DC Bias Effects on Optimizing ScAlN Air-Coupled pMUT Performance Parameters

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***Abstract*—In this work, we demonstrate that the performance of ScAlN pMUTs can be enhanced by adjusting DC bias voltages. DC biases up to 80 V on ScAlN pMUTs contribute to film stress alleviation and enhance pMUT performance. Laser Doppler Vibrometry characterization was performed to evaluate an improvement in displacement transfer according to the DC bias, as well as to investigate the ferroelectric effect of 15% scandium-doped AlN film. As a result, both transmission sensitivity and receive sensitivity are improved by 11% and 50%, respectively, at 80V bias compared to 0V. Additionally, a 55% enlargement in the -3dB bandwidth (BW) has been achieved.**

Keywords—PMUT, ultrasound, DC bias, scandium aluminum nitride, transmit sensitivity, receive sensitivity.

I. INTRODUCTION

Piezoelectric Micromachined Ultrasonic Transducers (pMUTs) have been developed with various types of piezoelectric films for different applications. One of the most used films, Lead-zirconate-titanate (PZT), has been known to use bias DC voltage to tune its frequency and transmit sensitivity by varying DC biases from a range of 0 to 40 V in air-coupled devices [2]. This is followed by improvements in electromechanical coupling coefficient (k_t^2) changing from 1 to 7.3%, and its tunability of frequency ranges from 210 kHz to 120 kHz, respectively, which far out-performs Aluminum nitride (AlN) based pMUTs in terms of transmission sensitivity. AlN devices have been reported to display receive sensitivities approximately 10 times more than that of PZT [4], which are more relevant to use as sensors for various applications such as distance ranging [5], gesture detection [6] and temperature sensing [7]. For AlN devices, bias application to tune the performance of such pMUTs has been shown to yield minuscule improvements in a small tunable range of 4.66 kHz for a 114 kHz device and a 1 nm/V displacement sensitivity improvement from 5 nm/V [1].

This work describes the first demonstration of the result of DC bias on the performance of $Sc_{0.15}Al_{0.85}N$ air-coupled pMUTs. To maximize performance, high DC voltages of up to 80 V were applied to fully flatten the membrane. The mechanical and acoustic characteristics of the ScAlN pMUT were also measured and compared to determine the effects of complete film stress alleviation on ScAlN devices via DC voltage application. We experimentally validated that 15% ScAlN pMUT does not exhibit hysteresis characteristics within the -80 V to 80 V range.

II. DEVICE AND FABRICATION

The device tested consists of a 1 µm thick, 15% scandium-doped aluminum nitride piezo film which is placed in between two molybdenum (Mo) electrodes. The piezoelectric stack was formed on a 4 µm thick epi-polysilicon membrane and the device was patterned using etch process where metal interconnects route the top and bottom electrodes through the passivation layer to bond pads at the edge of the die. The membrane of each pMUT is then released via back-port etch through the substrate. [3]

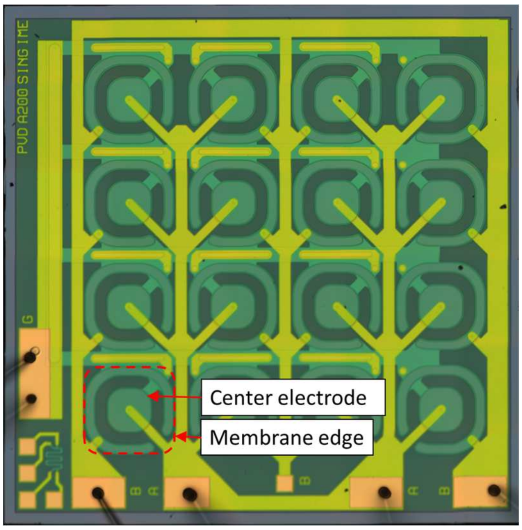

Fig. 1. Optical profiler image of the tested ScAlN device.

The 3.5×3.5 mm die consists of 16 membranes that are connected to each other in parallel with a bond pad to the top electrodes and another bond pad for the bottom electrodes, as shown in Fig. 1. Each device membrane has an approximate width of 600 µm and a center electrode that spans around 300 µm. There is an outer ring electrode in this device that is not utilized in this work.

