance of the device and the dynamic deflection of individual cells. Impedance measurements (Agilent 4294A, Agilent, Palo Alto, CA) were made in air under applied DC voltage (SRS PS310) to measure the frequencies of the fundamental and higher order modes. To examine the effects of these modes on dynamic behavior in air, we applied a 2 V_{pp} sinusoidal tone-burst (Agilent 33250A Function Generator, Agilent, Palo Alto, CA) superimposed with a DC voltage that was 80% of the collapse voltage. We used a frequency associated with the maximum displacement of the membrane. A tone-burst excitation with 100 cycles to reach steady-state was used to investigate the CW response of the device. Using a laser interferometer (Polytec OFV511, Polytec Corporation, Tustin, CA), we measured the displacement over time for spatial locations every 20 μm over a 1.5-by-1.5 mm area, equal to one-quarter of the test transducer. From these time signals, we generated time-dependent 3-D

measurements of the surface displacement of the transducer. Because our device has four-fold symmetry, measuring one-quarter of the transducer was sufficient to understand the behavior of the whole device (Fig. 4a).

Dynamic performance in immersion was then investigated by measuring both dynamic displacement of the cells and the total acoustic output pressure. Oil was used as the immersion medium for electrical isolation and acoustical properties, which are similar to tissue [3]. We used a 30-cycle, tone-burst excitation at 2.5 MHz, the center frequency of the CMUT in oil, superimposed with a DC voltage that was 80% of the collapse voltage. Dynamic displacement measurements were made using the interferometer with the same area scan methods as in air. We compensated for the index of refraction of oil, 1.47 [25], to calculate the displacement of the membrane surface. We assumed this index of refraction was constant since acousto-optical effects were shown to be negligible in this setup [25], [26], and the maximum pressure output of the transducer never exceeded 500 kPa peak to peak.

The farfield acoustic pressure was also measured in oil using a PZT_Z44_0400 needle hydrophone (Onda Corporation, Sunnyvale, CA) placed 2 cm from the surface of the transducer (Fig. 4b). The measurement data was then corrected for the frequency response of the hydrophone [27], acoustic attenuation, and diffraction [28] to calculate the pressure at the surface of the transducer.

C. Simulation

To understand the measurements, we used different finite element models (ANSYS 8.0, ANSYS Corporation, Canonsburg, PA) to simulate several simplified scenarios.

2-D models were used to calculate deflection and average output pressure of rectangular cells to first order accuracy. As the aspect ratio increases, the deflection and moments for a finite length rectangle approach the values for an infinite length rectangle. Because the aspect ratios used were larger than 1:3, the difference between finite length (3-D model) and infinite length (2-D model) rectangle is less than 6.5% [29]; for ratios over 1:4, this error drops to 1.5%. The 2-D model calculates a softer membrane that deflects more than the 3-D case because it does not have additional clamping points in the length. This simplification was adequate for deflection and ideal pressure calculations, but for modal analysis and calculation of the frequency of higher order modes, a 3-D model was required. The models and their uses are described below.

1) 2-D model for deflection—To understand cell-to-cell interaction, a four-cell, 2-D model was used to simulate designs A and B (Table I). This model simulates four neighboring cells that are clamped in the y direction at the bottom of the wafer and have coupled nodes in the x direction on the outermost sides (Fig. 5). The model focuses on interaction between the center two cells, separated by a support post. The two outermost cells were used as boundary cells so that the posts of the two center cells under study were not constrained. The silicon membranes, cavity oxide, and silicon wafer were modeled using PLANE42 elements; material properties used in the model are shown in Table II [30]. TRANS126 elements converted electrical voltage to mechanical force. These transducer elements were placed so that one node was at the upper surface of the substrate (ground electrode) and the second node was at the lower surface of the membrane (signal electrode). Because the silicon we used for the experiment was highly doped, larger than 10^{19} cm^{-3} , we could assume there was no intervening electrical medium. [21]. We verified our mesh size as sufficient by changing the mesh size and confirming that the results converge.

Fabrication inhomogenities such as variation of membrane thickness, undercut, and bonding quality are well known problems. Because we annealed the bonded wafers at over 1050°C,

microvoids at the bonding interface [31], [32] should be minimized and the bond strength of these microstructures should be independent of structure size [33]. In our model, we introduced undercut as the possible source of inhomogeneity by decreasing the support post width for every other cell by $0.4\ \mu\text{m}$.

