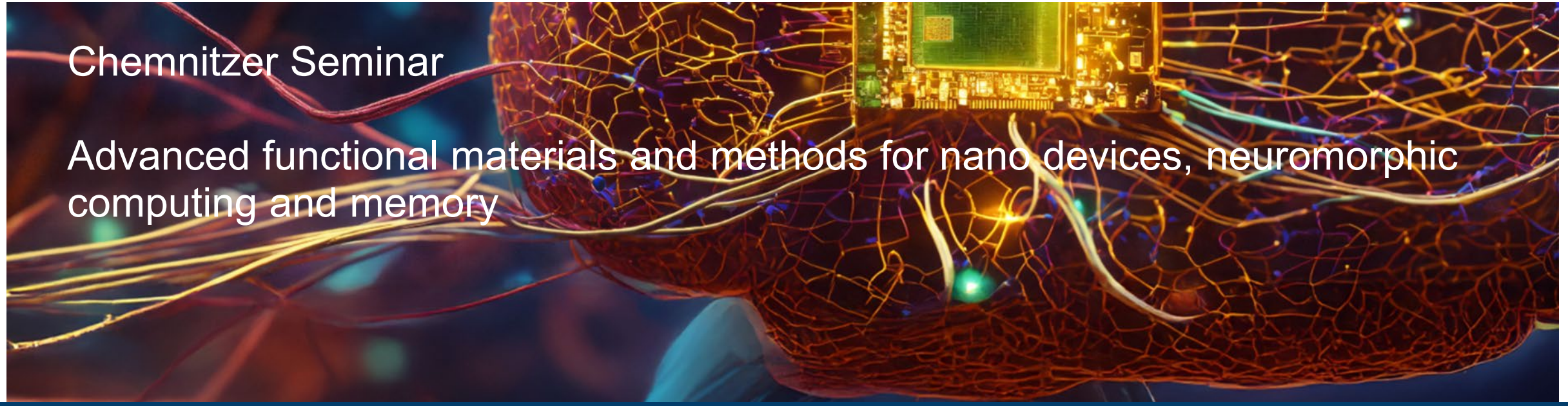


Threshold Switches made from Volatile Electrochemical Metallization Cells for Neuromorphic Computing Applications

Susanne Hoffmann-Eifert

Peter Grünberg Institute for Electronic Materials (PGI-7), Forschungszentrum Jülich GmbH, Jülich, Germany

Mitglied der Helmholtz-Gemeinschaft

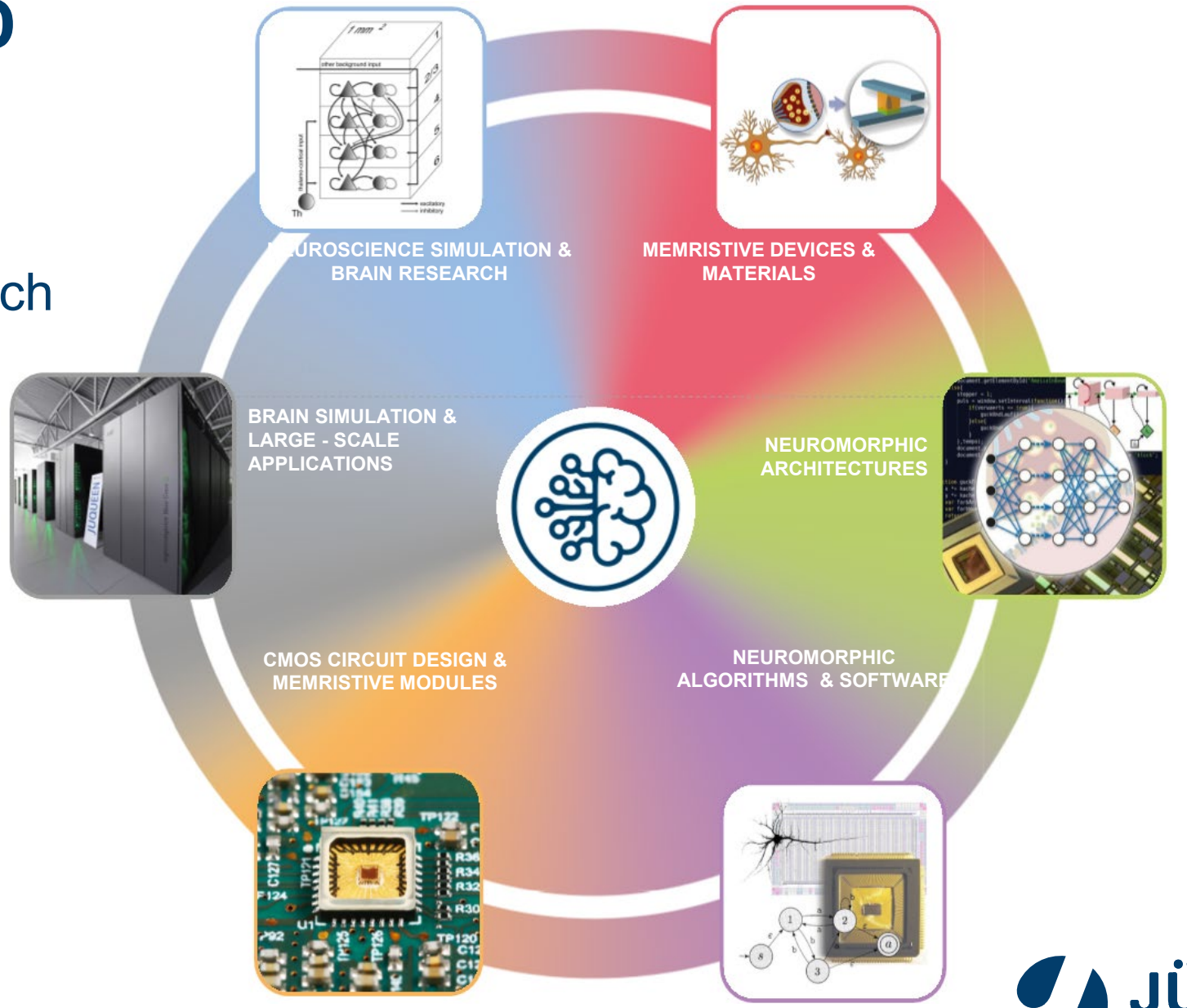
Fraunhofer ENAS

November 26th , 2025

JÜLICH Forschungszentrum
Wandel gestalten

RESEARCH FIELD NEUROMORPHIC COMPUTING

at Forschungszentrum Jülich



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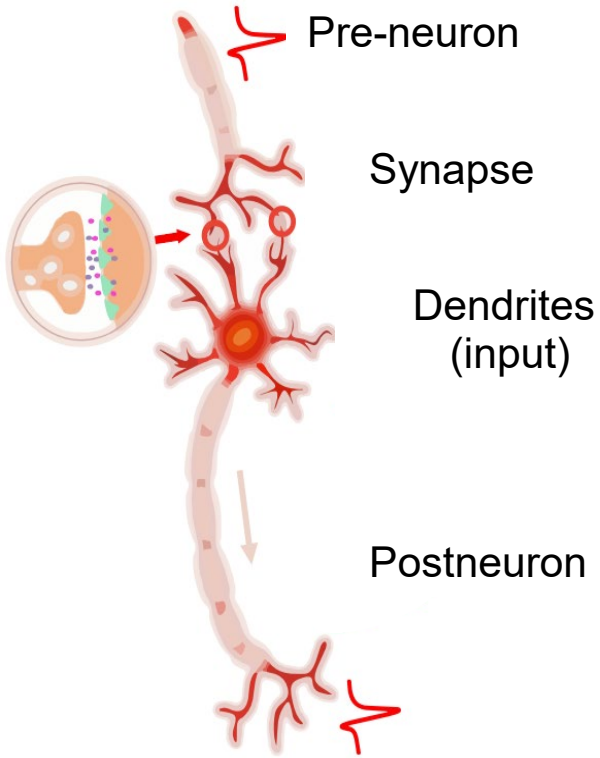
OUTLINE

