

# SCANDIUM DOPED ALUMINUM NITRIDE BASED PIEZOELECTRIC MICROMACHINED ULTRASOUND TRANSDUCERS

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## ABSTRACT

This paper presents the design, fabrication and characterization of piezoelectric micromachined ultrasound transducers (PMUTs) based on scandium doped aluminum nitride ( $\text{Sc}_x\text{Al}_{1-x}\text{N}$ ) thin films ( $x = 20\%$ ). ScAlN thin film was prepared with a dual magnetron system and patterned by a reactive ion etching system utilizing chlorine-based chemistry with an etching rate of 160 nm/min. The film was characterized by X-ray diffraction (XRD) which indicated a crystalline structure expansion change compared to pure AlN and a well-aligned ScAlN film. ScAlN PMUTs were fabricated by a 2-mask process based on cavity SOI wafers. ScAlN PMUTs with 50  $\mu\text{m}$  diameter had a large dynamic displacement sensitivity of 25 nm/V at 17 MHz in air, twice that of AlN PMUTs with the same dimensions. Electrical impedance measurements indicated that the ScAlN PMUTs had 20% greater electromechanical coupling coefficient ( $k_t^2$ ) compared to AlN PMUTs. The output pressure of a 7x7 ScAlN PMUT array was 0.7 kPa/V at ~1.7mm away from the array, which is ~3 times greater than that of an 8x8 AlN PMUT array with the same element geometry and fill factor measured at the same distance.

## INTRODUCTION

Micromachined ultrasonic transducers (MUTs) have been developed for many applications in recent years, such as medical imaging [1-2], gesture sensors [3], ultrasonic fingerprint sensors [4], and body-composition sensors [5]. Compared with conventional bulk ultrasonic transducers, MUTs have a better acoustic coupling, lower cost for two-dimensional array fabrication, and lower power consumption. Recently, piezoelectric micromachined ultrasonic transducers (PMUTs) have been rapidly developed due to the progress of piezoelectric thin films. Aluminum nitride (AlN) has been widely used for PMUT fabrication because it is available from a number of MEMS foundries and is compatible with CMOS manufacturing. However, compared to lead zirconate titanate (PZT), a piezoelectric material which requires high annealing temperature and is not process-compatible with CMOS, AlN has relatively low piezoelectric coefficient ( $e_{31,f}$ ), which leads to low sensitivity and low electromechanical coupling ( $k_t^2$ ) [6].

Recently scandium (Sc) doping has been proposed as a means to increase the  $e_{31,f}$  of AlN, while maintaining process compatibility with existing AlN-based manufacturing [7]. Studies also found that with the increase of Sc doping concentrations, the stiffness of the thin film decreased and the dielectric constant increased [8]. Most of the previously-reported work on ScAlN focused on bulk acoustic wave (BAW) resonators or surface acoustic wave (SAW) devices which utilize the longitudinal piezoelectric mode and require high stiffness to achieve high frequency operation and high quality factor ( $Q$ ) [9-10]. In this paper, we present flexural PMUT devices which use the transverse piezoelectric mode and where the reduced stiffness of ScAlN may provide a benefit over conventional AlN.

The schematic of each PMUT is shown in Figure 1. The PMUT was composed of a 1  $\mu\text{m}$  thick ScAlN piezoelectric layer, a 200nm Mo layer as bottom electrode and a 2.5  $\mu\text{m}$  thick silicon membrane. The vacuum cavity underneath the silicon membrane eliminates

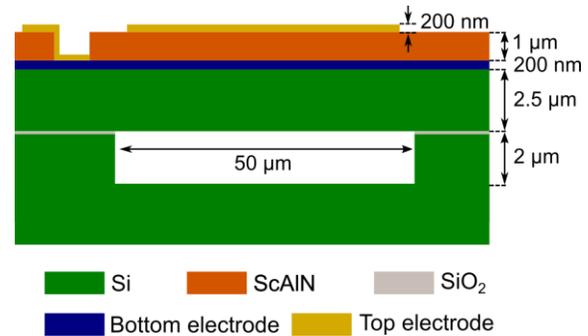


Figure 1: Schematic of ScAlN PMUT.

possible squeeze-film damping between the PMUT membrane and the Si substrate.

