NOVA SCHOOL OF
SCIENCE & TECHNOLOGY

DEPARTMENT
OF MATERIALS SCIENCE

CENIMAT
CENTRO DE INVESTIGAÇÃO DE MATERIAIS

i3N
INSTITUTO DE NANOESTRUTURAS, NANOMODELAÇÃO E NANOFABRICAÇÃO

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Fundação para a Ciência e a Tecnologia
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Design of new intelligent materials and devices using nanotechnology

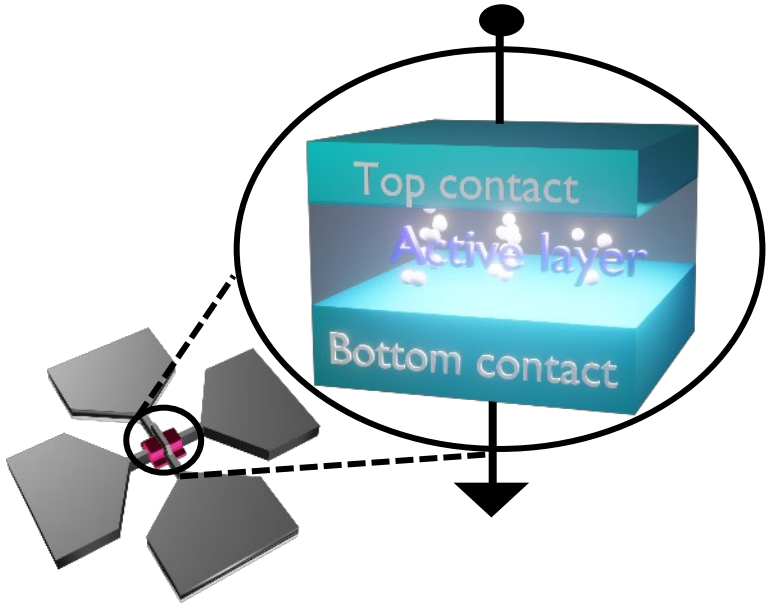
Asal Kiazadeh

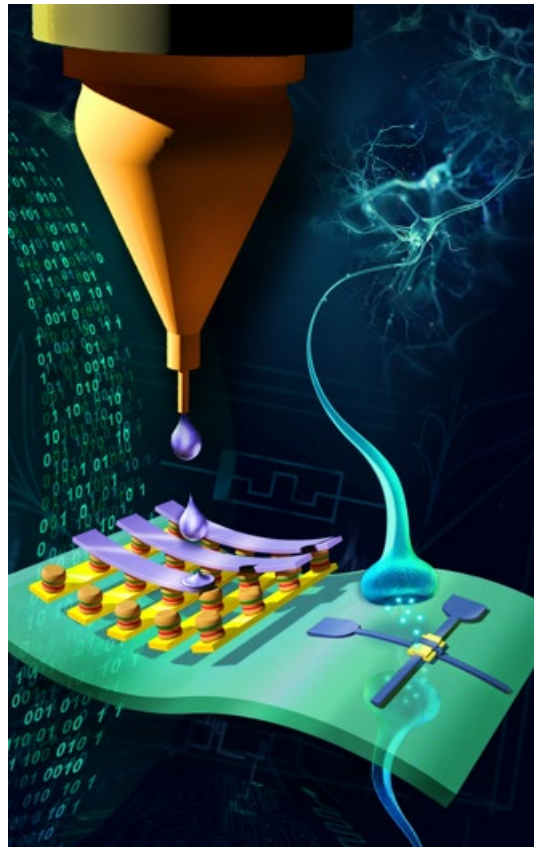
Outline

- Overview of nanotechnology
- Role of nanotechnology in communication applications

Case Studies at CENIMAT/I3N:

- Memristor as artificial synapses
- Memristors as RF switch





Adv. Mater. 2020, 2004328 (review article)

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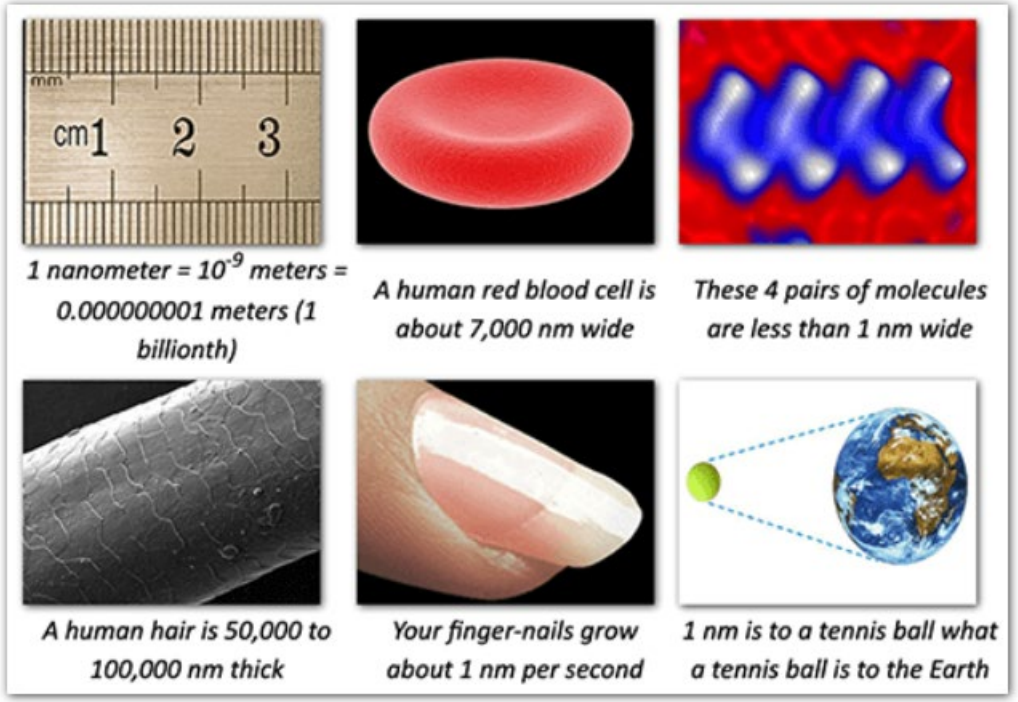
Nanotechnology in developing intelligent materials

