Electronic synapses enabled by epitaxial Hafnia-based ferroelectric field effect memristors on Silicon

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National Center for Scientific Research DEMOKRITOS, Athens, Greece

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

Collaborators

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

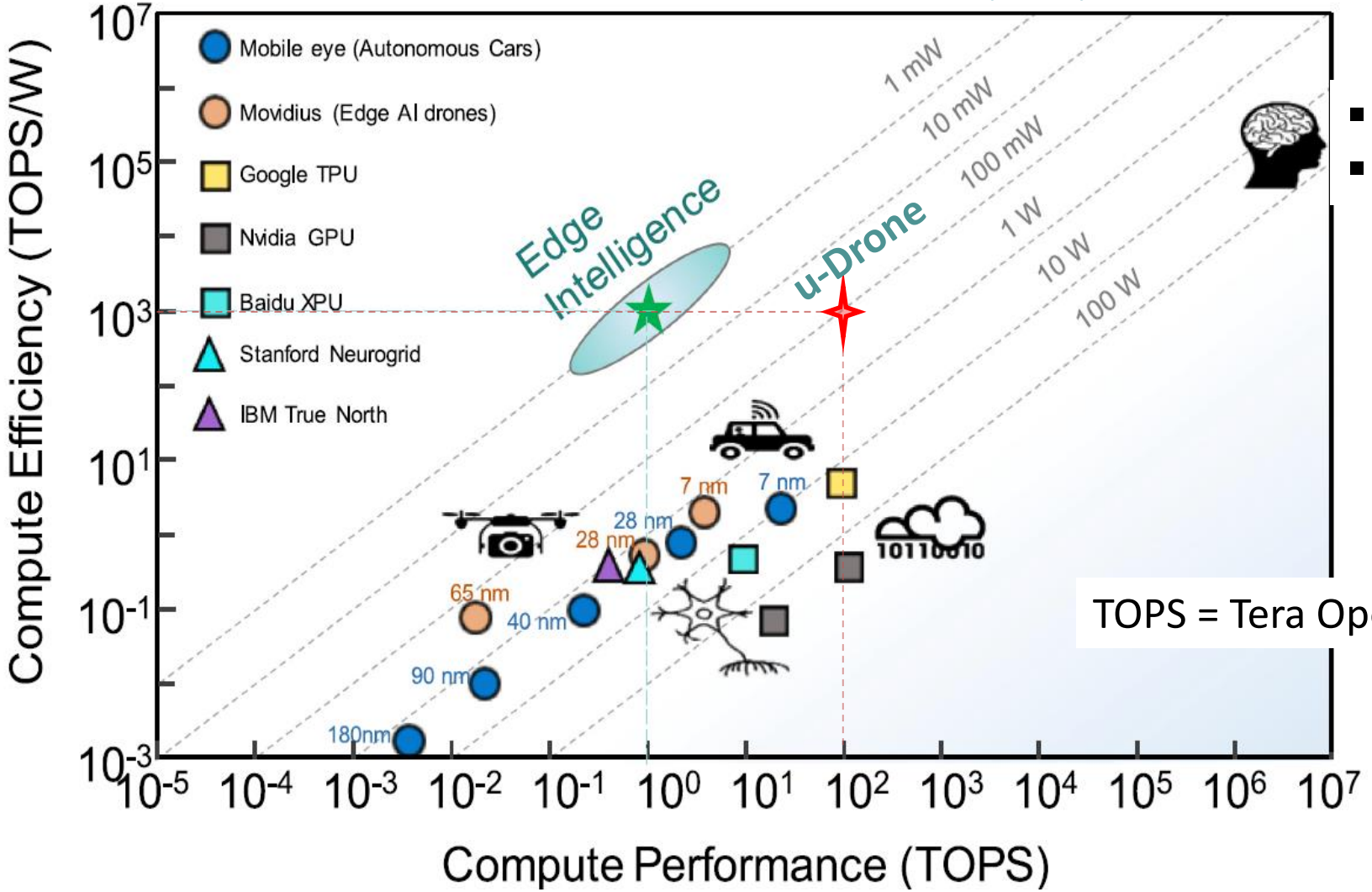
HZB: D.-J Kim W. Hamouda and C. Dubourdieu
Growth of epi n-STO/Si wafers

NIMP: C. Istrate and L. Pintilie
HR TEM

IKZ: M. Schmidbauer
X-ray Diffraction

Energy efficient edge computing

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



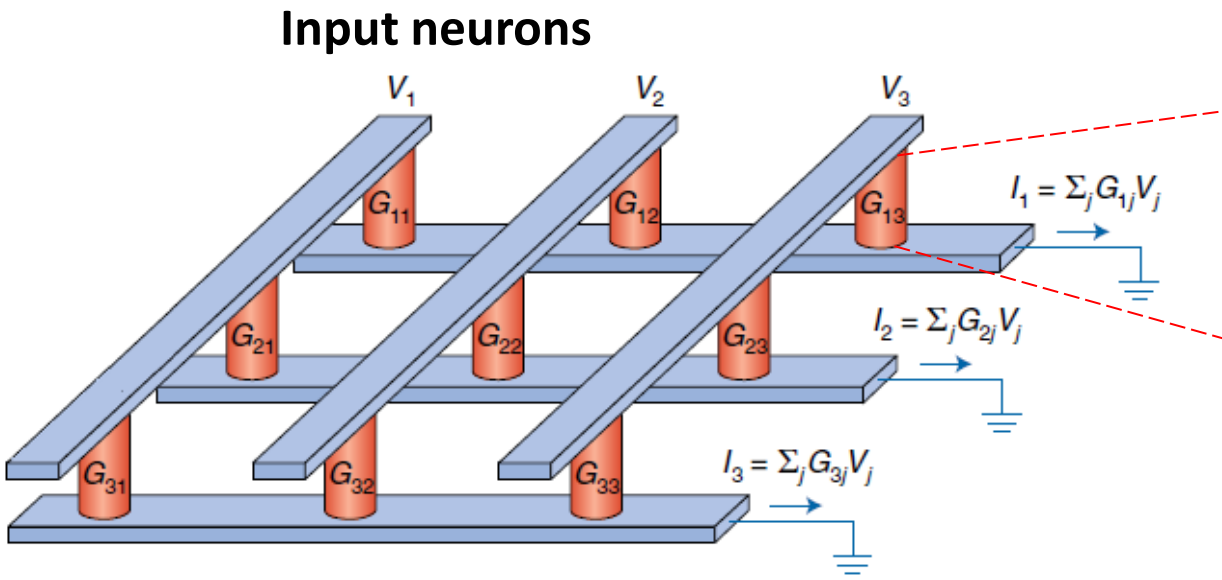
- Massive parallelism
- in-memory computing

TOPS = Tera Operations Per Second

ANNs in hardware

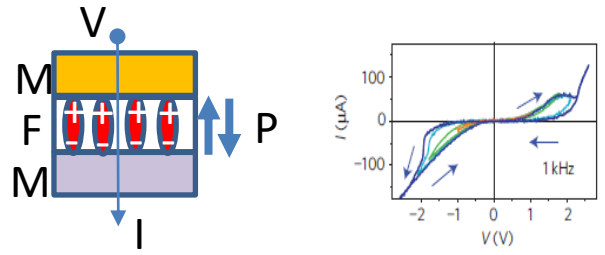
Cross bar arrays-AI accelerators

Multiply and Accumulate



A. Chanthbouala et al.,*Nat. Mater.* **11**, 860 (2012)
D. J. Kim et al., *Nano Lett.* **12**, 5697 (2012)
Perovskite ($BaTiO_3$)

Ferroelectric memristor synapses



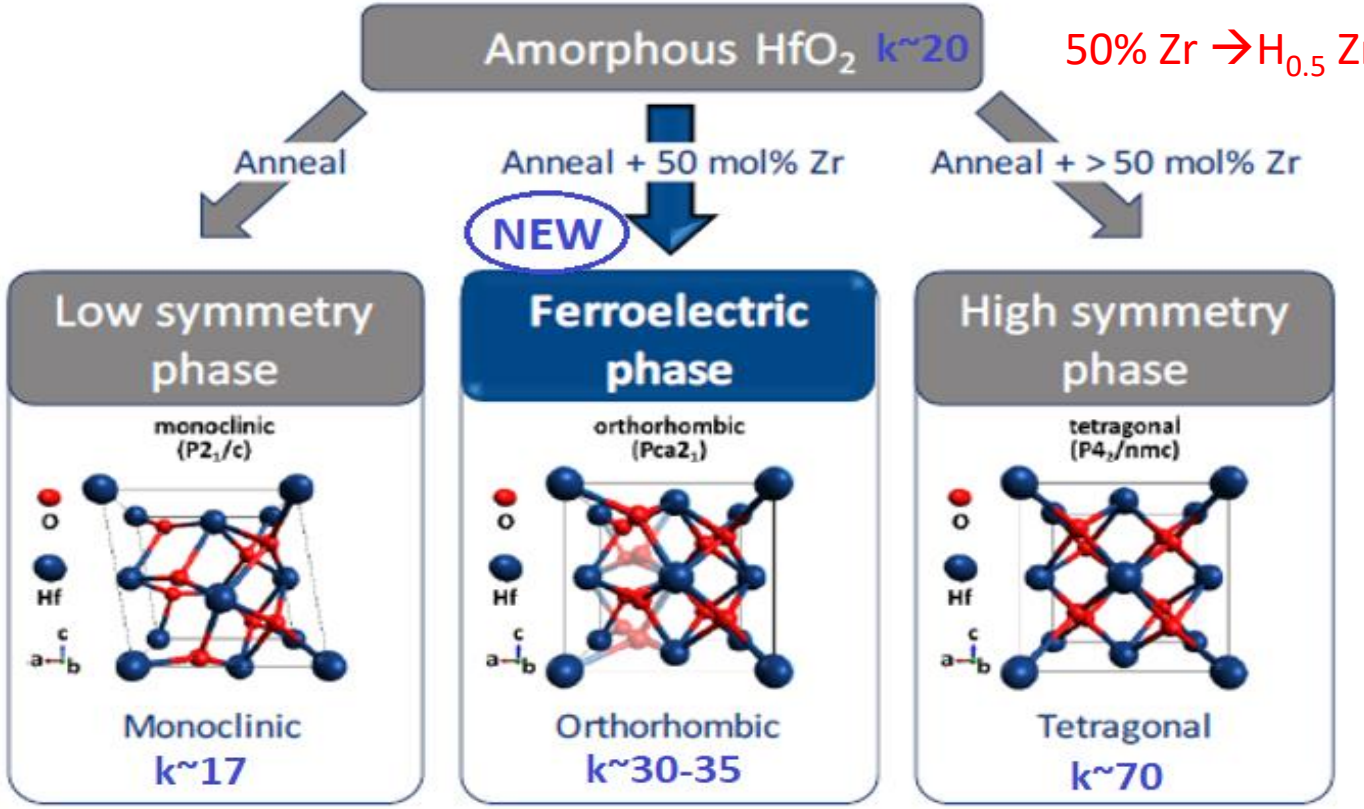
- Update and store conductance weights
- Analog **in-memory** computing
- Voltage driven memristors→ low power