## FABRICATION

### ScAlN thin film deposition

$\text{Sc}_x\text{Al}_{1-x}\text{N}$  thin film ( $x = 20\%$ ) of 1  $\mu\text{m}$  thickness was sputtered on 6 inch cavity SOI wafers (IceMOS Technology) in an Advanced Modular Systems (AMS) cluster tool with AlN deposition chambers and ion beam trimming module. The system used a standard dual conical magnetron with an AC deposition source. The ScAlN deposition process was in deep poison mode using targets composed of Al and Sc pieces. Locally adjusted magnetic field for target pieces of both Al and Sc guaranteed a constant thin film composition over the entire target life. Substrate rotation was utilized to compensate for the variation of the sputtering yield for different materials and composition non-uniformity across the substrate.

A 30 nm thick ScAlN was firstly deposited on the cavity SOI as a seed layer. Then a 200 nm thick molybdenum (Mo) layer was sputtered as the bottom electrode in a different chamber in the system without breaking the vacuum. Finally, 1  $\mu\text{m}$  thick ScAlN was sputtered on the Mo layer.

### ScAlN PMUT fabrication

ScAlN PMUTs were fabricated based on a simple 2-mask process with cavity SOI wafers as reported in [6]. The process requires etching the ScAlN film to open vias to the Mo bottom electrode. An initial study of wet etching the ScAlN thin film using heated positive photoresist developer (Microposit MF-319) mainly composed of tetramethylammonium hydroxide (TMAH) showed that the ScAlN etch rate was ~50 nm/min at 60°C to 70°C, approximately 4 times slower than that of AlN thin films with the same thickness and at the same etching temperature. Then reactive ion etching (RIE) was studied with a combination of  $\text{Cl}_2$ ,  $\text{BCl}_3$  and He gases in a transformer coupled plasma (TCP) etcher. He gas is used as diluent to improve etch uniformity. A 6.5  $\mu\text{m}$  thick g-line photoresist (OCG 825 35S, Fujifilm) was spin coated, patterned, and hard baked for 16 hours to be used as a mask. An etch rate of 160 nm/min was achieved with the recipe shown in the Table 1 with an etching selectivity of 0.4 to the mask. A 200 nm thick aluminum

Table 1: Parameters for RIE of ScAlN thin film

Parameters	Values
Cl <sub>2</sub> flow rate (sccm)	90
BCl <sub>3</sub> flow rate (sccm)	30
He flow rate (sccm)	100
TCP RF Power (W)	550
RF Bias Power (W)	150

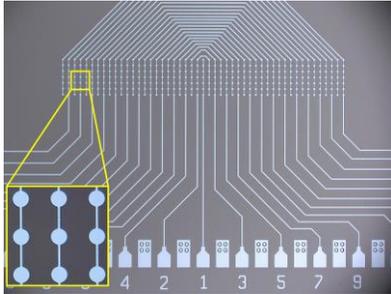


Figure 2: An optical microscope image of a 7x49 PMUT array. The individual PMUTs are 50  $\mu\text{m}$  diameter and the array pitch is 70  $\mu\text{m}$ .

(Al) layer was evaporated and patterned by a lift-off process to form the top electrode and contact pad for the bottom electrode. A PMUT array composed of 7x49 single PMUTs with 50  $\mu\text{m}$  diameter and 70  $\mu\text{m}$  pitch is shown in Figure 2. A cross-section scanning electron microscope (SEM) image of a PMUT, Figure 3, shows the dense columnar structure of the ScAlN film and Mo bottom electrode.

## CHARACTERIZATION

### ScAlN thin film characterization

The ScAlN crystalline structure was studied by X-ray diffraction (XRD). Figure 4(a) shows a comparison of the XRD peaks of pure AlN and ScAlN thin film with 1  $\mu\text{m}$  thickness. The (002) peak of ScAlN was slightly shifted to a lower angle compared with that of AlN, indicating an expansion of the crystalline lattice according to Bragg's law. The rocking curve of the ScAlN (002) peak was also measured and is shown in Figure 4(b). The full-width-half-maximum (FWHM) of the peak is 1.7°, indicating that the c-axis of the ScAlN thin film is well aligned and predicting good

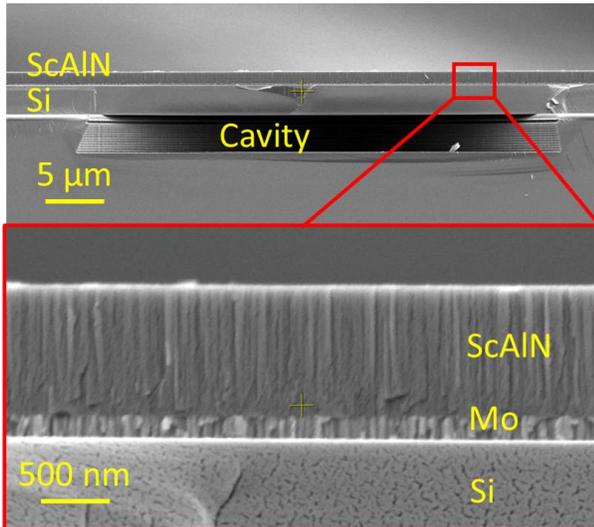


Figure 3: Cross-sectional SEM image of a ScAlN PMUT.