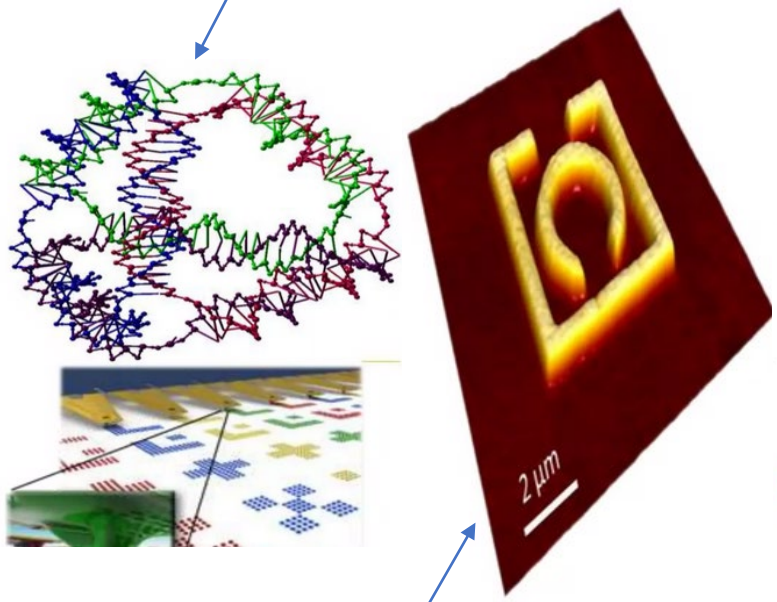
Nanotechnology is a branch of science and technology that deals with materials and devices at the nanoscale, typically involving dimensions less than 100 nanometers.

- A nanometer is one billionth of a meter.



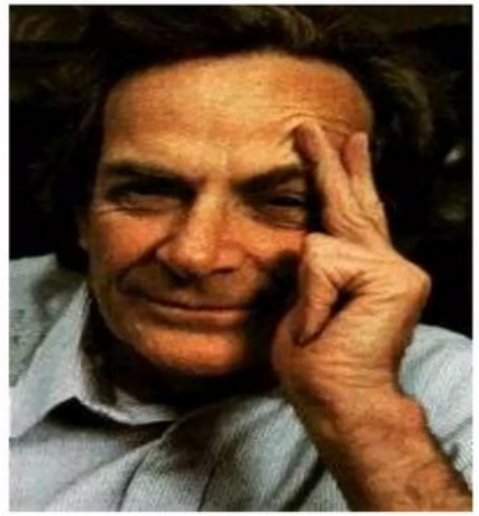
https://www.nanowerk.com/nanotechnology/introduction/introduction_to_nanotechnology_1.php

1. Bottom-up approach



2. Top-down approach

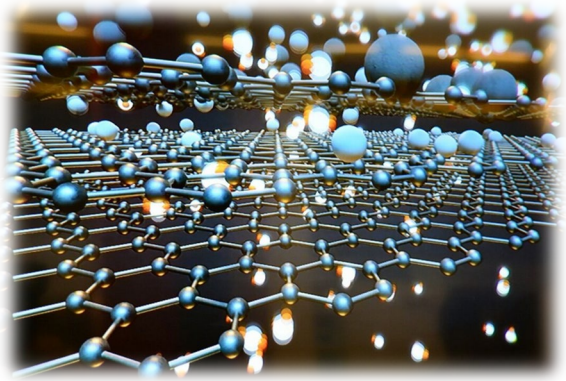
The concept was presented in 1956 by the famous professor of Physics Richard Feynman.

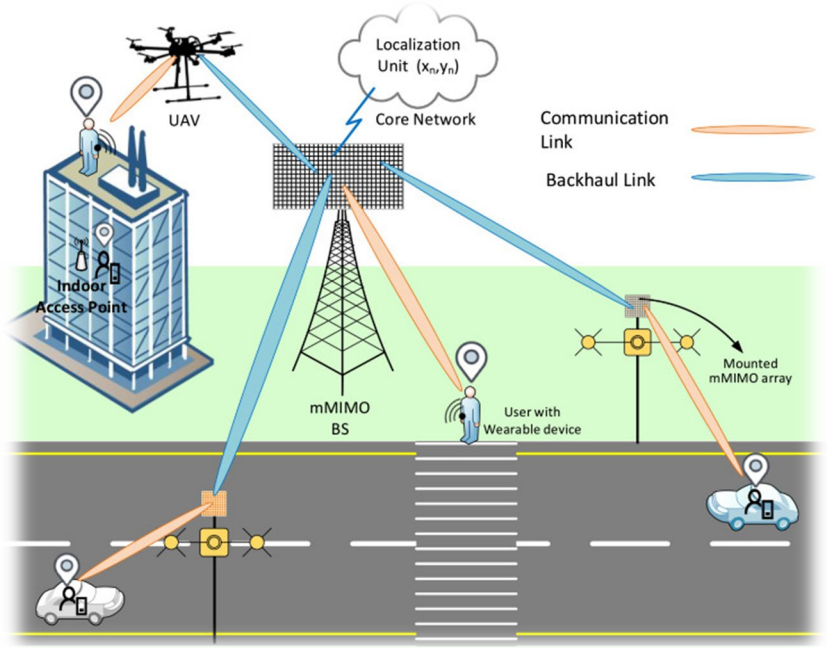


THERE'S PLENTY OF ROOM AT THE BOTTOM

Nanotechnology can provide several benefits to communication

- ❑ Miniaturization and Integration
- ❑ Enhanced Data Transfer Rates
- ❑ Intelligent Nanomaterials for Antennas
- ❑ Advanced Materials for THz Communication
- ❑ Energy-Efficient Devices
- ❑ Nano-sensors for Network Monitoring
- ❑ Smart Surfaces for Signal Enhancement
- ❑ Flexible and Wearable Devices,…





Massive MIMO, https://doi.org/10.1016/j.adhoc.2020.102353

Complex computations is involved in **M**ultiple **I**nput **M**ultiple **O**utput (**MIMO**) signal processing.

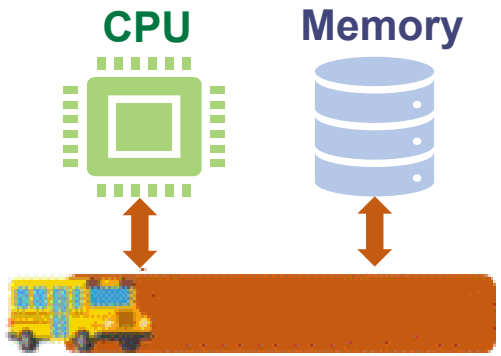
https://rbmigroupofinstitutions.wordpress.com/2021/08/31/

Power-efficient computation system

The cloud

Data centers

Von Neumann architecture and CMOS technology



Modern age AI

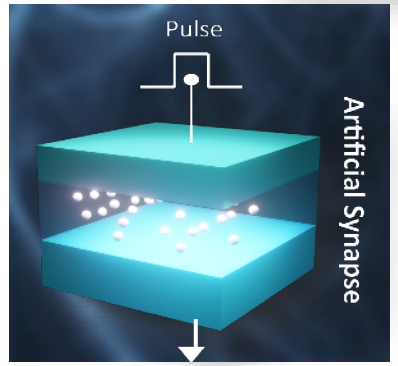
Latency issues
Privacy issues
Huge power consumption
Approaching scaling limits