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

Hafnia-based fluorite ferroelectrics

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

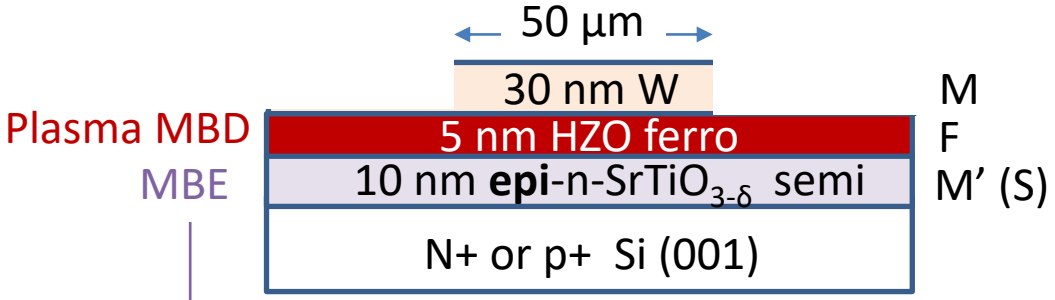
Stabilization of the ferroelectric phase: doping (Si, Zr,..), stress, annealing, film thickness …



50% Zr → $H_{0.5}Zr_{0.5}O_2$ (HZO)

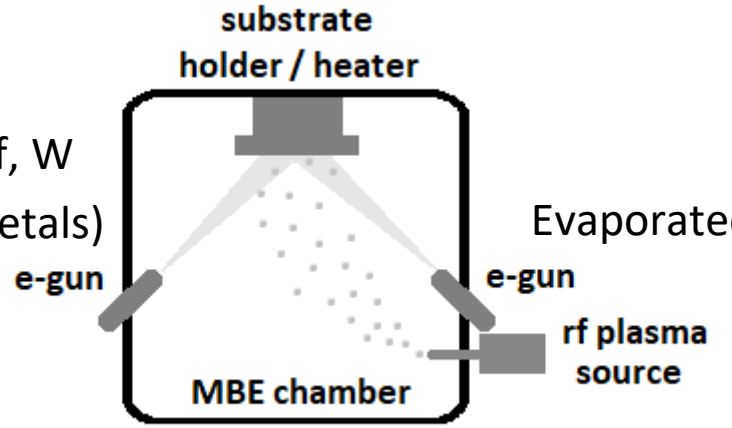
Compatible with Si processing
(HfO_2 used as high-k dielectric/CMOS scaling)

Plasma Assisted MBE/MBD



- 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
- Optical litho + etching or lift-off

Molecular Beam Epitaxy (MBE)



UHV
base pressure:
5×10^{-10} Torr

reactive O
neutral atomic beam

350 W
2×10^{-5} Torr

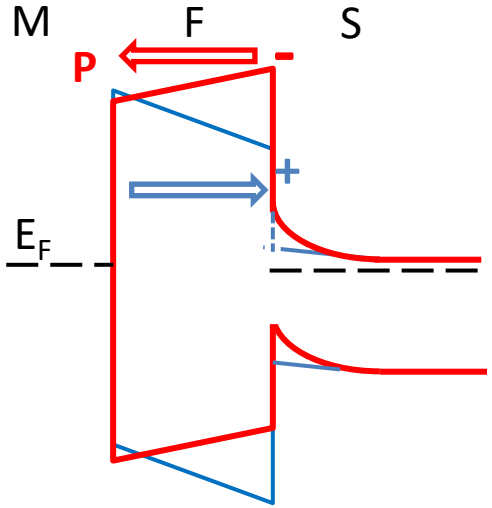
C. Zacharaki et al., *Appl. Phys. Lett.*, **114**, 112901 (2019)

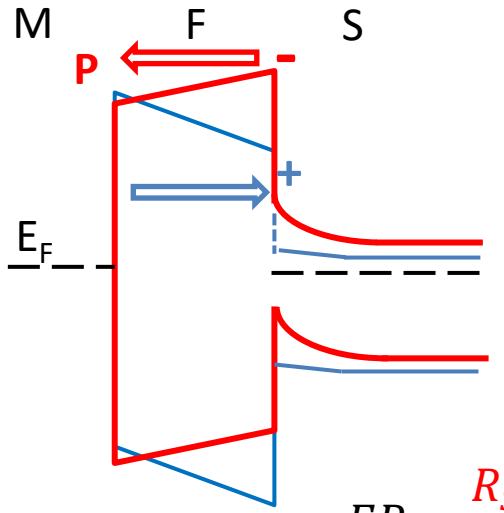
C. Zacharaki et al., *ACS Appl. Electron. Mater.* **4** 2815 (2022)

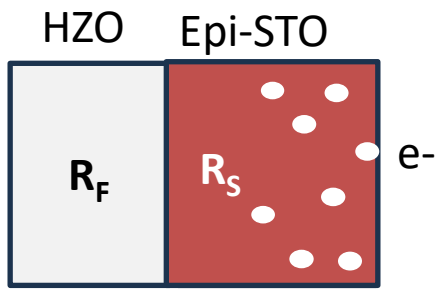
Ferroelectric Field Effect Junction

Ferroelectric programming of the semiconductor resistance

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

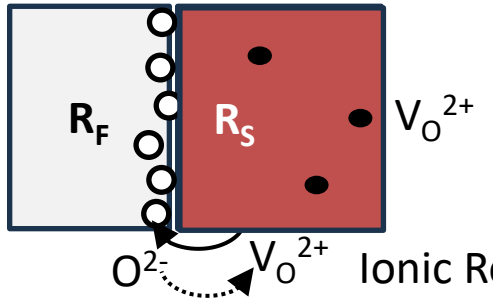






Electronic field effect

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

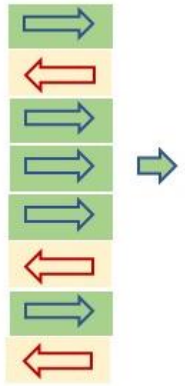


Ionic Redox

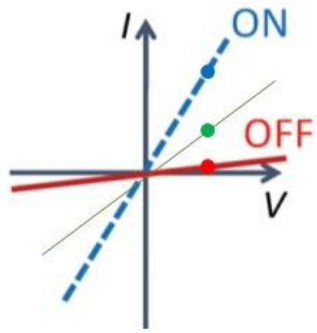
Below 5 nm HZO, ferroelectricity is unstable

