SAND2022-16853C

Exceptional service in the national interest

Sandia National Laboratories



Ferroelectric microelectronic devices utilizing NbN / Nb electrodes with thin film ferroelectric $(Hf,Zr)O_2$

M. David Henry[1], Shelby Fields[2], Samantha Jaszewski[2], Giovanni Esteves[1], Travis Young[1], Steve Wolfley[1], and Jon Ihlefeld[2]

[1]*Microsystems Engineering, Science and Applications, Sandia National Laboratories, Albuquerque, New Mexico, 87123, USA*

[2]*Department of Materials Science and Engineering, University of Virginia, Charlottesville, Virginia, 22904*

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.

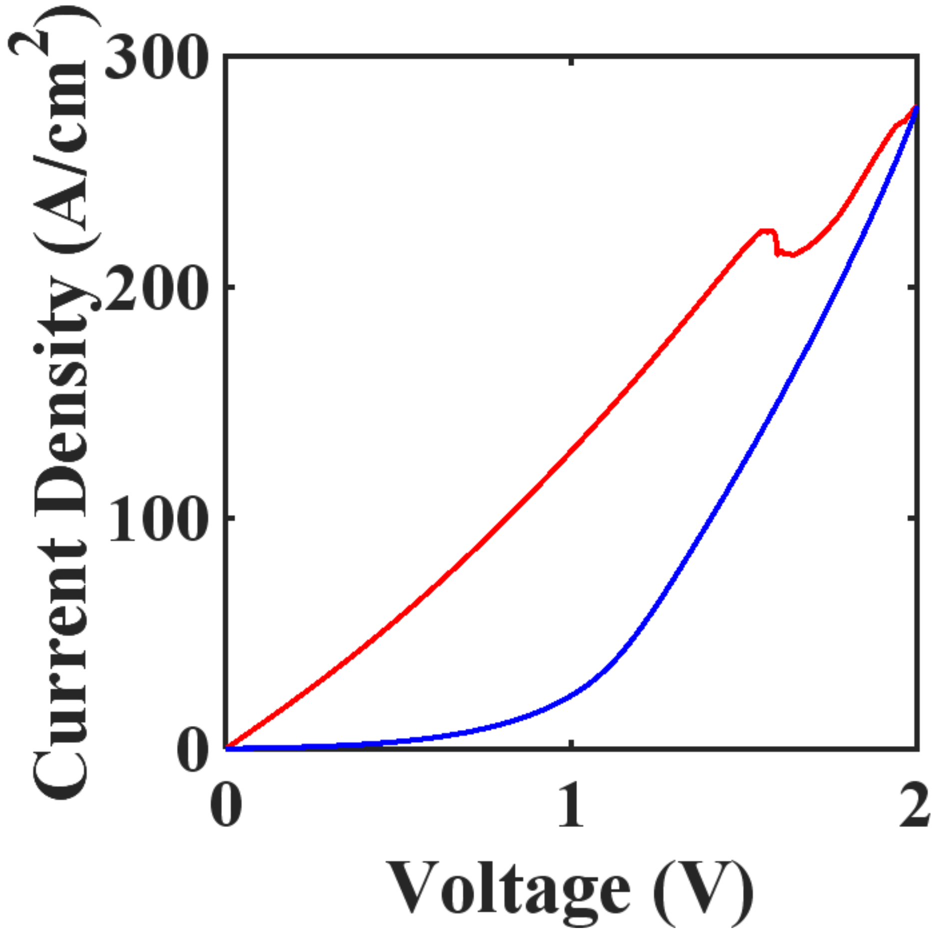
U.S. DEPARTMENT OF ENERGY

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

National Nuclear Security Administration

Overview

- Introduction into select ferroelectric devices
  - FeRAM / FTJ - how they work and why we find them interesting
- NbN and Nb based electrodes
  - FeRAM NbN devices and performance in PE loops
  - Effects of dieletric/ferroelectric combinations
  - FeRAM Nb devices - we still orient!
- Beginnings of FTJ based device
  - Nb vs NbN as bottom electrode - note directionality
  - HfO_2 vs HZO 9:1
- Next directions

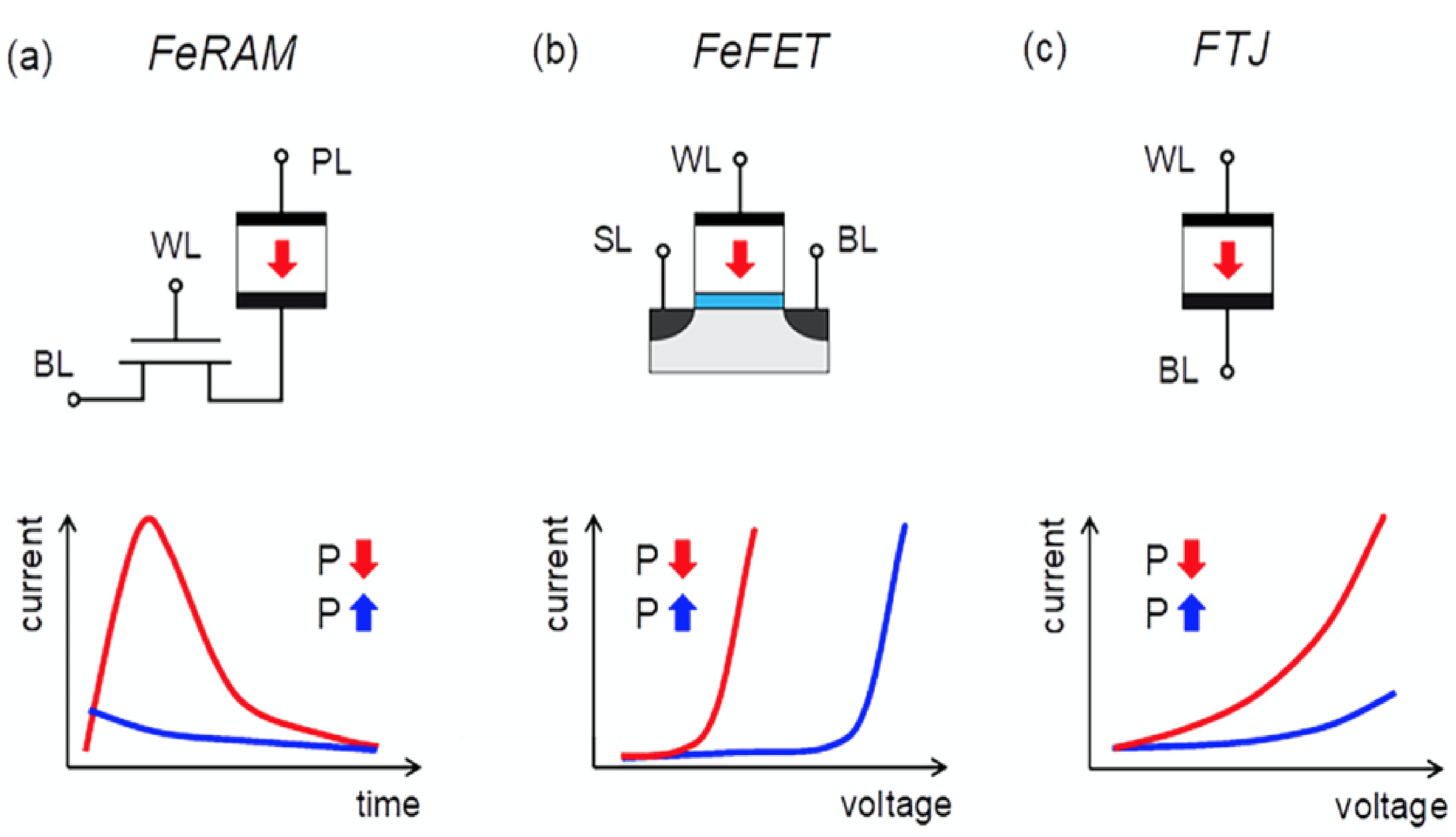


Multiple states of an FTJ

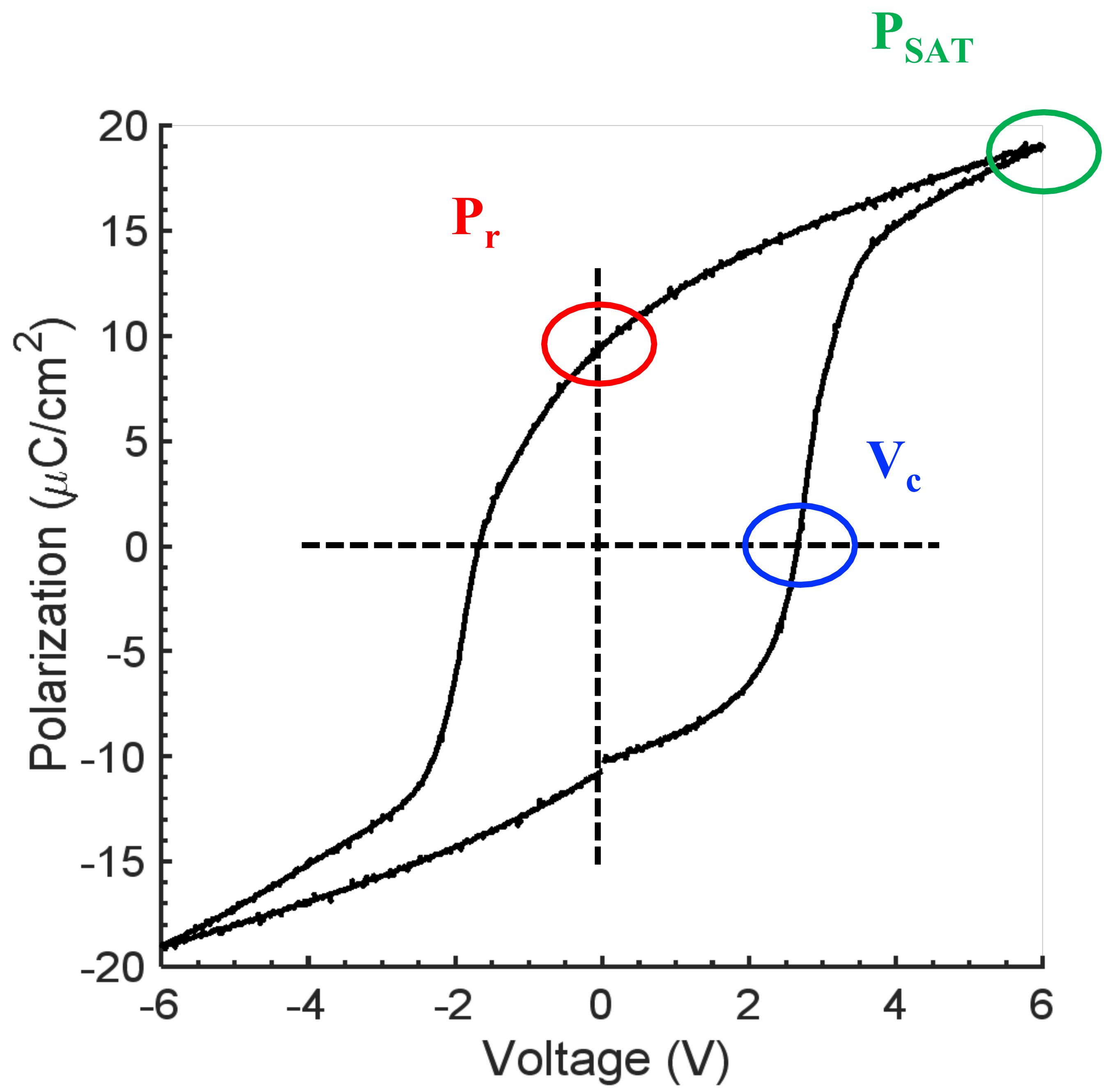
This effort was supported as part of the center for 3D Ferroelectric Microelectronics (3DFeM), an Energy Frontier Research Center funded by the U.S. Department of Energy (DOE), Office of Science, Basic Energy Sciences under Award Number DE-SC0021118.

