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Investigation of Capacitive Micro-Machined Ultrasonic Transducers using Transparent Conductive Film

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ABSTRACT: This paper introduces two different 2×3 arrays of capacitive micromachined ultrasonic transducers using AZO, ITO transparent conductive material. The AZO, and ITO transparent conductive materials use as two upper electrodes of the transducers, and compared with the transducer used gold electrode as the signals, life, and transparency. Initially, the two transparent transducers were measured and studied for their signals. In terms of usage time, these two transparent materials generate signals for a short time. When using the OM microscope to observe, the surface of the electrode has a fracture or breakage of the phenomenon. For further verification, this study needs to be developed and observe the operational status of the electrode surface temperature. Research has revealed that it is possible to fabricate a transparent capacitive micromachined ultrasonic transducer for future manipulation or wearable devices.

KEYWORDS: Capacitive Micromachined Ultrasonic Transducers, Transparent Conductive Film.

I. INTRODUCTION

Capacitive Micromachined Ultrasonic Transducer (CMUT) is constructed using lithography process technology, and the principle is based on the capacitive effect generated by the electric field between two electrodes. Analyzing ultrasonic signals is achieved by receiving signal changes through appropriate circuits and amplifiers. The schematic diagram of the CMUT's working principle is shown in Fig. 1.

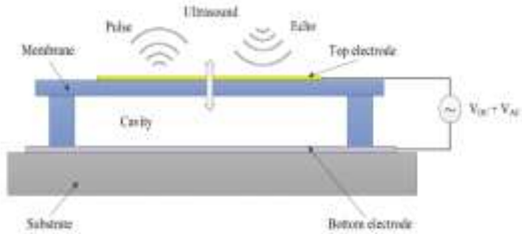


Fig. 1. Schematic diagram of CMUT structure

In 1954, Rupprecht [1] first discovered that indium oxide was conductive and used indium as a target material to deposit it on a quartz substrate by evaporation to obtain a transparent indium oxide film with a conductivity of 10^{-1}-$10^{-5}(\Omega\cdot cm)^{-1}$. In 2007, Zhinong et al. [2] studied ITO conductive films' flexible electrical and optical properties, which prepare using a 90In-10Sn (wt%) doping ratio and ion beam-assisted reactive evaporation technology. In 2010, Kumar and Zhou [3] mainly focused on tin-doped indium oxide to discuss alternative materials, such as carbon nanotube film, graphene film, metal nanowires, metal grids, etc. It can also achieve a sheet resistance of 16 Ohms/sq and up to 86% transparency. In 2011, Alzoubi et al. [4] used commercially available 200Å ITO, 127mm PET to perform ITO-PET repeated bending test. It found that the smaller the radius of curvature, the more significant the increase in resistance after repeated bending. 2005 Park et al. [5] used magnetron sputtering to make AZO transparent conductive films on different substrates at 100°C and 200°C. They found that sputtering AZO on flexible substrates was better than on glass substrates. The light transmission characteristics are good, and the sheet resistance and soft transmission characteristics are also good when the deposition temperature is high. In 2012, Chen et al. [6] designed an array of infrared transparent capacitive micromachined ultrasonic transducers (CMUT). The imaging system is fabricated using the infrared wavelength-transmissible silicon-based principle and illuminates the image target through the CMUT array. The array between the light source and the transducer array increases signal reception and makes illumination more uniform. In 2014, Brodie et al. [7] used lithium niobate (LNO) ceramic materials to make optically transparent piezoelectric ultrasonic transducers. This transducer has good transparency in visible light and near-infrared wavelengths, and its acoustic performance is comparable to traditional. There is little difference when using silver to make electrodes; a spectrophotometer measures the visible light transmittance at about 70%.

In 2017, Pang et al. [8] developed a CMUT array of polymer-based materials with 12 resonant frequencies ranging from 0.83MHz to 1.63MHz. This transducer has transparent electrodes and provides good transmittance, which is suitable for finger hover-sensing dial pad applications.

This paper proposes a transparent ultrasonic transducer to apply to suspension control, wearable devices, and OLED lighting systems in the future.

II. MATERIALS SELECTION

Transparent Conductive Material Combined with the CMUT

This research develops a transparent ultrasonic transducer because the ultrasonic wave has a non-contact function; it can be applied to suspension control, wearable devices, OLED lighting systems, and places with hygiene and safety considerations.

