

Impact of Device Materials on Neuromorphic Circuits

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Abstract. Facing the rapid development and energy-efficiency demands of artificial intelligence and neuromorphic computing, traditional von Neumann architectures struggle with storage and power consumption bottlenecks. Neuromorphic devices, as next-generation computing technologies, have been validated using machine-learning software and CMOS hardware, but still face issues in power consumption and learning speed. This paper introduces four distinctive device mechanisms. Zein-based memristive synapses combine biocompatibility with mechanical flexibility, offering a naturally sustainable solution for wearable neuromorphic systems. Low-dimensional nanomaterials exploit quantum confinement and van der Waals heterojunctions to realize ultra-low-energy plasticity and gate-tunable multistate storage, outperforming conventional CMOS in integration density and energy efficiency. Y_2O_3 memristors, analyzed via coupled electro-thermal modeling, demonstrate that surface roughness and yttrium oxygen-reservoir layers strongly modulate conductive-filament stability and switching voltages, providing quantitative guidelines for nanoscale interface engineering. WO_{3-x} -based electrochemical random-access memory leverages oxygen-rich/oxygen-poor phase separation to achieve non-volatile retention under short-circuit conditions, satisfying the requirements of low-power inference chips. These material pathways collectively drive neuromorphic hardware toward brain-like, scalable, and ultra-low-power computation.

Keywords: Neuromorphic, Zein, nanomaterials, Y_2O_3 , WO_{3-x}

1. Introduction

Neuromorphic computing is a brain-inspired computational paradigm that emulates the activity of neurons and the connectivity among synapses to achieve high efficiency. Unlike the conventional von Neumann architecture, it co-locates information processing and storage, thereby enhancing computational efficiency and reducing energy consumption. Neuromorphic circuits constitute the hardware foundation of neuromorphic computing and typically comprise circuits that emulate neurons and synapses; they perform computational tasks by mimicking membrane-potential dynamics and spike-generation mechanisms [1]. The properties of the devices dictate the properties of the circuits. Memristive devices are electronic elements whose internal states can be reversibly modulated by electrical stimuli, enabling non-volatile, continuous, or discrete tuning of resistance, and have been intensively investigated as artificial synaptic devices [2]. To overcome the limitations

of traditional CMOS circuits and to address diverse application and power demands, devices with distinct material properties must be developed. This study examines four materials — zein, low-dimensional nanomaterials, Y_2O_3 , and WO_{3-x} — using a cross-scale approach. Experiments include thin-film device fabrication, bending tests, biocompatibility assessments, and MNIST evaluations. Theoretically, electro-thermal models elucidate conductive-filament evolution. Characterization involves in-situ TEM, EDS, and spectroscopy to link defects with electrical properties. This provides design guidelines and evidence for neuromorphic chips targeting wearability, high density, and low power, advancing devices from prototypes to practical use.

2. Biocompatible artificial synapses based on a zein active layer derived from maize

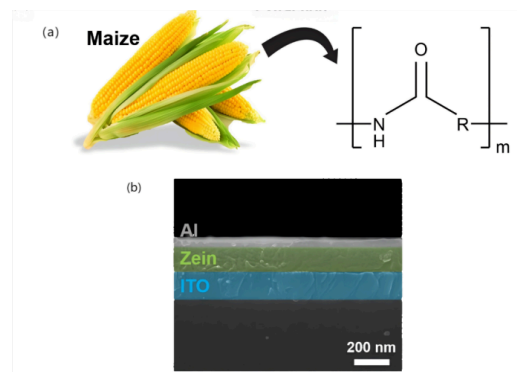


Figure 1. (a) Optical images of the maize and the zein powders, and chemical structure of zein. (b) Cross-sectional SEM image of the Al/zein/ITO structure [3]

Zein protein, extracted from natural maize in Fig 1(a), was dissolved in a mixture of methanol, ethanol, isopropanol, and acetic acid to prepare a homogeneous 1 wt% solution. This solution was then spin-coated onto a clean, dry ITO substrate at 2000 rpm for 40 s, forming an active layer approximately 185 nm thick after thermal curing at 50 °C. A top aluminum electrode (250 μm diameter, 40 nm thickness) was deposited via thermal evaporation, completing the Al/Zein/ITO memristive device, as shown in Fig 1(b). Biocompatibility tests confirmed the device's high biosafety, with zein films showing no cytotoxicity towards normal human dermal fibroblasts (HS27 and Detroit551 cell lines) after 72 hours of exposure at concentrations up to 100 μM . Electrical characterization revealed stable bipolar resistive switching (BRS) behavior, with SET and RESET voltages of 0.62 ± 0.16 V and -2.20 ± 0.23 V, respectively, and a high resistance ratio ($R_{\text{ON}}/R_{\text{OFF}}$) of $\sim 4 \times 10^4$. The underlying switching mechanism was attributed to the dynamic formation and rupture of carbon-based conductive filaments (CFs) induced by Joule heating [4-5]. For neuromorphic functionality, the device successfully emulated synaptic weight plasticity: its conductance was progressively modulated by training pulses. The energy consumption per event for potentiation and depression operations was remarkably low, measured at 0.08 μW and 0.41 μW , respectively. Furthermore, the application of more than 10 programming pulses triggered the transition from short-term memory (STM) to long-term memory (LTM), accurately mimicking biological synaptic behavior. A single-layer neural network based on this device achieved an accuracy of 87.59% in the Modified National Institute of Standards and Technology (MNIST) handwritten digit recognition task. Crucially, the device demonstrated exceptional mechanical robustness, with performance variations remaining below 2% even under mechanical stress induced by bending to a radius of 3.5 mm. This study pioneers the use of zein for constructing high-performance artificial synapses that combine biocompatibility and flexibility, paving the way for

