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Capacitive micromachined ultrasonic transducers using commercial multi-user MUMPs process: capability and limitations

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Abstract

The objective of this work is to construct capacitive micromachined ultrasound transducers (cMUTs) using multi-user MEMS (MicroElectroMechanical Systems) process (MUMPs) and to analyze the capability of this process relative to the customized processes commonly in use. The MUMPs process has the advantages of low cost and accessibility to general users since it is not necessary to have access to customized fabrication capability such as wafer-bonding and sacrificial release processes. While other researchers have reported fabricating cMUTs using the MUMPs process none has reported the limitations in the process that arise due to the use of standard design rules that place limitations on the material thicknesses, gap thicknesses, and materials that may be used. In this paper we explain these limitations, and analyze the capabilities using 1D modeling, Finite Element Analysis, and experimental devices. We show that one of the limitations is that collapse voltage and center frequency can not be controlled independently. However, center frequencies up to 9 MHz can be achieved with collapse voltages of less than 200 volts making such devices suitable for medical and non-destructive evaluation imaging applications. Since the membrane and base electrodes are made of polysilicon, there is a larger series resistance than that resulting from processes that use metal electrodes. We show that the series resistance is not a significant problem. The conductive polysilicon can also destroy the cMUT if the top membrane is pulled in the bottom. As a solution we propose the application of an additional dielectric layer. Finally we demonstrate a device built with a novel beam construction that produces transmitted pressure pulse into air with 6% bandwidth and agrees reasonably well with the 1D model. We conclude that cMUTS made with MUMPS process have some limitations that are not present in customized processes. However these limitations may be overcome with the proper design considerations that we have presented putting a low cost, highly accessible means of making cMUT devices into the hands of academic and industrial researchers.

Keywords

capacitive micromachined ultrasonic transducer; MUMPS; finite element analysis

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1. Introduction

Capacitive micromachined ultrasonic transducers (cMUTs) use the deformation of a suspended thin-film membrane to transmit and detect ultrasonic waves. Applying a large voltage and causing the membrane to collapse to the bottom electrode can transmit large energy. Alternatively, more energy can be transmitted more linearly by the use of a DC bias between the electrodes. Reciprocally, when acoustic waves are incident on the membrane, between which and the fix electrode a DC bias is applied, the membrane deforms and results in electrical field changes, which reveal the amplitude, frequency, and phase of the ultrasound. When an AC signal is applied, the physical response is non-linear; so the DC bias is needed to linearize the AC response for small signals [1]. At DC bias voltages near the collapse voltage, very high electromechanical coupling can be achieved [2–4].

Many customized fabrication processes for cMUTs have been reported. Khuri-Yakub and colleagues have developed a sacrificial release process [5,6], a wafer-bonding technique [6, 7], and a process integrating cMUTs with electrical trough-wafer interconnects [8]. More recently, they reported the fabrication of long rectangular cMUTs featuring high fill factor using the direct-fusion, wafer-bonding process [9]. Eccardt, Niederer and colleagues showed a standard BiCMOS process with additional modifications [10–12]. They also published another customized process using polysilicon as both membrane and sacrificial layer material [13]. Knight and Degertekin reported a low-stress plasma enhanced chemical vapor deposition (PECVD) for cMUTs fabrication, which is suitable for CMOS electronics integration on a single chip providing test arrays with significantly reduced parasitic capacitance [14,15]. Caliano, et al. also used PECVD as a part of the fabrication process [16]. They further introduced polyimide as the sacrificial layer in their customized process where a structural SiO_x layer and the SiN_x membrane layer are deposited by thermal evaporation and by PECVD respectively [17–19]. Midtbo and colleagues presented a successful realization and electrical characterization of cMUT array using silicon-to-silicon wafer-bonding process. The structural feature was pre-bonded at room temperature and further bond-annealed at 1050 °C for two hours [20]. Yeow group fabricated cMUT phased arrays using a novel wafer-bonding process where both the insulation layer and the membrane are user deposited silicon nitride [21]

Clearly, several groups have advanced the manufacturing process for cMUTs. However, the novel and expensive manufacturing capabilities required for such designs may limit broader development of cMUT designs. Process capabilities are typically only available in large universities and companies. The commercial multi-user MEMS process (MUMPS) that allows standardized device manufacture at low cost is a possible solution. MUMPS has the advantages of significantly lower cost and general accessibility. The cost for a full wafer costs a total of \$4000, but the process allows for building up to 25 shared designs on a single wafer so that 15 2mm × 2mm devices can be obtained for \$160 to \$180 (<12 per chip). Recently, it has been used to fabricate single and multiple-element cMUT transducers [22–25]. These papers do not, however, report the capability and limitations of this process compared to customized processes in terms of electrical and acoustical performances. This paper intends to fill this vacancy.