To examine the degree of post bending, we applied voltage to the TRANS126 elements of the four cells in 1 V increments until one set of cells collapsed. We calculated the distance between the point with maximum height and the axis of symmetry between the cells, defined as the asymmetry distance (Fig. 8). The asymmetry distance was used instead of the post's bending angle because our devices were sealed, so the post angle was not measurable; since only the deflection measurement is possible, we used the asymmetry distance, which we could calculate from our model and observe through deflection measurements. For a rigid post, there is no bending and the maximum height of the membrane and the axis of symmetry of the cell are the same, so the asymmetry distance is zero. As the post bends, this causes the membrane of the neighboring cell to bulge upwards, which moves the maximum height of the membrane beyond the axis of symmetry. This model was then used to calculate the degree of post bending for different support post widths for a given design.

2) 3-D model for studying higher order modes—To observe the effects of higher order modes where the length plays a significant role, we used a simplified 3-D model comprised of a single clamped membrane (Fig. 6) [21] to model designs C-E (Table I). This membrane was constructed with SOLID145 elements and clamped in all directions at the edge nodes. TRANS126 elements that provided electrostatic force were attached to the bottom surface of the membrane (signal electrode) to an arbitrary point (ground electrode). We used a prestressed modal analysis [34] to observe the mode shapes of the rectangle. As the length of the rectangle decreases, the length has a larger influence on the mode shape and modal frequency of the response [29], [35]. A prestressed harmonic analysis [34], sweeping from 1-10 MHz was used to compare resonant frequencies with the impedance response measured. We used the data and model to understand the frequency separation of different modes.

3) 2-D model for calculating the ideal output pressure—To examine the first order output pressure and compare this ideal case to measurement, a 2-D symmetric model was used (Fig. 7) to simulate designs C-E (Table I). This model assumed an infinite length rectangle and did not account for higher order modes. The CMUT was constructed similarly to the four-cell model; the oxide and silicon layers were simulated with elements of type PLANE42. TRANS126 elements were attached between the lower surface of the membrane and the upper surface of the substrate. The major difference from the four cell model was that we loaded the cell with a lossless column of FLUID29 elements that was two wavelengths high and terminated it with an absorbing boundary [34]. The pressure was calculated using a prestressed transient analysis [34] with a sinusoidal excitation voltage of varying magnitude. The output pressure was averaged in the fluid column, half a wavelength from the surface of the cell, to determine the total surface acoustic pressure [21], [36].

IV. Results and Discussion

The fill factor of rectangular cells can be increased by reducing the support post width and increasing the aspect ratio. However, careful consideration of these two parameters is needed to avoid effects that negatively impact performance. Reducing the support post width decreases the stiffness of the post. The bending of these posts can reduce uniformity. Increasing aspect ratios brings higher order modes closer in frequency to the fundamental mode. Depending on the operation medium and excitation, these modes detract from the overall acoustic output pressure of the device. We present examples of these situations and discuss improvement of the design and performance of high fill factor rectangles.

A. Support Post Width and Static Deflection

The cell-to-cell spacing is determined by the support post width, which holds the membrane above the cavity; the support post width can be fabricated as narrow as $2\ \mu\text{m}$, within the controllability of MEMS processing. Choosing the support post width is a tradeoff between the fill factor of the device and the mechanical stiffness and isolation of the sub-cells. Reducing support post width compromises the stiffness of the support and results in support post bending, which amplifies nonuniformities. The stiffness per length, M_l [37], of a support post with width (w), gap height (h), and Young's modulus (E), is given by

$$M_l = \frac{4Ew^3}{h^3}. \quad (1)$$

In design A with 95.4% fill factor, small nonuniformities caused one cell to collapse at a lower voltage than a neighboring cell. These collapse voltages differed by 27 V, which is 18.4% nonuniformity, compared to a collapse voltage of 147 V (Fig. 9). The collapse of one cell bent the support post, which caused the membrane on the neighboring cell to bulge upwards (Fig. 8). The point of the membrane with the maximum height, marked with a star in Fig. 8, and its distance to the central axis of the cells describes the isolation of the cells. If the post was sufficiently stiff, the collapse of one cell does not cause the membrane of the neighboring cell to bulge upwards, and the maximum height remains at the center axis of the support post. However, if the post bends and the neighboring membrane bulges upwards, the point of the maximum height will be different than the axis of symmetry between the two cells. This asymmetry distance increases as the support post becomes more flexible.