wearable and implantable neuromorphic electronics. However, the long-term biosafety of such devices within physiological environments requires further validation [3].

3. Low-dimensional nanomaterials

Zero-Dimensional (0D) Materials primarily encompass semiconductor quantum dots (QDs) and metal nanoparticles. Materials can be synthesized as InAs/InGaAs and CsPbBr₃ perovskite colloidal QDs [6]. Additionally, ReRAM can be realized by embedding metal nanoparticles and QDs into organic or inorganic matrices. The multi-band emission of QDs allows for emulating both excitatory and inhibitory synaptic responses, though integration with photonic waveguides remains challenging. Bottom-up synthesis provides atomically precise size and structure, enabling short-term and long-term plasticity under electrical and optical stimuli. QDs also enable quantum memristors based on Josephson junctions and quantum neural networks based on QD arrays. However, the ultimate realization of quantum neural networks requires quantum coherence between QDs and high-mobility semiconductors, unlike the metal oxides typically used [7].

One-Dimensional (1D) Materials mainly include carbon nanotubes (CNTs), semiconductor and inorganic nanowires, and polymers. CNT-based thin-film transistors (TFTs) can be fabricated using aligned arrays or random networks, serving as synaptic transistors or integrated with vertical metal oxide memristors in 3D architectures [8]. Single-walled CNTs are pursued for post-silicon digital logic due to their high charge carrier mobilities. However, the intrinsically lateral geometry of CNT synaptic transistors limits their density in crossbar arrays and typically lacks inherent NVM functionality. Polymers offer advantages such as mechanical flexibility, biocompatibility, and chemical sensitivity, exploited in memristors and organic electrochemical transistors (OECTs). Integrating CNT logic layers with memristors in 3D architectures enhances sensing efficiency [7].

Two-dimensional (2D) materials, such as graphene, transition metal dichalcogenides (TMDs), and hexagonal boron nitride (h-BN), are ideal for neuromorphic sensing due to their atomic-scale thickness and tunable bandgap. Devices constructed with them can efficiently emulate biological synaptic plasticity (LTP/LTD), enabling low-energy multimodal perception. However, grain boundary defects inherent in material synthesis lead to insufficient device uniformity (>20% variation), and the integration yield of heterostructures remains below 80% [9]. Future efforts focus on defect-engineered materials and wafer-scale 3D stacking technologies, coupled with spiking neural network architectures, to ultimately achieve brain-level energy efficiency (10⁻¹⁵ J/event) in bio-inspired perception systems, driving breakthroughs in applications such as medical robotics and environmental monitoring [10].

4. Functional oxides: Y₂O₃

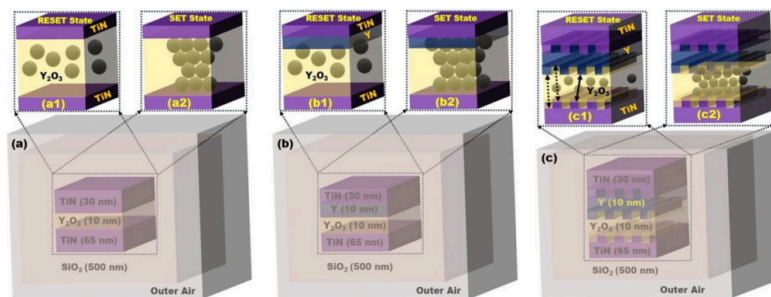


Figure 2. Three-dimensional (3D) memristor structure used in COMSOL Multiphysics with associate external device environment comprising: (a) TiN/Y₂O₃/TiN, (b) TiN/Y₂O₃/Y/TiN [11]

The memristor device structure utilizing nanoscale Y_2O_3 features a stacked design of TiN(65 nm)/ Y_2O_3 (10 nm)/TiN(30 nm) or TiN(65 nm)/ Y_2O_3 (10 nm)/Y(10 nm)/TiN(30 nm), as illustrated in Fig. 1a-b. The yttrium metal layer acts as an oxygen reservoir, enhancing conductive filament (CF) stability and reducing switching voltages. The formation and rupture of CFs dictate the device's low- and high-resistance states. Y_2O_3 demonstrates high endurance for long-term data retention [12], low variability, and multilevel current programming capabilities. CF formation involves ion migration, redox reactions, and oxygen vacancy dynamics.

