3D Stackable Ferroelectric Nanodendrite for Asynchronous Spike-Sequence Decoding

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Three-dimensional (3D) integration intensifies thermal constraints because volumetric heat generation increases faster than surface-limited heat dissipation. Spike-order–based dendrocentric computing mitigates this bottleneck by encoding information in temporal permutations rather than spike rate or amplitude, enabling energy consumption to scale with spike events rather than clocked frequency [1]. While spike-sequence decoding has been previously demonstrated using Si-channel ferroelectric devices [2], those implementations require high-temperature front-end processing (> 600 °C) and are therefore not back-end compatible, preventing monolithic 3D integration with permutation networks.

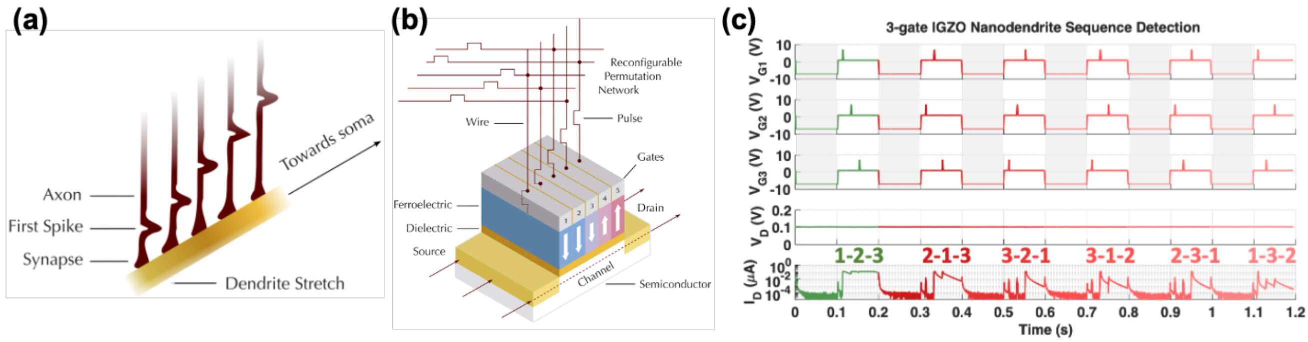

Figure 1: (a) Biological dendrites detect spike sequences. (b) Schematic of the multi-gate FeFET nanodendrite implementing spike-sequence decoding. (c) Measured spike-sequence discrimination in the three-gate IGZO/HZO nanodendrite. Only the correct order (1–2–3, green) reaches the compliance limit (100 nA); other permutations pass at most a tenth of this current.

Inspired by biological dendrites (Fig. 1(a)), here we present a three-gate ferroelectric nanodendrite that functions as a spike-sequence decoder (Fig. 1(b)). This multi-gate architecture can be naturally extended to more than three inputs, enabling higher-order sequence decoding. The device uses an amorphous IGZO channel with an HZO ferroelectric layer and is fabricated entirely below 400 °C for monolithic 3D integration above CMOS. While IGZO-based ferroelectric transistors have been previously reported [3], their operation has been limited to memory functionality, and sequence decoding has not been demonstrated. The 3-gate IGZO-based FeFET nanodendrite has a ~4 V memory window and enables immediate readout after programming (which is not the case for FeFET reported in the literature [4]). When stimulated with all six permutations of three input pulses, only the canonical sequence produces a high-current state, while incorrect orders remain suppressed by 1 to 3 orders-of-magnitude (Fig. 1(c)). This large current contrast enables robust asynchronous spike-sequence discrimination, establishing the ferroelectric nanodendrite as a compact device primitive for spike-sequence computing in thermally scalable 3D neuromorphic systems.

[1] Boahen, K., Nature, 612, 43–50, 2022. [2] H. J.-Y. Chen et al. IEDM, 2023. [3] Yoo, S., Kim, T.J., Nam, SG. et al. Nature 648, 320–326, 2025 [4] K. Toprasertpong, et al., Appl. Phys. Lett., 116, 242903, 2020. This work is supported in part by the NSF BRAID (2223827), SRC JUMP 2.0 CHIMES Center, member companies of the Stanford Non-Volatile Memory Technology Research Initiative (NMTRI), Stanford HAI Hoffman-Yee Research Grants and AFOSR ExPlor Center (FA9550-22-1-0532).