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ENERGIZE

Energy-efficient Neuromorphic 2d Devices And Circuits For Edge AI Computing

ENERGIZE – EU-ROK collaborative project to enable energy efficient neuromorphic two-dimensional devices for edge computing

Dmitry Chigrin, AMO GmbH, Aachen, Germany

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NRF National Research Foundation of Korea

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Sogang University

Sungkyunkwan University

EPFL

AMO

Gwangju Institute of Science and Technology

Korea University

Università di Pisa

Universidad de Granada

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Energy-efficient Neuromorphic 2d Devices
And Circuits For Edge AI Computing

What

Expertise

Materials, Devices and Circuit Modelling

UNIVERSIDAD DE GRANADA

UNIVERSITÀ DI PISA

High-quality Material Growth

EPFL

Advanced Device Fabrication

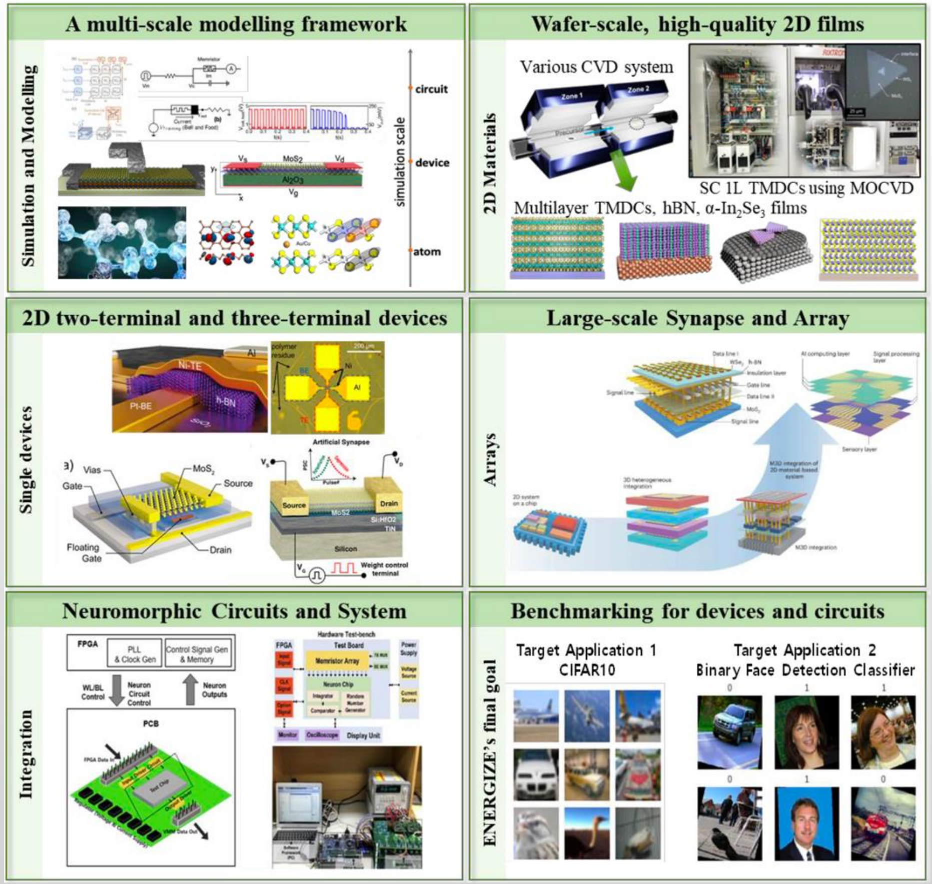
EPFL

AMO

KOREA UNIVERSITY

Cutting-edge Circuit Design

SOGANG UNIVERSITY



2D Devices and Circuits for edge AI computing

ENERGIZE's vision is to leverage the potential of **wafer-scale, 2D materials-based neural networks** to develop **energy-efficient neuromorphic devices and circuits for edge AI computing**.

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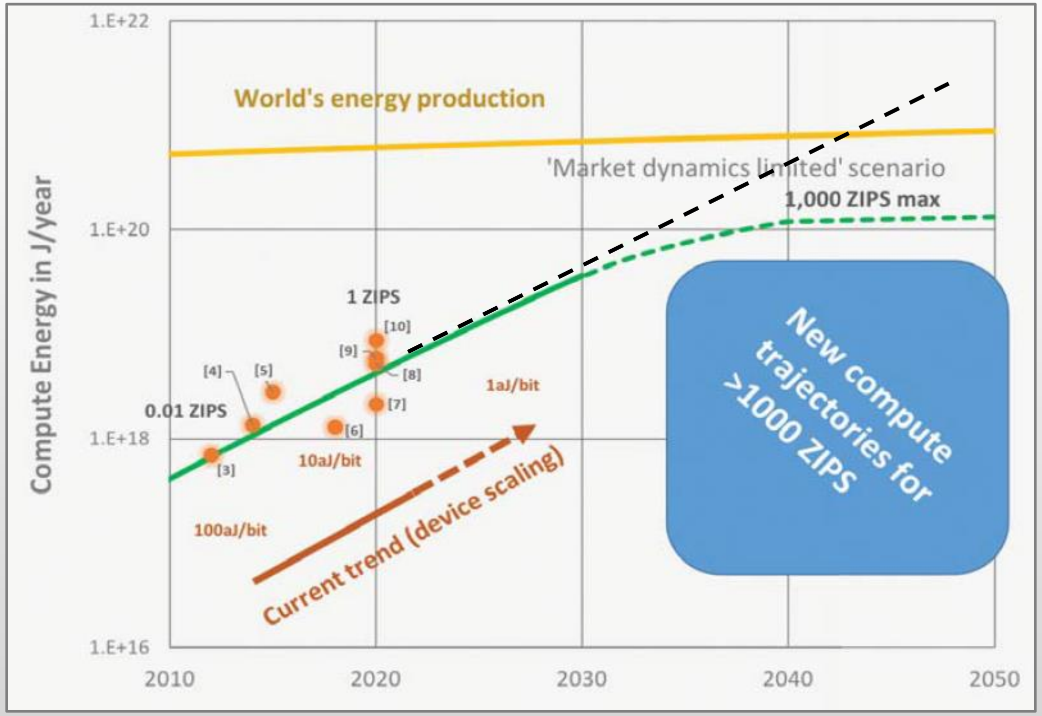
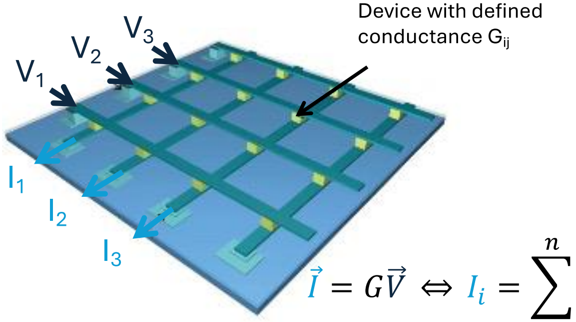
Why

