SAND2024-16901C

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Multistate Resistance Stability for 5 Bit, 32 State Ferroelectric $(Hf,Zr)O_2$ Tunnel Junctions

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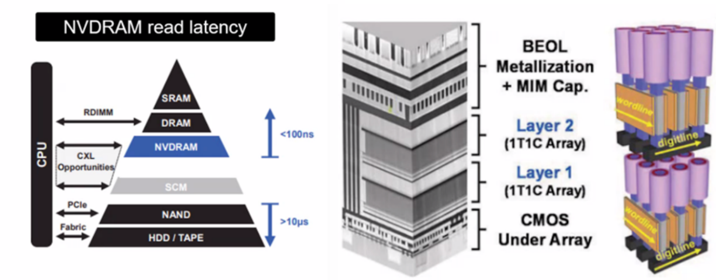
Ferroelectrics

- Introduction into select ferroelectric devices
  - Ferroelectric $(Hf,Zr)O_2$ - a quick refresher in applications
  - FTJ work continued from WINDS 2023
- TaN and Ta based electrodes
  - Basis of an individual FTJ device, area scaling
  - Conduction mechanisms – NbN/Nb electrodes (WINDS 2022)
- Multi (2) resistance state FTJ devices
  - Multistate resistance using write voltage and read voltage stability
  - Pyroelectric measurements for why it isn't stable
- Multi State (32) resistance with read stability

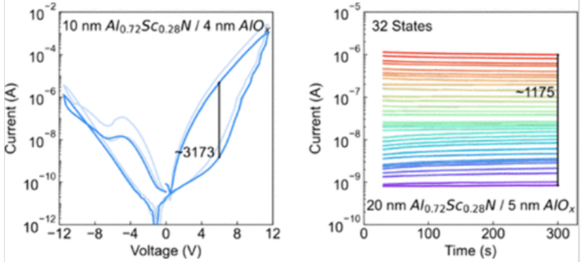
What’s a useful app for a ferroelectric?

FeRAM – Micron’s 32Gb NVDRAM



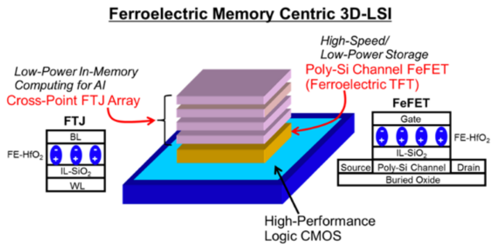
Ramaswamy, N., et al. "NVDRAM: A 32Gb dual layer 3D stacked non-volatile ferroelectric memory with near-DRAM performance for demanding AI workloads." *2023 International Electron Devices Meeting (IEDM)*. IEEE, 2023.

Emerging high temperature AlScN devices



Kim, K. H., Han, Z., Zhang, Y., Musavigharavi, P., Zheng, J., Pradhan, D. K., ... & Jariwala, D. (2024). Multistate, Ultrathin, Back-End-of-Line-Compatible AlScN Ferroelectric Diodes. *ACS nano*.

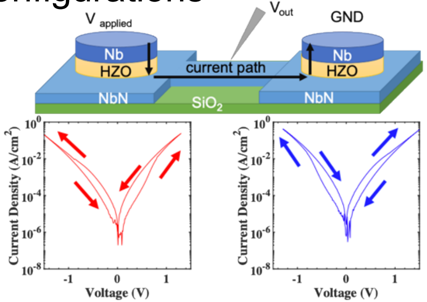
Toshiba Memory efforts with Sony



M. Saitoh et al., "HfO2-based FeFET and FTJ for Ferroelectric-Memory Centric 3D LSI towards Low-Power and High-Density Storage and AI Applications," 2020 IEEE International Electron Devices Meeting (IEDM), San Francisco, CA, USA, 2020, pp. 18.1.1-18.

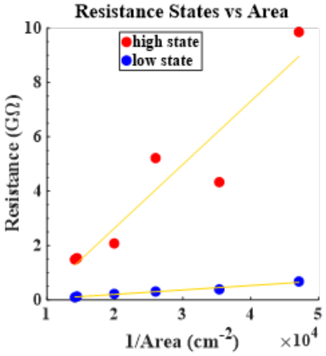
Unique logic configurations

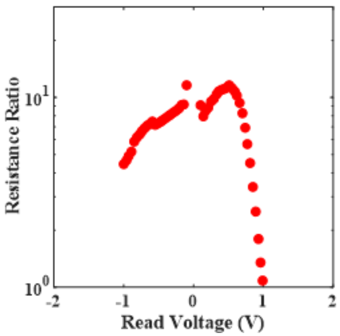
Haglund-Peterson, J., Aronson, B. L., Jaszewski, S. T., Habermehl, S., Esteves, G., Conley, J. F., ... & Henry, M. D. (2024). Nonvolatile memory cells from hafnium zirconium oxide ferroelectric tunnel junctions using Nb and NbN electrodes. *Journal of Applied Physics*, *135*(9).

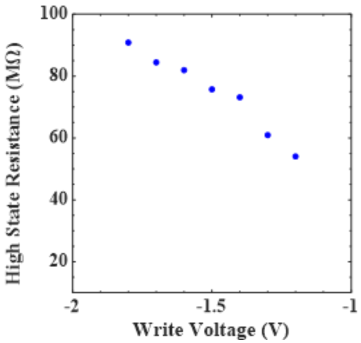


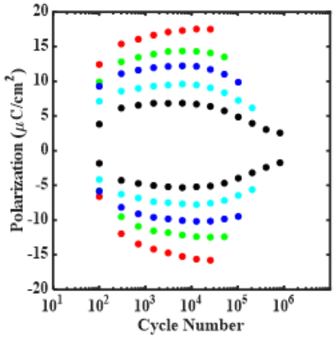
Last year at WINDS

- Progress in TaN/Ta based FTJ for insertion into a BEOL, MIM Cap module process.
- Control over resistance is complex but interesting for a circuit designer, via:
  - Area scalable
  - Read Voltage
  - Write Voltage









- With a whole lot of in between states needing repeatability.

