36% Scandium-doped Aluminum Nitride Piezoelectric Micromachined Ultrasonic Transducers

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Abstract—Piezoelectric micromachined ultrasonic transducers (PMUTs) using 36% Scandium-doped aluminum nitride (ScAlN) thin-film are presented in this work. ScAlN is known to exhibit higher piezoelectric properties compared to pure AlN leading to significant improvements in various MEMS applications including PMUTs. Here, the concentration of Sc in the actual sputtered 1 µm thick ScAlN film was 36% that is slightly below the phase boundary. The piezoelectric coefficient is close to maximum at this high concentration leading to significant improvement in the PMUT performance. The ScAlN film quality was verified via X-Ray Diffraction (XRD), electron probe microanalysis (EPMA), and $d_{33}$ meter. The operation frequency was designed to around 80 kHz to achieve long range detection, where the air absorption loss is low. The displacement sensitivity of 1 mm diameter ScAlN PMUT was 806 nm/V at 84 kHz resonant frequency. A large displacement of 4.8 µm was achieved at 20 Vpp input at the fixed frequency of 84 kHz. This represents a factor of 9 increase in transmit amplitude compared to prior art air-coupled AlN PMUTs.

Keywords—MEMS, PMUT, ultrasonic transducer, Scandium, ScAlN

I. INTRODUCTION

Ultrasonic transducers have been widely used in 2D/3D rangefinding applications including object detection, gesture recognition, automotive driving assistance, and non-destructive imaging. Recently, interest in piezoelectric micromachined ultrasonic transducers (PMUTs) has increased dramatically due to the miniature size, low cost, low power consumption, ability to fabricate transducer arrays, and easy integration with CMOS circuitry. For instance, ultrasonic gesture recognition [1], 3D rangefinder [2], [3] and fingerprint sensor [4], [5] were demonstrated. Despite this progress, PMUTs have not yet achieved the high sound pressure level (SPL) and long range required for applications such as automotive parking assist.

The two major piezoelectric materials used in PMUTs are lead zirconium titanate (PZT) and aluminum nitride (AlN), where AlN has ~10x lower transmitting sensitivity but ~10x higher receiving sensitivity compared to PZT. Scandium aluminum nitride (Sc$_x$Al$_{1-x}$N) retains many features of AlN (e.g. CMOS compatibility, ease of deposition/etching) but possesses significantly increased piezoelectric properties compared to pure AlN [6], [7]. However, most of the devices published to date have used Sc concentrations below 20%, where the piezoelectric coefficients are only modestly improved [8], [9] because alloy targets are difficult to manufacture at higher concentrations.

Here, we demonstrate PMUTs fabricated with 36% Sc films, a concentration slightly below the phase boundary from wurtzite to cubic structure where the piezoelectric coefficient is close to the maximum. Through this increase in piezoelectric coefficient and improved mechanical design, we seek to realize air-coupled PMUTs that are capable of 10x greater transmit pressures than earlier AlN air-coupled PMUTs and comparable to pressures achieved in conventional bulk transducers.

For air-coupled transducers, the operation frequency directly affects the detection range of the pulse-echo sensing because absorption loss in air scales with frequency [10]. In this work, the target operation frequency was set to 80 kHz to achieve low absorption loss in air enabling longer detection range (5 to 10 m) than prior art air-coupled PMUTs which operated around 200 kHz and achieved a maximum range of 1 to 2 m [2], [3].
II. PMUT DESIGN AND FABRICATION

A. Geometry

As shown in Fig. 1, a simple unimorph circular membrane shape was selected for the PMUT design in this work. The diameter and thickness of PMUT stack layers were optimized using the analytical model. Since the residual stress of the thin films greatly affect the resonant frequency $f_n$ of the device, the Si device layer of the SOI wafer needs to be thick enough to maintain the small $f_n$ variation. However, increasing the membrane thickness will result in reducing the bandwidth, and thus we optimized the thickness to $5 \mu m$. PMUT devices with membrane size of $1 \text{ mm}$ diameter was fabricated. The radius of the top electrode was optimized to $70\%$ of the membrane size.

