Fabrication of pMUT Arrays for Medical Ultrasonic Imaging

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ABSTRACT

The development of piezoelectric micromachined ultrasonic transducers (pMUTs) is mostly driven by the need in the medical diagnosis community for higher bandwidth transducers for harmonic imaging and for improved axial resolution and penetration. In contrast to the conventional bulk piezoelectric transducers, pMUTs rely on isolated micro-sized vibrating membranes as the radiating elements. Typically, the size of a membrane is on the order of 10's or 100's of micrometers in width (or diameter) while the total thickness is on the order of few micrometers. The main structural component for building such membranes is a silicon wafer, while the manufacturing processes are the standard IC fabrication processes. The present study will examine the function of arrays of pMUTs for use in medical ultrasonic imaging. Two designs are fabricated, one containing 30 pMUT elements in each array, and the other with 50 elements. Each element will consist of two narrow top electrodes overlapping a wide bottom electrode. Each 76.2 mm wafer contains twelve of the 50 element arrays, and thirteen of the 30 element arrays to provide a large number for statistical analysis. The arrays are fabricated with multiple layers of different materials such as SiO_2, Pt, Pb $(Zr,Ti)O_3$ and Au. These arrays are tested for their impedance measurement, which yields their coupling coefficient, resonance frequency, quality factor and efficiency. The overall focus of the work was processing and characterization of pMUT arrays for medical imaging applications.

INTRODUCTION

Piezoelectric micro-machined ultrasonic transducers (pMUTs) are micro scale membranes which vibrate through the piezoelectric effect when a voltage is applied across the top and bottom electrodes. This vibration causes at such a frequency that it creates ultrasonic signals. The ultrasonic signals can be sent through a material to characterize it. This works because the material, for instance a human body, will cause the sound waves to travel at different speeds depending on the acoustic impedance of the materials. In a human body, the skin, bones, muscle, and fat tissues all have different rates at which they transmit and reflect sound wave, therefore, different tissues will respond to the input signal differently via travel time. The relative delays in response to the signal are recorded, called pulse-echo mode, when the signal is collected, and can be interpreted to provide an idea of what was in the material and how far is it from the surface. This technique is non-destructive and benign that is even safe to use on a fetus, because sound waves do not cause damage to the tissues as do x-rays.

pMUTs are fabricated on silicon wafers by adopting IC fabrication techniques. pMUT performance can be improved by optimizing the design parameters of single element [1]. In this work, the goal was to create arrays of membranes of width 50 micron and length 750 micron on 200 micron silicon wafers. It was attempted to pack as many membranes into an area as possible in order to generate the most powerful signal. As will be detailed later, the membranes must be separated by a minimum distance which is dictated by the thickness of the wafer that is used. Therefore, to minimize the size of array pMUTs and improve packing efficiency, in this study relatively thin 200 micron silicon wafers were used.

DESIGN AND FABRICATION

To build pMUTs on a silicon wafer, first the design was laid out in an imaging program. All membranes were designed with 50 micron width membrane, and two top electrodes with a 25 micron width. Figure 1 is a schematic of the individual array elements where it can be seen that the bottom electrode is overlapped on each side by the two top electrodes. There were two designs on this wafer, one containing arrays of 30 elements and the other one with arrays of 50 elements. The spacing of the elements in the arrays for a 200 micron thick wafer is such that both the arrays are 1.132 centimeters long; the 50 element arrays are 0.216 cm wide and the 30 element arrays are 0.130 cm wide. Twelve 50 element arrays and thirteen 30 element arrays were printed on each Si wafer of 76.2 mm diameter to ensure repeatability in experiments.

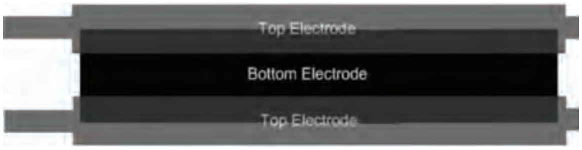

Figure 1: Schematic top view of single element.

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The arrays were fabricated by a multi-step process that can be found in reference 2 [2]. This process results in the structure seen in Figure 2. The silicon wafer is oxidized in a controlled environment then the backside is masked off, positive photolithography is performed, then the silicon oxide layer is removed from select areas by wet etching in a buffered oxide etch. Because the silicon is bare in certain areas, it can now be etched with ethylene diamine pyrocatechol (EDP). EDP etches along a preferred plane in the silicon, therefore, it results in a 54.7 degree angle, which can be seen on the bottom of Figure 3. This etching angle is what dictates the distance between adjacent elements in an array, because elements cannot be designed any closer than what the angle will allow. This leaves the wafer with thin windows of silicon/silicon oxide which will eventually allow the piezoelectric lead zirconate titanate (PZT) to activate the membrane. Figure 3 shows a picture through one such window to the backside membrane on the back side of the wafer. Next, titanium is sputtered as an adhesion layer, then a layer of platinum is deposited as the bottom electrode. Finally, a layer of PZT is spin coated on the wafer, which vibrates when an AC voltage is applied across it, causing the composite membrane to vibrate. Finally, a top layer of gold is deposited, then masked with positive contact photolithography, and etched to leave the pattern of the top electrode. In order to test the electrode, a small area on the wafer is etched down to the platinum layer to contact the bottom electrode.