There are several limitations on the MUMPS process that must be considered. One is that only certain membrane thicknesses and gaps are allowed, as we will explain below. Another is that the conductivity of the polysilicon must be used for some of the electrical connections. This also results in increased parasitic capacitance for similar inactive area. It is also necessary to leave openings in the membrane structure that are large enough for etching of the sacrificial layers. For immersion-based imaging applications, these must be filled. The filling process would ordinarily be done using a polymer. Unless the process is performed in a vacuum this would result in an air gap, which is also true for open cavities. Air in the gap makes it possible for a failure to occur due to air breakdown. Since the breakdown voltage of a 2μm air gap at

atmosphere pressure is around 500V and that of a 0.75 μ m air gap is around 3000V according to Paschen curve, this will create an upper limit on the bias voltage of approximately these values. Fortunately the limit is fairly high. Finally, the membrane and bottom electrode will short if pull-in occurs, destroying the cavity.

The last two topics can be addressed in a relatively straightforward fashion. Although large etch openings were used in prior experimental units, it is not necessary to leave large holes to accomplish the etching. Small holes should allow the etchant to work yet still allow covering with a polymer material as has been described previously [23].

One solution for avoiding pull-in is to ensure that the device never operates dangerously close to the pull-in voltage. This will limit the performance in many applications. We proposed a novel solution that deposits dielectric material in the gap using atomic layer deposition (ALD). ALD is a coating method that has shown promise in cMUT applications [26] and that is now commercially available (Cambridge NanoTech Inc. or Picosun USA LLC). This does add cost to the assembly but at, \$1000/run, with each run holding three 6-inch in diameter wafers, the cost increase is smaller than \$5 per chip maintaining our objective of creating a cost effective process.

ALD is often used to address nano-scale interface issues by providing pinhole-free coating at surface-to-surface contacts in MEMS devices [27,28]. In the fabrication of cMUTs, ALD is used to deposit very thin alumina dielectric layers uniformly across the chip. Our experiments in air demonstrated the cMUT after ALD with 40nm alumina layer withstood 80V DC bias (higher than the cMUTs without ALD) and had a 50.5% increase in output pressure as a transmitter than the cMUT before ALD running in 20V DC bias. We will present a separate paper on ALD process, modeling results and experimental results in details. In this paper, we focus on our findings and solutions to the first two limitations.

2. Fabrication Technology

MUMPS (Multi-User MEMS Processes), based on surface micromachining technology, is a commercial program that provides a set of standard MEMS processes for cost-effective prototyping. One of these processes, PolyMUMPs, provides alternating layers of polysilicon and oxides built on a polysilicon base isolated by SiN (silicon nitride). Up to three layers of polysilicon (Poly 0, 1, 2) may be deposited, masked and etched. The oxide layers are deposited and patterned between the polysilicon layers to provide a sacrificial material that is later removed by immersion etching. A metallization layer may be added to provide electrical connections. The layer thicknesses for standard processing are: Poly0 – 0.5 μ m, Oxide1 – 2 μ m, Poly1 – 2 μ m, Oxide2 – 0.75 μ m, Poly2 – 1.5 μ m, Metal – 0.5 μ m. Full design rules can be found elsewhere [29].

This process can be used to make cMUTs for experimentation [22–25]. Because of the specific thicknesses of the structure layers (Poly0, 1, 2) and the sacrificial layers (Oxide 1, 2), the only standard configurations in MUMPs cMUTs can be one of the four designs found in Table 1. Design 1 and 3 are the most common configurations.

The structure of the cavity used for analysis and experiment in this paper is shown in Figure 1 below.

As one may notice, compared to the customized processes where the users can precisely control the structural dimensions, the membrane thickness and the gap in the MUMPs process need to be one of the standard values. This fact leads to certain limitations on cMUTs using the MUMPs process.

One limitation is that the resonant frequency and collapse voltage can not be specified independently. A second limitation is that the mechanical impedance of the membrane can not be reduced by use of reduced thickness. The third concern is the resistivity of the electrodes. In MUMPs cMUTs, we use polysilicon instead of metals as electrodes; thus, the low conductivity of polysilicon compared to that of metals must be considered.