Machine Learning and Artificial Intelligence need new hardware → Neuromorphic Computing



Source: SRC Decadal Plan, 2020

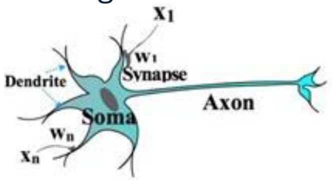
Computing in memory



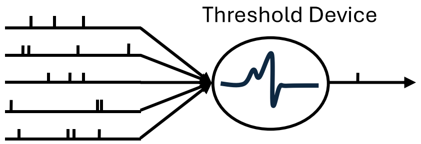
$$\vec{I} = G\vec{V} \Leftrightarrow I_i = \sum_{j=1}^{n} G_{ij}V_i$$

Adapted from:
Mehonic *et al.*, Advanced Intelligent Systems. 2, 2000085 (2020).

Biological Neural Network

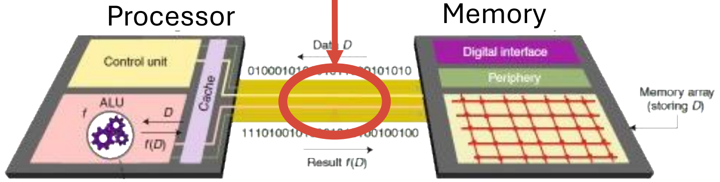


Spiking Neural Network



Adapted from:
X. Zhang *et al.*, physica status solidi (a). 215, 1700875 (2018).

Von-Neumann bottleneck



Sebastian et al., Nat. Nanotechnol., 1–16, 2020

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Who

- AMO GmbH (AMO)
- Universita di Pisa (UNIPI)
- Universidad de Granada (UGR)
- Ecole Polytechnique Federale de Lausanne (EPFL)
- Sungkyunkwan University (SKKU)
- Korea University (KU)
- Gwangju Institute of Science and Technology (GIST)
- Sogang University (SGU)

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Simulation and Modelling

UNIVERSITÀ DI PISA

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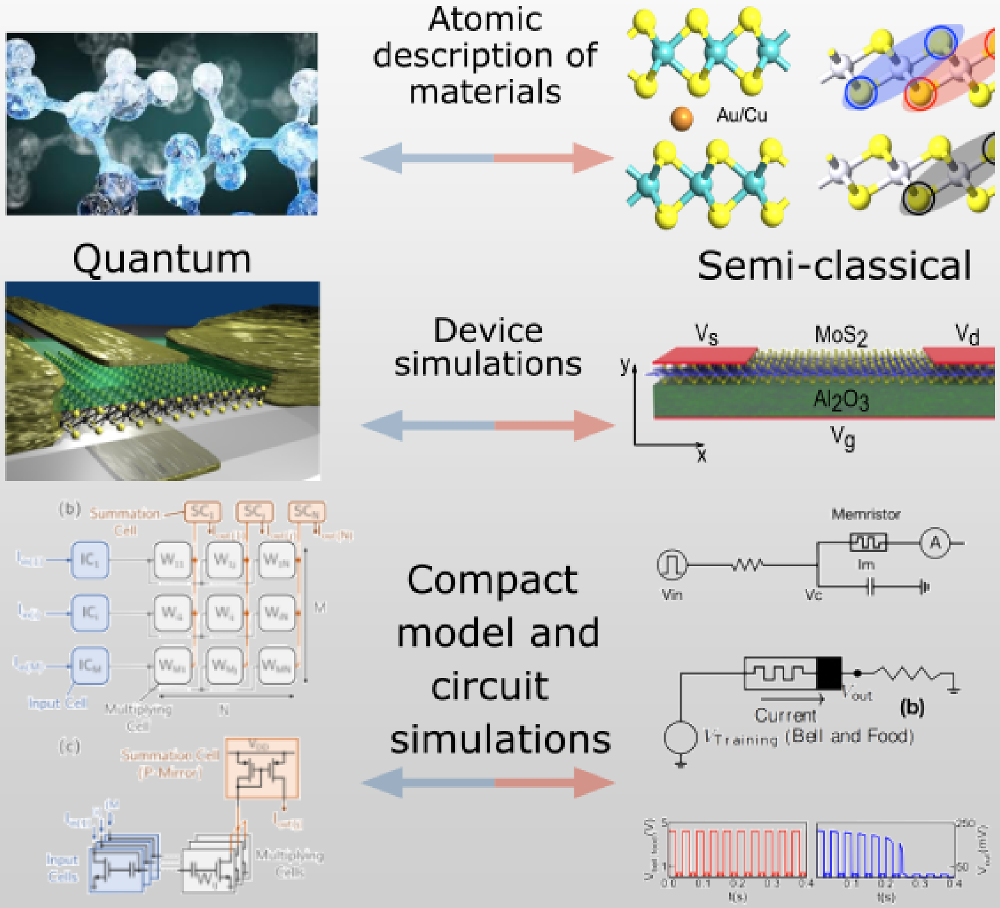
Objective:

- To provide a multiscale simulation approach for the study of devices for neuromorphic electronics, spanning from atomistic to large scale circuit emulations.

