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Relaxor ferroelectrics for neuromorphic computing

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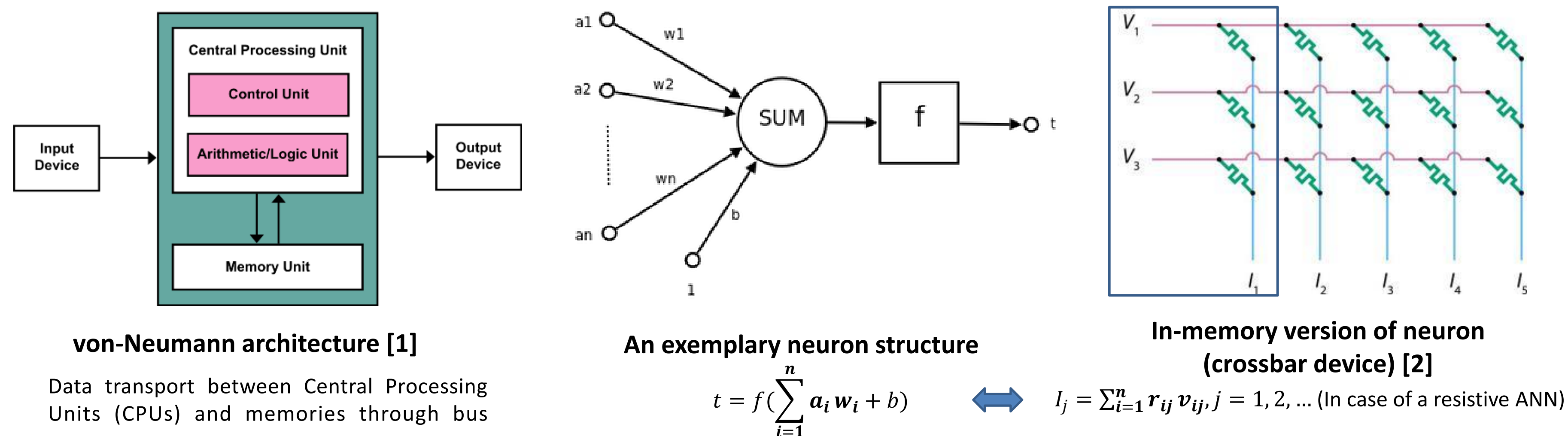
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Context

Neuromorphic computing: Recreating brain functions using Artificial Neural Networks (ANN) and its hardware implementations. Essential units: neurons and synapses

Conventional ANN: von-Neumann architecture, computing outside of memory, high energy consumption due to data transportation ("von-Neumann bottleneck")

