HZO-based FerroNEMS MAC for in-memory computing

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ABSTRACT
This paper demonstrates a hafnium zirconium oxide (HZO)-based ferroelectric NEMS unimorph as the fundamental building block for very low-energy capacitive readout in-memory computing. The reported device consists of a $250 \times 30 \mu m^2$ unimorph cantilever with 20-nm-thick ferroelectric HZO on 1-μm SiO2. Partial ferroelectric switching in HZO achieves analog programmable control of the piezoelectric coefficient ($d_{31}$), which serves as the computational weight for multiply accumulate (MAC) operations. The displacement of the piezoelectric unimorph was recorded by actuating the device with different input voltages $V_{in}$. The resulting displacement was measured as a function of the ferroelectric programming/poling voltage $V_p$. The slopes of central beam displacement ($\delta_{max}$) vs $V_{in}$ were measured to be between 182.9 nm/V (for $-8 V_p$) and $-90.5$ nm/V (for $8 V_p$), which corresponds to displacement proportionality constant $\beta$ of 68 nm/V² for $+ve V_p$ and 47 nm/V² for $-ve V_p$, demonstrating linear behavior of the multiplier unit. The resultant $\delta_{max}$ from AC actuation is in the range of $-18$ to $36$ nm and is a scaled product of $V_{in}$ and programmed $d_{31}$ (governed by the $V_p$). The multiplication function serves as the fundamental unit for MAC operations with the ferroelectric NEMS unimorph. The displacement from many such beams can be added by summing the capacitance changes, providing a pathway to implement a multi-input and multi-weight neuron. A scaling and fabrication analysis suggests that this device can be CMOS compatible, achieving high in-memory computational throughput.

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Neuromorphic computation is of great interest to computing theory and practical implementations due to the potential for low-power, high efficiency, and small form factor information processing with deep neural networks (DNNs). The building blocks of DNNs are perceptron blocks, which inherently necessitate brain-like synaptic functions achieved through arrays of multiply accumulate (MAC) units. With the ever-increasing number of variables required for neuromorphic computation with high accuracy, there is an urgent need to develop highly energy-efficient device architectures. The energy used per MAC unit is, therefore, a useful metric to compare technologies. Ferroelectric field-effect transistors (Fe-FET) have been used to mimic analog synaptic operation with gate-ferroelectric switching in silicon and germanium channel devices to realize multi-level conductance modulation with potentiation and depression with $50-100$ ns switching pulses and $3-5$ MV/cm fields. FET-based in-memory computation architectures are susceptible to large read and write energy consumption and high leakage currents in idle mode, particularly with gate dielectric thickness scaling down to $<$5 nm. Resistive random access memory (RRAM) enables neuromorphic synaptic functionality but necessitates current-based control circuitry that can limit the dynamic range and the effective number of bits. Nano Electro-Mechanical Systems (NEMS) switches and beams offer an alternate pathway to zero-leakage in-memory compute synaptic functionality, provided that the beam actuation has embedded programmable weights in the form of tunable capacitive or piezoelectric coupling. Such switches are especially useful where infrequent update of neuromorphic weights is needed and the analog programming can be done at DC or low frequencies. We have previously reported a graphene-on-HZO ferroelectric device that uses potential gradients across the graphene to achieve fractional switching, with the modulated graphene resistance also used for resistive memory readout. While analog in-memory computing has been demonstrated using different architectures that use transistors or memristors, few prior works have used an NEMS-based approach that takes advantage of a released beam structure to eliminate energy leakage in an idle state. In previous work, the idea of using nanomechanical electrostatic actuators to...
produce MAC units has been described.\textsuperscript{13} In contrast, we present a ferroelectric/piezoelectric beam transducer to enable the multiplication that can be readout capacitively, eliminating any DC currents.

This paper presents a technique to store the neural net weights in the form of the programmable piezoelectric coefficient $d_{31}$ of an HZO-driven unimorph. Similar to a fixed–free unimorph, the fixed–fixed unimorph displacement is proportional to $d_{31}$.\textsuperscript{1} The $d_{31}$ is modulated by applying a polarization switching voltage $V_p$. After polarization programming, different actuation inputs ($V_{in}$) actuate the cantilever such that the unimorph displacement is a scaled product of the form of the programmable piezoelectric coefficient $d$ that can be readout capacitively, eliminating any DC currents.

A ferroelectric/piezoelectric beam transducer to enable the multiplication and stored weights in the form of beam-bending in a unimorph. In addition to the active ferroelectric material properties, beam geometry, Young’s modulus, etc. We can design the multiplier to achieve linear behavior in the transfer characteristics curve along the rising and falling slopes of the PE loop to accomplish a multiplicative function for parallel MAC operations.