- Motivation
- Switching Principle of volatile ECM Devices
- SET Kinetics and Relaxation Dynamics of Ag/HfO_2/Pt Devices
- Spiking Behavior of Integrate-and-Fire Neurons
- Summary

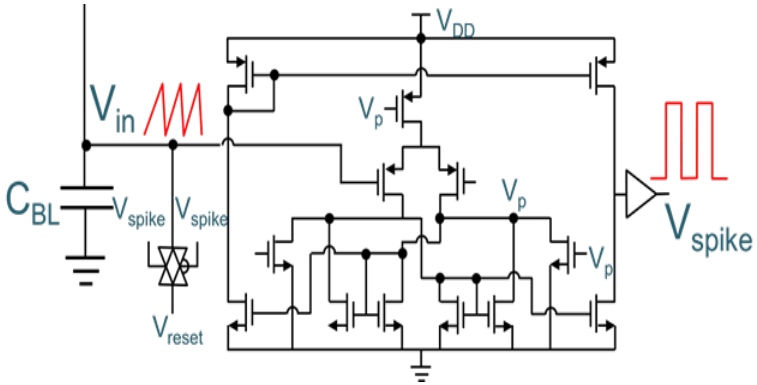
MOTIVATION

Biology



Duan et al., *Nature comm.* (2020)

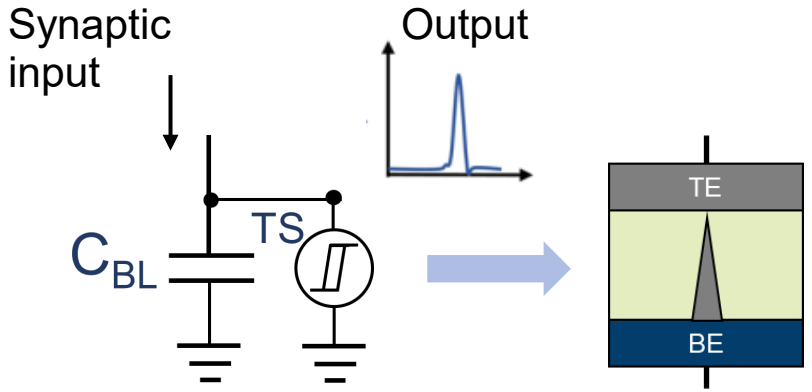
Neuron realized in CMOS



- Large footprint
- Energy and time inefficient

Rubino et al., *IEEE ICECS* (2019)

Threshold switching-based neuron



- Simple in structure and scalable
- Energy efficient
- Leveraging internal temporal dynamics of the device

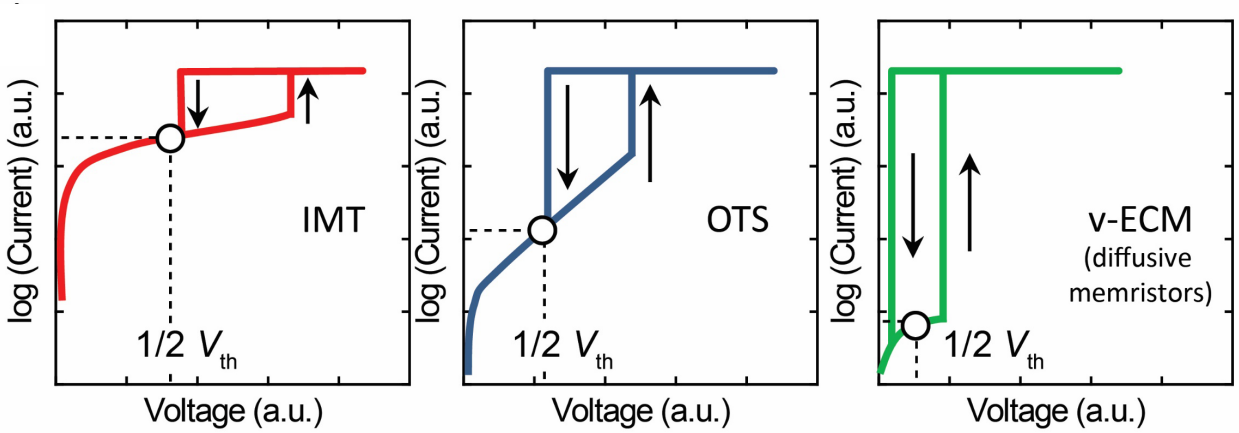
Moon et al., *Mater. Horiz.* (2024)

THRESHOLD SWITCHING DEVICS

Insulator to Metal Transition (IMT)

Ovonic Threshold Switch (OTS)

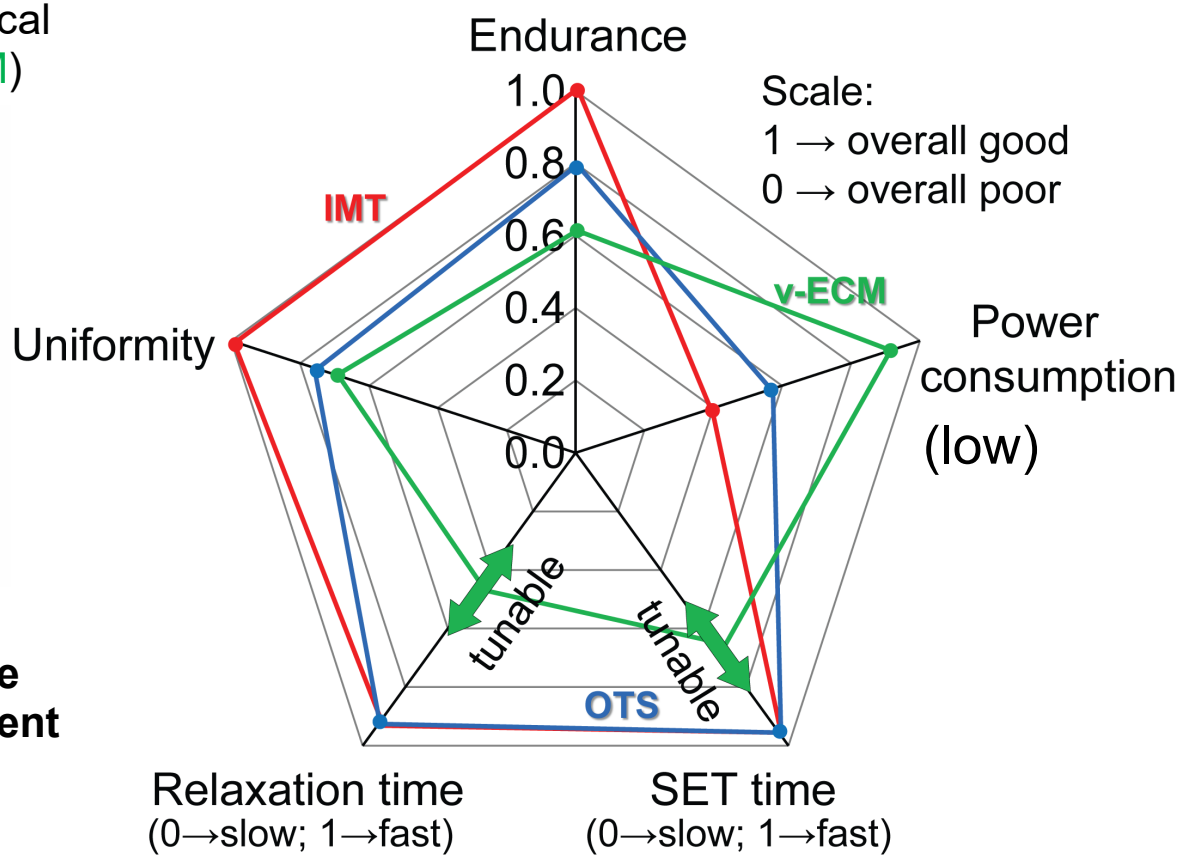
Volatile Electrochemical Metallization (vECM)



