FIXIT

Dynamics of Ferroelectric Memristor Synapses

A. Dimoulas, NCSR DEMOKRITOS, Athens, Greece

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OUTLINE

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BIG DATA VARIETY

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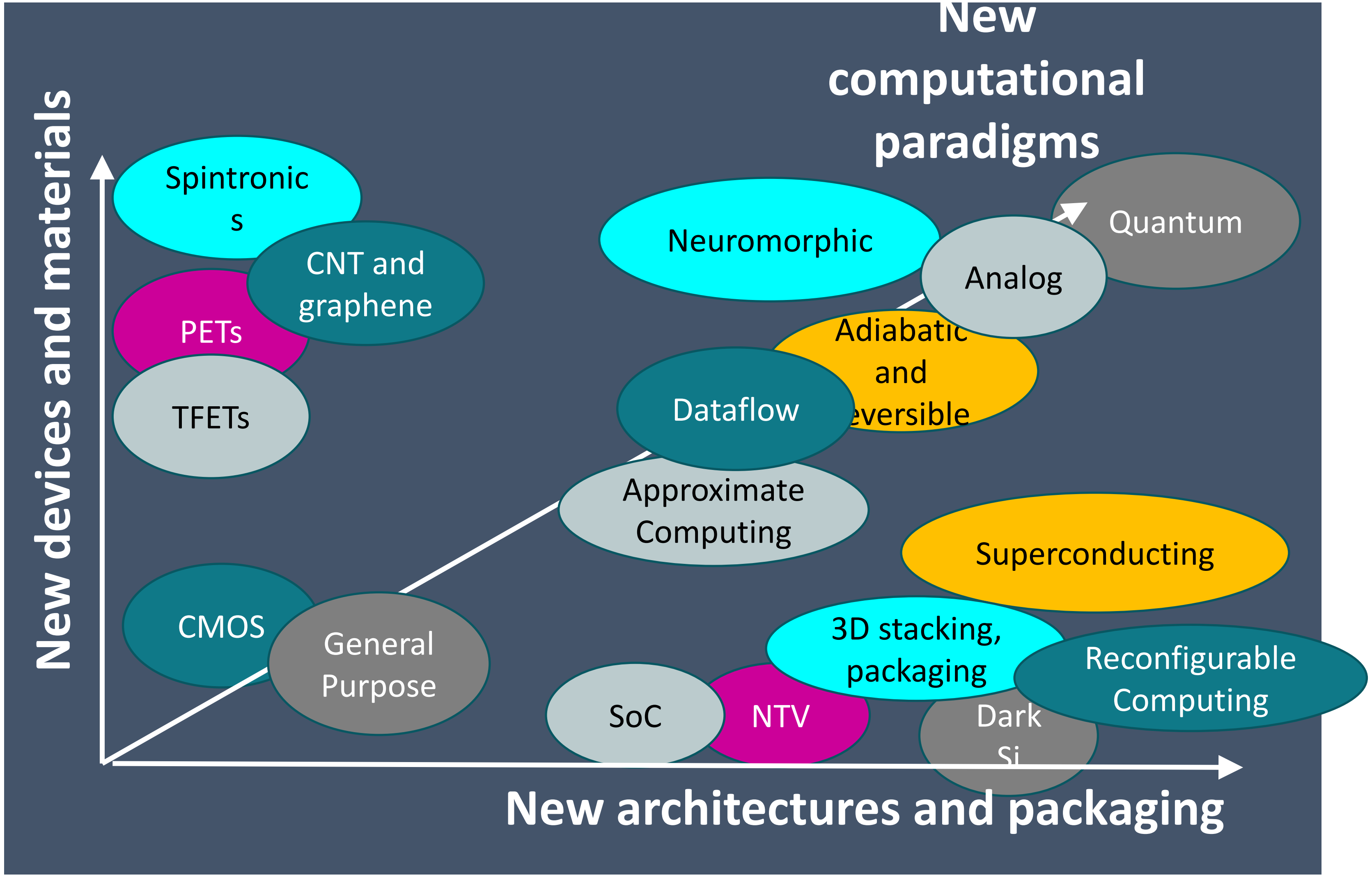
TECHNOLOGY OPTIONS



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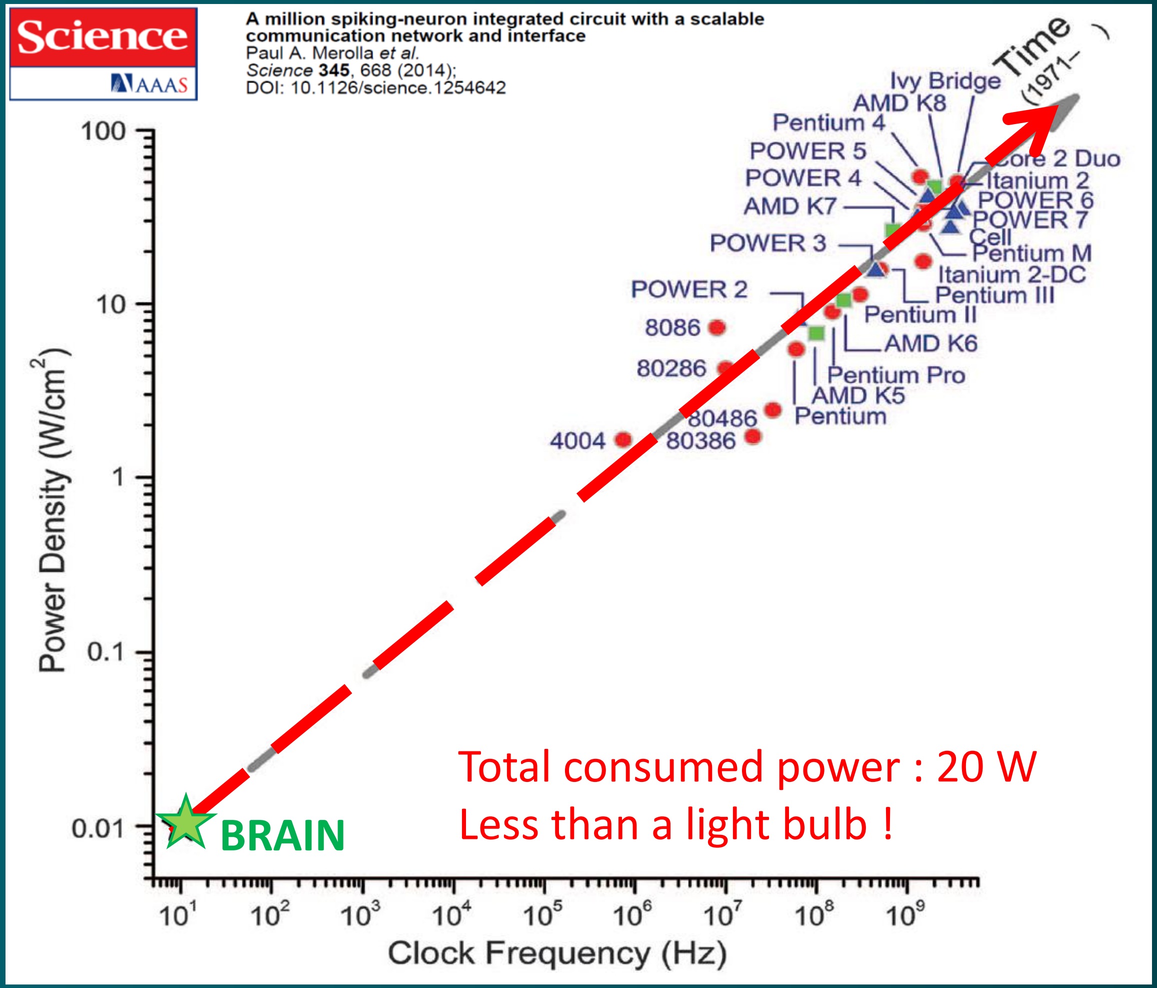
VON NEUMANN BOTTLENECK



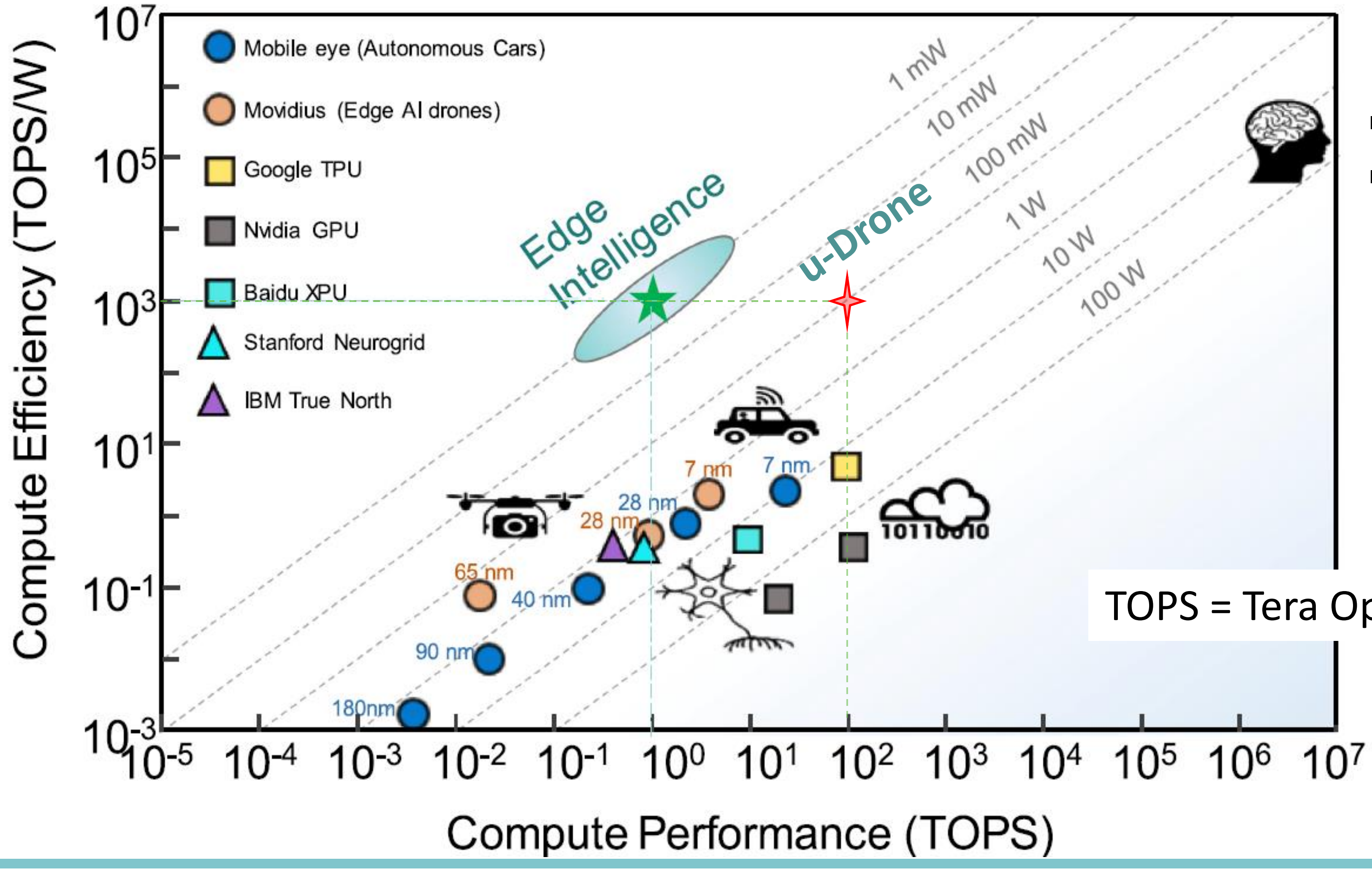
Power Issue

Von Neumann chips are moving away from the brain's efficiency

ENERGY EFFICIENT EDGE COMPUTING

FIXIT

A. Keshavarzi *et al.*, *IEEE Micro.* **40**, 1 (2020)



- Massive parallelism
- in-memory computing

TOPS = Tera Operations Per Second

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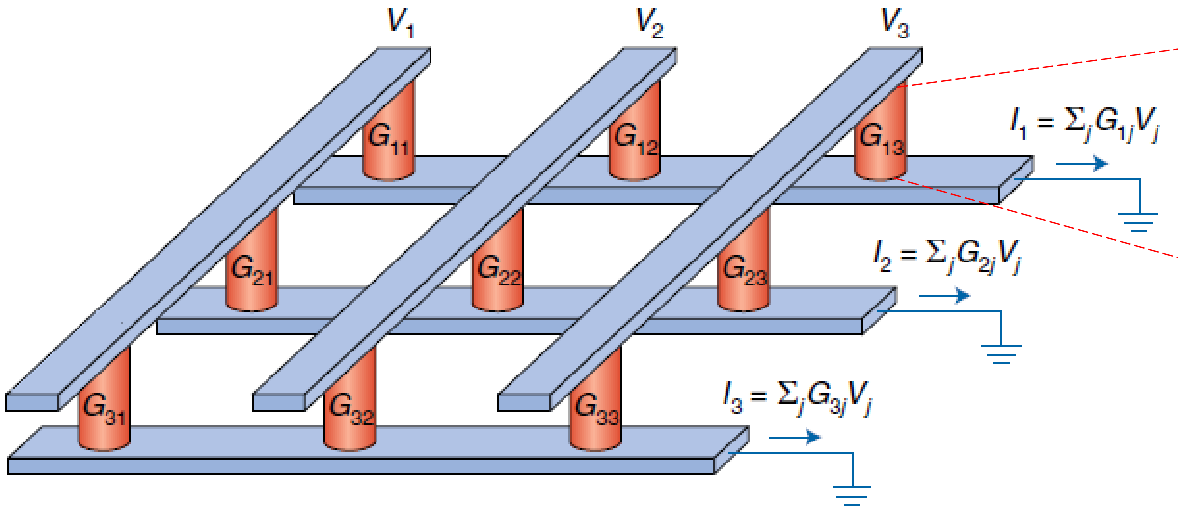
- Cross bar arrays-AI accelerators

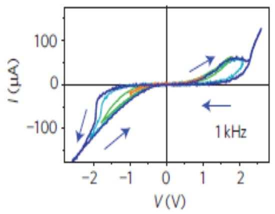
Multiply and Accumulate

Input neurons



Output neurons

memristor synapses



- Update and store conductance weights
- Analog **in-memory** computing
- Voltage driven memristors→ low power

D. Ielmini, H.-S. P. Wong, *Nat. Electron.* **1**, 333 (2018)

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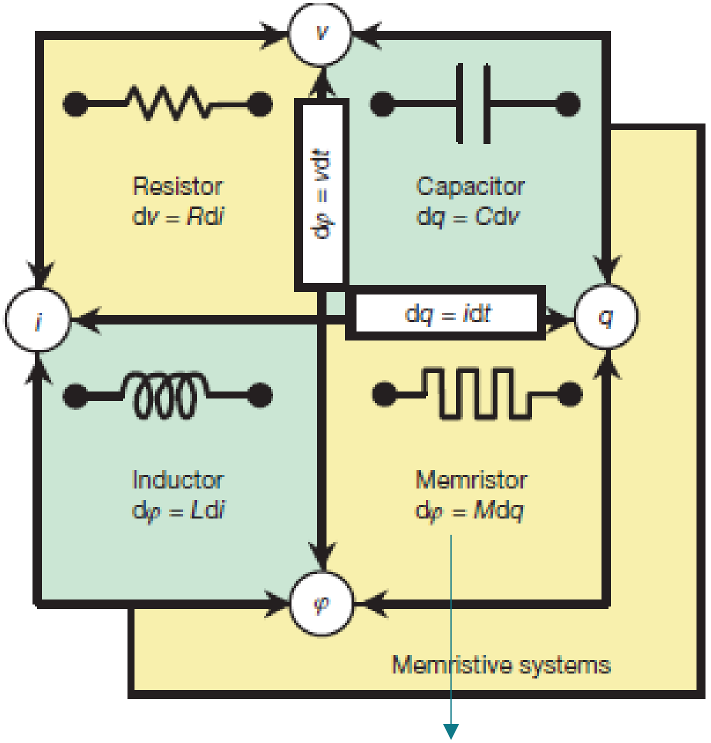
Resistor with memory

