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# INCREASING RANGING ACCURACY OF ALUMINUM NITRIDE PMUTS BY CIRCUIT COUPLING

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## ABSTRACT

This paper proposes a method to increase the accuracy of distance measurement for piezoelectric micromachined ultrasonic transducers (PMUTs) through introducing stable circuit coupling. The proposed method can characterize the distance through adjustable wavelength. When the ultrasonic flight distance is an odd multiple of the half wavelength, the coupling signal and the piezoelectric response signal are superimposed to produce a sharp ditch. Consequently, such ultrasonic distance measuring technique could be used for the high precision applications.

## KEYWORDS

Aluminum Nitride, PMUT, rangefinder, circuit coupling

## INTRODUCTION

With the rapid development of micro-electromechanical systems (MEMS) technology, micromachined ultrasonic transducers (MUTs) based on piezoelectric (PMUTs)[1] have attracted a wide attentions due to the advantages of low power consumption and small size. PZT has been mainly investigated as a transducer material for PMUT due to its outstanding piezoelectricity[2], [3]. However, Aluminum Nitride (AlN) thin film based PMUT has been also developed because the its manufacturing process is fully compatible with current CMOS technology [4]. Moreover, AlN has a very high chemical and thermal stability, a high thermal conductivity (about 200 W/m. K), and a friendly high electrical breakdown voltage.[5] We have developed and studied AlN film based PMUTs for the ultrasonic ranging application.

The ultrasonic time of flight (ToF) method has been widely used in medical imaging techniques, like fingerprint sensors, rangefinders and so on[2], [6], [7]. There are two basic modes of ToF range finding have been discussed. One mode is pulse-echo (PE), and the other is continuous wave (CW). Narrowband CW systems has a Fatal flaw of suffering from multipath fading which will cause large range errors[8]. Although the problem can be solved by frequency modulated continuous wave (FMCW) excitation, but it requires very high dynamic range since the transmitted signal interferes the return signal. In PE excitation mode, the transmitting pulse and return echoes must be separated in time, which limits the number of pulses that transmitter send. As a result, the output amplitude of the receiver will be very small. The variations of temperature and humidity could be compensated by employing the environmental sensors to the ultrasonic system[1]. The ring-down time of PMUTs can be reduced by the phase shift technique of driving waveform[9].

However, the problem of delay in detecting echo signal in ToF method has not been well solved since the initial signal is too weak. In this paper, we introduced a new circuit design to enhance the signal of receiver's output and at the same time produce a distinctive signal feature. An acoustic signal is detected immediately when it reaches the receiver. Distinctive signal ditch can indicate not only the arrival of sound waves at the receiver, but also the relationship between sound wavelength and frequency. In addition, this method can be applied for most of the ultrasonic transducers.

## PMUTs FABRICATION

The PMUT shown in Fig.1 consists of 1 µm AlN film sandwiched by bottom and top Mo electrodes, silicon dioxide layer and silicon cavities. Completed device consists of a group of circular piezoelectric films in a form of 3*1 array. A zoomed picture of single element of the array is shown in the Fig. 1. The circular Mo/AlN/Mo diaphragm has a diameter of 600 µm. The design of the array structure increases the effective area without changing the resonance frequency. The Fabrication process flow of PMUT is shown in Fig.2. Firstly, Mo/AlN/Mo stack structure is deposited (a). Secondly, the upper Mo metal layer is etched to form the upper electrode (b). A $SiO_2$ layer is deposited to protect the top metal and then etched to form the contact via. Bottom contact via requires both $SiO_2$ and AlN films etching with minimal overetch on bottom Mo metal layer (c)(d). Next, thick Al film is deposited and then etched to form the contact electrodes(e). Finally, the substrate silicon is backside etched by DRIE to form the cavity with the etching stop at the SOI wafer BOX layer (f).