Last year at WINDS

- Progress in TaN/Ta based FTJ for insertion into a BEOL, MIM Cap module process.
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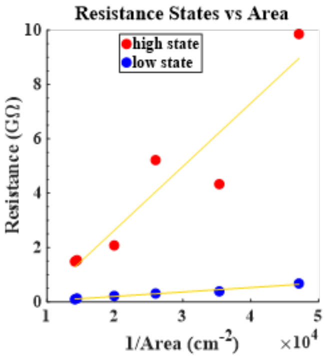
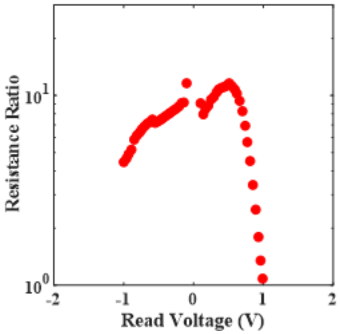
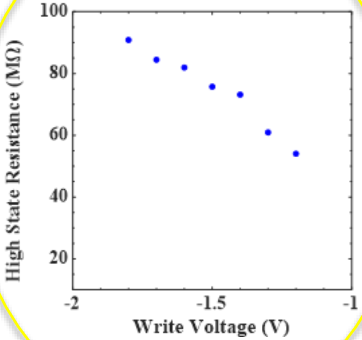
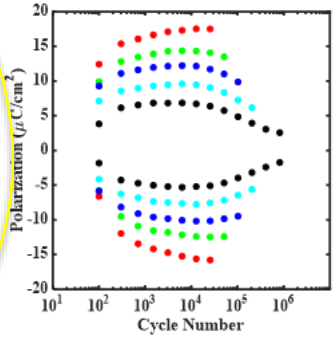


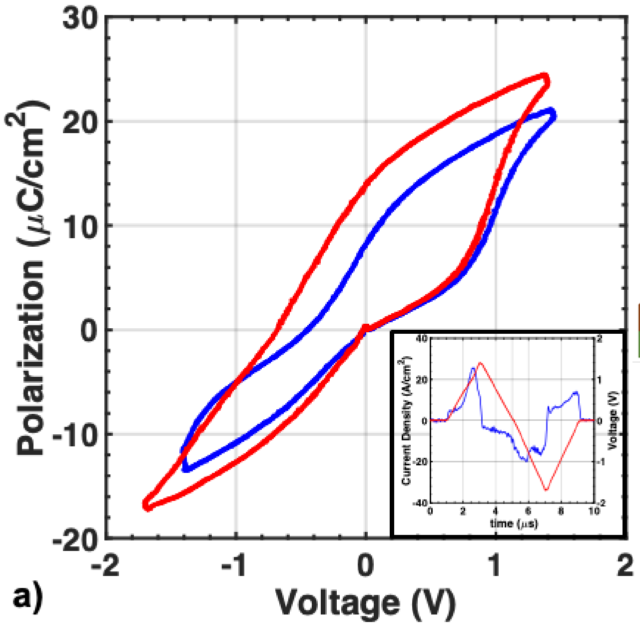


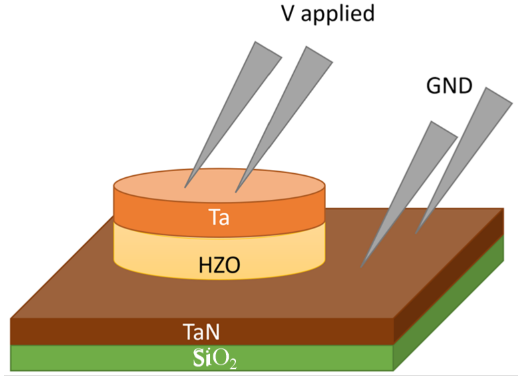


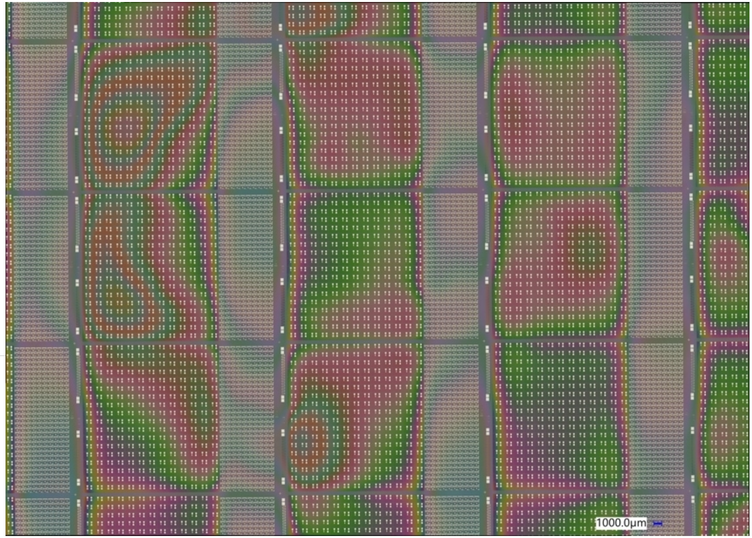


- With a whole lot of in between states needing repeatability.

Back to basics - how do we build this

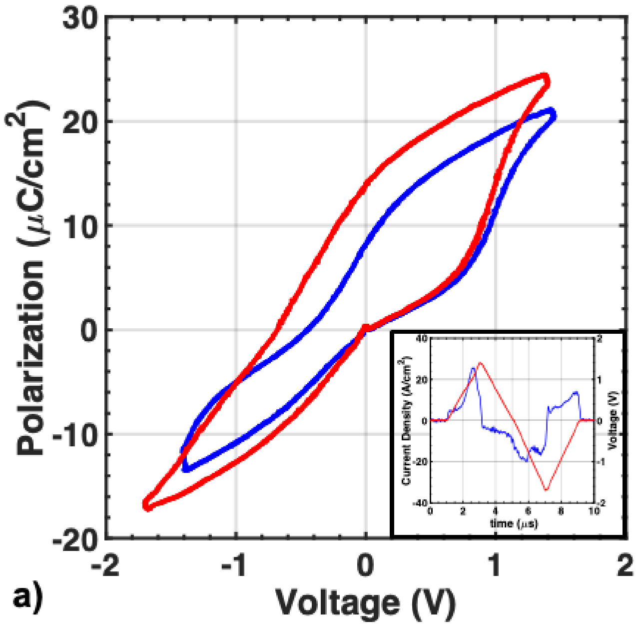


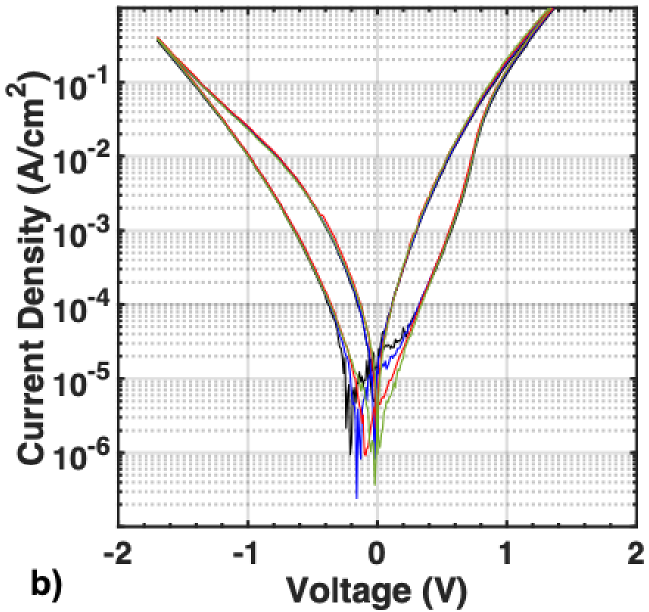




Devices were fabricated using a planarized 3 metal layer, 150 mm process. Bottom layer is TaN with a 6 nm HZO and Ta top electrode. The wafer is planarized with CVD oxide and vias etched to connect to a top electrode (Ti/Al).