In contrast, design B (Fig. 10 a) with 80.4% fill factor, has wider support posts and a smaller gap. Thus, its support posts are comparatively stiffer than design A, $91.0\ \text{GPa}/\mu\text{m}$ versus $1.17\ \text{GPa}/\mu\text{m}$, respectively. Though the cells have nonuniform deflection, the collapse of one cell does not affect the neighboring cell, and the variation of collapse voltages is less than 1 V, 1.9% of the collapse voltage (Fig. 10 a).

When the collapse of one cell does not effect the deflection or collapse voltage of a neighboring cell, the support post is sufficiently stiff. Circular cells fabricated on the same wafer as our rectangular designs also have a minimum spacing of $5\ \mu\text{m}$ between cells, but the average support post width is larger (Fig. 1a). The nonuniformity in collapse voltage of circular cells fabricated on the same wafer as our rectangles was 3 V, compared to a collapse voltage of 150 V; this 2.0% nonuniformity is reasonable and ideal since it is within the limits of expected fabrication-related nonuniformity [38]. For Design B, with low fill factor and stiff support posts, the variation in collapse voltage is also small and comparable with the fabrication-related nonuniformity seen in our circular cells. In contrast, design A with smaller average support post width showed a nonuniformity in collapse voltage of 18.4%. This is much higher than the nonuniformity we expect from fabrication-related defects alone.

Because there are many sources of nonuniformity that are difficult to measure accurately for every single cell, we cannot produce an exact model of the cells we measured. However, we can understand the effects of small nonuniformities on deflection and collapse voltage by using our four cell model and introducing a small variation in the cell width. This variation was made by decreasing the support post width of one of the cells by less than 1% of the total width. The simulation results illustrate the effects of post bending (Fig. 9 and 10 b), which shows a similar trend to the measured deflection. The discrepancy between the drive voltages can be explained by the softening from using a 2-D model with infinite length rather than a 3-D model. Also charging of the oxide layer causes an opposing electric field in the oxide; thus, larger voltages have to be applied than expected to achieve the same deflection.

Because the required post stiffness is highly dependent on many factors including the membrane stiffness, it is difficult to give a general design rule regarding the width of the support post. However, we can use our model as a guideline to choose the minimum support post width to prevent post bending. This will maximize the fill factor, while retaining mechanical cell-to-cell isolation and uniformity. We analyzed the effects of support post width on design A and observed the asymmetry distance, depicted in Fig. 8, to evaluate post bending as a function of post width. As the support post width decreases, the difference between first and second collapse voltages increases from 1 V to 20 V, and the bending of the post increases. For design A, a 10 μm support post seems sufficiently stiff, 9.36 GPa/ μm when calculated using Timoshenko beam theory [37]. It has minimal bending and shows a difference in collapse voltage of 2 V between cells (Fig. 11). By using this model to choose a support post width, uniformity can be maintained while retaining a reasonable fill factor of 91% for our design. Note that for design A, a support post of 8 μm was not stiff enough for the dimensions of the device, while for design B, 8 μm provided adequate support. This shows there is no absolute support post width; this quantity depends on a variety of factors including membrane stiffness.

B. Aspect Ratios and Higher Order Modes

Increasing the aspect ratio of a rectangular cell can improve fill factor. However, the aspect ratio dictates the frequency of higher order modes relative to the fundamental mode. This ratio needs to be designed so higher modes are outside the region of interest.

1) Air Operation—We compared the impedance in air of designs C-E, 110 μm wide rectangles with aspect ratios of 1:4, 1:5, and 1:6. The resonance peak with the largest amplitude corresponds to the fundamental, (1,1) mode (Fig. 12 a). The (1,2) mode (Fig. 12 b) is anti-symmetric and produces a zero average displacement, so the next observable resonant peak is the (1,3) mode (Fig. 12c). The (2,1) mode is much higher in frequency and not visible in our impedance response.

