# Intrinsically Switchable Gigahertz Ferroelectric ScAlN SAW Resonators

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Primary CNF Tools Used: SÜSS MA-6 Contact Aligner, CVC SC-4500 Odd-Hour Evaporator, JEOL 6300 Electron-Beam Lithography, Zeiss SEM

## Abstract:

**This work details intrinsic switching of 1-3 gigahertz (GHz) ferroelectric scandium aluminum nitride (ScAlN) surface acoustic wave (SAW) resonators. Reversible switching is demonstrated for SAW devices fabricated on 22-30% ScAlN, with metal interdigitated transducers (IDTs) of widths 1 µm-400 nm patterned with a combination of contact and electron-beam lithography. Two-state switching of the resonator is demonstrated with single-sided pulses of ± 6 MV/cm, which demonstrates reversible on-off switching of piezoelectricity in ScAlN. The results show a method of programmable RF signal processing and sensing using ferroelectric ScAlN.**

## Summary of Research:

Aluminum nitride (AlN) is used in MEMS RF resonators due to its excellent piezoelectric properties and CMOS-compatible processing. Fundamental limits in the piezoelectric properties of AlN have necessitated the exploration of new materials with improved performance. One such material is scandium aluminum nitride ($Sc_xAl_{1-x}N$), which can increase the piezoelectric coefficient by up to ~ 4x with Sc-incorporation. More recently, the discovery of ferroelectric switching in high Sc-concentration $Sc_xAl_{1-x}N$ ($x>0.22$), has generated significant interest as the first III-V ferroelectric [1].

To demonstrate reconfigurable and adaptive filtering, it is desirable to achieve programmable piezoelectric coupling in ScAlN with ferroelectric switching, which can then be used to tune the filter frequency and transmission level. We have previously reported on the ferroelectric properties of various ScAlN compositions across a range of device sizes, templating electrodes, film stress, and frequency of switching with a goal of identifying reduced switching voltages, including a reduction in the coercive field by 37% with *in situ* ovenization [2,3]. This work builds on the materials characterization and development we have performed previously by demonstration intrinsic polarization switching in ScAlN resonators [4].

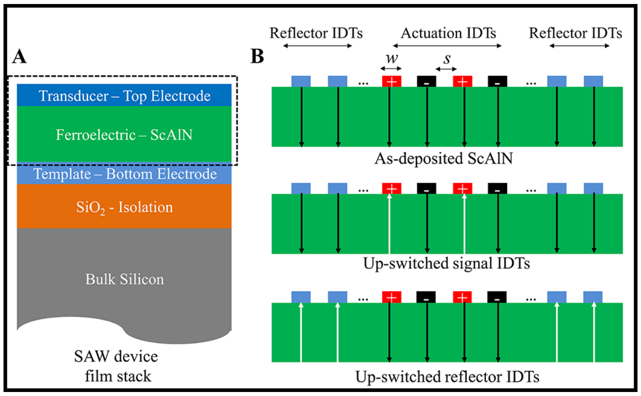

*Figure 1: A) SAW device consisting of $SiO_2$ isolation, template bottom electrode, wurtzite ferroelectric ScAlN, and top electrodes for SAW actuation. B) Schematic of the transducer IDTs and ferroelectric ScAlN showing three distinct configurations of ScAlN polarization: as-deposited N-polar ScAlN with polarization pointing downward, up-switched ScAlN under signal IDTs to program piezoelectric coupling in the active region, up-switched ScAlN under reflector IDTs to program acoustic wave boundary conditions.*

The film stack used to make the resonator comprises of a continuous bottom electrode which serves as the template for the ferroelectric, c-axis wurtzite ScAlN and the top electrode for patterning the SAW IDTs (Figure 1A). The IDTs with width *w* and spacing *s* enable lithographic definition of the resonance wavelength: $\lambda = 2(w+s)$. Passive reflectors enable energy confinement in the acoustic cavity defined by the IDTs. It is, hence, possible to switch the polarization of ScAlN under signal electrode IDTs, ground electrode IDTs, reflectors, or a combination of these for local tuning of the piezoelectric coupling, to program the resonator frequency and $S_{11}$ reflection coefficient as shown in Figure 1B. 200 nm ScAlN films with 22% and 30% doping were deposited on continuous Pt and Mo bottom electrodes respectively by reactive co-sputtering (Sc) of scandium and aluminum (Al) in nitrogen at an external vendor. A double-layer lift-off process was used to evaporate 10 nm/100 nm Ti/Au metal electrodes in the odd-hour evaporator.