Back to basics - how does this perform





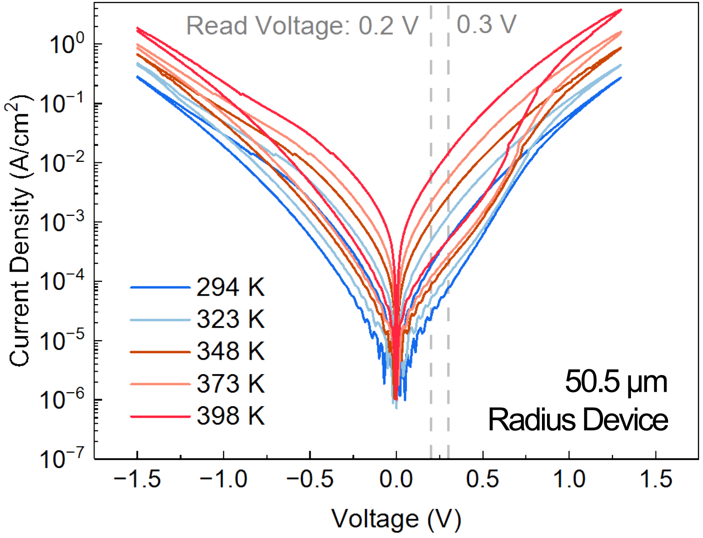
Area normalized 20, 30, 40, and 50 μm radius devices.

With a voltage range of -1.7 V to 1.4 V, and noting the imprint in the PE loop, we observe a repeatable FTJ with 10x change in resistance.

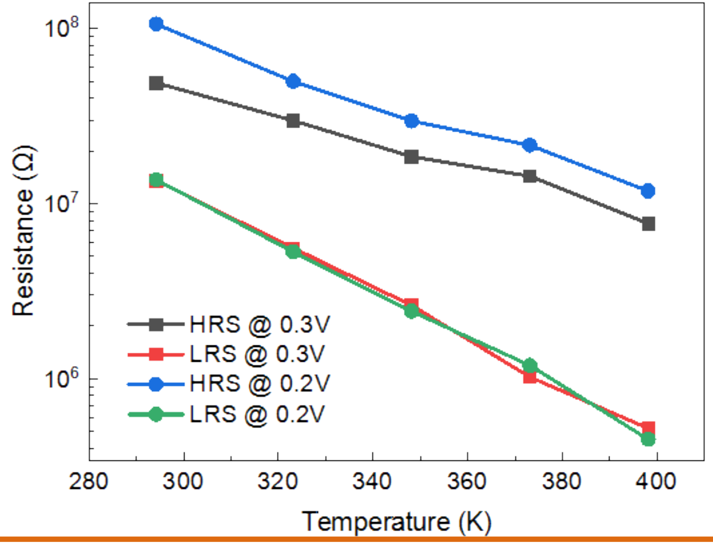
Temp Dependence of Current – Fitting the Conduction (Nb & NbN electrodes)

- Temperature used to derive current transport mechanisms
- Devices cycled 5 times at ~ 1Hz for wakeup
- Chuck temperature varied from 21 °C (294 K) to 125 °C (398 K)

LRS demonstrates **higher** temperature dependence than **HRS**

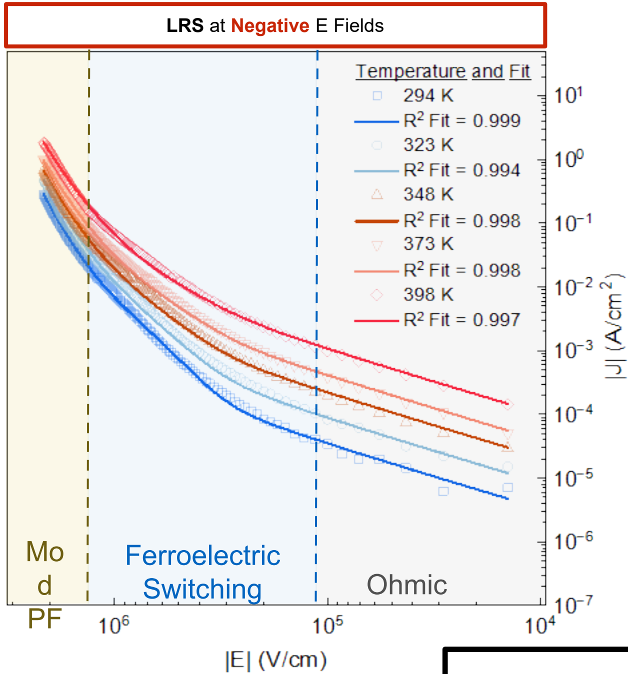


Current Density vs. Voltage Curves



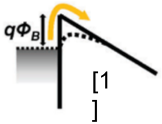
High Resistance State (HRS) & Low Resistance State (LRS) Across Temperature

Low Resistance State Current Transport (Nb & NbN electrodes)



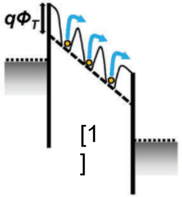
Current Transport =

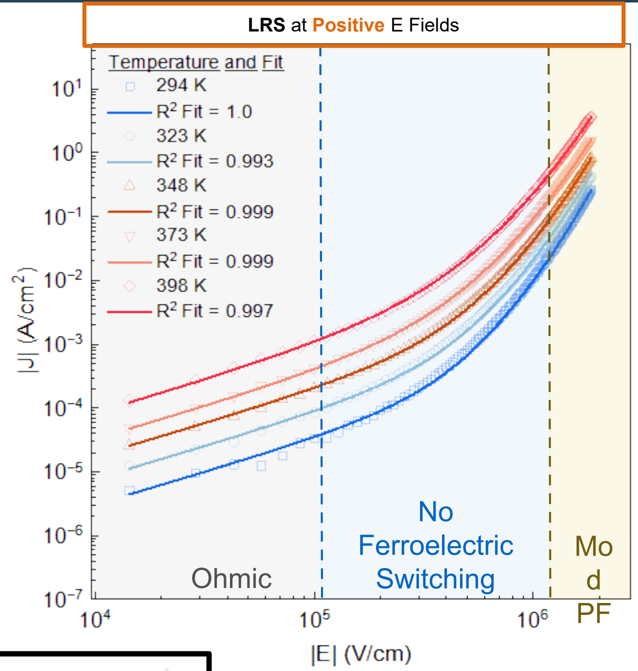
Ohmic +



Ferroelectric Switching from Domain Nucleation +

Modified Poole-Frenkel Conduction





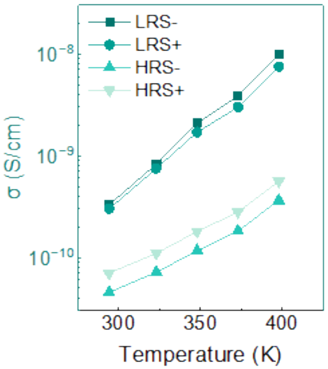
$$J = \sigma E + C e^{\frac{-\alpha}{E}} + q\mu N_t E e^{\frac{-q\left(\varphi - \sqrt{\frac{qE}{4\pi\varepsilon_i\varepsilon_0}}\right)}{kT}}$$

[1] Hwang, J., et al. (2024). Small 20(9): e2305271.

