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PIEZOELECTRIC MICROMACHINED ULTRASOUND TRANDUCER ARRAY FOR PHOTOACOUSTIC IMAGING

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ABSTRACT

A piezoelectric micromachined ultrasonic transducer (pMUT) array designed for photoacoustic imaging is presented in this paper. Two-dimensional pMUT arrays containing 144 elements (12×12 array) were bulk micromachined in silicon substrate. The devices were formed using two backside masks with deep reactive ion etching to create PZT thin film membranes and suspended silicon beams. The membrane radius is 25μm, with an 80μm element pitch. The total area for the pMUT array is approximately 1.6×1.6mm². This membrane consists of 0.6μm PZT layer, 1μm elastic layer (SiO_2) and 5μm supporting layer. Impedence and vibration measurements shows the resonant frequency of the pMUT elements is around 10MHz. Acoustic signal is detected using Pulse-Echo method. This high density acoustic sensor array has high array spatial gain and wide reception angle that can be used in photoacoustic imaging systems.

KEYWORDS

Micromachined ultrasound sensors; pMUT; Photoacoustic Imaging.

INTRODUCTION

Photoacoustic imaging (PAI) is a non-invasive medical imaging technique that takes advantage of the high contrast of optical imaging and the high spatial resolution of ultrasound imaging [1]. Recent studies have shown that PAI can be used in vivo for tumor angiogenesis monitoring, blood oxygenation mapping, functional brain imaging, skin melanoma detection etc. [2]. The acoustic sensor is an important component of the PAI system. Advances in electronics over the years have brought extraordinary improvement to all the parts of PAI but little to the acoustic sensor. Photoacoustic imaging using miniaturized scanning probes represents a new direction in this field. Previously, a miniature photoacoustic imaging probe using MEMS scanning micromirrors and a ring-shaped polyvinylidene fluoride (PVDF) acoustic sensor has been proposed [3]. However, the sensitivity and bandwidth of small size PVDF are low.

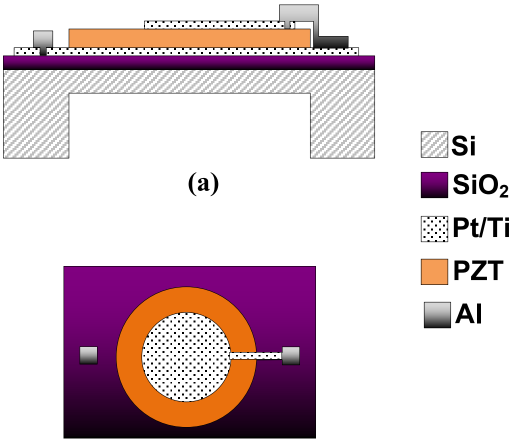
Micromachined ultrasound transducers (MUTs) provide a promising alternative. Currently, there are two types of MUTs being developed: capacitive MUTs (cMUTs) and piezoelectric MUTs (pMUTs). Although the former can realize compact 2-D arrays, the ultra-small sensing capacitance requires enormous effort in interface circuits design [4]. The pMUT is thought to be a possible solution to avoid such disadvantages. pMUTs are based on piezoelectric effect, which is a higher energy transduction mechanism. pMUTs have much larger impedance compared to cMUTs with similar size [5]. Thus, pMUTs are much more insensitive to parasitic capacitance [6]. A significant challenge for pMUTs is the limited bandwidth.

Commercial 2D pMUTs are typically limited to operating frequencies of less than 5MHz [7]. Many research groups also fabricated several 2D pMUT arrays for medical imaging. Dausch *et al.* reported 5×5 pMUT arrays in which the membrane widths ranged from 50 to 200μm, with element pitch from 100 to 300μm. The element resonant frequency ranged from 4-11MHz. But the large element pitch limit the directivity and thus the spatial receiving range [8]. An 8×8 high element density pMUT arrays using epitaxial PZT films on epitaxial SRO/Pt/γ-Al_2O_3/Si structures were fabricated by *Akai et al.,* but the resonant frequency is limited to few MHz [9].