Ferroelectric HZO fundamentals

Applications of ferroelectric devices come in 3 basic flavors:
Capacitive Transistor Resistive

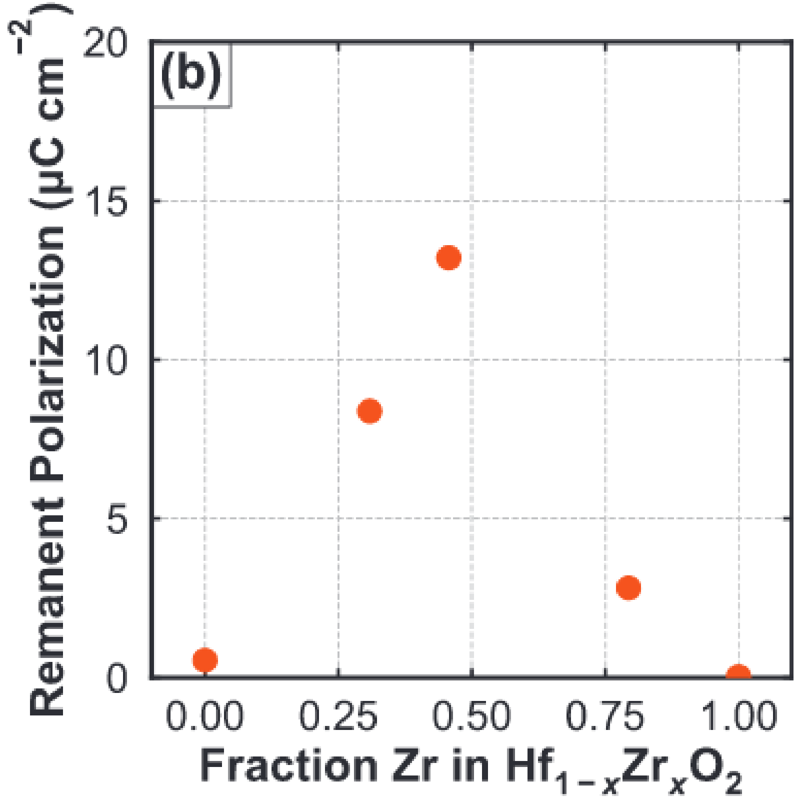


T. Mikolajick *et al.*, Journal of Applied Physics 129, 100901 (2021)

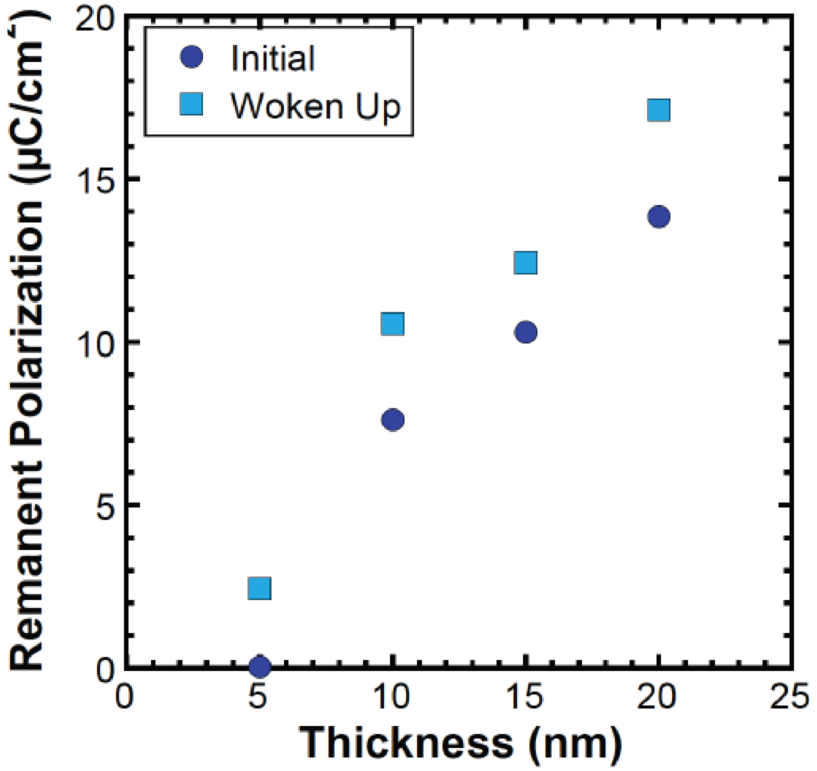


Hysteresis matters! If one can discern between two states electrically, one can utilize the feature to retain state information. This is a memory using HIGHLY CMOS compatible films with decades ($) of understanding!

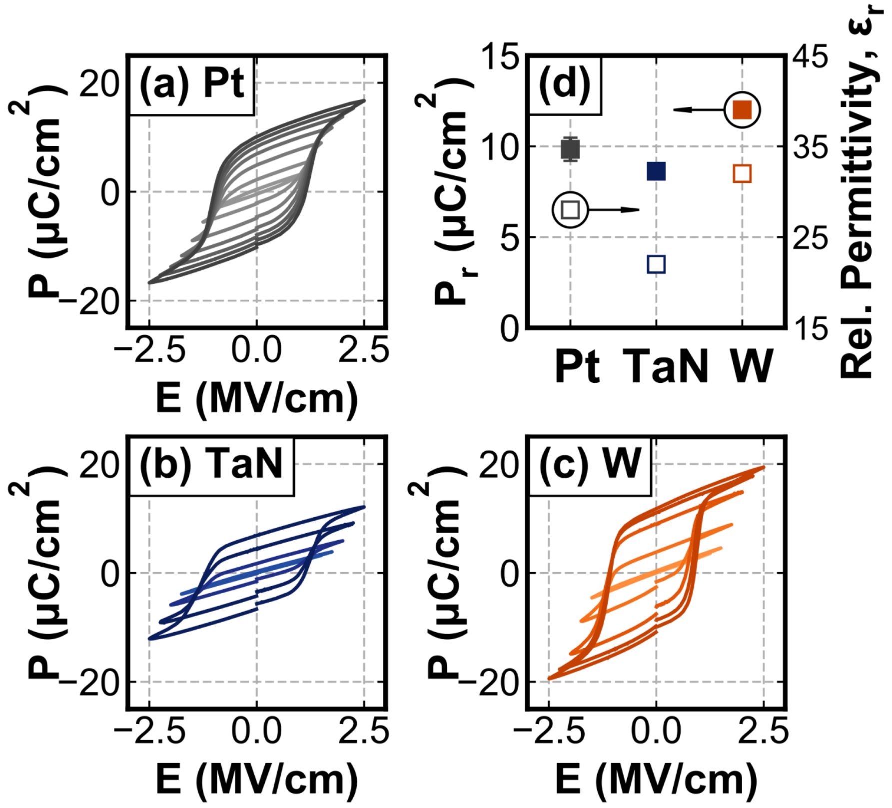
Ferroelectric HZO – how to modulate the response



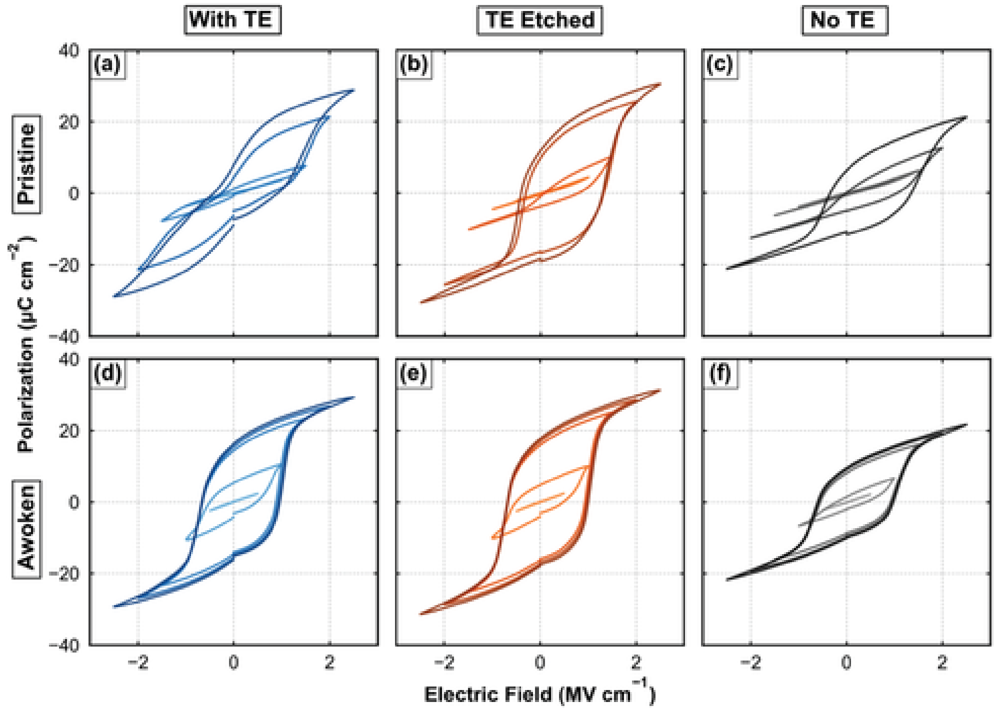
S Fields et al., Appl. Phys. Lett. **118**, 102901 (2021)



Smith, Sean W., et al. "Thickness scaling of pyroelectric response in thin ferroelectric Hf1− x Zr x O2 films." *Applied Physics Letters* 113.18 (2018): 182904.



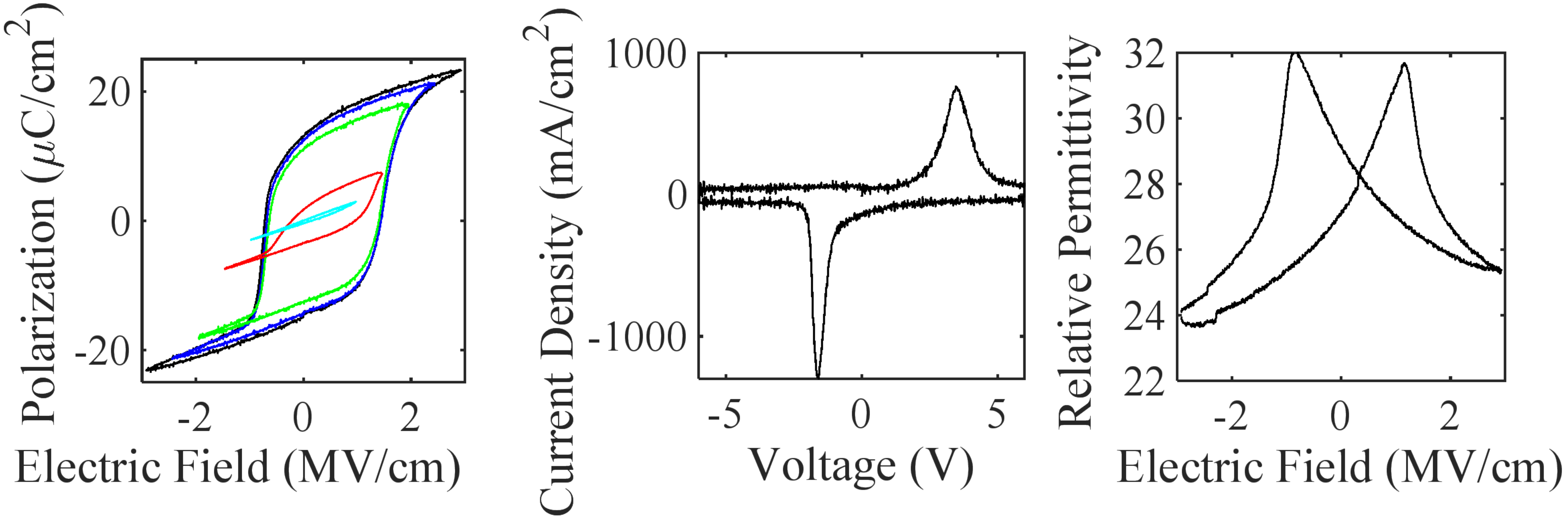
Fields, Shelby S., et al. "Phase-exchange-driven wake-up and fatigue in ferroelectric hafnium zirconium oxide films." *ACS applied materials & interfaces* 12.23 (2020): 26577-26585.



Fields, Shelby S., et al. "Origin of Ferroelectric Phase Stabilization via the Clamping Effect in Ferroelectric Hafnium Zirconium Oxide Thin Films." *Advanced Electronic Materials* (2022): 2200601.

Important points of what has been learned for controlling the HZO polarization is that stoichiometry and thickness matters, what type of electrode is used matters, and why an electrode on top is needed.