Joule heating driven
→ Uniform switching
→ Large leakage

Field-induced carrier trap/de-trap
→ Fast switching
→ Large variability

Formation & rupture of conductive filament
→ Low leakage
→ High stochasticity
→ Tunable dynamics

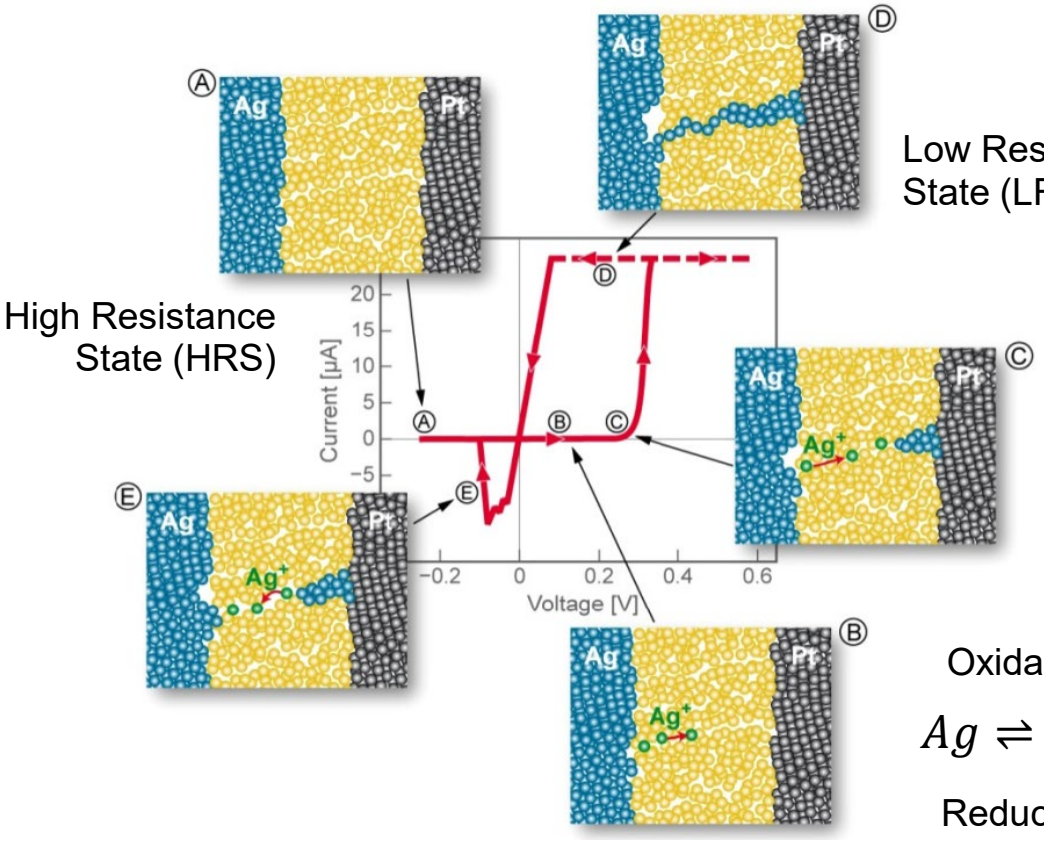


Lee et al., *Adv. Electronic Materials* (2019)

Chekol S. A., et al., *Device Research Conference* (2023)

ELECTROCHEMICAL METALLIZATION CELLS (ECMs)

ECM Memory



Low Resistance State (LRS)

High Resistance State (HRS)

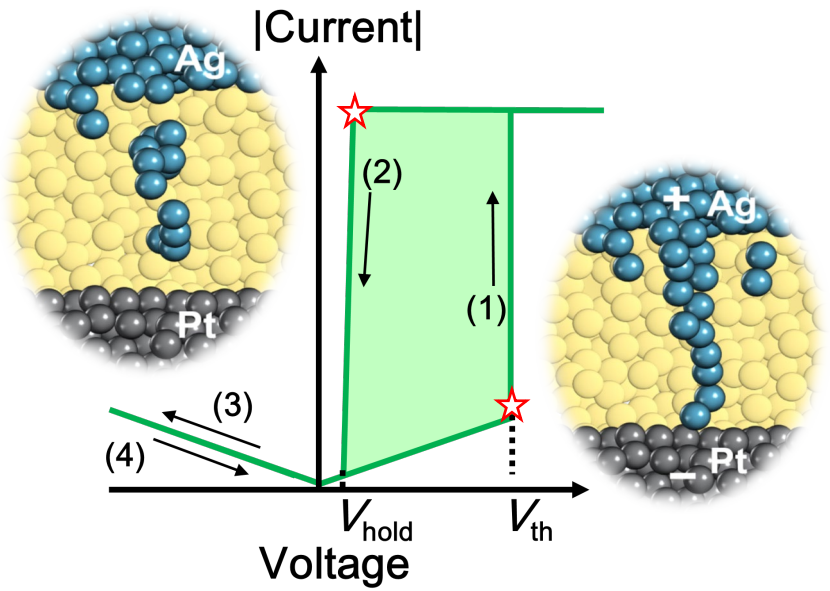
Oxidation

$$Ag \rightleftharpoons Ag^{+} + e^{-}$$

Reduction

Valov I., et al., *Nanotechnology* (2011)

Volatile ECM (Diffusive Memristor)

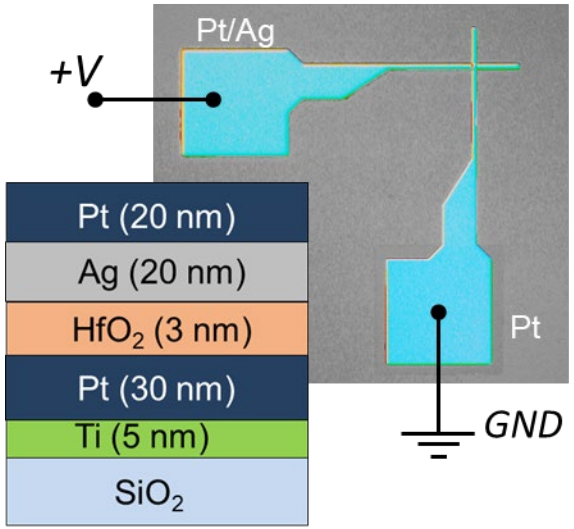


Self-relaxation due to filament instability

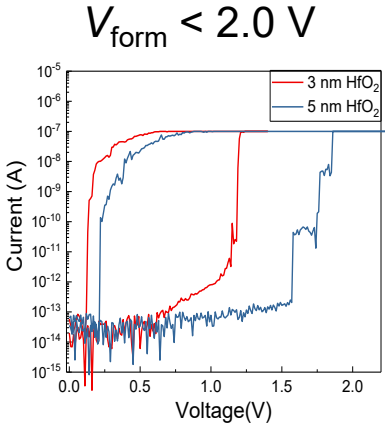
Chekol S. A., et al., *Adv. Funct. Mater.* (2022) 32, 2111242