III. RESULTS AND DISCUSSION

The device mentioned in Fig. 1 was packaged on a COB and placed under an optical profiler (Sensofar Neox) for surface profile measurement. The top electrodes were connected to the positive terminal of a high-voltage power supply (Keysight B2962), while the bottom electrodes were connected to the negative terminal.

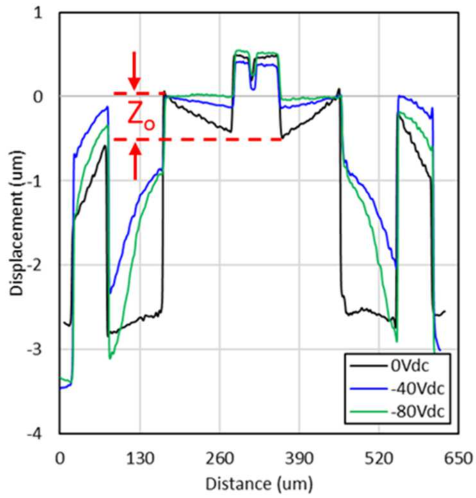

Fig. 2. Topography of a single membrane with DC voltage.

An initial topography measurement was done without applying any bias voltage as reference followed by DC bias voltages of -40 V and -80 V applied to the center electrode (Fig. 2). The deflections, Z_O, of the piezo stack measured at the center of the membrane were 0.55µm, 0.18µm and 0µm for 0 V, -40 V and -80 V bias, respectively. This confirms that -80 V bias would be the optimum bias for compensating the residual moment within the device membrane. The applied DC bias would then have an effect of the resonant frequency, f_0 from the device which can be expressed as [8]

$$f_0 = \frac{t}{r^2}\sqrt{[1 + \frac{0.8\sigma}{Y}\left(\frac{r}{t}\right)^2 \frac{Y}{\rho}}$$

where r represents the radius of the pMUT membrane, t, represents the total layer thickness, σ is denoted as the stress caused by the DC bias voltage, and Y is the average plate modulus.

The top electrode of the ScAlN device was then connected to the function generator (Keysight 33522B), and an oscilloscope (Keysight Keysight InfiniiVision DSOX4024A)(Fig. 3). The bottom electrode of the same device was connected to the positive terminal of a high-voltage power supply (Keysight B2962), and a 200 V, 22 µF rated capacitor was placed in parallel between the positive and negative terminals of the same DC power supply. The negative terminal then forms a common ground point for the function generator, the 10 MΩ, RS-PRO passive probe and the input or output signals of the pMUT which can be read from the oscilloscope for testing with the Laser Doppler Vibrometer (LDV), and acoustic transmit (TX) or receiver (RX) testing with a microphone.

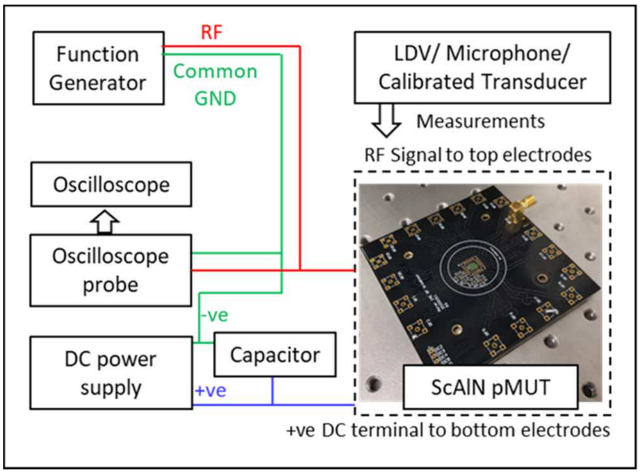

Fig. 3. Test setup for LDV, TX and RX measurements.