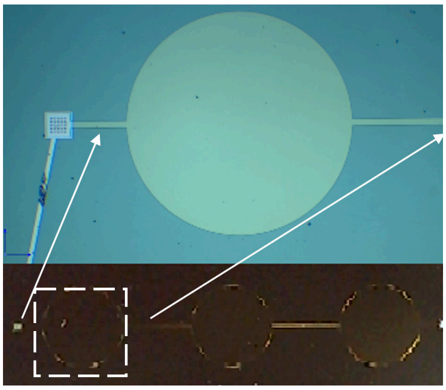

*Figure1: The topography of single PMUT element from a 3*1 array.*

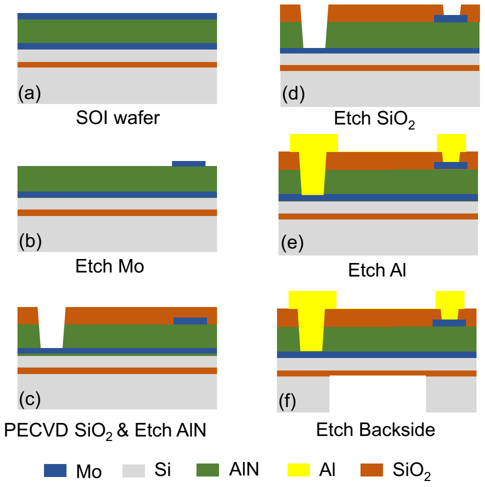

*Figure2: Fabrication process flow of PMUT.*

Fig.3 shows the first three vibration modes on single PMUT element measured by Polytec MSA-600 vibrometer. The first resonant frequency measured in the Doppler analyzer is 127.071 kHz. The frequencies of its second and third modes are 458.324 kHz and 997.778 kHz, respectively. The quality factor ($Q$-factor) of the circular diaphragm is approximately 95 at the air when excited at the resonance frequency of 127.071 kHz. The vibration sensitivity is approximately 7nm/V at the center of the diaphragm.

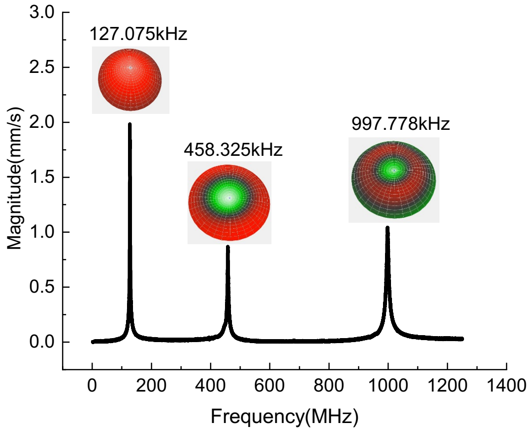

*Figure 3: The top three pictures are the transient states of the dynamic picture analyzed by the Polytec MSA-600 instrument, and the bottom is the position of the three states of resonance on the frequency spectrum.*

## CIRCUIT DESIGN AND ANALYSIS

The traditional ultrasonic ranging methods use the pulse-echo method, which obtains the distance between the transmitting and receiving devices by measuring the ultrasonic time of flight (ToF).

The receiver and transmitter use the same PMUTs. Setup for evaluation of the rangefinding ability of PMUT is shown in the Fig.4. The oscilloscope measures the signal of the excitation source and the receiver response amplified by the amplifier. As shown in Fig.5, when distance is constant, measure the receiver's response amplitude by different excitation voltage and cycles. The horizontal axis is the cycles, and the vertical axis is the amplitude of the receiver response. The receiver's voltage amplitude increases with the increase of cycles and excitation voltage.