Ag/HfO_2/Pt vECM DEVICES

Device structure

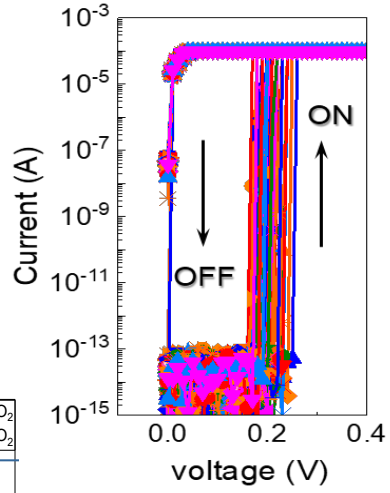


Micro crossbar devices
(2 µm x 2 µm)

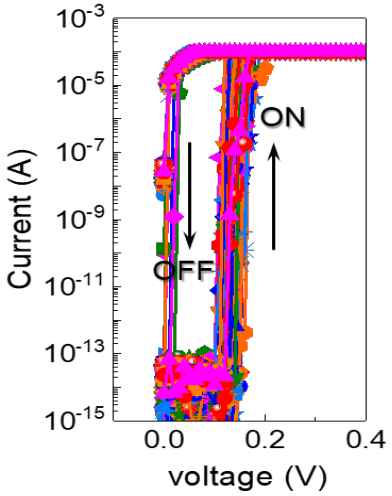


Electrical characteristics

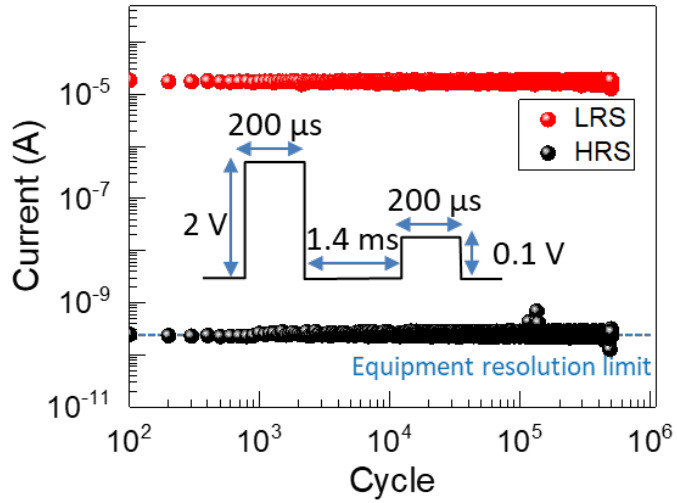
Ag/5 nm HfO_2/Pt



Ag/3 nm HfO_2/Pt



Endurance



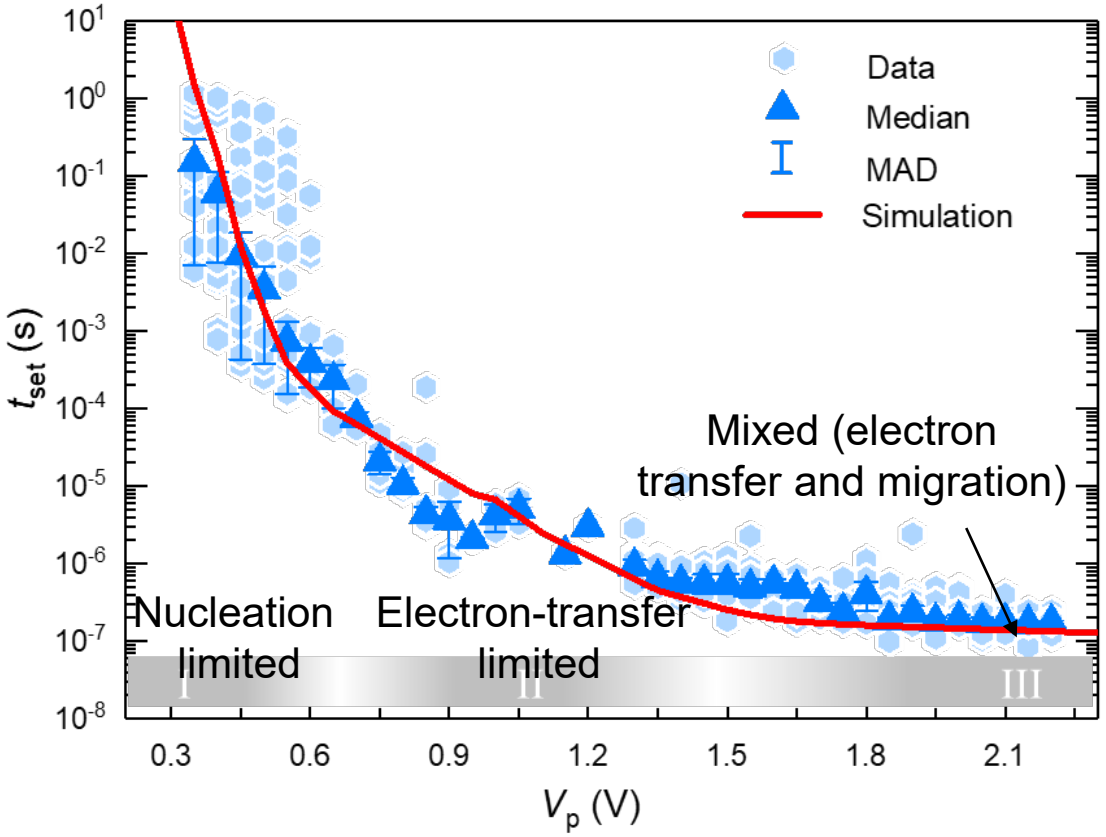
- Ultra low leakage current (< 10 fA)
- Low threshold voltage (< 0.2 V)
- Good cycling endurance (> $5 \cdot 10^5$)

Chekol S. A., et al., *Adv. Funct. Mater.* (2022) 32, 2111242

Chekol S. A., et al., *IEEE Int. Memory Workshop, Dresden, Germany* (2021) pp.1-4

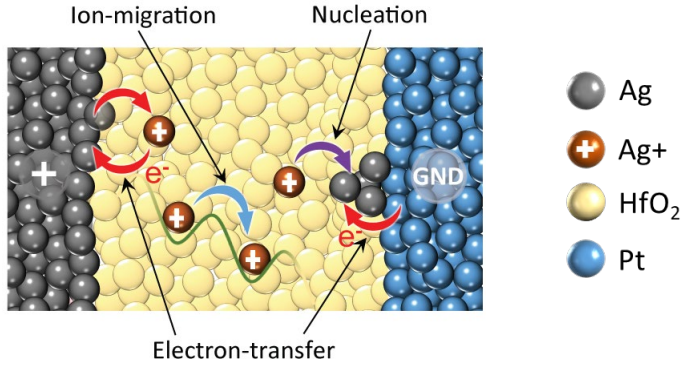
SET SWITCHING KINETICS AND SIMULATION

Ag/3 nm HfO_2/Pt



Chekol S. A., et al., *Adv. Funct. Mater.* (2022) 32, 2111242

The physical model (JART ECM v1)



