A FIRST EXPERIMENTAL VERIFICATION OF MICROMACHINED CAPACITIVE LAMB WAVE TRANSDUCERS

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Abstract— **Capacitive Micromachined Ultrasonic Transducers (cMUTs) are generally used to transmit and receive ultrasound in both air and water. These devices can be made on silicon and manufactured using standard CMOS processing techniques. When cMUTs are used in this way, significant effort is made to minimize energy loss into the substrate. If this loss is instead exploited so that the devices are optimized to couple energy into the silicon bulk, Lamb waves and Rayleigh waves are generated with high efficiency. These waves can then be detected using a similar device structure. With this method it is possible to fabricate Lamb wave devices on silicon using conventional integrated circuit processing techniques. This paper discusses the manufacturing and characterization of the first of these devices: a 1 MHz Lamb wave transducer that is fundamentally based on cMUT technology. The characterization of this device demonstrates that the energy coupled into the substrate results in a Lamb Wave where the lowest order anti-symmetric mode (A_0) is dominant. The insertion loss of this device in air is 43.06 dB.**

Keywords— **Lamb Waves, Surface Acoustic Waves, Capacitive Ultrasonic Transducer, cMUT**

I. Introduction

Acoustic wave devices have many applications in the fields of sensors and filters. At lower frequencies, Lamb wave based sensors are used in areas such as the monitoring of chemical reactions, the measurement of thin film thickness, and the detection of various gasses [1]-[5]. At higher frequencies, Surface Acoustic Waves (SAWs) are used for filtering and for analog signal processing [6], [7]. The physics used in all of these devices is dependent on the presence of piezoelectric materials such as Lead Zirconium Titanate, Lithium Niobate, and Zinc Oxide. The disadvantage in using such materials is that they are not compatible with standard IC fabrication processes. As a result, there is an inherent limitation on the integration of these devices with their accompanying electronics.

A viable alternative to piezoelectric based Lamb and SAW devices can be found through the use of Capacitive Micromachined Ultrasonic Transducer (cMUT) technology. The cMUT is a capacitive acoustic transducer that can easily be fabricated using techniques pioneered by the integrated circuits industry. The device consists of a metalized silicon membrane supported by two posts over a silicon wafer. When a DC voltage is applied between the membrane and the device's substrate, electrostatic forces deflect the membrane towards the silicon; the bending stiffness of the membrane and its inherent stress resist the attraction. With the superposition of a time harmonic signal on top of the DC bias, acoustic waves are generated in the surrounding medium. Recent experiments have shown that an unavoidable side-effect in the cMUT is the leakage of some energy into the substrate on which the device is built. This coupling between the membrane and the substrate occurs through the membrane supports. Radiation pattern measurements in liquid media clearly identify this energy as that of a Lamb wave. [8]. At an operating frequency in the range of 1 MHz, a Lamb wave device can be created by exploiting this phenomenon such that the cMUT is optimized to couple energy into the substrate. This paper discusses the manufacturing and characterization of such a device. The guidelines for the device geometry as well as the expected measurement results follow the calculations presented by Yarlioglu et al. in these conference proceedings.

II. Device Geometry and Fabrication

The device consists of a series of rectangular membranes that work together to emit and detect the Lamb waves. An example is shown in Figure 1. As indicated, the length and width of the device are 1 cm and 100 μm respectively. Furthermore, the thickness of the membrane is 1 μm and the substrate is a 500 μm thick (100) silicon wafer. Calculations indicate that these dimensions should result in a resonant device at 1 MHz. It is important to note that the long dimension of the membrane is much larger than the acoustic wavelength in the substrate, thus enabling it to be considered a plane wave source.

The process used to fabricate this Lamb wave device closely follows that of the conventional cMUT [9] and is presented in Figure 2. An n-type (100) 4 inch silicon wafer is cleaned and then heavily doped to produce a layer with

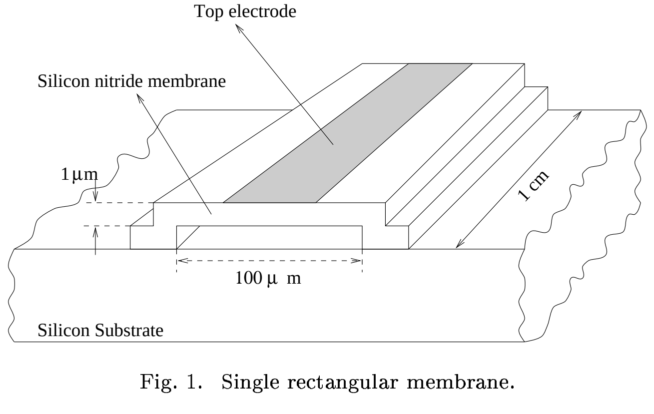

Fig. 1. Single rectangular membrane.