This study used a 2×3 array of the CMUT for experiments. A single CMUT is composed of 416 hexagonal cells with a circle diameter of 140µm, the thickness of the oscillating membrane is 5µm, the cavity height is 2µm, and the single size of the CMUT is 3mm×3mm, as shown in Fig. 2.

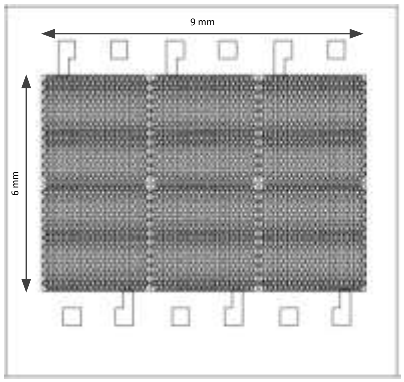


Fig. 2. Schematic of the CMUT array

Selection of Transparent Conductive Materials

The transparent conductive film must have a light transmittance of more than 80% in the visible light range (wavelength about 380~780nm), and the resistivity of the materials should be lower than 10-4Ω·cm. Transparent conductive materials are generally divided into two categories one is a thin metal film, and the other is a metal oxide. Currently, widely used materials are ITO, AZO, PEDOT, CNT, Nano Silver, etc...

In this study, ITO and AZO were selected for testing. Their selection is mainly due to their flexibility, transparency, and electrical conductivity, as shown in the comparison table of transparent materials in Table 1.

Table 1. Comparison of transparent materials [9]

	ITO	AZO	PEDOT	CNT
Transparent (%)	85~ 90	85~ 90	85~ 90	85~ 88
Flexible	possibl e	possibl e	good	good
Resistance (Ω/sq)	5~ 250	50~ 250	200~ 250	3.5~ 50
Color	Transp a-rent	Transp a-rent	Slight blue	Slight black

Made of Transparent Conductive Material

This study uses the vacuum evaporation method to fabricate ITO conductive thin films. The evaporation conditions are 10-5torr, a deposition rate of 1.5Å/s, and the film resistance measured by a four-point probe is 180 ~220Ω/sq.

The AZO conductive thin film was fabricated by using the magnetron sputtering method. The sputtering conditions included a vacuum value of 10-3torr and a deposition rate of 0.5Å/s. After the fabrication completion, the film resistance was measured with a four-point probe as 230~270Ω/sq.

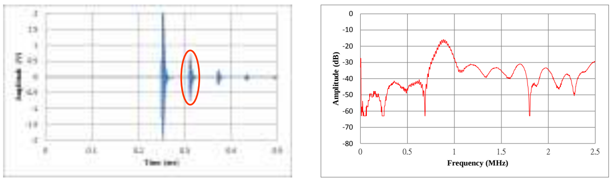
III. MEASUREMENT OF CMUT CHARACTERISTICS

Basic Measurement of the CMUT

This study initially uses gold as the top electrode of the CMUT for signal and frequency experimental measurements. It uses the same conditions to measure the transparent CMUT and analyze its feasibility. Fig. 3 shows a physical diagram of the experimental measurement structure. JSR Pulse Receiver and DC Power Supply provide AC and DC energy. The AC and DC signals are input to the two electrodes of the component through the bias tee, and the oscilloscope intercepts the signal.

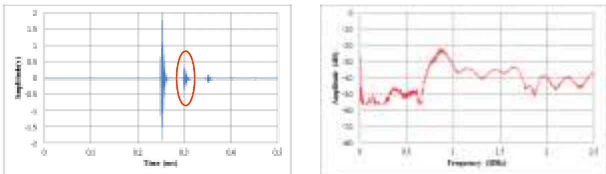
Fig. 3. Photo of the experimental setup

The measurement conditions of this experiment applied an AC voltage of 300V and a DC voltage of 100V to the two electrodes of the CMUT, and the vertical distance between the reflective surface and the CMUT is 10mm. The first reflected signal of the CMUT with the electrode of gold is 840 mV, and the natural resonance frequency is 0.87 MHz, as shown in Fig. 4. The signal of the CMUT with ITO electrode is 306 mV, and the natural resonance frequency is 0.87 MHz, as shown in Fig. 5. The signal of the CMUT with AZO electrode is 184 mV, and the natural resonance frequency is 0.87 MHz, as shown in Fig. 6. The signal of the CMUT with AZO-SU8 coating electrode is 120mV, and the natural resonance frequency is 0.93MHz, as shown in Fig. 7.