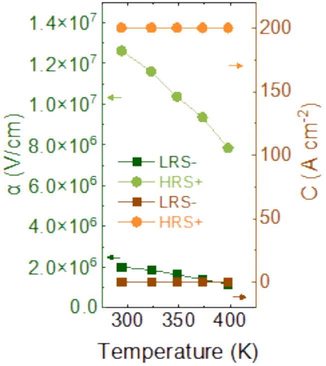
Fitted Constants for Current Transport Equation (Nb & NbN electrodes)

$$J = \sigma E + Ce^{\frac{-\alpha}{E}} + q\mu N_t E e^{\frac{-q\left(\varphi - \sqrt{\frac{qE}{4\pi\varepsilon_i\varepsilon_0}}\right)}{kT}}$$

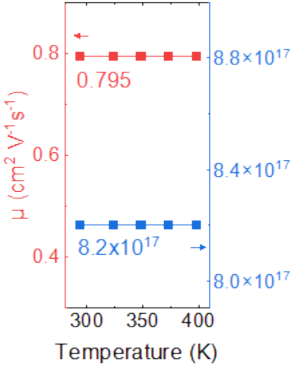
Conductivity (σ)



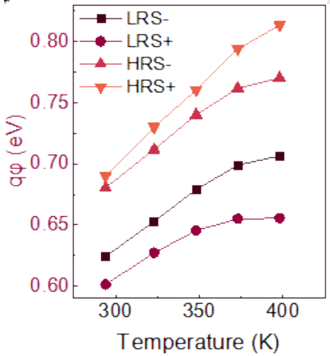
Activation Energy (α) & Switching Constant (C)



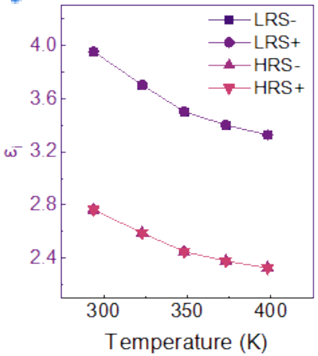
Electron Mobility (μ) & Trap Density (N_t)



Trap Level ($q\varphi$)

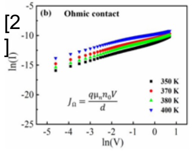


Optical Permittivity (ε_i)



Matches literature magnitude $\sigma \approx$ 3x10^{-10} S/cm [1] & trend with temperature [2]

[2]



[1] Reddy, P. R. S. (2024). *Materials Technology Reports 2 (1).*

[2] Zhang, Y., et al. (2020). *ACS Appl Mater Interfaces 12*

Ferro. Domain Nucleation [3]: $i_{switch} = C\frac{dn}{dt} = Ce^{\frac{-\alpha(T)}{E}}$

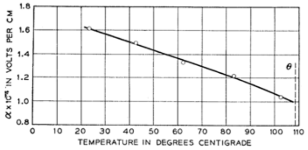
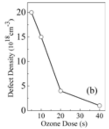


FIG. 16. Activation energy α *versus* temperature.

Constant for all resistance states. Matches literature: $\mu \approx 0.43$ cm^2 V^{-1}s^{-1} [4], $N_t \approx 1\text{x}10^{18}$ [5]

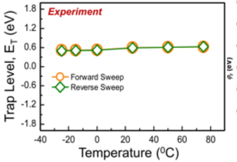


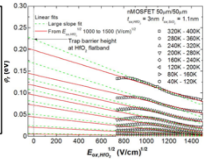
[5

[4] Wang, M.-T., et al. (2005). *Journal of The Electrochemical Society 152 (3).*

[5] Pal, A., et al. (2017). *Applied*

Matches literature: $\varphi_t \approx 0.6$ eV [6] and trend with temperature [7].

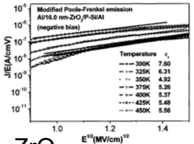




[6] Mallick, A., et al. (2023). Applied Physics

[7] Southwick, R. G., et al. (2010). Transactions on

Matches literature: $\varepsilon_i \approx$ 4.5 [6], and trend with temperature [4].

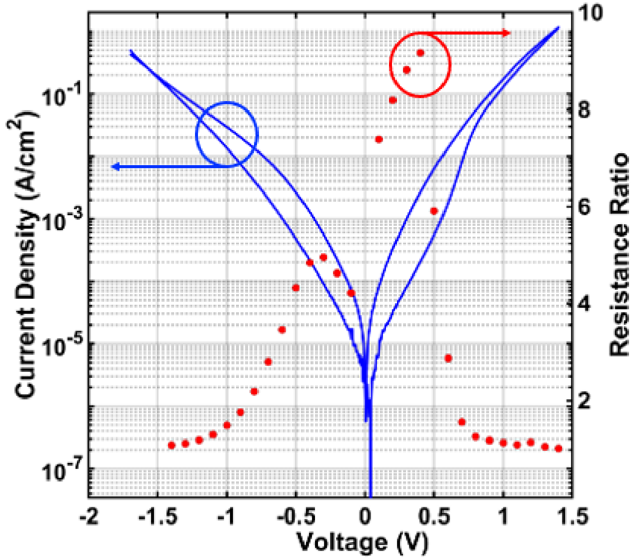


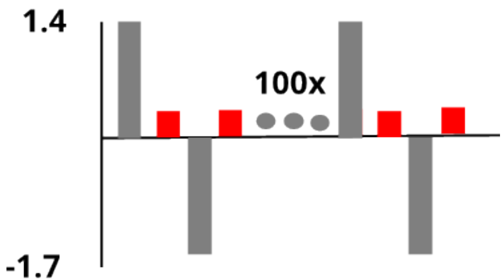
[4]