Solution

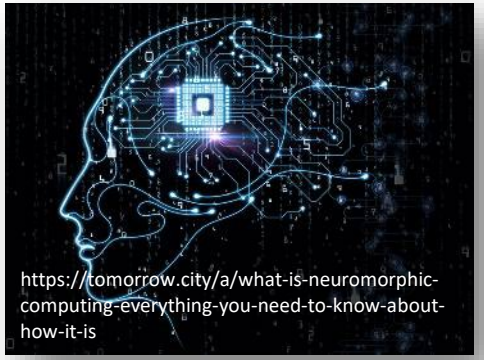
Next generation AI

Real time data analysis
In-memory computation
Power-efficient systems
High density information

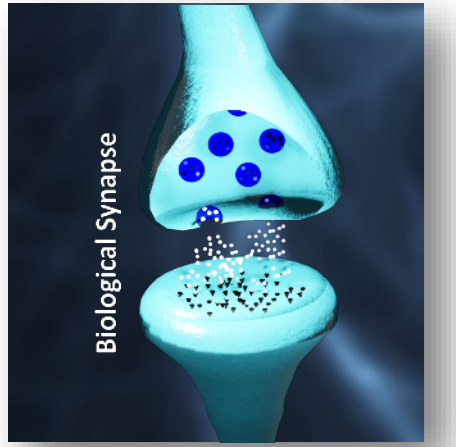
Memristor



Neuromorphic computing



Based on emulating biological neurons synapses



nature Vol 453|1 May 2008|doi:10.1038/nature06932

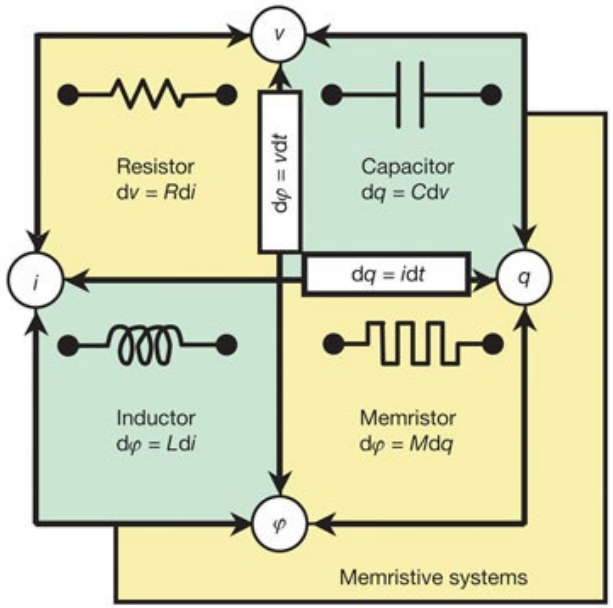
LETTERS

The missing memristor found

Dmitri B. Strukov[1], Gregory S. Snider[1], Duncan R. Stewart[1] & R. Stanley Williams[1]

It took about 40 years for the memristor to be implemented in a physical form!

Thanks to Nanotechnology



Leon Ong **Chua** is an American electrical engineer and computer scientist. He is a professor in the electrical engineering and computer sciences department at the **University of California, Berkeley**.

Richard **Stanley Williams** is research scientist in the field of nanotechnology and a Senior Fellow and the founding director of the Quantum Science Research **Laboratory** at **Hewlett-Packard (HP)**.

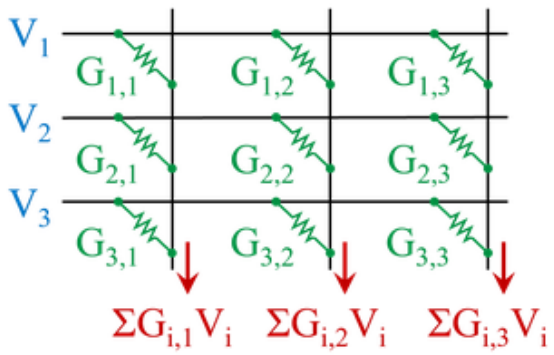
Analog MVM machine: Very energy efficient, fast and compact

Mathematical

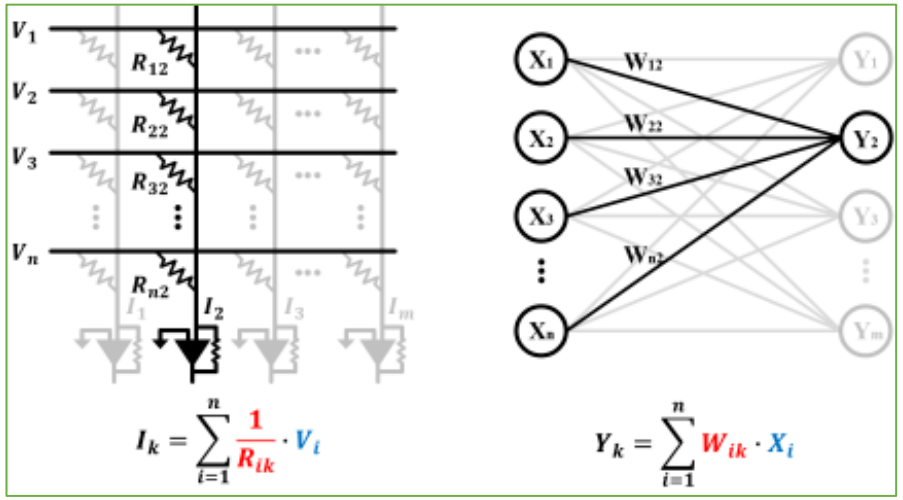
$$\mathbf{y} = \mathbf{W}\mathbf{x}$$

$$\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} \begin{bmatrix} W_{1,1} & W_{1,2} & W_{1,3} \\ W_{2,1} & W_{2,2} & W_{2,3} \\ W_{3,1} & W_{3,2} & W_{3,3} \end{bmatrix} = \begin{bmatrix} \Sigma W_{i,1}x_i & \Sigma W_{i,2}x_i & \Sigma W_{i,3}x_i \end{bmatrix}$$

