CMUTs on Glass with ITO Bottom Electrodes for Improved Transparency

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Abstract — **In this work, we fabricated capacitive micromachined ultrasonic transducers (CMUTs) on a glass substrate with indium tin oxide (ITO) bottom electrodes for improved transparency. A 2-µm vibrating silicon plate was formed by anodic bonding. The fabrication process requires three masks. The fabricated devices show approximately 300% improvement of optical transmission in the visible to NIR wavelength range (400 nm – 1000 nm) compared to the devices with chromium/gold (Cr/Au) bottom electrodes. The measured static surface profile confirmed that the fabricated devices are vacuum-sealed. The electrical input impedance measurement shows the device has a resonant frequency of 4.75 MHz at 30-V DC voltage. The series resistance of the device is ~1 kΩ, which is mainly due to the ITO bottom electrode connections. Using a full bottom electrode or using parallel connections to the pads could reduce the resistance. The main hurdle for the transparency at shorter wavelength range is the 2-µm silicon plate. The transfer-matrix model shows the transparency could be improved to ~80% across the measured spectrum, if silicon is replaced with a more transparent plate material such as ITO or silicon nitride.**

Keywords—CMUT; ITO; Glass; Anodic bonding; Transparency

I. INTRODUCTION

The combination of ultrasonics and optics is desired in many applications such as integrating ultrasound sensing with flat panel displays, embedded optical vibrometry, and photoacoustic imaging [1][2]. The opacity of materials used in conventional piezoelectric transducer constructs has severely restricted such applications. Lithium niobate with indium tin oxide (ITO) electrodes has been investigated to build a transparent piezoelectric transducer [3]. However, transparent capacitive micromachined ultrasonic transducers (CMUTs) are desired because of the benefits such as ease of fabrication and integration, and broad bandwidth [4]. We have previously reported a three-mask process to fabricate CMUTs on a glass substrate using anodic bonding [5]. In addition to the reduced process complexity and parasitic capacitance, the glass substrate provides optical transparency that enables novel applications merging optics with acoustics.

Indium tin oxide (ITO) has high optical transparency and electrical conductivity, and hence has been used as a transparent conductor in devices such as light emitting diodes (LED) and liquid crystal displays (LCD) [6]. In this work, we use ITO as the bottom electrode of CMUTs to improve the optical transparency.

The CMUTs with ITO bottom electrodes are fabricated based on our anodic bonding process. We had also applied the process to make CMUTs that has silicon nitride instead of metal on the silicon plate [7]. Glass substrate and silicon nitride have good transparency. The thin silicon plate has some limited transparency in the red to NIR wavelength range. The major limitation in the total transmission through the CMUT structure we have reported in our previous work was the metal (Cr/Au) bottom electrodes. In this work, we use ITO as bottom electrode material instead of Cr/Au. In the next sections the fabrication process and the optical and acoustical characterization results are presented.

II. FABRICATION PROCESS

The simplified fabrication process flow is shown in Fig. 1. The fabrication process starts with a 0.7-mm-thick, 100-mm diameter borosilicate glass wafer (Borofloat33, Schott AG, Jena, Germany) that has a RMS surface roughness of 0.7 nm and a warp less than 0.05%. The cavities were patterned using a 2-µm thick photoresist (Fig. 1a). The patterned wafer was hard-baked for 10 minutes at an elevated temperature of 125°C to promote the adhesion between the substrate and the photoresist. The glass cavities were etched down to 350 nm in 10:1 BOE solution in two cycles of a total of 15 minutes. An interval hardbake at 125°C was performed between the etching cycles to avoid photoresist peeling off. The wet etch process had a lateral to vertical etch rate ratio of 10:1. Therefore we achieved 3.5-µm lateral undercut after the glass etching, which is beneficial for the later ITO lift-off step.