L.O Chua, IEEE Trans. Circuit Theory **18**, 507-519 (1971)



$V = MI$

Generalized equations of motion
For a current controlled resistor

$$V = M(x, I)I$$

$$\frac{dx}{dt} = f(x, I)$$

$$x = state\ variable$$

Special case

$x = Q$ (charge)

$$V = M(Q)I$$

$$\frac{dQ}{dt} = I$$

voltage controlled memristor

$$I = G(x, V)V$$

$$\frac{dx}{dt} = f(x, V)$$

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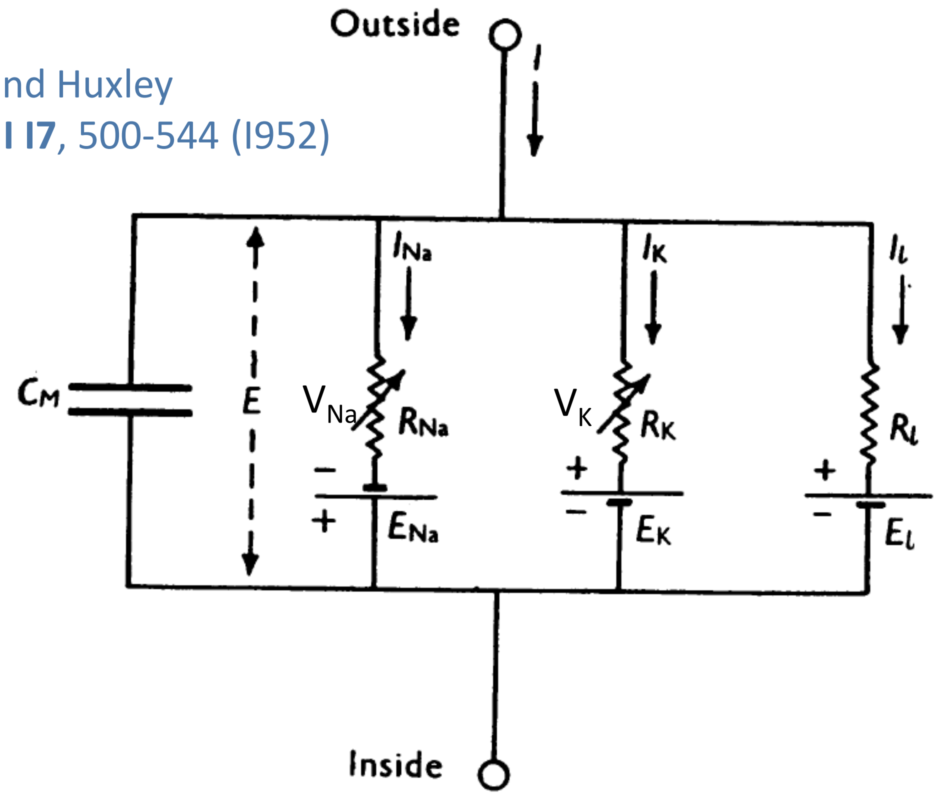
ELECTRICAL MODEL OF A BIOLOGICAL SYNAPSE

FIXIT

Hodgkin and Huxley
J. Physiol. I I7, 500-544 (I952)



$$\alpha(V_K, E_K) = -0.125 \exp\left(\frac{v_K + E_K}{80}\right)$$

$$\beta(V_K, E_K) = \frac{0.01\,(v_K + E_K + 10)}{\exp[(v_K + E_K + 10)/10] - 1}$$

$$I_K = G_K(n)V_K \qquad G_K(n) = G_{K,0}n^4$$

$$\frac{dn}{dt} = \alpha(V_K, E_K)n + \beta(V_K, E_K)(1-n) = f(n, V_K)$$

n=K ion concentration

voltage controlled memristor $x \to n,\ V \to V_K$

$$I = G(x, V)V$$

$$\frac{dx}{dt} = f(x, V)$$

A memristor can emulate a biological synapse as described by Hodgkin and Huxley

Chua and Kang Proc. IEEE 64, 209 (1976)

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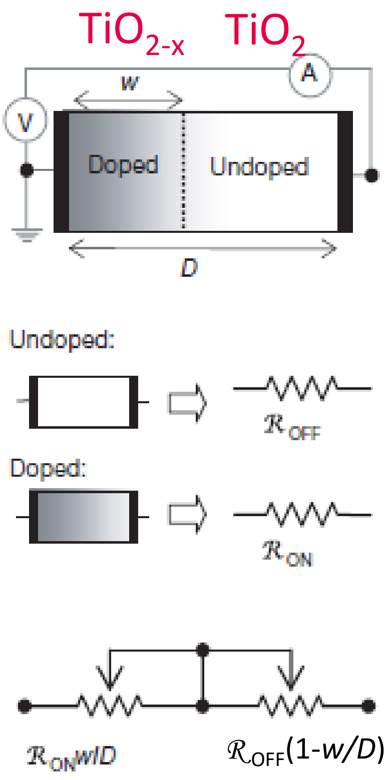
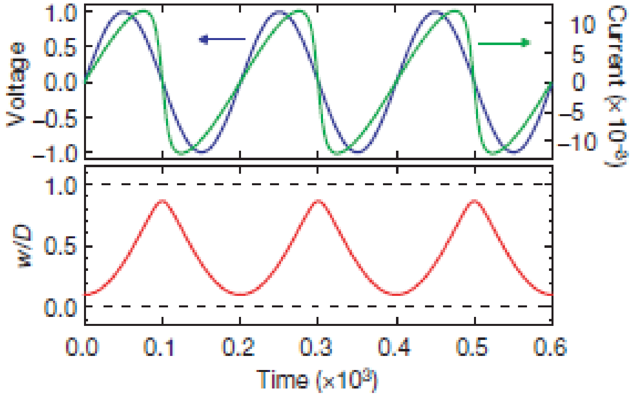
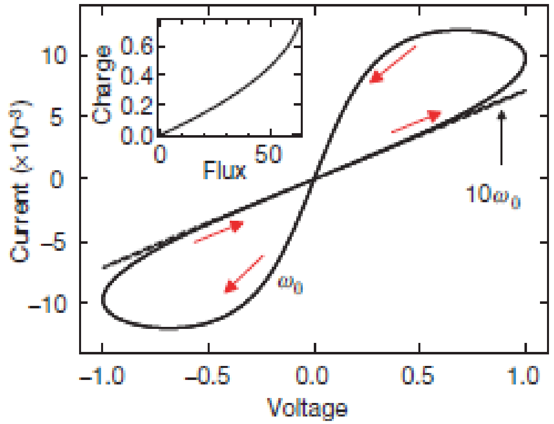
THE FIRST MEMRISTOR REALIZED

Strukov et al., *Nature* **453**, 80 (2008), Hewlett Packard

Oxygen vacancies: mobile charged dopants







$M(w(t))$=memristance

$$V(t) = \left[R_{ON}\frac{w(t)}{D} + R_{OFF}\left(1 - \frac{w(t)}{D}\right)\right] I(t)$$

$$\frac{dw}{dt} = \mu_V E = \mu_V \frac{V}{w} = \mu_V \frac{1}{w} R_{ON} \frac{w}{D} I = \mu_V \frac{R_{ON}}{D} I$$

$$\frac{dw}{dt} = \mu_V \frac{R_{ON}}{D} I(t) \qquad w(t) = \mu_V \frac{R_{ON}}{D} Q(t)$$

$$M(Q(t)) \approx R_{OFF}\left(1 - \mu_V \frac{R_{ON}}{D^2} Q(t)\right) \qquad (R_{ON} \ll R_{OFF})$$

$$V = M(Q)I \qquad \frac{dQ}{dt} = I$$

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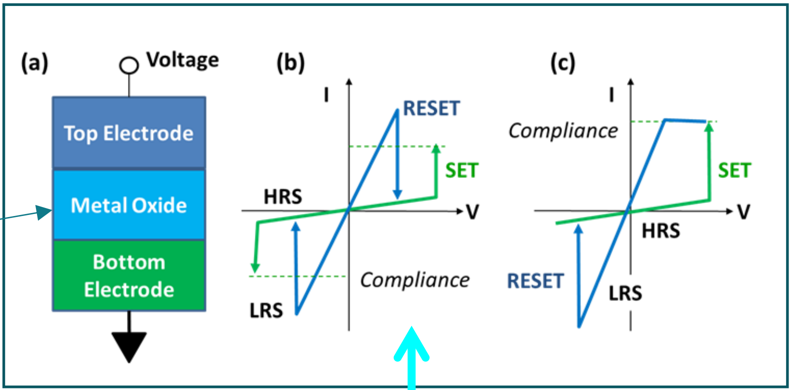
NVM FUNCTIONING AS MEMRISTORS

Resistive RAMs (ReRAM)

Oxide RAM (OXRAM)

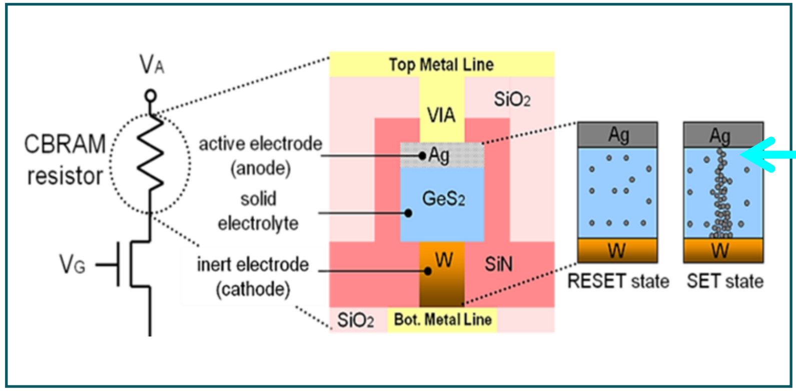
Oxygen vacancies
Electronic effect

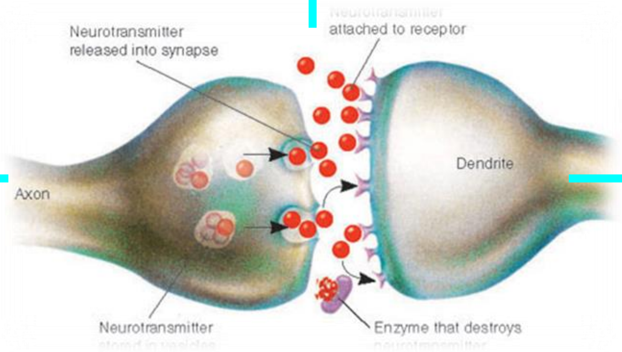
HfO_2



Electrochemical effect
Ionic conduction

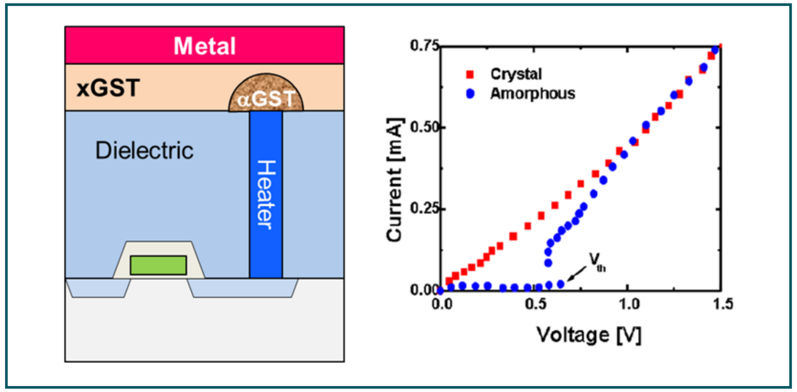
Conductive Bridge RAM (CBRAM)





Thermal effect

Phase change RAM (PCRAM)



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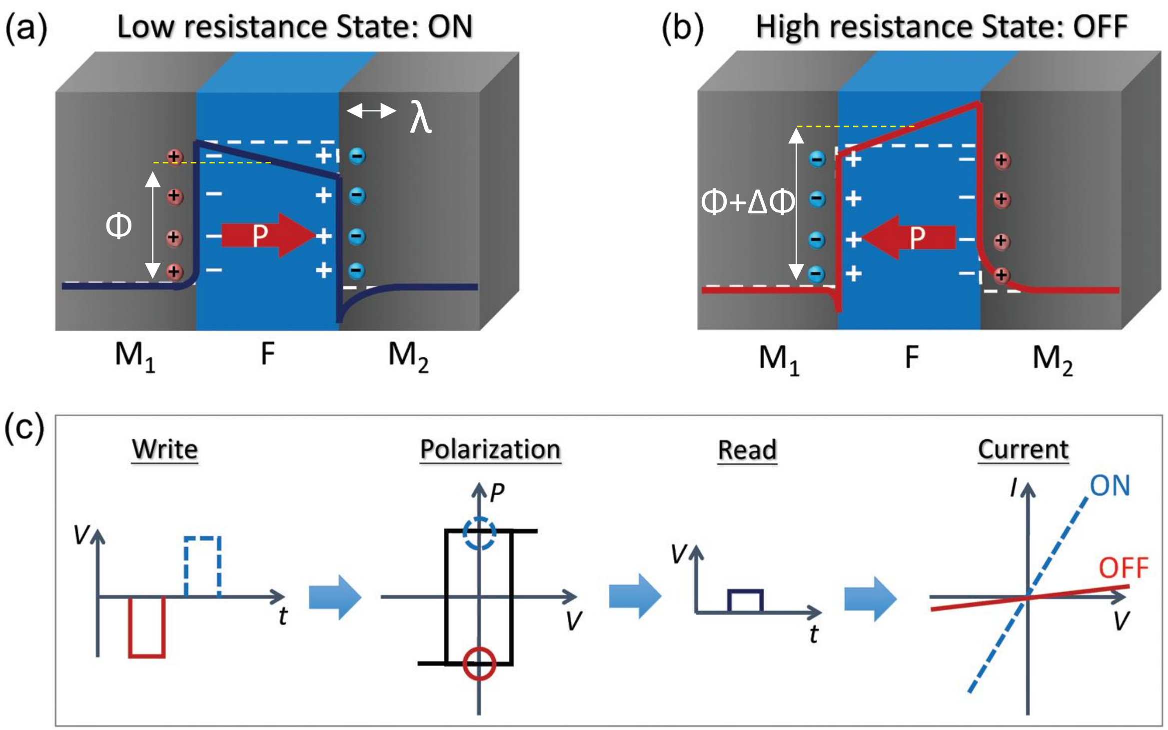
NVM: FERROELECTRIC TUNNEL JUNCTION

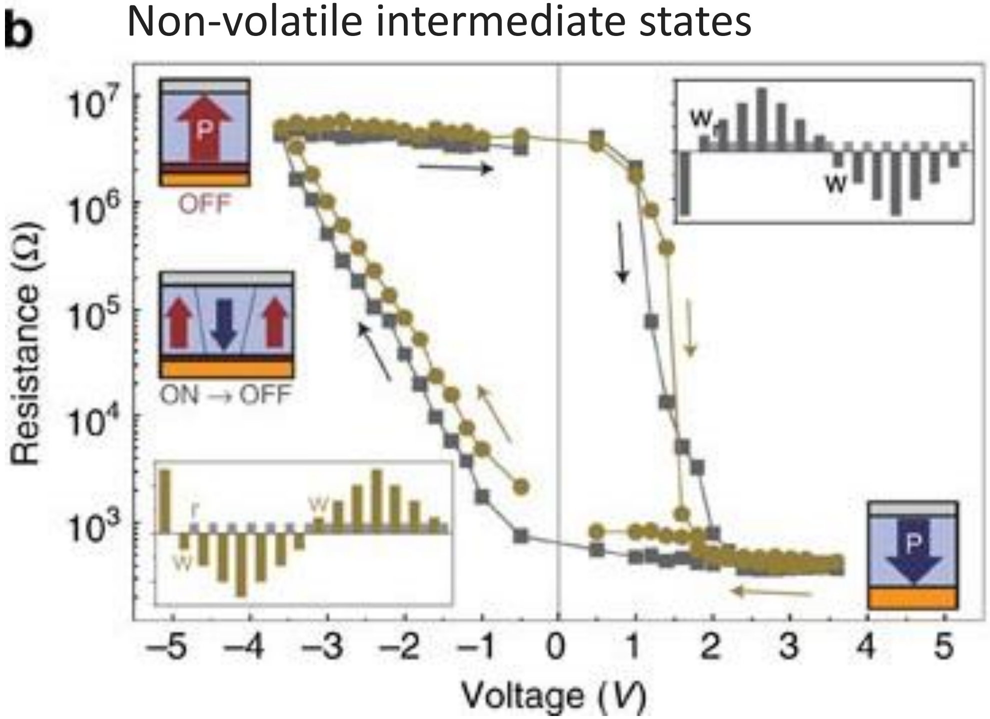
Z. When, D. Wu, *Adv. Mater* (2019)
https://doi.org/10.1002/adma.201904123