The setup was positioned under an LDV (Polytec MSA-500). The function generator was set to send a $1V_{pp}$, single pulse, unipolar, square wave of 144 kHz which was near the resonant frequency of the ScAlN pMUT when it was not subjected to a bias voltage. The LDV then measures the maximum velocity of a single membrane in the pMUT which was converted to displacement using the formula

$$\upsilon = \pm\sqrt{(A^2 - \omega^2)}$$

Where υ is the velocity measured, A is the amplitude and ω is the angular velocity of the measured device. An FFT was performed on the LDV signal, and the resonant frequency was extracted from the corresponding FFT peak. The measurements are repeated for bias values starting from 0 to -80 V, then to 80 V and back to 0 V again in 10 V increments (Fig. 4).

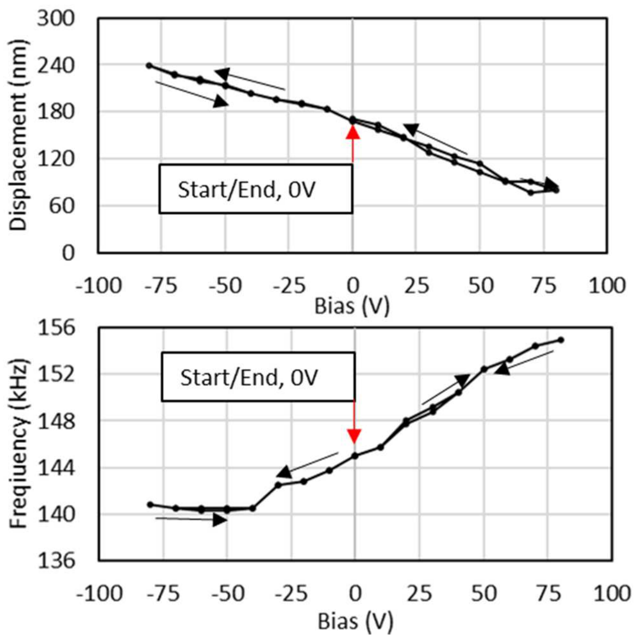

Fig. 4. Hysteresis displacement and frequency curves.

The ScAlN pMUT, exhibit negligible hysteresis when bias was swept back and forth. The frequency reduces minimally to 141 kHz when swept below -40 V and increases to 155 kHz when 80 V bias was applied. Correspondingly, the peak-peak displacement increases from 168 nm to 240 nm when -80 V bias was applied and decreases to 80 nm when 80 V was applied.

Next, the acoustic characteristic was evaluated using the same setup shown in Fig. 3 with a condenser ultrasound microphone (Avisoft-bioacoustics CM16/CMPA40-5V, positioned 7.5 cm above the pMUT). A 25-cycle sin-wave signal with incremental frequency from 80 to 220 kHz was applied to the ScAlN pMUT to measure the TX sensitivity for DC biases 80 V, 0 V and -80 V, respectively. The signal from the microphone was recorded and plotted against each frequency data point (Fig. 5).

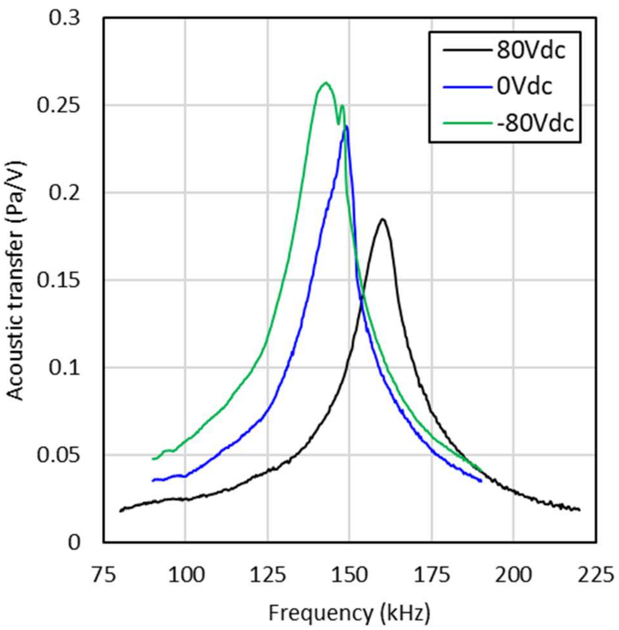

Fig. 5. Acoustic TX transfer with bias

When 80 V bias was applied with the positive potential on the top electrode, the pressure transfer for 16 membranes shows 0.184 Pa/V at a resonant frequency of 160 kHz, with a -3dB bandwidth of 7.2%. Subsequently, when a 0 V bias was applied, the pressure transfer for 16 membranes shows 0.238 Pa/V at a resonant frequency of 148 kHz, with a -3dB bandwidth of 7.4%. Finally, when -80 V bias was applied, a transfer of 0.263 Pa/V was recorded at 143 kHz with a -3dB bandwidth of 11.5%.