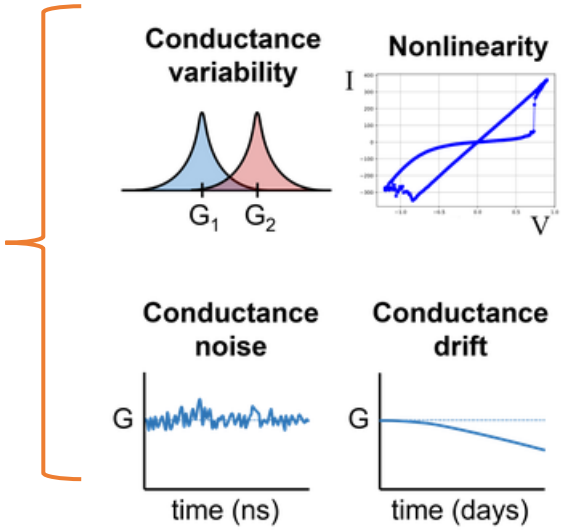
Electrical

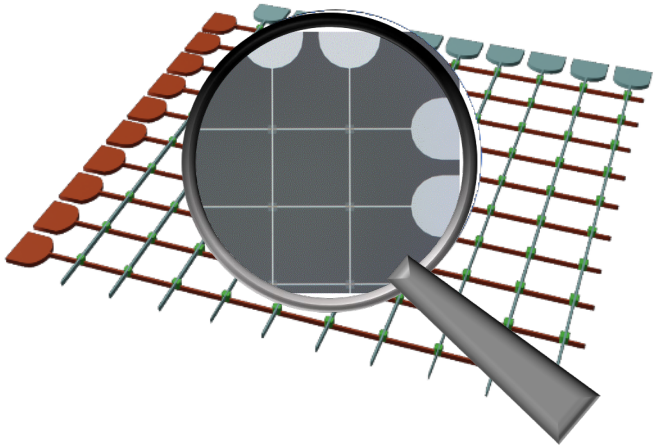


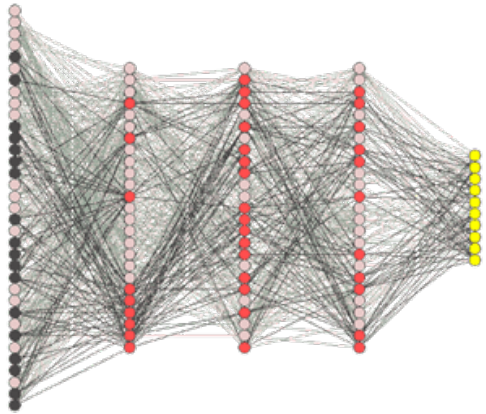
A physical system directly mapping the AI algorithm



Challenges of ANN hardware

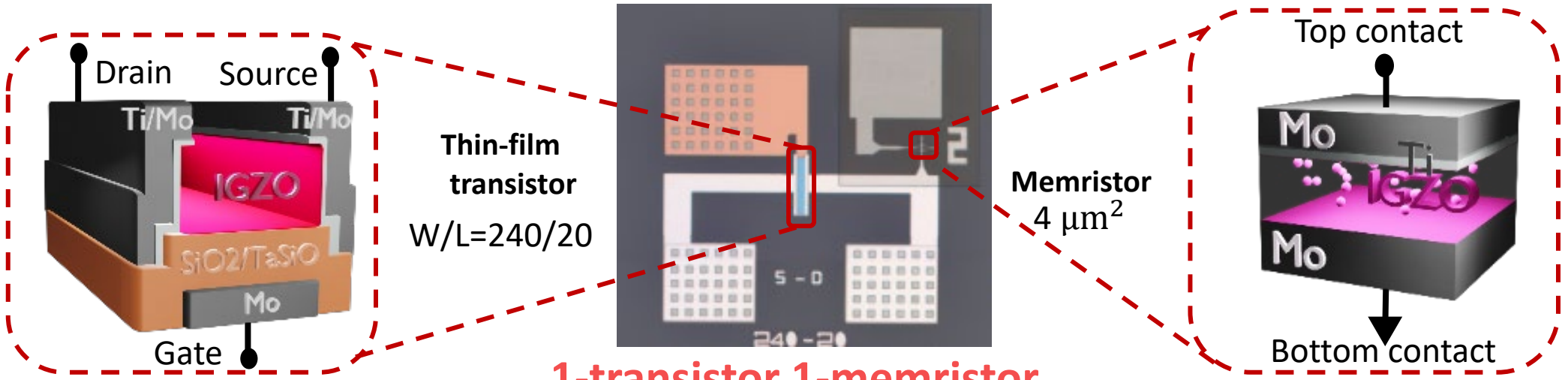






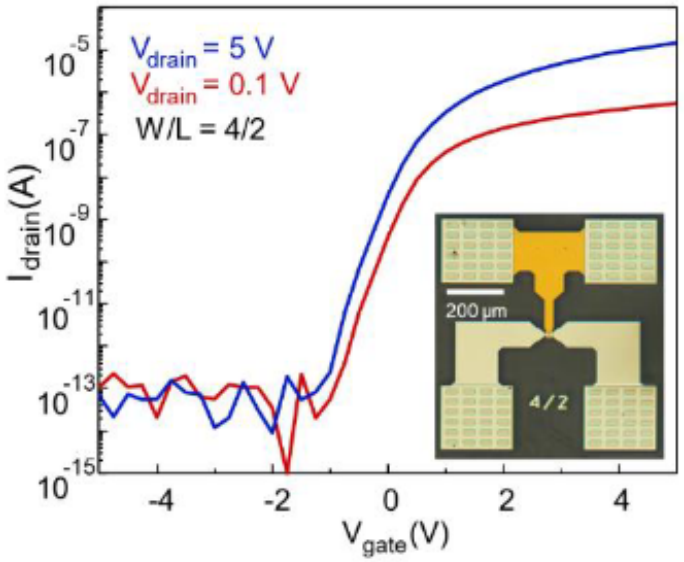
MVM: matrix vector multiplication
ANN: Artificial neural network

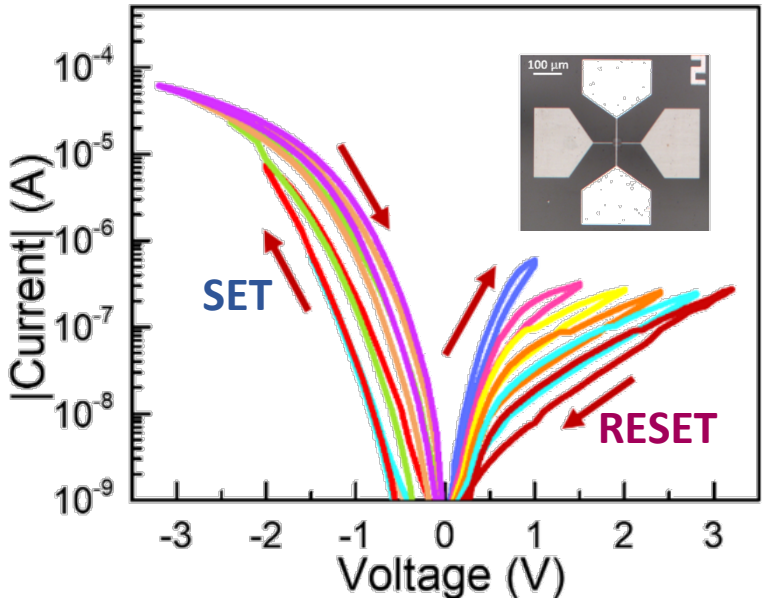
IGZO memristor devices & its integration



1-transistor 1-memristor

- TFT's S/D electrode is **directly connected** to memristor's top contact, All Mo electrodes
- Fabrication: **conventional clean-room techniques**: RF magnetron sputtering depositions and photolithography
- Optimization of layers for **compatibility** with both devices.

