Identifying the Electronic and Ionic Transport in Area-Dependent VCM

"Allowing engineering and simulation of memristive devices for neurmorphic circuits"

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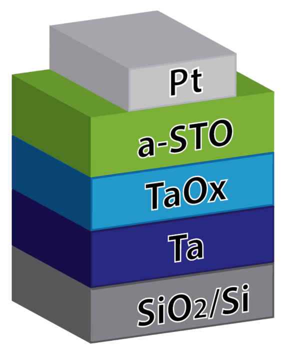
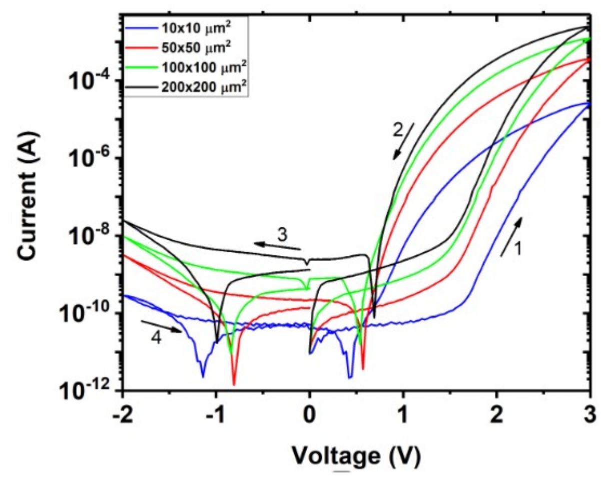
Motivation: Gradual Area-Dependent memristive devices are needed for analog computing and neuromorphic applications[1]

Feature	Gradual, Area-Dependent Switching	Binary / Abrupt Filamentary Switching
Synaptic Behavior	Analog (continuous weight tuning)	Digital (discrete on/off states)
Learning Performance	High precision and stable convergence	Poor convergence and limited learning accuracy
Variability	Inherently low due to homogenous switching	High due to random nature of filament formation
Update Control	Fine, incremental conductance changes	Sudden, large conductance jumps
Suitability for Neuromorphic Systems	✅ Ideal — mimics biological synapses	❌ Limited — too discrete for analog learning. Good for memory applications.

Model system: Area-dependent volatile a-STO based VCM devices



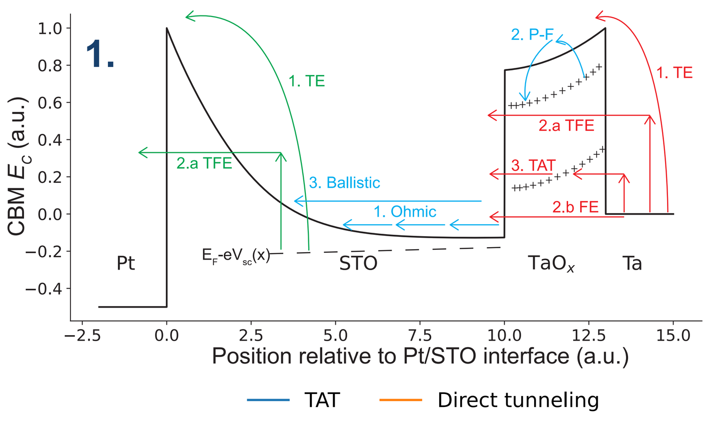
- Area-dependent 8-wise switching.
- Gradual switching.
- CMOS BEOL compatible fabrication process.
- Very low variability.
- Self-rectifying, current compliance-free operation.
- Great endurance $>5 \cdot 10^6$ cycles
- Volatile behavior with tunable retention times (milliseconds to several seconds), enabling the emulation of short-term plasticity (STP) in neuromorphic circuits.