I=GV, R=1/G

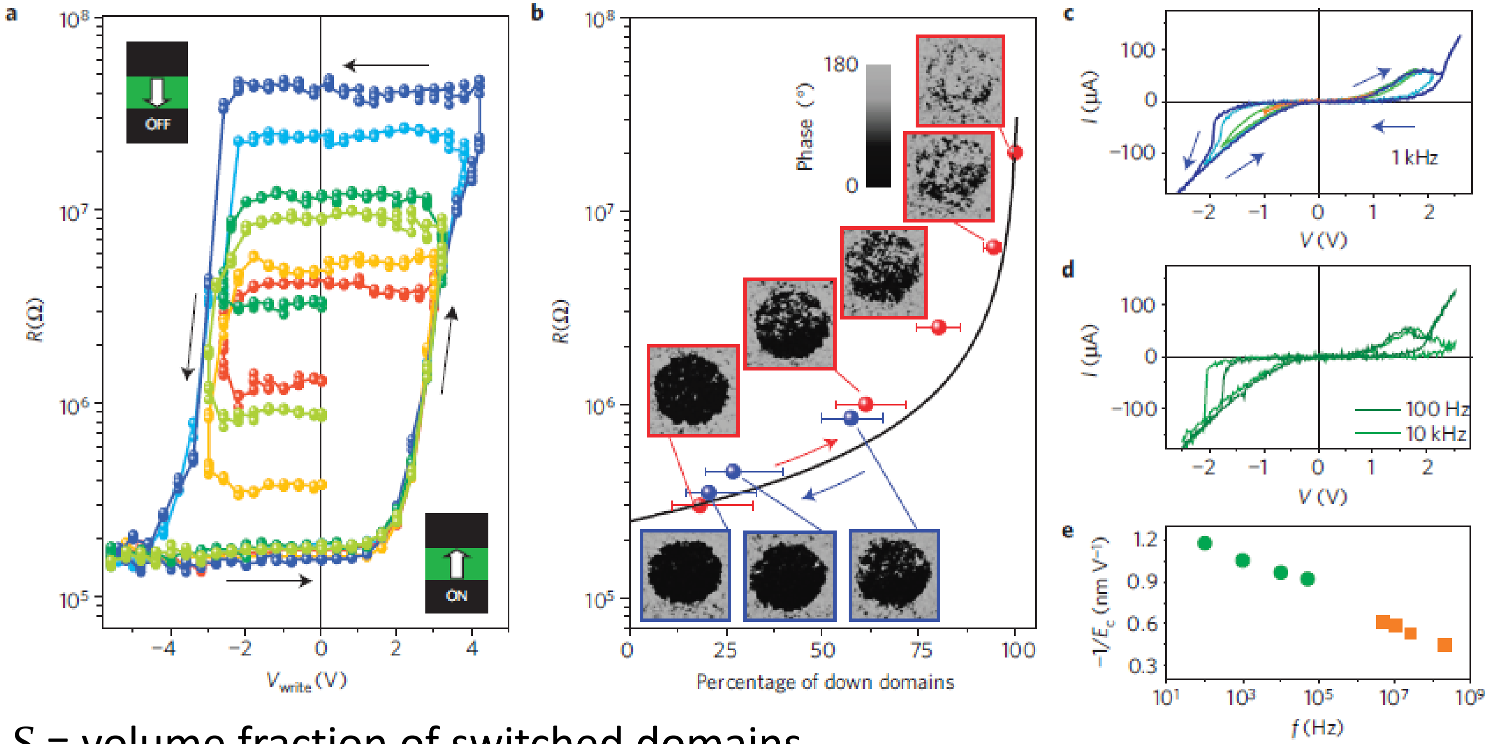
V. Garcia, M. Bibes
Nature Commun. **5**, Article No 4289 (2014)

Partial polarization:
Non-volatile intermediate states



THE FIRST FERROELECTRIC MEMRISTOR

A. Chanthbouala et al., *Nat. Mater.* (2012) DOI: 10.1038/NMAT3415



$$V(t) = R(\sigma, V, i)i(t)$$

$$d\sigma/dt = f(\sigma, V, t)$$

S = volume fraction of switched domains

$$s = \sum_{i=1}^{N(i)} S_i * h(t - \tau_N^i) * \left\{1 - \exp\left[-\left(\frac{t - \tau_N^i}{\tau_P^i}\right)^2\right]\right\}$$

$$ds/dt = (1 - s) \times \left\{\frac{2}{\tau_P(V)}\left(\frac{t - \tau_N(V)}{\tau_P(V)}\right)\right\} = f(s, V, t)$$

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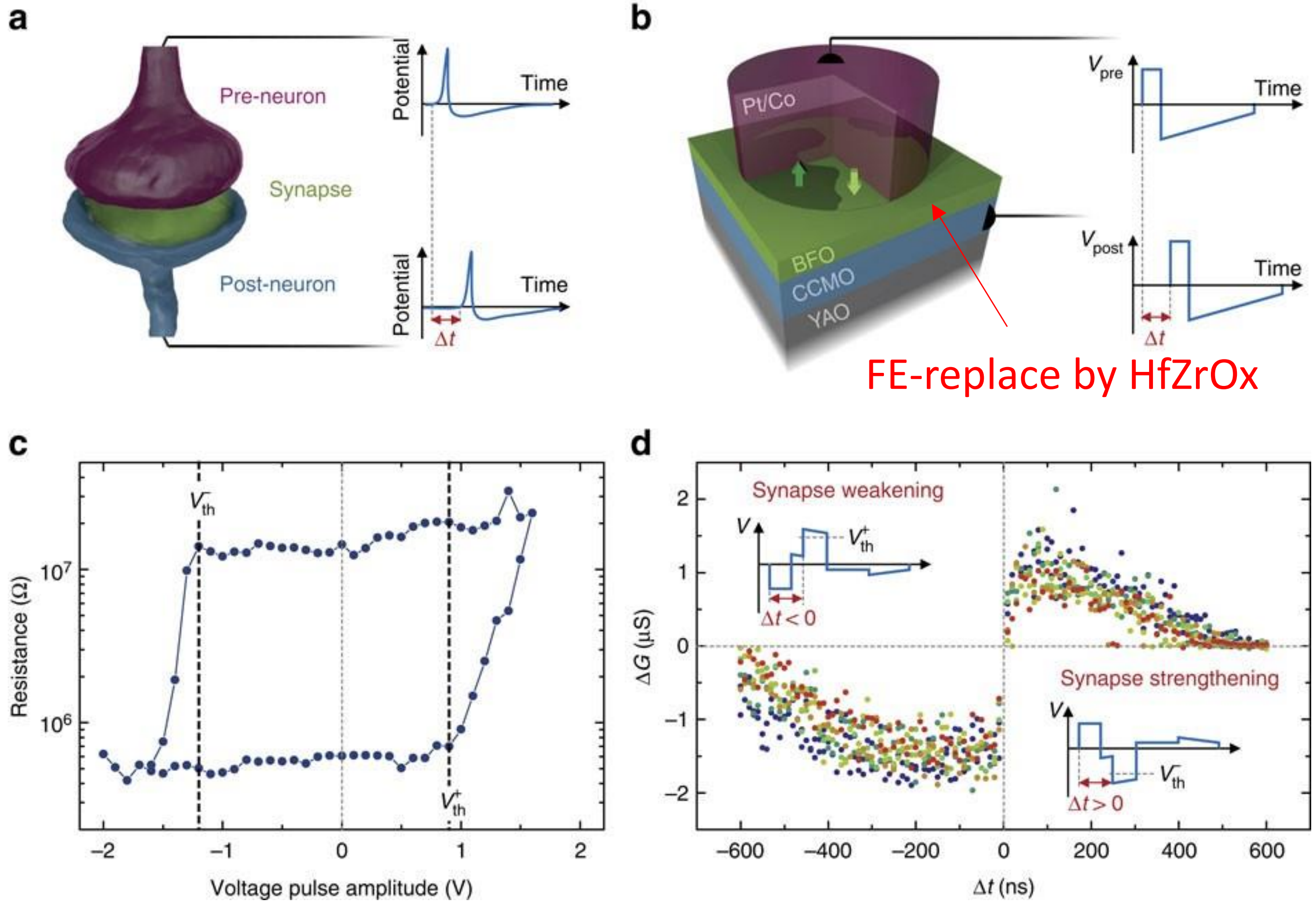
FERROELECTRIC SYNAPSES WITH STDP PLASTICITY

FIXIT

Unsupervised learning with ferroelectric synapses

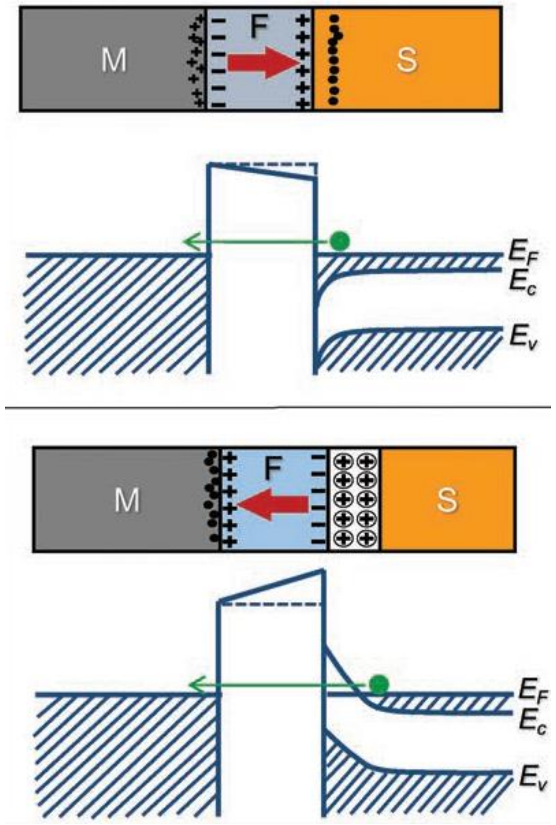
S. Boyn et al., *Nature Commun* **8**, Article number: 14736 (2017)



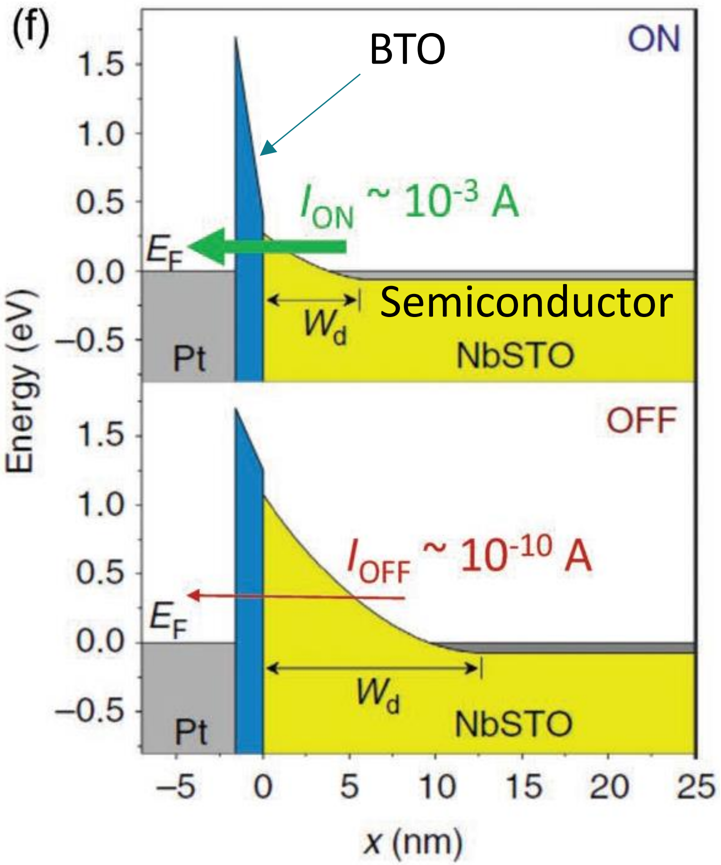
STDP activity-fast response

METAL/FERROELECTRIC/SEMICONDUCTOR FTJ

Z. Wen et al., *Nat. Mater.* **12**, 617 (2013)



Z. Xi, et al.,*Nat. Commun.* **8**, 15217 (2017)



- MFS/FTJ: best performance -**Giant TER > 10^7**
- Predominant effect of Schottky barrier for thin FE

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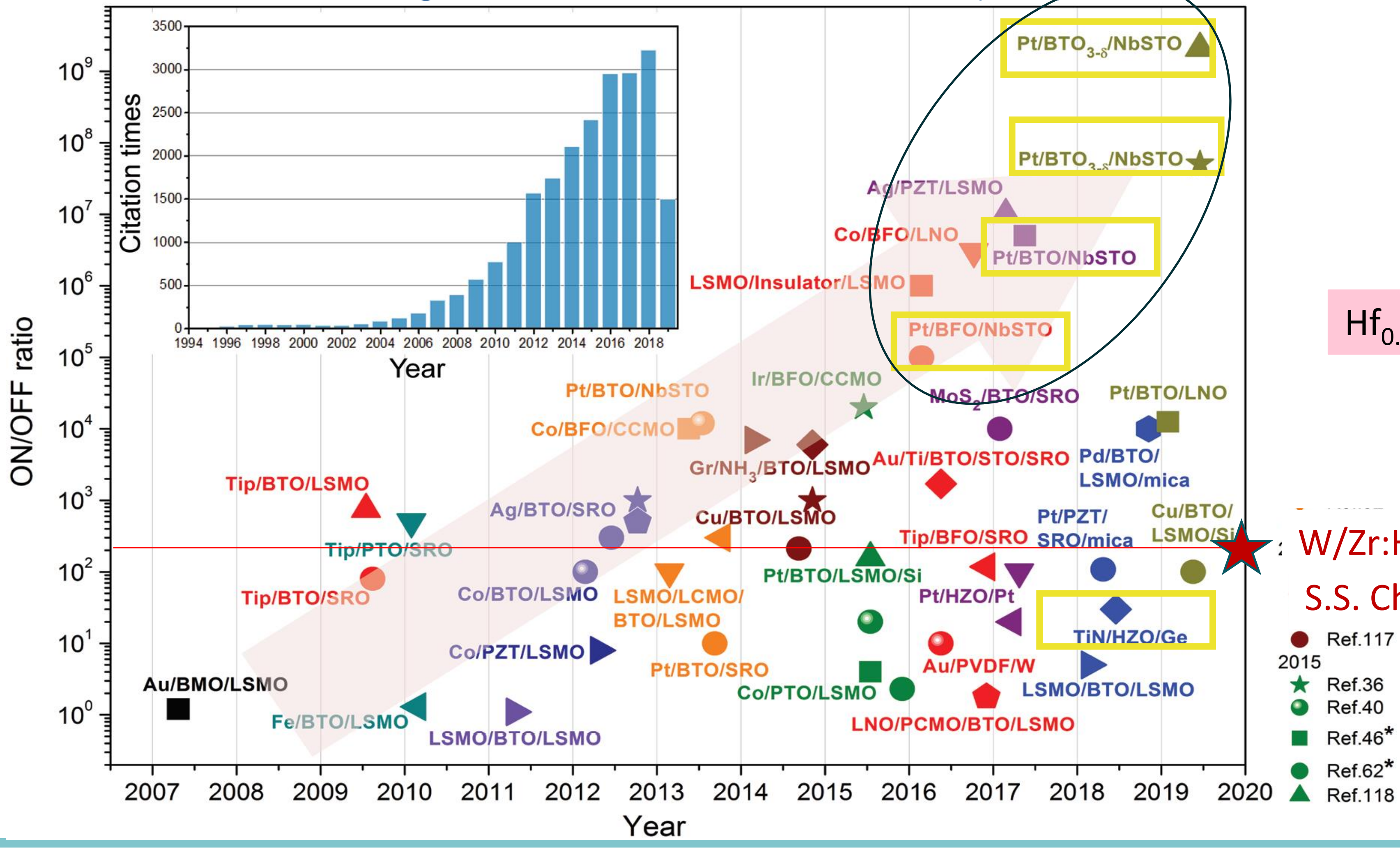
MATERIALS COMBINATIONS

Review: Zheng Wen & Di Wu, *Adv. Mater.*, 1904123 (2019)



$Hf_{0.5}Zr_{0.5}O_2$ /$SrTiO_3$?