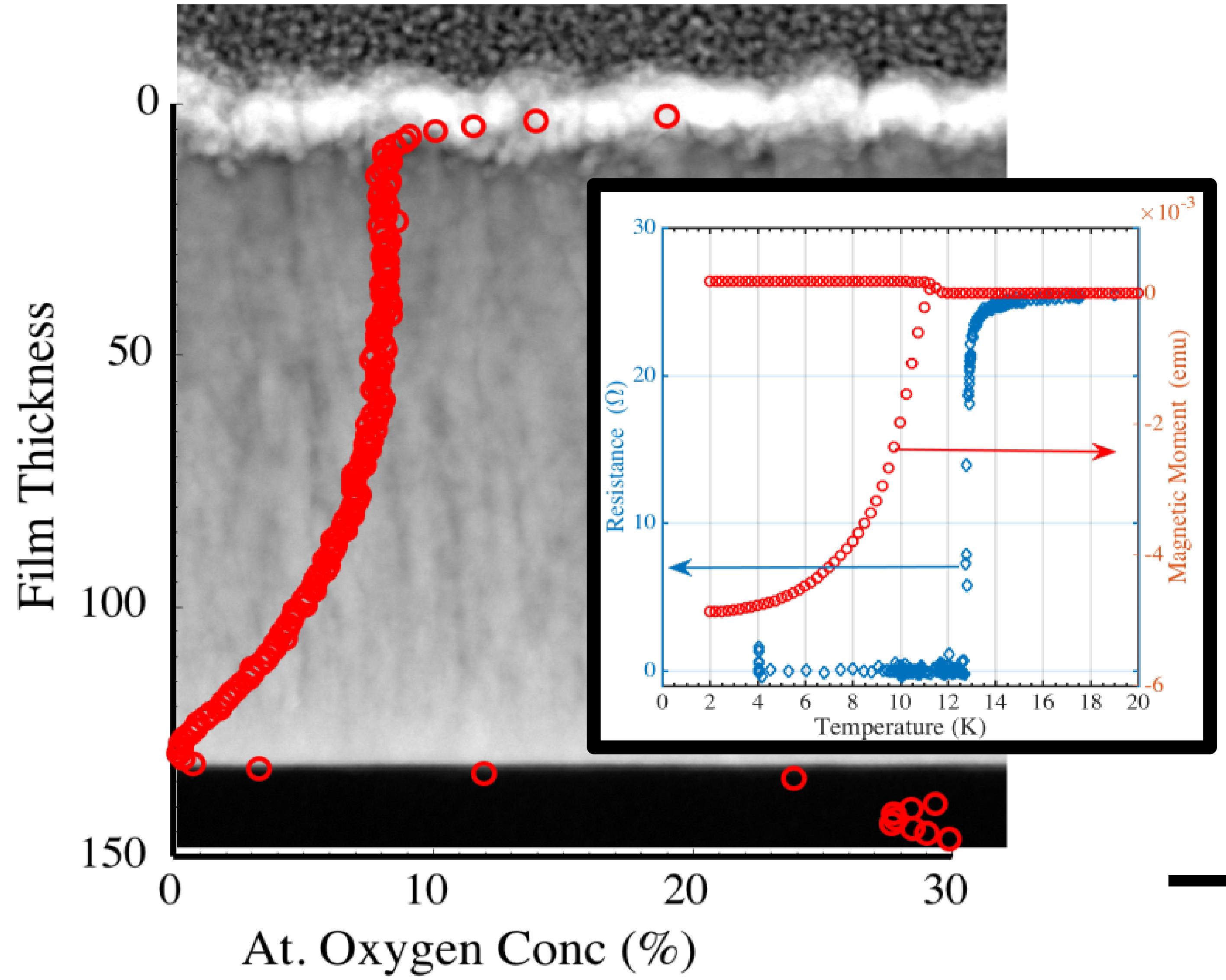
Ferroelectric HZO demonstrated with NbN electrodes



Polarization of HZO occurs well with a ferroelectric phase yielding a $2P_r$ at 28 μC/cm².

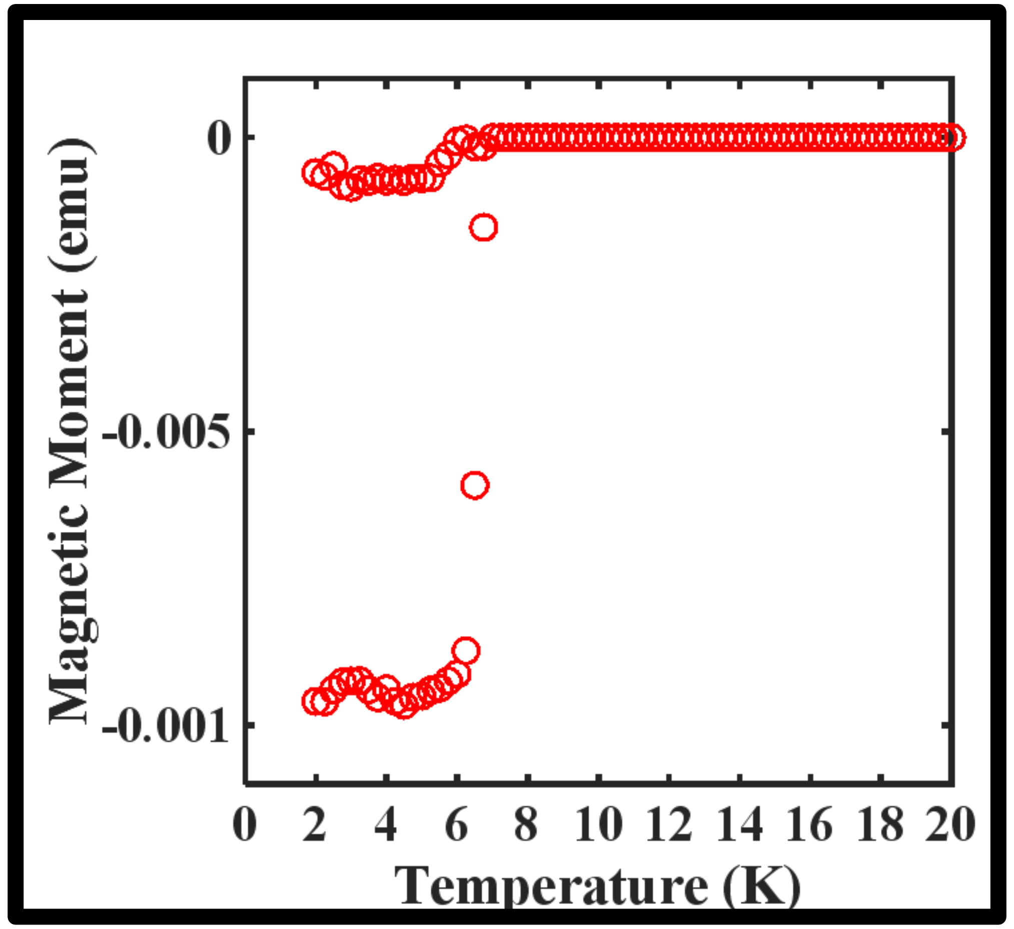
Devices were fabricated with 200 nm sputtered NbN (BE), Ultratech Savannah ALD reactor for Al_2O_3 and 20 nm $Hf_{0.6}Zr_{0.4}O_2$, then capped with 20 nm NbN and evaporated Ti /Pt . Rapid Thermal Anneals were 600C for 30 sec.

NbN electrodes degradation, due to RTA



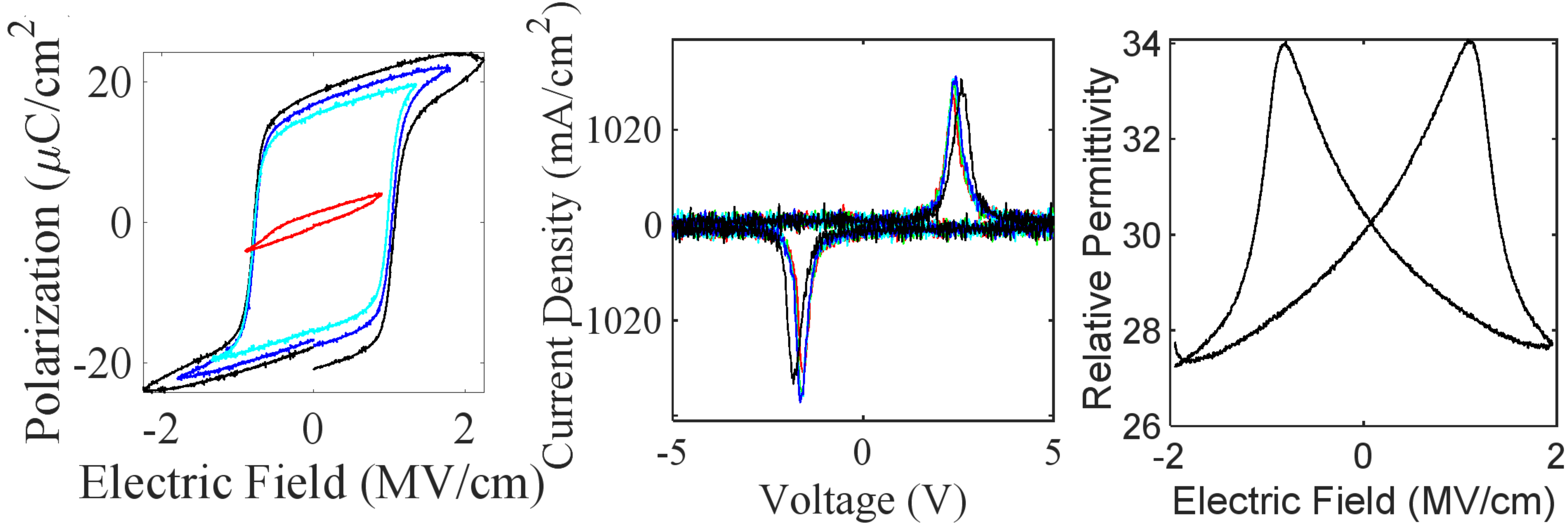
RTA observed to degrade the NbN film, likely due to oxygen movement thru it creating a NbO_x.

RTA 600C 30 sec



However, developing the ferroelectric phase of HZO comes at the cost of degradation to the NbN as viewed by Meissner superconducting measurements. For a room temp device, it may not matter much.

Ferroelectric HZO demonstrated with Nb electrodes

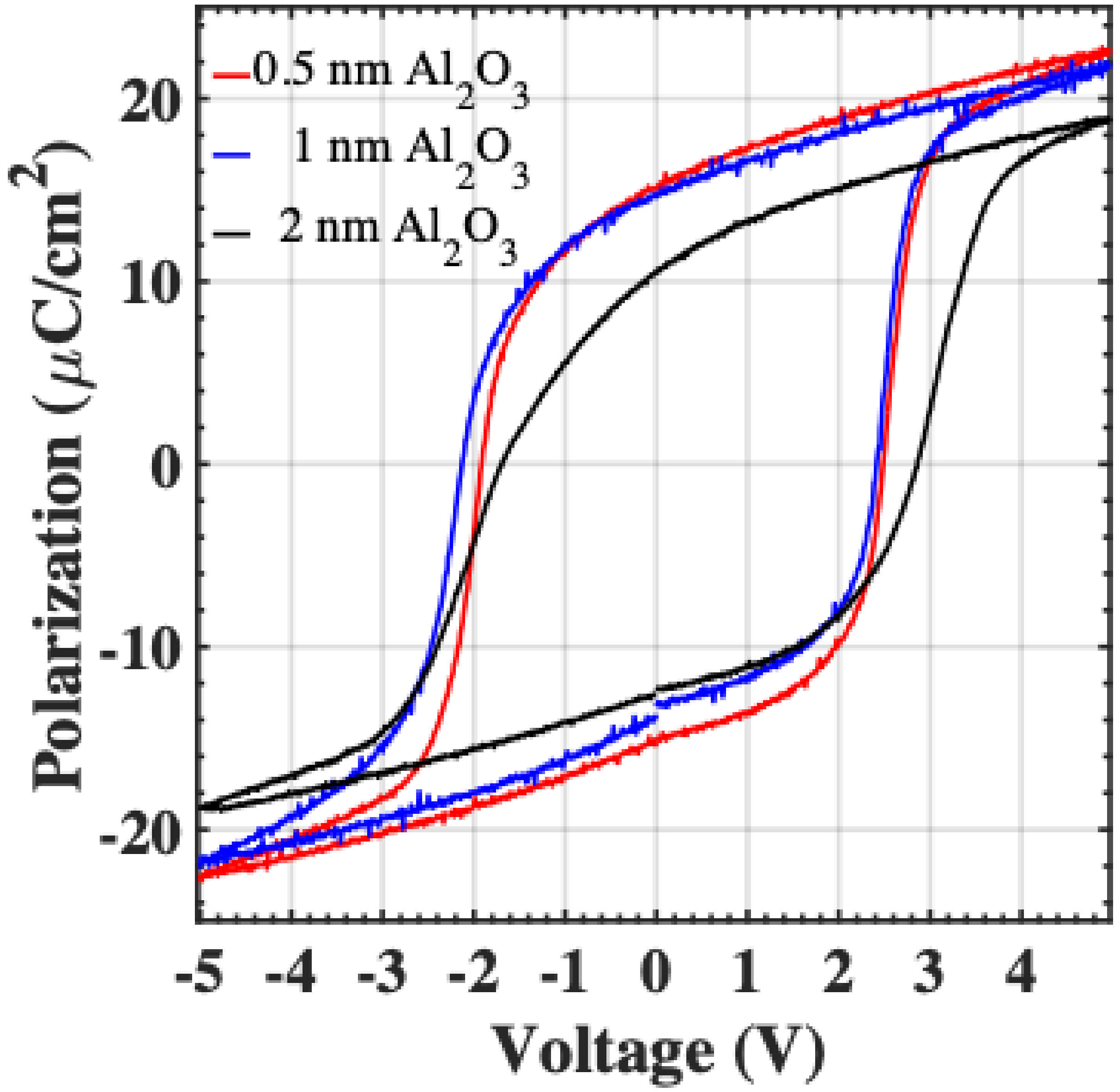


Polarization of HZO occurs well with a ferroelectric phase yielding a $2P_r$ close to 36 μC/cm². Note two important attributes: $2P_r$ increased by 30% and P_s-P_r decreased.

Devices were fabricated with 200 nm sputtered Nb (BE), Ultratech Savannah ALD reactor for Al_2O_3 and 20 nm $Hf_{0.6}Zr_{0.4}O_2$, then capped with 20 nm Nb and evaporated Ti /Pt . Rapid Thermal Anneals were 600C for 30 sec.