As the aspect ratio of the rectangular cell increases with constant width, the frequency of the (1,1) mode decreases. More importantly, as the aspect ratio is increases, the relative frequency difference between the (1,1) and (1,3) modes decreases (Fig. 13). We can understand this behavior by examining resonator theory and a clamped 3-D model FEM under harmonic analysis. According to theory, the frequency, f , of a rectangular mode is a function of the width, w , and length, l , [14]:

$$f \propto \frac{1}{w^2} + \frac{1}{l^2}. \quad (2)$$

In the (1,1) mode, the whole length moves in unison. For the rectangles under study, the width dominates the frequency of the (1,1) mode, so all aspect ratios will have similar fundamental resonant frequencies. For smaller aspect ratio rectangles, the length is smaller and plays a larger role in the determination of the fundamental frequency. Thus, lower aspect ratio cells will have slightly higher frequencies. We can treat the (1,3) mode as a rectangle with a length that is one-third of the actual rectangle length for this analytical analysis. Because the frequency is inversely dependent on the length, smaller lengths produces greater effects in the modal frequency. Because of this, the separation between the (1,1) and (1,3) modes for lower aspect ratio rectangles is greater. These measurement results also verified our 3-D finite element model; we found that the simulated frequencies matched measurement within 10% (Table III).

When higher order modes are sufficiently separated in frequency from the (1,1) mode and the excitation is narrow band, the cells actuate in (1,1) mode shape. We operated the rectangles with a narrowband CW excitation in air and found that the rectangles operated entirely in the

(1,1) mode (Fig. 15). Some of the boundary rectangles show lower amplitude because the boundary conditions on those cells are different than the center cells. For CW air operation with narrowband excitation, the aspect ratio can be arbitrarily large to maximize fill factor, provided the excitation is narrowband enough to exclude the resonant frequency of these higher order modes.

We used our 3-D model to predict the ratios of the (1,1) modal frequency to the (1,3) modal frequency for rectangles of 1:1.5 to 1:10 aspect ratio. We did not simulate rectangles less than 1:1.5 aspect ratio because at that point, the modal responses behave more like square cells rather than the modes we described for rectangular cells (Fig. 12). As seen from Fig. 14, the (1,3) and (1,1) modal frequencies become similar for aspect ratios larger than 1:6. For air operation, with a narrow tone-burst excitation, we have demonstrated that rectangles up to 1:6 aspect ratio are sufficiently narrowband so that higher order modes are not excited (Fig. 15). However, for (1,3) modal frequencies that are at least twice as high as the (1,1) modal frequency, aspect ratios of 1:1.5 to 1:2 should be considered.

2) Immersion Operation—Unlike air operation, immersion operation is heavily influenced by dispersive guided modes. These modes are determined by the periodic structure of the cells and propagate along the surface of the membrane, causing different pressures to be exerted on different cells [25], [39]–[42]. In CW excitation, standing waves can be formed along the surface of the transducers with wavelengths on the order of the cell size, which cause the cells to operate asynchronously.

To observe the effects of the dispersive guided modes on our rectangular cells, we excited them at 2.5 MHz, the center frequency of the cells in immersion [25], [40]. While the first cycle for 1:4, 1:5, and 1:6 rectangles (Fig. 16 a,c,f) shows the rectangles displacing synchronously in the (1,1) mode, successive cycles in steady-state show dynamic behavior in a higher mode in the lengthwise direction (Fig. 16 b,d,e). The 1:5 rectangles (Fig. 16 c) operate in an asynchronous mode similar to a (1,5) mode shape in steady state. Because parts of the membrane act asynchronously, the average output displacement is dramatically reduced than the ideal case, the (1,1) mode. For the 1:4 and 1:6 rectangles (Fig. 16 a and f), the dispersive guided modes cause nulls in the lengthwise direction that divide the rectangle length into 2 and 3 segments, respectively. These segments actuate in phase. Effectively, the 1:4 and 1:6 aspect ratios act as if they are a collection of 1:2 aspect ratio rectangles in parallel.

Because the dynamic displacement of the rectangles operating in higher order modes is less than the operation in the (1,1) mode, the output pressures measured are smaller than calculated in the ideal 2-D model. The 1:4 and 1:6 rectangles have similar displacements and similar output pressures, but the 1:5 rectangles show output pressures that are 30% less than 1:4 and 1:6 rectangles (Fig. 17).

These immersion results indicate that our rectangular cells with aspect ratios 1:4, 1:5, and 1:6 cannot be operated in the (1,1) mode under CW excitation at the center frequency of 2.5 MHz because standing waves are formed in the lengthwise direction that are several times smaller than the length of the rectangle.