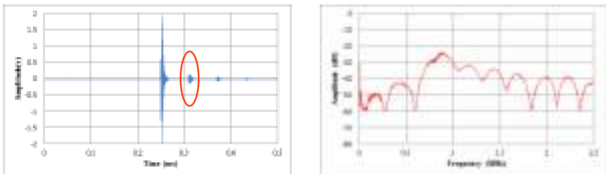
(a) **(b)**

Fig. 4. (a) Time response and (b) Frequency response of the CMUT with gold electrodes



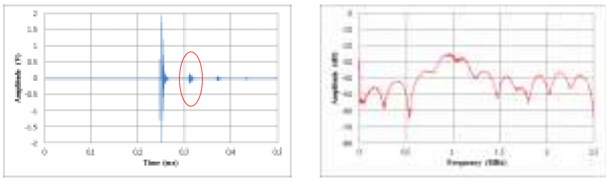
(a) **(b)**

Fig. 5. (a) Time response and (b) Frequency response of the CMUT with ITO electrodes



(a) **(b)**

Fig. 6. (a) Time response and (b) Frequency response of the CMUT with AZO electrodes



(a) (b)

Fig. 7. (a) Time response and (b) Frequency response of the CMUT with AZO-SU8 coating electrodes

Table 2. Signal comparison of different materials

Top electrode material	Gold	ITO	AZO	AZO-SU8 coating electrode
Measuring distance	10mm			
Applied voltage	AC 300V and DC 100V			
Resonance frequency (MHz)	0.87	0.87	0.87	0.93
Time domain amplitude (mV)	840	306	184	120
Frequency domain amplitude (dB)	-17.5	-21.9	-24.3	-25.4
Film resistance (Ω/sq)	50	160~ 200	230~ 270	240~270

This experiment preliminarily proves the feasibility of applying transparent conductive materials to the CMUT. The difference in the magnitude of the experimental signal may be related to the film resistance of the top electrode. The current resistance of the electrode with the gold film is about 50Ω/sq, the ITO film resistance is about 180~220Ω/sq, and the AZO film resistance is about 230~270Ω/sq. Further experimental verification is needed to reduce the film resistance in the future.

Lifetime Measurement of the CMUT

The lifetime of different materials in this research is tested to find out. The gold electrode is used as the standard for life measurement, and the two transparent electrodes are tested and compared. The test conditions are to apply an AC voltage of 300V and a DC voltage of 100V. The testing is continuous for 8 hours, intercepting the signal once an hour, and observing its changes, as shown in Fig. 8. When the highest signal is attenuated by more than 3dB from -17dB, it is determined that the CMUT cannot be used.

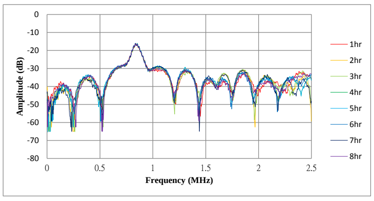
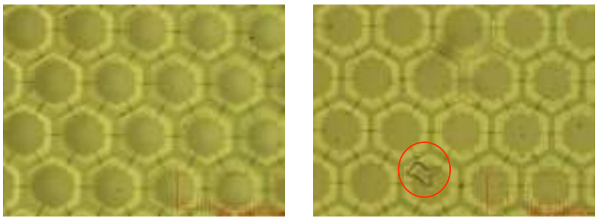


Fig. 8. The lifetime testing of the CMUT with gold electrode

The lifetime testing of the ITO electrode and AZO electrode were carried out under the same experimental conditions. It was found that after a few minutes, the components had no signal at all. The reason was further investigated with an optical microscope (OM). The electrodes of the CMUT were taken OM photos before and after testing.