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

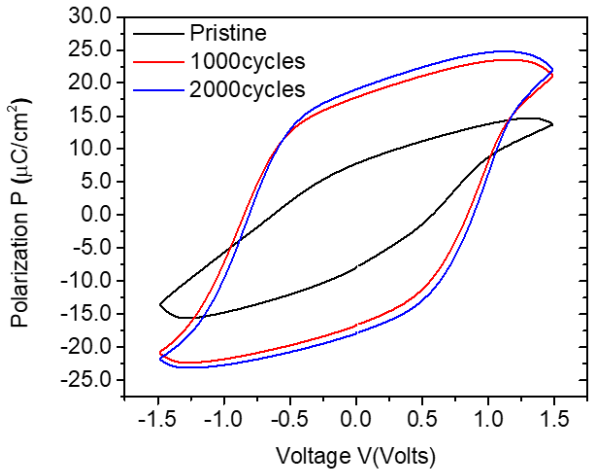
Partial Polarization



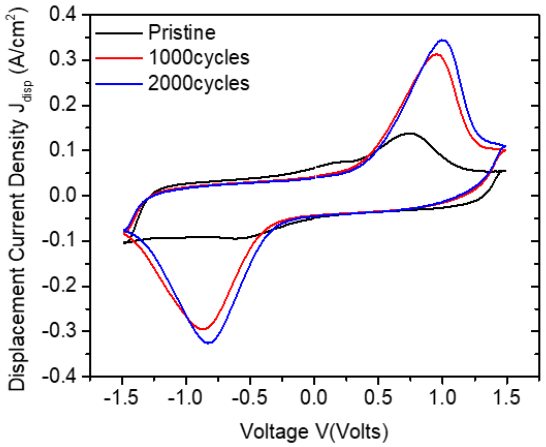
Intermediate NV resistance states

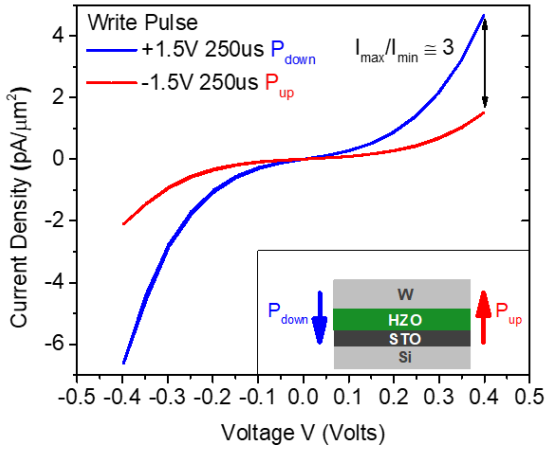


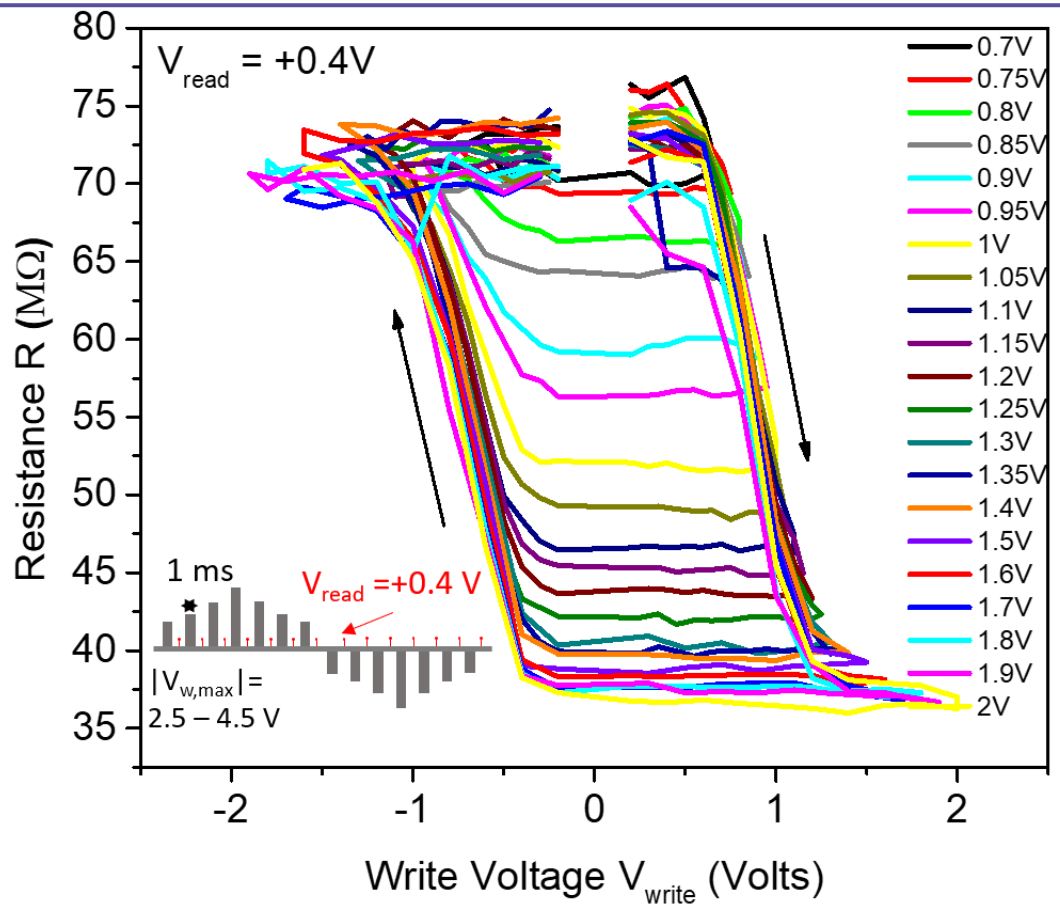
Main Characteristics



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



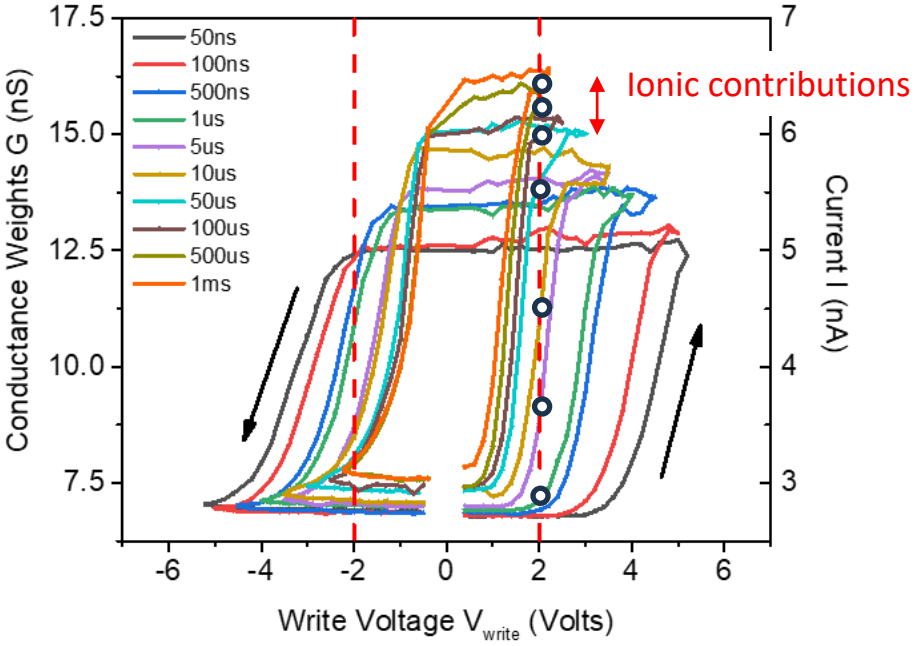


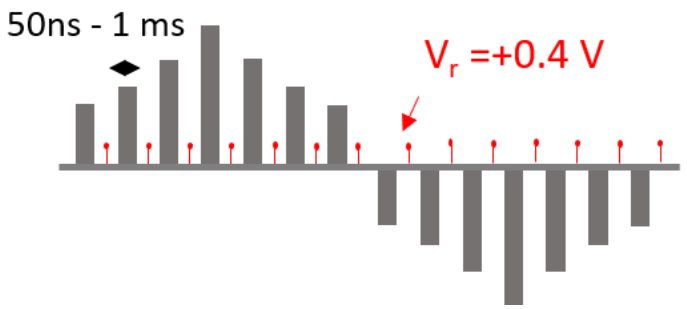


- Narrow memory window ± 1V →
  compatible with ferroelectric switching (V_c =1V)
- Many stable intermediate resistance states (16, 4bit)