Addition of linear dielectric to ferroelectric

NbN 200 nm /Al_2O_3/ HZO 20 nm / NbN 20 nm

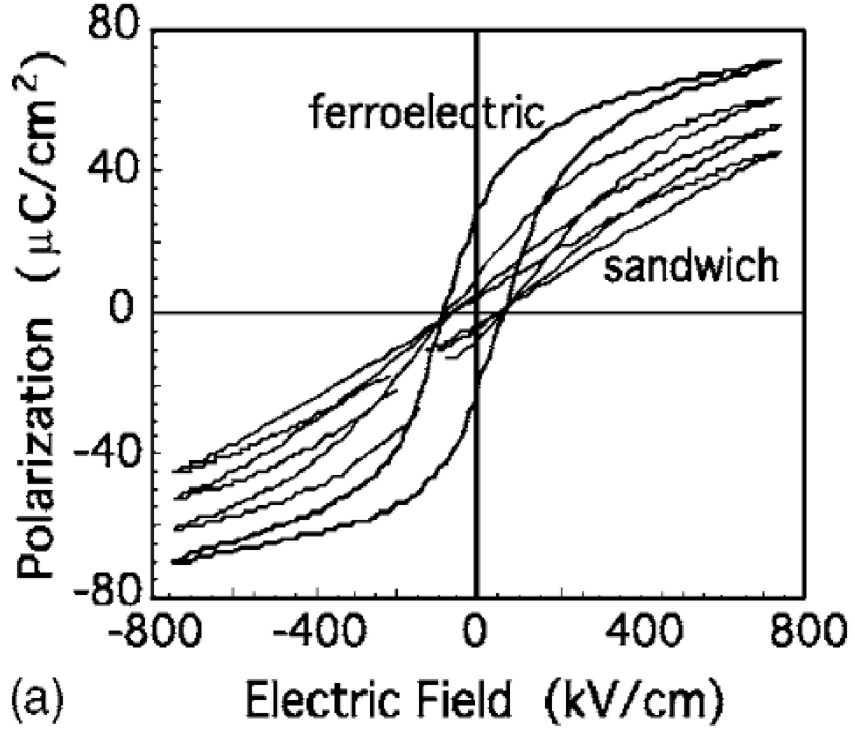


Depolarization at zero volts

$$E_{dep} = \frac{P_r}{\varepsilon_{hzo}\epsilon_o}\left(1 + \frac{\varepsilon_d t_{hzo}}{\varepsilon_{hzo} t_d}\right)^{-1}$$

Voltage divider at P_s

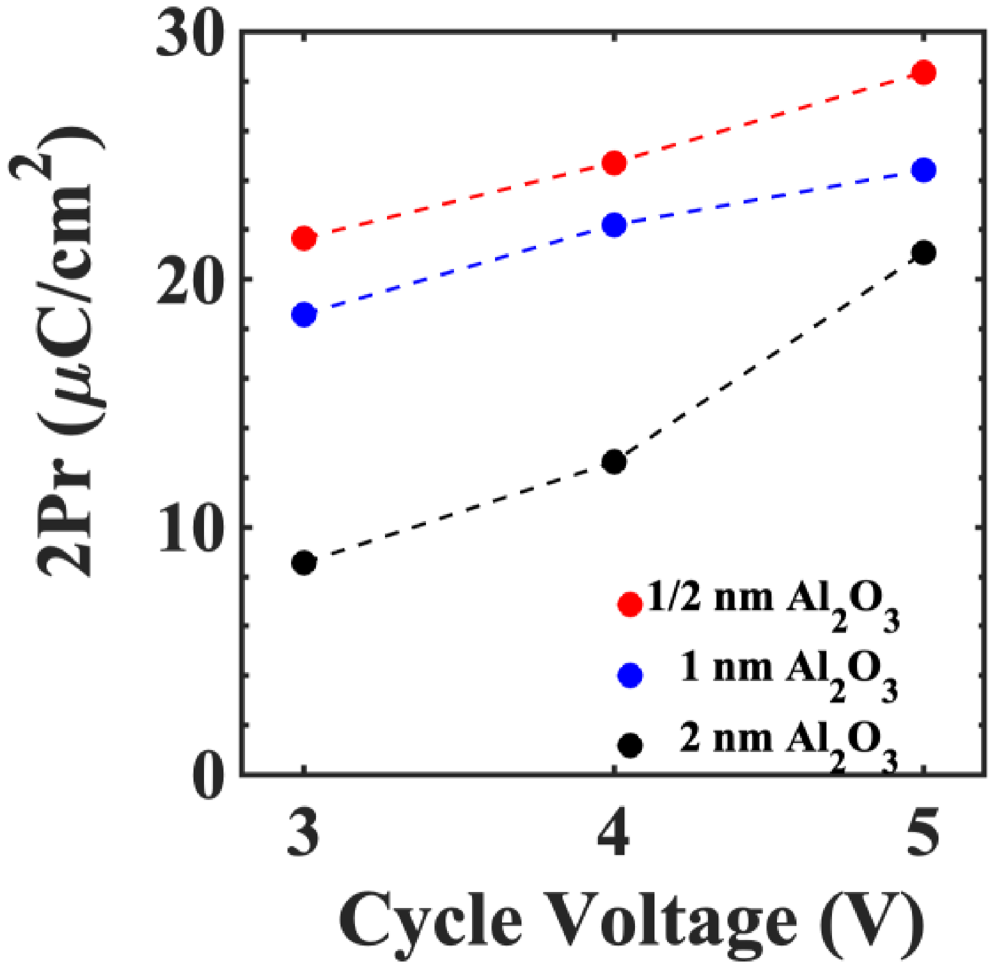
$$E_{hzo} = V_{app}\frac{\varepsilon_d}{\varepsilon_d * t_{hzo} + \varepsilon_{hzo} * t_d}$$



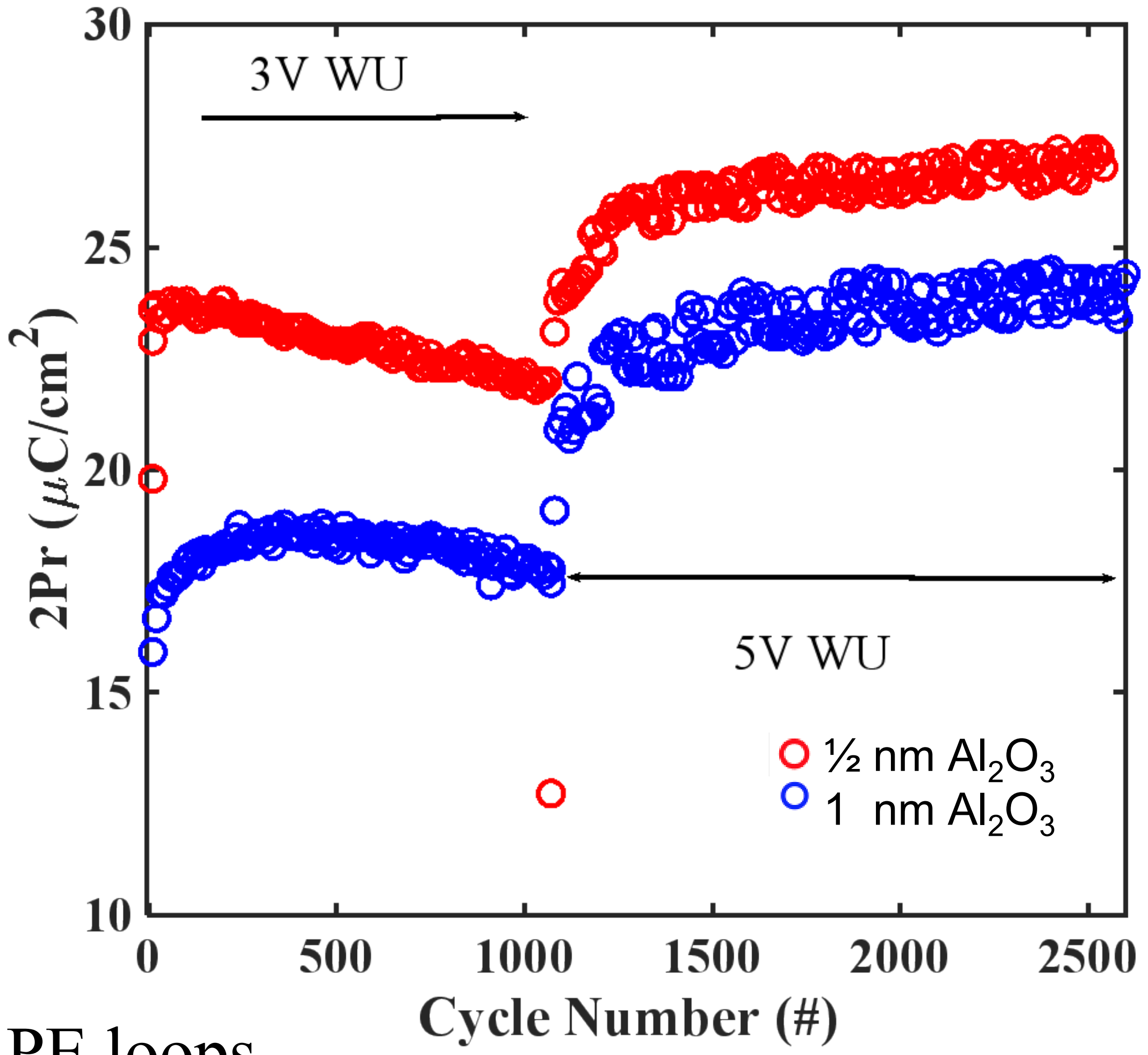
Tagantsev et al., J. Appl. Phys. 100, 051607 (2006);

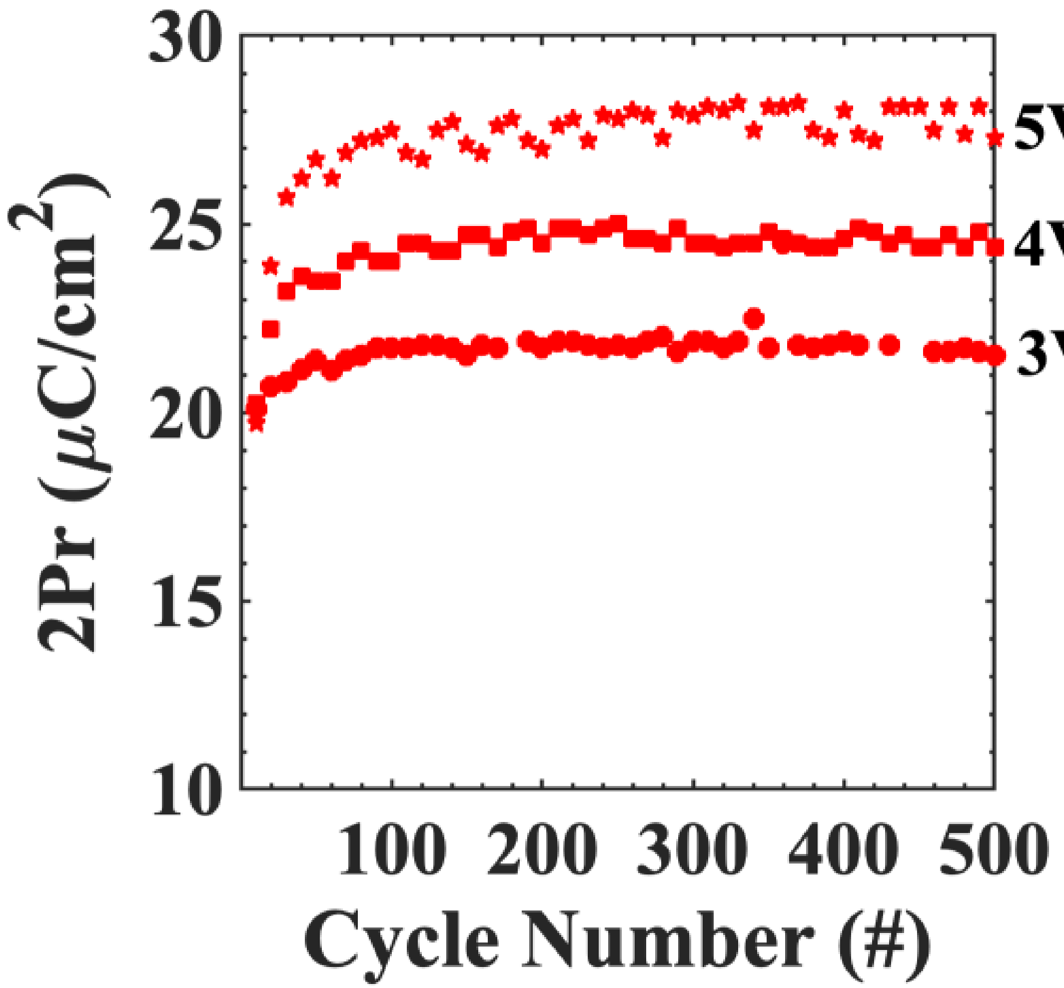
With a linear dielectric addition, a depolarizing field reduces the P_r. When voltage is applied, there is a distribution between the two which effectively reduces the electric field across the ferroelectric.