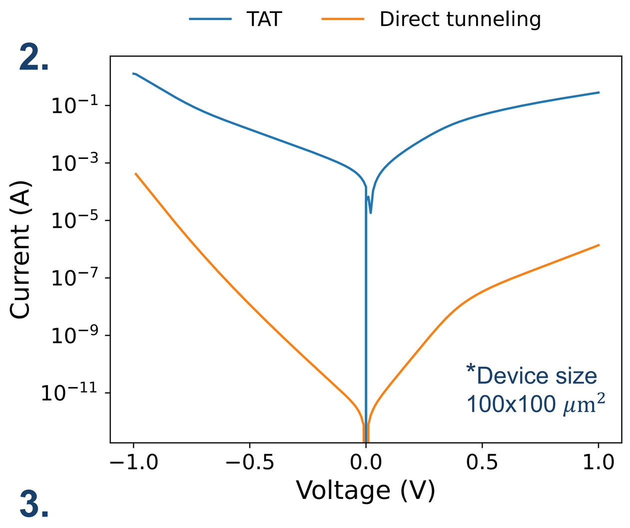


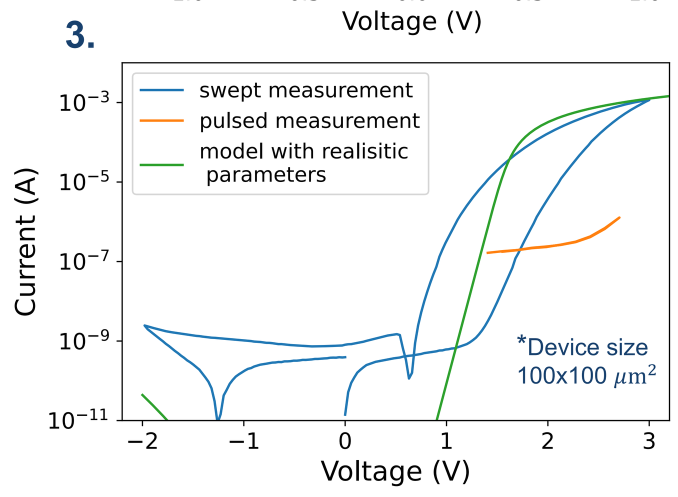
Missing: **Good physical understanding of these type of devices for device engineering and circuit simulations.**

Electronic Model: Understanding the electron transport through heterostructure

Band diagram and possible conduction mechanisms





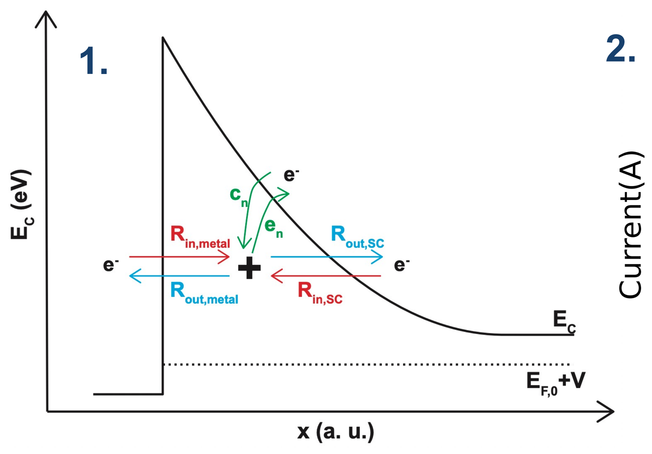


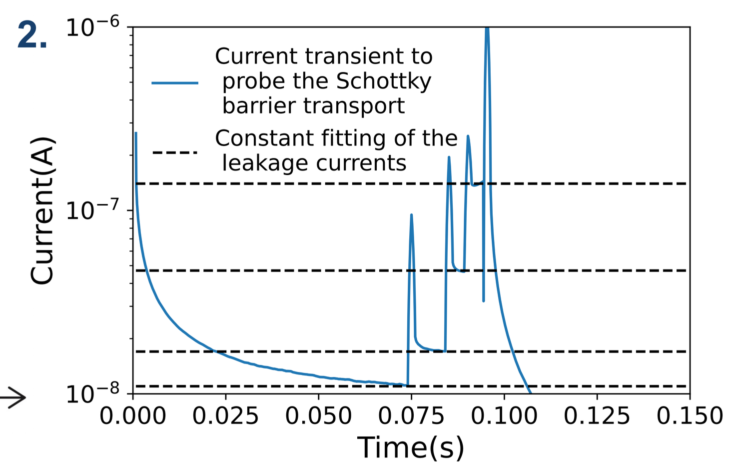
1. Conduction band minimum (CBM) including all the potential conduction-limiting transport mechanisms.
2. Estimation of the current density through the TaO_x barrier with a newly presented trap assisted tunneling (TAT) model shows that the **TaO_x barrier is not current limiting**
3. Standard transport analysis shows tunneling through Pt/a-STO barrier is current-limiting but cannot explain the observed behavior.
4. Model fittings fail to match both switching and tranport measurements

