A New Detection Method for Capacitive Micromachined Ultrasonic Transducers

A. Sanlı Ergun, Burak Temelkuran*, Ekmel Özbay*, and Abdullah Atalar
Department of Electrical and Electronics Engineering (*Department of Physics), Bilkent University
Bilkent, Ankara, 06533 TURKEY

Abstract— **Capacitive micromachined ultrasonic transducers (cMUT) have become an alternative to piezoelectric transducers in the past few years. They usually consist of many small membranes all in parallel. In this work we report a new detection method for cMUT's. We arrange the membranes in the form of an artificial transmission line by inserting small inductances between the membranes. The vibrations of the membranes modulate the electrical length of the transmission line, which is proportional to the total capacitance and the frequency of the signal through it. By measuring the electrical length of the artificial line at a RF frequency in the GHz range, the vibrations of the membranes can be detected in a very sensitive manner. For the detector structure we considered a minimum detectable displacement in the order of 10^{-7} Å/$\sqrt{\text{Hz}}$ is expected.**

Keywords— **Capacitive micromachined ultrasonic transducers, ultrasonic detection, displacement sensing**

I. Introduction

NON-CONTACT air-coupled ultrasonic measurements and nondestructive evaluation are attractive because of their non-contact nature and the short wavelengths of ultrasound in air. In the past few years silicon capacitive micromachined ultrasonic transducers became an alternative to conventional piezoelectric transducers in NDE applications [1], [2]. Using the standard silicon processes developed in the past 30 years, along with micromachining technology, scientists developed reliable, small, and cheap transducers and transducer arrays with comparable performance [3], [4]. These capacitive transducers consist of many circular membranes in parallel, and are used for both generation and detection of ultrasound. The cross-sectional view of a typical membrane is shown in Figure 1.

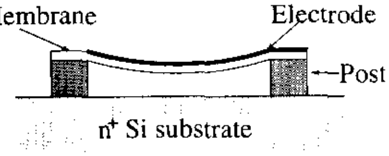

Fig. 1. Cross-section of a typical membrane

The electrode and the substrate make up a simple parallel plate capacitor. The detection of ultrasound depends on the vibration of the membrane due to an incident ultrasonic signal. The displacement of the membrane results in a capacitance change which is measured by monitoring the current under a constant bias voltage. The magnitude of the current resulting from n parallel membranes can be expressed as,

$$I = 2\pi f_1 V_{dc} n C \frac{\Delta x}{x_0} \tag{1}$$

where f_1 is the ultrasound frequency, V_{dc} is the bias voltage, C is the capacitance of a single membrane, x_0 is the spacing between the electrode and the substrate, and Δx is the magnitude of the displacement. The resulting current is then amplified with a transimpedance amplifier.

The disadvantages of the conventional detection method are the large detector area needed to achieve good sensitivity, the dependence of the output current on the ultrasound frequency, which degrades the sensitivity at low frequencies, and the large DC voltage used. In this work we propose an alternative method to detect the displacement of a membrane in a more sensitive manner.

II. The New Method

The new detection method involves the use of a high frequency RF signal as the probing signal instead of the DC bias voltage. In this method, the membranes are connected through inductors to make up an artificial transmission line (Figure 2). An n-section artificial transmission line consists of n shunt capacitors (C) linked through inductors (L). Disregarding the losses, the characteristic impedance (Z_a), and the propagation constant (β) are given by

$$Z_a = \sqrt{\frac{L}{C}} \tag{2}$$

$$\beta = 2\pi f_0 \sqrt{LC} \tag{3}$$

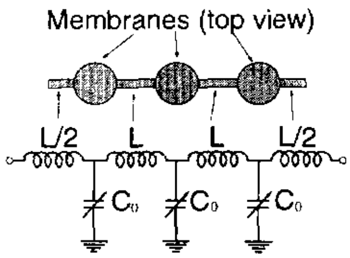

Fig. 2. Layout and schematics of a 3-section artificial transmission line.

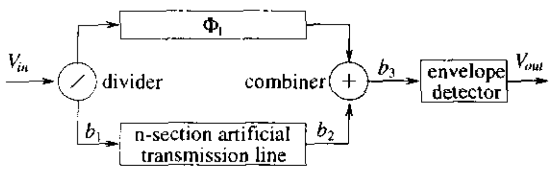

Fig. 3. The Interferometric scheme to detect ultrasound.

where f_0 is the RF frequency, and β is in units of rad/section. The inductors are designed such that the characteristic impedance of the line is around 50 Ω to prevent reflections.

A capacitance change results in a change in the characteristic impedance and the electrical length ($\Phi_0 = n\beta$) of the artificial transmission line. For small capacitance variations the change in the characteristic impedance is negligible, whereas the change in the electrical length can be significant depending on n and f_0. Very small capacitance variations can be detected by measuring the electrical length of the artificial transmission line at a high RF frequency. An incident ultrasound signal of frequency f_1 vibrates the membranes, and changes their capacitance. This results in the phase-modulation of the RF signal transmitted through the artificial line. The ultrasound signal can be extracted by demodulating the transmitted RF signal. One obvious way to do this is to use an interferometric method. The interferometer translates the phase-modulation into an amplitude-modulation. Subsequent envelope detection and amplification resolves the ultrasound signal (Figure 3).