Impact of linear dielectric to ferroelectric



NbN 200 nm /Al_2O_3/ HZO 20 nm / NbN 20 nm



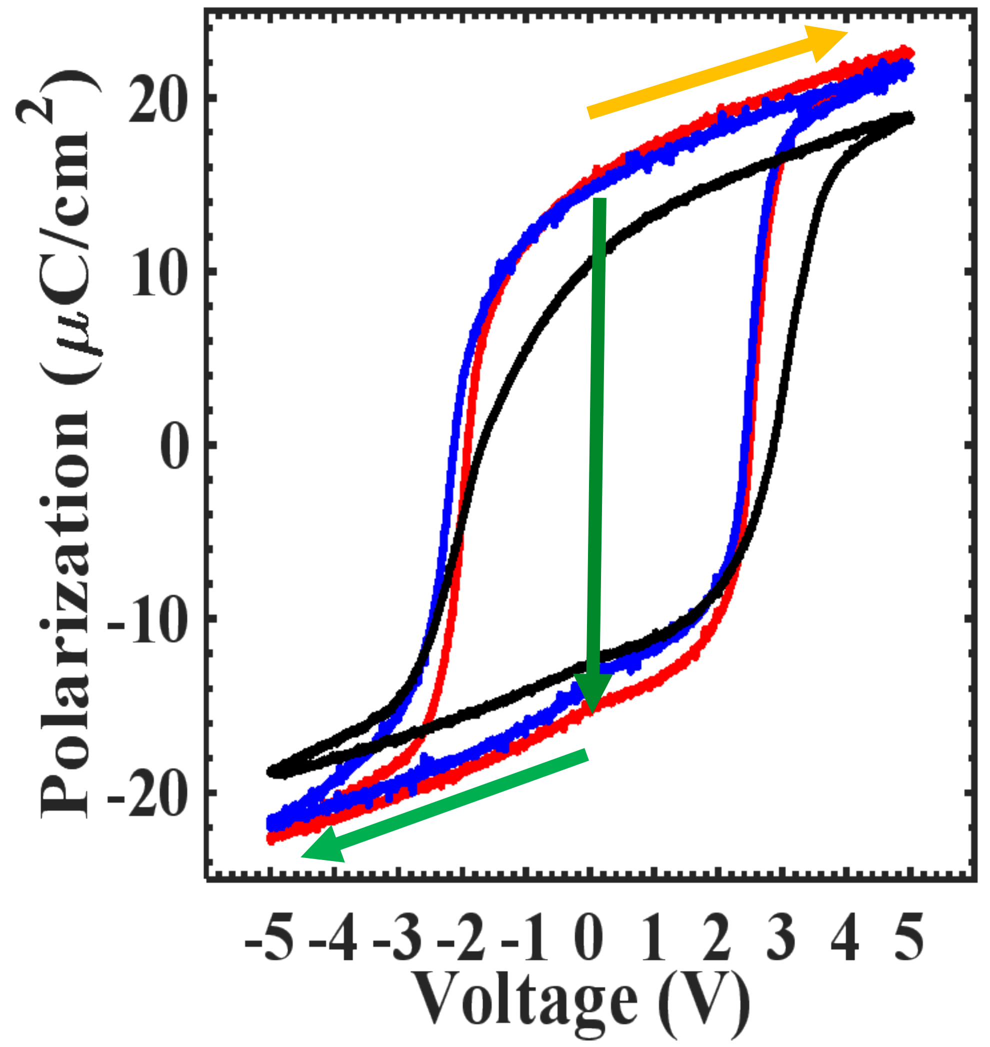


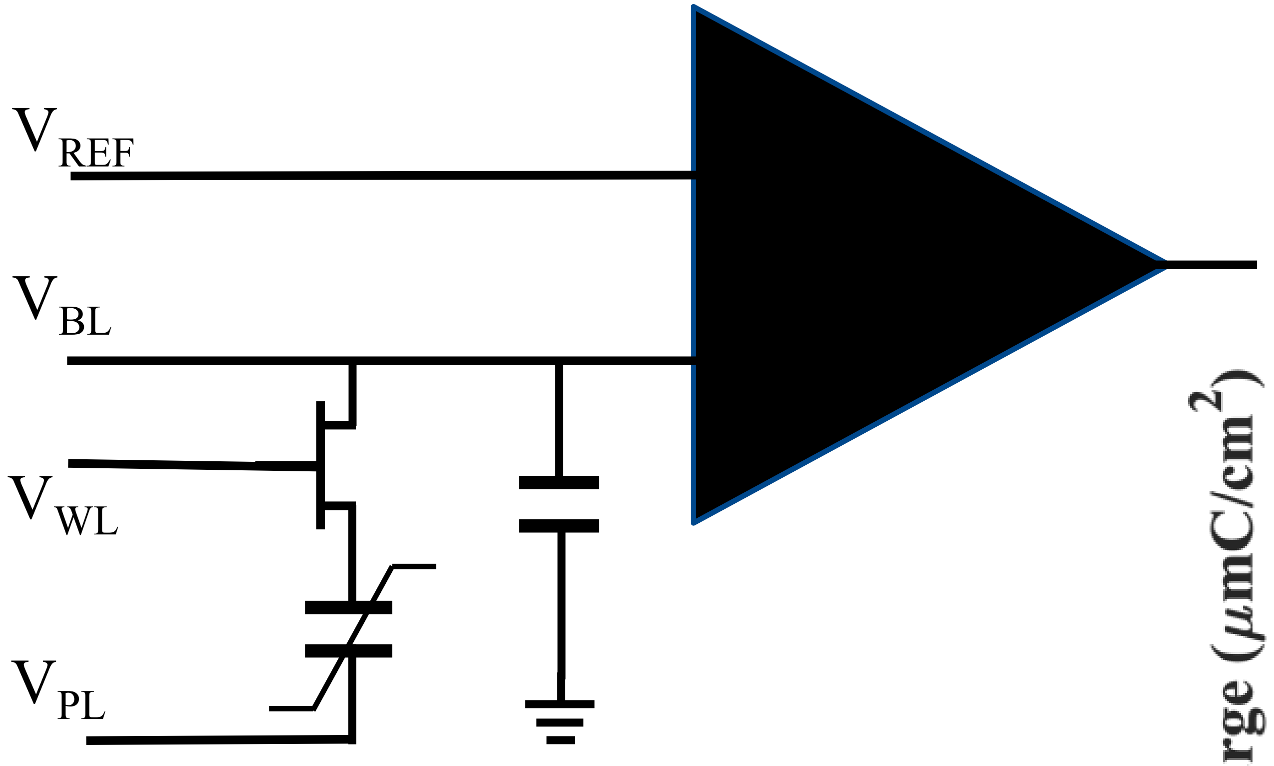
½ nm Al_2O_3

*all $2P_r$ are measured with 5V 10 ms PE loops

As HZO cycles, a wake up occurs in which $2P_r$ increases and the E_c shifts. Cycling voltage (1 Hz square wave) has a dramatic impact on the polarization. Depending on wakeup, you can achieve at 28 or 8 μC/cm2.

Working towards a FeRAM…

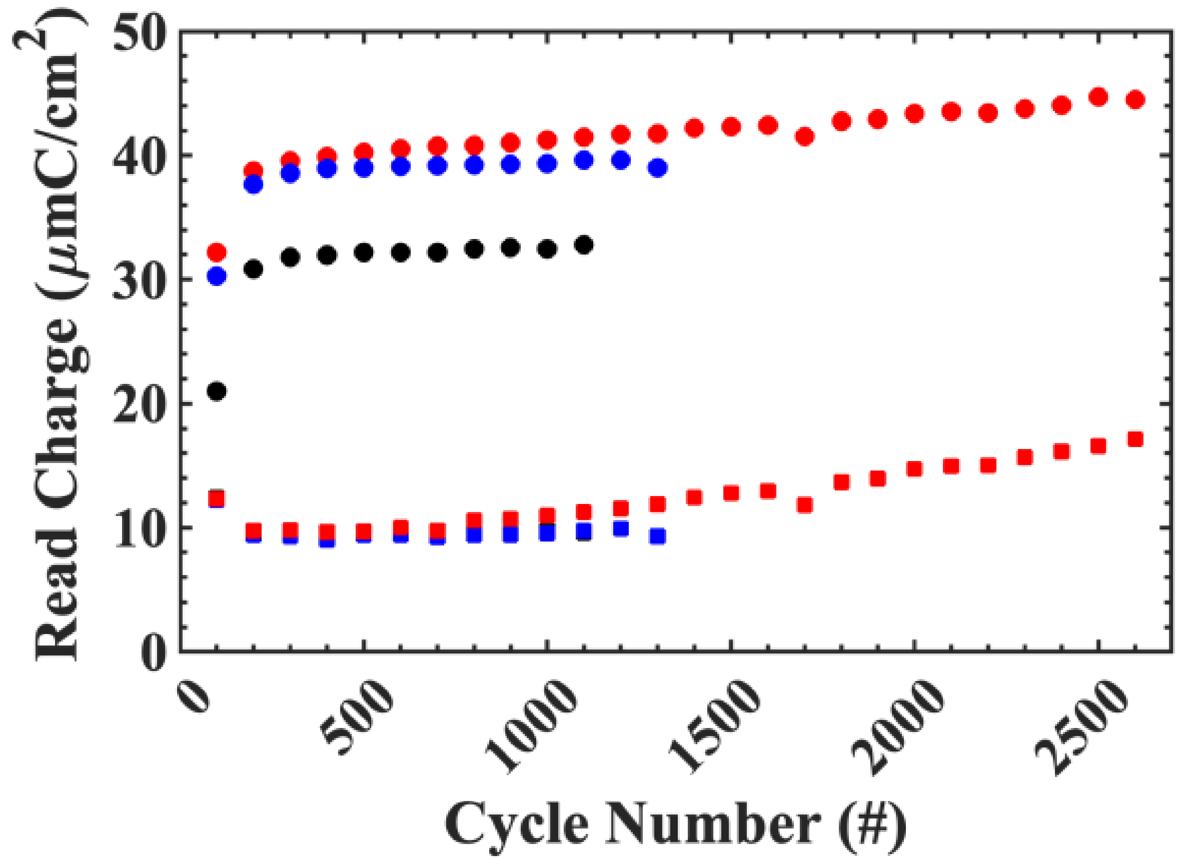




$$V_{BL} = \frac{2 * Q}{C} = \frac{2\, P_r * A_{MFIM}}{C}$$

Same State Read = (P_s-P_r)

Opp State Read = 2P_r +(Ps-P_r)



How this would affect an FeRAM? In this type of FeRAM cell, the reduction in 2P_r has impact as to where you can distinguish between states. Wake up also shifts 'read charge' over cycle numbers.

Ferroelectric Tunnel Junctions

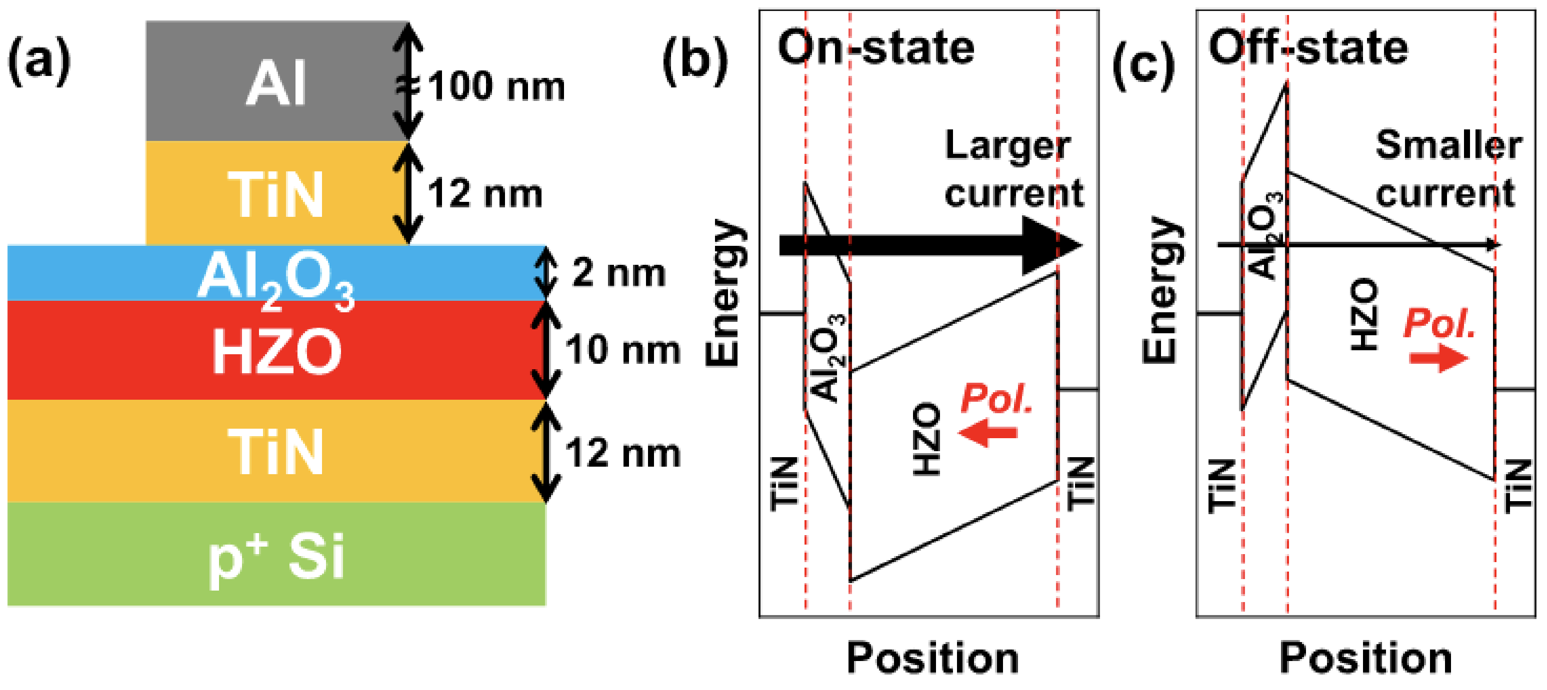


Fig. 1. (a) Schematic of the ferroelectric HZO-based capacitors fabricated and energy band diagrams for FTJ at (b) ON-state and (c) OFF-state.

