Design and Implementation of an AlScN-Based FeMEMS Multiplier for In-Memory Computing Applications

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Primary Tools Used: SUS MA-6 contact aligner, CVC SC-4500 Odd-hour evaporator, Zeiss SEM, OEM Endeavor M1, Plasma-Therm Takachi HDP-CVD, Arradiance ALD, AJA sputter deposition, Oxford PECVD, Oxford 81/82, Primaxx Vapour HF Etcher, PT770 Etcher, YES EcoClean Asher, Xactix Xenon Difluoride Etcher, AJA ionmill, Heidelberg Mask Writer-DWL2000, P7 Profilometer, Zygo Optical Profilometer, Flexus Film Stress Measurement

Abstract:

This paper reports on the design, fabrication, and experimental validation of an aluminum scandium nitride (AlScN) based Ferroelectric Micro-Electro-Mechanical Systems (FeMEMS) Multiplier — a core component for multiply-accumulate (MAC) operations in next-generation in-memory computing applications. The FeMEMS multiplier leverages ferroelectric polarization switching in AlScN to change the piezoelectric coefficient (d_{31}), facilitating non-volatile, analog memory storage for weights in a neural network. The piezoelectric parameters of the films are then used to change a capacitive gap for readout. The ferroelectric thin films could be partially polarized and reached a peak remnant polarization of 216 μC/cm^2 at a voltage of 100V V_P (5MV/cm). Experimental results on optically measured displacements confirmed the AlScN unimorph multiplier's operation. The maximum resonance mode displacement was linearly dependent on the polarization and input voltages. This work provides foundational insights into the utilization of AlScN in in-memory computing, opening new avenues for high-speed, low-power, and high-accuracy computing applications.

Summary of Research:

To address the computational limitations of traditional von-Neumann architectures, researchers are exploring in-memory computing. A fundamental building block of this approach is the MAC unit, which is capable of performing matrix multiplication and summative operations [1]. The research highlights the potential of micro and nanoelectromechanical systems (M/NEMS) to provide zero standby leakage power and offer efficient computation [2,3].

The recently discovered ferroelectricity in scandium-alloyed aluminum nitride (AlScN) has enabled the implementation of MEMS MAC units in III-V systems [4,5]. This research presents the design, fabrication, and characterization of a ferroelectric aluminum scandium nitride (AlScN) based programmable nano-electromechanical system (NEMS) multiply and accumulate (MAC) unit.

A 500 μm Si substrate wafer was used to fabricate the ferroelectric unimorph. A 1 μm thermal SiO_2 layer serves as the elastic layer. Next, a continuous layer of sputtered 200 nm Pt was deposited as the bottom electrode. A ferroelectric AlScN film, with a thickness of 200 nm and 22% Sc content, was deposited on this Pt electrode. This film stack was achieved through reactive co-sputtering of scandium (Sc) and aluminum (Al) in a nitrogen environment. Next, a lift.off process was employed to evaporate 10nm/100nm Cr/Au metal top electrodes. Reactive ion-etching and ion-milling were then used to etch through the thin-film stack to fabricate etch-holes for releasing the unimorph. This step was followed by a vapor-phase bulk isotropic etching of the underlying silicon substrate using XeF_2 to release the unimorph. This process flow resulted in the successful creation of released cantilevers, clamped-clamped beams, and membranes, all on the same wafer (Figure 1).