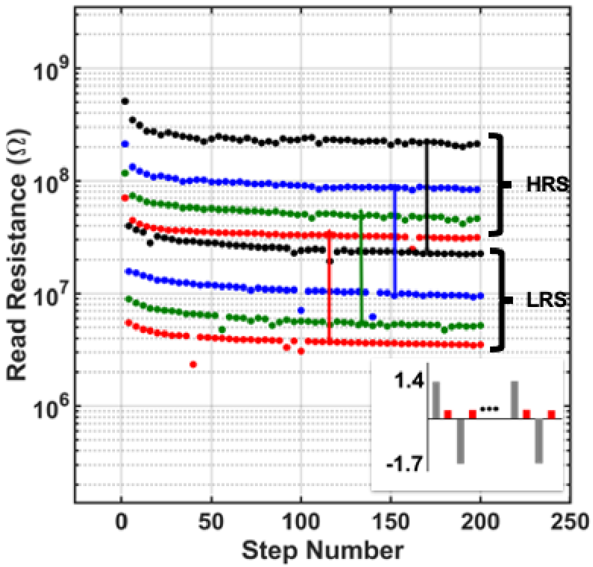
ZrO

2

FTJ flips conduction from polarization – 2 state

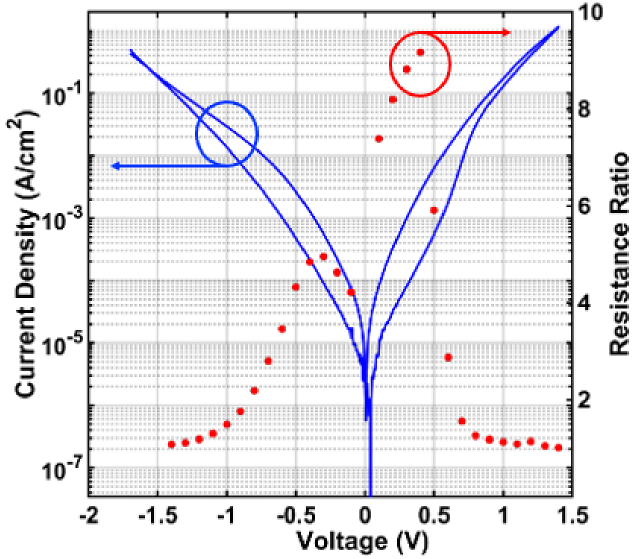


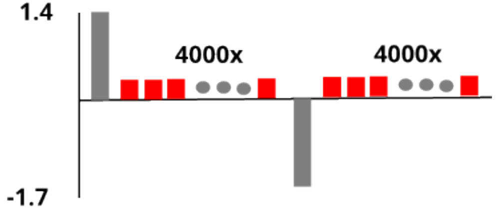


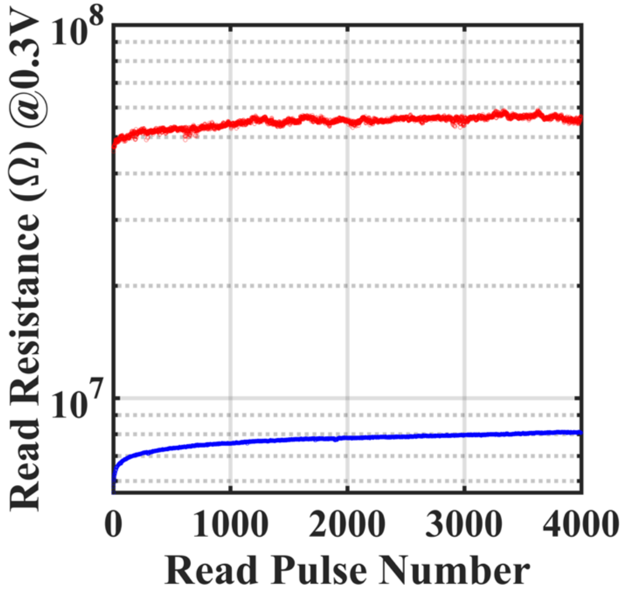


As the polarization switches, the HZO undergoes wake up; a process in which cycling the film moves oxygen vacancies. This stabilizes the orthorhombic phase and increases the Pr – for the FTJ it means increasing the current density.

FTJ flips conduction from polarization – 2 state

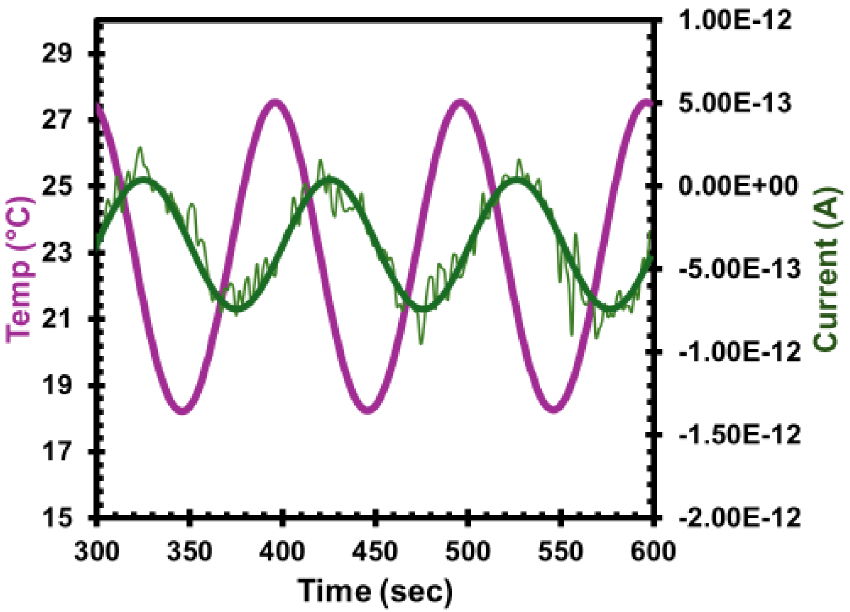




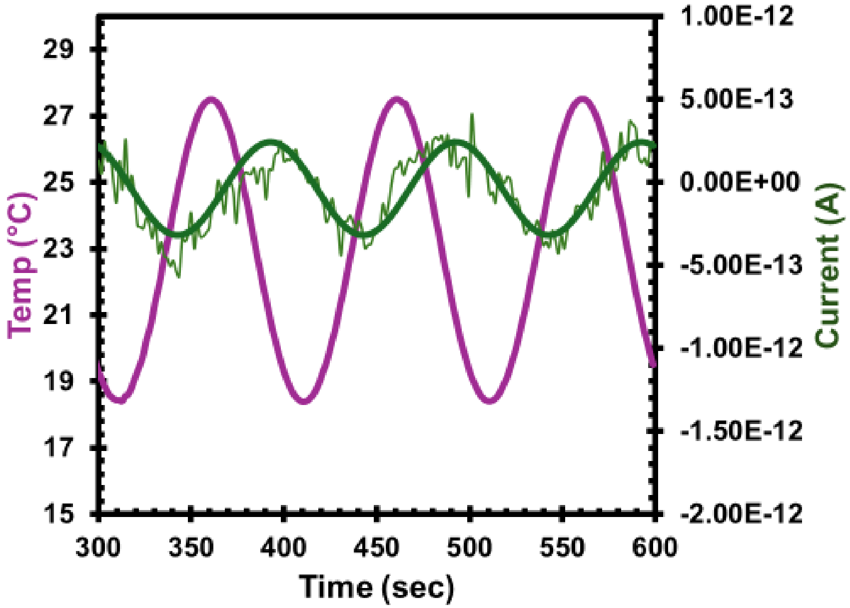


But what happens if you write a state and want to read it out … a lot. Turns out, the act of reading depolarizes the HZO and how much depends on direction of polarization.