Nucleation time: $t_{nuc} = t_{0,nuc} \exp\left(\frac{\Delta G_{nuc}}{k_B T}\right) \exp\left(-\frac{(N_C + \alpha_{nuc})ze}{k_B T} \Delta\varphi_{nuc}\right)$

Tunneling current: $I_{tu} = C \frac{3\sqrt{2m_{eff}\Delta W_0}}{2x} \left(\frac{e}{h}\right)^2 exp\left(-\frac{4\pi x}{h}\sqrt{2m_{eff}\Delta W_0}\right) A_{fil} V_{tu}$

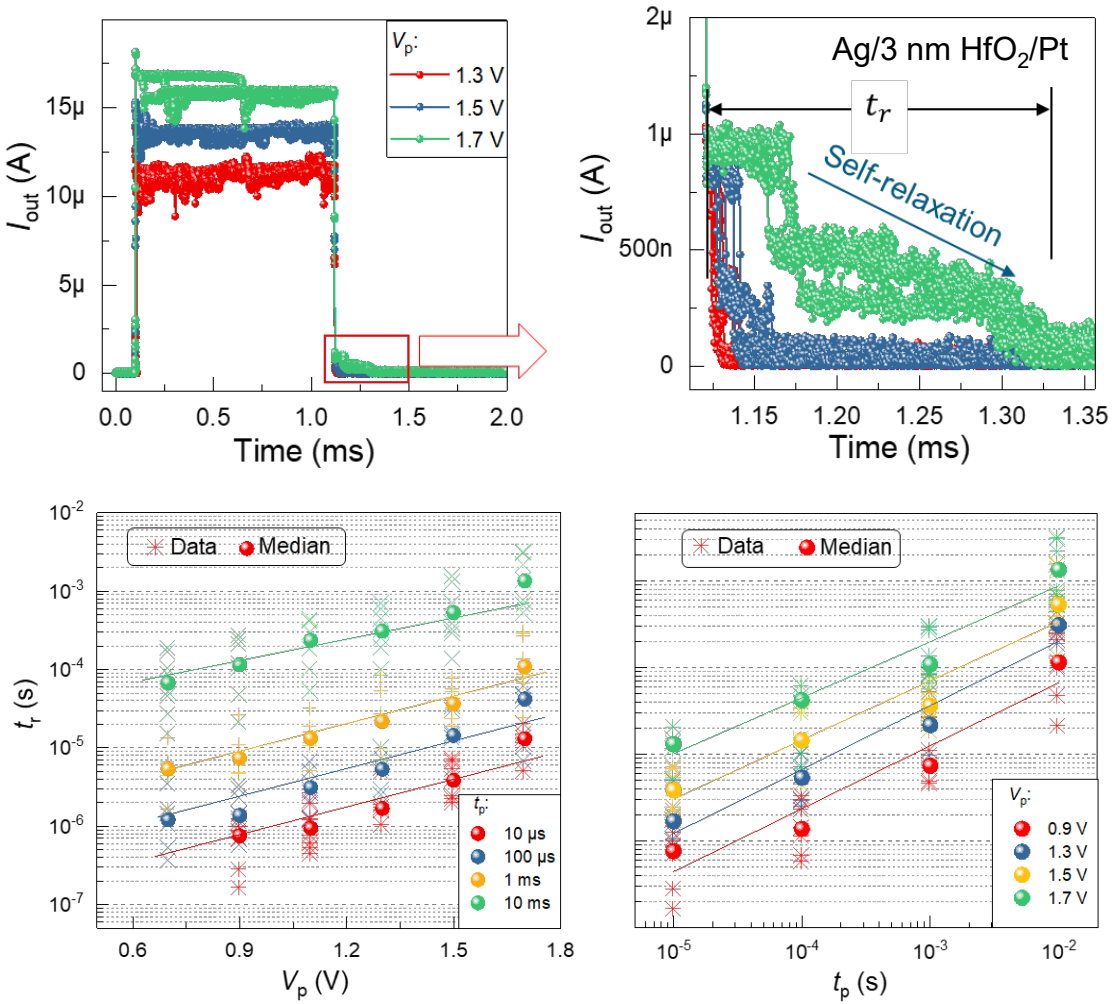
Ionic hopping current: (Mott-Gurney-law) $I_{hop} = 2zecaf \exp\left(-\frac{\Delta G_{hop}}{k_B T}\right) \sinh\left(\frac{aze\Delta\varphi_{hop}}{2k_B T x}\right) A_{hop}$

Electron transfer reaction: (Butler-Volmer-equation)

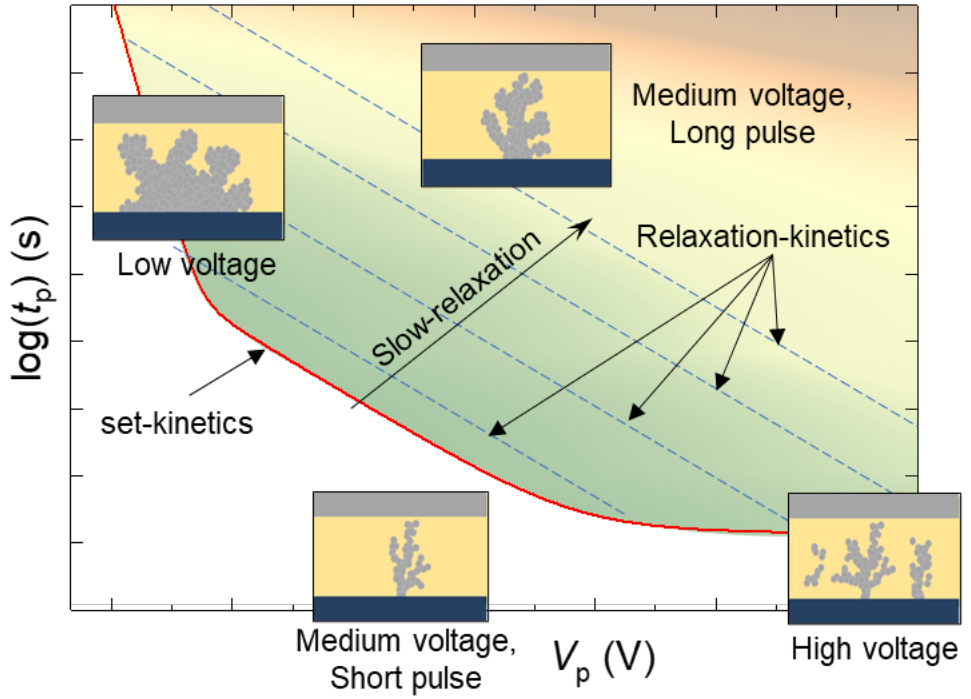
$$I_{fil/ac} = \pm zeck_{0,et} \exp\left(-\frac{\Delta G_{et}}{k_B T}\right)\left[\exp\left(\frac{(1-\alpha_{et})ze}{k_B T}\Delta\varphi_{fil/ac}\right) - \exp\left(-\frac{\alpha_{et} ze}{k_B T}\Delta\varphi_{fil/ac}\right)\right] A_{fil/ac}$$

Menzel S., et al., Phys. Chem. Chem. Phys. (2013)