3. Capability and Limitations

Below we make certain assumptions about design requirements and investigate the performance limitations that these constraints produce.

Series Resistance

The first limitation we address is the effect of polysilicon electrical conductivity. The series resistance in MUMPs cMUTs was compared to that in the cMUTs from a customized process. The top and bottom electrodes are polysilicon (resistivity $\sim 2\text{e-}5\Omega\cdot\text{m}$) for the former and gold (resistivity $\sim 2.44\text{e-}8\Omega\cdot\text{m}$) for the latter. For a rectangular electrode with length 80 μm , width 50 μm and thickness 0.75 μm (Poly0), the resistance is 43 Ω for polysilicon electrode, almost 1000 times of that of gold electrode. This represents a series resistance that will produce heating on transmit and limit the signal to noise ratio on receive. The magnitude of these effects is dependent on the size of the total cavity impedance for heating, (the total impedance limits the current and thus the power lost in the resistor) and the size of the real impedance from a signal to noise perspective. However the real part of the impedance of a single cavity loaded even in air is many orders of magnitude higher. In the case described above it is over 10,000 Ω and the capacitive reactance is even higher. This minimizes the effects of the series resistance.

If many cavities are used in parallel the total impedance goes down. However, the many parallel paths in polysilicon also decrease the series resistance. So the ratio of total series resistance and total impedance keeps the same. Since a large series resistance will results in heating during transmit and worsen the signal to noise ratio on receive, we strongly recommend a metal layer (gold) on the top electrode (or membrane) in MUMPs cMUTs to reduce the resistance of the top electrode and that resistance be considered in modeling of MUMPs devices.

The second effect of polysilicon conductivity is that parasitic parallel capacitance is increased. In standard processes the parallel capacitance is determined by the presence of dielectric material between the top and bottom electrodes and traces. In the MUMPs devices much of the material that creates the support walls surrounding the cavity is conductive. In Figure 1 it is apparent that the Poly 1 of the top electrode and the poly 0 which is used as a support are shorted together. They are separated from the conductive substrate by a thin layer of SiN. The Poly 0 that forms the center electrode is also separated by the thin SiN layer. This creates a parallel capacitance path that is larger than for other processes and must be considered in modeling.

Frequency and Collapse Voltage

The four standard cMUTs configurations introduce more constraints than processing systems that use a wider variety of materials and in which the choice of gap and membrane thickness is arbitrary.

For many transducer designs the choice of resonant frequency is constrained by the application. We assume that this will be part of a requirements specification. We address the limitations on resonant frequency created by the specific choices of membrane thickness using Mason's model [30]. To simplify our analysis, we assumed the cMUTs have circular membranes where the only variable is the radius of the membrane. Figure 2 demonstrates that MUMPs cMUTs

can cover a wide frequency range (0.6MHz~143MHz) by adjusting the diameter to account for membrane thickness.

An additional constraint for CMUT designs is the magnitude of bias voltage that can be applied. The operating bias voltage is often chosen to be near the pull-in voltage in order to achieve a high coupling factor [2–4]. In many cases, this operating frequency will need be selected to match the capability of an existing drive system.

From earlier work [1,30], the expressions of resonant frequency and collapse voltage for a circular membrane can be found and are provided in equation (1) and (2), where “ Y_0 ”, “ σ ”, “ ρ ” are respectively the Young’s modulus, Poisson’s ratio and the density of the membrane material; “ t_m ”, “ a ” are respectively the thickness and the radius of the membrane; “ d_0 ” is the distance between top and bottom electrodes at rest and “ S ” is the area of the capacitor plates; “ ϵ ” is the electric permittivity of the material between top and bottom electrodes. Since density and membrane thickness are determined by the process, it is apparent that frequency can only be changed by adjustment of radius “ a ”. The gap is also set by the process so all variables in “ V_{collapse} ” are determined after the frequency has been specified

$$f = \frac{(2.4)^2}{2\pi} \sqrt{\frac{Y_0}{12\rho(1-\sigma^2)} \frac{t_m}{a^2}} \quad (1)$$

$$V_{\text{collapse}} = \sqrt{\frac{8 k d_0^3}{27 \epsilon S}} \quad \text{Where } k = \frac{16 \pi Y_0 t_m^3}{(1-\sigma^2) a^2} \quad (2)$$

Figure 3 shows the resulting limitation. For a certain operational frequency, the collapse voltage can only be one of the four optional values, all of which are relatively high. Moreover, except for design 2, it is difficult to obtain a higher frequency (>10MHz) with an acceptable collapse voltage (<500V). The one-to-one relationship between resonant frequency and collapse voltage in MUMPs cMUTs restricts the possible solution for a specific application.

