Investigation on Electrode Size of High Frequency Ultrasonic Transducers

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***Abstract*—This paper presents a concept to increase the performance of high frequency ultrasonic transducers. For a sandwich high frequency ultrasonic transducer, the top electrode should be smaller than the piezoelectric plate to avoid shortcuts and edge effects. However, its size can influence properties of the transducer, and until now there is no research about it published. A theoretical investigation about influence of the top electrode size on properties of a transducer is conducted in this paper. First, two factors related with the top electrode size based on transmission coefficient and stored energy are proposed; Then, analysis on an Al-AlN-Al on silicon wafers with different electrode sizes are performed and the results prove the effectiveness and the validity of the proposed factors. Finally, electrical impedance matching experiments are conducted to improve the properties of transducers with different electrode sizes, and the experiment results show that the improved resolution and sensitivity after matching.**

Keywords-Electrode size; electric impedance matching; ultrasonic transducer

I. INTRODUCTION

In high-power ultrasonics and underwater acoustics, a sandwich piezoelectric structure is the most popular one. It is composed of piezoelectric elements, sandwiched between two metal films[1-2], and the analysis of sandwich piezoelectric ultrasonic transducers has been studied for many years[3-5].

Generally, sizes of the top electrode, the bottom electrode and the piezoelectric plate in a sandwich piezoelectric structure are same. However, for high frequency transducers, it is very easy for the two electrodes to get shortcuts or edge effects, as the thickness of the piezoelectric plate is very thin. Therefore, some researchers proposed the pyramid structure: the bottom electrode size is the biggest, then the smaller piezoelectric plate, and the top electrode is the smallest[1, 6-7]. Although, this structure can effectively avoid shortcuts and edge effects, the smaller top electrode can decrease the effective size of the active element, and it must have influence on the properties of the transducer. Therefore, it is important to research how the size of the top electrode can influence the properties of high frequency ultrasonic transducers. In this paper, through analysis on the echoes of transducers with different top electrode sizes and the Fourier transformation of them, we proposed two factors to explain the pattern that the top electrode size influences the transducers' properties and conducted electrical impedance matching experiments to improve the properties of them.

The content of the paper is listed as follows: in Section II, two factors are proposed to explain the relationship between the transducers' properties and the top electrode size; then in Section III, analysis on an Al-AlN-Al structure on silicon wafers with different electrode sizes are performed and the results present the effectiveness of the proposed factors; Electrical impedance matching experiments are conducted to improve the properties of transducers with different electrode sizes in Section IV, and Section V is the conclusion.

II. TWO IMPORTANT FACTORS

In a sandwich ultrasonic transducer with pyramid structure, the top electrode is smaller than the piezoelectric plate, and the active area of the piezoelectric plate is equal to the size of the top electrode, that means *A=A'* in Fig. 1. So the size of the top electrode can influence the properties of the piezoelectric plate. In this section, we would explain its influence from the following two aspects.

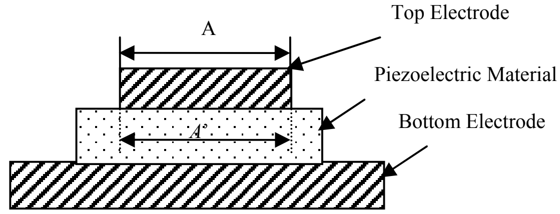

Fig. 1 Sketch of a pyramid structure transducer

A. Energy transmission coefficient

In electronics, when the electrical impedance of a load and a source is known, the fraction from the load can be calculated with Eq. (1), and the value produced is known as the reflection coefficient.

$$R = \left(\frac{Z_l - Z_s}{Z_l + Z_s} \right)^2 \tag{1}$$

where Z_l and Z_s are the impedances of the load and the source, respectively.

The transmission coefficient, which represents the transmission fraction from the load to the source, is calculated by simple substrate the reflection coefficient from one,

$$T = 1 - R = 1 - \left(\frac{Z_1 - Z_s}{Z_1 + Z_s} \right)^2 \quad (2)$$

Therefore, in order to transmit more energy into a transducer, the first important factor in practice is to match the electrical impedance of the transducer and the source, and increase the transmission coefficient.

$$\max(T) = \max(P_T) = \min(Z_s - Z_{in}) \quad (3)$$

where T is the transmission coefficient; P_T is the energy transmitted into the transducer; Z_{in} is the electrical impedance of the transducer. If the electrical impedance, which is in proportion with the top electrode size, is far away from the ideal value, the signal-to-noise ratio (SNR) will be influenced and more noise will be received by the receiver [8].