Hur, J., Park, C., Choe, G., Ravindran, P. V., Khan, A. I., & Yu, S. (2022). Characterizing HfO 2-Based Ferroelectric Tunnel Junction in Cryogenic Temperature. *IEEE Transactions on Electron Devices*, *69*(10), 5948-5951.

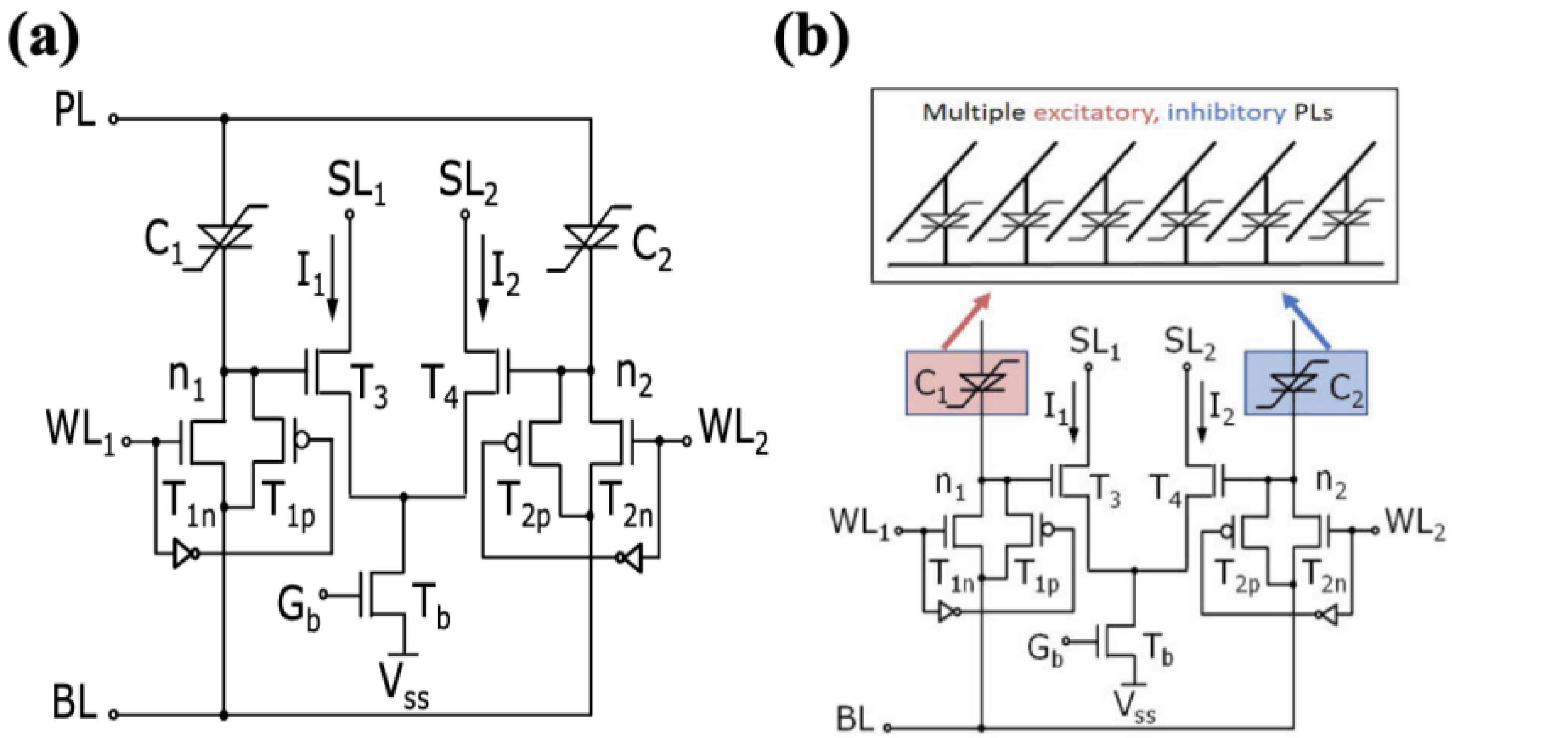


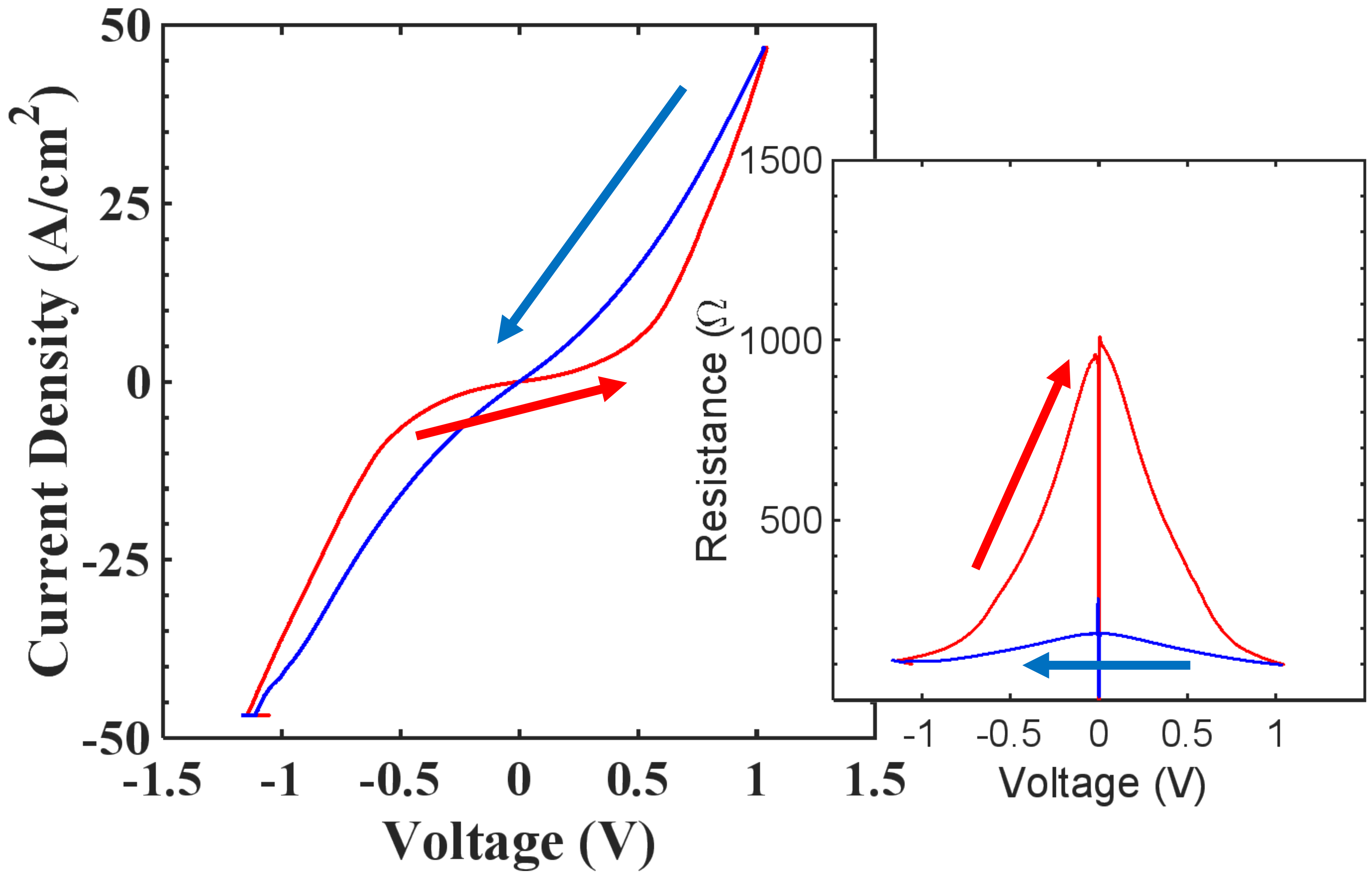
Fig. 1. (a) Differential synaptic cell using two FTJ devices. © 2021 IEEE. Reprinted, with permission, from [8]; (b) differential synaptic cell using multiple parallel FTJ devices.

Lancaster, S., Duong, Q. T., Covi, E., Mikolajick, T., & Slesazeck, S. (2022, September). Improvement of FTJ on-current by work function engineering for massive parallel neuromorphic computing. In *ESSCIRC 2022-IEEE 48th European Solid State Circuits Conference (ESSCIRC)* (pp. 137-140). IEEE.

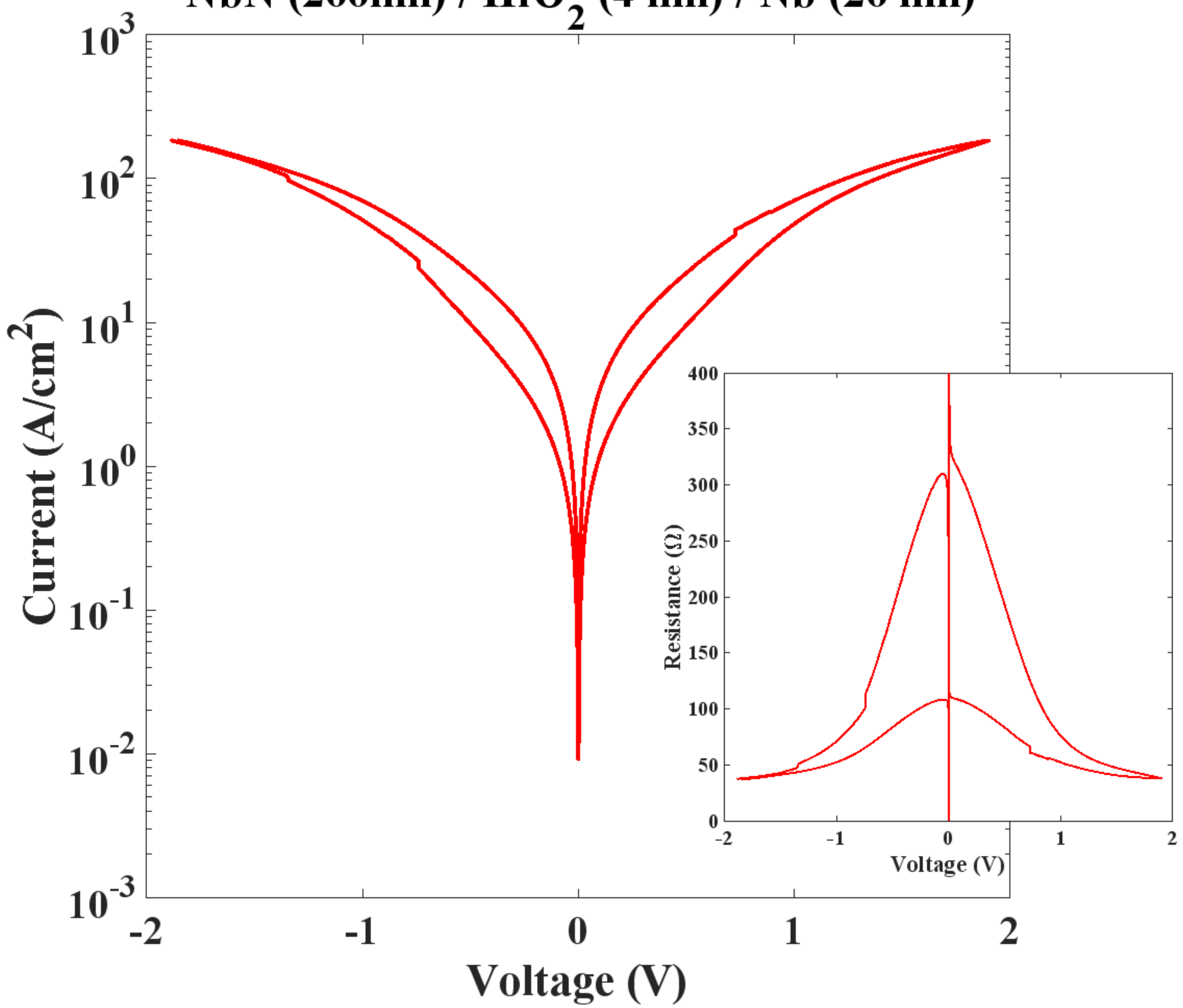
The how and the why of FTJs. This is an exciting application of ferroelectrics which relies on a scalable current density and tunable devices based on electrodes and HZO/HfO_2 thickness.

