Fabrication of CMUT Cells with Gold Center Mass for Higher Output Pressure

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Abstract. For decades, high intensity focused ultrasound (HIFU) transducers have been developed for minimally invasive and non-invasive therapies. Capacitive micromachined ultrasonic transducer (CMUT) technology is a promising candidate for HIFU therapy as it allows the fabrication of arbitrary array geometries and is inherently magnetic resonance (MR) compatible. In this study we investigate a way to improve the output pressure of a single CMUT cell by a modification to the basic CMUT cell structure: adding a gold mass over the center of the top CMUT plate. Using the direct wafer bonding fabrication process we realized linear 1D CMUT arrays. On top of the 0.86 μm thick silicon plate, a 200-nm thick aluminum layer and a 10-nm thick titanium adhesion layer were deposited. A lift-off technique was used to deposit a gold mass on top of the adhesion layer, at the center of each cell. The 1-μm thick gold layer was deposited in multiple steps with intervening cool-down periods to ensure low thermal-induced stress between the gold and the metalized CMUT plates. Electrical impedance measurements of the devices reveal improved performance due to the gold mass, and the average resonance frequency in air for the elements in the 1D array decreased from 7 MHz to 3.6 MHz with a standard deviation of 0.125 MHz and 0.157 MHz, respectively. A direct comparison of cells with and without the gold mass in terms of measured output pressure at the surface of a single cell demonstrated a 23% improvement. When biased with a DC voltage equal to 75% of the pull-in voltage, the device with the gold mass delivered 1.875 MPa peak-to-peak surface pressure at a frequency of 2.6 MHz (single cell measurement). The results indicate that adding a center-mass to regular CMUT cells improves device performance in terms of acoustic output pressure. In the future, we plan to investigate the acoustic crosstalk between cells and ways to mitigate it.

Keywords: CMUT, gold center mass, HIFU, output pressure.

INTRODUCTION

In recent years, there has been great interest in high intensity focused ultrasound (HIFU) therapy because it is either minimally invasive or non-invasive. Currently piezoelectric transducers dominate the market for HIFU, even though their performance is limited by their material properties [1]. They face serious drawbacks in HIFU applications due to high self-heating, thermal instability and magnetic resonance (MR) incompatibility. On the other hand, capacitive micromachined ultrasonic transducer (CMUT) technology overcomes these challenges, and provides further advantages such as ease of integration with electronics, the ability to fabricate large 2D arrays with arbitrary geometries and the ability to be combined with multiple modalities. To achieve a successful HIFU treatment, the required acoustic pressure is significantly higher than for medical imaging. Previous research [4, 5] proposed a CMUT design with a center mass on top or beneath the CMUT plate to achieve increased output pressure. Various shapes of the additional mass have been fabricated and characterized and have shown improvements [5]. In this work we fabricated devices with a center gold mass by adding only one extra fabrication step. Further, we perform a direct comparison to CMUTs without any gold mass in terms of the acoustic output pressure.

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DESIGN

Huang and Wong [2,5] have previously proposed a new design for a compound plate device using a central mass to improve output pressure. HIFU transducers differ from conventional medical imaging transducers in that output pressure is the primary figure of merit. Thus, the reduction in quality factor by adding gold mass is outweighed by the improved output pressure. The central mass partly decouples the equivalent mass and stiffness of the moving plate, and provides a means to control the mass and stiffness independently [4]. It increases the stiffness of the central region of the moving plate, resulting in lower flexion and hence a relatively flat active moving surface and a more uniform displacement profile as compared to a conventional CMUT. This leads to a higher average electrostatic field inside the vacuum cavity, which translates into higher output pressure [5]. Finite element simulation results [2, 3] have shown that adding a mass to the center of the CMUT plate is a promising method to increase output pressure. Gold was chosen to form the central mass due to its high density and MR-compatibility. Also, the gold mass can be added with only one extra lithography step. In this research, we used 40 µm square cell with 0.5 µm gap height, 0.2 µm insulation layer, 0.86 µm plate thickness, and 0.2 µm of aluminum layer for conventional CMUT [Fig. 1(a)] and added central gold mass with 20 µm square and 1 µm in thickness [Fig. 1(b)].