Partners:

- **UNIPI**: Atomistic **simulations** of 2DMs, multiscale transport simulation of devices up to circuit level.
- **UGR**: **Simulation** of 2DMs, devices and circuits, compact modelling of devices and validation.



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2D Materials

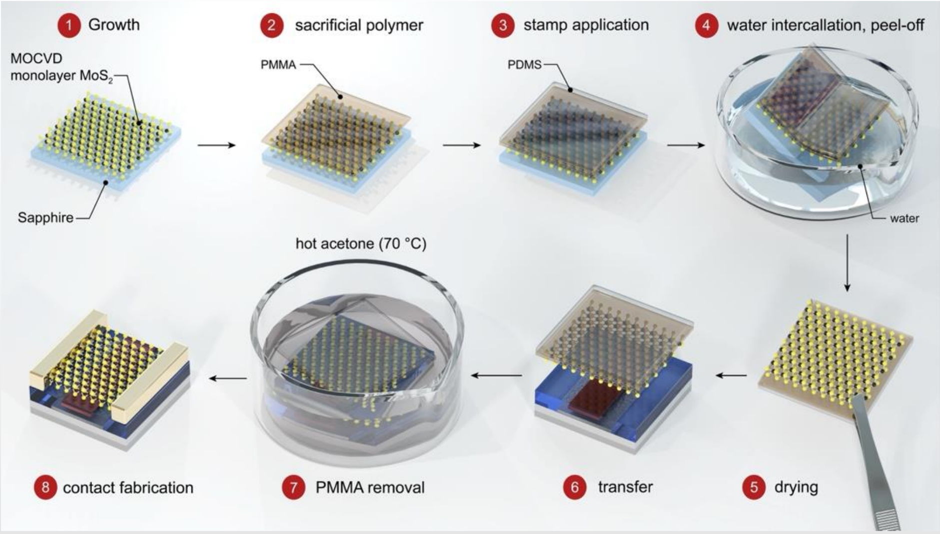
Objective:

- To develop wafer-scale growth of multilayer 2DMs, including semiconducting TMDCs, insulating hBN, and ferroelectric α-In2Se3, for neuromorphic devices and circuits.

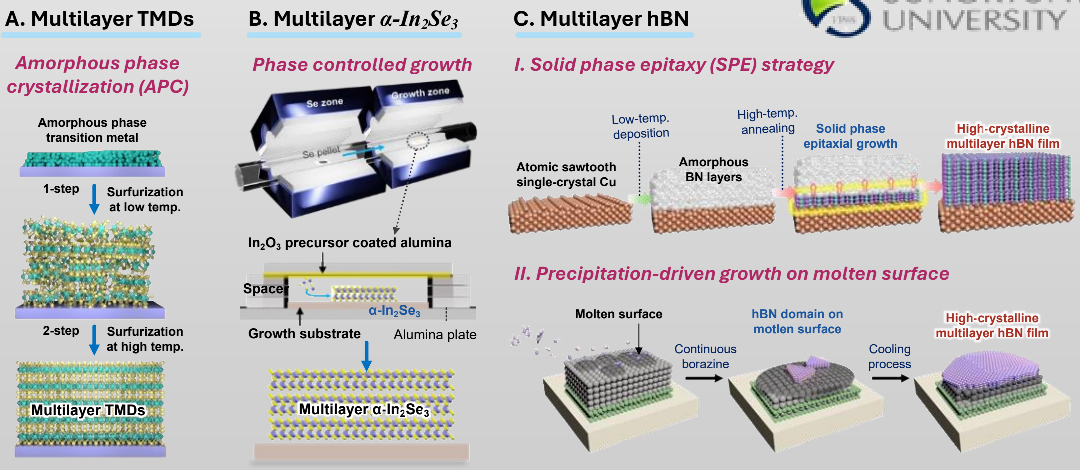
Partners:

- **EPFL:** Devices and circuits **fabrication** based on 2DM, electrical and optical **characterization**
- **SKKU:** Wafer-scale, high-quality **2DMs growth**, qualitative and quantitative characterization of the materials, three or more terminal **memtransistor array** and its application for neural network.

MOCVD growth & transfer



EPFL



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2D-based Devices

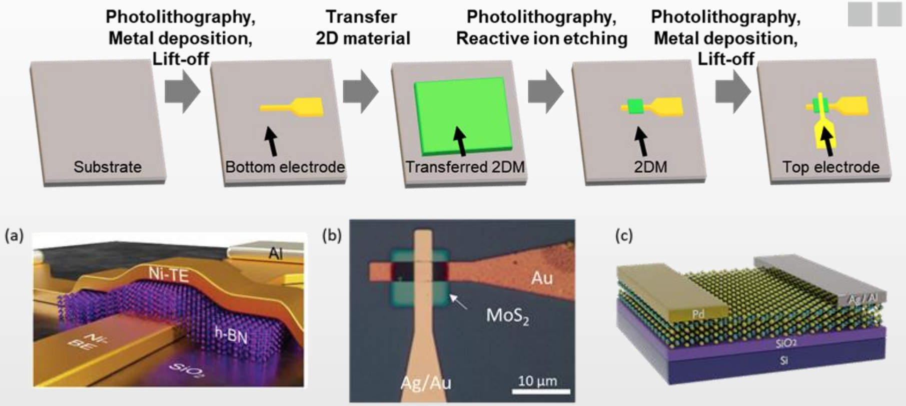
Objective:

- To establish reliable fabrication and characterization processes for 2D two-terminal and three-terminal devices.