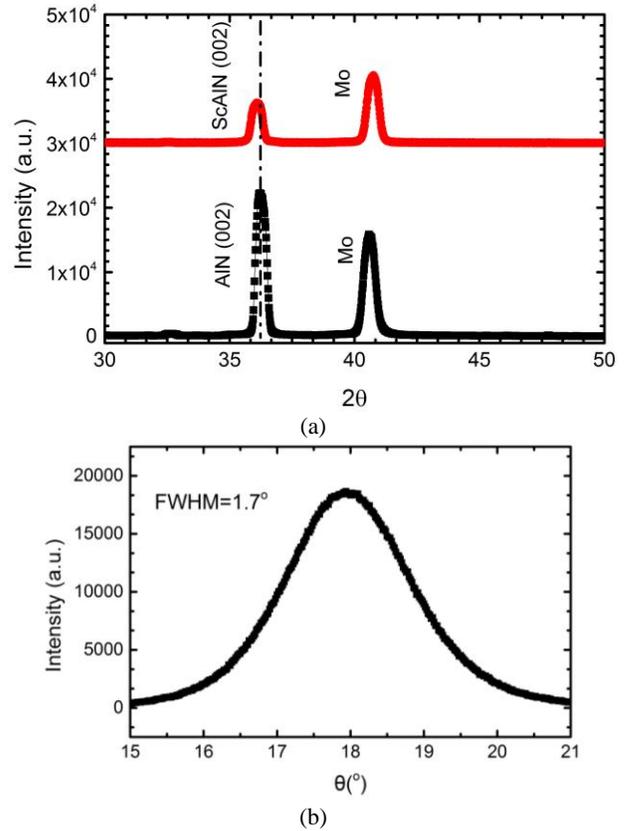


Figure 4: (a) Normal coupled XRD measurement of ScAlN and AlN films; (b) Rocking curve measurement of ScAlN (002) peak.

piezoelectric properties.

### Dynamic characterization

The frequency response of ScAlN PMUTs and AlN PMUTs with the same geometry were tested in air using a laser Doppler vibrometer (LDV) in conjunction with a network analyzer. LDV measurements were collected on 16 ScAlN PMUTs across the wafer, resulting in a 17.5  $\pm$  1.5 MHz natural frequency and 22  $\pm$  4 nm/V dynamic displacement sensitivity at resonance. The results are shown in Figure 5. Cross-section SEM image showed that the Si thickness varied from 2.40  $\mu\text{m}$  to 2.93  $\mu\text{m}$ . Using equation (1), the observed variation in natural frequency is consistent with the measured thickness variation. Figure 6 compares the LDV results of ScAlN and AlN PMUTs. The dynamic displacement sensitivity of

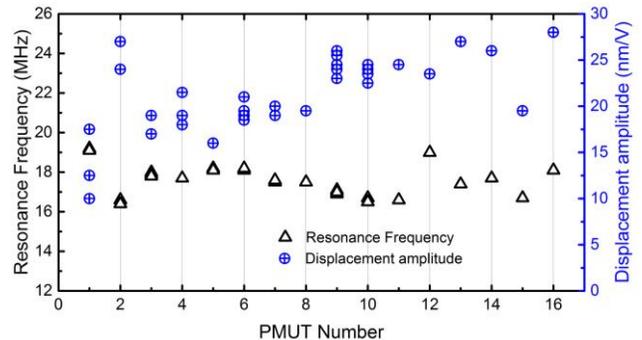


Figure 5: Measured resonance frequency and dynamic displacement at resonance for ScAlN PMUTs with 50  $\mu\text{m}$  diameter and 2.5  $\mu\text{m}$  nominal Si thickness.