It is possible to relieve this constraint to some degree by design changes that are not considered in the simplest models. Changing the mechanical properties of the membrane by geometry may change the resonant frequency, and changing the size of the bottom electrode may change the collapse voltage [1,30]. Based on this, we propose two modifications. One is to change the size of the bottom electrode, which affects collapse voltage but not resonance frequency. The other is to use alternative shapes such as beams to modify the effective membrane stiffness, as briefly explored below.

Although 1-D analysis is more difficult, similar frequency and collapse restrictions exist for a rectangular membrane. We chose a rectangular membrane structure with two edges clamped (Figure 4) to demonstrate how some additional design flexibility can be achieved by the addition of beam supports. Radial beams around a circular membrane are also possible.

Figure 5 shows the collapse voltage as a function of the size of the bottom electrode. In this figure the length and the width are presented as the ratio of electrode length to membrane length. The ratio of electrode width to membrane width was made the same. Since the membrane geometry and dimensions were not changed, the resonant frequency remains constant. It is apparent that, when other design parameters are fixed, the collapse voltage decreases as the width and length of bottom electrode increases. The change covers a wide

range: from 450V to 200V. This is because the area of the capacitor creating the electrostatic force is changed. The results are in agreement with results seen by others [31]. We conclude that in MUMPs cMUTs design, the size of the bottom electrode may be used to allow greater design flexibility in selecting resonance frequency and pull-in voltage. It should be noted that the change in electrode size may affect other performance parameters.

In another simulation, we fixed all the parameters except the design of the beams to examine the change of the collapse voltage with the change of the beam design. Figure 6 shows the three beam designs analyzed. Table 2 shows that three designs have very similar resonance frequencies but different collapse voltages. It demonstrates that the fixed relationship between resonant frequency and collapse voltage can be modified to some degree by this approach. In a full design, the trade off with active area would also need to be analyzed.

As a summary, by designing the electrode and the beams, we obtain variations in the frequency – collapse voltage trade off. A full bottom electrode in MUMPs cMUTs applications helps to reduce the required collapse voltage but should be considered with other considerations such as parasitic capacitance when creating a specific design.

The different design on beams can generate variations in collapse voltage. The exact shift on voltage ranging from a few volts to a hundred volts depends on the specific design parameters, such as the beam width and length, the beam locations and the thickness of the supporter. In the design examples mentioned above, design A, B and C have identical length and width of the beams. But design A has the lowest collapse voltage. We believe this is due to the larger distance between the two parallel beams (130um instead of 120um in design B or 70um in design C). Compared to design B, design C has lower collapse voltage, which is due to a thinner supporter (5um instead of 15um). So, to further reduce collapse voltage without changing resonant frequency, we recommend narrower beams and thinner supporters with a well-chosen beam location.

Beams are useful design parameters one can control in MUMPs cMUTs design. However the use of beams reduces the active area. Also the beam structure creates large openings between membranes that can cause sealing problem for immersion applications. To solve these problems, a better design, which utilizes beams while having membranes with different sizes and shapes on the same chip to maximize the active area and minimize the openings, may be feasible and is a topic of on-going research.

Mechanical Impedance

In a design with fixed membrane thickness there will also be constraint on the mechanical impedance of the membrane. The striking advantage of electrostatic devices compared to piezoelectric transducers is the fact that the no impedance matching is necessary between the membrane and the medium.

The low-mechanical impedance of the membrane is usually negligible for cMUTs operating in water. This results in efficient coupling of the sound waves into and from the sound-bearing medium. Since MUMPs cMUTs have a much thicker membrane (2um for this design) than cMUTs from customized processes (0.6 um for the comparative design), the effect of mechanical impedance should be considered. Here we compare the mechanical impedance of two designs using the customized process and the MUMPs process. Since the resonant frequency depends on the membrane radius and the membrane thickness, the radii of the two designs were chosen to result in the same frequency. A 25um membrane radius with 0.6um membrane thickness was selected to represent a typical cMUT using customized process and 45um membrane radius with 2um membrane thickness to represent a typical cMUT using MUMPs process. They both work in frequency range 2~6MHz (x-axis in the figures).