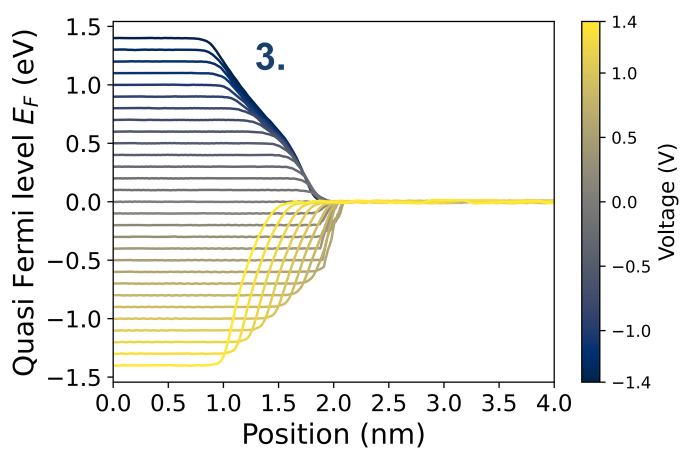
No here considered transport mechanism can explain the measured current-voltage relation with realistic parameter

Consideration trap based electron exchange effects

The standard measurement and fitting approach does not work for transport study



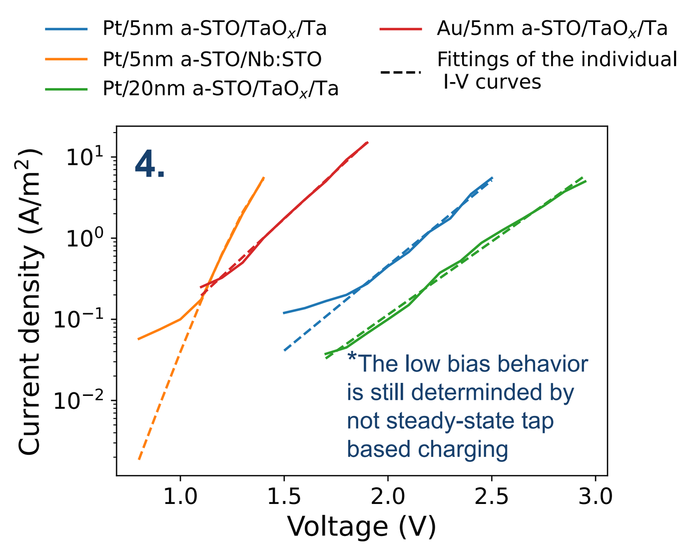




1. Schematic representation of electron trap exchange mechanisms via tunneling or thermal exchange. The ionized trap density follows the differential equation:

$$\frac{dD_t(x,\phi_t,t)}{dt} = \frac{1}{d\phi_t}\left(R_{out,\mathrm{SC}} + R_{out,\mathrm{metal}} + e_n - R_{in,\mathrm{SC}} - R_{in,\mathrm{metal}} - c_n\right)$$

2. Time dependent current response of electron trap exchange dynamics and corresponding steady-state current under a sequence of increasing applied biases
⟹**Accurate steady-state I-V data can only be obtained by this method**



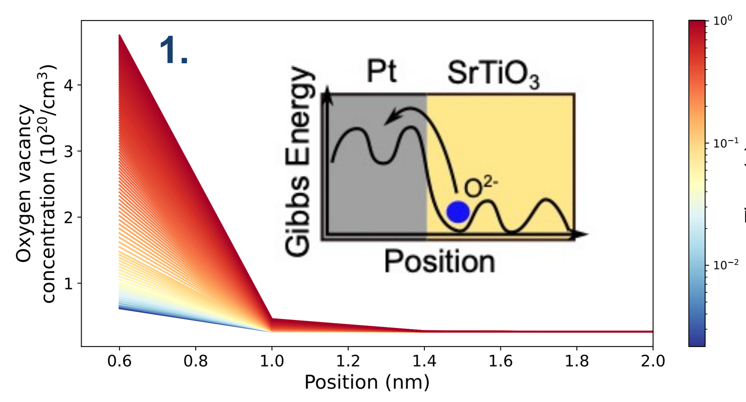
3. Under steady-state conditions, the electron concentration - controlled by trap exchange - can be represented by the voltage dependent **quasi-Fermi level determining electron transport through the Schottky barrier.**