RELAXATION DYNAMICS



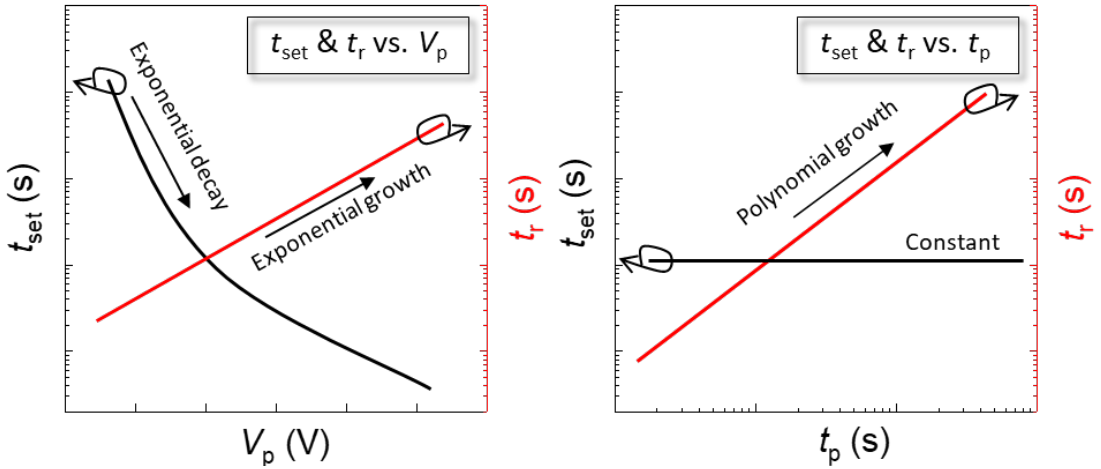
Chekol et al., Adv. Funct. Mater. (2022)



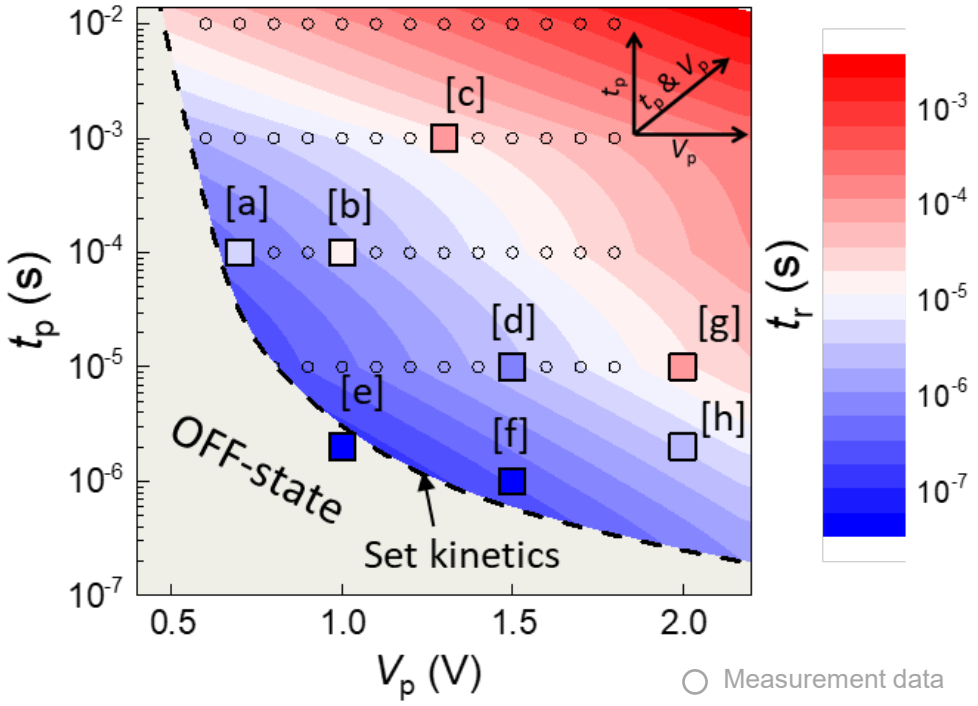
- t_r proportional to exp (V_p)
- Power law relationship between t_r and t_p

⇨ Possibility of tuning t_{set} and t_r by means of V_p and t_p

INTERDEPENDENCE OF SET AND RELAXATION



A trade-off exists between SET and relaxation times with respect to pulse voltage amplitude.



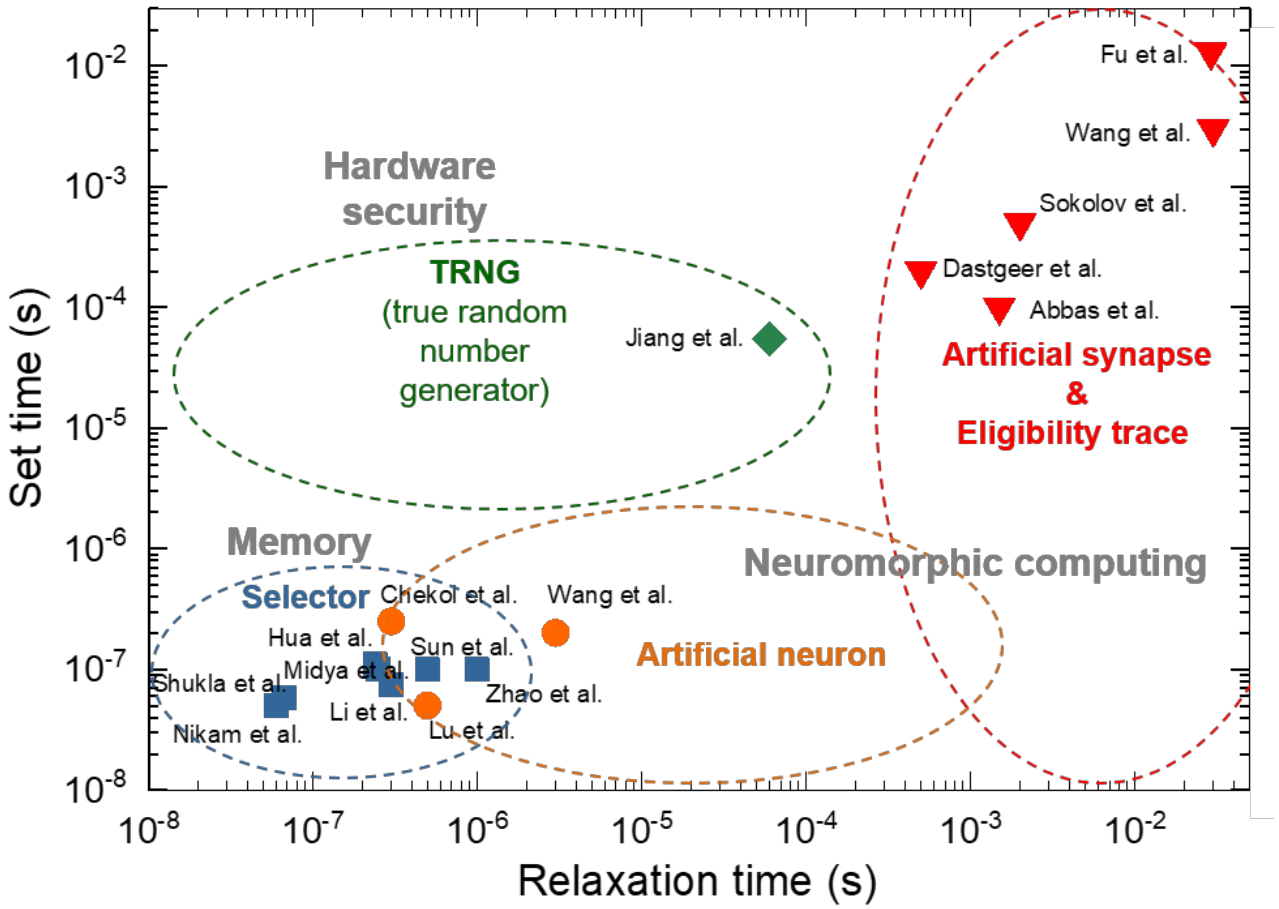
○ Measurement data

[1] J. Yoo *et al.*, *APL* 2017
[2] Y. Wang *et al.*, *J. Elec Mater.* 2019
[3] Y. Zhao *et al.*, *IEEE TED* 2018
[4] J. Yin *et al.*, *J. Phys. Chem. C* 2019
[5] R. D. Nikam *et al.*, *Small* 2021
[6] Y. Li *et al.*, *Adv. Sci.* 2020
[7] M. Wang *et al.*, *Adv. Mater.* 2018
[8] N. Shukla *et al.*, *IEEE IEDM* 2016