V. Conclusion

In this paper, we studied wafer-bonded, rectangular-shaped CMUT cells with different fill factors. The parameters of cell-to-cell spacing, or support post width, and aspect ratio were studied with regard to performance.

First, our results indicate that cell-to-cell spacing that is too small causes undesirable interactions between neighboring cells through post bending. This causes nonuniformity in the static membrane deflections among cells. We observed nonuniformities in the collapse voltages of neighboring cells up to 18.4%, compared to the expected 2.0% from fabrication defects alone. For our designs, a support post width to membrane thickness ratio of 1.67 resulted in support posts with enough rigidity to withstand the forces from the deflection of the membranes and isolate neighboring cells. However, for specific uniformity requirements in terms of collapse voltages, finite element modeling is needed to determine the minimum possible cell spacing. In the case of our designs, we determined a maximum fill factor of only 91%.

Second, the aspect ratios of the cells need to be designed with caution depending on the medium in which the devices are operated. In general, design parameters for operation in air are less critical than operation in immersion. In our designs, for air operation, we found that cells with aspect ratios as high as 1:6, when excited with CW signals at the center frequency of the device, performed well in the desired (1,1) mode. However, for immersion, even with a CW excitation at the center frequency, our results demonstrate that designs with 1:4, 1:5, and 1:6 aspect ratios do not operate in the (1,1) mode, resulting in poor performance and acoustic output pressure. Pressure waves propagating along the solid-fluid interface of the CMUT have a severe influence on the mode shape. Rectangular shaped cells are highly sensitive to this pressure. Therefore, our devices with aspect ratios of 1:4, 1:5 and 1:6, targeted for 2.5 MHz operation, are not suitable for CW applications in immersion.

For future work, we plan to use 3-D finite element models to investigate whether rectangular-shaped cells, featuring high fill factors, in combination with high acoustic output pressures for CW operation, can be designed for immersion applications, such as HIFU.

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Biography

Serena Wong was born in Stanford, CA. She received her B.S. and M.S. degrees in electrical engineering from Stanford University, Stanford, CA, in 2002 and 2003, respectively. She is currently a Ph.D. candidate in electrical engineering at the E. L. Ginzton Laboratory of Stanford University. She is a 2002 National Science Foundation Fellow, 2002 Stanford Graduate Fellow, and a member of Tau Beta Pi.

From 1998 through 2001, she worked as a research assistant in the Pre-polarized Magnetic Resonance Imaging (pMRI) laboratory at Stanford University in an effort to develop a cost-effective MRI system. This system would greatly reduce costs of imaging technology and improve accessibility for patients. Recently, she has been interested in high intensity focused ultrasound (HIFU) as a minimally-invasive therapeutic tool for treatment of cancer. She is presently working with capacitive micromachined ultrasonic transducers (CMUTs) for HIFU applications such as the treatment of lower abdominal cancers.

Mario Kupnik is currently a research associate in electrical engineering at Edward L. Ginzton Laboratory at Stanford University. He received his Ph.D. from the University of Leoben, Austria, in 2004, and the Diplom Ingenieur degree from Graz University of Technology, in 2000. From summer 1999 to October 2000, he worked as an Analog Design Engineer for Infineon Technologies AG, Graz, on the design of ferroelectric memories and contactless smart card (RFID) systems. His present research interests include the design, modeling, fabrication, and application of micromachined sensors and actuators, with a main focus on capacitive micromachined ultrasonic transducers mainly for air-coupled applications, including high gas temperatures. Examples are transit-time gas flowmeters for hot and pulsating gases, ultrasonic nondestructive evaluation using non-contact ultrasound, nonlinear acoustics, and bio/chemical gas sensing applications (electronic nose). Dr. Kupnik has more than 5 years teaching experience in the field of electrical engineering and he is a member of the IEEE.

Xuefeng Zhang received the B.S. degree from Louisiana State University, Baton Rouge, LA, in 2002, and the M.S. degree from Stanford University, Stanford, CA, in 2004, both in electrical engineering. He is currently pursuing a Ph.D. degree in electrical engineering at Stanford University. His research interests include the design, fabrication, and packaging of capacitive micromachined ultrasonic transducer arrays, and their integration with medical imaging systems.

