Towards Low-Coercive Field Operation of Sputtered Ferroelectric $Sc_xAl_{1-x}N$

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Primary CNF Tools Used: AJA sputter deposition, AJA ion mill, PT770, Oxford PECVD, SEM

Abstract:

This work reports on the ferroelectric properties of scandium aluminum nitride ($Sc_xAl_{1-x}N$) thin films with an Sc-concentration between 22-30%. The goal of this work is to engineer a low coercive field in $Sc_xAl_{1-x}N$ for low-voltage post-CMOS compatible RF frontends. Films between 200 and 300 nm $Sc_xAl_{1-x}N$ were deposited on platinum (Pt) and molybdenum (Mo) electrodes. Lateral and vertical capacitors were tested over a range of electric fields, frequencies, and electrode sizes. Measured coercive field (EC) and remnant polarization (Pr) values were between 3.9-6.2 MV/cm and 58-170 $\mu C/cm^2$. Frequency, temperature, and device area-dependence were studied to identify trends towards low coercive field operation of the material. An anomalous observation relating Sc-concentration and film stress, with EC and Pr is reported to present prospects for decoupled tuning knobs to engineer lowered EC in $Sc_xAl_{1-x}N$.

Summary of Research:

Aluminum nitride (AlN) is the material of choice for MEMS RF resonators due to its excellent piezoelectric properties and CMOS compatibility. Fundamental limits in the piezoelectric properties of AlN have inspired the exploration of alloys of AlN towards enhanced piezoelectric properties. One such alloy is scandium aluminum nitride ($Sc_xAl_{1-x}N$), which presents a tuning mechanism to increase the piezoelectric coefficient by ~ 4x with scandium incorporation. Theoretical calculations predict that monotonically increasing Sc-concentration can decrease the energy barrier between the parent wurtzite structure and the hexagonal phase in $Sc_xAl_{1-x}N$ to produce ferroelectric switching. The recent discovery of ferroelectric switching in high Sc-concentration $Sc_xAl_{1-x}N$ ($x > 0.27$), has confirmed these predictions and generated significant interest as the first III-V ferroelectric [1]. Ferroelectricity has been demonstrated with Sc-concentration as low as 10%, and $Sc_xAl_{1-x}N$ has been used for ferroelectric resonators [2,3]. A major challenge to use $Sc_xAl_{1-x}N$ for device applications is the requirement for high on-chip voltages (>100V) due to its high EC. Here, we present results that map the design space of parameters which present a pathway towards lower EC in $Sc_xAl_{1-x}N$ [4,5].

Fabrication. Multiple film stacks were made for testing the impact of bottom electrode and substrate on $Sc_xAl_{1-x}N$. Ti/Pt was deposited on blanket silicon in the AJA sputtering tool followed by $Sc_xAl_{1-x}N$/Mo deposition at an external vendor (OEM). In another variation, SiO_2 was deposited in the Oxford PECVD followed by Mo/$Sc_xAl_{1-x}N$/Mo deposition at OEM. The film stacks were deposited in a cluster-line tool followed by etching of the top Mo and $Sc_xAl_{1-x}N$ in the PT770 etcher. For the bottom electrode, Ti/Pt was etched in the AJA ion mill whereas the Mo was etched in the PT770. For etch-calibration, AlN films were deposited in the OEM Endeavor M1 and etched in the PT770.

Results. A setup with continuous wave positive-up-negative-down (PUND) was used for ferroelectric testing of $Sc_xAl_{1-x}N$ (Figure 1A). The P and N pulses include both switching and leakage currents. The U and D pulses include only the leakage and can be subtracted from P and N pulses respectively to get the switching current (Figure 1B). Representative polarization vs. E-field (PE) loops are shown in Figure 1C.

In situ heating of capacitors on 300 nm $Sc_{0.30}Al_{0.70}N$ shows a monotonic decrease in E_C without a significant change in P_r (Figure 2A). The temperature coefficient of E_C for this sample is ~ 8.8 kV/°C (Figure 2B). Figure 3 shows the area and frequency-dependence of E_C and P_r across a range of electrode sizes and frequencies from 20-100 μm diameter and 1-8 kHz. E_C increases with an increase in

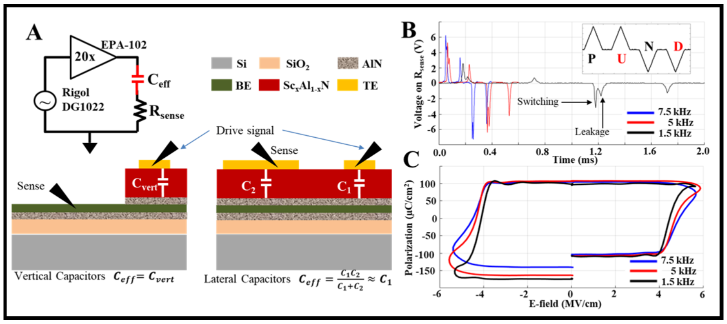

Figure 1: A) Modified Sawyer-Tower circuit for testing ferroelectric ScAlN capacitors and probing configurations for testing vertical and lateral configurations. B) Raw output voltage waveforms at various switching frequencies for PUND test (generic input waveform inset) C) Polarization vs. E-field (PE) loops generated by integrating switching currents from B.