Figure 7 shows the comparison of a circular CMUT reported using a customized process [5] and the circular MUMPS Design 1 given in Table 1. Note that the impedance at 2 and 6 MHz is approximately 3.5×10^5 for the MUMPS CMUT and 1.1×10^5 for the customized processes. Since the impedance of water is 1.48×10^6 both membranes have smaller impedance over this frequency range. However the assumption that the membrane impedance is less than that of the medium will break down for the 2 micron membrane at a smaller frequency range than for the 0.6 micron membrane. Both would be a limitation on bandwidth performance in air. This assumption should be verified for either system on a case-by-case basis. For this case we observed a narrower notch in the impedance plot for the 2 μm MUMPS membrane than for the 0.6 μm membrane. The implications for sensitivity and bandwidth are discussed below.

Sensitivity and Bandwidth

The sensitivity of a transducer is critically dependent on the transformer ratio, which is inversely proportional to the square of the cavity depth. One can achieve high-transformation ratios at lower bias voltages with cMUTs because surface micromachining allows the manufacture of relatively small gaps. MUMPS cMUTs have fixed gaps (0.75 μm , 2 μm or 2.75 μm), but high coupling can be achieved by increasing the bias voltage. This does not compensate for the mechanical impedance differences discussed above. To investigate the net effect of the gap constraints on sensitivity and bandwidth, the performance was modeled using Mason's model as shown by Olcum [4]. The MUMPS material properties used are listed in Table 3.

All designs were achieved to operate at the same frequency (4MHz) and with DC bias at 90% of their collapse voltages. Calculations were done for water loading and the series resistance was included in the calculations. Designs 1, 2, 3, and 4 from Table 1 were compared to design 5 that used a customized process. Based on the definition of sensitivity $20 \times \text{Log}(\text{receiving voltage} / \text{receiving pressure})$ dB, the sensitivity of all the designs are calculated and listed in the Table 4. Note that the highest sensitivity is produced by the customized process but design 4 is only 3dB less sensitive. This results in a lower bandwidth. Other designs are as much as 13 dB less sensitive. This model was done for comparison only and does not include all of the parameters that would need to be included to model a fully functional device. Bandwidths in fully functional devices are typically much smaller.

4. Electrical and Acoustical Characterization

To evaluate the MUMPS process experimentally and to validate our modeled results, CMUTs were constructed as follows: Poly0 was laid down to form the base electrode and electrical connections (Figure 8a). The first oxide layer was deposited to form the gap between electrodes after removal. Poly1 was laid down to provide the resonant membrane and electrical connection for the top electrode (Figure 8b). Metallization was used to form the pad. A dimensioned side view showing both the active and inactive cross section was shown in Figure 1.

A design with 121 single elements on the same chip was fabricated in MEMSCAP (commercial foundry). After fabrication, the devices were diced and released in hydrofluoric acid (HF), and then packaged using a 24-pin through-hole package with wire bonding (Figure 9).

Since the design contained relatively large open sections to the gap it was not possible to seal the cavity from water. Consequently the characterizations reported below were measured in air. This shows much more limited bandwidth than can be achieved in water but can be used to compare the model to a realized device.

The electrical impedance of our device was measured using an impedance analyzer. Figure 10 is the diagram of the electrical connection, where we have impedance analyzer (HP, 4194A,

impedance/gain-phase analyzer) connected to a computer interface to capture data. A high power supply (HP, E3612A, DC power supply) was used to provide DC bias. The electrical connection used to protect the impedance analyzer from the DC bias is also shown.

The electrical impedance of the cMUTs was measured in air as a function of DC biases. Figure 11 gives the electrical impedance of MUMPs cMUT. From the electrical impedance plots we note that the MUMPs cMUTs have a resonant frequency around 2.7MHz.

We then used a laser interferometer (Polytec OFV511, fiber interferometer) at Stanford University (Palo Alto, California) for an AC deflection test. Figure 12 shows the experimental setup. Function generator 1 (HP, 34401A) was used for the AC supply and function generator 2 (Agilent, 32250A) was used for the DC bias supply. A personal computer with Labview (National Instruments, Austin, Texas) was connected to a digital oscilloscope (HP Infiniium, 500MHz, 2GS/s) to capture data. A CCD camera (CCD-IRIS/RGB color video camera) was mounted on the top of the microscope through an adapter (Polytec, 072 microscope adapter).