In order to increase the receiving sensitivity without sacrificing the spatial receiving range, two dimensional high density pMUT arrays have been designed and fabricated using two different backside masks (SiO_2 and photoresist) with two DRIE steps. The element resonant frequency is around 10MHz. The measured characterizes of this pMUT array show which provides show potential to be used in PAI system.

pMUT ARRAY DESIGN

An acoustic sensor with the diaphragms clamped on all edges has been chosen as the enabling microarray element. A schematic of a pMUT element is shown in Fig. 1. Such a sensor can offer high sensitivity to acoustical pressure variations, is not affected greatly by temperatures variations, and has low power requirements. The acoustic sensor is composed of an Al/Pt//Ti/PZT/Pt/Ti/SiO_2/Si multilayer membrane. The multilayer membrane works in a flexure mode to sense acoustic energy. This is significantly different from conventional thickness mode used in bulk ceramic transducers.



(a)

(b)

Fig. 1 Cross-sectional (a) and top view (b) of the pMUT.

There are three key design parameters in pMUT array design: resonant frequency, sensitivity and directivity. Ultrasonic transducers operate as resonant devices. The sensitivity of the transducers is much larger at the resonant frequency than at other frequencies. The ultrasonic sensor should thus be designed to work at its resonant frequency. Based on the PAI system, the desired working frequency of the acoustic sensor is 3-12MHz. Higher working frequencies can achieve higher resolution imaging, but the tradeoff is smaller acoustic transmission distance. A resonant frequency of 10MHz was chosen as a good tradeoff between imaging resolution and the transmission distance. The expression for the fundamental natural frequency of a clamped circular plate can be calculated [10]:

$$f_0 = 0.47\frac{t}{a^2}\sqrt{\frac{E}{\rho}}$$

where f_0 is the fundamental natural frequency (Hz); t is the thickness of the multilayer membrane (μm); a is the radius of the membrane (μm); E is the average Young's modulus (N/μm^2) and ρ is the average density (kg/μm^2).

There are two effective ways of achieving a high resonant frequency given a set material stackup process: decrease the membrane radius or increase the membrane thickness. Finite element analysis (FEA) is commonly used to more accurately determine the parameters of the pMUT. The FEA modal simulation results using COMSOL are shown in Fig 2. For a pMUT membrane radius of 25μm, and 5μm silicon layer, the resonant frequency was found to be 10.32MHz.

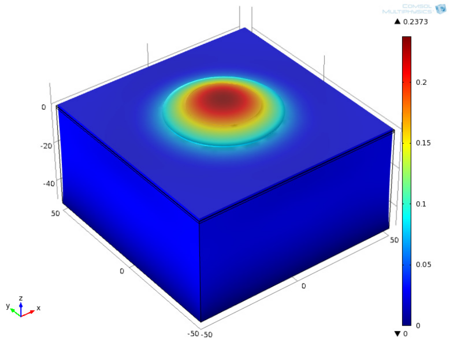


Fig. 2 FEA modal simulation of the pMUT.

In order to attain a large receiving sensitivity, the receiver should have a high spatial gain (AG). A pMUT array structure is used to achieve such a spatial gain. The AG, which measure the receiver sensitivity of the array, can be defined as [11]:

$$AG = 10\log\frac{N_{output}}{N_{input}}$$

where N_{output} is the output Signal-to-Noise ratio (SNR) of the array and N_{iutput} is the input SNR of the array. The denser transducer elements in the pMUT array will yield a higher AG. It has been observed that the square array has superior performance compared to the line array and the circle array [12], thus the square transducer array has been utilized for the PAI system. There is however a tradeoff with the utilization of a transducer array utilization. Most transducer arrays will generate sound power concentrated on the major lobe, but the PAI system is supposed to detect the acoustic signal in a large space range. As mentioned earlier, directivity is an important part for the pMUT array design. A good transducer array should be able to achieve 60° detection angle (or beam width) for PAI applications. Nearer spacing between adjacent elements is one way to increase the beam width. The maximum array size in this application, however, is limited by the dimensions of the miniature PAI probe. This limit imposes a constraint on the maximum diaphragm area and adjacent sensor spacing. A good design should have a high sensitivity, large detectable range and a small diaphragm area.