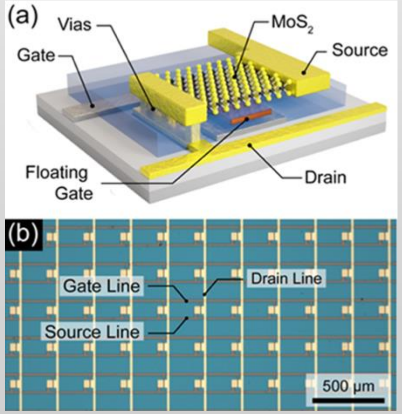
Partners:

- **AMO**: **Fabrication** of devices based on 2DMs, 2DM film deposition, material and device **characterization**
- **EPFL:** Devices and circuits **fabrication** based on 2DM, electrical and optical **characterization**

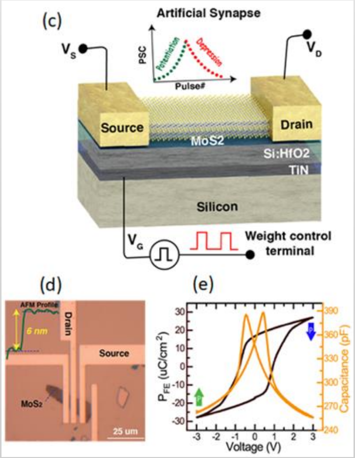
2D two-terminal memristive devices



2D three-terminal FGFET



2D three-terminal FeFET



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Large-scale Synapse Array

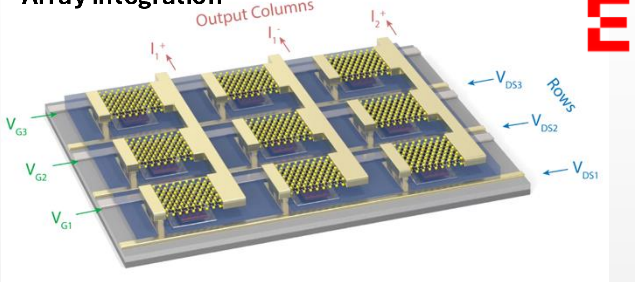
Objective:

- To develop 2D two-terminal and three-terminal arrays with reliable performance.
- To implement a neuromorphic system that integrates 2DM-based neurons and synapses

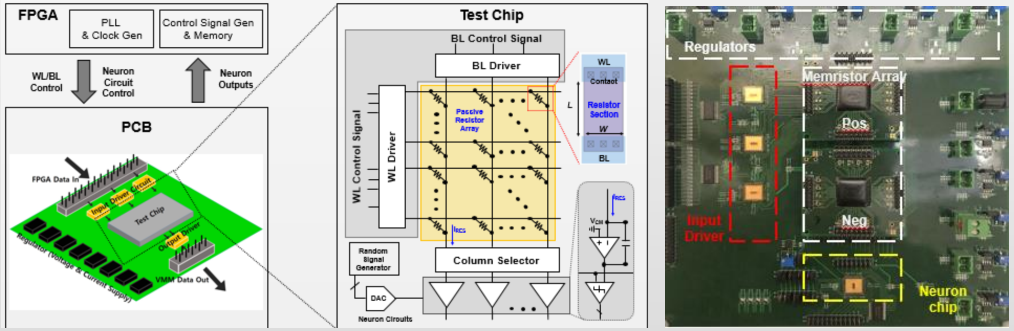
Partners:

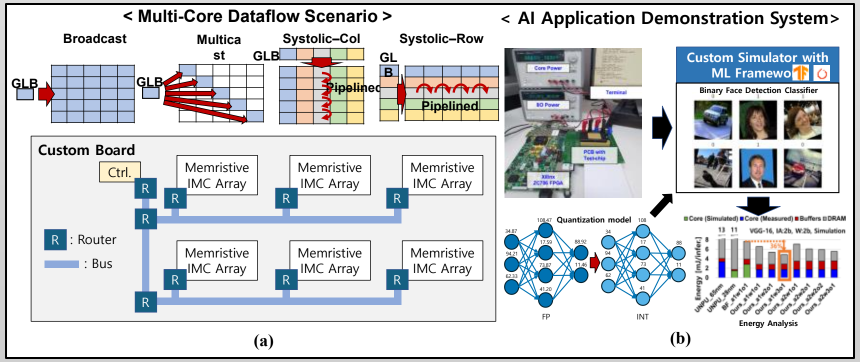
- **KU**: Non-volatile memory, **memristor**, memristive **array**, reservoir array, 1D/2D **heterojunction** device.
- **GIST**: Neuromorphic **circuits and systems design** employing memristive devices.
- **SGU**: **Neural network** compression, digital circuit design, software-to-hardware mapping, **software-hardware co-optimization**.
- **EPFL & SKKU**

Array integration



Synapse device based VMM Circuit Design





Large-scale synapse array

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Highlights

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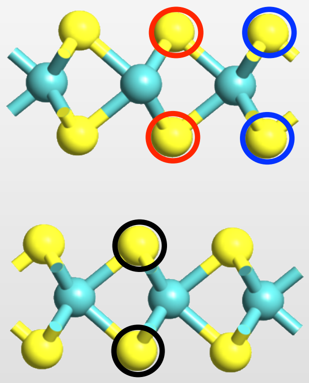
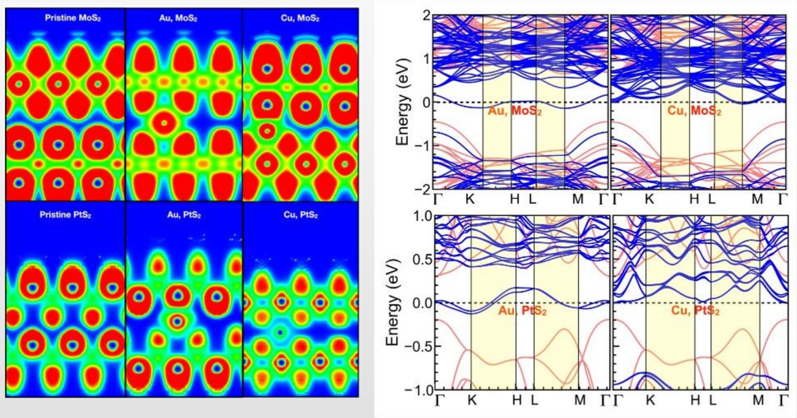
Atomistic simulations of of Point Defects and Grain Boundaries in Resistive Switching Mechanisms of 2D Transition Metal Dichalcogenides