We captured the AC deflection for DC biases of 10V to 50V with a fixed AC of 10V. Figure 13 compares the center displacement of the membrane for 10V DC bias and 50V DC bias. We observed an increase of center displacement with an increase of DC bias (Figure 14).

The derivative of displacement, multiplied by the impedance of the medium, gives the pressure in air (Figure 15). The spectrum shows a resonant frequency at 2.7MHz (Figure 16), which agrees with the impedance test (see Figure 11). The effective mechanical impedance of the energy loss term (caused by viscoelastic damping and spurious waves) is in series with the mechanical impedance of the cMUT in Mason's model. Since it can not be measured easily, we chose a reasonable number 6000Rayls. We achieved good agreement for the pressure waveform and its spectrum between experimental results and the 1D Mason's model developed in MATLAB. In Mason's model, we chose zero tension for the membrane to fit the spectrum curve. The agreements provide some confidence in the modeled results reported above.

5. Conclusion and Future Work

In this paper, we analyzed the capability and limitations of the MUMPs process for cMUTs fabrication. Our results show that MUMPs cMUTs have potentially comparable performance with cMUTs from other processes. We also noticed that the cMUTs fabricated using MUMPs process are destroyed by collapse due to the conductivity of the membrane that makes them very risky to work with. We propose that atomic layer deposition (ALD) can be used to provide isolation of the upper and lower electrode, which will be discussed in a subsequent paper. Since we have an open structure, which makes sealing more challenging, we propose to spin coat a thin and flexible adhesive and then press our chip onto the thin membrane to form a bonding. This proposal is investigated in on-going work.

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Fig. 1.
Cross section of MUMPs cMUTs

Fig. 2.
Resonant frequency vs. radius of membrane

Fig. 3.
Collapse voltage vs. resonant frequency (above: all designs; below: the designs with voltage < 500V)

Fig. 4.
Rectangular membrane (layout and FEA model)

Fig. 5.
Collapse voltage vs. bottom electrode size

Fig. 6.
Design A, B and C (layout and FEA model)

Fig. 7.
Mechanical impedance (above: cMUTs from a customized process; below: MUMPs cMUTs)

Fig. 8.
Layout of MUMPs cMUTs (8a.Poly 0; 8b.Poly 1)

Fig. 9.
Electronic packaging

Fig. 10.
Diagram of the electrical connection

Fig. 11.
Electrical impedance

Fig. 12.
Laser interferometer setup

Fig. 13.
Displacement from experiments

Fig. 14.
Experimental displacement for different DC bias

Fig. 15.
Peak-to-peak pressure

Fig. 16.
Peak-to-peak pressure spectrum

Table 1

Configurations of cMUTs using MUMPs

	Membrane Thickness	Gap
Design 1	2um (Poly1)	2um (Oxide1)
Design 2	1.5um (Poly2)	0.75um (Oxide2)
Design 3	1.5um (Poly2)	2.75um (Oxide1+Oxide2)
Design 4	3.5um (Poly1+Poly2)	2um (Oxide1)

Table 2

Resonant frequencies and collapse voltages

	1 st resonant frequency (MHz)	2 nd (MHz)	3 rd (MHz)	Collapse Voltage (V)
Design A	0.43	0.81	0.95	122.8
Design B	0.48	0.85	1.08	156.0
Design C	0.45	0.49	0.90	144.7

Table 3

Material properties of polysilicon

Young's modulus (GPa)	169
Poisson's ratio	0.22
Density (kg/m ³)	2330
Resistivity ($\Omega \cdot m$)	$1.61e^{-5}$ (Poly0)
	$2.38e^{-5}$ (Poly1)
	$3.57e^{-5}$ (Poly2)

Table 4

Comparison of five different designs

	Design 1	Design 2	Design 3	Design 4	Design 5
Membrane thickness (um)	2	1.5	1.5	3.5	0.6
Gap (um)	2	0.75	2.75	2	1.1
Radius (um)	45	39	39	60	25
Frequency (MHz)	4	4	4	4	4
Collapse voltage (V)	460	92	648	595	100
DC Bias (V)	414	82.8	583.2	535.5	90
Bandwidth in water (%)	183	188	188	170	195
Sensitivity in water (V/Pa-dB)	-198	-199	-202	-192	-189