B. Stored Energy

For a sandwich ultrasonic transducer, energy stored in it can be calculated with voltage, electrode area and capacitance,

$$P_s = \frac{1}{2} C_0' A V^2 \quad (4)$$

where P_s is the energy stored on the capacitor; A is the top electrode size of the transducer; C_0' is the capacitance per unit area given as,

$$C_0' = \frac{\varepsilon}{L} \quad (5)$$

where L is the maximal displacement along the thickness direction; ε is the permittivity of the piezoelectric under no applied voltage.

The voltage between two electrodes is,

$$V = \frac{q(t)}{C_0'} - h\psi_T(t) \quad (6)$$

where $q(t)$ is the electric charge per surface area on each electrode; $h\psi_T(t)$ is the mechanical displacement of a plate from its equilibrium position,

$$h\psi_T(t) = h(\psi(L,t) - \psi(0,t)) \quad (7)$$

where h is the piezoelectric constant; $\psi(L,t)$ is the mechanical displacement of a plate from its equilibrium position.

Suppose $P_{s0}=C_0'V^2$, if the thickness of the piezoelectric plate is fixed, the bigger the electrode is, the higher the stored energy. Therefore, the sensitivity, which is the ability of an ultrasonic system to defect defects, of a transducer with a constant thickness is proportional to the top electrode size.

In order to design a transducer with high sensitivity, we should consider,

$$\max(P_s) = \max(\frac{1}{2} P_{s0} A) = \max(A) \quad (8)$$

Since both the transmission coefficient and the stored energy are related with the top electrode size, we should choose an optimal electrode size to improve the sensitivity and resolution of a transducer in real applications.

III. ANALYSIS ON DIFFERENT ELECTRODE SIZE

In order to validate these factors, we analyzed Al-AlN-Al transducers on silicon wafers with different top electrode sizes. In the experiment, a 500μm thick silicon substrate is used, on which a square shaped Al electrode with a large area is deposited. On the top of it, a squared shaped AlN layer with thickness of 10μm and area of 25mm^2 is deposited, followed by a squared Al top electrode with an area of 25mm^2, 1mm^2, 0.25mm^2 and 0.09mm^2, respectively as shown in Fig. 2.

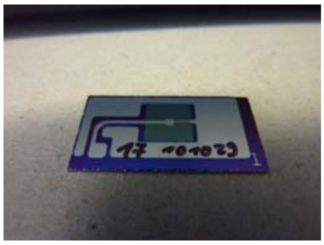

Fig. 2 Our AlN transducer

First, we calculated the transmission coefficient from the source to the transducers with different electrode sizes and the energy stored on the capacitors with our theory, and the result can be seen in Table 1.

TABLE 1 TRANSMISSION PARAMETERS AND ELECTRODE SIZE

Electrode Size (mm^2)	25	1	0.25	0.09
Transmission Coefficient(%)	19.8	97.3	51.9	22.9
Stored Energy* P_{s0} (Joules)	12.5	0.5	0.125	0.045

From it, we can see that when the electrode size is 1mm^2, both the transmission coefficient and the stored energy are high. While when the electrode is 25 mm^2, even its transmission coefficient is as low as 19.8%, the energy stored on the capacitor is 12.5P_{s0} in Joule, which is very high. So the amplitude of it should be higher than that of the echoes whose transmission coefficient is 51.9%, but the stored energy is only 0.125P_{s0} in Joule. When the electrode size is 0.09mm^2, the stored energy and the transmission coefficient are both low, so the amplitude should be too low to be separated with noise.

Then, we measured the practical echoes of the transducers above and did Fourier transformation for them. The pulser and receiver DPR 500 (JSR Ultrasonics) was used to excite the transducers with a needle pulse at high amplitude (-143V) and very short pulse time (~1.4ns), and the input impedance of DRP 500 is 50 ohms. The receiver was set to a gain of 10 dB and a high frequency pass filter between 5MHz and 500MHz was used. The illustration in Fig. 3 shows the schematic setup of the measurement and the detailed measurement can be seen in Literature [9, 10]. Fig. 4-5, Fig. 6-7, Fig. 8-9 and Fig. 10-11 are the results when the top electrode size is 25mm^2, 1mm^2, 0.25mm^2 and 0.09mm^2, respectively.