Finally, after confirming that negative bias application was beneficial to the TX performance of the ScAlN pMUT and positive bias does the contrary, we evaluated the RX sensitivity of the pMUT. A pre-calibrated air-coupled transducer was placed 7.5 cm directly above the ScAlN pMUT device under test (DUT) and the function generator in figure 3 was disconnected from the RX pMUT. The transmitter devices were pulsed with 25 sinusoidal cycles of 1.69 Pa and 2.59 Pa peak-peak at 148 kHz and 142 kHz respectively to match the resonant frequencies of the DUT when 0 V and -80 V bias was applied. The RX signal trace was recorded when 0 V bias and -80 V bias was applied to the ScAlN pMUT (Fig. 6). The peak-peak RX signal recorded was 10.9 mV and 25.0 mV for 0 V bias and -80 V DC bias applications and the RX sensitivity at resonance can be deduced to be 6.43mV/Pa and 9.67mV/Pa respectively.

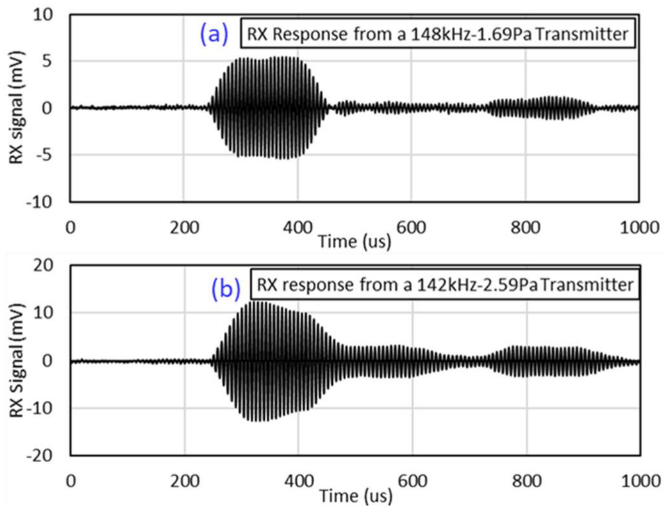

Fig. 6. RX signals from ScAlN pMUT when excited when (a) 0 V bias is applied (b) -80 V bias was applied.

TABLE I. Acoustic Performance of ScAlN pMUT with Bias

DC Bias (V)	$Sc_{0.15}Al_{0.85}N$ Air-coupled pMUT			
	fo (kHz)	*TX Transfer (Pa/V)*	*RX Transfer (mV/Pa*	*-3dB BW %*
0	148	0.238	6.43	7.4
-80	143	0.263	9.67	11.5
Performance improvement %	-	10.5	50.4	55.4

IV. Conclusion

We have demonstrated how DC bias application can affect ScAlN-based membrane stress when a negative bias is applied on the top electrode which provides compressive stress to compensate the initial tensile deformation in the film. This allows for manipulation and tuning of the film which can increase the transmit sensitivity of a non-ferroelectric material like $Sc_{0.15}Al_{0.85}N$ by 10.5%, improve the RX sensitivity of by 50.4% and enlarge the -3dB bandwidth of the device by 55.4% when the tensile stress of the membrane that defines the pMUT device is alleviated completely. Conversely, if a positive bias is applied on the top electrode of a pMUT, tensile stress may be induced in the device which may help in devices that are initially stressed in a compressive manner.

Acknowledgment

This research was supported by A*STAR under the "Piezo Specialty Lab-in-a-Fab" (Grant No. I1901E0050) and "Nanosystems at the Edge" (Grant No. A18A4b0055).

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