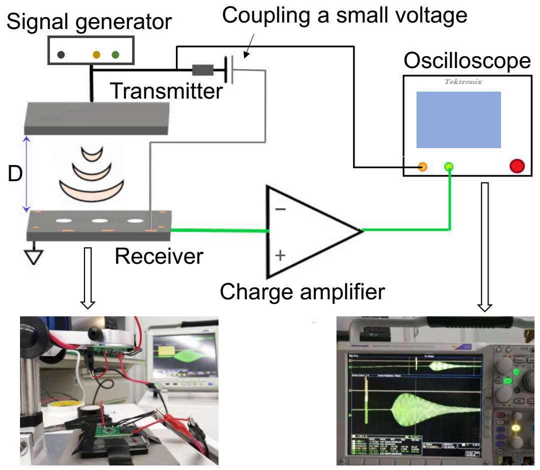

*Figure 4: Setup for evaluation of the rangefinding ability of PMUT.*

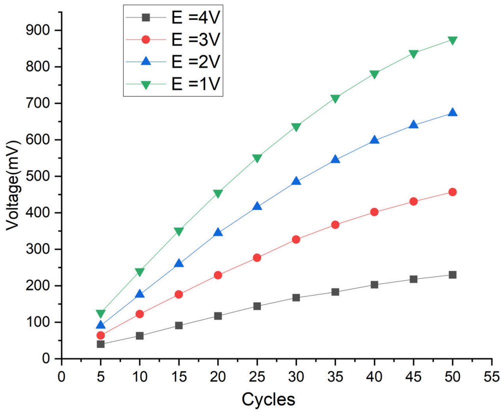

*Figure 5: Different voltage response caused by different cycles and voltages.*

The waveform of the circuit coupling is shown in Fig. 6. The circuit coupling signal and the excitation signal have the same phase., but the amplitude of the former is much smaller than the latter. The coupling amplitude can be controlled by changing the parameters of R and C. According to the propagation law of mechanical waves, the relationship between its wavelength ($\lambda$) and frequency ($f$) of sound wave is $C = \lambda \times f$, where $C$ is the speed of sound waves propagating in the air. Since $C$ is usually a constant, the wavelength can be changed by changing its frequency. If the distance ($D$) between the receiver and the transmitter is half a wavelength plus an integer multiplying the wavelength ($D = n\lambda + \lambda/2$,$n$ is integer). The phase of the electrical signal converted by the receiver is opposite to the electrical signal on the transmitter. According to Kirchhoff's voltage law, if the amplitude of the signal is the same, then the sum of the two signals is zero. Also, we can think it as "destructive interference" of electric signal.

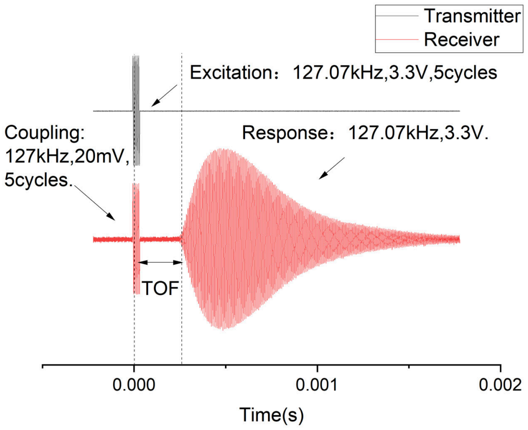

*Figure 6: Time-of-flight measurement with coupling.*

## Experiments and Results

Increase the number of cycles at the transmitter until the coupling signal at the receiver overlaps the piezoelectric response signal. Because the two signals have same frequency, and the piezoelectric response is increasing at beginning. The superposition of the two signals could be zero in some certain conditions. This is the waveform graph will produce a sharp ditch. The sharp ditch effect of the coupled signal and the received signal is shown in the Fig.7. Obvious signal superposition effect can be observed. The amplitude of the signal coupled by the circuit is $V_{pk\text{-}pk}$. It generates value zero at the intersection place. At the end of coupling signal, the gap of receiver's signal is $V_{pk\text{-}pk}$ /2. Signals with this characteristic can be easily detected. Zero point means that the distance is an integer multiple of the wavelength plus half the wavelength, and cap represents the end of the transmitted signal. We discovered that there are two ways to generate such characteristic signals

Fig. 8 shows the first way, it contains three steps. The first step is to excite the transmitter with five 127.07kHz pulses. Second to adjust the frequency from the center frequency. We found that near the resonance frequency, there is always a specific frequency value that makes the output port voltage of the receiver drop to zero, as shown in the bottom of Fig. 8. Five sets of data are recorded in Table 1. These data show that in a wide range of distances, the coupling signal and the receiver signal can destructively interfere with each other through frequency modulation.