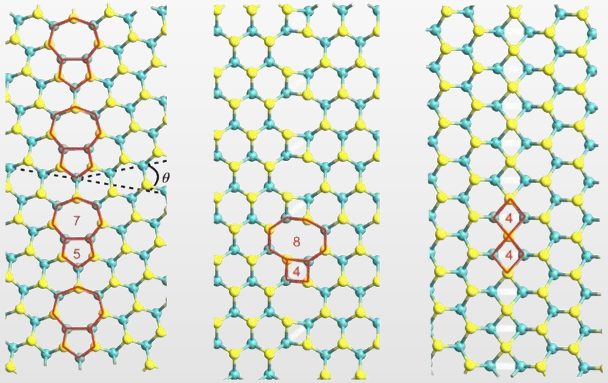
Vacancy Filament



Metal Filament



Grain Boundaries

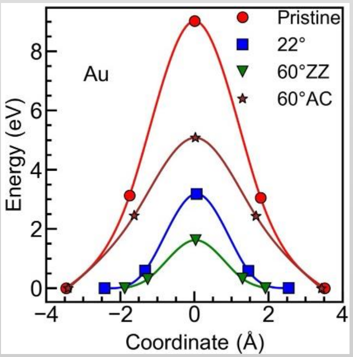


22⁰ 60⁰ Zig-Zag 60⁰ Armchair

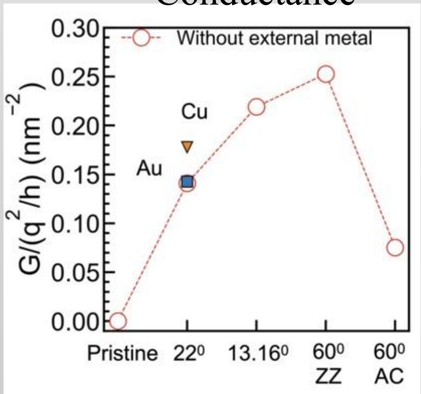
Intrinsic Vacancies alone are insufficient for significant conductivity change; metal atom intercalation is crucial

Trade-off: Grain boundaries can lower switching voltage but also reduce the switching ratio

Diffusion Barriers



Conductance



M.D. Ganeriwala *et. al., ACS Applied Nano Materials (2024), 7(21), 24857-24865*
M.D. Ganeriwala *et. al., Nanoscale (2025) (accepted)*

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Highlights

UNIVERSIDAD DE GRANADA

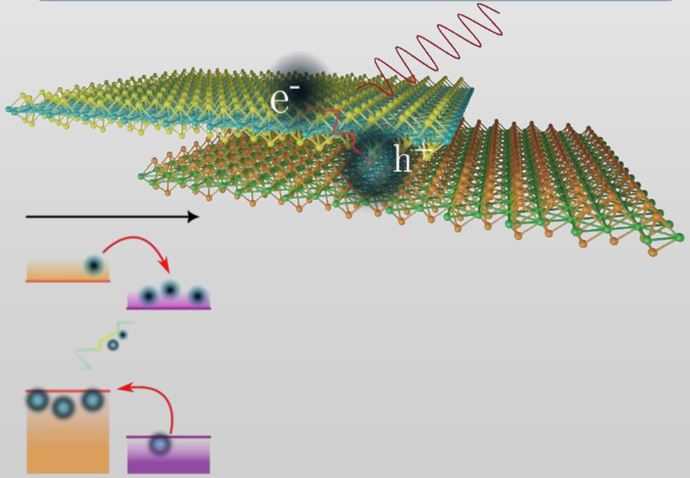
In-house tools for mesoscopic numerical simulations (contact: agodoy@ugr.es)

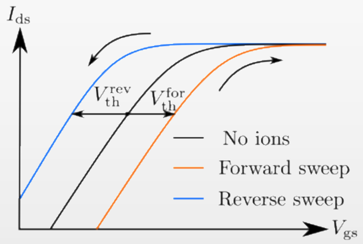
$$\vec{\nabla}\cdot\left(\varepsilon\vec{\nabla}V\right) = -\rho$$

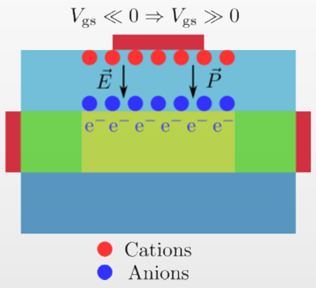
$$\vec{\nabla}\cdot\vec{J}_n = \vec{\nabla}\cdot\left[q\mu_n n\vec{\nabla}E_{F,n}\right] = +q\frac{\partial n}{\partial t}$$

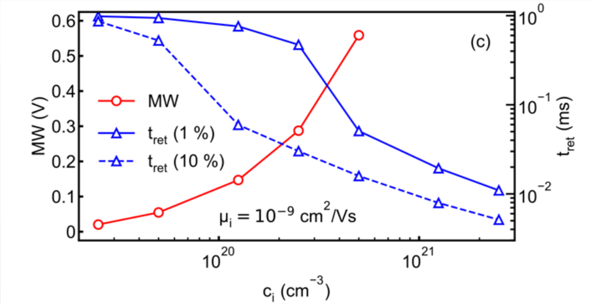
$$\vec{\nabla}\cdot\vec{J}_p = \vec{\nabla}\cdot\left[q\mu_p p\vec{\nabla}E_{F,p}\right] = -q\frac{\partial p}{\partial t}$$

$$\vec{\nabla}\cdot\vec{J}_i = \vec{\nabla}\cdot\left[-z_i q D_i e^{-s_i\Phi}\vec{\nabla}\left(c_i e^{s_i\Phi}\right)\right] = -z_i q\frac{\partial c_i}{\partial t}$$