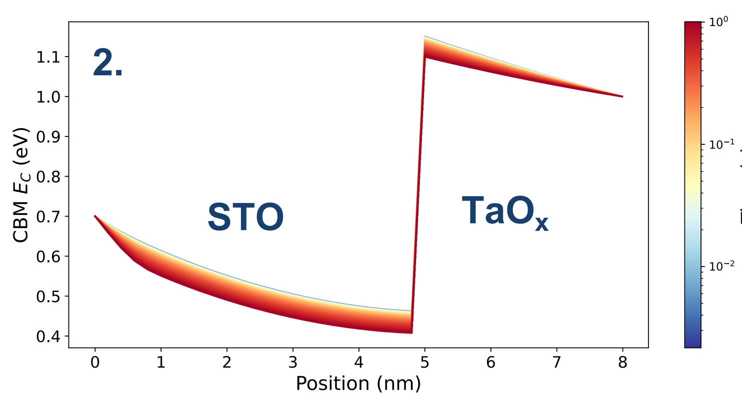
4. Only Tsu-Esaki tunneling conduction including the shape of the quasi Fermi level can describe the I-V relation

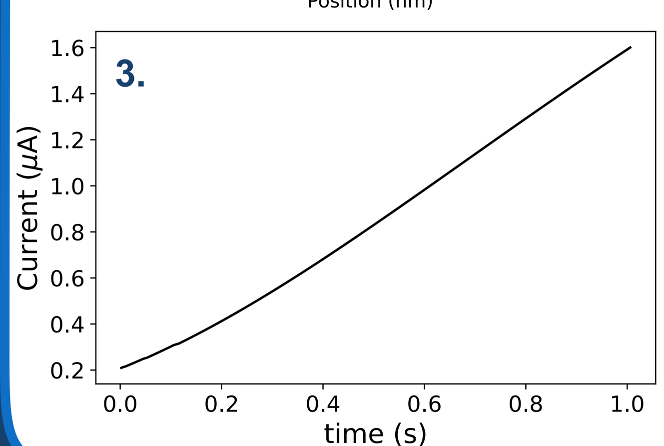
Ionic model : Understanding switching based on Oxygen vacancy migration

Semi-analytical ion migration model

First model explaining switching for all type 1 memristive devices





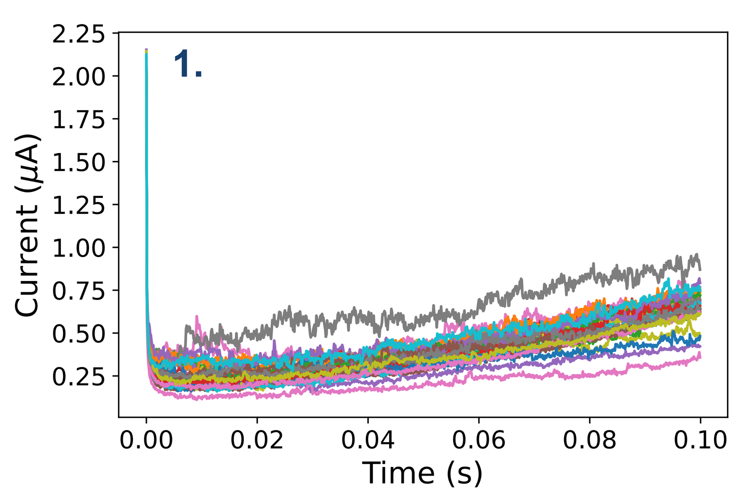


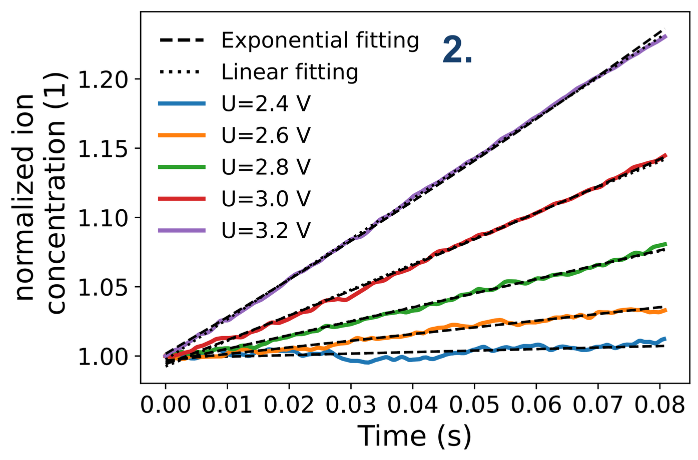
We developed a rigorous ion migration model through the Gibbs Free energy by solving a system of differential equations[2,3].