Pyroelectric Measurements with -1.5 V pole, -1.5 V write, with 50 x, +0.3V reads



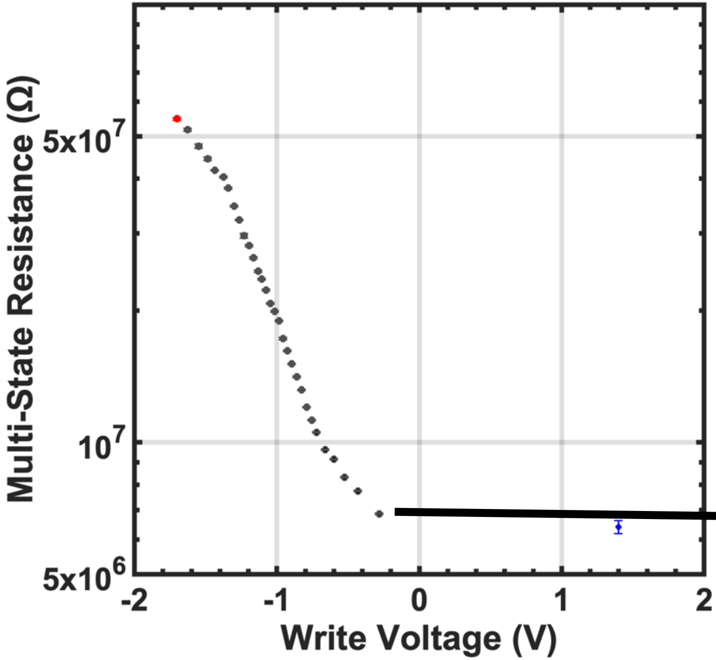
Pyroelectric coefficient: -23.14 μC m^{-2} K^{-1}



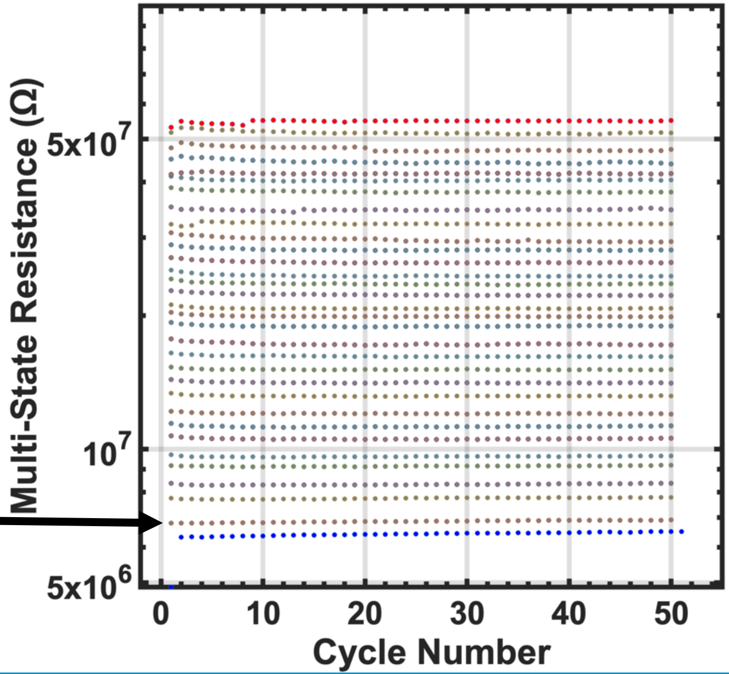
Pyroelectric coefficient: -15.83 μC m^{-2} K^{-1}

Decrease in magnitude of pyroelectric coefficient consistent with domain depoling.