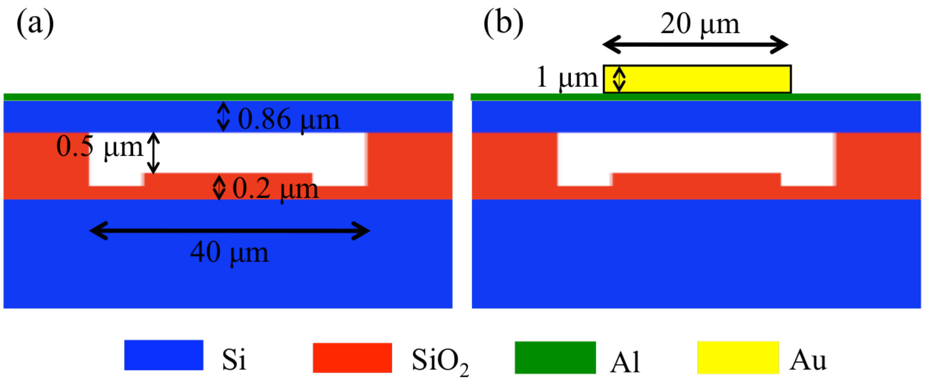


FIGURE 1. Cell geometry: (a) a conventional CMUT cell; (b) a CMUT cell with gold center mass – thin titanium adhesion layer is not shown (not to scale).

FABRICATION PROCESS

Fabrication starts by thermally oxidizing a heavily-doped silicon wafer [Fig. 2(a)]. This oxide layer is patterned with standard photolithography processes and wet etched in buffered oxide etch (BOE) to define the CMUT cavities. After the oxide is etched to the silicon (etch stop), the wafers are cleaned and oxidized again to insulate the bottom electrode with a well-defined thickness. The differential oxide growth defines the total cavity height. Next, a second lithography step is performed to remove the oxide bulging created during the double oxidation process. This step can ensure a high quality bond and good yield. At this point the cell cavities have been defined and the top silicon plate can be direct bonded to the substrate [Fig. 2(b)]. A silicon-on-insulator (SOI) wafer with a 1-µm thick device layer was thermally oxidized to a final device layer, i.e. plate thickness, of 0.86 µm. The temperature- assisted direct bonding step [Fig 2(c)] is done under low-pressure conditions ($< 10^{-5}$ mbar), which ensures vacuum-sealed device cavities [6]. The bond strength is increased by high-temperature annealing at 1000°C for 4 hours. After annealing the handle wafer is mechanically ground to remove the majority of the silicon. The final silicon handle thickness is removed by heated tetramethylammonium hydroxide (TMAH) etching. The box layer is then removed by BOE. Next electrical contacts are added. Before metal deposition another photolithography is done to expose the substrate silicon for ground contacts [Fig 2(d)]. An aluminum layer is sputtered over the whole wafer. The aluminum and top plate silicon layers are then patterned to separate the array elements and contacts [Fig 2(e)]. At this point a conventional CMUT device is completed [Fig 1(a)]. For the CMUTs with gold central mass, an extra fabrication step is needed. Resist is coated and patterned on top of the aluminum layer. A 10-nm thick titanium adhesion layer is sputtered and 1-µm thick gold layer is deposited over the adhesion layer, in multiple steps. The intervening cooling periods help to reduce the thermally induced stress during sputtering [7]. To avoid problems with the selectivity, the gold is patterned by lift-off lithography and not etched. After the resist is removed by using standard developers, the gold only remains on the center of the plate and CMUT with gold mass is completed [Fig. 1(b), Fig. 2(f)].