Beginning development of a manufacturable FTJ

NbN (200 nm BE) / $HfZrO_2$ 9:1(4.4 nm)* / Nb (20 nm TE)

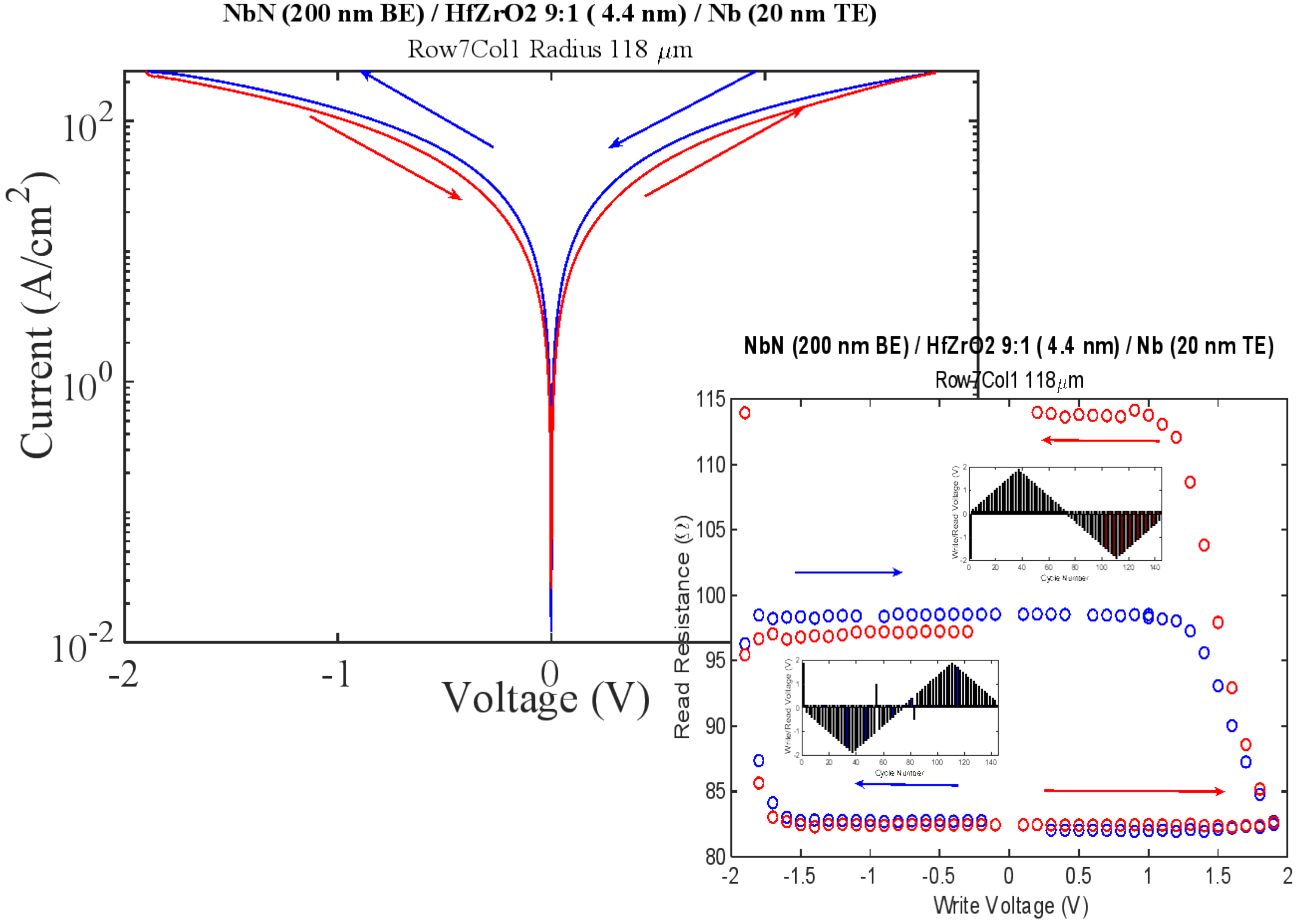


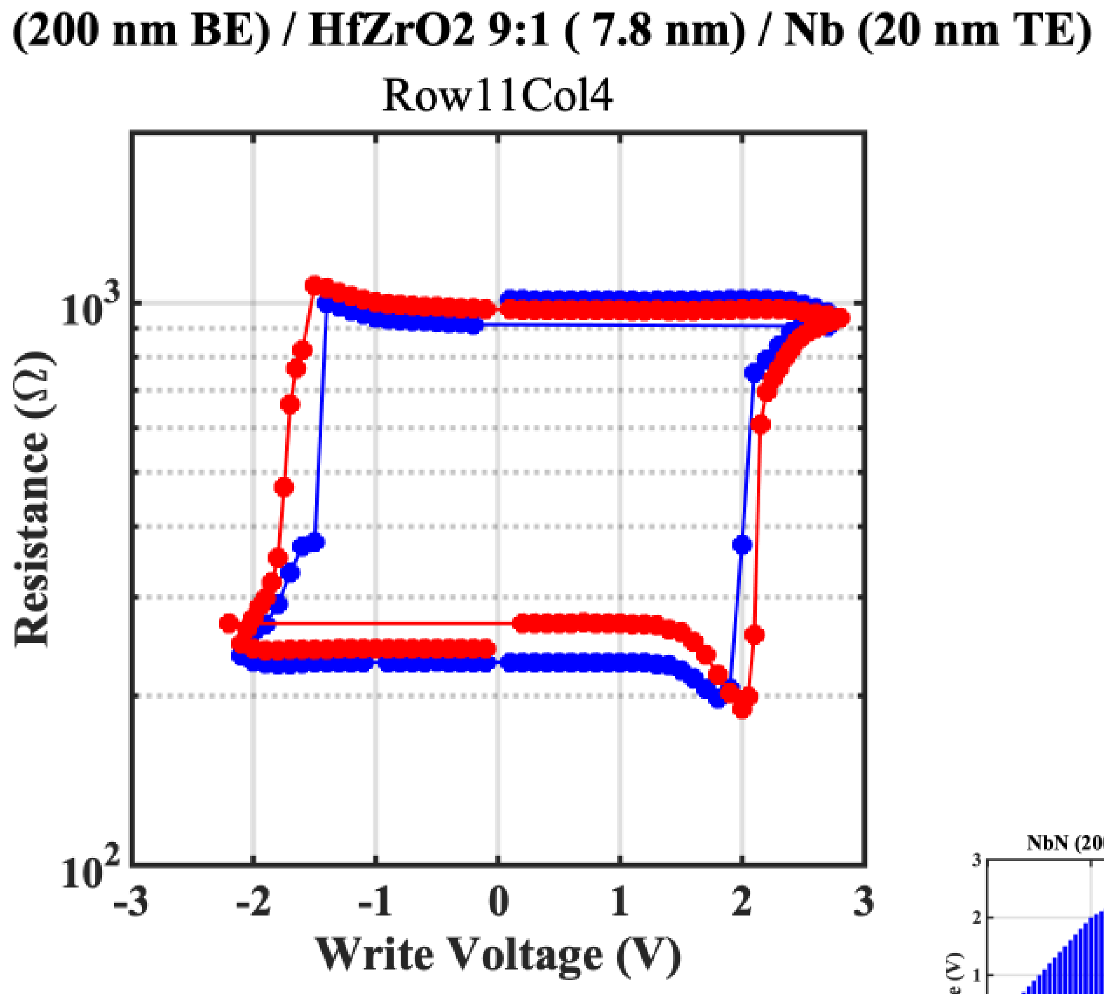
NbN (200nm) / HfO_2 (4 nm) / Nb (20 nm)

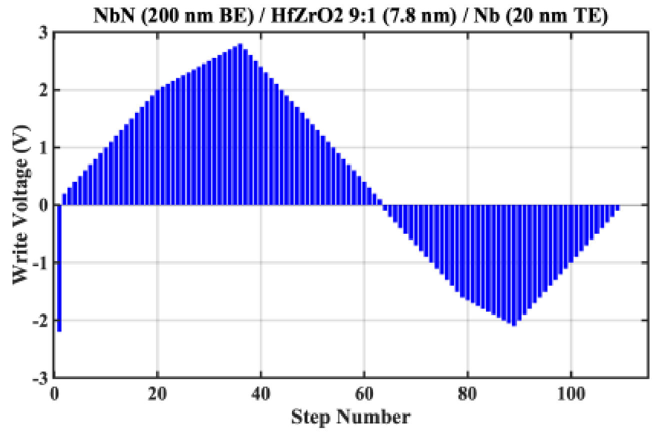


Signatures of an FTJ are there, with a polarization based current. Utilizing both HZO (left) and HfO_2, devices on NbN bottom electrode were able to see switching behavior.