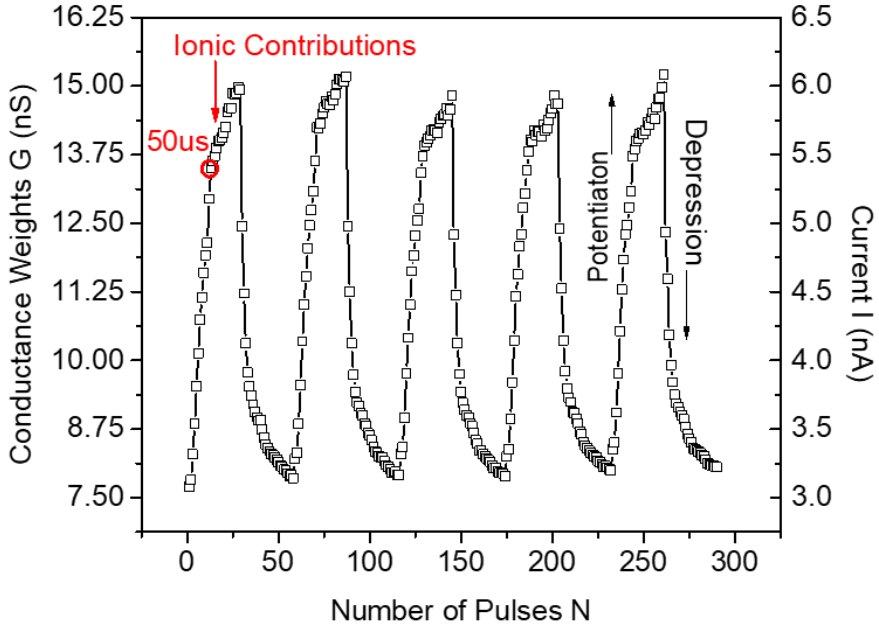
Time response and synaptic plasticity

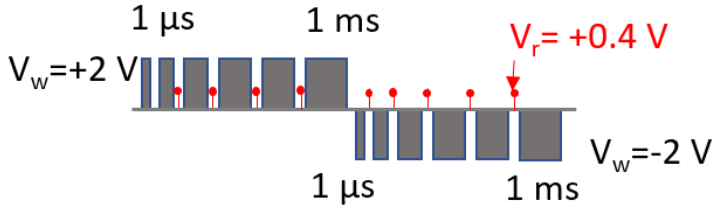
Time-voltage trade-off





Variable width pulses

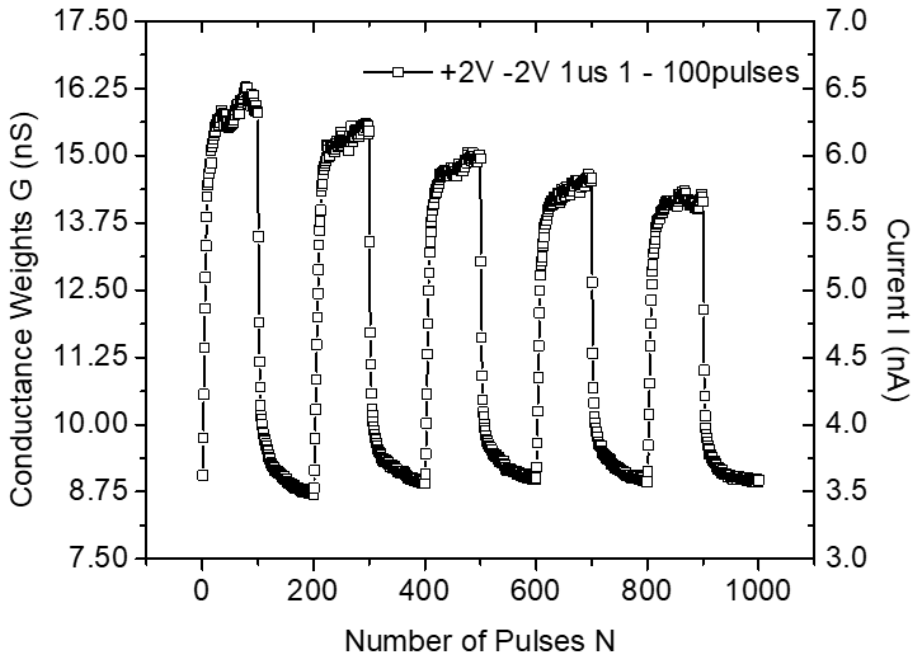




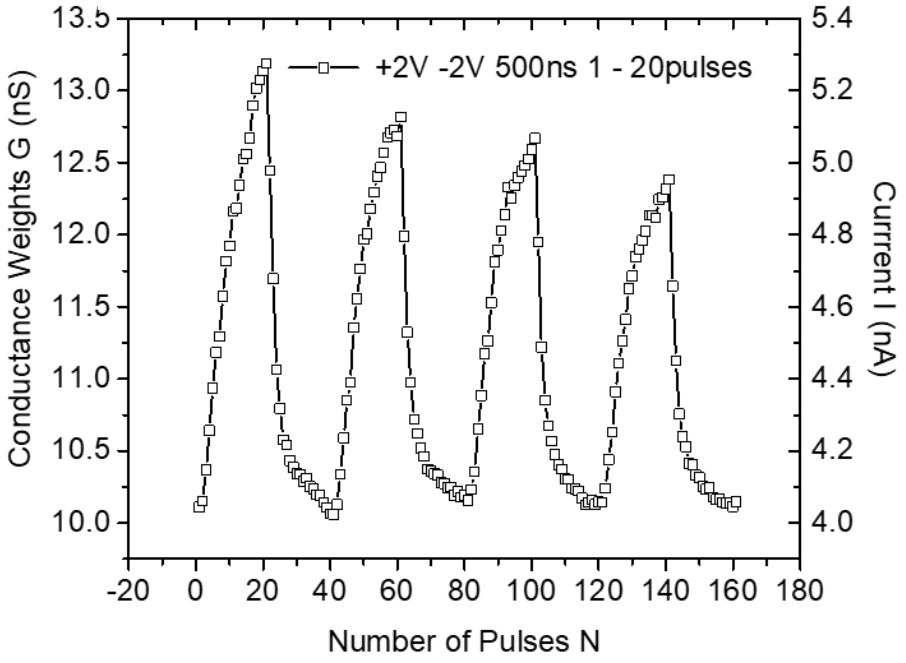
Also: M. Halter et al., *Commun. Mater* **4**, 14 (2023)

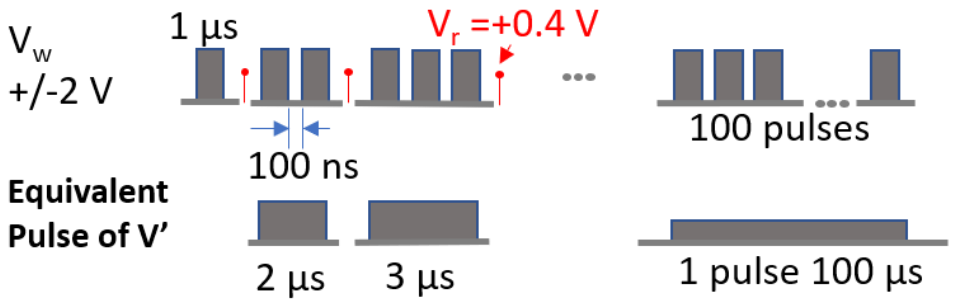
Weight update- Identical pulses

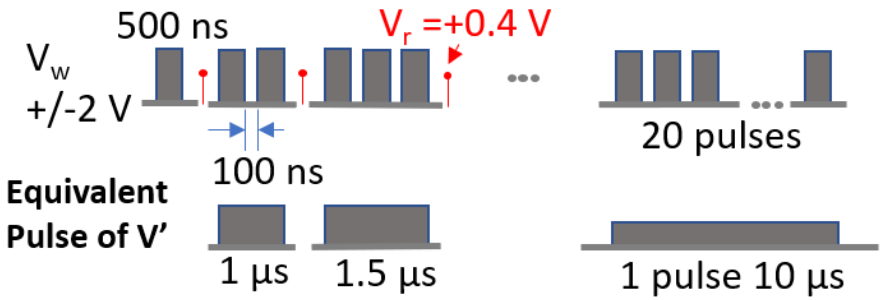
Short delay-time correlated



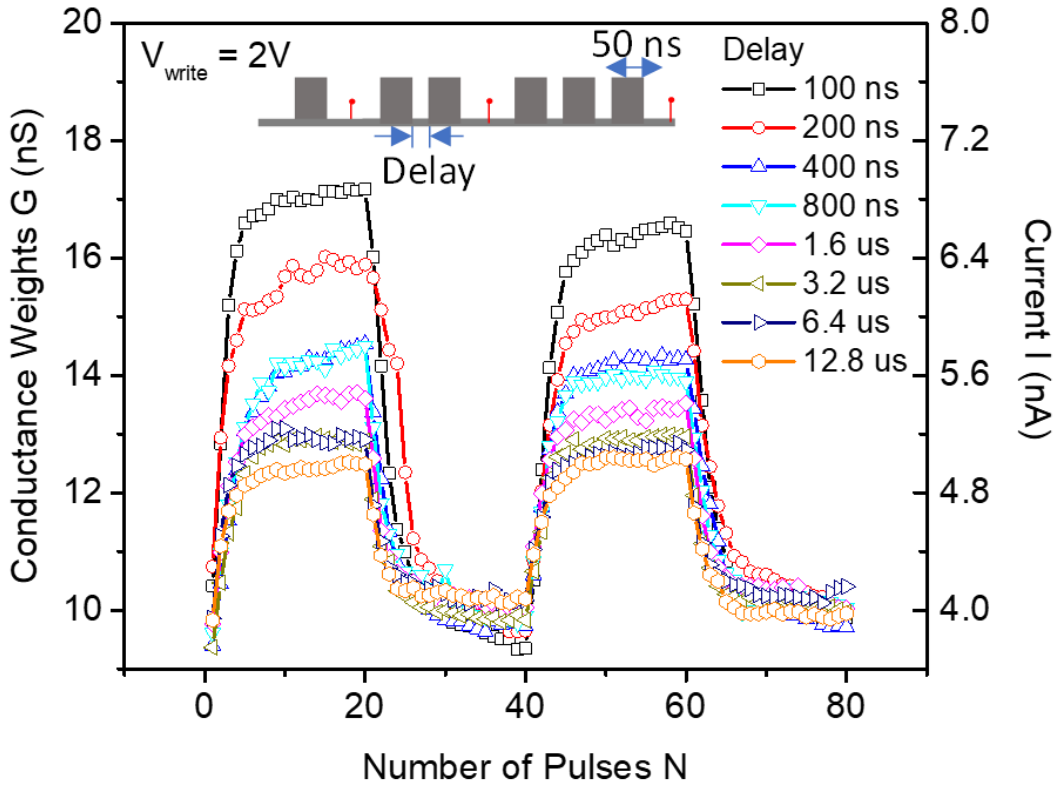
Nearly ideal (linear & symmetric)