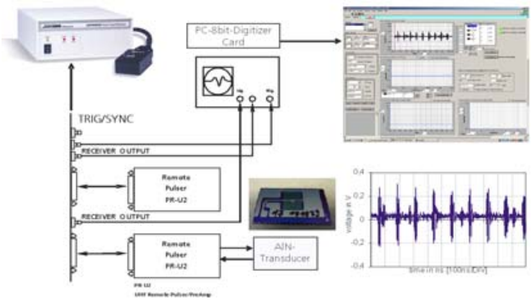

Fig. 3 Measurement setup and connection

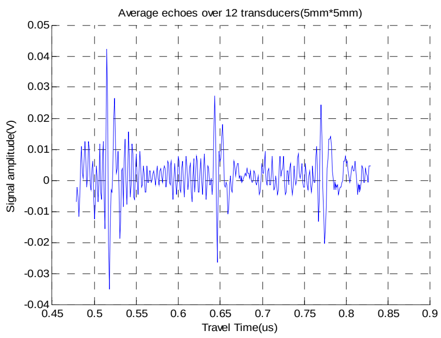

Fig. 4 First three echoes from substrate back wall

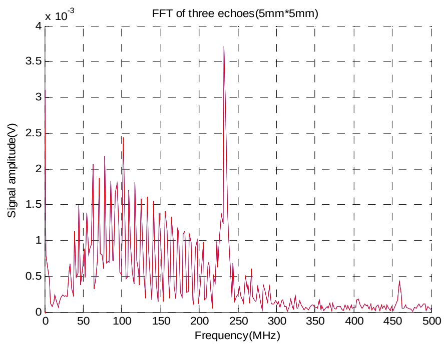

Fig. 5 FFT of first three echoes

From Fig. 4-5, we can see that when the electrode is 25mm^2, the maximal amplitude of the echoes is about 0.041 V, which is related with the sensitivity of the transducer. That means the higher the amplitude of an echo is, the higher the sensitivity of the transducer is. However, the noise is also serious compared to the signal due to the lower transmission coefficient. From the Fourier transformation result, we can see that there is an obvious narrow peak at 232.5MHz. However, most frequency concentrates on the range from 50MHz to 200MHz, and there is a smaller peak around 100MHz because of noises.

Therefore, although the amplitude, or the sensitivity, of this kind of transducers is high, the transmission coefficient is lower and the bandwidth of the maximal frequency is only about 7.8 MHz.

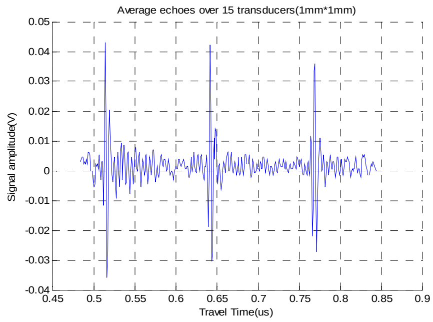

Fig. 6 First three echoes from substrate back wall

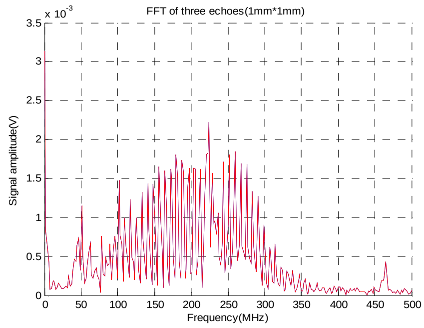

Fig. 7 FFT of first three echoes

When the electrode is 1mm^2, the maximal amplitude of the echoes is about 0.042 V and the noise is very small. That means the sensitivity of it is higher and at the same time the transmission coefficient is higher. From Fig. 7, we can see that there is only a peak at about 222MHz which is a little smaller than the peak frequency when the electrode is 25mm^2. However, on the both sides of the peak, the voltage decreases slowly, and there is no other peak. While in Fig. 8, when the electrode is 0.25mm^2, the maximal amplitude of the echoes is about 0.013 V and the noise is also obvious. There two obvious peaks at 235MHZ and 100MHz in Fig. 9, and both of them are very sharp.