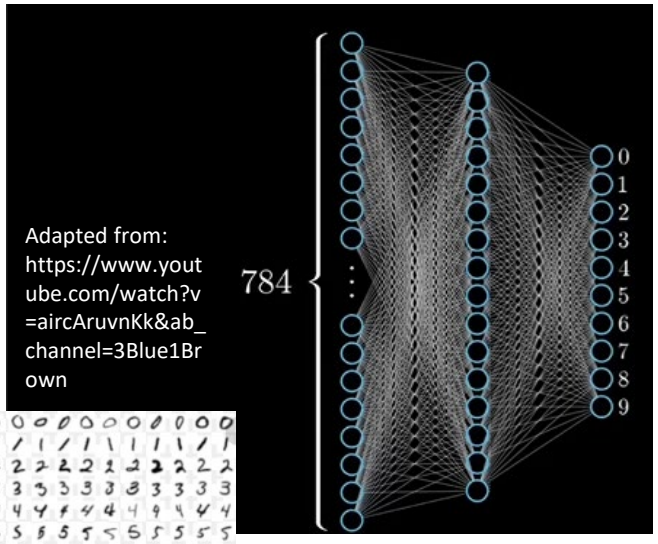


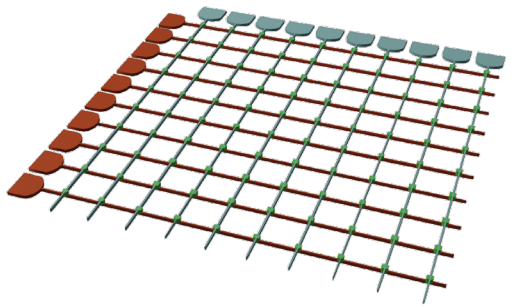


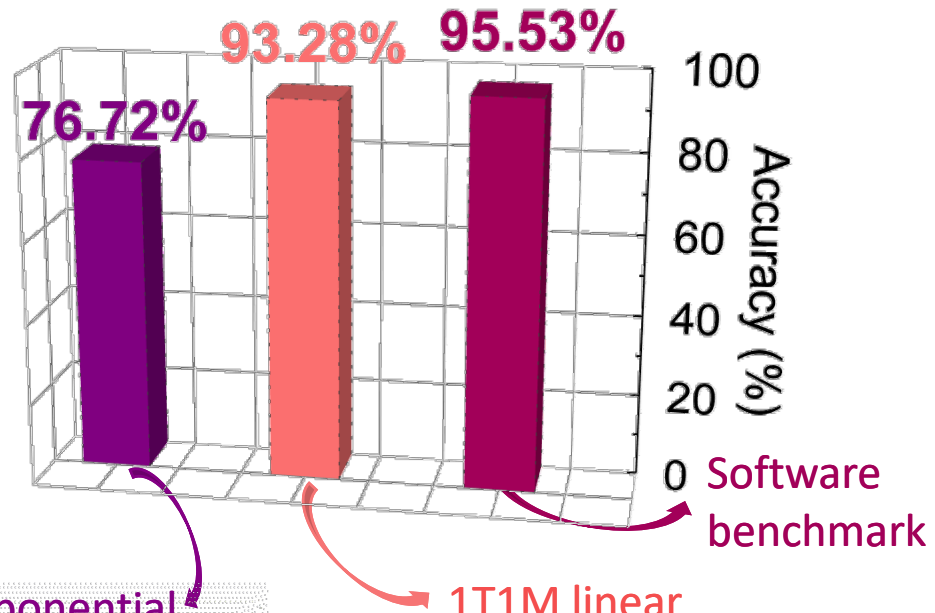
Adv. Electron.Mater.2022, 8, 2200642

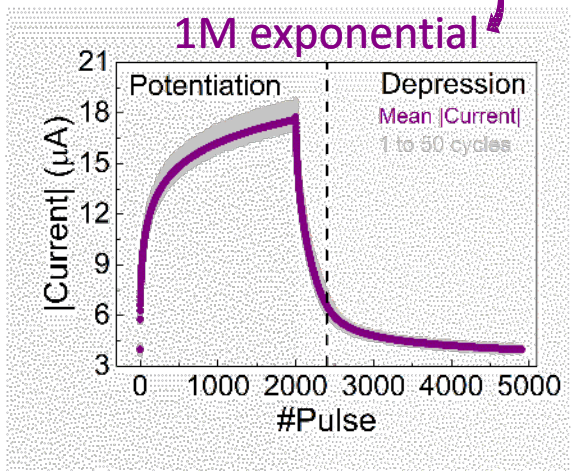
Pattern recognition applications: CrossSIM simulation

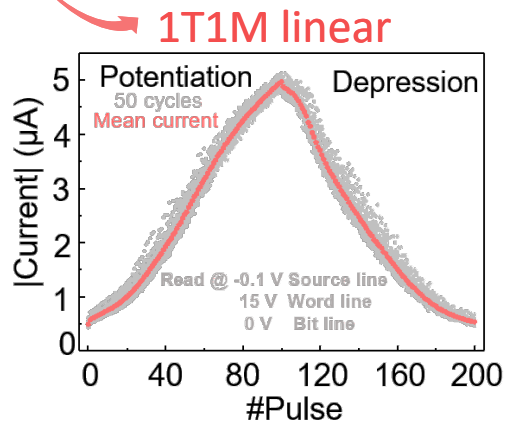
- Deep neural networks for pattern recognition of the **MNIST Handwritten Digits** with original data of 28x28 pixels
- Network architecture is multilayer perceptron (MLP) with structure 784x30x10
- Training algorithm is Gradient Descent
- The impact of non-linearity, asymmetry, C2C variability and noise can be accurately considered in CrossSim.