The wafer was transferred into a RF sputtering system without removing the photoresist. 150-nm ITO was sputtered over the wafer at room temperature and then the lift-off was done in heated N-Methyl-2-pyrrolidone (NMP@70°C) solution (Fig. 1b). The optical and AFM images in Fig. 2 show the ITO electrode in the etched glass cavities. The RMS roughness was 0.5 nm on the ITO surface and 0.7 nm on the glass post. After this step, the wafer was annealed at 450°C for 5 min in a rapid thermal annealing (RTA) system (Fig. 1c). The ITO conductivity and transparency significantly improved after annealing. The sheet resistance of the ITO bottom electrode before annealing was 300 Ω/sq, and reduced to 20 Ω/sq after

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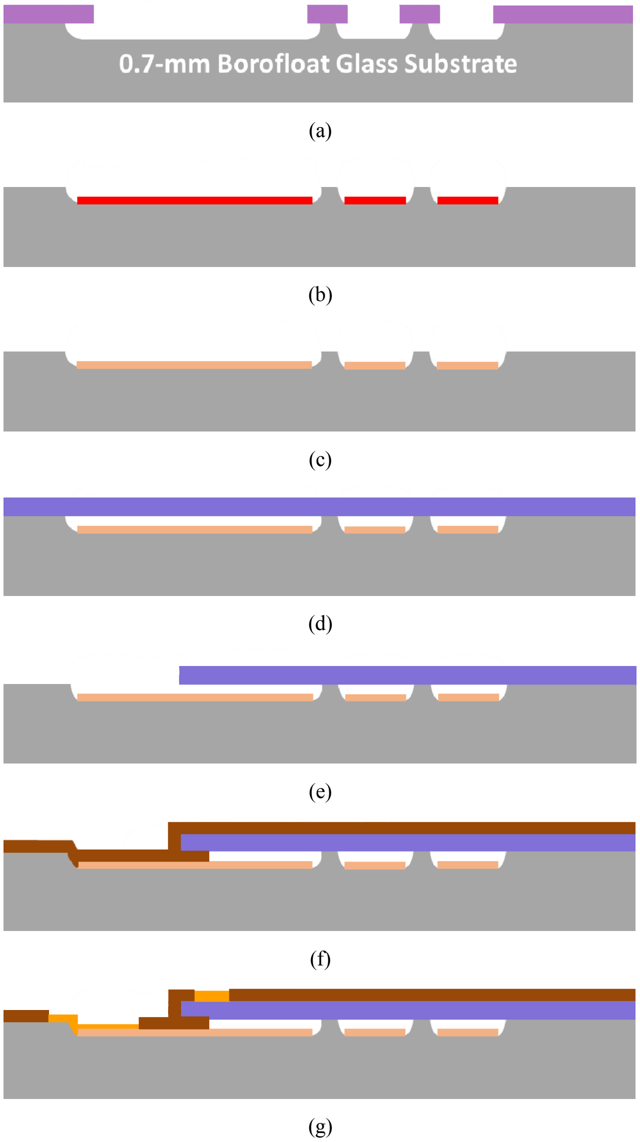

(a)

(b)

(c)

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(e)

(f)

(g)

Fig. 1. Simplified fabrication process flow. (a) Pattern and wet etch the glass substrate down 350 nm; (b) ITO sputter and lift-off; (c) Annealing; (d) Anodic bonding; Handle and BOX layer removal; (e) Silicon plate etch; (f) Deposit PECVD silicon nitride for sealing; (g) Etch silicon nitride and form electrical contacts.

annealing. The ITO optical properties before and after annealing are discussed in Section III.

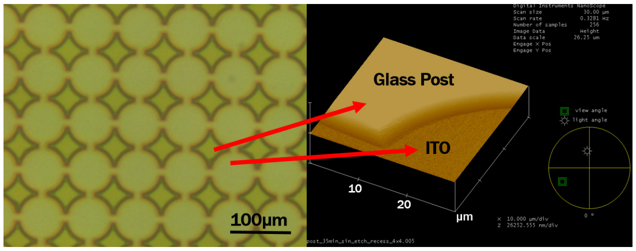


Fig. 2. Optical image after the ITO bottom electrode definition (left). AFM image showing the profile of the glass post and ITO bottom electrode (right).