According to classical phased-array theory [11], for small uniformly spaced array elements, the directivity function of two-dimensional (2-D) planar square arrays with a plane wave incident can be approximated as:

$$D(\alpha,\theta,\omega) = \frac{\sin(\frac{\pi M d_1}{\lambda}\cos\alpha\sin\theta)}{M\sin(\frac{\pi d_1}{\lambda}\cos\alpha\sin\theta)}\cdot\frac{\sin(\frac{\pi N d_2}{\lambda}\cos\alpha\sin\theta)}{N\sin(\frac{\pi d_2}{\lambda}\cos\alpha\sin\theta)}$$

where M is element number in every row, N is the element number in every column, d1 and d2 are the adjacent element spacing, λ is the wavelength of the acoustic wave, θ and α are the azimuths.

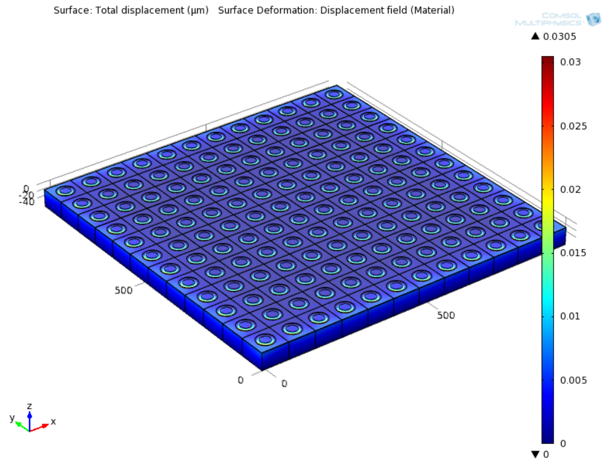


Fig. 3 The 12×12 square transducer array.

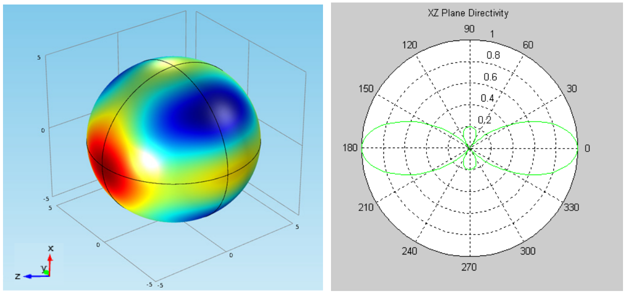


Fig 4. The pMUT array directivity simulation results.

A diagram of a square transducer array is shown in Fig. 3. Fig.4 shows the 3D and XZ plane directivity simulation patterns from COMSOL. The directivity of the proposed pMUT array is much higher along the z axis than in any other direction. To get a better sensitivity for the photoacoustic imaging system, the pMUT should be oriented with the x-axis facing the specimen. The XZ plane directivity pattern clearly shows a 60º reception angle for the pMUT array.

FABRICATION

The PZT based pMUT array is fabricated using a combination of thin film and bulk micromachining process. The multilayer membrane, which consists of Pt, PZT and SiO_2 layers, is fabricated using thin film deposition and pattern transfer process.

The process shown in Fig.5, the key step is the backside DRIE etch. Two different backside masks (SiO_2 and photoresist) with two DRIE steps are used to create the differential height structures. This step is used to decrease the elements spacing and form the high density pMUT array. The backside silicon is etched by DRIE and the 1 µm thick buried oxide layer in the SOI wafer is then etched by RIE. After the barrier SiO_2 etching, the device Si is etched by precisely controlled DRIE to obtain 5µm Si supporting layer.