Compute-in-memory (CIM): emerging solution of the von-Neumann bottleneck

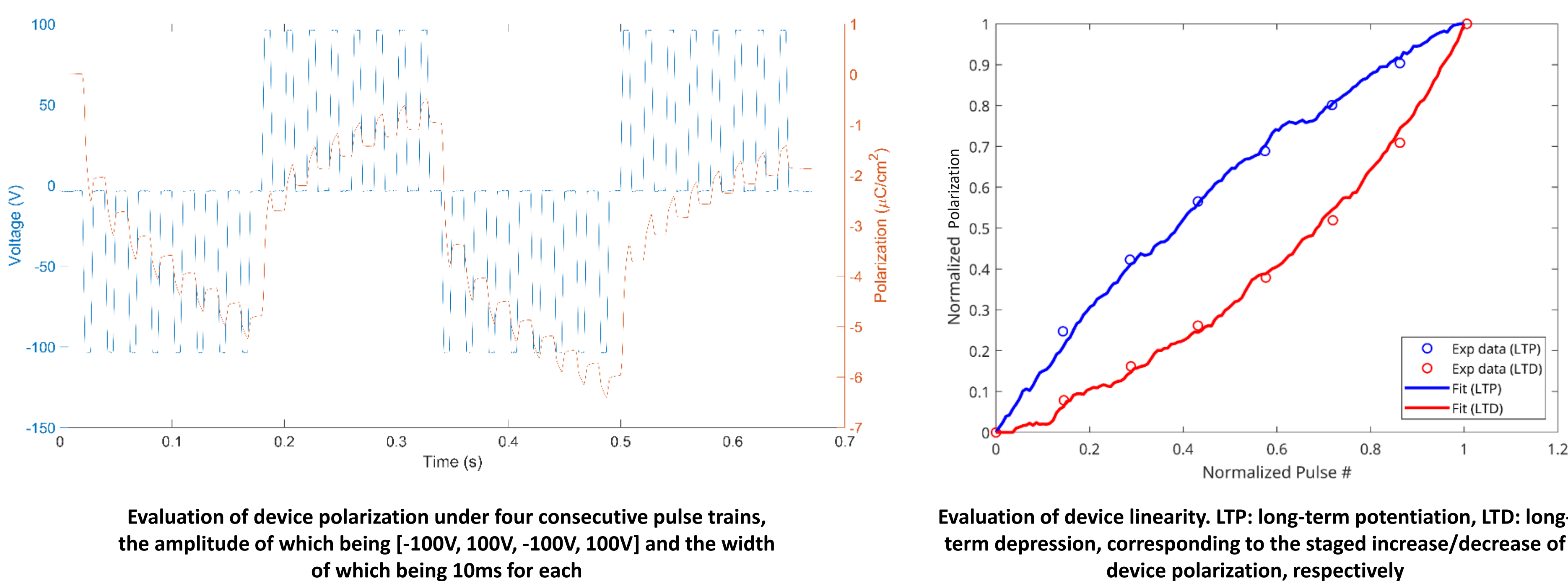


Requirements for analog states in crossbar device: nonvolatile, readily programmable, high ON/OFF ratio, long retention time, good endurance

Devices used in crossbar ANNs: resistive devices, ferroelectric diodes, **capacitive devices** (most promising due to its near-zero static power)

State Establishment of Relaxor Ferroelectrics

The evaluation of the state establishment ability of PZN-4.5PT was performed. Four consecutive pulse trains with the amplitude of [-100V, 100V, -100V, 100V] and the width of 10ms were applied to the material.



Observations:

- (1) PZN-4.5PT demonstrates distinct long-term potentiation (LTP) and long-term depression (LTD) behavior, showing the ability of manageably updating device state and mimicking the biological synapses of human brain;
- (2) PZN-4.5PT shows the ability to access multiple polarization states by simply changing the profile of applied electric pulse;
- (3) The linearity factor A of PZN-4.5PT is derived from [3,4]