For a given $V_p$ and $V_{in}$ the NEMS beam displacement is, a scaled product of weights and inputs (detailed derivation in the supplementary material, Sec. IA)

$$\delta_{\text{max}} = \beta \cdot V_p \cdot V_{in}. \quad (1)$$

Here, $\beta$ is the displacement proportionality constant that depends on ferroelectric material properties, beam geometry, Young’s modulus, etc. We can design the multiplier to achieve linear behavior in the transfer characteristics curve along the rising and falling slopes of the PE loop to accomplish a multiplicative function for parallel MAC operations. Figure 1(c) represents the multiplier unit with a capacitive readout to measure the output voltage. The left and right beams are poled with the same voltage amplitude but opposite polarity. Thus, for the same input voltage $V_{in}$ the left and right beams displace such that the difference between the two represents the product of $V_{in}$ and $V_p$. The differential motion causes differential capacitance between left and right capacitive parallel plates. The output voltage is given by

$$V_{\text{out}} = \frac{V_{dd} \left( \frac{C_l - C_R}{C_l + C_R} \right)}{2g} \delta_{\text{max},L} - \delta_{\text{max},R} = SF \cdot V_p \cdot V_{in}. \quad (2)$$

Here, $\delta_{\text{max},L}$ and $\delta_{\text{max},R}$ are left and right beam center displacements with initial gap $g$. $\gamma$ is a constant, which relates $\delta_{\text{max}}$ to the parallel plate displacement at sense electrode (see the supplementary material, Sec. IA, for detailed derivation). Several multipliers can then be

![FIG. 1. (a) PUND loop of 20-nm-thick HZO film. (b) Polarization-dependent bending moment generated in ferroelectric-on-elastic unimorph at various points along the PE loop (E$_C$ is coercive field). (c) Schematic for multiplier unit with ferroelectric actuation and capacitive readout. The output voltage is the product of $V_{in}$ and stored weights in the form of $d_{31}$ coefficients. (d) Several multipliers with capacitive readout can be placed in parallel to form a MAC unit that can perform accumulation operation by summing up the capacitances from each device.](image-url)
further connected in parallel with an activation unit to form a perceptron. The output voltage of the MAC unit [Fig. 1(d)] is

$$V_{out\ MAC} = V_{dd} \sum_{i=1}^{N} C_{L,i} - \sum_{i=1}^{N} C_{R,i} = SF \sum_{i=1}^{N} V_{p,i} \cdot V_{in,i}. \quad (3)$$

Figures 2(a) and 2(b) show the top and cross section views, respectively, of the clamped-clamped ferroelectric unimorph used to demonstrate piezoelectric coefficient programming. 1-μm-thick thermal SiO₂ forms the elastic layer underneath 20 nm ferroelectric HZO. The HZO is capped by 3 nm of alumina (Al₂O₃), followed by annealing at 400 °C to crystallize the HZO in its ferroelectric orthorhombic phase. 200 nm platinum (Pt) and 100 nm aluminum (Al) were deposited to form the bottom and top metal contacts for the HZO, respectively. The beam was released by isotropic etching of the silicon substrate using Xactix XeF₂ etcher (full process flow shown in the supplementary material, Sec. II). A scanning electron microscope image of the fabricated device is shown in Fig. 2(c). After release, the beams were observed to be buckled due to residual film-stress generated during microfabrication. A 3D optical profilometer (Zygo TM system) was used to measure the beam buckling profile [Fig. 2(d)]. The observed center-buckling for a 250 × 30 μm² was 4.98 μm.

HZO ferroelectric characterization was performed using a Sawyer–Tower circuit configuration on a custom probe station with continuous wave (CW) positive-up-negative-down (PUND) input waveforms to extract the coercive field (E_C) and remnant polarization (P_r). In prior work, we have used electrical breakdown under a large top metal pad to contact the bottom electrode with 5–10 Ω resistance. The PUND input signal has 83 μs rise, fall, and wait times (corresponding to 1 kHz PUND frequency), and a peak-to-peak amplitude of 15 V. Figure 3(a) shows time-domain input voltage and output sense current measured with an 11.8 kΩ sense resistor. The P and N pulses show a switching current peak below the peak voltage, indicative of polarization switching, whereas the U and D pulses show capacitive displacement current and low leakage. This confirms ferroelectricity in the released HZO films without any degradation, consistent over more than 10,000 cycles of switching with CW operation. Figure 3(b) plots the switching current density (J) vs E-field. The PUND measurement was performed on multiple such released NEMS beams with a range of lengths from 100 to 400 μm and widths spanning 15–39 μm. The overlay from these measurements is shown with multiple dotted lines in Fig. 3(c). For comparison, the PUND loop for an unreleased 80 μm diameter circular electrode is also shown on the same plot (solid black line). This shows that there is little/no degradation of ferroelectric properties of the HZO before and after release; P_r is unchanged and E_C has a small increase in ~14%, a likely result of the reduced slope-steepness of the PE curve, due to stress relief in released devices. Multiple release devices with different electrode sizes show overlapping loops suggesting high repeatability. PUND measurements yield an extracted E_C ≈ 1.5 MV/cm and P_r ≈ 10 μC/cm², consistent with previously reported values. The devices were also tested for DC breakdown as shown in Fig. 3(d). The device’s current density exceeds 10 μA/cm² at 3.15 MV/cm.