Surface perturbation height (0.1–1.5 nm) significantly affects switching characteristics: higher perturbations enhance localized filament formation, reducing SET/RESET voltages, but may lead to RESET failures due to non-uniform CF heights. The ON/OFF current ratio decreases linearly with increased perturbation, while shorter CF lengths at higher perturbations raise filament temperatures. Y_2O_3 memristors emulate synaptic learning and support multi-state storage, making them suitable for neural network weight updates [12]. However, voltage fluctuations and reduced ON/OFF ratios may impair synaptic plasticity precision. Future work should aim to control surface perturbations and integrate oxygen reservoir layers for improved reliability in neuromorphic computing [Conclusions]. Limitations include unresolved RESET failures at high perturbations, as shown in Fig. 6a, and insufficient validation of thermal field distributions in sub-10-nm devices [11].

5. Phase separated oxide: WO_{3-x}

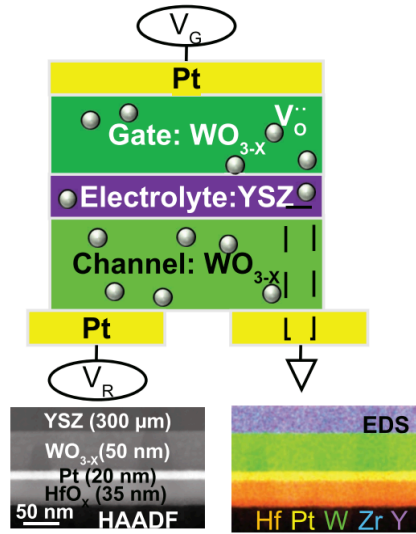


Figure 3. Tungsten suboxide based ECRAM cell used in this work. a) Schematic and cross-section TEM of the WO_{3-x} ECRAM cell. This cell stores and switches analog information states as the concentration of oxygen vacancy ions in the channel [13]

ECRAM is a non-volatile memory technology based on the reversible migration of ions between solid electrolytes and electrode materials, often regarded as a specialized category of emerging resistive random-access memory (ReRAM). An amorphous WO_{3-x} channel layer was fabricated on a single-crystal YSZ substrate via reactive sputtering, with its oxygen vacancy concentration validated by EDS as $x \approx 0.5$. An HfO_x passivation layer was integrated to suppress environmental oxidation, with the entire process meeting BEOL thermal budget compatibility requirements, as shown in Fig 3 [14]. This ECRAM device demonstrated breakthrough performance, achieving over 200 linear symmetric analog state switches under ± 2 V stimulation, with a write current density as low as 10^{-14}

A/ μm^2 , approaching key neuromorphic computing metrics [15,16]. Importantly, the conductance state displayed non-volatile characteristics under short-circuit conditions. At 200°C, high- and low-resistance states showed stable retention for over 24 hours, with an extrapolated retention time exceeding 150 hours. This stability arises from irreversible changes in oxygen vacancy concentration due to phase separation. Using a temperature extrapolation model based on a 1.2 eV activation energy for ion transport in YSZ, the projected retention time at 85°C is estimated to be 15–35 years, aligning with industrial benchmarks for ReRAM and phase-change memory. However, challenges remain, including conductance degradation in the low-resistance state during high-temperature retention due to slow oxidation by residual oxygen, as the passivation layer does not fully block oxygen permeation. The kinetics of phase separation are still unclear, potentially involving electric double-layer relaxation or nucleation barriers. Advanced in situ characterization techniques are needed for direct verification of amorphous phase-separated microstructures [13]. These achievements signify a pivotal paradigm shift in the ECRAM field. The phase separation effect in WO_{3-x} enhanced retention time by 3–4 orders of magnitude compared to conventional ECRAM, laying the foundation for building high-efficiency neuromorphic inference engines [15]. Future developments should focus on sub-micron thin-film YSZ electrolytes to accelerate ion transport and enable CMOS integration, while exploring phase-transition materials like $\text{SrCoO}_{2.5}$ to address switching kinetics bottlenecks [13].

6. Conclusion

This paper centers on the urgent demand for high energy efficiency in neuromorphic computing and focuses on how physical mechanisms at the device level dictate performance. The paper concludes that the four representative material pathways collectively drive neuromorphic hardware toward brain-like, scalable, and ultra-low-power operation while furnishing universal design rules and experimental evidence for cross-material engineering. Future efforts should prioritize cross-material heterogeneous integration, combining natural organics, low-dimensional nanomaterials, functional oxides, and electrochemical memories. This approach aims to address diverse applications, including wearable electronics, edge intelligence, and cloud-based neuromorphic computing. Additionally, researchers should explore wafer-level 3D stacking, back-end-of-line (BEOL) compatible processes, and solution-based manufacturing methods to facilitate the transition from laboratory prototypes to large-scale commercial deployment. By pursuing these avenues, we can enhance the versatility and scalability of neuromorphic technologies, ensuring they meet the demands of various real-world scenarios.

However, the paper exhibits certain shortcomings in bridging material exploration with application implementation. Although it showcases the performance merits of individual materials, it lacks an in-depth discussion of how to realize material complementarity and cooperative optimization within a single chip or system, and should therefore further investigate heterogeneous integration and cross-platform compatibility.

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