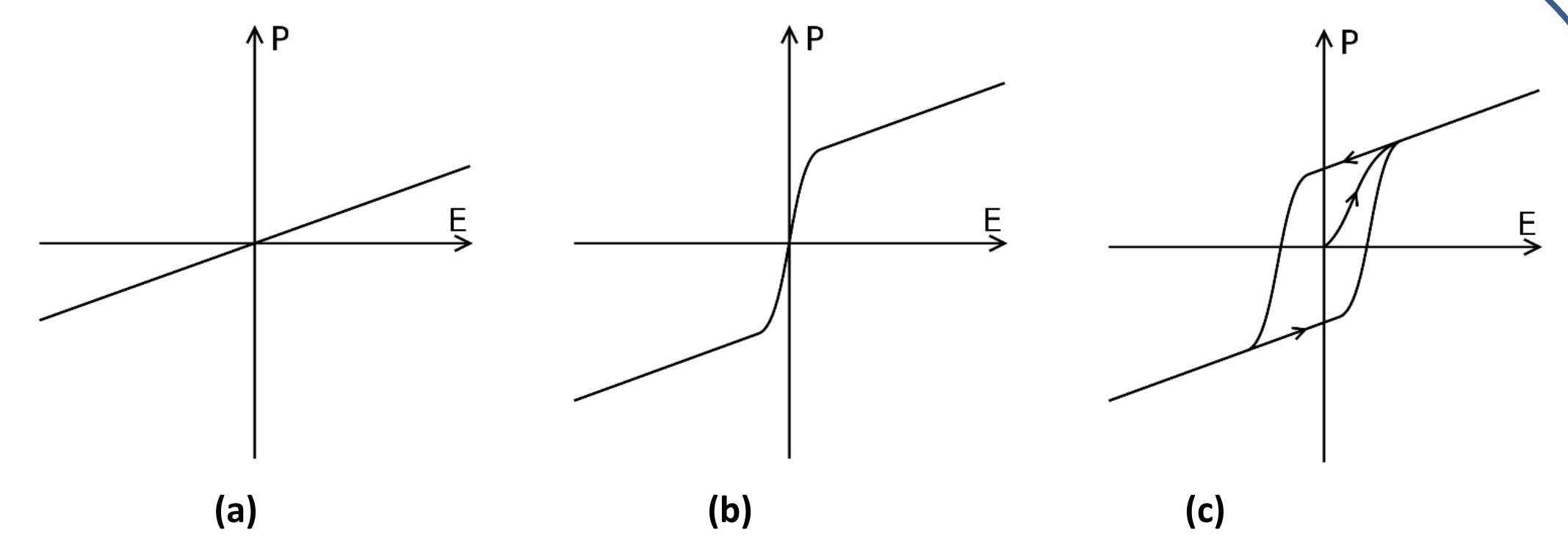
$$\begin{cases} P_{LTP} = B \left(1 - \exp\left(-\frac{N}{A}\right) \right) + P_{min} \\ P_{LTD} = -B \left(1 - \exp\left(-\frac{N - N_{max}}{A}\right) \right) + P_{max} \\ B = \frac{P_{max} - P_{min}}{1 - \exp\left(-\frac{N_{max}}{A}\right)} \end{cases}$$

where P stands for device polarization, N stands for number of pulses, and P_{min} , P_{max} and N_{max} were extracted from the experimental data.

The calculated A equals to **1.28** for long-term potentiation (LTP) and **-2** for long-term depression, ensuring relatively low accuracy degradation during the learning works [4].

From the observation above, we can conclude that PZN-4.5PT is a potential candidate for neuromorphic computing.