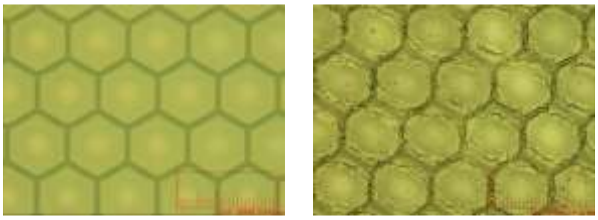
Fig. 9(a) shows the ITO electrode before the test, and the ITO film seems complete. Fig. 9(b) shows that after the test of the ITO electrode, the red circle is the broken film, and the electrode is damaged. Many ITO films are broken off, which makes the component unable to work.

Fig. 10(a) shows the AZO electrode before being tested. Since the film is not etched, the entire surface is the AZO electrodes. Fig. 10(b) shows the AZO electrode after the test; there were many cracks on the surface, which caused poor conductivity and made the element unable to work.



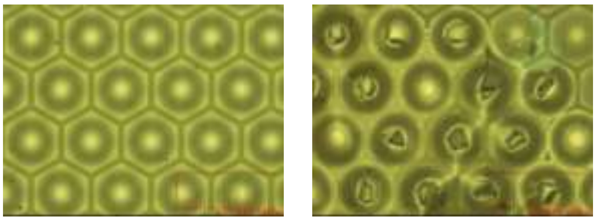
(a) (b)

Fig. 9. The OM photo of ITO electrode (a) Before testing and (b) After testing



(a) (b)

Fig. 10. The OM photo of AZO electrode (a) Before testing and (b) After testing



(a) (b)

Fig. 11. The OM photo of AZO-SU8 coating electrode (a) Before testing and (b) After testing

In this experiment, a layer of SU8 photoresist was applied as a protective electrode after the AZO electrode was fabricated and tested. Fig.11(a) is the SU8 coating electrode, and Fig. 11(b) is the tested electrode. Because the protective electrode process needs to bake, the original expansion increases, and some parts break. Fig. 12 shows the 3D photo of the AZO-SU8 coating electrode's damage testing using a Keyence VK-X250 3D laser microscope.

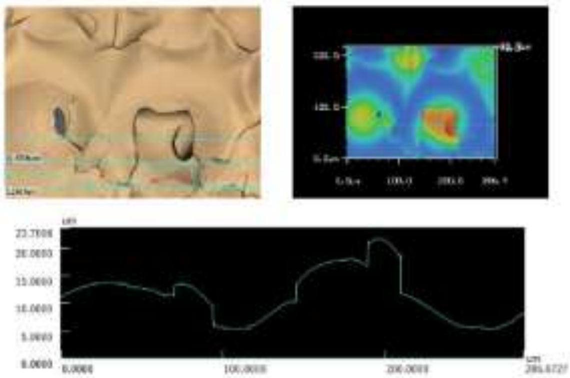


Fig. 12. The 3D photo of damage testing of AZO-SU8 coating electrode

Thermal Imaging Measurement of the CMUT

This experiment is to clarify the main problem of electrode damage after the ITO and AZO transparent electrodes are measured. The electrode is burned due to the heat generated by the applied voltage, or the electrode is damaged due to the vibration of the film.

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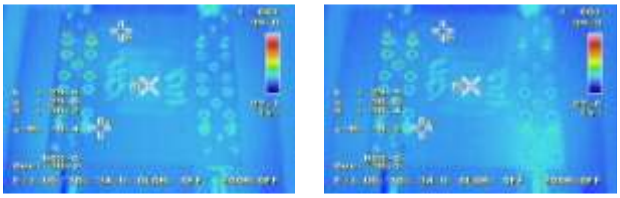
An NEC Avio'sInfReC series G120EX thermal imager was used for experimental measurement. The thermal imaging specifications are shown in Table 3.

Table 3. Thermal Imaging Specifications [10]

Item	G120EX
Measuring range	-40°Cto1500°C
Resolution(NETD)	0.04°C
Accuracy	±2°C
Infrared detectors	Uncooled Focal Plane Array
Thermal image pixels	300 (H) × 240 (V)
Spectral range	8~14 μm
Field of view spatial	32°(H) × 24°(V)
Frame rate	60 frames/sec
Resolution (IFOV)	1.78 mrad
A/Dresolution	14 bits
Minimum focus distance	10 cm