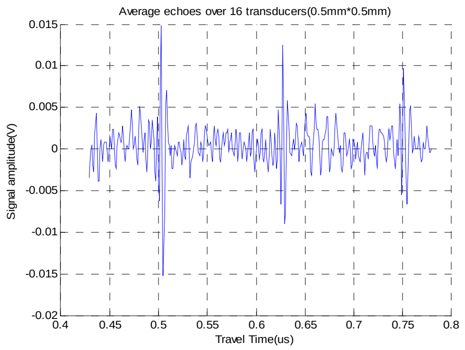

Fig. 8 First three echoes from substrate back wall

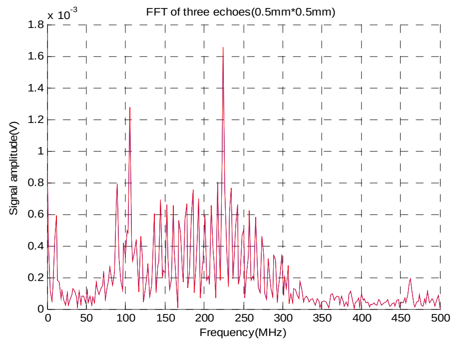

Fig. 9 FFT of first three echoes

When the electrode is 0.09mm^2, the maximal amplitude of the echoes in Fig. 10 is about 0.001 V and the noise is too obvious that it is hard to distinguish the signal. From the Fourier transformation result in Fig. 11, we can see that there are two obvious peaks at 222MHz and 100MHz. At the both sides of the peaks, the voltage decreases sharply. Therefore, the sensitivity and revolution of the transducer are both lower.

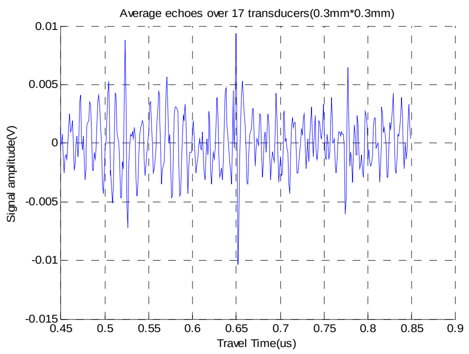

Fig. 10 First three echoes from substrate back wall

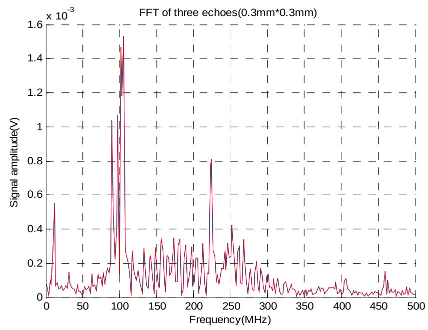

Fig. 11 FFT of first three echoes

From these results, we can see the top electrode size of a transducer not only can influence the amplitude of echoes, but also can influence the maximal frequency and the bandwidth. For our transducers, when the area is 1mm^2, the echoes from the substrate back wall are very clean, the resonant frequency of the transducer is high and the bandwidth is large. That means the sensitivity and resolution are both higher compared with other situations. In Table 1, from theoretical calculation the transmission coefficient of 1 is the highest, and the stored energy is $0.5P_{s0}$ in Joule which is also high. Therefore, the measurement results match our calculations in Table 1 very well.

During designing a transducer, both of the stored energy and the transmission coefficient need to be considered appropriately, and the top electrode size is a really important parameter. In real applications, we could choose an appropriate top electrode size of a transducer first and then improve the resolution and the sensitivity through electrical impedance matching.

IV. ELECTRICAL IMPEDANCE MATCHING

During electrical impedance matching, normally the first step is to suppress the influence of the clamped capacitor C_0 with a parallel inductor, and use a transformer or a parallel resistor to regulate the input impedance, as shown in Fig. 12. For our transducer, when the electrode size is 1mm^2, the inductor is10nH, and the electrical impedance after inductor matching is 414ohms, so we can use a parallel 55ohms resistor to match the electrical impedance to 50ohms. When the electrode size is 0.25 mm^2, the matching inductor is 40nH and the parallel resistor is 50ohms.