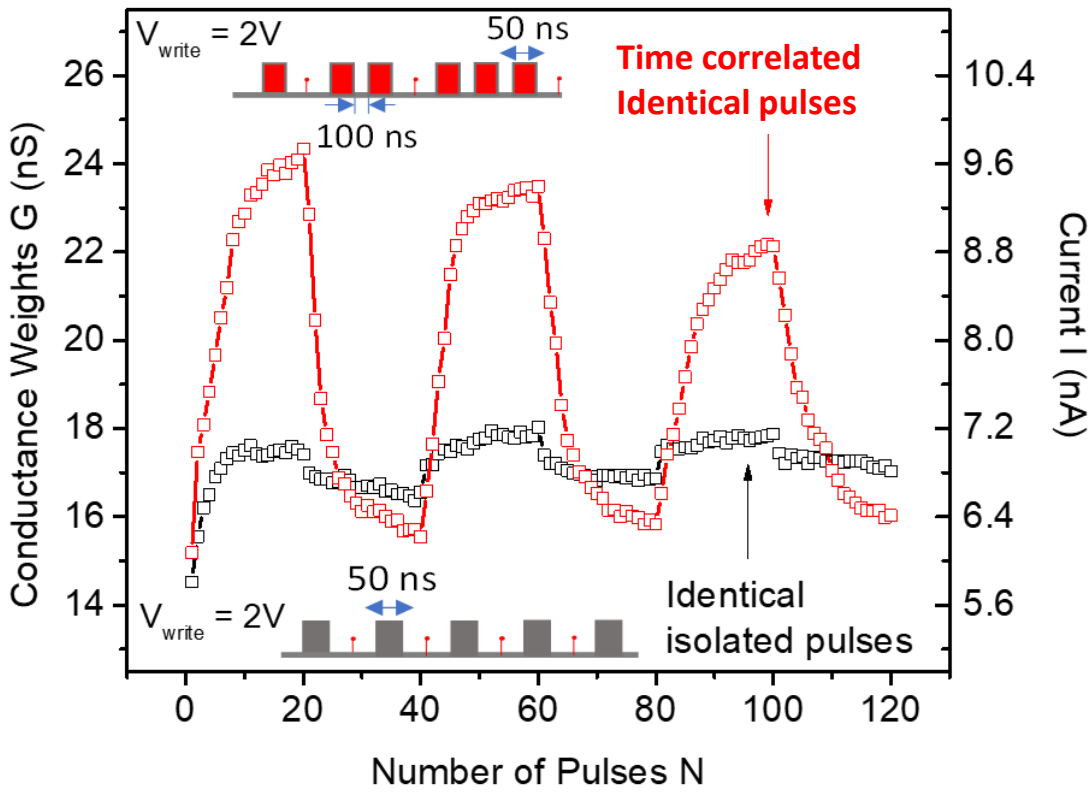






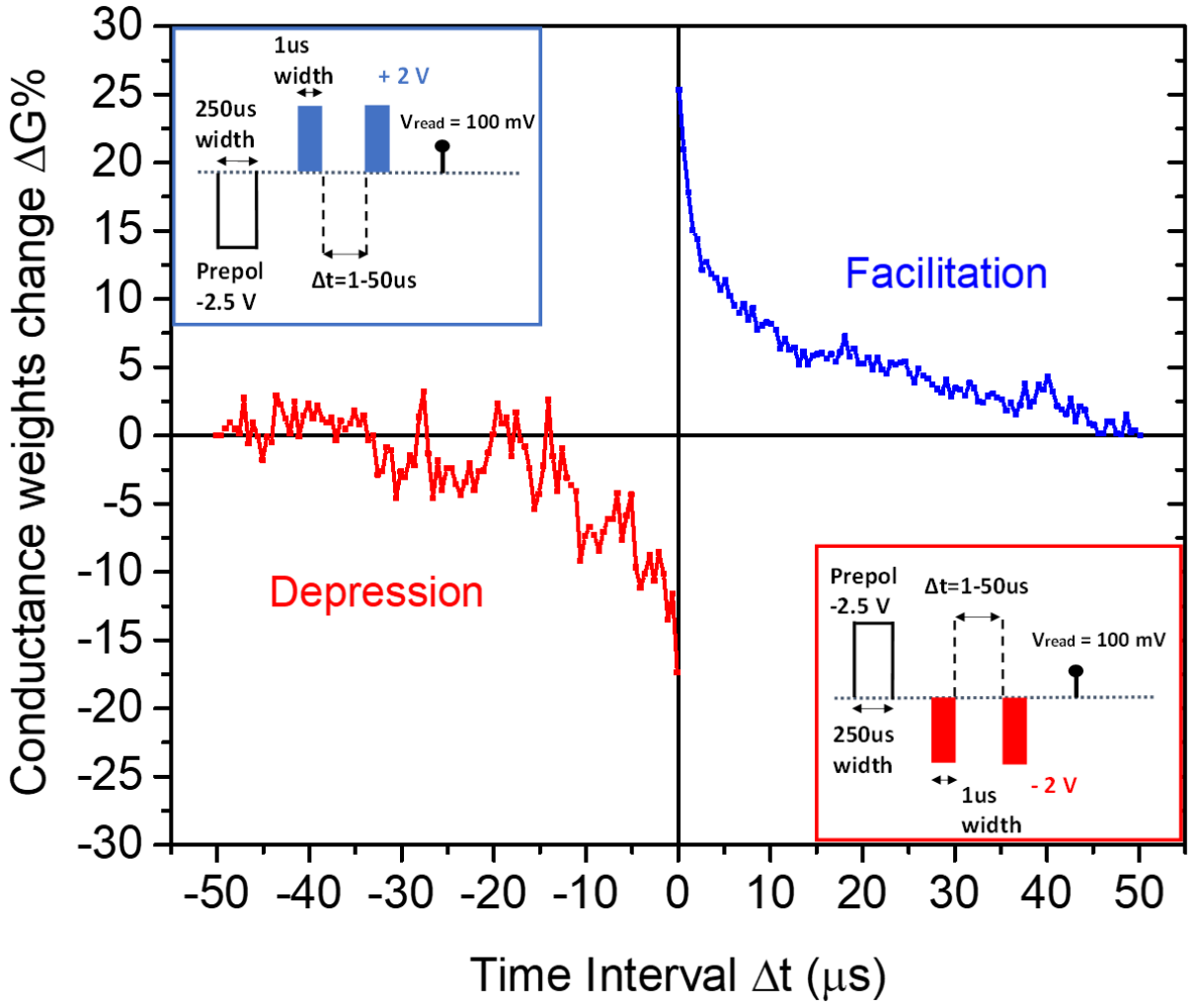
Time correlated vs isolated pulses





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

Paired Pulse Facilitation

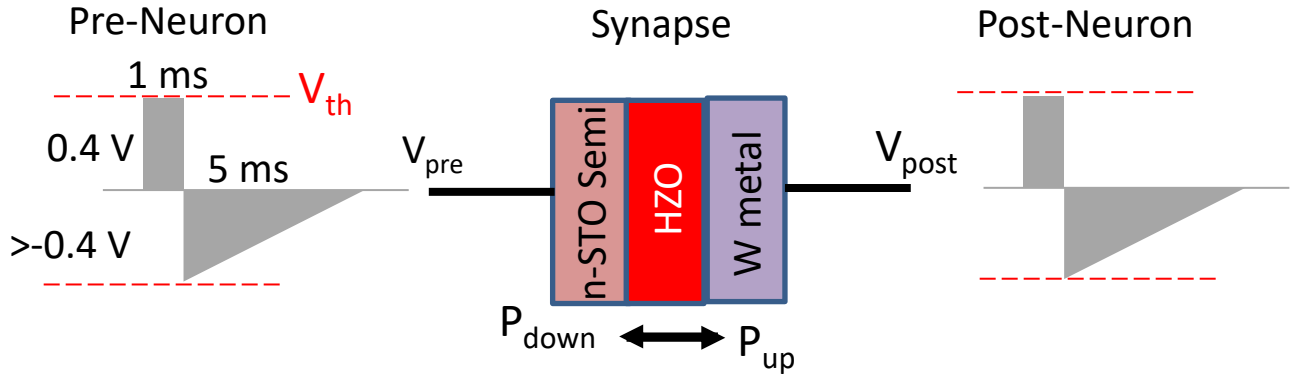


Short term plasticity

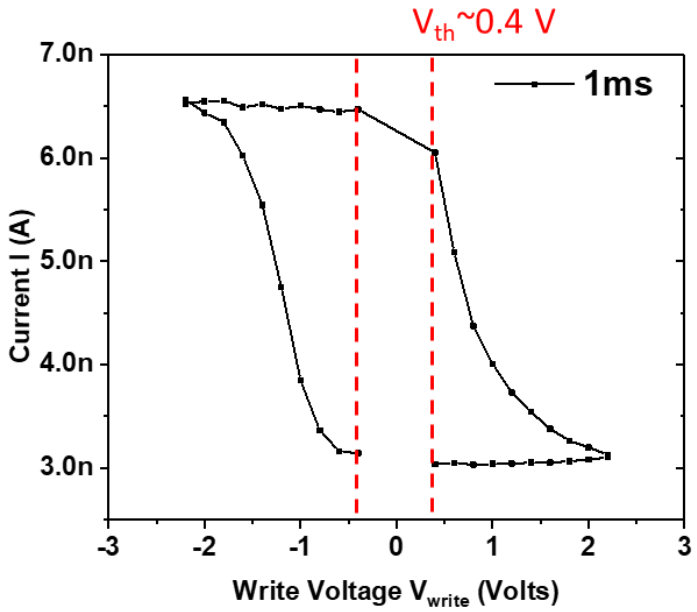
Decode temporary audio/visual info in biological systems

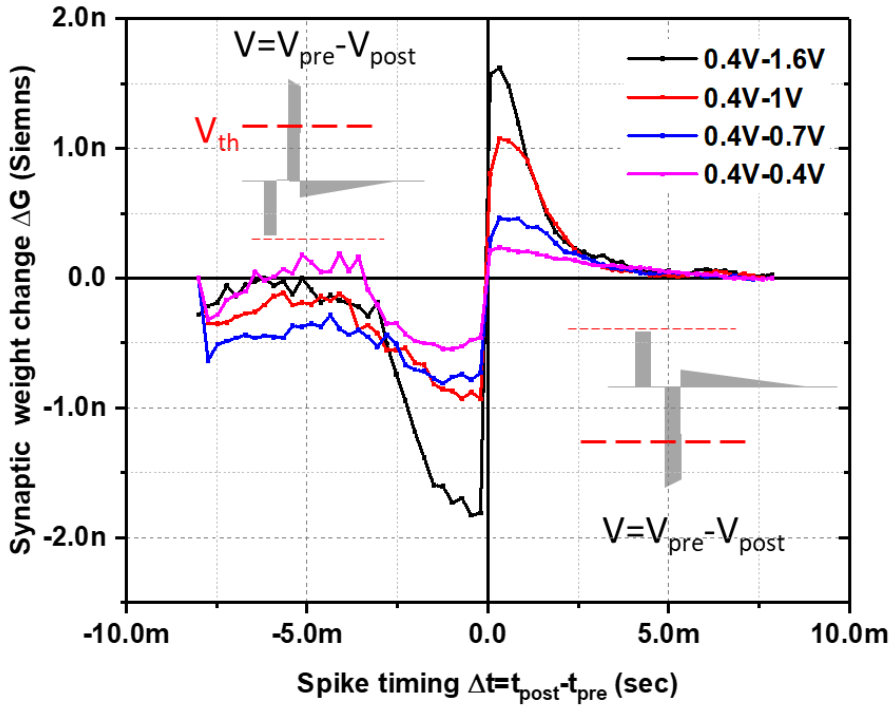
Spike Timing Dependent Plasticity (STDP)