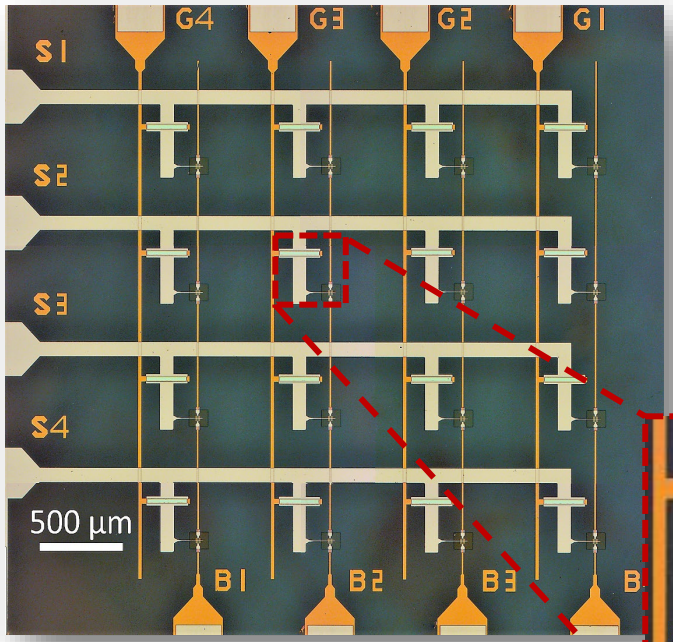


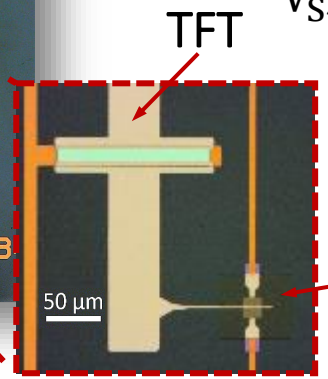


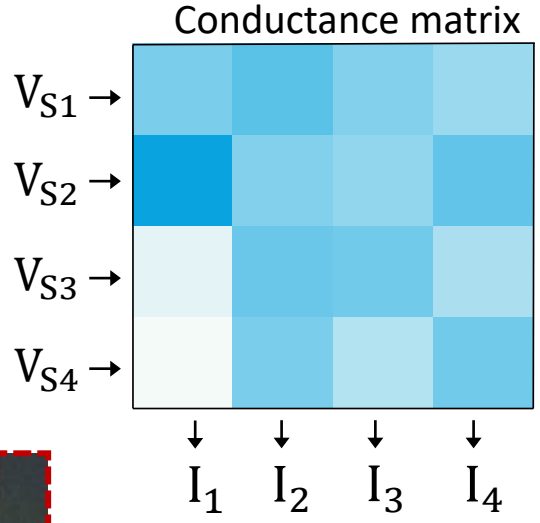
APL Mater. 10, 011113 (2022)

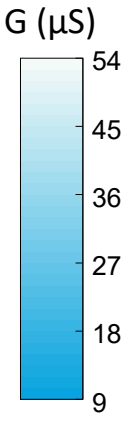
Adv. Electron. Mater., p. 2200642, 2022.

Vector-matrix multiplications





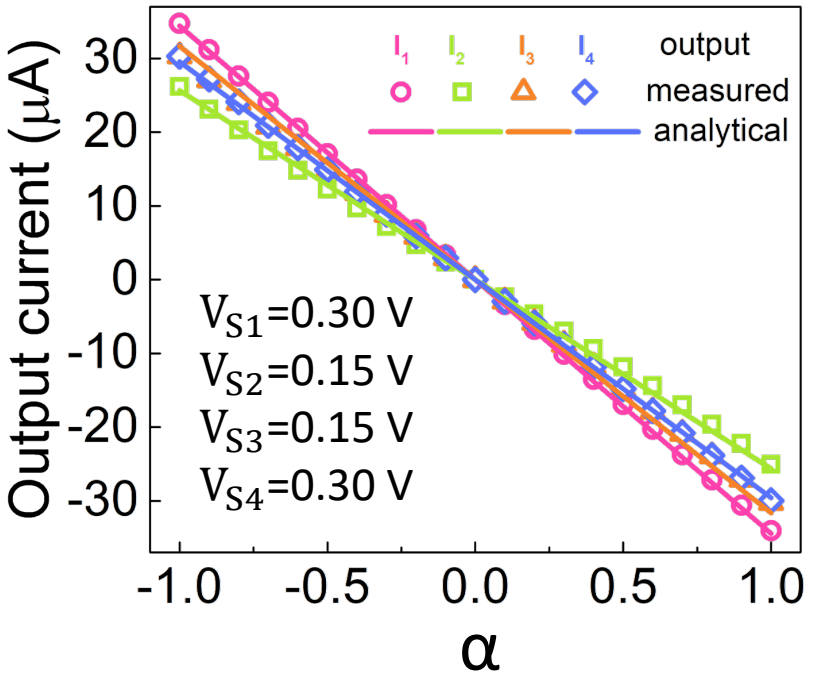




$$\alpha \begin{bmatrix} V_{S1} \\ V_{S2} \\ V_{S3} \\ V_{S4} \end{bmatrix} \times \begin{bmatrix} G_{1,1} & G_{1,2} & G_{1,3} & G_{1,4} \\ G_{2,1} & G_{2,2} & G_{2,3} & G_{2,4} \\ G_{3,1} & G_{3,2} & G_{3,3} & G_{3,4} \\ G_{4,1} & G_{4,2} & G_{4,3} & G_{4,4} \end{bmatrix}$$

$$= (V_{S1}G_{1,1} + V_{S2}G_{2,1} + V_{S3}G_{3,1} + V_{S4}G_{4,1}) + (\ldots) + (\ldots) + (\ldots)$$

$$= [I_1 \quad I_2 \quad I_3 \quad I_4]$$



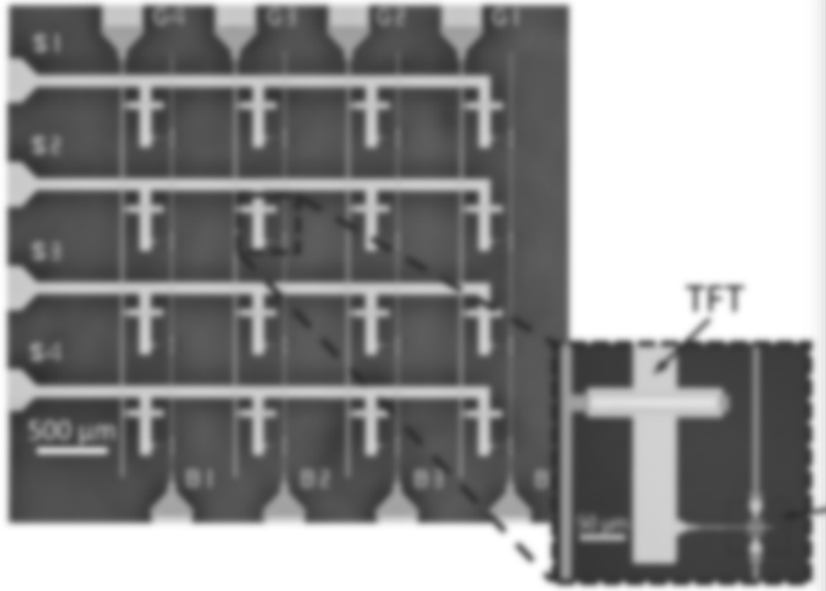
Active crossbars

✓ 1T1M **solves the sneak-path currents** effect.