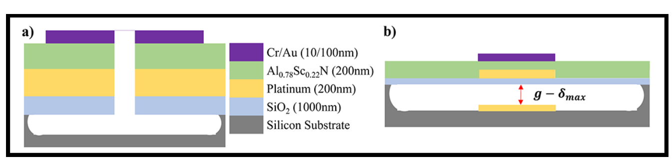
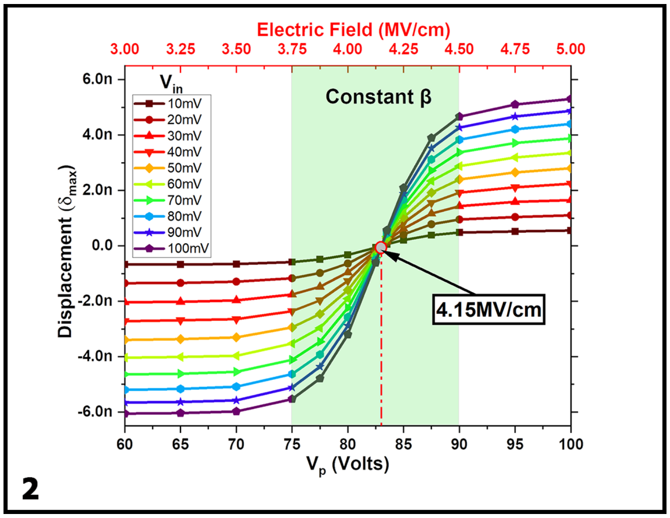


Figure 1: Schematic cross-section view of the FeNEMS.



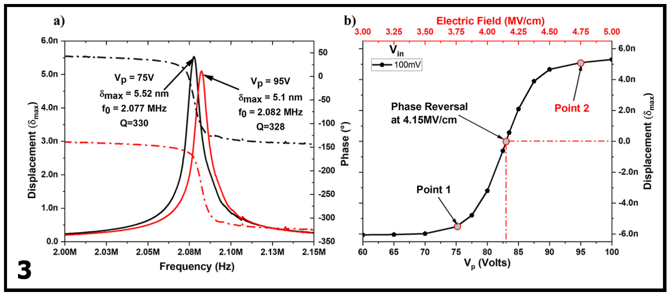


Figure 2, left: The transfer characteristics of the FeMEMS multiplier device. Figure 3, above: Magnitude and phase plot of state 1 (depicted in black) and state 2 (in red) versus frequency, illustrating the characteristic ferroelectric domain reversal phenomenon.

The device operation is based on the principle of partial polarization switching in AlScN. The polarization-switching voltage (V_P) is used to define the weights of the MAC operation. The piezoelectric coefficient (d_{31}) can be tuned by applying varying V_P voltages. The polarization switching was studied using a Radiant Technologies Precision Premier II Ferroelectric Tester. An increase in VP resulted in a gradual increase in the remnant polarization (P_r) until a maximum of $2P_r$ = 216 $\mu C/cm^2$ at V_P = 100V (5 MV/cm).

Once the weights are programmed by applying V_P voltages, the input voltage (V_{in}) is fed to the device to generate an output. The device behaves as a multiplier, where the maximum out-of-plane displacement (δ_{max}) of the unimorph actuator is a scaled product of the V_P and V_{in}. This displacement was measured using a Polytec MSA-400 Laser Doppler Vibrometer (LDV). The device functionality was verified by measuring δ_{max} as a function of V_P and V_{in}. The measurements showed a linear relationship between δ_{max} and the product of V_P and V_{in} for V_P and V_{in} in the range of 75V to 90V, confirming the multiplication operation (Figure 2).

For V_P values greater than the threshold, the polarity of δ_{max} changed, which indicates a reversal in the polarization of the AlScN. This causes a phase change in the unimorph response. This was verified by recording a phase reversal around the V_P = 83.5V, resulting in a zero displacement at this point with a complete phase inversion on either side (Figure 3).

Conclusions:

This research presents an innovative design of a Ferroelectric AlScN-based NEMS MAC unit, leveraging partial polarization switching in AlScN for in-memory computing. This approach enhances latency, power consumption, and operational efficiency in wideband gap III-V platforms, demonstrating the unit's ability to effectively store multi-level computational weights. The device's function as a multiplier was validated through a correlation between maximum displacement, polarization, and applied voltages. Notably, phase reversal was observed at V_P = 83.5V (4.15MV/cm), indicating the device's versatility. The FeMEMS multiplier's minimal standby leakage power and compatibility with III-V platforms enhance its overall efficiency. This study paves the way for future exploration of AlScN in high-speed, low-power, and high-accuracy computing applications, as well as advancements in zero standby power computing.

References:

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