Hebbian learning in biological systems

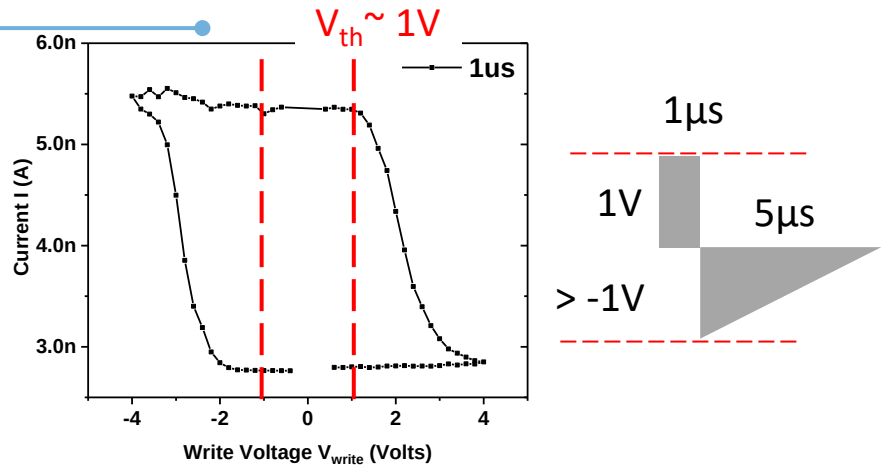


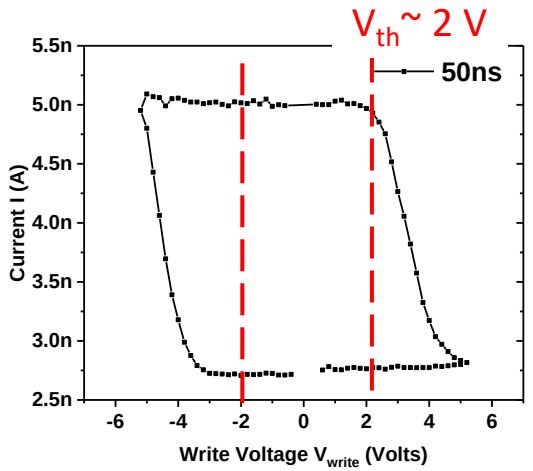
Spiking Neural Networks

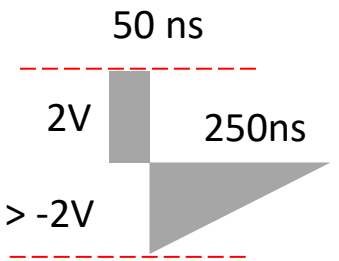


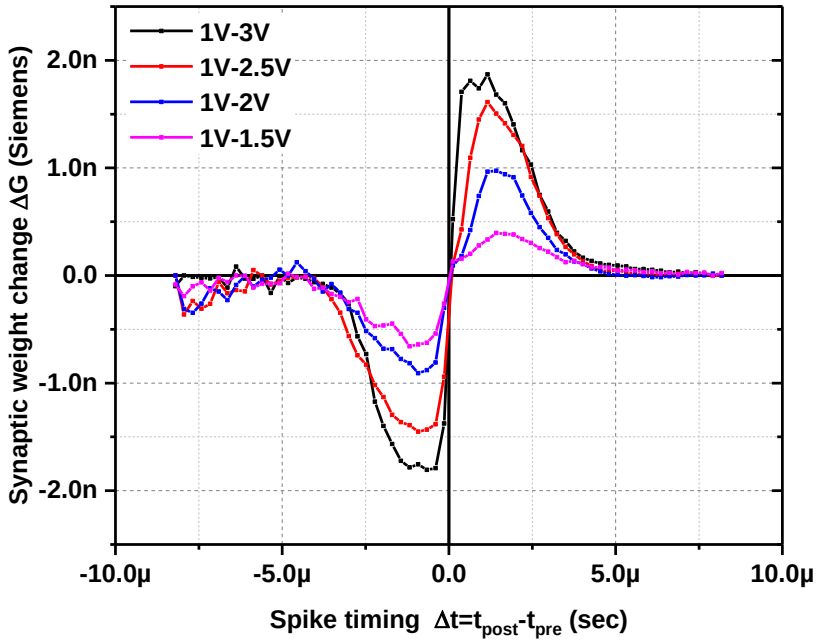


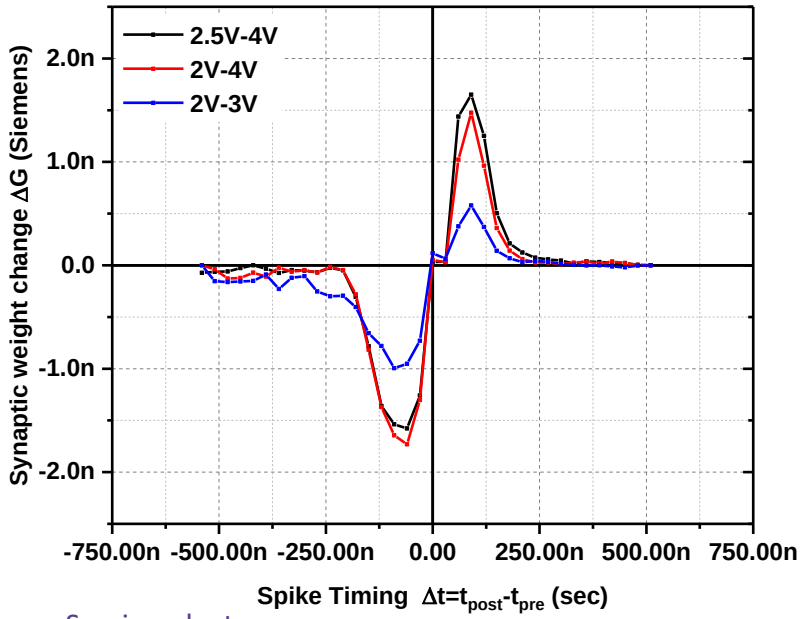
STDP-shorter time scales



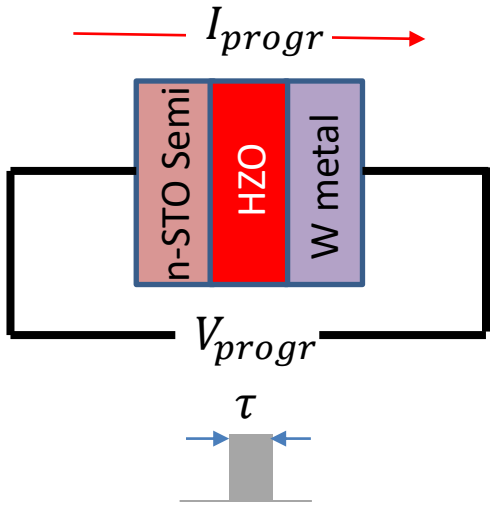








Energy per programming event



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

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

Voltage driven (FE)
Energy to charge a capacitor

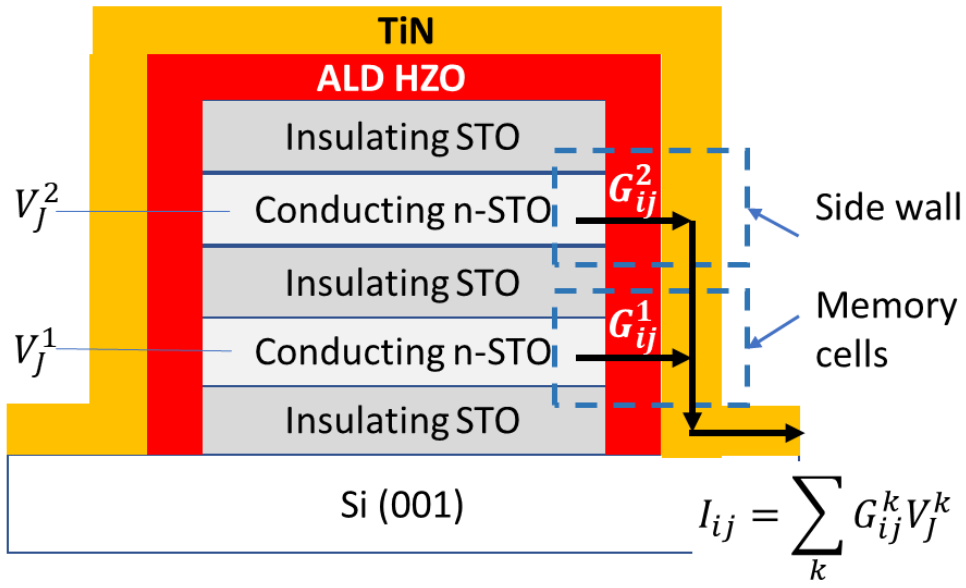
$$E=QV=2PAV$$

P=20 μC/cm2
V=2-4 V
A=100 x100 nm

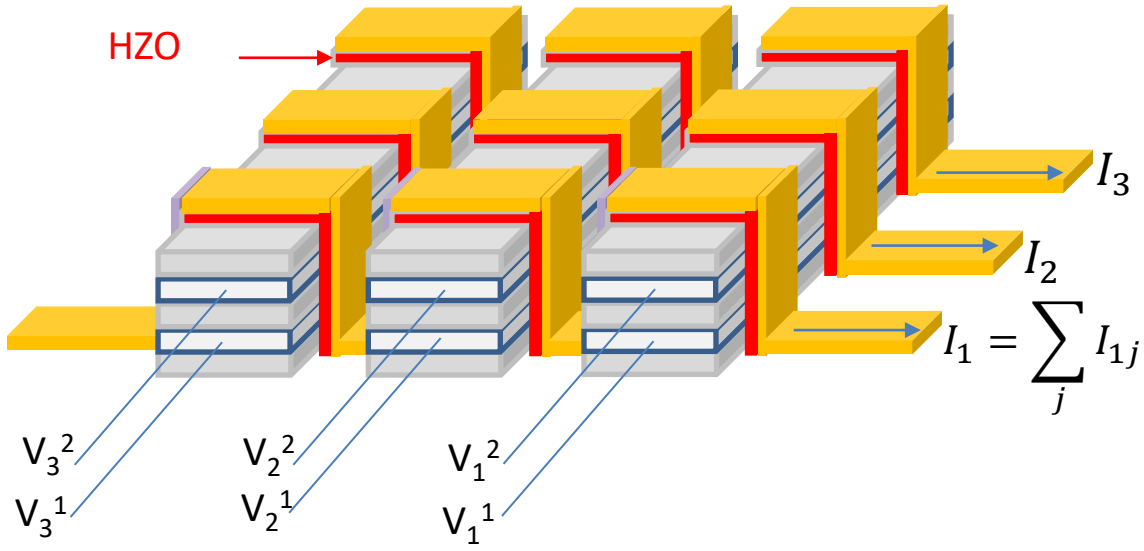
	V_{prog}	I_{progr}	Pulse width τ	Energy E (Joule heat)	Energy (charging)	Area
Biological	10 mV	1 nA	1 ms	10 fJ		
RRAM	1V	10 μA	100 ns	1 pJ		
PCMRAM				10 pJ		
FTJ (our work)	**2V**	**0.1 pA**	**1 ms**	**0.1 fJ**	**8 fJ**	**(100x100 nm)**

Integration

"Multi-floor" Synapses



3D AI accelerator cross bar array



Highly resistive memristor → suitable for large and dense AI accelerator arrays