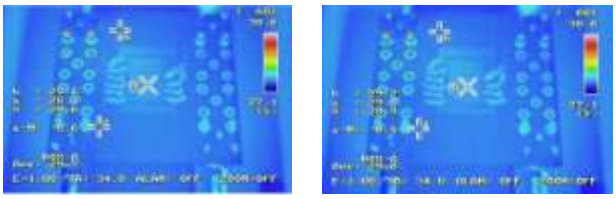
The distance between the installation of the experimental machine is 10cm. Because the emissivity coefficient of each material is different, the temperature of the thermal imager is calibrated after the machine is set up, and the working voltage is applied after the temperature is corrected. Wait for a few minutes, observe the temperature changes of the thermal imager and the signal of the oscilloscope at any time, and finally let the machine automatically calibrate the current surface temperature and take pictures. Repeat until the element is damaged, and compare its temperature change.

Fig.13 shows that the ITO electrode rises by 0.2 degrees during the working time. It can be seen from Figure 14 that the AZO electrode rises by 0.3 degrees in total during the working time. Comparing this experiment with the optical microscope photos, the reason why the transparent CMUT element can is not because of the temperature. It may be due to the destruction of the electrode surface due to membrane vibration.



(a) (b)

Fig. 13. Thermal Imaging of the CMUT with ITO electrode (a) Before tested and (b) After tested



(a) (b)

Fig. 14. Thermal Imaging of the CMUT with AZO electrode (a) Before tested and (b) After tested

Transparency Measurement of the CMUT

The primary purpose of this experiment is to measure whether the transparent ultrasonic transducer developed in this research can achieve a light transmittance of more than 80% in the visible light wavelength. A Shimadzu UV-1800 UV/Visible Scanning Spectrophotometer was used in this experiment. The specifications of the UV-visible spectrophotometer are shown in Table 4.

Two kinds of transparent conductive materials, ITO and AZO, were used to make the transparent CMUT, as shown in Fig. 15. Fig. 16

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shows the light transmittance is above 80% when the measurement wavelength is 200-1000nm.

Table 4. The specifications of the UV-visible spectrophotometer [11]

Item	UV-1800
Wavelength range	190~1100nm
Bandwidth	1nm
Wavelength accuracy	±0.1nm
Wavelength reproducibility	±0.1nm
Metering type	Double beam

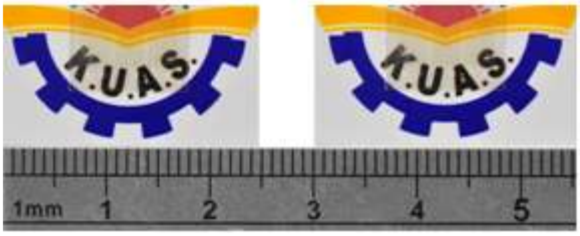

Fig. 15. Photo of the CMUT with ITO electrode (left)and AZO electrode (right)

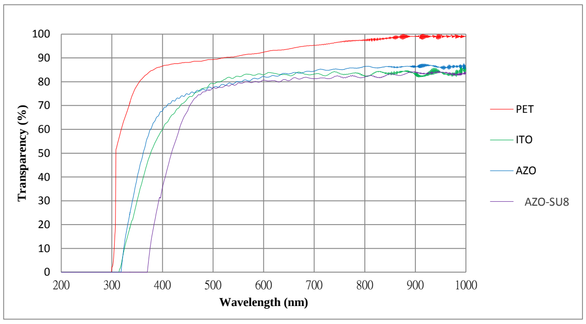

Fig. 16. Transmittance of the transparent CMUT

IV. CONCLUSIONS

This study uses ITO and AZO transparent conductive materials to develop a transparent ultrasonic transducer with more than 80% light transmittance. However, the top electrodes of ITO and AZO transparent conductive materials are flexible but cannot flex repeatedly. The membrane vibrates the electrode is damaged, which leads to life problems and cannot be combined with suspension control, wearable devices, and OLED lighting systems.

This study compares the experimental results of the optical microscope and the thermal imager to verify that the thin film vibration of the CMUT is an essential factor affecting the lifetime of the transparent conductive electrode.

A SU-8 photoresist is used for coating the surface to protect the electrode. After testing, the life span is similar to the original; it does not change much. There are two reasons for this: one needs to bake many times to cause expansion, and the other is that the electrode material cannot flex repeatedly.

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