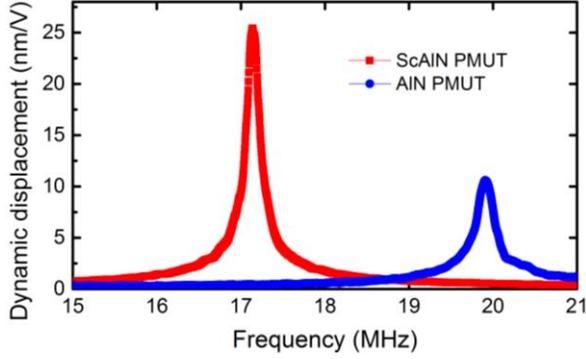


Figure 6: LDV measurement results for 50  $\mu\text{m}$  diameter ScAlN and AlN PMUTs

the ScAlN PMUT is two times as large as that of the AlN device. The difference in the resonance frequency of ScAlN and AlN PMUTs is due to the stiffness reduction from Sc doping as mentioned earlier. The Young's modulus of ScAlN was estimated to be 200GPa via equation (1), which is consistent with the reported values obtained from ScAlN BAW devices [11],

$$f = \frac{1.63}{r^2} \sqrt{\frac{D}{\sum \rho_i t_i}} \quad (1)$$

where  $r$  is the radius,  $D$  is rigidity,  $\rho$  and  $t$  are the density and thickness of the PMUT layers. The rigidity  $D$  can be expressed as

$$D = \int_{\text{bottom layer}}^{\text{top layer}} \frac{E_z z^2}{1-\nu_z^2} dz \quad (2)$$

where  $E_z$  is the Young's modulus and  $\nu_z$  is the Poisson's ratio of the material at a distance  $z$  from the neutral axis. The average quality factor of the PMUTs is  $Q = 140$ . The static displacement sensitivity, which is the peak displacement normalized by  $Q$ ,  $d_s = d_y/Q$ , is  $\sim 180$  pm/V.  $d_s$  is related to the transverse piezoelectric coefficient  $e_{31,f}$  via:

$$d_s \propto \frac{e_{31,f} Z_n}{D} \quad (3)$$

where  $Z_n$  is the distance from the middle of the piezoelectric layer to neutral axis. The estimated  $e_{31,f}$  is  $\sim 1.6$  C/m<sup>2</sup> which is  $\sim 60\%$  higher than that of AlN.

### Electrical characterization

Impedance measurements of ScAlN and AlN PMUTs, Fig. 7, were performed in air using a GSG RF probe calibrated with an impedance substrate standard (Cascade Microtech). The electromechanical coupling factor  $k_t^2$  was calculated by:

$$k_t^2 = \frac{\pi^2 f_r f_a - f_r}{4 f_a f_a} \quad (4)$$

where  $f_a$  and  $f_r$  are the anti-resonant and resonant frequency respectively.  $k_t^2$  was 1.8% for ScAlN PMUTs, 20% higher compared to the AlN PMUT's 1.47% which was close to the value expected for a pure AlN device operating in transverse mode. The relative dielectric permittivity ( $\epsilon_{\text{ScAlN}}$ ) of ScAlN was also estimated from the impedance test as  $\sim 12$  which is around 20% higher than that of pure AlN.

### Acoustic characterization

An array of ScAlN PMUTs was immersed in Fluorinert (FC-70, 3M) and the output acoustic pressure was measured with a 70  $\mu\text{m}$  diameter needle hydrophone (Precision Acoustic, Inc.). The results are shown in Figure 8. A 7x7 ScAlN PMUT array was driven by 4.9 MHz 11 Vpp pulses from a function generator (Rigol, DG-4102). The measured pressure generated by the ScAlN PMUT array was detected at  $\sim 2.5$   $\mu\text{s}$  after the pulse generation, which

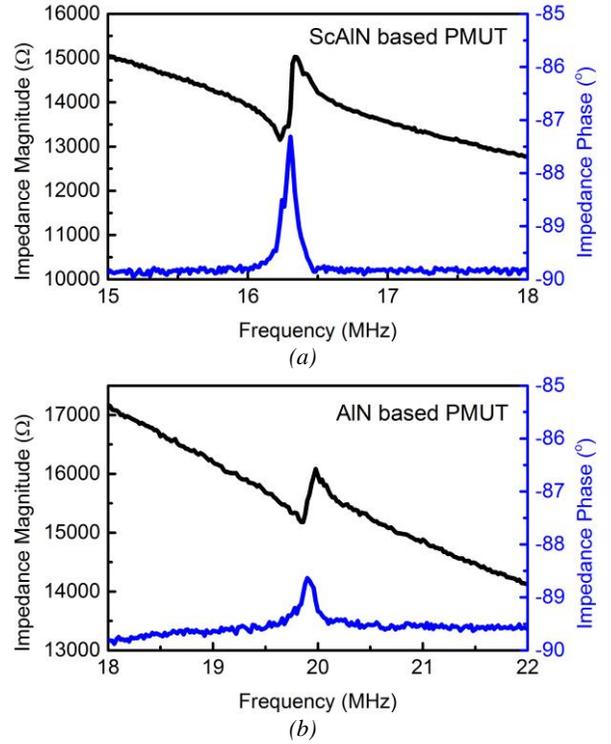


Figure 7: Impedance measurement results for 50  $\mu\text{m}$  diameter (a) ScAlN PMUT and (b) AlN PMUT.