W/Zr:HfO_2/SiO_2/Si

S.S. Cheema et al., *Nature* (2020)

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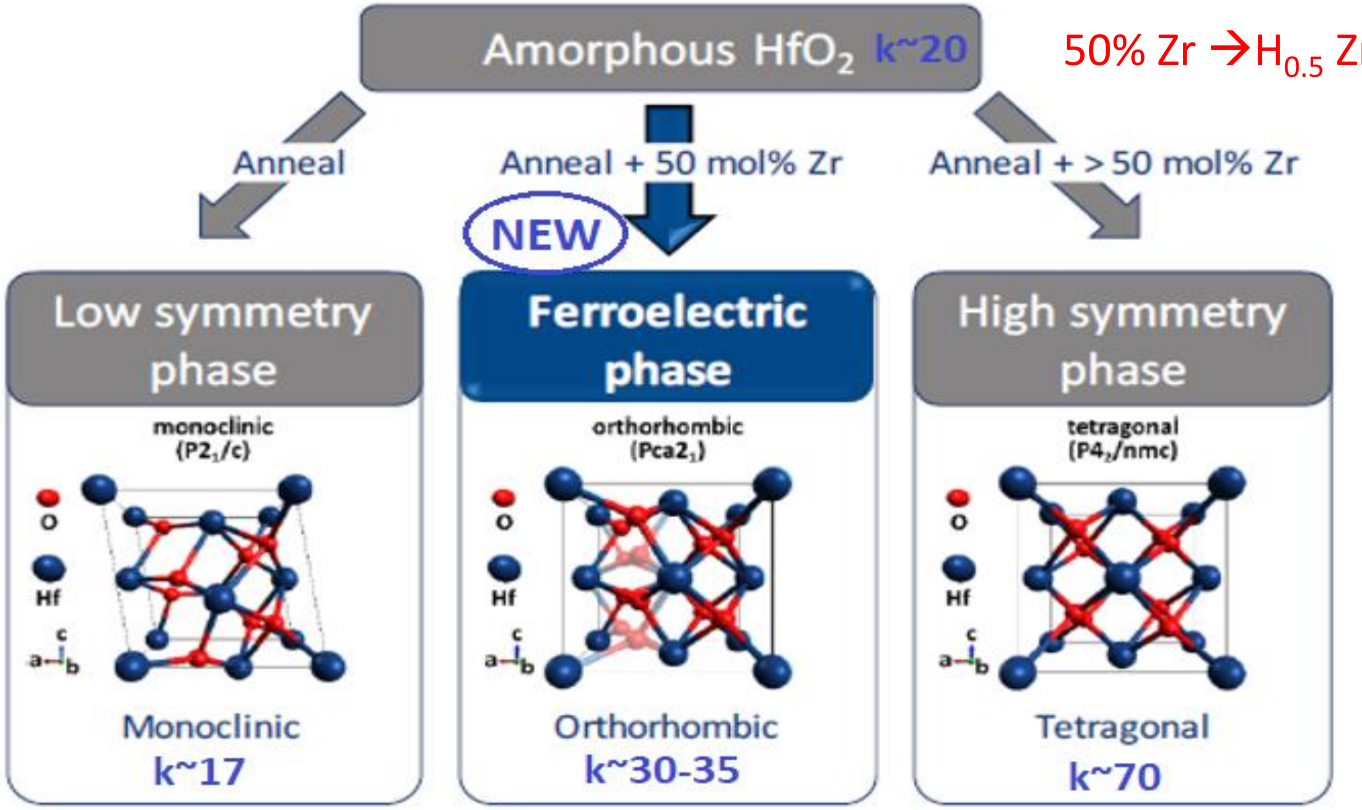
FLUORITE HAFNIA-BASED FERROELECTRICS

FIXIT

Discovered in 2007-first published 2011, Qimonda T. S. Böscke et al, *Appl. Phys. Lett*. **99**, 102903 (2011)

Stabilization of the ferroelectric phase: doping (Si, Zr,..), stress, annealing, film thickness …



50% Zr → $H_{0.5}Zr_{0.5}O_2$ (HZO)

Compatible with Si processing
(HfO_2 used as high-k dielectric/CMOS scaling)

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PLASMA-ASSISTED MBE/MBD

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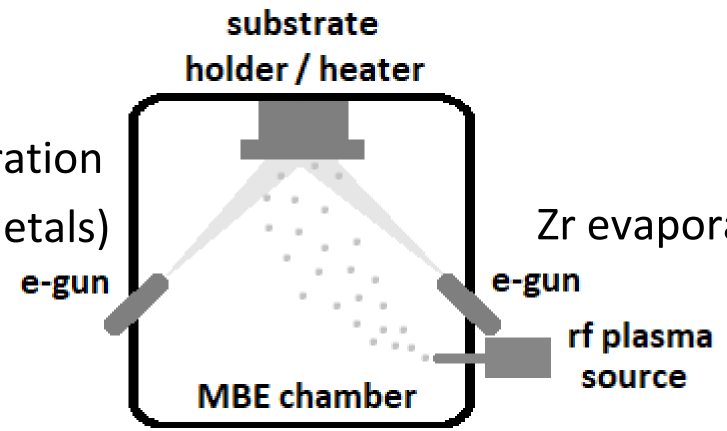
Molecular Beam Epitaxy (MBE)

Hf, W evaporation

(Refractory metals)



Zr evaporation

UHV
base pressure:
5×10^{-10} Torr

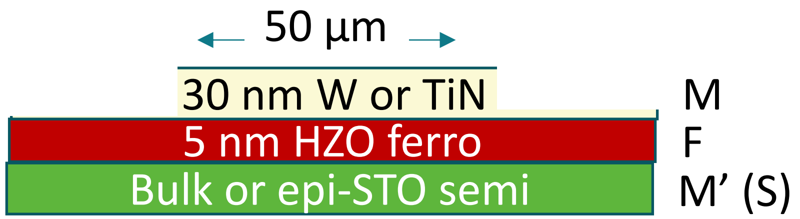
reactive O
neutral atomic beam

350 W
2×10^{-5} Torr

C. Zacharaki et al., *Appl. Phys. Lett.*, **114**, 112901 (2019)

C. Zacharaki et al., *ACS Appl. Electron. Mater.* **4** 2815 (2022)

Plasma MBD



Bulk : Nb:STO

Epi-STO on Si (001)

- Deliberately grown O deficient to act as bottom electrode
- O vacancy donors V_O=0.56% → N-type ρ=0.02 Ωcm

- T_{growth}(HZO)=120°C, amorphous
- Crystallization annealing 420 ^{0}C, 400 s → **Epitaxial**
- Optical litho + etching or lift-off

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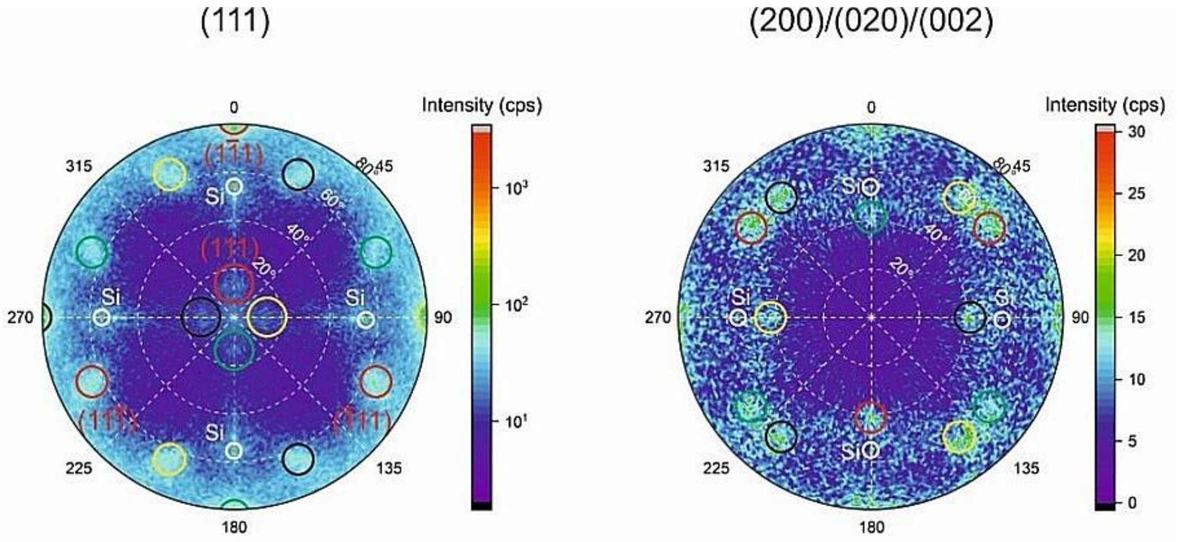
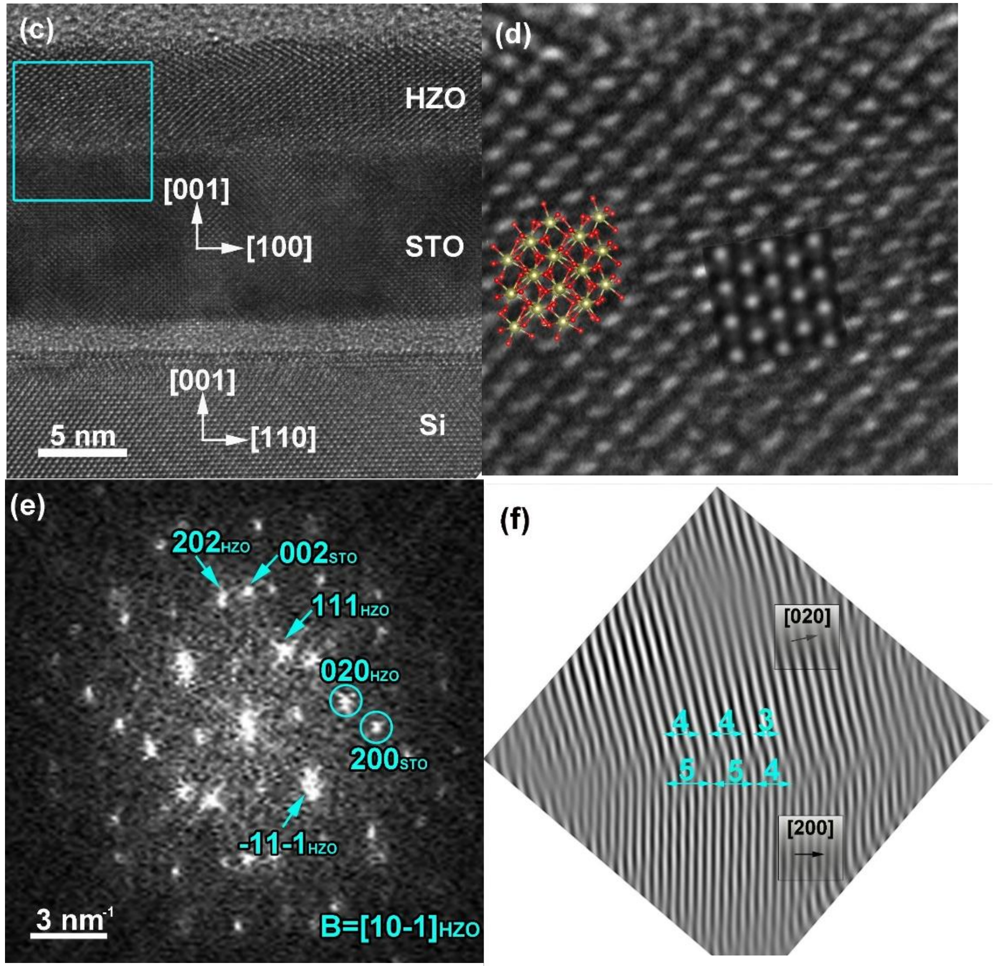
EPITAXIAL HZO ON STO/SILICON

FIXIT

XRD pole figures



- [111] HZO 15 deg off vertical
- 0, 90, 180, 270 deg rotated domains
  due to 4-fold symmetry of STO substrate



Domain Matching Epitaxy

S. Estandia et al., *Cryst. Growth Des*. **20**, 3801 (2020)

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HZO THICHNESS SCALING TRENDS

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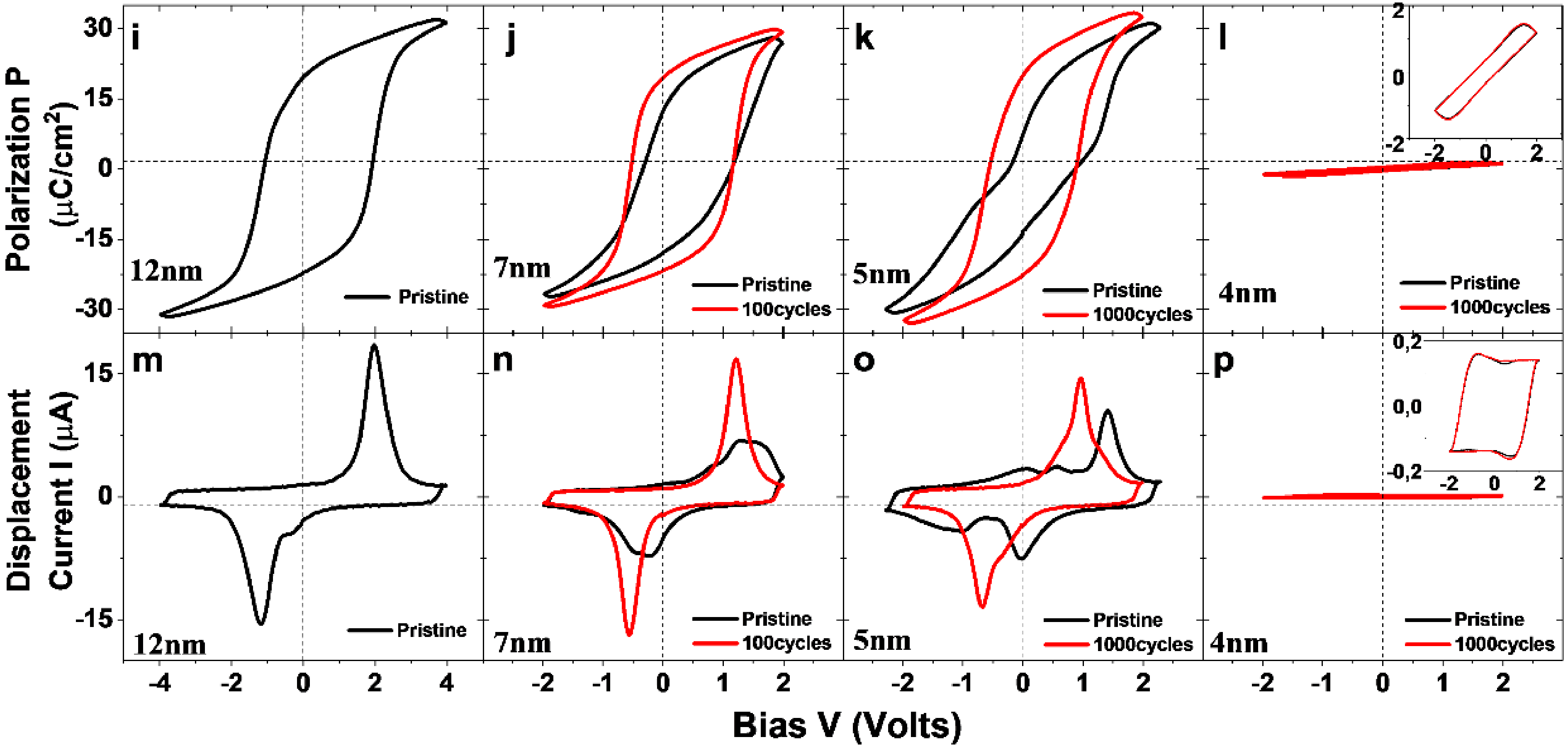
Nb:STO/HZO/TiN