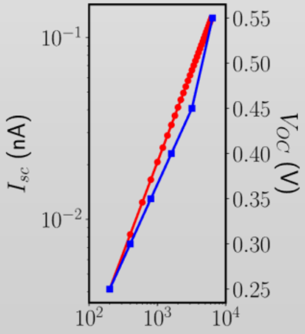


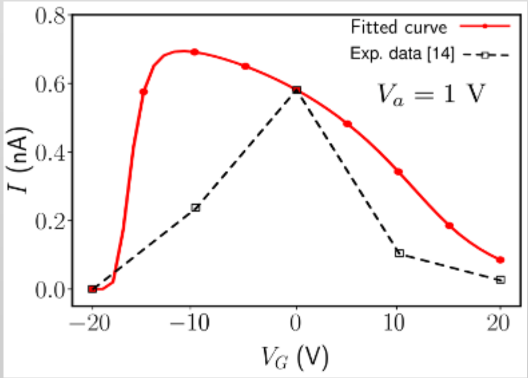




In-house simulator for coupled ionic-electronic simulations. Showing the working of ferroelectric-like device as memristor

J. Cuesta-Lopez et. al. J. Appl. Phys. 2024, 136 (12), 124501





In-house simulator to analyze 2DM-based heterojucntion as photodectors

A. Diaz-Burgos et. al. ESSERC. 2024

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Highlights

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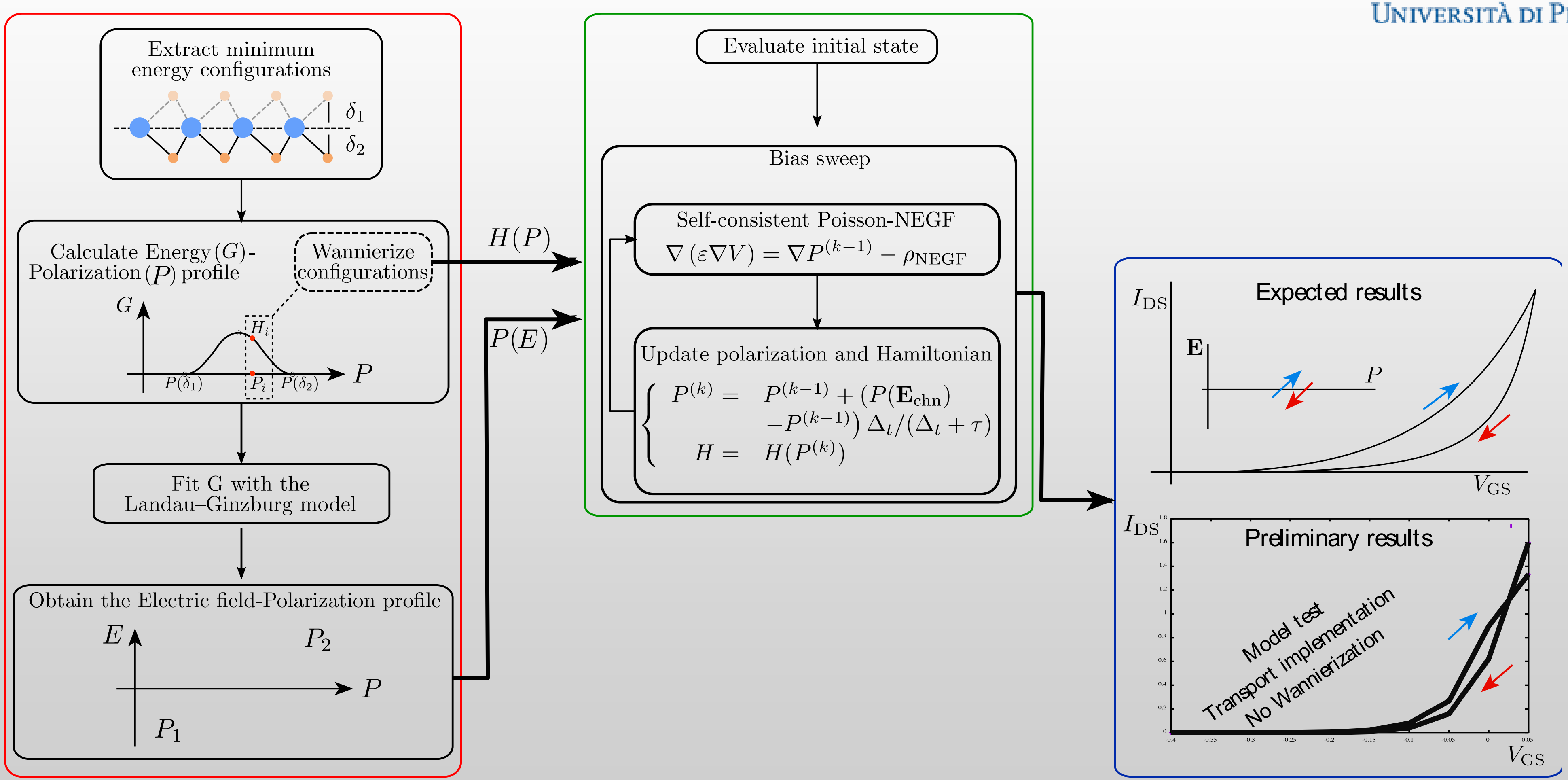
Fully multiscale simulator for Ferro-eletrics 2D-based devices