For small capacitance variations phase modulation

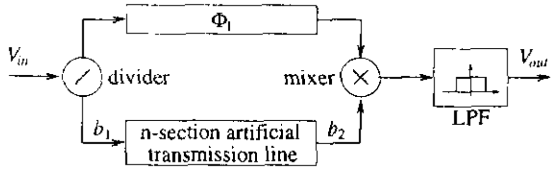

Fig. 4. The down-conversion scheme to detect ultrasound.

is equivalent to amplitude modulation. Therefore, the spectrum of the transmitted signal contains a main signal at f_0, and sidebands at $f_0 \pm f_1$. Thus, the ultrasound signal that vibrates the membranes can be obtained by down-converting the output of the artificial transmission line (Figure 4).

A. Mathematical Formulation

Assume an input of $V_{RF}\sin(2\pi f_0 t)$. Then, the transmitted signal is

$$V_t = V_{RF}\sin(2\pi f_0 t - \Phi_0 - \Delta\Phi(t)) \tag{4}$$

where $\Delta\Phi(t)$ is the time varying component of the phase. By assuming a very small membrane vibration of $\Delta x \sin(2\pi f_1 t)$ one can determine

$$\Delta\Phi(t) = -\frac{1}{2}(n2\pi f_0 C)Z_a\frac{\Delta x}{x_0}\sin(2\pi f_1 t) \tag{5}$$

where x_0 is the membrane separation from the ground. For $\Delta x \ll x_0$ equation 4 can be expanded as

$$V_t = V_{RF}\sin(2\pi f_0 t - \Phi_0) - \Delta\Phi(t)V_{RF}\cos(2\pi f_0 t - \Phi_0) \tag{6}$$

By combining equations 5 and 6, we obtain the output signal. It contains a carrier signal at f_0 and sidebands at $f_0 \pm f_1$. The magnitude of the signal at the sidebands (in terms of current for a better comparison) is

$$I_{out} = \frac{V_{RF}}{4}2\pi f_0 nC\frac{\Delta x}{x_0} \tag{7}$$

Comparison of equations 1 and 7 shows the difference of our method clearly. The DC bias voltage (which is usually large) in the conventional method is replaced by a few volts of RF amplitude in our method. The reduction in voltage magnitude is compensated with the replacement of the ultrasound frequency f_1 by the RF frequency f_0. Considering an ultrasound frequency in the MHz range, and an RF signal in the GHz range, considerable improvement in the sensitivity over the conventional method is possible. For applications which involve lower ultrasound frequencies or audio frequencies, the improvement can be even higher.

B. Effect of the Loss

The use of an RF signal in the detection of ultrasound makes the loss analysis an important issue, because it is the loss that sets limits on the sensitivity. There are two basic loss mechanisms in an artificial transmission line. One of them is the substrate losses which is modeled as a resistance, R_1, in parallel with the capacitance. The other one is the metallization loss which is modeled as a resistance, r_2, in series with the inductors. Using this loss model the attenuation constant of the artificial transmission line can be obtained as

$$\alpha = \frac{r_2}{2Z_a} + \frac{Z_a}{2R_1} \tag{8}$$

where r_2 and R_1 values can be obtained through electromagnetic simulations.

Although the calculation of the loss is quite complicated its inclusion is very simple. The attenuation term, $e^{-\alpha n}$, comes as a scaling factor to the expression in equation 7, and $1/\alpha$ gives the optimum n value beyond which the sensitivity drops with increasing n.

III. Experiments

A. Device Fabrication

To verify the method we fabricated devices both on Si and GaAs using surface micromachining techniques. Because of the low resistivity of the Si substrate devices fabricated on Si did not work well at high RF frequencies. We used air-bridges, and short sections of high impedance transmission lines to make an artificial line (Figures 5 and 6). Because of the simple fabrication process we preferred to use air-bridges instead of membranes as the first phase of the work. A short description of the process is given in [5].

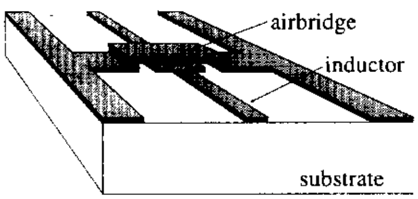

Fig. 5. Oblique view of an artificial transmission line section

B. Mechanical Properties of Air-bridges

An air-bridge is a plate clamped at both ends. The width of the bridge is usually much larger than its thickness. Then, we can assume that the plate is infinite along the width, and solve the two-dimensional problem. In two-dimensions the plate reduces to a bar clamped at both ends [6]. Then the expression for the mechanical resonance is,

$$\nu_n = \frac{\pi}{2\sqrt{12}} \frac{t_b}{l_b^2} \sqrt{\frac{Q}{\rho}} \cdot \beta_n^2 \tag{9}$$

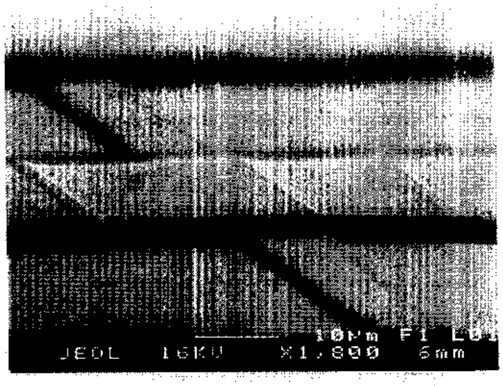

Fig. 6. SEM photograph of an artificial transmission line section

where Q is the Young's modulus, and ρ is the density of the bridge material. β_n are the constants with the values $\beta_1 = 1.5056$, $\beta_2 = 2.4997$, and $\beta_n = n + 0.5$.