Der-Song Lin received the B.S. and M.S. degrees in civil engineering from National Taiwan University, Taipei, Taiwan, in 1995 and 1997 with the master research of Non-Destructive-Evaluation, and the M.S. degree in mechanical engineering from Stanford University, Stanford, CA, in 2006. He is currently working toward the Ph.D. degree in mechanical engineering at Stanford University. He worked as a consultant engineer in Sinotech Engineering Consultant Inc., Taipei, Taiwan, from 1999 to 2001. He joined Redin International, Inc., Taipei, Taiwan, as a special assistant to the CEO during the years of 2001 to 2003. He is now working as a research assistant in E. L. Ginzton Laboratory, Stanford University. His research interests

include MEMS technology, micromachined ultrasonic devices, and medical devices. Mr. Lin was a recipient of the National Ministry of Education Award, Taiwan, in 2004.

Kim Butts-Pauly Kim Butts Pauly received a B.S. degree in physics from Duke University, Durham, NC. She received her Ph.D. in biophysical sciences from the Mayo Graduate School in Rochester, MN. In 1996, she joined the faculty at Stanford University's Department of Radiology, where she has been working on MR-guided high intensity focused ultrasound, cryoablation, RF ablation, and biopsy. She has also been involved with the development of a truly integrated X-Ray and MRI system.

Butrus T. (Pierre) Khuri-Yakub is a Professor of Electrical Engineering at Stanford University. He received the BS degree in 1970 from the American University of Beirut, the MS degree in 1972 from Dartmouth College, and the Ph.D. degree in 1975 from Stanford University, all in electrical engineering. He was a Research Associate (1965-1978) then Senior Research Associate (1978-1982) at the E. L. Ginzton Laboratory of Stanford University and was promoted to the rank of Professor of Electrical Engineering in 1982. His current research interests include medical ultrasound imaging and therapy, micromachined ultrasonic transducers, smart bio-fluidic channels, microphones, ultrasonic fluid ejectors, and ultrasonic nondestructive evaluation, imaging and microscopy. He has authored over 400 publications and has been principal inventor or co-inventor of 76 US and International issued patents. He was awarded the Medal of the City of Bordeaux in 1983 for his contributions to Nondestructive Evaluation, the Distinguished Advisor Award of the School of Engineering at Stanford University in 1987, the Distinguished Lecturer Award of the IEEE UFFC society in 1999, a Stanford University Outstanding Inventor Award in 2004, and a Distinguished Alumnus Award of the School of Engineering of the American University of Beirut in 2005.

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Fig. 1.

Various cell shapes illustrating different fill factors, defined as the active area (white) to the total area. Fill factor increases as the shape changes from circles (a) to hexagons (b) to rectangles (c) to tents (d). Rectangular cells (d) show a good compromise between fill factor and mechanical cell-to-cell isolation and are discussed in our paper. A cross-section of a rectangular cell is shown in (e).

Fig. 2.

Fill factors for circular, hexagonal, rectangular, and tent cells with diameter or widths from 20-200 μm . The support post width is kept at a constant 5 μm for this analysis.

Fig. 3.

The wafer bonding process allows flexibility in shapes and structures because the cavity and membrane are defined on separate wafers. First, cavities are defined on the prime wafer by oxidation followed by an oxide etch (a). A second oxidation forms the insulation at the bottom of the cavity (b). Then, the membrane is wafer bonded to the cavities and the handle wafer and BOX layer are removed (c). Finally the electrodes are metallized (d), and the elements are defined (e).

Fig. 4. Laser interferometer setup used to measure membrane displacement in air (a) and also in oil. Hydrophone measurement setup for output pressure measurements in oil (b).

Fig. 5. 2-D finite element model of neighboring rectangular cells, which are infinite in length. The model was used to examine effects of small undercuts on the support post bending; two boundary cells were used to avoid constraining the posts of the cells under study.

Fig. 6.
3-D finite element model used to understand the modal and frequency response of rectangles in air.

Fig. 7. 2-D model used to simulate ideal rectangular output pressure assuming a rectangle with infinite length and no effects from higher order modes.

Fig. 8.

Exaggerated illustration of post bending that occurs when the post width is too narrow. Collapse of one cell causes the membrane of the neighboring cell to bulge upwards as the support post bends. This causes the collapse voltage of the neighboring cells to be dramatically different.