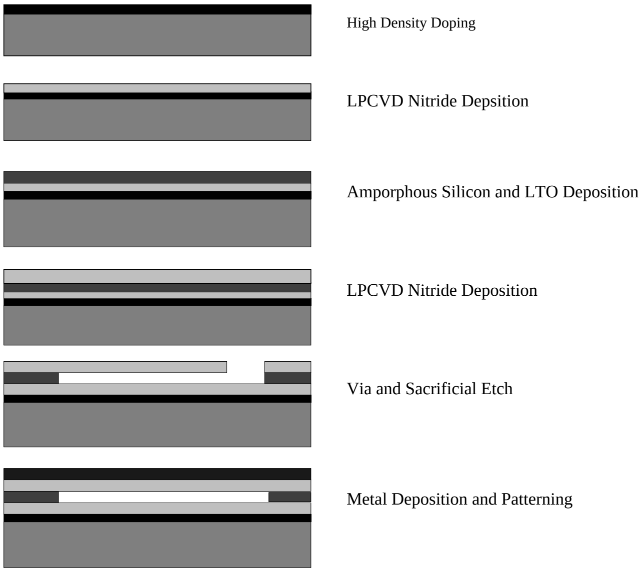

Fig. 2. Major steps of device fabrication.

a resistivity on the order of 1.1 Ω/square. A 3000 Å layer of LPCVD Nitride is then deposited. The purpose of this layer is to establish electrical isolation between ground and the membrane as well as to act as an etch stop for KOH. At this point amorphous silicon and low temperature oxide are introduced as sacrificial layers. A second layer of LPCVD nitride, which will act as the membrane material, is then introduced. This deposition is 1 μm thick. A pattern of etchant holes are then created in these layers using an electron beam lithography process. This is followed by the etching of sacrificial layers using first KOH for the amorphous silicon and then Hydroflouric Acid for the oxide. The final step in this process flow is the evaporation of .5 μm of Aluminum and its subsequent patterning on the wafer. Note that these devices could also have been vacuum sealed, but this is an option that was not exercised.

The layout of the final device is shown in Figure 3. The Lamb wave is generated and transmitted into the bulk by the four fingers on the left side. Each finger consists of five membranes that are connected in parallel to each other. The transmit fingers are spaced one wavelength apart so that their resulting Lamb waves will interfere constructively. The receiver, on the other hand, is multiple wavelengths away from the transmitter and has only one finger consisting of a single membrane.

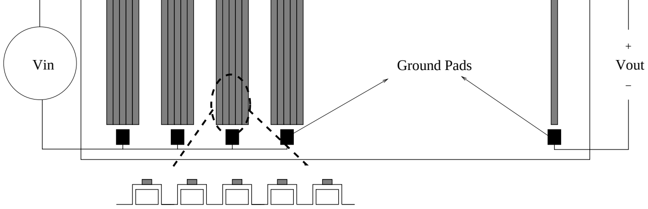

Fig. 3. Device Layout

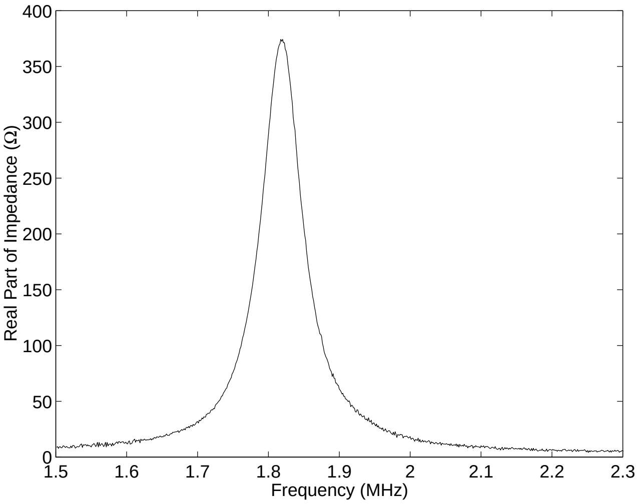

Fig. 4. Real part of the device input impedance.

III. Characterization

The results that follow demonstrate the first Lamb wave device that has been processed without the use of piezoelectric materials.