The resonant frequency of the circular membrane can be calculated from the laminated plate vibration theory based on thickness $t$, diameter $d$, and material properties including Young’s modulus $E$, density $\rho$ and Poisson’s ratio $\nu$ of each layer. The fundamental $(0,0)$ mode frequency is

$$ f_{00} = \frac{\lambda_{00}}{d^2} \sqrt{\frac{D}{\mu}} 
$$

where the $\lambda$ is the eigenvalue of the vibration mode ($\lambda_{00} = 1.63$), $D$ is flexural rigidity of the plate ($= \frac{1}{12} E t^2 (1-\nu^2)$) and $\mu$ is the mass per unit area ($= \sum t_i \rho_i$) weighted by the layer thicknesses in this multi-layer stack.

In addition, finite element method (FEM) was used to simulate the frequency variation due to the gradient residual stress in the thin film across the $6''$ wafer. The resonant frequencies were simulated with various residual stresses in the $1\mu m$ thick piezoelectric layer to optimize the passive layer thickness, which is the device Si layer in this work. Fig. 2 shows the FEM simulation results of $3$ and $5\mu m$ Si layer with $0.5, 1, 2 \mu m$ thick ScAlN layer. Apparently, $5 \mu m$ thick Si layer results in smaller frequency variation compared to $3 \mu m$. With $1 \mu m$ ScAlN, for example, frequency varies nearly $40$ kHz from $0\text{MPa}$ to $100\text{MPa}$ using $3 \mu m$ Si layer, while the variation is reduced to $10$ kHz using $5 \mu m$ Si. For the ScAlN layer, the thinner results in lower frequency variation but does not affect as much as Si layer. Here, we selected $5 \mu m$ Si layer and $1 \mu m$ ScAlN layer to reduce the frequency variation across the wafer.

B. Fabrication

A simple 3-mask fabrication process flow is shown in Fig. 3. PMUTs consisting of an Al/ScAlN film stack were fabricated.
fabricated on a custom SOI wafer. The 5 μm thick Si device layer of the SOI wafer was Boron-doped to achieve low resistivity and used as the bottom electrode. High Sc concentration 1 μm thick ScAlN film was sputtered using a ScAl alloy target at Denso Corporation. The target contained 40% Sc. The ScAlN layer was etched to form contact vias using chlorine-based reactive ion etching (RIE) in a transformer coupled plasma (TCP) etcher. 300 nm thick Aluminum top electrode and contact pads were then formed by a lift-off process. The PMUT membrane was defined by a backside Si deep reactive ion etching (DRIE) followed by the 1μm thick BOX layer removal.

III. RESULTS
A. ScAlN film characterization

The actual Sc concentration in the sputtered film was analyzed by electron probe microanalysis (EPMA). The result showed 36% Sc which is 4% lower than the Sc concentration in the alloy target. The ScAlN crystal quality was evaluated using X-ray diffraction (XRD). The 2theta-omega scan of the ScAlN thin film at the center and edge of the wafer are shown in Fig.4(a). The rocking curve of the ScAlN (002) peak at center and edge of the wafer are shown Fig. 4(b). The angle shift at the two measured points indicates that the c-axis orientation is tilted approximately 2˚ at the edge of the wafer. The FWHM of the (002) peak was 1.5˚ at the center indicating the good crystal quality. The FWHM at the outer side of the wafer was 2.2˚. The smaller FWHM results in higher piezoelectric coefficient, and generally below 2.0˚ is the desired value for both AlN and ScAlN films. The tilt of the c-axis orientation at the edge explains the larger FWHM and lower crystal quality.