Fig. 9.

Deflection versus voltage measurements show the influence of support post width on uniformity. Zygo measurements of design A (a) show that narrow posts cause bending that moves the point of the membrane with the maximum height (*) away from the center axis, marked by the vertical line. The asymmetry distance in design A corresponds to 13 μm . FEM (b) shows similar behavior. The discrepancy between the drive voltages can be explained by softing of the model because we used a 2-D approximation and also from charging effects.

Fig. 10.

Deflection versus voltage measurements show the influence of support post width on uniformity. Design B (a) with a stiffer and wider support post does not suffer from the post bending effect. FEM (b) shows similar behavior.

Fig. 11.

Simulation of design A with varying support post width. The asymmetry distance, the distance between * (Fig. 8) and the center axis of the support post, reflects the degree of post bending.

b) mode (1,2)

c) mode (1,3)

Fig. 12.

Mode shapes of the (1,1) (a), (1,2) (b), and (1,3) (c) modes of the rectangular shape. The (1,2) mode is antisymmetric, and is not visible as a resonant peak in the impedance, while the (1,1) and (1,3) modes are visible.

Fig. 13.

Real and imaginary part of the impedance for 1:4, 1:5, 1:6, rectangular cells (Designs C-E). An increase in aspect ratio reduces the spacing between the (1,1) and (1,3) modes.

Fig. 14.
Ratio of the modal frequency of the (1,3) mode to the (1,1) mode for rectangles of 1:1.5 to 1:10 aspect ratio.

Fig. 15.

Dynamic deflection during CW excitation at the center frequency of the devices (3.70 MHz, 3.63 MHz, and 3.58 MHz for 1:4, 1:5, and 1:6 rectangles, respectively) measured in air by an interferometer over 1/4 of a test transducer for aspect ratios of 1:4 (a), 1:5 (b) and 1:6 (c). The dynamic response of the rectangles corresponds to the (1,1) mode.

Fig. 16.

Immersion response of one quarter of a transducer element for a 1:4 (a,b), 1:5 (c,d), and 1:6 (e,f) aspect ratio rectangular cells in the first cycle (a,c,e) and steady-state (b,d,f), excited by a 2.5 MHz sinusoidal signal and measured by a laser interferometer. While the rectangles operate in the (1,1) mode in the first cycle of operation (left column), successive cycles show a higher order mode (right column) in the lengthwise direction.

Fig. 17.

Output pressure measured from transducers containing rectangles of different aspect ratios excited with a 2.5 MHz sinusoidal signal. Dispersive guided modes cause rectangles to operate in a different mode than the (1,1) mode. This is one of the reasons the output pressure calculated using a 2-D model differs so greatly from the measured results.

TABLE I
Dimensions of cells used for investigating the effect of support post width on uniformity (designs A and B) and higher order modes in air and immersion (designs C-E)

parameter	design A	design B	design C	design D	design E
width	130 μm	40 μm	110 μm	110 μm	110 μm
length	520 μm	220 μm	440 μm	550 μm	660 μm
aspect ratio	1:4	1:5.5	1:4	1:5	1:6
support post width	5 μm	8 μm	5 μm	5 μm	5 μm
membrane thickness	6 μm	1.4 μm	6 μm	6 μm	6 μm
gap height	0.38 μm	0.15 μm	0.38 μm	0.38 μm	0.38 μm
insulation thickness	0.57 μm	0.3 μm	0.57 μm	0.57 μm	0.57 μm
fill factor	95.4%	80.4%	95.2%	95.4%	95.6%

TABLE II

Material properties used for simulations

-	silicon	silicon oxide
Young's modulus	150 GPa	73 GPa
density	2332 kg/m ³	2200 kg/m ³
Poisson's ratio	0.170	0.170
Dielectric constant	3.78	11.7

TABLE III
Comparison of measured and simulated frequencies

Aspect Ratio	mode (1,1) Measured (MHz)	3-D FEM (MHz)	Error %	mode (1,3) Measured (MHz)	3-D FEM (MHz)	Error %
1:6	3.58	3.42	-4.68%	3.73	3.72	-0.05%
1:5	3.63	3.44	-5.53%	3.86	3.90	1.05%
1:4	3.70	3.47	-6.57%	4.20	4.26	1.38%