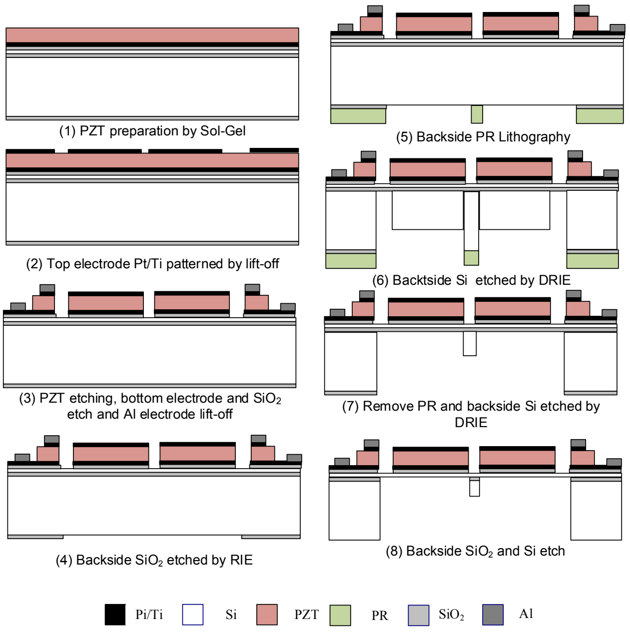


Fig. 5. Process flow of PZT-based micromirror fabrication.

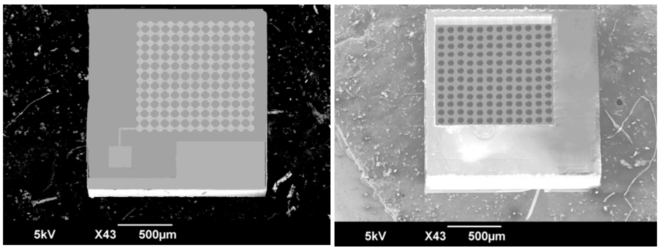


Fig. 6. The SEM of a fabricated device

The SEM of the fabricated pMUT Array is shown in Fig 6. The chip size is 1.6mm×1.6mm and the pMUT radius is 25 µm. The devices consist of PZT thin film membranes and suspended silicon beams, which can effectively increase the element density of the pMUT array. Increasing the element density is crucial to realize the 2-D pMUT array for practical 3-D medical imaging.

EXPERIMENTAL RESULTS

The mechanical characteristics of a piezoelectric device are determined by its material properties and geometries. The X-ray diffraction spectrum of the patterned PZT film on the device is shown as Fig .7. The pMUT can also be evaluated electrically by measuring its impedance response. For example, the impedance reaches its minimum when the frequency of input signal equals to the resonance frequency of the device (series resonance). The pMUT array is tested using an Agilent 4294A impedance analyzer at room temperature. The impedance spectrum of the fabricated pMUT array is shown in Fig. 8. The resonant frequency of the pMUT is 9.6MHz, which is close to the simulation results (6.9% difference).

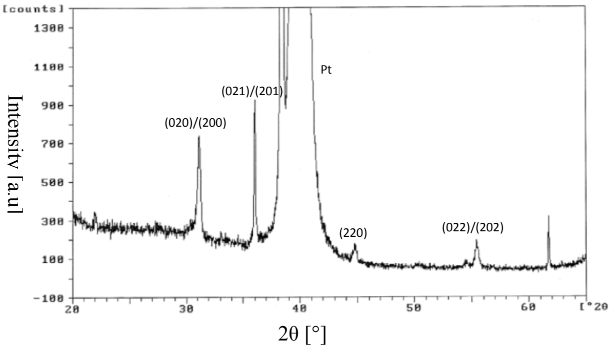


Fig. 7. The XRD spectrum of the PZT film.

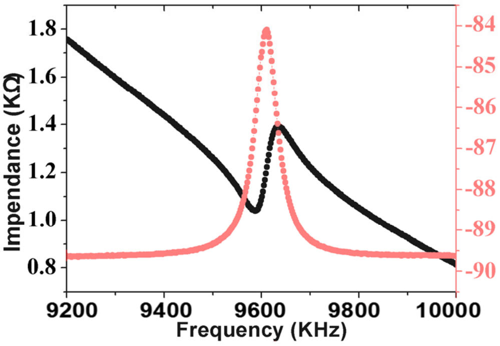


Fig. 8. The impedance spectrum of the pMUT array.