The longitudinal piezoelectric coefficient $d_{33}$ was measured using a $d_{33}$ meter on a 1 μm thick 36% ScAlN film deposited on a Si test wafer using the same sputtering conditions used for PMUT wafers. The result, $d_{33} = 17$ pC/N, is plotted along with previously-reported values for $d_{33}$ and $d_{31}$ [6], [7] in Fig. 5, showing good agreement with the value expected at 36% Sc. As $d_{33}$ and $d_{31}$ are nearly proportional, this increase in $d_{33}$ indicates 2x higher transverse piezoelectric coefficient $e_{31,f} = -2.3$ [C/m²] compared to pure AlN.

B. Frequency Response

The displacement sensitivity of the center of a 1 mm diameter PMUT membrane was measured in air via laser Doppler vibrometer (LDV). A large displacement of 806 nm/V calculated from velocity of 425 mm/s/V at the 84 kHz resonant frequency was observed as shown in Fig 6. This displacement sensitivity agrees with calculated value using $e_{31,f} = -2.0$ [C/m²] in the analytical model. This large membrane displacement sensitivity was approximately 2x of AlN PMUTs ($e_{31,f} = -1.0$ [C/m²]) agreeing with the improvement in the piezoelectric properties. The LDV frequency response of four identical ScAlN PMUTs from different locations across the wafer were measured as shown in Fig. 6.
in a short distance. Here, the bandwidth is preferred for the PMUT design to detect an object where the object to be detected. Thus, minimum detection range of-flight of the round trip between the PMUT and the first object when it is transmitting, proportional to the bandwidth of the transducer, is required for square wave at the resonant frequency of 84 kHz, shown in Fig. 7(a). A short transmission time, that is inversely proportional to the bandwidth of the transducer, is required for PMUTs to achieve high resolution and short minimum detection range [11], which can be calculated from the time of pulse length \( t_{\text{pulse}} \). Because a PMUT cannot receive ultrasound when it is transmitting, \( t_{\text{pulse}} \) needs to be shorter than the time-of-flight of the round trip between the PMUT and the first object to be detected. Thus, minimum detection range \( R_{\text{min}} \) of the transducer can be expressed using time-constant \( \tau \) as

\[
R_{\text{min}} = \frac{t_{\text{pulse}} \cdot c}{2} = \frac{6\tau \cdot c}{2} = \frac{3c}{BW}
\]

where \( c \) is the speed of sound in air. Hence, the wide bandwidth is preferred for the PMUT design to detect an object in a short distance. Here, the \( R_{\text{min}} \) was 17 cm with \( t_{\text{pulse}} \) of approximately 1 ms when the PMUT was excited by 40 cycles burst. The \( R_{\text{min}} \) could be shorten by reducing the burst cycle number.

D. Maximum Achievable Displacement

The maximum transmit pressure of a PMUT is usually limited by mechanical “spring-hardening” nonlinearity at large vibration amplitudes. The LDV experiments were conducted to measure the maximum displacement at driving voltages up to 20 Vpp (Fig. 8) using both a fixed 84 kHz input frequency and by adjusting the input frequency by a few kHz to follow PMUT resonance frequency. A large displacement of 4.8 \( \mu m \) was achieved at 20 Vpp input at the fixed frequency at 84 kHz. This represents a factor of 9 increase in transmit amplitude compared to prior art air-coupled PMUTs.

IV. CONCLUSIONS

Air-coupled PMUTs based on 36% Sc-doped AlN were demonstrated in this paper. The PMUT layer thicknesses were optimized based on FEM simulations to minimize the frequency variation due to the residual stress in the piezoelectric thin film. The sputtered ScAlN thin film obtained good crystal quality confirmed with 1.5° FWHM of XRD rocking curve. The high piezoelectric properties predicted from the high Sc concentration were verified experimentally from LDV measurements. A large velocity sensitivity was 425 mm/s/V at 84 kHz resonant frequency and transmission time was 1 ms. The maximum achievable displacement with 20 Vpp driving voltage was 4.8 \( \mu m \) at the fixed input frequency. These results indicate a significant improvement in the transmit pressure compared to the prior art air-coupled PMUTs.

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