The first step in the characterization process is to analyze the transmit and receive membranes individually and confirm their operation. Figures 4 and 5 show the real and imaginary parts of the input impedance of a single transmit finger. Note that since a single finger consists of five membranes, these plots actually represent the impedance of five membranes in parallel with each other. The shape of both curves is identical to that of a typical cMUT and their main characteristic is the obvious resonance near 1.8 MHz. The deviation of this resonant frequency from the prescribed value of 1 MHz outlined above in the process flow is a result of equipment inaccuracies during processing. Specifically, the thickness of the nitride during the second LPCVD deposition was 1.24 μm instead of 1 μm. This results in a thicker membrane and consequently a higher resonant frequency. Similar graphs for the input impedance of the receiver fingers have the same shape but magnitudes that are on the order of a factor of five larger. This follows from the fact that the receiver consists of a single membrane.

The key to the operation of a cMUT and, consequently, this Lamb wave transducer, is the displacement of its membrane in response to an electrical signal or an incident acoustic wave. The verification of membrane displacement thus constitutes the second step of the characterization process. Figure 6 is a representative plot of the displacement per unit of applied voltage of a single device membrane over frequency. This data was taken using an optical heterodyne interferometer on an electrically excited membrane. Note that the frequency of maximum displacement matches the resonant frequency of 1.8 MHz determined from impedance measurements. The jagged edges on the sides of the peak may represent the presence of higher order modes on the vibrating membrane.

The third characteristic of interest lies in the device's

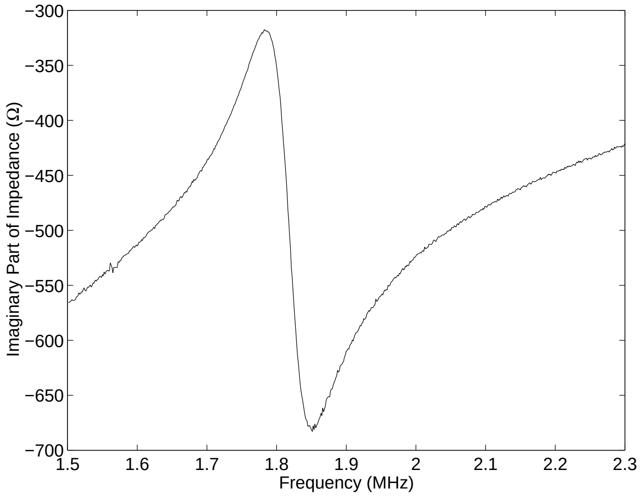

Fig. 5. Imaginary part of the device input impedance.

ability to propagate a Lamb wave from the four transmit fingers to the receiver. To evaluate this, a single-cycle RF tone burst at 1.8 MHz was superimposed on a 20 V DC bias. The output was monitored by an oscilloscope that followed a 60 dB amplifier. Of particular interest in this experiment was the travel time over the 3.87 mm from the transmitter to the receiver. As the lowest order antisymmetric mode of the Lamb wave (A_0) is dominant at 1.8 MHz, its dispersion relation should determine the velocity of the wave as it propagates in the silicon bulk. Figure 7 shows both the measured and theoretical waveforms at the receiver. In the calculations, a single cycle sine wave is propagated from the transmit end to the receiver through the A_0 dispersion relation. The resulting waveform is then convolved with the membrane response. Note that the arrival times of the two waveforms agree closely, giving confirmation to the fact that this device is indeed a Lamb wave transducer. The phase difference between the calculated and measured data is due to the electrical parasitic capacitances which were not included in the theoretical model.

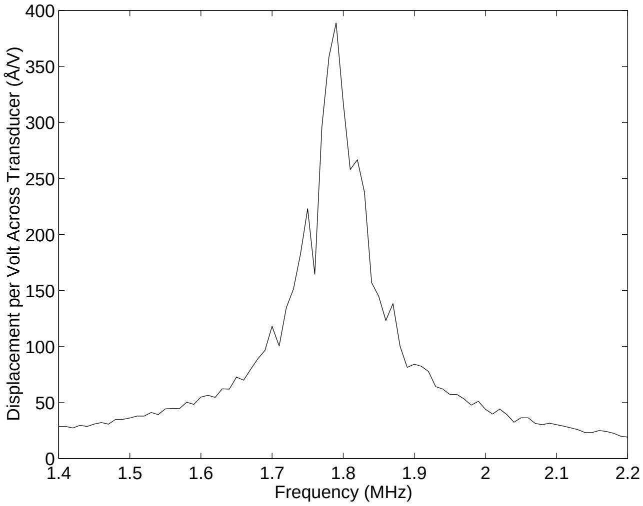

Fig. 6. Displacement per unit of applied voltage for a typical membrane.