Below 5 nm HZO, ferroelectricity is unstable N. Siannas et al., *Comms. Phys*. **5**, 178 (2022)



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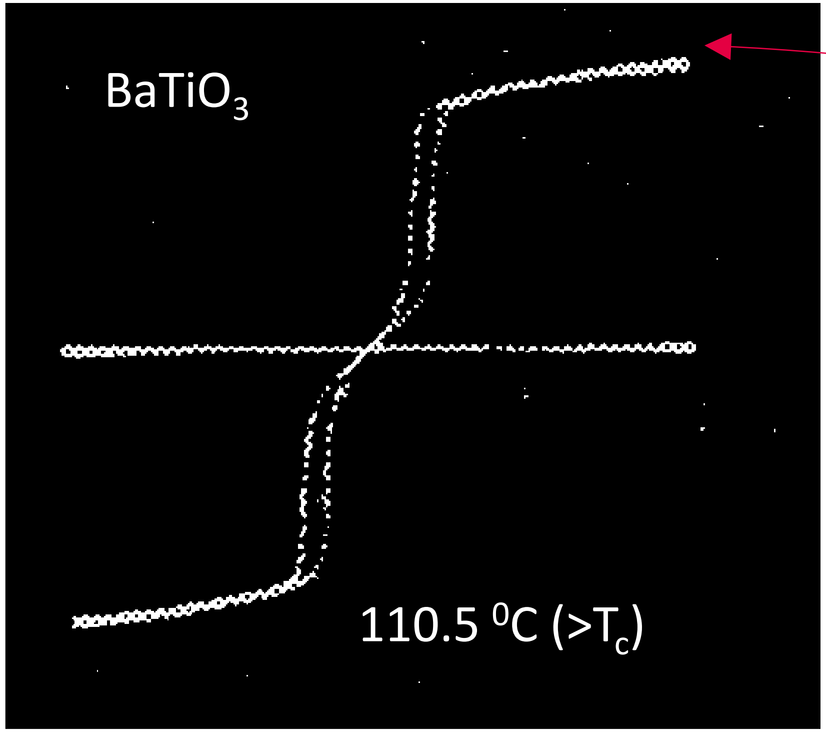
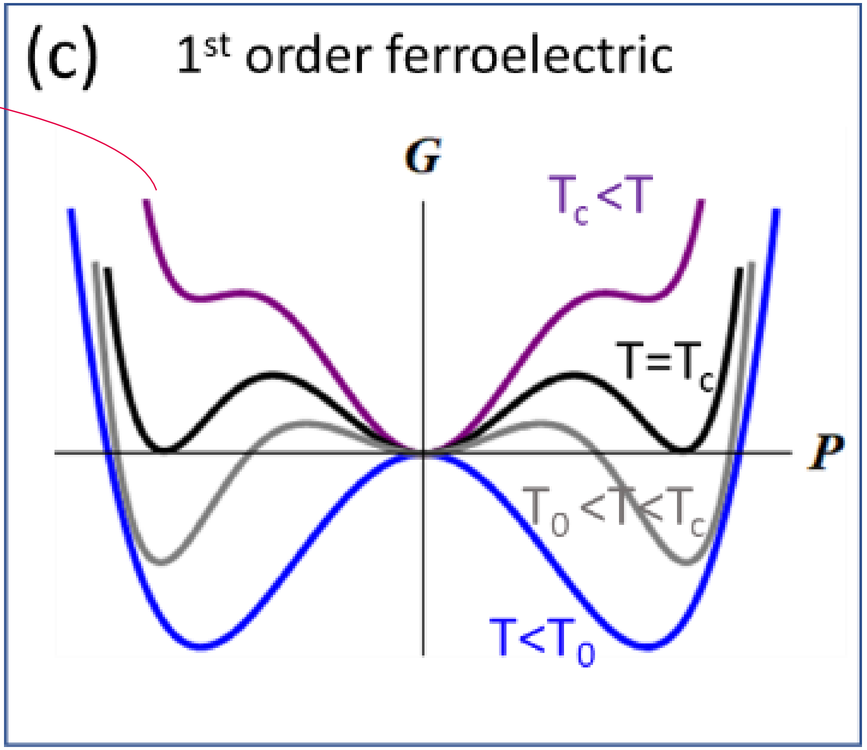
POSSIBLE ORIGIN OF DOUBLE LOOP HYSTERESIS

Walter J. Merz ,*Phys. Rev*. **91**, 513 (1953)





Double loop behavior originates from triple potential well slightly above T_c

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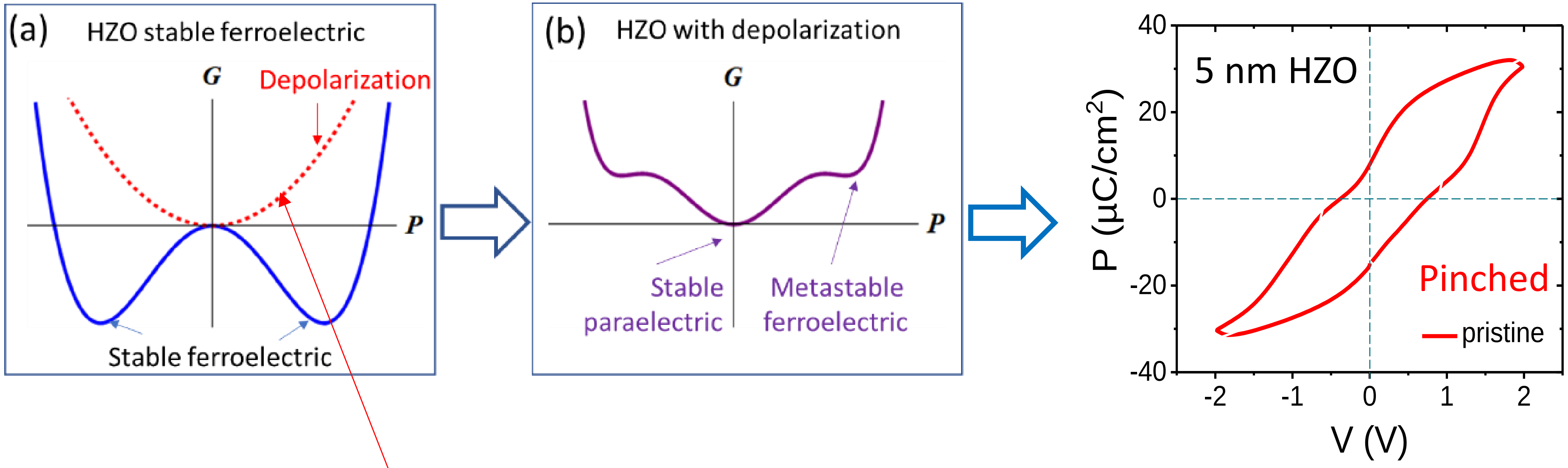
N. Siannas et al., *Comms Phys* **5**, 178 (2022)

HZO with depolarization resembles a 1st order FE above T_c

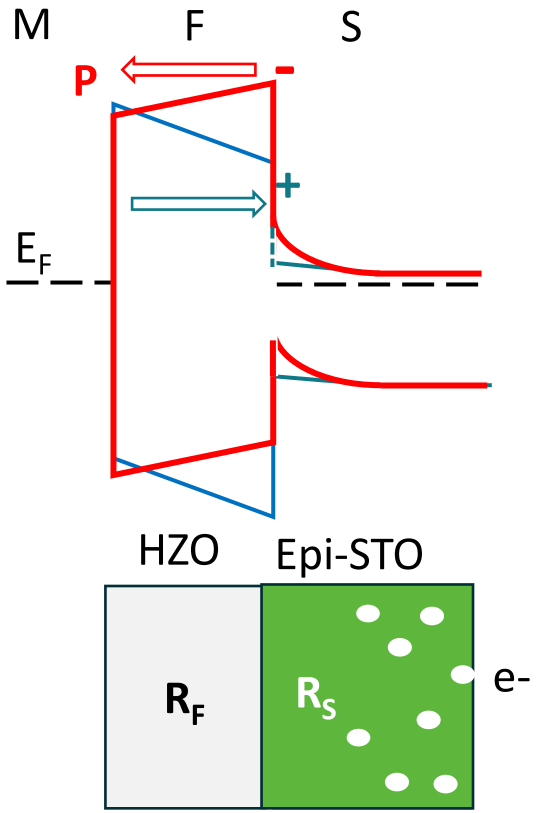


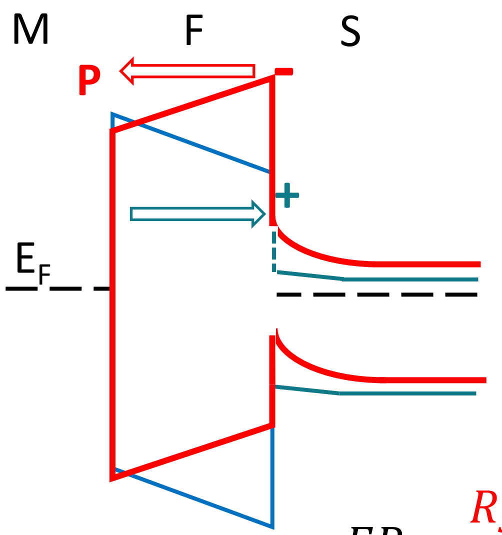
$$G = -\frac{1}{2}|a|P^2 - \frac{1}{4}|\beta|P^4 + \frac{P^2}{\varepsilon_0 \varepsilon_F \left(1 + \frac{C_{int}}{C_F}\right)} + \frac{1}{6}\gamma P^6$$

FERROELECTRIC FIELD EFFECT JUNCTION

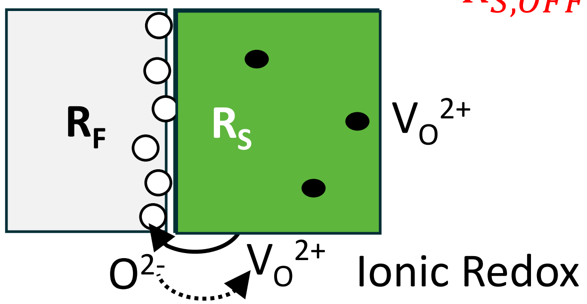
- Ferroelectric programming of the semiconductor resistance

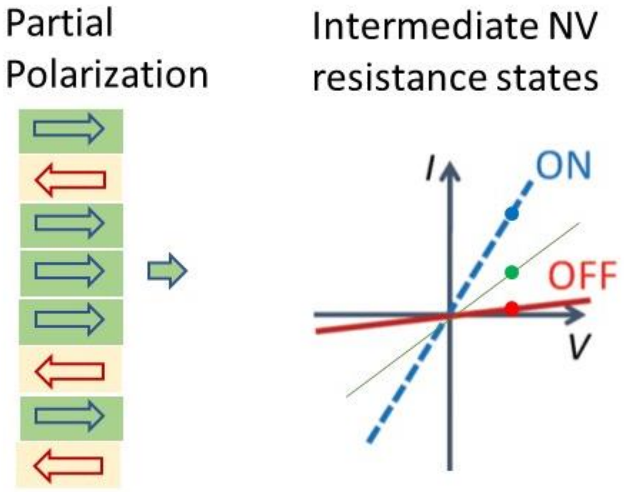
N. Siannas et al., *Adv. Funct. Mater*. (2023); doi: 10.1002/adfm.202311767





$$ER = \frac{R_{S,OFF} - R_{S,ON}}{R_{S,OFF}}$$





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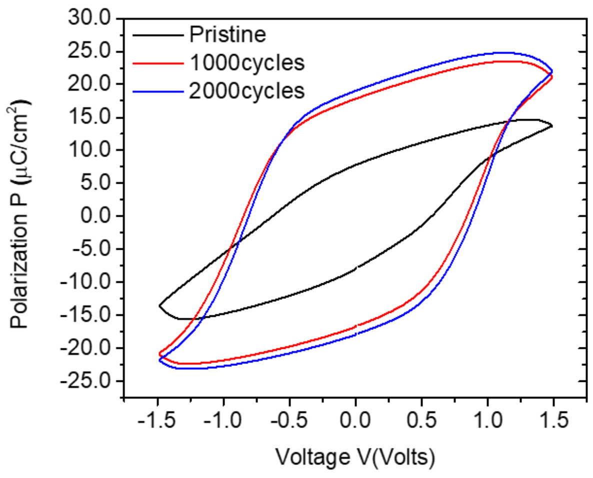
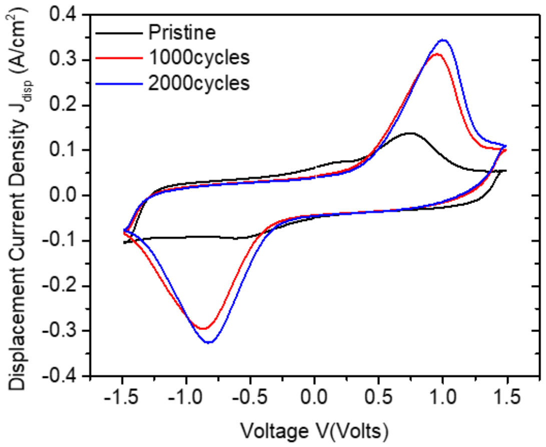
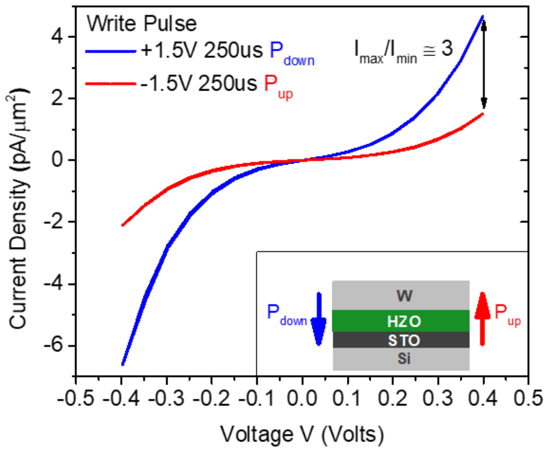
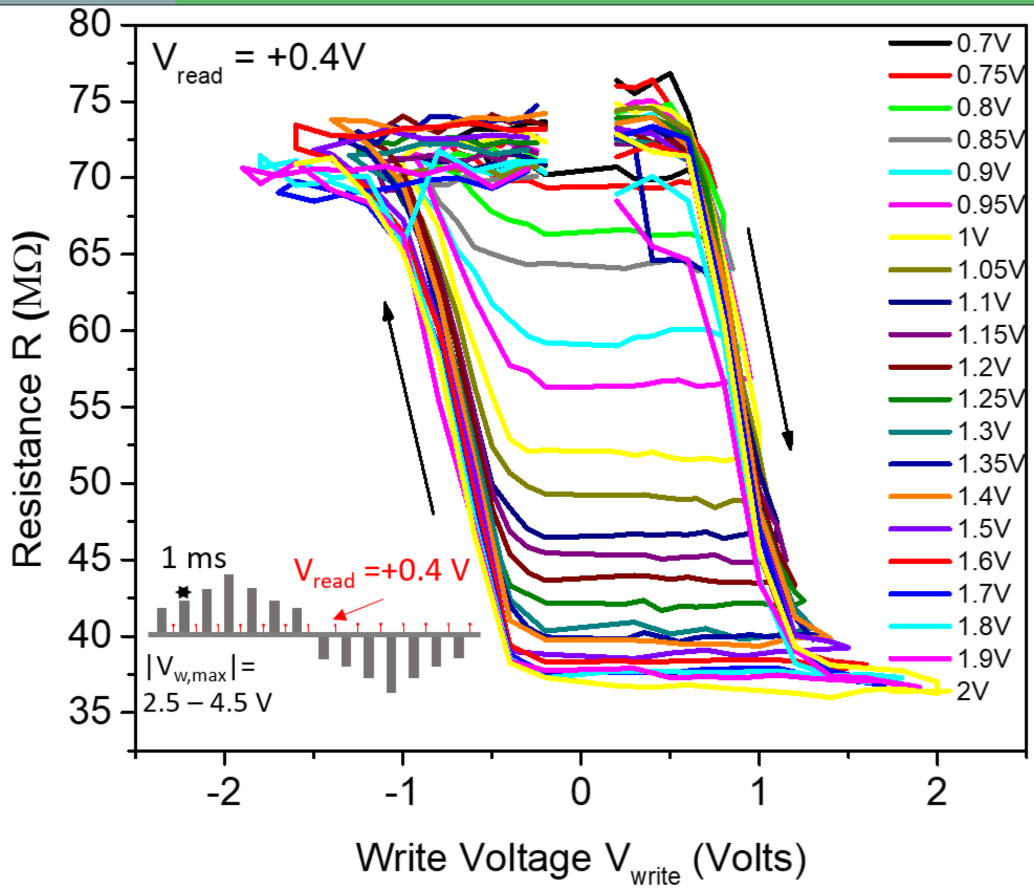
MAIN CHARACTERISTICS