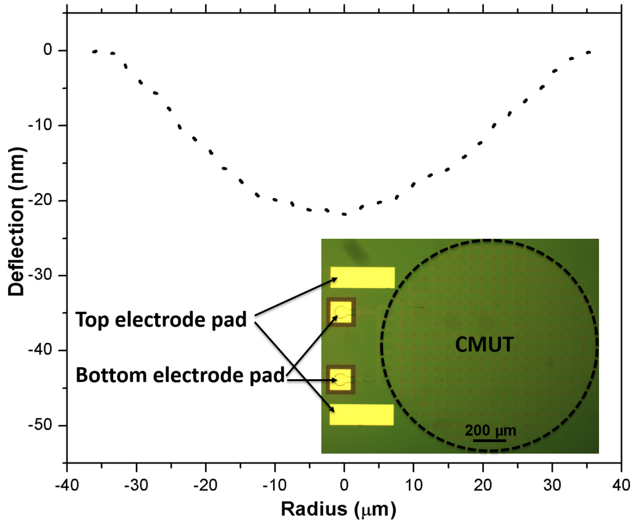


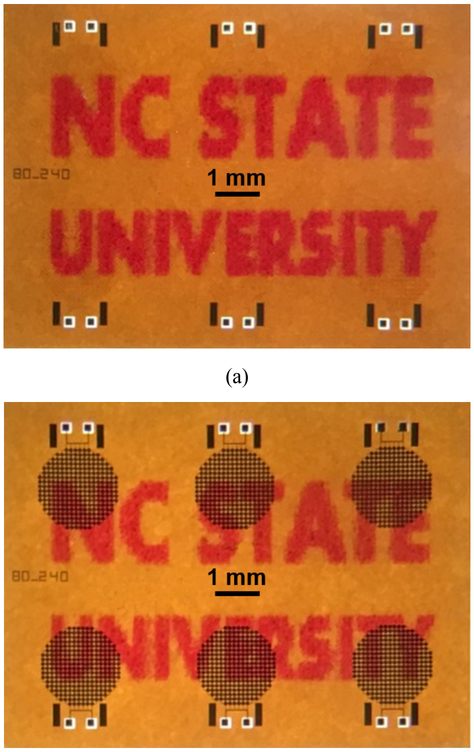
Fig. 3. Atmospheric deflection measurement of a finished CMUT element. The inset shows a finished CMUT element.

An SOI wafer device layer was used to form the CMUT top plate. The device layer was n-type silicon with 0.001 to 0.005 Ω·cm resistivity. The SOI device layer and the processed glass surface were bonded together at 350°C under 2.5-kN down force and 700-V bias voltage in vacuum. Then the handle wafer was ground down to 100 µm. The top plate was released after removing the remaining handle layer using heated tetramethylammonium hydroxide solution (10% TMAH at 80°C) and BOX layer using 10:1 BOE solution (Fig. 1d). Then the silicon plate was etched on the pad locations to evacuate the trapped gas inside the cavities and to reach bottom electrodes (Fig. 1e). The device was re-sealed using 1-µm conformal PECVD silicon nitride (Fig. 1f). Then the sealing silicon nitride was etched in order to reach the top plate and bottom electrode for electrical contacts. The device was finished after evaporating and lifting off a stacked layer of 20-nm chromium and 180-nm gold to form the bond pads (Fig. 1g). Fig. 3 shows the optical image of a finished CMUT element with ITO bottom electrode and circular cells with a diameter of 78 µm and a plate thickness of 2.5 µm. The atmospheric deflection measurement in the center of a cell confirmed the devices are vacuum-sealed.

III. CHRACTERIZATION

Fig. 4a shows the optical images of the CMUTs fabricated with ITO bottom electrodes under microscope with backside illumination. The die with six CMUT elements was placed above a “NC STATE UNIVERSITY” logo. In comparison, Fig. 4b shows the same setup with CMUTs fabricated with Cr/Au bottom electrodes. From the optical image, it is clear that the device with ITO bottom electrode has a much improved transparency in visible light range.