The pMUT mechanical frequency response was directly measured in atmosphere using a microscopic scanning Laser Doppler Vibrometer (LDV) from Polytec. Electric contact of the bottom electrode was obtained from the clamped edge, whereas the upper electrode was connected using a very fine lead probe which has minimal disturbance with the piezoelectric actuation. A 0.1 V chirp voltage signal was applied to the top electrode of the membrane. The spectrum was then calculated by the LVD. The measured frequency response of the pMUT is shown in Fig.9(a). The resonant frequencies of the acoustic sensor are 9.9 MHz, which is coincide with the impedance analyzer test results. Fig.9(b) shows the 3D mode at fundamental resonant frequency of the proposed pMUT, which was drawn by the LVD automatically.

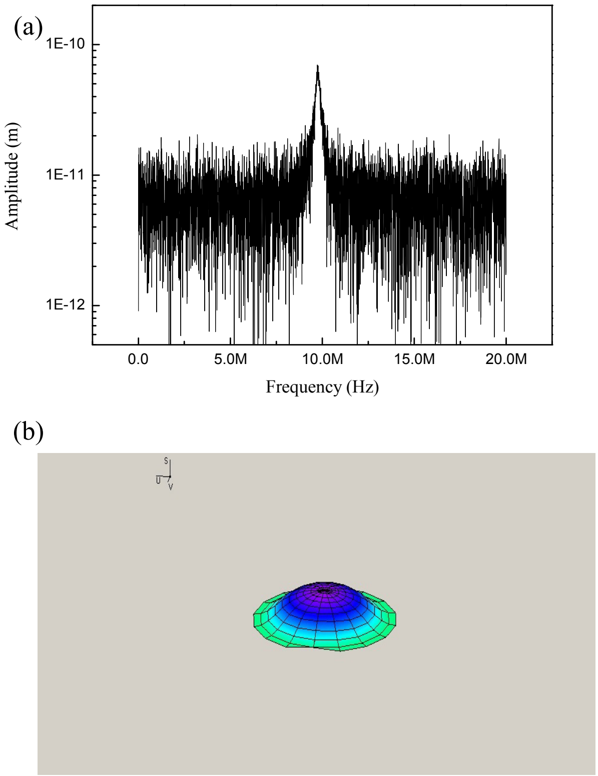


Fig. 9. The frequency response and vibration mode of the pMUT array

The ultrasound portion of testing was done using the pulse-echo method. An estimate of the vibrations was made by probing the device on a probe station. A burst is transmitted/received at the same time to/from the device. The reflector surface (fiber bundle end) was placed to reflect the acoustic wave and water was used as the coupling medium. A 60dB low noise amplifier was used to amplify the echo signal. Fig.11 shows the echo signal in time domain and its FFT result. The pMUT array can detect the acoustic wave. It was found that the resonant frequency is 10.2MHz.

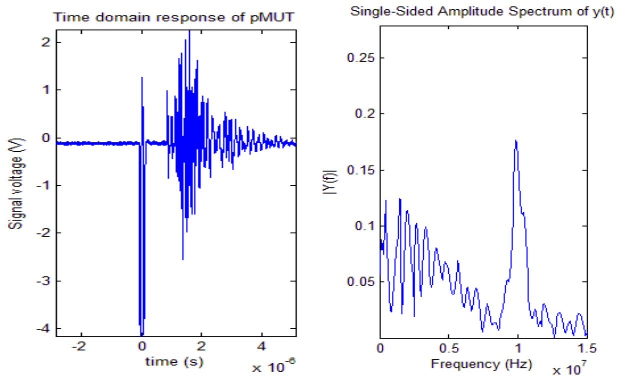


Fig. 11. The ultrasound testing results.

CONCLUSION

Novel 12×12 pMUT arrays with high element density, excellent performance and suitable working frequency are designed, fabricated and characterized. Experimental results show promising results that the developed pMUT arrays have huge potential to be used in PAI system.

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