- P_r ~ 14 μC/cm²
- V_c < 1V
  low voltage operation
- Low I_{ON}/ low ER







- Narrow memory window ± 1V →
  compatible with ferroelectric switching (V_c =1V)
- Many stable intermediate resistance states (16, 4bit)

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MAIN CHARACTERISTICS

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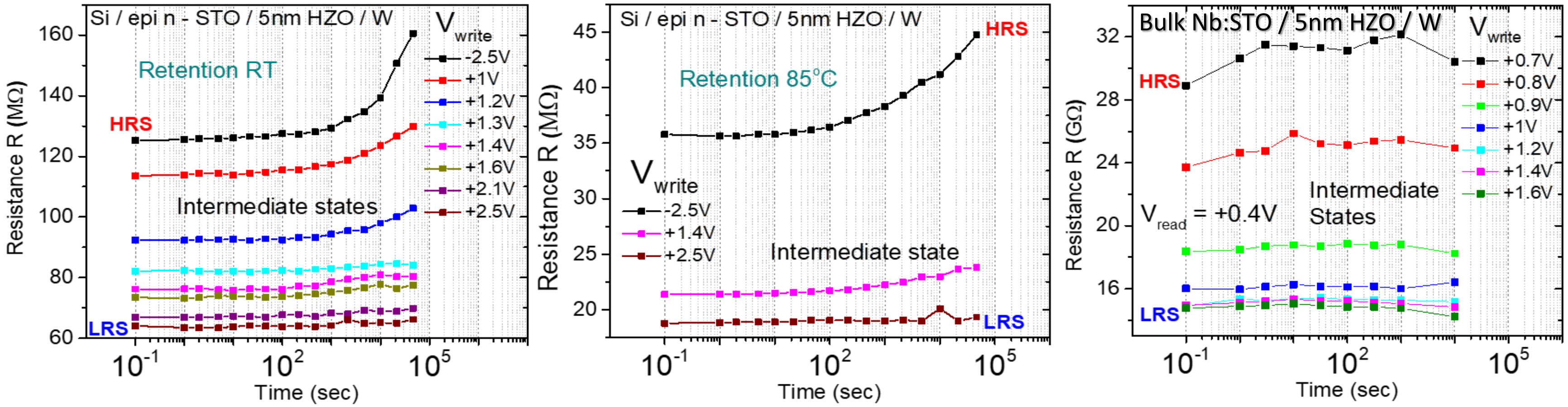

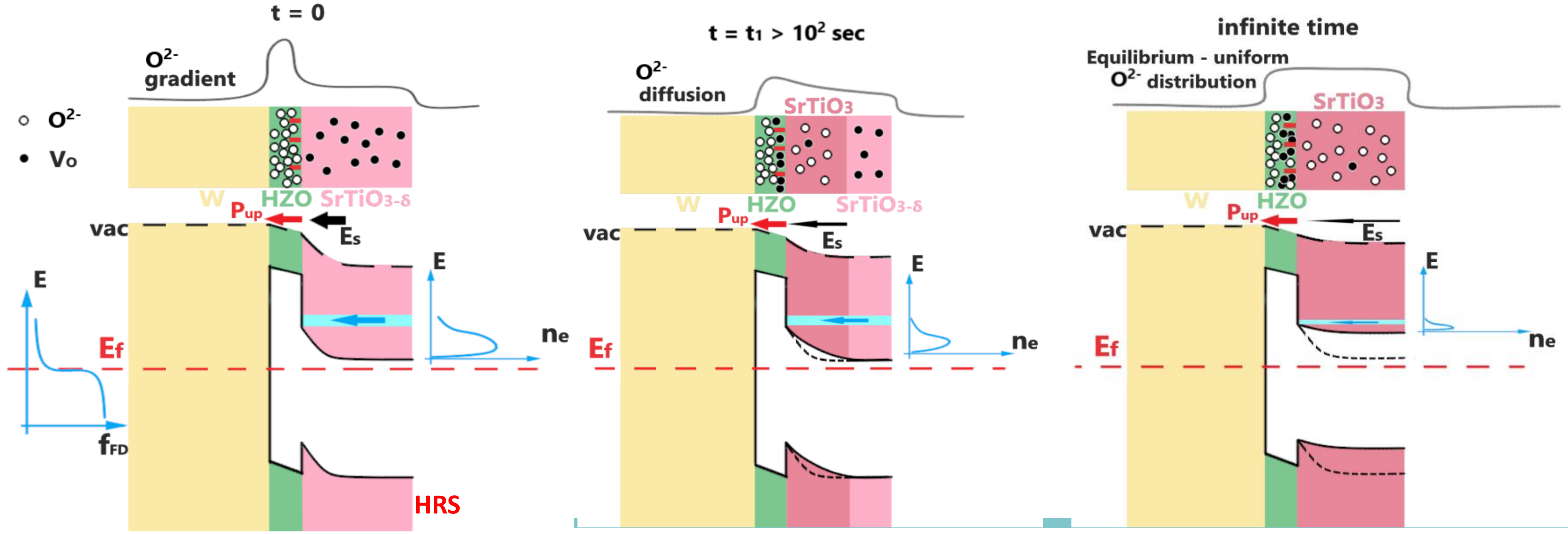

- HRS drifts to larger resistance
- Memory window increases at longer times !

- O^{2-} acceptors diffuse inside STO and compensate the V_o donors
- STO becomes an intrinsic semiconductor increasing its resistance
- Ionic effects occur at shorter timescales too (< 1 ms)

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FREQUENCY DEPENDENCE

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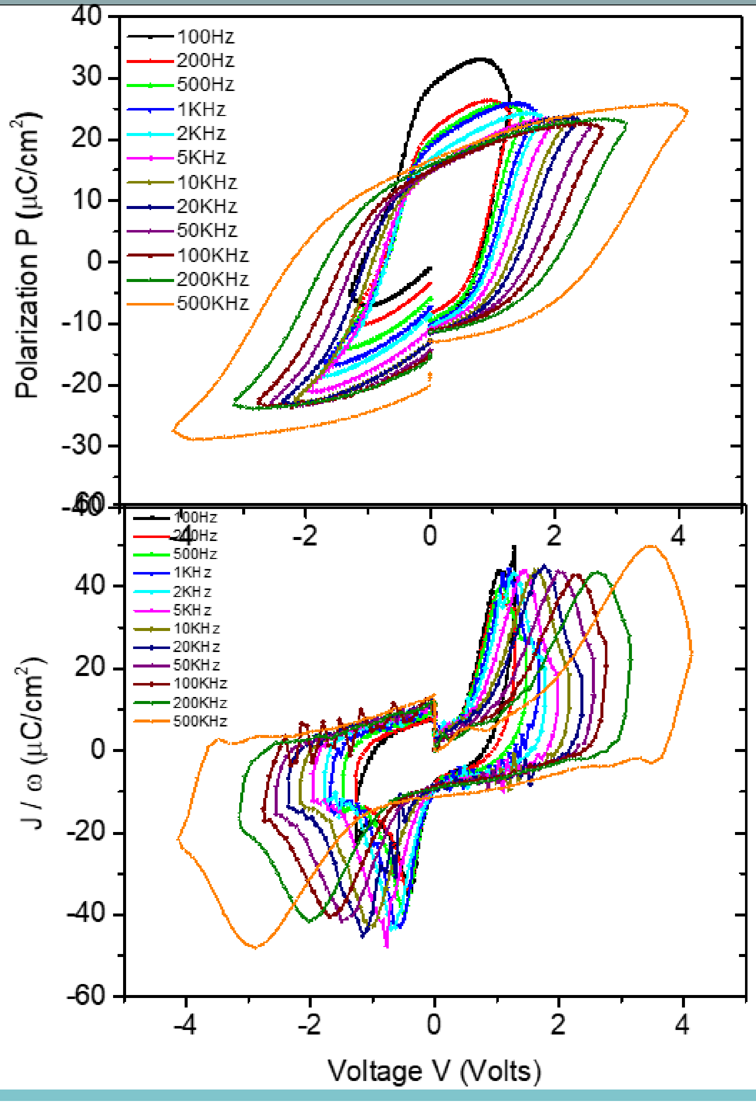

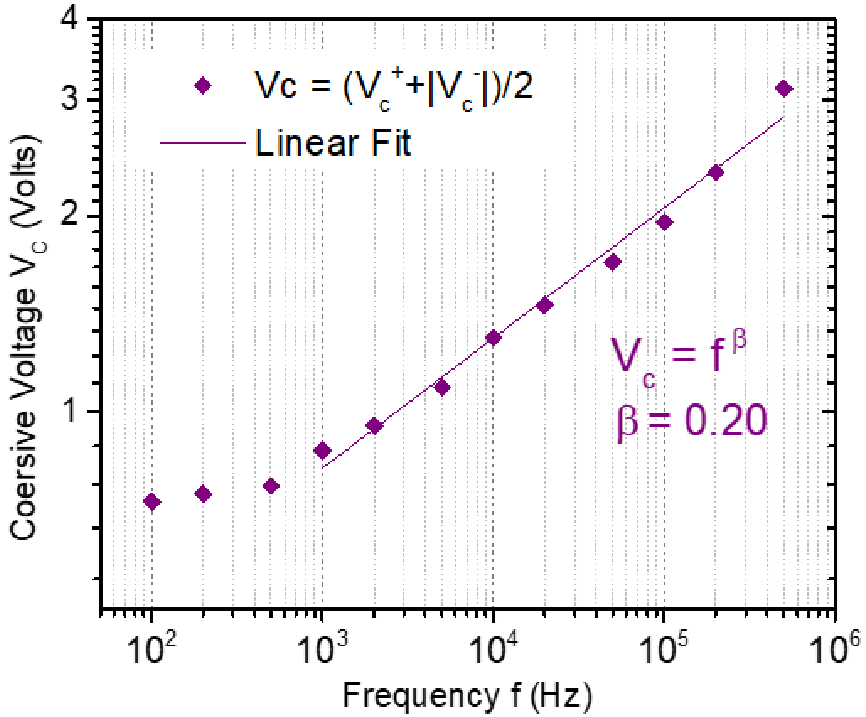

Typical behavior
for epitaxial ferroelectrics (e.g. perovskites)

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TIME RESPONSE AND SYNAPTIC PLASTICITY

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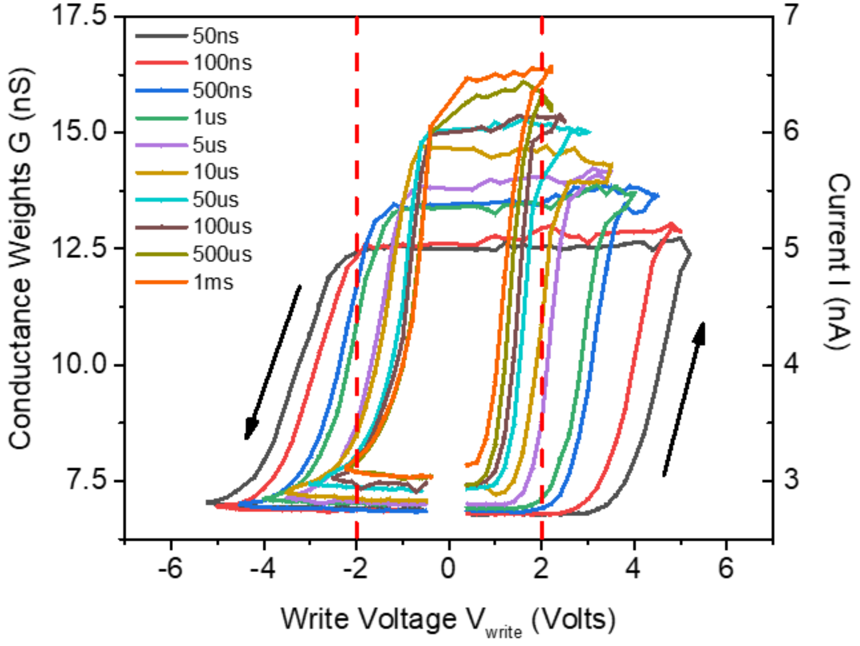
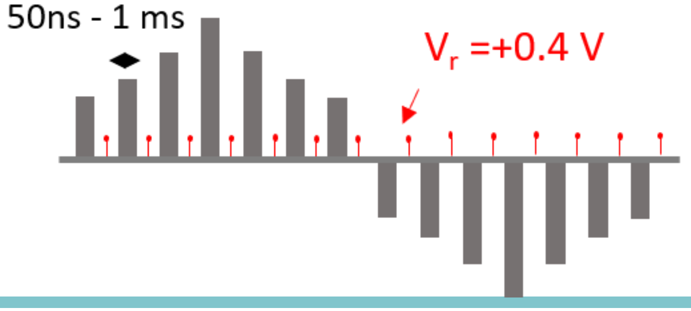
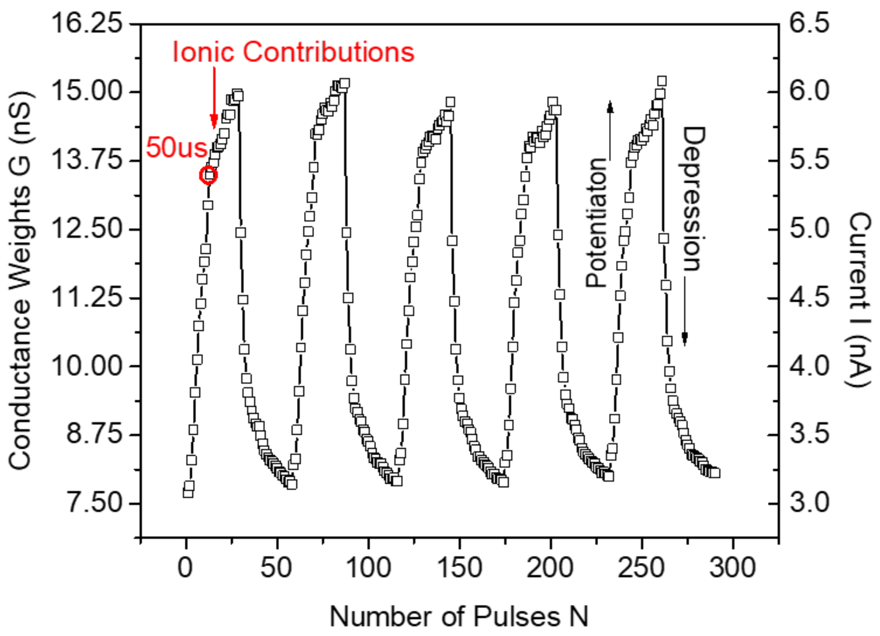
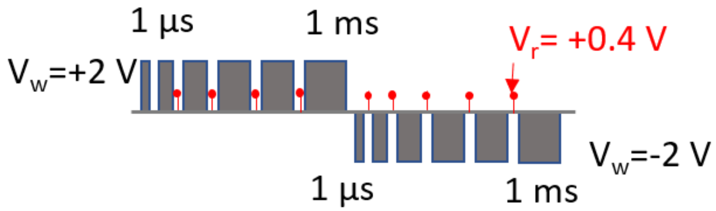
Time-voltage trade-off