The second way is shown in Fig.9. It shows the wave-electric interference at different distances when the transmitter works at the center frequency ( $f = 127.07\,kHz$). When the frequency of the transmitter's source is constant, we can fine-tune the distance to generate a zero point. Adjust the distance slowly and we find that the amplitude of specified position of the waveform can quickly shrink to zero. If we continue to adjust the distance in the same direction, the peak-to-peak value of the specified location will change periodically. The two sets of experiments above provide a new idea for PMUT-based ultrasonic ranging applications. The zero- point generated by the interference of two signals increases the convenience of signal detection which help to design high precision displacement detector and rangefinder. The approximate distance can be measured in a traditional ultrasonic ToF method, and then the waveform appears a sharp ditch through modulating frequency. This phenomenon represents a certain relationship between the distance and the wavelength. The relationship is that the distance equals to an integer multiple of the wavelength plus half the wavelength (Odd multiple of half wavelength). This means that the distance is a series of discrete values. Compare with the result of the ToF method and select the closest value. This compared value is closer to the true distance than the value measured by the traditional ToF method.

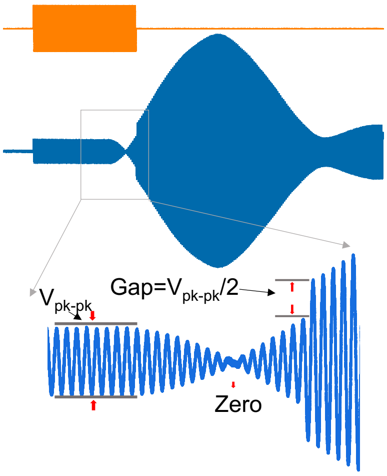

*Figure 7: The phenomenon of signal superposition to a sharp ditch*

*Table 1: Main parameters of figure 8. $f_0$ is the center frequency or first-order resonance frequency $f$ is the target frequency.*

| ***Distance(cm)*** | 4.6 | 6.5 | 8.8 | 11.2 | 14.3 |
|---|---|---|---|---|---|
| ***Cycles*** | 30 | 40 | 50 | 60 | 70 |
| $f_0$***(kHz)*** | 127.07 | 127.07 | 127.07 | 127.07 | 127.07 |
| $f$ ***(kHz)*** | 127.92 | 129.25 | 128.56 | 127.09 | 128.63 |

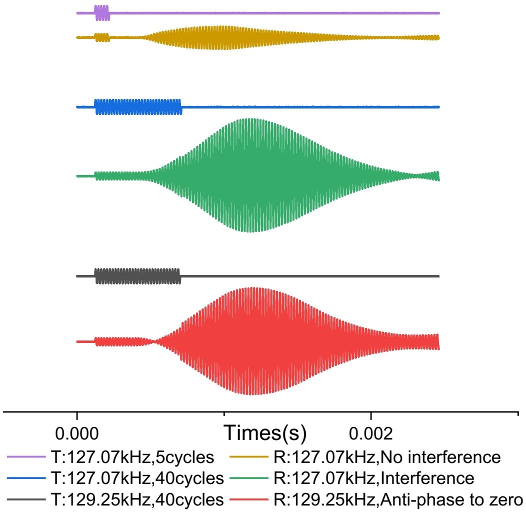

*Figure 8: Three sets of waveforms.*

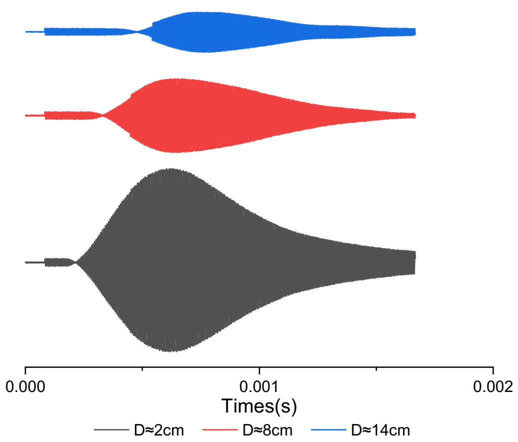

*Figure 9: Waveform of different distance under 127.07kHz、3V and 100 cycles excitation*

## CONCLUSION

We have fabricated and characterized the ultrasonic rangefinder using AlN thin film based PMUT devices. The wavelength of the sound wave generated by the AlN thin film is adjustable by changing the frequency of the excitation source on the transmitter. A stable signal is coupled from the transmitter excitation source to the receiver's output. This new proposed circuit coupling characterization method allows the transmitter to send long excitation signals without considering the separation time compared to the traditional ToF method, which enhances the response signal of the receiver. Such characteristics enable easy detection and high accuracy of the PMUT, which can be potentially used in high precision distancing applications.

## ACKNOWLEDGEMENTS

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