Cycling of the NbN/HZO/Nb FTJ

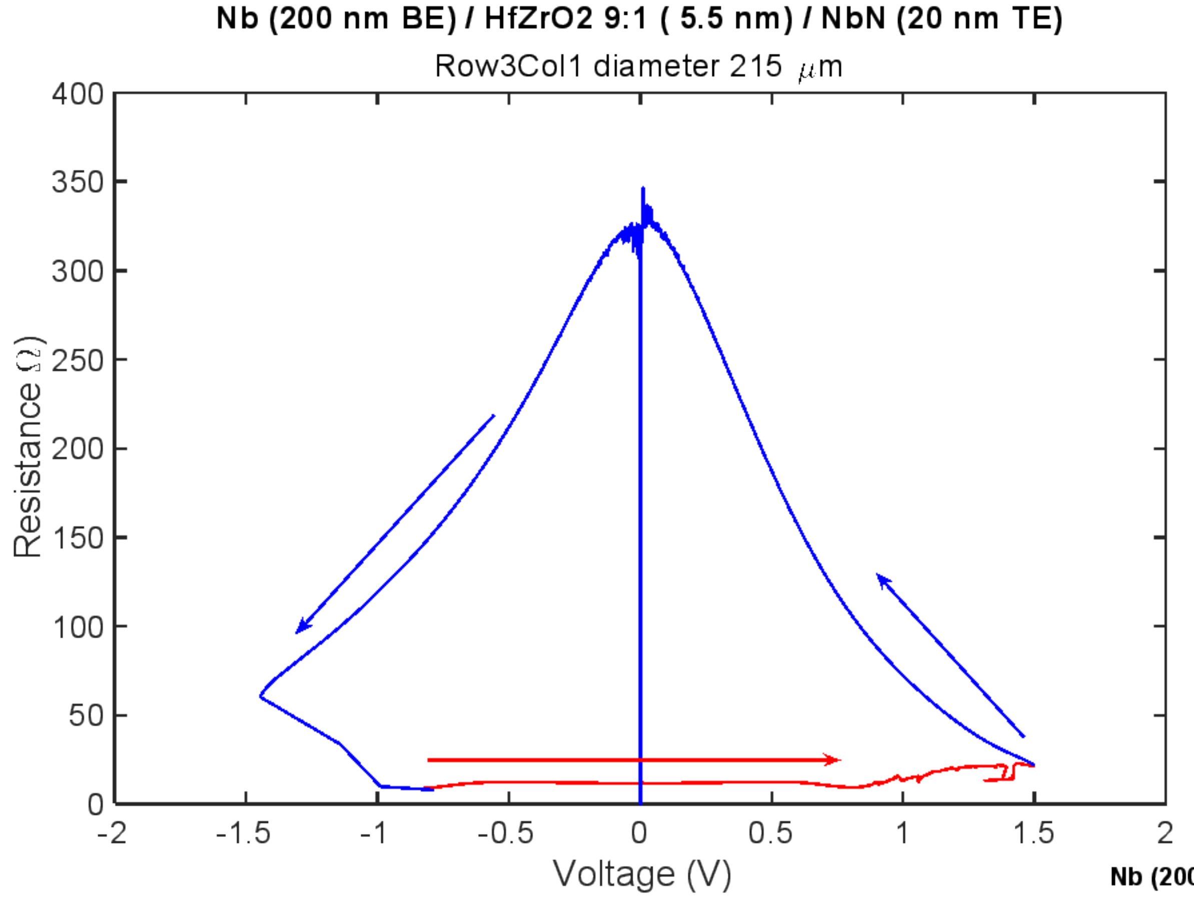


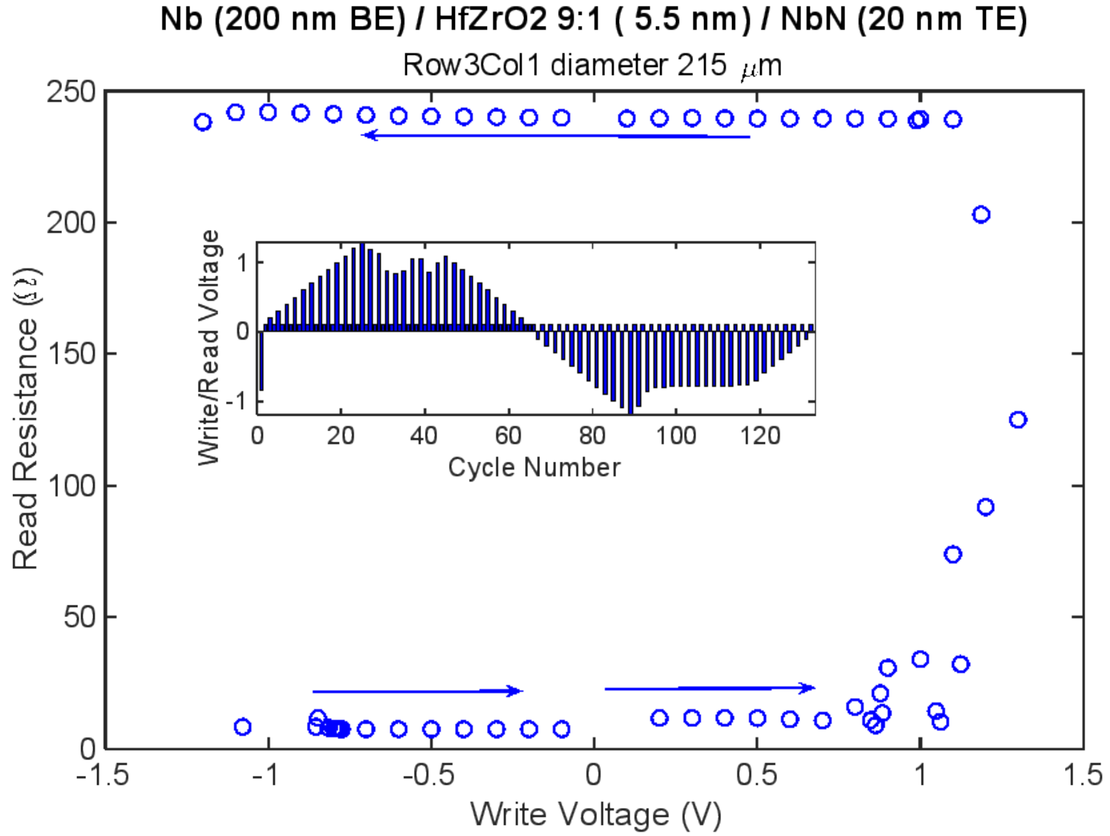


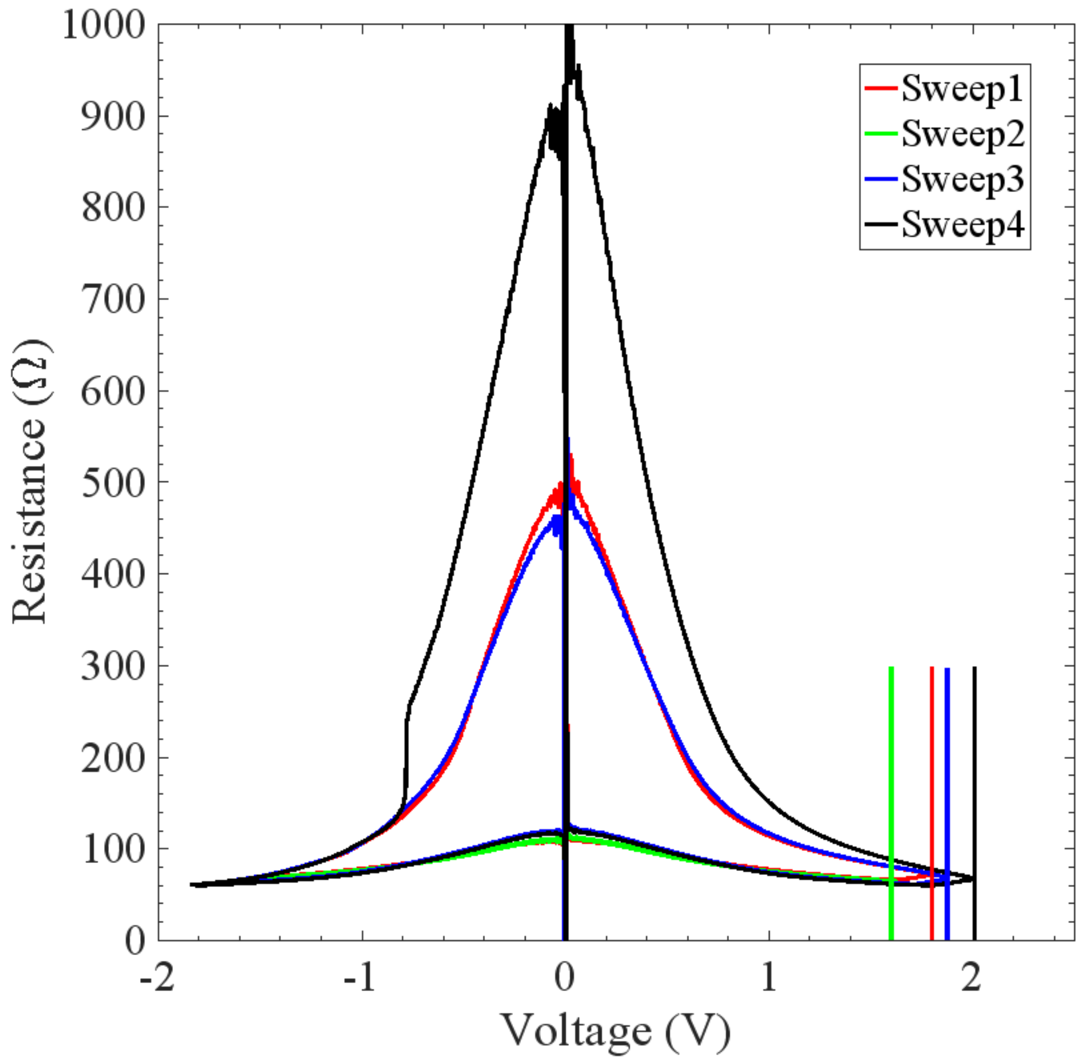


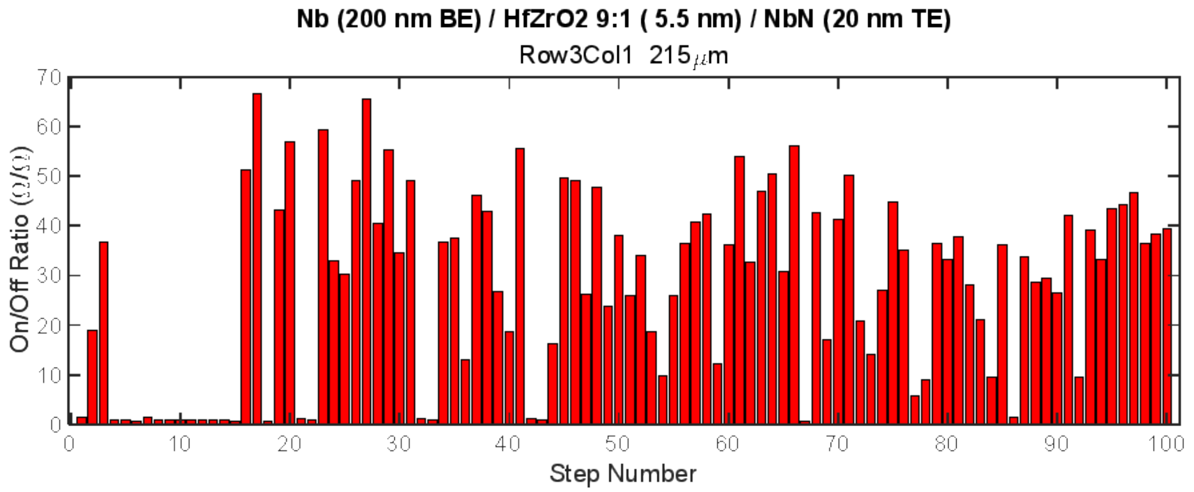
But after some amount of cycling, an event occurs which seems to degrade the devices. We 'think' that a pinhole thru the ferroelectric breaks down providing a current shunt thru the device.

So, reverse the electrodes… Nb as the bottom electrode.





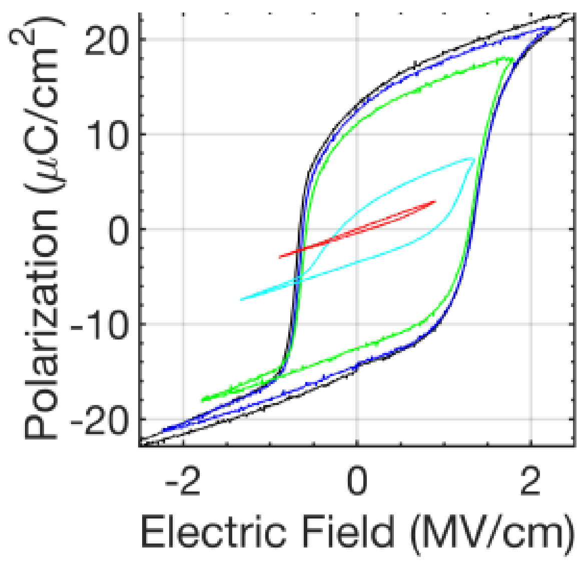


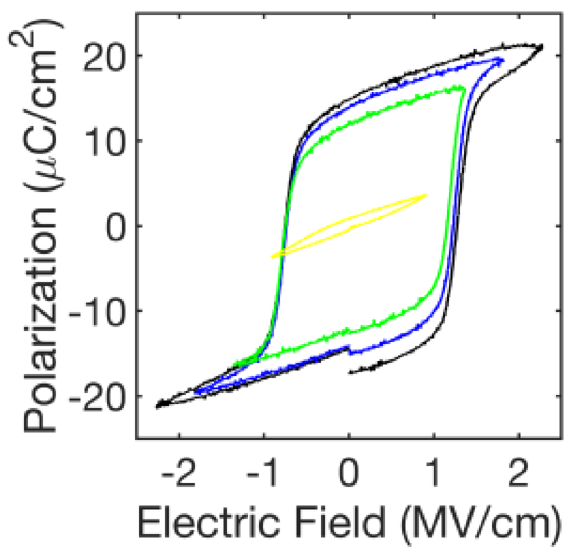


Things look ok, we get big reversals in current, but the state resistance is 'flat' and the current densities are high. A polarization dependent switch does occur (right graph) even with a breakdown event.

Conclusions

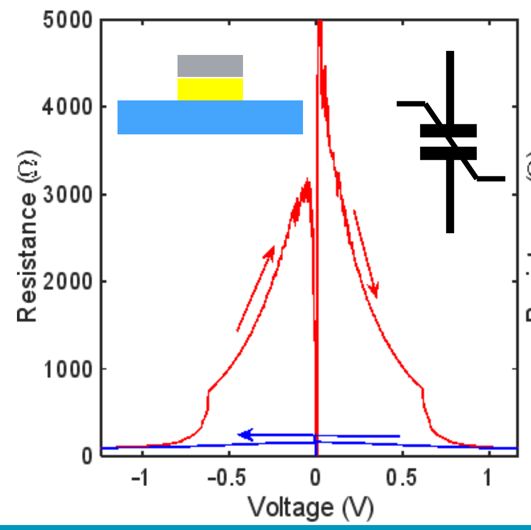
- Ferroelectric HZO and HfO_2 on NbN and Nb
  - FeRAM: $NbN/Al_2O_3/HfZrO_2/NbN$ $Nb/Al_2O_3/HfZrO_2/Nb$

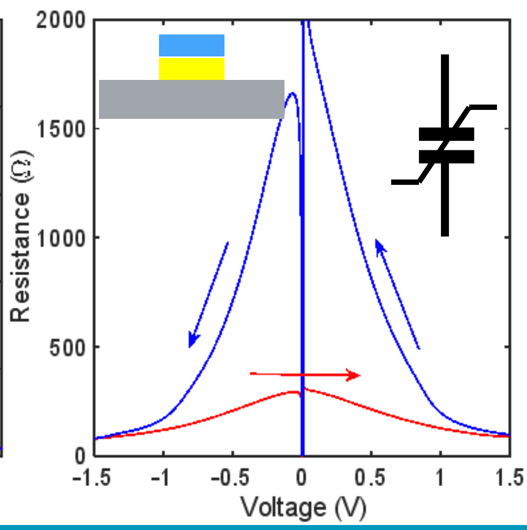




  - FTJ devices:

Nb
$HfZrO_2$
NbN





NbN
$HfZrO_2$
Nb

Mahalo for your attention, and I welcome questions.