Variable width pulses





Also: M. Halter et al., *Commun. Mater* **4**, 14 (2023)

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WEIGHT UPDATE-IDENTICAL PULSES

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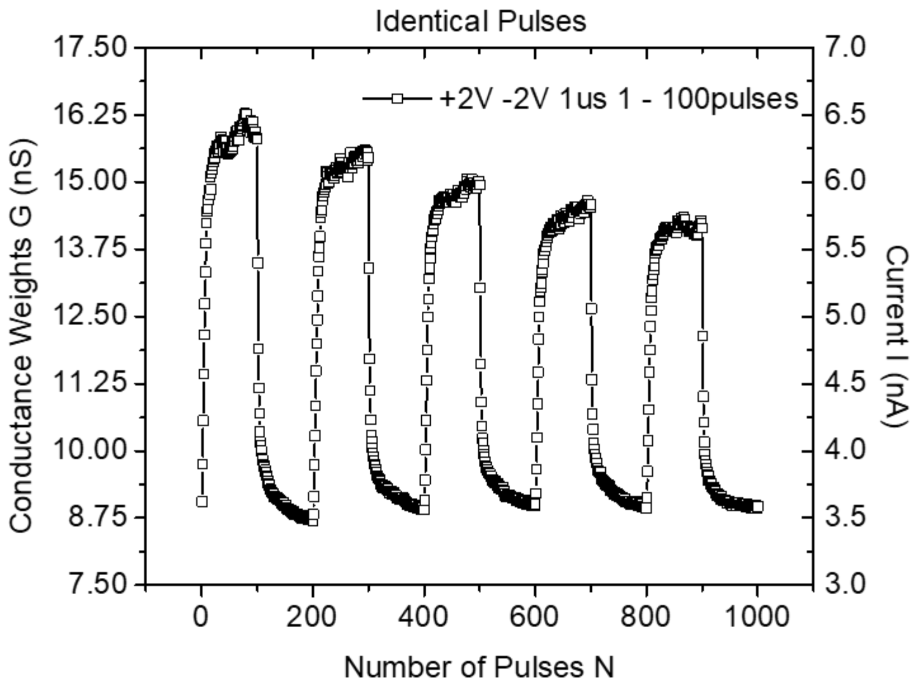

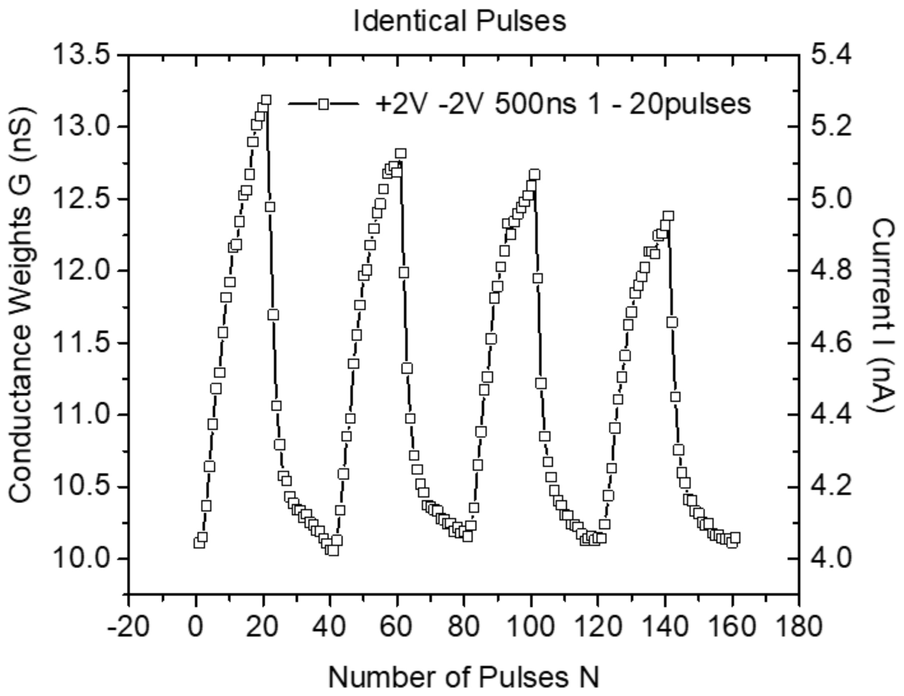

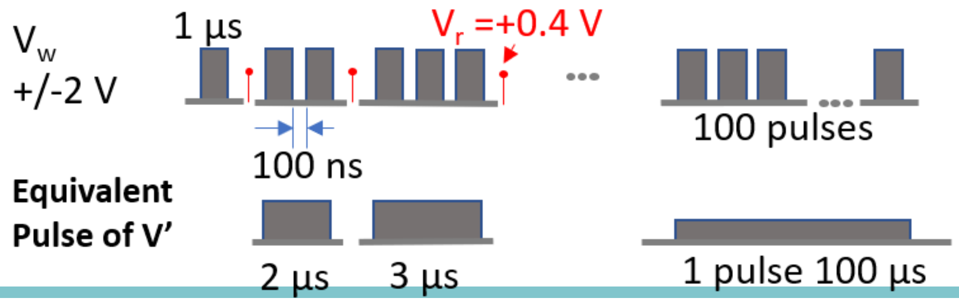

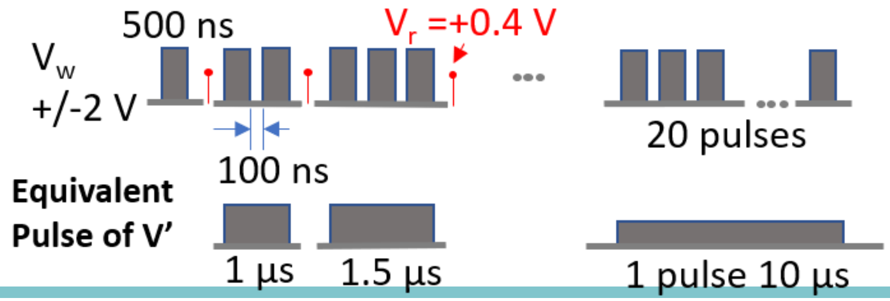

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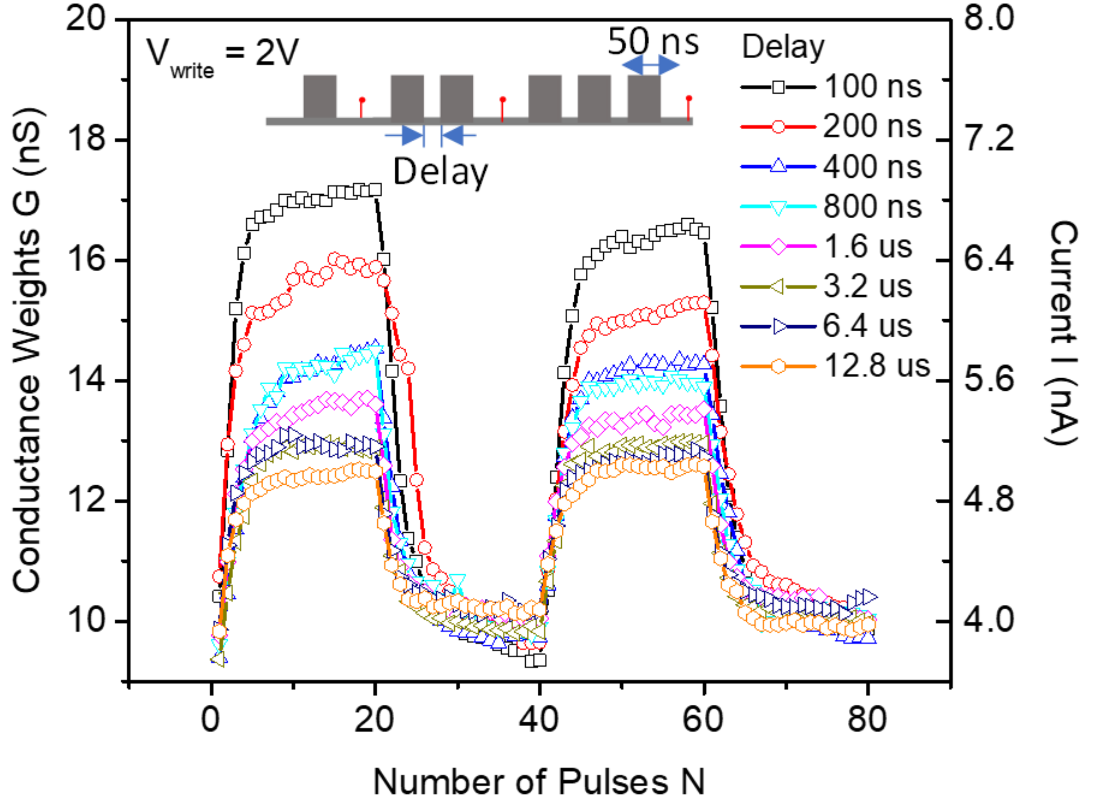
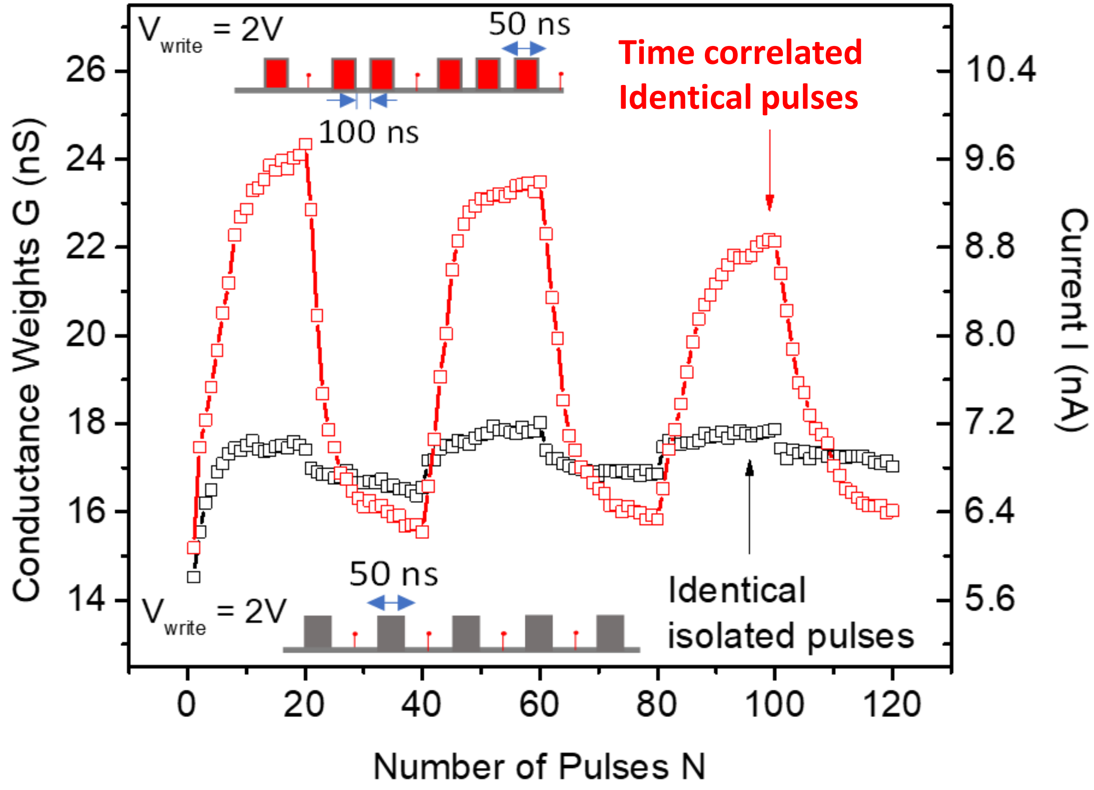
TIME CORRELATED *vs* ISOLATED PULSES

FIXIT





Synapse potentiation and depression is only possible with time correlated identical pulses (short delay)

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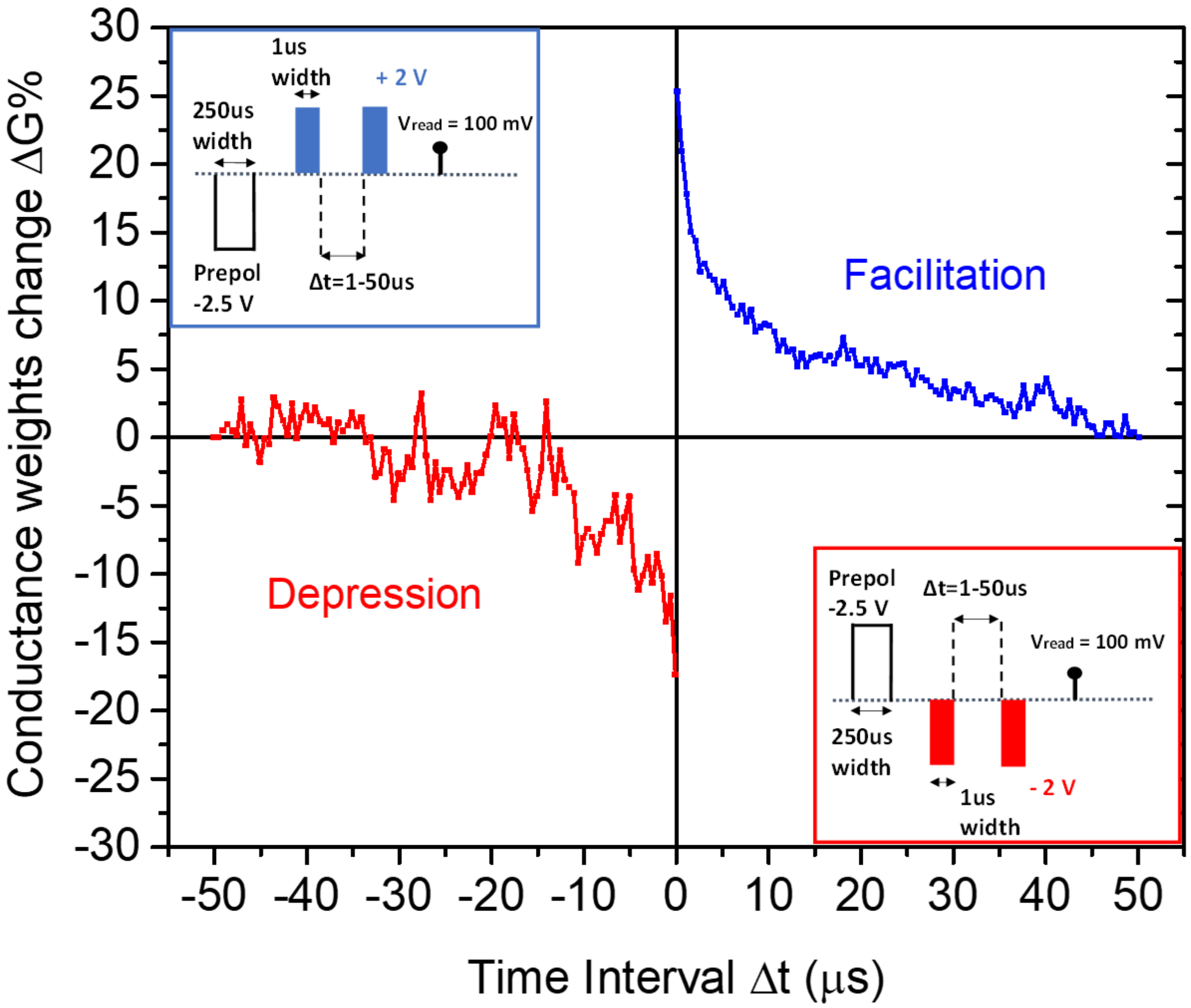
PAIRED PULSE FACILITATION