- ✓ The minimum t_p for a successful SET event at any given V_p gives the minimum t_r.
- ✓ Little control over t_r at low and very high voltage regions.

Chekol S. A., et al., *Adv. Funct. Mater.* (2022) 32, 2111242

APPLICATION AREAS OF v-ECM DEVICES



- ✓ Possibility of tuning the t_{set} and t_r by several orders of magnitude by means of V_p and t_p.

Chekol S. A., et al., *Adv. Funct. Mater.* (2022) 32, 2111242

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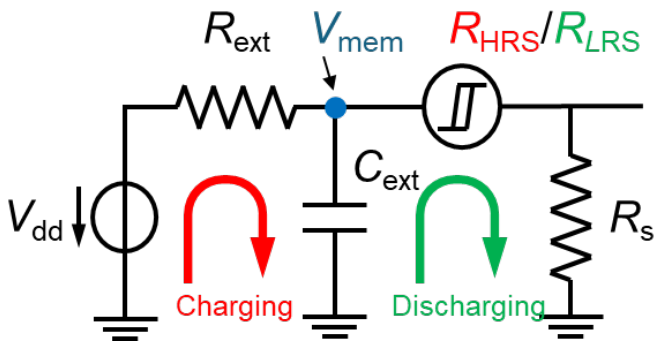
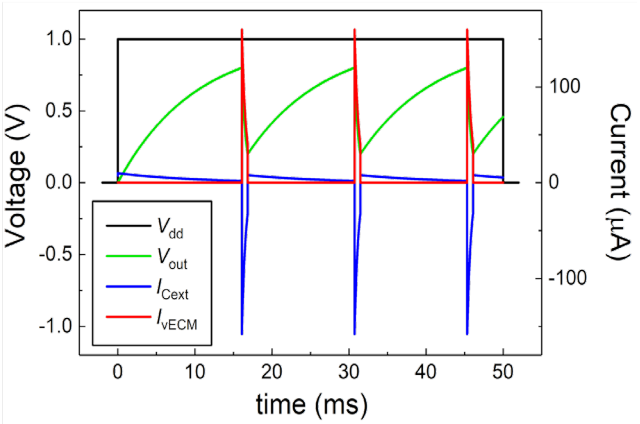
INTEGRATE-AND-FIRE (I&F) NEURONs WITH v-ECMs

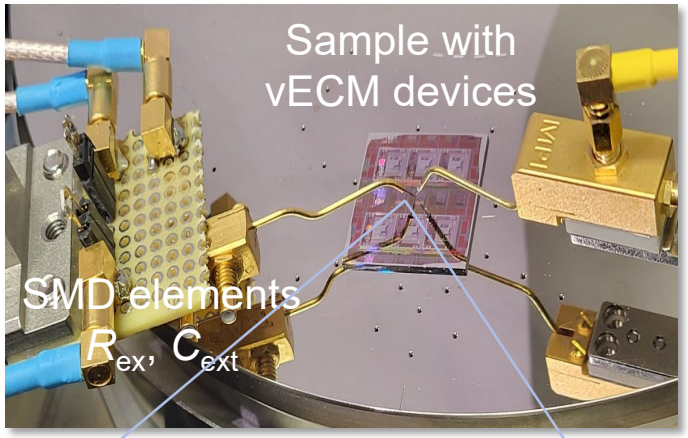
… from threshold switches

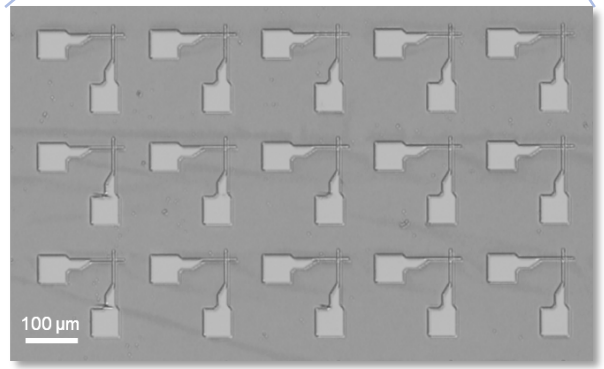




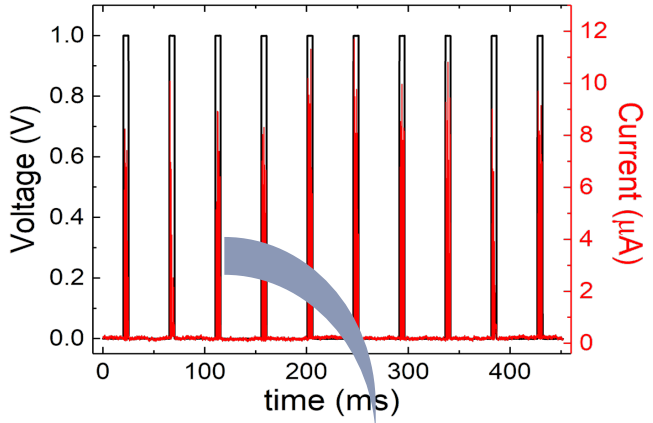
Rasbach J., et al., *to be published.*

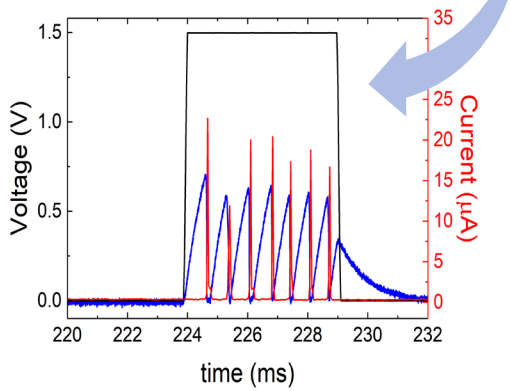
Experimental setup





Spiking behavior

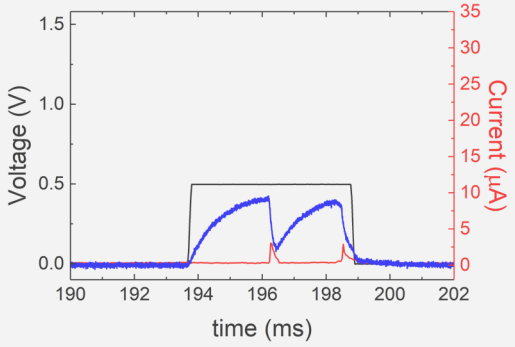




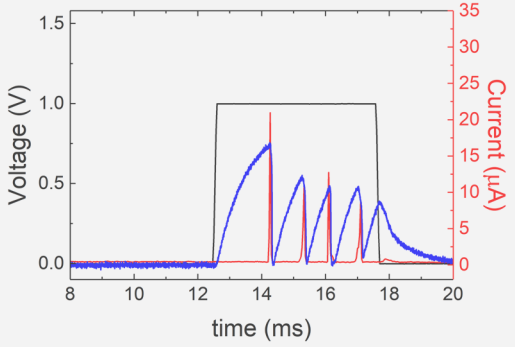
Effect of external parameters V_{dd}, R_{ext}, C_{ext} on spiking:
no of spikes
Δt_{spikes}
spike current I_{spike}