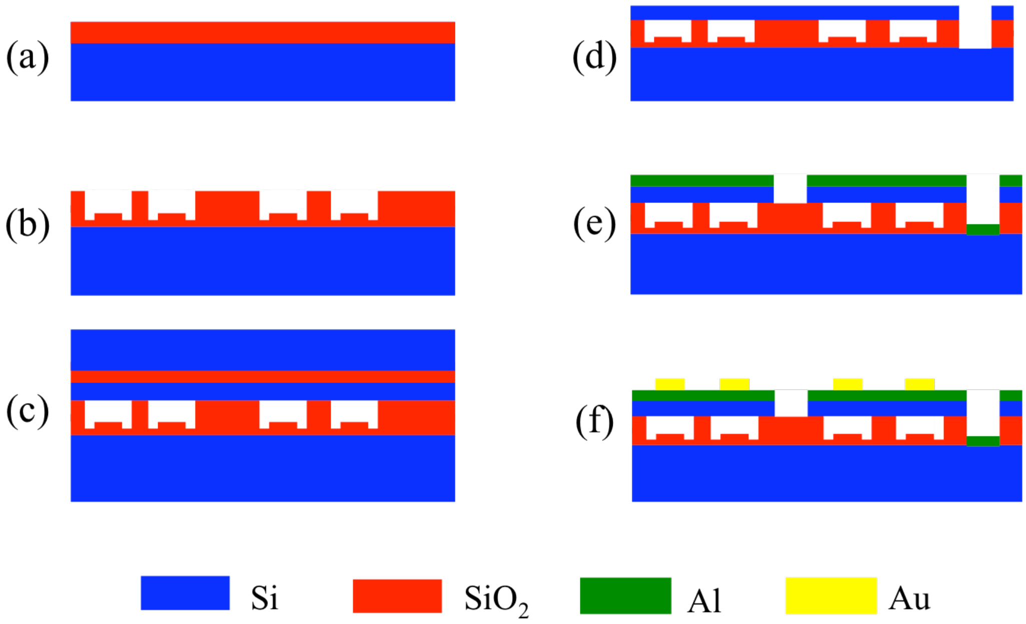


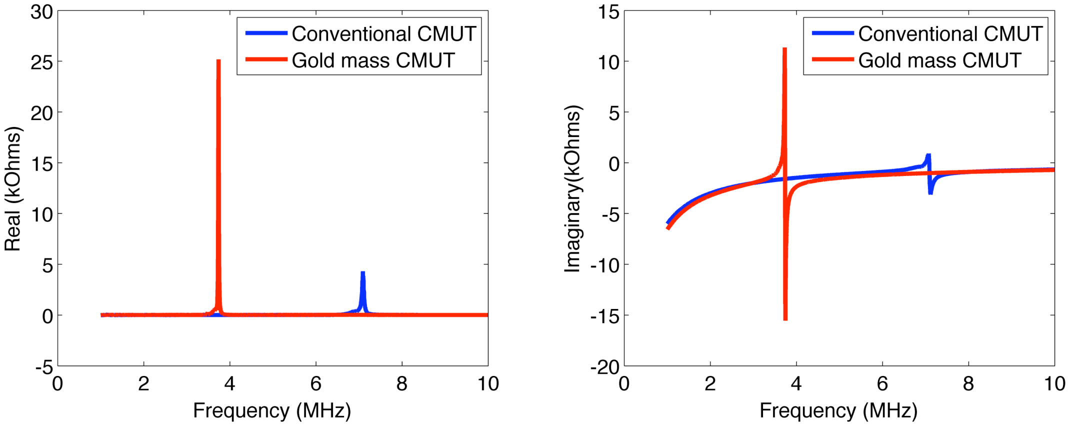
FIGURE 2. Fabrication process flow: (a) thermally oxidized silicon wafer; (b) gap cavities formed by etching; (c) temperature-assisted bonding to an SOI wafer; (d) handle wafer and box layer removed and ground contacts opened; (e) 200-nm thick aluminum layer deposited and elements separated for forming a conventional CMUT; and (f) a CMUT with gold mass on top of the plate realized by lift-off process. Figures show cross sections of two neighboring elements containing two cells (not to scale).

RESULTS

First the electrical input impedance in air was measured to test that the device fabrication was successful. Additionally the output pressure of single cells from both the CMUT without and with gold mass was measured in immersion using a laser interferometer.

Electrical impedance in air

The electrical input impedance in air was measured by probing the electrodes on the front side of the device using an impedance analyzer (Model 4294A, Agilent Technologies, Palo Alto, CA). The dc bias voltage (SRS PS310, Stanford Research Systems, Stanford, CA) was varied starting from 0 V up to the pull-in voltage in 10 V steps. The ac excitation amplitude of the impedance analyzer was set to 50 mV. Due to the additional mass, the CMUT with gold central mass has a larger input impedance at its center frequency (Fig. 3). Since the central gold mass increases the equivalent stiffness of the plate, the pull-in voltage is increased for the gold central mass CMUT. The resonant frequency of the CMUT with gold central mass is shifted down from 7 MHz to 3.6 MHz when biased at 75% of the respective pull-in voltage of the two cases (Table 1). This is expected because the resonant frequency is proportional to the square root of the spring constant divided by the effective mass. As mentioned earlier, the spring constant is less affected, but the effective mass is significantly increased due to the gold central mass, resulting in a reduced resonant frequency.