To further characterize the transmission coefficient, the ITO and Cr/Au bottom electrodes and the finished devices were measured using a spectrophotometer (Cary 60 UV-Vis, Agilent Technologies, Santa Clara, CA) from 400 nm to 1000



(a)

(b)

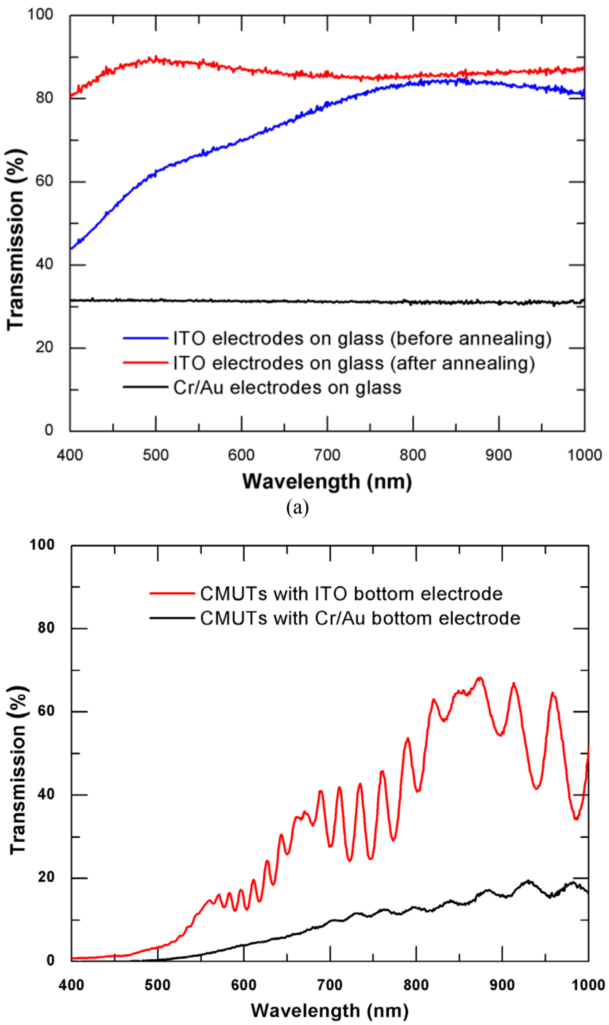
Fig. 4. (a) Six CMUT elements with ITO bottom electrodes show the improved transparency of the bottom electrodes. (b) Six CMUT elements with Cr/Au bottom electrodes presented for comparison.

nm wavelength range. Fig. 5a shows the transmission through the 150-nm ITO bottom electrode on glass before and after annealing, in comparison to 150-nm Cr/Au bottom electrode on glass. Fig. 5b shows the optical transmission through the final device with ITO bottom electrodes and Cr/Au electrodes. It is clear that the CMUTs with ITO bottom electrodes have a significant transmission improvement in the measured wavelength range. However the 2-µm silicon plate is the main hurdle for the transmission in the shorter wavelength range.

The electrical input impedance of a fabricated CMUT element was measured in air (Fig. 6). The CMUT showed 4.75-MHz resonant frequency at a DC voltage of 30 V (~80% pull-in voltage). The series resistance of the fabricated device is ~1 kΩ, which corresponds to the expected 50 squares for the bottom electrode. Using the thicker bottom electrodes or parallel connections to the pads could reduce the series resistance.

IV. DISCUSSION

CMUTs fabricated with the Cr/Au bottom electrodes of 150-nm thickness show <20% optical transmission. By using ITO as the bottom electrode instead of Cr/Au, the optical transmission through the device is improved to ~50% in the wavelength range from 700 nm to 1000 nm. The low optical transmission in the lower wavelength regime is mainly caused by the absorption in the vibrating plate, which we aim to reduce by exploring alternative materials. The potential candidate could be a silicon nitride plate or an ITO plate. Also, we propose to use HfO_2 as the insulation layer between top and bottom electrodes, which could serve as a reliable high-k dielectric without affecting the transparency. The proposed device structure is shown in Fig. 7a.



(a)