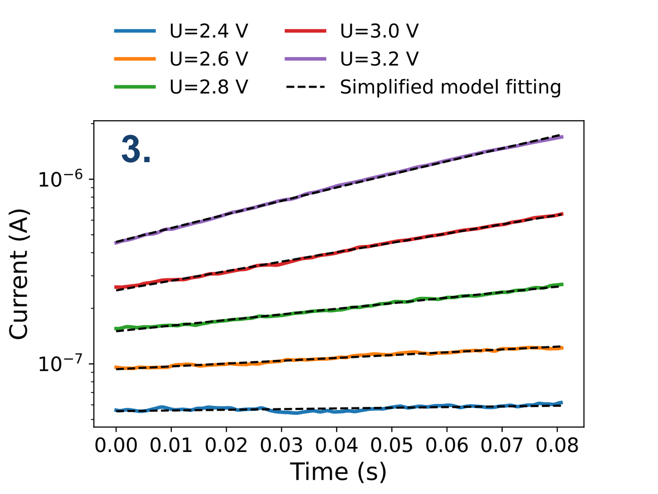
1. Time dependent Oxygen vacancy concentration under an applied forward bias, showing **Oxygen being extracted at the Pt/a-STO interface[4].**
2. Modulation of the CBM with time due to the increased oxygen vacancy concentration. The **TaO_x acts as a protective layer limiting the electric field in the a-STO.**
3. The modulation of the Pt/a-STO barrier leads to a **modulation of the tunneling current and switching.**

[1] D. V Christensen et al., Neuromorph. Comput. Eng. 2, 022501, 2022.
[2] J. Hellwig et al., Adv. Electron. Mater. 10.12, 2400062, 2024
[3] S. Menzel et al., Adv. Funct. Mater. 21, 4487-4492, 2011
[4] D. Cooper et al., Adv. Mater. 29, 1700212, 2017

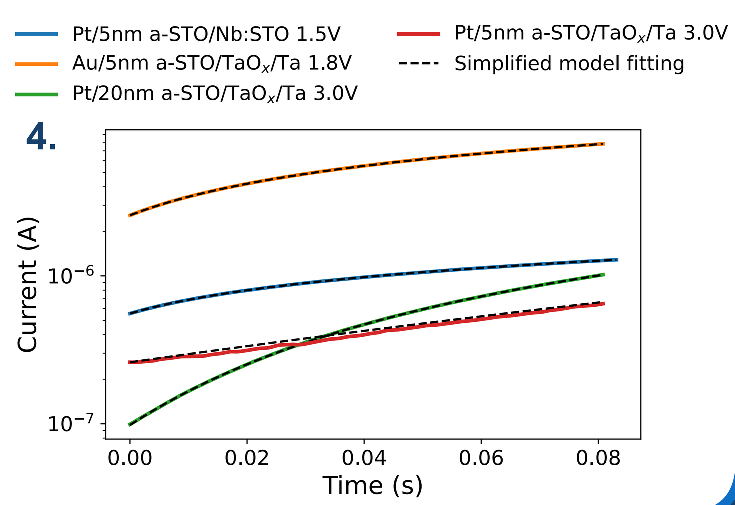
Simplified model for fitting the measured switching behavior







1. Measured switching I-t transients for U=3.0 V applied to the device.
2. Using averaged switching transients and the quasi-Fermi–based transport model, we determine the trap concentration via a simplified single-rate switching fit.
3. The fitted concentration and quasi-Fermi including transport model predict the I–t switching transient, enabling comparison with measurements.
4. **The I-t switching transients match the measurements with reasonable parameters ⟹ Models are accurate**



Summary and Outlook:

- Explained the electron transport by including the shape of the quasi–Fermi level being determined by trap based electron exchange effects.
- Explained switching by the first rigorous ion migration model also applicable for type 1 memristive devices.
- The model allows insights into the **accurate estimation of currents, read-out times and switching times** enabling predictions of the device performance and **compact modeling.**
- It also provides insights into **device functionality** and **parameter extraction for material and device optimization.**

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