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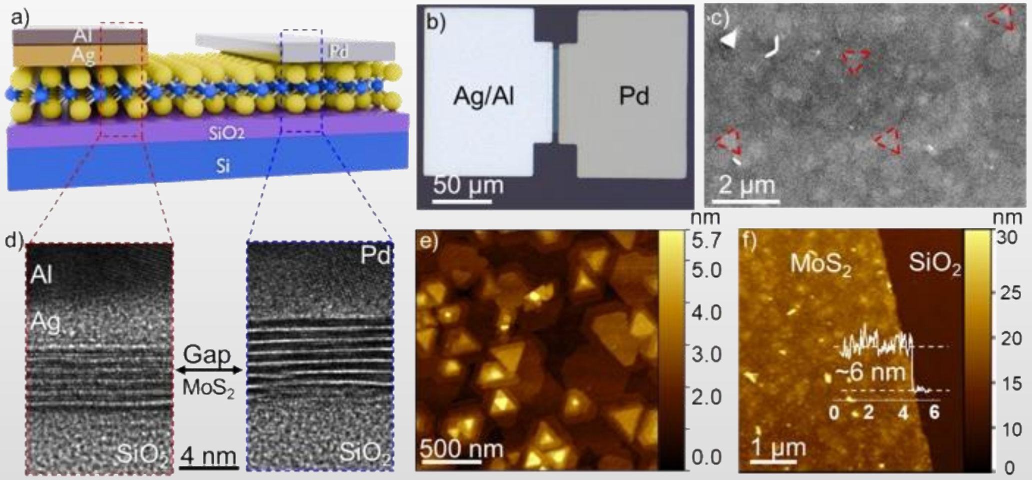
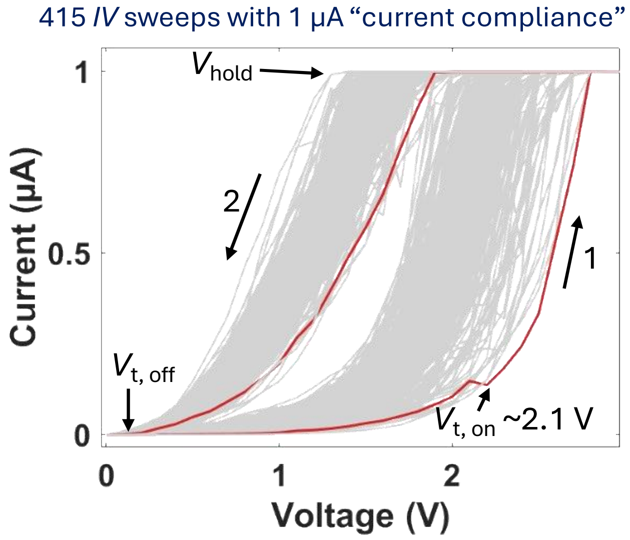
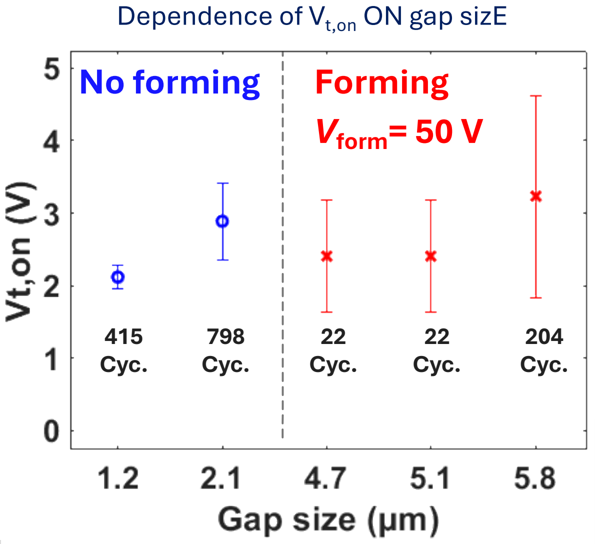
Highlights

Ion Transport in lateral layered MoS2



As-grown MOCVD MoS_2 — MoS_2 after transfer to SiO_2/Si





- Lateral Pd-MoS_2-Ag/Al memristors
- Variation of the gap size

- Forming-free operation for gaps < 2 μm

Jimin Lee *et al.*, *IEEE EDTM 2025* (Poster WP-19)
Cruces *et al.*, Small Science, 2025

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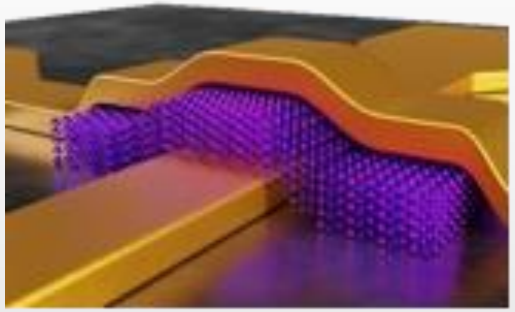
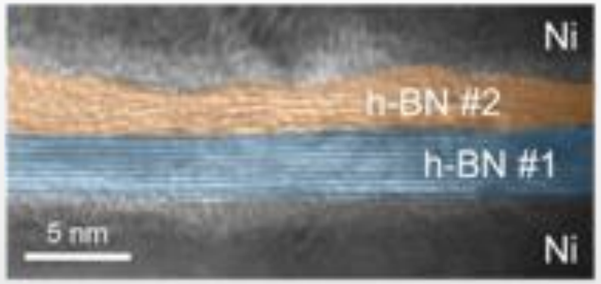
Highlights