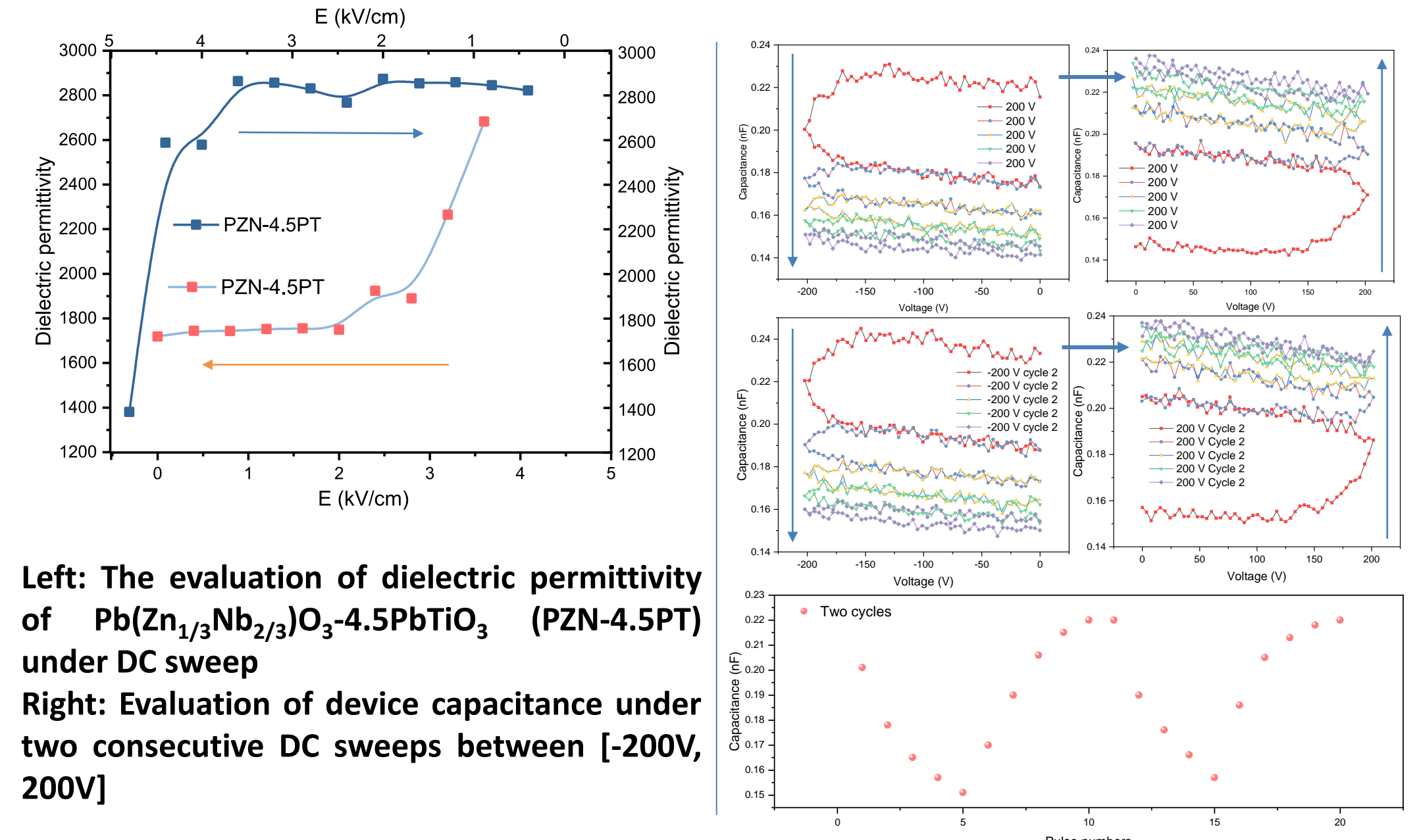
Relaxor Ferroelectrics



Polarization - Electric field (P-E) relationship of (a) linear dielectric, (b) paraelectric, and (c) ferroelectric materials