I&F NEURON – VARIATION OF INPUT VOLTAGE

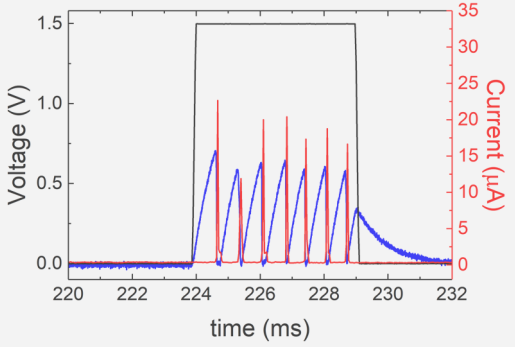
V_{dd} = 0.5 V



V_{dd} = 1.0 V

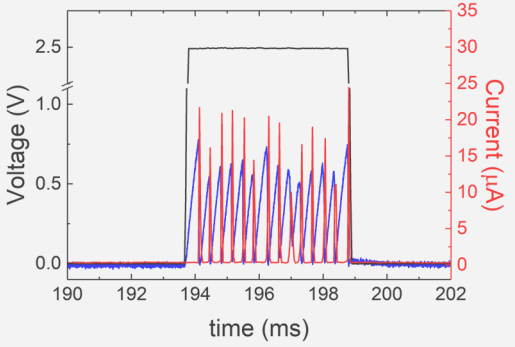


V_{dd} = 1.5 V

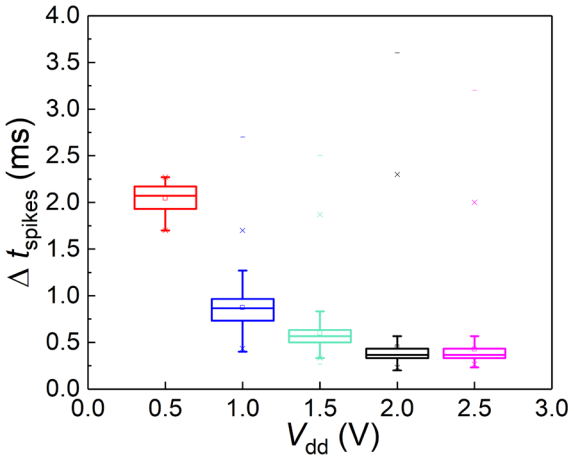


...

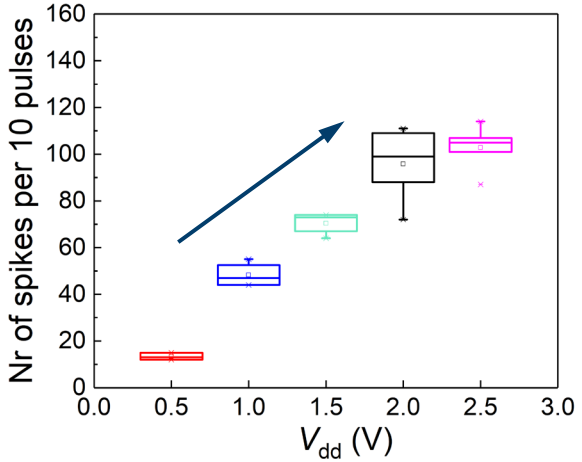
V_{dd} = 2.5 V



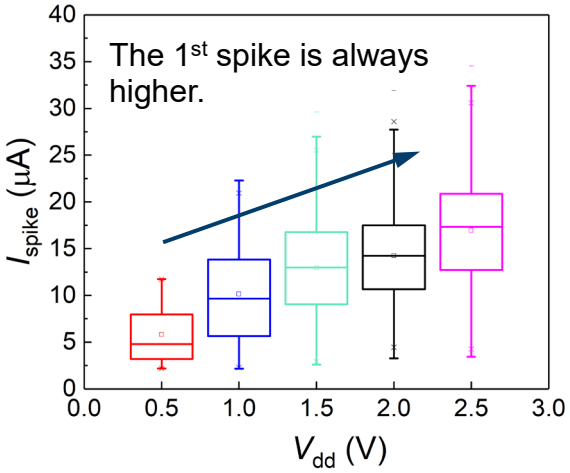
$\Delta t_{spikes} \approx$ 2 ms – 0.3 ms



$\#_{spikes}|_{10} \approx$ 12 - 100



$I_{spike} \approx$ 5 µA – 20 µA



V_{dd} = 0.5 V – 2.5 V

t_p = 5 ms

t_{wait} = 25 ms

R_{ext} = 1 MΩ

C_{ext} = 1 nF

Rasbach J., et al., *to be published.*

SUMMARY

- Volatile electrochemical metallization (vECM) devices (also: diffusive memristors) show a threshold-type switching behavior that is interesting for energy efficient computing:
  → low threshold voltage, → low V_{th}, and → ultra-low leakage current.
- The set and relaxation behavior of vECMs are understood from physical modelling.
- This study focuses on devices with 3 nm amorphous HfO_2.
- I&F neurons are built from Ag/3 nm HfO_2/Pt cells and studied under different operation conditions. The number of spikes and the max. spike current vary proportional to V_{dd}.

Publications:

- S. A. Chekol, F. Cüppers, R. Waser and S. Hoffmann-Eifert, "An Ag/HfO_2/Pt Threshold Switching Device with an Ultra-Low Leakage (< 10 fA), High On/Off Ratio (> 10^{11}), and Low Threshold Voltage (< 0.2 V) for Energy-Efficient Neuromorphic Computing," *2021 IEEE International Memory Workshop (IMW)*, Dresden, Germany, 2021, pp. 1-4, doi: 10.1109/IMW51353.2021.9439601.
- S. A. Chekol, S. Menzel, R. W. Ahmad, R. Waser, S. Hoffmann-Eifert, “Effect of the Threshold Kinetics on the Filament Relaxation Behavior of Ag-Based Diffusive Memristors”, *Adv. Funct. Mater.* 2022, 32, 2111242, doi: 10.1002/adfm.202111242
- S. A. Chekol, S. Menzel, R. Waser, S. Hoffmann-Eifert, “Strategies to Control the Relaxation Kinetics of Ag-Based Diffusive Memristors and Implications for Device Operation”, *Adv. Electron. Mater.* 2022, 8, 2200549, doi: 10.1002/aelm.202200549
- R. W. Ahmad, S. A. Chekol, J. Rasbach, S. Hoffmann-Eifert, S. Menzel, “Compact Modeling of Volatile-Switching Electrochemical Metallization Memory Cells by Means of the Electromotive Force”, *Adv. Intell. Syst.*. 2025; 000, e202501018, doi: 10.1002/aisy.202501018

FUNDING

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