(a) (b)

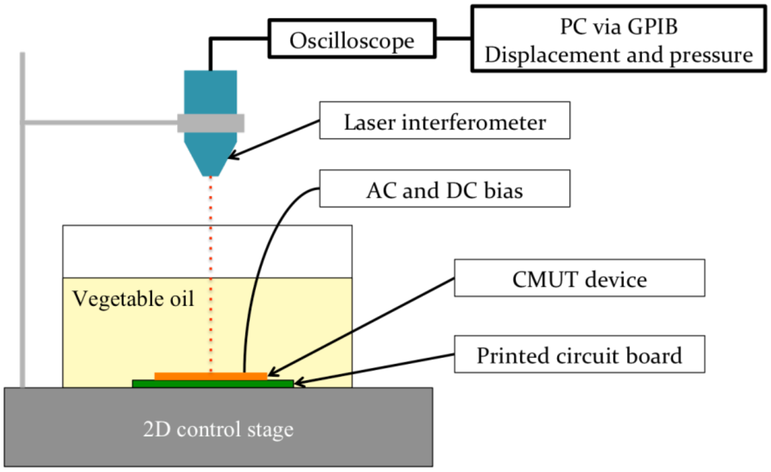
FIGURE 3. Direct comparison of electrical input impedances measured in air at 75% of the respective pull-in voltage: (a) Real part; (b) imaginary part.

TABLE (1). Static properties in linear response and resonant frequencies at 75% of pull-in voltage.

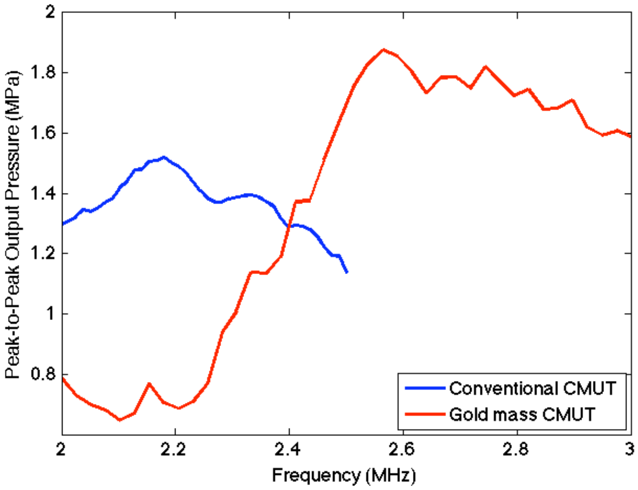
Cell type	**Pull- in voltage (V)**	**Resonant frequency (MHz)**	**Output pressure (MPa)**
Conventional CMUT	160	7.0	1.520
Gold mass CMUT	200	3.6	1.875

Output pressure in immersion

The two CMUT devices, i.e. with and without gold central mass, were wire-bonded to a printed circuit board (PCB) and placed in a tank filled with soybean oil [Fig. 4(a)]. Both devices were biased at 75% of their pull-in voltage and excited with a large ac signal from a waveform generator (Agilent 33250A, Agilent, Palo Alto, CA), which was then amplified by a 3-W amplifier (ENI 403LA, Electronic Navigation Industries, Richardson, TX). An optical fiber interferometer OFV-511 (Polytec GmbH, Waldbronn, Germany) attached to a common microscope by a microscope adapter PFV-072 (Polytec) was used to measure the displacement of single CMUT plate cells. A wide-band displacement decoder OVD-30 (Polytec) was used, which was connected to a digital oscilloscope (Infiniium 500 MHz, 2 Gs/s, Agilent Technologies Inc., Palo Alto, CA). The stored displacement signals where converted into surface acoustic pressure signals by considering the refractive index of soybean oil (1.47), the frequency information, and the acoustic impedance of the soybean oil. The frequency was swept for both devices to determine the operating point for maximum acoustic pressure. The conventional CMUT produced a maximum pressure of 1.520 MPa peak-to-peak at a frequecny of 2.20 MHz, whereas the CMUT with the gold central mass produced 1.875 MPa peak-to-peak pressure at 2.56 MHz [Fig. 4(b)]. Thus, the maximum output pressure from the CMUT plate improved by ~23% by adding the gold central mass.



(a)



(b)

FIGURE 4. The setup and main result of surface pressure measurement of a single CMUT plate: (a) simplified measurement setup using the laser interferometer; (b) surface pressure of both devices.

DISCUSSION AND CONCLUSION

We successfully conducted an experiment for comparing a conventional CMUT cell design and a gold central mass CMUT cell design in terms of surface pressure. The gold central mass CMUTs can be easily fabricated from conventional CMUTs with the addition of one lift-off step. The central gold mass increased the CMUT electrical input impedance response. Further, the gold mass shifted the static properties of the device including pull-in voltage and resonant frequency. The acoustic output pressure at the surface of the device improved by 23% after the gold central mass was added on top of the plate. Because so far, we only performed single cell measurements, future work is required. In particular, the effect of acoustic crosstalk [4] occurring between cells and elements must be investigated for the designs presented in this work, because it can decreases the total output pressure of the CMUT. Further, the option of better electrical tuning with inductors needs to be considered to lower the resonant frequency to 1 MHz, which is more common for HIFU applications.

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