Low total power consumption / Minimization of sneak paths

Funding and Future plans

Horizon 2020 Programme

BeSynaptic

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

Work continues in HORIZON CL4 projects

Horizon Europe 2021-2027

FIXIT

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

Horizon Europe 2021-2027

concept

Crystalline Oxides for Next Generation Computing and Emerging Photonic Technologies

Finanțat de Uniunea Europeană NextGenerationEU

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

Romanian Recovery and Resilience Plan "ARSYF"

THANK YOU

ICOS International Cooperation On Semiconductors

European Commission

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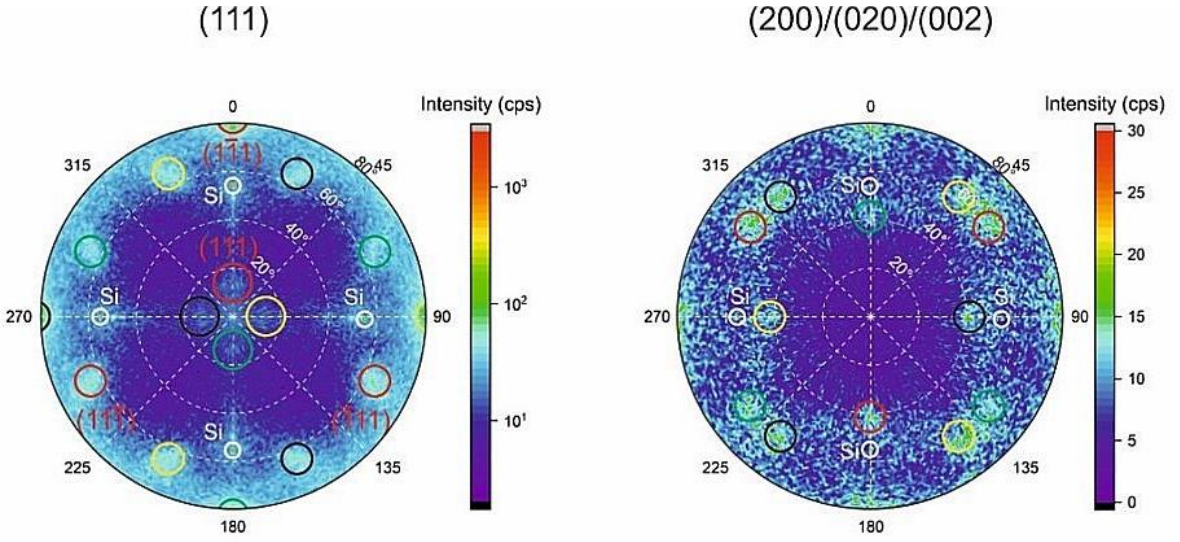
EU – SOUTH KOREA – Joint Researchers Forum on Semiconductors

www.icos-semiconductors.eu

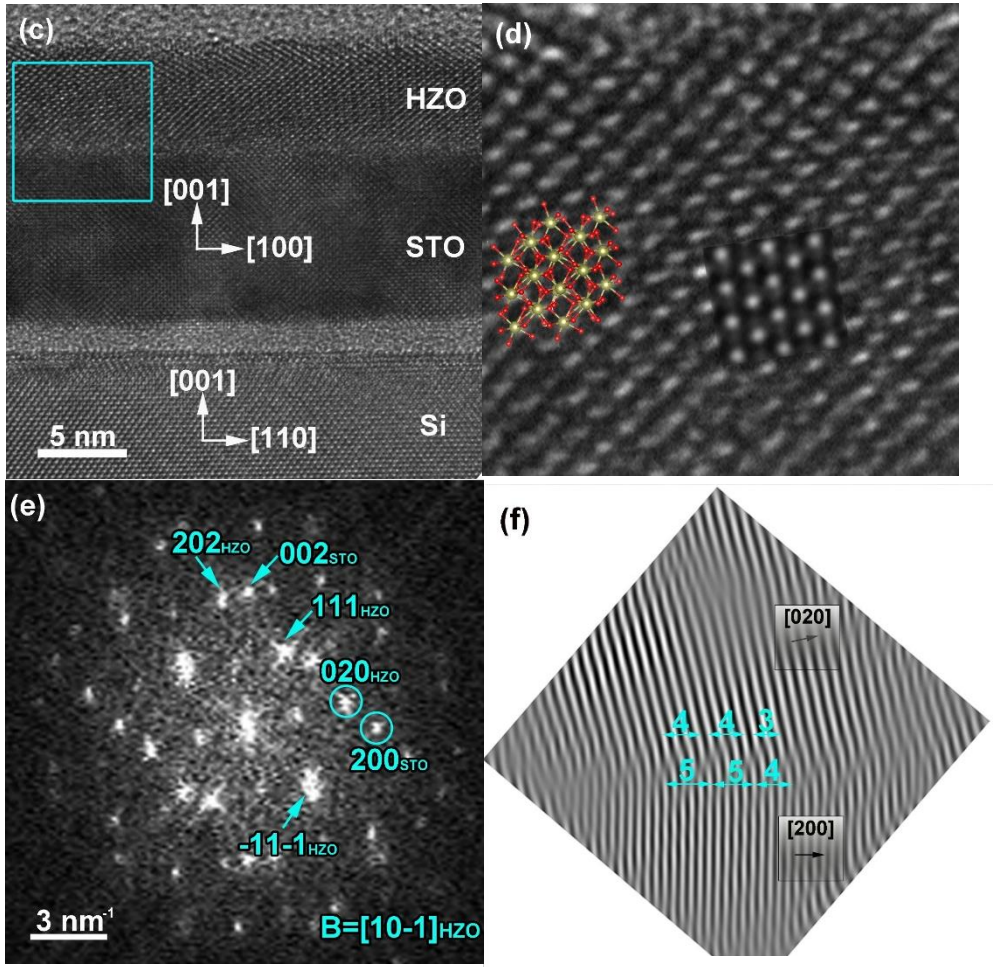
Supporting Files

Epitaxial HZO

XRD pole figures



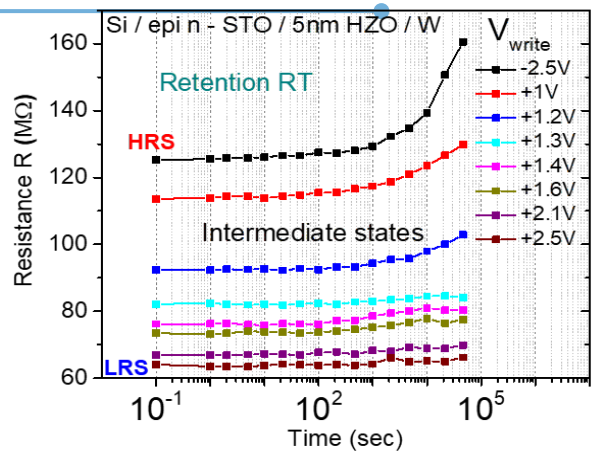
- [111] HZO 15 deg off vertical
- 0, 90, 180, 270 deg rotated domains due to 4-fold symmetry of STO substrate