Adv. Electron. Mater., p. 2200642, 2022.

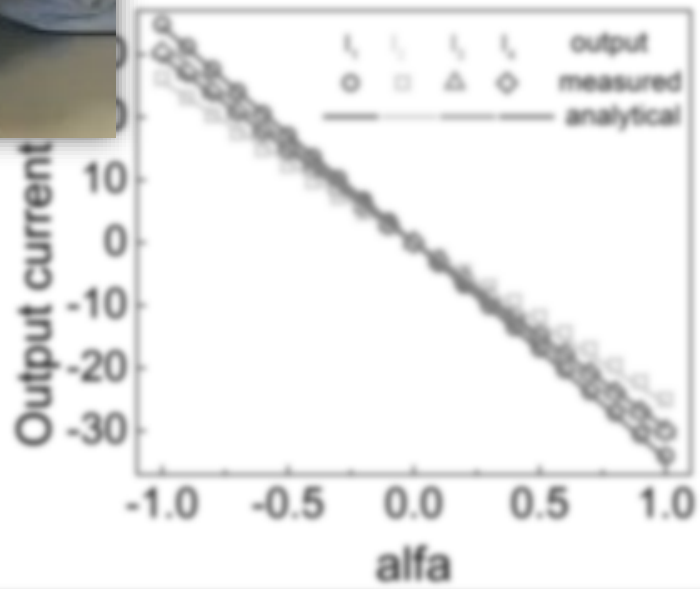
Flexible active crossbars

M.E. Pereira et al., "Flexible active crossbar arrays using amorphous oxide semiconductor technology towards artificial neural networks hardware", submitted to npj Flexible Electronics, 2022.



$$\begin{bmatrix} V_{S1} \\ V_{S2} \\ V_{S3} \\ V_{S4} \end{bmatrix} \times \begin{bmatrix} G_{1,1} & G_{1,2} & G_{1,3} & G_{1,4} \\ G_{2,1} & G_{2,2} & G_{2,3} & G_{2,4} \\ G_{3,1} & G_{3,2} & G_{3,3} & G_{3,4} \\ G_{4,1} & G_{4,2} & G_{4,3} & G_{4,4} \end{bmatrix}$$

$$= [I_1 \quad I_2 \quad I_3 \quad I_4]$$

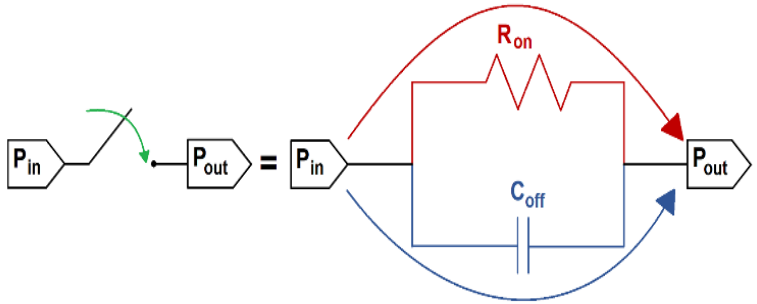


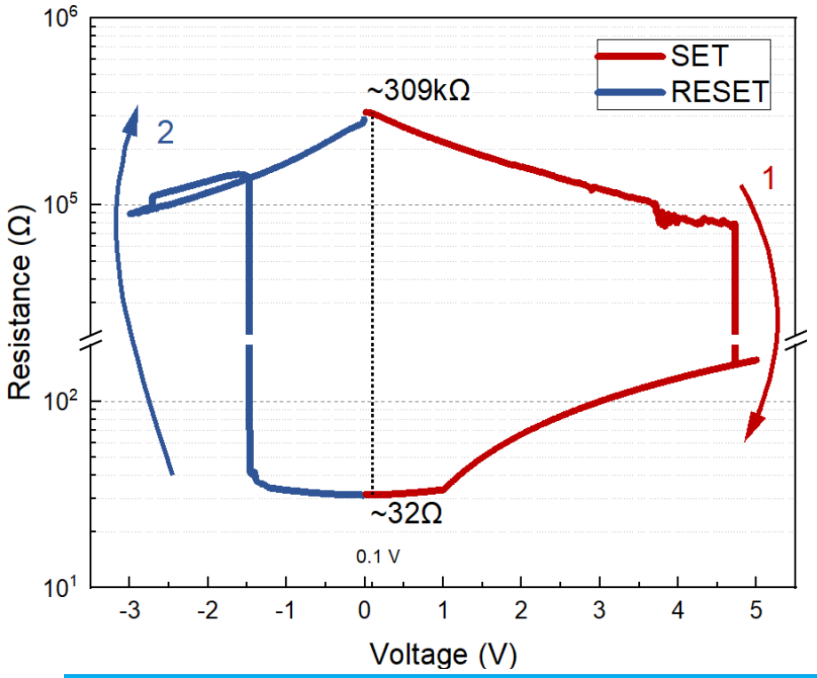
Flexible artificial neural network

✓ Flexible! Built on a polyimide substrate.

Memristive RF switch in 6G technology

Conventional switches (diode, transistor) are volatile, dissipate both dynamic (switching event) and static energy (required hold voltage).