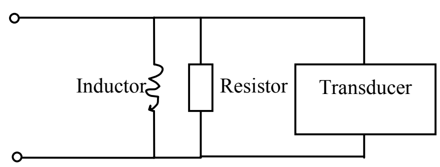

Fig. 12 Electrical impedance matching circuit

First, we matched the electrical impedance with electrode size of 1mm^2, and the echoes and the FFT of the first echo are shown in Fig. 13-14, where the blue line represents the result after matching and the red line with “x” represents the situation before matching.

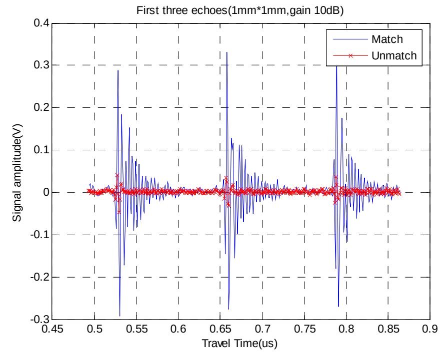

Fig. 13 Echoes from the substrate

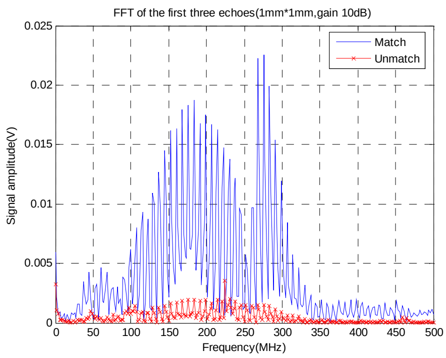

Fig. 14 FFT of the first echo

From them, we can see that the maximal amplitude of the first three echoes before matching is 0.0391V, while after matching it is 0.3438 V, so it increases 8.8 times; The peak frequency of the first echo before matching is 225MHz, while after matching it is 275MHz. Therefore, after matching, the resolution and the sensitivity are both improved.

Second, we matched the electrical impedance with electrode size of 0.25mm^2, and the result is shown in Fig. 15-16. In this case, the maximal amplitude of the first three echoes before match is 0.0164V, while the maximal amplitude of the first echo after match is 0.0651V; the peak frequency of the first echo before match is 225MHz, while the peak frequency of the first echo after match is 275MHz.

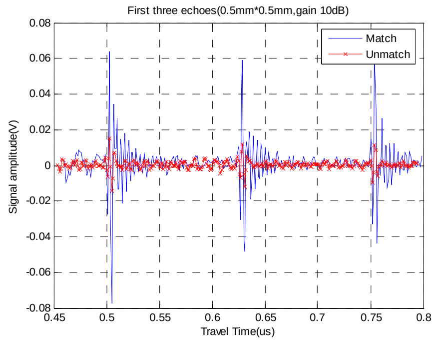

Fig. 15 Echoes from the substrate

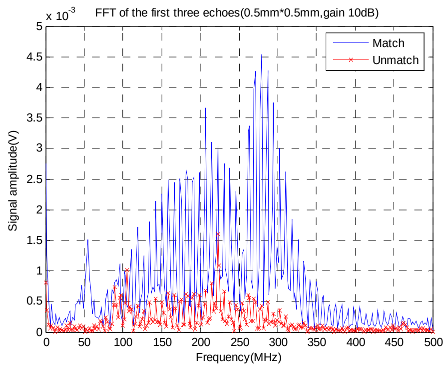

Fig. 16 FFT of the first echo

From these experiment results, we can see that through electrical impedance matching, the energy transmission coefficient can be improved and more energy can be transmitted into the transducers. So the amplitude of echoes improves so much and the working frequency of the transducers is close to the ideal frequency.

V. CONCLUSION

In this paper, we analyzed the influence of the top electrode size on the properties of a high frequency ultrasonic transducer based on transmission coefficient and stored energy in it. It turns out from our investigation that the top electrode size should be larger to improve the sensitivity of it, and the transmission coefficient, as well as SNR, can be improved by electrical impedance matching. Our contributions are as following aspects: 1) Two factors related with the top electrode size are proposed to explain the relationship between the top electrode size and the properties of the transducer; 2) Analysis on an Al-AlN-Al structure on Si wafers with different electrode sizes are performed and the results present the effectiveness and the validity of the proposed factors; 3) Electrical impedance matching experiments are conducted to improve the properties of transducers with different electrode sizes, and it turns out that the resolution and sensitivity have been improved by electrical impedance matching.

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