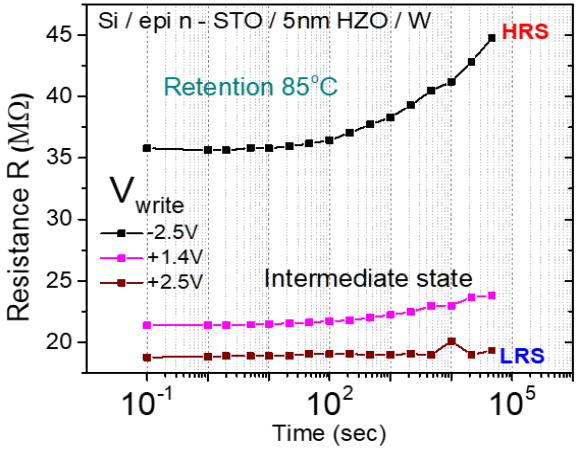


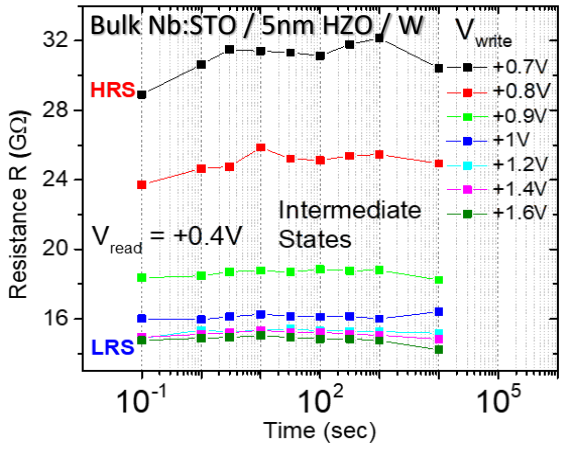
Domain Matching Epitaxy

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

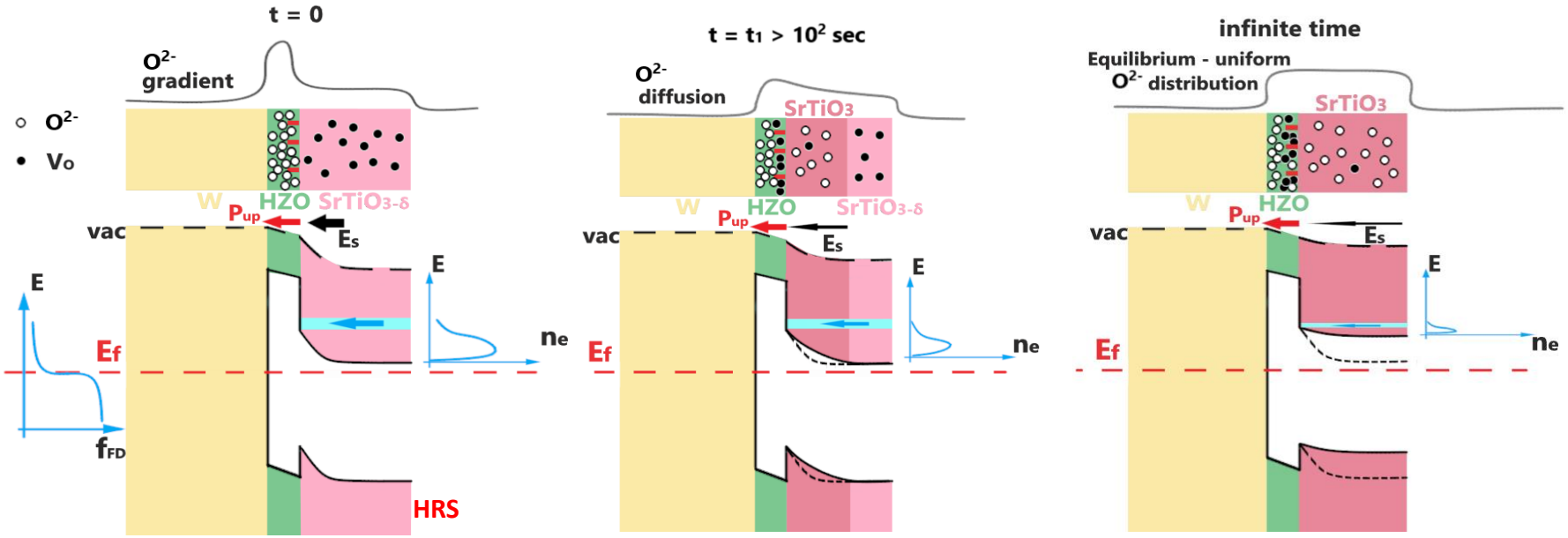
Retention-ionic effects







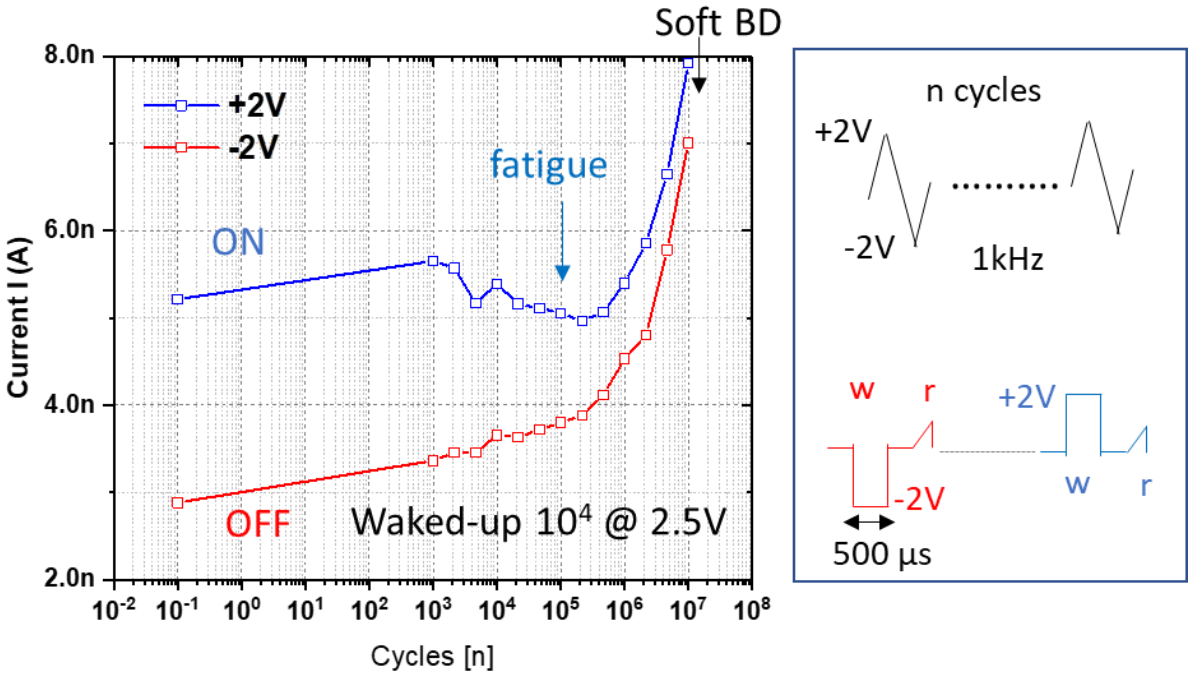
- HRS drifts to larger resistance
- Memory window increases at longer times !

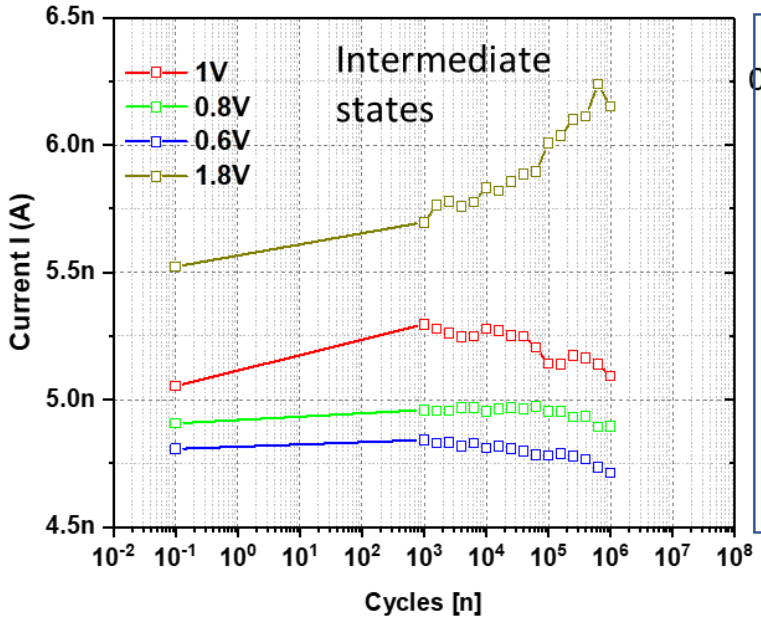


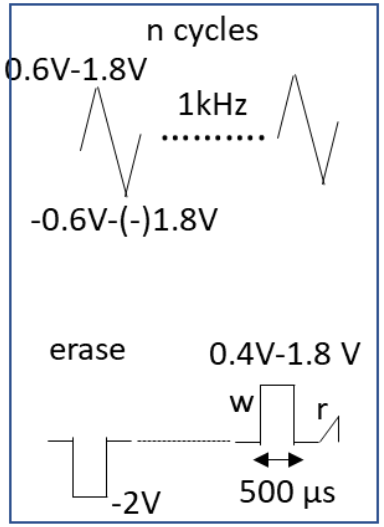
- O^{2-} acceptors diffuse inside STO and compensate the V_o donors
- STO becomes an intrinsic semiconductor increasing its resistance
- Ionic effects occur at shorter timescales too (< 1 ms)

Endurance

ON, OFF and intermediate states







- Fatigue : appears in devices requiring large wake-up / corelated with Pr fatigue
- Soft breakdown: related to large cycling bias (>2V)
- Intermediate states cycled and read at low V < 1V) show better endurance