The contact pads, routing lines, and test capacitors were patterned using SÜSS MA-6 contact photolithography (smallest features = 3 µm), and the metal IDTs were patterned using JEOL 6300 electron-beam lithography. The IDT widths were designed to 1 µm-400 nm, corresponding SAW frequencies in the 1-3 GHz range.

Figure 2 shows a Zeiss scanning electron microscope (SEM) image and zoom-in of a ScAlN SAW device with 400 nm IDTs including a process simulation to verify high-fidelity contact with the 2-layer evaporation.

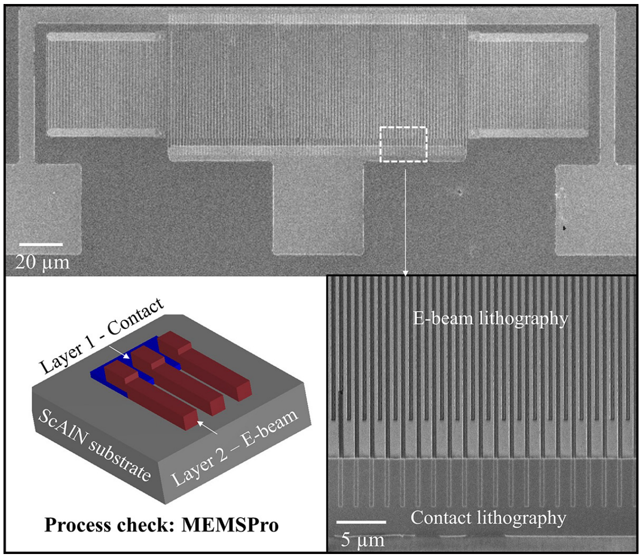

*Figure 2: SEM image of a SAW device with 400 nm IDTs, including a zoom-in view of the overlapping metal layers patterned with e-beam and contact lithography. A 3D isometric view serves as a process check to confirm high-fidelity contact between the two layers.*

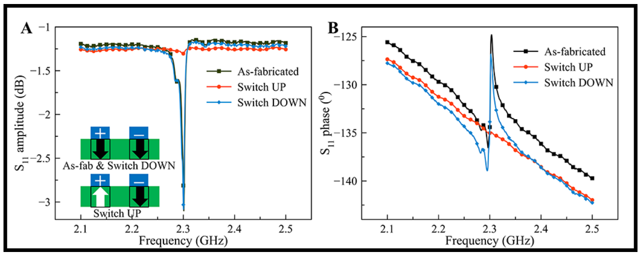

*Figure 3: A) S11 amplitude (in dB) and B) phase (in 0) for a 2.3 GH 22% ScAlN SAW resonator showing two-state ScAlN programming. The as-fabricated, up-switched, and down-switched responses demonstrate reversible polarization switching, which enables turning off of the piezoelectric coupling and its full recovery to demonstrate a programmable resonator.*

## Results:

A setup with continuous wave positive-up-negative-down (PUND) was used for ferroelectric testing of $Sc_xAl_{1-x}N$ [2]. Single-sided triangular pulses of ± 6 MV/cm (larger than the coercive field), were applied to the SAW signal IDTs to sequentially up-switch and down-switch the ScAlN underneath them, followed by $S_{11}$ measurements. Figure 3 shows S11 amplitude and phase responses of a 2.3 GHz 22% ScAlN SAW device for as-fabricated, up-switched and down-switched (±6MV/cm) pulses. The resonance vanishes with up-switching of ScAlN due to an ensemble switching off of the piezoelectricity, but can be fully recovered with down-switching. This process is repeatable over multiple cycles, demonstrating reversible switching of the resonator with minimal ScAlN degradation. The results show a pathway towards a CMOS-compatible filter with programmable frequency and amplitude control.

## 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] 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.

[3] V. Gund, et al., "Towards Realizing the Low-Coercive Field Operation of Sputtered Ferroelectric $Sc_xAl_{1-x}N$," IEEE Transducers, 2021.

[4] V. Gund, K. Nomoto, H. G. Xing, D. Jena, and A. Lal, "Intrinsically Switchable GHz Ferroelectric ScAlN SAW Resonators," IEEE ISAF, 2022.