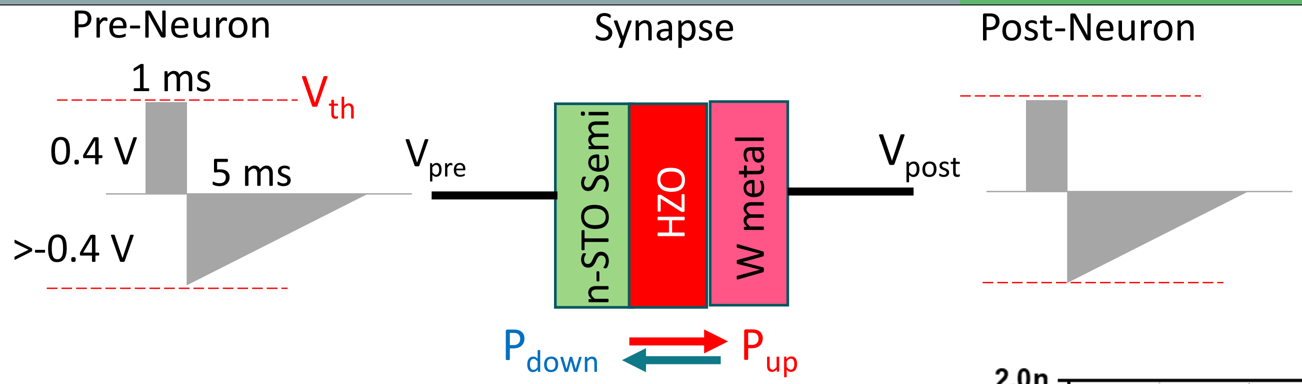


Short term plasticity

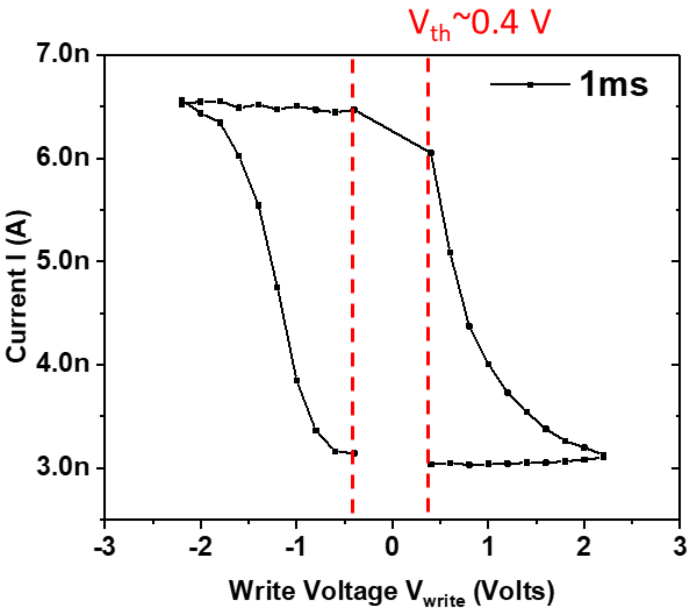
Decode temporary audio/visual info in biological systems

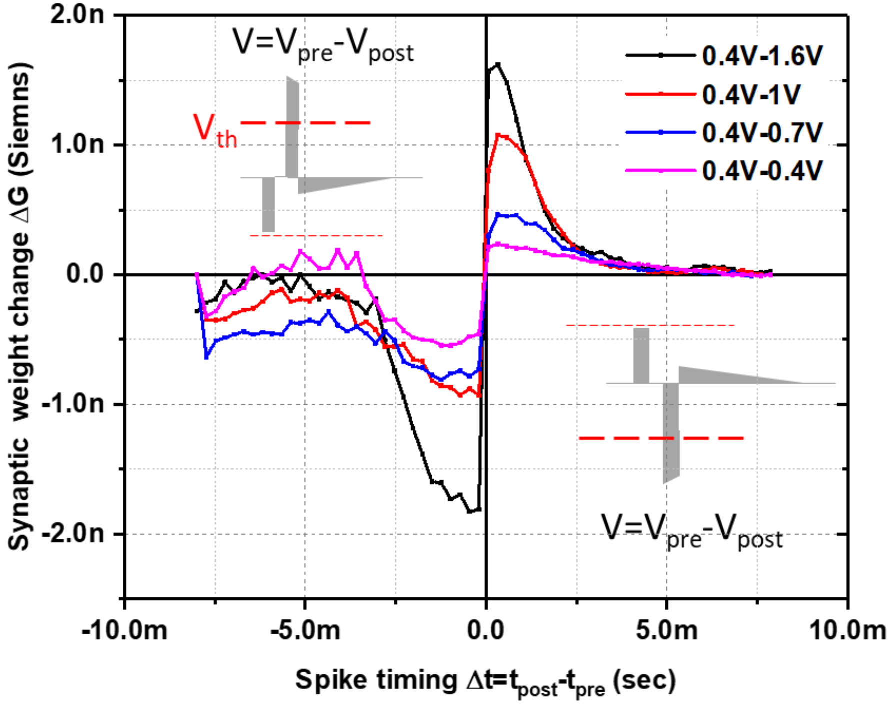
SPIKE TIMING DEPENDENT PLASTICITY (STDP)

Hebbian learning in biological systems



Spiking Neural Networks





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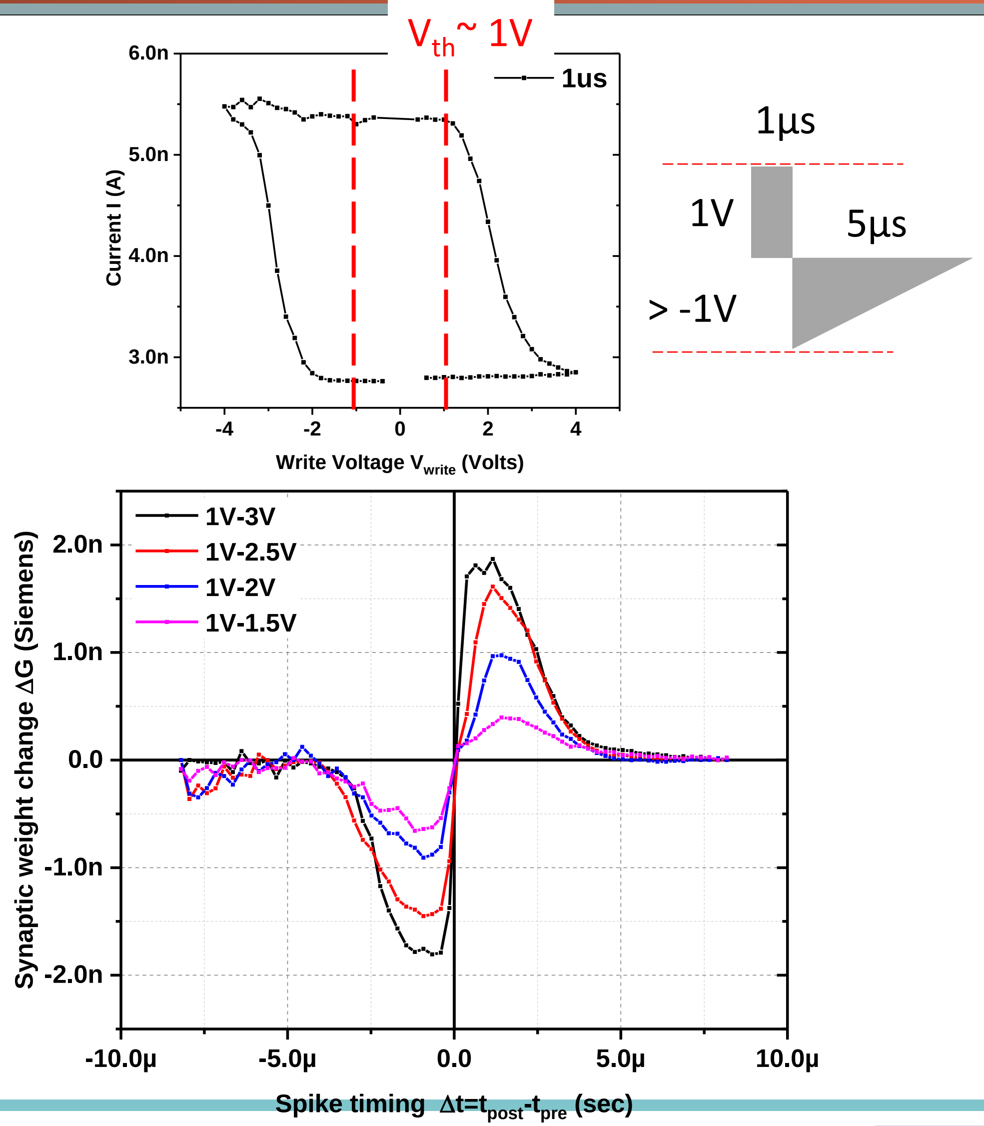
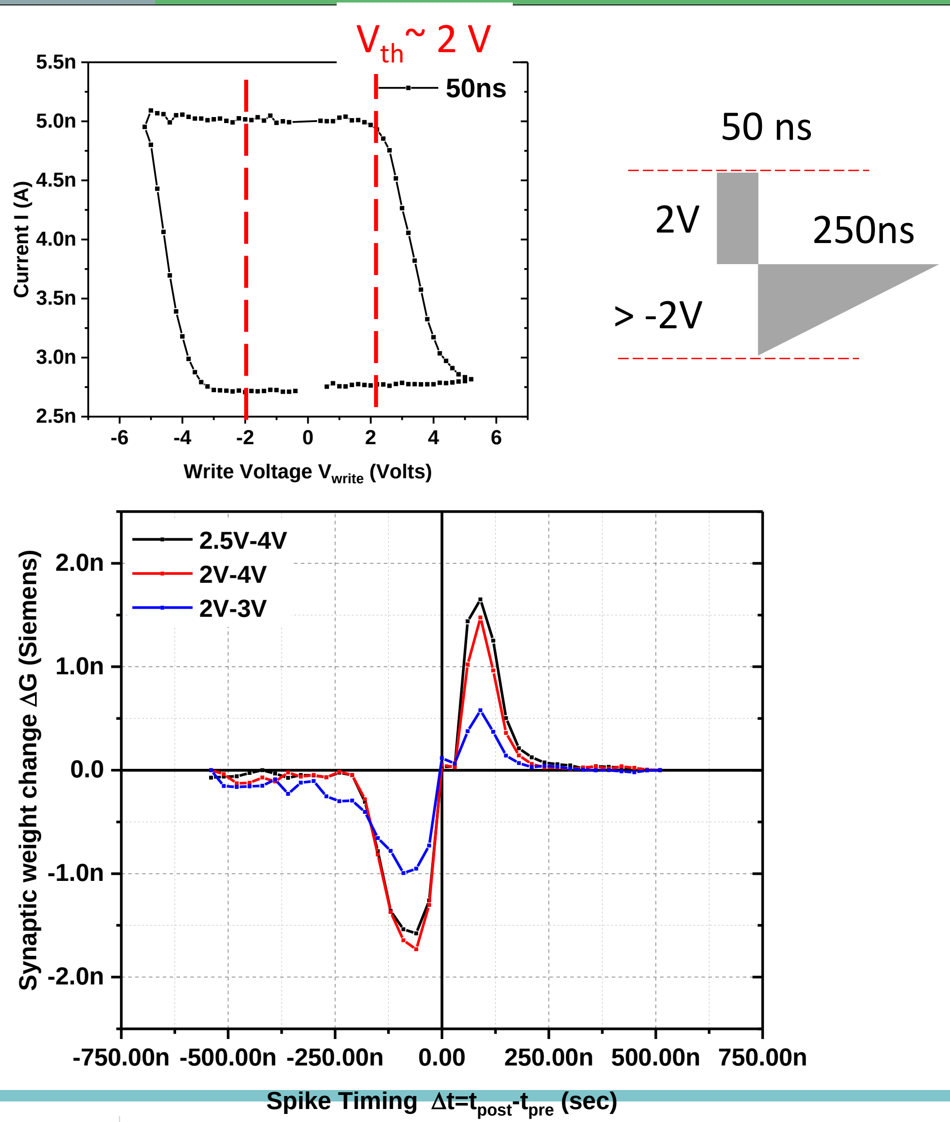
STDP-SHORTER TIMES

FIXIT





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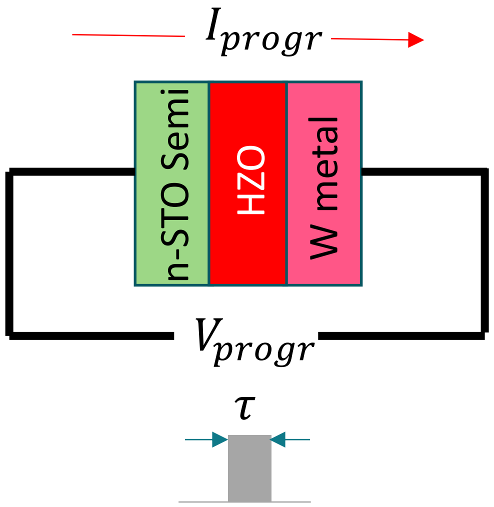
ENERGY PER PROGRAMMING EVENT

FIXIT



Current driven (RRAM, PCRAM, bio)
Energy spent as Joule heating

$$E = V_{progr} I_{progr} \tau$$

Voltage driven (FE)
Energy to charge a capacitor

$$E=QV=2PAV$$

P=20 µC/cm2
V=2-4 V
A=100 x100 nm

	V_{prog}	I_{progr}	Pulse width τ	Energy E (Joule heat)	Energy (charging)	Area
Biological	10 mV	1 nA	1 ms	10 fJ		
RRAM	1V	10 µA	100 ns	1 pJ		
PCMRAM				10 pJ		
FTJ (our work)	2V	0.1 pA	1 ms	0.1 fJ	8 fJ	(100x100 nm)

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SUMMARY

- **Epitaxial HZO/STO/Si**
  Ferroelectric field effect junctions-non volatile modulation of the STO semiconductor

- **Two effects**: electronic field effect + ionic redox → contribute additively enhancing performance

- **More than 16 stable intermediate states** can be accessed

- **Time to voltage trade off** :
  Essential for potentiation and depression by variable width and identical pulses

- **Bio-inspired synaptic response**:
  -Pair pulse facilitation (PPF)
  -Spiking time dependent plasticity (STDP) operating at a large time rage from ms to 100 ns

- **Extremely low energy per programming event**: ~ 10 fJ, comparable to biological synapses

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SUMMARY

FIXIT

NCSRD: N. Siannas, C. Zacharaki, P. Tsipas and A. Dimoulas
Growth, processing, physical and electrical characterization

HZB: D.-J Kim W. Hamouda and C. Dubourdieu
Growth of epi n-STO/Si wafers

NIMP: C. Istrate and L. Pintilie
HR TEM

IKZ: M. Schmidbauer
X-ray Diffraction

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FUNDING & FUTURE PLANS

FIXIT

Horizon 2020 Programme

BeSynaptic

BEOL technology platform based on ferroelectric synaptic devices for advanced neuromorphic processors

Work continues in HORIZON CL4 and JU-CHIPS projects

Horizon Europe 2021-2027

FIXIT

Scaled **F**erroelectr**I**c **X**-bars for A**I**-driven sensors and actua**T**ors

Synaptic behavior in small area memristors

Horizon Europe 2021-2027

concept

Crystalline Oxides for Next Generation Computing and Emerging Photonic Technologies

Epitaxial HZO, ionic effects

Horizon Europe 2021-2027

ViTFOX

Vision Transformers with Ferroelectric Oxides

Integration

Chips JU KOR-EU

Finanțat de Uniunea Europeană NextGenerationEU

GUVERNUL ROMÂNIEI

Artificial synapses based on ferroelectric tunnel junctions for neuromorphic and analogue computing

Romanian Recovery and Resilience Plan "ARSYF"

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THANK YOU!

QUESTIONS?

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