The central concept of this work is to use analog weight storage in the bending motion of the NEMS beam for in-memory computation, which relies on the programming of the d31 coefficient of the device by using different poling voltages. The test methodology used for this experiment is as follows:

**Step 1:** Device poling with CW single-sided pulses at 3 kHz. The configuration used for poling is depicted in Fig. 3(a) (inset). The test signal is applied to the top electrode, and the ground

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**Fig. 2.** (a) Schematic top and (b) cross-sectional view of the ferroelectric beam. (c) Scanning electron microscopy (SEM) image of the beam showing released structure. (d) 3D profile of the released beam measured using Zygo TM profilometer showing beam curvature due to residual stresses in the stack. For 250 × 30 μm² beam, the measured maximum displacement at the center was 4.98 μm.
connection is made to the bottom electrode by breaking down the 
HZO under a large top metal pad to short it to the bottom 
electrode.

**Step 2:** Beam actuation with a small $V_{in}$ to measure the displacement amplitude, without additional polarization switching.

**Step 3:** Increase poling voltage by 0.5 V and repeat steps 1–2, while tracing the PE loop counterclockwise from 0 V to $8 \pm 0$ V.

This voltage sweep for $V_p$ is similar to the PUND loop with one key difference. In this technique, we stepped the $V_p$ by 0.5 V and then measured the beam displacement with a fixed $V_{in}$ amplitude, unlike the PUND measurements in CW operation with increasing voltages.

A Polytec MSA-400 laser Doppler vibrometer (LDV) was used to measure the beam motion. For a $250 \times 30 \mu m^2$ beam, a 0.1 V amplitude frequency chirp from 1 kHz to 1 MHz was applied. A resonance at $f_0 = 455.23$ kHz was identified with a quality factor of $Q = 305$. After each poling, AC voltage $V_{in} = 0.1$ V was used to actuate and measure amplified beam displacement at $f_0$ to achieve improved displacement resolution compared to low-frequency or DC actuation. Figure 4(a) shows the peak beam displacement $d_{max}$ and resonant frequency $f_0$ vs poling voltage $V_p$ plot for the nominal $250 \times 30 \mu m^2$ ferroelectric clamped–clamped beam. $d_{max}$ (red line) is modulated for different values of $V_p$ and traces a hysteresis loop, similar to the PE loop from PUND measurements. The net effect of the number of upward and downward pointing dipoles that control the macroscopic polarization in the beam (induced due to $V_p$) also changes the beam stiffness resulting in resonance frequency modulation (black line), which presents a separate modality of weight storage in the beam. The two dips in $f_0$ correspond to the positive and negative coercive fields of the HZO film, where the net polarization is almost zero. As illustrated in Fig. 1(b), domain randomization is a potential cause for likely film relaxation at these points causing $f_0$ to drop.

From Fig. 4(a), the positive linear dependence of $d_{max}$ can be seen in the voltage interval $2.5 V \rightarrow 8 V$ (rising slope). Similarly, negative linear dependence in the interval $-2.5 V \rightarrow -8 V$ (falling slope). Here, the slope of $d_{max}$ vs $V_p$ for constant $V_{in}$ is $\beta$ as defined in Eq. (1). The effect of $V_{in}$ on $d_{max}$ is explained in paragraph. Two points were selected on the positive slope to show the resonance vibration magnitude and phase plots of the vibrating beam [Fig. 4(b)]. Points 1 and 2 have nearly the same displacement magnitude but exactly opposite phases. This 180° phase difference is a signature of polarization

**FIG. 3.** (a) Plot of input voltage and output current over 1 PUND cycle showing much larger switching currents as compared to leakage currents. (Inset) Configuration for poling the NEMS beam. (b) Switching-current density ($J$) vs electric field ($E$) showing ferroelectric switching peaks. (c) Measured PE characteristics of released beam devices with different lengths and widths showing repeatability. The measured PE loop of the standard unreleased circular electrode is shown with a solid black line. (d) DC-IV of the device showing high current density above 3.15 MV/cm indicating leakage.
inversion corresponding to a sign change for $d_{\text{max}}$. To show the effect of $V_{\text{in}}$ on $d_{\text{max}}$, $V_{\text{in}}$ was swept from 0.02 to 0.20 V for different values of the $V_{p}$ [Fig. 5(a)].