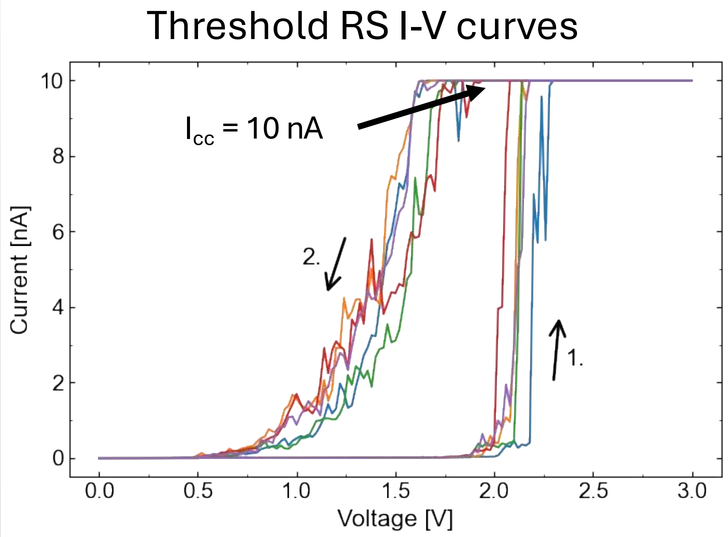
AMO

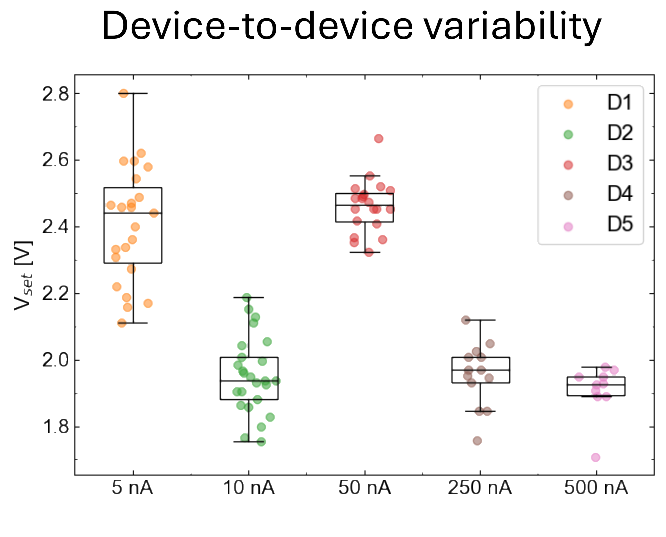
Threshold Resistive Switching in hexagonal Boron Nitride (h-BN)





- Threshold RS with low currents in HRS
- DC endurance of ca. 600 cycles
- Mean V_{set} = 1.96 ± 0.10 V





Völkel *et al.*, Adv. Funct. Mat. 2024
Völkel *et al.*, IEEE SNW, 2021

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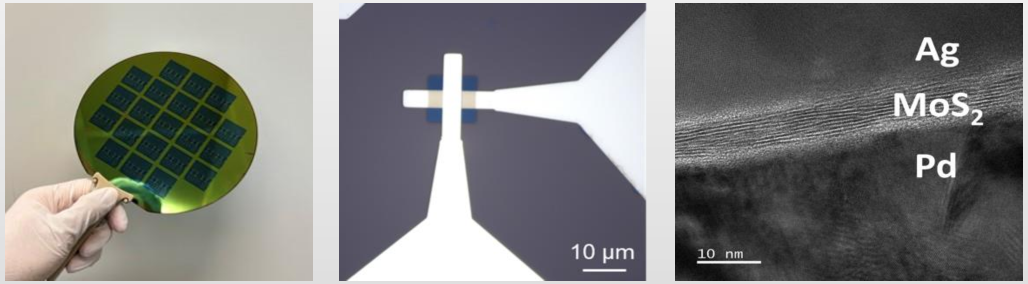
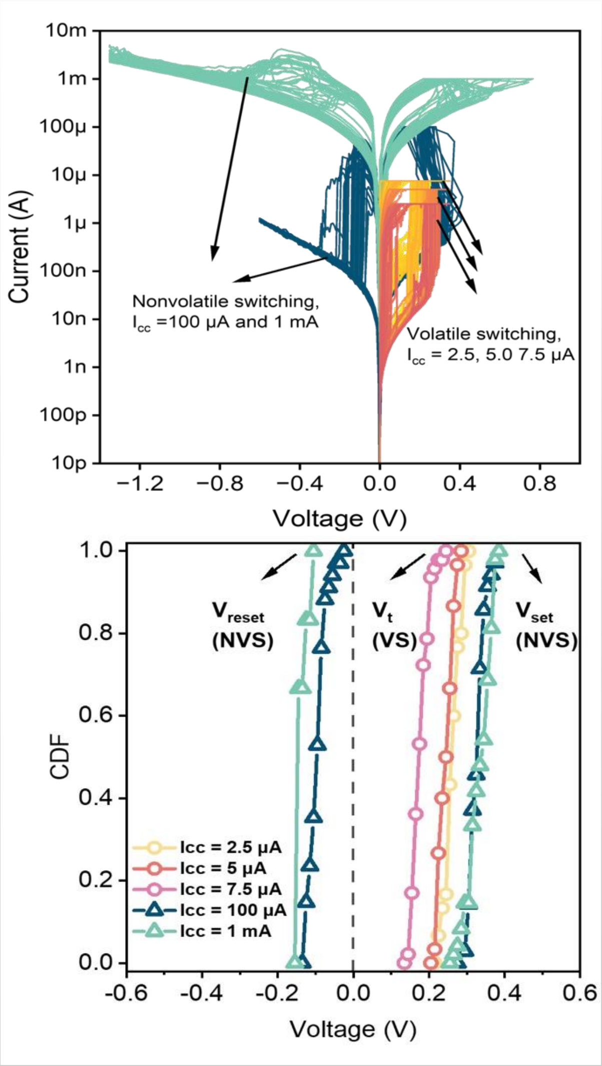
Wafer-scale MOCVD MoS2 Memristors



- Wafer-scale fabrication of MOCVD MoS_2-based memristors
- Back and top electrodes patterned via e-beam evaporator and lift-off
- Wet tranferred MoS_2 patterned via RIE etching



- Threshold and nonvolatile behavior depending on current compliance I_{cc}
- Two stable nonvolatile regimes
- Low voltage threshold, set and reset voltages within ± 1 V

Fa *et al.*, MemriSys 2024

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Thank you

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