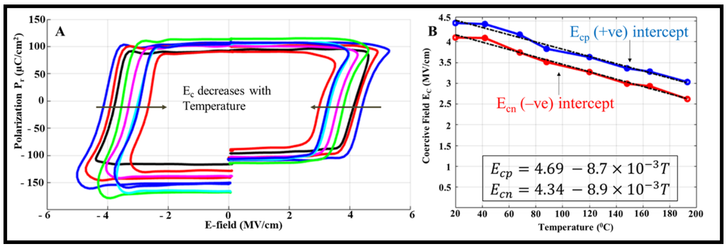

Figure 2: A) Polarization vs. E-field (PE) loops for 40 μm capacitor on 300 nm $Sc_{0.30}Al_{0.70}N$ between RT and 195°C. B) Linear decrease in E_C with increase in temperature with a coefficient of ~ 8.8 kV/cm/°C.

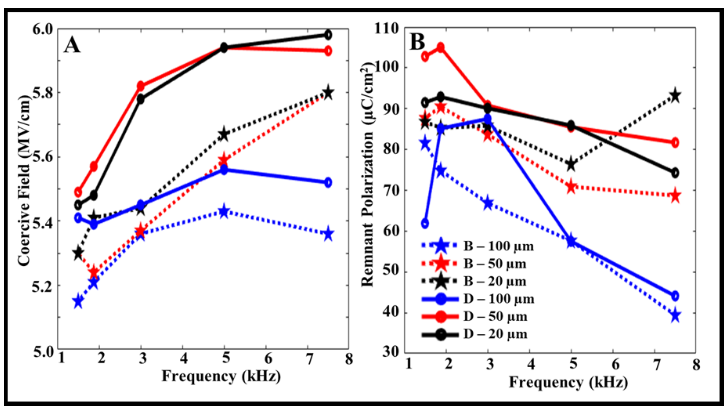

Figure 3: Plots of A) E_C and B) P_r versus frequency for capacitors of 20-100 μm diameter with Sc-concentration of 30% and 22% on Mo and Pt electrodes to map frequency and area-dependence of ferroelectricity.

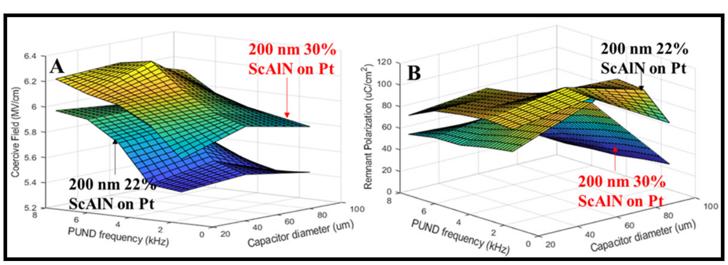

Figure 4: 3D map of A) E_C and B) P_r for 30% and 22% ScAlN on Pt electrodes tested over the range of capacitor sizes and frequencies. The 22% ScAlN has lower E_C and higher P_r due to a favorable tensile film stress of 102 MPa.

frequency and decreases with an increase in electrode size because a larger capacitor has more domains for ferroelectric switching and a lower frequency allows for more complete switching. P_r decreases with an increase in electrode size due to higher leakage in larger devices.

Figure 4 shows an anomalous dependence of E_C on Sc-concentration across a range of electrode sizes and frequencies — a lower Sc-concentration shows lower E_C due to a favorable tensile stress of 102 MPa compared to a compressive stress of 80 MPa. This stress-control shows a path towards decoupled knobs for tuning ferroelectricity, other than Sc-concentration.

Conclusions and Future Steps:

Our work maps out the design space of low E_C-operation (as low as 2.5 MV/cm) in $Sc_xAl_{1-x}N$ with *in situ* heating, and high frequency operation.

The use of this low E_C in ferroelectric transistors, resonators, transducers, and NEMS devices is the subject of on-going research.

References:

[1] S. Fichtner, N. Wolff, F. Lofink, L. Kienle, and B. Wagner, "AlScN: A III-V semiconductor based ferroelectric," Journal of Applied Physics, 2019.

[2] S. Yasuoka, et al., "Effects of deposition conditions on the ferroelectric properties of $(Al_{1-x}Sc_xN)$ thin films," Journal of Applied Physics, 2020.

[3] J. Wang, M. Park, S. Mertin, T. Pensala, F. Ayazi, and A. Ansari, "A Film Bulk Acoustic Resonator Based on Ferroelectric Aluminum Scandium Nitride Films," Journal of Microelectromechanical Systems, 2020.

[4] V. Gund, et al., "Temperature-dependent Lowering of Coercive Field in 300 nm Sputtered Ferroelectric $Al_{0.70}Sc_{0.30}N$," IEEE ISAF, 2021.

[5] V. Gund, et al., "Towards Realizing the Low-Coercive Field Operation of Sputtered Ferroelectric $Sc_xAl_{1-x}N$," TRANSDUCERS 2021- 21st Int. Conf. Solid-State Sensors, Actuators Microsystems, 2021.