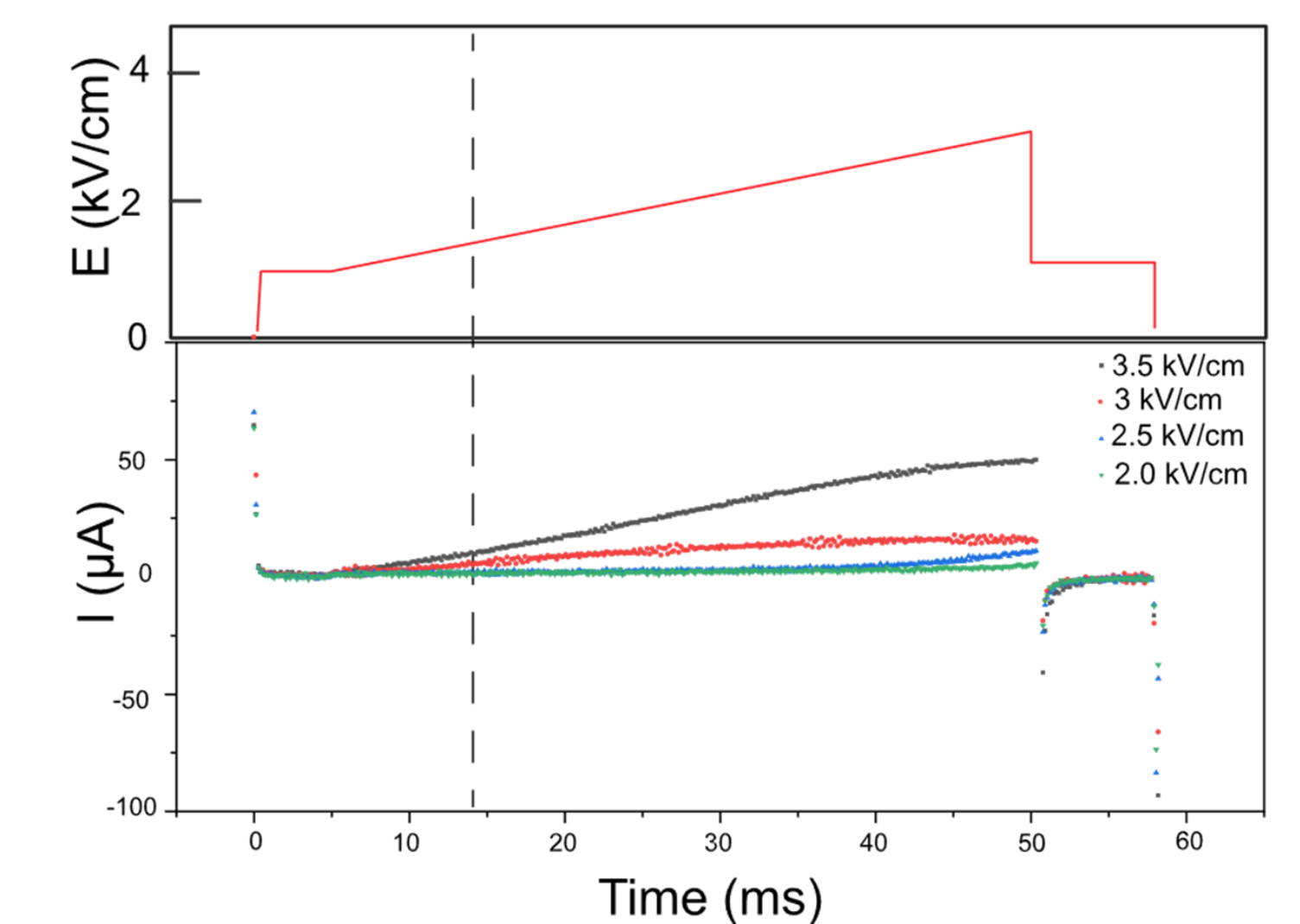
Relaxor ferroelectrics: a category of ferroelectric materials with with strong electric field instabilities, permitting readily state programming

Representative RFEs: PMN, PZN, PMN-xPT, PZN-xPT, PLZT...