corresponds to  $\sim 1.7$  mm from the PMUT surface to the hydrophone. The peak-to-peak pressure detected was  $\sim 8$  kPa, which was 30% larger than  $\sim 6$  kPa pressure generated from a 8x8 AlN PMUT array driven at 25 Vpp, suggesting 3x greater transmit efficiency from the ScAlN array. The dynamic displacement of a 17x17 ScAlN PMUT array driven with 11 Vpp was measured via LDV, Fig. 9. A  $\sim 1$  nm displacement of the center ScAlN PMUT was measured during the transmit (TX) excitation. The plot shows that the PMUT displacement from the returning echo is also visible 10  $\mu\text{s}$  after the TX pulse is sent. The 6.8 mm round-trip distance calculated from this pulse echo measurement is consistent with  $\sim 3.4$  mm height of the Fluorinert above PMUT array. The echo generated deformation of PMUT was  $\sim 1$  nm indicating a  $\sim 20$  dB insertion loss from TX displacement to the RX echo displacement. This result is consistent with 16 dB spreading loss (which was verified using hydrophone

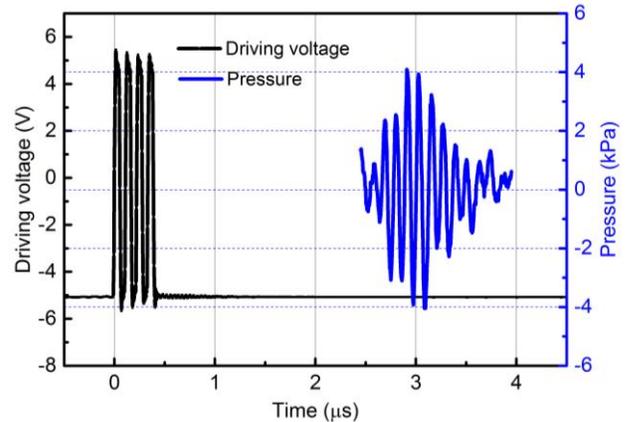


Figure 8: Pressure measurement results for 7x7 ScAlN PMUTs array

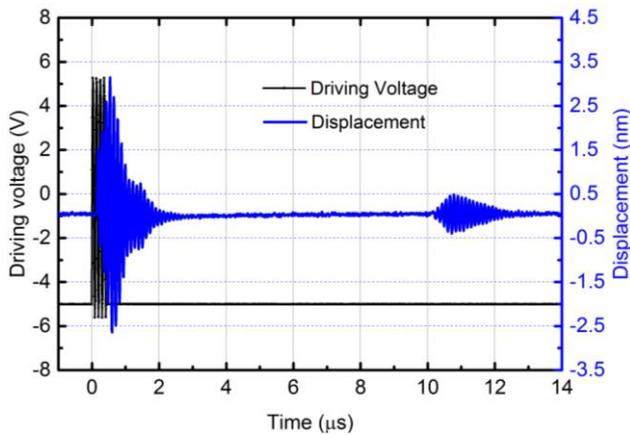


Figure 9, LDV measurement of pulse-echo from a ScAlN PMUT in the center of 17x17 Array

Table 2, A comparison of piezoelectric materials properties

Material	$e_{31,f}$ (C/m <sup>2</sup> )	$\epsilon_{33}$	E (GPa)	$\frac{e_{31,f}^2}{\epsilon_{33}\epsilon_0}$ (GPa)
PZT [12]	-14.0	1200	65	18.5
AlN [12]	-1.05	10.5	390	10.8
ScAlN (this work)	-1.6	12	200	24.1

measurements at different distances) and 4 dB of loss due to the 40% fill-factor of the array.

## CONCLUSION

ScAlN PMUTs appear to have important performance advantages over AlN PMUTs. The manufacturing process of the ScAlN PMUT is nearly identical to that of the earlier AlN device. A summary of the measured properties of the ScAlN film used here is presented in Table 2. Importantly, the figure of merit shown in the table's last column shows that ScAlN is 1.3 times better than PZT for PMUTs.

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