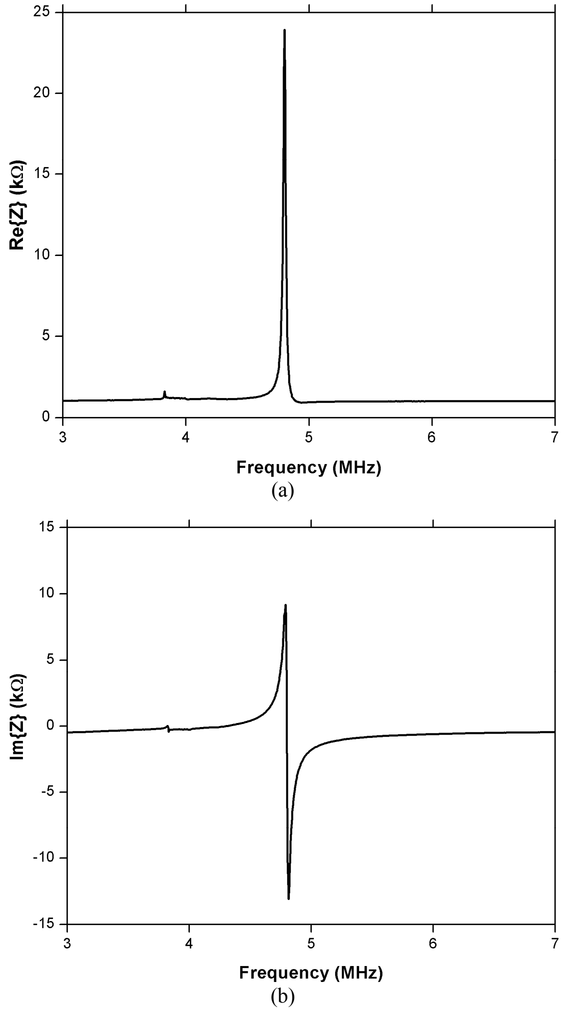
(b)

Fig. 5. Transmission measurement. (a) Transmission of the bottom electrodes. (b) Transmission of the final devices.

We compared the measured transmission through the fabricated CMUTs with ITO bottom electrodes to simulation results based on transfer matrix method [8]. The good agreement between measured and simulated results suggests that we could use this model reliably to design structures with even higher transparency. The simulation shows that an improved transparency (~80% transmission) across the visible to NIR spectrum could be achieved if the plate is also implemented using ITO (Fig. 7b).

V. CONCLUSION

In this paper, we reported on CMUTs fabricated on a glass substrate with ITO bottom electrodes for improved transparency. The CMUT plate was formed by anodic bonding a 2-µm thick SOI silicon device layer on to borosilicate glass. The fabricated device shows an improved transparency in the



(a)

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Fig. 6. Measured electrical input impedance of the fabricated device (V_{DC} = 30 V). (a) Real part; (b) Imaginary part.

visible to NIR wavelength range, especially from 700 nm to 1000 nm, which is a wavelength range commonly used in photoacoustic imaging. The fabricated device is vacuum-sealed. Electrical input impedance measurement shows that the CMUT on glass with ITO bottom electrodes has a resonant frequency of 4.75 MHz at 30-V DC voltage. The series resistance is measured as ~1 kΩ. An improved device structure is then proposed, aiming to replace the silicon plate with a material with better transparency in the visible wavelength range. Simulation results show that by using silicon nitride or ITO as the plate material, the transparency in the measured spectrum could be further improved to ~80%.

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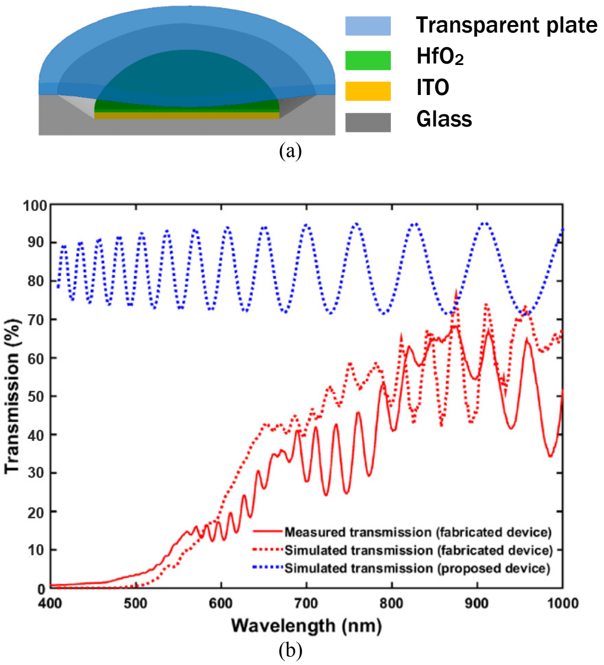

(a)

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Fig. 7. (a) 3-D drawing showing the different layers in the proposed device. (b) Transmission simulation using transfer matrix method.

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