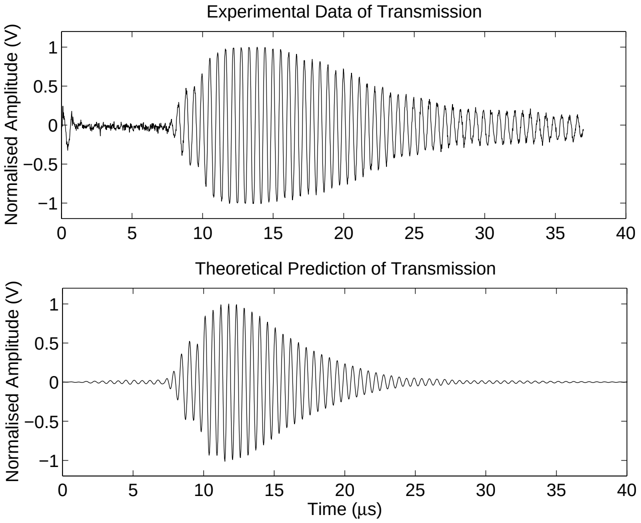

Fig. 7. Theoretical and measured propagation data.

The efficiency of this transducer can be characterized by its insertion loss. An optical interferometer was used to determine this value. As shown in Figure 8, each membrane on the transmit side vibrates with a certain amplitude (they should, of course, all vibrate at the same amplitude, but they do not due to fabrication non-uniformities). Ideally the resulting Lamb waves would constructively interfere to produce the sum of the transmit amplitudes at the receiver. Due to the deviation of the resonant frequency of the membranes from 1 MHz, the waves interfere with each other both constructively and destructively resulting in a smaller displacement at the receiver. Another source of loss in this device is due to the bi-directionality of the transducer; when the Lamb wave is emitted, it will propagate in both directions away from the membrane. As a result, only half the generated power will reach the receiver. After taking these loss mechanisms into account, the expected displacement of the receiver membrane assuming perfect coupling between the membranes and the substrate is 5324.29 Å . The actual displacement for the same membrane is 37.41 Å , resulting in an insertion loss of 43.06 dB. This value is also consistent with what one would expect from a Lamb Wave device: Figure 9 presents the impedance of both the device and of air. When extrapolated to 1.8 MHz, this plot shows an impedance differential

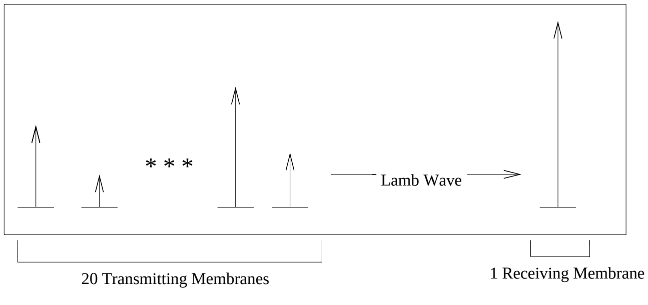

Fig. 8. Insertion Loss measurement.

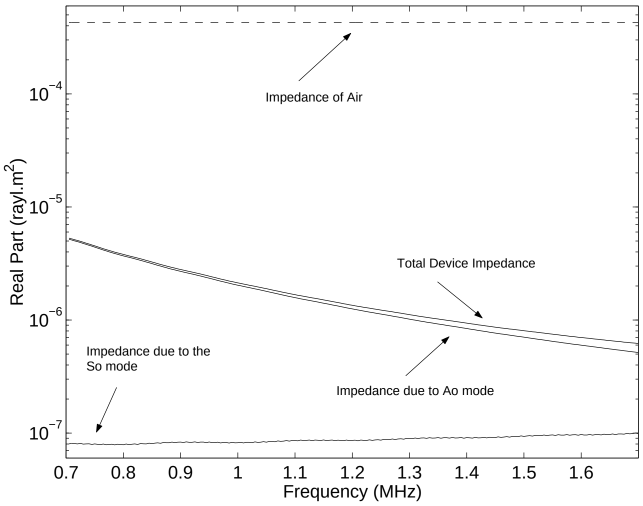

Fig. 9. Device and air impedances.

a little more than two orders of magnitude, corresponding to a loss a little more than 40 dB.

Conclusion

The distinct advantage of the cMUT Lamb wave devices presented in this paper is its compatibility with IC manufacturing processes. The resulting transducer will thus be inexpensive and easy to integrate with electronic devices. As the membranes that make up the device are based on cMUT technology, their characteristics mirror each other. The key to the Lamb wave devices is that they are optimized to couple energy into the substrate rather that into the surrounding medium. Propagation experiments confirm that the dominant mechanism of this device is the lowest order antisymmetric mode of the Lamb wave.

Acknowledgments

This work was supported by the United States Office of Naval Research.

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