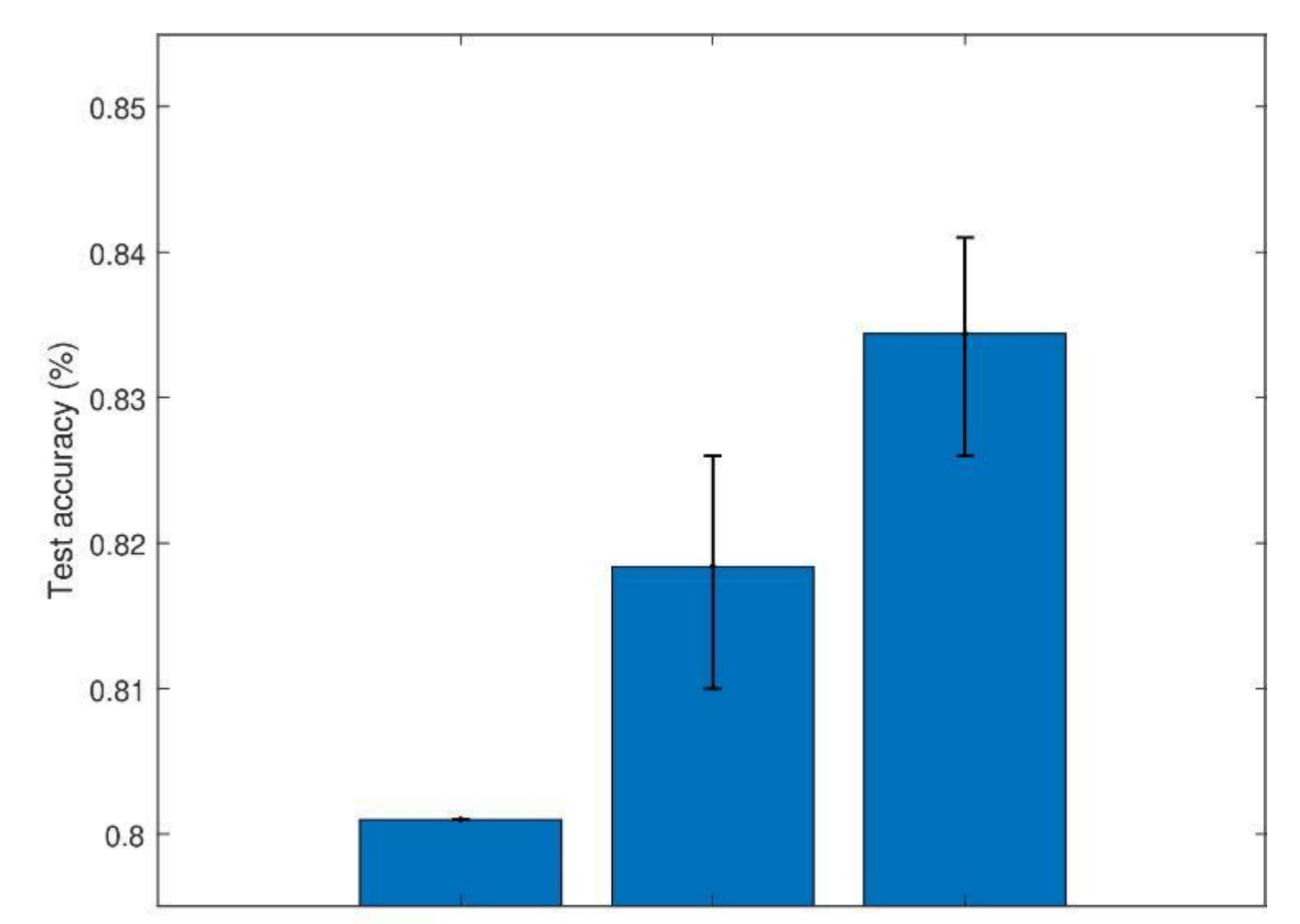


Observation: RFEs like PZN-PT can exhibit multiple nonvolatile and readily programmable capacitive states, giving it great potential to be used in neuromorphic computing

Relaxor Ferroelectrics in Neural Networks



Integration of signals for PZN-4.5PT under different electric fields, resembles the dendrite in the human brain



Comparison of the recognition accuracies for the simplified SVHN dataset in a neural network [5] with three different dendrites. w/o: test accuracy of the network without dendrite [5]

Reservoir node	Test error	a_1	a_2	a_3	a_4
[6]	0.7944	0.96	1.0	0.9867	1.0
PZN-4.5PT	0.7343	1.0	1.0	0.9933	1.0

Comparison of the performance of a reservoir system [6] on dynamic gesture recognition (DGR) with different reservoir node. a_i : The recognition accuracy of the i -th gesture.

[1] Von Neumann architecture. *Wikipedia* (2022)

[2] D. Joksas, A. Mehonic. *SoftwareX*, **12**, 100617 (2020)

[3] W.-Q. Zhang *et al.* *Nat. Electron*, **3**(7), 2022

[4] P.-Y. Chen *et al.* 2017 *IEDM*, **6.1.1-6.1.4** (2017)

[5] X. Li *et al.*, *Nat. Nanotechnol.*, **15**, 776 (2020)

[6] Y. Zhong *et al.*, *Nat. Electron.*, **5**, 672-681 (2022)