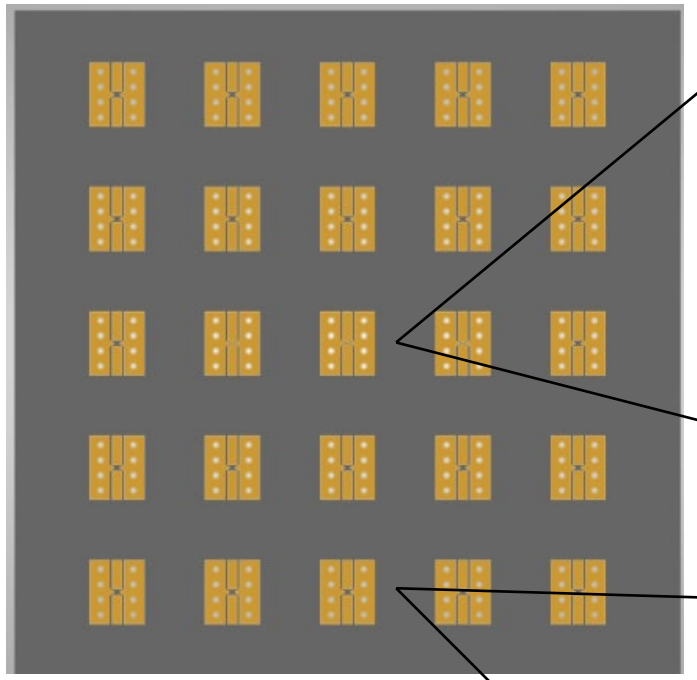


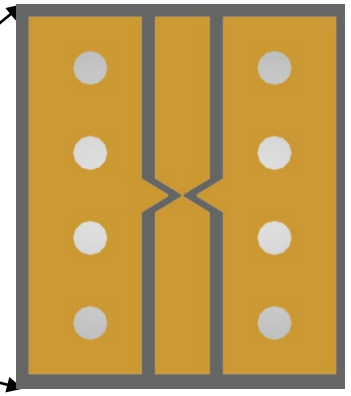


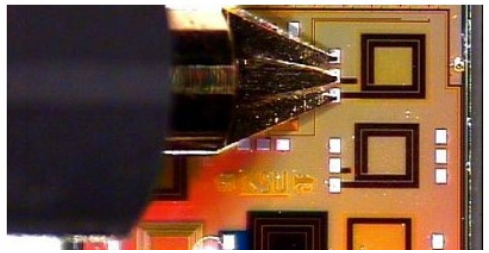
$$F = 1/2\pi R_{LRS} C_{HRS}$$

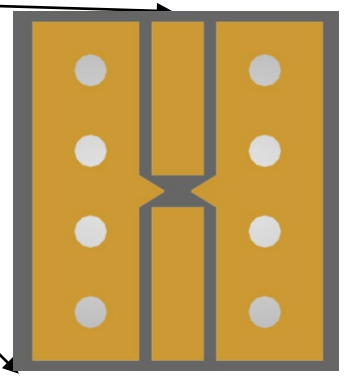
R_{LRS} <<50 Ω Insertion loss

C_{HRS}~20 fF/µm² Isolation





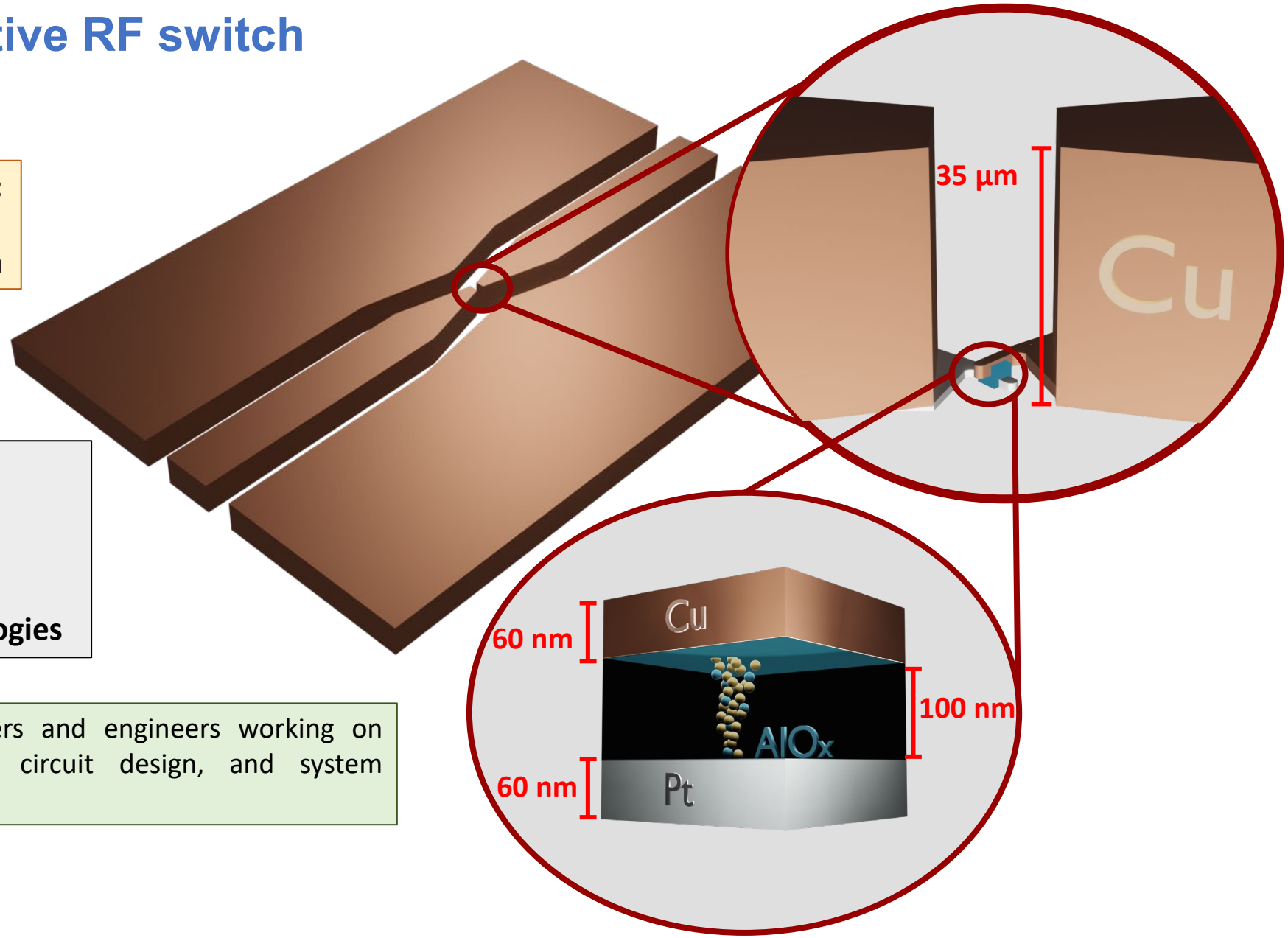




Challenges of memristive RF switch

2D material & Conductive bridge RAM:

Electrochemical conduction mechanism



- **Non-idealities**
- **Temperature sensitivity**
- **Endurance and reliability**
- **Cost-effective fabrication**
- **Integration with existing technologies**

✓ collaborative efforts from researchers and engineers working on materials science, device physics, circuit design, and system integration.

Thank You

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CENIMAT/ i3N

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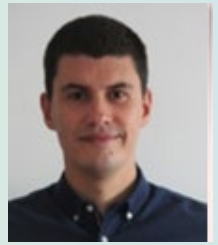
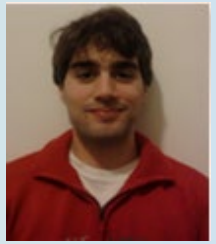
Dr. Jonas Deuermeier

Prof. Pedro Barquinha



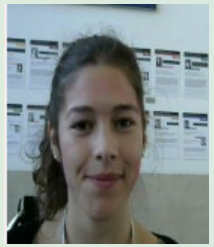
Dr. Emanuel Carlos



Dr. Jorge Martin

Dr. Adam Kelly

Carlos Silva

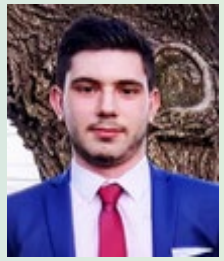


Raquel Martins

Miguel Franco

Tomas Mintages

Maria Pereira



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