Figure 2: Schematic of pMUT layers.

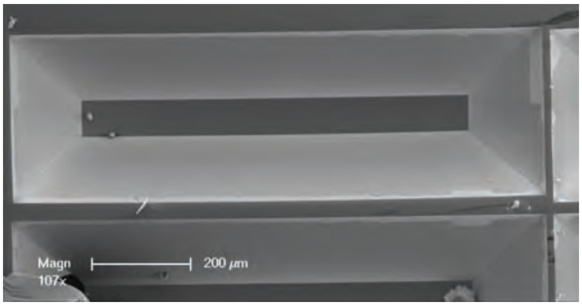


Figure 3: SEM image of backside of Si membrane.

An impedance analyzer was used to test the pMUT arrays. The resonance (F_r) and anti-resonance frequencies (F_a) were determined by scanning through the frequency range to search for the first significant peak. Plots such as the one in Figure 4 were measured, and the resonance and anti-resonance frequencies were noted from the plot. In addition, at the resonance frequency, the quality factor, Q, was calculated as well.

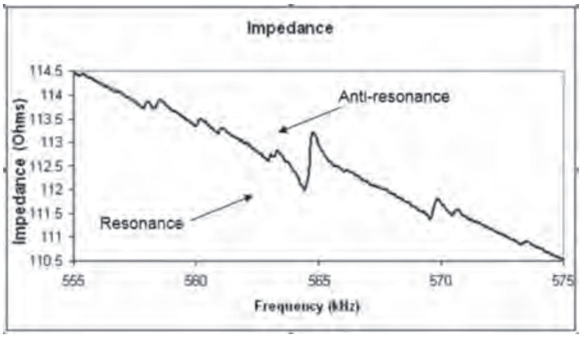


Figure 4: Impedance plot showing signal.

RESULTS AND DISCUSSION

From the resonance, anti-resonance frequencies and quality factor, the effective coupling coefficient (K^2_{eff}) can be calculated as shown in equation 1. The quality factor and effective coupling coefficient can then be combined to determine the overall device efficiency (η) as shown in equation 2 [3].

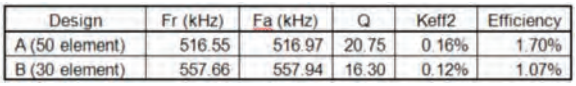
$$\frac{k_{eff}^2}{1-k_{eff}^2} = \frac{F_a^2 - F_r^2}{F_r^2} \tag{1}$$

$$\eta = \frac{k_{eff}^2 / 2(1-k_{eff}^2)}{1/Q + k_{eff}^2 / 2(1+k_{eff}^2)} \tag{2}$$

Six arrays containing 50 elements and seven arrays containing 30 elements were tested. From SEM images, it was found that the actual width of the membranes, which is the controlling factor of the resonance/anti resonance frequencies, was an average of 87 microns, instead of the designed 50 microns. This occurred because the chemical etching which is done to etch out the backside will not only etch along the 54.7 degree angle, but also a small amount outwards, parallel with the surface of the wafer. In addition, variations in photolithography and wafer thickness could also contribute to this outward etching, causing the membranes to be bigger than anticipated.

Because the width was wider than desired, the resonance frequency was at a considerably lower value than expected. The resonance and anti-resonance frequencies and quality factors were averaged from the data from these arrays, and shown in Table 1.

Table 1: Impedance data.



Design	Fr (kHz)	Fa (kHz)	Q	Keff2	Efficiency
A (50 element)	516.55	516.97	20.75	0.16%	1.70%
B (30 element)	557.66	557.94	16.30	0.12%	1.07%

It can also be seen from the graph in Figure 4 that all the membranes are not vibrating at the same frequency. The small spikes in frequency in other locations than the resonance frequency indicate that individual elements in the arrays are vibrating at different frequencies. This effect may also contribute to the low efficiency.

These low coupling coefficient and efficiency values point to problems in the fabrication of the arrays. Because the resolution of the design of the mask was approaching the edge of the capabilities of our printing facility, it could have caused some of these problems. Also, the same errors in microfabrication added to cause a low coupling coefficient and efficiency.

CONCLUSION

pMUT arrays containing 30 and 50 elements have been fabricated on 200 micron thick wafers. This allowed the elements to be packed together in a small area. The arrays were tested with an impedance analyzer to determine that the 50 element design showed slightly better characteristics than the 30 element design.

The results of the study are, however, inconclusive. The study should be repeated with tighter control of processing parameters. If the membranes were fabricated with the desired dimensions, this method shows promise for creating higher bandwidth arrays of transducers which can find applications in non-destructive ultrasonic medical imaging.

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