Multistate Resistance - 32 States

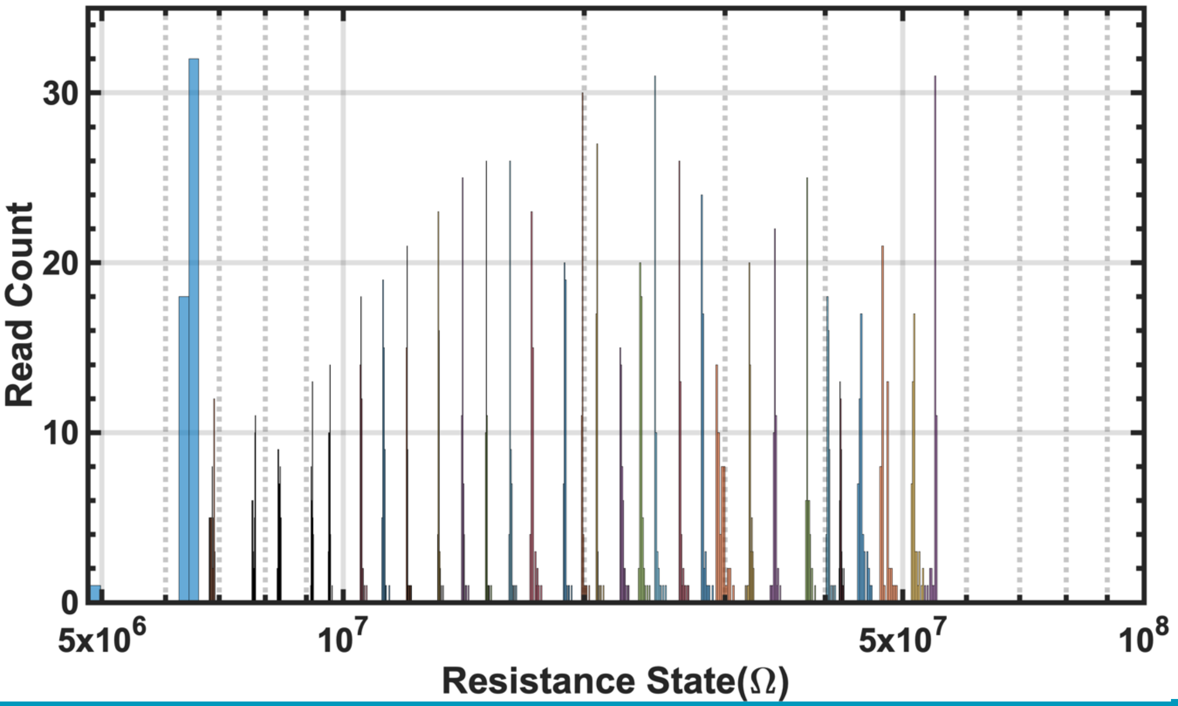


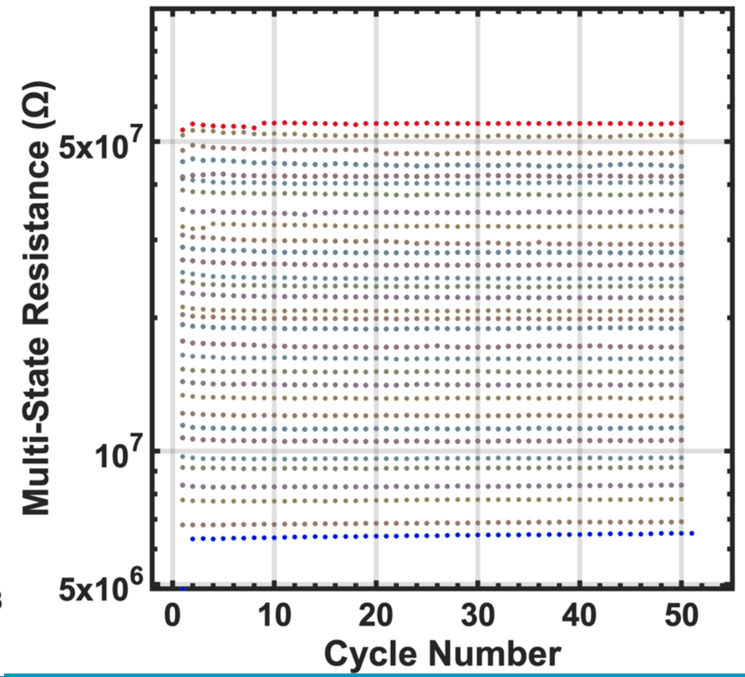
Each memory state is set by a write voltage partially depolarizing the HZO to set the intermediate resistance state between the LRS and HRS.



Here we separated the writes from 0 to -1.7 V (wrote 2x) and then read each state 50 times. There is some curvature in the stability of the reads and that is due to the read pulse depolarizing the HZO.

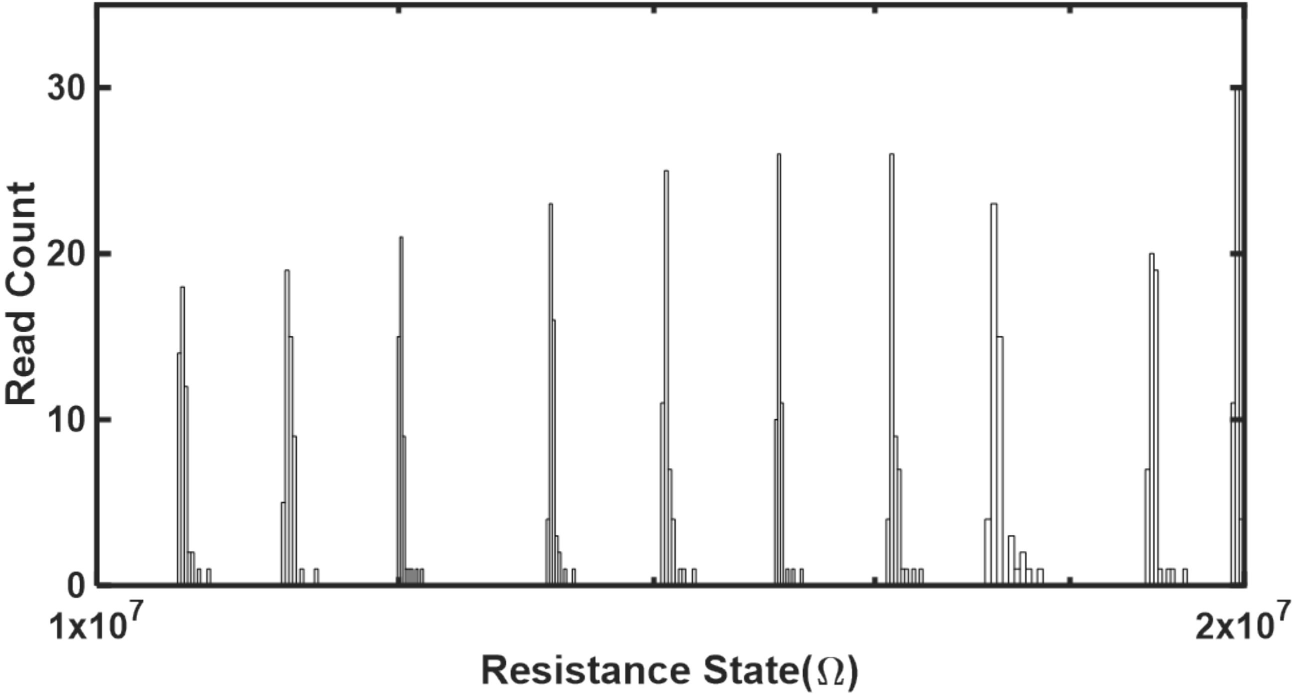
Multistate Resistance - 32 States





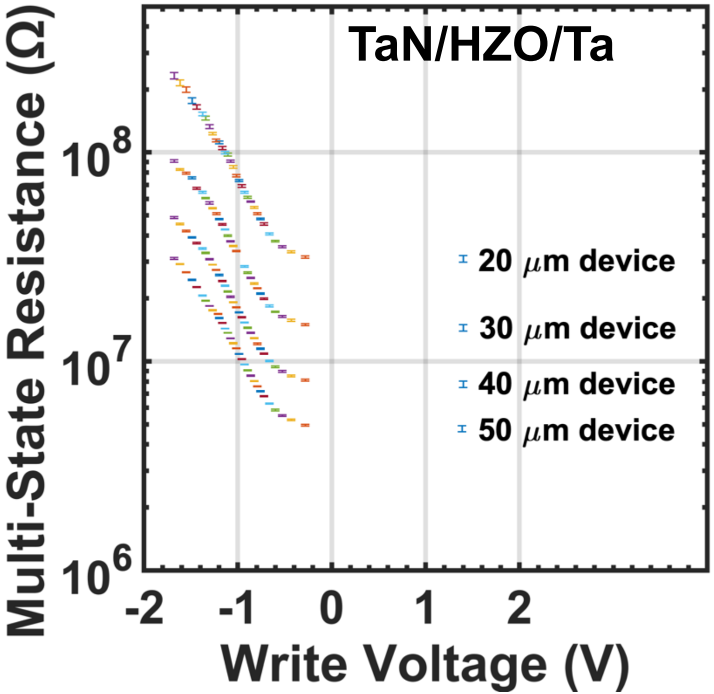
To get an idea of the movement and guarantee of separation, the read resistances were binned into 10 bins. The negative write state starts in a high resistance and settles lower.