Figure 5(a) plots $d_{\text{max}}$ vs $V_{\text{in}}$ at different values of $V_{p}$, which emulates the transfer characteristics of the analog multiplier. For a fixed poling voltage, an input voltage sweep yields a linear increase in displacement value. Similarly, for constant inputs, different poling voltages outputs different displacement values. The slope of the plot in Fig. 5(a) is the experimental $\beta/C_{2} V_{p}$. We can calculate the displacement proportionality constant $\beta$ from Fig. 5(a) as follows:

$$\beta = \frac{d_{\text{max}}}{V_{p} V_{\text{in}}}$$

Equation (4) demonstrates that $d_{\text{max}}$ is the scaled product of inputs ($V_{\text{in}}$) and weights ($V_{p}$). This is a linear equation in the range of $-5.5$ to $8$ V $V_{p}$ and $0$ to $0.2$ V $V_{\text{in}}$ for the device tested here ($250 \times 30$ $\mu$m$^2$ beam).

Figure 5(b) shows the experimentally measured values of $\beta$ in the positive (rising edge of PE) and negative (falling edge of PE) regions are 68 and 47 nm/V$^2$, respectively. Both values are relatively constant over the range of $\pm 5.5$ to $\pm 8$ V $V_{p}$. Thus, our assumption of constant $\beta$ and in turn constant SF holds true. An asymmetry of the electrodes (Al on top and Pt on bottom) as well as the presence of any non-switchable polarization in the material is likely the reason for difference in the negative and positive $\beta$ value. Thus, for the same $V_{p}$ actuation with opposite polarity will have an unequal effect on the partial polarization resulting in different $d_{\text{max}}$ values. This inequality can be mitigated by scaling $V_{p}$ accordingly (see the supplementary material, Sec. IB, for more details).
frequency-tuning was also observed, which can be further explored to achieve an electrically reconfigurable filter. For a $250 \times 30 \, \mu m^2$ beam poled at 8 V, $\delta_{\text{max}} = 18 \, \text{nm}$ and $f_0 = 455.23 \, \text{kHz}$ was measured with a $Q = 305$. The $\delta_{\text{max}}$ vs $V_{\text{in}}$ plot at different values of $V_p$ demonstrate the operation of an analog NEMS multiplier. While this study uses AC actuation of the beam, in the future, DC input voltages are anticipated for DNN applications. A capacitive readout of the beam motion can be used instead of a topical readout for much higher resolution [as illustrated in Fig. 1(c)].

The dimensional and voltage scaling of the prototype device demonstrated is critical for CMOS-integrated adoption while maximizing computational throughput. For CMOS compatibility, <1 V operation is necessary. This sets an upper bound for HZO film thickness of <7 nm for $E_r = 1.5 \, \text{MV/cm}$. Non-resonant actuation of the devices would require a settling time of $\sim 2Qf_p$. Assuming two operations per device, multiplication and addition, the computation speed (FLOPS per device) and power consumption can be estimated as $f_p$ and $E_p$, respectively. Here, $E$ is the energy per operation for an individual device given by $\frac{1}{2} C_{\text{HZO}} V_p^2$. For example, a unimorph device of size $5 \times 0.5 \, \text{mm}^2$ and thickness 28 nm (4× HZO thickness) with a $Q = 10$, which can be realized by high-pressure gas damping, yields $f_p \sim 20 \, \text{MHz}$ and computation speed of 2 MFLOPS/device.

Considering driving electrodes of size $1 \times 0.3 \, \text{um}$ with 7-nm-thick HZO between $V_{\text{in}}$ (0.1 V) and GND, the energy consumption per operation can be calculated as $\sim 500 \, \text{aJ}$ ($E = \frac{1}{2} C_{\text{HZO}} \cdot V_{\text{in}}^2$). Combining both results results in 2 PFLOPS/watt computational performance. This computation speed with ultra-low energy consumption and zero leakage current will pave the path toward brain-level computation efficiency.

See the supplementary material for further details.

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**AUTHOR DECLARATIONS**

**Conflict of Interest**

The authors have no conflicts to disclose.

**Author Contributions**

Shubham Avinash Jadhav: Conceptualization (equal); Data curation (lead); Formal analysis (equal); Methodology (lead); Visualization (lead); Writing – original draft (equal); Writing – review & editing (equal).

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**DATA AVAILABILITY**

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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