We used aluminum as the bridge material which have been shown to have very good mechanical properties [7], at least suitable for this kind of application. Using the material properties of Al, and geometrical considerations we designed the bridges to resonate in the MHz range (2 MHz for a bridge length of 50 μm and bridge thickness of 1 μm).

C. The Experiment Setup

We have done two basic experiments: detection and excitation experiments. In the detection experiment we mounted the sample on a piezoelectric source, and measured the bridge vibrations by monitoring the transmitted RF signal with a spectrum analyzer. This measurement is a good verification of the method, but does not provide good information about the mechanical properties of the bridges, because of the mechanical response of the piezoelectric source. In the excitation experiment, the sample is excited electrostatically with a signal in the MHz range which vibrates the bridges. At the same time it is probed with a RF signal in the GHz range. These two signals are combined and separated with bias-T's. Thus, the simultaneous excitation and measurement of the sample is done.

D. Experiment Results

Figure 7 shows the results of the excitation experiments done on the GaAs sample for various bridge lengths. The RF signal frequency and power are 4.65 GHz and 10 mW, respectively. The mechanical resonance of the bridges occurred at higher frequencies than we expected, probably due to some inaccurate material parameter. On the other hand, the shift in the resonance frequency with changing bridge length is observed clearly. The mechanical-Q of the bridges turned out to be moderately low.

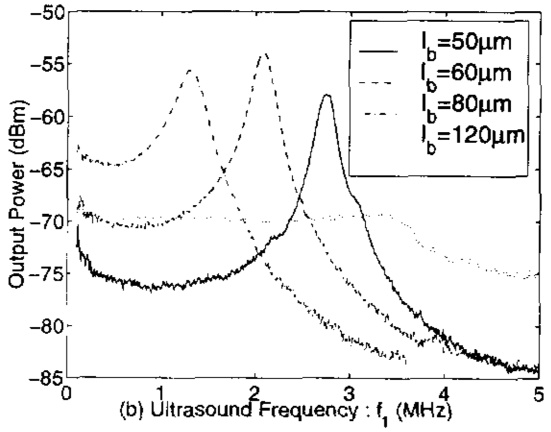

Fig. 7. GaAs sample : The output power measured as a function of the ultrasound frequency.

We have also performed detection experiments on the same device. We kept the ultrasound frequency constant and varied the RF signal frequency. As expected the sensitivity increases with frequency. The losses begin to effect near 20 GHz, and the optimum frequency where the sensitivity is maximized occurs above 20 GHz. The plot of the measurement results are shown in Figure 8 together with a simulation result for a Δx value (40 Å)that best fits the measurement results. Comparing the output signal power with the thermal noise power we obtain a minimum detectable displacement of $\sim 4 \times 10^{-5}$Å$/\sqrt{\text{Hz}}$. Note that the detector contains only 22 sections.

IV. Conclusion

We have introduced a new detection method for micromachined ultrasonic transducers. The derived expressions for the sensitivity of the new method suggests a considerable improvement over the conventional detection method. The improvement is even higher for low ultrasound frequencies, because this method also eliminates the dependence of the detected signal on the ultrasound frequency. According to the simulation and measurement results we see that a displacement sensitivity in the order of 10^{-7} Å$/\sqrt{\text{Hz}}$ is achievable by further decreasing x_0, and increasing n and f_0. The enhanced sensitivity in this method gives

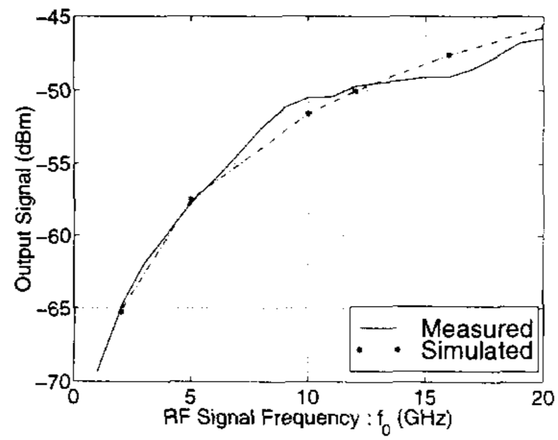

Fig. 8. GaAs sample : The measured data and the simulated data for $\Delta x = 40$ Å.

us a flexibility in choosing our detector size. Since considerable sensitivity can be achieved in a small area, this method can make the fabrication of detector arrays easier.

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