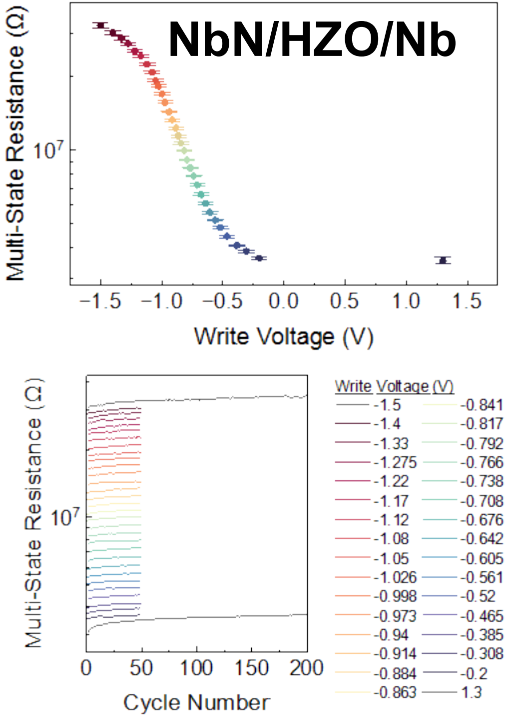
Multistate Resistance - 32 States

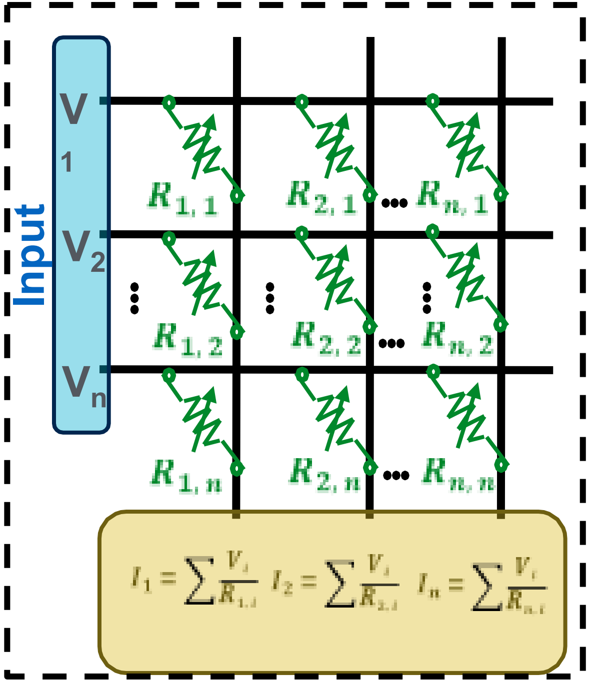


Zooming in on the 1-2 x 10^7 Ω. We note that the resistance starts high and drops low.

Multistate Resistance - 32 States – Area Scaling

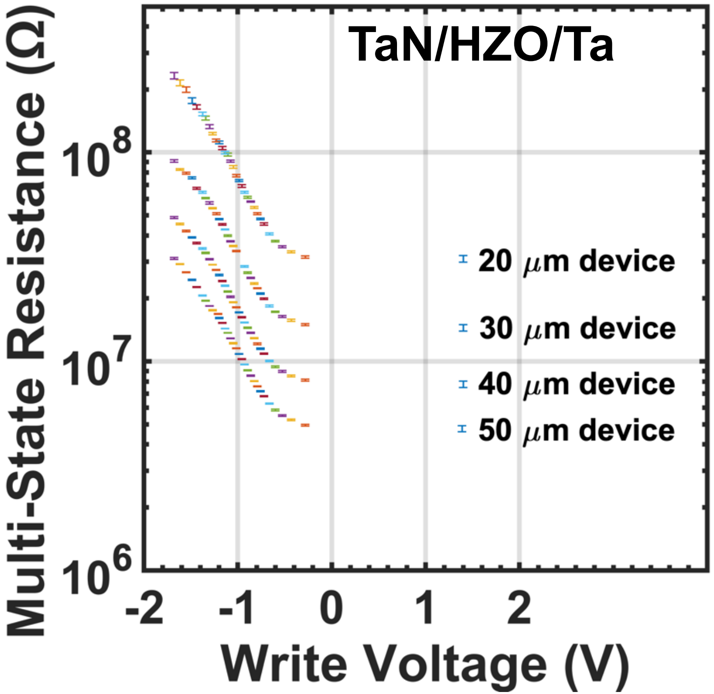


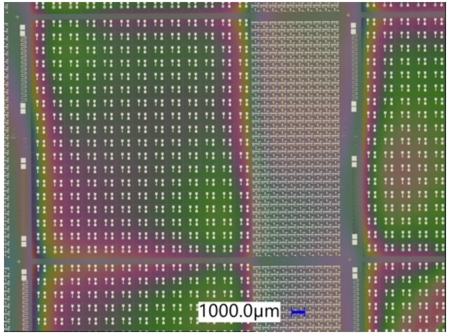


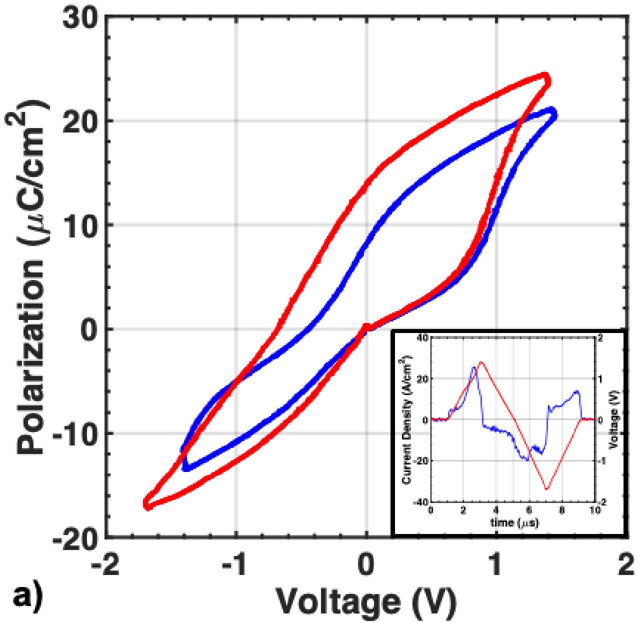


It is interesting that we can now make a matrix where each column can be area scaled and resistance set in one of 32 resistance states…

Mahalo! A hui hou!







This material is based on work supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences Energy Frontier Research Centers program under Award Number DE-SC0021118. S.T.J. gratefully acknowledges support as a Jill Hruby Fellow. Supported by the LDRD Program at Sandia National Laboratories. Sandia is managed and operated by NTESS under FOE NNSA contract DE-NA0003525.